

Fisica Nucleare e Subnucleare II

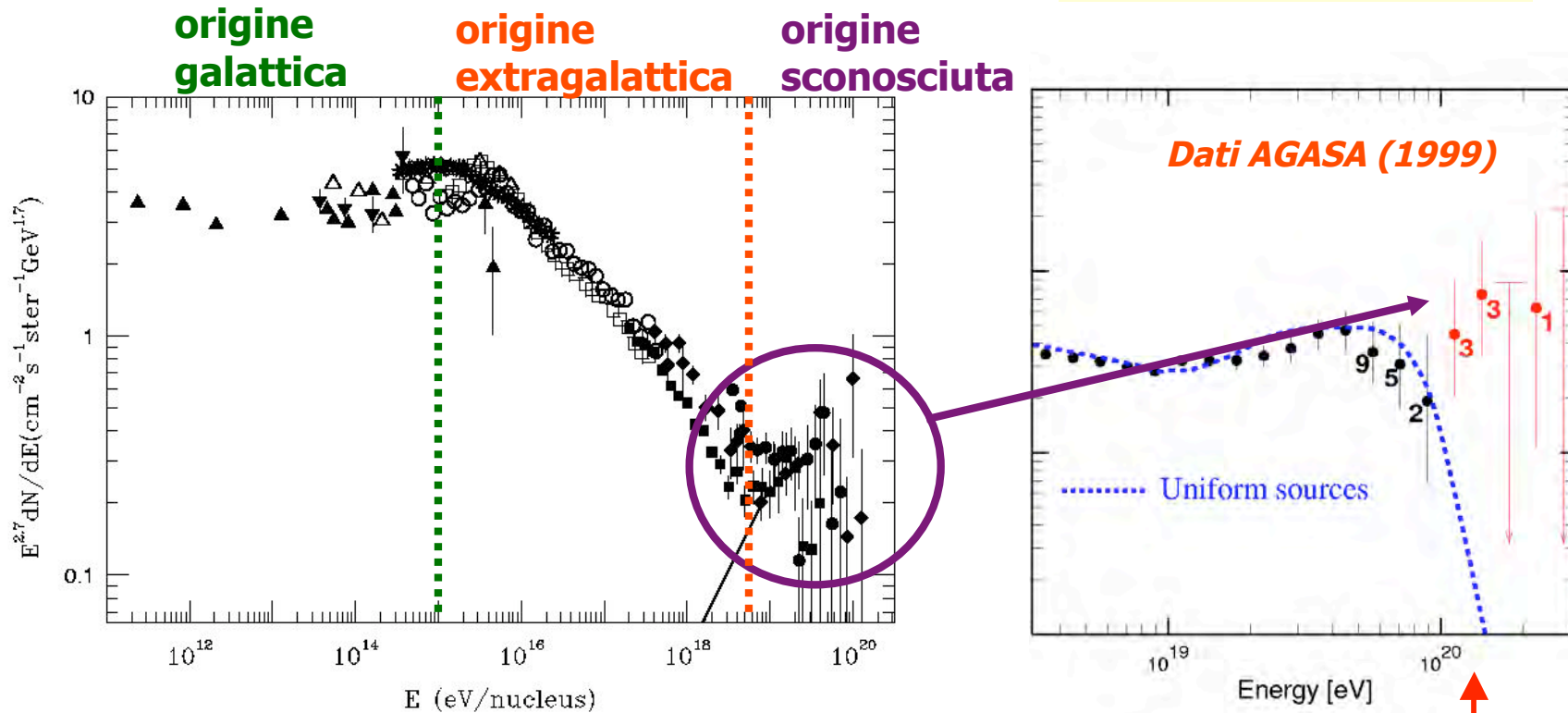
Lezioni n. 45/46

- Rivelazione di neutrini astrofisici con $E_\nu > 10^{13}$ eV
 - Motivazioni per “astronomia con neutrini”
 - Tecniche di rivelazione con apparati tradizionali di prima generazione (SOUDAN, MACRO) e con apparati Cherenkov.
 - Flussi di eventi aspettati, segnale e rumore
 - Esperimenti di 2^a generazione: BAIKAL, AMANDA, NESTOR, ANTARES, NEMO: apparati sperimentali, sensibilità, risultati
 - Astronomia con neutrini in ICECUBE/KM³ nel Mediterraneo

... osservati raggi cosmici di altissima energia

- protoni e gamma di altissima energia
- Gamma Ray Burst

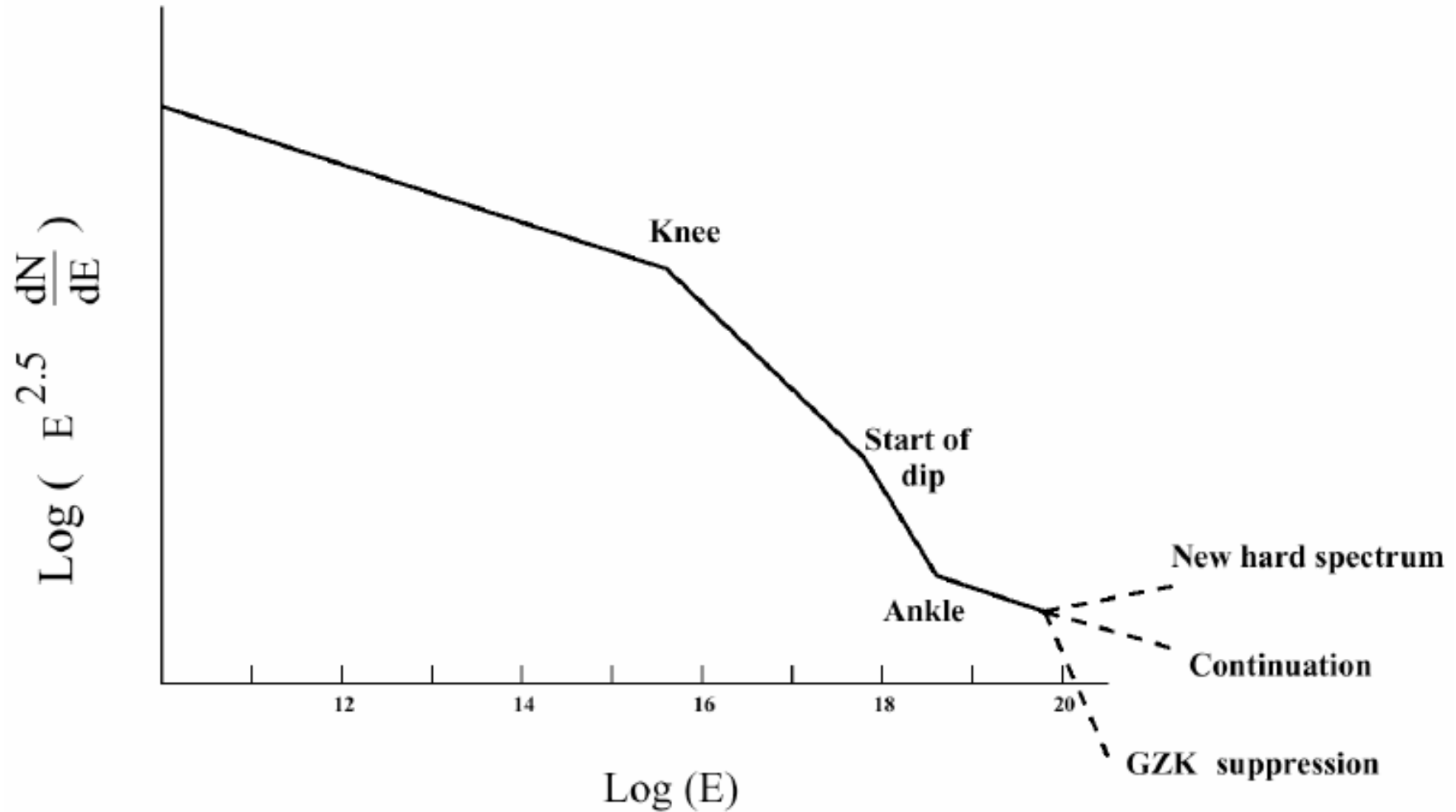
10^{20} eV \approx 17 Joules



Raggi cosmici: protoni, altre particelle cariche, radiazione elettromagnetica, neutrini

Cut-off atteso dovuto all'effetto GZK

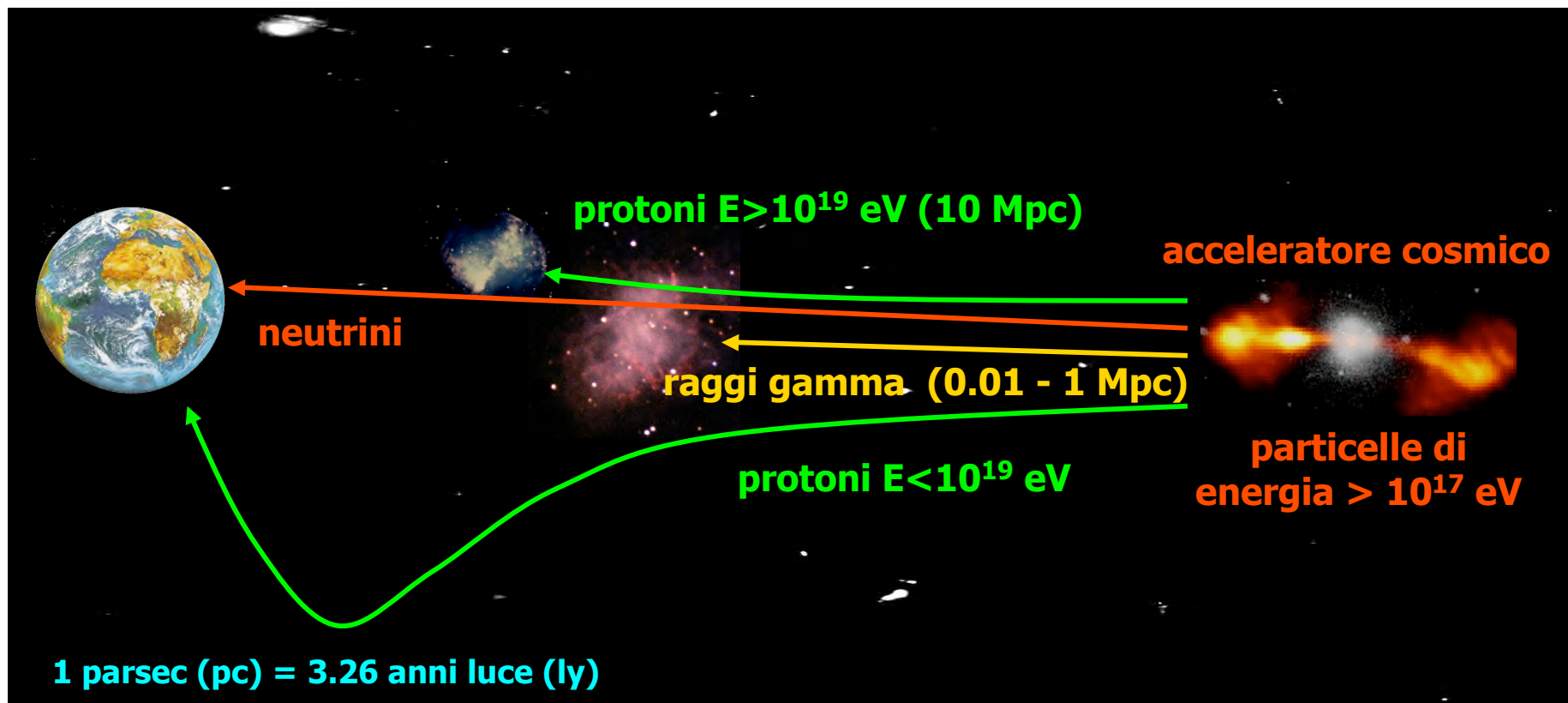
... cosa dovremmo aspettarci ad altissima energia ?



Sommers (ICRC2001)

... e quali particelle possono dall'Universo estremo arrivare a noi ?

- i protoni e i raggi gamma possono essere assorbiti o deviati dalla materia e dalla radiazione interstellare, ad alte energie "l'effetto GZK"
- i neutrini interagiscono solo debolmente e permettono di osservare l'Universo lontano



Motivazioni per l'Astronomia con neutrini

Strumenti per l'osservazione dell'Universo: fotoni, protoni con $E \geq 10^{19}$ eV e neutrini

neutrini sono “meno assorbiti” dei fotoni

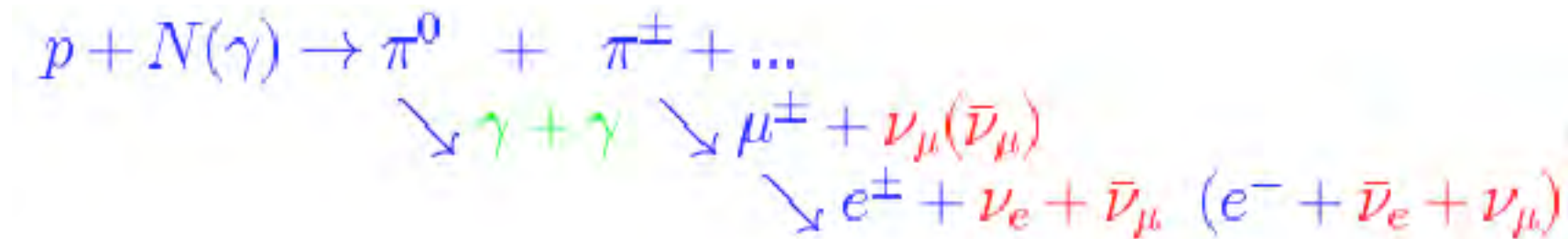
fotoni (produzione di coppie e^+e^- di fotoni di 10^{12} eV (TeV) con fondo di fotoni InfraRosso, di fotoni di 10^{15} eV (PeV) con fondo CMBR (microonde), di fotoni di 10^{18} eV (EeV) con fondo “radio”

protoni UHE (foto-produzione di pioni su MW background (CMBR) =) per $E_p \geq 5 \cdot 10^{19}$ eV (GZK cut-off nello spettro dei raggi cosmici: Protoni non possono arrivare a noi da piu' di 30 Mpc)

L'esistenza di neutrini di alta energia ($E \geq 100$ GeV) in “sorgenti astrofisiche” non e' ancora stata “provata”: la prova sara' un significativo “eccesso” di neutrini sul “fondo di neutrini atmosferici” in rivelatori “sotterranei”, “sottomarini” o nel “ghiaccio polare”

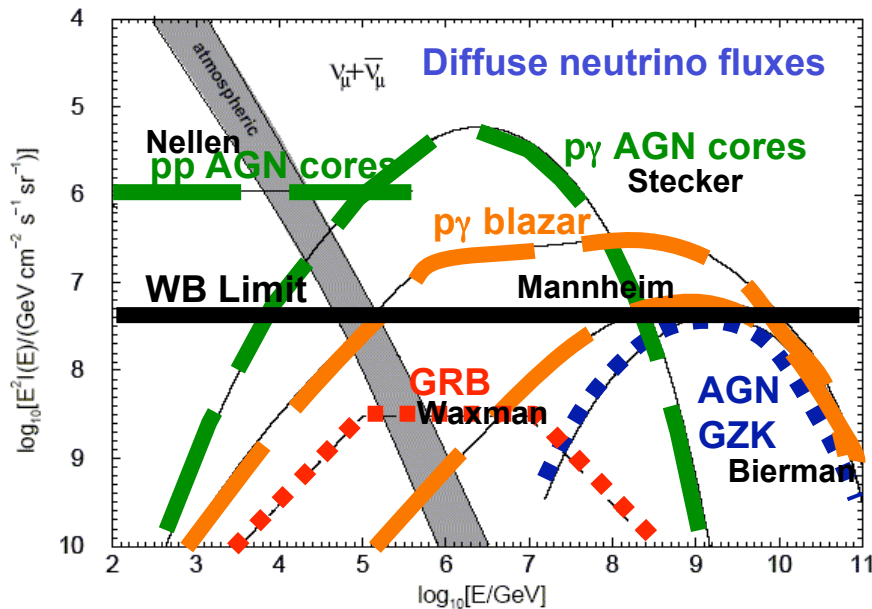
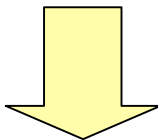
Un “**indizio importante**”: l'osservazione di sorgenti with $E \geq 10$ TeV (spiegata con accelerazione di protoni e successiva interazione ad energie non raggiungibili per fotoni prodotti da elettroni accelerati con successiva interazione di “Compton-Inverso” su fotoni emessi per “radiazione di sincrotrone” nel campo magnetico.

Neutrini “astrofisici” potrebbero essere prodotti nella interazione “Proton beam dump”



Spettri di neutrini da "Beam Dump"

Flussi aspettati da diverse "sorgenti e da neutrini atmosferici"



Il flusso dei neutrini atmosferici è dominante fino a $E_{\text{neutrino}} \sim 1-10 \text{ TeV}$

Neglecting γ absorption (high uncertainty) $\implies \Phi_\nu \sim \Phi_\gamma$

Cosmic accelerators produce a power law spectrum

$$\frac{dN}{dE} \propto E^{-(\gamma+1)}$$

with $\gamma \sim 1 + \epsilon$ (ϵ small) explained by 1st order Fermi acceleration mechanism in shocks expanding in interstellar medium with velocity V ($\frac{\Delta E}{E} \propto V$)

For ν s from sources: $\frac{dN}{dE} \propto E^{-2.5}$

For ν s from interactions of CRs on nuclei in atmosphere (π and K decays): $\frac{dN}{dE} \propto E^{-(2.7)3.7}$ for $E_\nu (< 100) > 100 \text{ GeV}$ due to containment in Galaxy

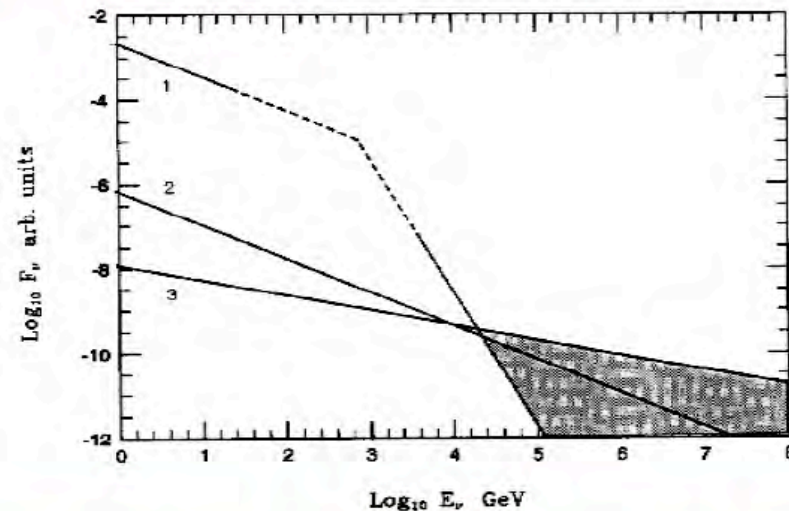


Figure 1: Scheme of fluxes of (1) atmospheric ν s; (2) ν s from cosmic ray interactions on galactic matter; (3) ν s from beam-dumps. Hatched area: where S/N is larger

Dai neutrini ai muoni rivelabili 1

ν detected through CC interactions with rock surrounding detectors as upward-going μ s (to discriminate atmospheric μ s):



La rivelazione dei neutrini tramite l'identificazione dei muoni comporta che tutti i muoni originati negli sciami atmosferici dal decadimento dei π^{\pm} e k^{\pm} rappresentano un "fondo", fra l'altro molto più frequente dei muoni da neutrini astrofisici quando l'energia del neutrino è $\leq 10\text{TeV}$. Ciò comporta che il flusso dei muoni atmosferici deve essere ridotto (ad esempio con schermature naturali (roccia, oceano, ...)), che gli eventi da rivelare devono essere di alta energia pertanto i flussi di neutrini sono molto poco intensi: ciò comporta che gli apparati devono essere enormi per ottenere una frequenza accettabile di eventi osservati

Probability that a ν with E_{ν} crossing the detector produces a μ with $E_{\mu} \geq E_{th}^{\mu} = 1\text{ GeV}$:

$$P_{\nu}(E_{\nu}, E_{th}^{\mu}) = N_A \int_{E_{th}}^{E_{\nu}} dE'_{\mu} \frac{d\sigma_{\nu}}{dE'_{\mu}}(E'_{\mu}, E_{\nu}) R_{eff}(E'_{\mu}, E_{th}^{\mu})$$

Dai neutrini ai muoni rivelabili 2

where μ effective range is the probability a μ with E_μ survives with $E_\mu \geq E_{th}^\mu$:

$$R_{eff}(E_\mu, E_{th}^\mu) = \int_0^\infty dX P_{surv}(E'_\mu, E_{th}^\mu, X)$$

evaluated from the μ energy loss

$$\frac{dE_\mu}{dX} = \alpha(E_\mu) + \beta(E_\mu)E_\mu$$

$\alpha \equiv$ ionization losses $\sim 2 \text{ MeV g}^{-1} \text{ cm}^2$

$\beta \equiv$ bremsstrahlung, pair production, nuclear interactions $\sim 4 \cdot 10^{-6} \text{ g}^{-1} \text{ cm}^2$

Dai neutrini ai muoni rivelabili 3

$E_\nu \lesssim 1 \text{ TeV}$: $\sigma_\nu \sim E_\nu$ and $R_{eff} \sim E_\mu$

$E_\nu \gtrsim 1 \text{ TeV}$: σ_ν dumped by W propagator and $R_{eff} \sim \ln(E_\mu)$

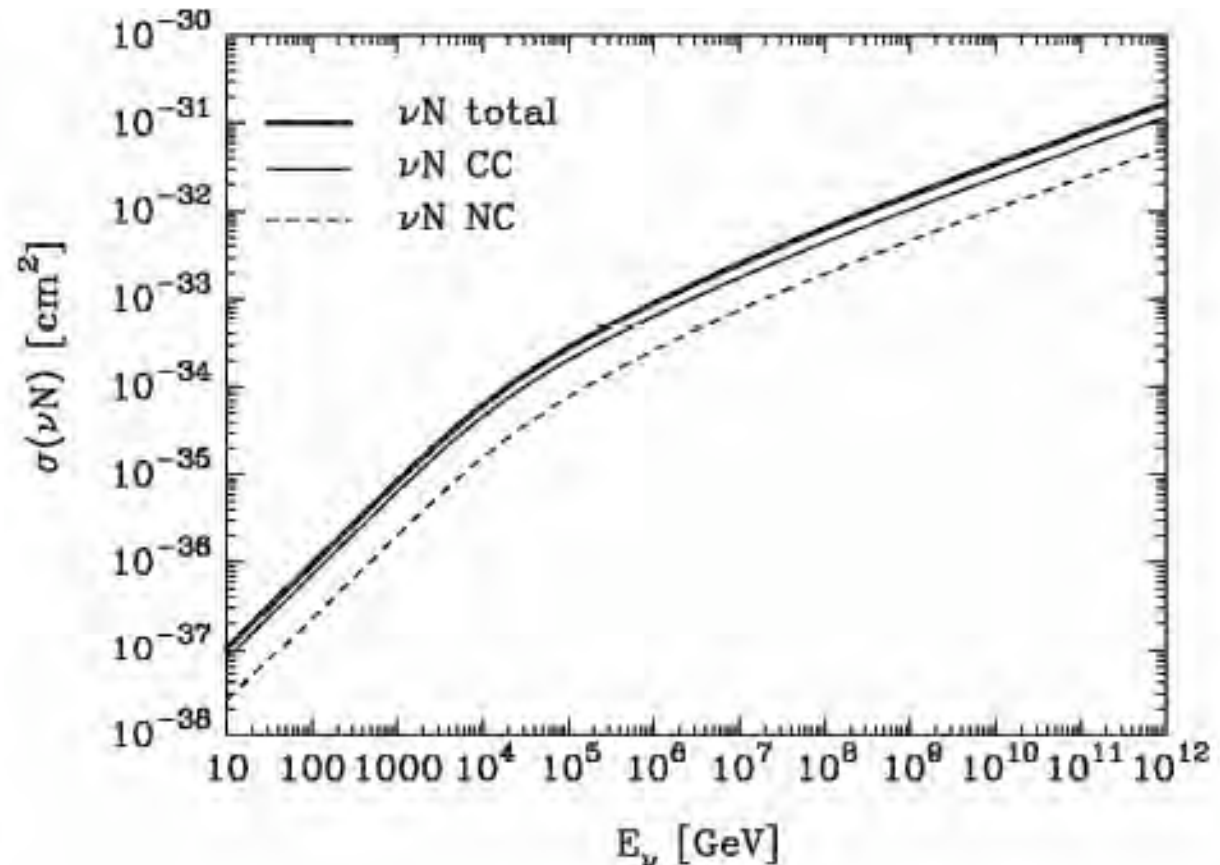
$$\frac{d^2\sigma}{dx dy} = \frac{2G_F^2 M E_\nu}{\pi} \left(\frac{M_{W,Z}^2}{Q^2 + M_{W,Z}^2} \right)^2 [xq(x, Q^2) + x\bar{q}(x, Q^2) (1-y)^2]$$

$$x = \frac{Q^2}{2M\varepsilon}$$

$$y = \frac{\varepsilon}{E_\nu}$$

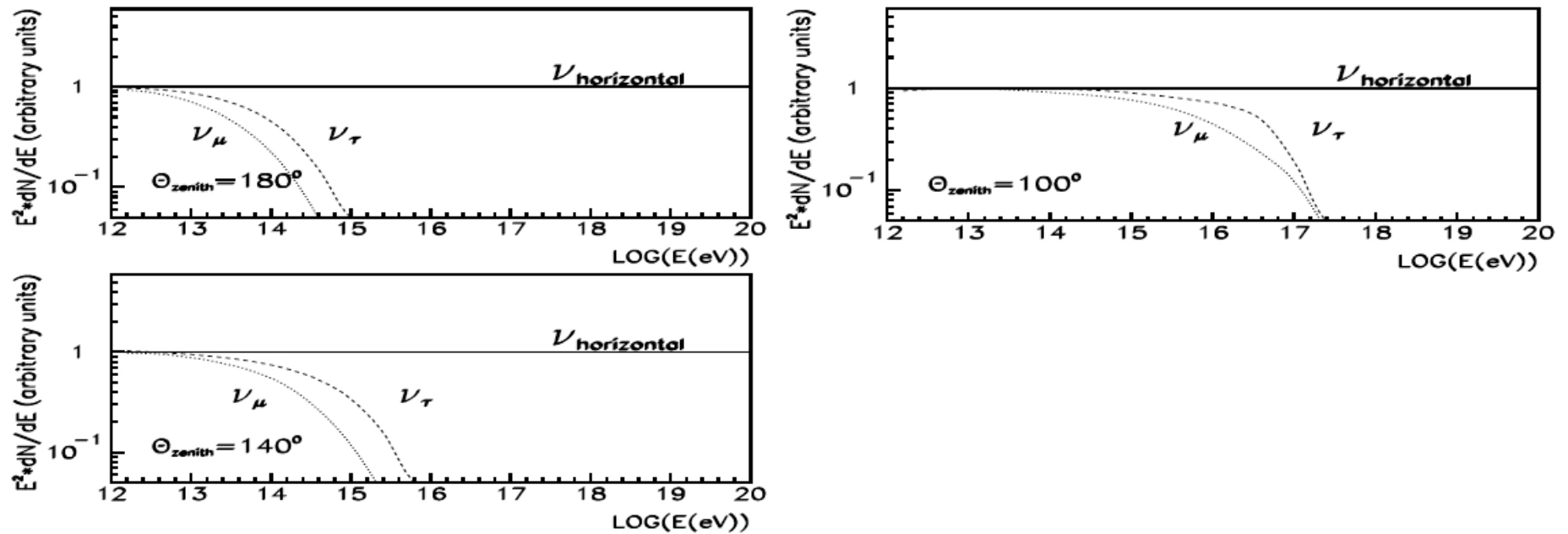
$$\varepsilon = E_\nu - E_l$$

E_ν	$P_{\nu \rightarrow \mu^-}$	$P_{\bar{\nu} \rightarrow \mu^+}$
10	8.15×10^{-11}	4.88×10^{-11}
10^2	9.05×10^{-9}	5.87×10^{-9}
10^3	5.79×10^{-7}	3.86×10^{-7}
10^4	1.52×10^{-5}	1.09×10^{-5}
10^5	1.35×10^{-4}	1.17×10^{-4}



Ad altissima energia la Terra non e' trasparente per i neutrini !

La sezione d'urto neutrino-nucleone cresce con l'energia e la probabilità che un neutrino attraversi la Terra senza interagire diminuisce ...



Brief History of Neutrino astronomy

1960

Markov introduces the idea (Proc. of the 1960 Int. Conf. on HE Physics, Rochester)

First estimates on

-diffuse flux by cosmic rays in Galaxy (Greisen, Ann. Rev. Nucl. Science 10 (1960) 1)

-and of HE flux from Crab (Bahcall and Frautchi, PR 135 (1964) 788)

1976

First Workshop on DUMAND, the first project of a giant underwater detector

1970 -1980

Operation of “first generation detectors”

1996

First neutrinos in the Baikal and AMANDA experiments. Work in progress and R&D towards a km³ detector

1998

Start of the Italian R&D INFN project Neutrino Mediteranean Observatory

2000

Construction in the Mediterranean of the 0.1 km² ANTARES (with Italian participation)

La prima "generazione" di *Telescopi per neutrini*

Fine tracking calorimeters:

- Kolar Gold Fields: proportional counters and Fe absorber, 350 ton, $S = 36 \text{ m}^2$, 6045 m.w.e. depth, intrinsic angular resolution $\sim 2.5^\circ$, source search in 5° , $188 \mu \uparrow (\theta > 60^\circ)$
(H. Adarkar et al, 24th ICRC in Rome (1995))
- Frejus: flash chambers, Geiger tubes and Fe planes, 900 ton, $S = 36 \text{ m}^2$, 4000 m.w.e. Horizontal and upward stopping μs (0 events with $> 140 \text{ MeV}$ per radiation length)
 \implies Upper limit (isotropic flux of νs)
(Astropart. Phys. 4 (1996) 217):

$$\frac{d\Phi_{\nu\mu}}{dE_\nu}(2.6\text{TeV}) < 7 \cdot 10^{-13} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} (90\% \text{c.l.})$$

Rivelatori Cherenkov e tradizionali come *Telescopi per neutrini*

Water Cherenkov technique (development of Cherenkov cone seen by an array of 1000-2000 PMTs):

- IMB: 3.3 kton of water, $S_{eff} = 390 \text{ m}^2$, 1570 m.w.e., Gaussian point spread function $\sigma = 3.4^\circ - 4.5^\circ$, $624 \mu \uparrow$
(Nucl. Phys. **B** (Proc. Suppl.) **38** (1995) 331)
- Kamiokande: 2.3 kton of water, $S_{eff} \sim 150 \text{ m}^2$, 2700 m.w.e., 2.5° includes 68% events from point source, $252 \mu \uparrow$ (PRD**39** (1989) 1481)
- Baksan: T.o.F. (res. 5 ns) with liquid scintillators ($\theta > 80^\circ$ at trigger level), $S \sim 290 \text{ m}^2$, 850 m.w.e., angular res. $\sim 2^\circ$, source search in 5° , $682 \mu \uparrow$, (Proc. of 24th ICRC, Rome (1995))

Telescopi per neutrini di 2^a generazione: SuperKamiokande

- Super-Kamiokande: 50,000 ton water Cherenkov (22.5 kton fiducial volume) with 20-inch 11146 PMTs and 1885 8-inch for veto, 2700 m.w.e., 1028 throughgoing μ \uparrow /923 d, no results on ν sources yet

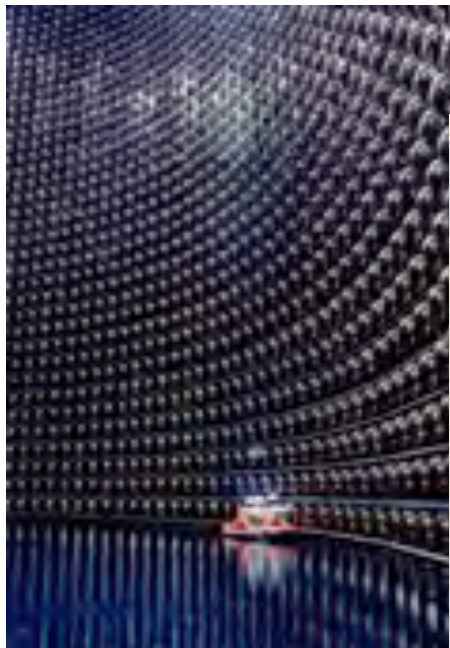
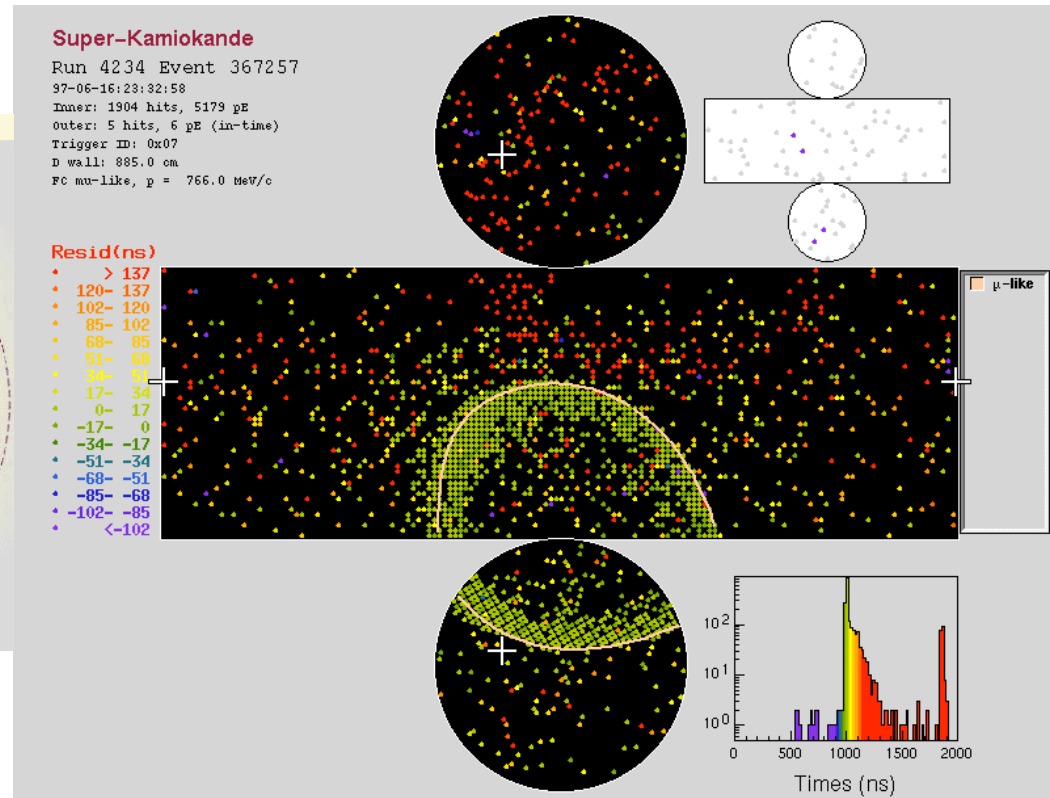
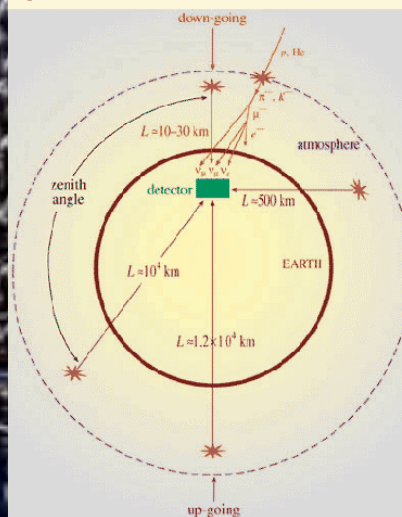
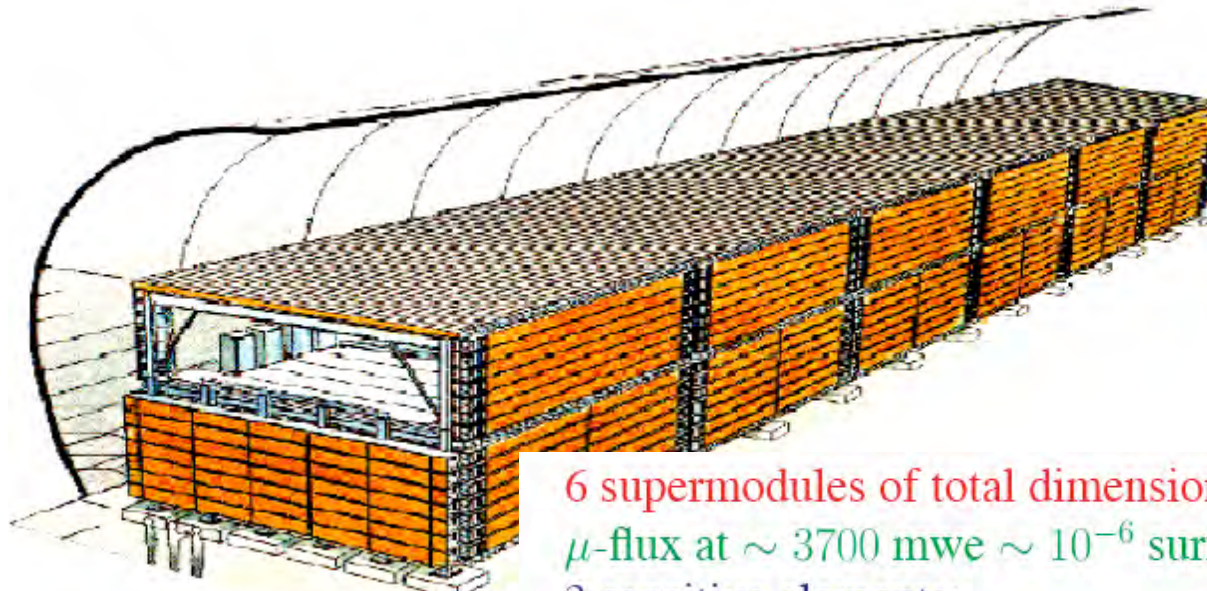


Figure 4



Telescopi per neutrini di 2^a generazione: MACRO, ai Lab. Naz. Gransasso

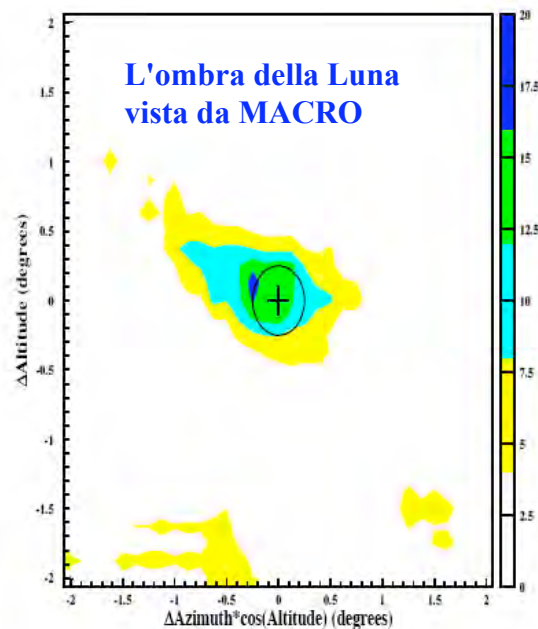


6 supermodules of total dimension $12 \times 76.6 \times 9 \text{ m}^3$

μ -flux at $\sim 3700 \text{ mwe} \sim 10^{-6}$ surface flux

3 sensitive elements:

1. 1263 m^2 track-etch (CR39+Lexan) in the middle of lower part, vertical E and N walls in “wagons” of $\sim 25 \times 25 \text{ cm}^2$ (etched 227 m^2 , exposure 7.6 yr)
2. ~ 600 tons liquid scintillators (time resolution $\sim 500 \text{ psec}$)
3. $\sim 20,000 \text{ m}^2$ limited ST for tracking (angular resolution $< 1^\circ$, pointing capability checked with Moon shadow, PRD59 (1999) 012003)

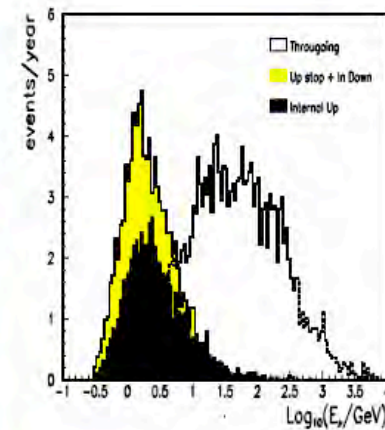
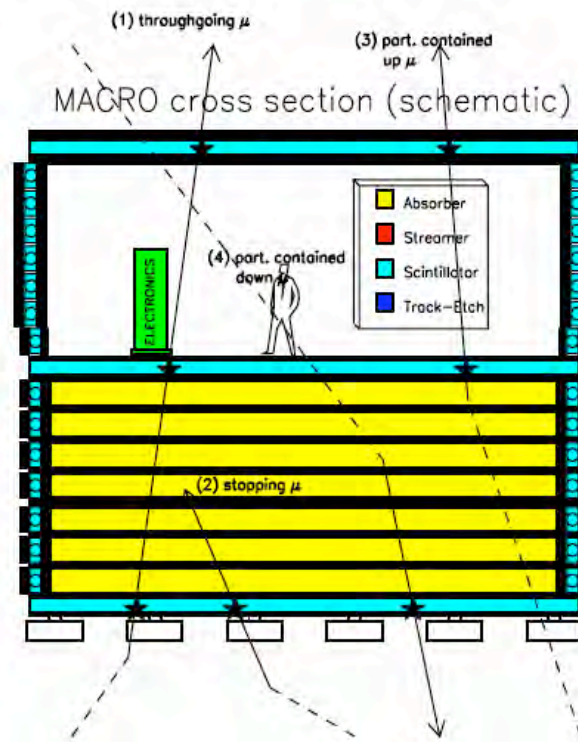


Minimum E_{th} set by rock absorber = 1 GeV for vertical μ s

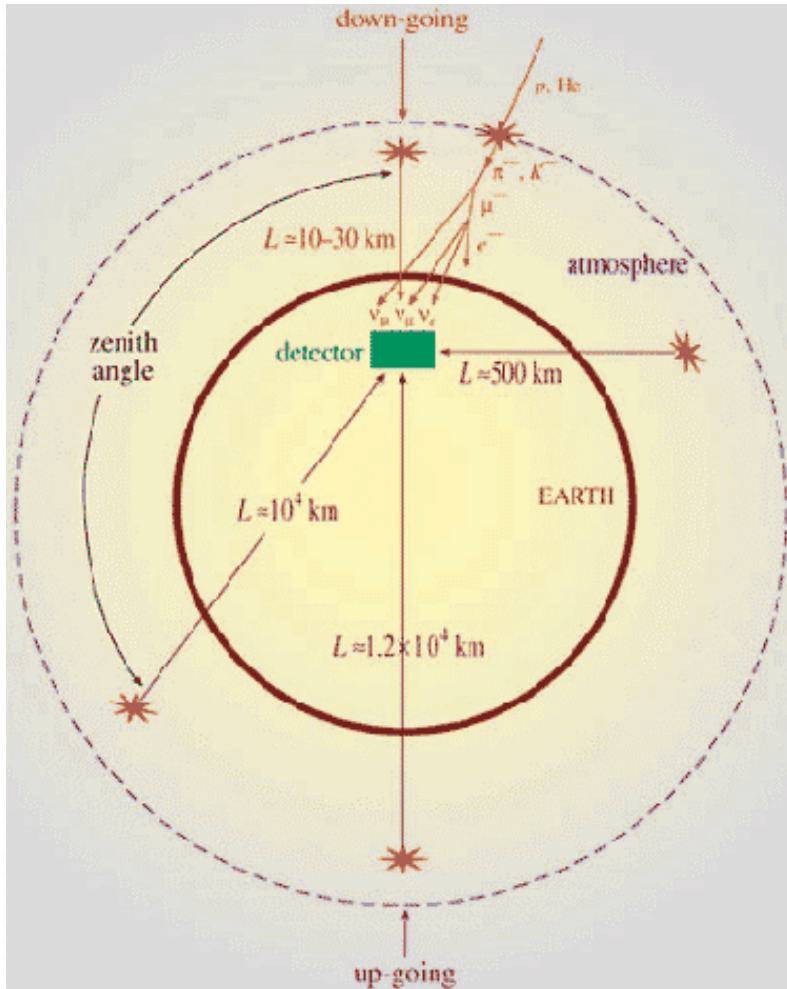
Selezione degli eventi in MACRO

3 Topologies of neutrinos detected:

- Upward Throughgoing μs ($\langle E_\nu \rangle \sim 100$ GeV): T.o.F. ($\sim 50\%$ through 3 scintillator planes)
- IU $\mu \equiv$ Internal Upgoing μs ($\langle E_\nu \rangle \sim 4$ GeV): T.o.F.
- ID $\mu \equiv$ Internal Downgoing μs + UGS $\mu \equiv$ UpwardGoing Stopping μs ($\langle E_\nu \rangle \sim 4$ GeV): topological constraints



Selezione dei "muoni dal basso"



Upward-going μ s discriminated against down-going atmospheric μ s ($\sim 5 \cdot 10^5$ times more numerous) through T.o.F.:

$$\frac{1}{\beta} = \frac{c\Delta T}{L} \quad (8)$$

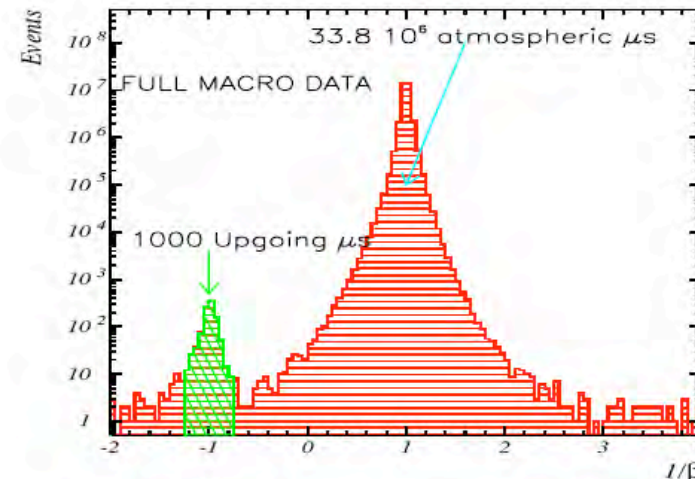
In our convention $1/\beta \sim -1(+1)$ for $\mu \uparrow (\downarrow)$ s

Upward-going μ definition: $1/\beta \in [-1.25, -0.75]$

$\sim 200 \text{ gr/cm}^2$ crossed in rock absorber for oscillation analysis to reject upward- π background (Astrop. Phys. **9** (1998) 105)

100 events with MACRO incomplete (26 events with 1/6 of lower detector, 1.38 yr, Mar 89-Nov 91; 19 events during construction, 0.2 yr, 55 events with lower detector, 0.41 yr, Dec 92-Jun 93) (Phys. Lett. **B357** (1995) 481)

1000 events with full detector, 29 Apr 94-22 Sep 99, 4.42 y (Phys. Lett. **B434** (1998) 451)

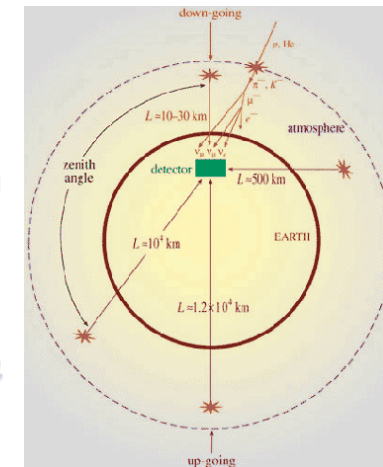


Calcolo del numero di eventi di μ^\pm aspettati in un rivelatore esteso per neutrini astrofisici (l'esempio di MACRO)

The response curve of MACRO for a source of declination δ for a neutrino spectrum $\frac{d\Phi_\nu}{dE_\nu} \propto E^{-\gamma}$:

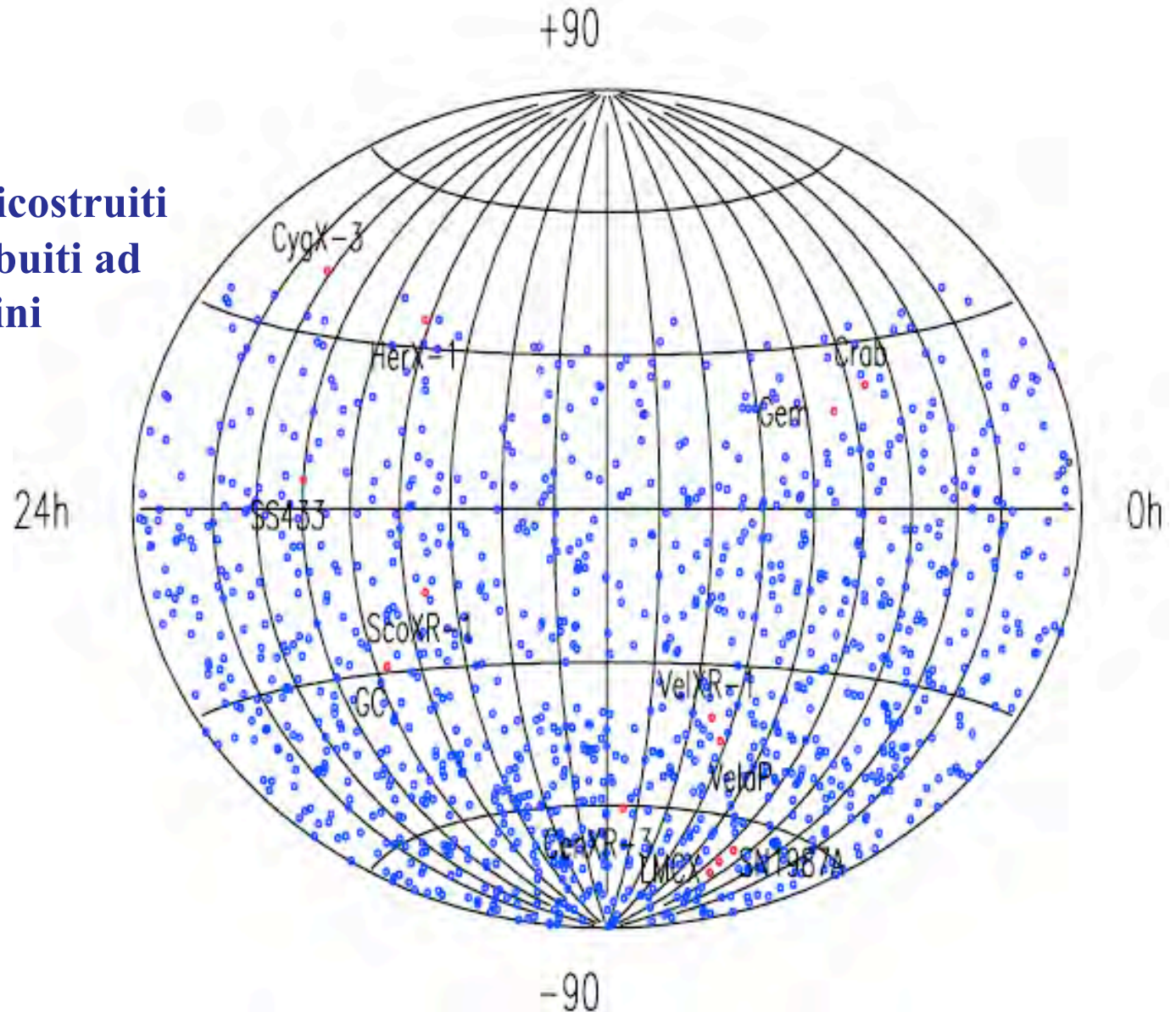
$$\Phi_\mu(E_\mu^{th}, E_\nu, \delta) = N_A \int_{E_\mu^{th}}^{E_\mu^{max}} \frac{d\sigma_\nu}{dE'_\mu}(E'_\mu, E_\nu) R_{eff}(E'_\mu, E_{th}^\mu) Area(E'_\mu, \delta) \Phi_\nu(E_\nu) dE'_\mu$$

with absorption: $\times e^{-N_A \sigma_{tot} X(\cos \theta)}$

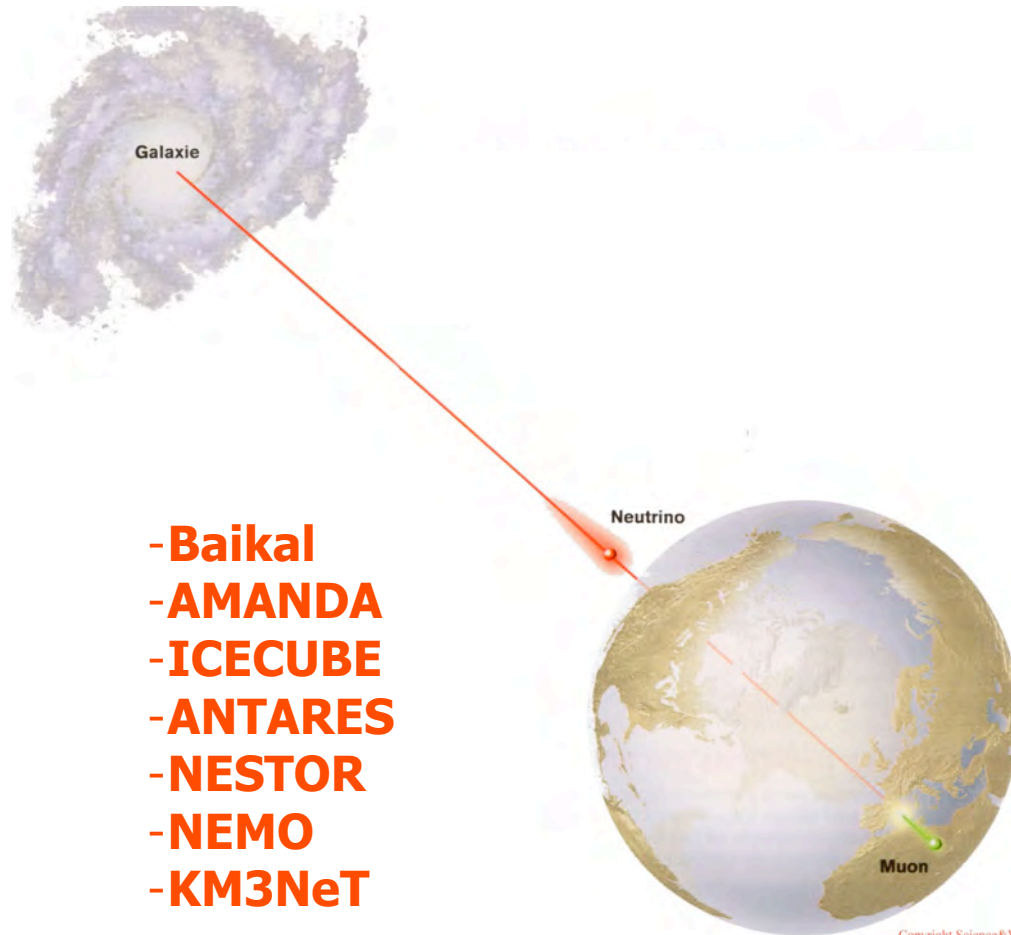


La mappa del cielo ricostruita da MACRO

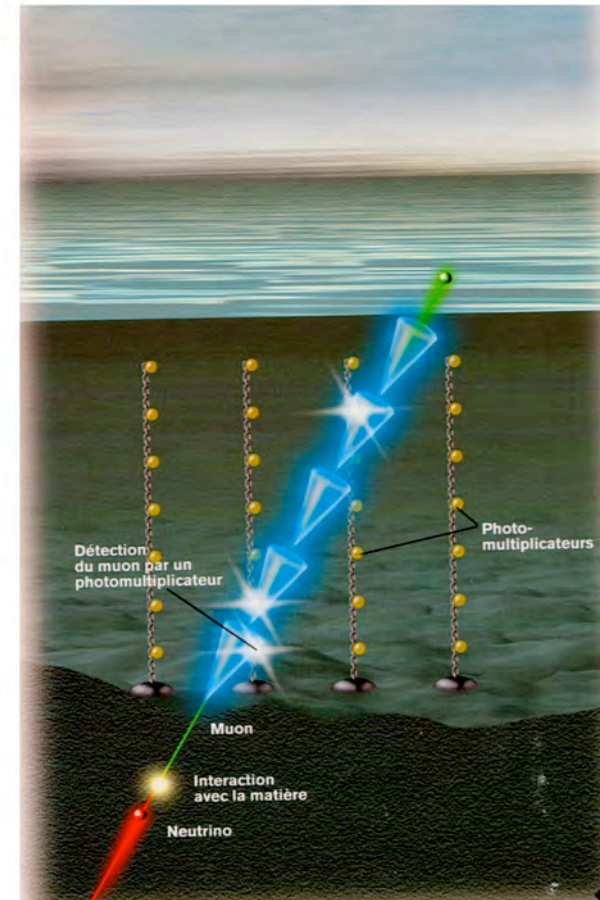
Piu' di 1100 μ ricostruiti
“upgoing” attribuiti ad
eventi da Neutrini
Astrofisici



Telescopi per neutrini



- Baikal
- AMANDA
- ICECUBE
- ANTARES
- NESTOR
- NEMO
- KM3NeT

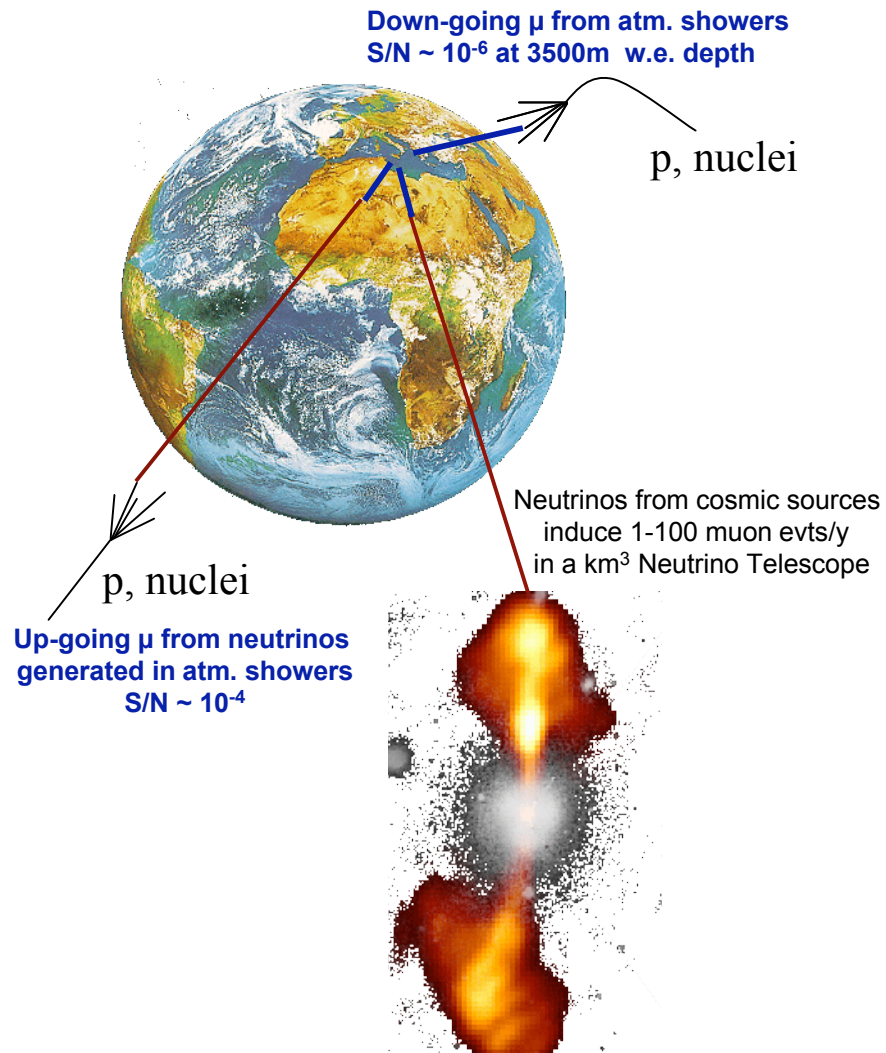


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Apparati per la rivelazione della luce Cherenkov indotta in acqua/ghiaccio dal passaggio di muoni relativistici originati da interazioni di neutrini di H.E.

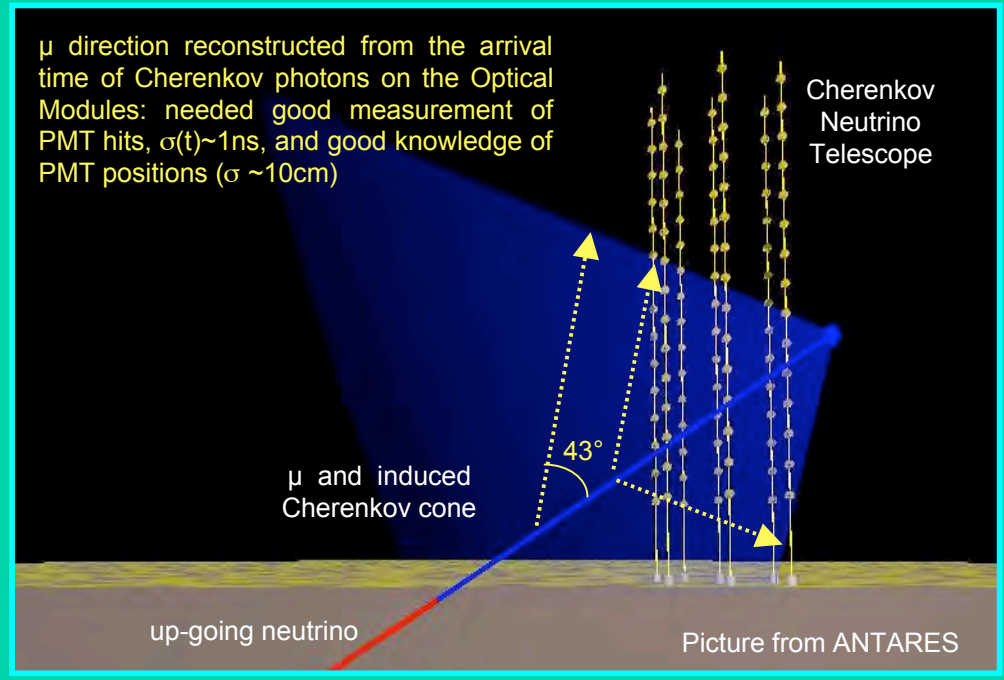
Il principio di rivelazione dei Telescopi Cherenkov per neutrini

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



- Atmospheric neutrino flux $\sim E_\nu^{-3}$
- Neutrinos flux from cosmic sources $\sim E_\nu^{-2}$
 - Search for neutrinos with $E_\nu > 1-10 \text{ TeV}$
- $\sim \text{TeV}$ 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

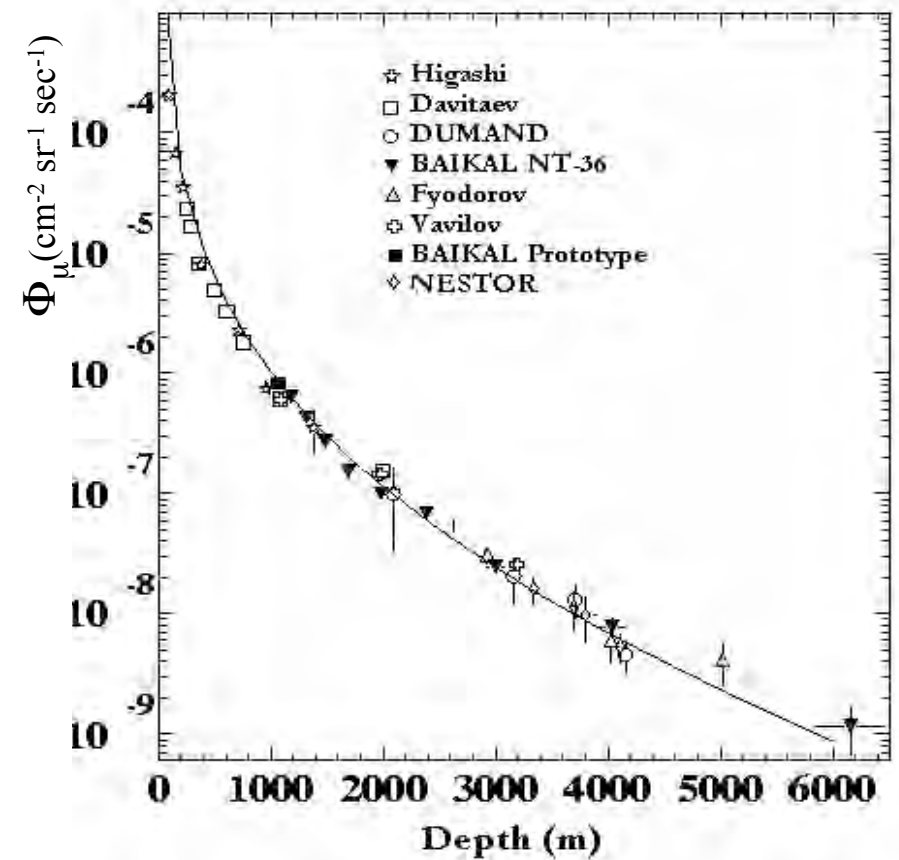
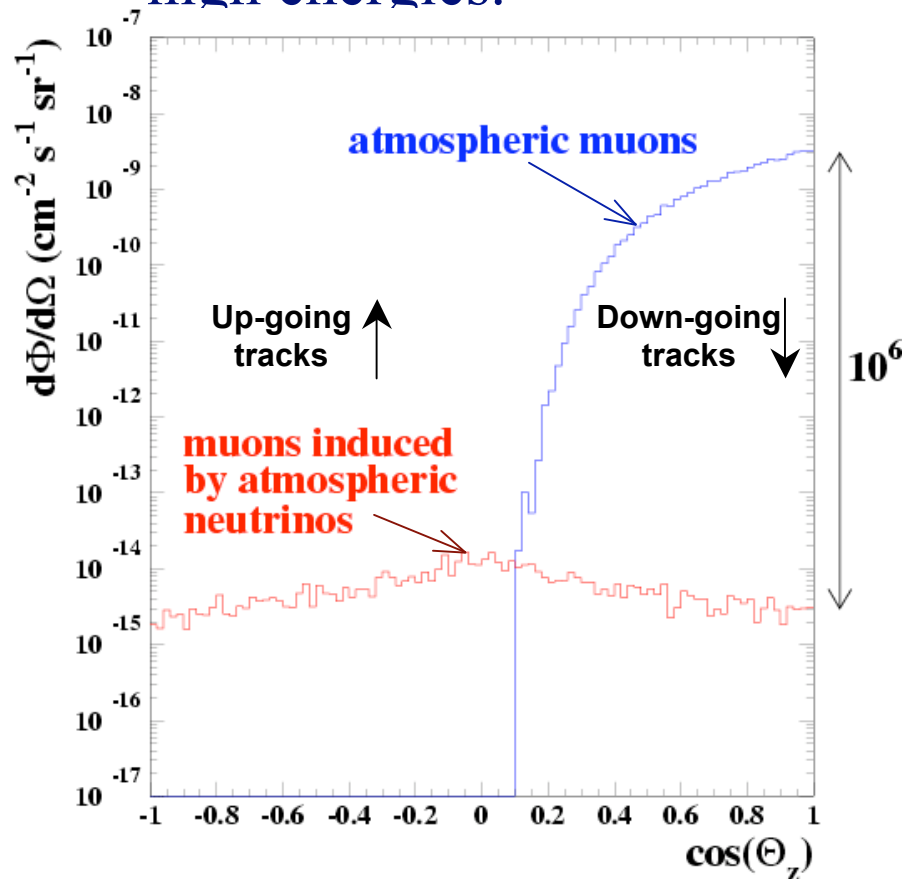
$$\text{For } E_\nu \geq 1 \text{ TeV } \theta_{\mu\nu} \sim \frac{0.7^\circ}{\sqrt{E_\nu [\text{TeV}]}}$$



I muoni "dal basso" originati dalle interazione dei neutrini atmosferici, sono il "background" residuo

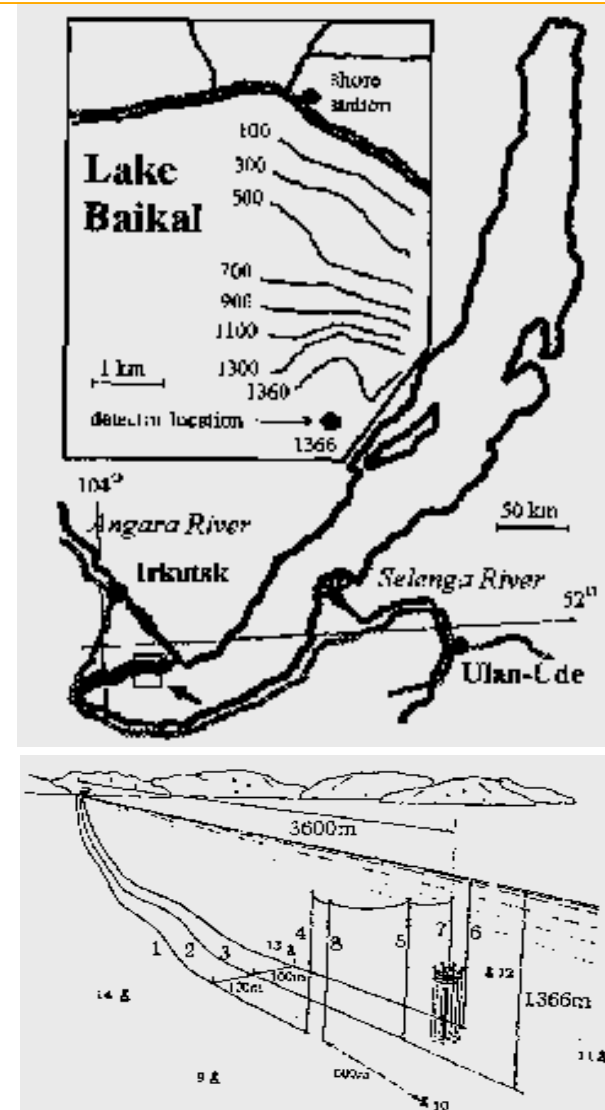
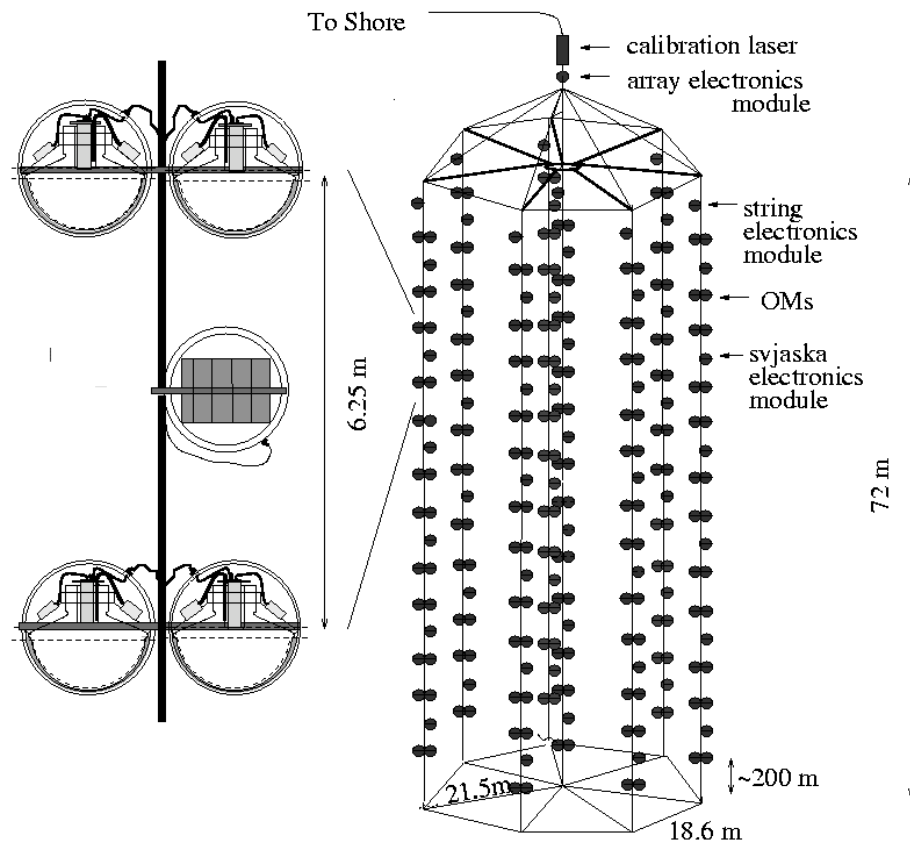
Muons can penetrate several km of water if $E_\mu > 1\text{TeV}$;

Identification of cosmic ν 's from above: needs showers or very high energies.



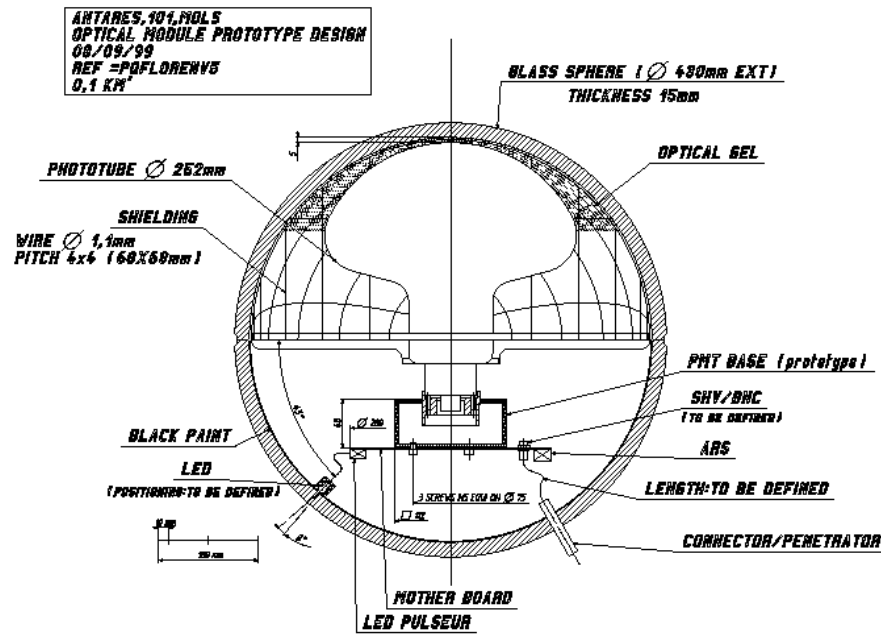
Baikal, il progetto pioniere

Lago Baikal, Siberia
1993 → 36 moduli ottici
1998 → 192 moduli ottici

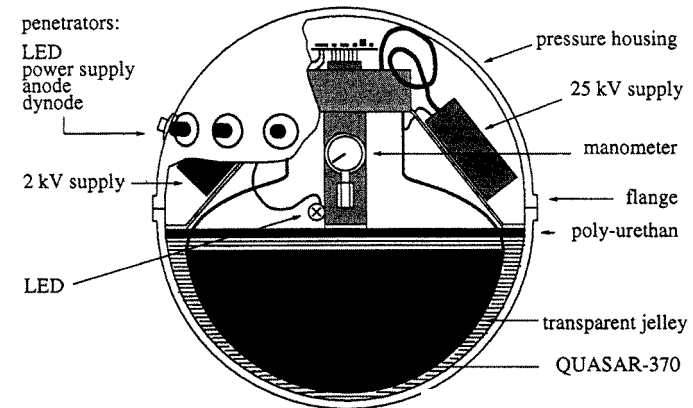
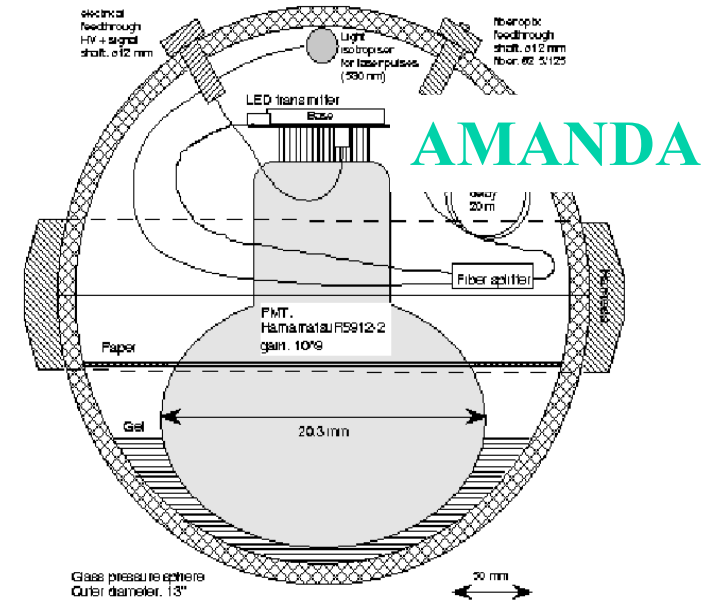


Moduli ottici per telescopi di ν sottomarini

Fotomoltiplicatori da 8÷15" in sfere di vetro, diametro 13-17" resistenti alla pressione (300-400 atm)



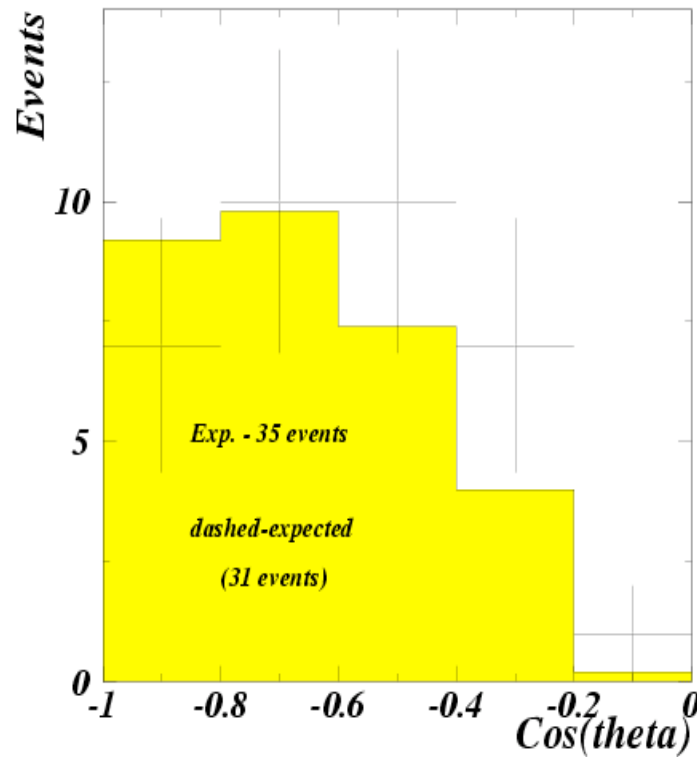
ANTARES



BAIKAL

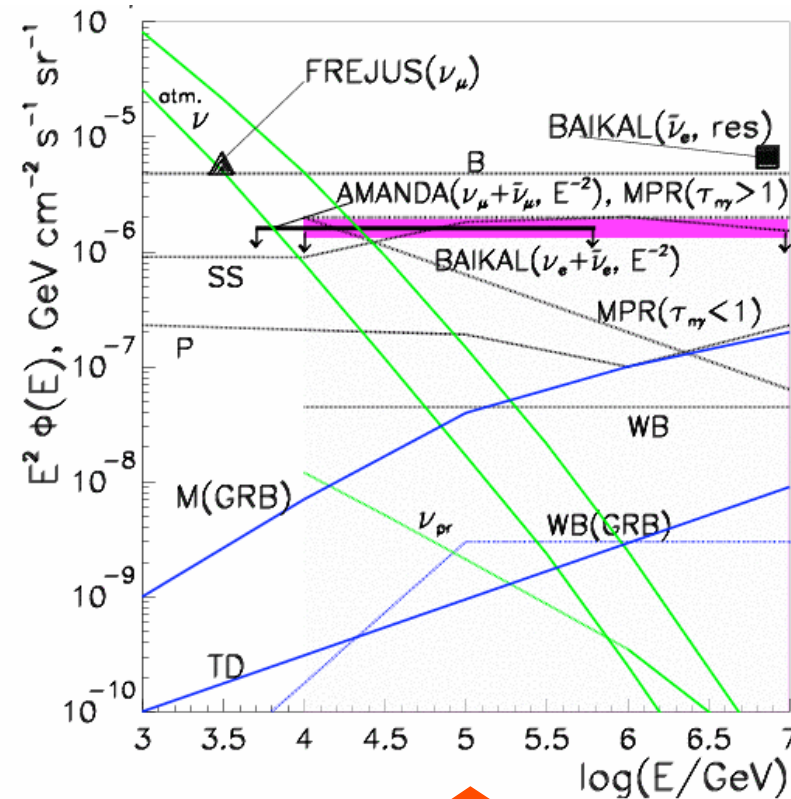
Primi risultati da Baikal

Muoni "dal basso"



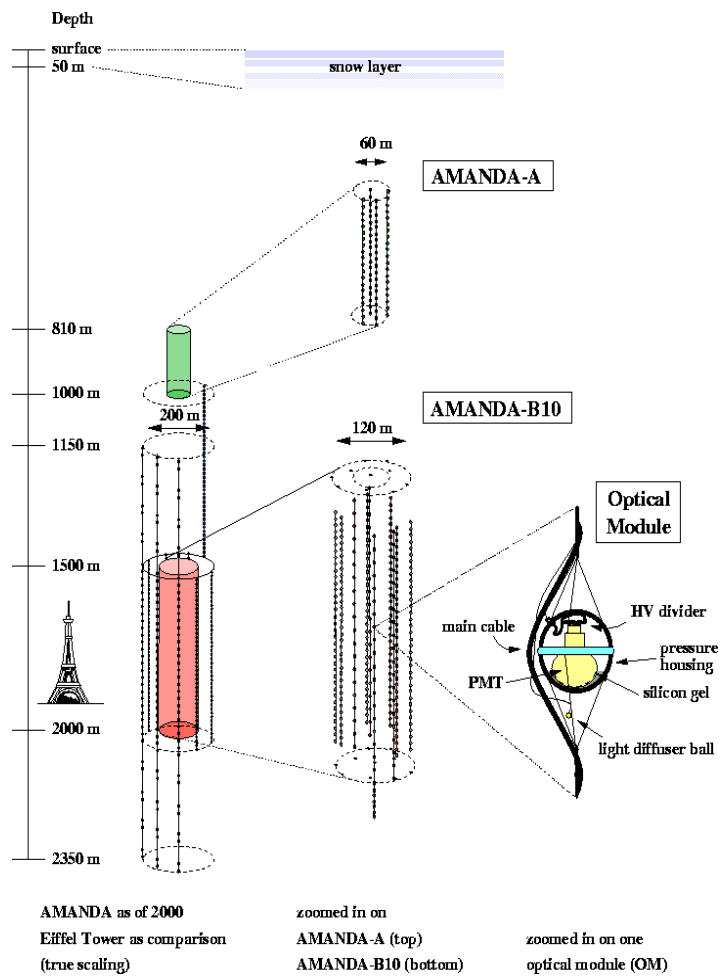
Neutrini atmosferici

Nuovi Limiti sui flussi di ν astrofisici

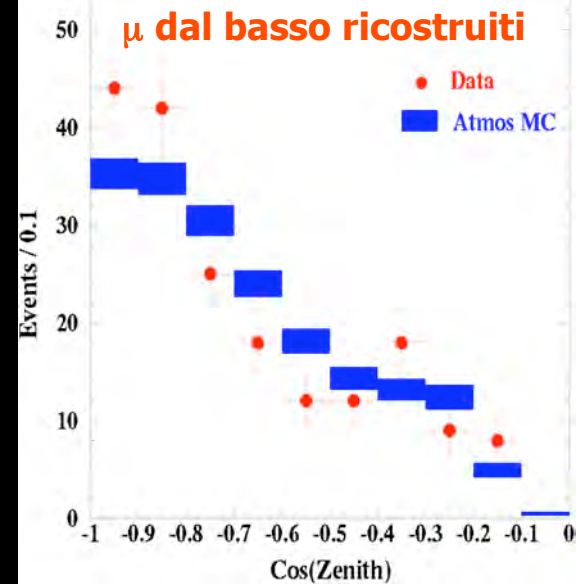
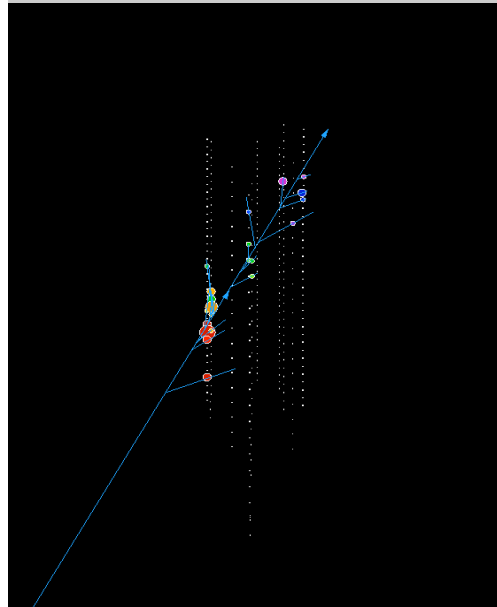


Limiti sui flussi di neutrini

AMANDA – Polo Sud – 2 km di profondità

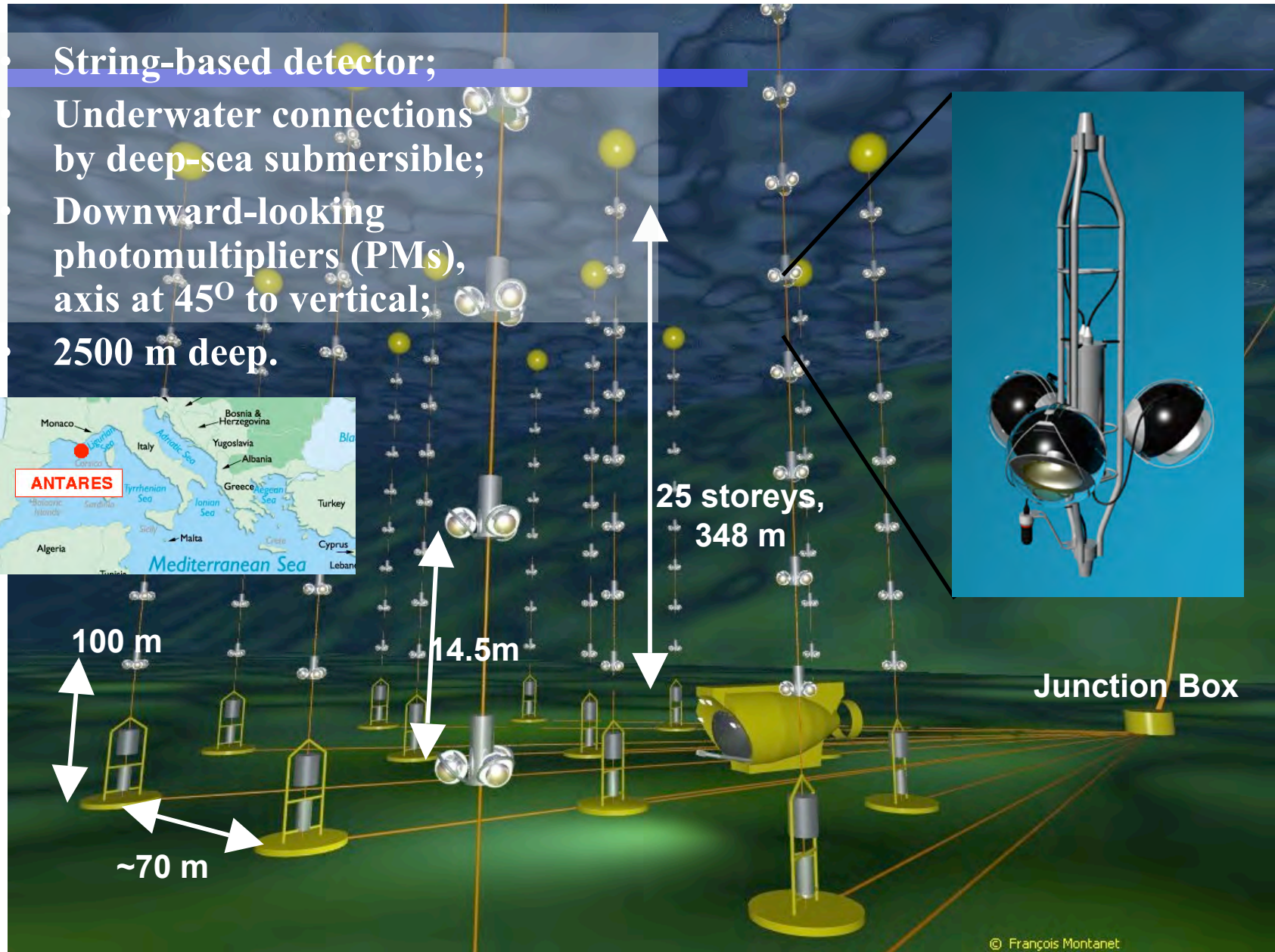


**Un problema: il ghiaccio
diffonde la luce, difficile la
ricostruzione delle tracce**



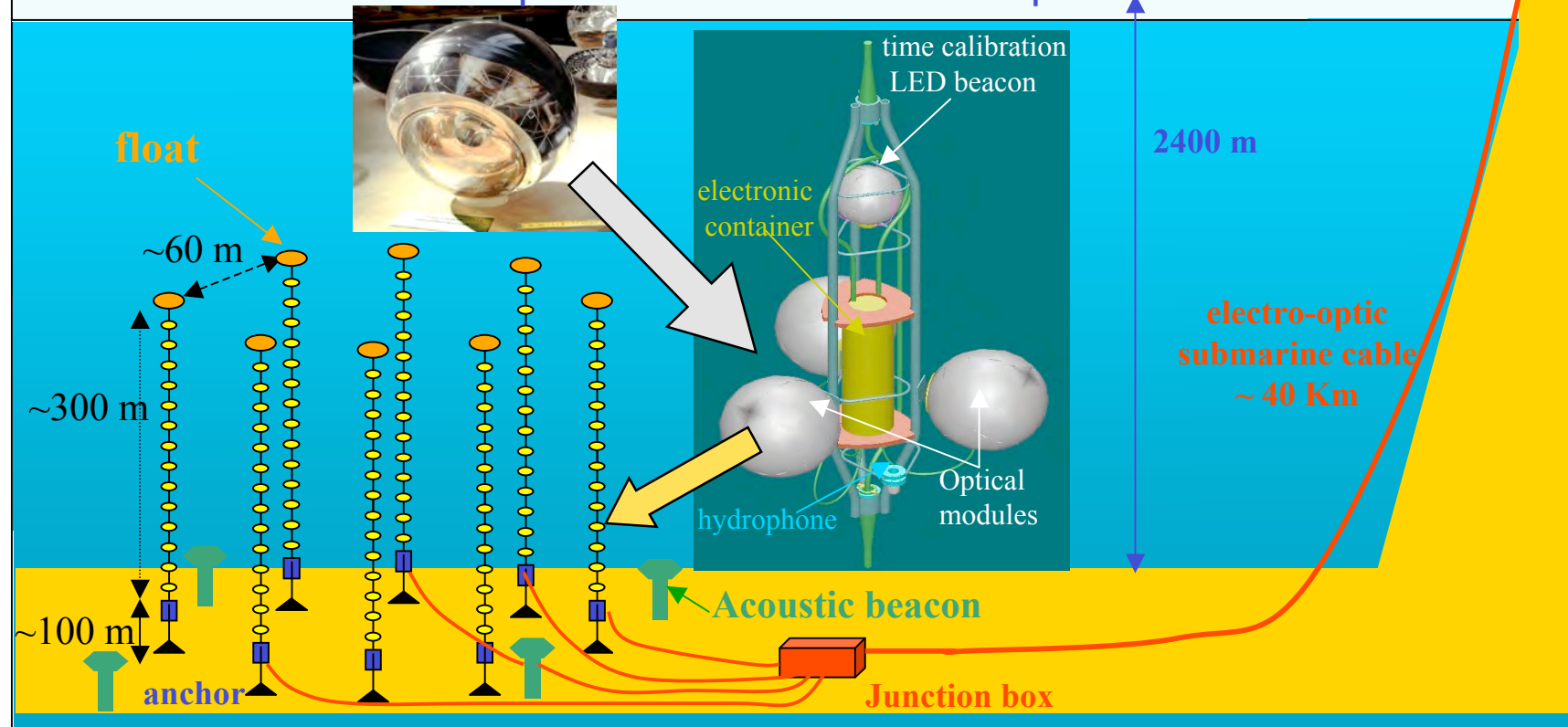
L'esperimento ANTARES

- String-based detector;
- Underwater connections by deep-sea submersible;
- Downward-looking photomultipliers (PMs), axis at 45° to vertical;
- 2500 m deep.



Il progetto ANTARES

Area efficace 0.1 km^2 , 12 "stringhe" verticali, 900 PMTs –
La costruzione cominciata nel 2002 è stata completata nel
2008. Il rivelatore ha acquisito dati anche se incompleto.

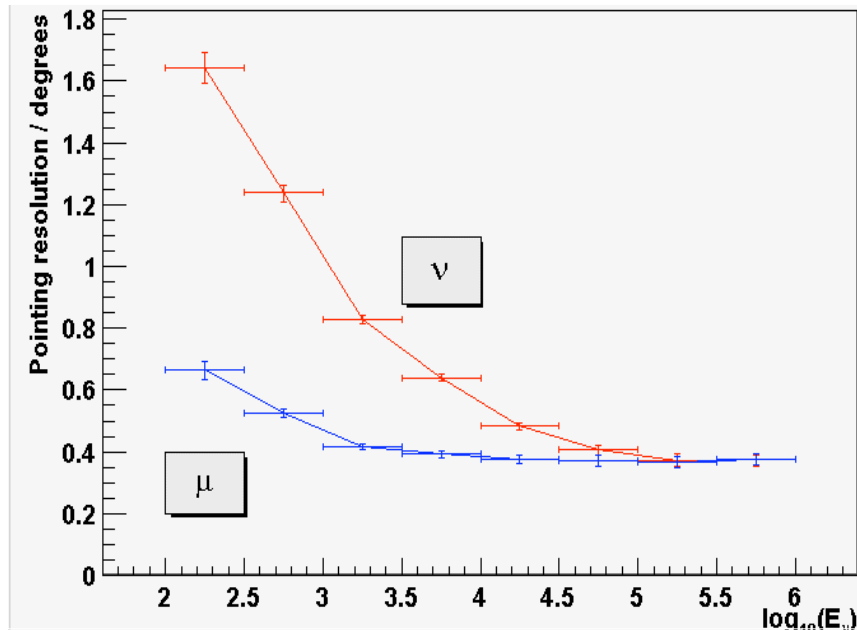


Una 13^a stringa è dedicata allo studio di parametri ambientali a completamento del rivelatore ottico

Risoluzione angolare ed in energia di ANTARES-0.1 km²

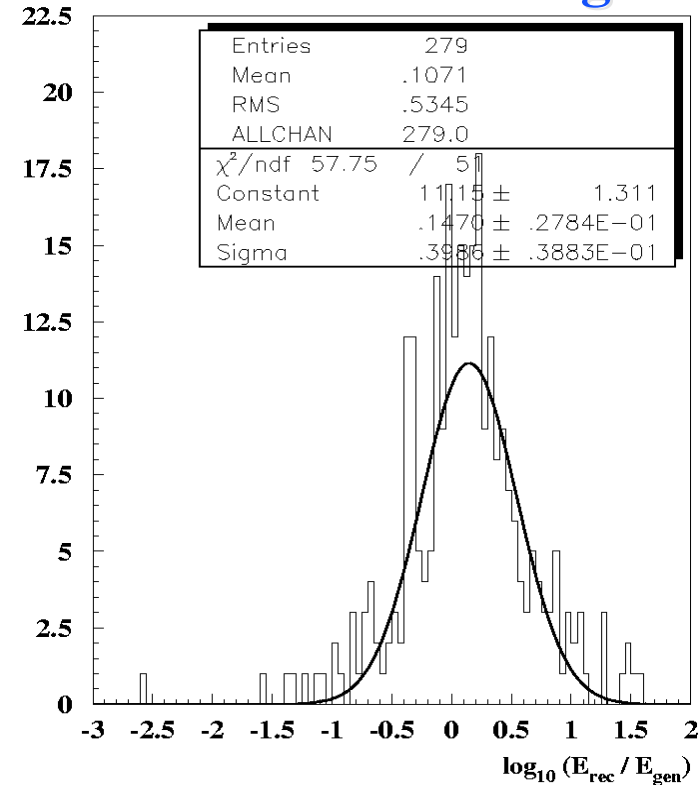
Simili a quelle degli altri rivelatori "in acqua" (BAIKAL, NEMO, NESTOR)

Risoluzione angolare



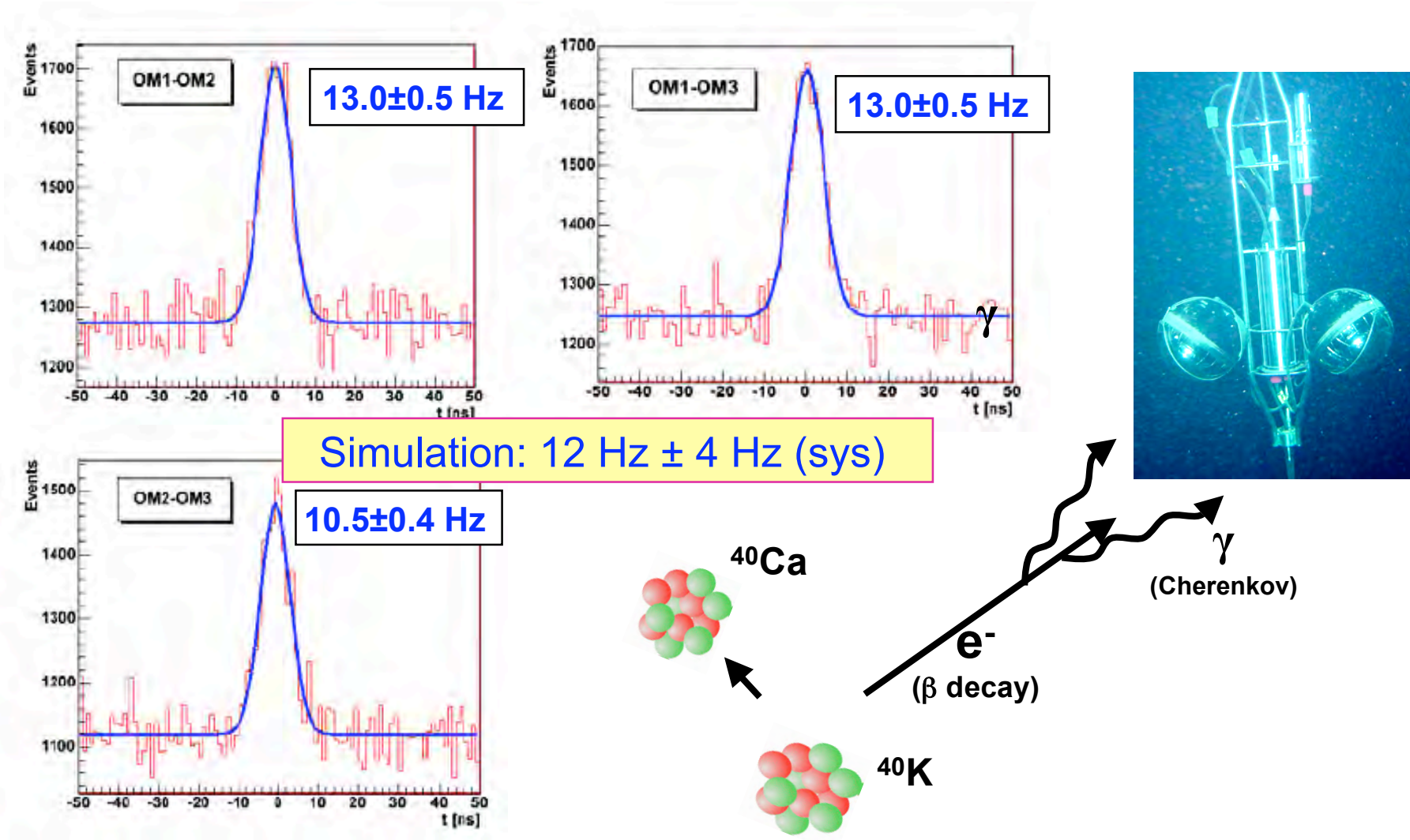
- $E_\nu < 10 \text{ TeV}$ errore angolare dominato dall'angolo fra ν e μ .
- $E_\nu > 10 \text{ TeV}$ errore angolare $\sigma_\theta < 0.4^\circ$ (errore di ricostruzione).

Risoluzione in energia

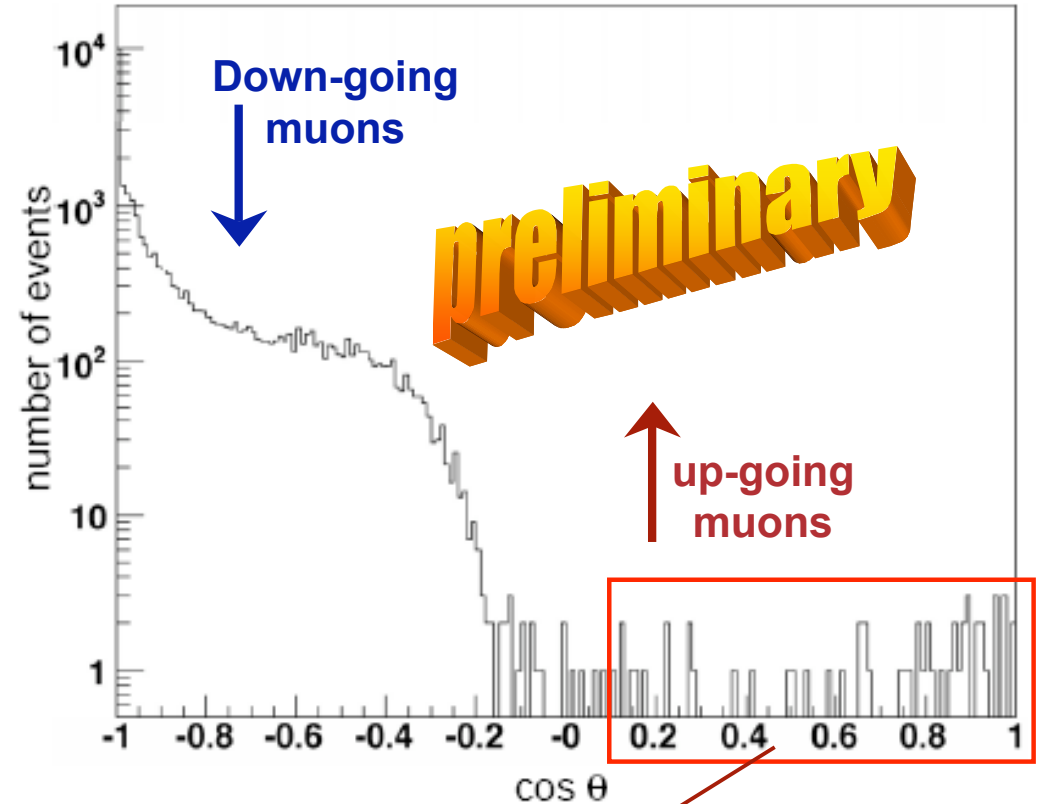
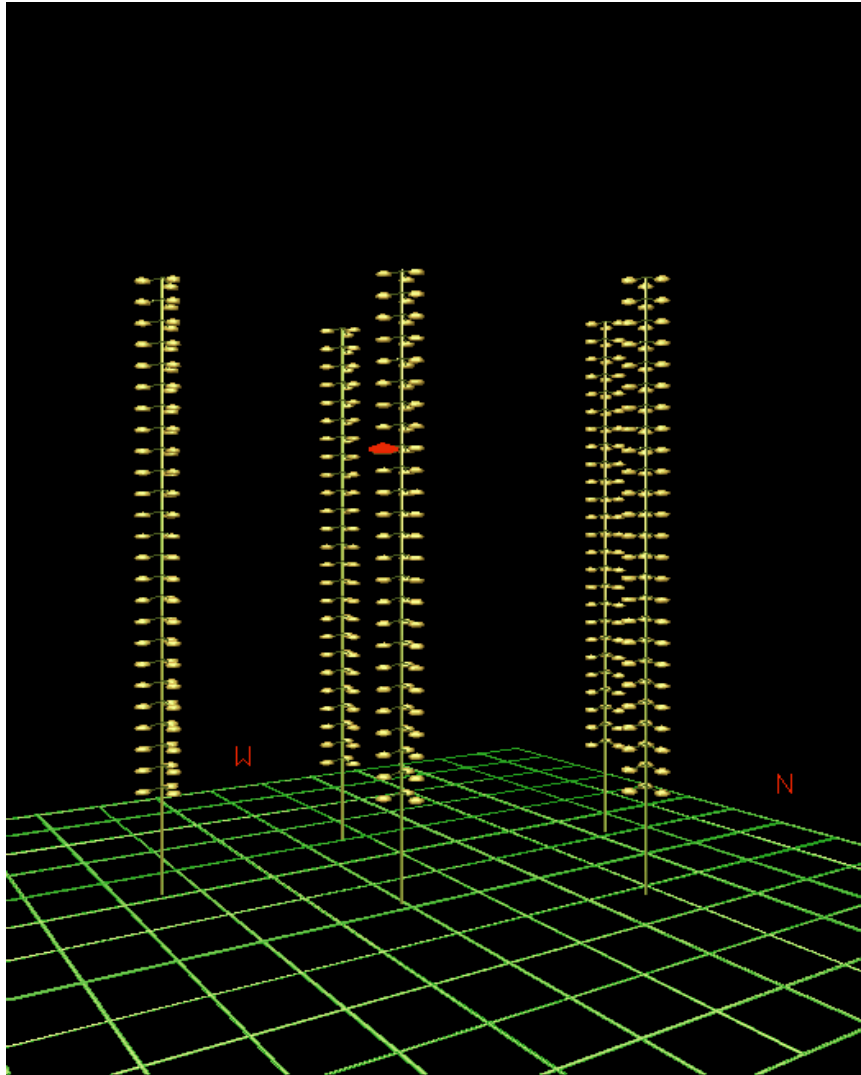


- $\sigma_E / E \approx 3$ ($1 \text{ TeV} \leq E \leq 10 \text{ TeV}$)
- $\sigma_E / E \approx 2$ ($E > 10 \text{ TeV}$)

ANTARES: il rumore ottico prodotto dal decadimento del ^{40}K studiato con la coincidenza “stretta” fra due PMT vicini



ANTARES: ...segnali da neutrini astrofisici con 5 Linee !



neutrino candidates

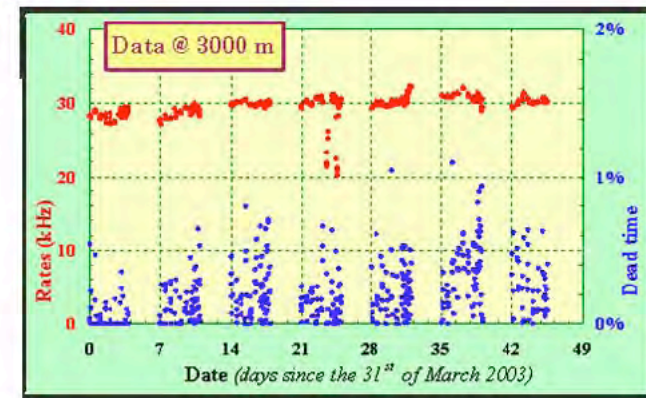
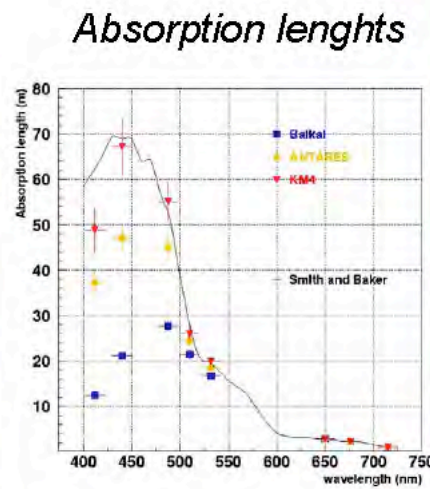
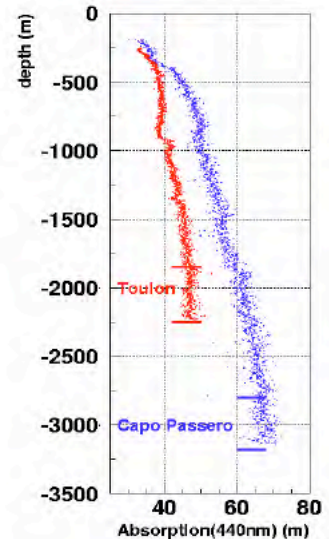
$4.35 \cdot 10^6$ reconstructed events
(from February to April) 2007

- **Quality cut for upgoing tracks**
- **No alignment used**

Il progetto NEMO

1998-2004 NEMO R&D and site selection

- Extensive site exploration of Mediterranean Sea: selected Capo Passero site near Catania, depth 3500 m
 - best optical properties out of studied sites $L_a \sim 70\text{m} @ 440\text{nm}$
 - No seasonal variations of water optical properties
 - extremely low background from bioluminescence
 - deep Sea water current are low (3cm/s avg.) and stable
 - Wide abyssal plain, far from the shelf break, allows for possible reconfigurations of the detector layout
- R&D towards km^3 : detector architecture, mechanical structures, electronics, readout, cables ..., junction box, all technological issues;
- Simulation

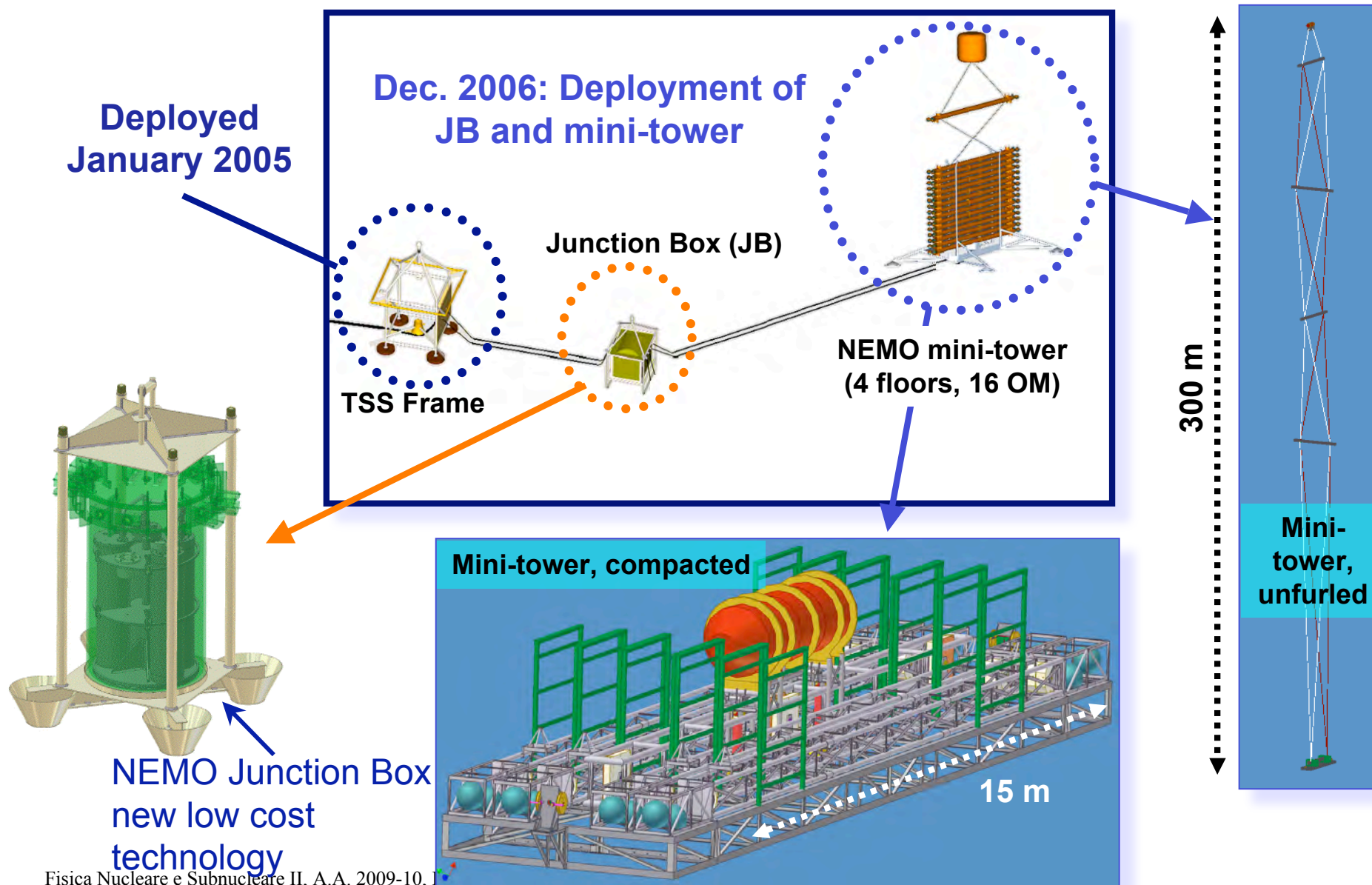


➤ PMT: 10"
➤ Thres: ~ 0.5 SPE

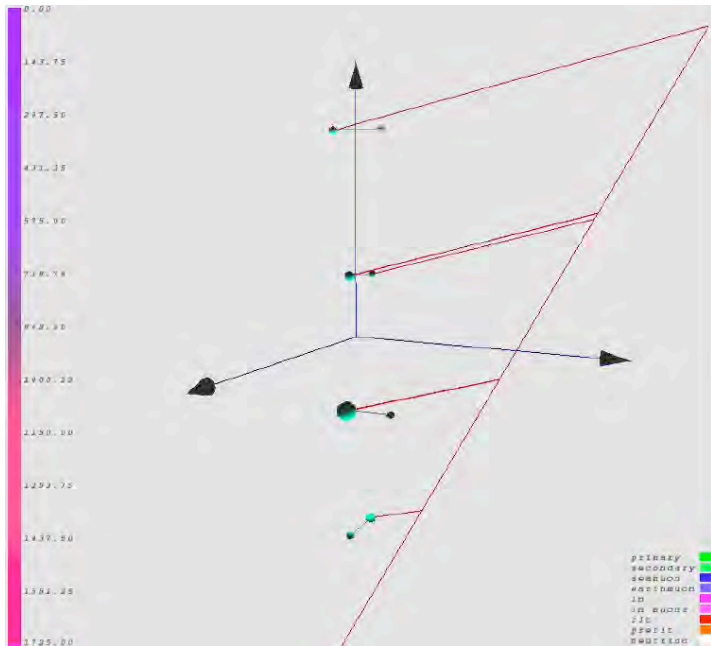
Fraction of time
 $R > 200$ kHz

NEMO Fase1: una torre di 4 piani @ 2000m di profondità

In the INFN NEMO Test Site, 20 km East of Catania



NEMO-Fase1- ricostruiti muoni atmosferici



January 2007
Run 23 file 1
Event 356615
11 PMT involved

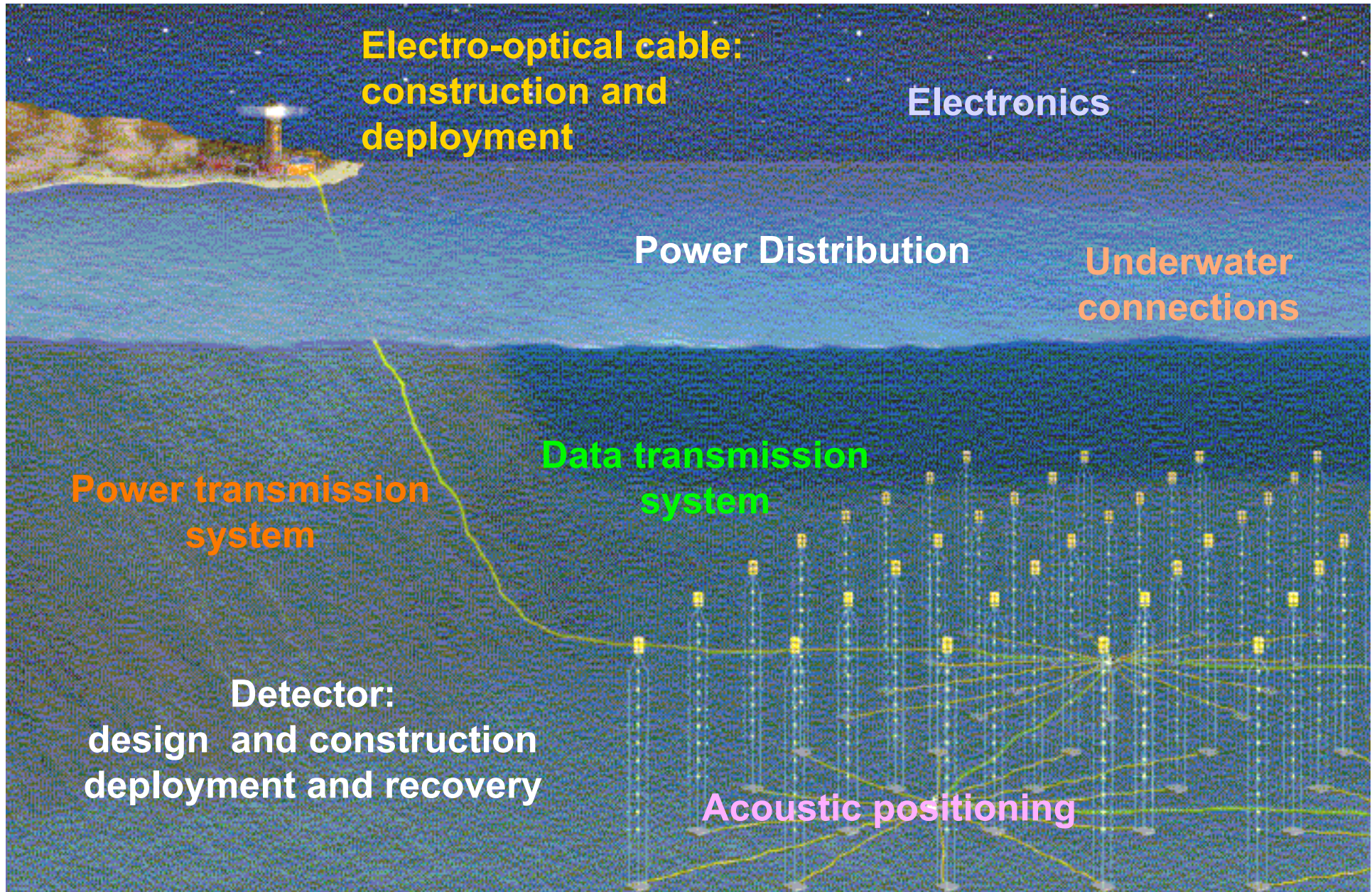
- Trigger local coincidence up-horizontal ($\Delta t=20\text{ns}$)
- Aart Reconstruction
- Background rejection -> causality with the highest in charge and in coincidence



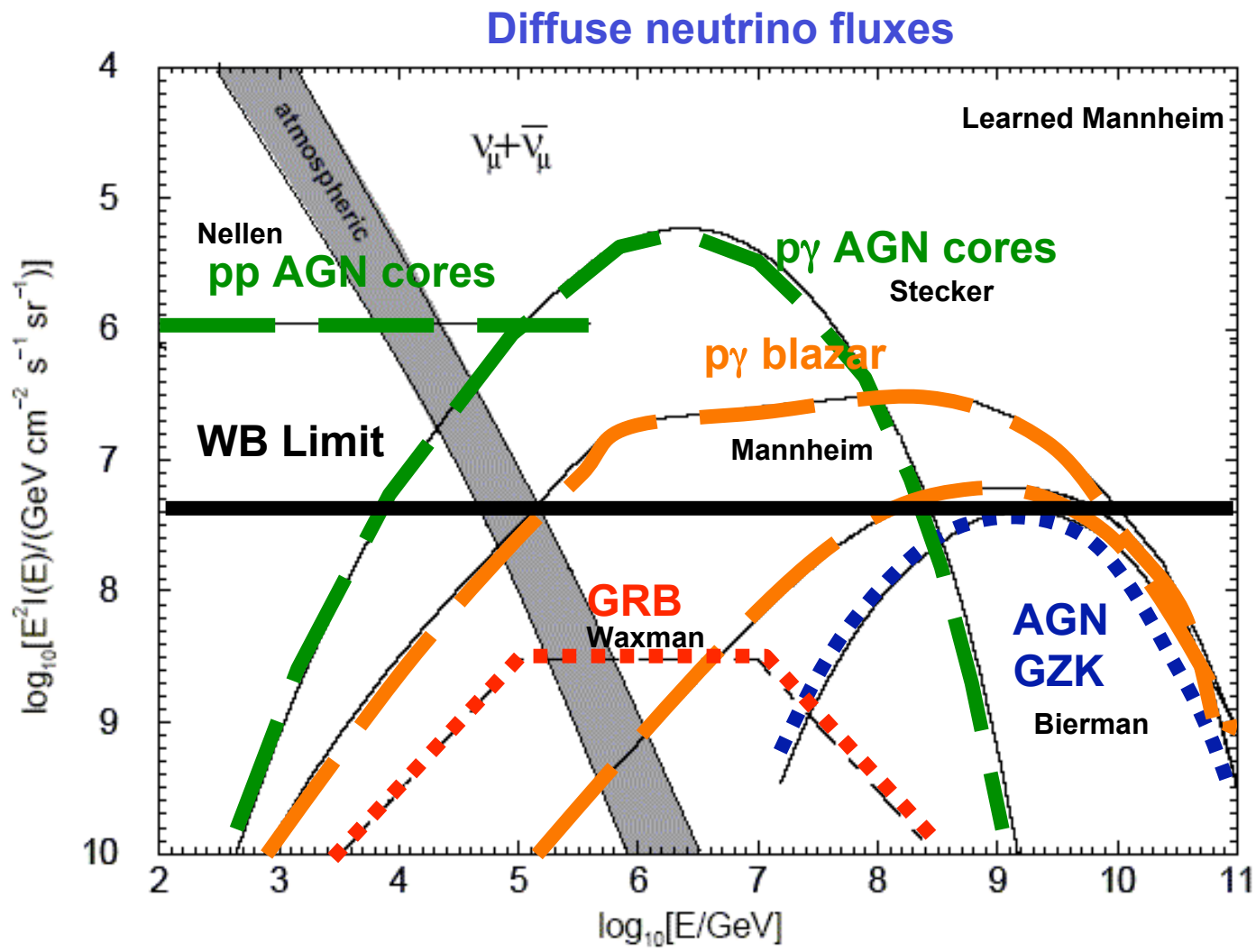
January 2007
Run 23 file 1
Event 189722
11 PMT involved

- Trigger local coincidence up-horizontal ($\Delta t=20\text{ns}$)
- Aart Reconstruction
- Background rejection -> causality with the highest in charge and in coincidence

Towards the Mediterranean km³



Possible extragalactic sources and fluxes



Candidate sources of High Energy Neutrinos and expected events

$$\frac{N_{\mu}(E_{\mu,\min}, \vartheta)}{AT} = \int_{E_{\mu,\min}}^{E_{\nu}} dE_{\nu} \Phi_{\nu}(E_{\nu}, \vartheta) \cdot P_{\nu\mu}(E_{\nu}, E_{\mu,\min}) \cdot e^{-\sigma_{\text{tot}}(E_{\nu})N_A Z(\vartheta)}$$

Neutrino flux

Probability to produce a detectable muon ($E_{\mu} > E_{\min}$)

Earth transparency

Expected events in a
1 km²
underwater
Cherenkov
Neutrino
Telescope

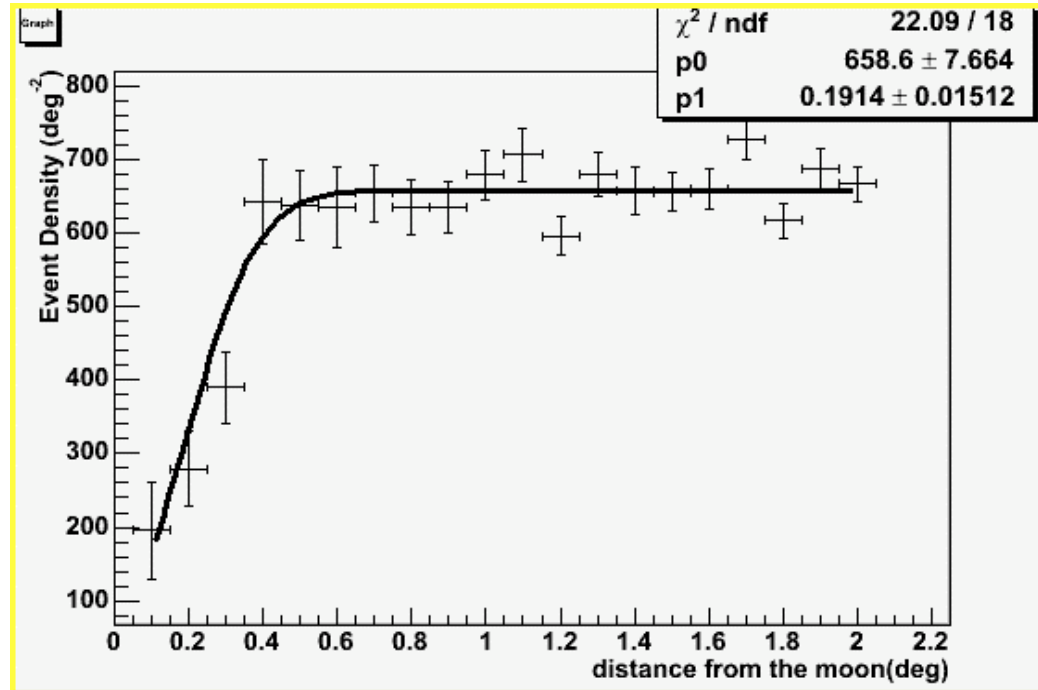
Diffuse fluxes

GZK neutrinos	0.5 / year
GRB (<i>Waxman</i>)	50 / year
AGN (thin) (<i>Mannheim</i>)	few / year
(thick)	>100 / year

Point-like sources

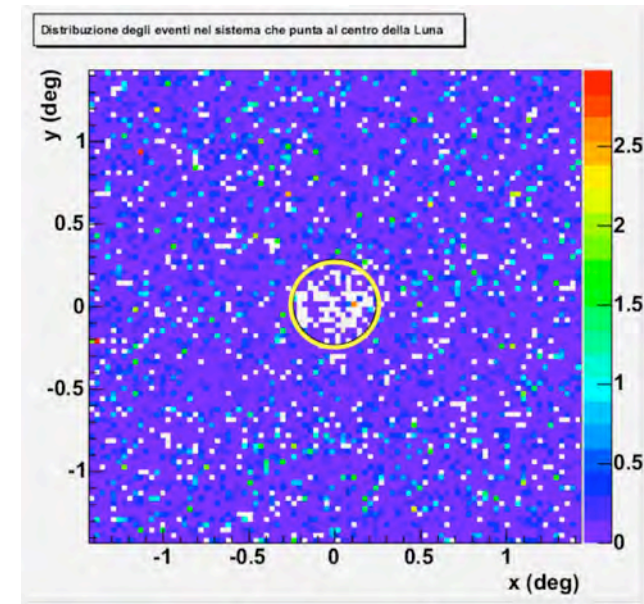
GRB (030329) (<i>Waxman</i>)	1-10 / burst
AGN (3C279) (<i>Dermer</i>)	few / year
Galactic SNR (RXJ1713, Vela) (<i>Aharonian, Vissani</i>)	few / year
Galactic MicroQuasar (<i>Distefano, Aharonian et al.</i>)	1-100 / year

Angular resolution and pointing accuracy



Observation of the Moon shadowing effect on the flux of atmospheric muons

(Simulated time = 1 year)



$$\frac{dN_{\mu}}{d\vartheta^2} = k \left(1 - \frac{\vartheta_{\text{moon}}}{2\sigma^2} e^{-\frac{\vartheta^2}{2\sigma^2}} \right)$$

$$k = 659 \pm 8 \text{ deg}^{-2}$$

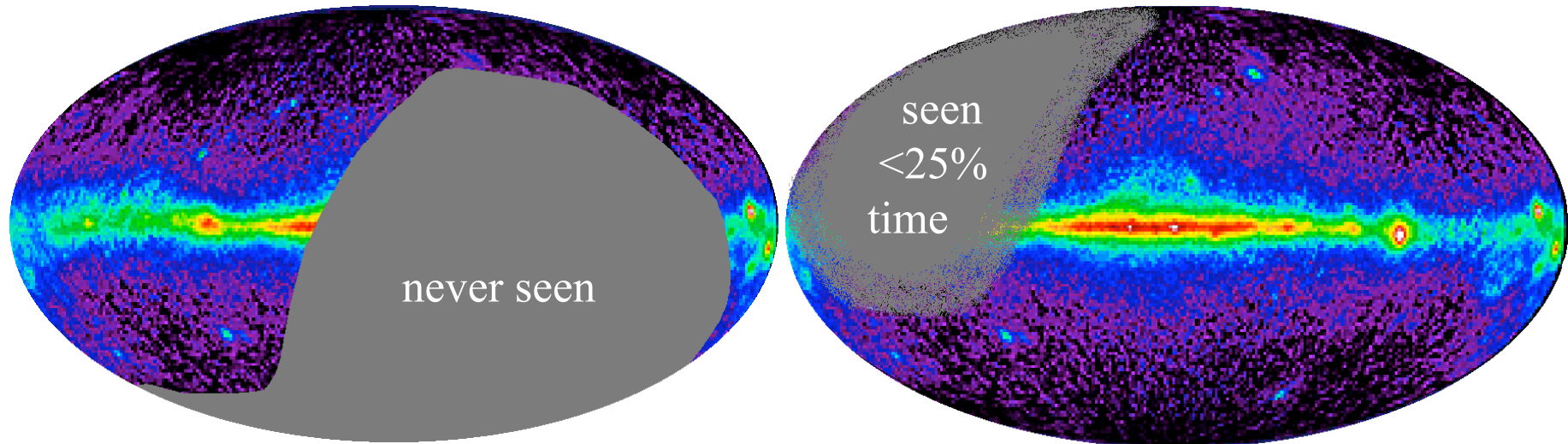
$$\sigma = 0.19 \pm 0.02 \text{ deg}$$

100 days needed to observe a 3σ effect

Quanti Telescopi per neutrini ??

Sarà importante "osservare" l'Universo in tutto l'angolo solido

Gamma ray flux >100 MeV observed by EGRET



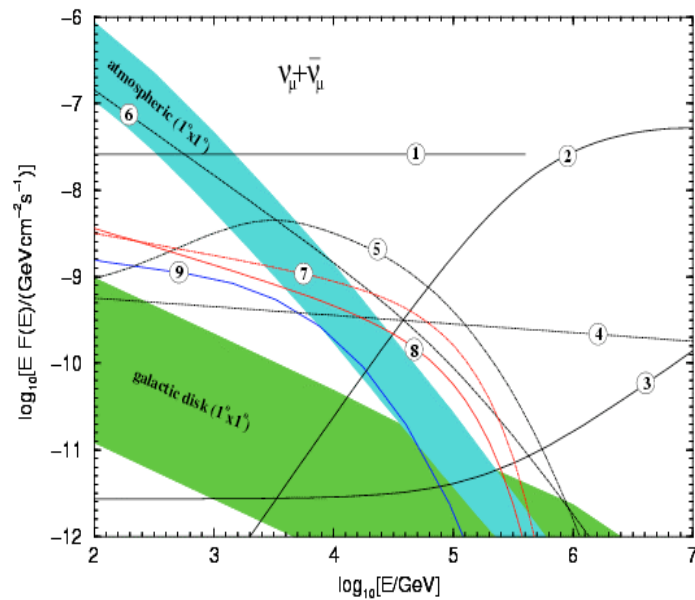
AMANDA, ICECUBE

ANTARES, Baikal, NEMO, NESTOR

EGRET Tipo di Sorgente	Numero di sorgenti	Viste dall'emisf. Nord	Viste dal Polo Sud
All	271	89%	43%
AGN	94	86%	52%
Pulsars	5	100%	40%
Non ident. Piano Galattico	55	93%	36%
Non ident. fuori Piano Gal.	116	90%	40%

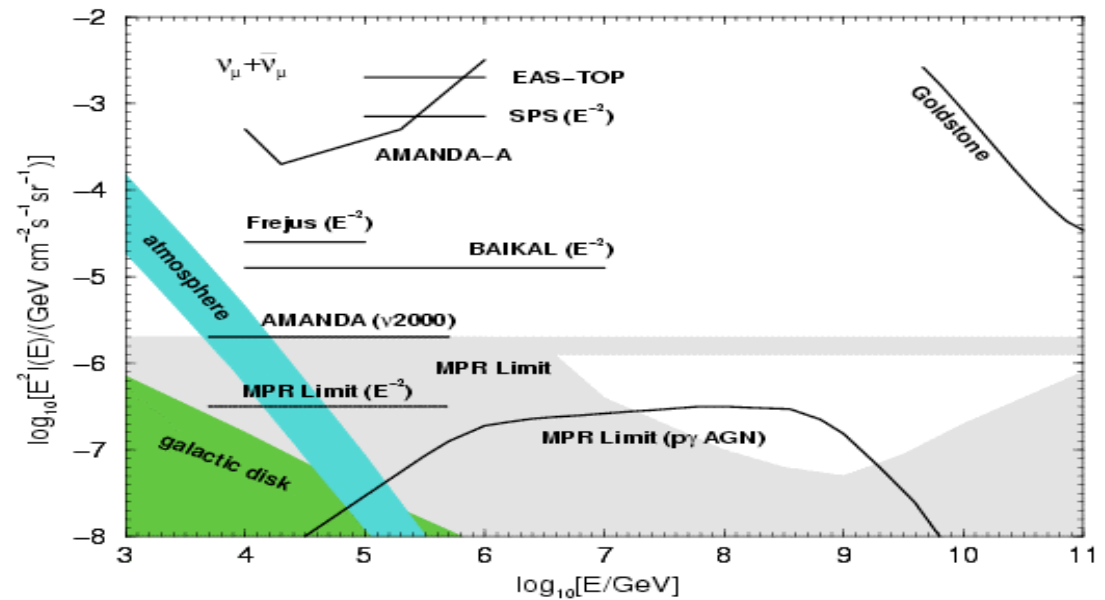
Molti modelli predicono flussi di ν da AGN...

modelli ...



Learned and Mannheim, 2000

Limiti Sperimentali

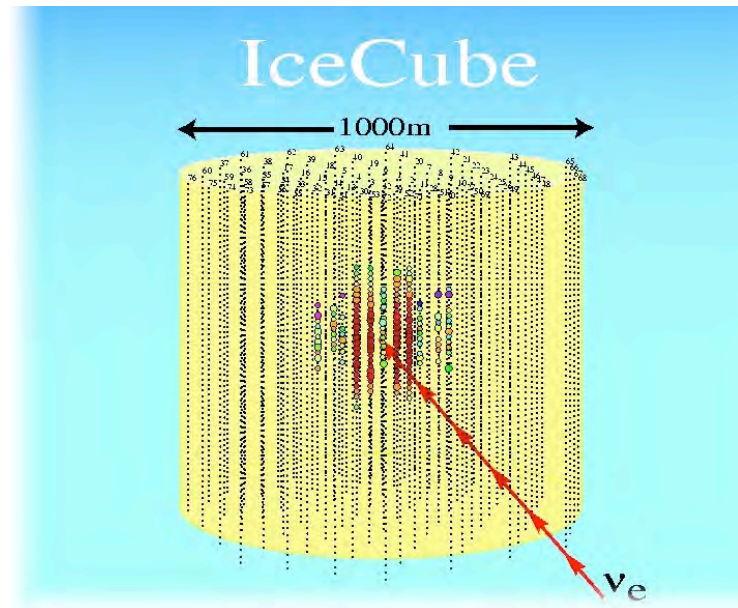
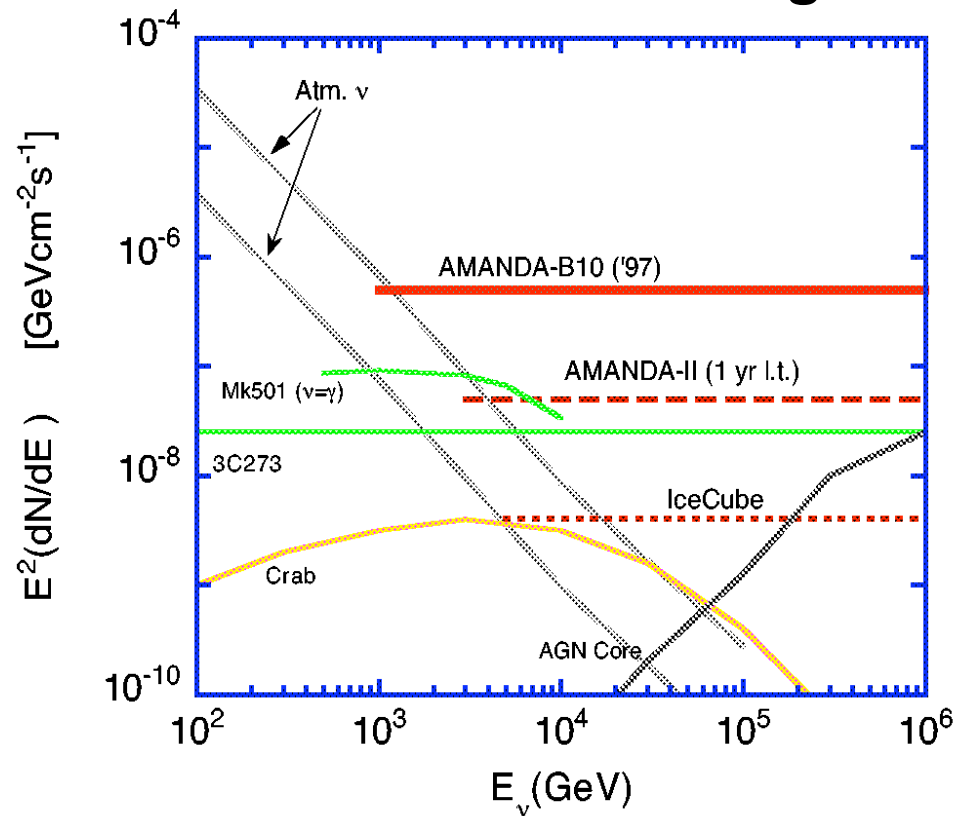


I limiti attuali sono vicini alle predizioni

Il futuro al Polo Sud: ICECUBE

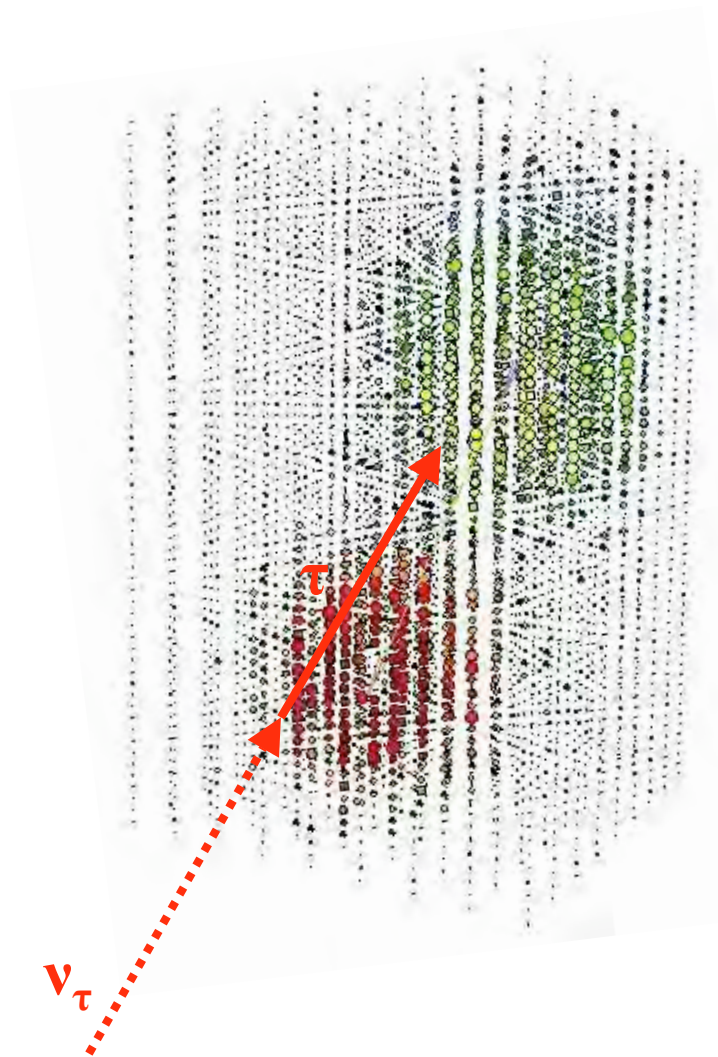
Un telescopio per neutrini nel ghiaccio da 1 Km³, in avanzato stato di realizzazione nel ~ 2008

Decisione del Congresso USA - Autunno 2001



- 86 stringhe, 60 PMT ognuna, in totale: 5160 moduli ottici
- $V \approx 1 \text{ km}^3$, $E_{\text{th}} \sim 0.5 \div 1 \text{ TeV}$

ICECUBE e la fisica in un telescopio da 1 km³



- Inizia l'astronomia con ν
- Aspettati 10÷100 eventi/anno da sorgenti puntiformi
- Confronto fra astronomia γ e ν
- Mappa dettagliata delle sorgenti racchiuse nell'angolo osservato
- Estensione dell'orizzonte di osservazione
- Chiara segnatura per eventi dovuti a correnti cariche di ν_τ (con $E \sim \text{PeV}$)
- ... l'imprevisto ...