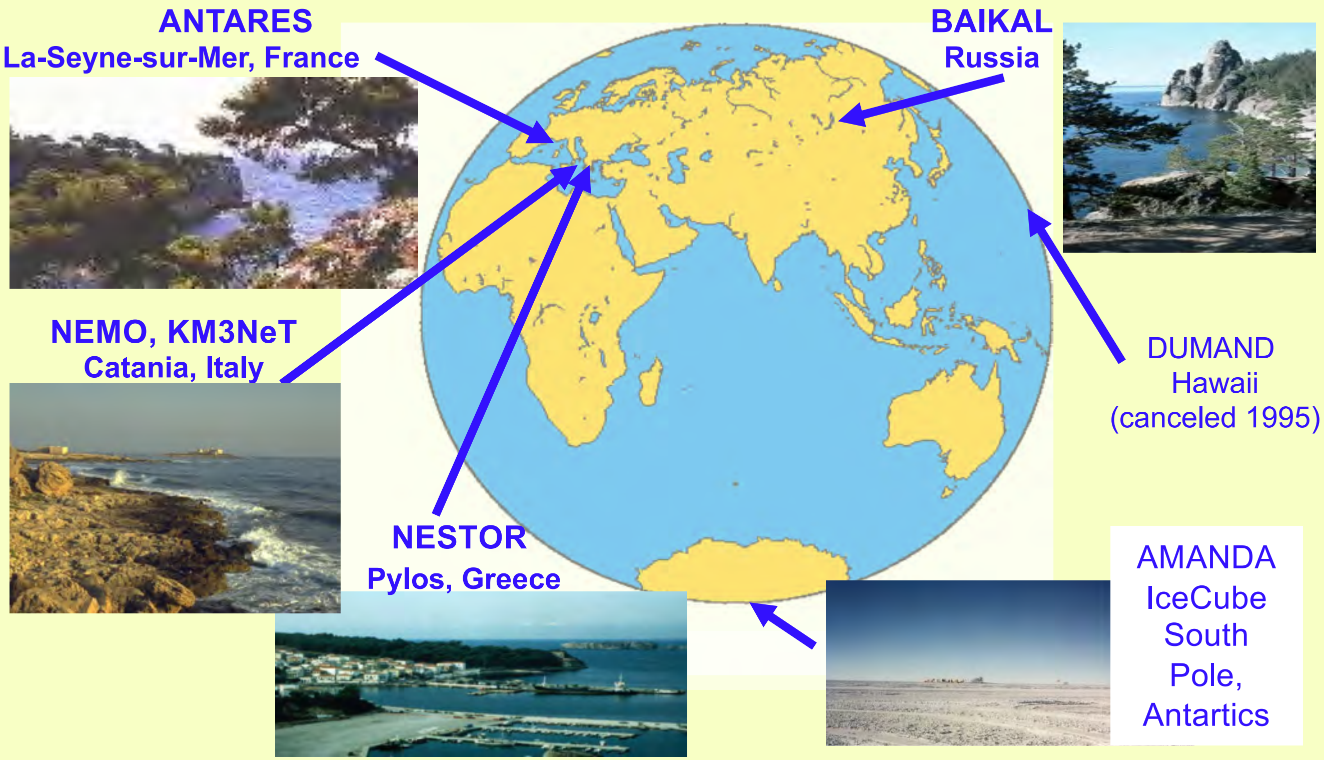
Lessons 15 and 16

- How to dimension a High Energy Astrophysical Neutrino Telescope (like BAIKAL, AMANDA, ANTARES, IceCube, KM3NeT…)
- Evaluation of neutrino fluxes adopting the “hadronic model” for known point-like high energy gamma sources
- First results

Present Cherenkov Neutrino Telescopes



ANTARES
La-Seyne-sur-Mer, France

BAIKAL
Russia

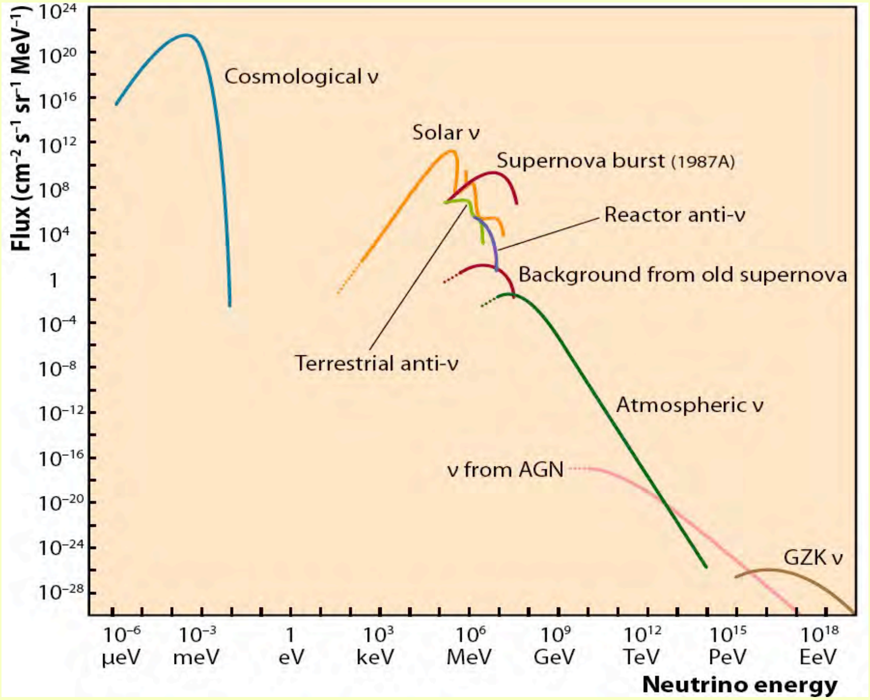
NEMO, KM3NeT
Catania, Italy

DUMAND
Hawaii
(canceled 1995)

NESTOR
Pylos, Greece

AMANDA
IceCube
South
Pole,
Antartics

Why a ~km^2 scale for a ν telescope? a quick calculation



The flux of neutrinos at ~ TeV is

$$\frac{dN_\nu}{dE_\nu} \approx 10^{-18} E_\nu^{-2} \frac{\nu}{cm^2\ s\ sr\ MeV}$$

$$\approx 10^{-12} E_\nu^{-2} \frac{\nu}{cm^2\ s\ sr\ TeV}$$

The number of neutrino interactions in a detector with $A_{eff} \approx 1\,m^2$ and in 1 year time (3.2*10^7 s) is given by

$$N_{int.} = \int_{1\,TeV}^{1PeV} \frac{dN_\nu}{dE_\nu} \cdot A_{eff} \cdot T \cdot\ \Delta\Omega\, dE_\nu$$

$$N_{int.} = \int_{1\,TeV}^{1PeV} \frac{dN_\nu}{dE_\nu} \cdot A_{eff} \cdot T \cdot\ \Delta\Omega\, dE_\nu = 10^{-12} \left[-\frac{1}{E_\nu}\right]_{1}^{1000} A_{eff} \cdot T \cdot\ \Delta\Omega = 10^{-12} \left[\frac{1}{E_\nu}\right]_{1000}^{1} A_{eff} \cdot T \cdot\ \Delta\Omega$$

If we consider $A_{eff} = 1m^2 = 10^4 cm^2$; $T = 1year = 3.2\ 10^7 s$; $\Delta\Omega = 2\pi$ we obtain

$$N_{int.} = 10^{-12} \cdot 10^4 \cdot 3.2\ 10^7 \cdot 6.3 \approx 2 \text{ events.}$$

But: PAY ATTENTION !!!!! We used $A_{eff} = 1m^2$ as if all neutrinos crossing this area will be detected. We have to consider the probability that after the neutrino interaction the event (the muon) is detected …

Detector response function to astrophysical ν fluxes

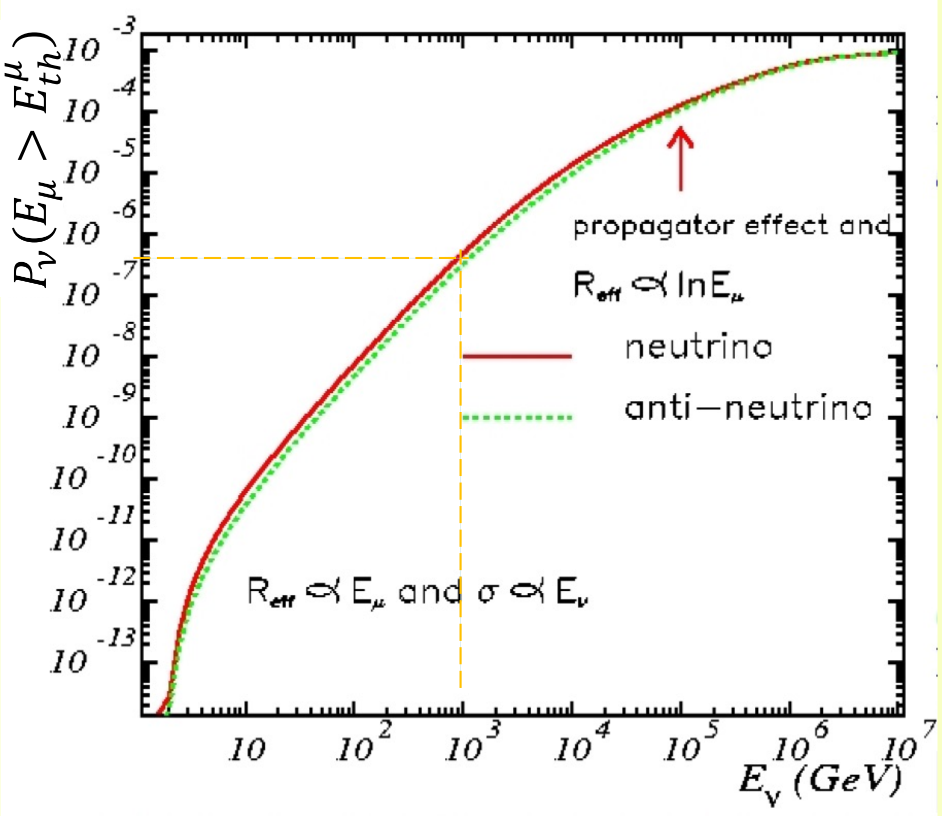
$$\nu_\mu(\bar{\nu}_\mu) + N \rightarrow \mu^+(\mu^-) + X$$

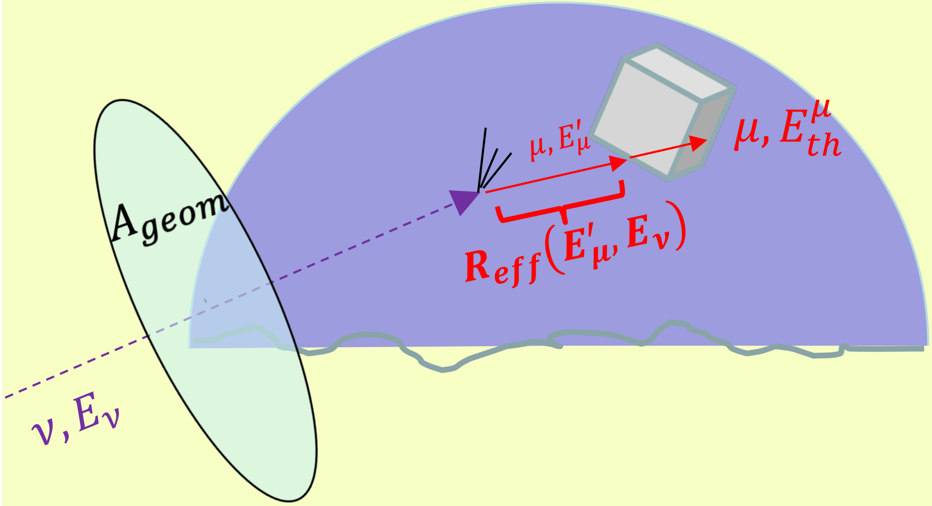
Let's define $P_\nu(P_\nu, E^\mu_{th})$ as the probability that a μ generated in a CC neutrino interaction with E'_μ enters into the detector volume with energy sufficient to be detected ($> E^\mu_{th}$):

$$P_\nu(P_\nu, E^\mu_{th}) = N_A \int_0^{E_\nu} dE'_\mu \frac{d\sigma_\nu}{dE'_\mu}(E'_\mu, E_\nu) R_{eff}(E'_\mu, E^\mu_{th})$$

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

accounts for the μ survival probability





So having defined $A_{eff} = A_{geom} * P_\nu(E_\nu, E^\mu_{th})$

since $P_\nu(E_\nu, E^\mu_{th}) \sim 10^{-7}$ in order to have

$A_{eff} \sim 1m^2 \quad \rightarrow \quad A_{geom} \geq 10^7\, m^2.$

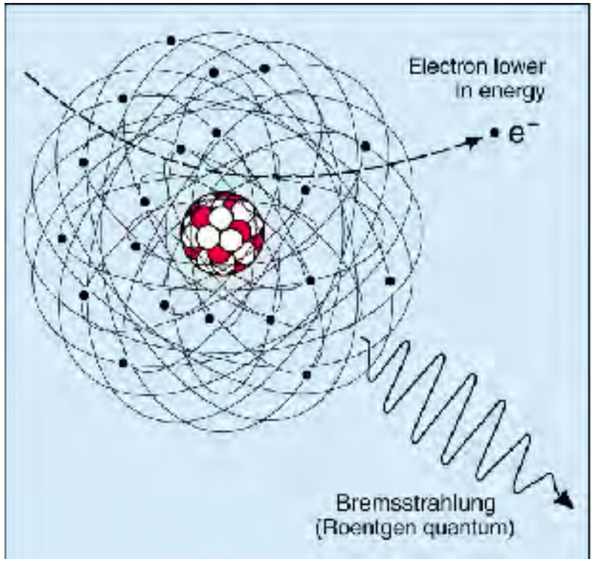
1 TeV muon can cross > 1km detector so the ideal detector dimensions → > km^3

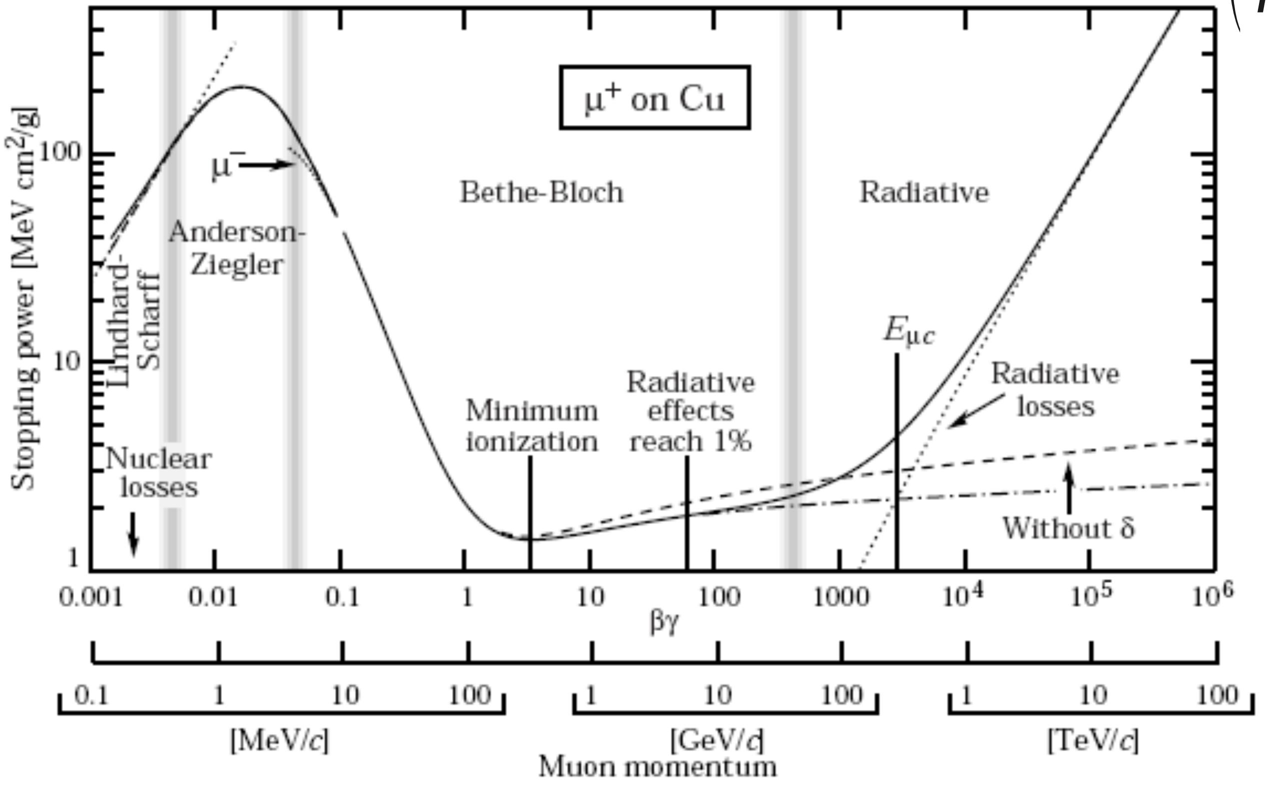
Muons radiate only at extreme energies

A charged particle of mass **m** radiates while being influenced the Coulomb field of a nucleus **Z**:

$$\frac{d\sigma}{dE} \propto \frac{Z^2}{m^2}\frac{\ln E}{E}$$

classically, radiation power $P \propto a^2 = \left(\frac{F}{m}\right)^2$



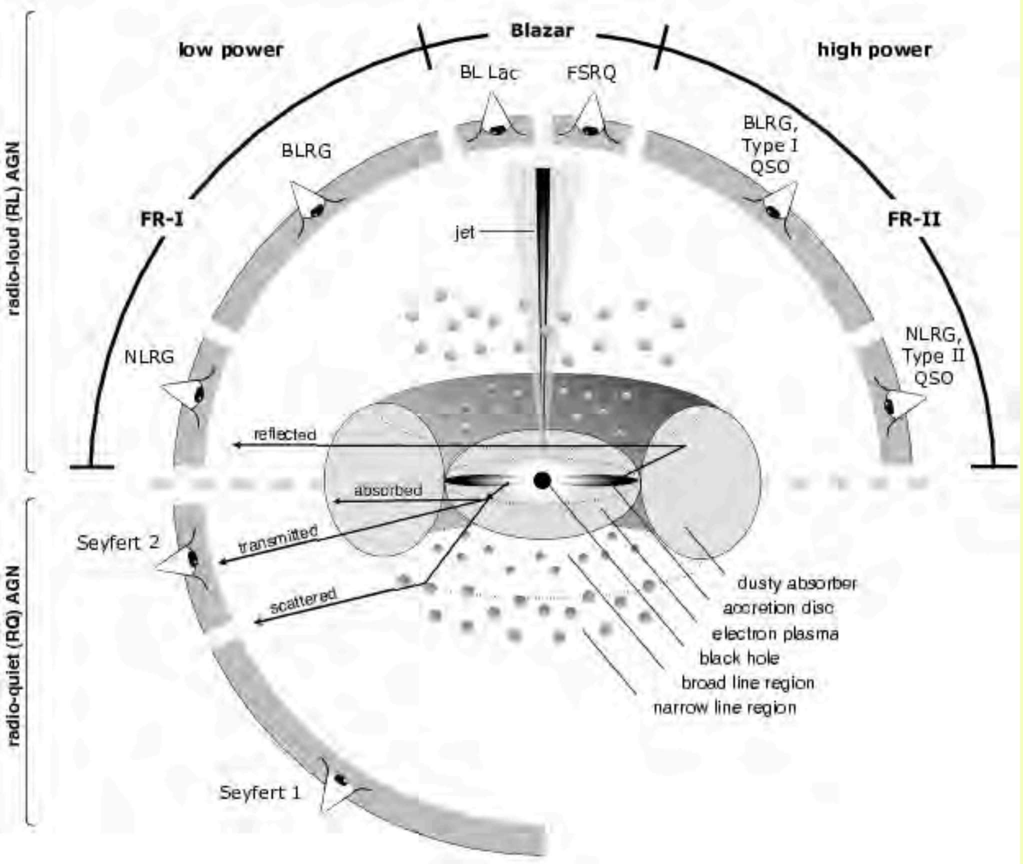


$$\frac{m_e^2}{m_\mu^2} = 2.3\cdot 10^{-5}$$

critical energy for muons is 450 GeV in copper, 200 GeV in lead.

ν from AGN

Active galactic nuclei (AGN) are the most powerful steady sources of luminosity in the Universe. They range from the nuclei of some nearby galaxies emitting about 10^{40} erg/s to distant quasars emitting more than 10^{47} erg/s. The emission is widely spread across the electromagnetic spectrum, often peaking in the ultraviolet, but with significant luminosity in the x-ray and infra-red bands, spatially unresolved except in the radio band. AGNs are presumably the most promising UHE neutrino sources, but the mechanism of neutrino production remains unclear.

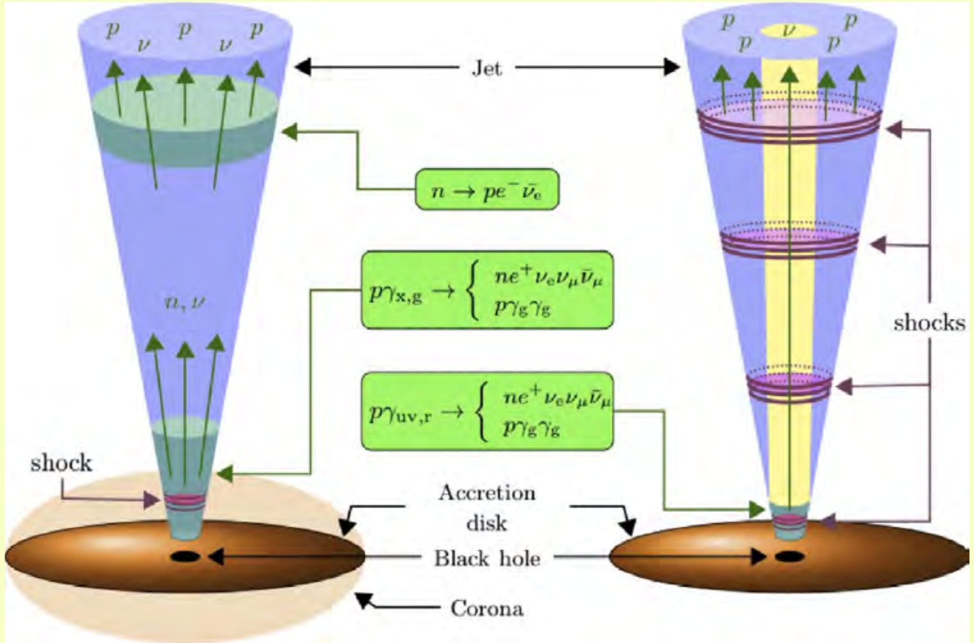


A pictorial scheme of an AGN with a black hole in the centre and an accretion disk perpendicular to the direction of two jets along its rotation axis. The type of object seen depends on the viewing angle, whether or not the AGN produces a significant jet emission, and how powerful the central engine is.

Beckmann, V. and Shrader, C. R. The AGN phenomenon: open issues (2013). Available from: https://inspirehep.net/record/1217833/files/arXiv:1302.1397.pdf, arXiv:1302.1397

ν from AGN

Schematic illustration of the jet structure (not to scale) of an AGN. On the left the so-called "KT" jet model, in which shocks at the base of the jet accelerate protons that subsequently interact with X-ray photons produced in inverse Compton processes in the corona. Neutrons and neutrinos escape the confining regions, however the neutrons suffer beta decays before leaving the jet, hence producing a population of CR protons, along with additional neutrinos.



On the right the "BB"jet model. At a few thousand gravitational radii, stable shocks accelerate protons that interact with the synchrotron photon field produced by relativistic electrons in the jet magnetic field. Neutrinos escape the jet in a collimated beam, whereas protons are continually accelerated along the jet, until they escape the jet as CR. The beam of the CR emission is therefore much larger than that of the neutrinos. Hence, UHE cosmic rays may be directly observed from AGN with greater viewing angles than sources producing point source neutrinos.

Jacobsen, I. B., Wu, K., On, A. Y. L., and Saxton, C. J. High-energy neutrino fluxes from AGN populations inferred from X-ray surveys. *Mon. Not. Roy. Astron. Soc.*, **451** (2015), 3649. arXiv:1506.05916.

Estimation of ν flux from γ fluxes measured from known point like sources

γ fluxes measured by EGRET, WHIPPLE, HESS, MAGIC, FERMI, ... allow to estimate ν_μ, ν_e (and antineutrinos) fluxes at Earth.

Hypothesis: h*adrons* (protons) are accelerated in a cosmic body and interact with local radiation and/or matter (p+γ) producing heavy barions (Δ^+) that then decay giving γ and/or ν.

Let's assume

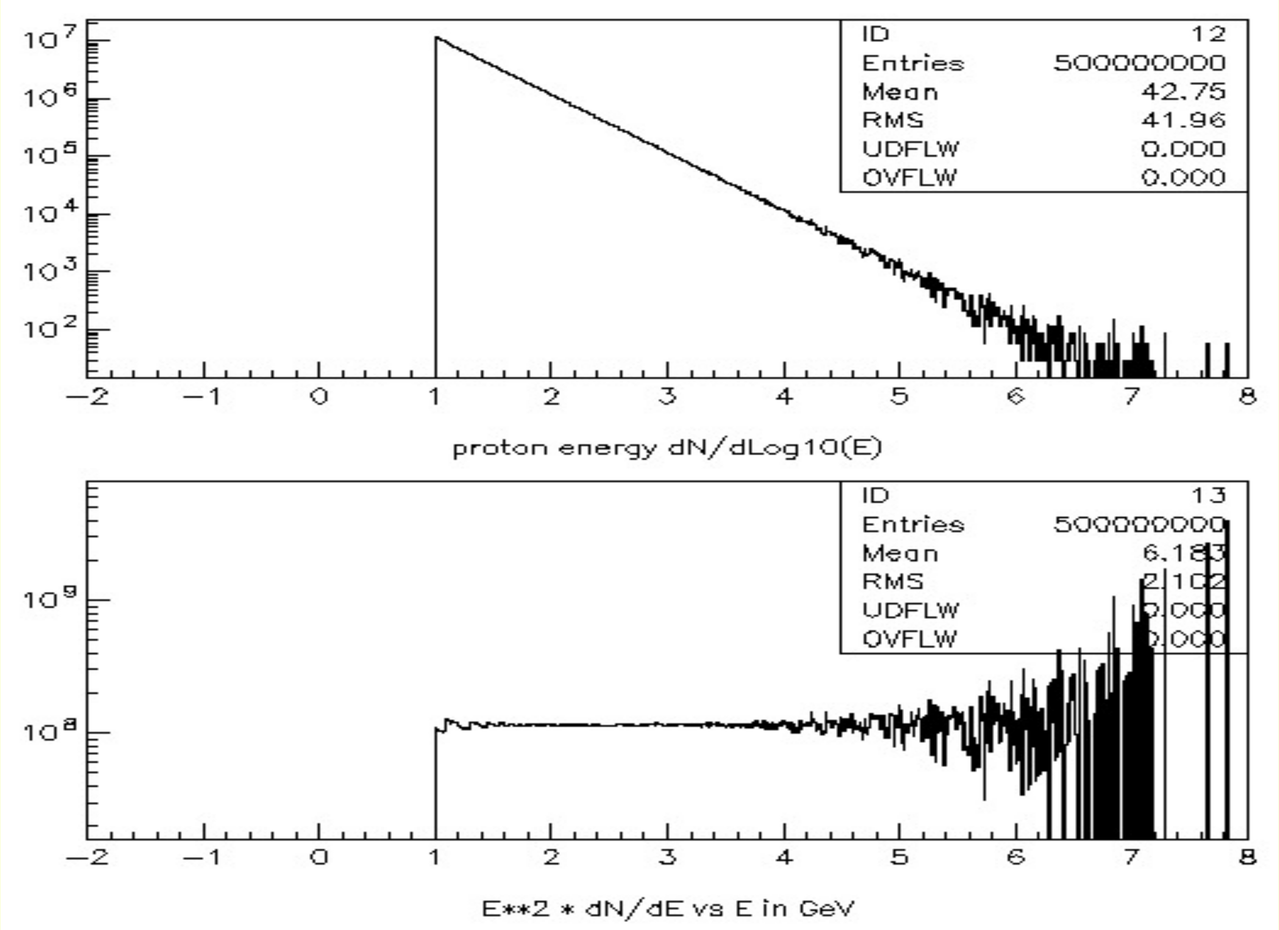
$$\frac{dN_p}{dE_p} = k_p \left(\frac{E_p}{1TeV} \right)^{-\alpha}$$

ν arriving at Earth are obtained adding up fluxes of ν_μ e ν_e (and of antineutrinos) taking into account the flavour neutrino oscillations: each flavour will be present with 1/3 of the flux at the cosmic source with small variation of the energy spectrum. ν and γ spectra (at the source) will follow a power law

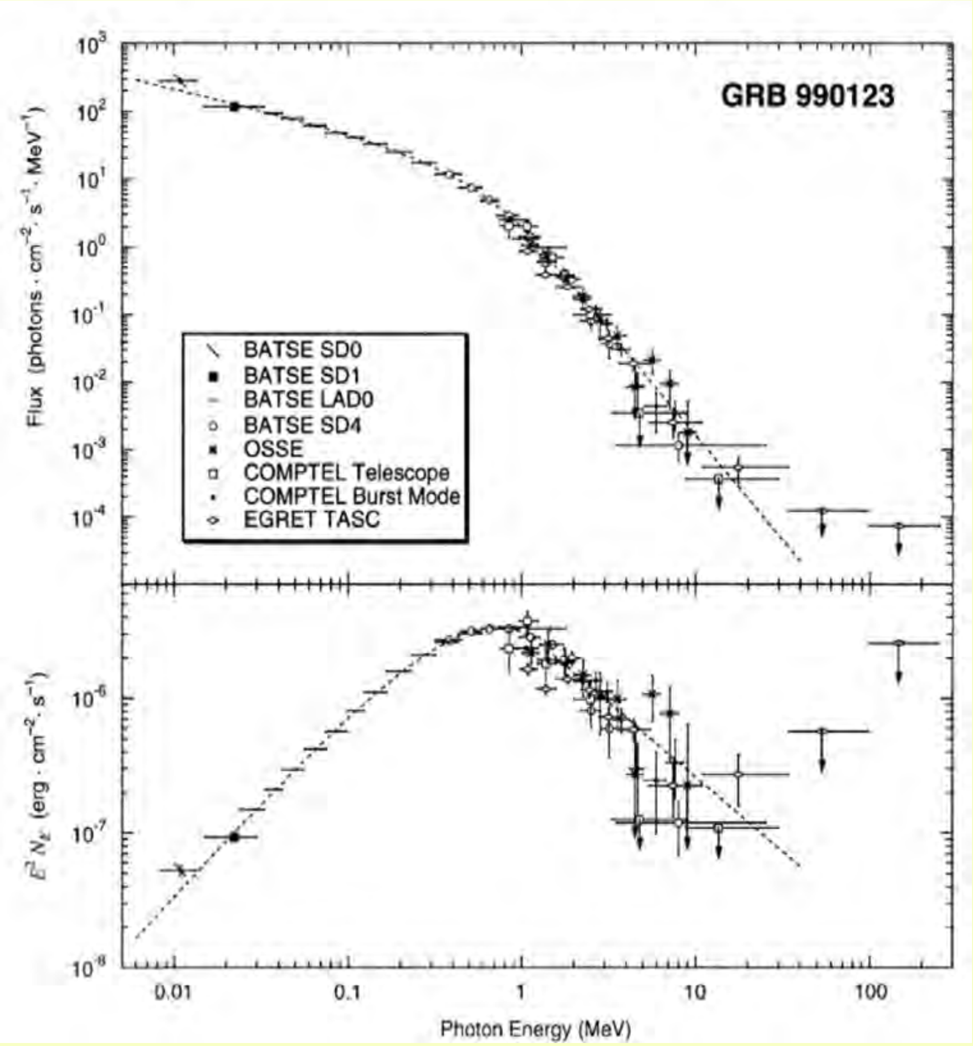
$$\frac{dN_{\gamma/\nu}}{dE_{\gamma/\nu}} = k_{\gamma/\nu} \left(\frac{E_{\gamma/\nu}}{1TeV} \right)^{-\Gamma}$$

strongly dependent upon the energy distribution of the target photons.

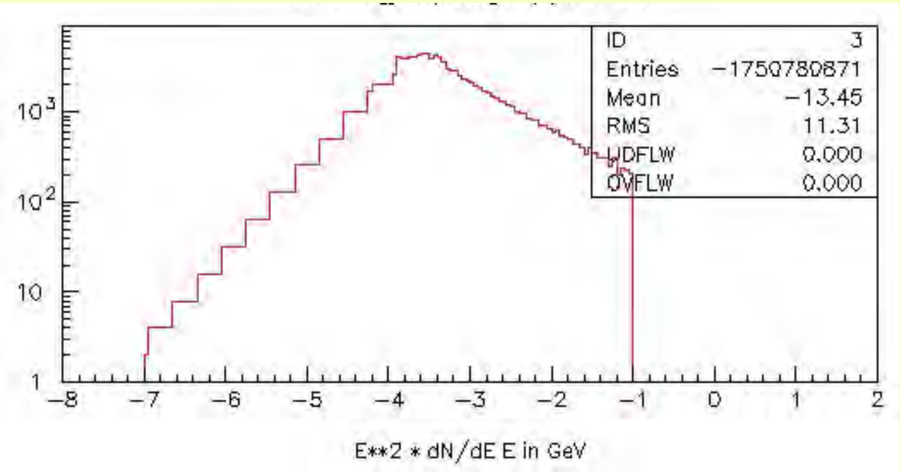
Protons generated according to the power law dN/dE ~ E^{-2}



From the GRB 990123: target photons generated according to measured flux



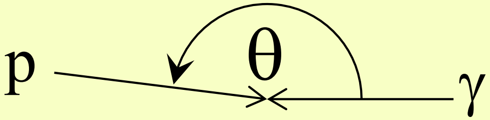
$$\frac{dN_{\mathrm{Band}}}{dE}(E) = A_{\mathrm{Band}}\begin{cases}\left(\frac{E}{100\,\mathrm{keV}}\right)^{\alpha}\exp\left[-\frac{E\,(2+\alpha)}{E_p}\right], & E \le E_b = E_p\,\frac{\alpha-\beta}{2+\alpha}\\ \left(\frac{E}{100\,\mathrm{keV}}\right)^{\beta}\left[\frac{E_p}{100\,\mathrm{keV}}\,\frac{\alpha-\beta}{2+\alpha}\right]^{\alpha-\beta} & \\ \times\exp[\beta-\alpha], & E > E_b = E_p\,\frac{\alpha-\beta}{2+\alpha}.\end{cases}$$



Simulation block diagram

We will consider 3 reference frames:

- the observer (laboratory) R.F. where $E_p=\gamma_p m_p$ E_γ = en. fotone, θ

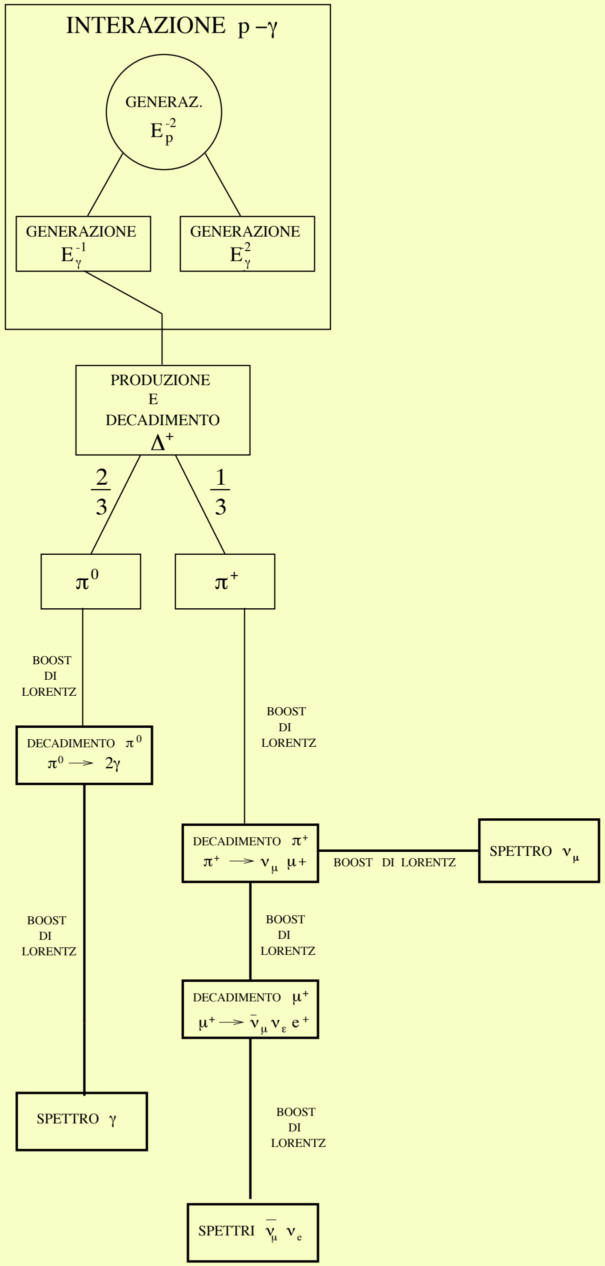


- a R.F. where the proton is at res (quantities with apices '): in such R.F. photons are confined in cone with average aperture

$$\tan\theta' \approx 1/\gamma_p \quad \text{and} \quad E'_\gamma = E_\gamma \gamma_p (1-\beta_\gamma \cos\theta)$$

- the centre of mass R.F. (with quantities indicated by *): in such R.F. the relativistic invariant in the final state of the π photo-production (p+γ=N+π) is

$$s = (m_N + m_\pi)^2 \quad \Rightarrow \quad s_{\min} = 1.16\ GeV^2$$


INTERAZIONE p – γ

GENERAZ. E_p^{-2}

GENERAZIONE E_γ^{-1}

GENERAZIONE E_γ^{2}

PRODUZIONE
E
DECADIMENTO
Δ^+

$\frac{2}{3}$

$\frac{1}{3}$

π^0

π^+

BOOST
DI
LORENTZ

DECADIMENTO π^0
$\pi^0 \longrightarrow 2\gamma$

BOOST
DI
LORENTZ

DECADIMENTO π^+
$\pi^+ \longrightarrow \nu_\mu\ \mu+$

BOOST DI LORENTZ

SPETTRO ν_μ

BOOST
DI
LORENTZ

BOOST
DI
LORENTZ

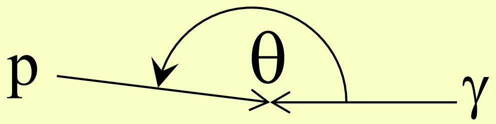
DECADIMENTO μ^+
$\mu^+ \longrightarrow \bar{\nu}_\mu \nu_\varepsilon e^+$

SPETTRO γ

BOOST
DI
LORENTZ

SPETTRI $\bar{\nu}_\mu$ ν_e

Kinematics of the interaction



- in the laboratory R.F., if ***p*** is the four-momentum

$$s=-p^2=\left(\vec{p}_p+\vec{p}_\gamma\right)^2-\left(E_p+E_\gamma\right)^2=m_p^2+2m_p\gamma_pE_\gamma(1-\beta_p\cos\theta)\ \Rightarrow\ \sqrt{s}=\sqrt{m_p^2+2m_pE'_\gamma}$$

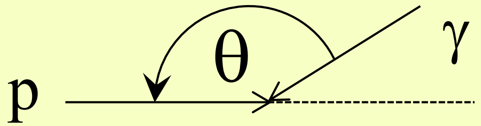
- if in the final state we have a π photo-production (neutral or charged) at rest (at the threshold energy)

$$s=\left(m_N+m_\pi\right)^2=m_N^2+2m_NE'_\gamma\ \Rightarrow\ E'_{\gamma,soglia}=m_\pi\left(1+\frac{m_\pi}{2m_N}\right)\approx 145MeV$$

where $E'_{\gamma,soglia}=E_\gamma\gamma_{p,soglia}(1-\beta_\gamma\cos\theta)$, the minimal photon energy (in the R.F. where the proton is at rest) to produce a π. This condition implies a minimum value for γ_p (when θ=180° and $cos\theta$=-1)

$$\gamma_{p,theshold}=\frac{E'_{\gamma,threshold}}{2\cdot E_\gamma}$$

Kinematics of the interaction



Let's assume that in the pγ interaction we have the energy sufficient to produce a Δ^+ that then can decay. We will study the decay into $p\pi^0$ or $n\pi^+$ in the center of mass R.F. Then the kinematics of the outgoing particles in the laboratory R.F. can be evaluated taking into account the Lorentz factor:

$$\gamma^* = \frac{E_p + E_\gamma}{\sqrt{s}} \approx \frac{E_p}{\sqrt{s}}$$

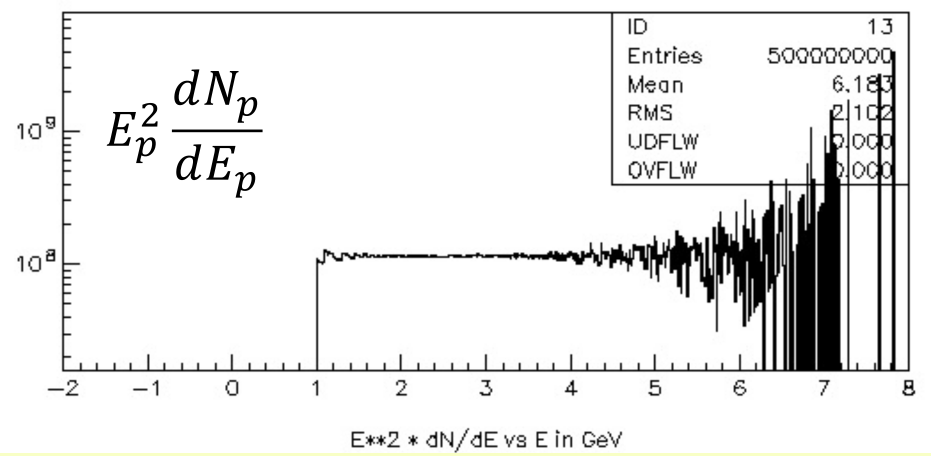
The centre of mass moves in the same direction as that of the incident proton.

We perform a simulation by accepting events where a Δ^+ is formed "at resonance" in the final state. This resonance then immediately decays to $p\pi^0$ or $n\pi^+$.

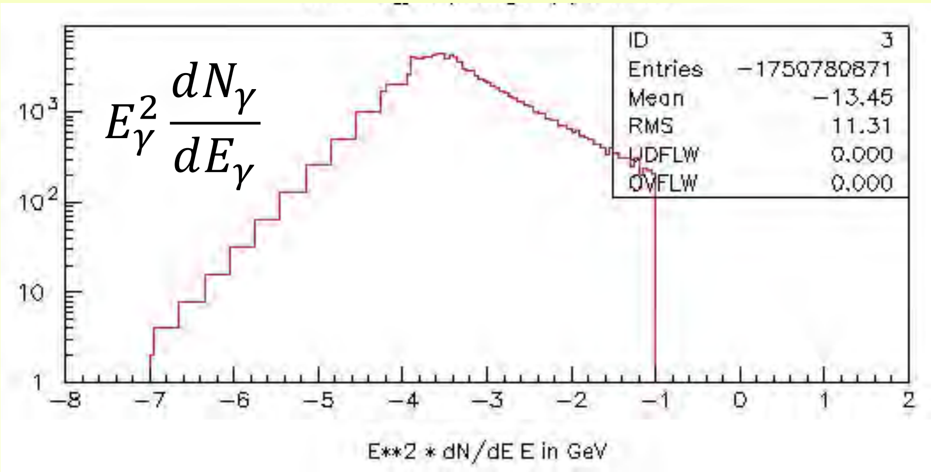
The spectrum of protons that can actually give such a reaction depends on the energy spectrum of the target photons.

The relative frequency of the two decay channels (Clebsch–Gordon coeff):

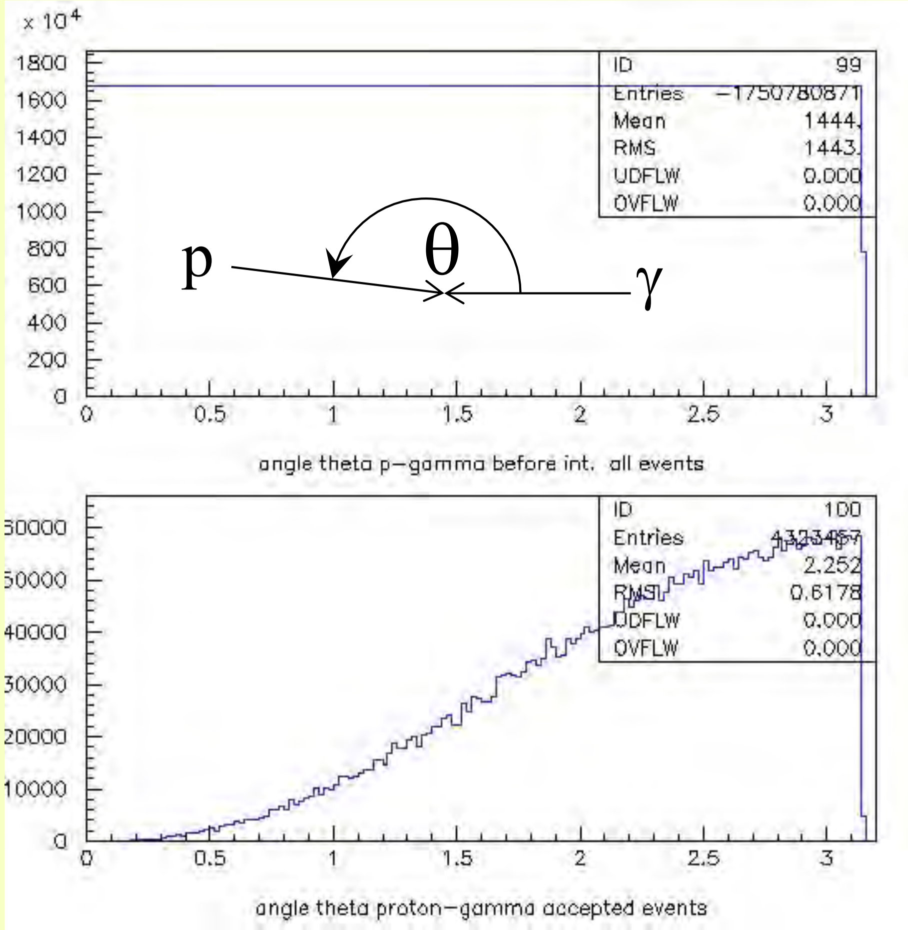
$$\frac{BR(p\gamma \to \Delta^+ \to p\pi^0)}{BR(p\gamma \to \Delta^+ \to n\pi^+)} \approx 2$$

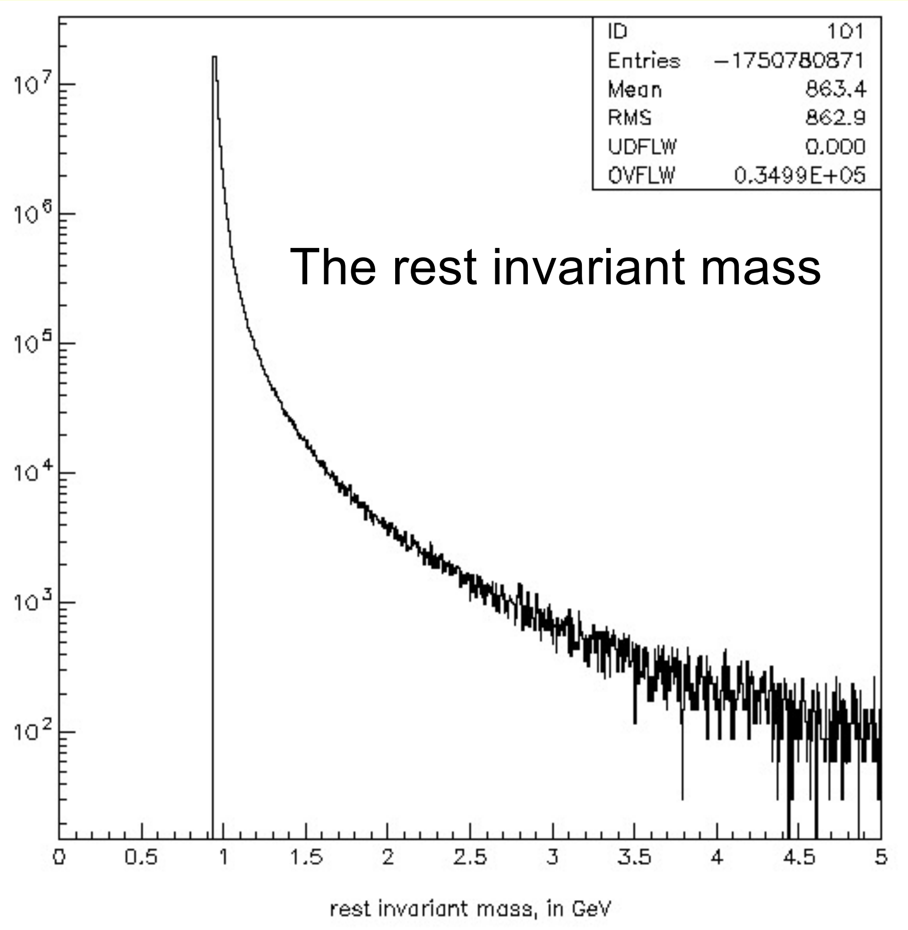


Energy spectra of all simulated p and γ



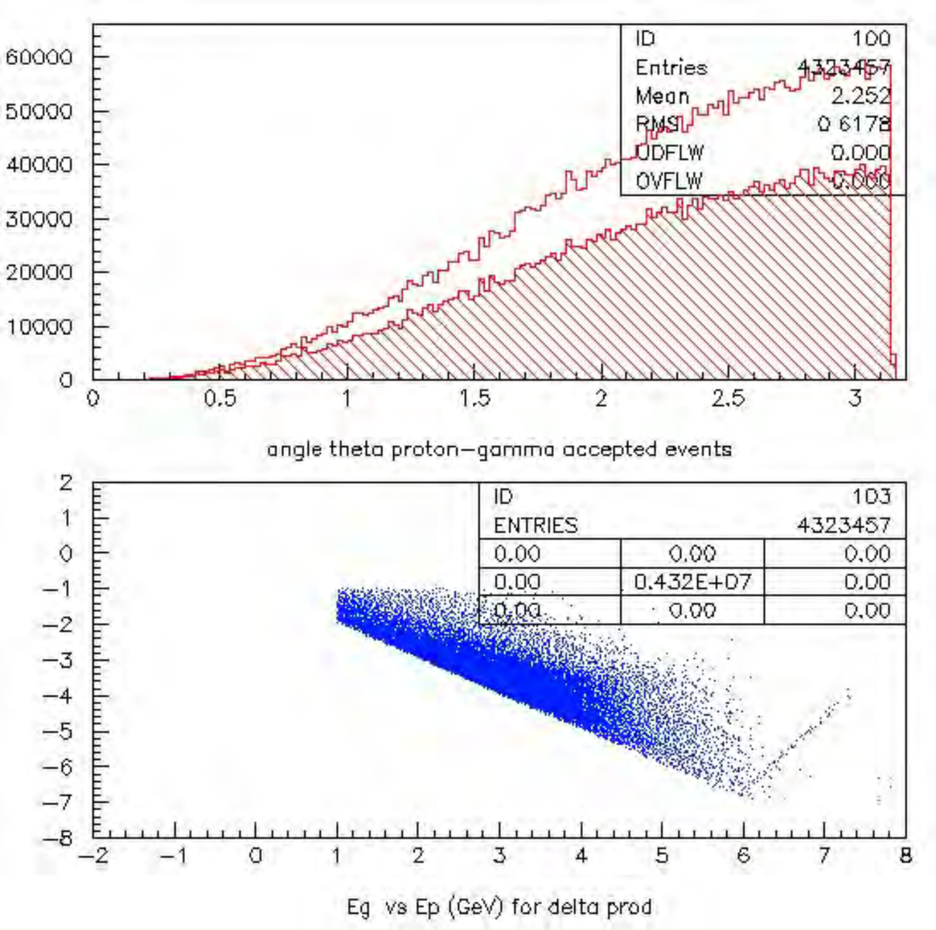
some kinematics in the c.m. reference system

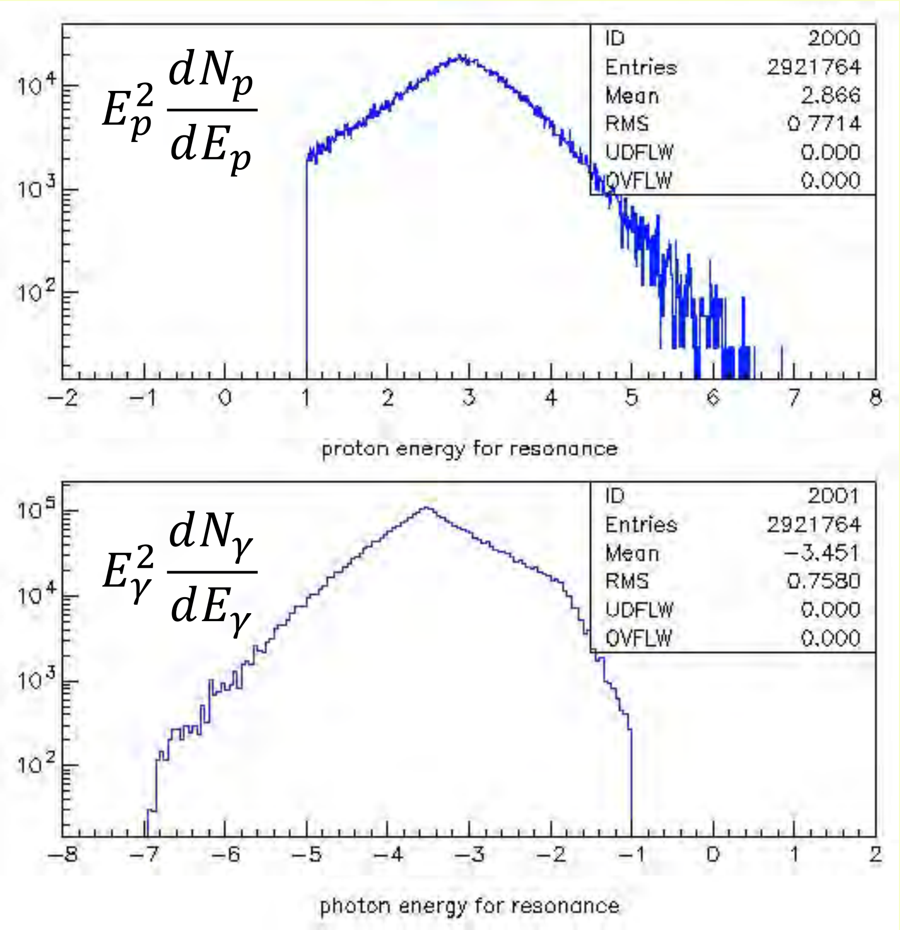




The rest invariant mass

Only events above the resonance condition





$$E_p^2\,\frac{dN_p}{dE_p}$$

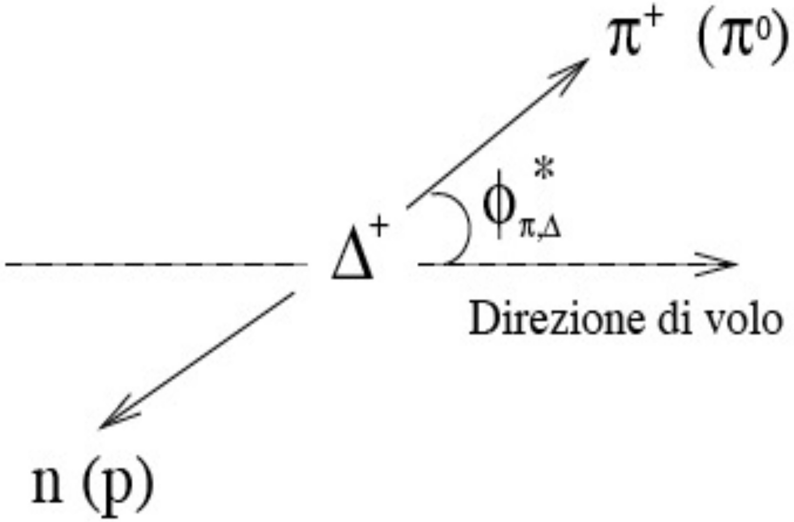
$$E_\gamma^2\,\frac{dN_\gamma}{dE_\gamma}$$

Δ^+ Decay

Let's assume $0^\circ \le \Phi^*_{\pi,\Delta} \le 180^\circ$ as the angle, in the centre of mass R.F, between the flight directions of the outgoing π and the interacting proton.

$$E^*_\pi = \frac{s + m_\pi^2 - m_N^2}{2\sqrt{s}}$$

$$E^*_N = \frac{s + m_N^2 - m_\pi^2}{2\sqrt{s}}$$



Decadimento della Δ^+ nel sistema di riferimento in cui è a riposo

We can evaluate E_π in the laboratory R.F. (that apparently moves with velocity $-\vec{\beta}$ towards the centre of mass along the flight direction of the incident proton, i.e. the direction that identify the astrophysical source under examination, taken as the x-axis

$$\begin{aligned} p_x &= \gamma(p^*_x + \beta E^*) \\ p_y &= p^*_y \\ p_z &= p^*_z \\ E &= \gamma(E^* + \beta p^*_x) \end{aligned}$$

Δ^+ decay: energy and momentum of π in the lab. R.F.

In the centre of mass R.F. we can evaluate the pion momentum:

$$p^*_\pi = p^*_N = p^*_{\pi,N} = \frac{\sqrt{s^2 - 2s(m^2_\pi + m^2_N) + (m^2_\pi - m^2_N)^2}}{2\sqrt{s}}$$

and then, using the Lorentz transformations, the energy of the pion in the lab. R.F.

$$E_\pi = \gamma^*(E^*_\pi + p^*_x) \longrightarrow E_\pi = \frac{E_{pi}}{\sqrt{s}}(E^*_\pi + p^*_{\pi,N} \cos\phi^*_{\pi,\Delta})$$

having assumed $\beta_\pi=1$ and E_{pi} = the incident proton energy.

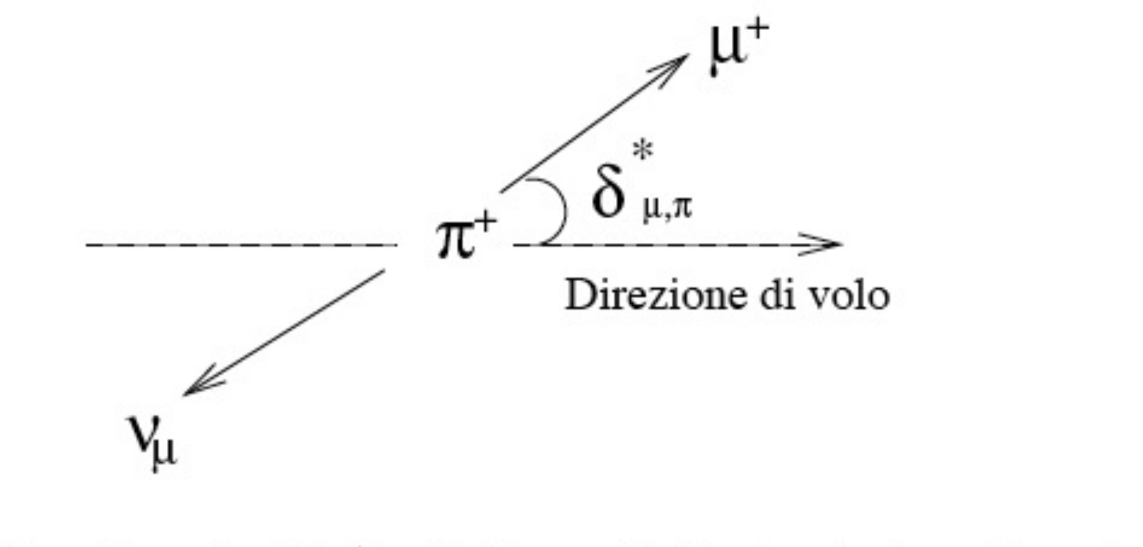
E_{pi} has to satisfy the condition $E_{pi} > E_{p,\text{threshold}}$ that depends strongly on the spectral index of the target photons.

π^+ then can decay giving ν_μ

Let's be $0^\circ \le \delta^*_{\mu,\,\pi} \le 180^\circ$ the angle, in the π^+ at rest R.F., between the directions of the flying π^+ and the one of the outgoing μ^+. In such R.F.

$$E^*_{\nu_\mu} = \frac{m^2_{\pi^+} - m^2_\mu}{2m_{\pi^+}} \quad ; \quad E^*_\mu = \frac{m^2_{\pi^+} + m^2_\mu}{2m_{\pi^+}}$$

$$p^*_{\nu_\mu,\mu} = p^*_{\nu_\mu} = p^*_\mu = \frac{m^2_{\pi^+} - m^2_\mu}{2m_{\pi^+}}$$



Decadimento del π^+ nel sistema di riferimento in cui è a riposo

We can then evaluate E_μ ed E_ν in the laboratory R.F.

$$E_\mu = \gamma_{\pi^+}(E^*_\mu + \beta_{\pi^+} p^*_{\nu_\mu,\mu} \cos\delta^*_{\mu,\pi^+})$$

$$E_{\nu_\mu} = \gamma_{\pi^+}(E^*_{\nu_\mu} - \beta_{\pi^+} p^*_{\nu_\mu,\mu} \cos\delta^*_{\mu,\pi^+})$$

$$\gamma_{\pi^+} = E_{\pi^+}/m_{\pi^+} = \frac{E_{pi}}{m_{\pi^+}\sqrt{s}}(E^*_\pi \; + \; p^*_{\pi,N} \cos\phi^*_{\pi,\Delta})$$

Evaluating the μ+ and ν_μ energies

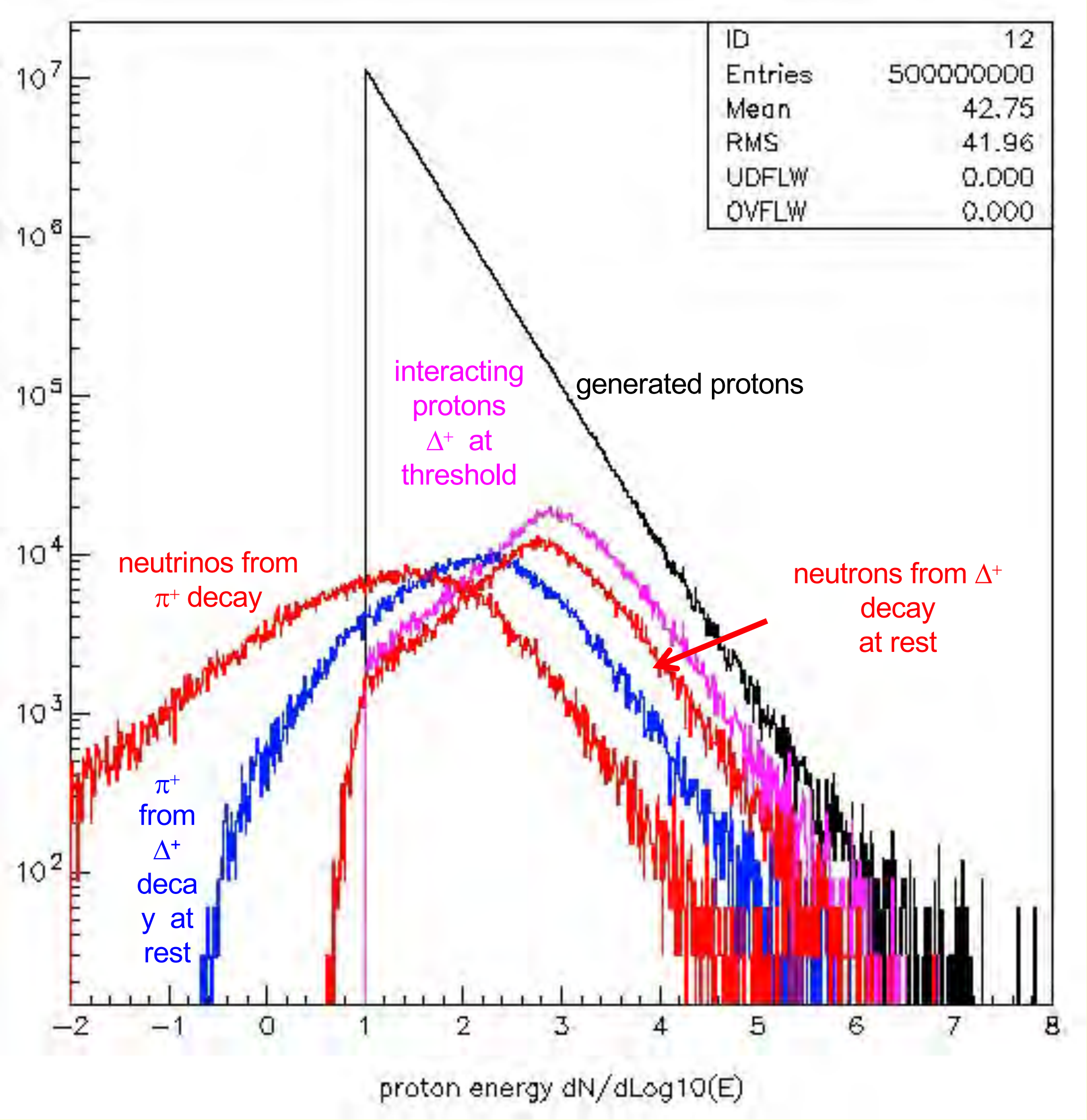
We can then calculate the expression of the neutrino and muon energies as a function of the incident protons energy:

$$E_\mu = \frac{E_{pi}}{m_{\pi^+}\sqrt{s}}(E^*_\pi + p^*_{\pi,N}\cos\phi^*_{\pi,\Delta})(E^*_\mu + \beta_{\pi^+}p^*_{\nu_\mu}\cos\delta^*_{\mu,\pi^+})$$

$$E_{\nu_\mu} = \frac{E_{pi}}{m_{\pi^+}\sqrt{s}}(E^*_\pi + p^*_{\pi,N}\cos\phi^*_{\pi,\Delta})(E^*_{\nu_\mu} - \beta_{\pi^+}p^*_{\nu_\mu}\cos\delta^*_{\mu,\pi^+})$$

and therefore also as a function of the target photons energy spectrum.

ν_μ from Δ^+ resonance decay into n + π^+



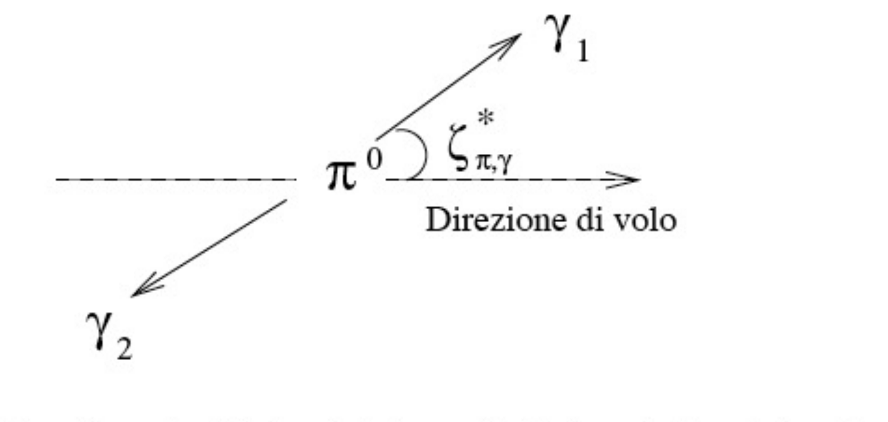
The same procedure allows to study $\Delta^+ \to p\pi^0$

In the R.F. where Δ decays:

$$E^*_{\pi^0} = \frac{s + m^2_{\pi^0} - m^2_p}{2\sqrt{s}}$$

The in the laboratory R.F. :

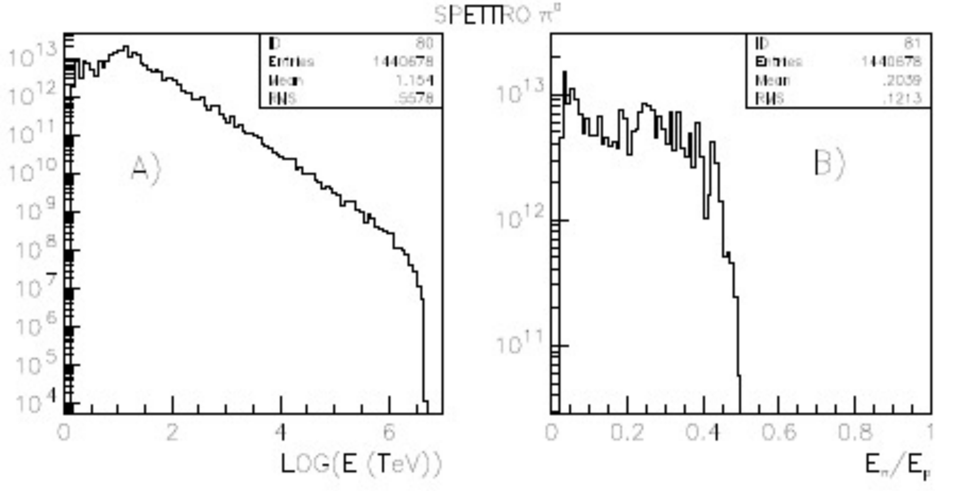
$$E_{\pi^0} = \frac{E_{pi}}{\sqrt{s}}(E^*_{\pi^0} + p^*_{\pi,N}\cos\phi^*_{\pi^0,p})$$



Decadimento del π^0 nel sistema di riferimento in cui è a riposo

dove $\phi^*_{\pi^0,p}$ è l'angolo di emissione del pione rispetto alla direzione di volo del protone incidente e $p^*_{\pi,N}$ è la quantità di moto del π^0 nel sistema in cui la Δ^+ è a riposo.

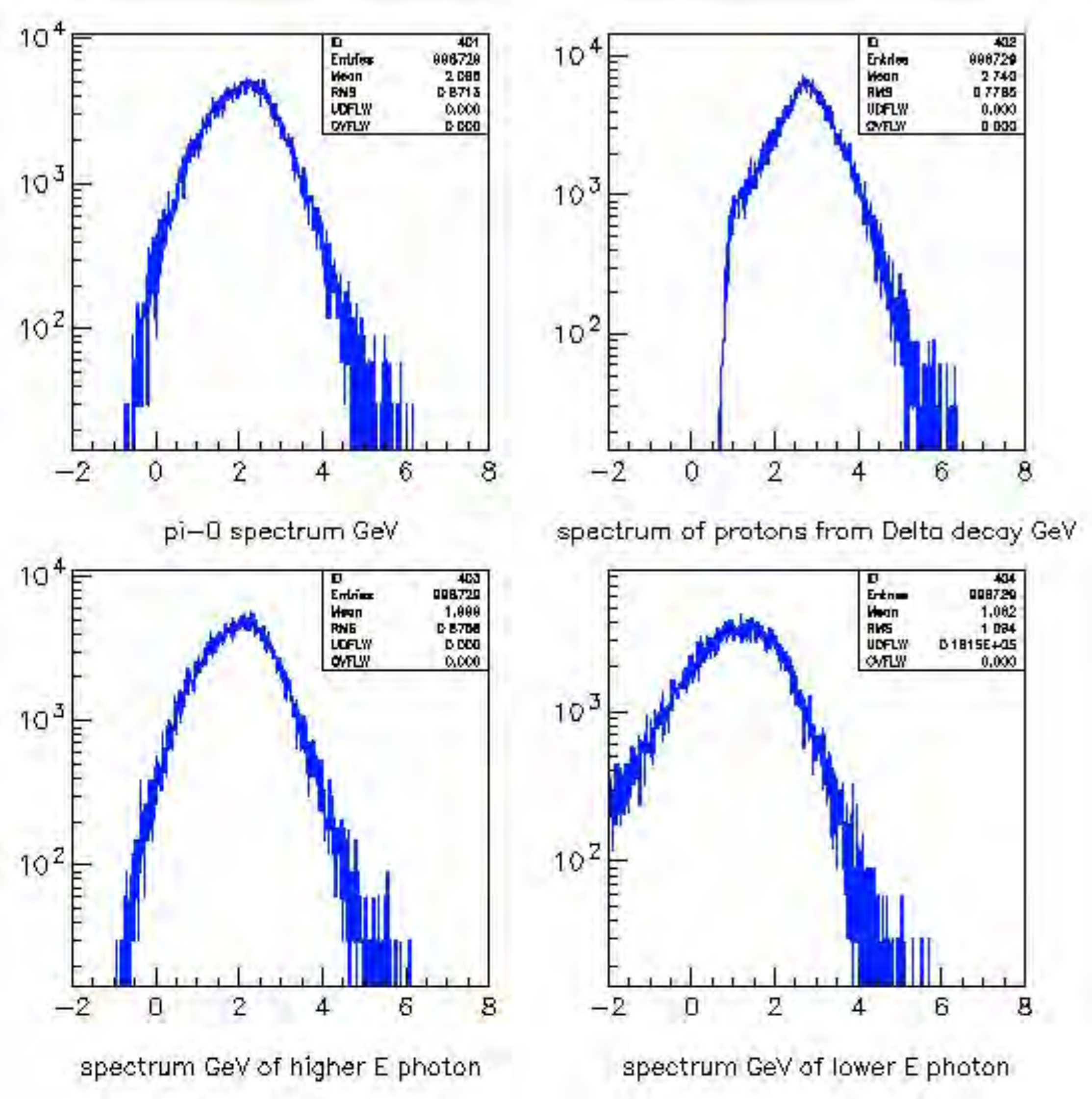
$$\frac{dN_\pi}{dE_\pi}$$



$$\frac{dN_p}{dE_p} = k_p\left(\frac{E_p}{1TeV}\right)^{-2}$$

$$\frac{dN_\gamma}{dE_\gamma} = k_\gamma\left(\frac{E_\gamma}{1TeV}\right)^{-1}$$

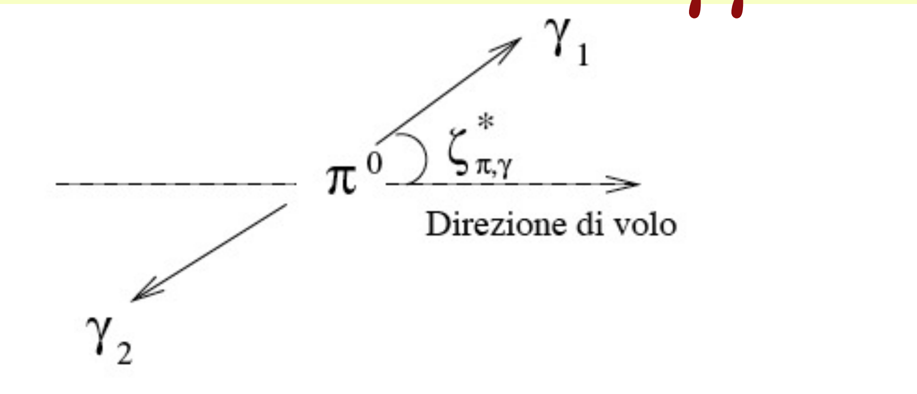
Δ^+ resonance decay into p + π^0



… and then we can simulate the π^0 -> $\gamma\gamma$

In the R.F. where π^0 decays:

$$p^*_\gamma = E^*_\gamma = \frac{1}{2} m_{\pi^0}$$

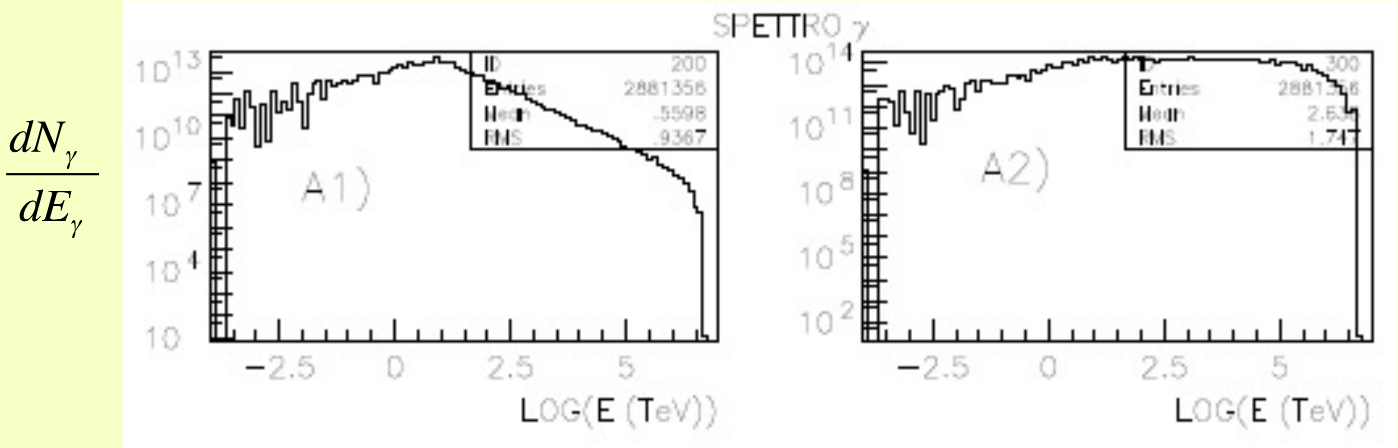


Decadimento del π^0 nel sistema di riferimento in cui è a riposo

and then in the laboratory R.F.:

$$E_\gamma = \gamma_{\pi^0}(E^*_\gamma \pm \beta_{\pi^0} p^* \cos\zeta^*_{\gamma,\pi^0}) = \frac{E_{\pi^0}}{2}(1 \ \pm \beta_{\pi^0} \cos\zeta^*_{\gamma,\pi^0})$$

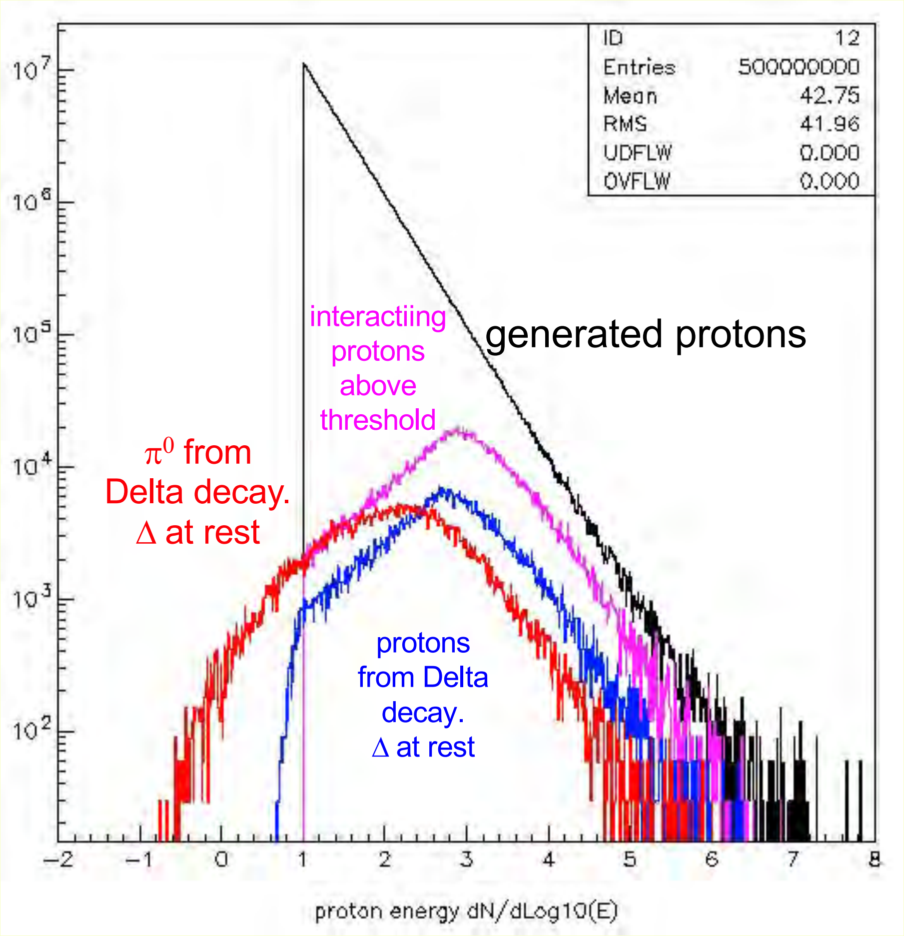
dove $\gamma_{\pi^0} = E_{\pi^0}/m_{\pi^0}$ e ζ^*_{γ,π^0} è l'angolo tra la direzione di emissione di uno dei due fotoni e la direzione di volo del pione



$$\frac{dN_p}{dE_p} = k_p \left(\frac{E_p}{1TeV} \right)^{-2}$$

$$\frac{dN_\gamma}{dE_\gamma} = k_\gamma \left(\frac{E_\gamma}{1TeV} \right)^{-1}$$

π^0, n and γ from Δ^+ resonance decay

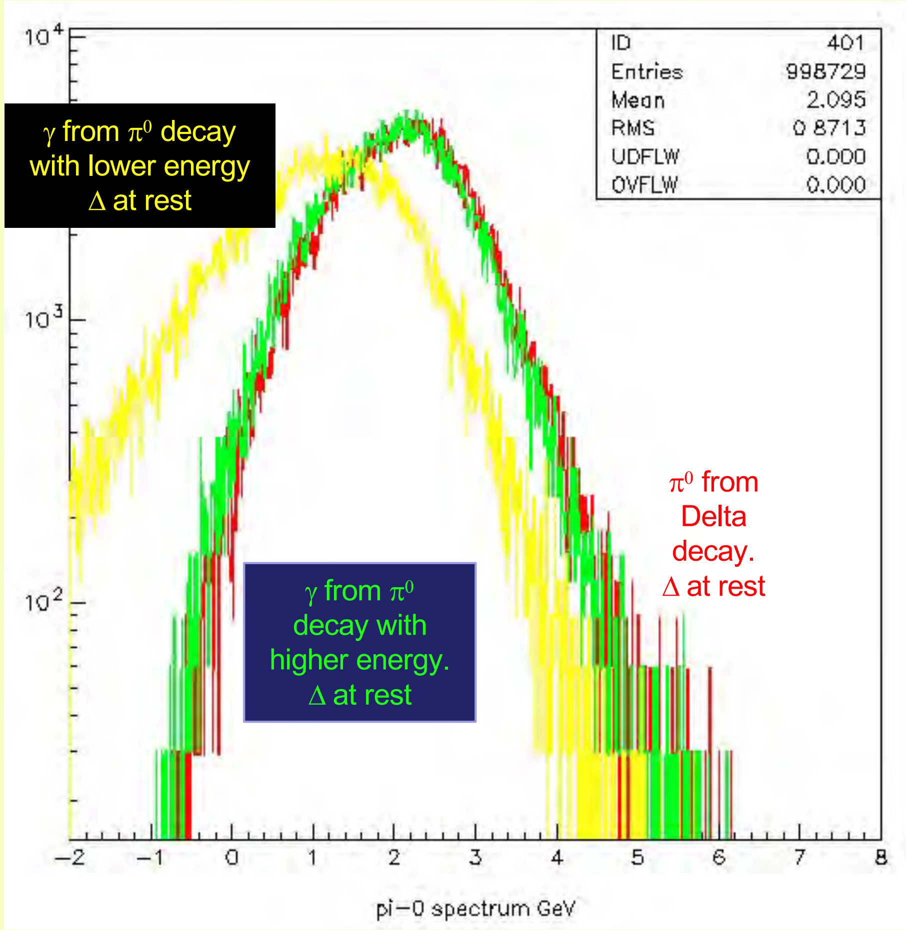


generated protons

interactiing protons above threshold

π^0 from Delta decay. Δ at rest

protons from Delta decay. Δ at rest

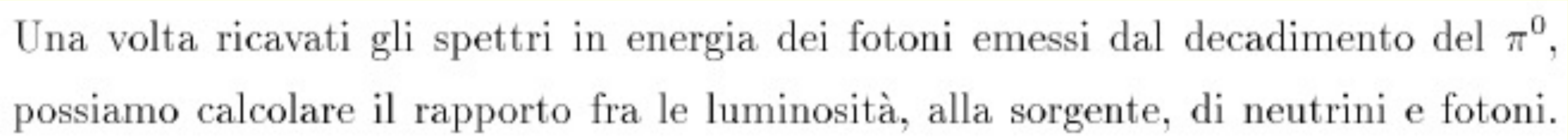


γ from π^0 decay with lower energy Δ at rest

γ from π^0 decay with higher energy. Δ at rest

π^0 from Delta decay. Δ at rest

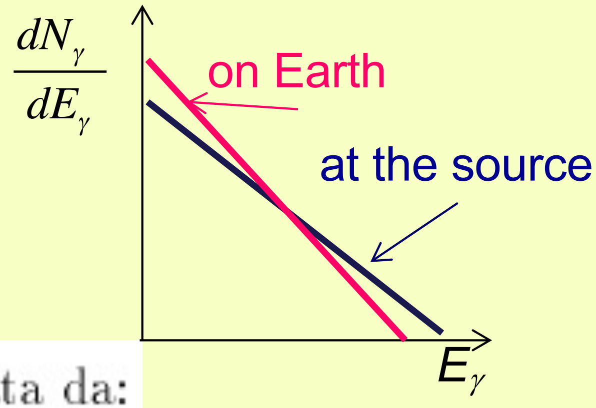
Comparison between γ and ν spectra "at the source"

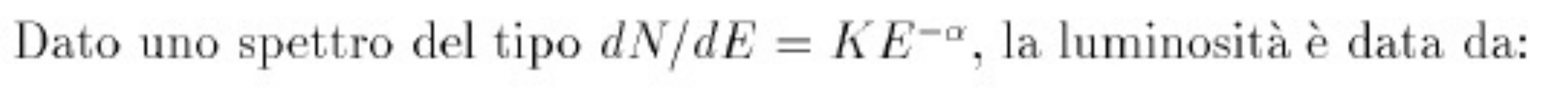


Una volta ricavati gli spettri in energia dei fotoni emessi dal decadimento del π^0, possiamo calcolare il rapporto fra le luminosità, alla sorgente, di neutrini e fotoni.

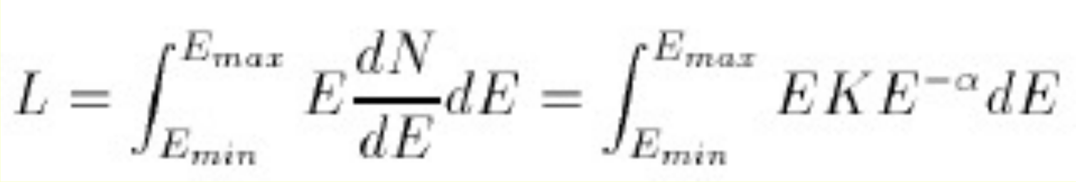
The theoretical spectra of photons should be compared with experimental observations made on Earth but ... the propagation from the source to the Earth modifies the spectra of the γ (while not changing the spectra of neutrinos).

During the propagation from the source to the Earth the photons can interact disappearing from the more energetic part of the spectrum reappearing in the less energetic part while preserving the "Luminosity"





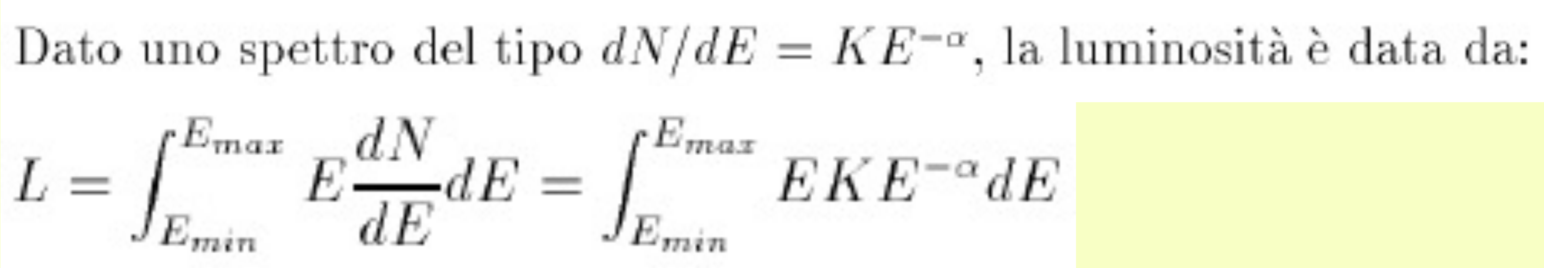
Dato uno spettro del tipo $dN/dE = KE^{-\alpha}$, la luminosità è data da:



$$L = \int_{E_{min}}^{E_{max}} E\frac{dN}{dE}dE = \int_{E_{min}}^{E_{max}} EKE^{-\alpha}dE$$

Of course, for each source, K can be derived from the observed spectra.

Comparison of γ and ν fluxes



Dato uno spettro del tipo $dN/dE = KE^{-\alpha}$, la luminosità è data da:

$$L = \int_{E_{min}}^{E_{max}} E\frac{dN}{dE}dE = \int_{E_{min}}^{E_{max}} EKE^{-\alpha}dE$$

K_γ, e K_ν for γ and ν respectively, can be derived from each of the estimated spectra.
For example if the target photons are distributed as E^{-2}

$$\frac{dN_{\nu_\mu}}{dE_{\nu_\mu}} \approx \frac{dN_{\bar{\nu}_\mu}}{dE_{\bar{\nu}_\mu}} \approx 1.7\cdot 10^{13}\cdot E_\nu^{-2} \qquad \frac{dN_{\gamma,tot}}{dE_\gamma} \approx 1.4\cdot 10^{14}\cdot E_\gamma^{-2}$$

if we then indicate with $\nu = \nu_\mu + \bar{\nu}_\mu$ we have $\boldsymbol{\frac{dN_\nu}{dE_\nu} = 3.4\cdot 10^{13}\cdot E^{-2} = \frac{1}{4{,}1}\frac{dN_\gamma}{dE_\gamma}}$

and in terms of Luminosity $\boldsymbol{L_\gamma = 4,1\cdot L_\nu}$

.

ν flux estimate from known γ astrophysical sources (1)

Let's examine an astrophysical source for which luminosity γ ($L\gamma$) is known and assume that this body is also the source of neutrinos with spectral distribution:

$$\frac{dN_\nu}{dE_\nu} = K_\nu \left[\frac{E_\nu}{E_{\nu\max}}\right]^{-\alpha} \quad \text{dove} \;\; \alpha{=}2 \text{ e } \; K_\nu \;\; [neutrini\ TeV^{-1}cm^{-2}s^{-1}] \;\; \text{è non nota}$$

In particular, consider Mrk 421 for whom EGRET has indicated the spectrum

$$\frac{dN_\gamma}{dE_\gamma} \approx (2.1 \pm 0.5)\cdot 10^{-0.8}\cdot\left(\frac{E_\gamma}{[GeV]}\right)^{-1.96\pm0.14} \quad fotoni\ cm^{-2}s^{-1}GeV^{-1} \qquad \text{con} \qquad MeV < E_\gamma < TeV$$

Assuming that the measured spectral dependence is valid for 10^{-2} TeV < E < 10^{6} TeV (region of interest for neutrino astronomy) one can calculate the Luminosity in photons:

$L_\gamma = 3.9 \bullet 10^{-10}$ TeV cm^{-2} s^{-1}

From $L_\nu = \int_{E\min}^{E\max} E_\nu K_\nu \left[\frac{E_\nu}{E_{\nu\max}}\right]^{-\alpha} dE_\nu = K_\nu E_{\max}^{\alpha} \int_{E\min}^{E\max} E^{1-\alpha}\, dE_\nu$ taking into account that $L_\nu = \frac{L_\gamma}{4.1}$

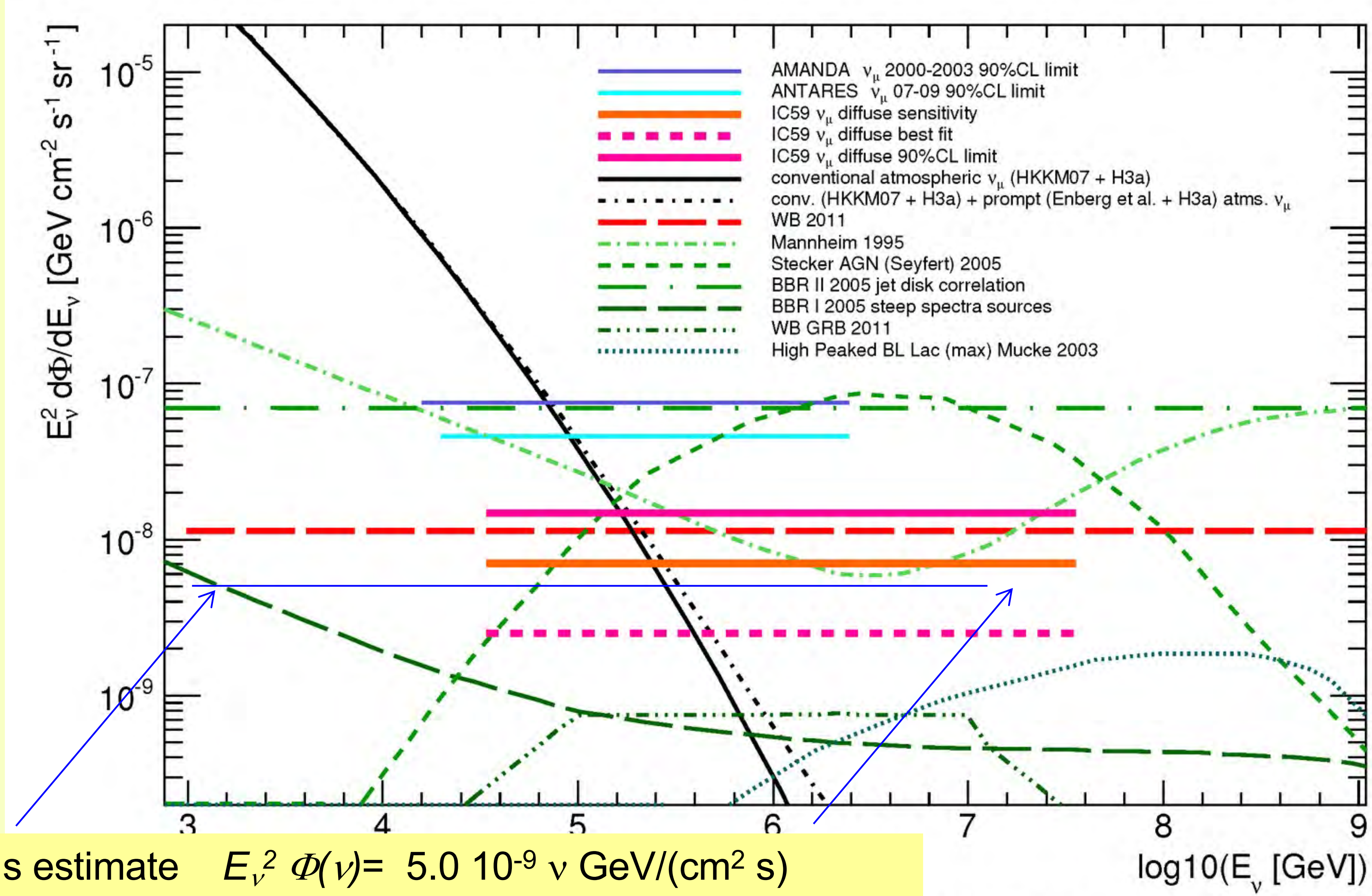
we obtain $K_\nu = \frac{L_\gamma}{4.11} \frac{1}{E_{\max}^{\alpha} \ln\left(\frac{E\max}{E\min}\right)} \approx 5.0\cdot 10^{-24}\, neutrini\ TeV^{-1}cm^{-2}s^{-1}$

ν flux estimate from known γ astrophysical sources (2)

From the result $$K_\nu = \frac{L_\gamma}{4.11} \frac{1}{E_{\max}^{\alpha} \ln\left(\frac{E\max}{E\min}\right)} \approx 5.0 \cdot 10^{-24} neutrini\ TeV^{-1} cm^{-2} s^{-1}$$

$$\frac{dN_\nu}{dE_\nu} = 5.0 \cdot 10^{-24} \left[\frac{E_\nu}{10^6 TeV}\right]^{-2} neutrini\ TeV^{-1} cm^{-2} s^{-1} = 5.0 \cdot 10^{-12} E_\nu^{-2} neutrini\ TeV^{-1} cm^{-2} s^{-1}$$

and the usual quantity SED = spectral energy density = $E_\nu^2 \phi_\nu$ becomes
$E_\nu^2 \phi_\nu = 5.0 \cdot 10^{-12}\ neutrinos \cdot TeV \cdot cm^{-2} s^{-1} = 5.0 \cdot 10^{-9}\ \nu \cdot TeV \cdot cm^{-2} s^{-1}$

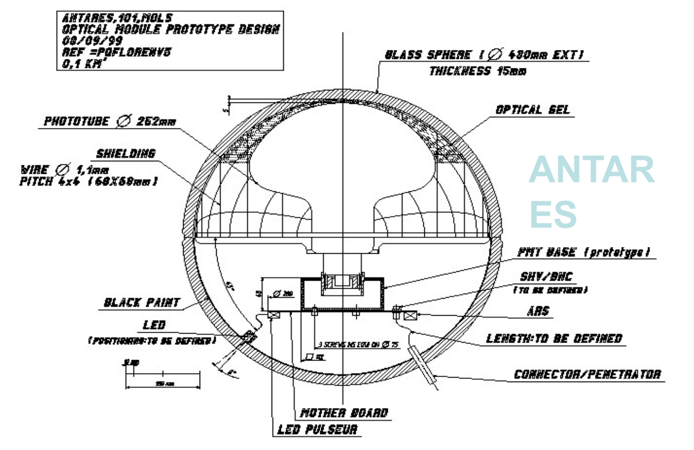


… this estimate $E_\nu^2\ \Phi(\nu)$= 5.0 10^{-9} ν GeV/(cm^2 s)

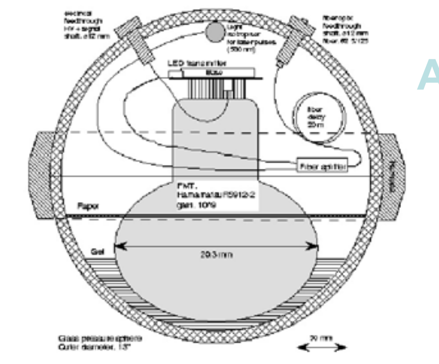
Limit on a muon neutrino astrophysical flux from this analysis in comparison to theoretical flux predictions and limits from other experiments. The black lines show the expected atmospheric neutrino flux with and without a prompt component. The red dashed line marks the Waxman-Bahcall upper bound. Green dashed lines represent various model predictions for astrophysical neutrino fluxes. Horizontal lines show limits and sensitivities from different experiments. The pink solid line is the 90% CL upper limit of this analysis, the orange solid line shows its sensitivity. Image: IceCube Collaboration.

Optical Modules for Cherenkov Neutrino Telescopes

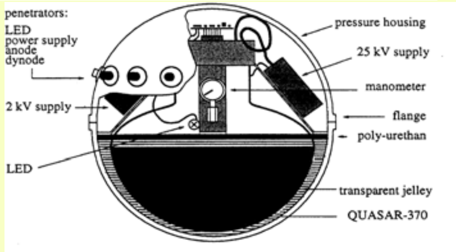
Photomultipliers (8÷15″ diameter) in
13-17″ diameter glass spheres
Pressure resistant up to 600 atm



ANTARES



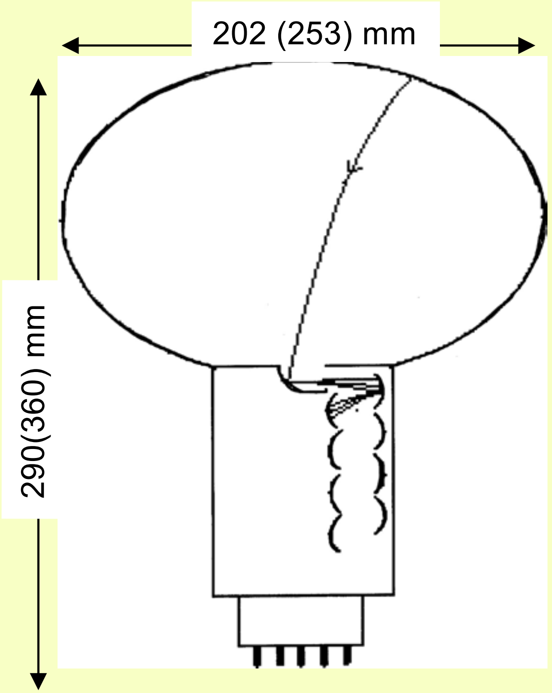
AMANDA



BAIKAL

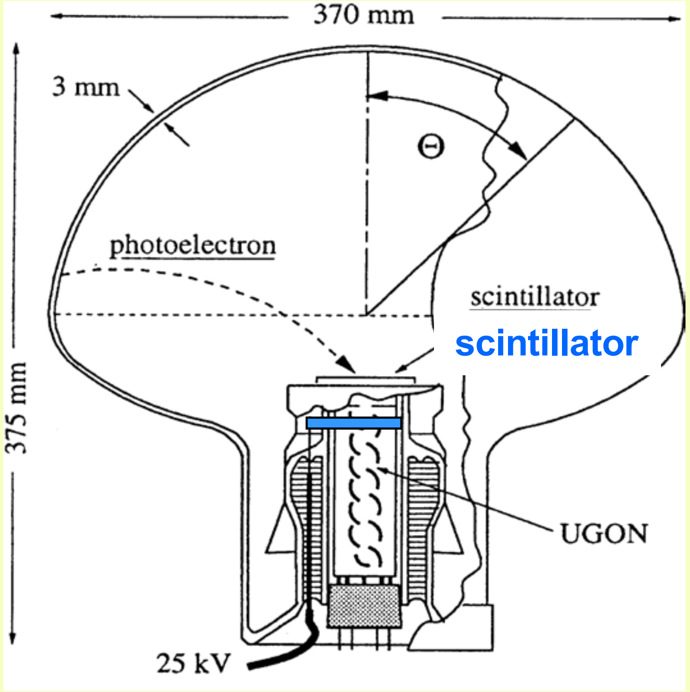
AMANDA, ANTARES

Use Hamamatsu: R5912-02, (P7081-20)
Developments by Photonis (ex Philips)
ETL (ex EMI)

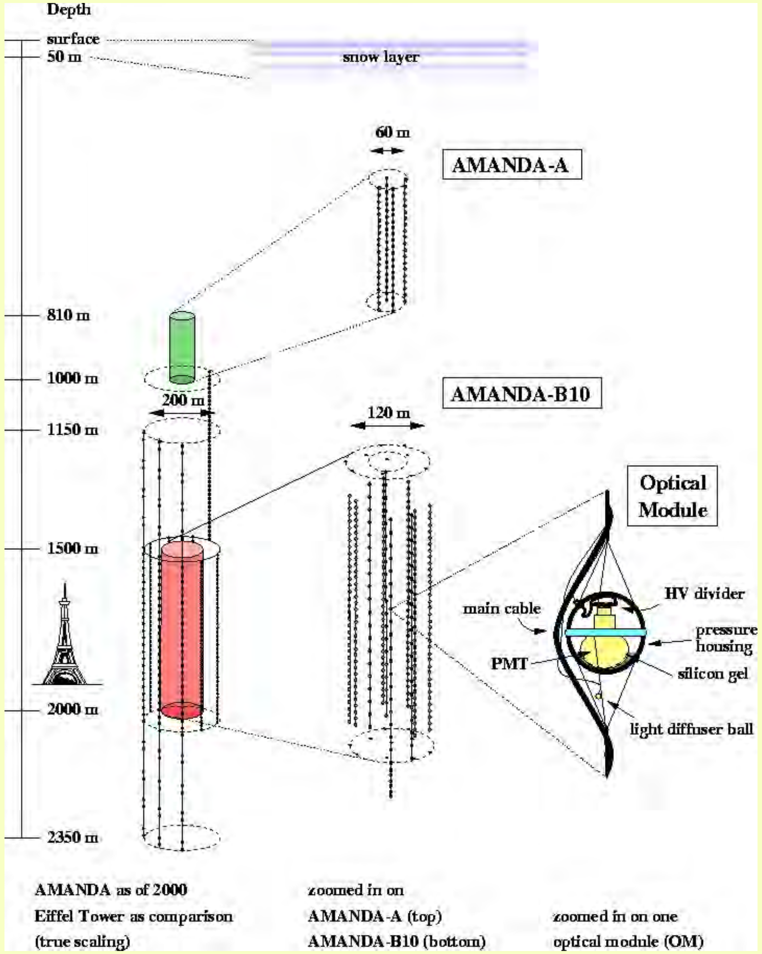


BAIKAL

Use EKRAN Quasar-370
(original idea from Philips)



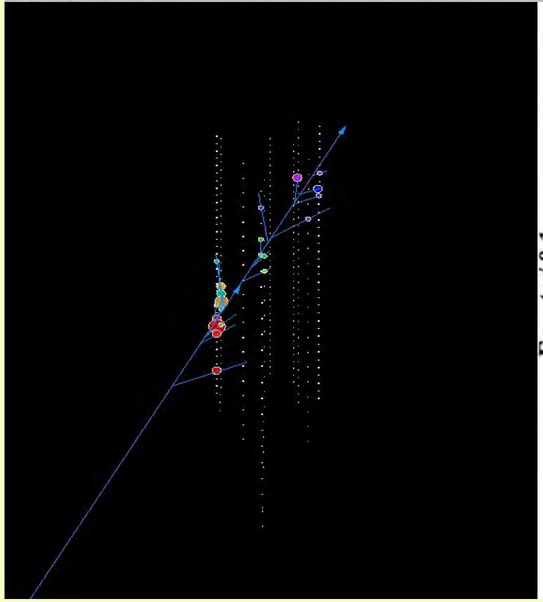
AMANDA – South Pole – 2 km depth

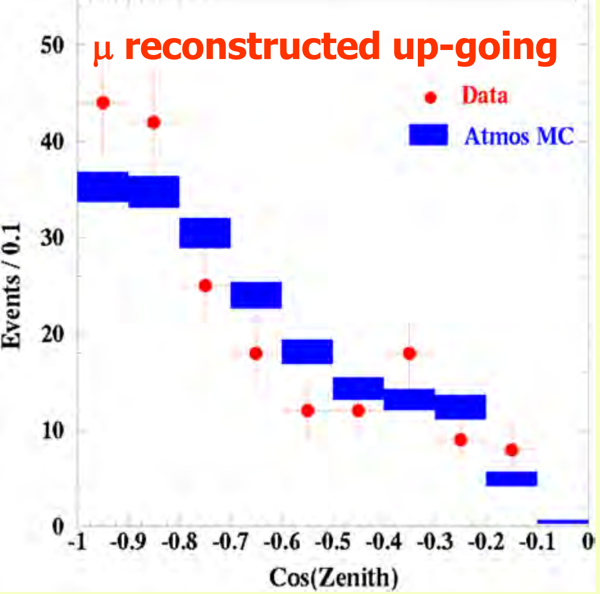


AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on one
optical module (OM)



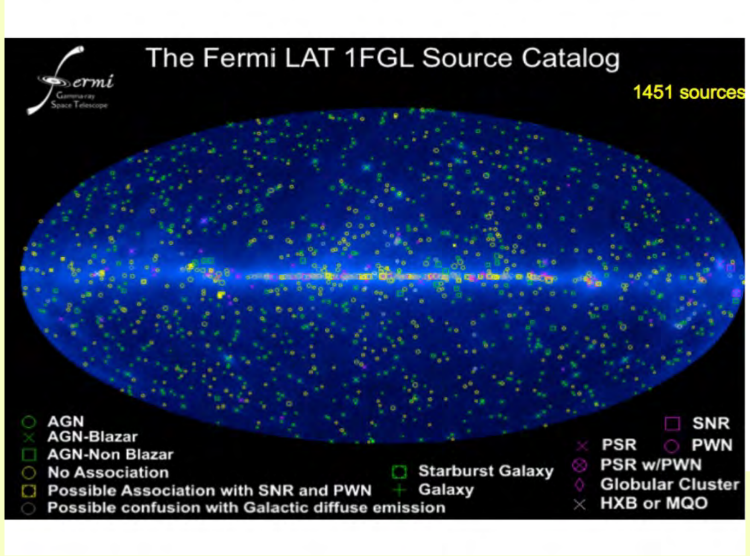


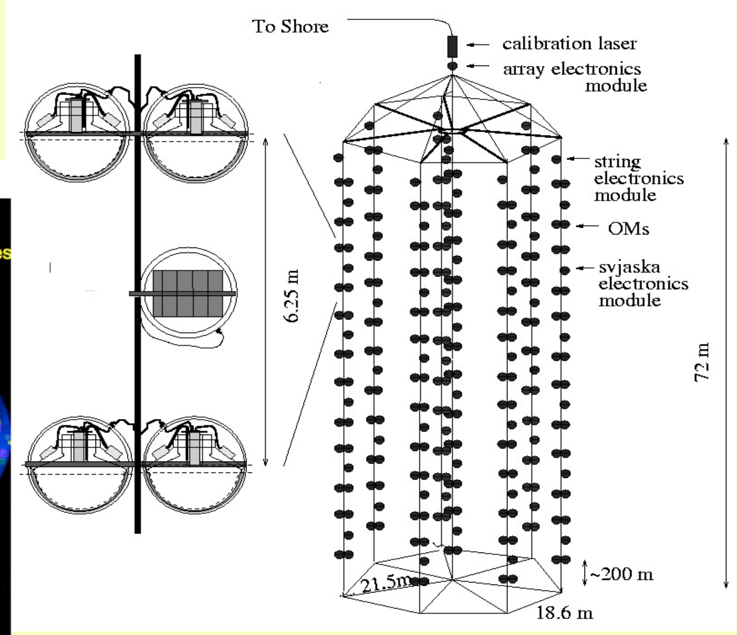
A problem: ice scatter light and deteriorate the track angular reconstruction.

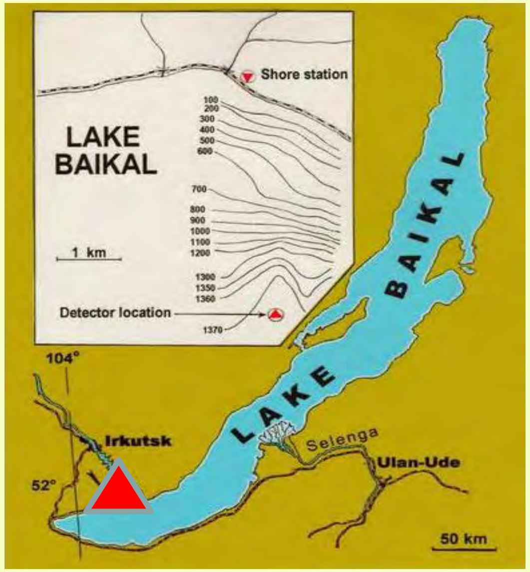
A.A. 2020-20121

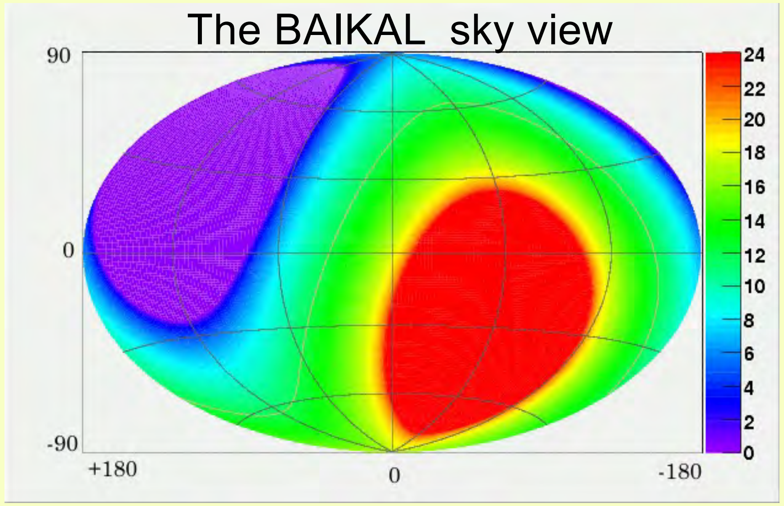
Baikal, the pioneer project

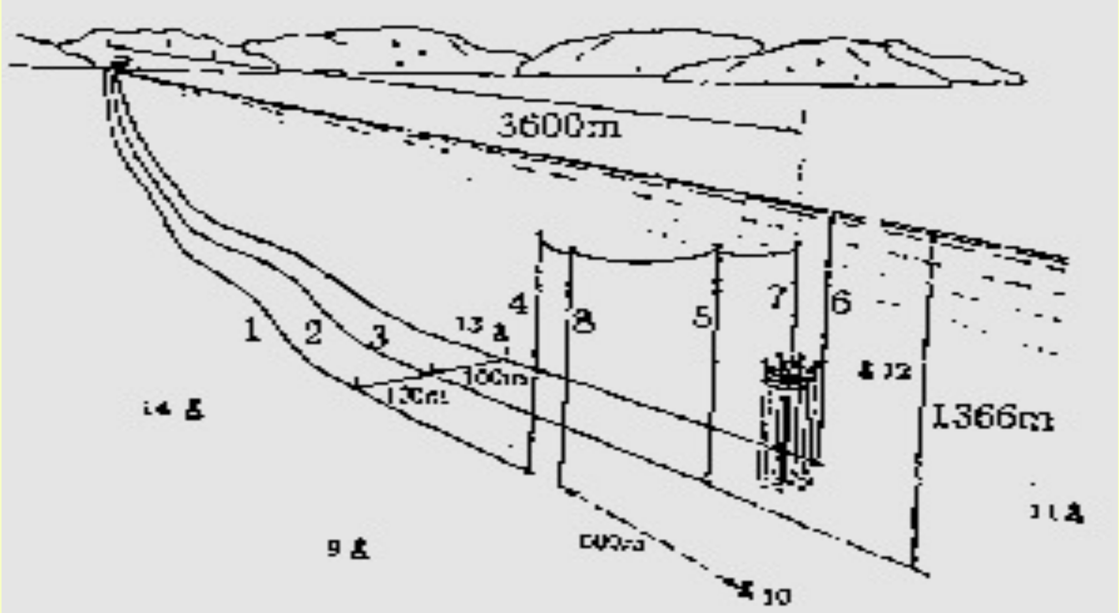
Baikal lake, Siberia
1993 → 36 optical modules
1998 → 192 optical modules











Gigaton Volume Detector: the future of Baikal Telescope

10368 photo-sensors at 216 strings

27 subarrays (clusters with 8 strings)

String: 4 sections, 48 photo-sensors

Active depths: 600 – 1300 m

To Shore: 4 – 6 km

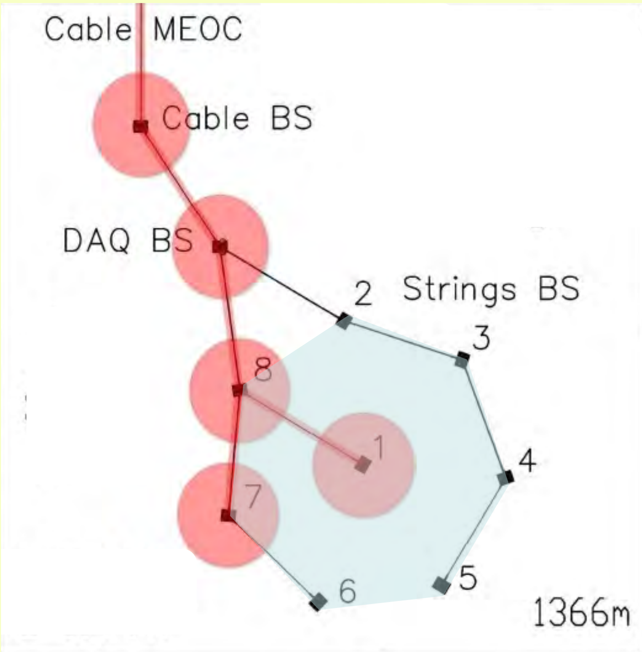
Instrumented water volume

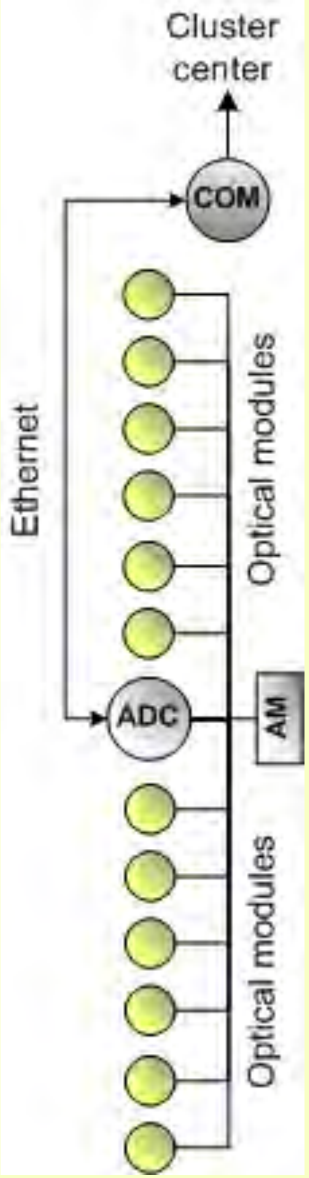
V= 1.5 km^3 S = 2 km^2

Angular resolution

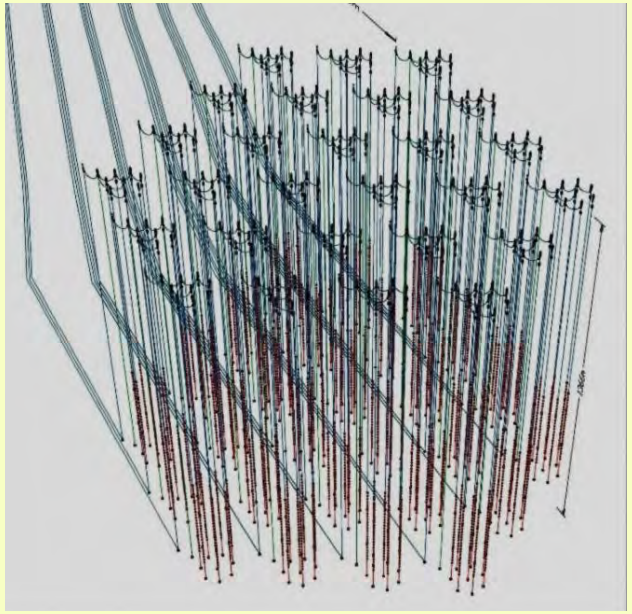
Muons: 0.25 degree

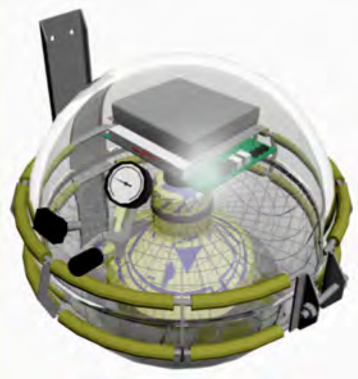
Showers: 3.5-5.5 degree



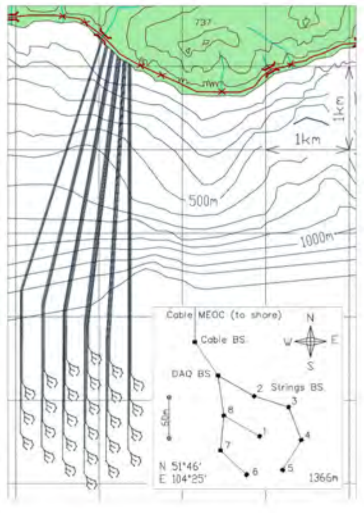


Section: basic detection unit





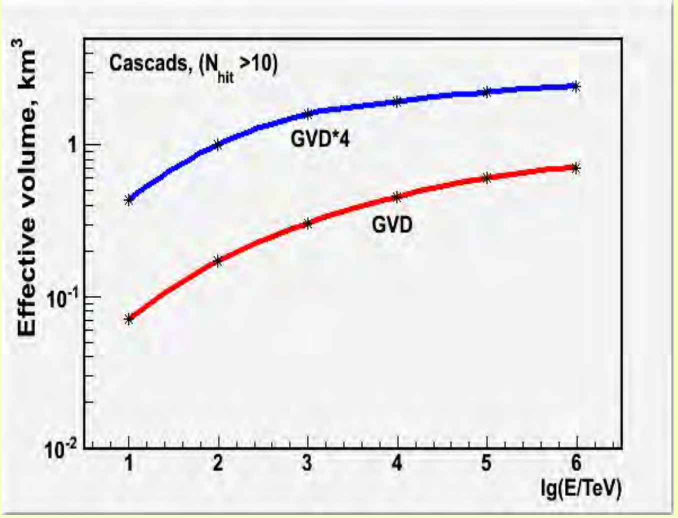
Optical module

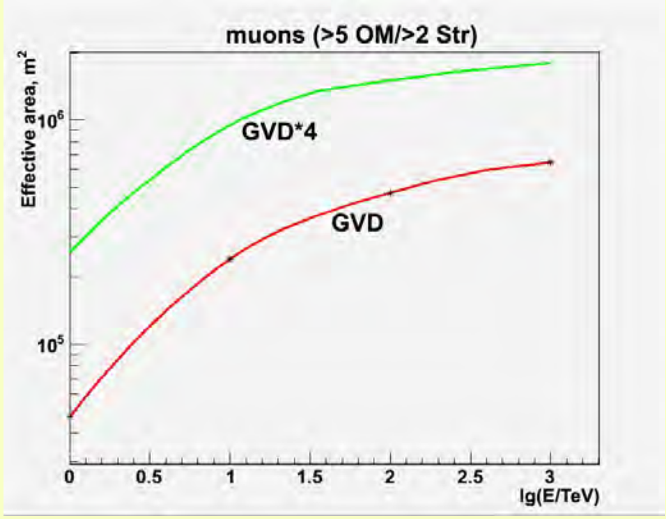


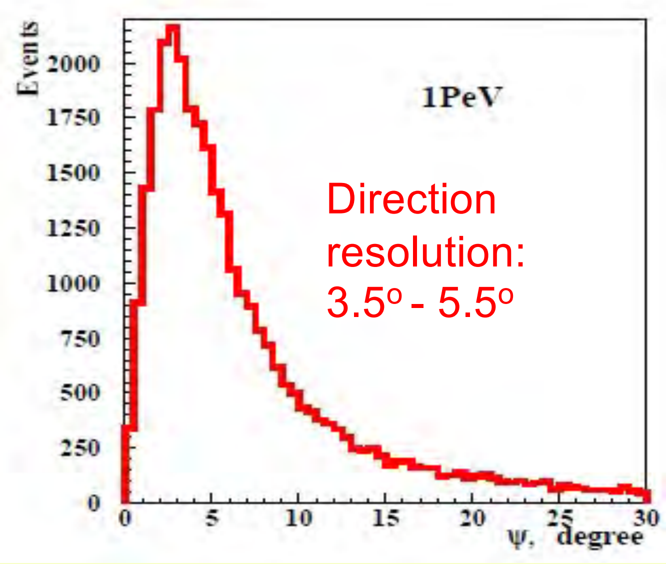
Gigaton Volume Detector: expected performances

Cascades: (E>10 TeV):
$V_{eff} \sim 0.4–2.4\ km^3$

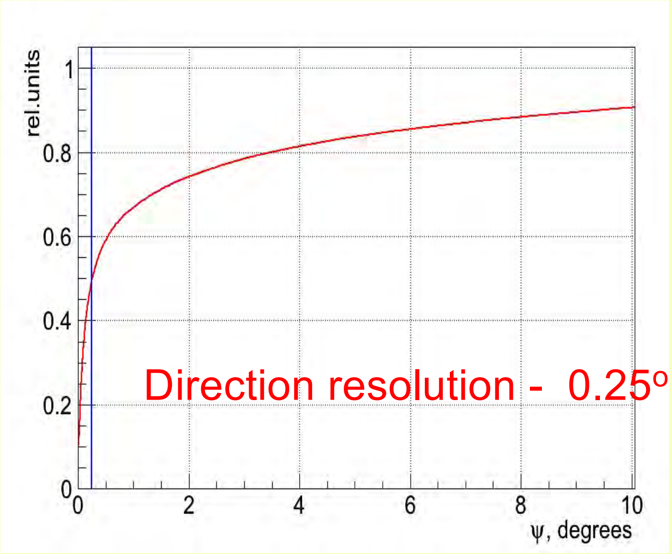
Muons: (E>1 TeV):
$S_{eff} \sim 0.3–1.8\ km^2$





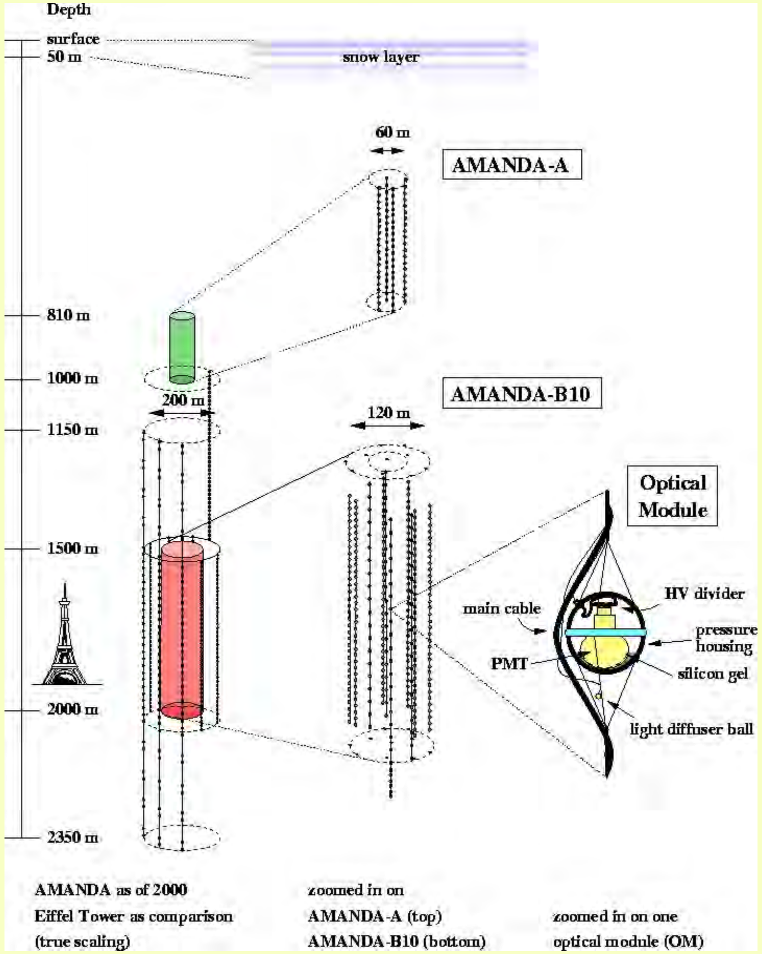


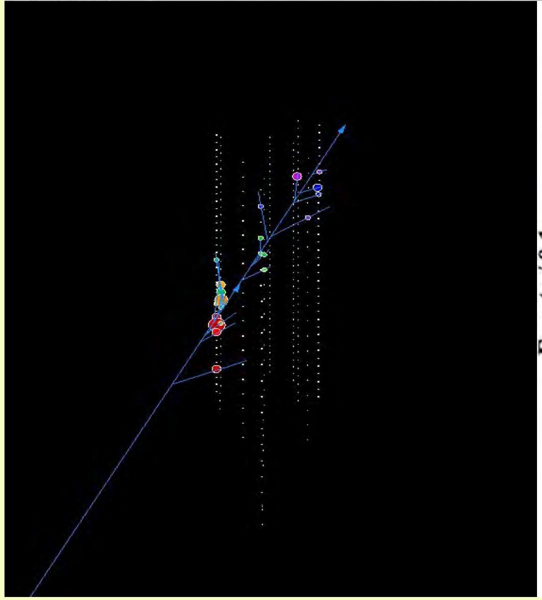
Direction resolution: 3.5° - 5.5°

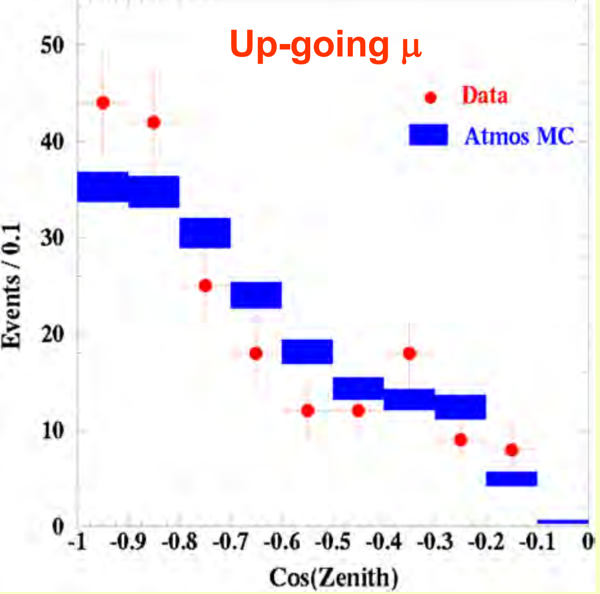


Direction resolution - 0.25°

AMANDA – South Pole – 2 km depth in ice

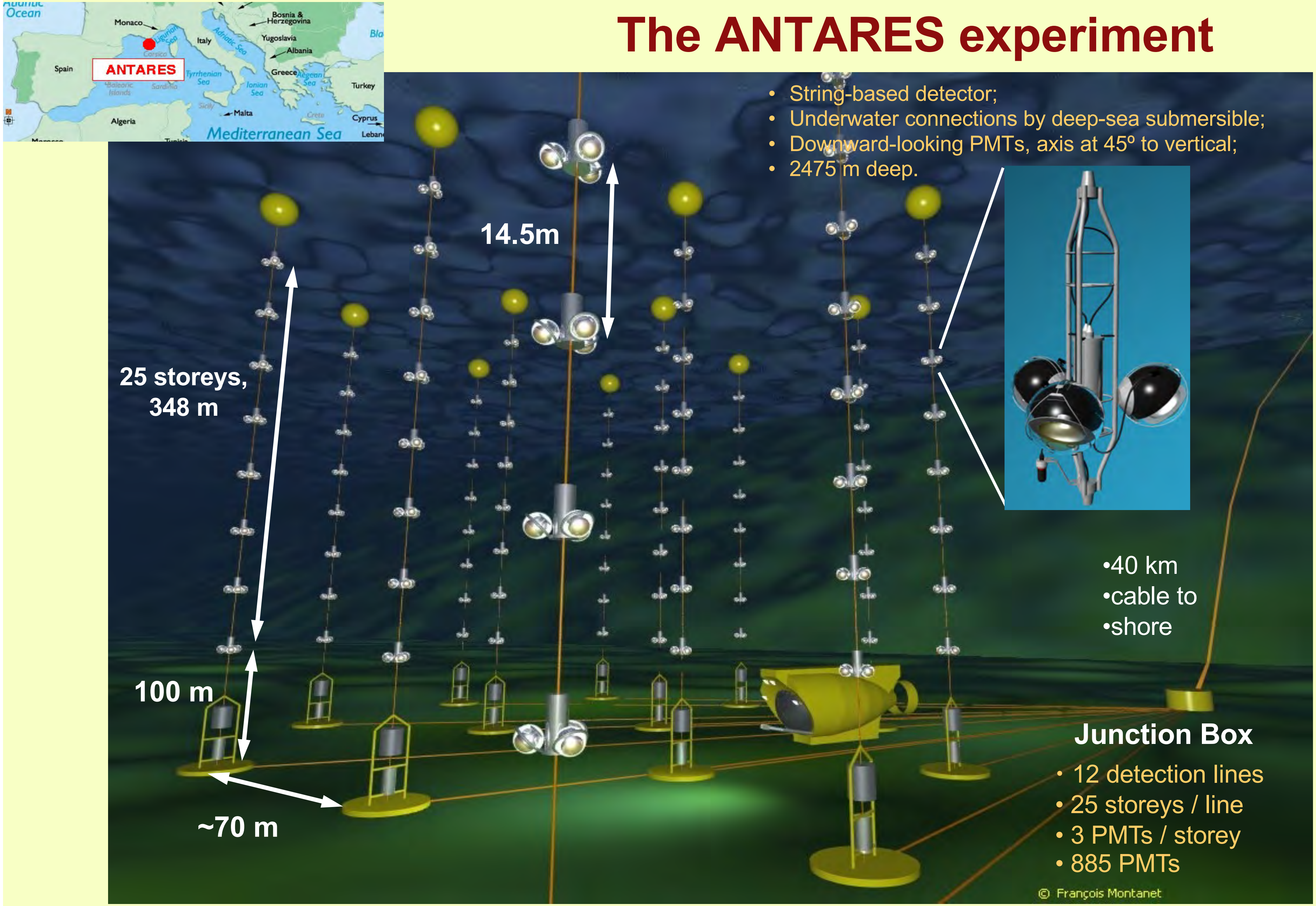






A problem: ice diffuses light and deteriorate the track reconstruction angular resolution

The ANTARES experiment



- String-based detector;
- Underwater connections by deep-sea submersible;
- Downward-looking PMTs, axis at 45º to vertical;
- 2475 m deep.

•40 km
•cable to
•shore

Junction Box

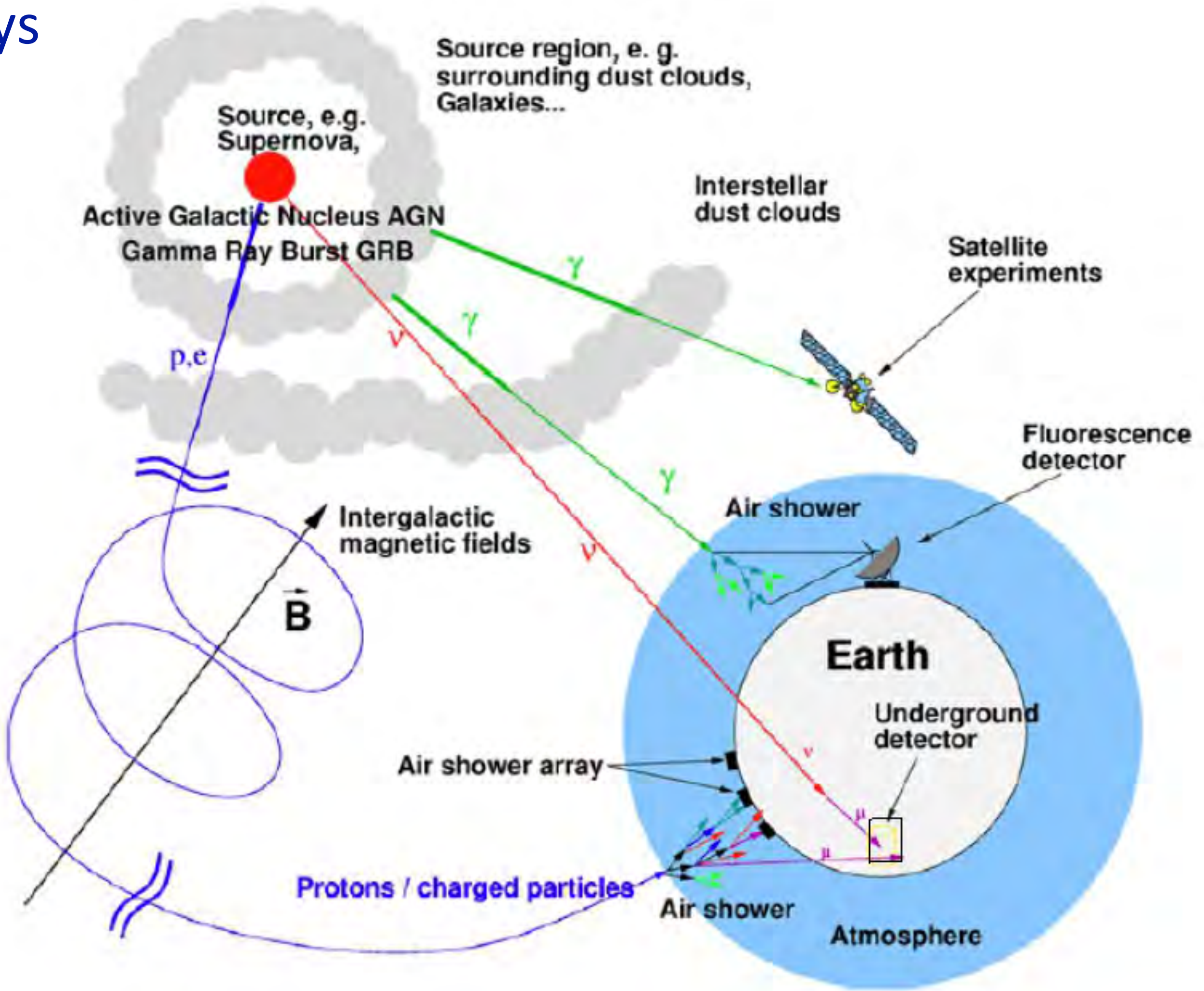
- 12 detection lines
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

© François Montanet

Multi-messenger astronomy

- Cosmic rays
- Photons
- Neutrinos

Only ν propagate freely through the cosmos



Cosmic ray – neutrino connection

- Cosmic rays are accelerated
  - *in galactic sources such as supernova remnants*
  - *In extragalactic sources such as active galaxies and gamma-ray bursts*
- Cosmic ray sources produce γ-rays in two ways
  - *From radiation by accelerated electrons*
  - *From decay of* π^0 *produced by interactions of accelerated cosmic-ray protons or nuclei with gas or photons*
- High energy ν are produced only in hadronic collisions:
  - *From decay of* π/K *produced when cosmic rays interact with gas in or near their sources*
  - *Or from photo-pion production on CMB or EBL*

Implications of astrophysical neutrinos

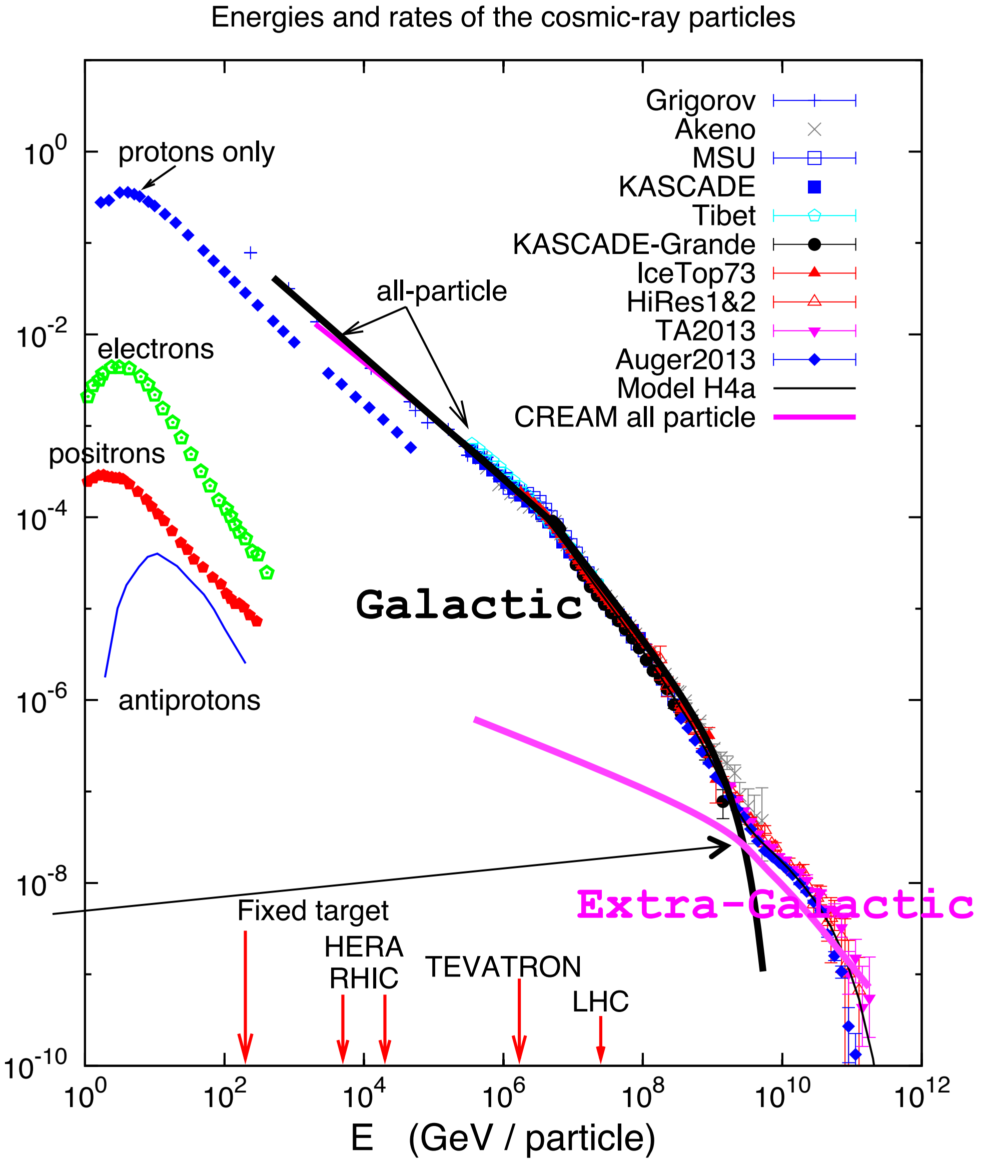
- Observations of $\gamma-$rays are often ambiguous
  - *Electrons radiate efficiently and usually explain the observations*
  - *Signatures of hadronic origin of photons are difficult to identify and prove*
- Neutrinos have a unique implication
  - *Observation of high energy extraterrestrial* ν *requires a hadronic origin*
  - *Neutrinos can emerge from deep inside a compact source without degradation by electromagnetic cascading*

Cosmic Rays …

- Energy content of CR determines possible sources of neutrinos
- Extra-galactic origin is likely
- Location of transition from galactic to extra-galactic affects energy estimate

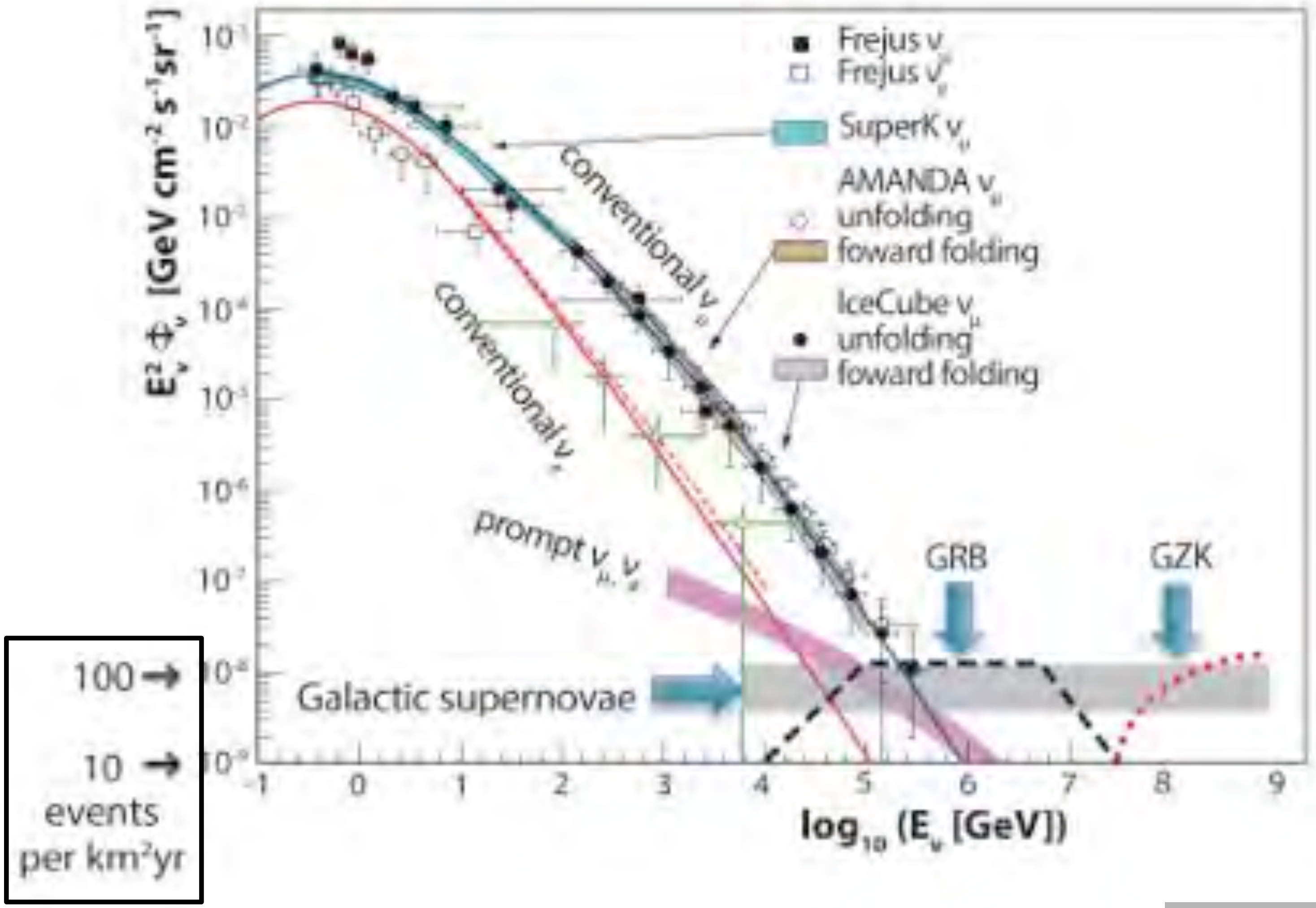
$$E\frac{dN}{d\ln E} \approx 3\times 10^{-8}\,\frac{\mathrm{GeV}}{cm^2 srs}$$

at $10^{10}\,\mathrm{GeV}$ $(10^{19}\,\mathrm{eV})$



Energies and rates of the cosmic-ray particles

… and neutrinos



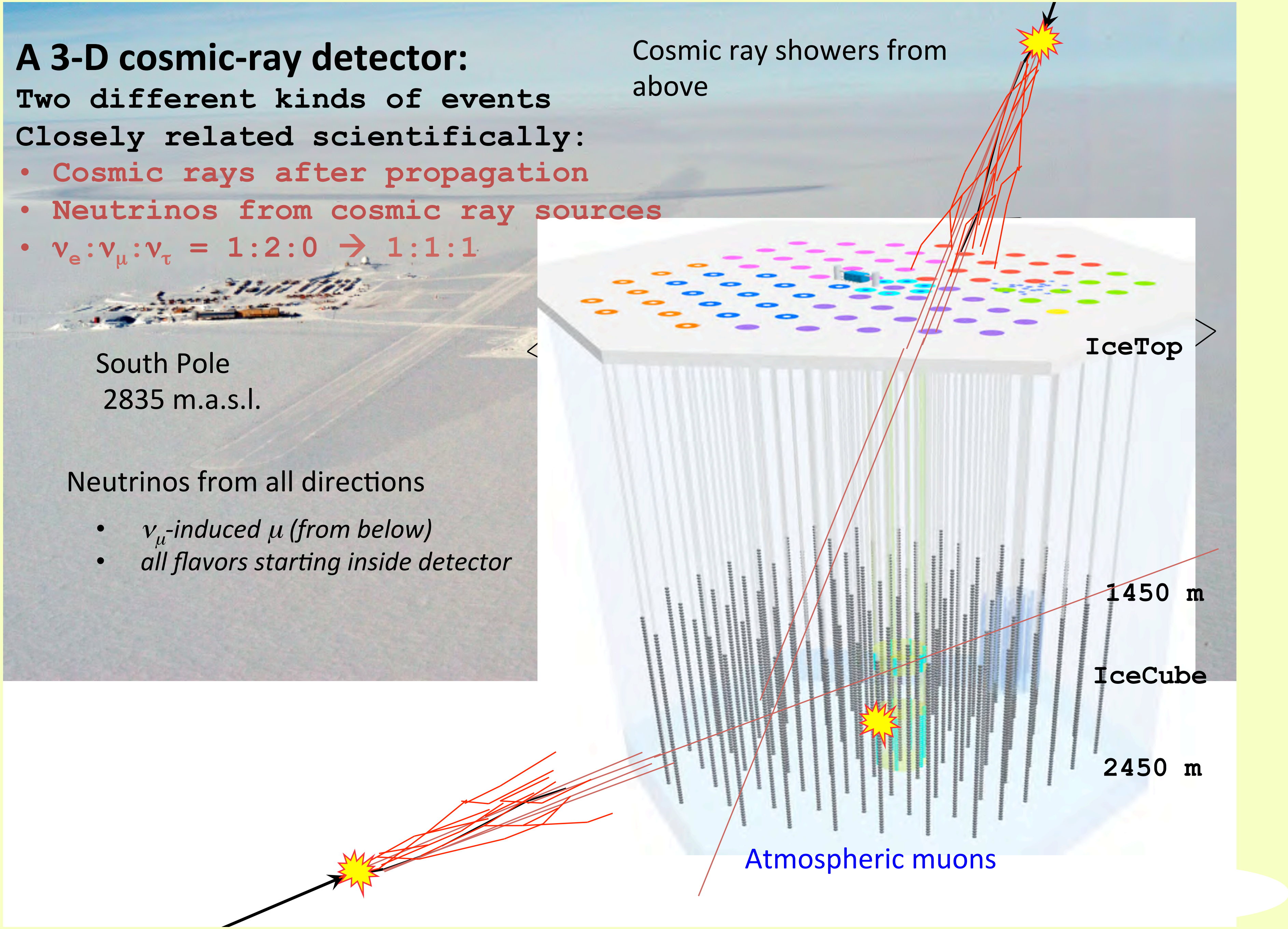
$$\Phi_\nu \equiv \frac{dN}{dE} \approx \frac{1}{E^2}$$

A 3-D cosmic-ray detector:

Two different kinds of events

Closely related scientifically:

- Cosmic rays after propagation
- Neutrinos from cosmic ray sources
- $\nu_e:\nu_\mu:\nu_\tau = 1:2:0 \rightarrow 1:1:1$



Cosmic ray showers from above

South Pole
2835 m.a.s.l.

Neutrinos from all directions

- ν_μ-induced μ (from below)
- *all flavors starting inside detector*

Atmospheric muons

ICECUBE

Deployment history

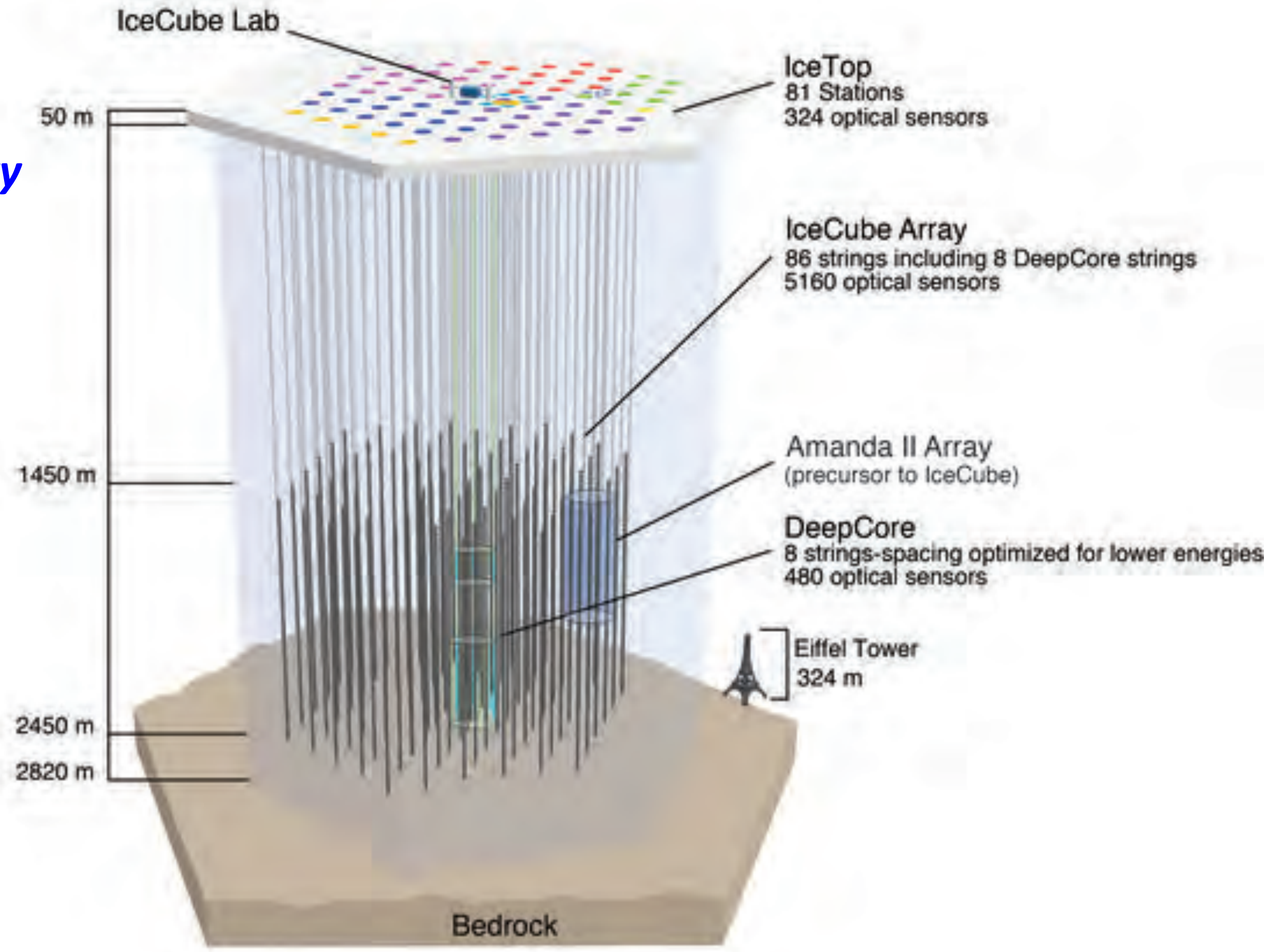
2002: proposal

2003-04 staging

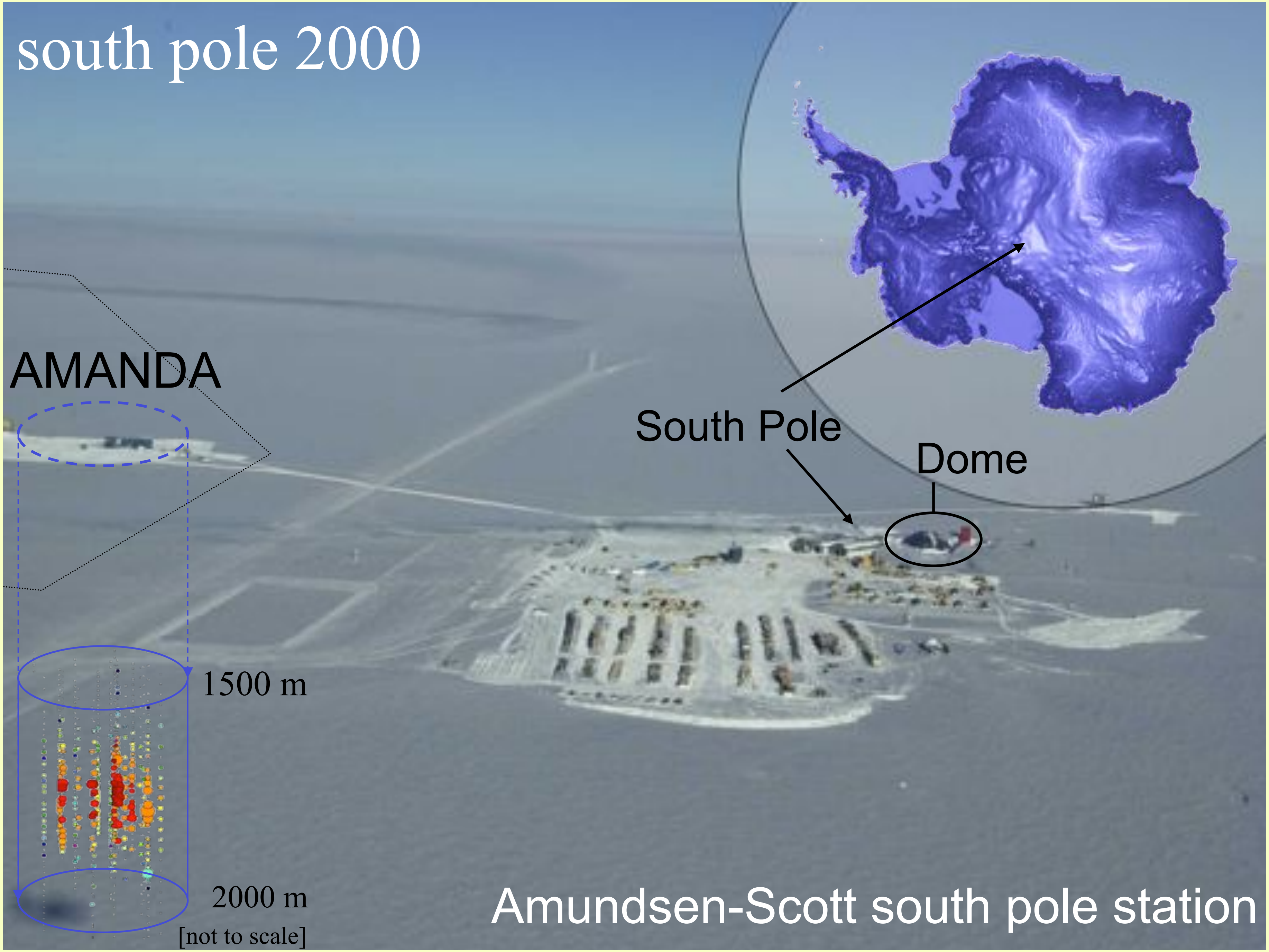
2004-05	**1**	**4**
2005-06	**9**	**16**
2006-07	**22**	**26**
2007-08	**40**	**40**
2008-09	**59**	**59**
2009-10	**79**	**73**
2010-11	**86**	**81**

Deep strings

Surface stations

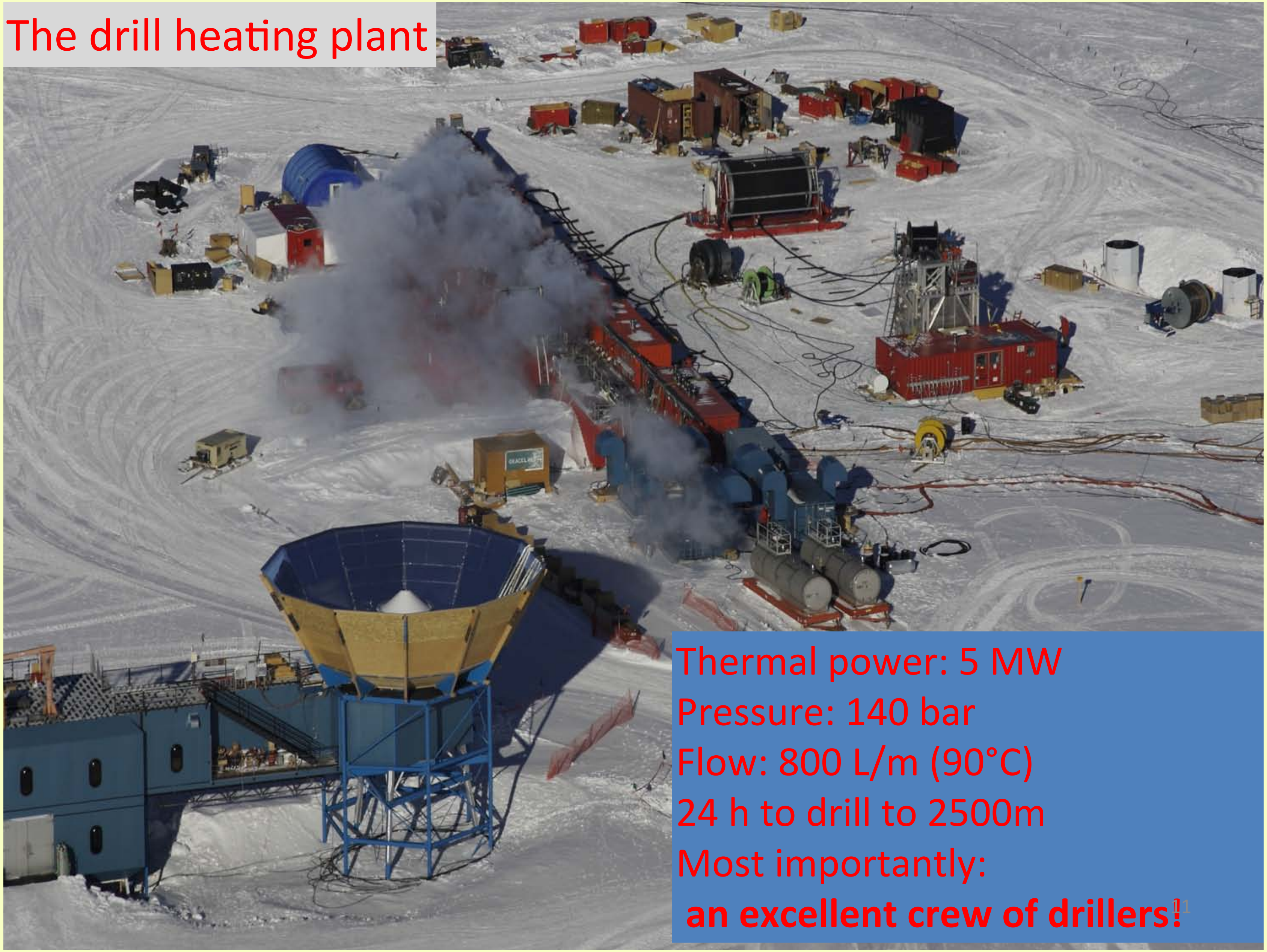


south pole 2000



ICECUBE: the South Pole equipment at the surface

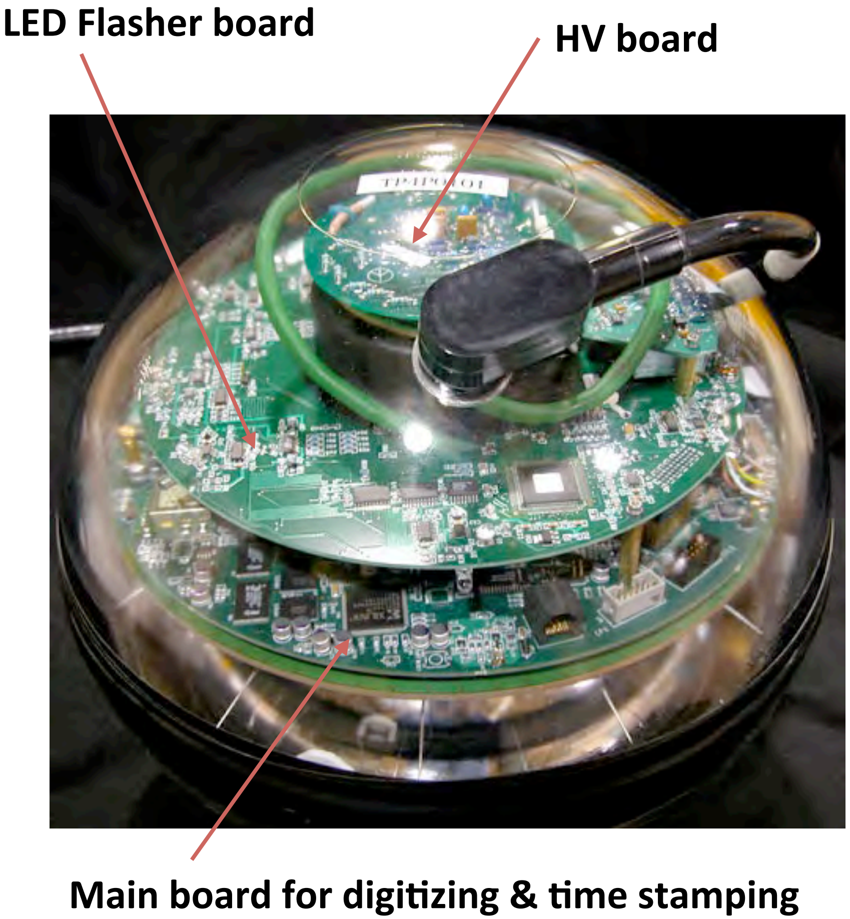
ICECUBE: the South Pole equipment at the surface



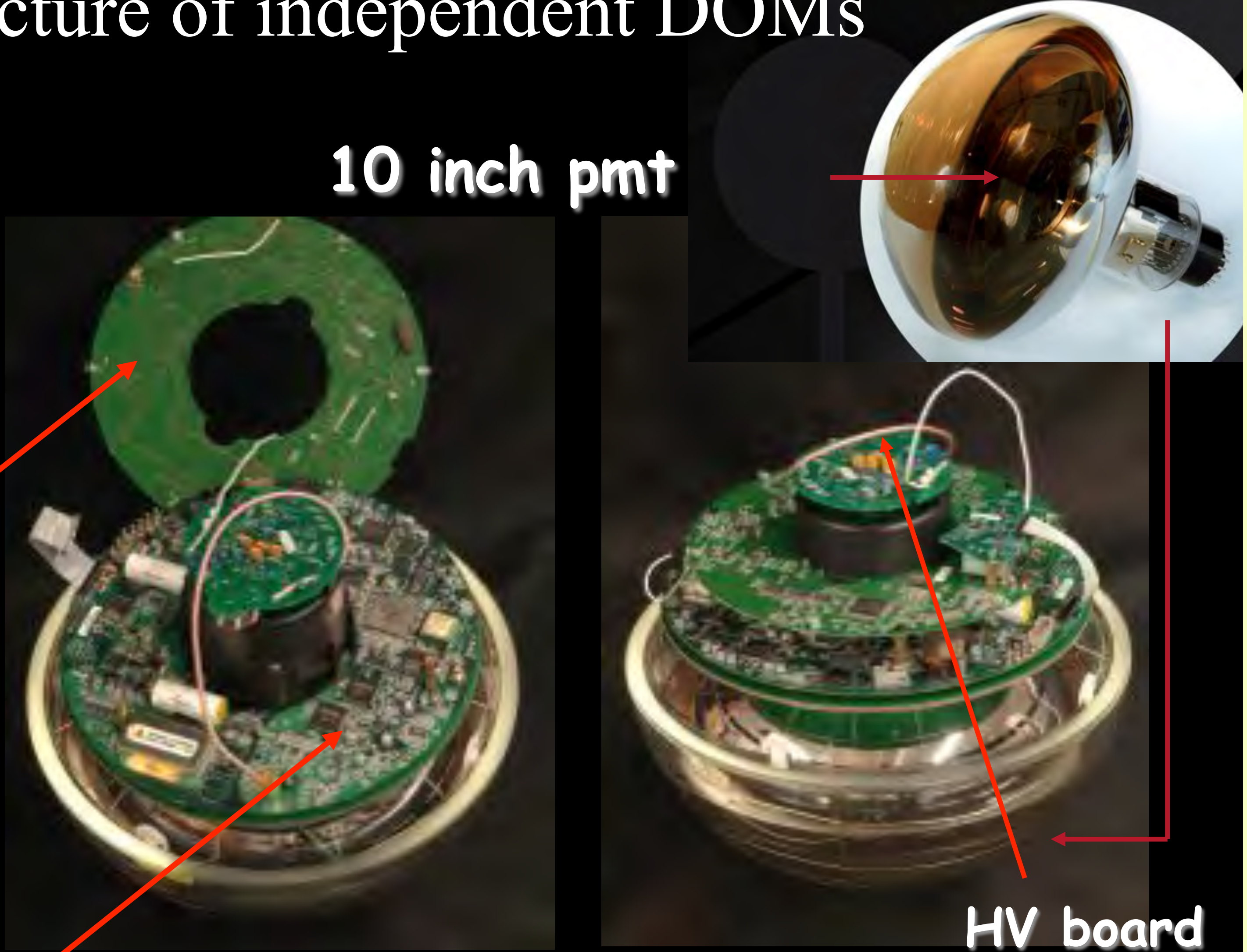
The drill heating plant

Thermal power: 5 MW
Pressure: 140 bar
Flow: 800 L/m (90°C)
24 h to drill to 2500m
Most importantly:
an excellent crew of drillers!

IceCube Digital Optical Module and deployment



architecture of independent DOMs



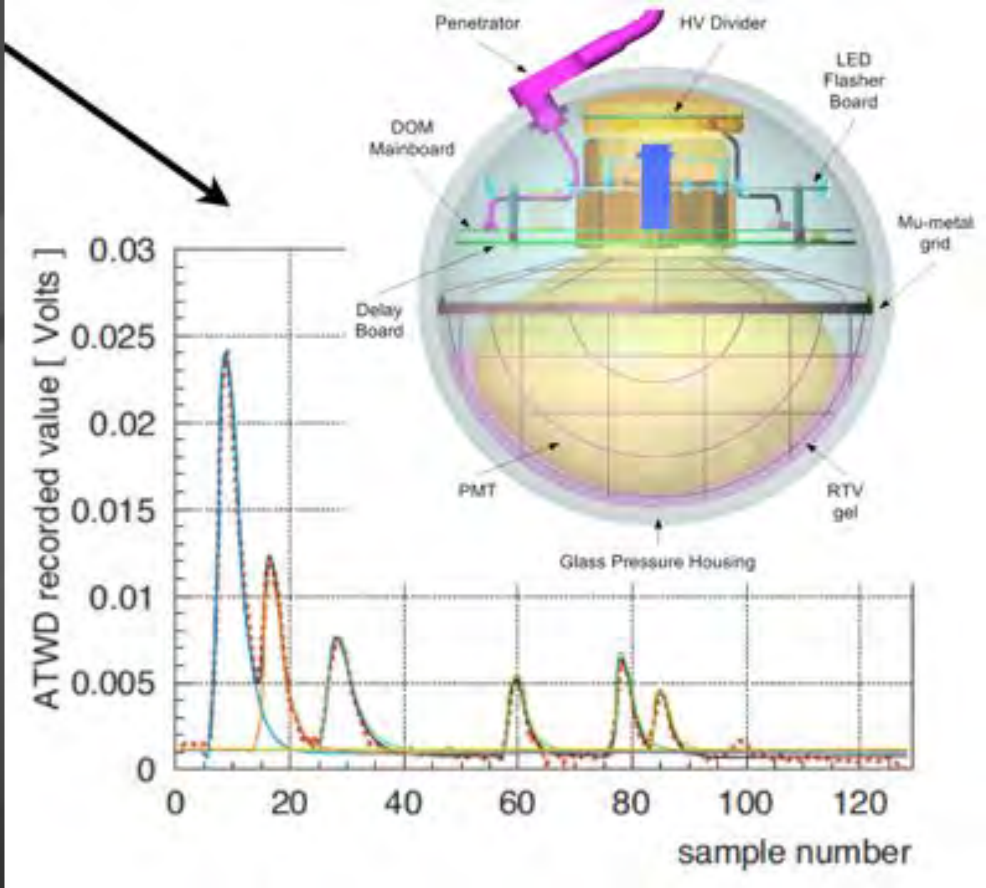
10 inch pmt

LED
flasher
board

HV board

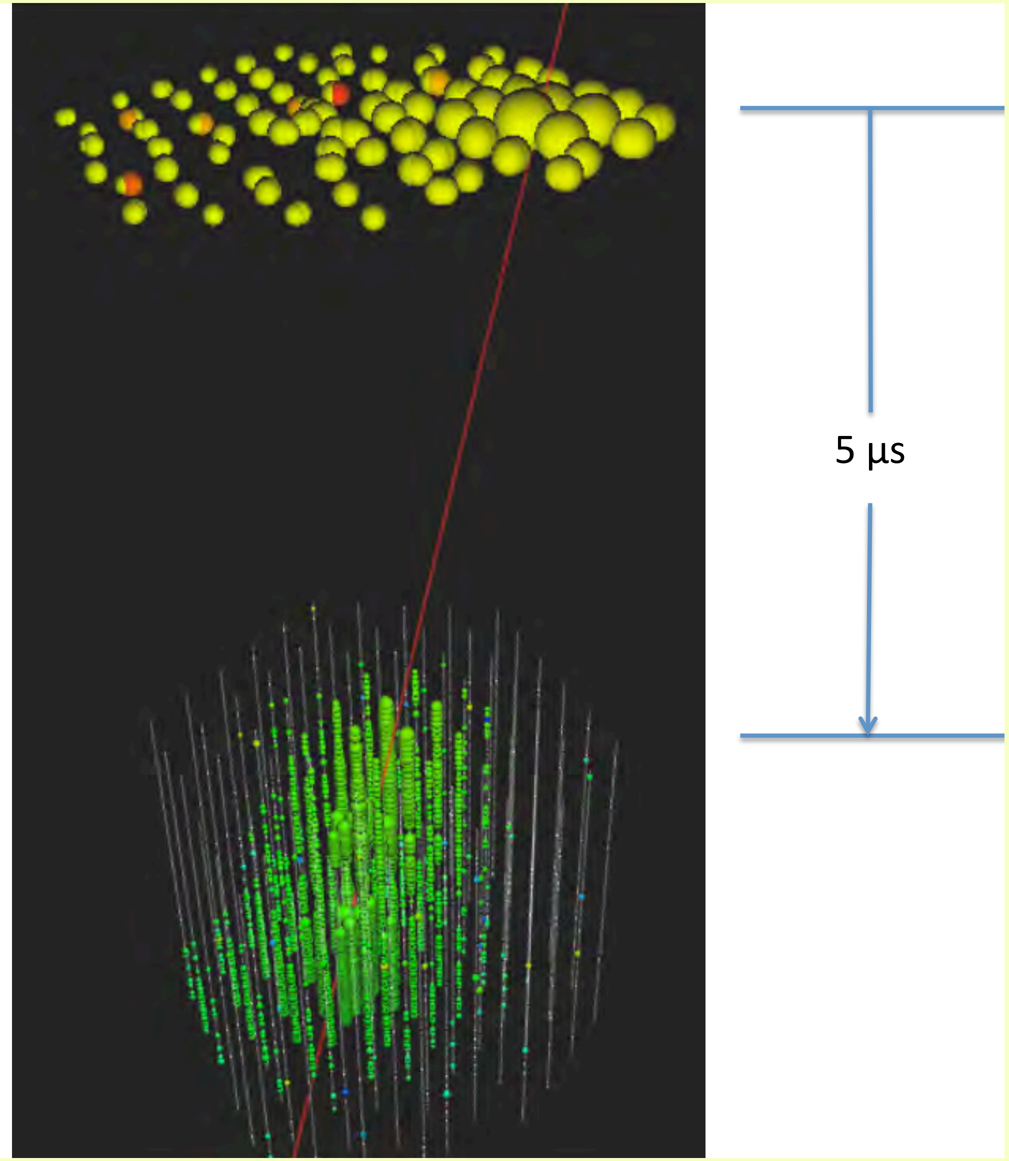
main
board

… each Digital Optical Module independently collects light signals like this, digitizes them,



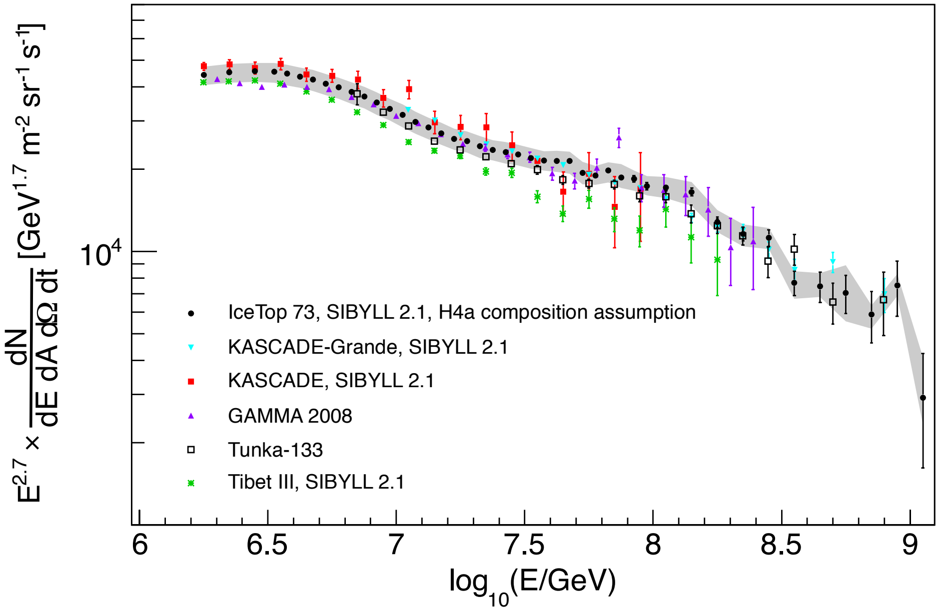
…time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events…

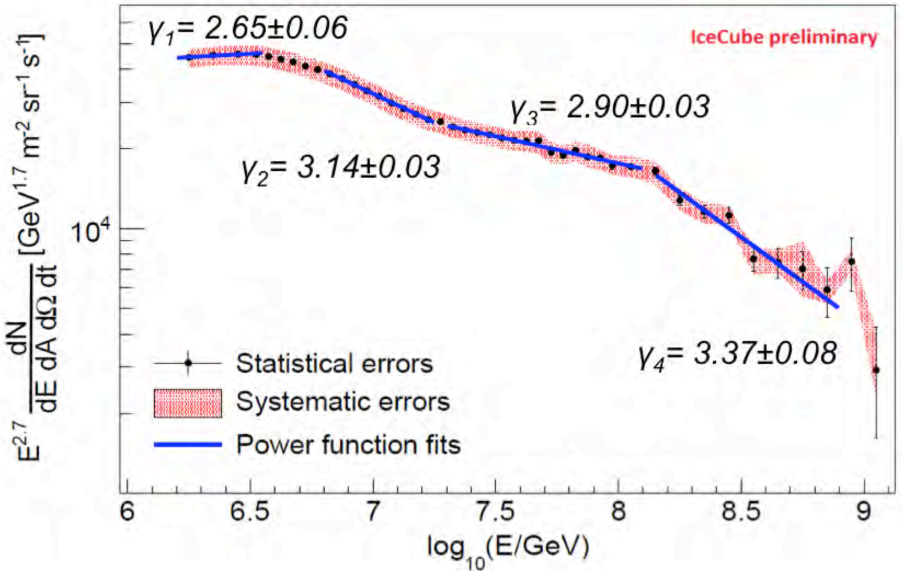
IceCube – IceTop: dimensions



Primary spectrum from IceTop

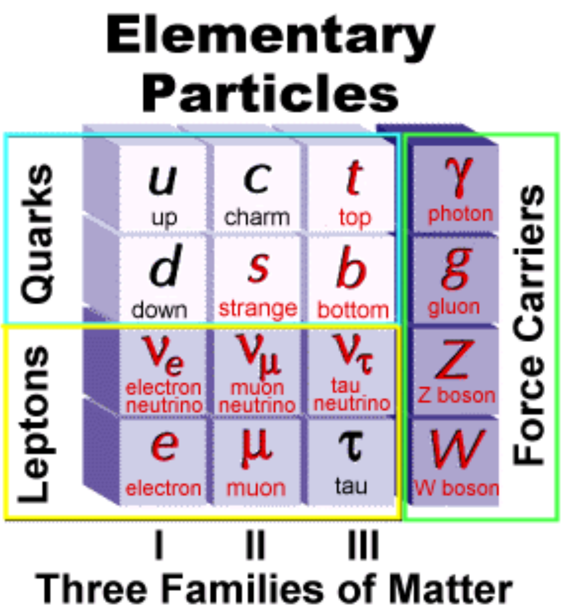
Phys. Rev. D 88, 042004 (2013).



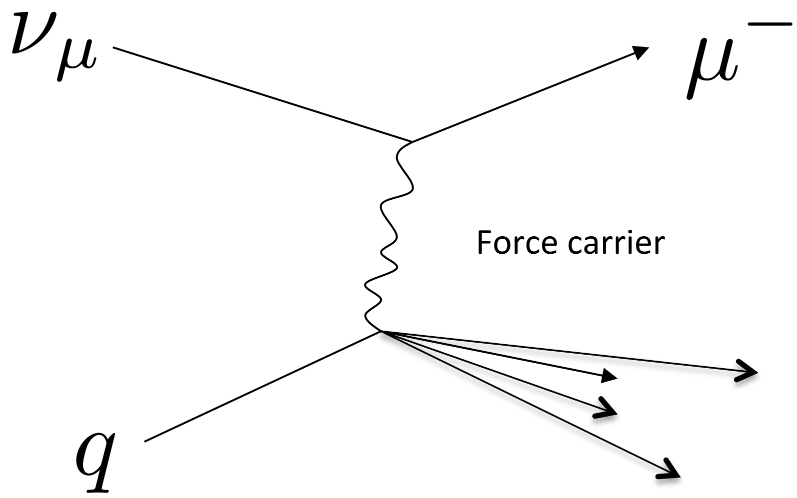


- $10^6 - 10^8$ GeV sets normalization for PeV ν
  - Directly for background atmospheric ν
  - At sources for astrophysical ν
- $10^7 - 10^9$ GeV: transition from galactic to extragalactic
  - Model dependent

Neutrino Interactions - 1



Charged current ν_μ:



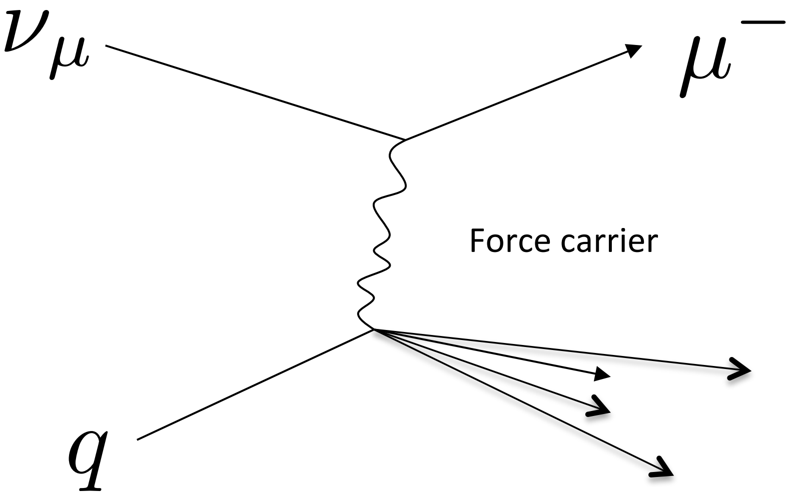
Also charged current $\nu_e \longrightarrow e$

and charged current $\nu_\tau \longrightarrow \tau$

and neutral current $\nu_\alpha \longrightarrow \nu_\alpha$

Neutrino Interactions - 2

Tracks
(because of μ)



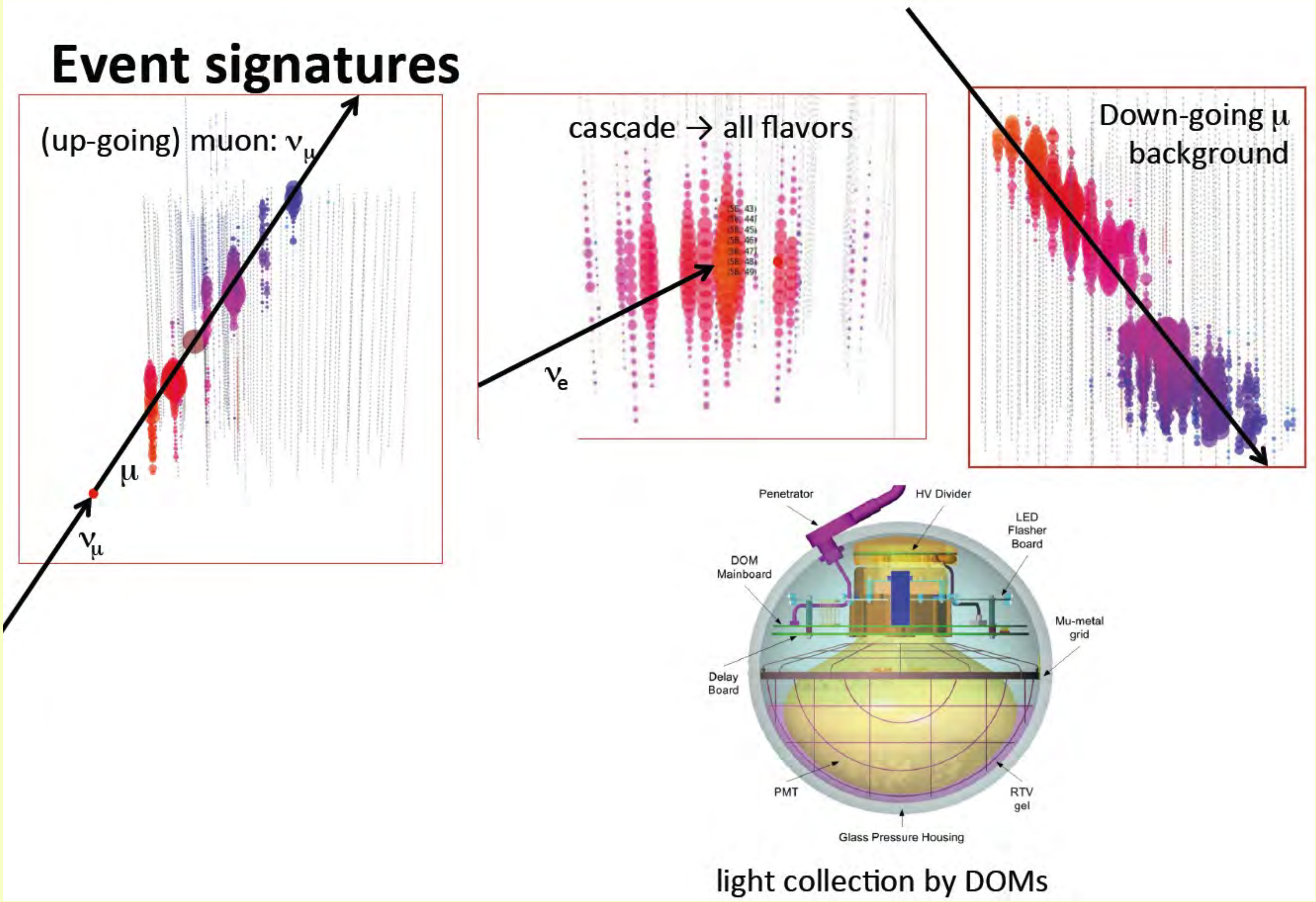
Cascades

Also charged current $\nu_e \longrightarrow e$

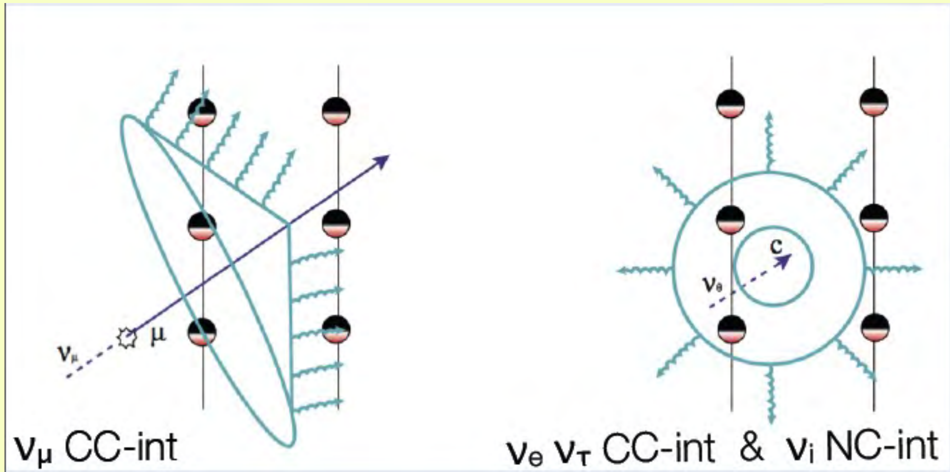
and charged current $\nu_\tau \longrightarrow \tau$

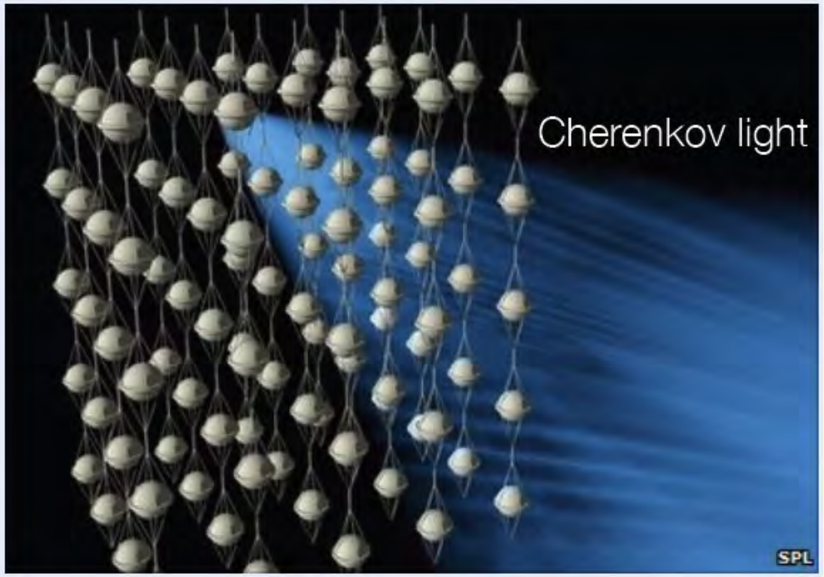
and neutral current $\nu_\alpha \longrightarrow \nu_\alpha$

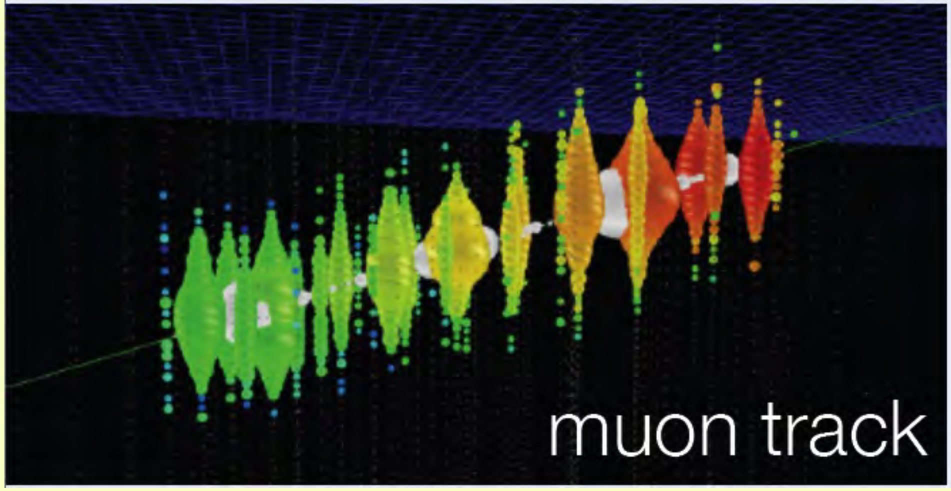
IceCube

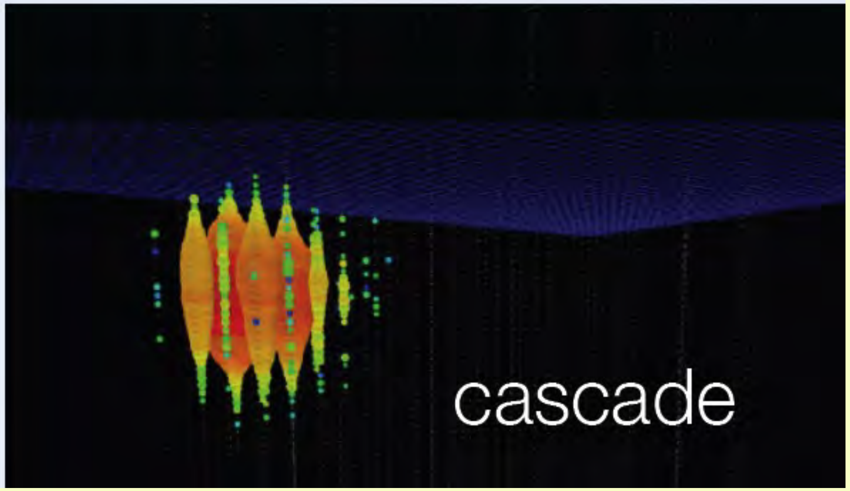

Event signatures
(up-going) muon: ν_μ
μ
ν_μ
cascade → all flavors
ν_e
Down-going μ background
Penetrator
HV Divider
LED Flasher Board
DOM Mainboard
Mu-metal grid
Delay Board
PMT
RTV gel
Glass Pressure Housing
light collection by DOMs

IceCube

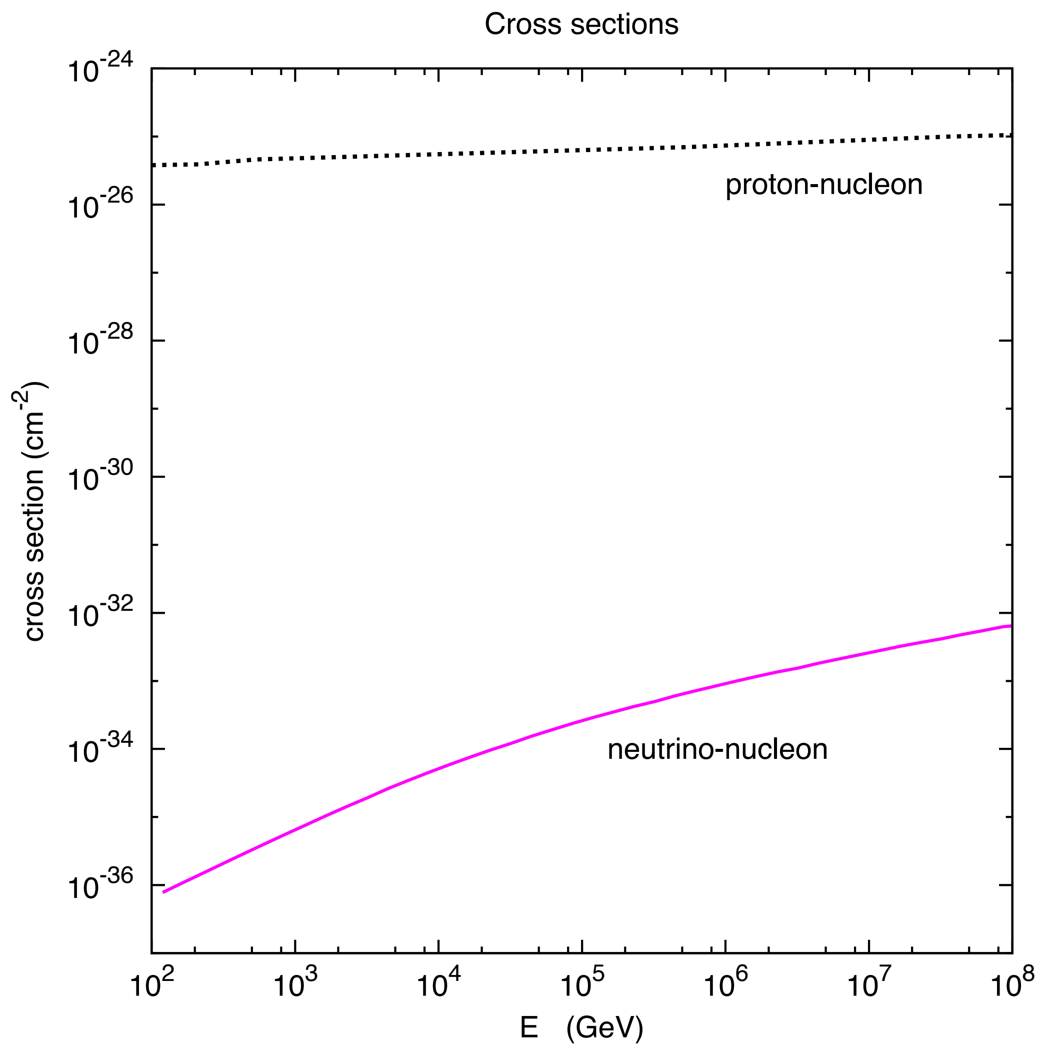

νμ
μ
νμ CC-int
νe
c
νe ντ CC-int & νi NC-int

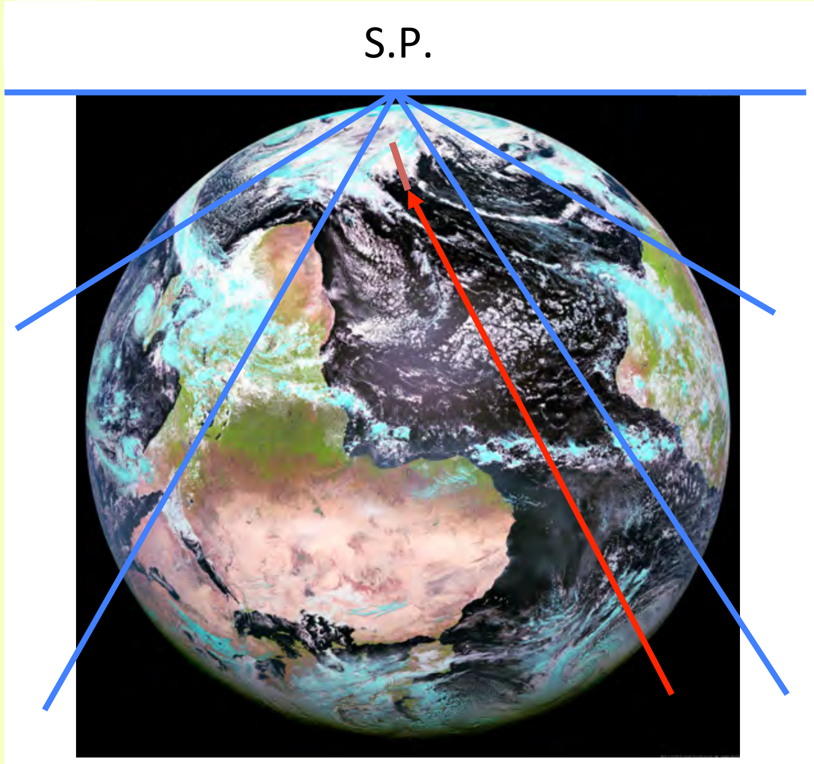

Cherenkov light
SPL

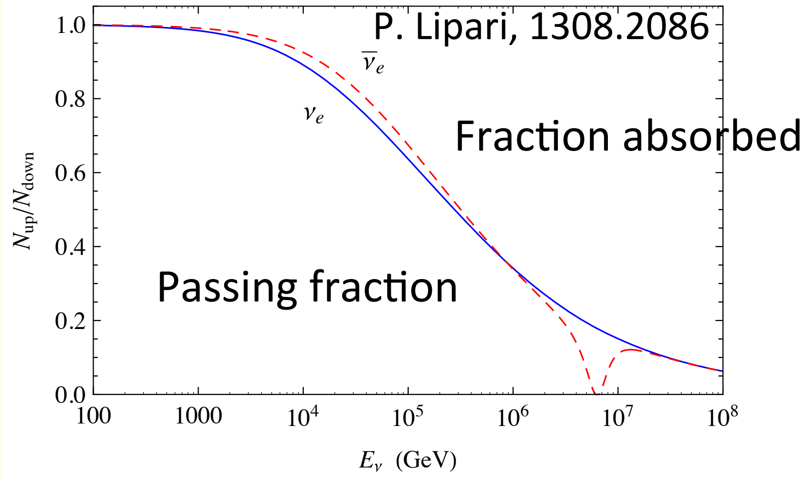

muon track


cascade

Upward neutrinos in IceCube





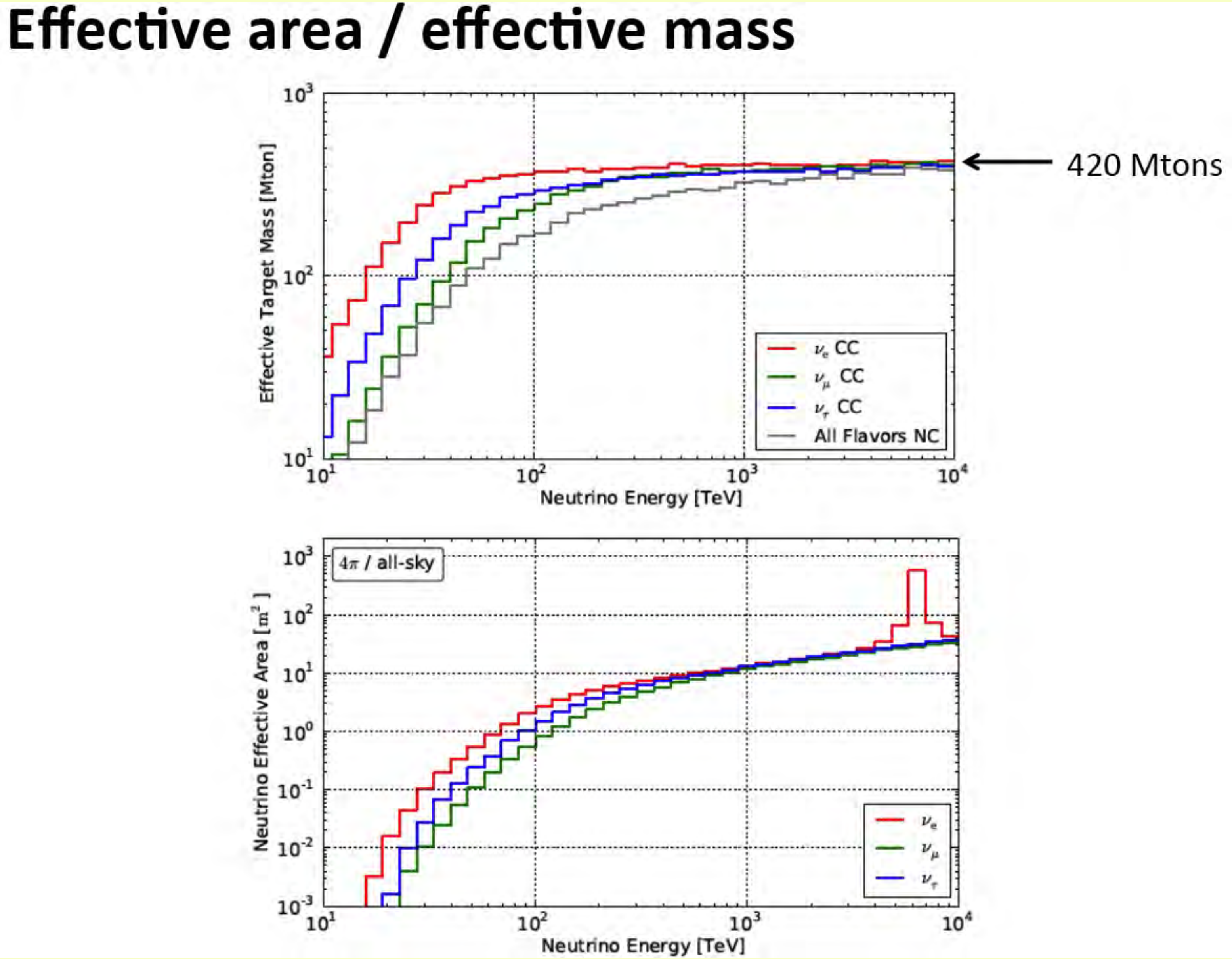


P. Lipari, 1308.2086

Fraction absorbed

Passing fraction

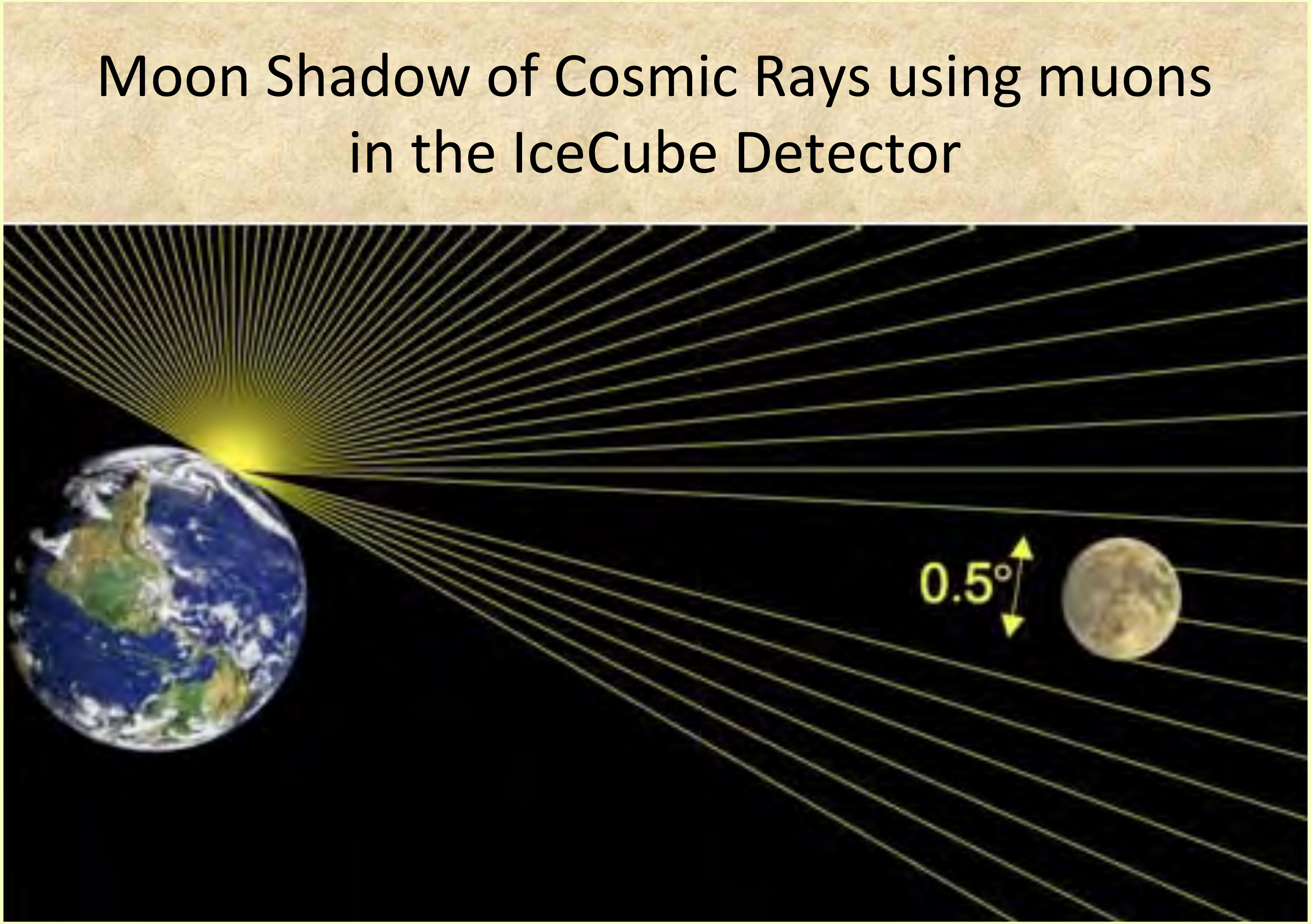
IceCube



Effective area / effective mass

420 Mtons

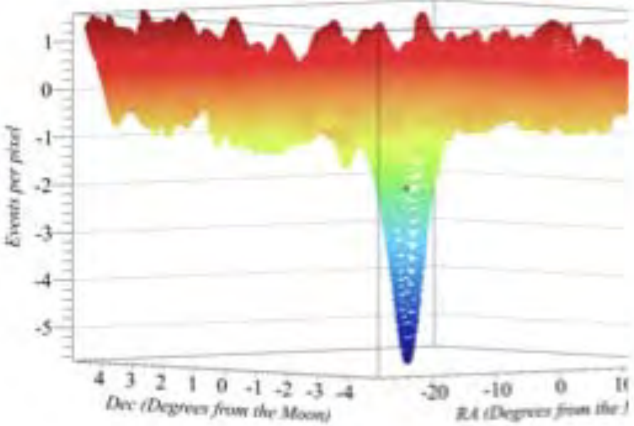
IceCube: check of the «pointing accuracy»

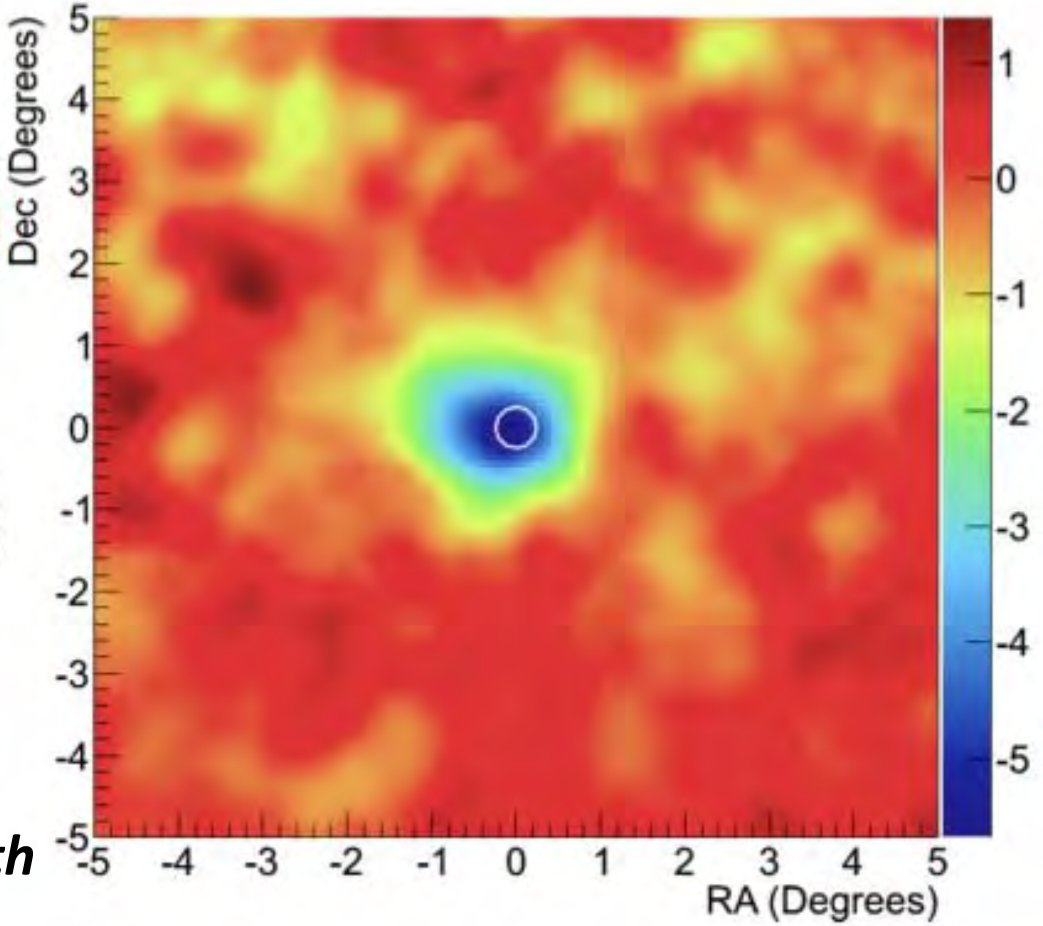


Moon Shadow of Cosmic Rays using muons in the IceCube Detector

IceCube: check of the «pointing accuracy»

Moon shadow observed in muons –
Check on IceCube pointing





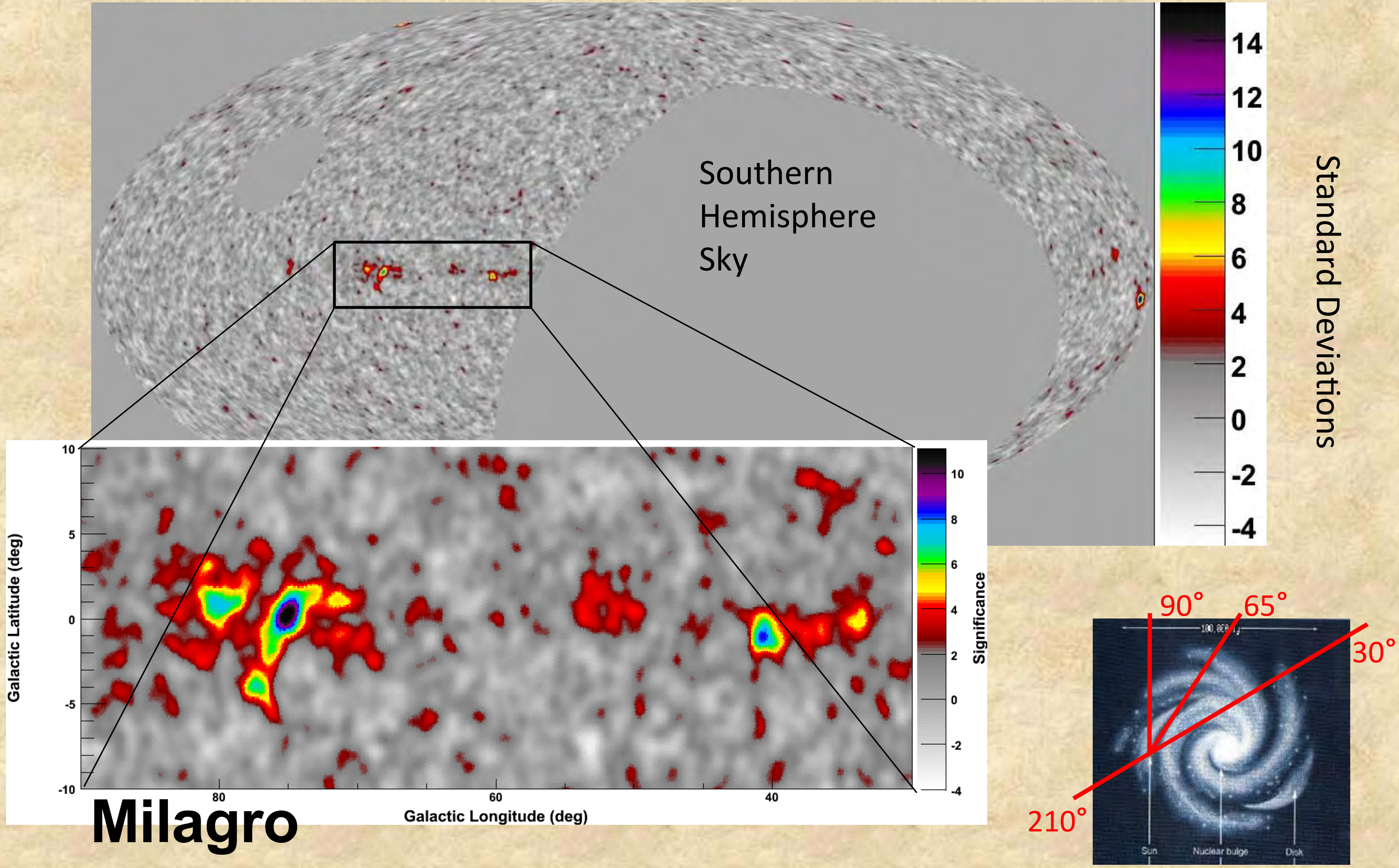
Center of moon is spot on
to a precision of <0.1 degrees.

Statistical significance with
IC 59: > 10 sigma

IceCube, an example: search for neutrinos from Galactic Source - 1

galactic plane in 10 TeV gamma rays :

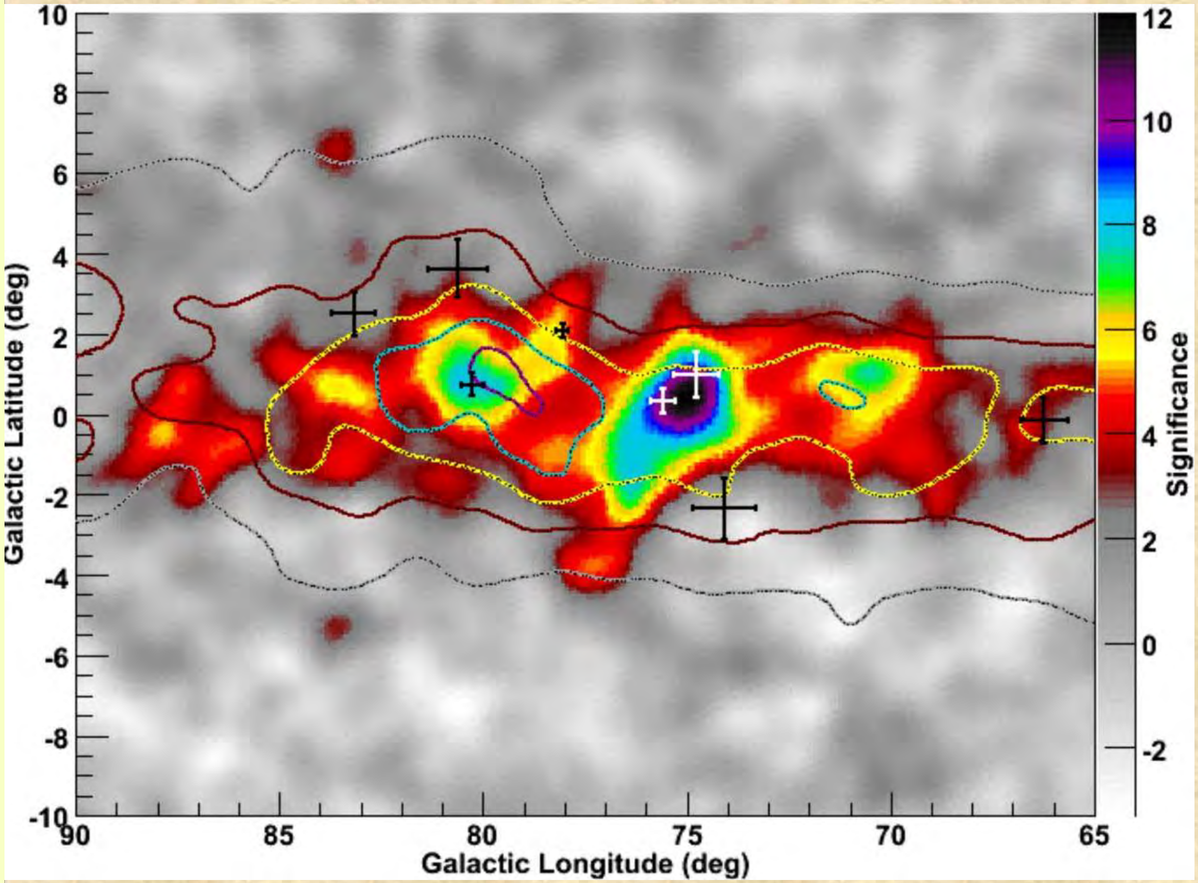
supernova remnants in star forming regions



Milagro

IceCube, an example: search for neutrinos from Galactic Source - 2

cygnus region : Milagro



Milagro

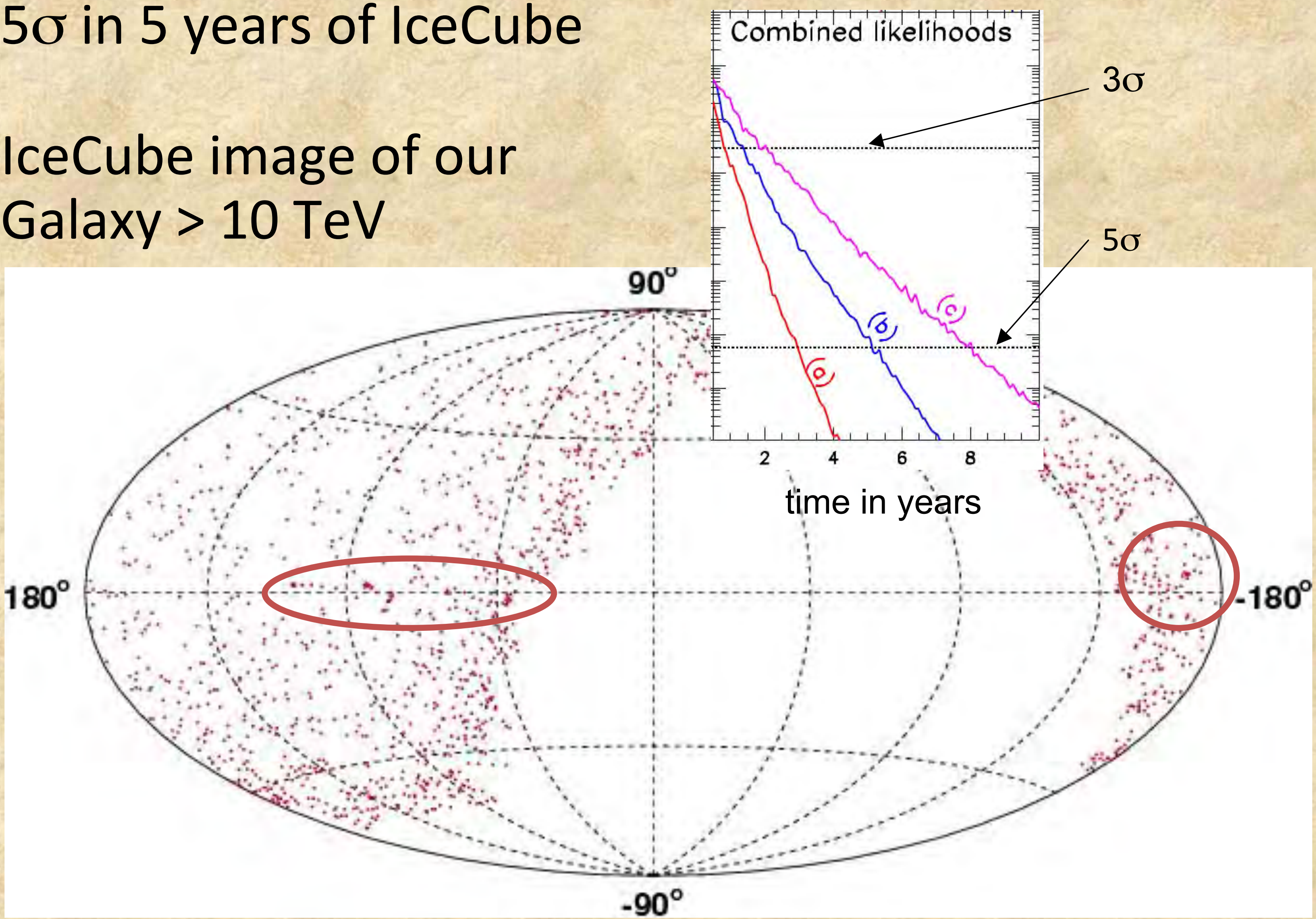
translation of
TeV gamma rays
into
TeV neutrinos

3 ± 1 ν per year in IceCube per source

IceCube, an example: search for neutrinos from Galactic Source - 3

5σ in 5 years of IceCube

IceCube image of our Galaxy > 10 TeV



M. C. Gonzalez-Garcia, F. Halzen, and S. Mohapatra, Astropart. Phys. **31**, 437 2009; e-print arXiv:0902.1176.

Upward neutrinos in IceCube

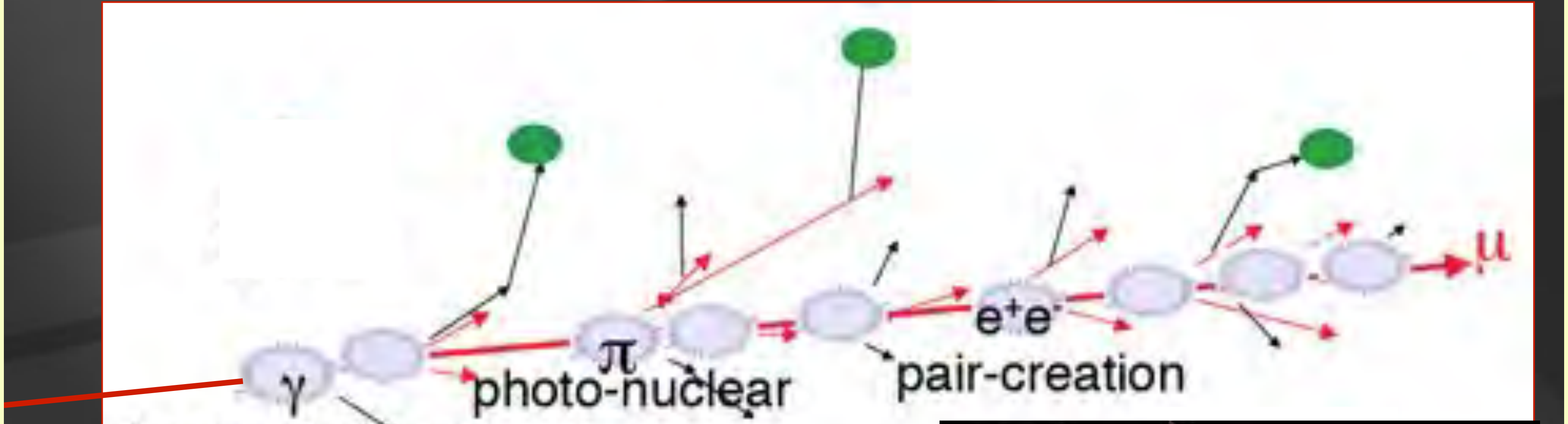
- Must have low enough energy to get through the Earth (depends on direction)
- Must produce a signal in the detector
  a. ν_μ – induced muon from neutrino interaction in the rock or ice below the detector (highest rate)
  b. Neutrino of any flavor interacts inside detector

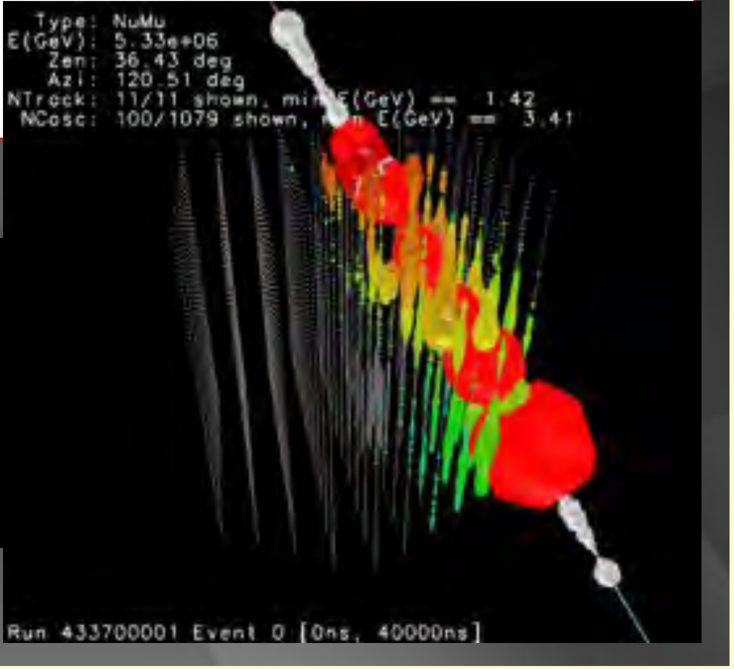
$$1\,\mathrm{km\,ice} = 0.91 \cdot 6 \times 10^{23} \cdot 10^{5} = 5 \cdot 10^{28}\,\mathrm{nucleons/cm}^{2}$$

$$\sigma_\nu \approx 2.6 \cdot 10^{-34}\,\mathrm{cm}^2 \ \mathrm{at}\ 10^5\,\mathrm{GeV}$$

Product ≈ 10^{-5} is fraction of ν of this energy that interact in detector

energy measurement (> 1 TeV)





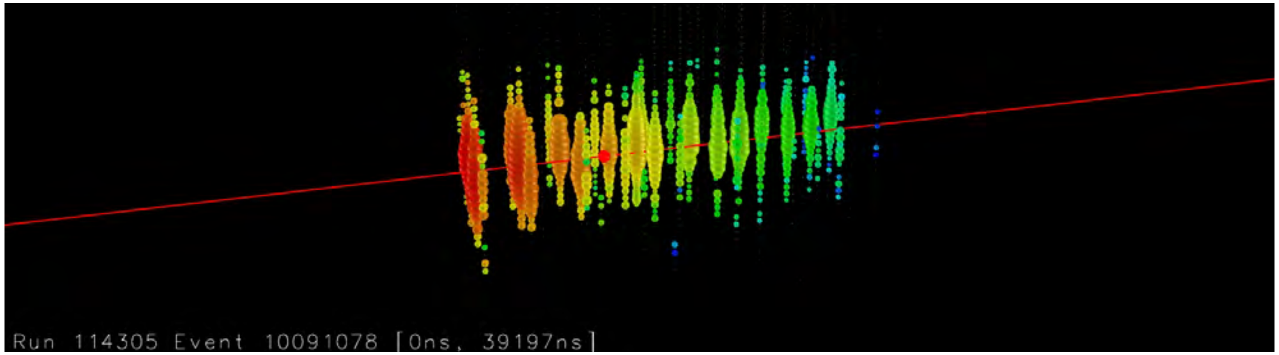
```
    Type: NuMu
E(GeV): 5.33e+06
    Zen: 36.43 deg
    Azi: 120.51 deg
NTrack: 11/11 shown, mi  E(GeV) ==  1.42
 NCosc: 100/1079 shown,     E(GeV) ==  3.41
```

```
Run 433700001 Event 0 [0ns, 40000ns]
```

convert the amount of light emitted to measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)

Neutrino Events

ν-induced μ entering from below



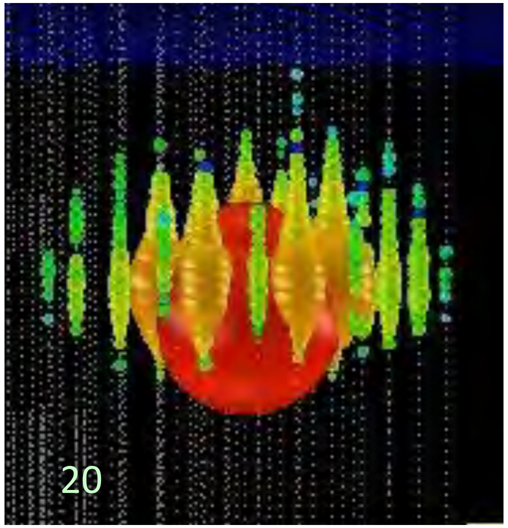
PeV = 10^6 GeV = 10^{15} eV. These are the highest energy neutrinos ever detected!

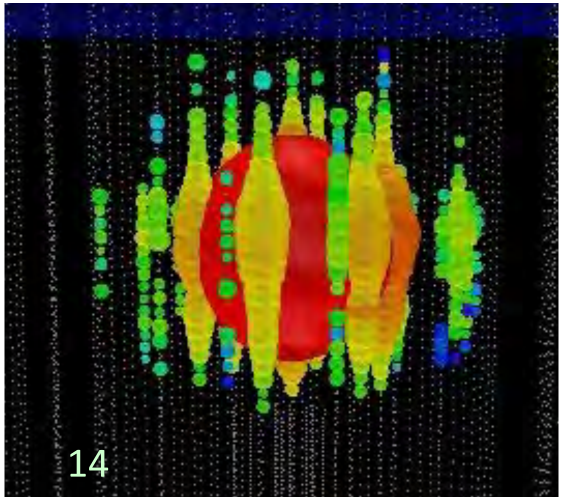
Two PeV cascades starting inside the detector

PRL ***111,*** *021103 (2013)*

Large energy

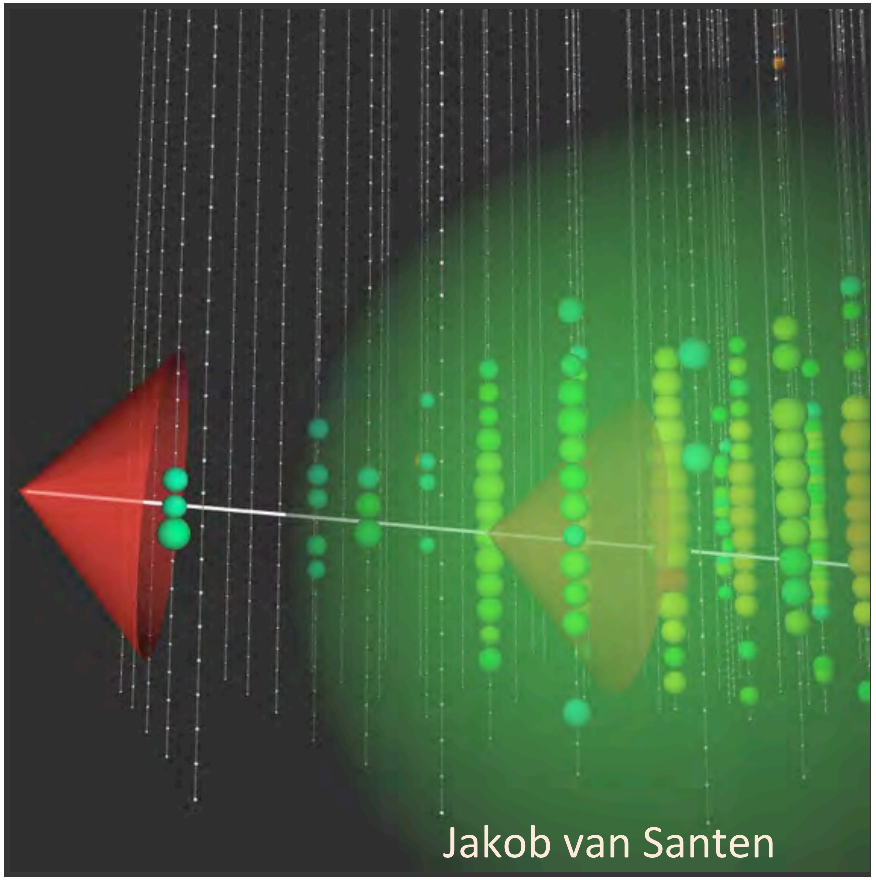
→ atmospheric origin unlikely



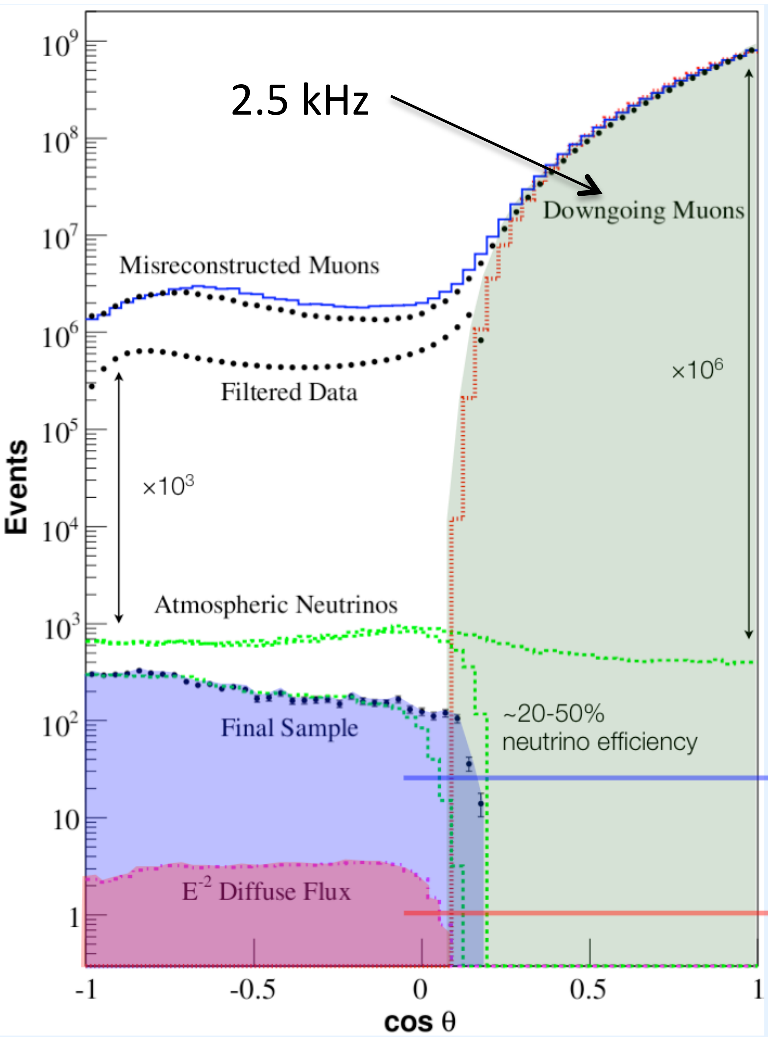


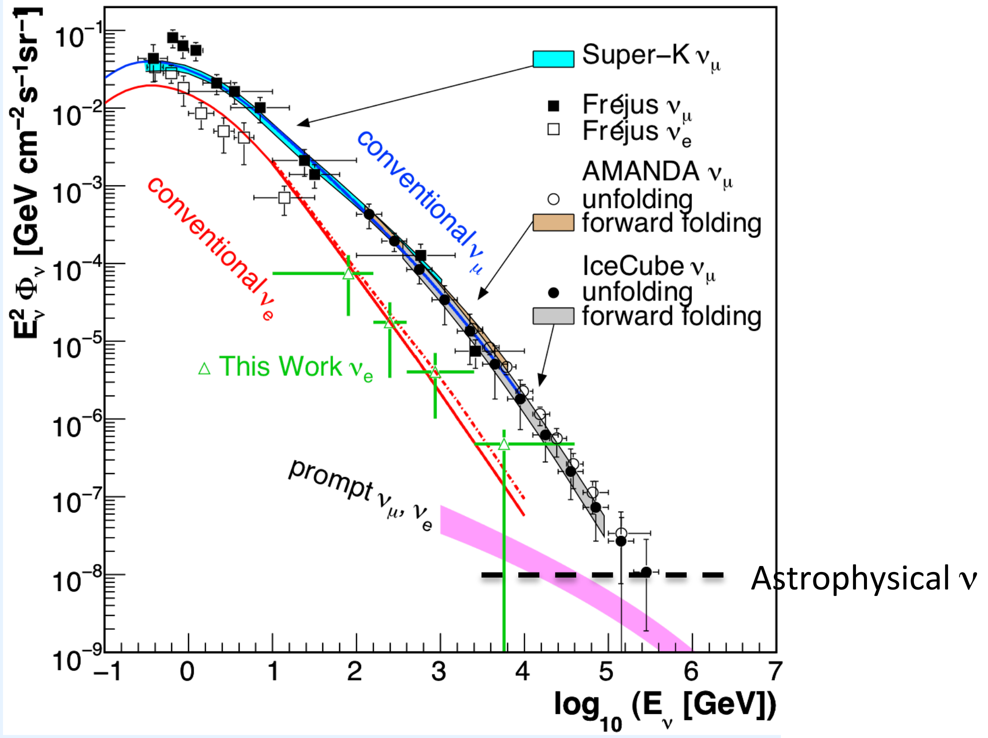
Starting $\nu_\mu \rightarrow \mu$ events

- Event starts in fiducial volume
- Light from vertex spreads spherically with v=c/1.31
- Muon moves ahead with v = c
- ID confirmation by timing


Jakob van Santen

Most events are not astrophysical neutrinos !!!





atmospheric neutrinos
~ 1 per million

extra-terrestrial neutrinos

~ 1 per billion