Lessons 13 and 14

The third generation (BAIKAL, AMANDA, ANTARES, IceCube, KM3NeT…)

- Physics goals
- Detection technique
- Properties of the Cherenkov medium (water, ice)
- Tracks and event reconstruction

Evaluation of neutrino fluxes adopting the “hadronic model” for known point-like high energy gamma sources

Motivations for present H.E. neutrino astrophysics

The U.H.E. Cosmic Rays (>10^{19} eV) require an explanation:

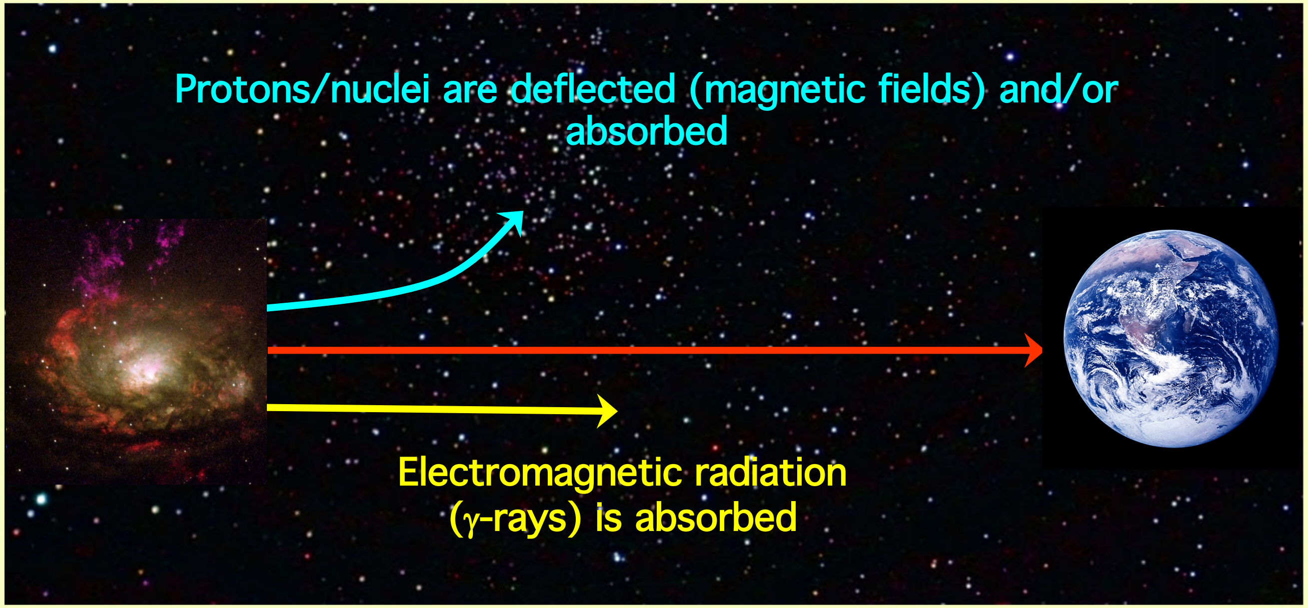
- **are they proton ? → then they should be "galactic"! → where is their source ?**
- **are they extragalactic protons ? where is their source ? → what about GZK ?**
- **are they heavier nuclei ? where is their source ?**

Confirmed gamma-ray sources still need to be understood. Do they accelerate hadrons or electrons ? These sources will be the first target of neutrino telescopes observations:

- search for neutrinos from point-like sources (list of known gamma-ray emitters, steady or transient). Measured γ-fluxes allow to evaluate the expected amount of ν events
- search for neutrinos from Fermi Bubbles and from the Galactic Plane;

-…

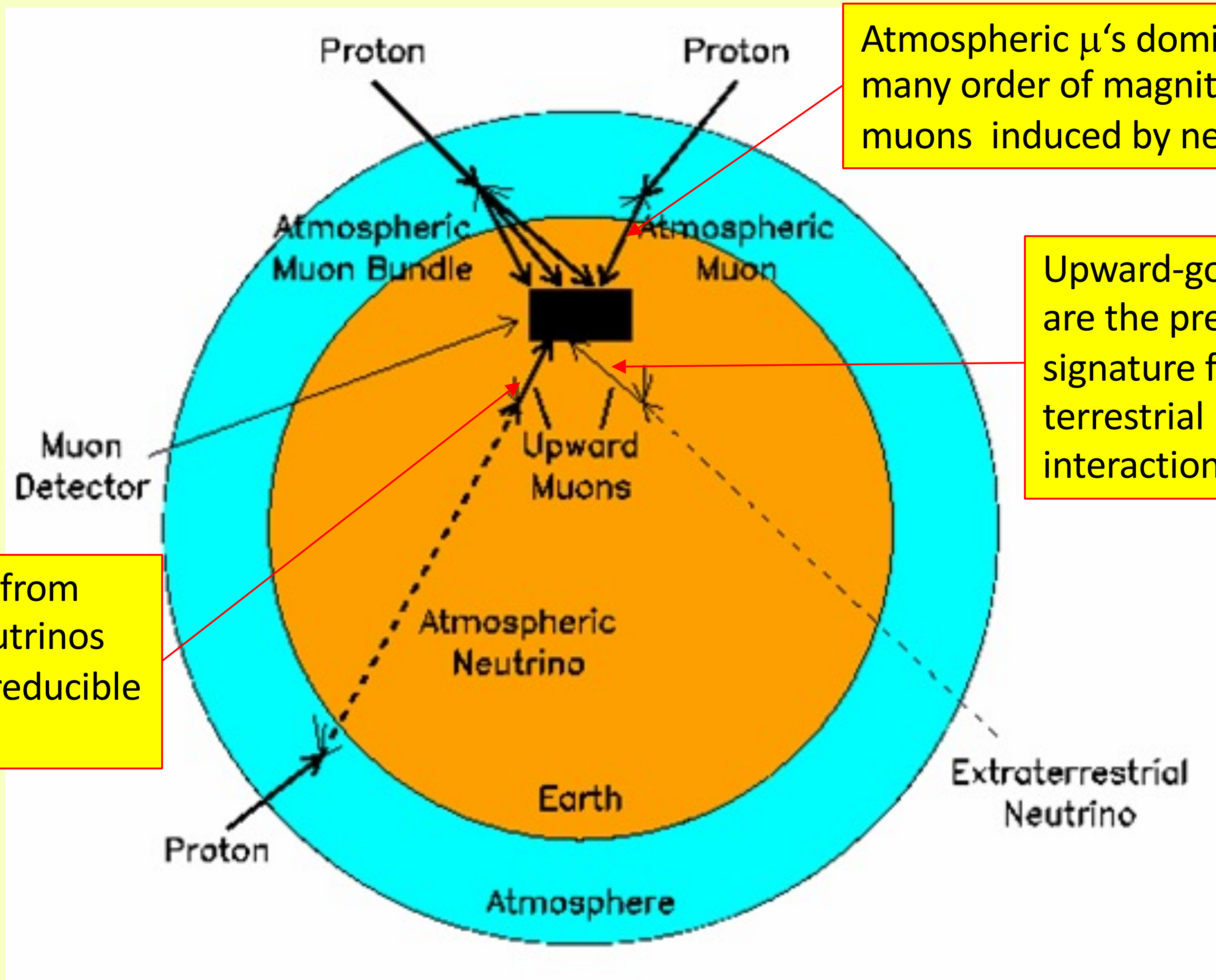
but let's not forget that neutrinos offer the unique possibility to "look" further away and deeper inside astrophysical objects revealing so far "hidden sources". **The horizon for a Neutrino Telescope is wider.**



Neutrino Telescopes: signal and background - 1

Atmospheric μ's dominate by many order of magnitude the muons induced by neutrinos

Upward-going particles are the preferred signature for extra-terrestrial neutrino interactions

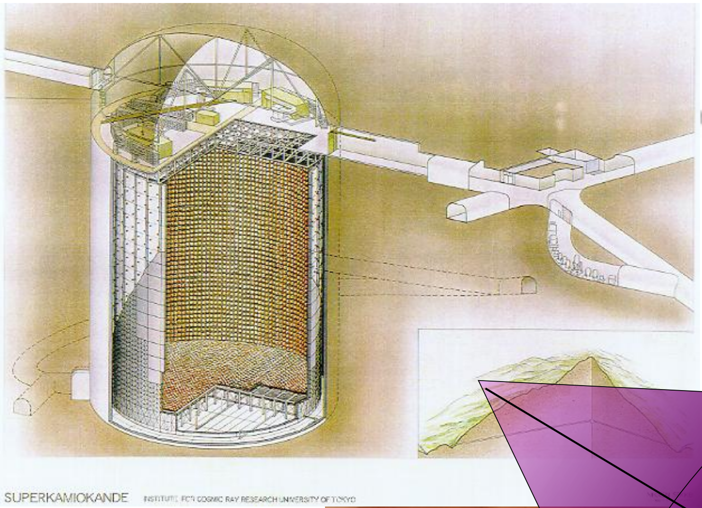


Upgoing muons from atmospheric neutrinos represent the irreducible background

Detecting neutrinos in H_2O

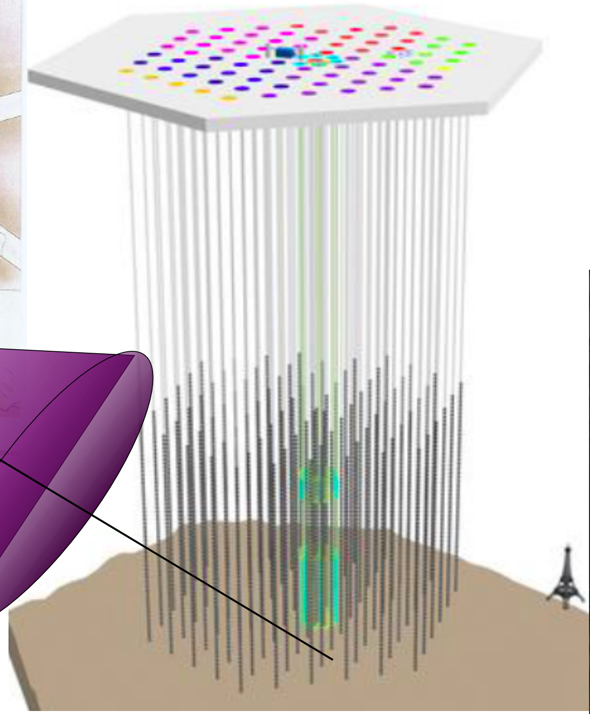
Proposed by Greisen, Reines, Markov in 1960

- DUMAND
- IMB
- Kamiokande
- Baikal
- AMANDA

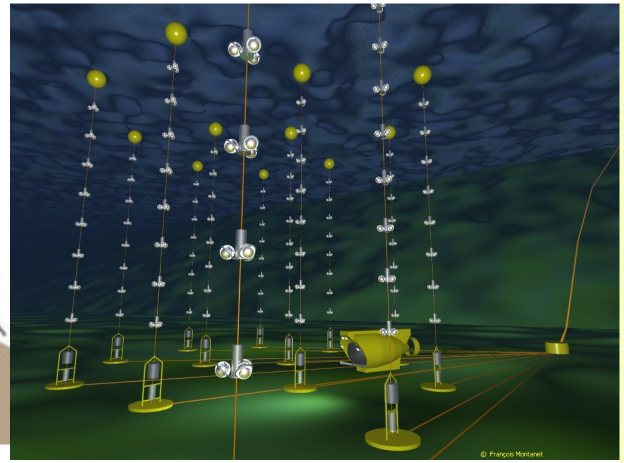


Super-K

SNO



IceCube



ANTARES

Neutrino must interact to be detected

Light propagation in water

In a transparent medium the light propagation is limited by absorption (the photon disappears)

$$I(x) = I_o\, e^{-ax}$$

$$L_a = 1/a$$

by diffusion (the photon changes direction),

$$I(x) = I_o\, e^{-bx}$$

$$L_b = 1/b$$

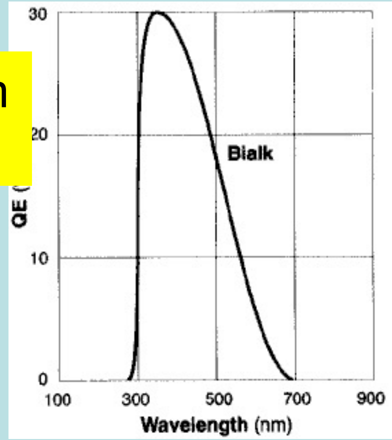
by attenuation

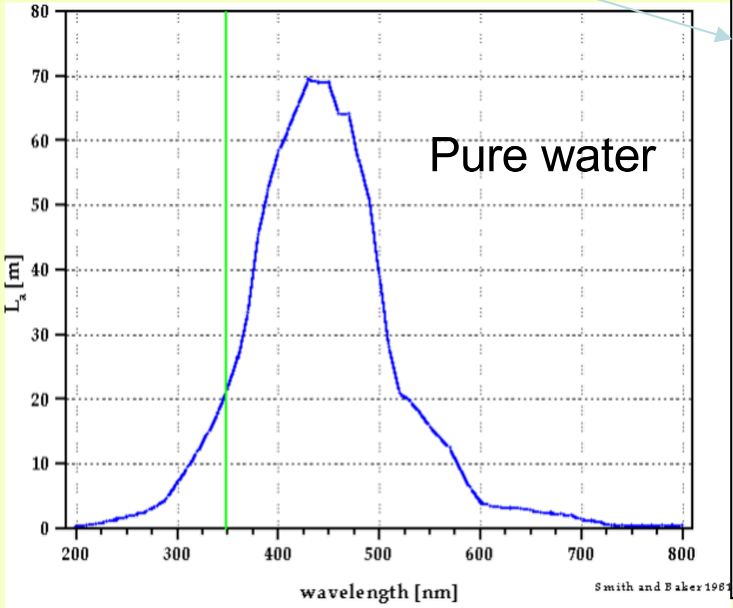
$$c = a + b$$

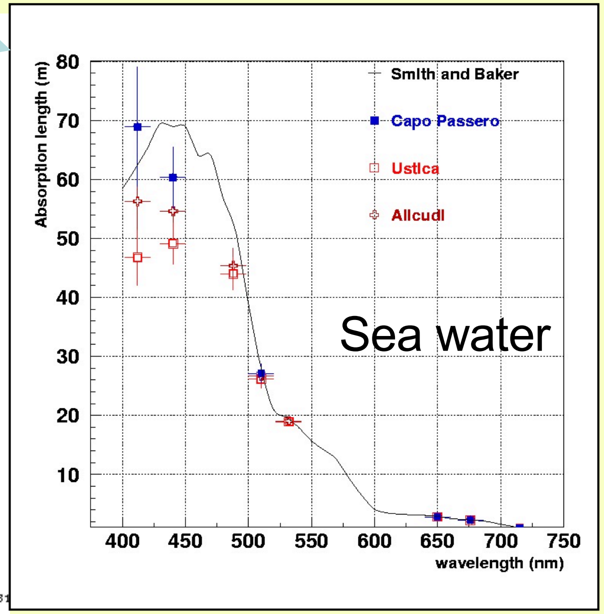
$$I(x) = I_o\, e^{-cx}$$

$$L_c = 1/c$$

PMT quantum efficiency



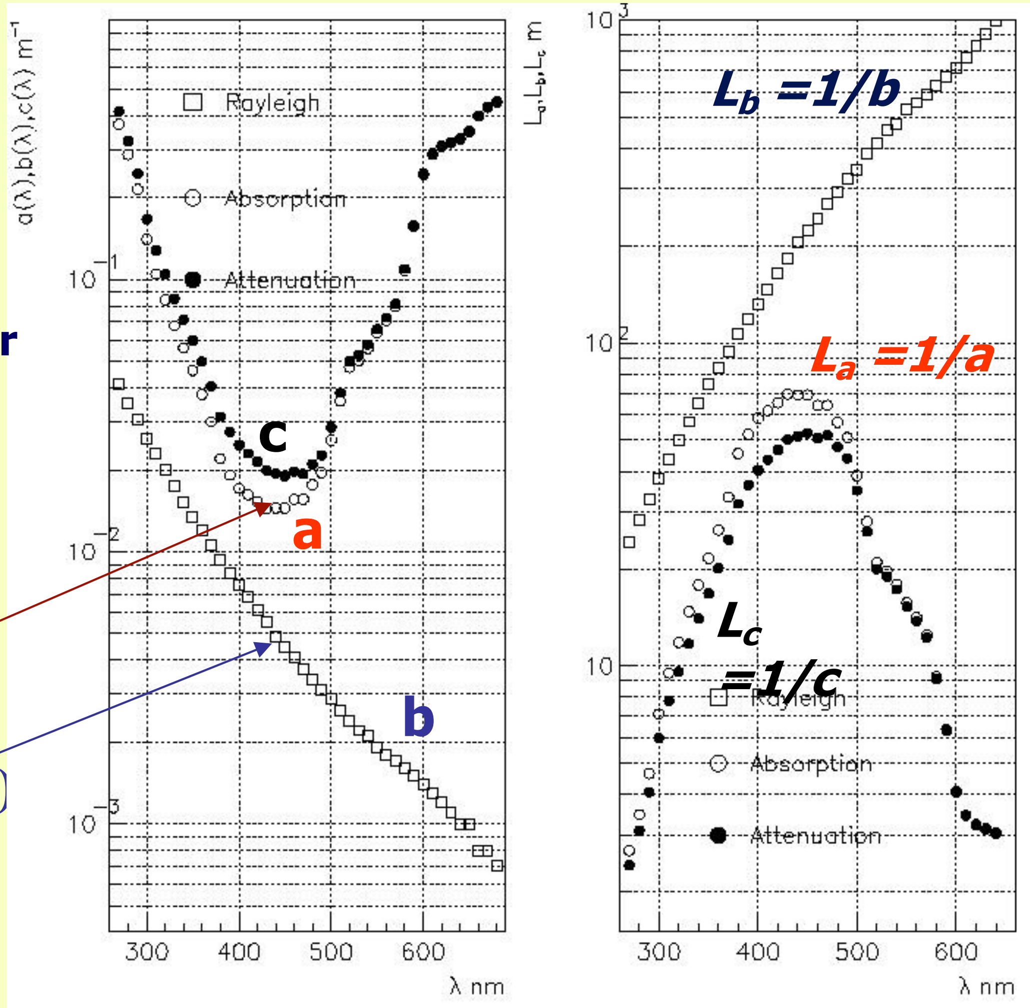




Pure water optical properties

Blue light:

- **maximum transmission in water**
- **peak of PMT q.e.**
- **Cherenkov emission region**



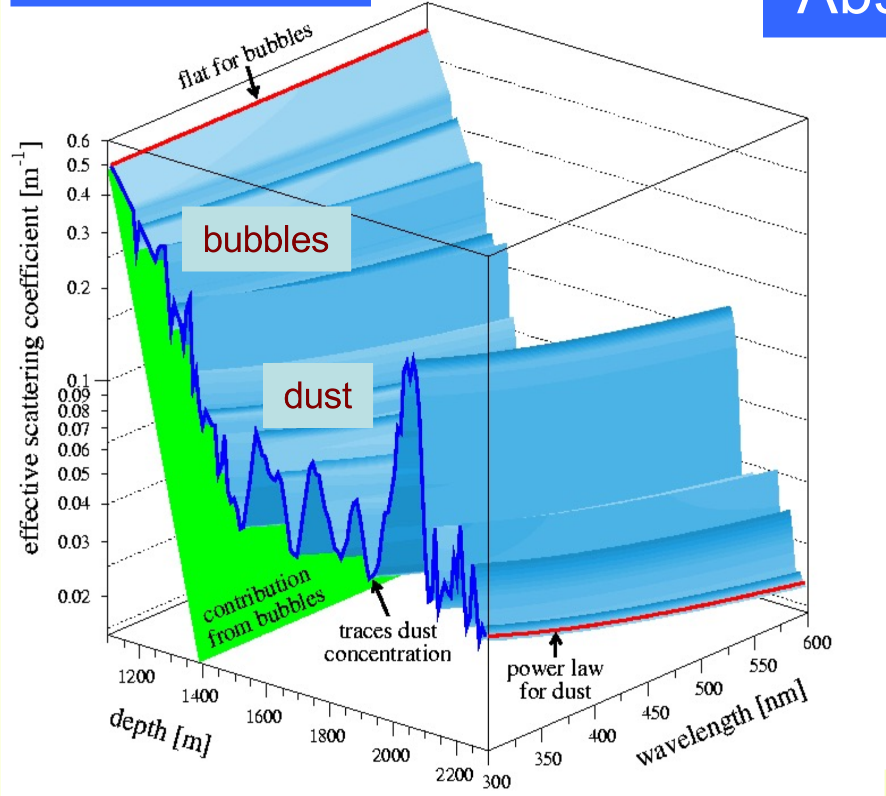
$$c(\lambda) = a(\lambda) + b_{rayleigh}(\lambda)$$

- **absorption (a)**
- **scattering (b)**
- **attenuation (c)**

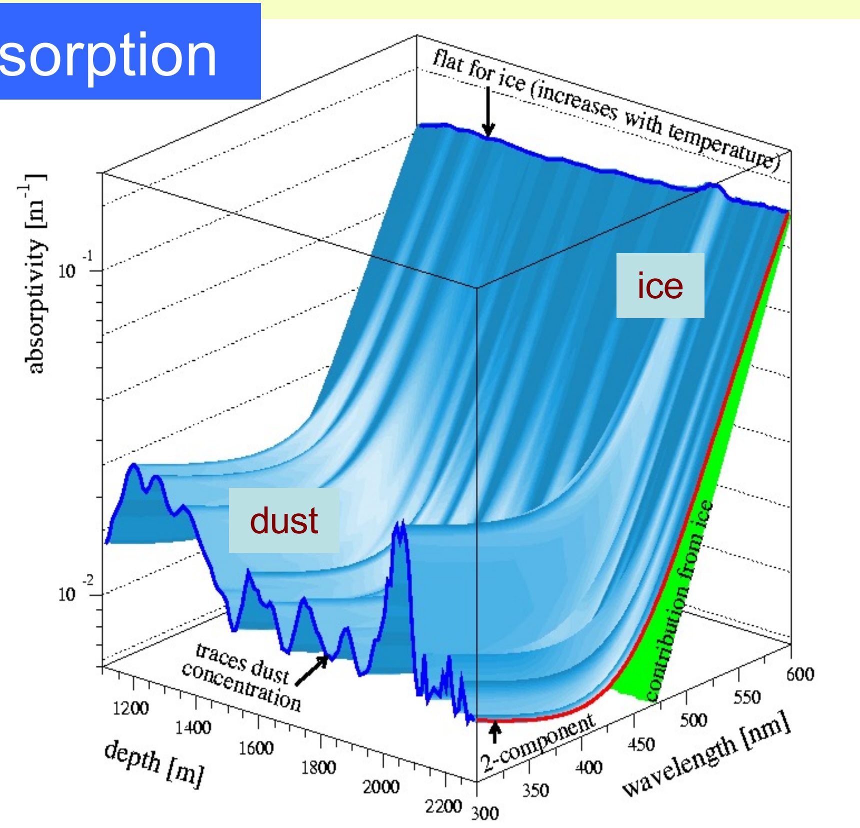
Smith & Baker (1986)

Ice (around IceCube) optical properties

Scattering



Absorption



Measurements:

- in-situ light sources
- atmospheric muons

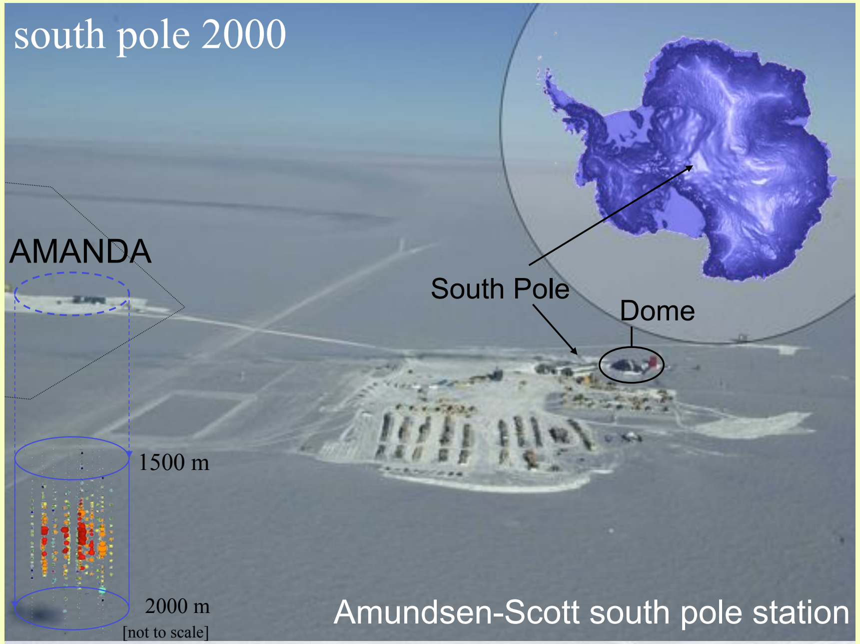
Average optical ice parameters:

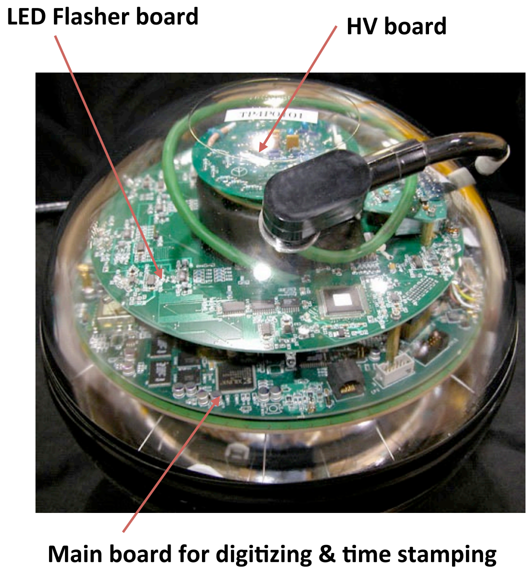
λ_{abs} ~ 110 m @ 400 nm

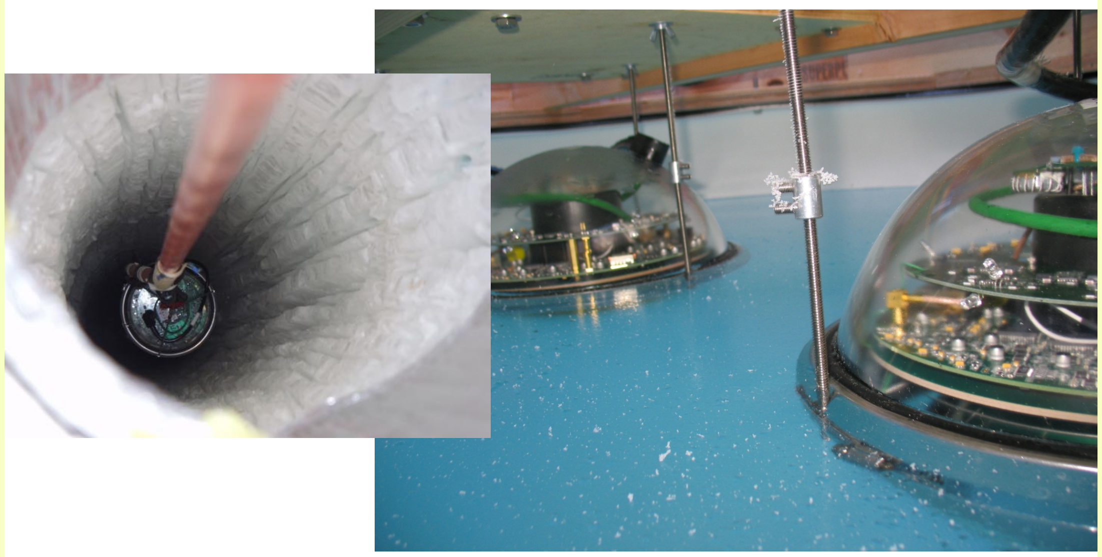
λ_{sca} ~ 20 m @ 400 nm

λ_{prop} ~ 27 m @ 400 nm

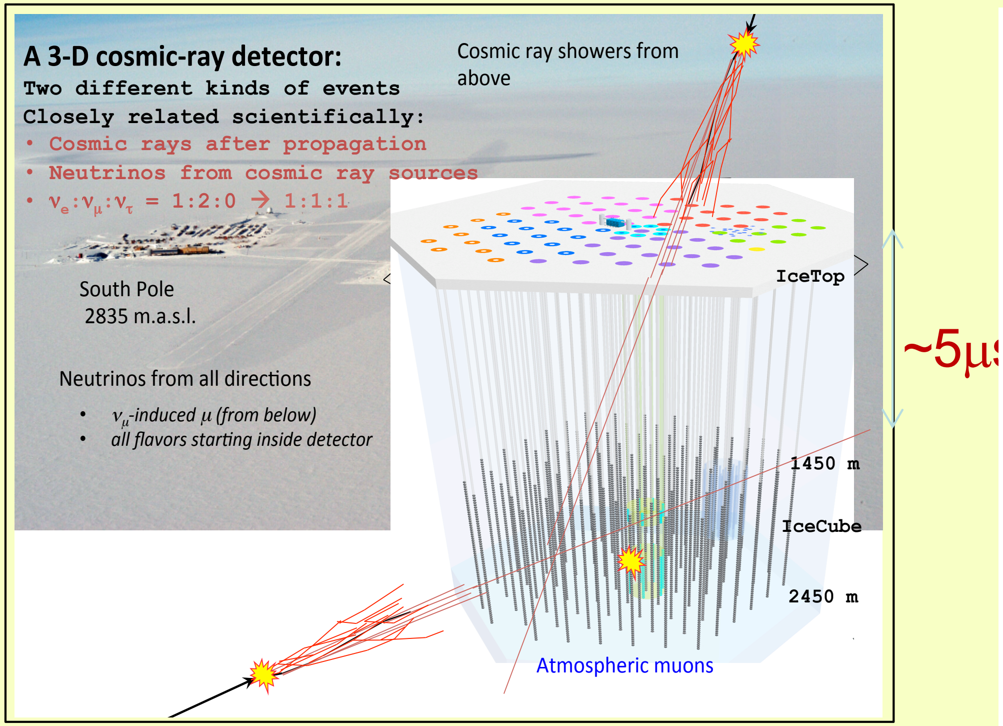
IceCube location and optical modules

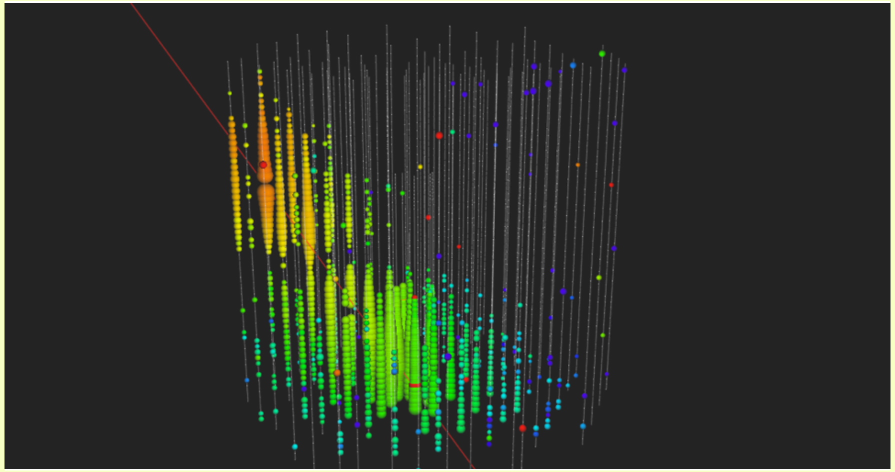


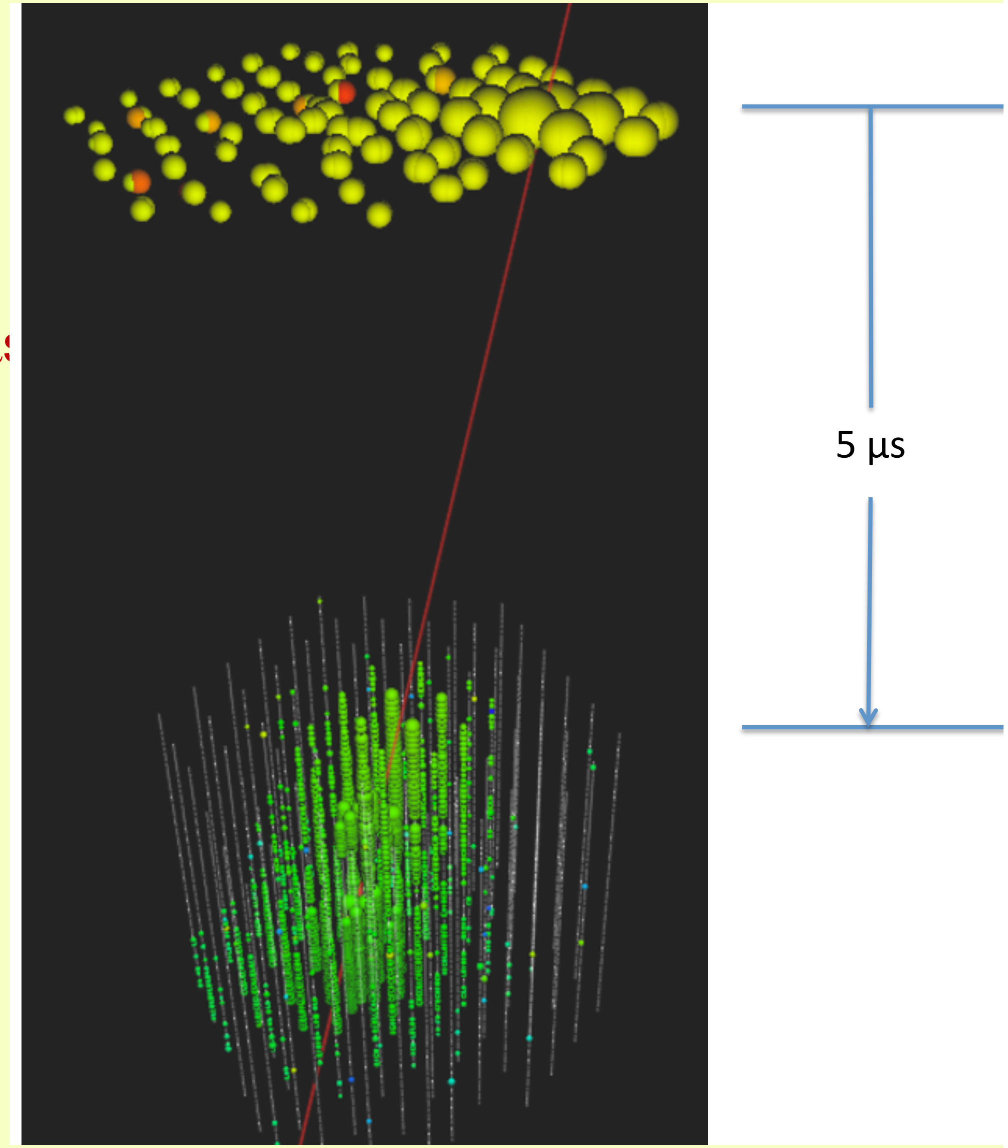




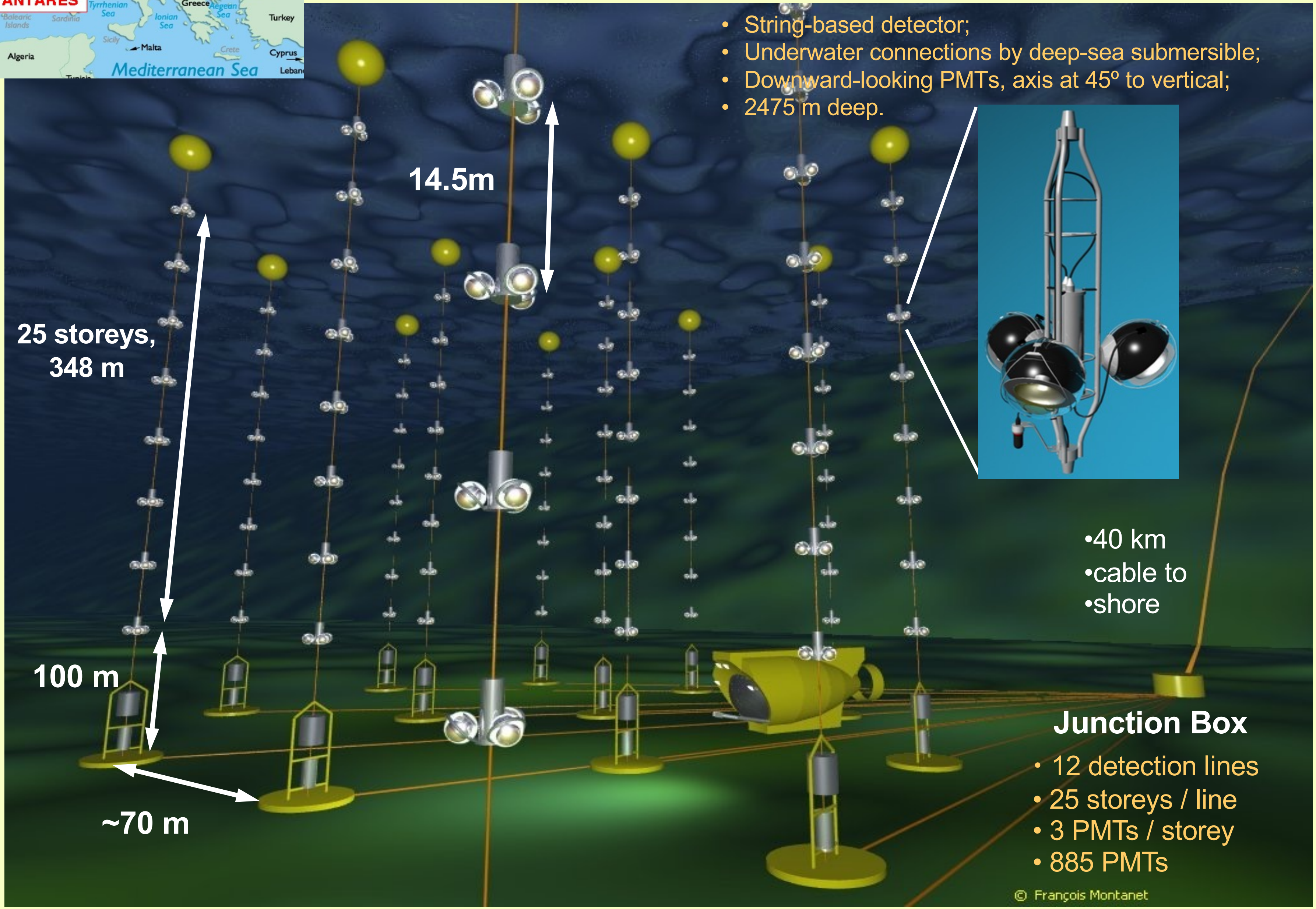
IceCube and IceTop @ South Pole



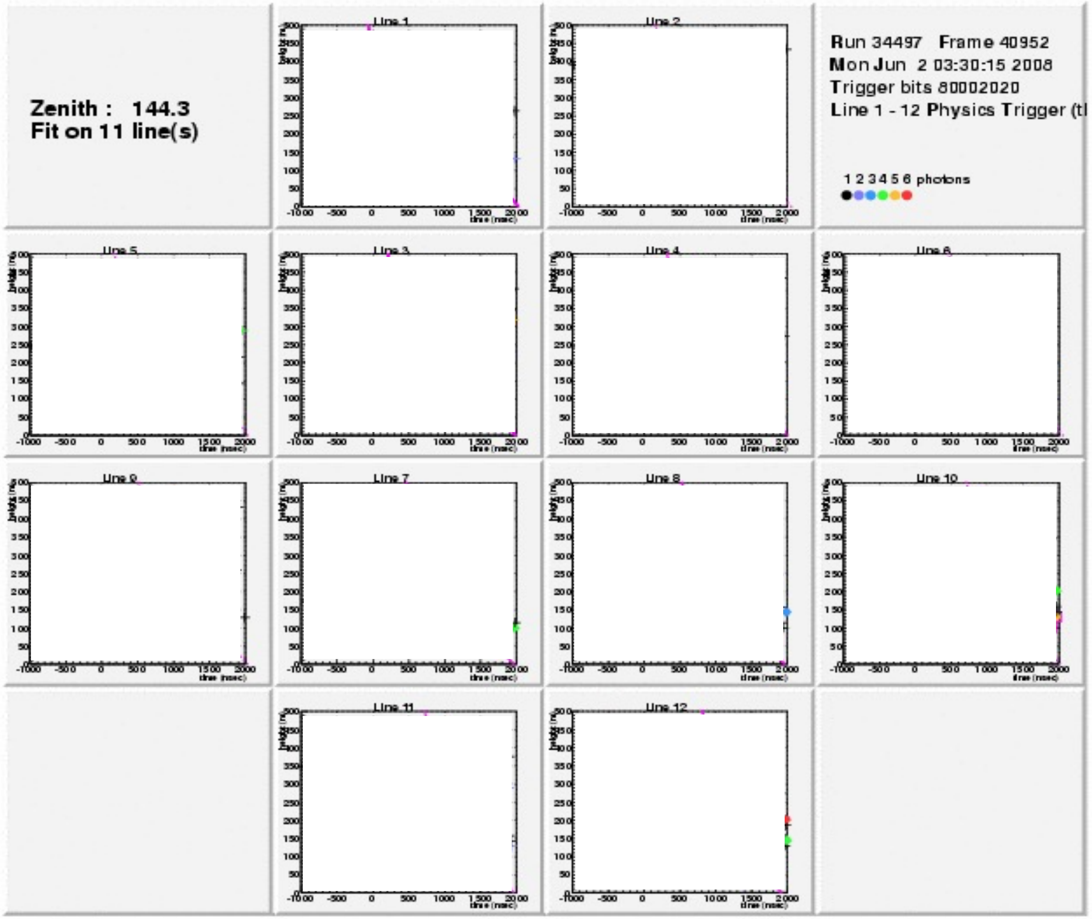




The ANTARES experiment

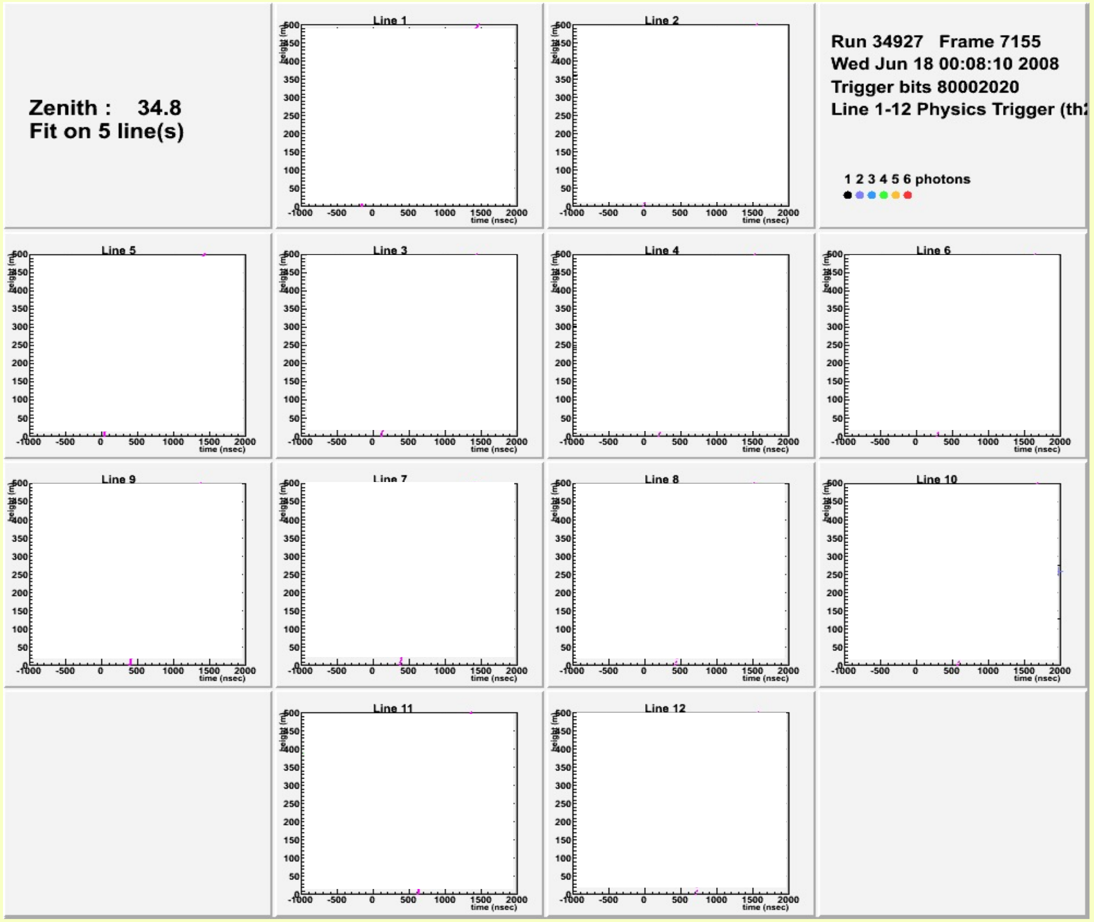


(multi-) muon Event

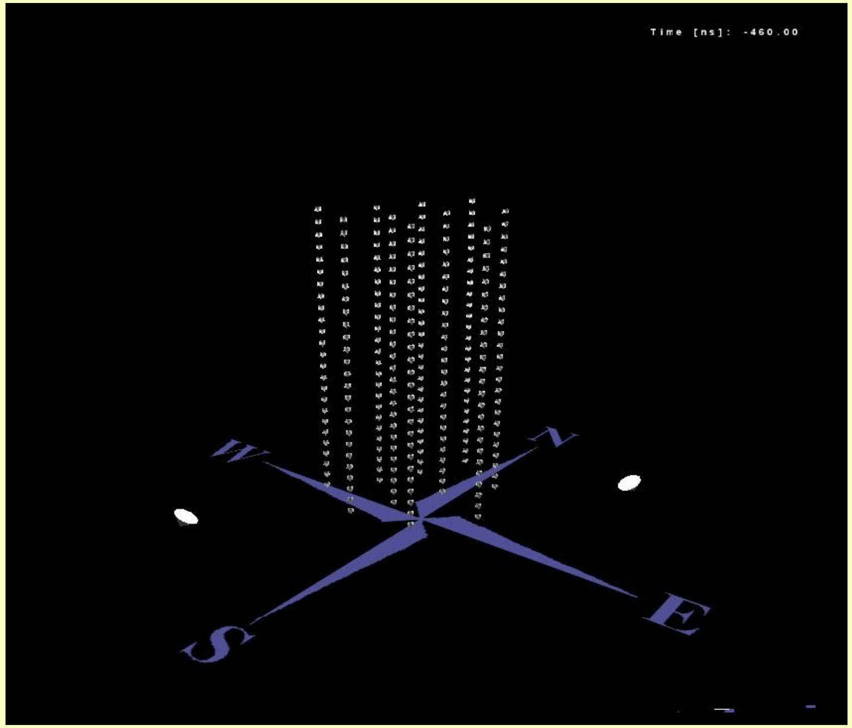


Example of a reconstructed down-going muon, detected in all 12 detector lines:

Up-going track: a neutrino candidate



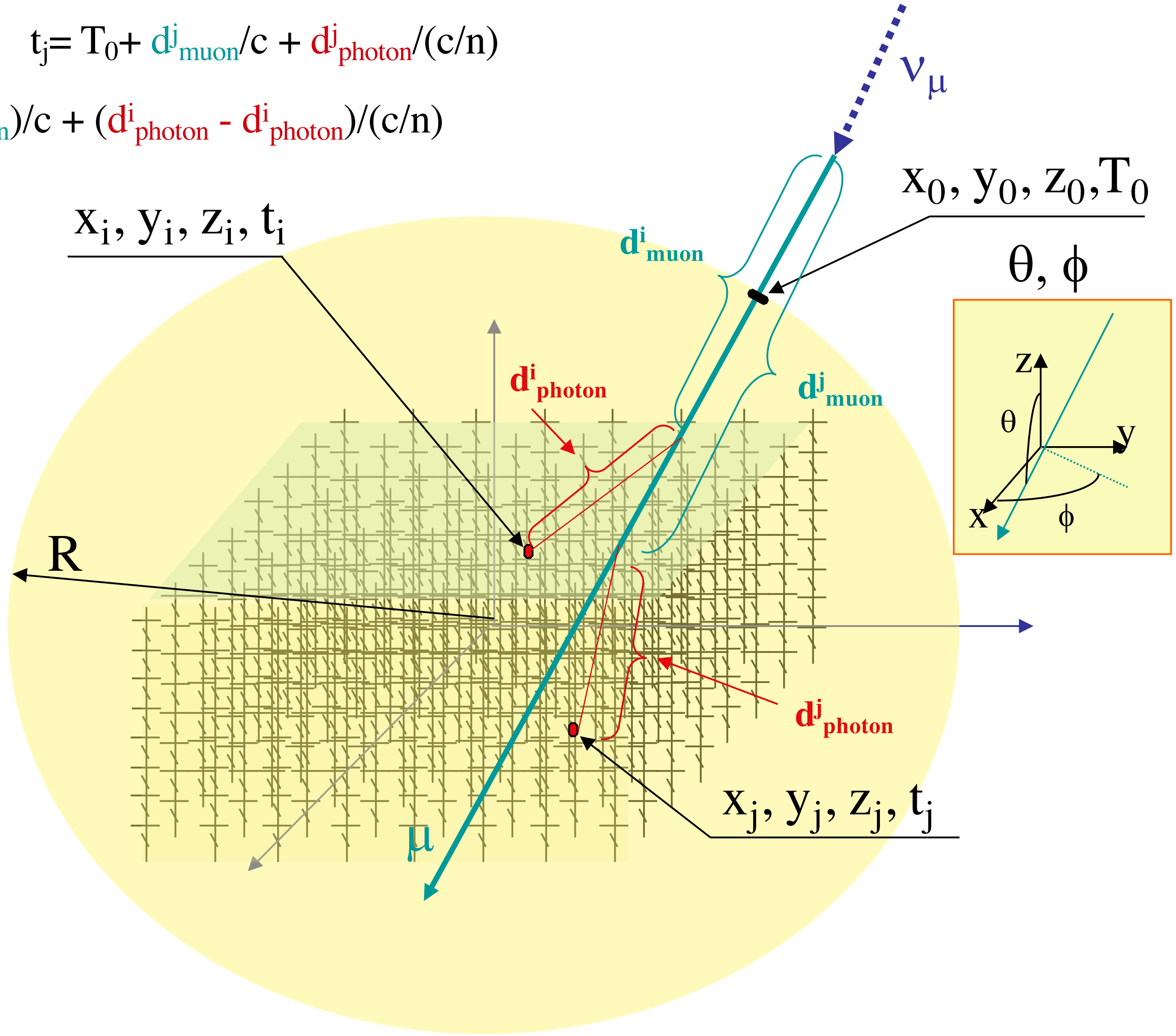
Example of a ***reconstructed up-going muon*** ***(i.e. a neutrino candidate) detected in 6/12 detector lines:***



A possible procedure for track reconstruction

$t_i = T_0 + d^i_{muon}/c + d^i_{photon}/(c/n)$; $t_j = T_0 + d^j_{muon}/c + d^j_{photon}/(c/n)$

$(\Delta t_{ij})^{sper} = t_i - t_j = (d^i_{muon} - d^i_{muon})/c + (d^i_{photon} - d^i_{photon})/(c/n)$



$x_\mu = X_0 + c_x * s$
$y_\mu = Y_0 + c_y * s$
$z_\mu = Z_0 + c_z * s$
s = ascissa curvilinea

$c_x = \sin(\theta)*\cos(\phi)$
$c_y = \sin(\theta)*\sin(\phi)$
$c_z = \cos(\theta)$

Procedimento di Fit-1

-ai PMT dell'evento si sommano PMT dovuti a ^{40}K

-si selezionano PMT che soddisfano le condizioni di essere *"segnali"* e la causalità

-fissato un set di valori di $X_0, Y_0, Z_0, T_0, \theta, \phi$ si calcola, per ogni PMT con segnali, il tempo di arrivo del fotone sul PMT

- si cerca il valore di s che corrisponde alla minima distanza fra il muone ed il PMT

$$s_{min} = (X_{PMT}-X_0)*c_x + (Y_{PMT}-Y_0)*c_y + (Z_{PMT}-Z_0)*c_z$$

-ciò permette di calcolare:

il punto sulla traccia del muone che corrisponde alla minima distanza:

$$x_\mu = X_0 + c_x * s_{min} ; \quad y_\mu = Y_0 + c_y * s_{min} ; \quad z_\mu = Z_0 + c_z * s_{min}$$

la minima distanza del PMT dalla traccia:

$$\Delta_{\mu PMT} = \{(X_{PMT}-x_\mu)^2 + (Y_{PMT}-y_\mu)^2 + (Z_{PMT}-z_\mu)^2\}^{0.5}$$

il percorso del fotone:

$$d^i_{photon} = \Delta_{\mu PMT} / \sin(\theta_{Cherenkov})$$

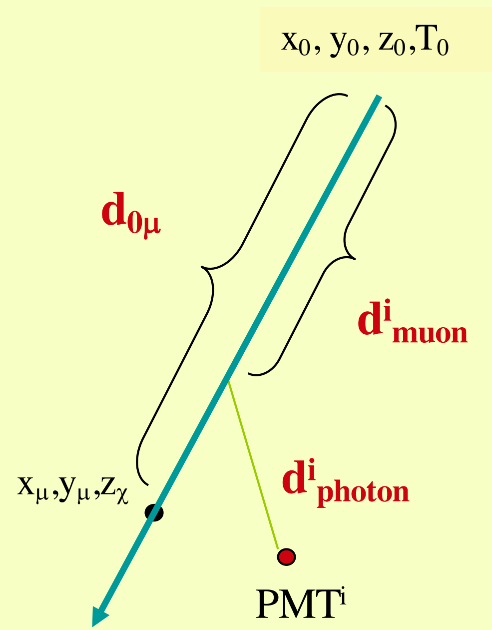
il percorso del muone fino al punto in cui il fotone è stato emesso:

$$d_{0\mu} = \{(X_0 - x_\mu)^2 + (Y_0 - y_\mu)^2 + (Z_0 - z_\mu)^2\}^{0.5}$$

$$d^i_{muon} = d_{0\mu} \quad \Delta_{\mu PMT} / tg(\theta_{Cherenkov})$$

e quindi il tempo di arrivo del fotone sul PMT

$$t_i = T_0 + d^i_{muon} / c + d^i_{photon}/(c/n)$$



Procedimento di Fit-2

Prendendo come riferimento ad esempio il "primo" *"segnale"* dell'evento --> t_1 per ogni PMT con segnale possiamo definire le quantità

$$(\Delta t_{i1})^{sper} = t_i^{sper} - t_1^{sper} \quad \text{e} \quad (\Delta t_{i1})^{teor} = t_i^{teor} - t_1^{teor}$$

$(\Delta t_{i1})^{teor}$ funzione dei parametri $X_0, Y_0, Z_0, \theta, \phi$ o meglio di $X_0, Y_0, Z_0, c_x, c_y, c_z$

Con fit basato su MINUIT si sceglie il set di valori $\tilde{X}_0, \tilde{Y}_0, \tilde{Z}_0, \tilde{T}_0, \tilde{\theta}, \tilde{\phi}$

che minimizza $$\sum \left[\frac{(\Delta t_{i1})^{teor} - (\Delta t_{i1})^{sper}}{\sigma_{i1}} \right]^2$$

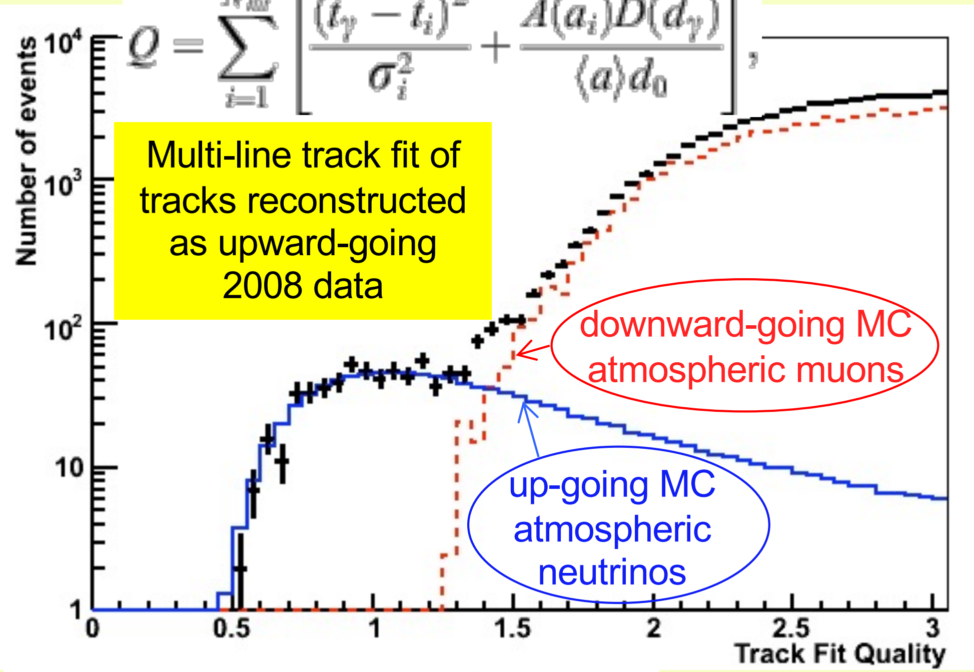
La procedura di fit inizia fornendo a MINUIT i valori di θ e ϕ ottenuti dal "prefit" ed imponendo alla retta così defnita di passare per un punto che corrisponde al "baricentro" di tutti i PMT che hanno superato il "filtro"

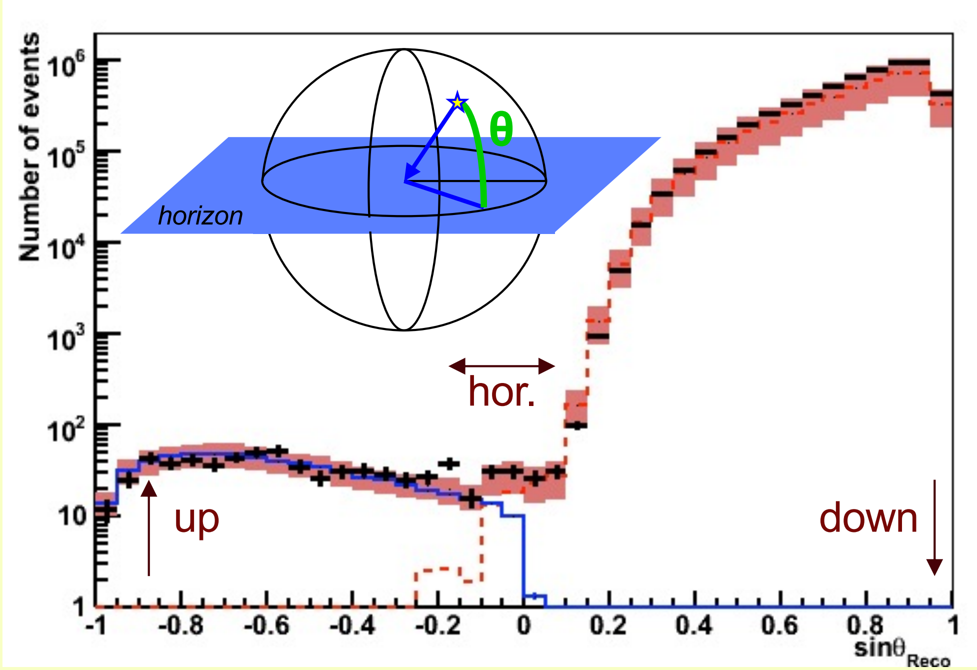
Le condizioni $\mathbf{c_x^2 + c_y^2 + c_z^2 = 1}$ e $\mathbf{X_0^2 + Y_0^2 + Z_0^2 = R^2}$ non vengono "imposte" prima del fit. Il fit viene effettuato sulle 6 variabili in modo da far lavorare MINUIT in uno spazio dei parametri quanto più "lineare"
Costringo il "fit" a restare nella regione fisica dei parametri aggiungendo un contributo al χ^2 quando $c_x^2 + c_y^2 + c_z^2 \neq 1$ o quando $X_0^2 + Y_0^2 + \neq R^2$

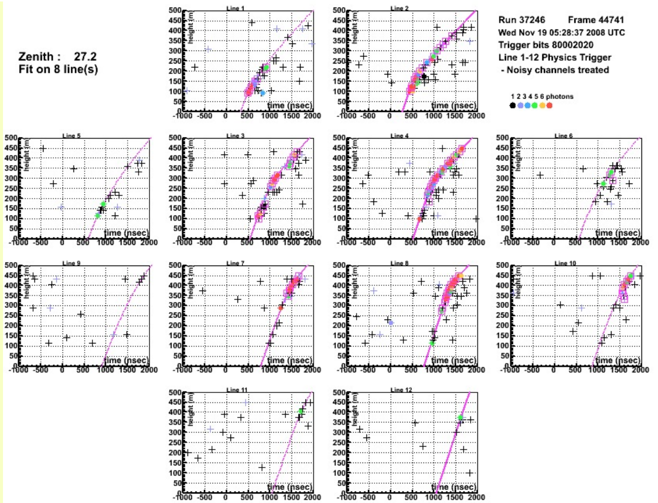
Reconstructing the muon track direction: χ^2 strategy

Track reconstruction based on χ^2 fit of the photon arrival times on fired PMTs

$$Q = \sum_{i=1}^{N_{hit}} \left[\frac{(t_\gamma - t_i)^2}{\sigma_i^2} + \frac{A(a_i)D(d_\gamma)}{\langle a \rangle d_0} \right],$$







Elevation angle distribution for events with Q<1.4
Data points are compared with the MonteCarlo predictions for atmospheric down-going muons and up-going neutrinos

A Fast Algorithm for Muon Track Reconstruction and its Application to the ANTARES Neutrino Telescope, Astroparticle Physics **34, Issue 9,** (2011) 652-662

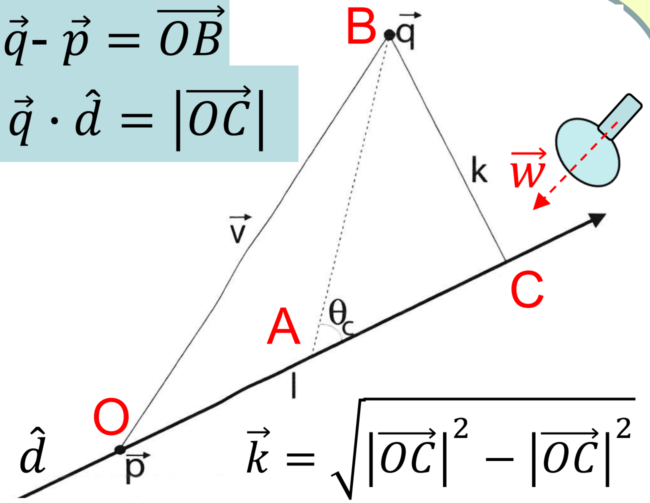
Reconstructing the muon track: Max. Likelihood strategy - 1

Maximization of a Likelihood function based on the knowledge of the probability density functions that a Cherenkov photon can reach the PMT_k, in position $\vec{q} = (x_k, y_k, z_k)$ at the time t_k^{sper} if originated by a track defined by the direction $\vec{d} = (d_x, d_y, d_z)$ and by the position of the muon at a time t_0: $\vec{p} = (p_x, p_y, p_z)$.

In the definition of the "hit probability density function" enter the knowledge of the Cherenkov emission (the ϑ_{Ch}), the absorption and diffusion of the light in water, the contribution background light (due to ^{40}K and/or to bioluminescence). The direction can be parameterised in terms of the azimuth and zenith angles θ and ϕ: $\vec{d}$=(sinθcosϕ, sinθsinϕ, cosθ).

$$\vec{v} = \vec{q} - \vec{p} = \overrightarrow{OB}$$

$$|\vec{l}| = \vec{q} \cdot \hat{d} = |\overrightarrow{OC}|$$



$$\vec{k} = \sqrt{|\overrightarrow{OC}|^2 - |\overrightarrow{OC}|^2}$$

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

Reconstructing the muon track: Max. Likelihood strategy - 2

The muon/neutrino direction can be parameterised in terms of the azimuth and zenith angles **θ and ϕ: $\vec{d}$=(sinθcosϕ, sinθsinϕ, cosθ).**

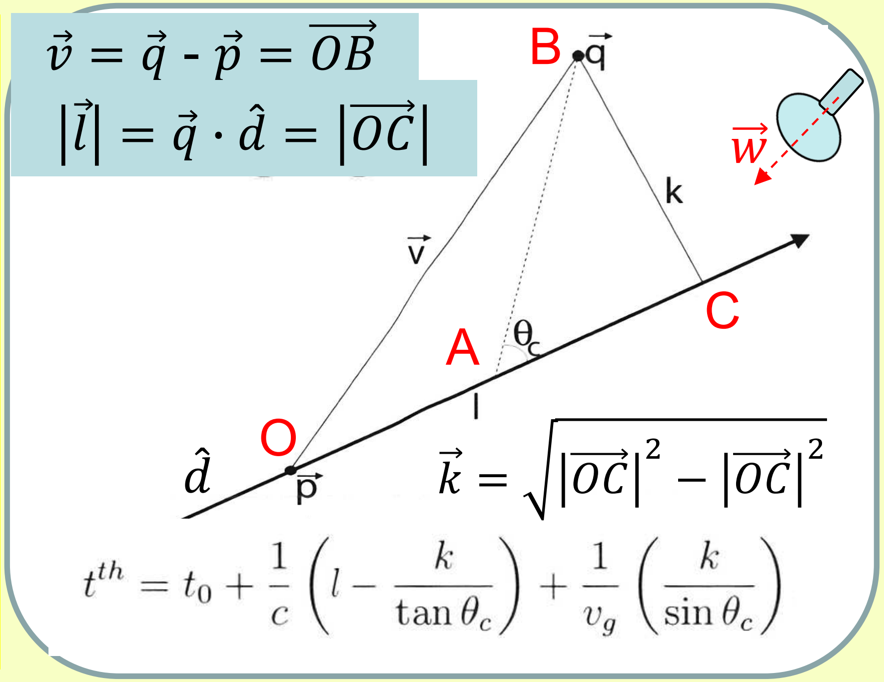
There are five independent parameters that are estimated by the reconstruction algorithm. For a given track (i.e. a given $\vec{d}$ and $\vec{p}$) the probability to obtain the observed event (hits on the "fired" OMs at positions $\vec{q}_k$ can be calculated: this probability is the likelihood of the event: $P(event|track) \equiv P(hits|\vec{p},\vec{d}) = \prod_i P(t_i^{sper}|t_i^{th}, a_i, b_i, A_i)$ where t_i^{sper} is the time of hit measured by PMT$_i$, **A_i** is the hit amplitude and, **a_i** and **b_i** are defined as

$$a = \left[\vec{v} - \vec{d}\left(l - \frac{k}{tan\theta_{Ch}}\right)\right]\cdot\vec{w} \quad ; \; b = \frac{k}{sin\theta_{Ch}}$$

where $\vec{w}$ is the pointing direction of the OM.

The Max. Likelihood estimate of the track is defined by the set of track parameters (like θ and ϕ) for which the value of the likelihood function is maxima.

In practice, the maximum of $P(event|track)$ is found by minimising $\Lambda = -\log(P(event|track))$



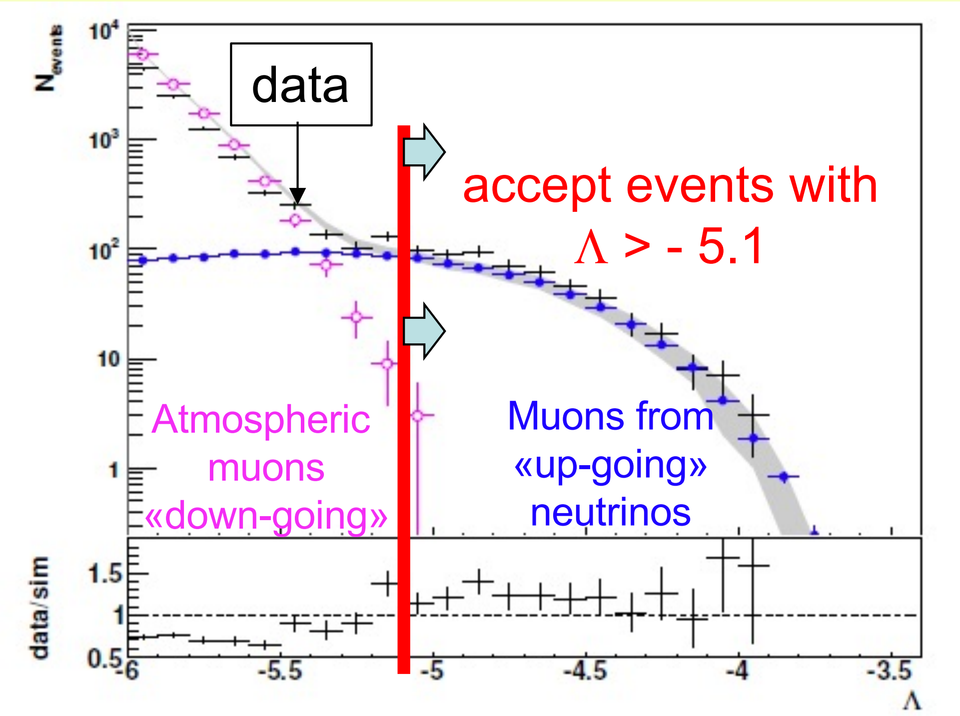
Reconstructing the muon track: Max. Likelihood strategy - 3

The probability that the track considered, with the azimuth and zenith angles ***θ* and *ϕ*** such that $\vec{d}$**=(sin*θ*cos*ϕ*, sin*θ*sin*ϕ*, cos*θ*)**, crossing the detector at a given position O(x_0, y_0, z_0) is the likelihood of the event:

$$P(event|track) \equiv P(hits|\vec{p}, \vec{d}) = \prod_i P(t_i^{sper}|t_i^{th}, a_i, b_i, A_i)$$

The Max. Likelihood estimate of the track is defined by the set of track parameters (like θ, ϕ, x_0, y_0, z_0) for which the value of the likelihood function is maxima.

The maximum of $P(event|track)$ is found by minimising $\Lambda = -\log(P(event|track))$

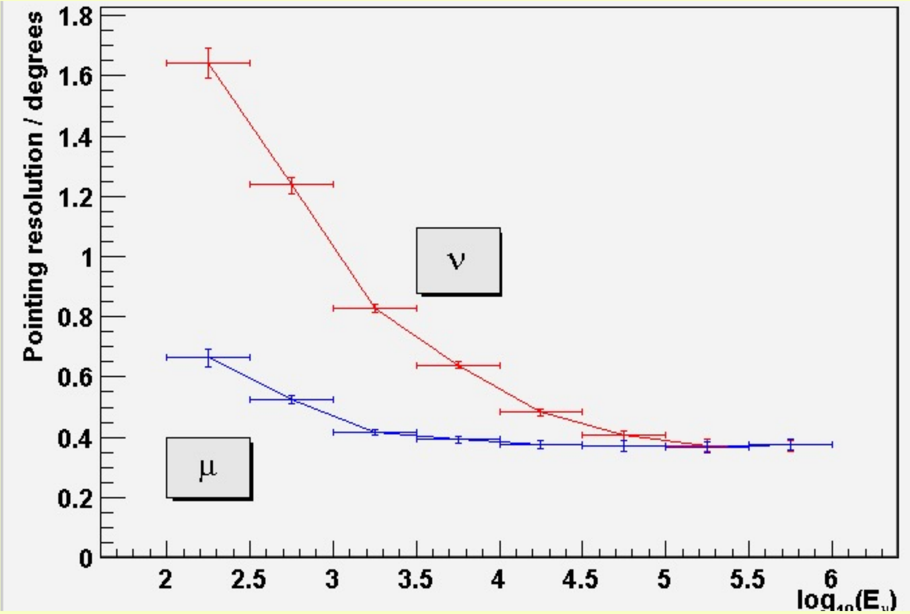


M.C. simulations allow to characterize the Λ value distribution for signal (muons from up-going neutrino interaction) and for background (atmospheric muons).

Accepting events with Λ > cut is possible to reduce the background to an appropriate amount.

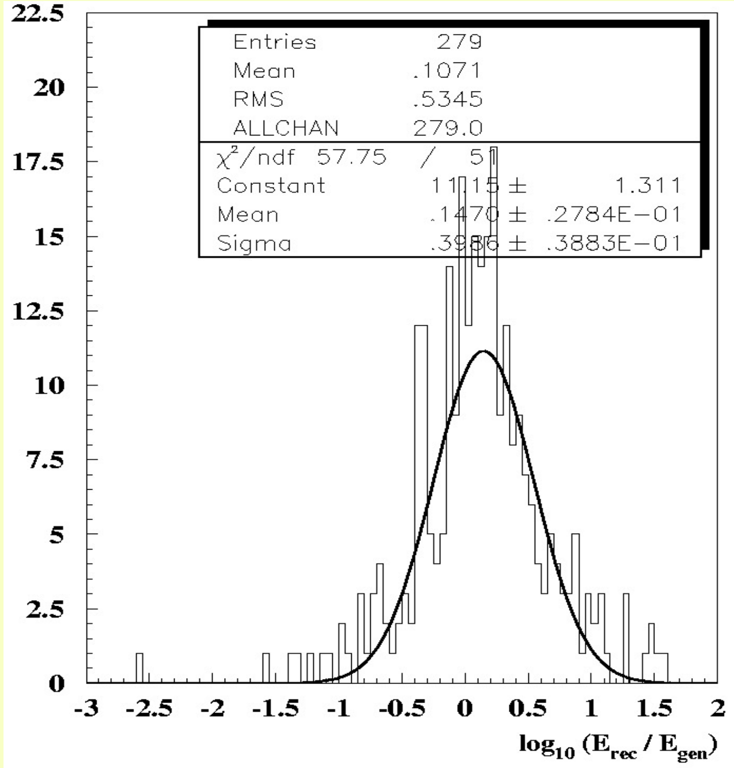
ANTARES - 0.05 km^2 - characteristics

Angular resolution



- E_ν ~10 TeV angular error dominated by ν-μ physical angle.
- E_ν ~10 TeV angular error $\sigma_\Theta < 0.4°$ (track reconstruction error).

Energy resolution



- $\sigma_E / E \approx 3$ (1 TeV ≤ E ≤ 10 TeV)
- $\sigma_E / E \approx 2$ (E > 10 TeV)

ANTARES Performances

❖ 12-line data taking since 2008;
physics duty cycle ≈ 85%
(sea campaigns/high bioluminescence periods)

❖ ~20 atmospheric muons per sec

directional cut
+ quality cut on likelihood
of track fit
(based on PDFs of
hit time residuals)

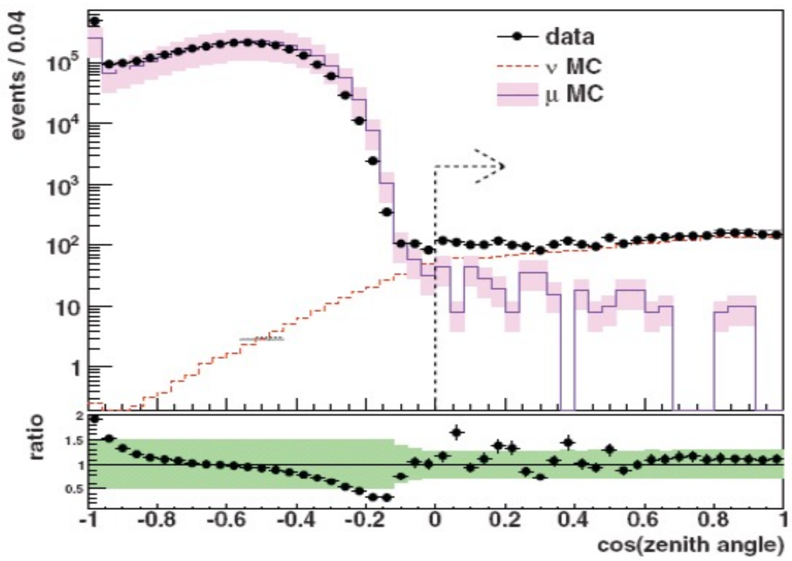
❖ ~5 atmospheric neutrinos per day
(> 7000 neutrinos detected so far)

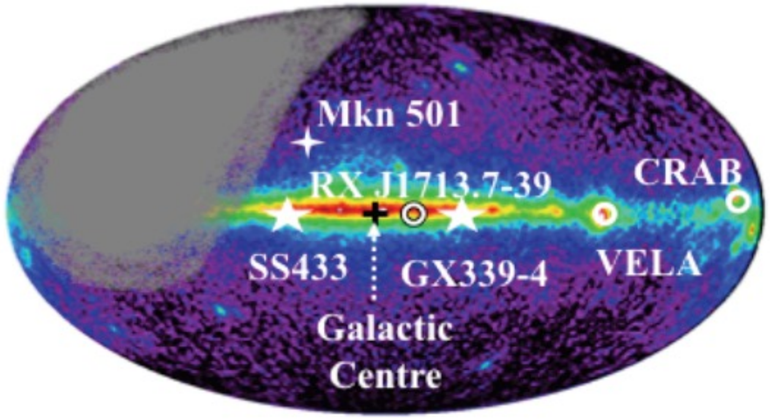
❖ Real-time data processing

❖ Effective area ≈ 1 m^2 at 30 TeV

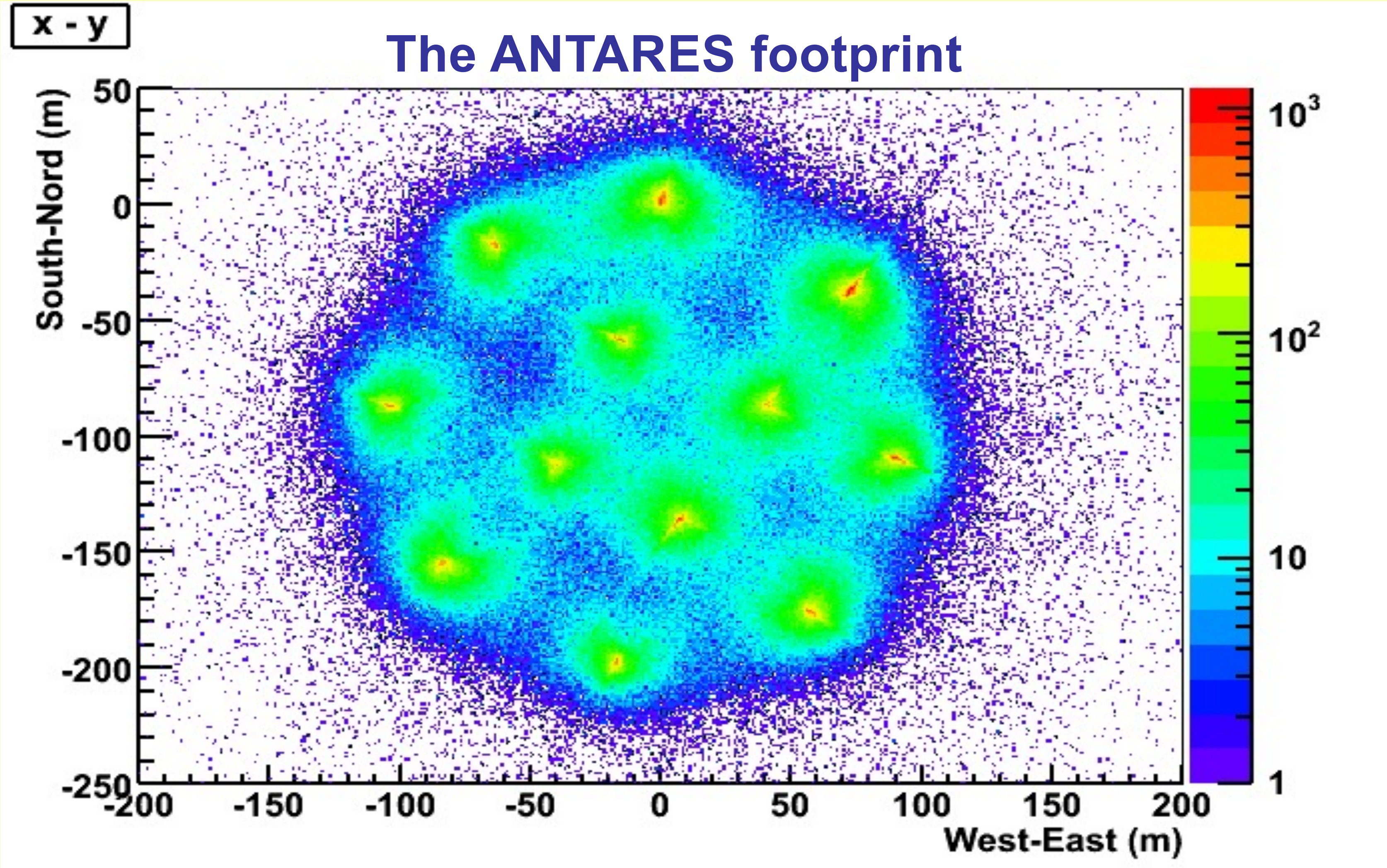
❖ Median angular resolution 0.3° – 0.4°

❖ Visibility: ¾ of the sky, most of
the Galactic Plane



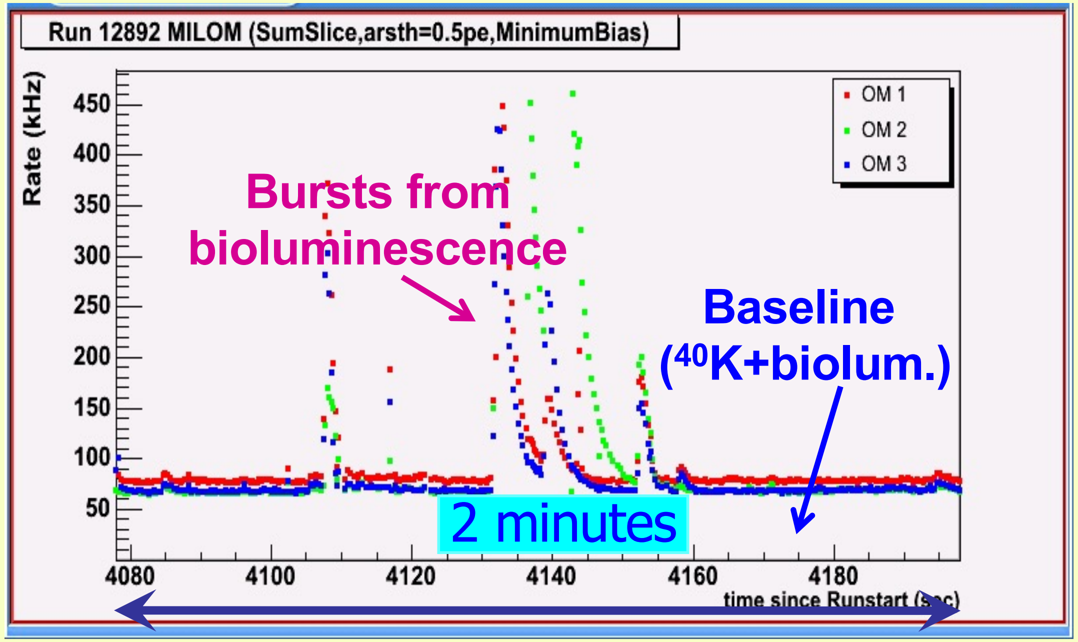


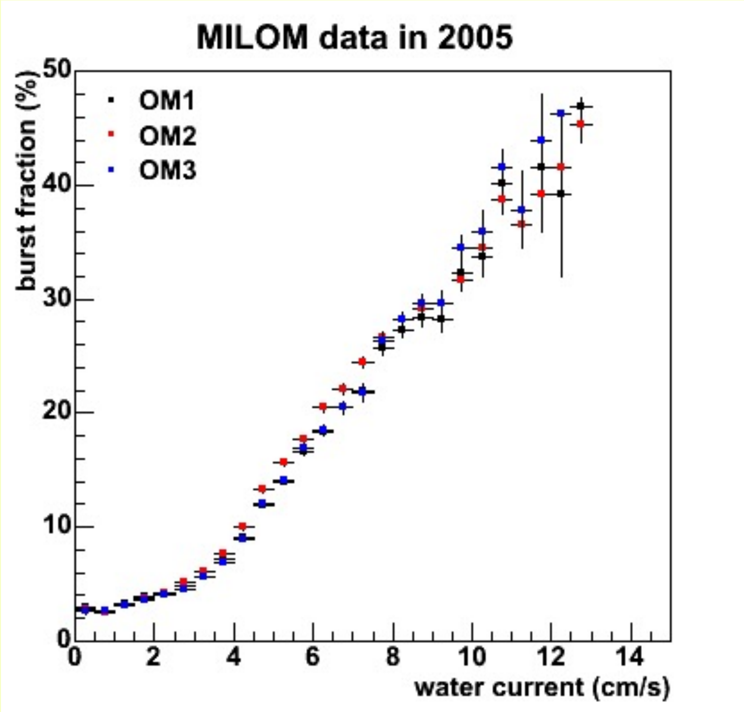
ANTARES "muon tomography"



Positions of reconstructed tracks of atmospheric muons at time of first triggered hit

ANTARES: background luminosity at 2500m Depth

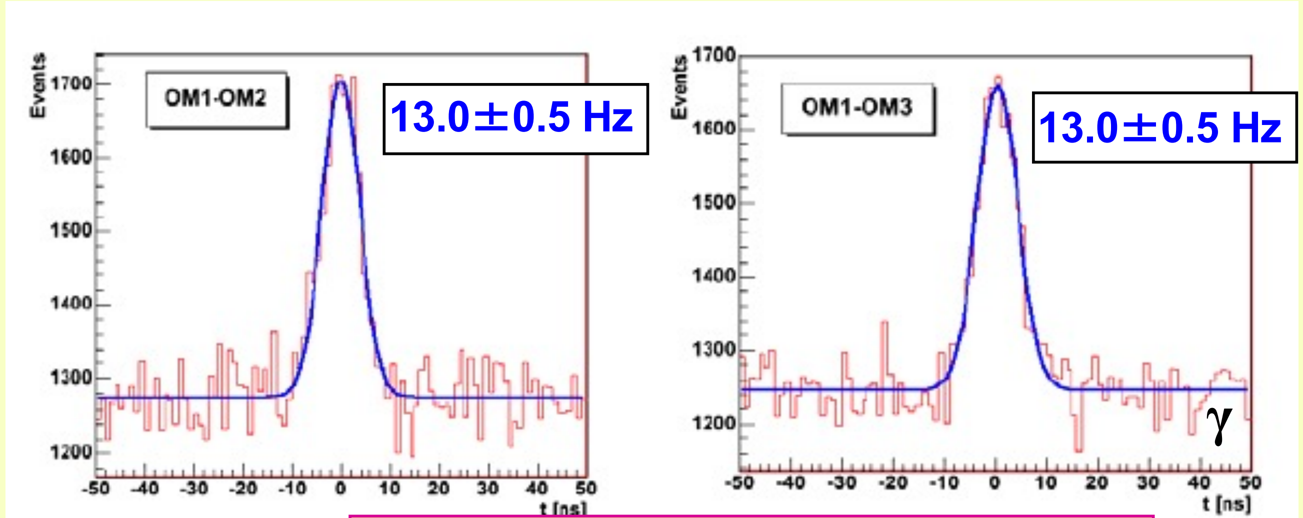




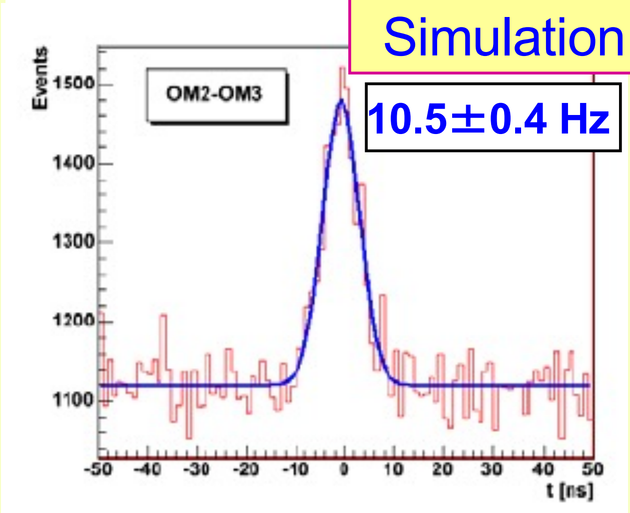
- Background light:
  - bioluminescence (bacteria, macroscopic organisms)
  - decays of ^{40}K (~30 kHz for 10" photomultiplier)
- Correlation with water current
  - Light bursts by macroscopic organisms – induced by pressure variation in turbulent flow around optical modules ?!

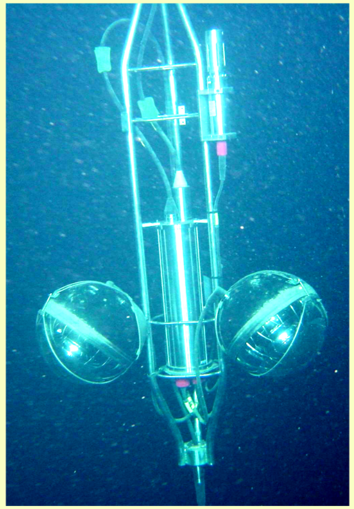
Burst-fraction:
fraction of time when rate > baseline + 20%

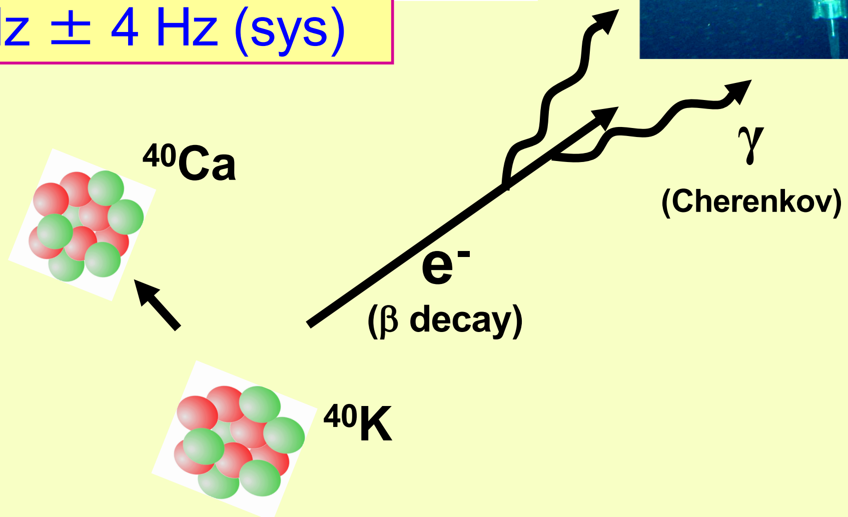
ANTARES: Coincidence rates from ^{40}K decays



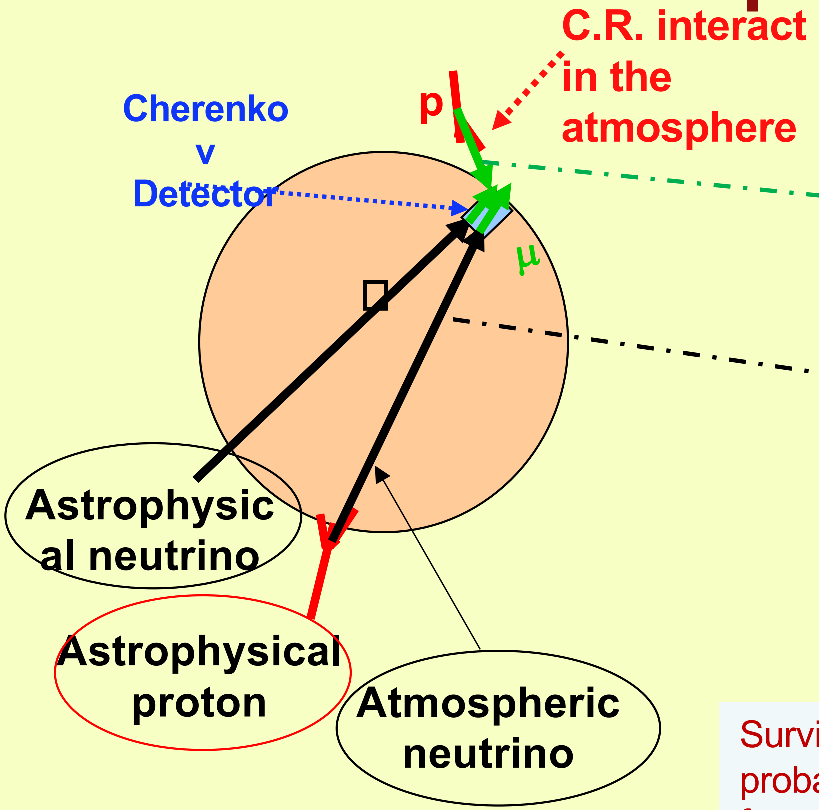
Simulation: 12 Hz ± 4 Hz (sys)



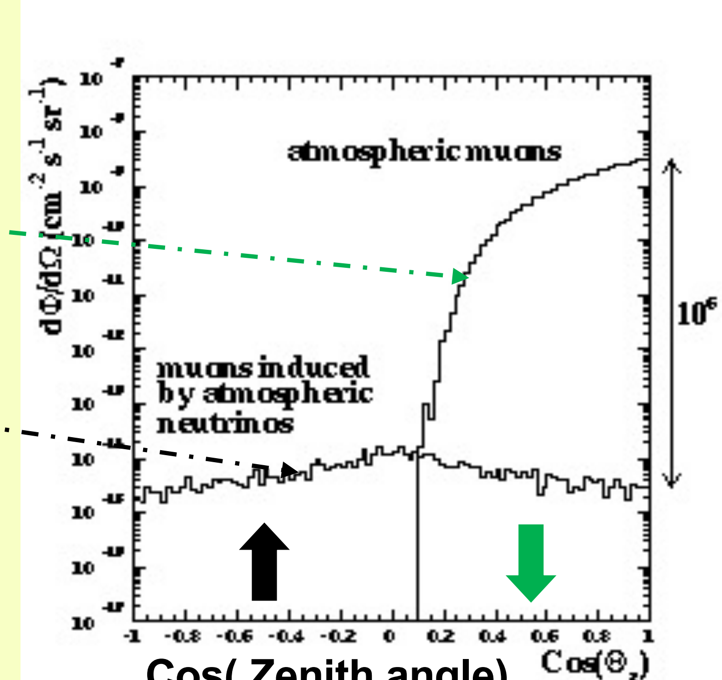




Neutrino Telescopes: signal and background - 2

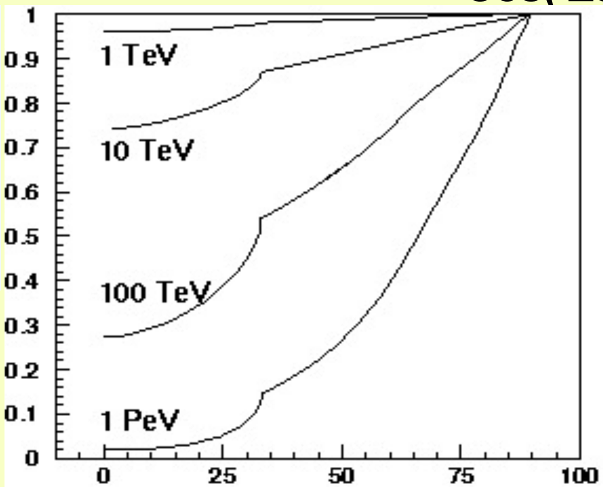


ν & μ : atmospheric background



Cos(Zenith angle)

Survival probability for neutrino crossing the Earth



Horizontal

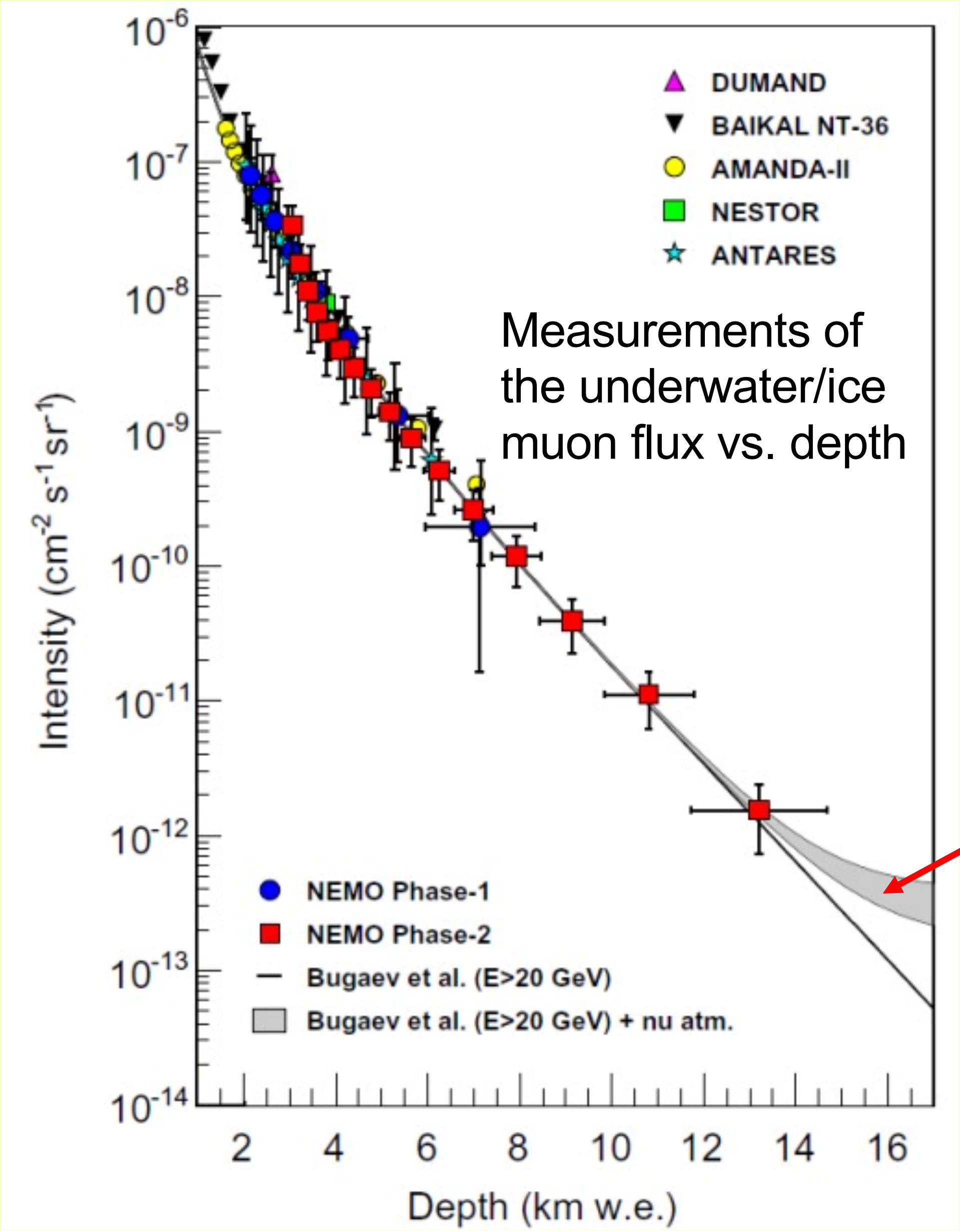
Vertical up-going

Zenith angle

For E_ν <100 TeV let's search for astrophysical neutrinos in the up-going tracks

For E_ν >1 PeV let's search for astrophysical neutrinos in the horizontal or down-going tracks (the muon background is also less intense at these energies)

Atmospheric muons (down-going): main background

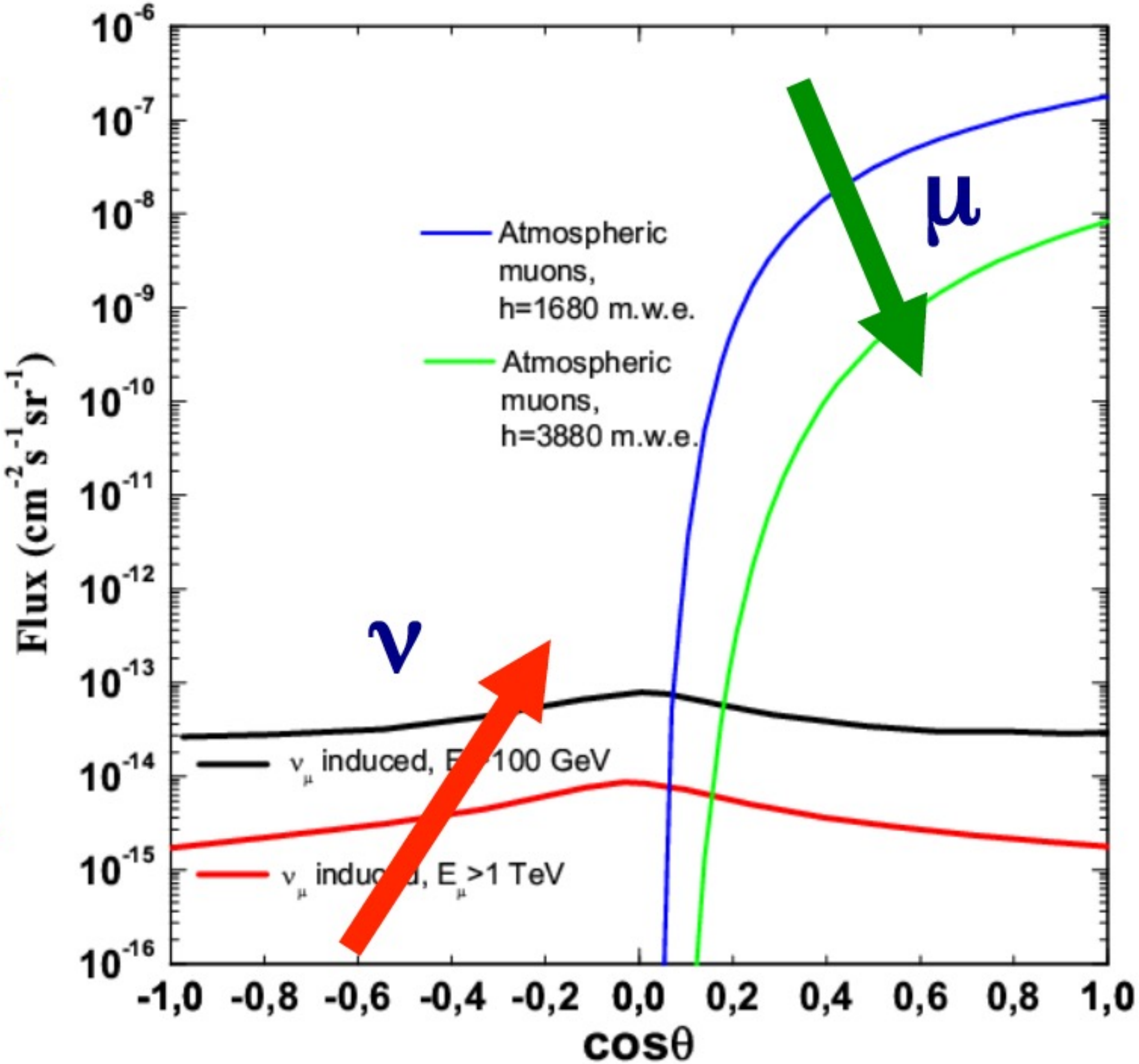


Events with a muon measured in a detector "protected" by > 15km of "water equivalent" are, probably, events where atmospheric neutrinos interact via CC giving a muon

Deep in a transparent medium

Water or Ice:

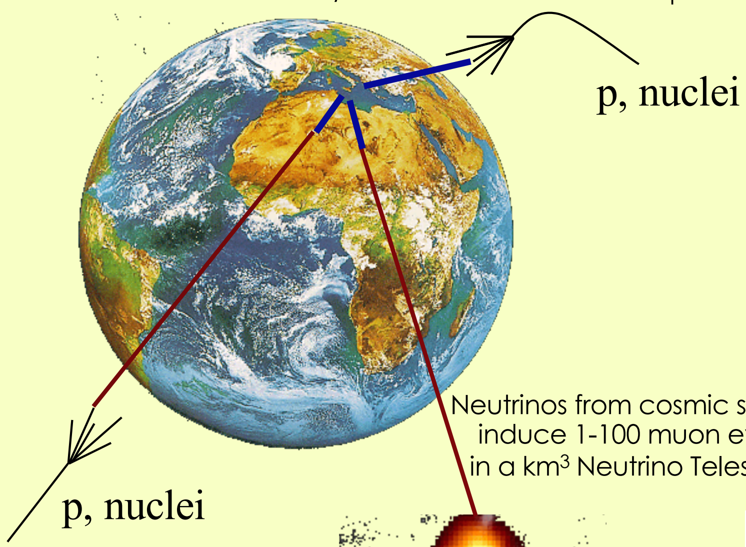
- large (and inexpensive) target for ν interaction
- transparent radiators for Cherenkov light;
- large deep: protection against the cosmic-ray muon background



Schematics of a Cherenkov Neutrino Telescope

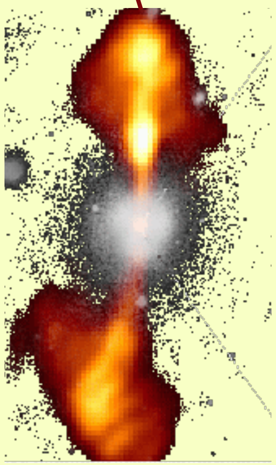
Search for neutrino induced events, mainly $\nu_\mu N \rightarrow \mu X$, deep underwater

Down-going μ from atm. showers
S/N ~ 10^{-6} at 3500m w.e. depth



Neutrinos from cosmic sources induce 1-100 muon evts/y in a km^3 Neutrino Telescope

Up-going μ from neutrinos generated in atm. showers
S/N ~ 10^{-4}

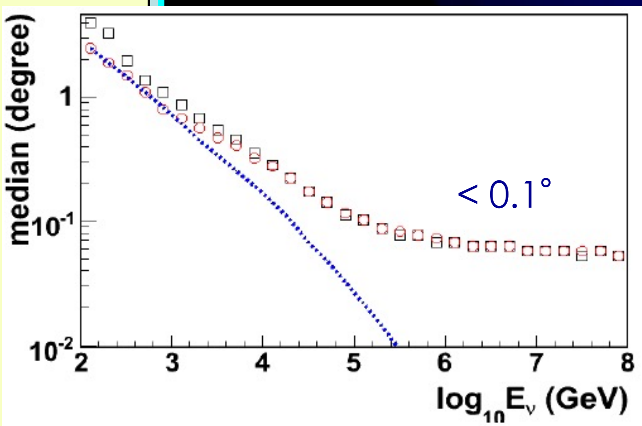


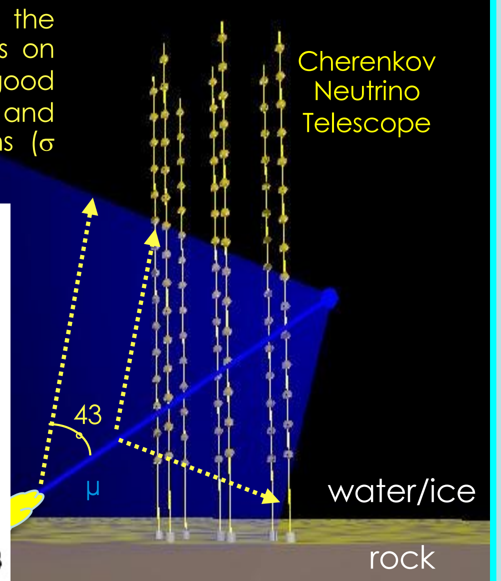
- Atmospheric neutrino flux ~ E_ν^{-3}
- Neutrino flux from cosmic sources ~ E_ν^{-2}
  - Search for neutrinos with E_ν>1÷10 TeV

- ~TeV muons propagate in water for several km before being stopped
  - go deep to reduce down-going atmospheric μ backg.
  - long μ tracks allow good angular reconstruction

$$For\ E_\nu \geq 1TeV \quad \theta_{\mu\nu} \sim \frac{0.7°}{\sqrt{E_\nu[TeV]}}$$

μ direction reconstructed from the arrival time of Cherenkov photons on the Optical Modules: needed good measurement of PMT hits, σ(t)~1ns, and good knowledge of PMT positions (σ ~10cm)

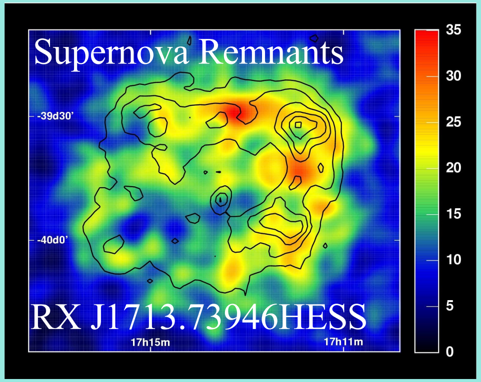


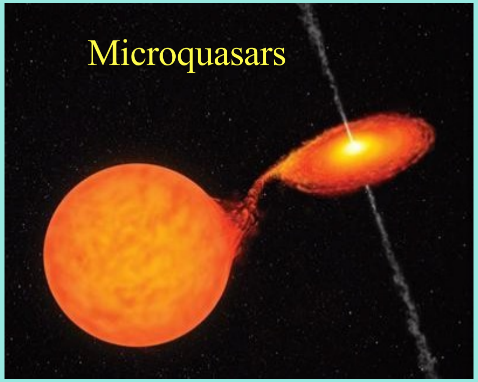


Picture from ANTARES

Search for "Point like" cosmic Neutrino Sources

Galactic

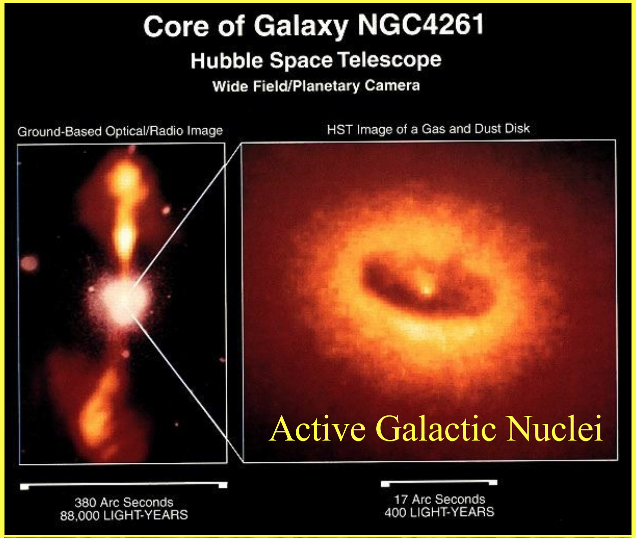


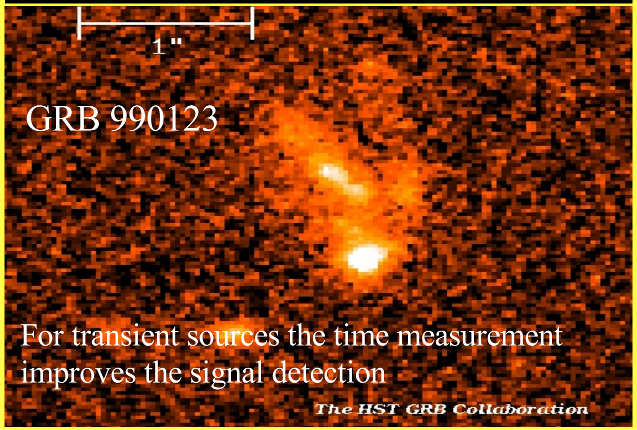


- Their identification requires a detector with accurate angular reconstruction

$$\sigma(\vartheta) \leq 0.5^\circ \text{ for } E_\nu \geq 1 TeV$$

Extragalactic



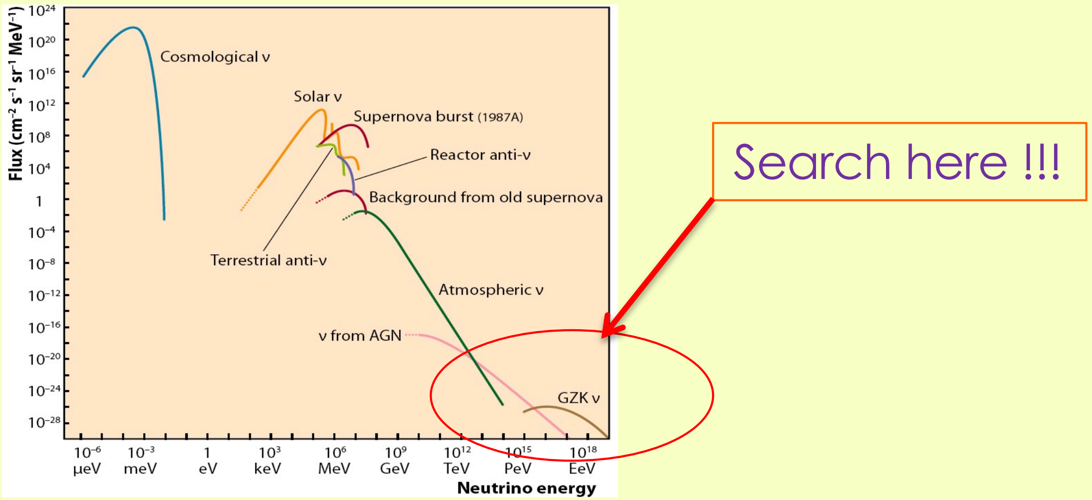


Experimental signal : statistical evidence of an excess of events coming from the same direction

Search for ν from "Diffuse Cosmic Neutrino Sources"

- **Unresolved AGN**
- **Neutrinos from "Z-bursts"**
- **Neutrinos from "GZK like" p-CMB interactions**
- **Neutrinos foreseen by Top-Down models**
- **….**

Their identification out of the more intense background of atmospheric neutrinos (and muons) is possible at high energies (E > TeV) and implies accurate energy reconstruction.



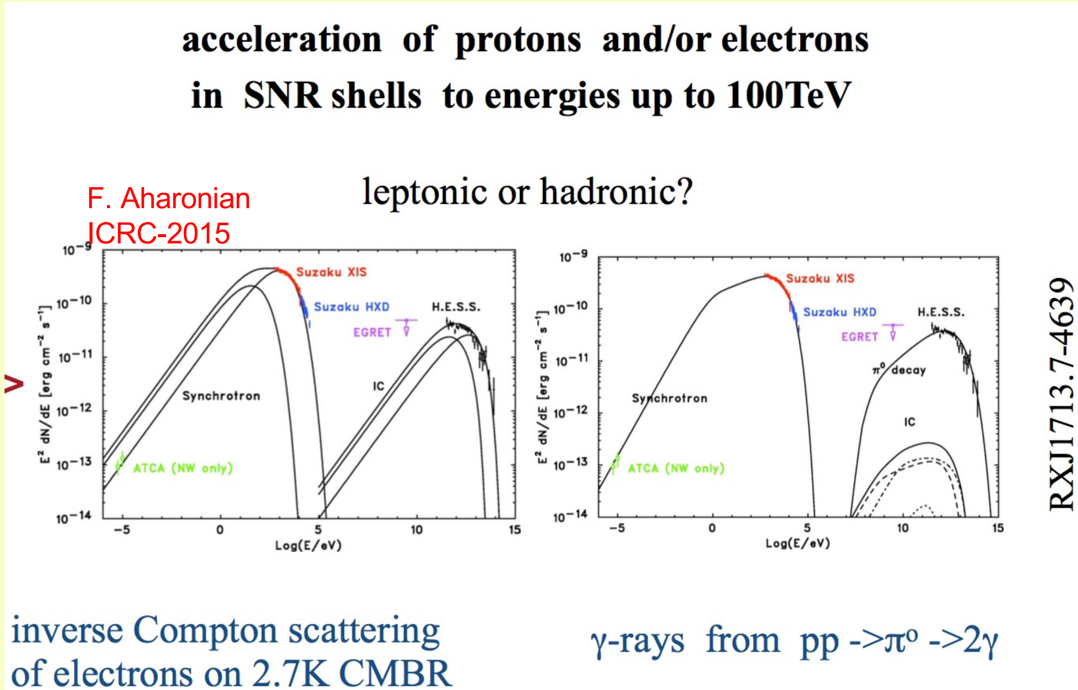
- **2013, first evidence for a diffuse flux of cosmic neutrinos: 28 contained VHE astrophysical ν events reported by IceCube**

The role of ν in multimessenger astrophysics

Neutrino production is strongly related to the acceleration of **cosmic rays** and to the production of **γ-rays**:

$$p + N,\gamma \rightarrow X + \begin{array}{l} \pi^{\pm} \rightarrow \text{neutrinos} \\ \pi^{o} \rightarrow \gamma\text{-rays} \end{array}$$

The detection of neutrinos from a SNR would help in understanding the high-energy γ production mechanism: leptonic (I.C. of accelerated e^- on Synchroton radiation) or hadronic ?



Present Cherenkov Neutrino Telescopes