Ingredienti per l'astronomia con neutrini

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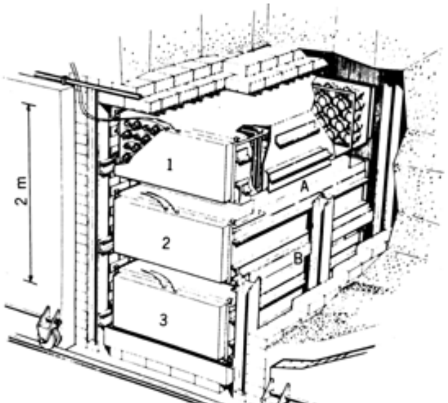
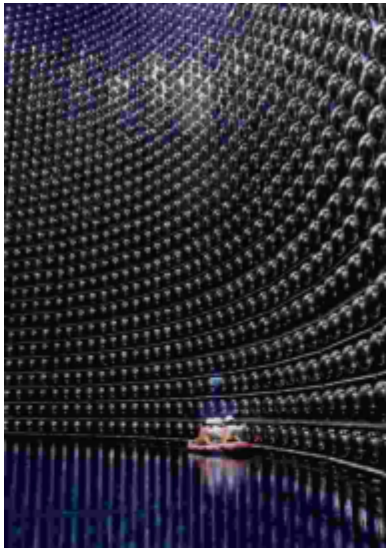
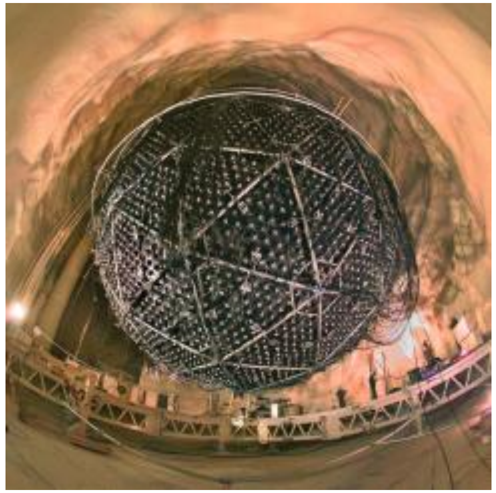
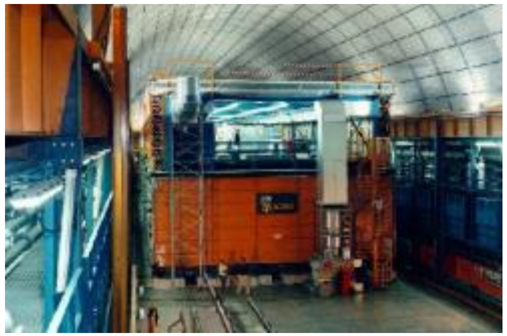
1. La fisica del neutrino (1954-2002) in tre slides



The experimental apparatus used by Reines and Cowan to detect the electron neutrino.

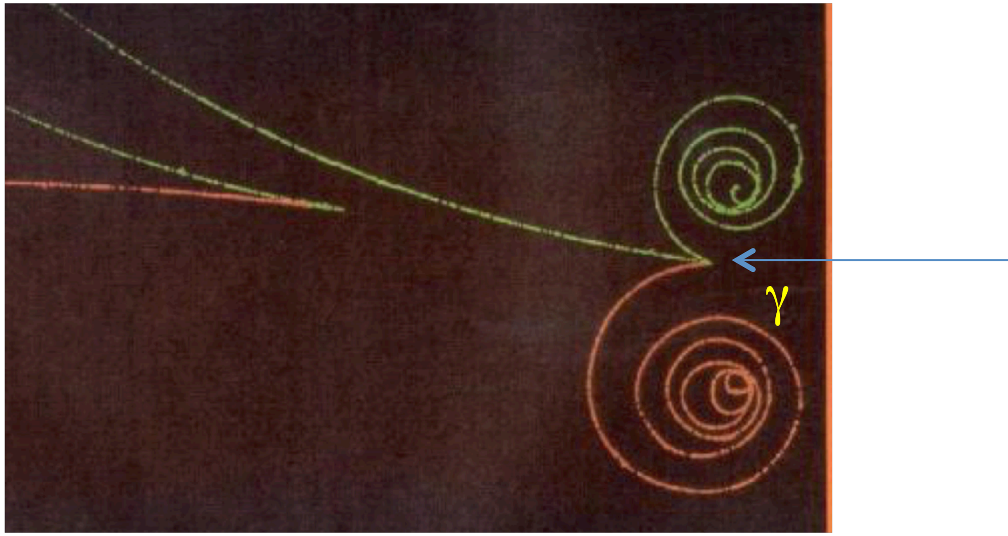




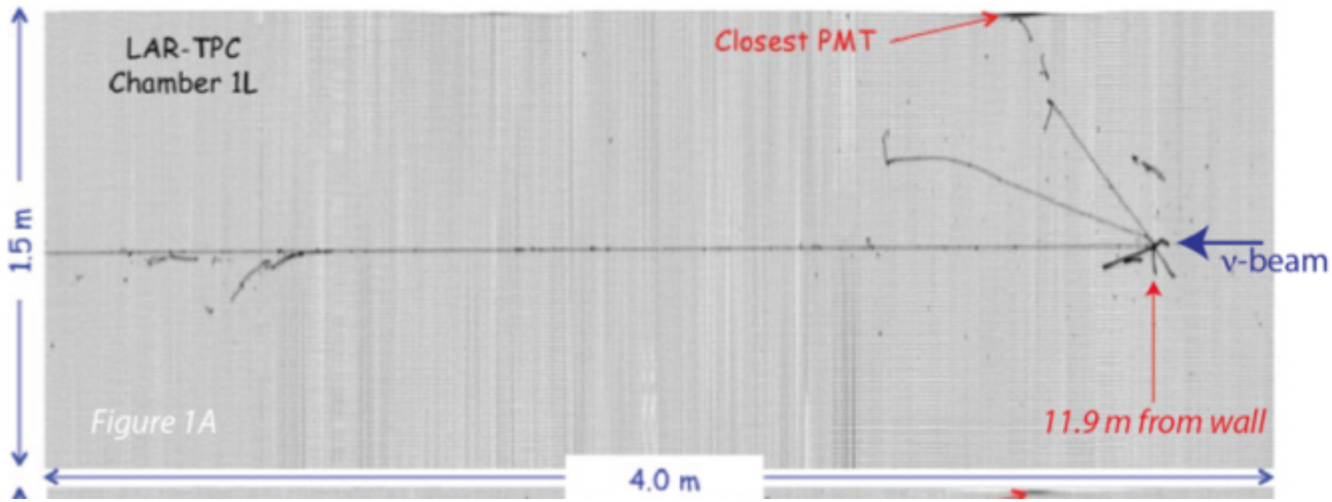


Perché il ν è difficile da rivelare?

- Perché non ha carica elettrica
  - Non eccita/ionizza la materia attraversata e non si manifesta nei rivelatori di particelle
- Perché ha ″accoppiamento″ ridotto con particelle cariche rispetto al γ.

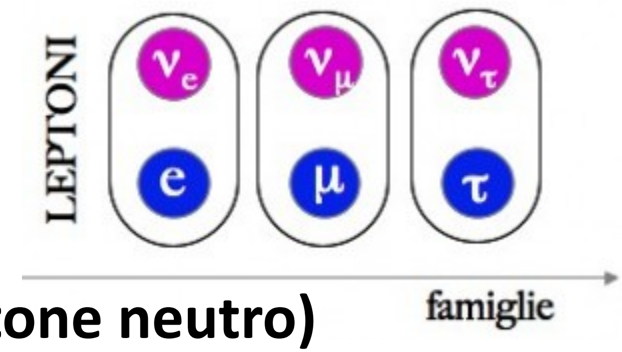


- Si manifesta solo attraverso le cosiddette ″**interazioni deboli**″, interazioni estremamente poco probabili con la materia



Esperimento «Icarus»

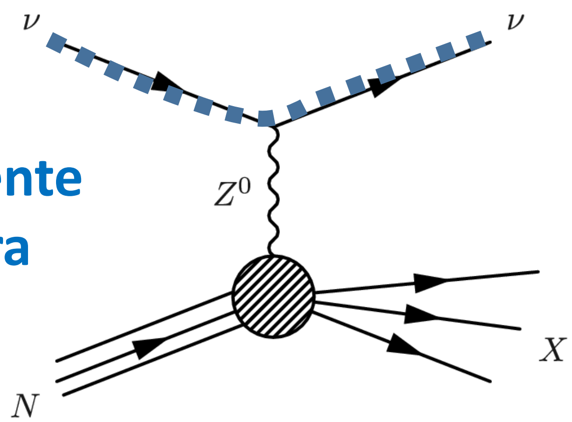
Interazioni deboli: regolamento

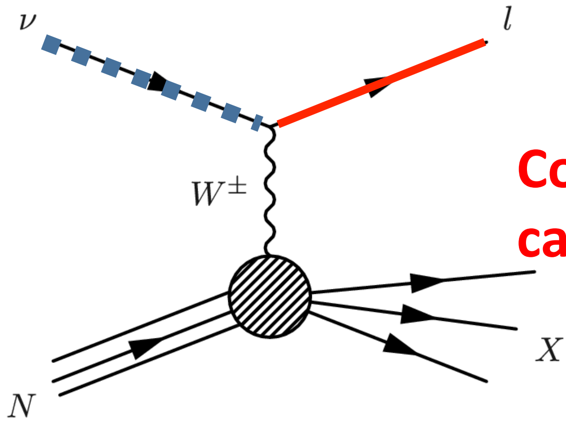


- **I leptoni esistono in tre famiglie (ν = leptone neutro)**
- **Quando i neutrini interagiscono**, possono

1. o rimanere neutrini, cedendo parte dell'energia (ad un e^-, oppure per la creazione di un sistema di adroni nel caso di interazioni su nucleoni)
2. o trasformarsi nel corrispondente leptone carico della famiglia

Corrente neutra





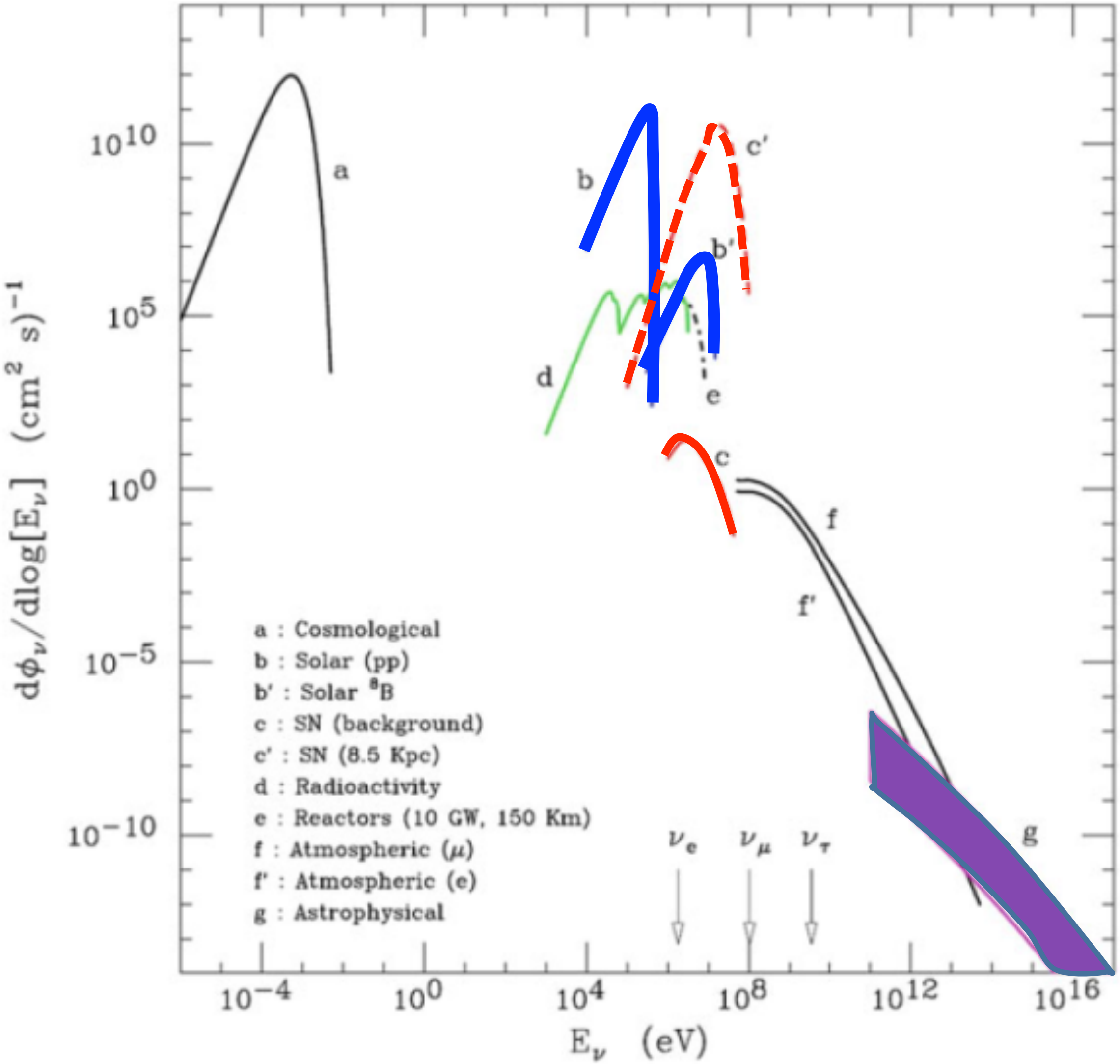
Corrente carica

- **E' principalmente il leptone carico prodotto che determina la «visibilità»**

Oscillazione dei neutrini

- Un «ν» è generato dalla **interazioni deboli** solo e soltanto con uno specifico «sapore»: ν_e, ν_μ,ν_τ (autostato di sapore)
- Per molto tempo si è pensato che i ν fossero di massa nulla
- In tutta generalità, durante la propagazione ciascun ν (ν_e, ν_μ,ν_τ) può essere pensato come sovrapposizione di tre «funzioni» differenti (autostato di massa)
- Oggi sappiamo che i tre autovalori di massa sono differenti e ben definiti e inducono il fenomeno delle oscillazioni
- Le **oscillazioni** sono il fenomeno che altera il «sapore» dei neutrini durante la propagazione, non il loro numero totale
- Per quanto ci interessa, questo fa si che in molte situazioni il flusso di neutrino astrofisici in arrivo sulla Terra sia distribuito secondo il rapporto $\boldsymbol{\nu_e : \nu_\mu : \nu_\tau}$ **. = 1: 1 : 1**

2. Neutrini dal cosmo



- Flux of neutrinos at the surface of the Earth.
- **Solar neutrinos**
- **Supernova**
- **Cosmic neutrinos**

The three *arrows* near the *x*-axis indicate the energy thresholds for CC production of the charged lepton

From P. Lipari

Energia dal sole ↔ Flusso di neutrini

Studio dettagliato della produzione di energia all'interno di una stella

- **Sorgente di energia**

$$4p + 2e^- \rightarrow {}^4\mathrm{He} + 2\nu_e$$

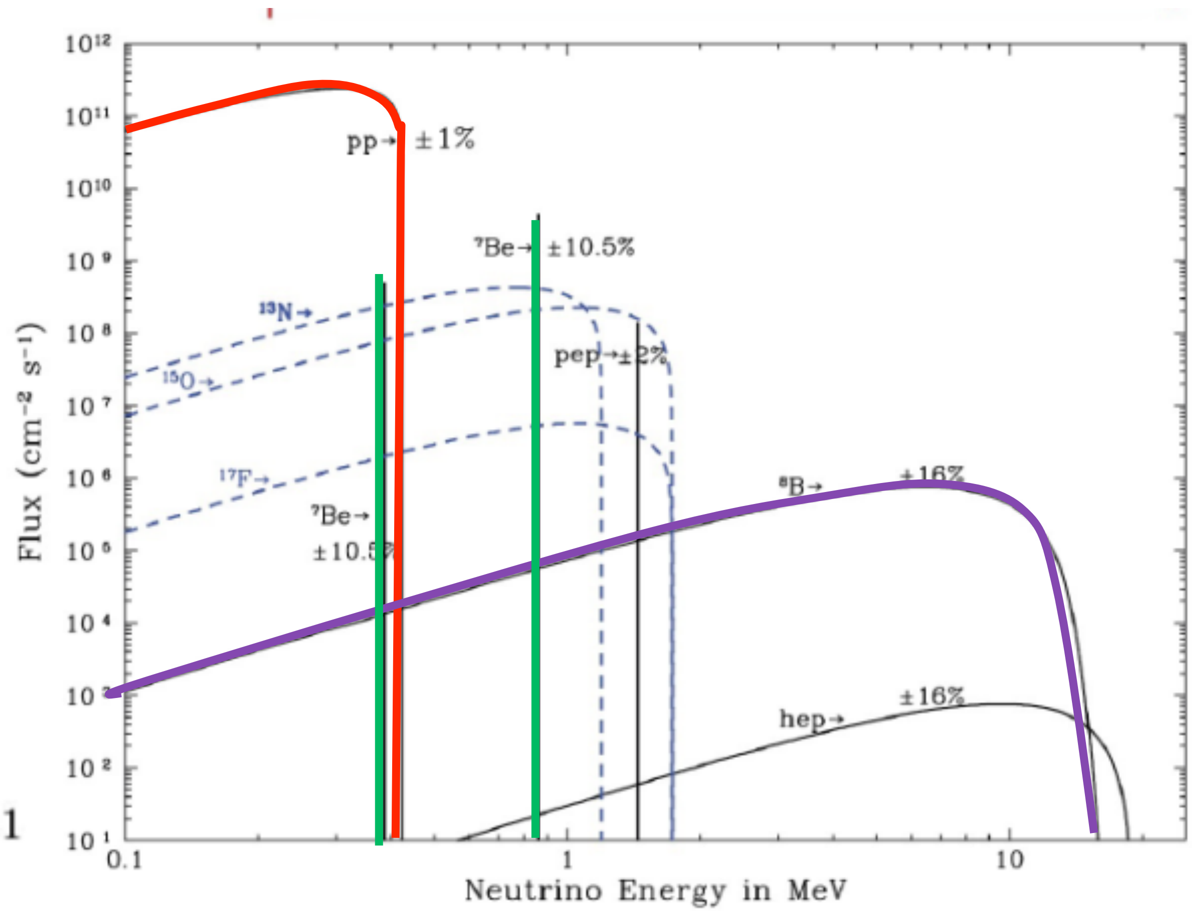
- **Energia per ciclo**

$$Q = 4m_p + 2m_e - m_{He} = 26.73 \text{ MeV}$$

- **Flusso di ν_e:**

$$\Phi_{\nu_e} \simeq \frac{1}{4\pi\, d_\odot^2} \frac{2\, L_\odot}{(Q - \langle E_\nu \rangle)}$$

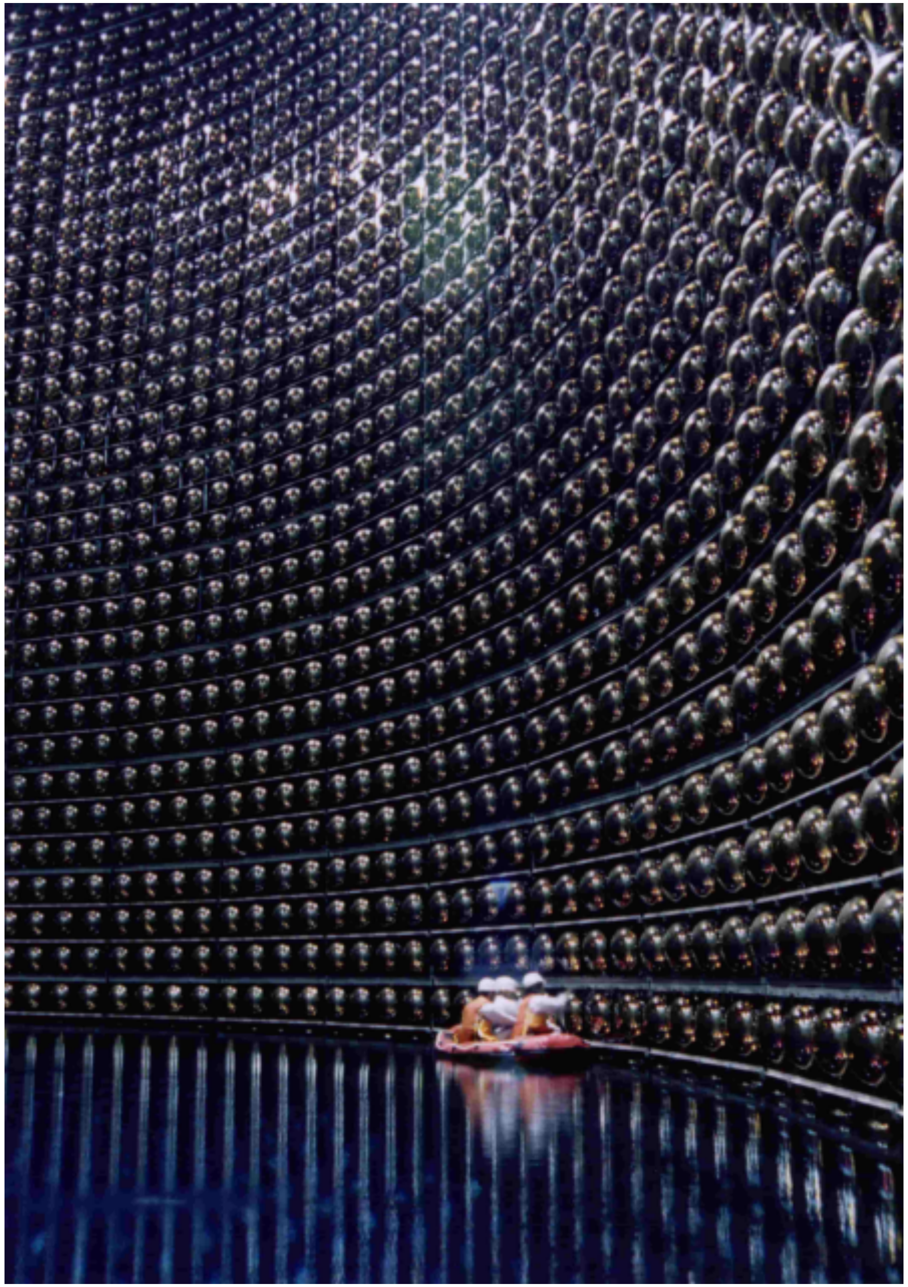
$$\phi_{\nu_\odot} \sim 6 \times 10^{10} \ (\mathrm{cm}^2 \ \mathrm{s})^{-1}$$



Rivelatori enormi!

Esempio: Super-Kamiokande in Giappone

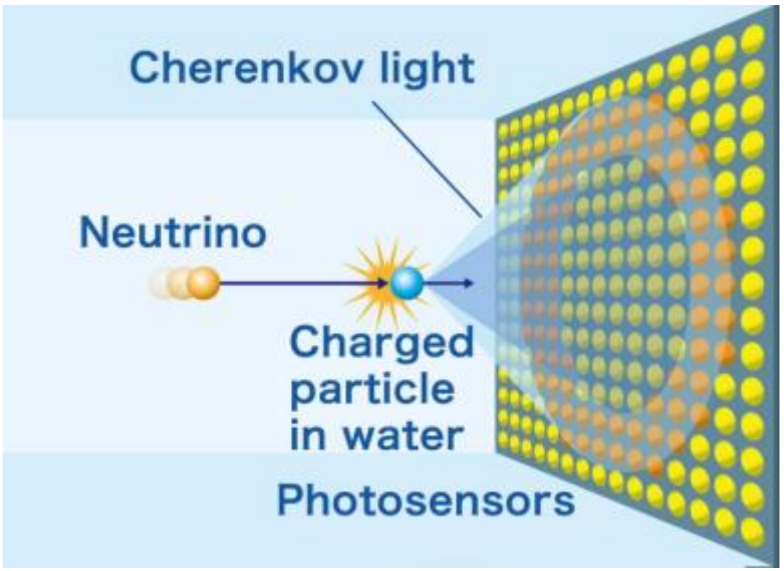
- 1000 m underground
- 50.000 ton di acqua purificata
- 11000 +2000 **fotomoltiplicatori** (PMTs)
- Attivo dal 1996

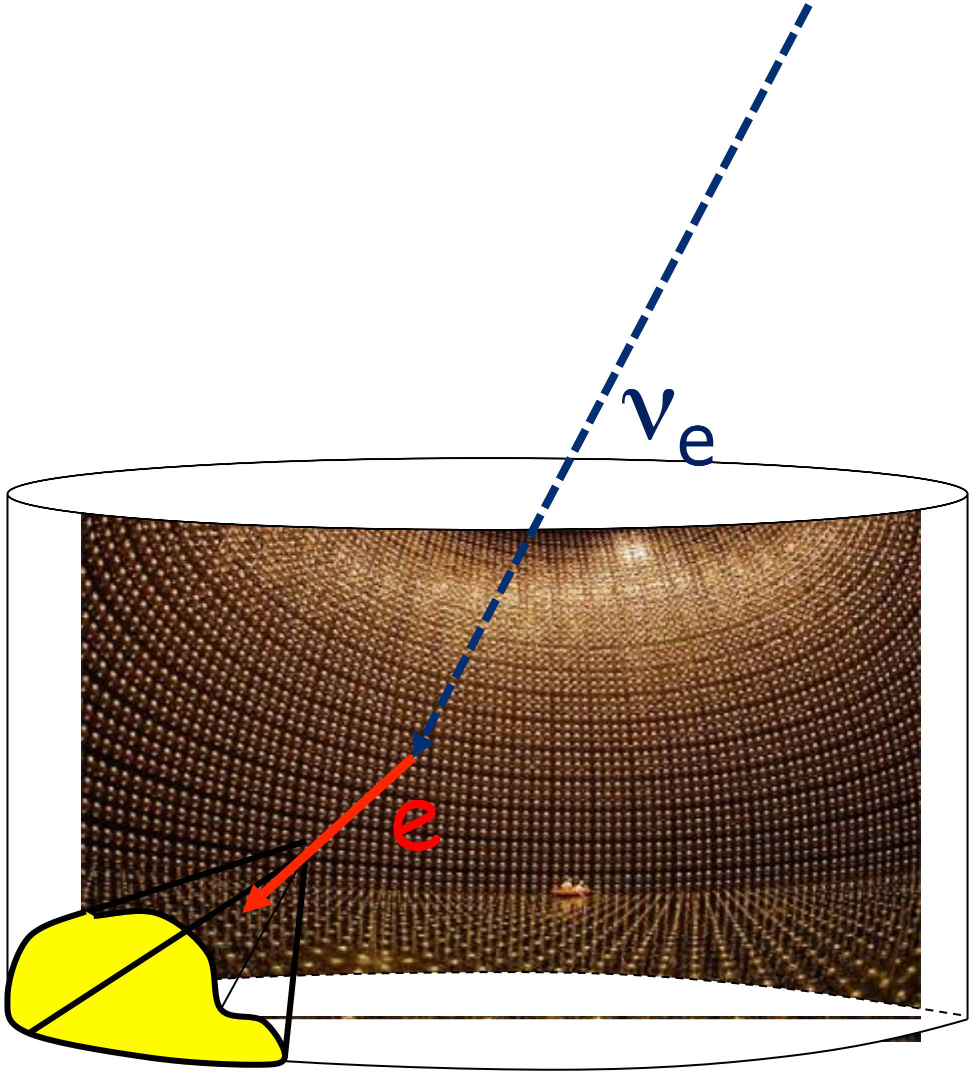


SuperKamiokande: Neutrini dal sole

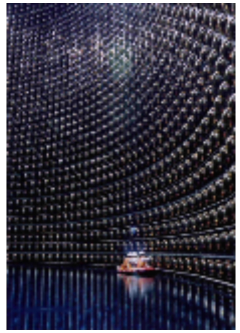
$\nu_e \, e \rightarrow \nu_e e$

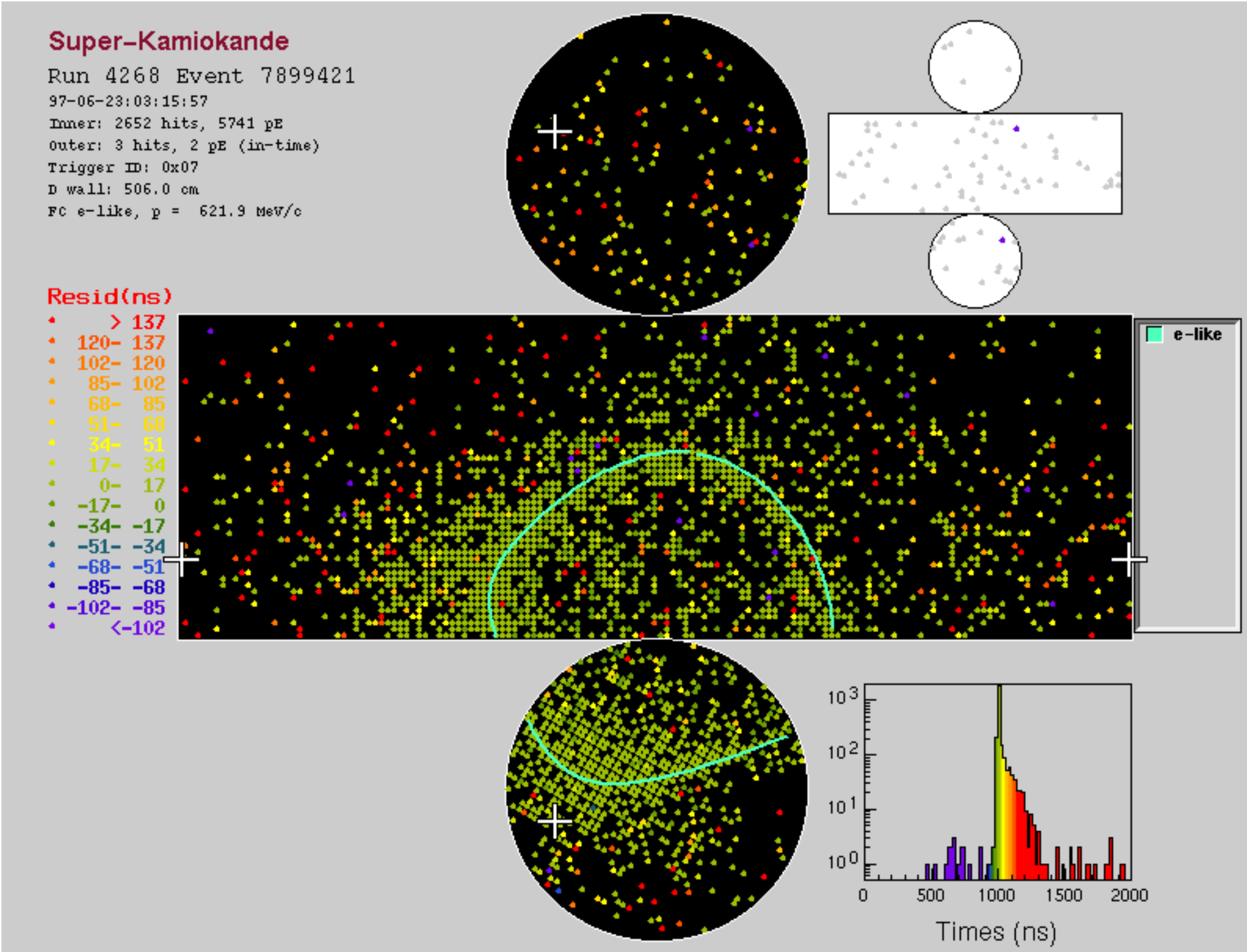
«effetto Cherenkov»



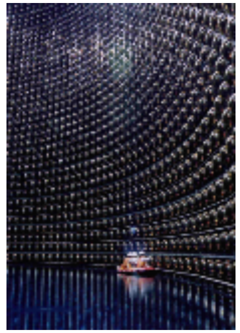


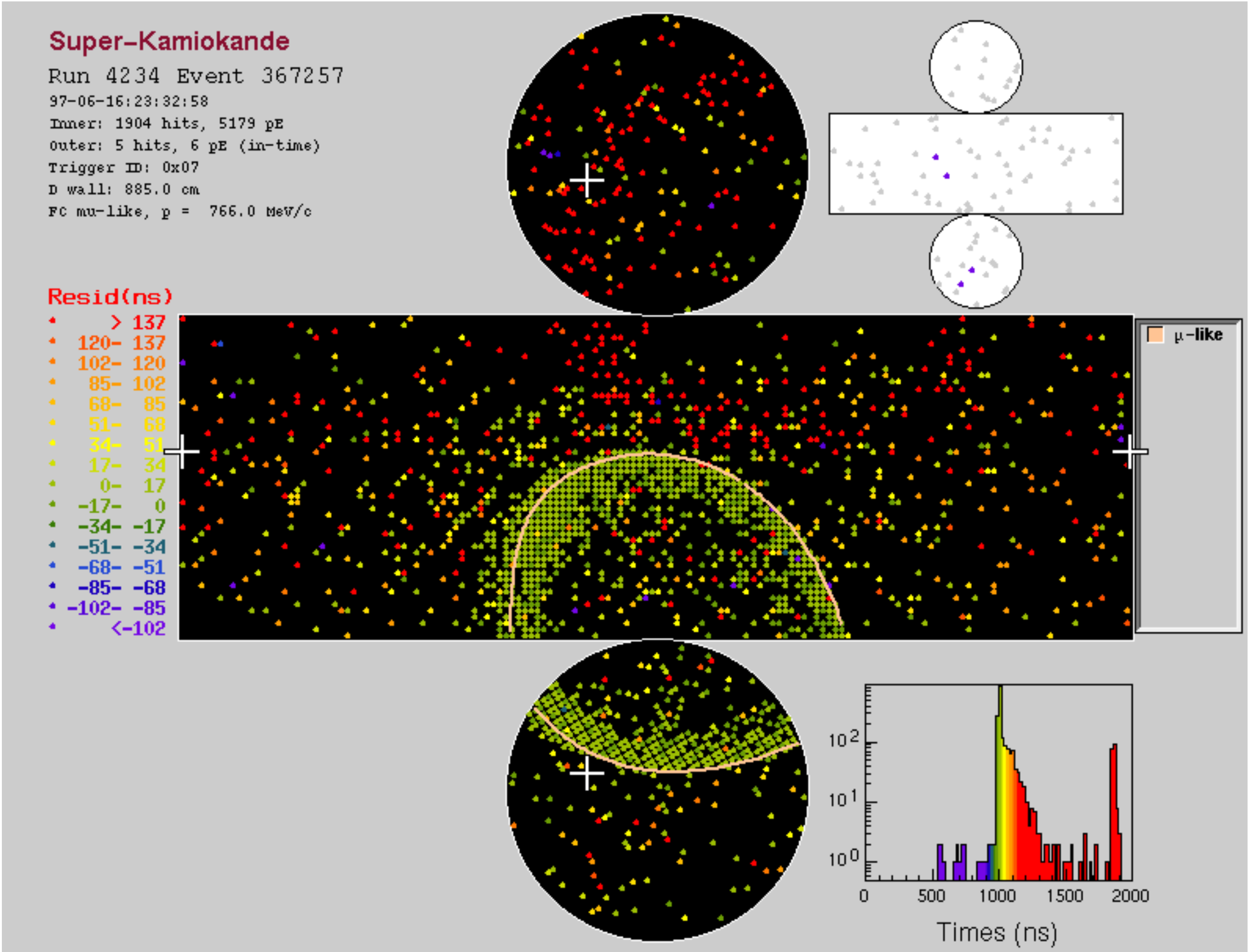
SuperKamiokande: ν_e





SuperKamiokande: ν_μ

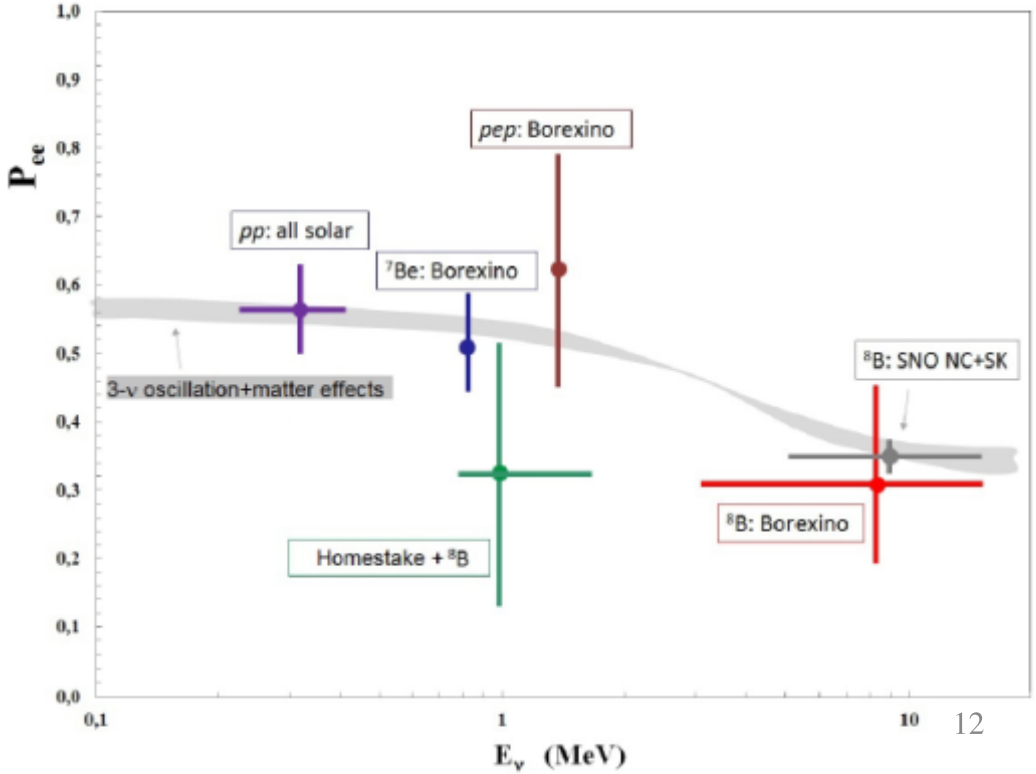




Neutrino oscillations and the Sun

ν React.	Interaction rate counts (day 100 ton)$^{-1}$	$\left(\frac{Data}{SSM}\right)$ ratio	$\Phi_{\nu_e}(E)$ ($10^8\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)	$\left(\frac{Data}{SSM}\right)/P_{ee}$ ratio
^{7}Be	$46.0 \pm 1.5 \pm 1.6$	0.51 ± 0.07	48.4 ± 2.4	0.97 ± 0.09
pep	$3.1 \pm 0.6 \pm 0.3$	0.62 ± 0.17	1.6 ± 0.3	1.1 ± 0.2
CNO	<7.9	–	<7.7	<1.5
^{8}B	$0.22 \pm 0.04 \pm 0.01$	0.31 ± 0.15	0.05 ± 0.01	0.91 ± 0.23
pp	144 ±13 ± 10	0.64 ± 0.12	660 ± 70	1.18 ± 0.22

Table: Summary of the interaction rates of the different neutrino species measured by **Borexino** (LNGS) and the ratios with respect to SSM (column 3)



Core-Collapse Supernovae (Type-II)

- The work U done by gravity in compressing a star of mass M and radius R in the core (neutron star) of radius R_{NS} and mass M_{NS} is:

$$U = \left|\frac{3GM^2}{5R} - \frac{3GM_{NS}^2}{5R_{NS}}\right| \simeq \frac{3GM_{NS}^2}{5R_{NS}} \simeq 3 \times 10^{53}\mathrm{erg}$$

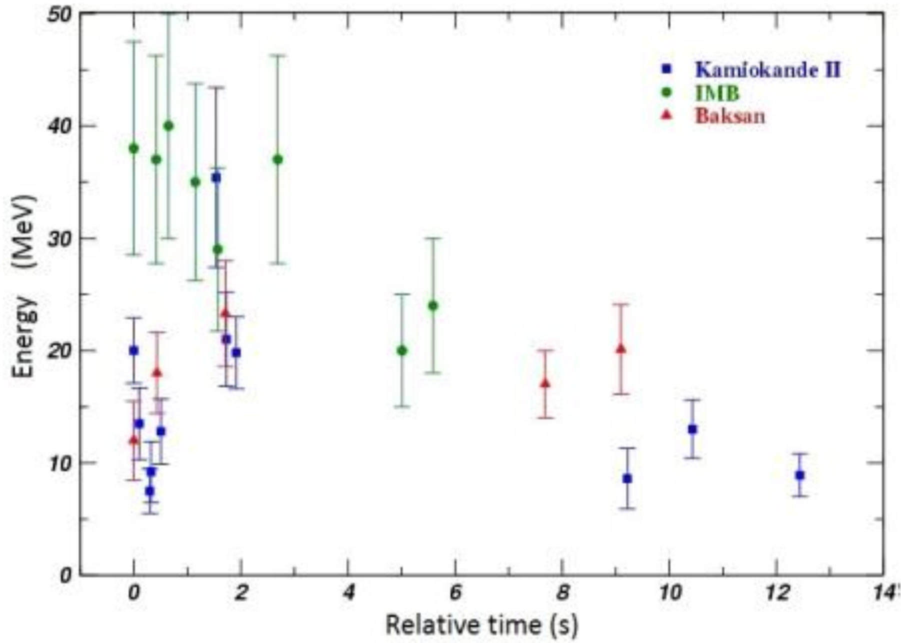
- This shows up as
  - **99% Neutrinos**
  - **1% Kinetic energy of the explosion**
    (few % of this into Cosmic Rays)
  - **0.01% Photons (outshine host galaxy)**

- Neutrino luminosity (while it lasts) outshines the photon luminosity of the entire Universe
  - **L_ν= 3x10^{53} erg/3 sec = 3x10^{19} L_{Sun}**

The SN1987A

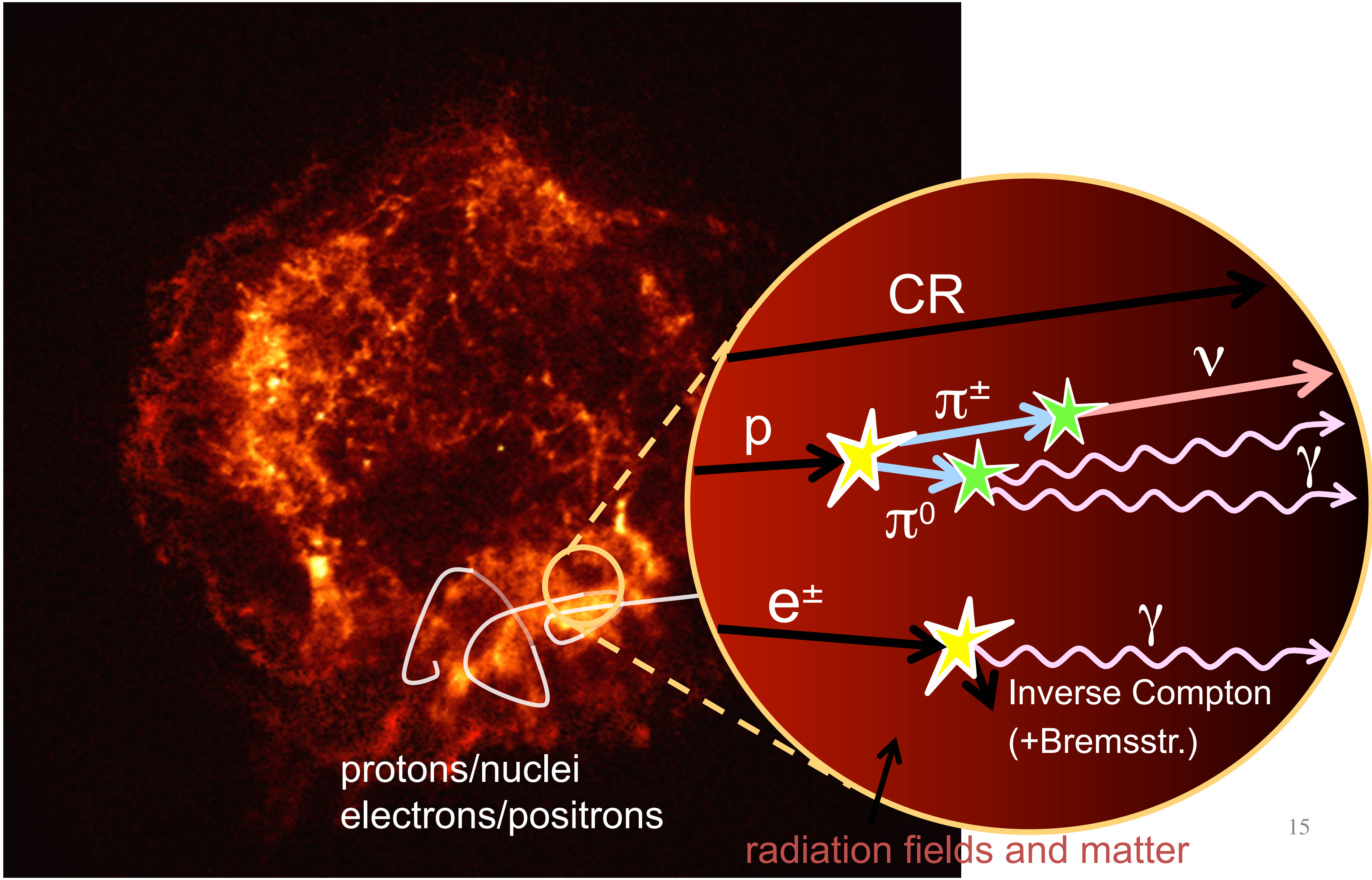
- **Kamiokande, IMB** and **Baksan** collected ~12, 8 and 5 ν candidates
- The 25 ν's were sufficient to give an exact time for the start of the explosion to which the light curve can be normalized and to confirm the baseline model of core-collapse:

- the observed events are in agreement with ~ **3 × 10^{53} erg luminosity** of a core-collapse;
- the **time distribution** in agreement with a ~10 s burst;
- their **energy distribution** gives a measure T ~ 4.2MeV of the ν-sphere



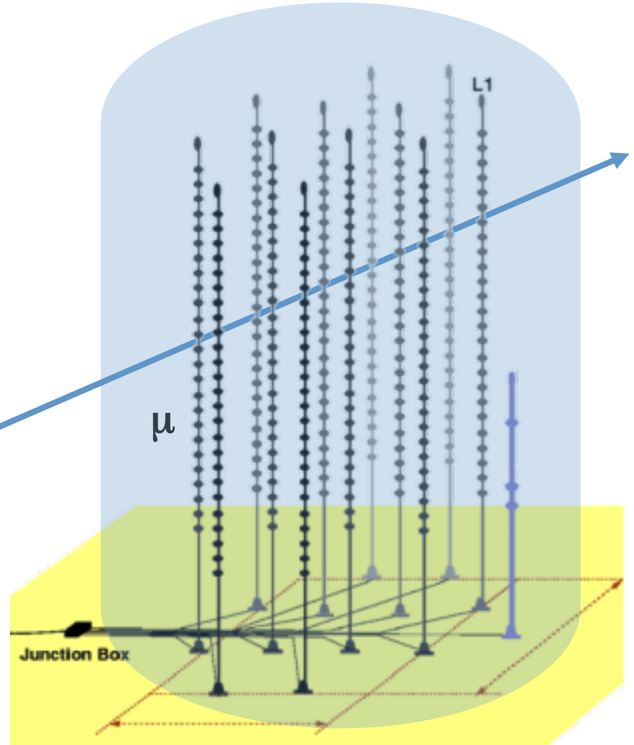
Relative time and energy of SN1987A neutrinos observed by Kamiokande, IMB and Baksan.
The time of the first event was arbitrarily set = 0

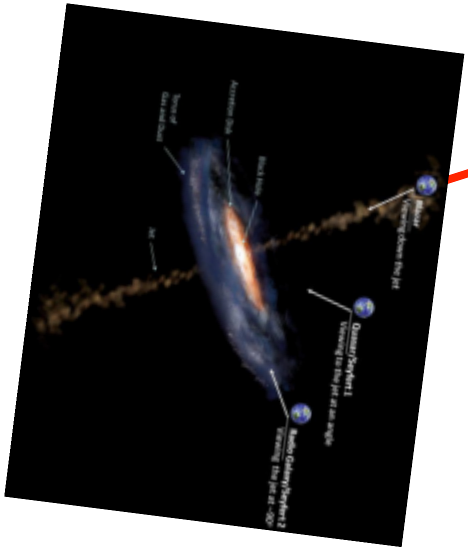
CRs, γ and ν in cosmic accelerators



Neutrino telescope =

Istrumented detector D<R_μ





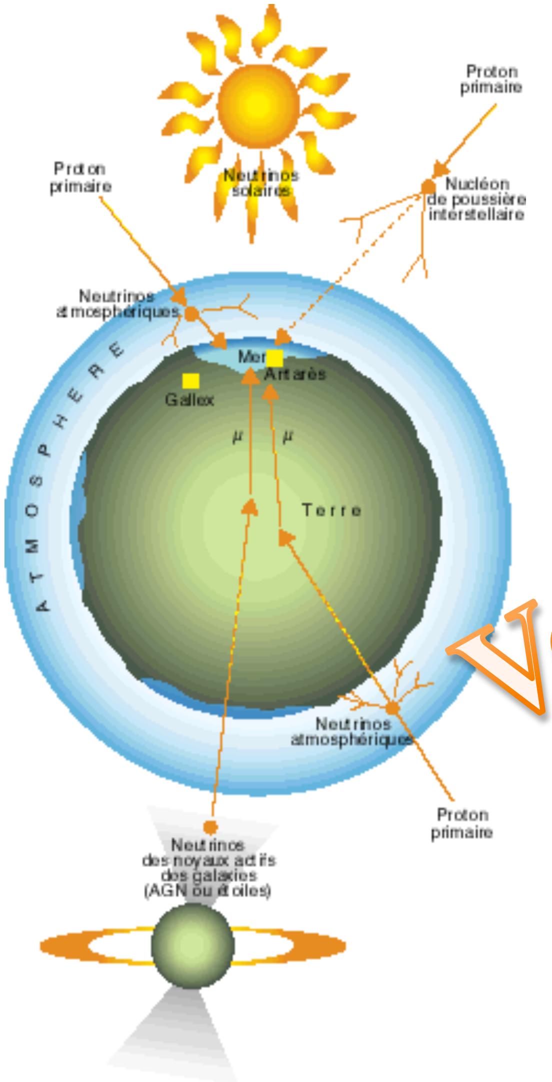
neutrino energy spectrum at source (ν/cm^2 s GeV)

Event rate (s^{-1})

$$\frac{N_\nu}{T} = \int \mathrm{d}E_\nu \cdot \frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu}(E_\nu) \cdot A_\nu^{\mathrm{eff}}(E_\nu)$$

neutrino-induced muon detection probability

Example: a Galactic source



TeV γ-rays and neutrinos can be produced from **hadronic processes**:

$p + \gamma \rightarrow \Delta^{+} \rightarrow \pi^{o} + p$

$p + \gamma \rightarrow \Delta^{+} \rightarrow \pi^{+} + n$

Neutral mesons decay in **photons**:

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

Charged mesons decay in **neutrinos**:

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

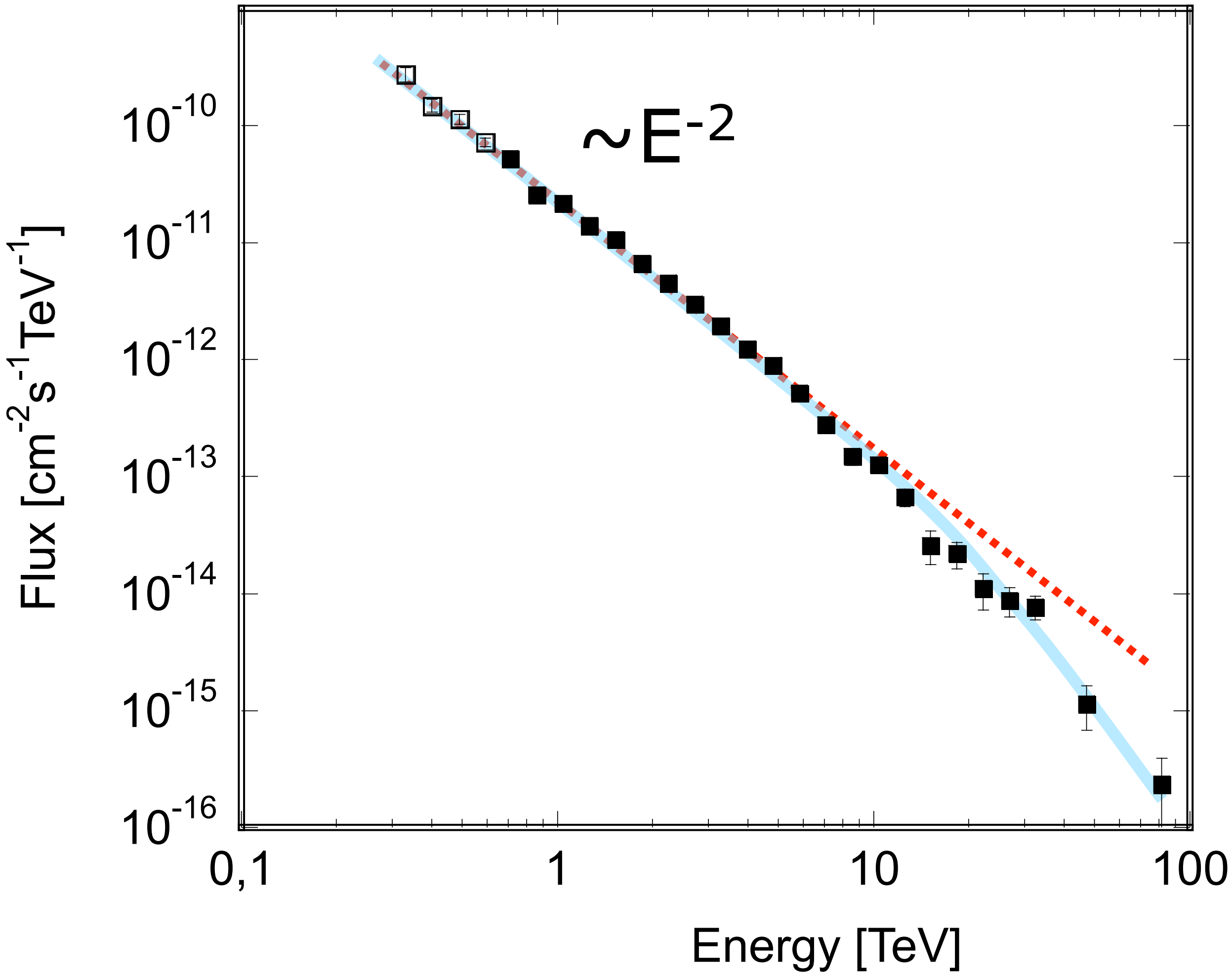
$\mu^{+} \rightarrow \nu_{\mu} + \nu_{e} + e^{+}$

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

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

#ν=#γ

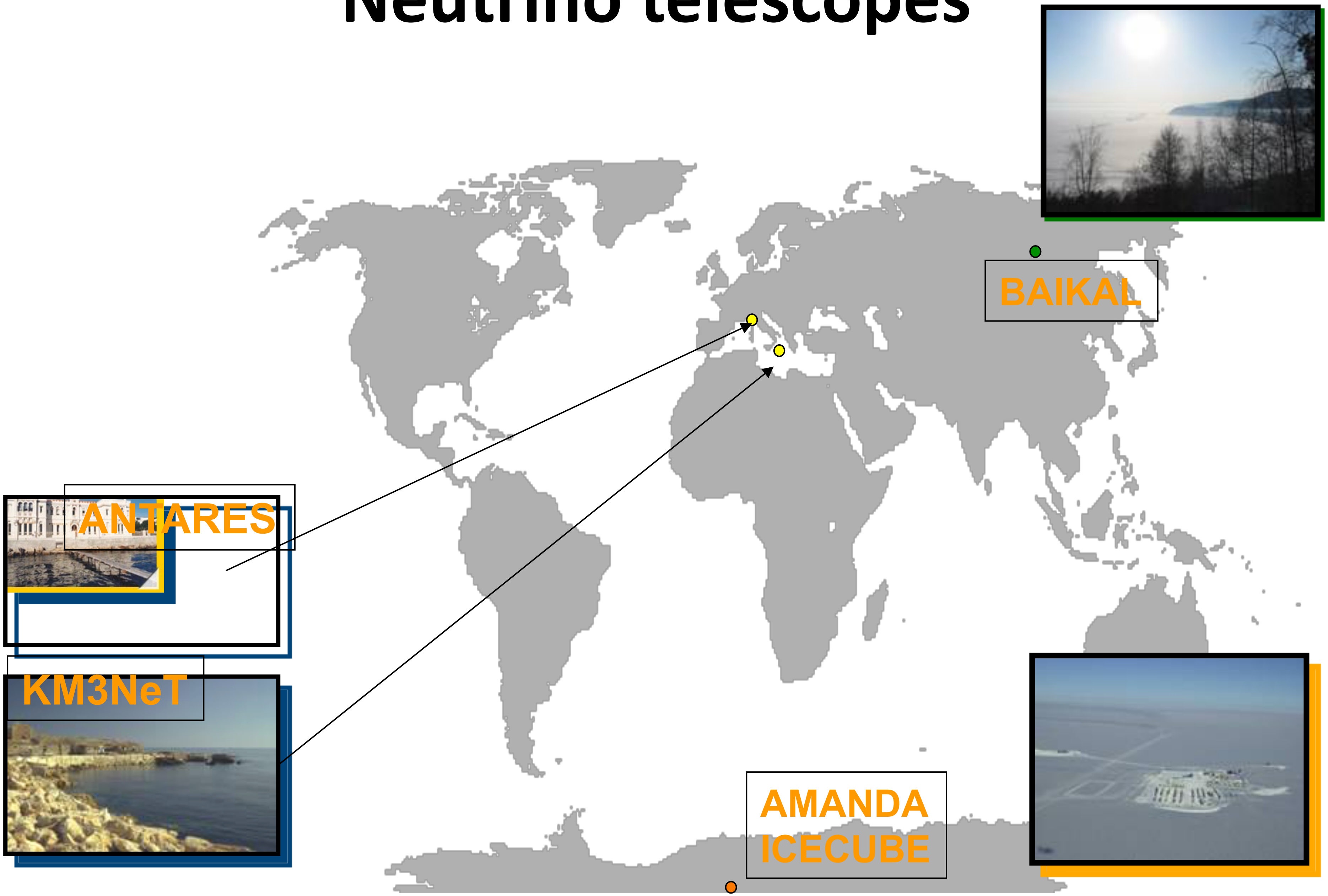
Per l'esercizio seguente: #ν=#γ da RX J1713.7-3946



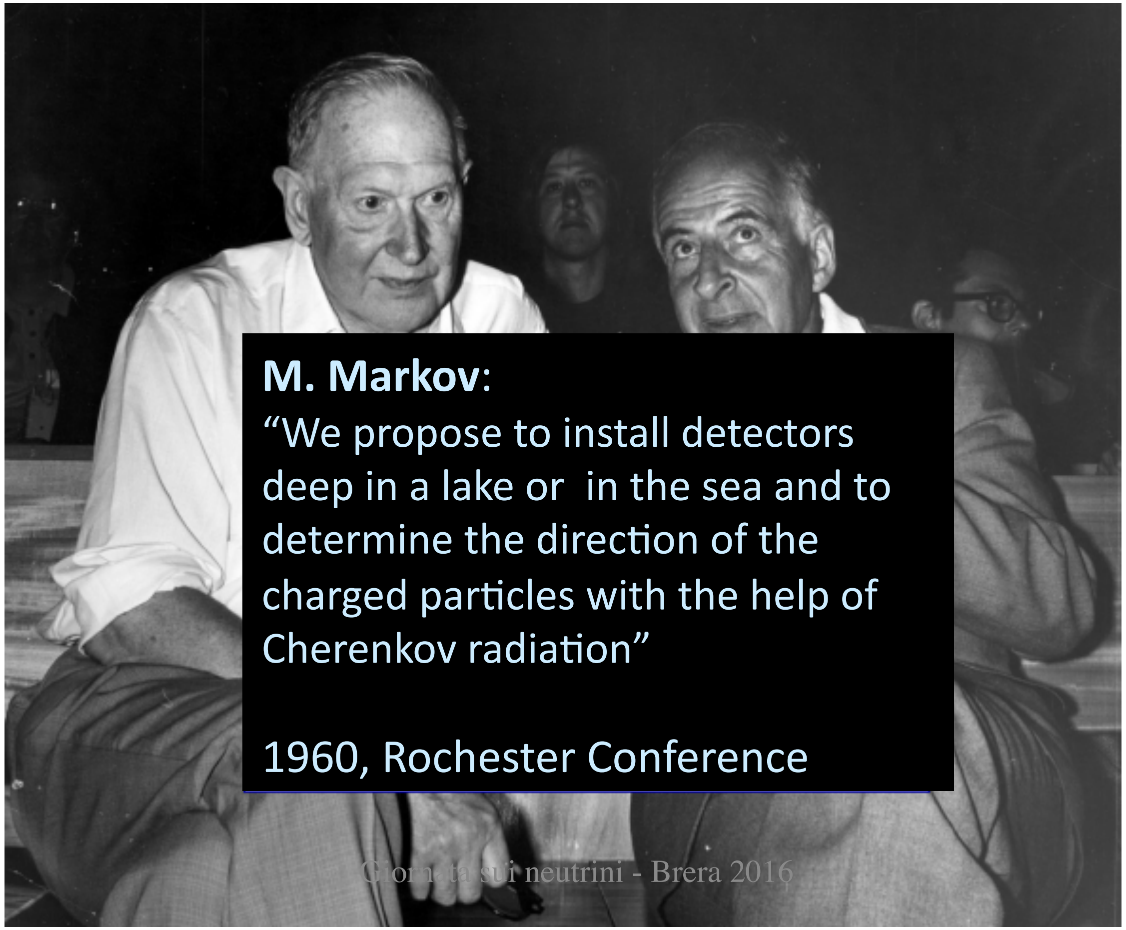
RX J1713.7-3946 seen by **HESS** (γ-rays)

$$E^2_{\nu,\gamma}\frac{d\Phi_{\nu,\gamma}}{dE_{\nu,\gamma}} = 10^{-11}\ \text{TeV cm}^{-2}s^{-1}$$

Neutrino telescopes



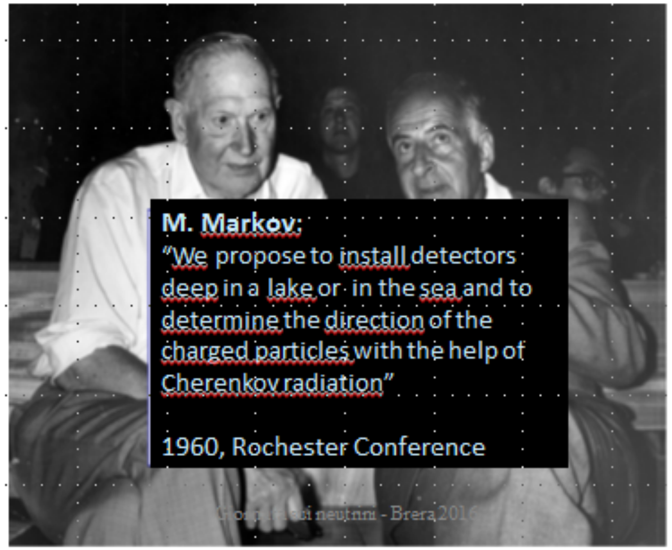
3. Ingredienti per un "Neutrino Telescope"



M. Markov:
"We propose to install detectors deep in a lake or in the sea and to determine the direction of the charged particles with the help of Cherenkov radiation"

1960, Rochester Conference

3. Ingredienti per un “Neutrino Telescope”



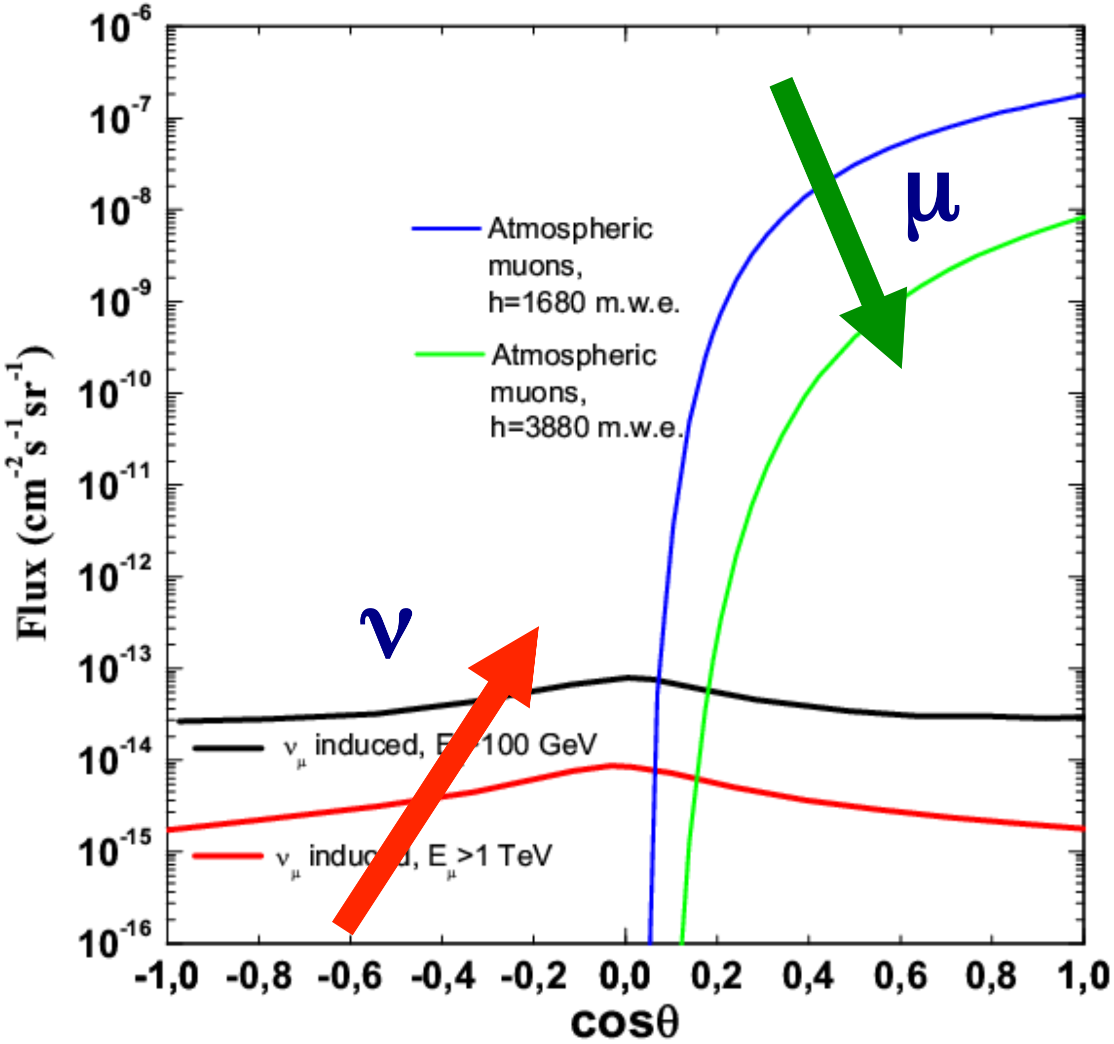
- 3.1 Depth
- 3.2 The effective area
- 3.3 Cherenkov radiation
- 3.4 Medium properties
- 3.5 Number of optical modules
- 3.6 Track/energy reconstruction
- 3.7 Angular resolution
- 3.8 Differences between water/ice
- 3.9 Optical background in water
- 3.10 Detector positioning

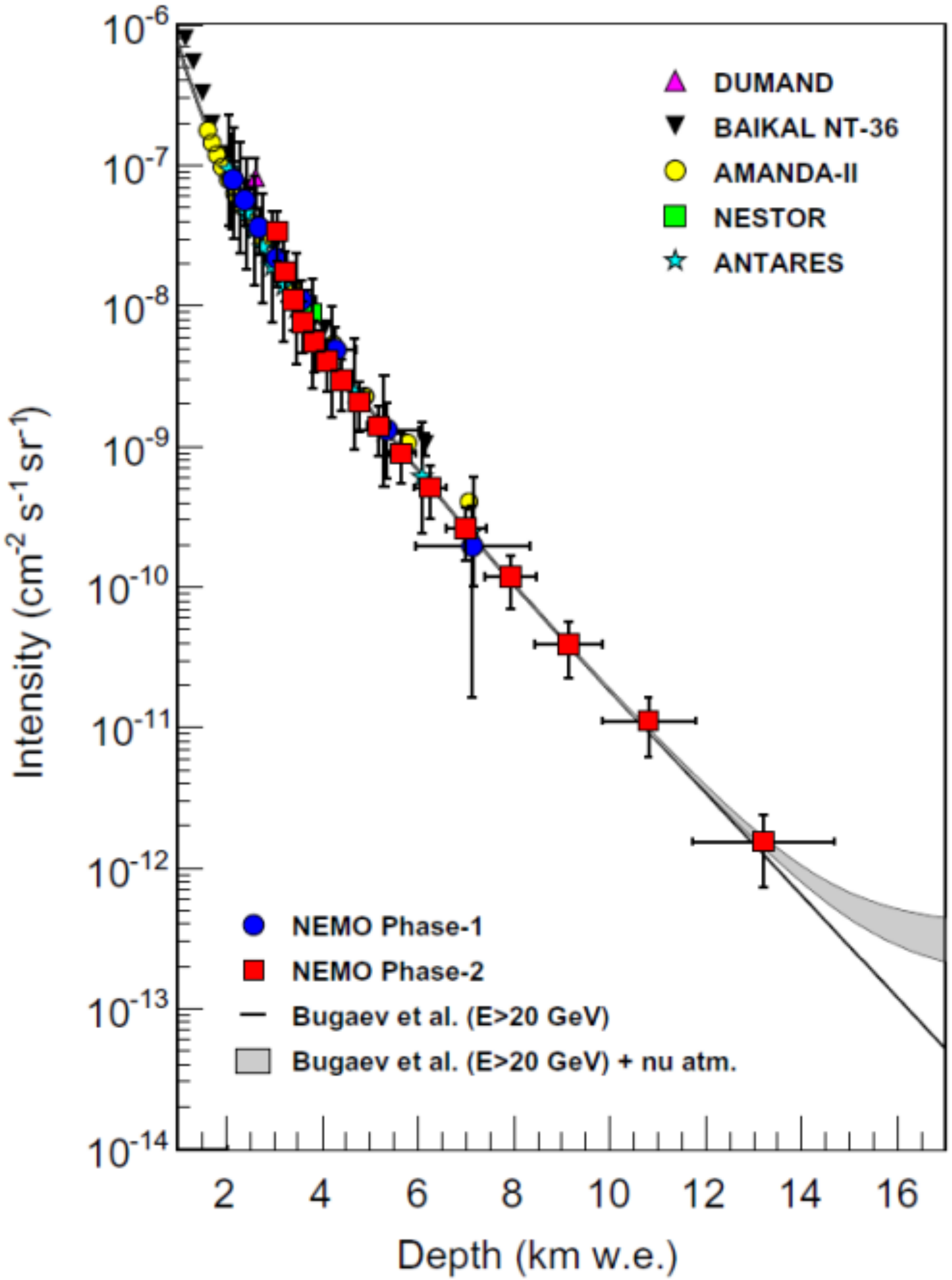
Giornata sui neutrini - Brera 2016

3.1 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





Atmospheric muon flux

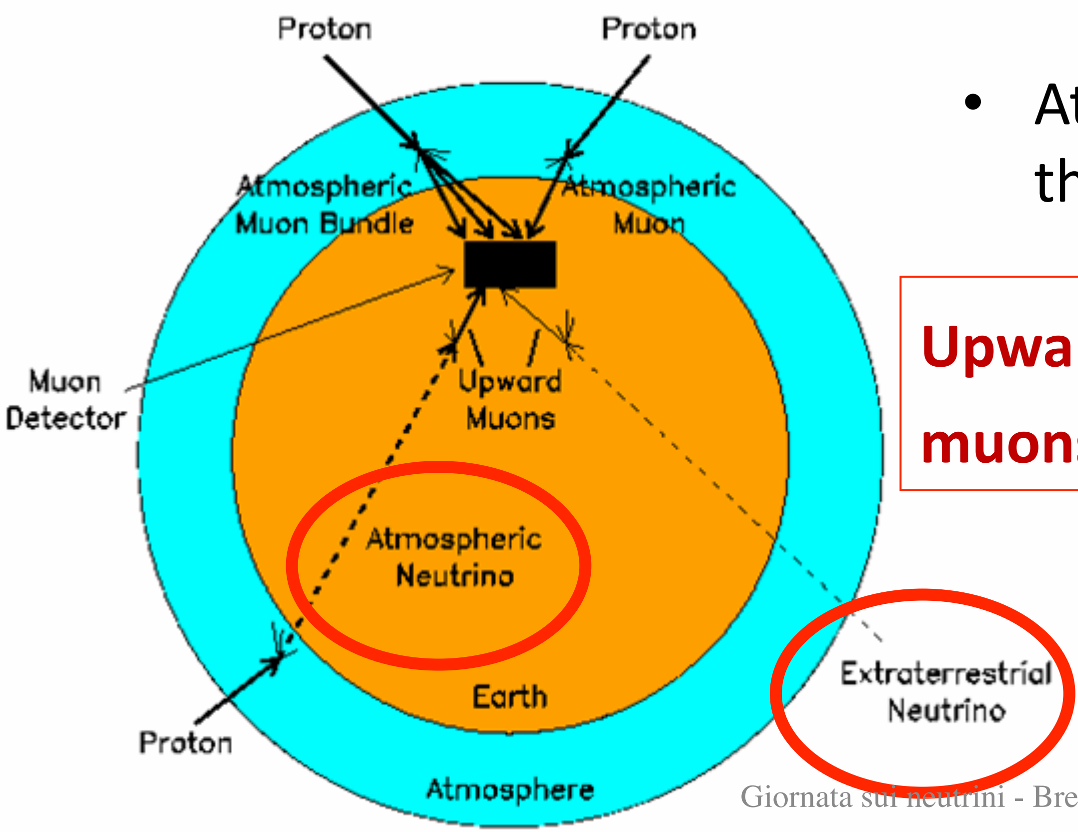
Muons cannot cross more than ≈ 15 km.w.e.

Measurements of the underwater/ice muon flux vs. depth

NT: detectors looking to the bottom

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

• Upward-going particles are candidate for extraterrestrial ν .

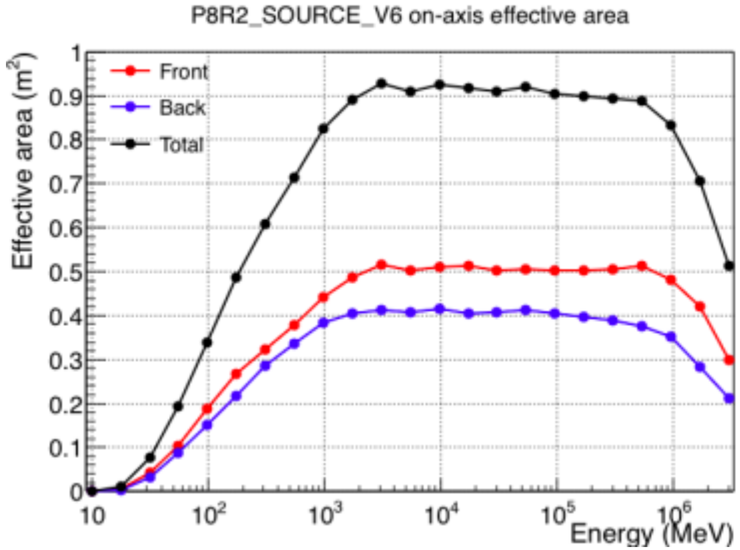


• Atmospheric neutrinos represent the irreducible background

Upward-going muons (or horizontal muons) ARE neutrino-induced!

3.2 Detector effective area

- The effective area A^{eff} is the **figure-of-merit** of one NT
- Quantity defined also for other experiments (cfr. **Fermi-LAT**)
- The NT effective area depends
  - *on the outgoing lepton*
  - *on the neutrino energy*
  - *(not strongly) on the direction*
  - *on the specific analysis (efficiency ε)*



***Fermi-LAT** effective area vs. E for normal γ-ray incidence*

- For the muon channel, the $\mathrm{A}^{\mathrm{eff}}$ can be written as:

$$A_{\nu}^{\text{eff}}(E_{\nu}) = A \cdot P_{\nu\mu}(E_{\nu}, E_{\text{thr}}^{\mu}) \cdot \epsilon \cdot e^{-\sigma(E_{\nu})\rho N_A Z(\theta)}$$

The quantity A (m^2) is the geometrical area of a detector

Detector effective area

$$A_\nu^{\text{eff}}(E_\nu) = A \cdot P_{\nu\mu}(E_\nu, E_{\text{thr}}^\mu) \cdot \epsilon \cdot e^{-\sigma(E_\nu)\rho N_A Z(\theta)}$$

Probability that a ν_μ induces a muon with energy $E>E^\mu_{thr}$ reaches the detector:

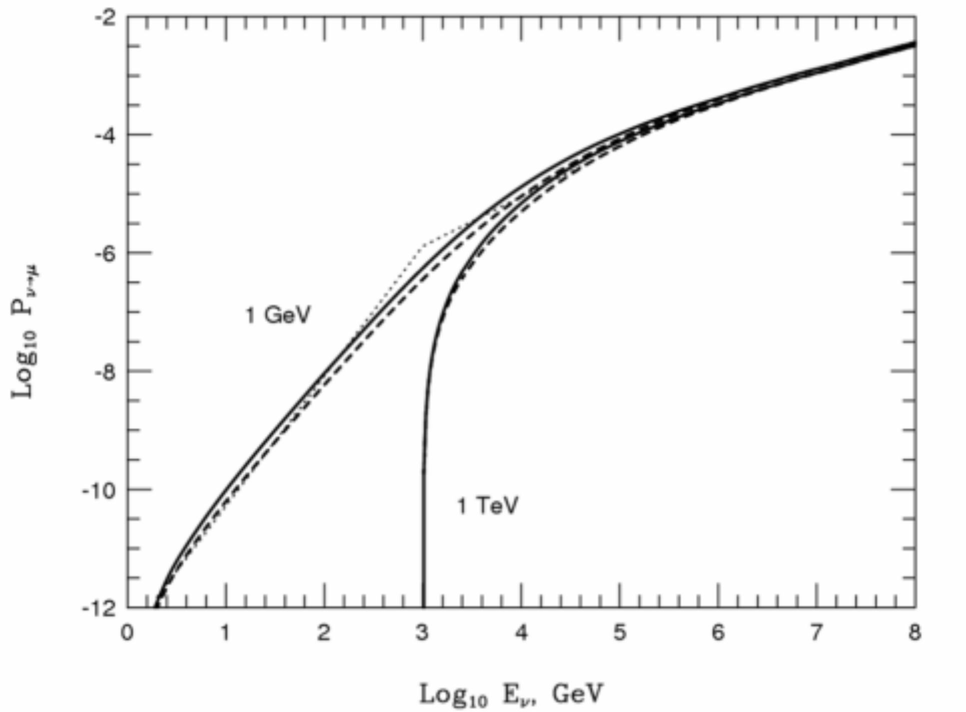
$$P_{\nu\mu} = \sigma_{\nu\mu}(cm^2) \times \rho\ (cm^{-3}) \times R\ (cm)$$

$$\sigma_{\nu\mu} \cong 10^{-35}\left(\frac{E}{TeV}\right)(cm^2)$$

$\rho \cong 10^{23}\ cm^{-3}$;

$R \cong 10^6\ cm$

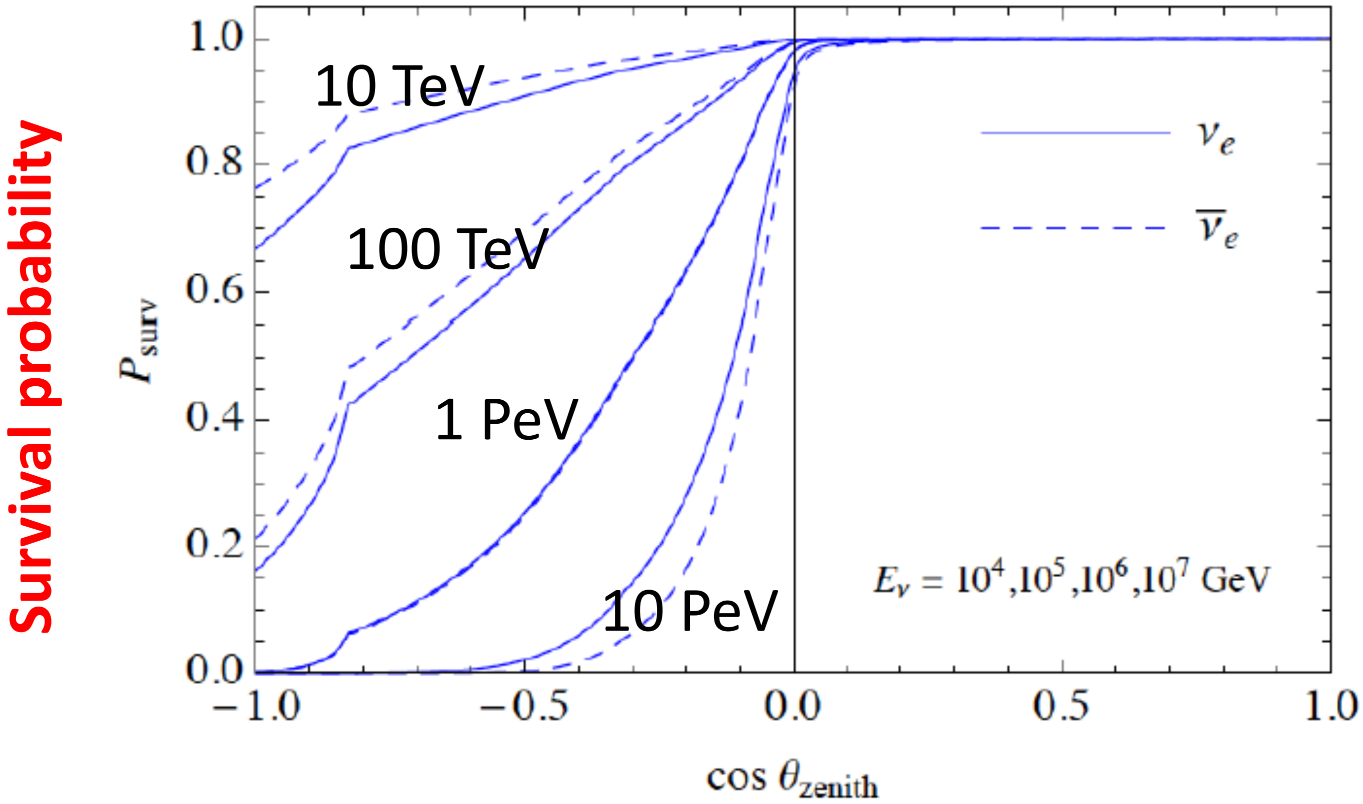
$$P_{\nu\to\mu} \cong 10^{-6}\left(\frac{E}{TeV}\right)$$



Detector effective area

$$A_\nu^{\text{eff}}(E_\nu) = A \cdot P_{\nu\mu}(E_\nu, E_{\text{thr}}^{\mu}) \cdot \epsilon \cdot e^{-\sigma(E_\nu)\rho N_A Z(\theta)}$$

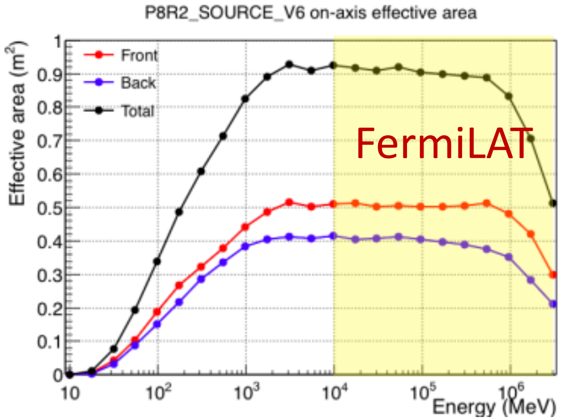
- Neutrinos can interact in the Earth and get absorbed
- The absorption probability depends on E and zenith angle

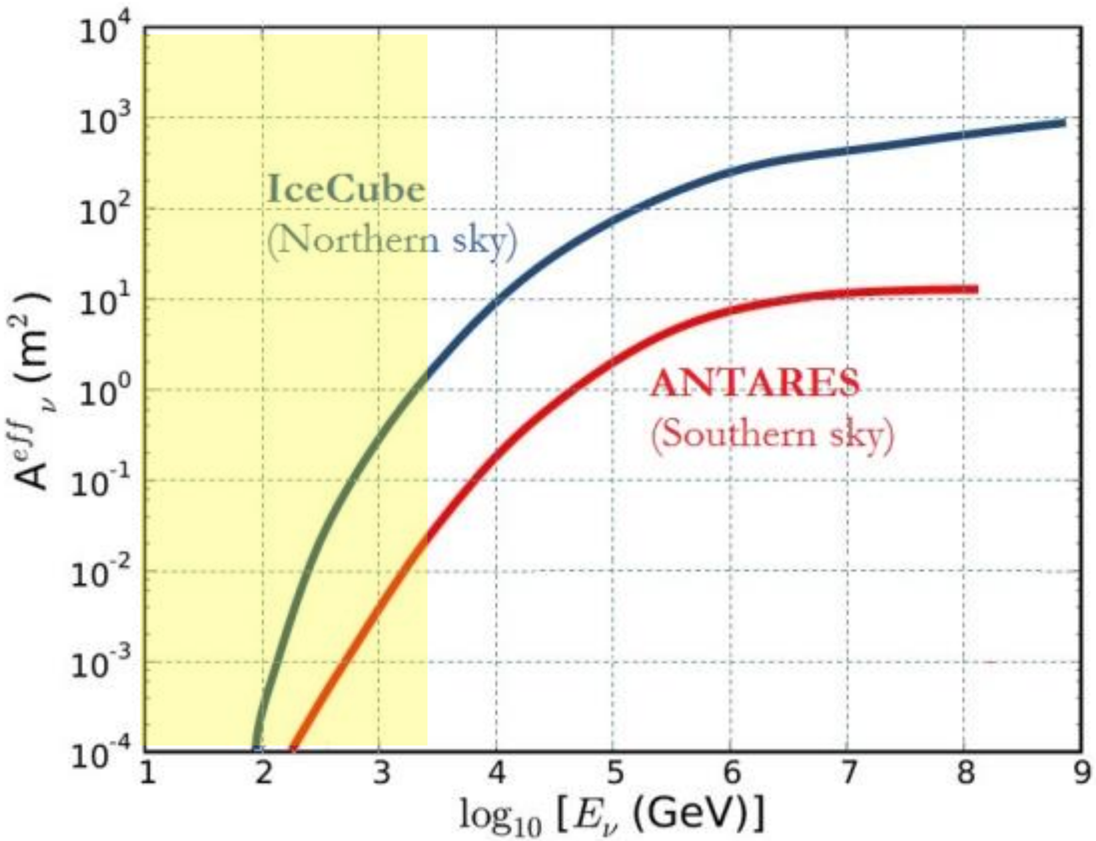


Detector effective area

$$A_\nu^{\rm eff}(E_\nu) = A \cdot P_{\nu\mu}(E_\nu, E_{\rm thr}^{\mu}) \cdot \epsilon \cdot e^{-\sigma(E_\nu)\rho N_A Z(\theta)}$$

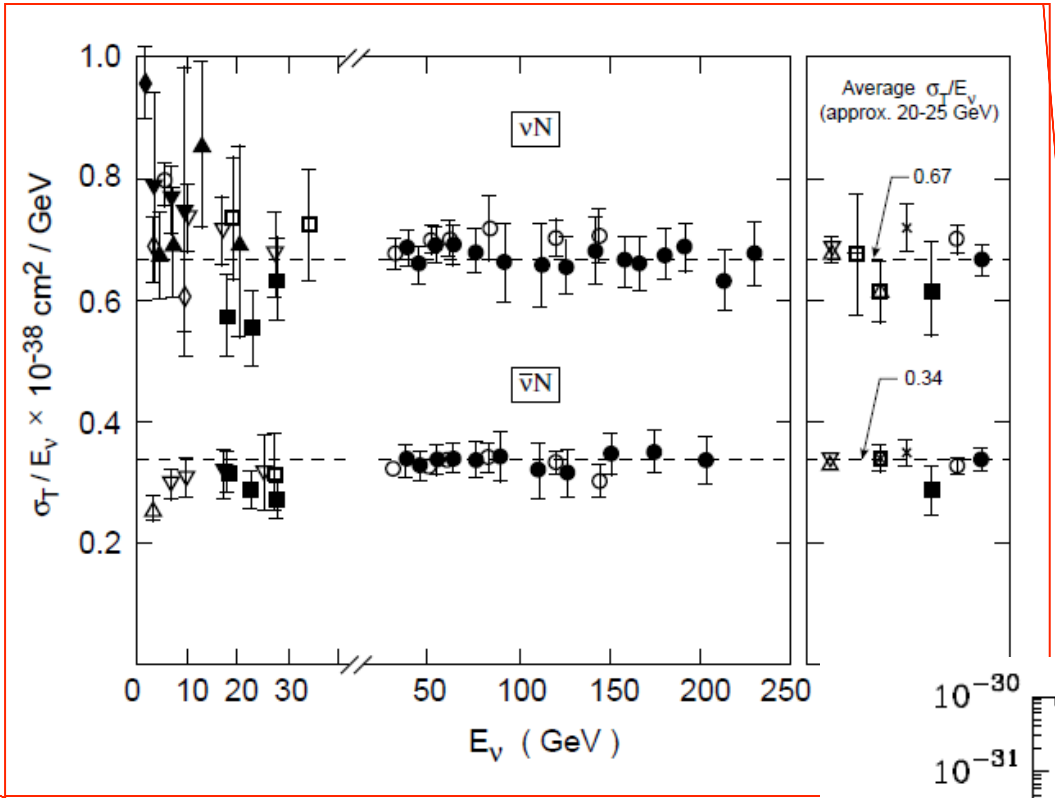
- Parameter dependent on the analysis
- ANTARES and IceCube $A^{\rm eff}$ for point-like sources (upgoing muons)

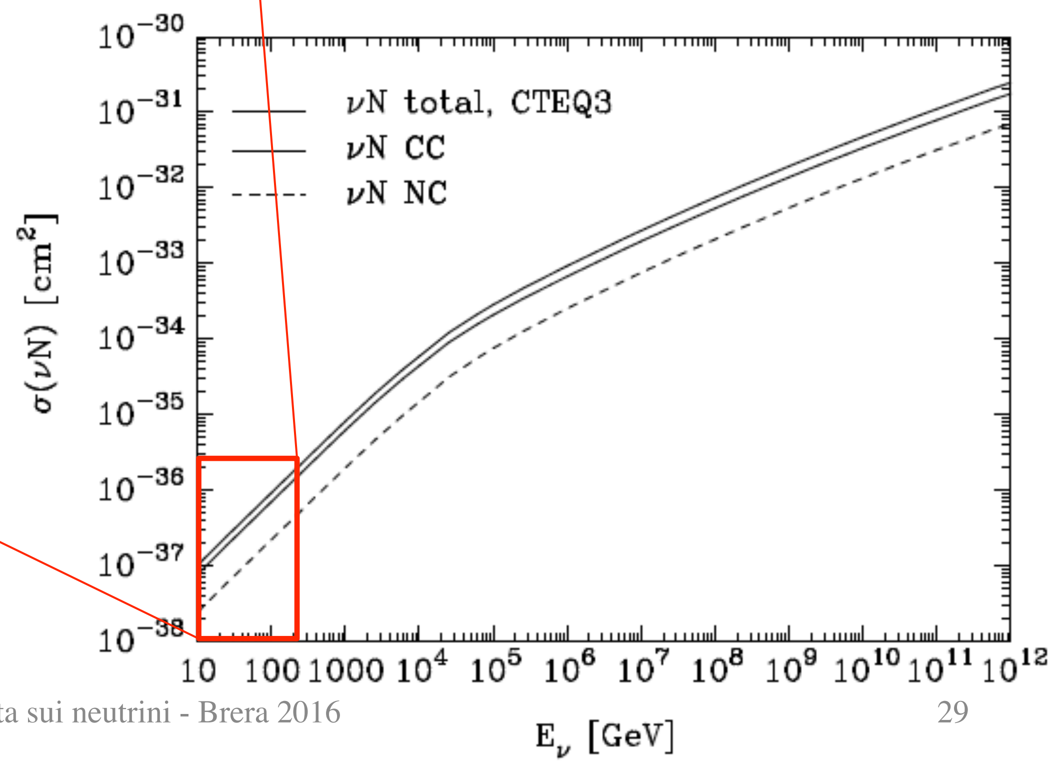




Neutrino cross section

$$\frac{d\sigma}{dE} = 0.5\times10^{-35}\,\mathrm{cm^2\,TeV^{-1}}$$



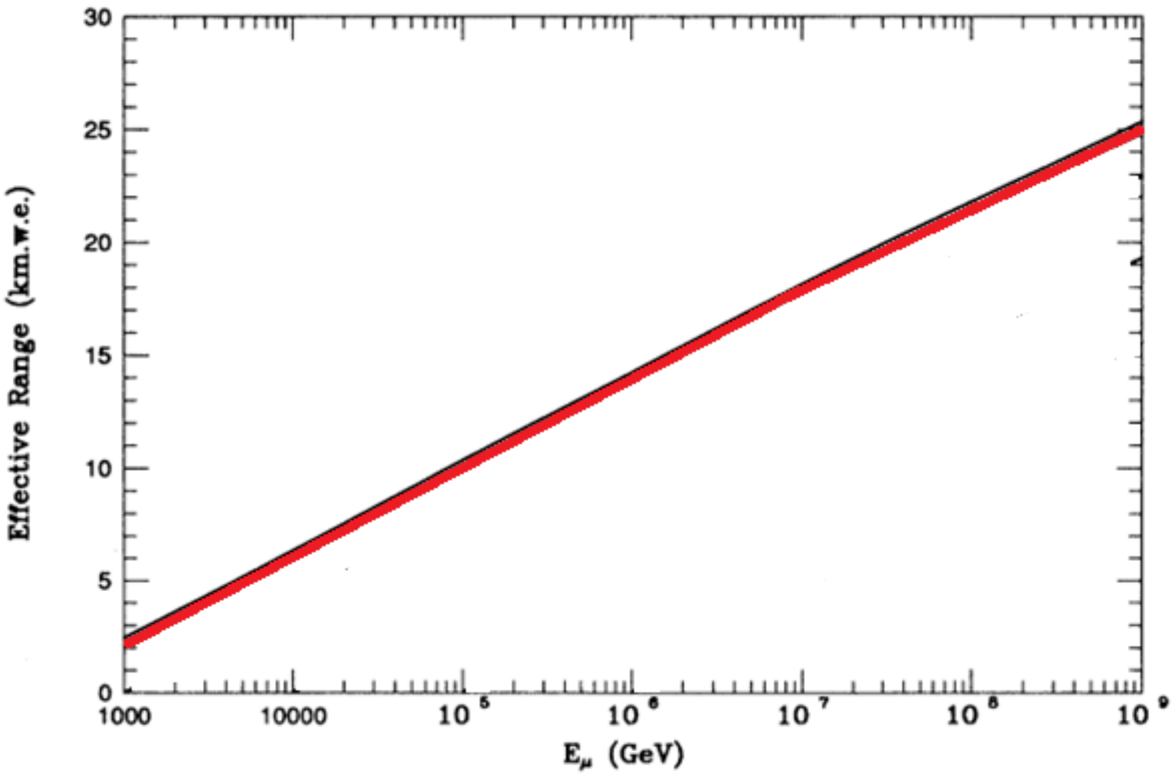


Muon Range (cm)

$$-\frac{dE}{dx} = a + bE \qquad a = 2\,\mathrm{MeV\,g^{-1}cm^{-2}}\ ;\ b = 4\times10^{-6}\,\mathrm{g^{-1}cm^{-2}}$$

$$a/b = 500\,\mathrm{GeV} = 0.5\,\mathrm{TeV}$$

$$\rightarrow\ x = \frac{1}{b}\ln\left(1+\frac{E}{a/b}\right) = 2.5\times10^{5}\,[\mathrm{g\,cm^{-2}}]\ln(1+2E[TeV])$$



Muon range (km.w.e.) vs. initial energy E_μ for E^{μ}_{thr} =100 GeV

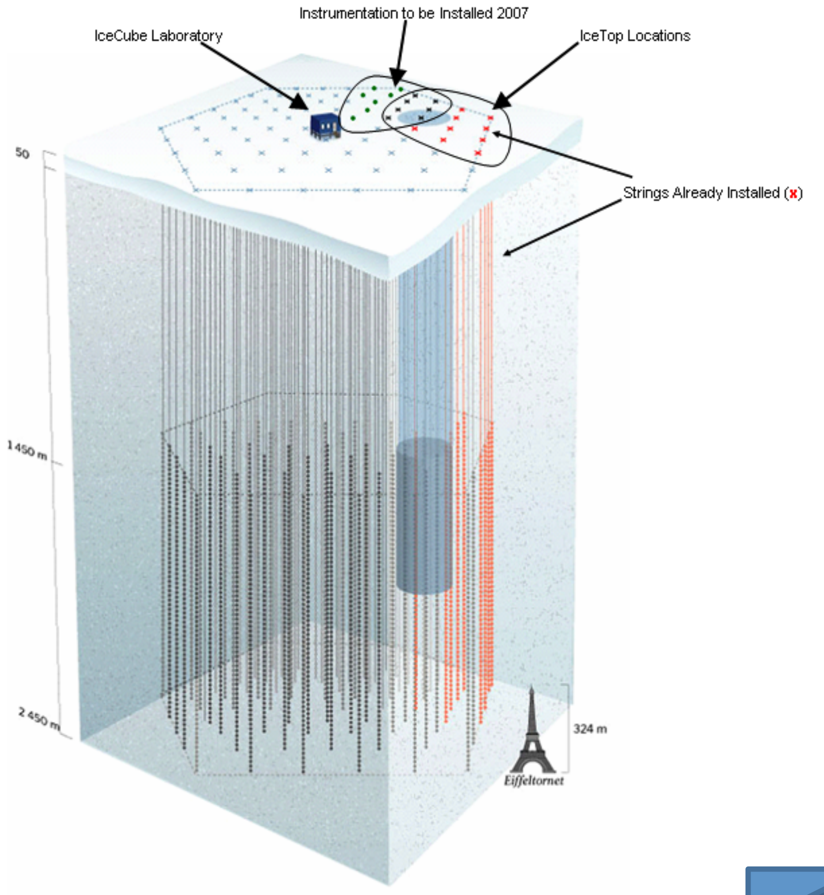
Number of events in a 1 km^3

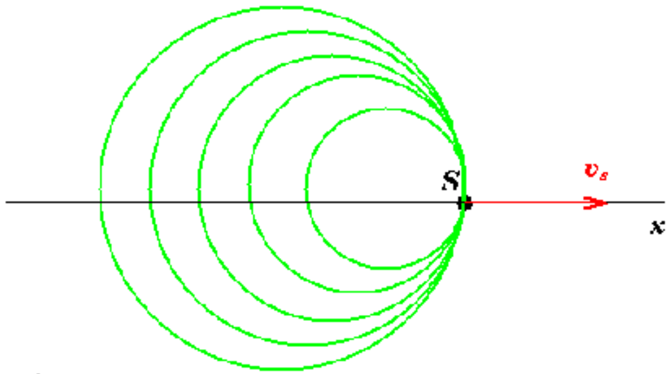
$$\frac{N_\nu}{T} = \int_{1\ \mathrm{TeV}}^{10^3\ \mathrm{TeV}} \mathrm{d}E_\nu \cdot (\Phi_\nu^0 E_\nu^{-2}) \cdot A \cdot (P_\circ E_\nu^{0.8}) \cdot \epsilon = 0.5\ 10^{-16} \cdot A \cdot \epsilon\ \ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

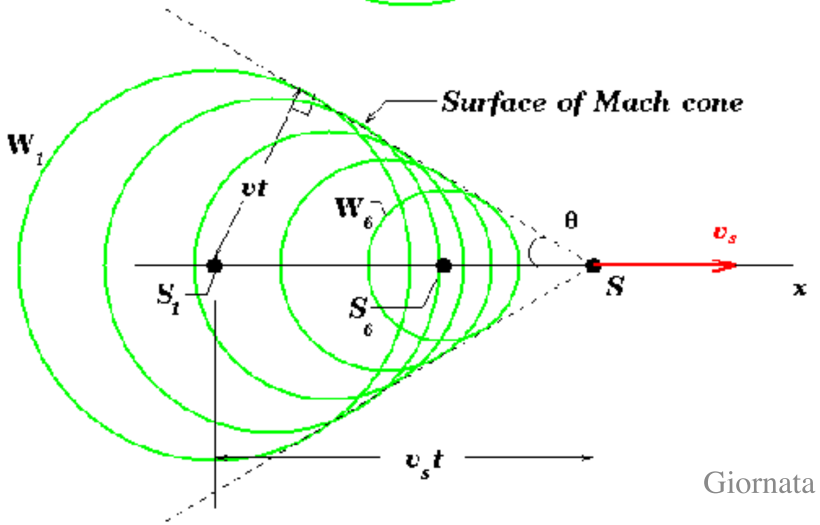
$$T = 3.15 \times 10^7\ s = 1\ y$$

$$A = 10^{10}\ \mathrm{cm}^2 = 1\ \mathrm{km}^2$$

$$N_\mu \approx 1.5\ \mathrm{events/y}$$



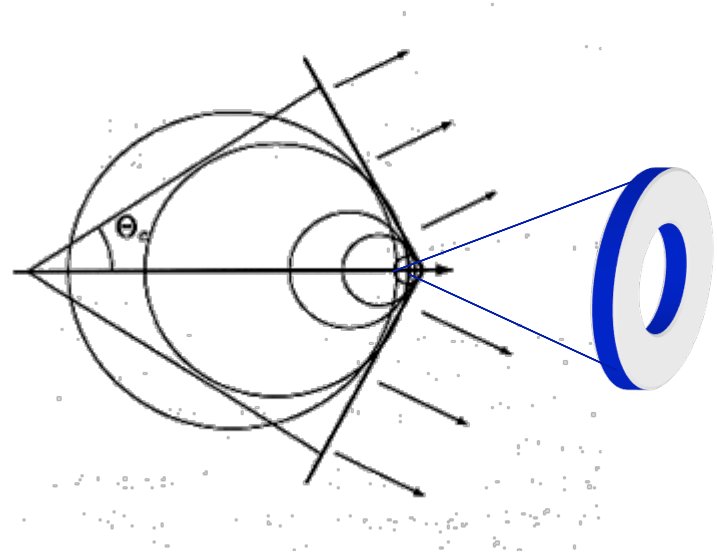




3.3 Cherenkov Radiation

- As a charged particle travels, it disrupts the local EM field.
- Radiation is emitted as insulator's electrons restore to equilibrium
- This radiation destructively interfere and no photons are detected.
- However, **when the disruption travels faster than light is propagating through the medium**, the radiation constructively interfere and intensify the observed Cerenkov photons.
- In water, **~300 Č photons/cm** in the range of 300-600 nm for a $\beta=1$ particle

Cherenkov light emission



- Cherenkov light emitted by relativistic particles in a transparent medium, with : $\beta n(\lambda) > 1$
- Dominant photon emission in the blue-UV band (see cap. 7).
- In the range in which water/ice are most transparent:

$$\frac{d^2 N_C}{dx d\lambda} = \frac{2\pi}{137\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right)$$

- In the range 300-600 nm and β=1:

N_C = 300/ cm

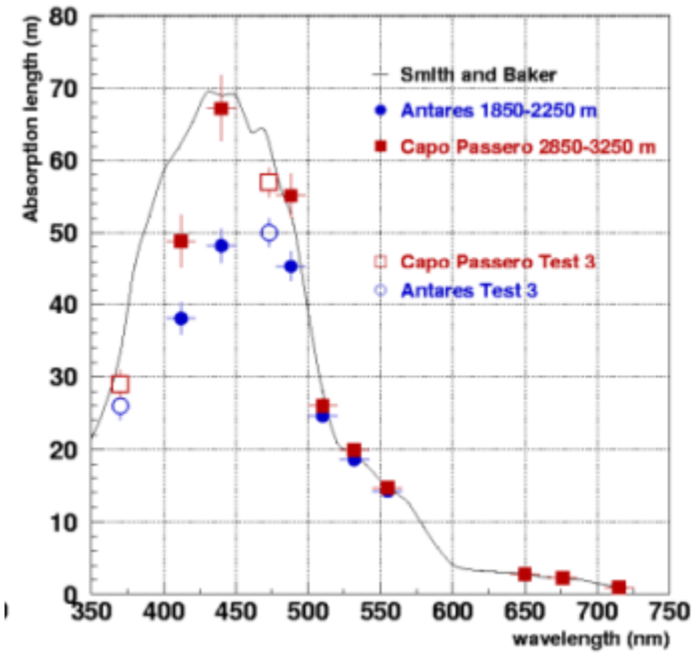
3.4 water/ice properties

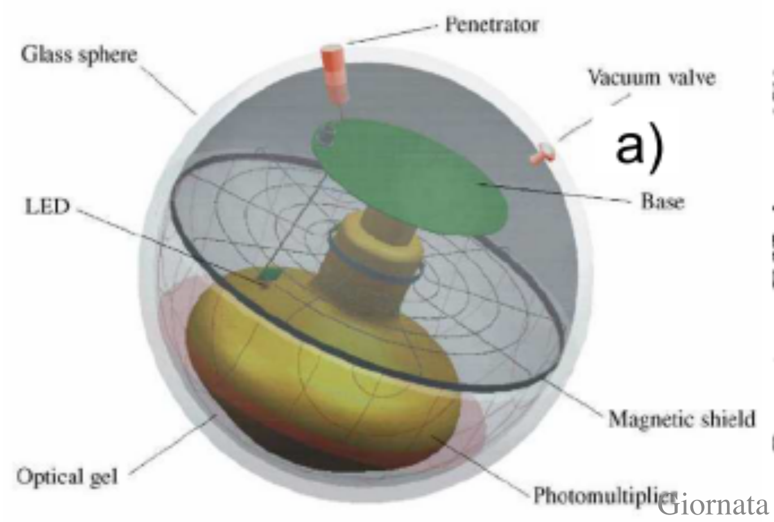
Water/ice characterized by two quantities

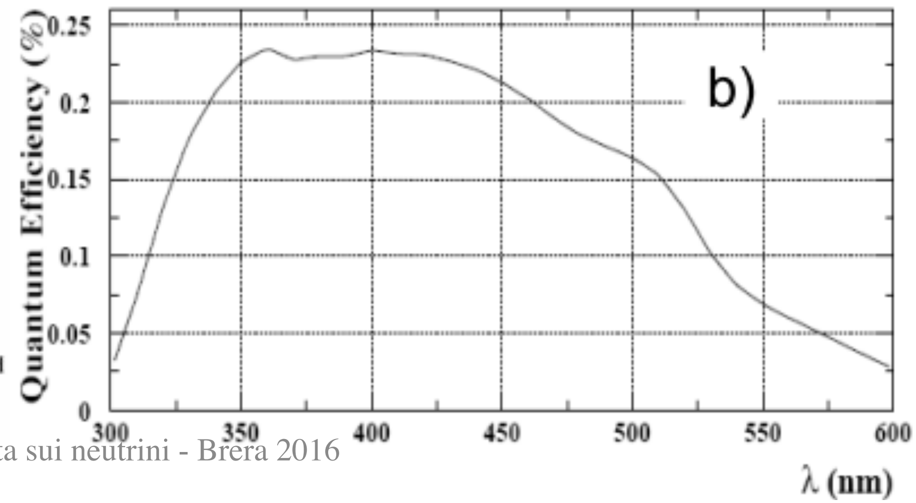
- ***absorption length***. It depends on λ, and it is order of 50 m (ice better than water)
- ***scattering length*** (water better than ice)

Cherenkov photons can reach a **PMT** in an **Optical Module (OM)** and produce a signal

- Typical OM efficiency: 20%



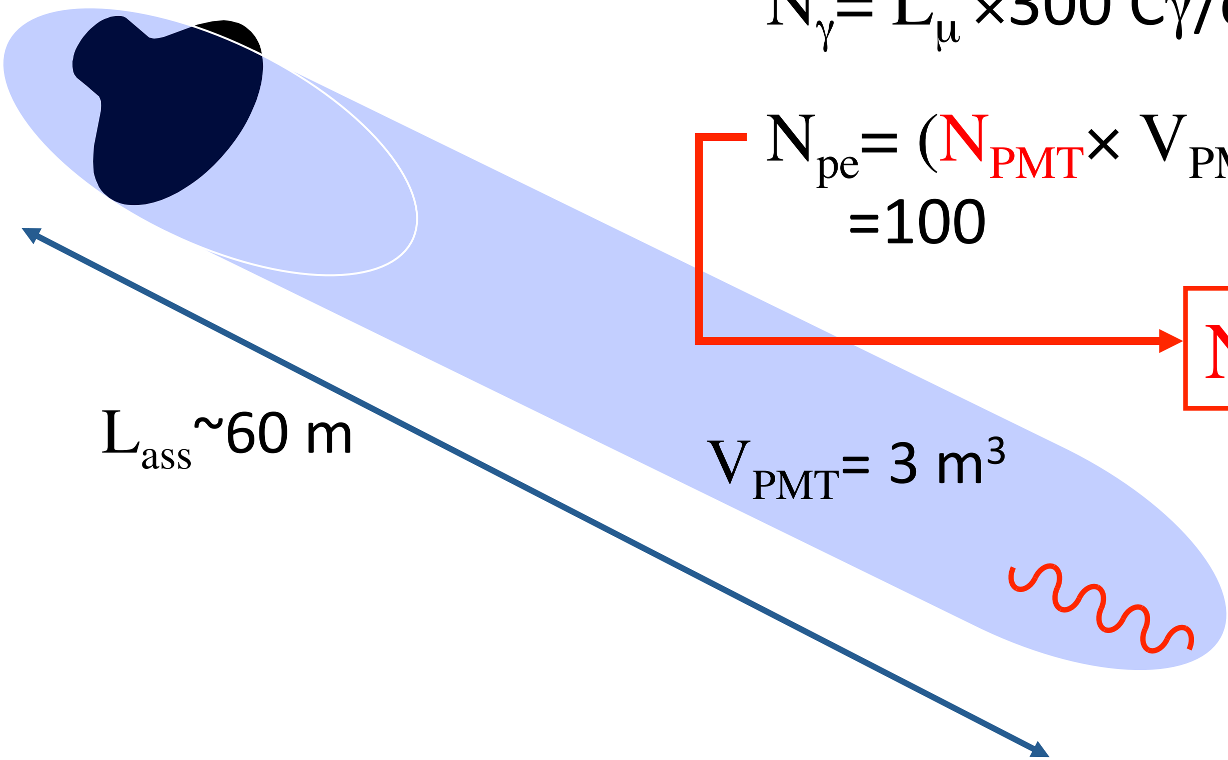




3.5 How many light sensors → € ?

- **Problem**: How many PMTs **(N_{PMT})** are needed in 1 km³ detector volume in order to detect ~100 p.e. (N_{pe}) ?
- Assume a muon track of L_μ=1 km.
- Assume 10″ PMTs in one OM (as IceCube/ANTARES)
- O(100 p.e.) in O(10) PMTs are necessary for track reconstruction

10” PMT =0.05 m²

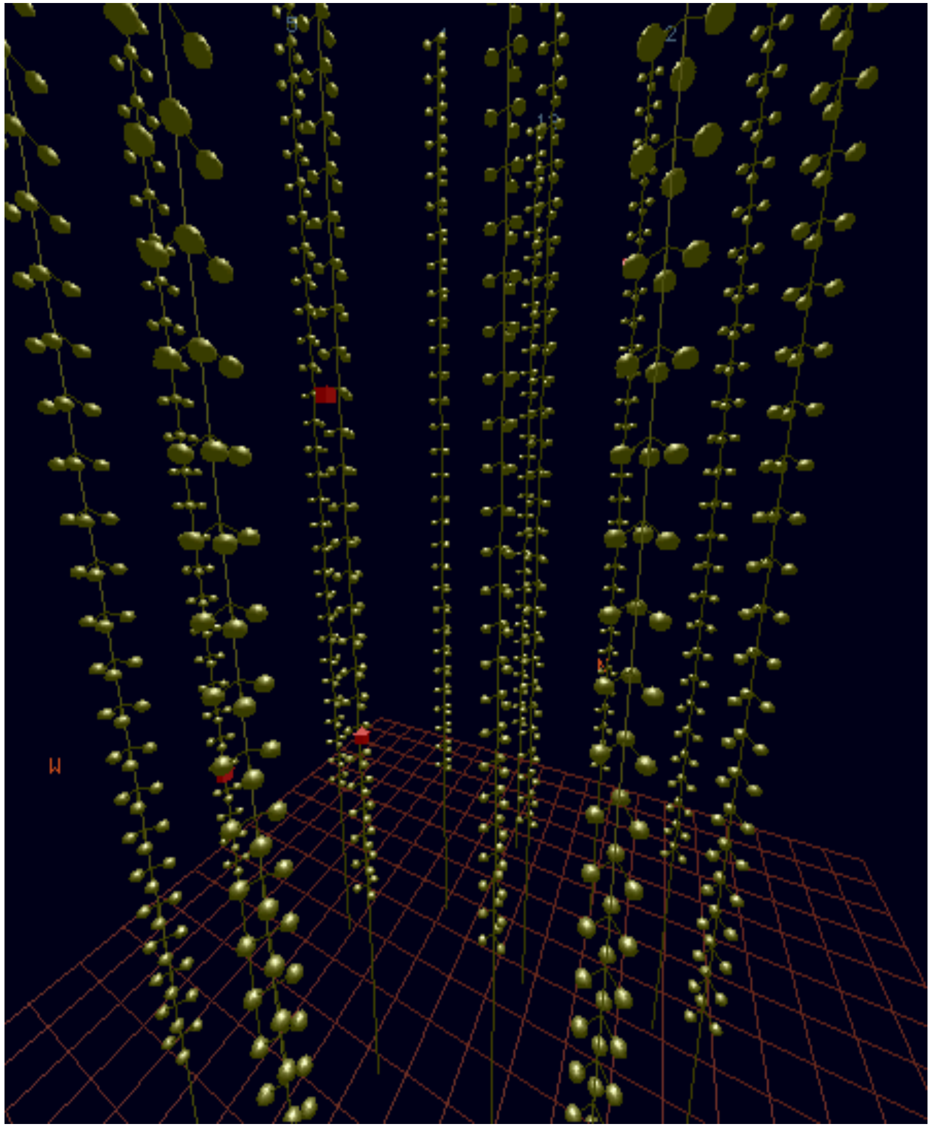


$N_\gamma = L_\mu \times 300$ Čγ/cm= 3×10^7 Čγ

$N_{pe} = (N_{PMT} \times V_{PMT} \times N_\gamma \times \varepsilon_{QE})/1$ km³ =100

N_{PMT}=5000

3.6 Track/cascades reconstruction



- ❑ Reconstructed from time-space correlation between ***hits***.
- ❑ energy reconstructed from amplitudes

Muon channel (CC ν_μ)

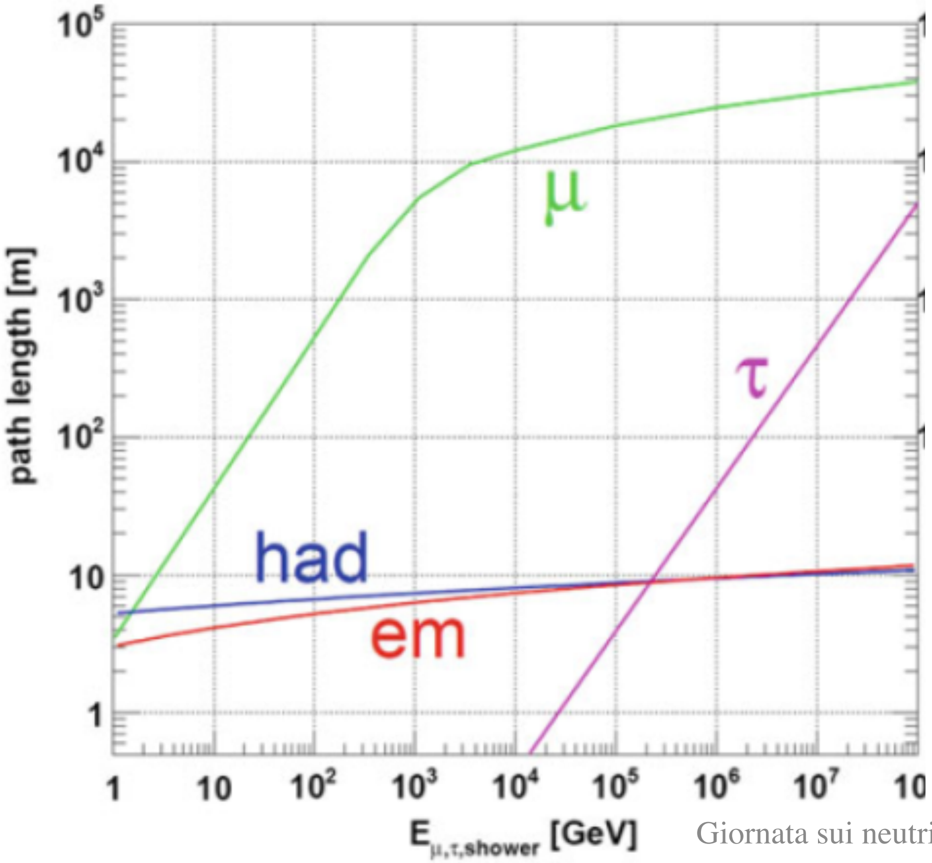
- Long pattern in the detector
- Cherenkov photons are correlated in space and time

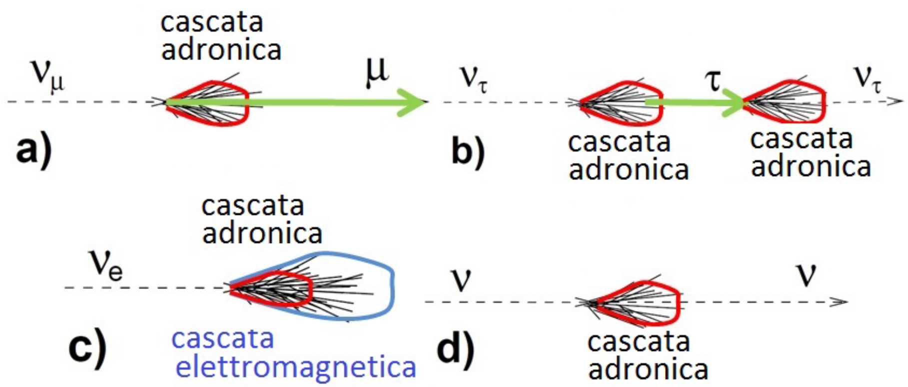
Cascades (CC ν_e+ NC)

- Short pattern (point like)

Track and showers

- ν_μ yield **tracks** in the detector
  - Better direction estimate (the muon collinear with the neutrino)
- ν_e,ν_τ, neutral currents: yield **showers** (or **cascades**) in the
  - Better energy measurement (energy dissipated in the detector)



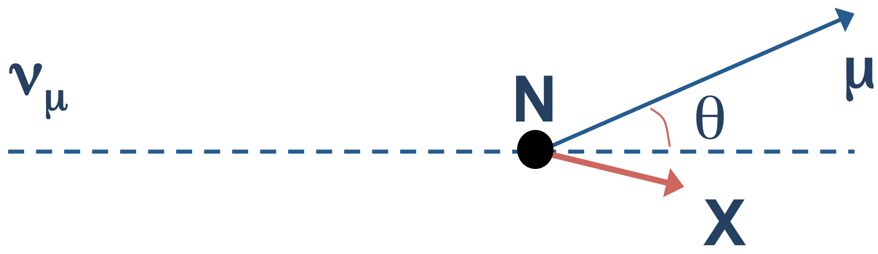


Path length (m) of tracks/cascades in water

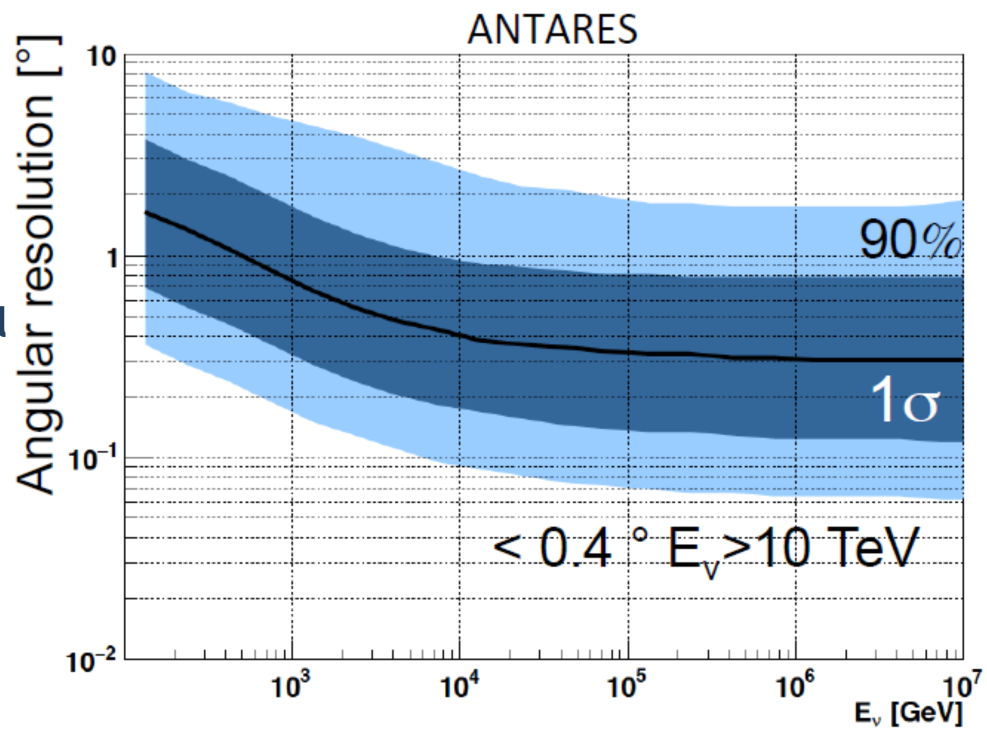
3.7 Angular/energy resolution for ν_μ

Muon = long track in the detector. The μ reconstruction allows the measurement of the ν direction (kinematics important for E<1 TeV)

- Neutrino ***direction*** much better that 1°. Water better than ice
- ***Energy resolution*** relatively poor (better for large detectors)

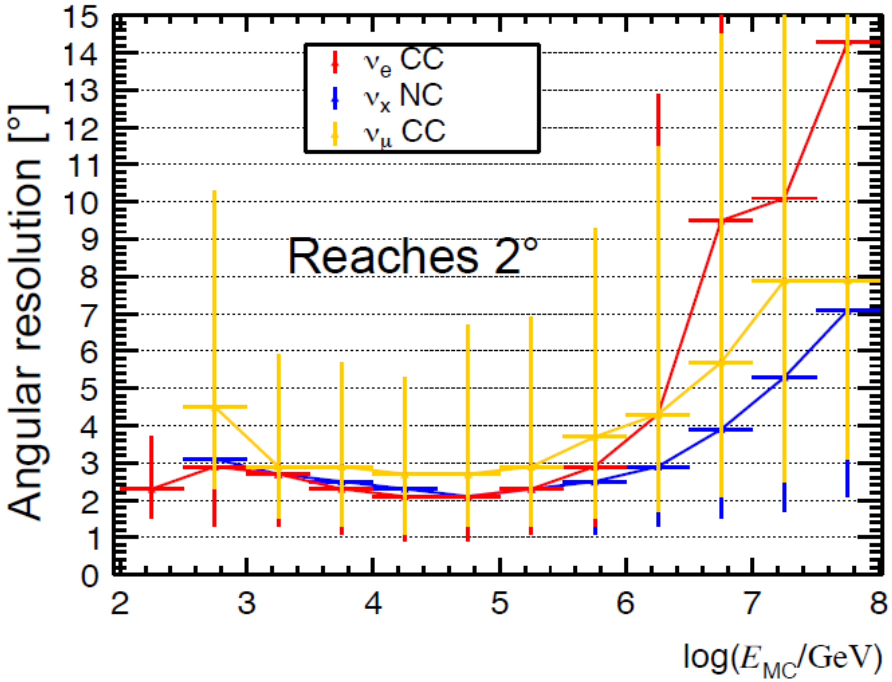


ANTARES angular resolution vs E



Angular/energy resolution for cascades

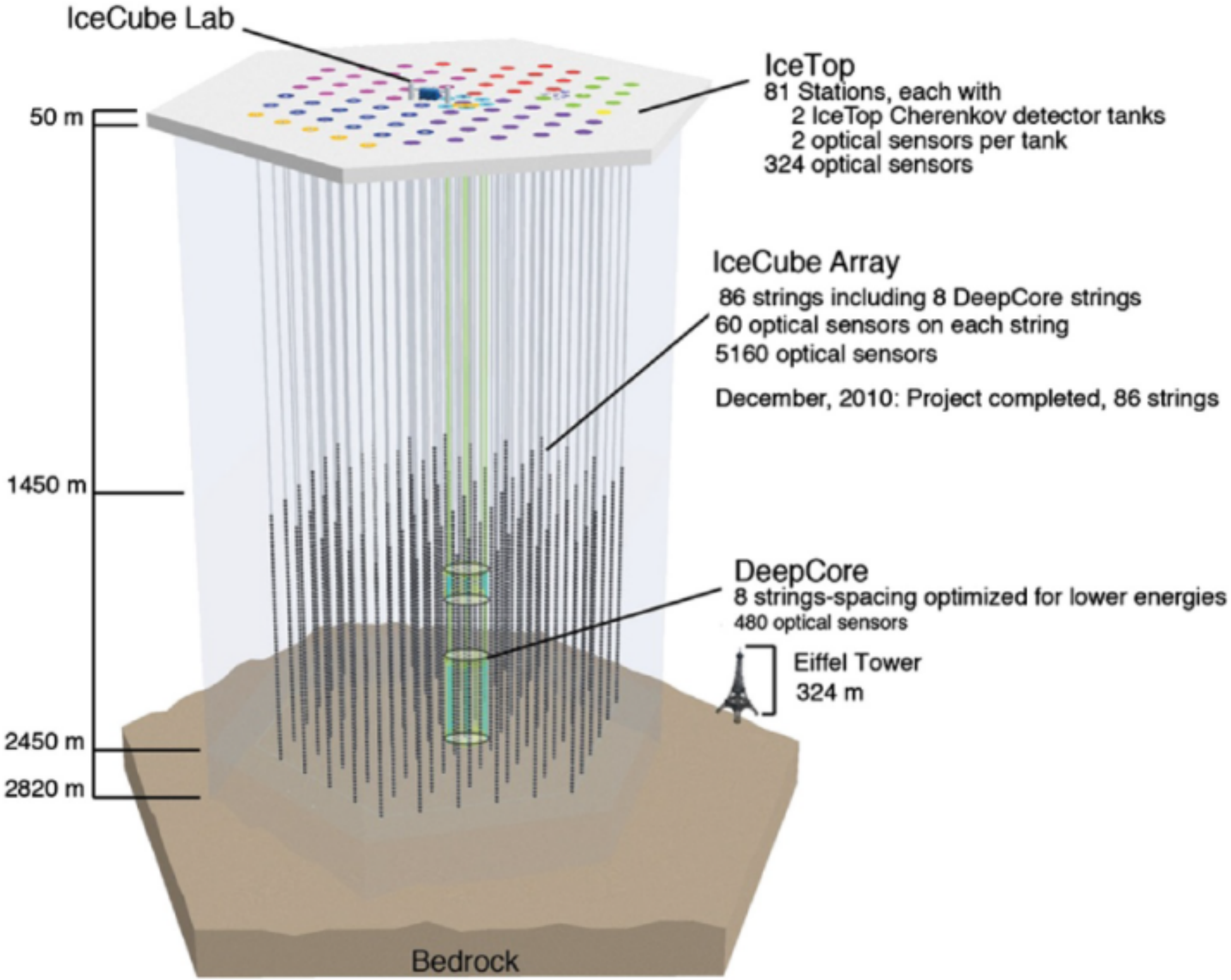
- Electromagnetic/hadronics cascades develop within ~10 m
- Very short tracks, poor ***angular resolution*** (depends on the detector. Ranges from few degrees to 15°-20°)
- Energy resolution much better (large fraction of the ν energy released in secondaries)



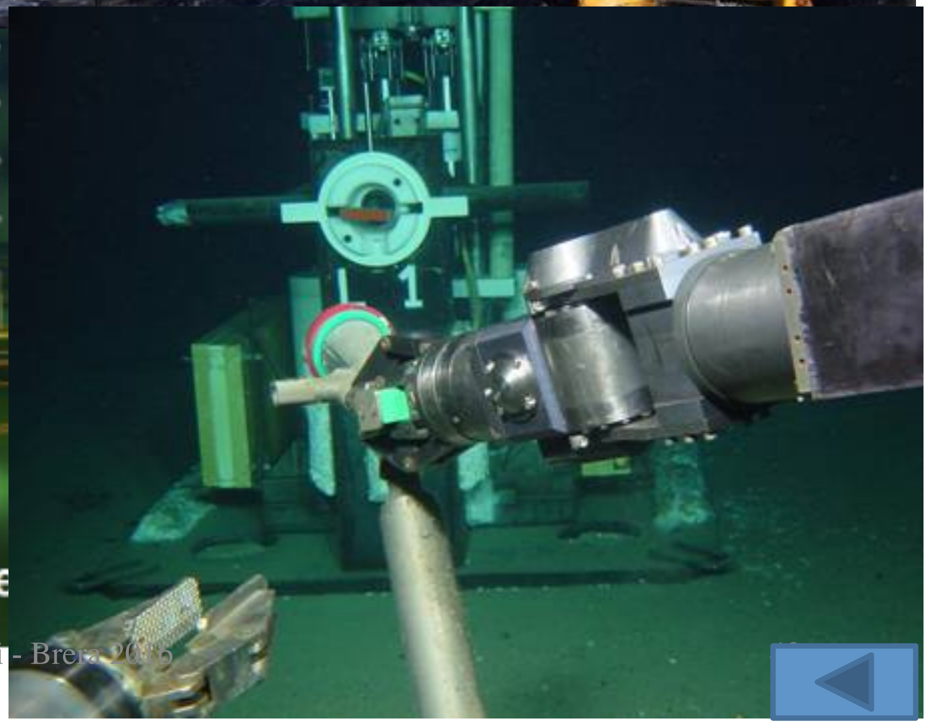
3.8 Difference between ice…

… and Mediterranean water

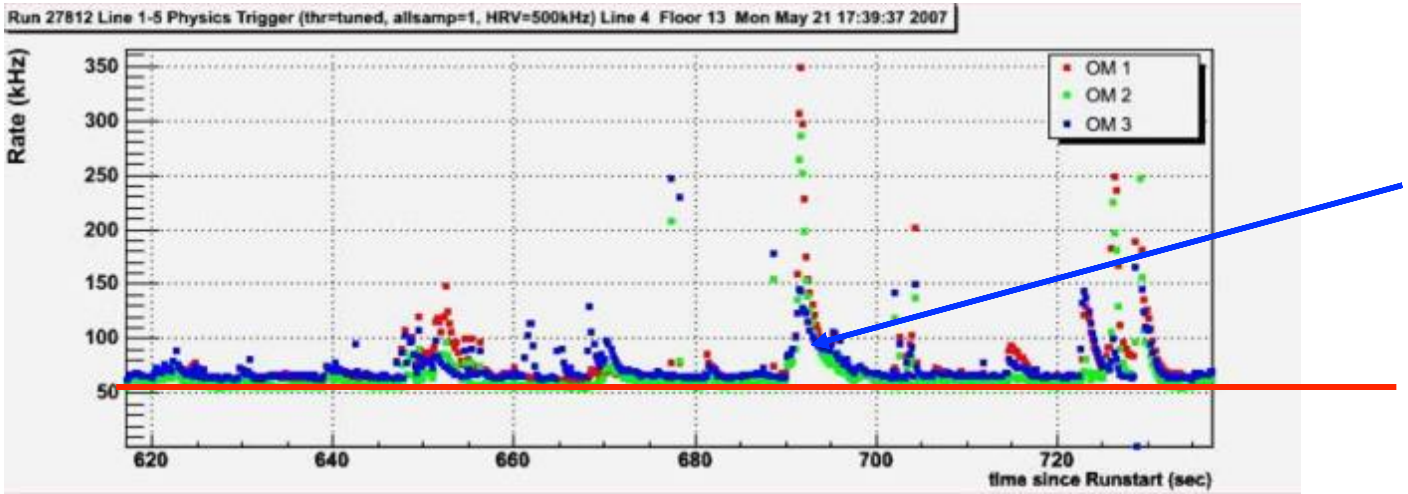
IceCube @South Pole



ANTARES @ Mediterranean Sea



3.9 Optical background in water

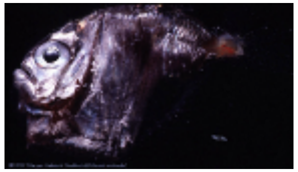


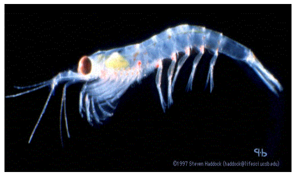
Baseline:

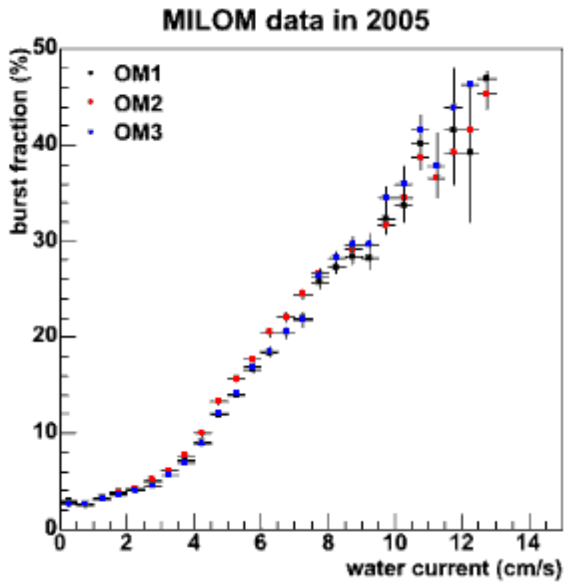
^{40}K decays + bacteria luminescence

Bioluminescence bursts:

Animal species which emit light by flashes, spontaneous or stimulated around the detector.

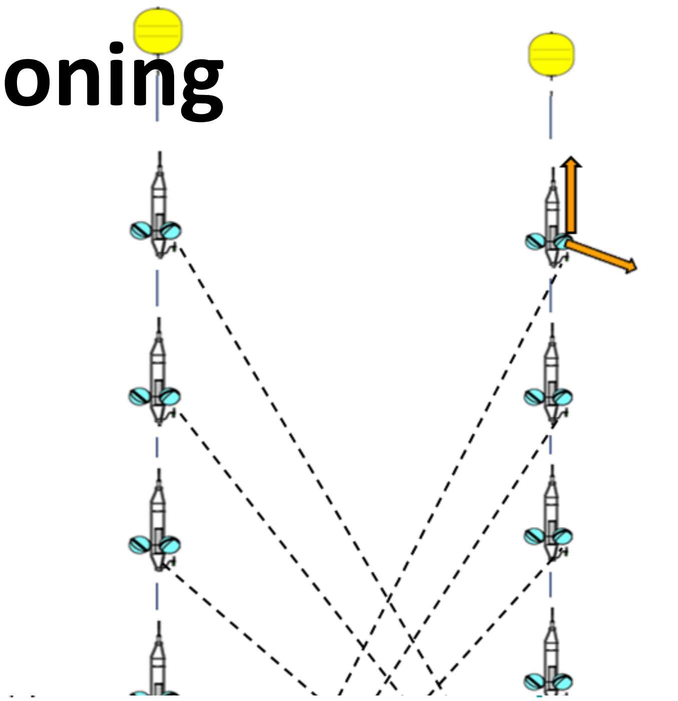


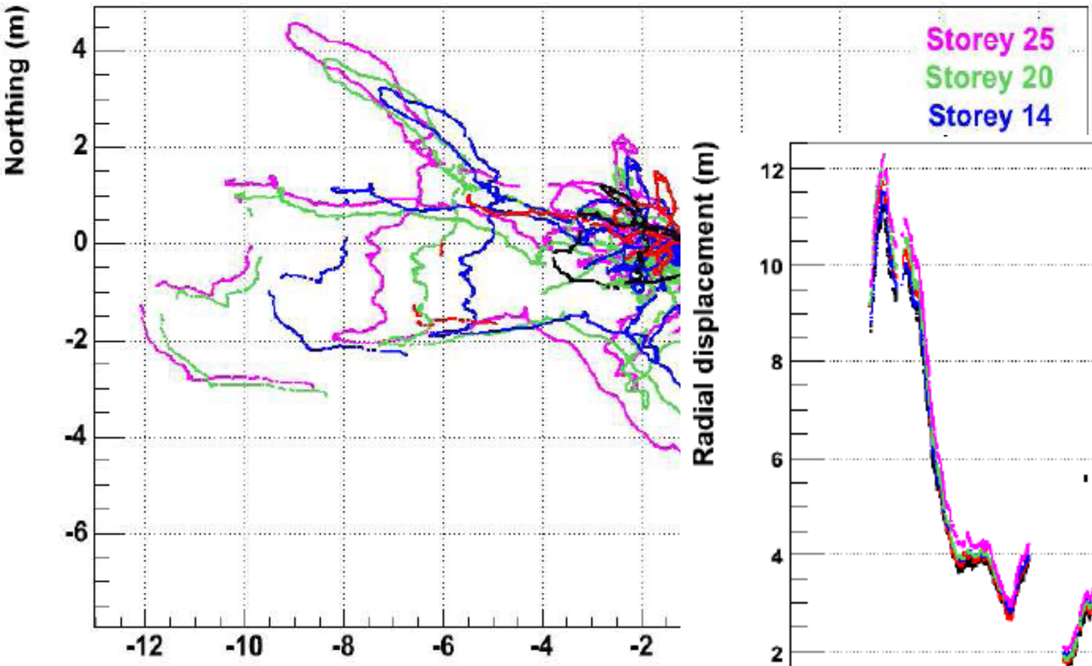


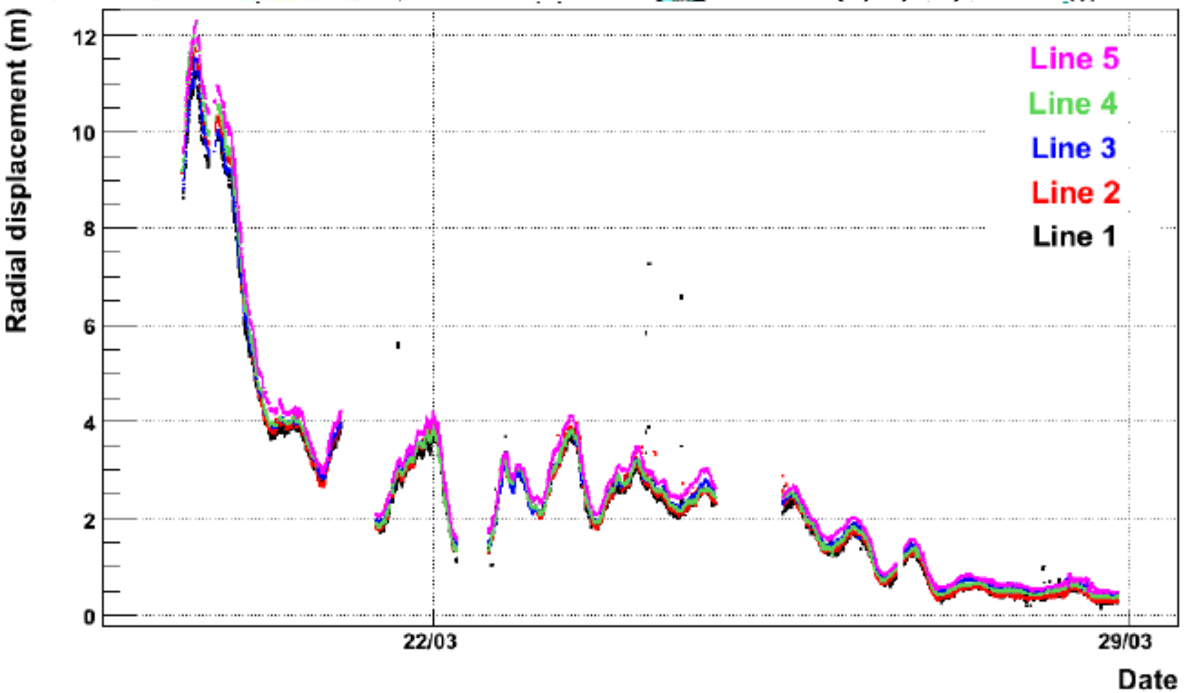


3.10 Detector positioning

- <10 cm accuracy on individual OM position
- Acoustic system.
- Additional devices provide independent sound velocity measurements

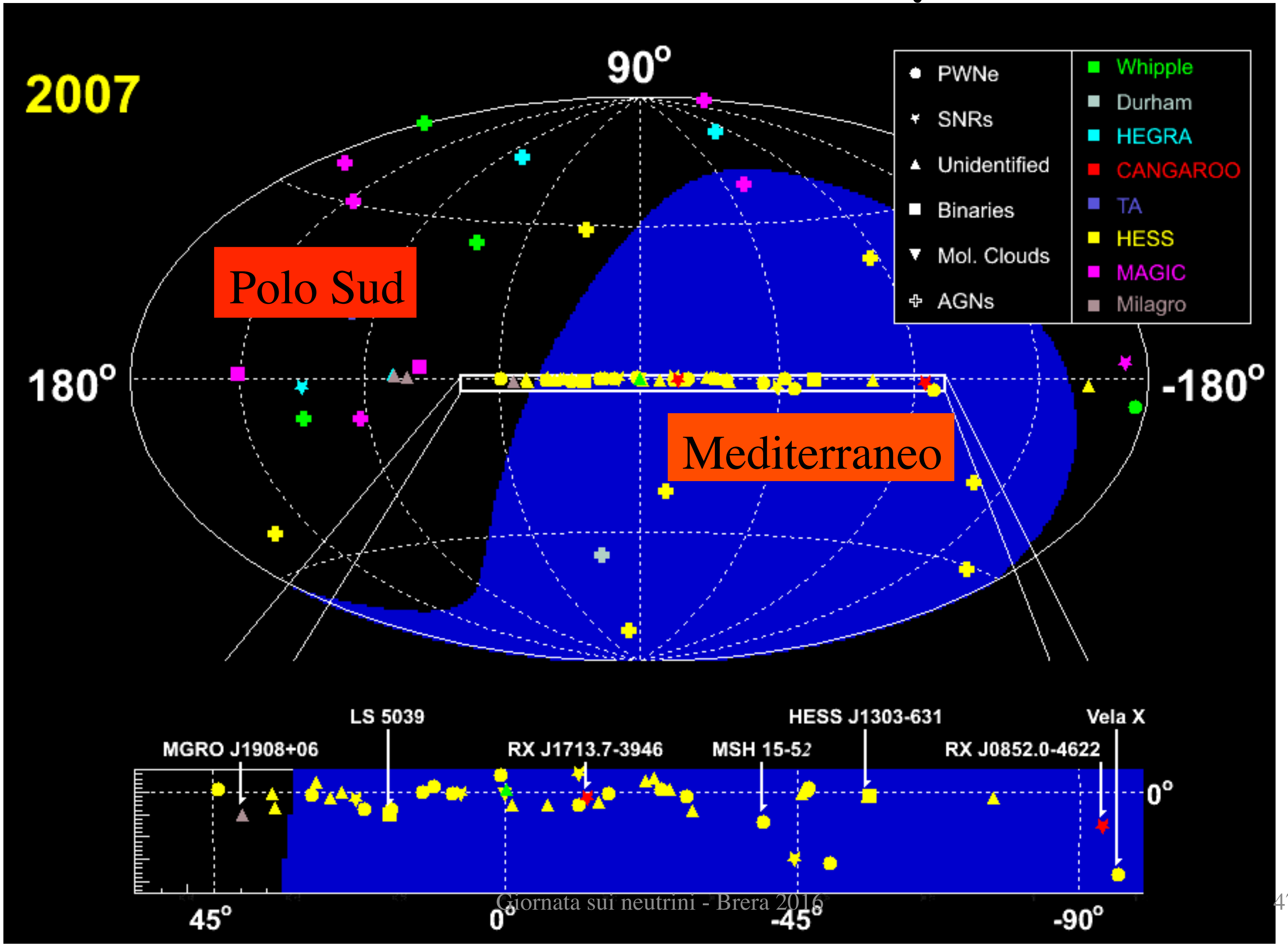






4. Detecting cosmic neutrinos: the twofold way

The catalog of TeV γ-rays



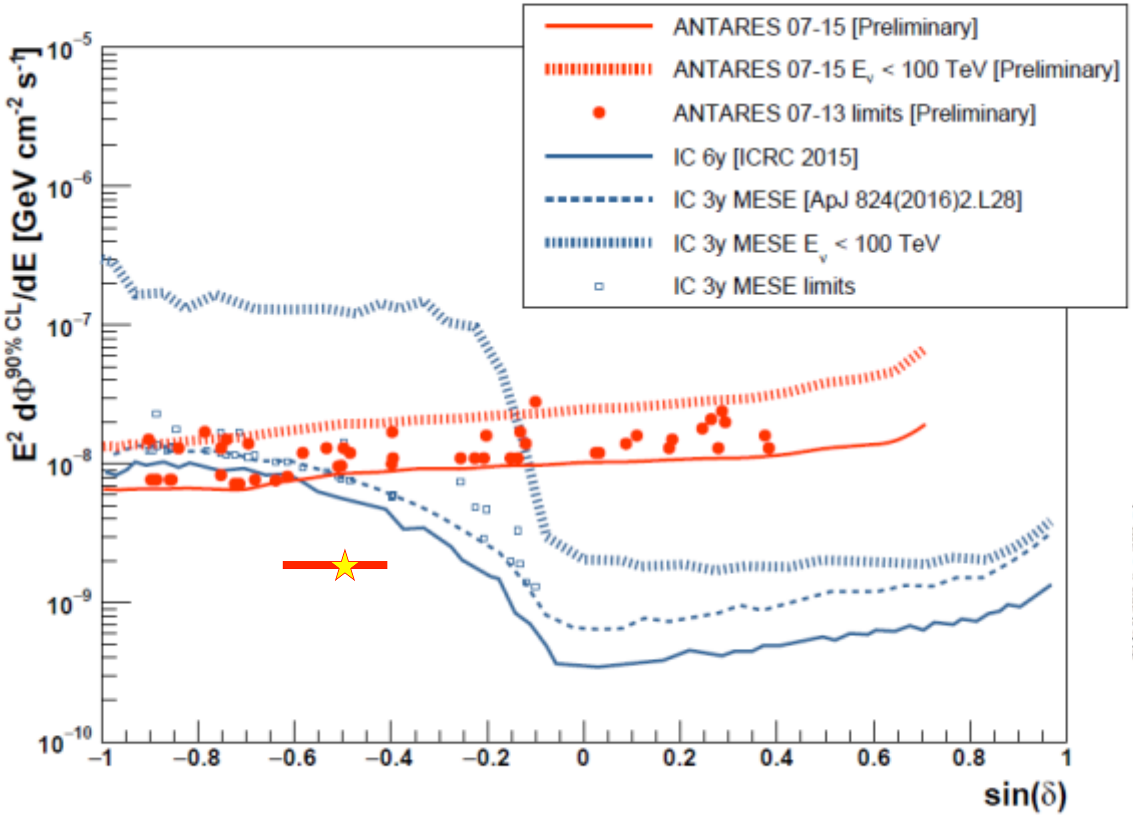
1) Measuring a significant excess of events from a given direction (**point-sources**).

- ν_μ mainly. And only upgoing events

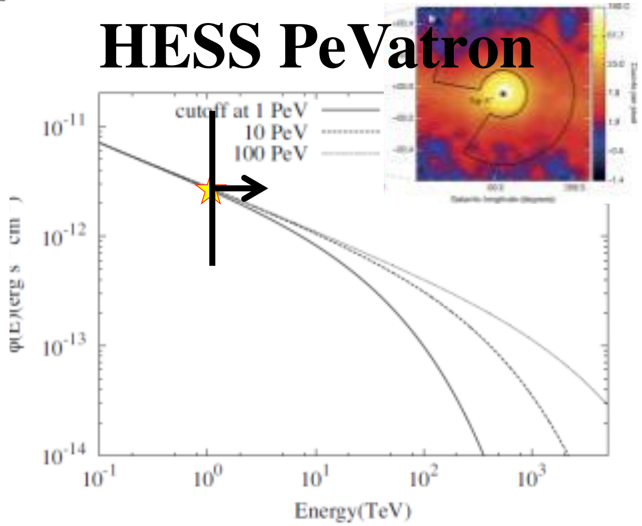
2) Measuring a significant excess of high-energy events with respect to the background (**diffuse**).

- All flavors. Tracks, showers and partially contained events.

Point Sources

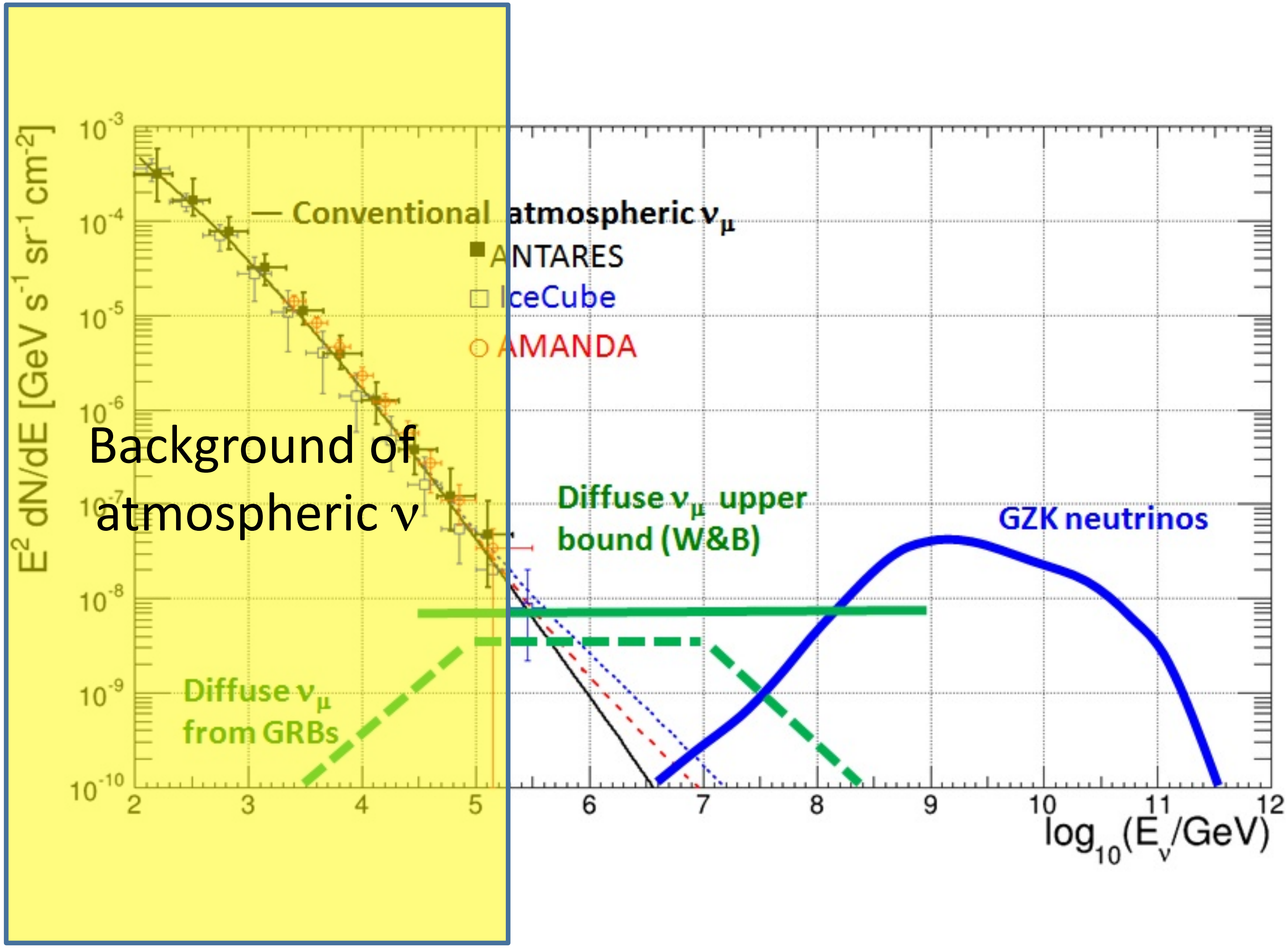


HESS PeVatron



Nature 531 (2016) 476

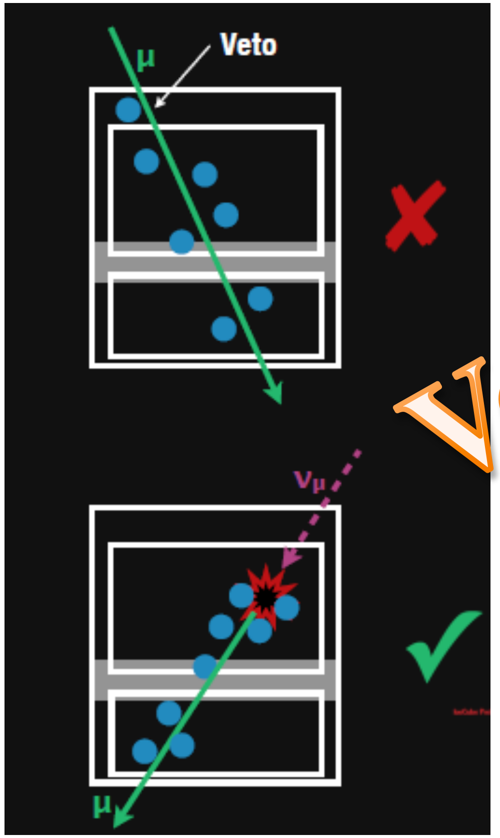
Diffuse flux of cosmic ν

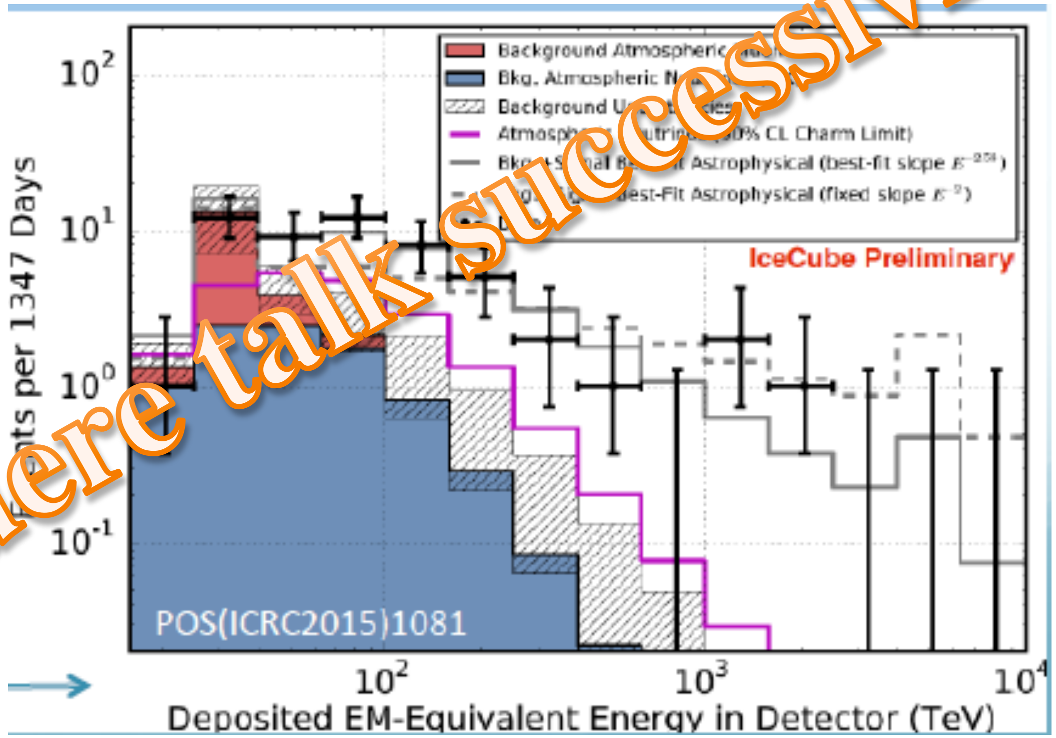


Excess of HE events over background

- High Energy Starting Events (HESE) in IceCube
- Events selected in a restricted fiducial volume (SK-like)
- Mostly showers with poor angular determination (>10°)

Vedere talk successivi



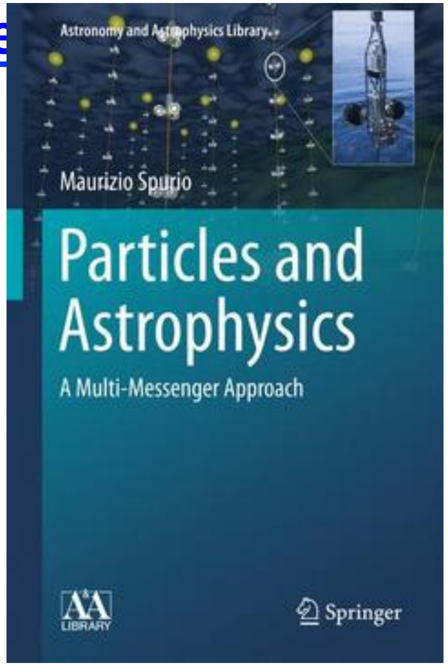


- Atmospheric muons
- Atmospheric neutrinos
- **Signal= excess of HE events**

Per approfondimenti

- M. Spurio:
  Neutrini in profondità: Vita, morte e miracoli dei neutrini rivelati sotto terra, sotto i ghiacci o in fondo al mare
  arXiv:1609.06710
- T. Chiarusi, M. Spurio:
  High-Energy Astrophysics with Neutrino Tele
  (2010) 649-701: **arXiv:0906.2634**

- M.S. **Particles and Astrophysic** (Springer)




Ancona
Arezzo
Perugia
San Benedetto del Tronto
Grosseto
Terni
Pescara
Termoli
Roma
200 km
Latina
Foggia

Neutrini nel cosmo

«di qua, di là, di giù, di sù li mena;
nulla speranza li conforta mai,
non che di posa, ma di minor pena. »

Inferno, Canto V

(si noti, siamo già «underground»)!