Lessons 11 and 12

Measurement of astrophysical neutrinos, 1st generation detectors

- Neutrinos, very interesting particle, only weakly interacting
- The first detectors for rare phenomena (searches for proton decay, atmospheric neutrinos, …) under mountains and/or in deep mines (Frejus, Kolar Mine, …)

The second generation detectors:

- Cherenkov detectors: Kamiokande, IMB
- Tracking detectors: MACRO, …

- Neutrino properties, neutrino interactions
- Detection of astrophysical neutrinos with $E_\nu > 10^{13}$ eV
  - First generation experiments: IMB, BAKSAN, Kamiokande, MACRO, …
  - 2^{nd} generation experiments: BAIKAL, AMANDA, NESTOR, ANTARES: detection technique, physics goals
- ANTARES
  - Search for point like sources.
  - Search for astrophysical neutrinos from "diffuse" sources

Standard Model particles

Family	Particle	Q/e	Mass
Leptons fermions: spin 1/2 Barionic numb. B=0 Leptonic numb. L=1	e - electron	-1	0.511 MeV
	ν_e – electron neutrino	0	< 15 eV
	μ - muon	-1	0.106 GeV
	ν_μ - muon neutrino	0	< 0.17 MeV
	τ - tau	-1	1.777 GeV
	ν_τ - tau neutrino	0	< 24 MeV
Quarks fermions: spin 1/2 Barionic numb. B=1/3 Leptonic numb. L=0	u - up	2/3	6 MeV
	d - down	-1/3	10 MeV
	s - strange	-1/3	0.25 GeV
	c - charm	2/3	1.2 GeV
	b - bottom	-1/3	4.3 GeV
	t - top	2/3	180 GeV
Vectorial Bosons : spin 1 Barionic numb. B=0 Leptonic numb. L=0	γ - photon	0	0 GeV
	$W^{\pm}$ - boson W	± 1	80.3 GeV
	Z° - boson Z	0	91.2 GeV
	g - gluon	0	0 GeV
Higgs Boson spin 0, scalar	H - Higgs	0	126 GeV

Standard Model Interactions

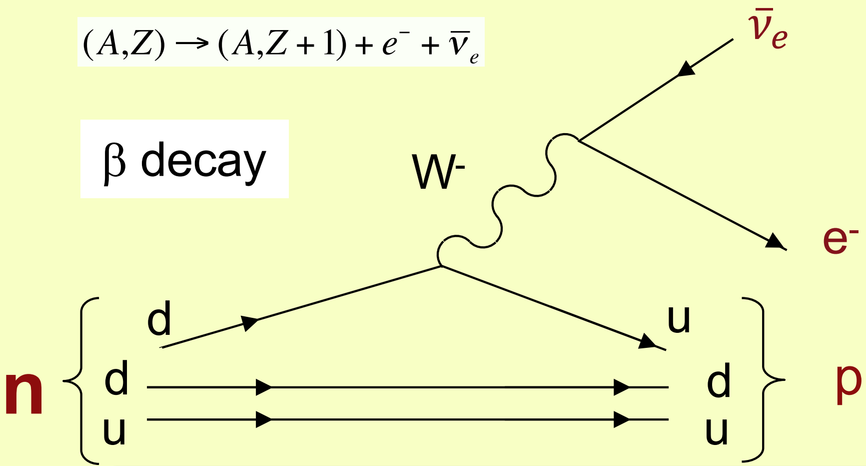
Interactions are characterized by:

- nature of the interaction
- force of interaction
- type (mass) of the "particle" exchanged during the interaction
- distance (range) of action of the interaction

To characterize the strengths of the forces they all are compared to the intensity of the strong interaction (at great distances), thus defining the adimensional coupling constants

Strong Interaction	**1**	$\frac{g^2}{\hbar c}; \quad \hbar c = 197.33 MeV \cdot fermi;$ $1 fermi = 10^{-15} m$
Elettromagnetic inter.	**α=1/137**	$\frac{e^2}{\hbar c}$
Weak interaction	**$1.166 \bullet 10^{-5}$**	$\frac{G_F M_p^2}{(\hbar c)^3}; \quad M_p = 938.3 MeV$
Gravitational inter.	**$6.707 \bullet 10^{-39}$**	$\frac{G_N M_p^2}{\hbar c}; \quad G_N = 6.672 \cdot 10^{-11} m^3 kg^{-1} s^{-2}$

Some Weak Interactions …

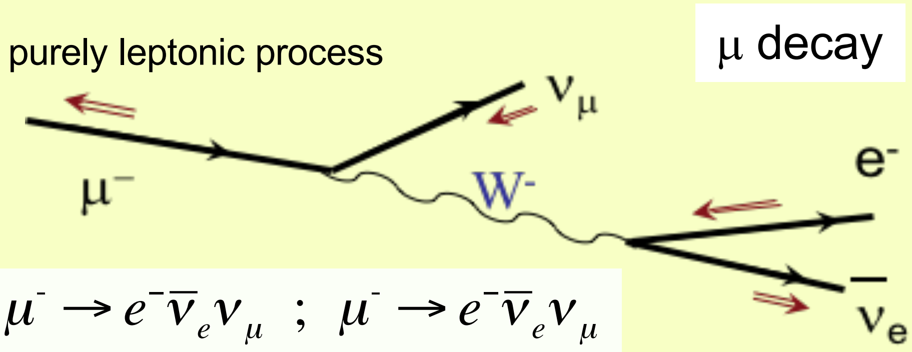


$(A,Z) \to (A,Z+1) + e^- + \bar{\nu}_e$

β decay

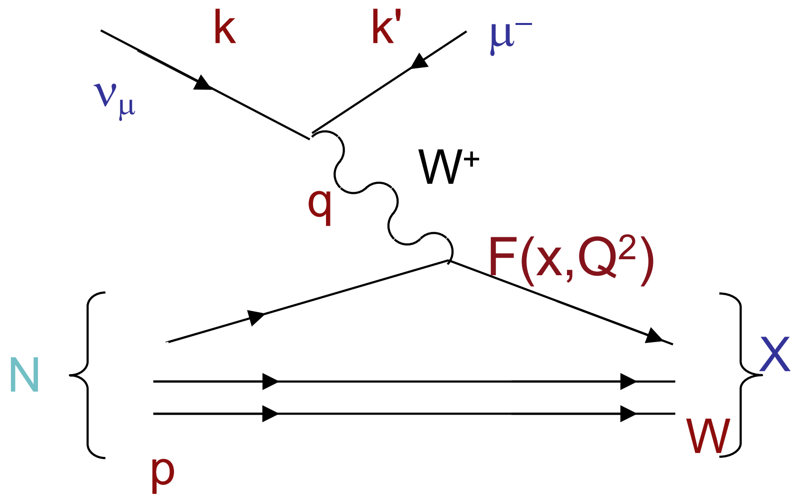
purely leptonic process

μ decay



$$\mu^- \to e^- \bar{\nu}_e \nu_\mu \ ; \ \mu^- \to e^- \bar{\nu}_e \nu_\mu$$

$$\tau_\mu = 2.2\ 10^{-6}\ \mathrm{s}$$



k and k'	are the four-momenta of neut. (entering)
and	lepton (exiting)
p and W	are the four-momenta of nucleon N
(entering) and	of hadronic system (exiting)
q= k - k'	is the transferred four-momentum
$F(x,Q^2)$	nucleon structure function: describes the
impulse	distribution of the constituents within the
nucleon $x = \frac{Q^2}{W^2-M^2+Q^2}$	fraction of the longitudinal impulse
of the nucleon	transported by the constituent (quark)
involved in	the interaction.
M_N	nucleon mass

$$Q^2 = 2M(E_\nu - E_\mu) = 4E_\nu E_\mu sin^2\, {}^{\theta}/_{2}$$

$y = \frac{E_\nu - E_\mu}{E_\nu}$ event inelasticity

Neutrinos, quarks and Weak Interactions

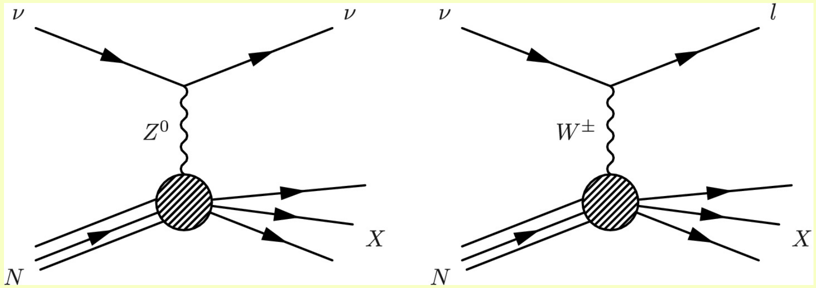
We know that leptons and quarks exists in 3 families:

$$\begin{array}{l} Q=0 \\ Q=-1 \end{array} \quad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \quad ; \quad \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{array}{l} Q=2/3 \\ Q=-1/3 \end{array}$$

leptonic electronic number

leptonic muonic number

leptonic tauonic number



Neutrinos interact with a quarks, or with a lepton, with Weak Interactions either exchanging a charged ($W^\pm$) or neutral (Z^0) boson.

Neutrino interaction Cross-Section -1

The interaction of ν and $\bar{\nu}$ with a nucleon (remember ν and $\bar{\nu}$ interact with one quark, or antiquark, of the nucleon, the other 2 quarks are “spectators) is well described by the **double-differential cross-section** in terms of the variables

$\boldsymbol{x = \frac{Q^2}{2M_p(E_\nu - E_\mu)}}$ (the fraction of the nucleon energy transported by the interacting quark)

$\boldsymbol{y = \frac{E_\nu - E_\mu}{E_\nu}}$ the event inelasticity (the fraction of neutrino energy transferred to the hadronic current).

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

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

where $\boldsymbol{s = 2M_t E_\nu}$ is the (centre of mass energy)^2 $\boldsymbol{q(x)}$ and $\boldsymbol{\bar{q}(x)}$ are the probability to find the interacting quark ($u, d, c, s, t, b, \bar{u}, d, \ldots$) with the fraction $\boldsymbol{x}$ of the nucleon momentum.

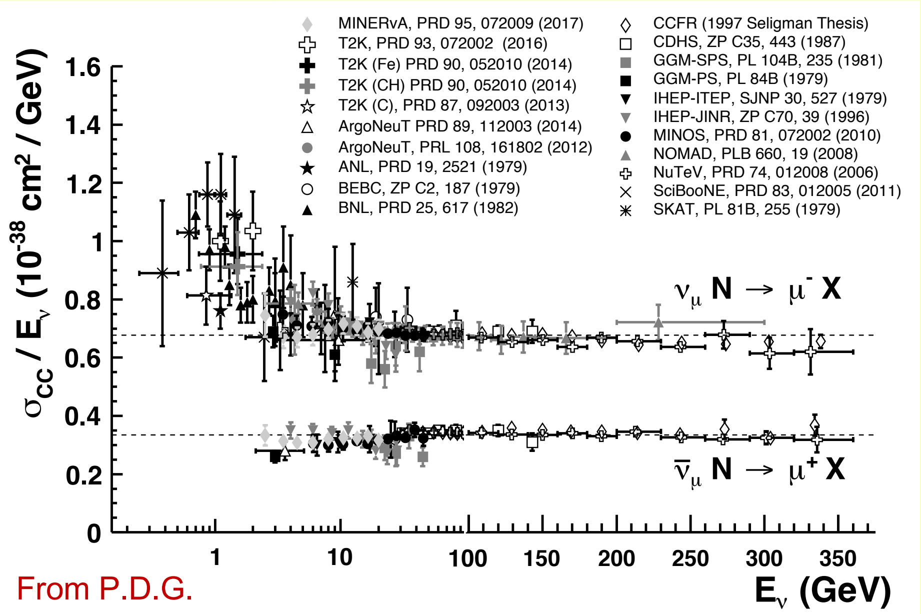
The term $\left(\frac{M_{W,Z}^2}{Q^2 + M_{W,Z}^2}\right)^2$ is due to the fact that the interaction is not “point like” but is mediated by the boson W or Z.

Neutrino interaction Cross-Section -2

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

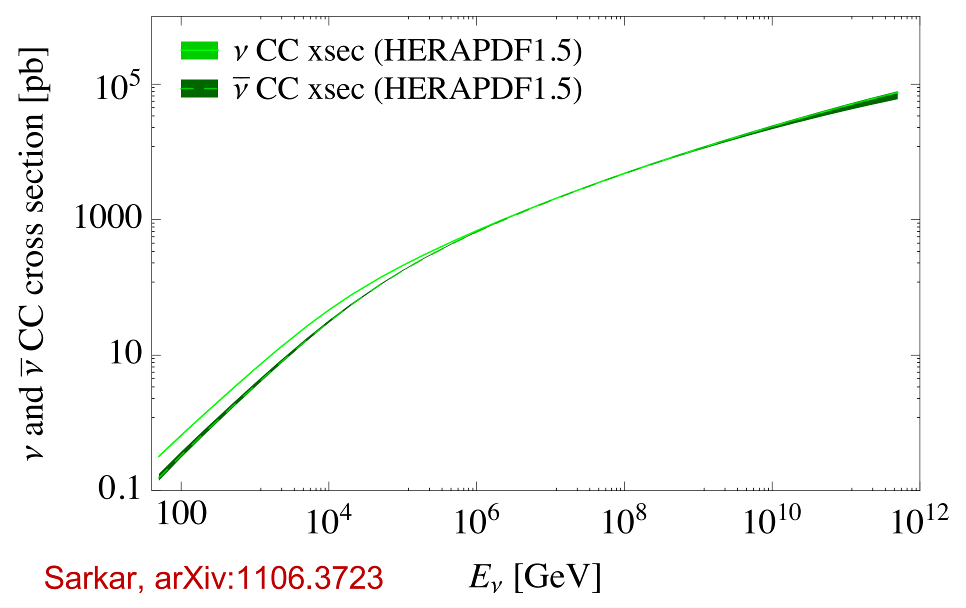
For $E_\nu < 450$ GeV the term $\left(\frac{M_{W,Z}^2}{Q^2+M_{W,Z}^2}\right)^2 \sim 1$ so the cross section grows linearly with E_ν .

For higher energies the cross section grows slowly with the energy.



From P.D.G.

Figure 50.1: Measurements of per nucleon ν_μ and $\bar{\nu}_\mu$ CC inclusive scattering cross sections divided by neutrino energy as a function of neutrino energy. Note the transition between logarithmic and linear scales occurring at 100 GeV. Neutrino cross sections are typically twice as large as their corresponding antineutrino counterparts, although this difference can be larger at lower energies. NC cross sections (not shown) are generally smaller compared to the CC case.



Sarkar, arXiv:1106.3723

Neutrino interaction Cross-Section -3

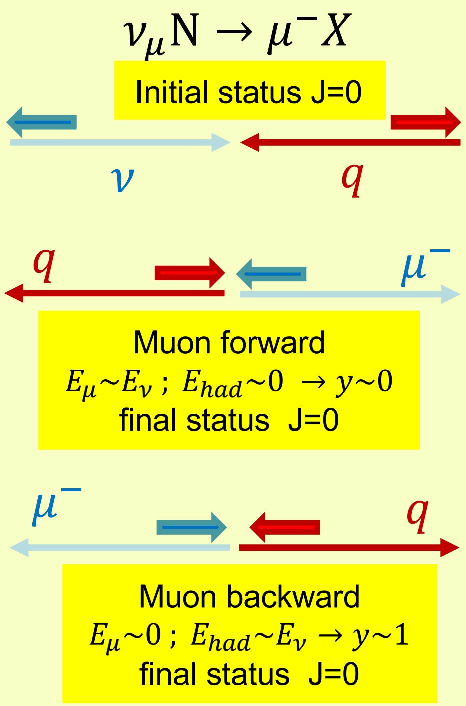
$$\frac{d^2\sigma^\nu}{dx\,dy} = \frac{G^2 2M_t E_\nu}{\pi}\left(\frac{M^2_{W,Z}}{Q^2 + M^2_{W,Z}}\right)^2 [q(x) + (1-y)^2 \bar{q}(x)]$$

$$y = \frac{E_\nu - E_\mu}{E_\nu}$$

$$\begin{cases} \frac{d\sigma}{dy}(for\ \nu q\ \ and\ \ \bar{\nu}\bar{q}) \sim cost \\ \frac{d\sigma}{dy}(for\ \bar{\nu} q\ \ and\ \ \nu\bar{q}) \sim (1-y)^2 \end{cases}$$

How should we interpret the “y” dependence of the cross section

Weak Interactions conserve angular momentum !!

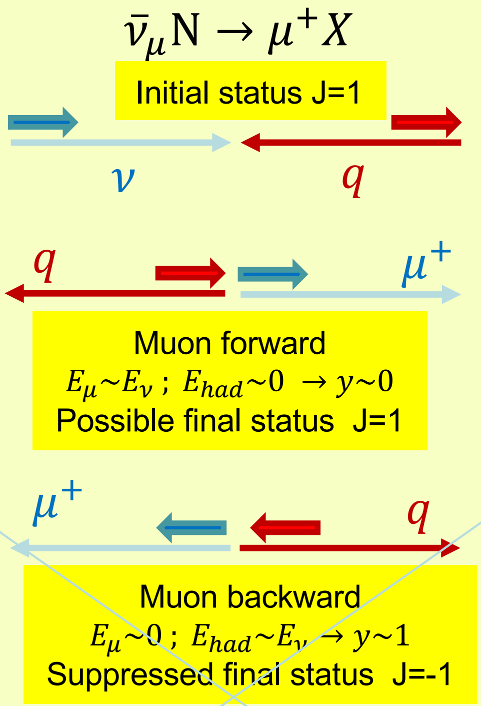


$\nu_\mu N \to \mu^- X$

Initial status J=0

Muon forward
$E_\mu \sim E_\nu$; $E_{had} \sim 0 \ \to y \sim 0$
final status J=0

Muon backward
$E_\mu \sim 0$; $E_{had} \sim E_\nu \to y \sim 1$
final status J=0



$\bar{\nu}_\mu N \to \mu^+ X$

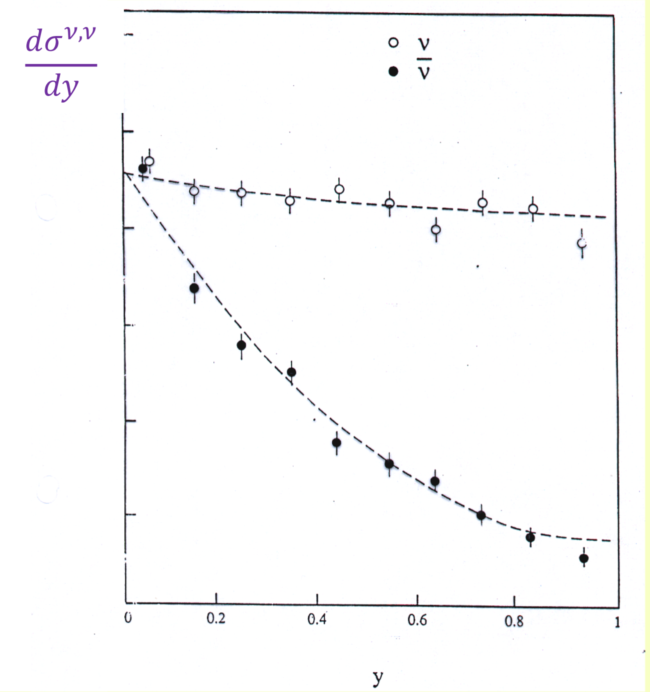
Initial status J=1

Muon forward
$E_\mu \sim E_\nu$; $E_{had} \sim 0 \ \to y \sim 0$
Possible final status J=1

~~Muon backward~~
~~$E_\mu \sim 0$; $E_{had} \sim E_\nu \to y \sim 1$~~
~~Suppressed final status J=-1~~

If θ is the angle between the μ and the ν in the c.o.m. system all the values of cosθ are “possible”: $\boldsymbol{\sigma^{\nu q}}$ and $\boldsymbol{\sigma^{\bar{\nu}\bar{q}}}$ do not depends on y

~~If θ is the angle between the μ and the ν in the c.o.m. system the values of cosθ~1, and y=0 are favoured : $\boldsymbol{\sigma^{\bar{\nu} q}}$ and $\boldsymbol{\sigma^{\nu\bar{q}}} \propto$ $(\mathbf{1-y})^2$~~



Brief History of Neutrino Astronomy

1960

Markov introduces the idea (Proc. of the 1960 Int. Conf. on HE Physics, Rochester) : *"We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by Cherenkov radiation"* Markov, M. A. On high energy neutrino physics. In Proceedings, 10th International Conference on High-Energy Physics (ICHEP 60), pp. 578–581 (1960). Available from: http://inspirehep.net/record/1341439/files/C60-08-25-p578.pdf

First estimates of neutrino fluxes and detector properties 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". Detectors built to search for other specific physic goals but capable to identify "neutrino events".

1996

First neutrinos in the Baikal and AMANDA experiments. Work in progress and R&D towards a km^3 detector

1998 – 2017 …..

NESTOR, IceCube, ANTARES, NEMO, KM3NeT, …

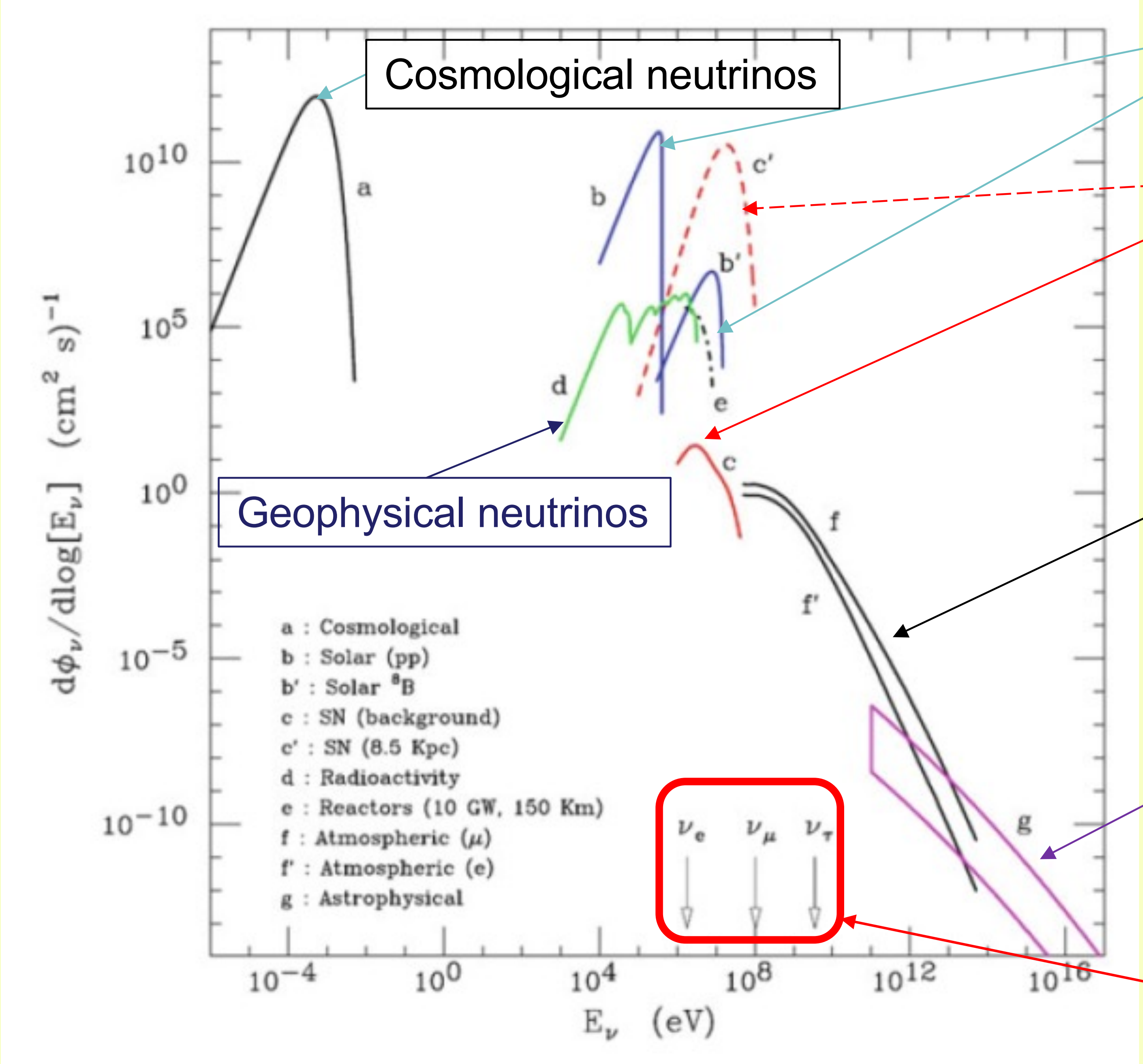
2013

IceCube measures a flux of Astrophysical diffuse neutrinos

2017-2018

Multimessenger analysis identify a common ν–γ astrophysical source (Blazar)

Neutrino fluxes on the Earth



Cosmological neutrinos

Solar neutrinos

Supernovae neutrinos

Geophysical neutrinos

Atmospheric neutrinos

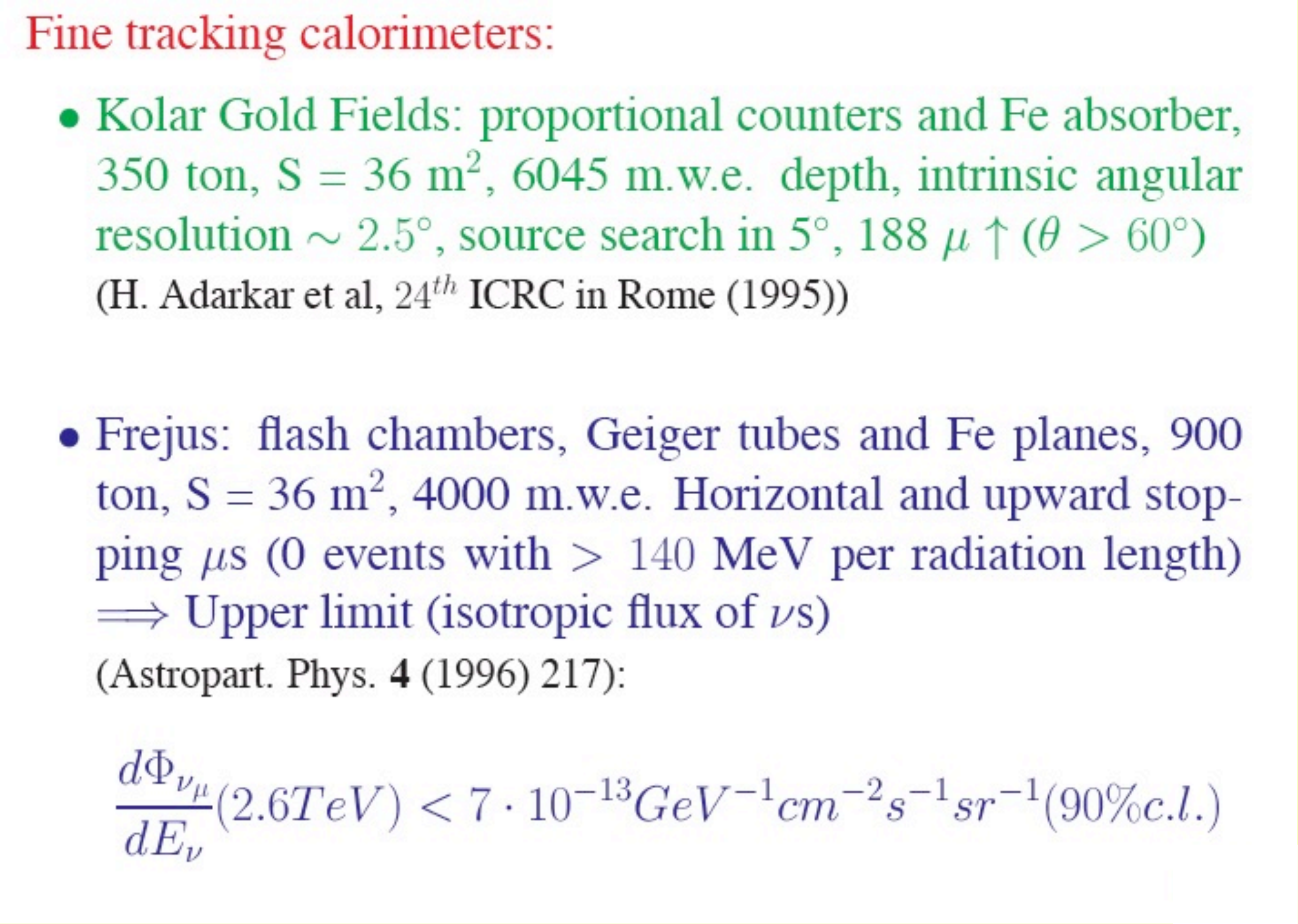
Cosmic, astrophysical neutrinos

The three arrows indicate the energy thresholds for CC production of the charged lepton

The 1st "generation" of Neutrino detectors

- **KGF**: detector built to study the cosmic ray muons (and later the proton life-time: a rare event, needs an environment background free !!!) using the crossed matter as "spectrometer", located in a gold-mine in the Kolar district of the state of Karnataka, India

- **Frejus**: built to study the proton life-time in tunnel under the Frejus mountain (France)



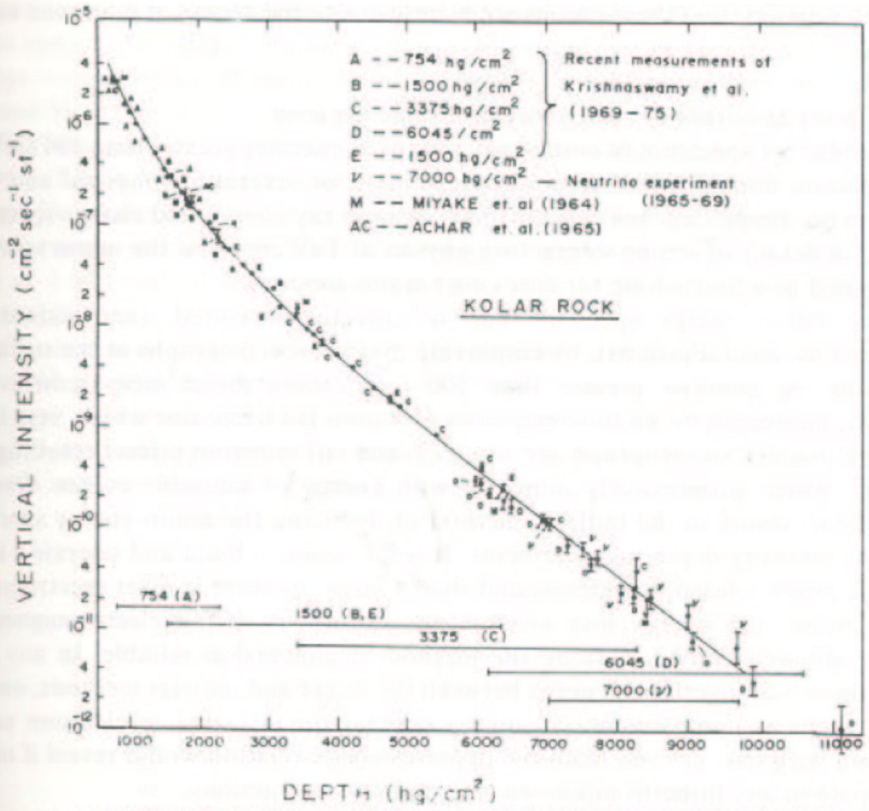
Fine tracking calorimeters:

- Kolar Gold Fields: proportional counters and Fe absorber, 350 ton, S = 36 m^2, 6045 m.w.e. depth, intrinsic angular resolution $\sim 2.5°$, source search in 5°, 188 $\mu \uparrow (\theta > 60°)$
  (H. Adarkar et al, 24^{th} ICRC in Rome (1995))

- Frejus: flash chambers, Geiger tubes and Fe planes, 900 ton, S = 36 m^2, 4000 m.w.e. Horizontal and upward stopping μs (0 events with > 140 MeV per radiation length) $\Longrightarrow$ Upper limit (isotropic flux of νs)
  (Astropart. Phys. **4** (1996) 217):

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

Kolar Gold Fields results

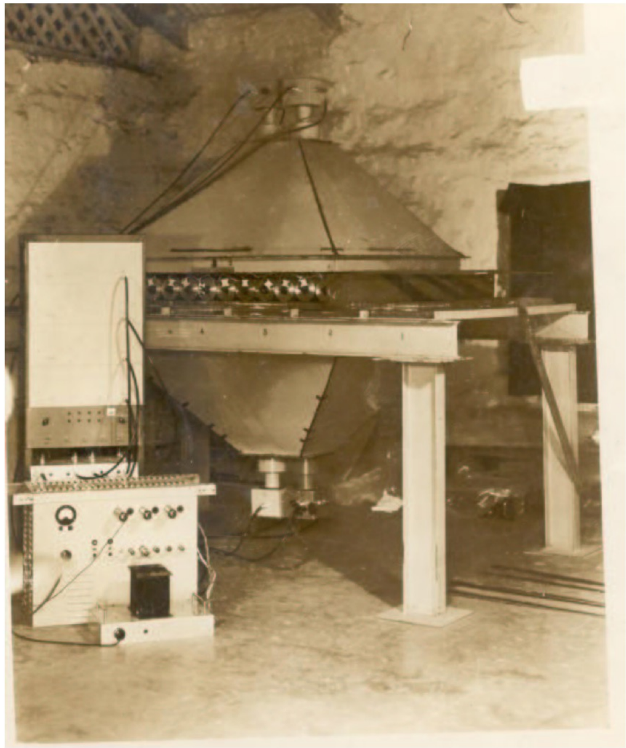


THE CONSOLIDATED DEPTH-INTENSITY RELATION FROM ALL WORKS DONE UNDER KOLAR ROCK

Depth vs. Intensity plot from all experiments conducted at KGF until 1970. Many points in this plot were extracted from angular distributions assuming that only pions and kaons are the parents of muons.

Summary of muon measurements by MNR experiment in KGF mines.

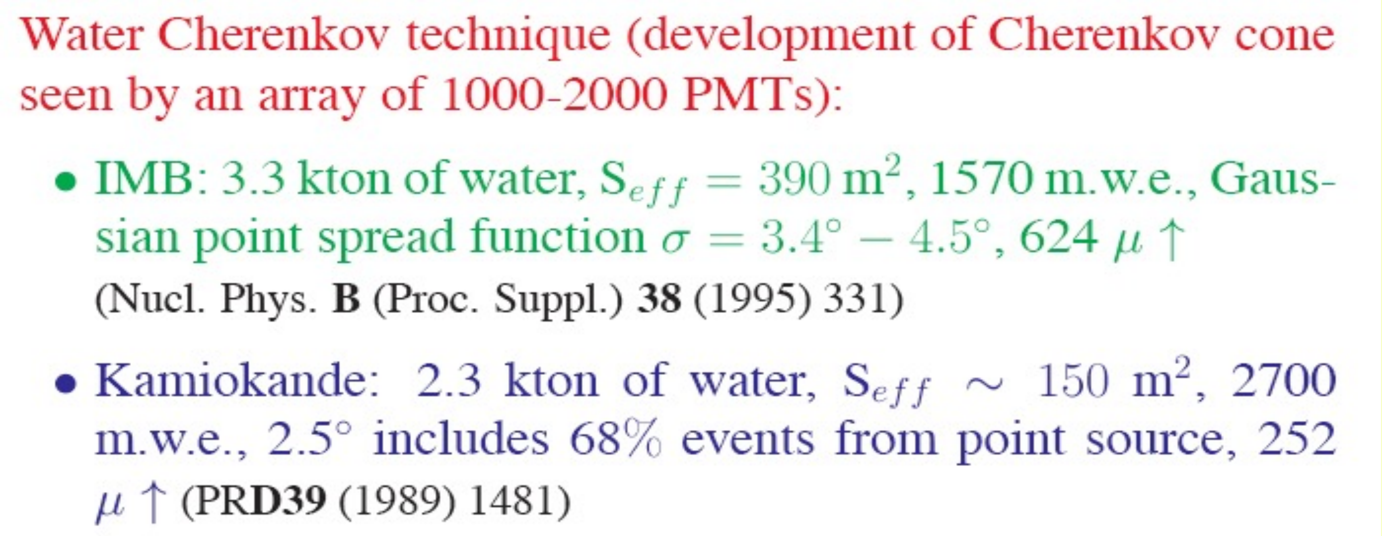
Depth from surface in meters	Depth from the top of the atmosphere (mwe)	Time of observation: Hrs. Mins.	Number of counts observed	Counting rate in counts/hr
270	810	60 - 20	10,152	168.3 ± 1.7
800	1812	100 - 28	1,029	10.23 ± 0.32
1130	3410	211 - 45	142	0.67 ± 0.056
1415	4280	944 - 06	127	0.132 ± 0.012
2110	6380	2992 - 40	18	$(6.0 \pm 1.4) \times 10^{-3}$
2760	8400	2880 - 00	none	$< 3.47 \times 10^{-3}$



The scintillator-lead-GM counter telescope used at great depths in KGF mines. A coincidence of pulses from PMTs viewing the two scintillators and the sandwiched GM counter array provided the signal with negligible background.

The 1st "generation" of Neutrino detectors

Cherenkov detector (built to study proton life-time)

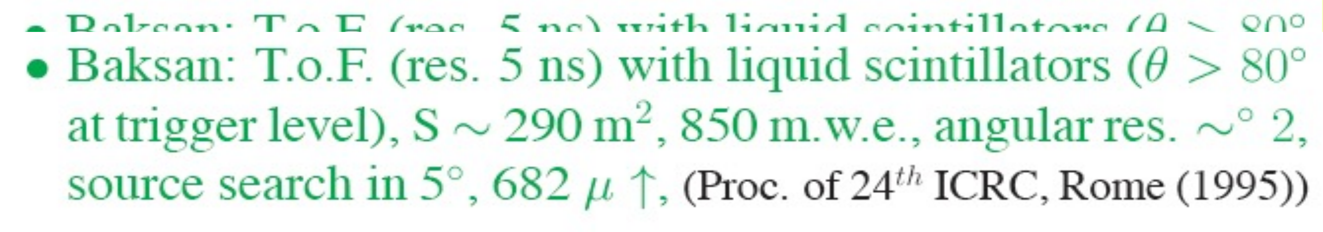


Water Cherenkov technique (development of Cherenkov cone seen by an array of 1000-2000 PMTs):

- IMB: 3.3 kton of water, $S_{eff} = 390\ m^2$, 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, $S_{eff} \sim 150\ m^2$, 2700 m.w.e., 2.5° includes 68% events from point source, 252 $\mu \uparrow$ (PR**D39** (1989) 1481)

A "scintillation detector" (built as neutrino detector)

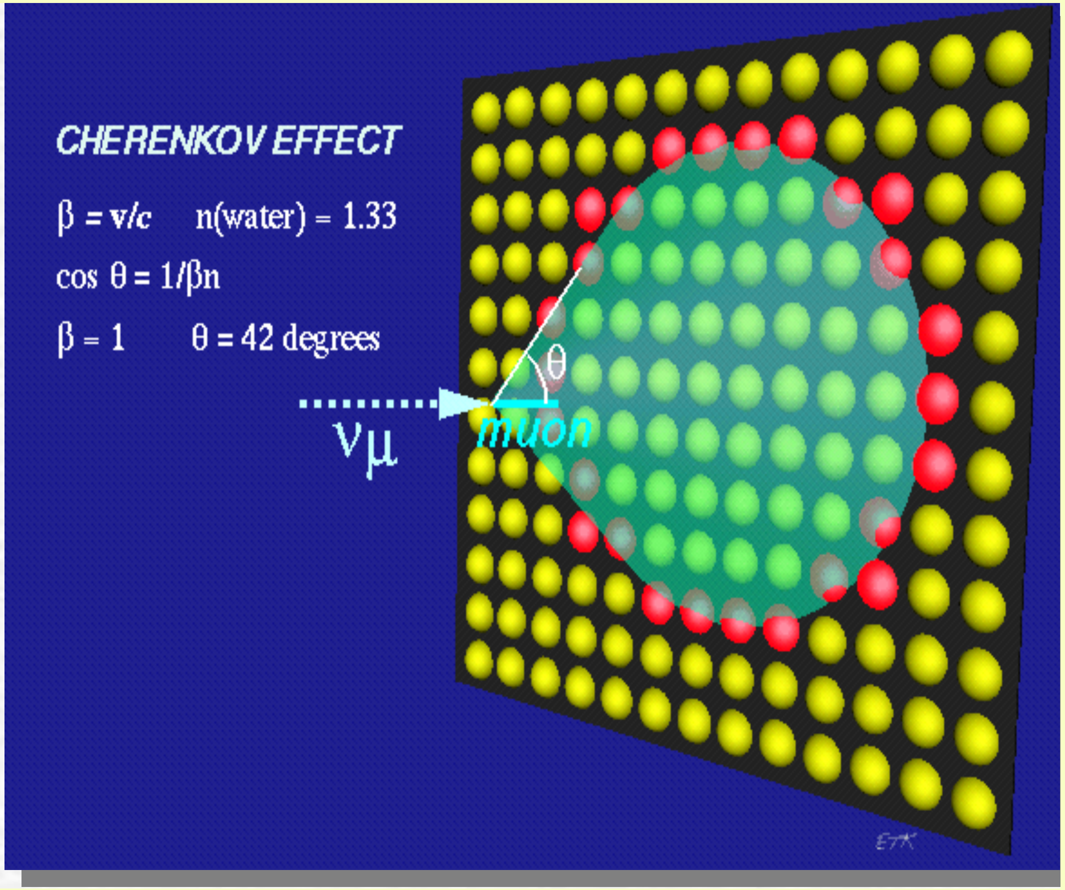
The INR Baksan Underground Scintillation Telescope, started operation in 1977. A multipurpose detector, located in an artificial cavern with a volume of 12,000 m^3. The telescope is a four-level underground building 11.1 m high with a base area of 280 m^2. The building, made of low-radioactivity concrete, houses 3180 detectors containing 330 tonnes of liquid scintillator.



- Baksan: T.o.F. (res. 5 ns) with liquid scintillators ($\theta > 80^\circ$ at trigger level), $S \sim 290\ m^2$, 850 m.w.e., angular res. $\sim^\circ 2$, source search in 5°, 682 $\mu \uparrow$, (Proc. of 24^{th} ICRC, Rome (1995))

The Water Cherenkov detector concept

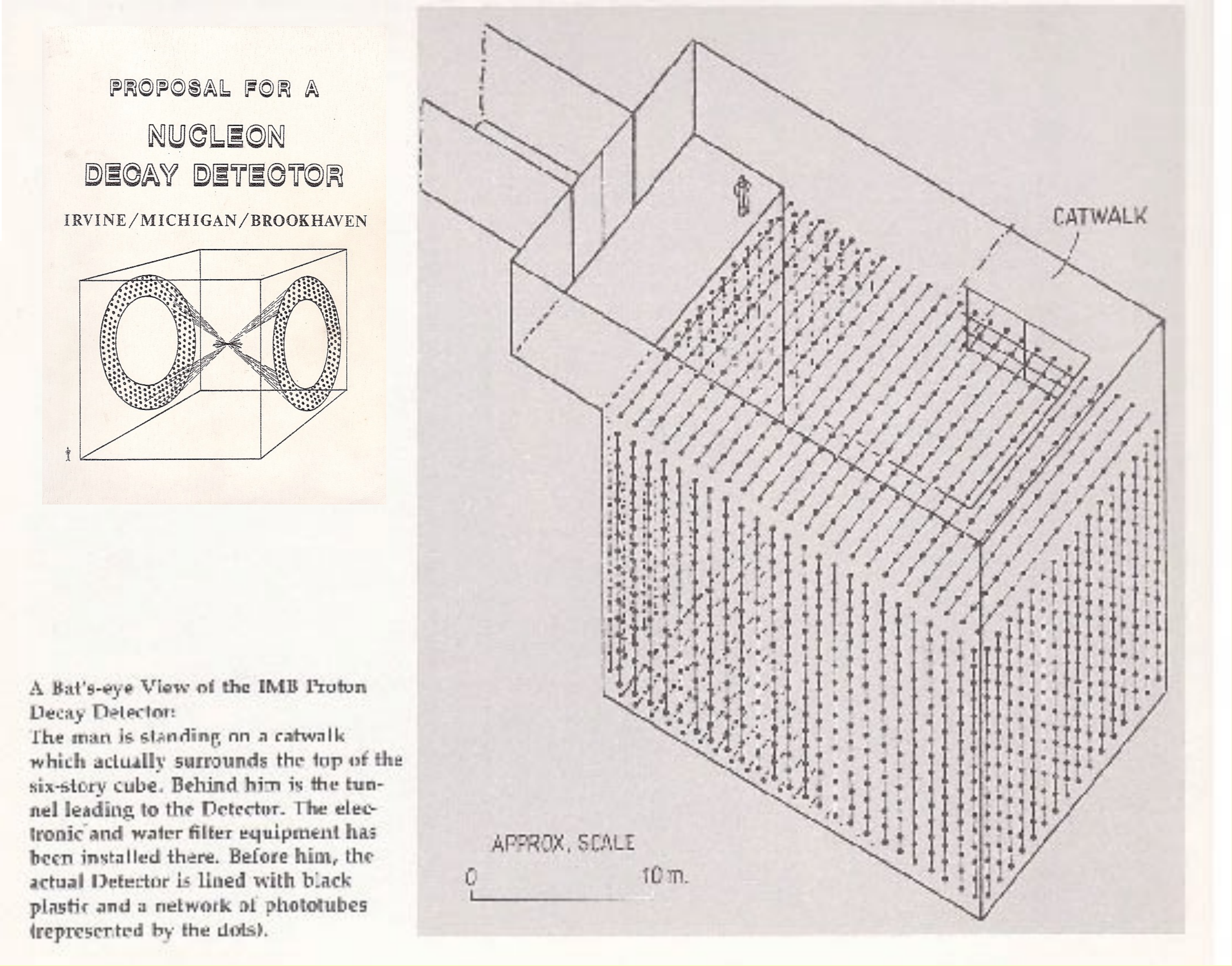
- Cheap target material
- Surface instrumentation
- Vertex from PMT timing
- Direction from ring edge
- Energy from pulse height, range and opening angle
- Particle ID from hit pattern and delayed muon decay signature
- Cherenkov threshold:
    - $\beta > 1/n \sim 0.75$



IMB: the Irvine Michigan Brookhaven "Proton Decay experiment"

$$p^{+} \rightarrow e^{+} + \pi^{0}$$

$$\pi^{0} \rightarrow 2\gamma$$



PROPOSAL FOR A

NUCLEON
DECAY DETECTOR

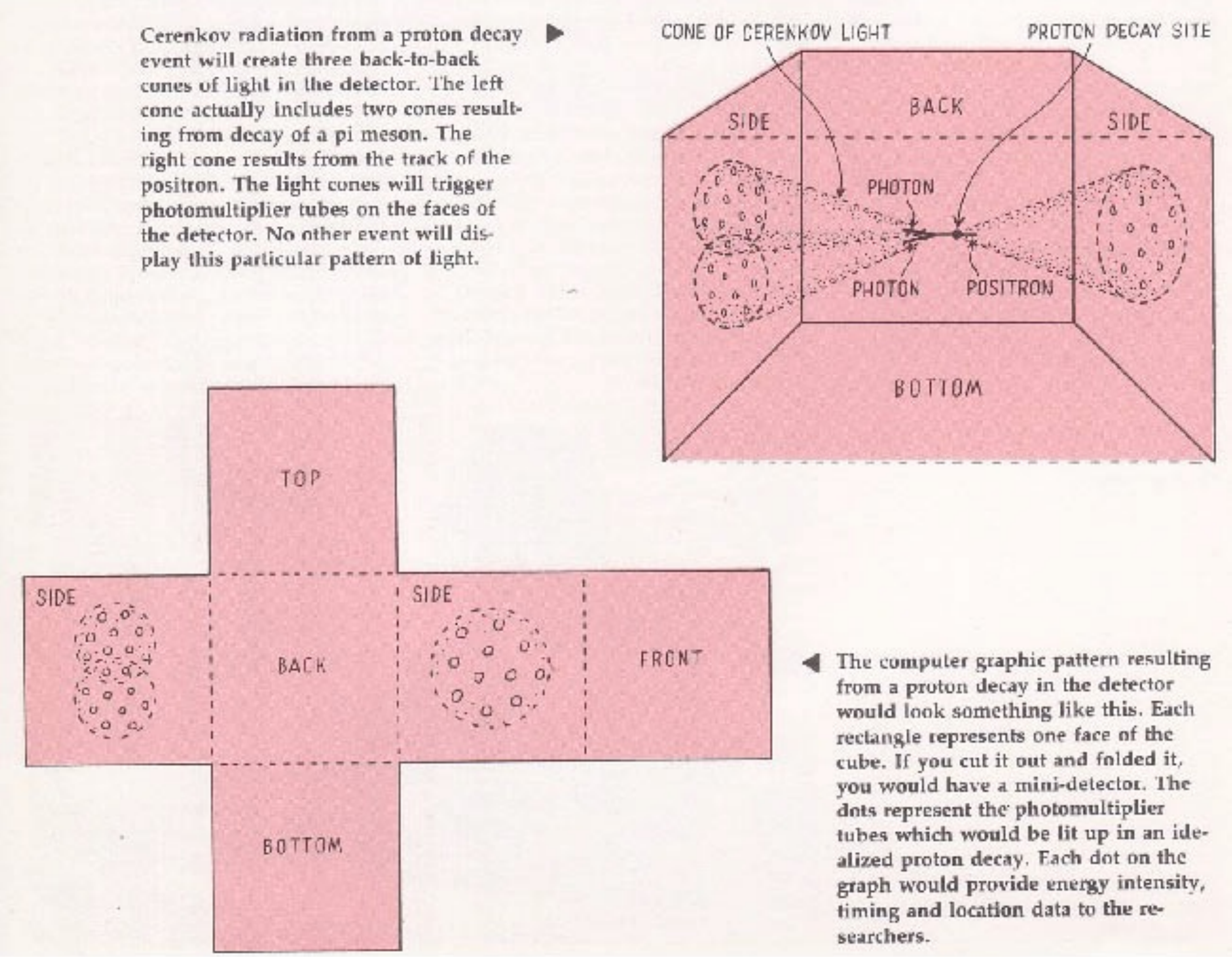
IRVINE/MICHIGAN/BROOKHAVEN

A Bat's-eye View of the IMB Proton Decay Detector:
The man is standing on a catwalk which actually surrounds the top of the six-story cube. Behind him is the tunnel leading to the Detector. The electronic and water filter equipment has been installed there. Before him, the actual Detector is lined with black plastic and a network of phototubes (represented by the dots).

IMB "Proton Decay experiment"

$$p^+ \rightarrow e^+ + \pi^0$$

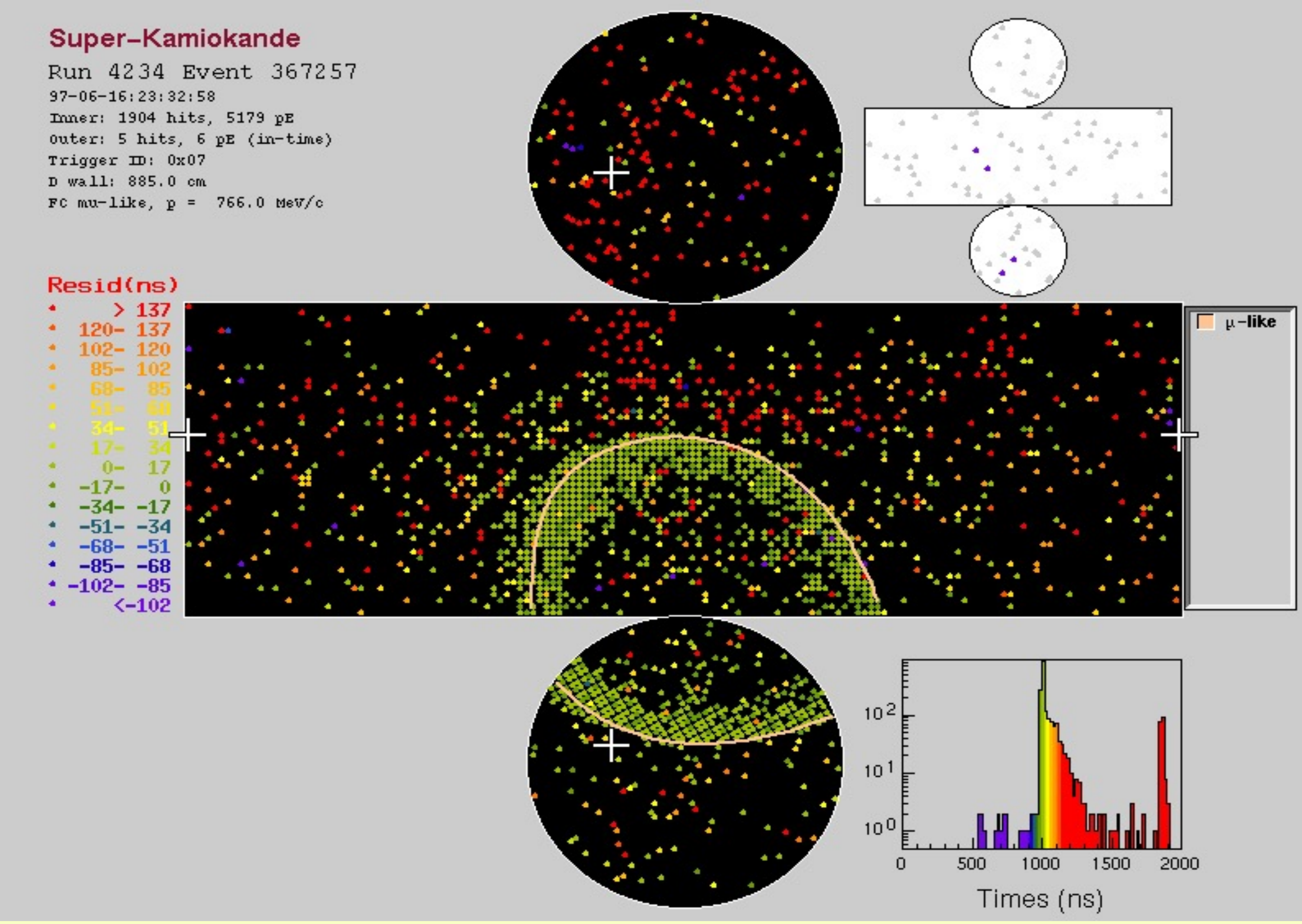
$$\pi^0 \rightarrow 2\gamma$$

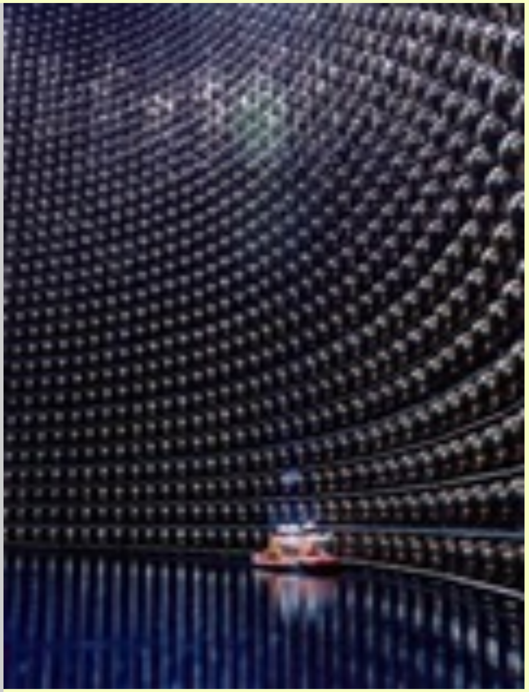


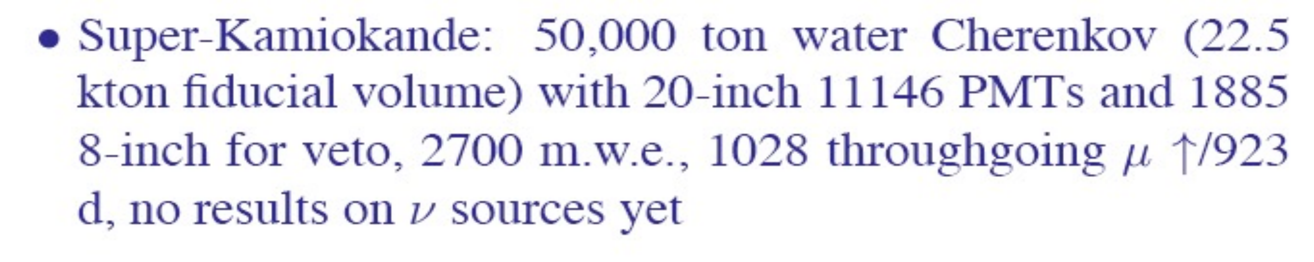
Cerenkov radiation from a proton decay event will create three back-to-back cones of light in the detector. The left cone actually includes two cones resulting from decay of a pi meson. The right cone results from the track of the positron. The light cones will trigger photomultiplier tubes on the faces of the detector. No other event will display this particular pattern of light. ▶

◀ The computer graphic pattern resulting from a proton decay in the detector would look something like this. Each rectangle represents one face of the cube. If you cut it out and folded it, you would have a mini-detector. The dots represent the photomultiplier tubes which would be lit up in an idealized proton decay. Each dot on the graph would provide energy intensity, timing and location data to the researchers.

2nd generation neutrino detectors: 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 ↑/923 d, no results on ν sources yet

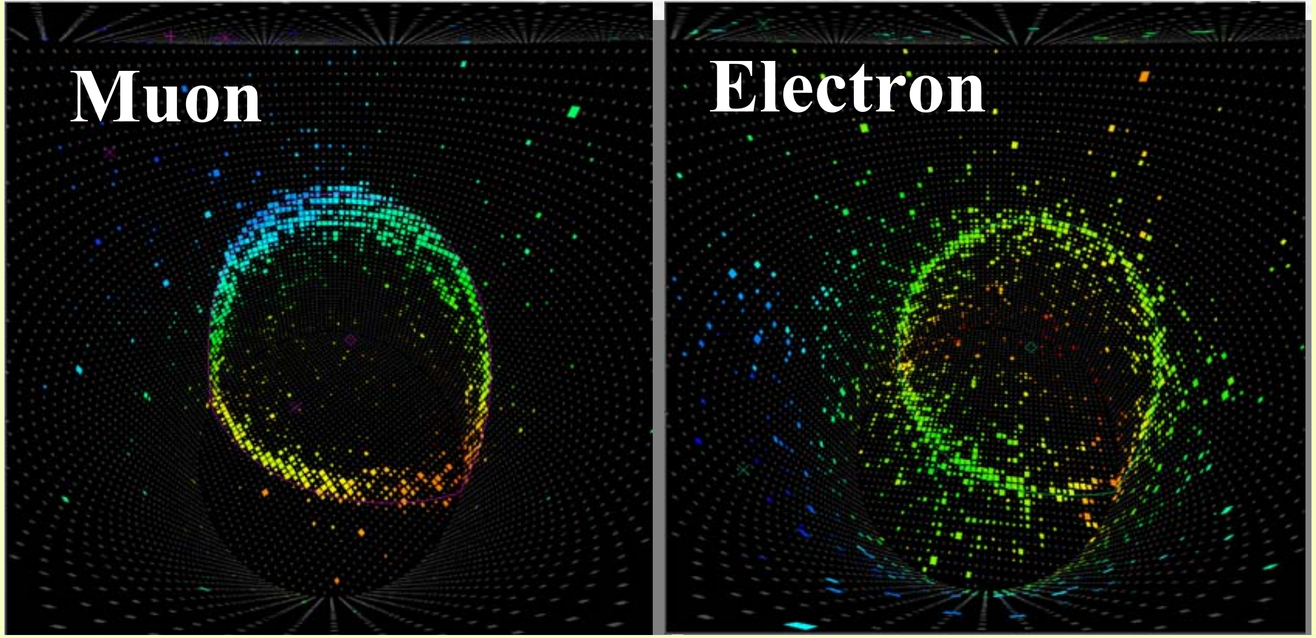
- Built in a cavern
- 50,000 T ultra-pure water
- 22.500 T fiducial mass
- 40m height
- 40m diameter
- PMT hemispheric
- 1200 m^2 effective area for μ (4MeV- 200GeV)
- → high number of up-going μ
- No signature of astrophysical ν !

2nd generation neutrino detectors: SuperKamiokande

Particle identification in SuperKamiokande: how to identify muons/electrons

Single-ring events are identified as e-like or μ-like, based on the geometry of the Cherenkov cone:

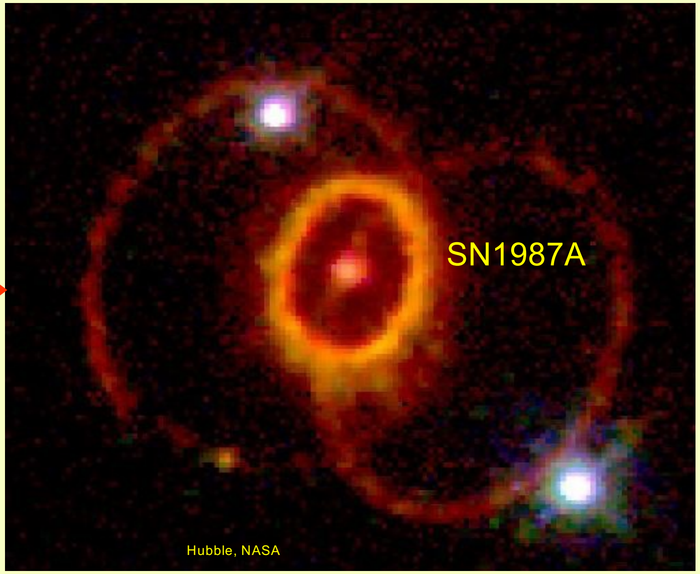
- e-like events, light by primary electron and shower: diffuse ring
- μ-like events, light only by muon, sharp edges of the ring

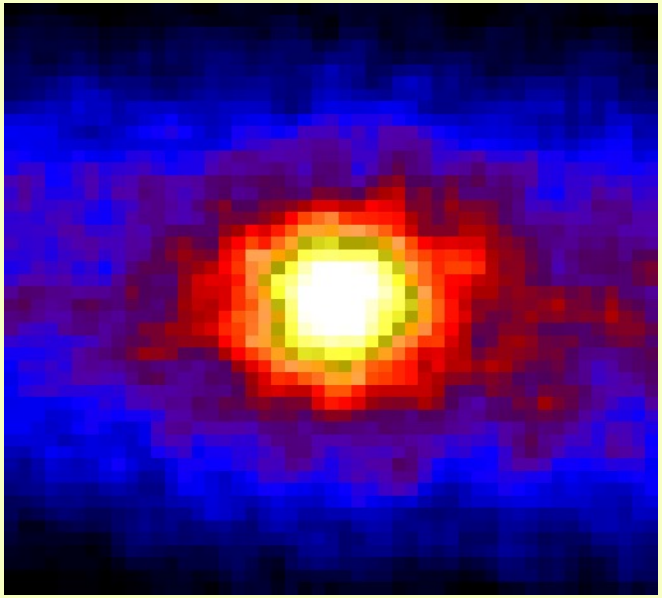


SuperKamiokande and low energy ν (MeV)

With SuperKamiokande the “low energy neutrino astronomy is already started:

1987:
detected neutrinos originated in a SuperNova event



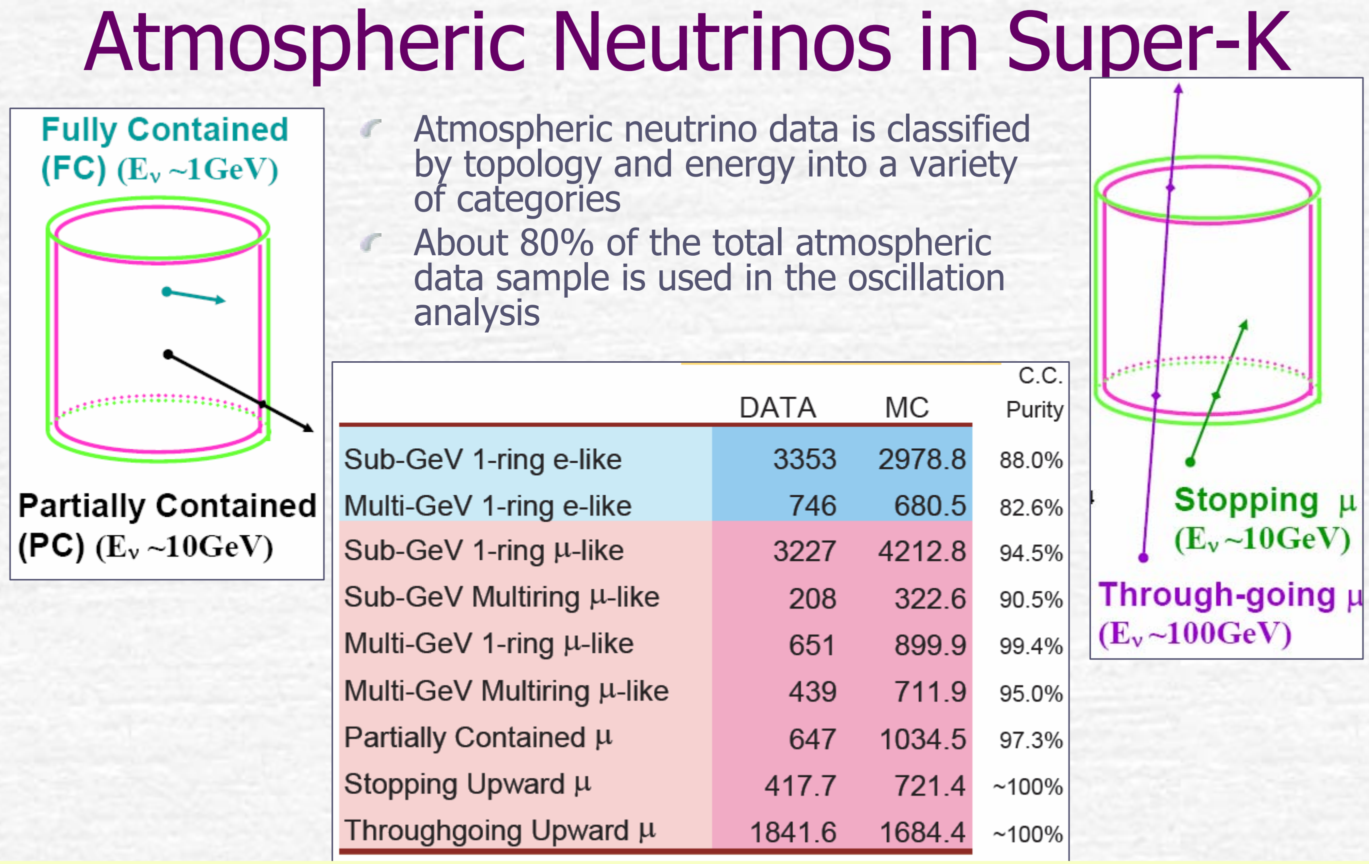


SuperKamiokande collected in an underground detector, neutrinos originated in the Sun

Superkamiokande and astrophysical neutrinos

The search for astrophysical neutrinos implies the reduction of the **atmospheric muon** and **neutrino** background.

The suppression of the atmospheric muon background is obtained by studying only "upgoing tracks" (muons cannot cross the Earth)



Atmospheric Neutrinos in Super-K

Fully Contained (FC) ($E_\nu \sim 1$GeV)

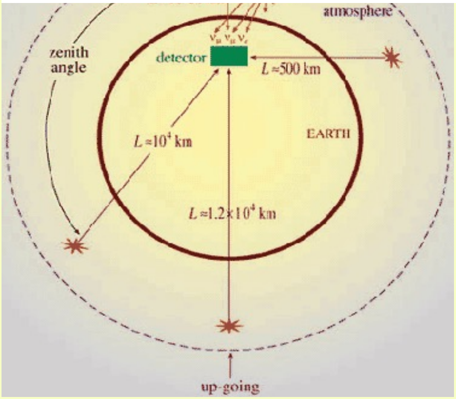
Partially Contained (PC) ($E_\nu \sim 10$GeV)

- Atmospheric neutrino data is classified by topology and energy into a variety of categories
- About 80% of the total atmospheric data sample is used in the oscillation analysis

	DATA	MC	C.C. Purity
Sub-GeV 1-ring e-like	3353	2978.8	88.0%
Multi-GeV 1-ring e-like	746	680.5	82.6%
Sub-GeV 1-ring μ-like	3227	4212.8	94.5%
Sub-GeV Multiring μ-like	208	322.6	90.5%
Multi-GeV 1-ring μ-like	651	899.9	99.4%
Multi-GeV Multiring μ-like	439	711.9	95.0%
Partially Contained μ	647	1034.5	97.3%
Stopping Upward μ	417.7	721.4	~100%
Throughgoing Upward μ	1841.6	1684.4	~100%

Stopping μ ($E_\nu \sim 10$GeV)

Through-going μ ($E_\nu \sim 100$GeV)

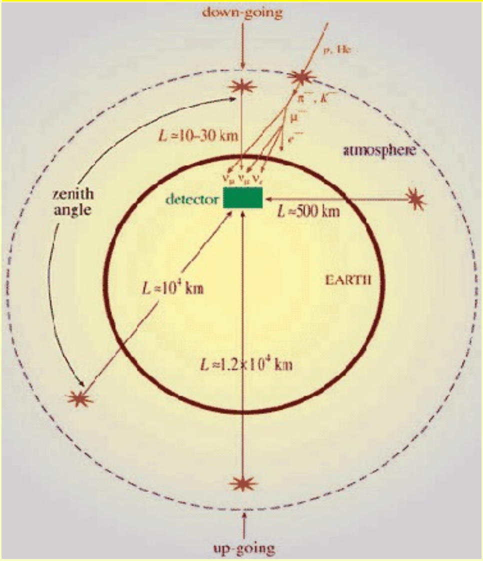


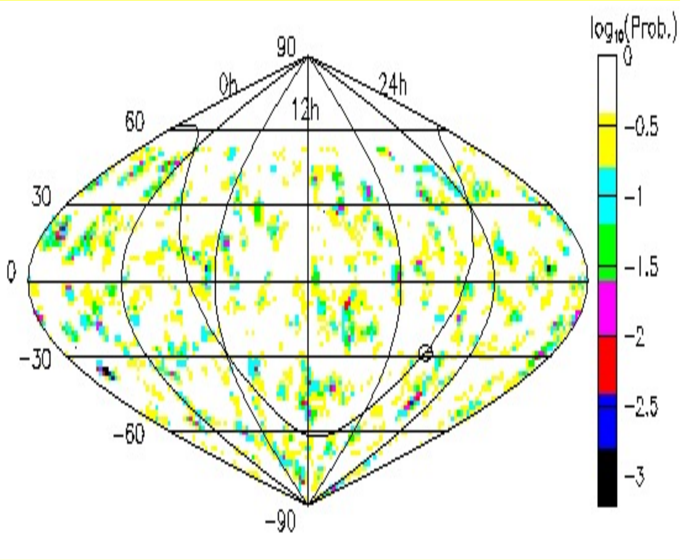
Astrophysical neutrinos cannot be distinguished on an event-by-event basis: they are expected to come from few astrophysical sources while atmospheric neutrinos they are expected uniformly distributed.

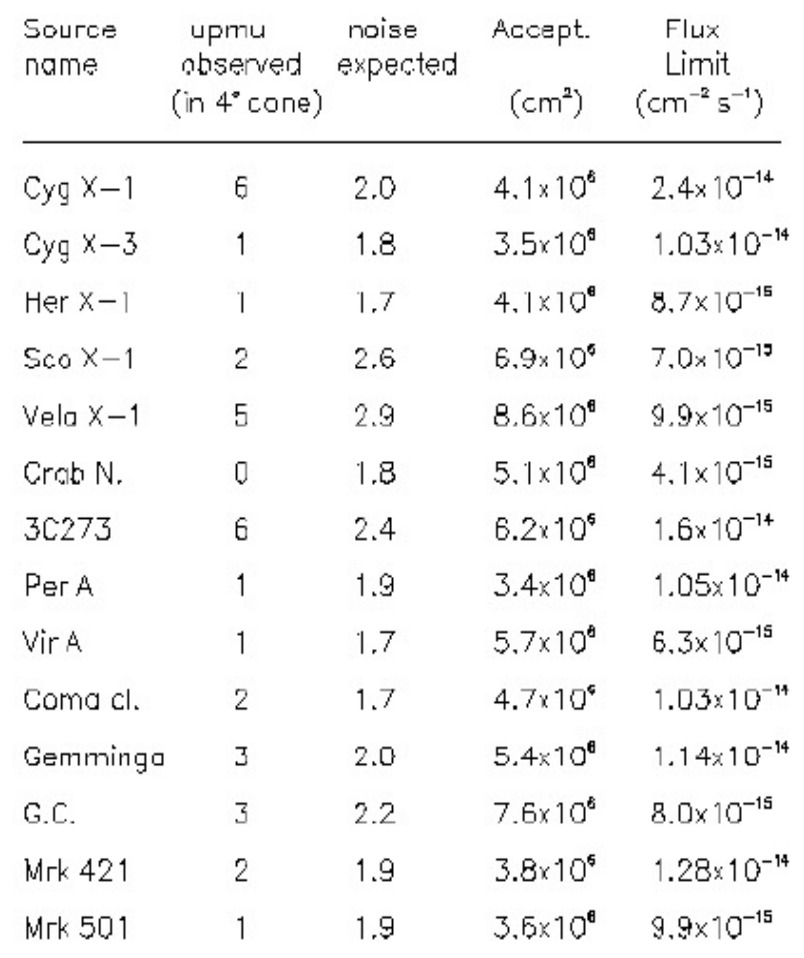
The flux of atmospheric neutrinos, from a given direction, can be estimated and subtracted.

Superkamiokande and astrophysical neutrinos

It was designed to study neutrino oscillations and carry out searches for the decay of the nucleon.
No astrophysical neutrino observed → limits on the neutrino fluxes from known sources.
Similar limits also from other experiments: MACRO, IMB, BAIKAL, Frejus, BAKSAN ,…

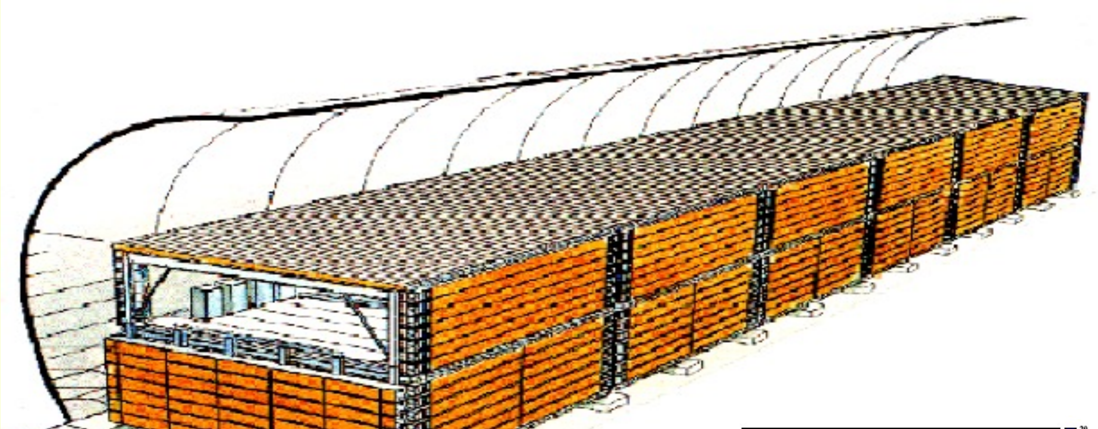


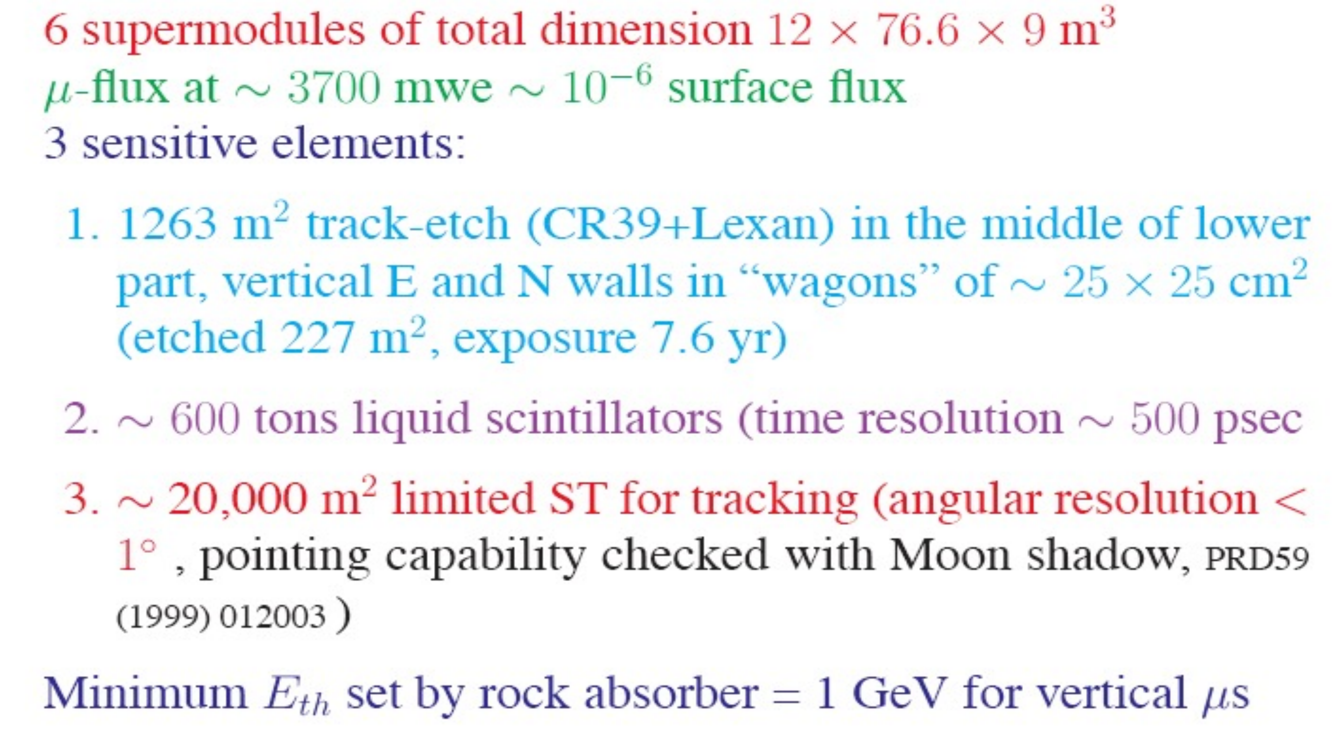




Source name	upmu observed (in 4° cone)	noise expected	Accept. (cm²)	Flux Limit ($cm^{-2} s^{-1}$)
Cyg X−1	6	2.0	4.1×10^{6}	2.4×10^{-14}
Cyg X−3	1	1.8	3.5×10^{6}	1.03×10^{-14}
Her X−1	1	1.7	4.1×10^{6}	8.7×10^{-15}
Sco X−1	2	2.6	6.9×10^{6}	7.0×10^{-15}
Vela X−1	5	2.9	8.6×10^{6}	9.9×10^{-15}
Crab N.	0	1.8	5.1×10^{6}	4.1×10^{-15}
3C273	6	2.4	6.2×10^{6}	1.6×10^{-14}
Per A	1	1.9	3.4×10^{6}	1.05×10^{-14}
Vir A	1	1.7	5.7×10^{6}	6.3×10^{-15}
Coma cl.	2	1.7	4.7×10^{6}	1.03×10^{-14}
Gemminga	3	2.0	5.4×10^{6}	1.14×10^{-14}
G.C.	3	2.2	7.6×10^{6}	8.0×10^{-15}
Mrk 421	2	1.9	3.8×10^{6}	1.28×10^{-14}
Mrk 501	1	1.9	3.6×10^{6}	9.9×10^{-15}

2^{nd} generation neutrino detectors : MACRO, at Gran Sasso Lab.





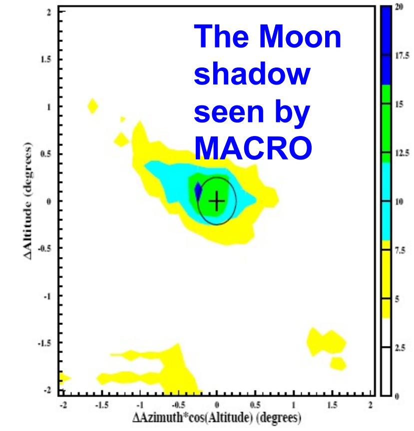
6 supermodules of total dimension $12 \times 76.6 \times 9$ m^3

μ-flux at ~ 3700 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 $\sim 25 \times 25$ cm^2 (etched 227 m^2, exposure 7.6 yr)
2. $\sim$ 600 tons liquid scintillators (time resolution $\sim$ 500 psec
3. $\sim$ 20,000 m^2 limited ST for tracking (angular resolution $< 1°$, pointing capability checked with Moon shadow, PRD59 (1999) 012003)

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

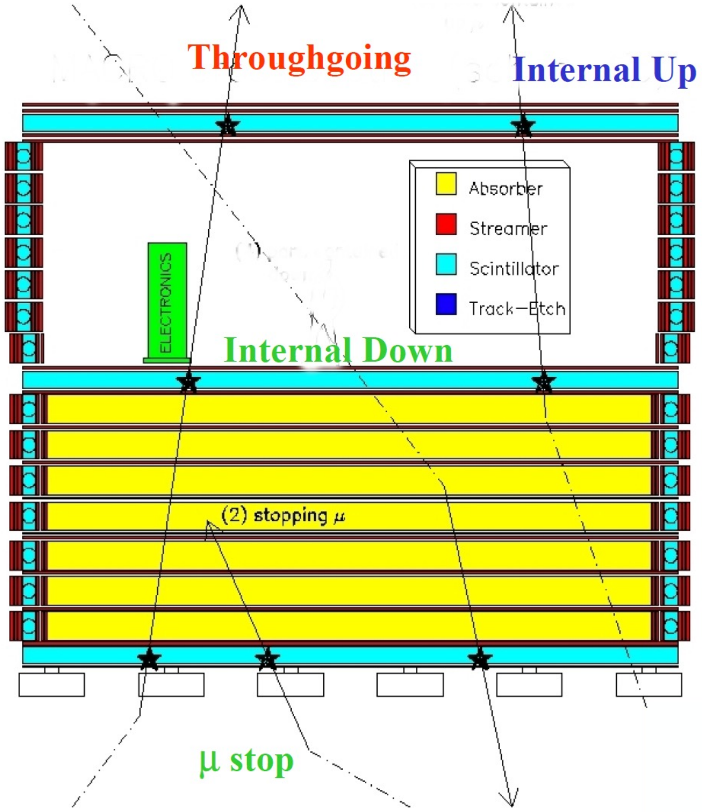


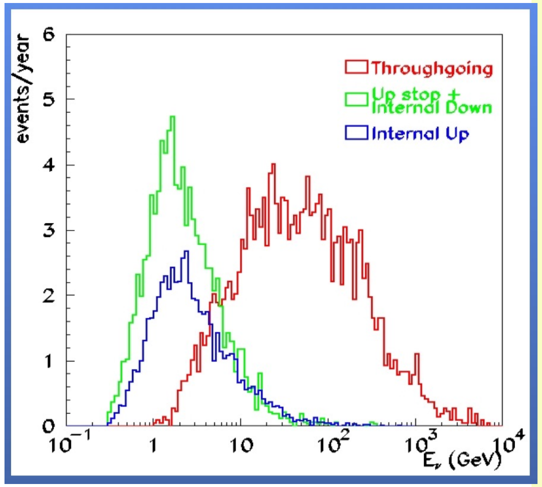
The Moon shadow seen by MACRO

MACRO search for astrophysical neutrinos - 1

3 Topologies of neutrinos detected:

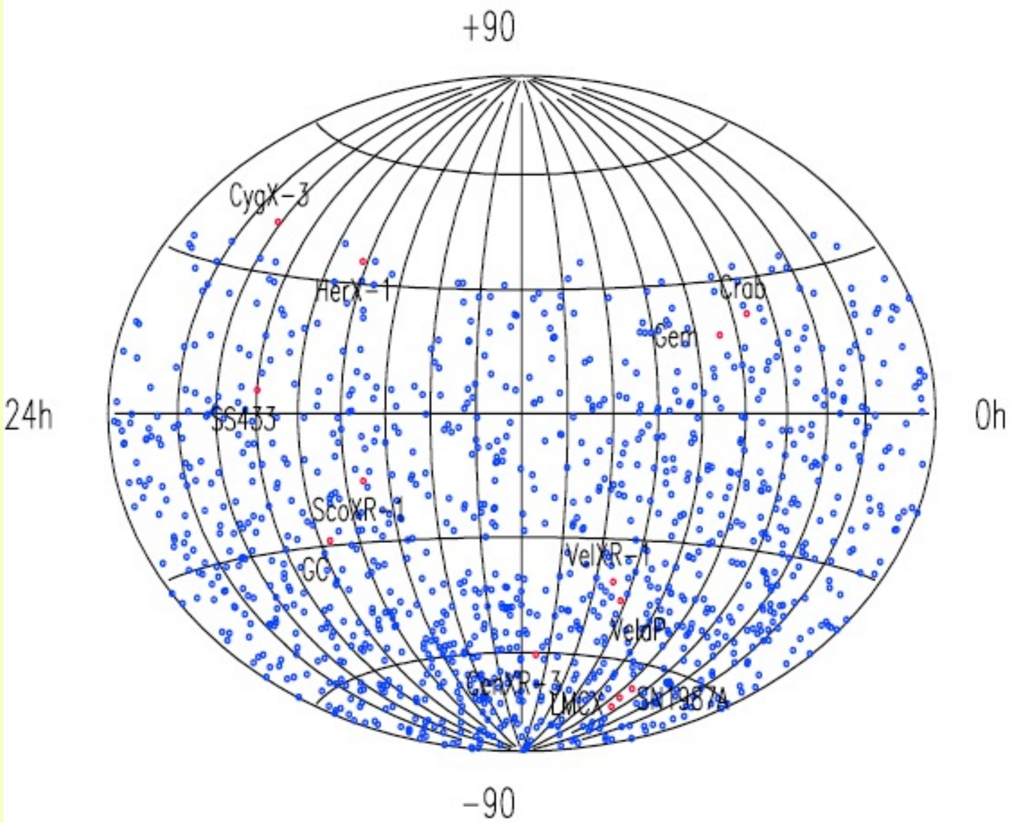
- Upward Throughgoing μs ($\langle E_\nu \rangle \sim 100$ GeV): T.o.F. ($\sim$ 50% through 3 scintillator planes)
- IUμ $\equiv$ Internal Upgoing μs ($\langle E_\nu \rangle \sim 4$ GeV): T.o.F.
- IDμ $\equiv$ Internal Downgoing μs + UGSμ $\equiv$ UpwardGoing Stopping μs ($\langle E_\nu \rangle \sim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



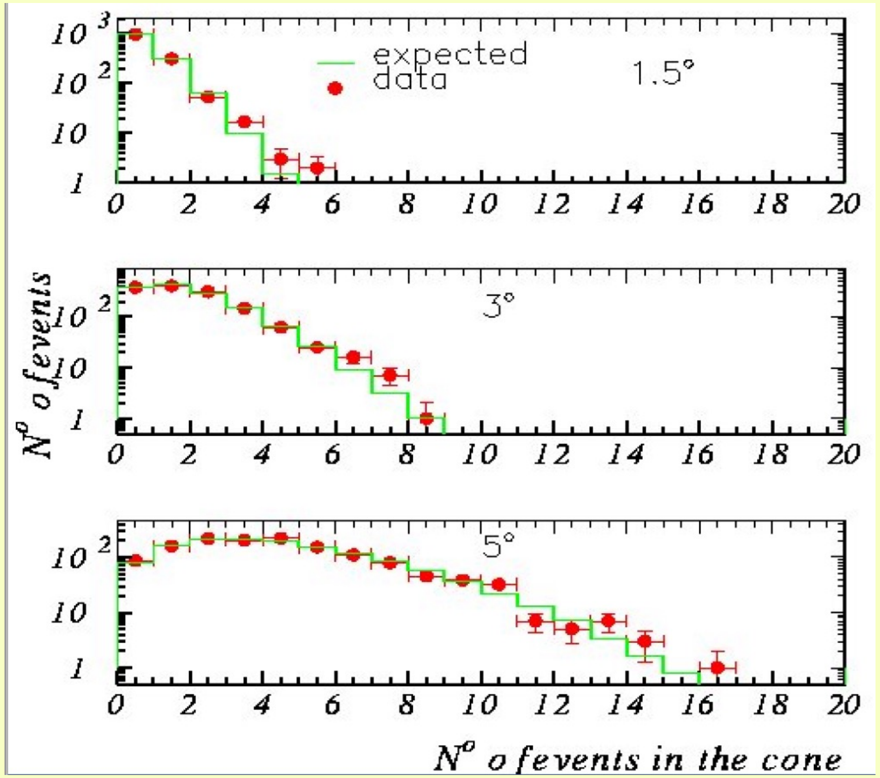


MACRO search for astrophysical neutrinos - 2

1356 μ reconstructed as “upgoing” and due to Neutrino (atm. + astrophysical) interactions



No evidence for a flux of ν from known point-like source of γ



Set upper limit on the flux of ν from these point-like source of γ

Motivations for present H.E. neutrino astrophysics

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

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

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

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

-…

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