XI.

Atmospheric Muons and Neutrinos

Astroparticle Physics a.a. 2021/22

Maurizio Spurio
Università di Bologna e INFN
maurizio.spurio@unibo.it

Content

11 Atmospheric Muons and Neutrinos . . . .

~~11.1 Nucleons in the Atmosphere~~ . . . .

~~11.2 Secondary Mesons in the Atmosphere~~ . . . .

~~11.3 Muons and Neutrinos from Charged Meson Decays~~ . . . .

11.3.1 The Conventional Atmospheric Neutrino Flux . . . .

11.3.2 The Prompt Component in the Muon and Neutrino Flux . . . .

~~11.4 The Particle Flux at Sea Level~~ . . . .

~~11.5 Measurements of Muons at Sea Level~~ . . . .

~~11.6 Underground Muons~~ . . . .

11.6.1 The Depth–Intensity Relation . . . .

11.6.2 Characteristics of Underground/Underwater Muons . . . .

11.7 Early Experiments for Atmospheric Neutrinos . . . .

11.8 Oscillations of Atmospheric Neutrinos . . . .

11.9 Measurement of Atmospheric ν_μ Oscillations in Underground Experiments . . . .

11.9.1 Event Topologies in Super-Kamiokande . . . .

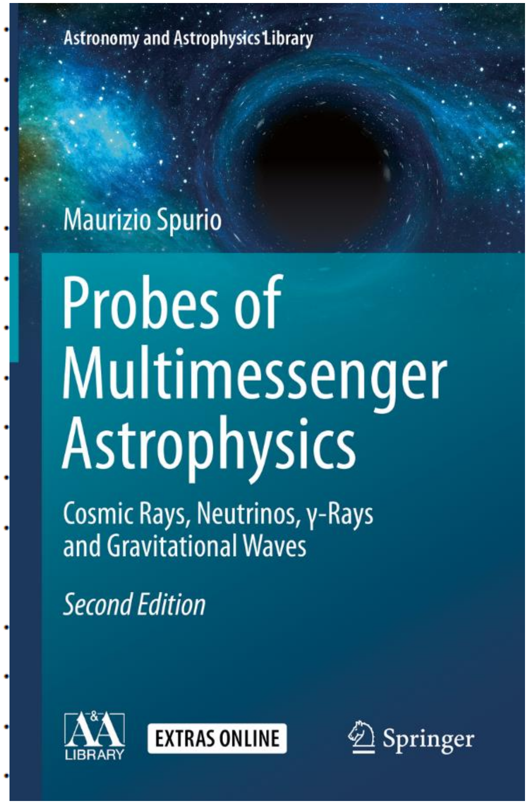
11.9.2 The Iron Calorimeter Soudan 2 Experiment . . . .

11.9.3 Upward-Going Muons and MACRO . . . .

11.10 Atmospheric ν_μ Oscillations and Accelerator Confirmations . . . . .

11.11 Atmospheric Neutrino Flux at High Energies . . . .

References . . . .



Astronomy and Astrophysics Library

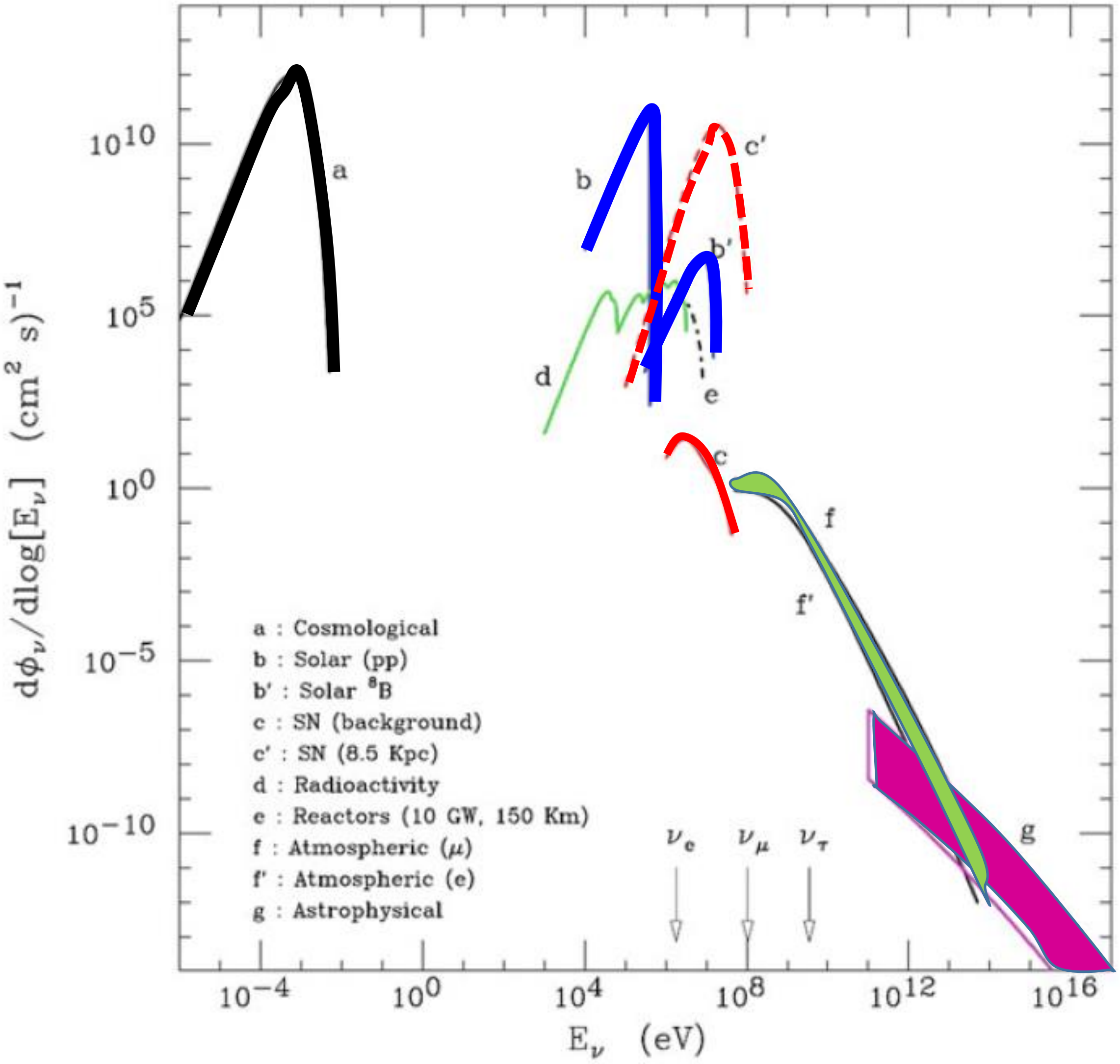
Maurizio Spurio

Probes of Multimessenger Astrophysics

Cosmic Rays, Neutrinos, γ-Rays and Gravitational Waves

Second Edition

Neutrinos from the Cosmos



Flux of neutrinos at the surface of the Earth.

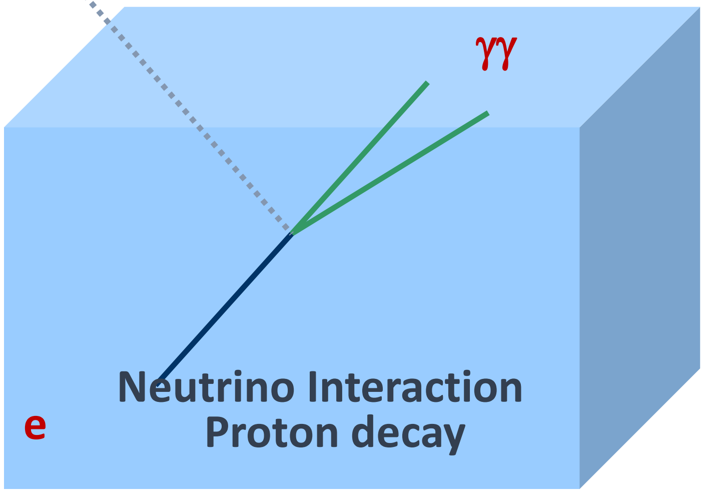
Arrow indicate the energy threshold for CC production of the charged lepton

- Big Bang neutrinos (no)
- Neutrinoss from the Sun (Cap. 12)
- Neutrinos from SNe (Cap. 12)
- Atmospheric neutrinos (Here)
- High-energy cosmic neutrinos (Cap. 10)

Once upon a time… GUT

- In the ‘80 Grand Unified Theories (**GUT)** predicted the proton decay with measurable livetime of the order of $\tau=10^{30}$ y (20 orders of magnitude $1/H_o$)
- **QUESTION: Which is $1/H_o$?**
- The proton was thought to decay in (for instance) $p \rightarrow e^{+}\pi^{0}$
- Detector size: 10^3 m^3, and mass 1kt (=10^{31} p)
- The main background for the detection of proton decay were atmospheric neutrinos interacting inside the experiment
- **QUESTION: How many p decays in 1 kt for $\tau= 10^{30}$ y, assuming 100% efficiency?**

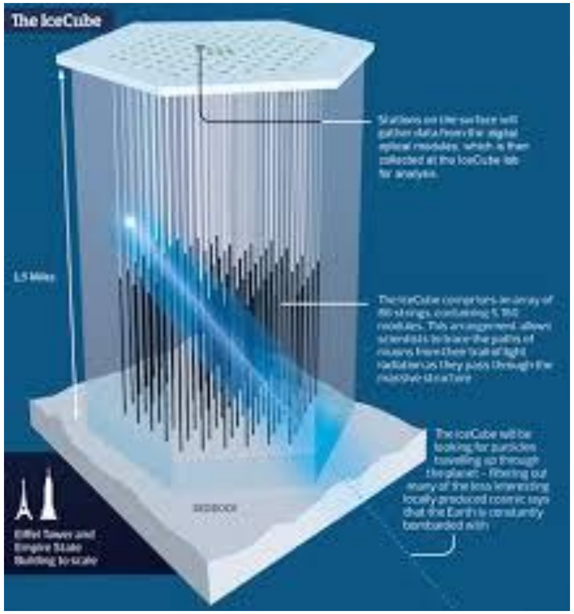
- **Water Cerenkov** Experiments (IMB, Kamiokande)
- **Tracking calorimeters** (NUSEX, Frejus, KGF)
- **Result**: NO p decay ! But some anomalies on the neutrino measurement!

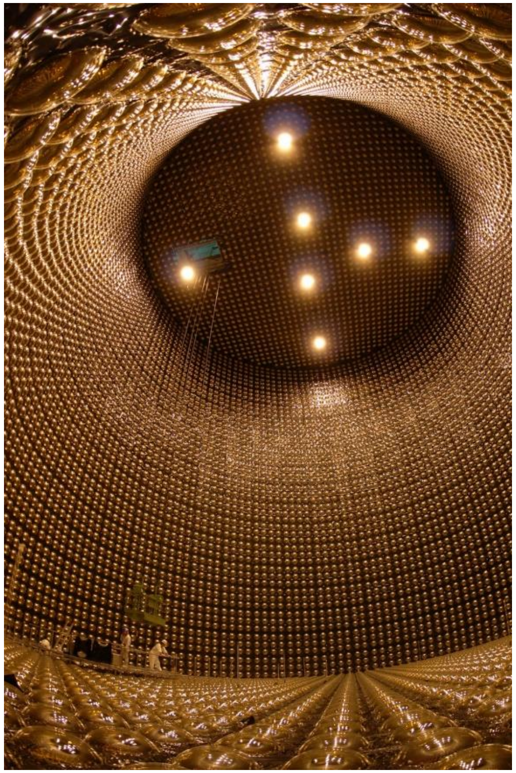


Neutrino Interaction
Proton decay

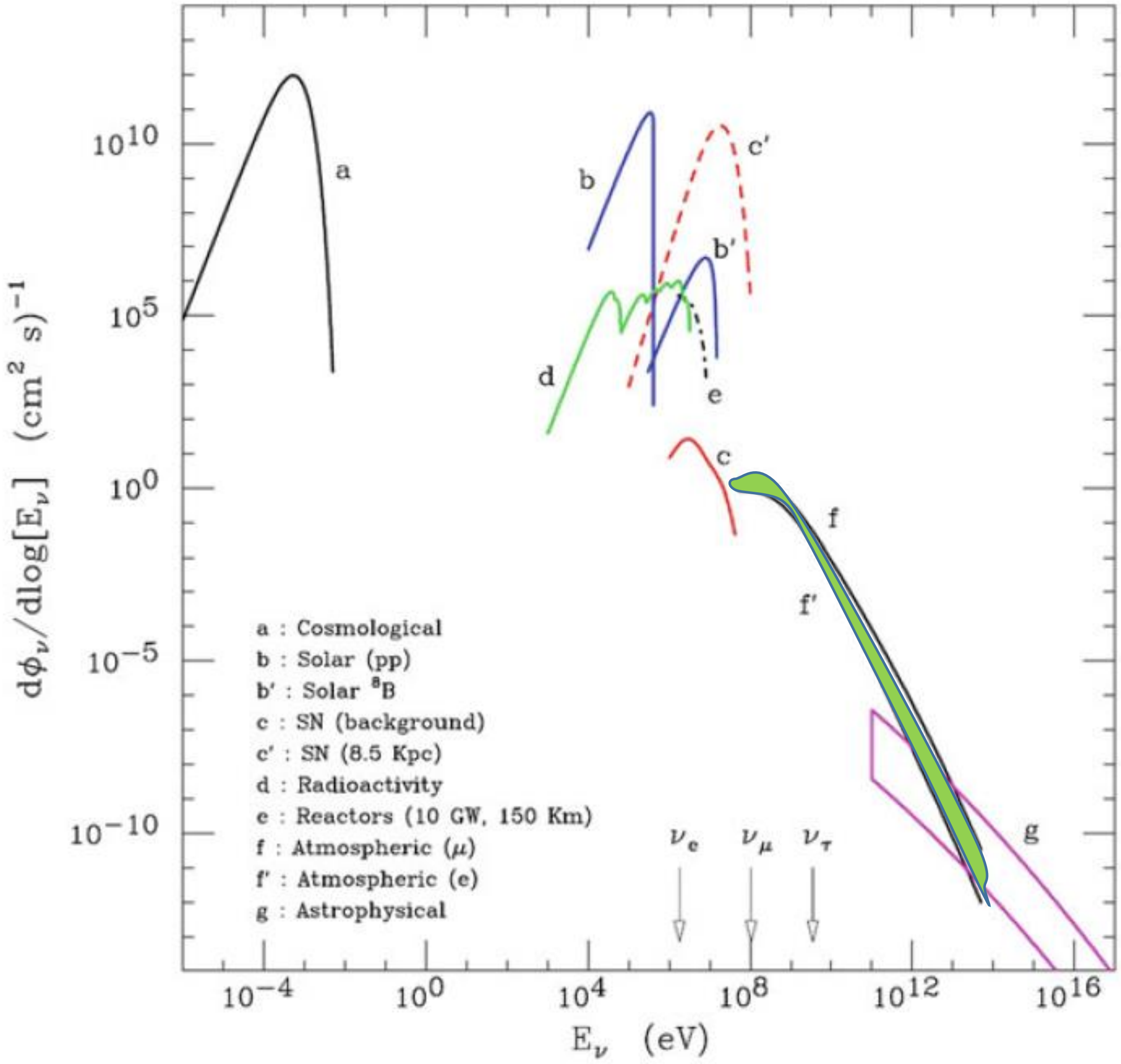
General problems for ν detectors

- Low cross section→ Large detector volume/mass
- Particle identification
- Energy/momentum measurement
- Direction measurement
- No magnetic field ($\nu = \bar{\nu}$)
- Backgrounds





Atmospheric neutrinos



Flux of neutrinos at the surface of the Earth.

Arrow indicate the energy threshold for CC production of the charged lepton

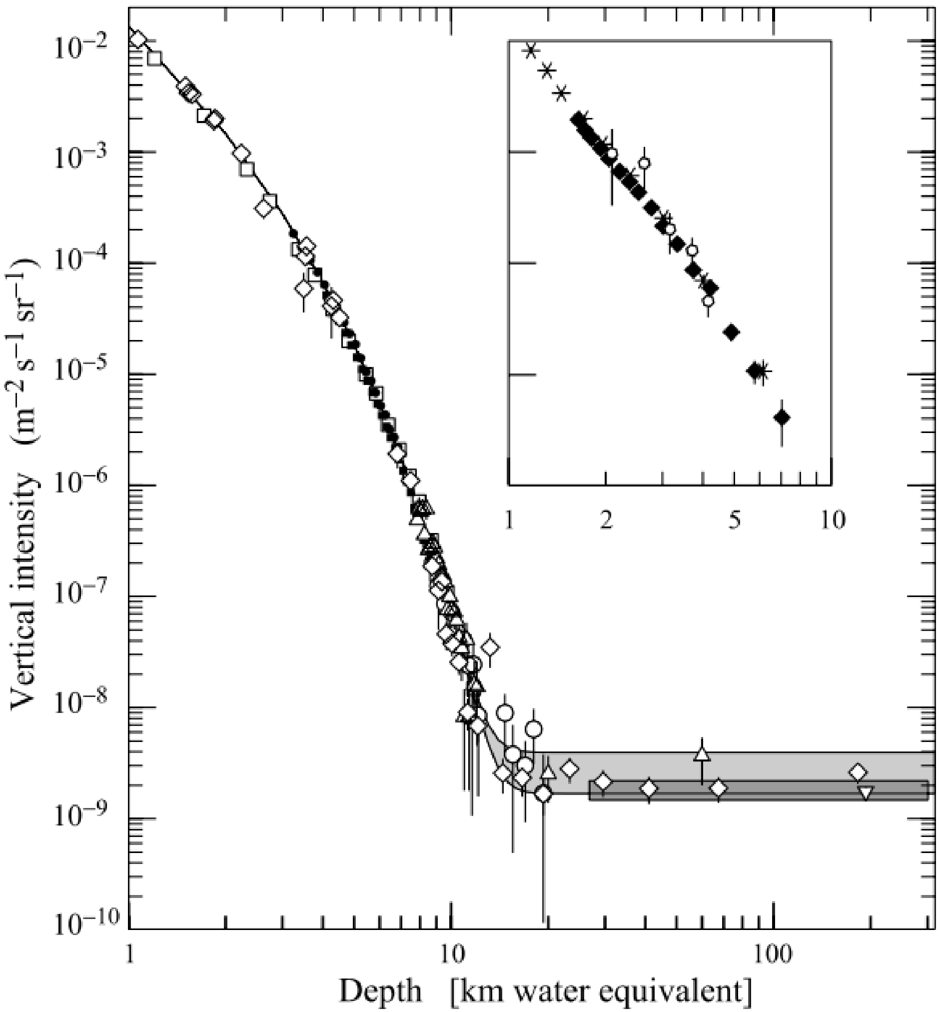
- Big Bang neutrinos
- Neutrinos from the Sun
- Neutrinos from SNe
- Atmospheric neutrinos
- High-energy cosmic neutrinos

The flux of atmospheric muons vs depth

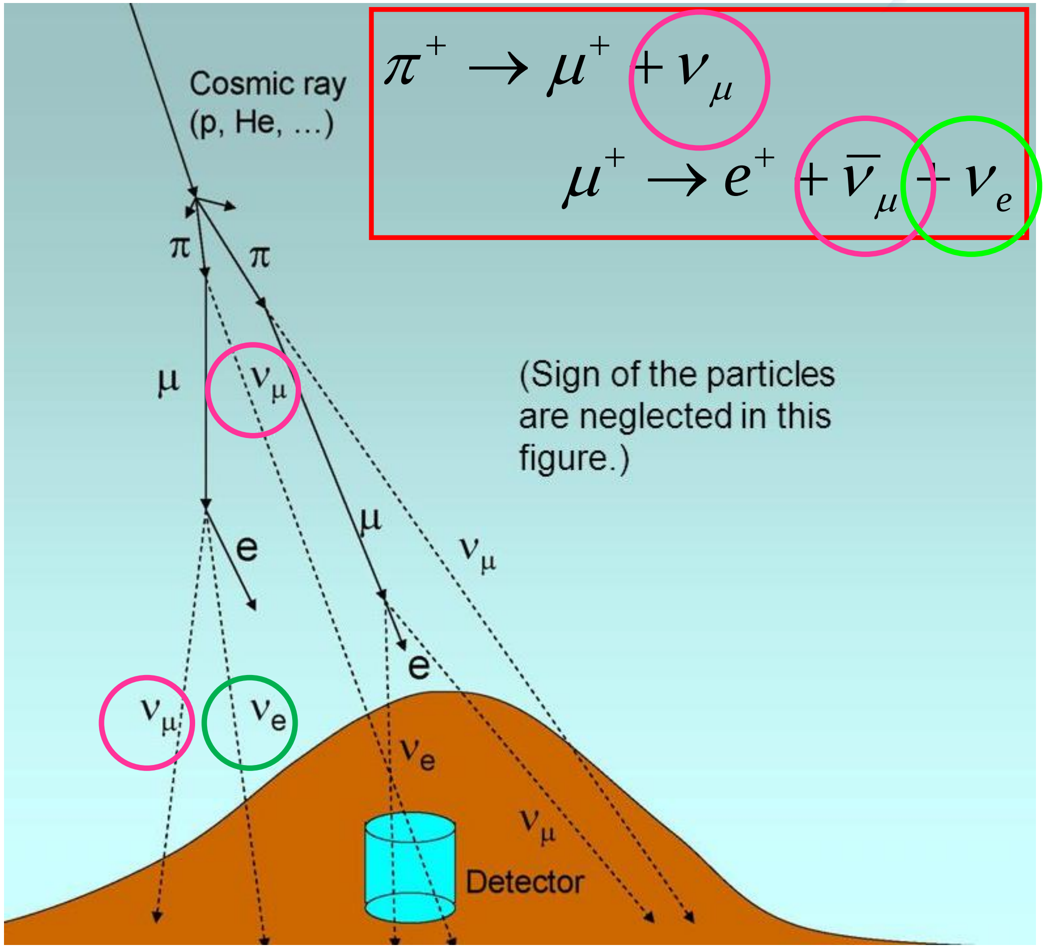
- A sea level, the muon flux is

  $$\Phi \cong 100\, m^{-2} s^{-1} sr^{-1}$$

- Vertical muon intensity vs depth (x-axis, in km.w.e=10^5 g cm^{-2})
- The shaded area at large depths represents neutrino-induced muons of energy >2 GeV.
- [The figure inset shows the vertical intensity measured under water/ice from nu telescopes.]
- Muons cannot cross more than ≈ 15 km.w.e.



Recipes for the evaluation of the atmospheric flux



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

$$\mu^{+} \rightarrow e^{+} + \bar{\nu}_{\mu} + \nu_{e}$$

Independently from the details of the computation of $\Phi\nu_\mu$ (E), $\Phi\nu_e$(E), one can obtain two very robust properties:

- At energies below few GeV, the flux of ν_μ is approximately twice as large as the *ve*, i.e.:

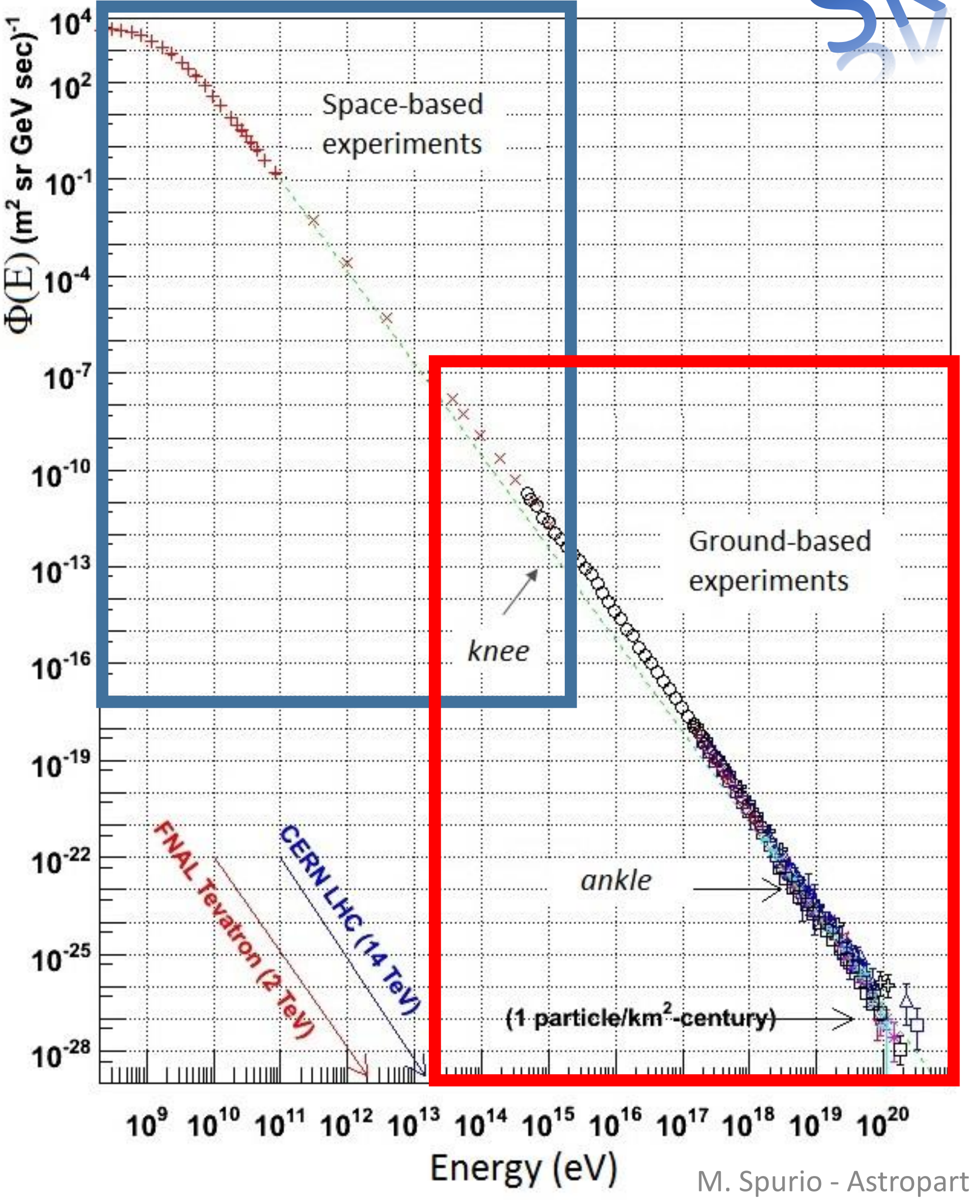
  $$\Phi(\nu_\mu)= 2\Phi(\nu_e)$$

- The ν_μ, ν_e fluxes are up-down symmetric in zenith ϑ, i.e.:

  $$\Phi_{\nu} (E_\nu, \theta) = \Phi_{\nu} (E_\nu, \pi - \theta)$$

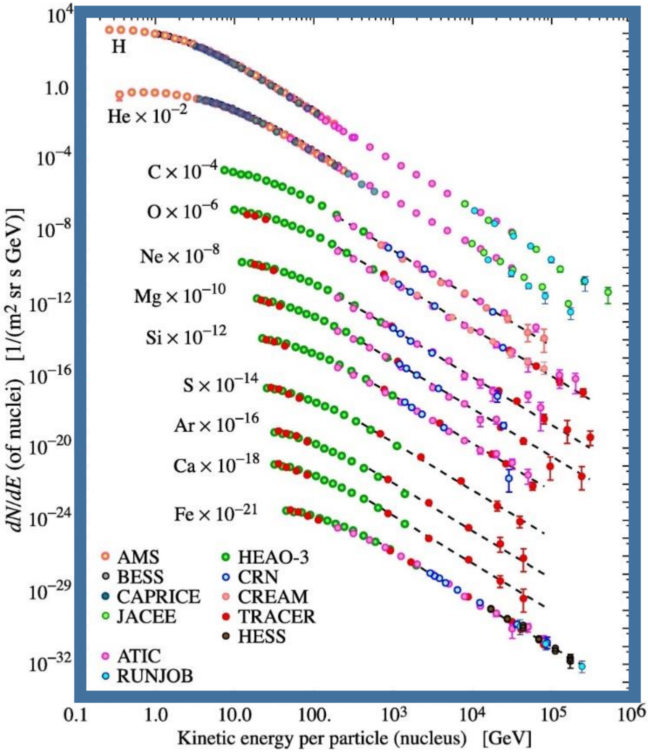
Question 1: why $\Phi(\nu_\mu)= 2\Phi(\nu_e)$ not hold at higher (>> GeV) energies?

Ingredient 1) The primary CR spectrum



Direct measurements

Indirect measurements



Ingredient 1) Cascade initiated by primary CRs

- Primary CR attenuation as function of X (g cm^{-2}) and E

$$\frac{\partial \mathcal{N}_N(E,X)}{\partial X} = -\frac{\mathcal{N}_N(E,X)}{\lambda_{IN}} + \int_E^\infty \frac{\mathcal{N}_N(E',X)}{\lambda_{IN}} F_{NN}(E,E') \frac{dE'}{E}$$

- Boundary condition:

$$\mathcal{N}_N(E,0) = \Phi(E) = KE^{-\alpha}$$

- From Feyman scaling:

$$\mathcal{N}_N(E,X) = \Phi_N(E) \cdot H_N(X)$$

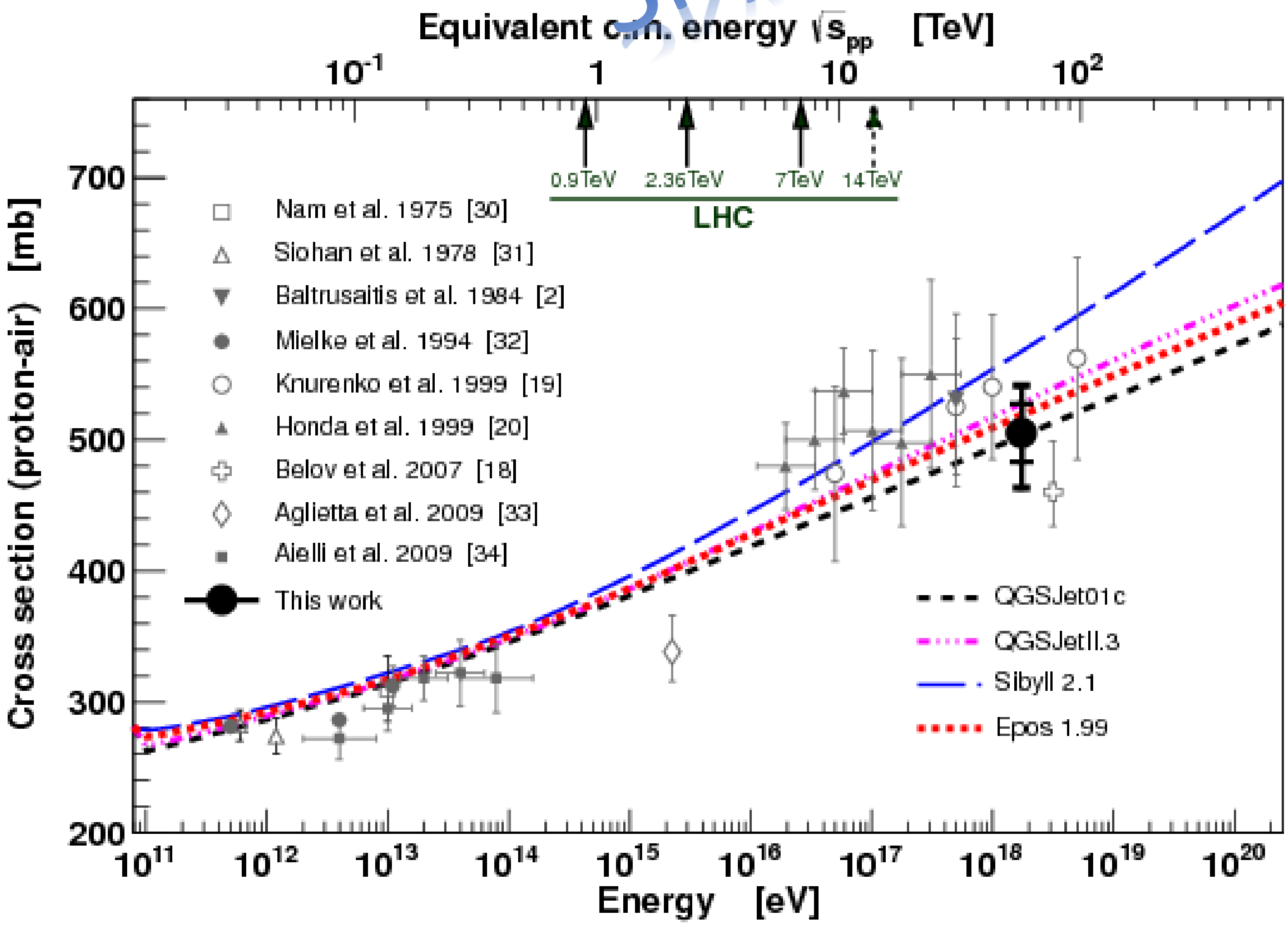
- The dependence on X depends on an effective attenuation length Λ_N:

$$\boxed{H_N(X) = H_N(0) \cdot \exp\left(-\frac{X}{\Lambda_N}\right)}$$

$$\boxed{\Phi_N(E) = KE^{-\alpha} \ .}$$

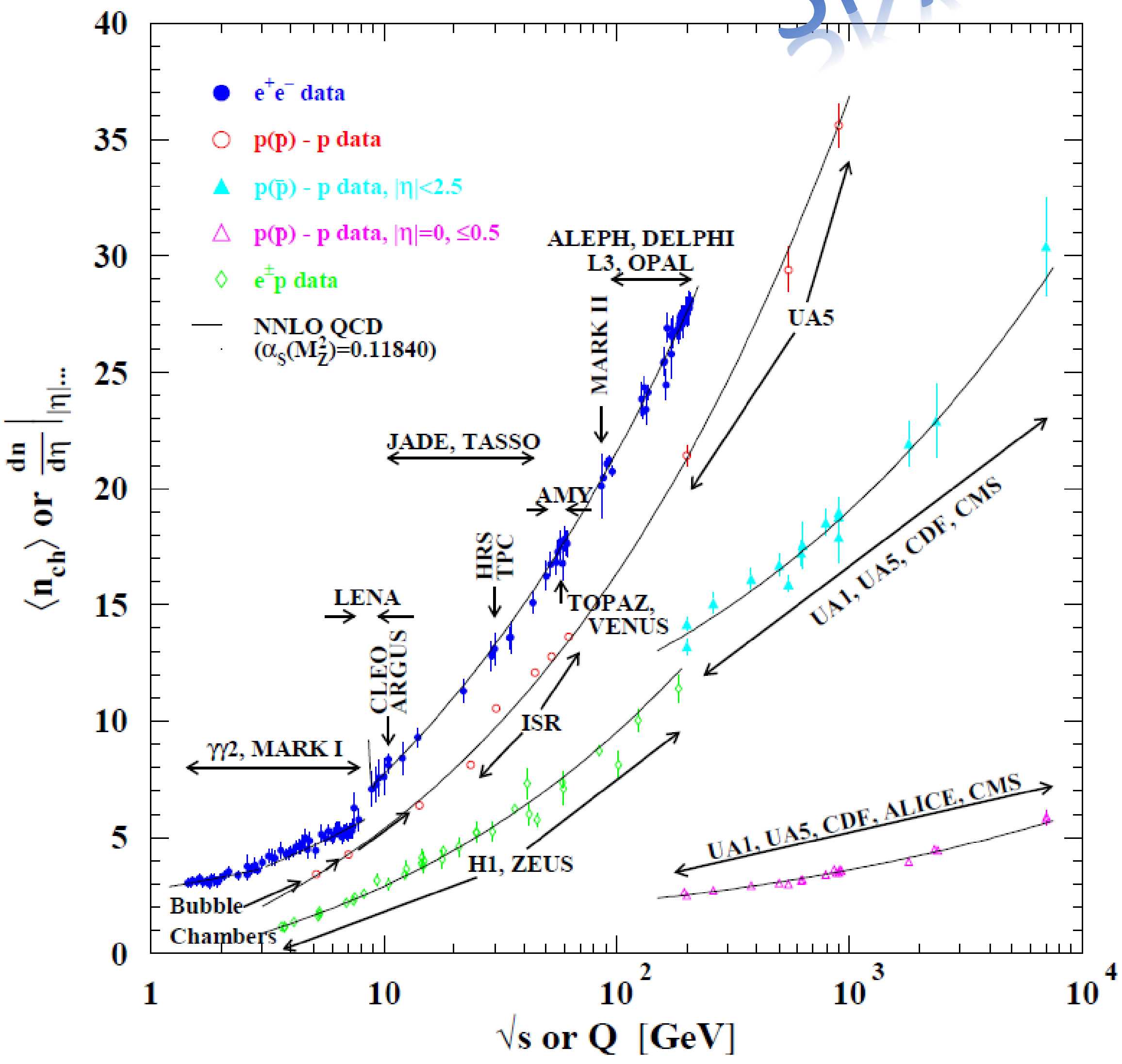
Ingredient 2) p-air cross section

SKYP



AUGER Coll. PRL 109 (2012) 062002

Ingredient 3) Secondary charged multiplicity



Average number of charged hadrons produced in pp (and $\bar{p}p$), e+e-, ep collisions versus center of mass energy

Ingredient 2), 3) → meson production

- The pion propagation in atmosphere is described by:

$$\frac{\partial \mathscr{N}_\pi(E,X)}{\partial X} = -\left(\boxed{\frac{1}{\lambda_{I_\pi}}} + \boxed{\frac{1}{d_\pi}}\right)\mathscr{N}_\pi(E,X) + \int_0^1 \frac{\mathscr{N}_\pi(\frac{E}{x^*},X)}{\lambda_{I_\pi}} \cdot F_{\pi\pi}(x^*) \cdot \frac{dx^*}{x^{*2}} + \int_0^1 \frac{\mathscr{N}_N(\frac{E}{x^*},X)}{\lambda_{I_N}} \cdot F_{N\pi}(x^*) \cdot \frac{dx^*}{x^{*2}} \tag{11.15}$$

- Competition between interaction and decay . The decay length:

$$\frac{1}{d_\pi} = \frac{1}{\Gamma c \tau_{\pi\pm} \rho(X)} = \frac{\boxed{m_\pi c^2 h_0}}{E c \tau_{\pi\pm} X \cos\theta} = \frac{\boxed{\varepsilon_\pi}}{E X \cos\theta}$$

- The pion decay constant ε_π=115 GeV.
- Pions start to increase with increasing depth X, reach a maximum and then decrease

- High-energy limit (E>> ε_π): the decay term d_π can be neglected:

$$\mathcal{N}_\pi^{he}(E,X) = \left[\frac{Z_{N\pi}}{1-Z_{NN}} \cdot \frac{\Lambda_\pi}{\Lambda_\pi - \Lambda_N}\left(e^{-X/\Lambda_\pi} - e^{-X/\Lambda_N}\right)\right] \cdot \boxed{KE^{-\alpha}}.$$

(the Z are the the *spectrum weighted moments*)

- Low-energy limit (*E* cosϑ << ε_π): we neglect the term $\lambda_{I\pi}$.

$$\mathcal{N}_\pi^{le}(E,X) = \left[\frac{Z_{N\pi}}{\lambda_{IN}} \cdot e^{-X/\Lambda_N} \cdot X\right] \cdot \frac{\cos\theta}{\varepsilon_\pi} \cdot \boxed{KE^{-\alpha+1}}$$

- Similar equations hold for other particles with different decay constants:

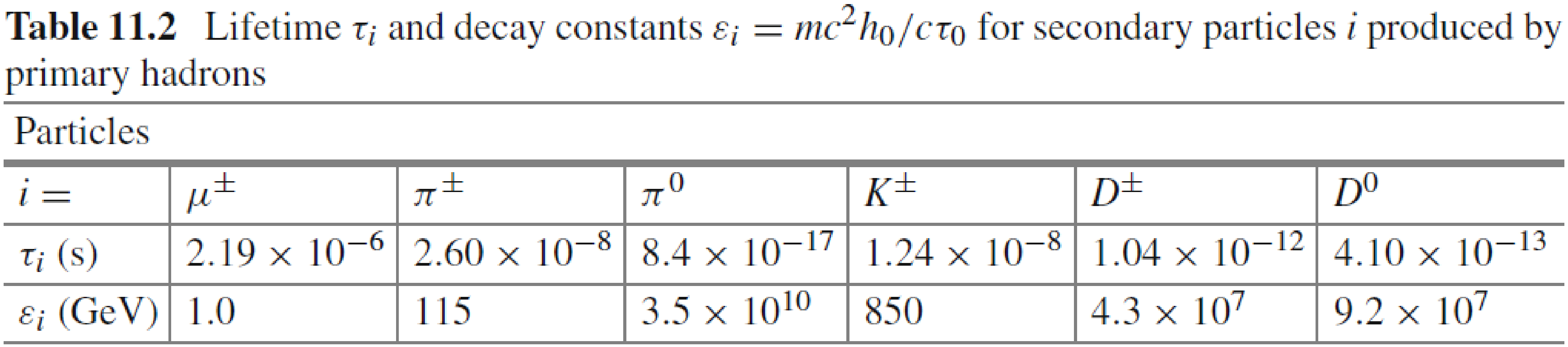


Table 11.2 Lifetime τ_i and decay constants $\varepsilon_i = mc^2 h_0/c\tau_0$ for secondary particles i produced by primary hadrons

Particles						
$i =$	$\mu^\pm$	$\pi^\pm$	π^0	$K^\pm$	$D^\pm$	D^0
τ_i (s)	2.19×10^{-6}	2.60×10^{-8}	8.4×10^{-17}	1.24×10^{-8}	1.04×10^{-12}	4.10×10^{-13}
ε_i (GeV)	1.0	115	3.5×10^{10}	850	4.3×10^7	9.2×10^7

Ingredient 2), 3) → neutrino production

- ***Conventional*** muons are produced by π and K decays:

$$
\left.
\begin{array}{l}
\pi^+(K^+) \rightarrow \nu_\mu + \mu^+ \\
\qquad\qquad\qquad \hookrightarrow \mu^+ \rightarrow \overline{\nu}_\mu + \nu_e + e^+ \\
\pi^-(K^-) \rightarrow \overline{\nu}_\mu + \mu^- \\
\qquad\qquad\qquad \hookrightarrow \mu^- \rightarrow \nu_\mu + \overline{\nu}_e + e^- \, .
\end{array}
\right\}
\begin{array}{l}
\dfrac{d\mathcal{N}_\pi}{dX} = -\dfrac{\mathcal{N}_\pi}{d_\pi} \\[2ex]
d\mathcal{N}_\mu = -d\mathcal{N}_\pi
\end{array}
$$

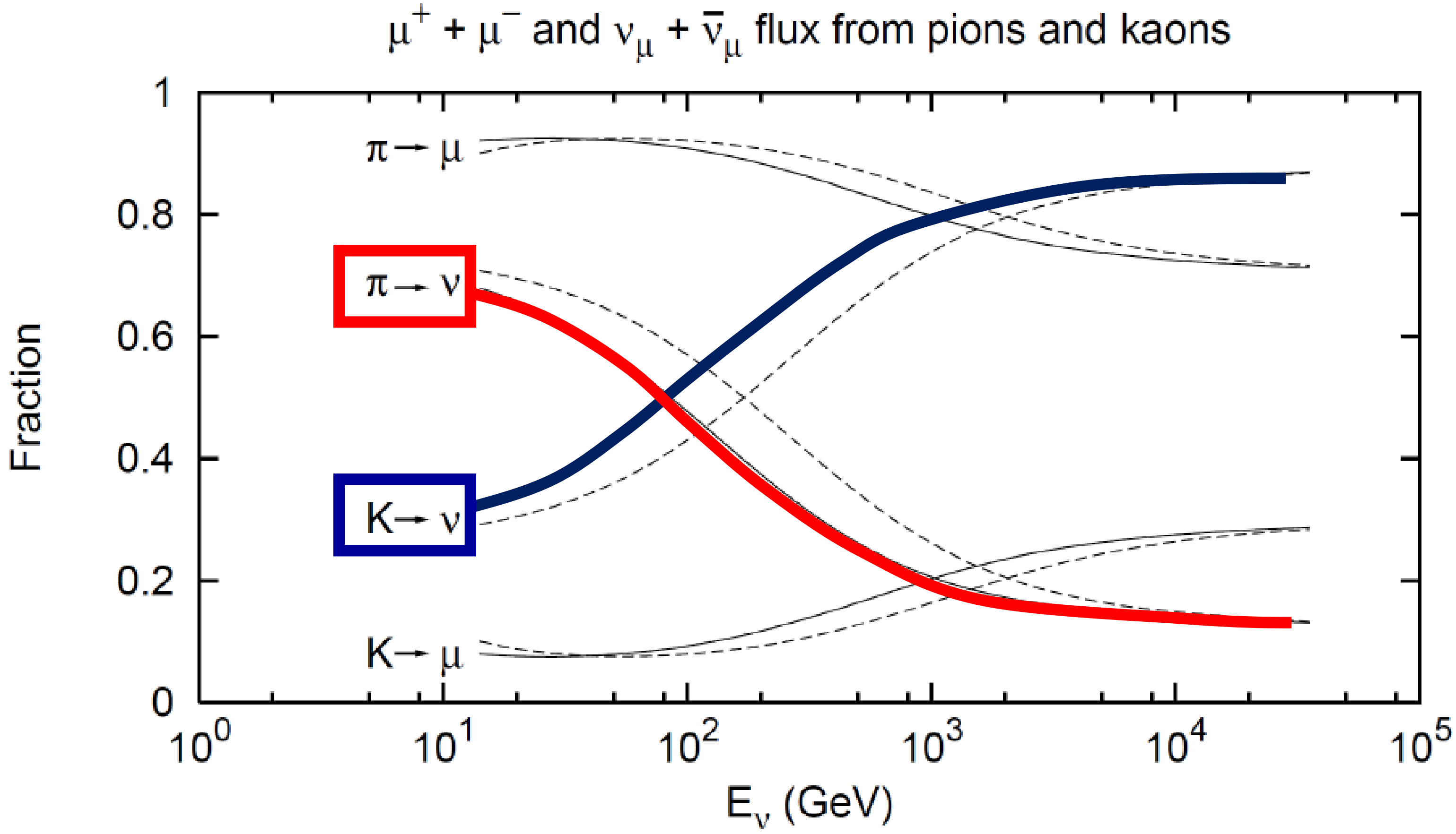
- ***Prompt*** muons by the decay of charmed mesons.
- The muon flux is thus described by the equation:

$$
\boxed{\Phi_\mu(E) = KE^{-\alpha}\left(\frac{A_\pi}{1+\left(\frac{B_\pi E}{\varepsilon_\pi}\right)\cos\theta} + \frac{A_K}{1+\left(\frac{B_K E}{\varepsilon_K}\right)\cos\theta} + \frac{A_c}{1+\left(\frac{B_c E}{\varepsilon_c}\right)\cos\theta}\right)}
$$

- The muon neutrino flux follows similarly.

The conventional ν flux: π and K

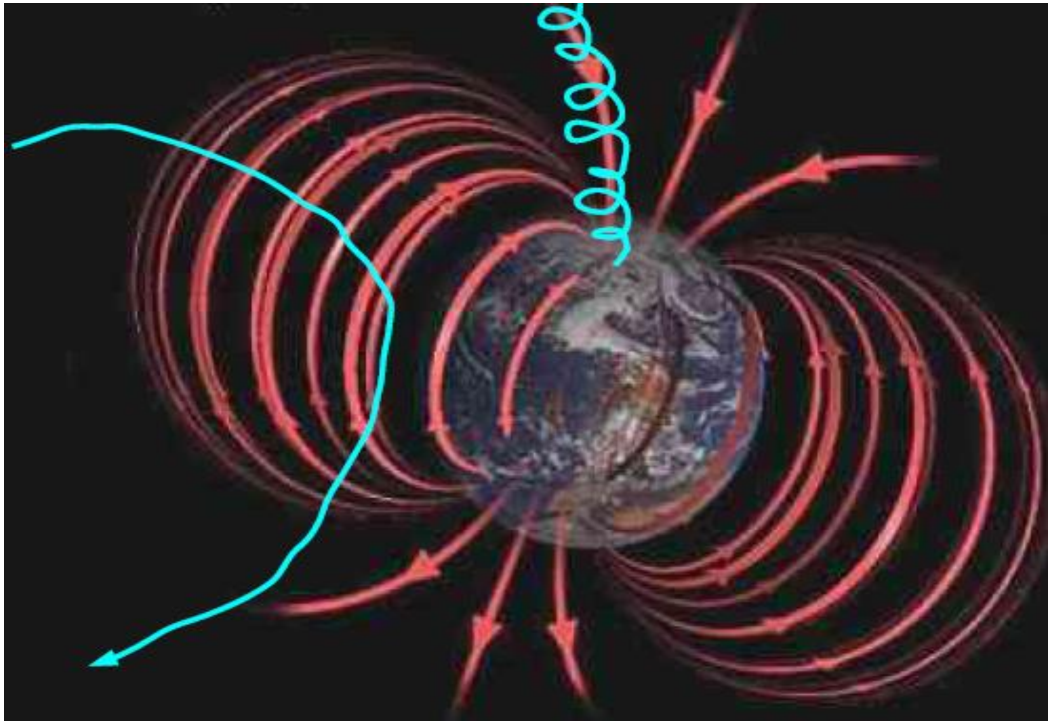
Solid lines: vertical, dashed lines: zenith 60°



T. K. Gaisser, Earth Planets Space **58** (2006), 1-5.

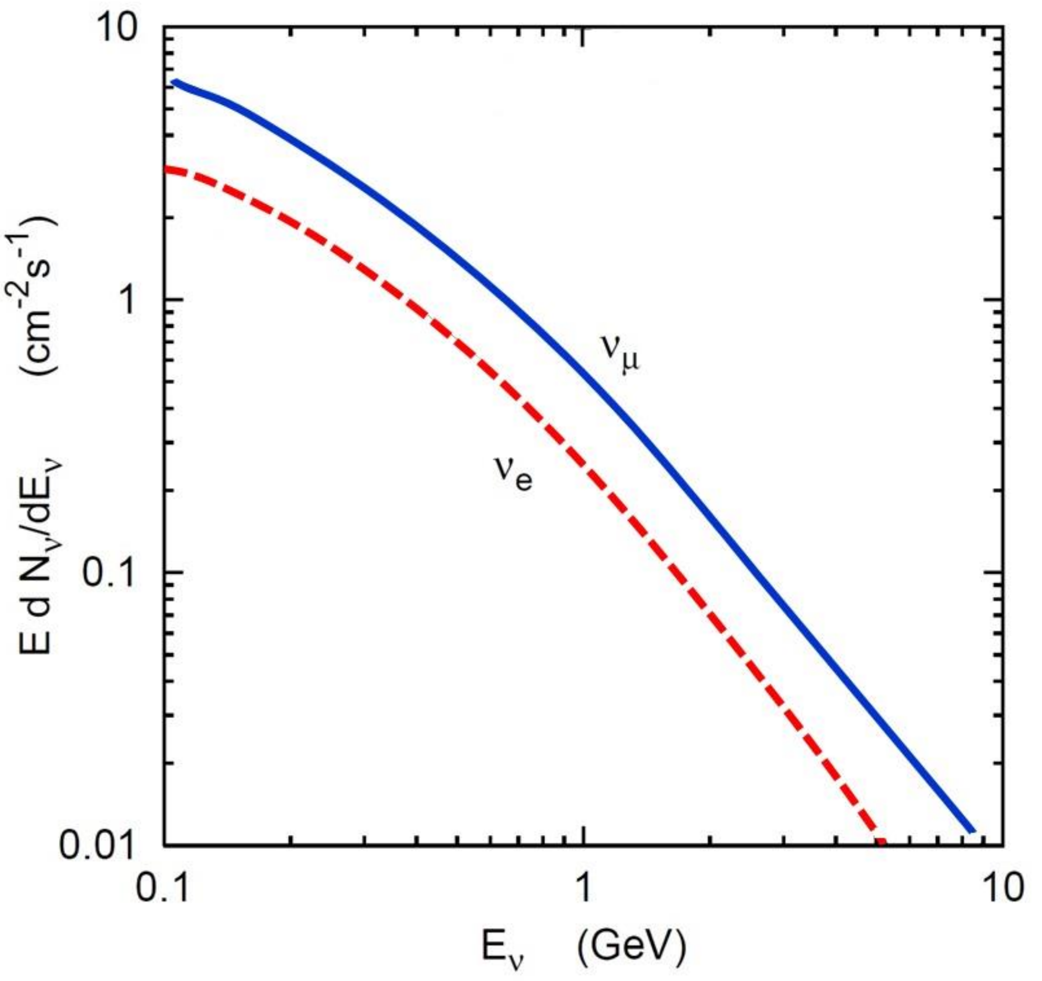
Ingredient 4) Solar effects+geomagnetic field

- high precision 3D calculations,
- refined geomagnetic cut-off treatment (also geomagnetic field in atmosphere)
- elevation models of the Earth
- different atmospheric profiles
- geometry of detector effects



The conventional ν flux (Honda)

M. Honda, et al. Phys. Rev. D 92, 023004 (2015)



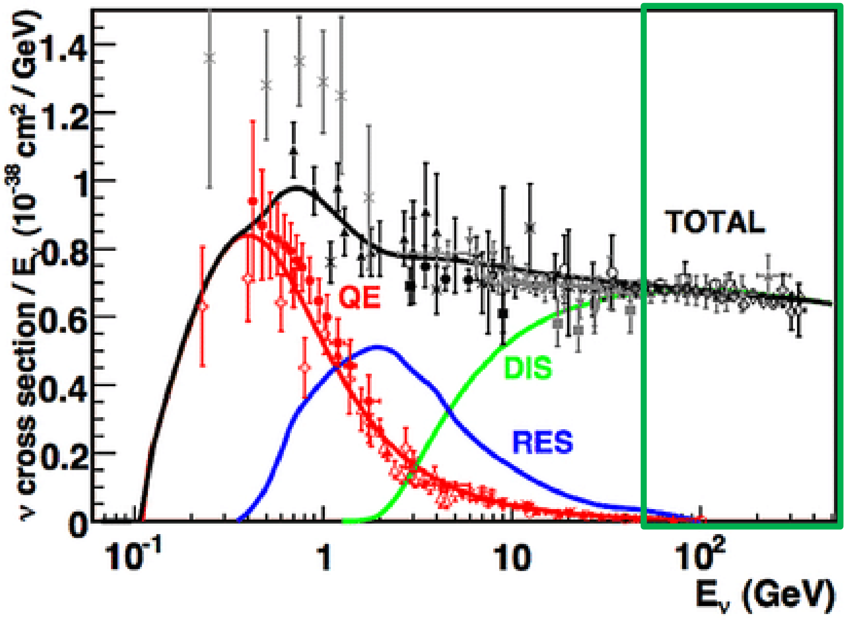
- The result of one of such calculations: the ν flux prediction (Honda) from MC simulations;
- Different models exist;

***Question 2**: Compute the number of ν interaction/y for E_ν>1 GeV in 1 kton detector (ε=1)*

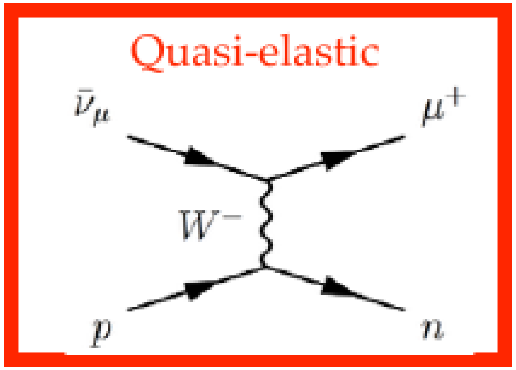
Question 3: Explain qualitatively the (ν_μ/ν_e) ratio

Question 4: Explain qualitatively why the $(\nu_\mu/\ \bar{\nu}_\mu)$ ratio increases with energy

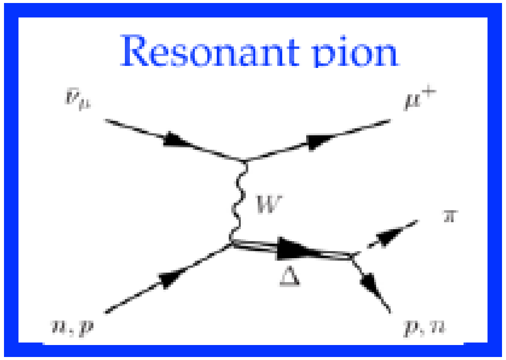
Neutrino interactions and cross section



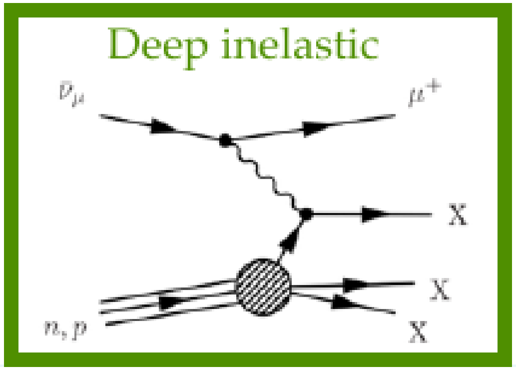
- Different processes for the neutrino interaction on nucleons
- QE: warning to the conservation laws!
- **Question**: why we do not mention the neutrino cross-section on electrons?
- Which is the expected behavior for ν+e?



QE



RES

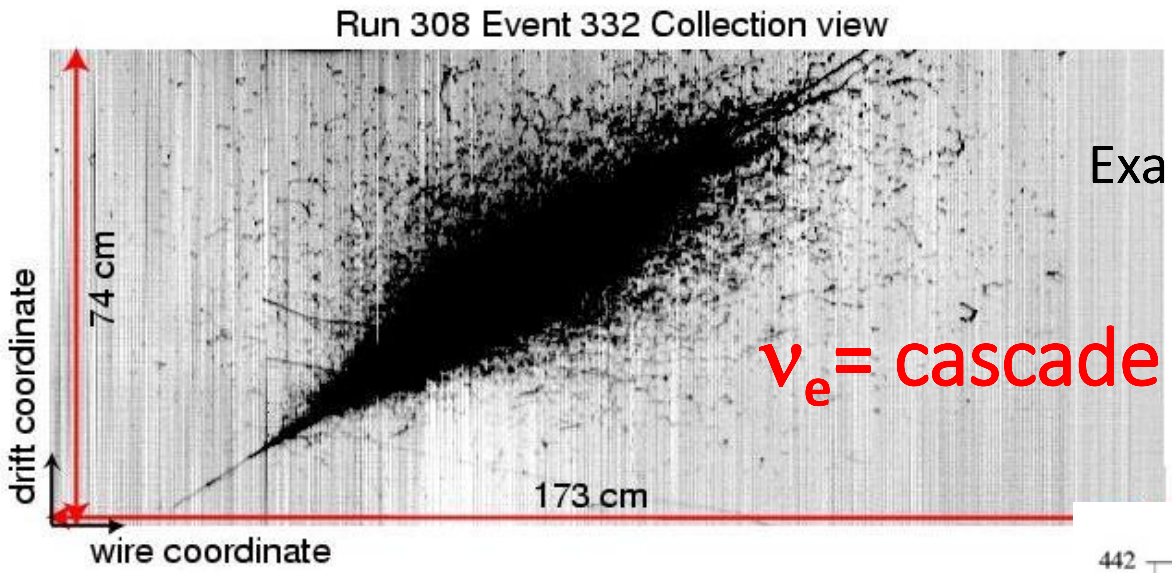


DIS

Energy threshold

- ν_e > 0.5 MeV
- ν_μ>105 MeV
- ν_τ>1700 MeV

Measurement of atmospheric ν‘s

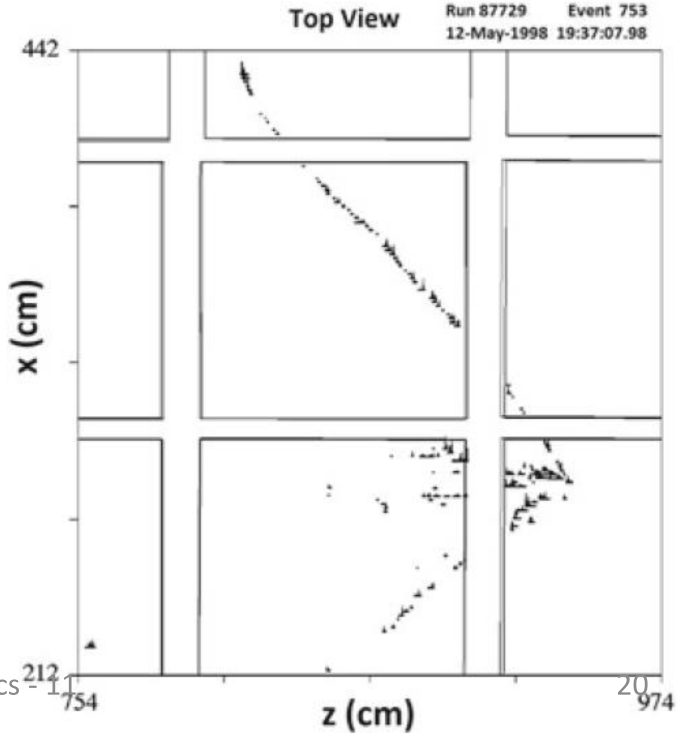


Example: Icarus@ Gran Sasso

ν_e= cascade

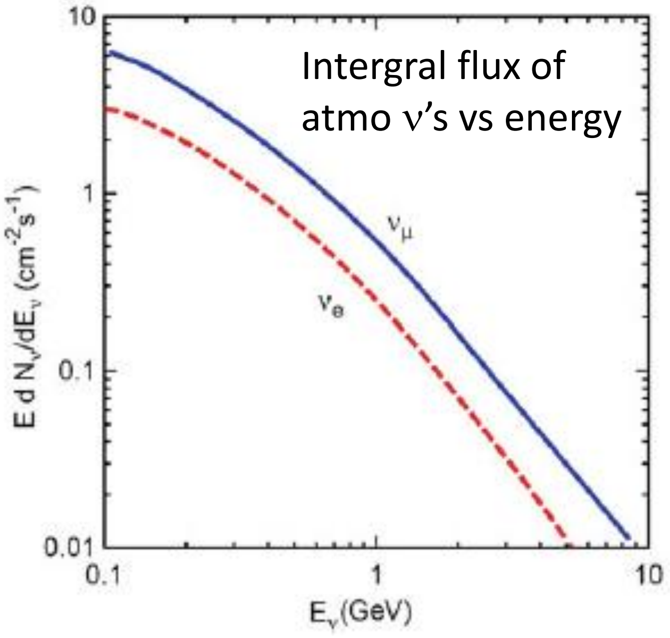
ν_μ=track

Example: Soudan II@ USA

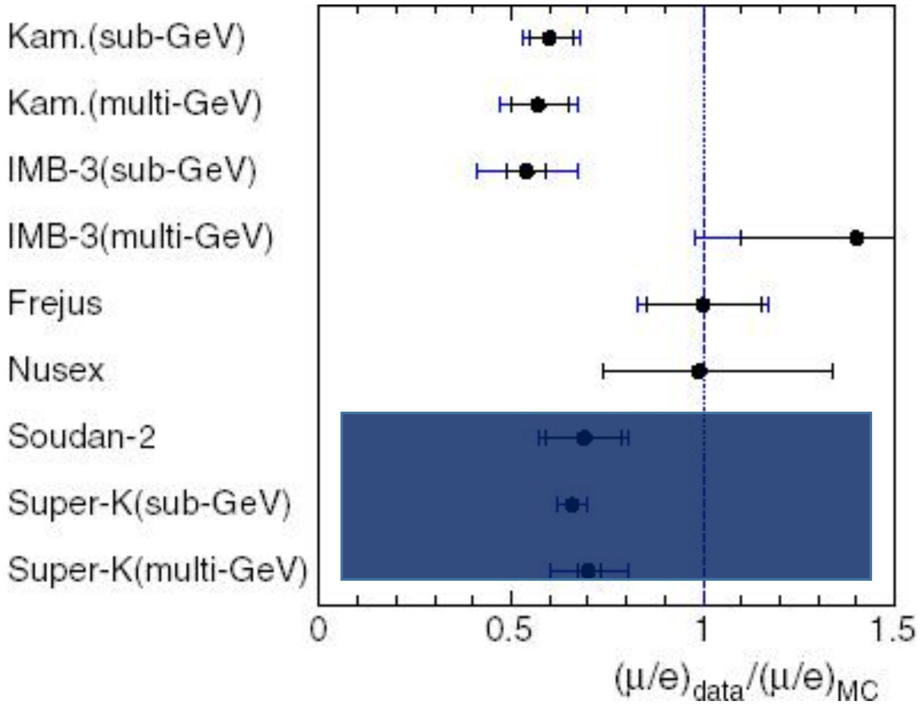


Early measurement of atmospheric ν's (<1990)

- Tracking calorimeter: Frejus, Nusex, Soudan (hard to find pictures on the web!)
- Water Cherenkov: IMB, Kamiokande
- Measured the number of neutrino interaction in the detector, separating tracks (=ν_μ) from showers (=ν_e)

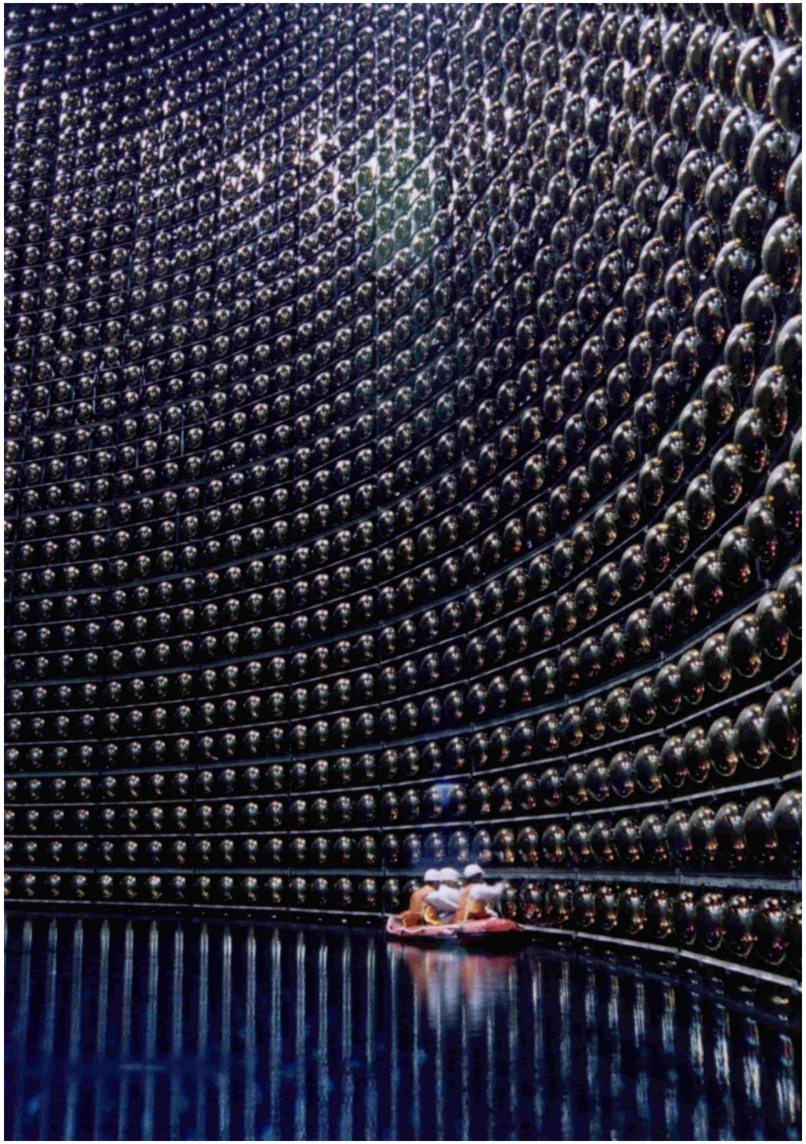


Intergral flux of atmo ν's vs energy



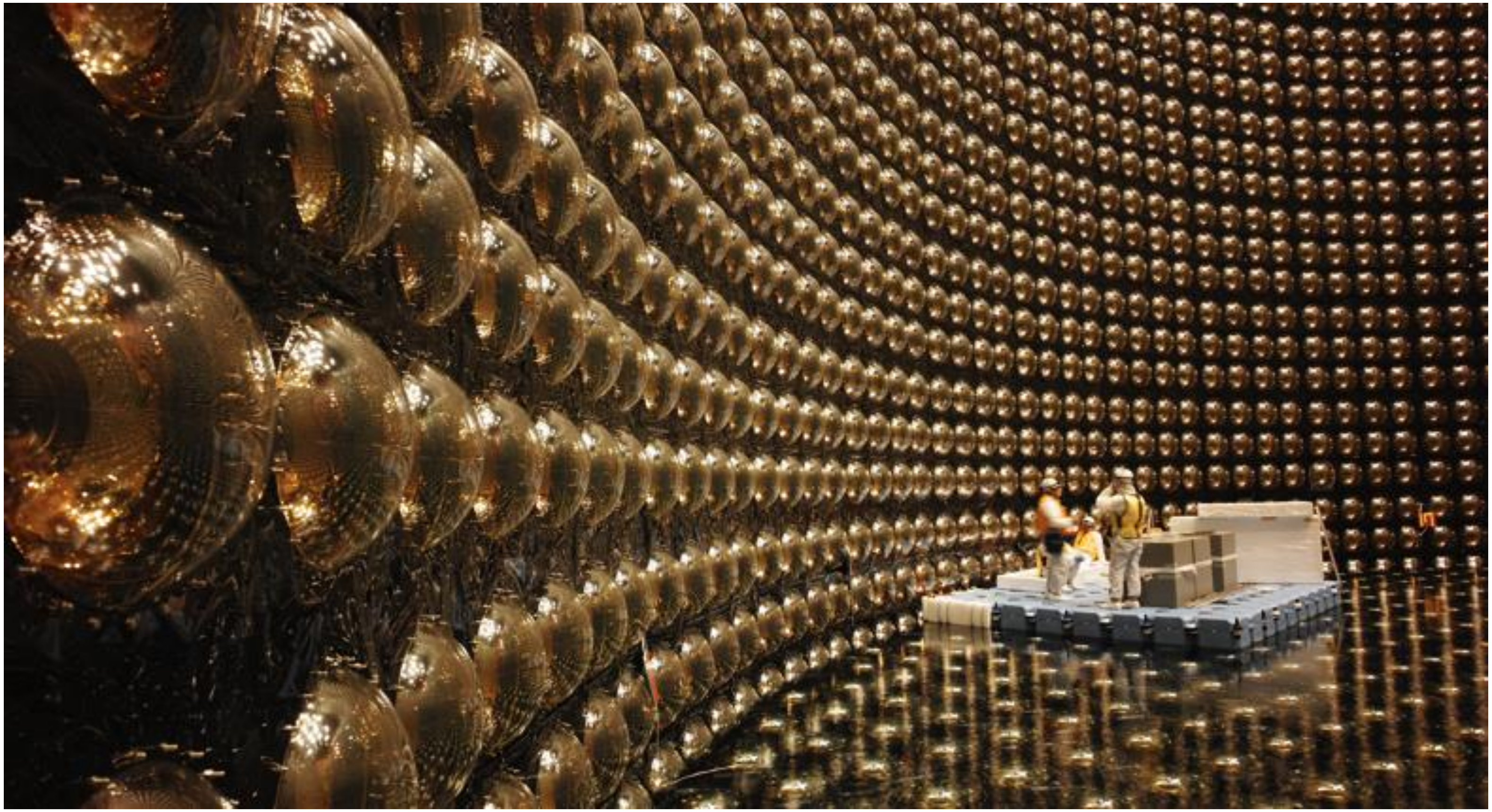
T. Kajita, *New J. Phys.* 6 (2004) 194.

The golden age (1995-2002): SK and MACRO



- SuperKamiokande (SK) is located in Japan, 1000 m Underground (1996 →)
- MACRO was located at LNGS in Italy (1990-2000)

Super-Kamiokande



- SuperKamiokande (SK) is located in Japan, 1000 m Underground
- Active since 1996
- Filled 50.000 ton water
- 11000 large PMTs +2000 PMTs

25 years of Super-Kamiokande

SK-I

1996.4 Start data taking

1998 Evidence of atmospheric ν oscillation (SK)

1999.6 K2K started

2001 Evidence of solar ν oscillation (SNO+SK)

2001.7 data taking was stopped
for detector upgrade

2001.11 Accident

SK-II

2002.10 data taking was resumed

2005 Confirm ν oscillation by accelerator ν (K2K)

SK-III

2006.7 data taking was resumed

2005.10 data taking stopped for full reconstruction

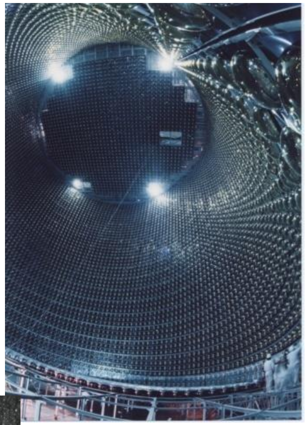
SK-IV

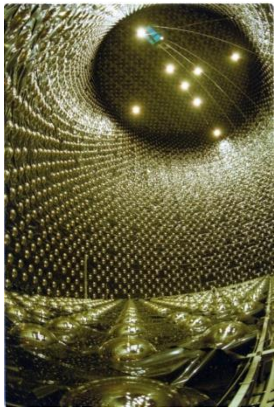
2009 data taking

2018.5 Stop SK-IV

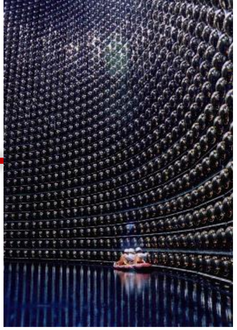
SK-V

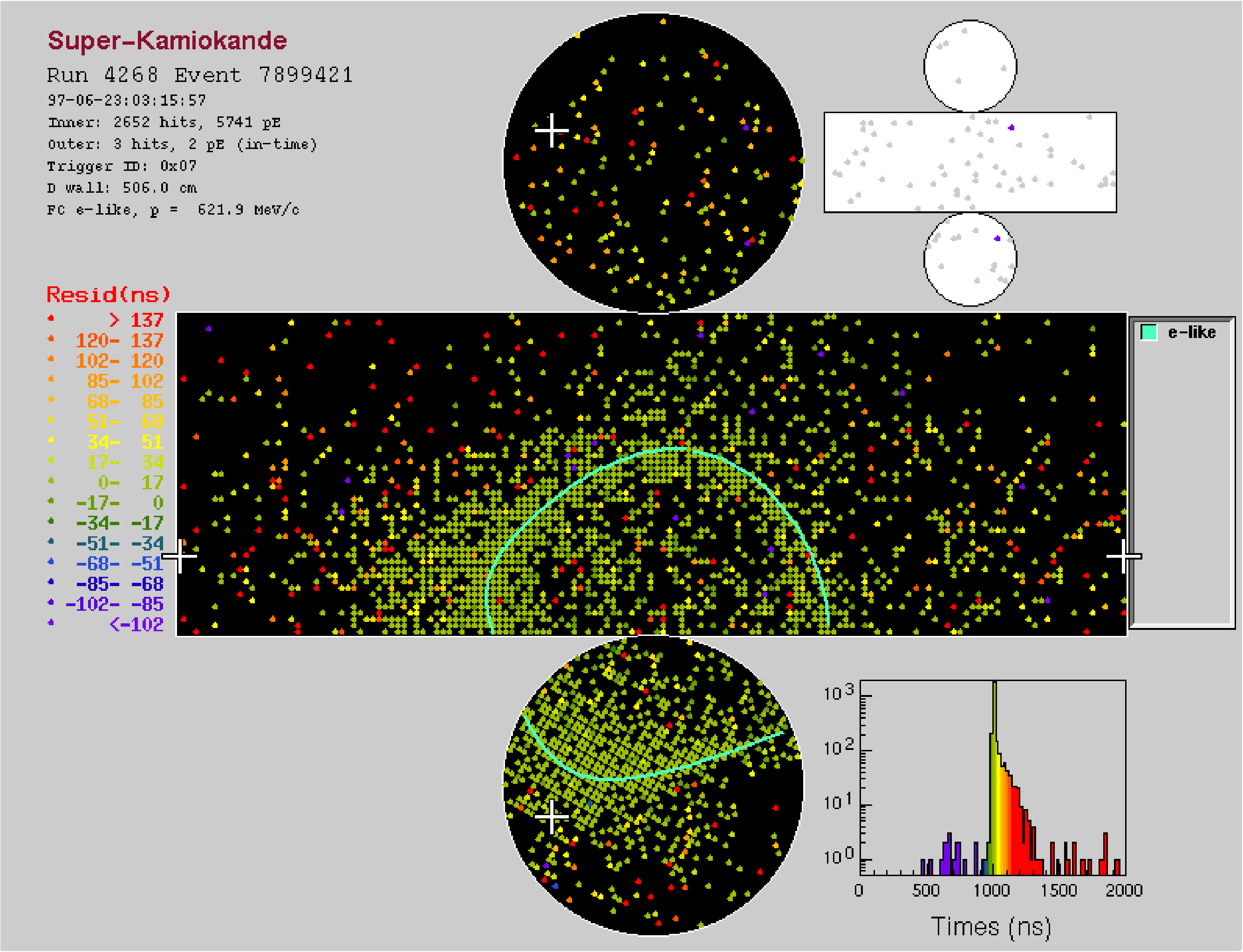
2019.1 Start





SuperKamiokande: ν_e

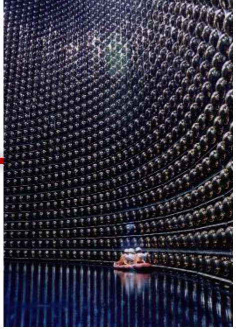


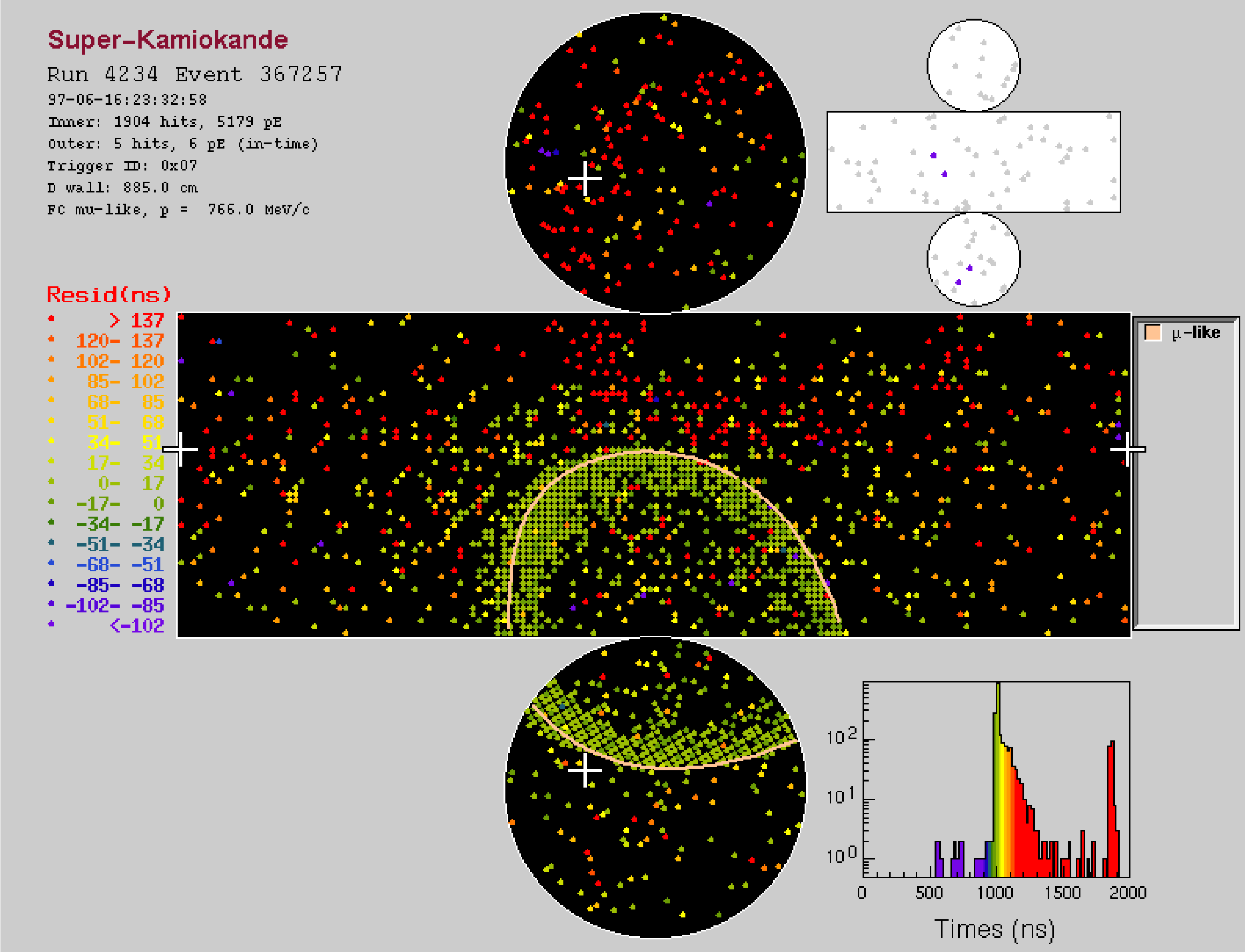


Super-Kamiokande

```
Run 4268 Event 7899421
97-06-23:03:15:57
Inner: 2652 hits, 5741 pE
Outer: 3 hits, 2 pE (in-time)
Trigger ID: 0x07
D wall: 506.0 cm
FC e-like, p =  621.9 MeV/c
```

SuperKamiokande: ν_μ

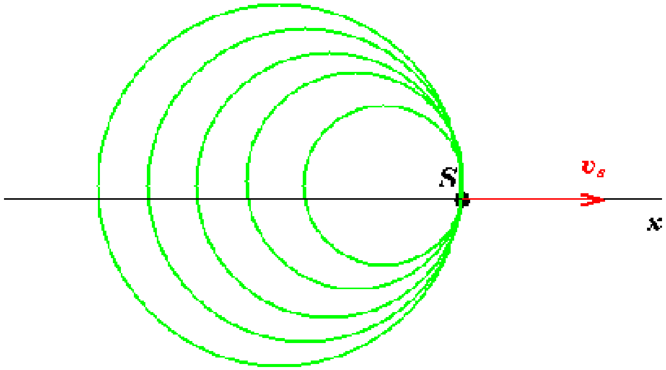


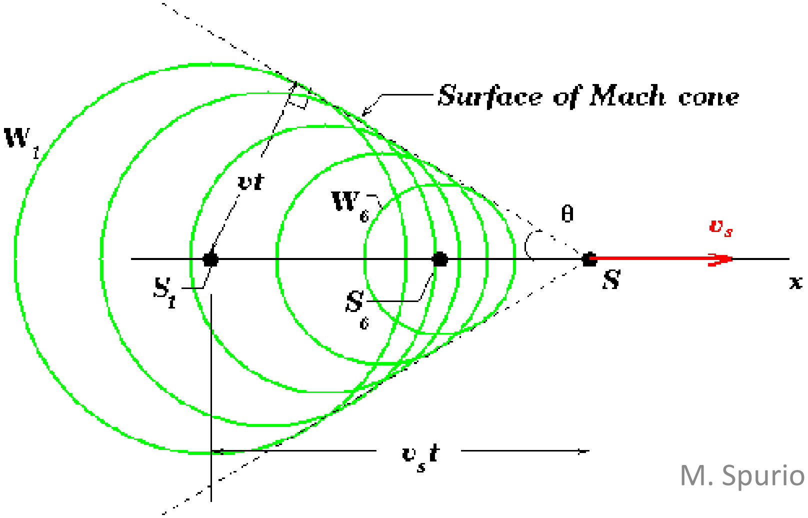


Super-Kamiokande

```
Run 4234 Event 367257
97-06-16:23:32:58
Inner: 1904 hits, 5179 pE
Outer: 5 hits, 6 pE (in-time)
Trigger ID: 0x07
D wall: 885.0 cm
FC mu-like, p =  766.0 MeV/c
```

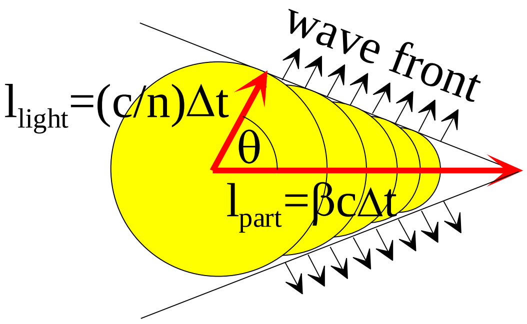
Cherenkov Radiation





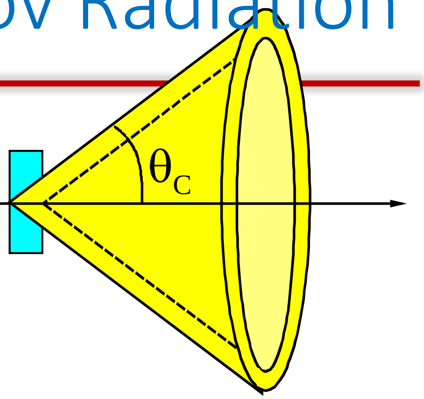
- As a charged particle travels, it disrupts the local electromagnetic field (EM) in a medium.
- Electrons in the atoms of the medium will be displaced and polarized by the passing EM field of a charged particle.
- Photons are emitted as an insulator's electrons restore themselves to equilibrium after the disruption has passed.
- In a conductor, the EM disruption can be restored without emitting a photon.
- In normal circumstances, these photons destructively interfere with each other and no radiation is detected.
- However, when the disruption travels faster than light is propagating through the medium, the photons constructively interfere and intensify the observed Cerenkov radiation.

Cherenkov Radiation



$$\boxed{\cos\theta_C = \frac{1}{n\beta}}$$

with $n = n(\lambda) \geq 1$

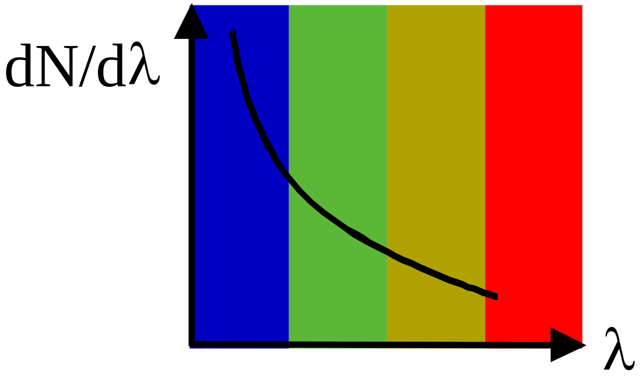


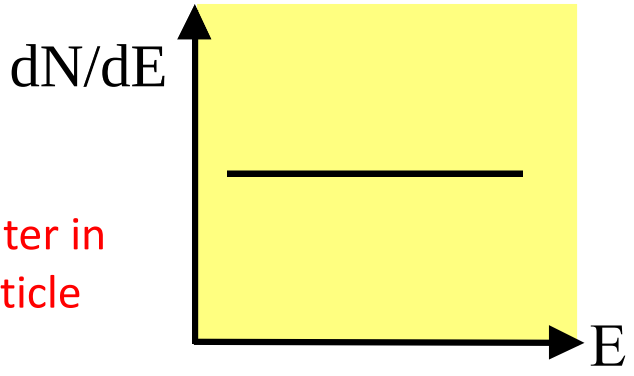
- Threshold velocity $\beta_T = 1/n \rightarrow \theta_T \sim 0$
- Angle of emission ($\beta=1$): $\theta_{max} = \arccos(1/n)$
- Distribution of emitted photons:

$$\frac{d^2N}{dx\,d\lambda} = \frac{2\pi z^2\alpha}{\lambda^2}\left(1-\frac{1}{\beta^2 n^2}\right) = \frac{2\pi\cdot z^2\alpha}{\lambda^2}\sin^2\theta_C$$

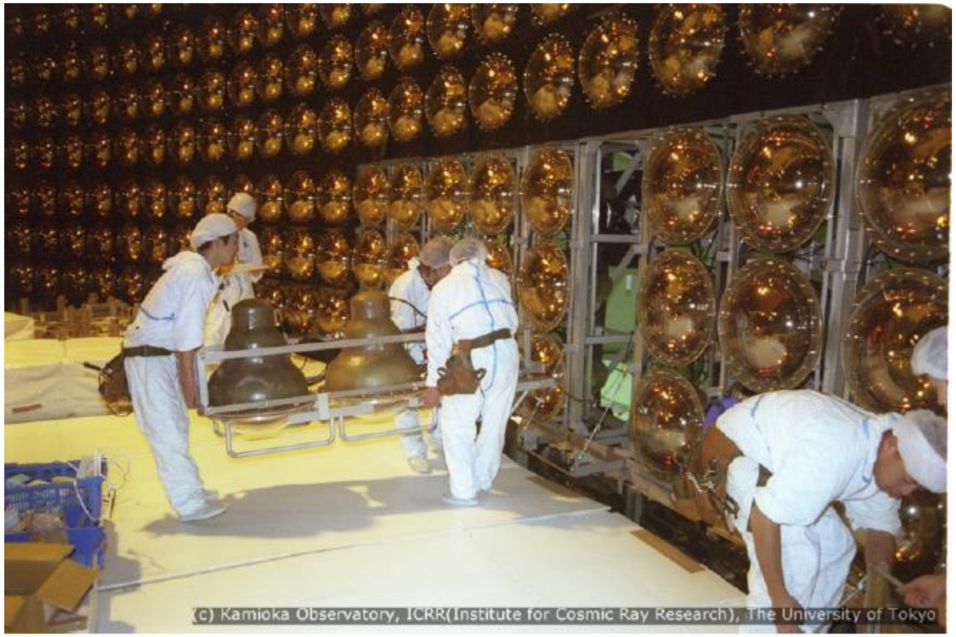
$$\frac{d^2N}{dx\,dE} = \frac{z^2\alpha}{\hbar c}\sin^2\vartheta_c .$$

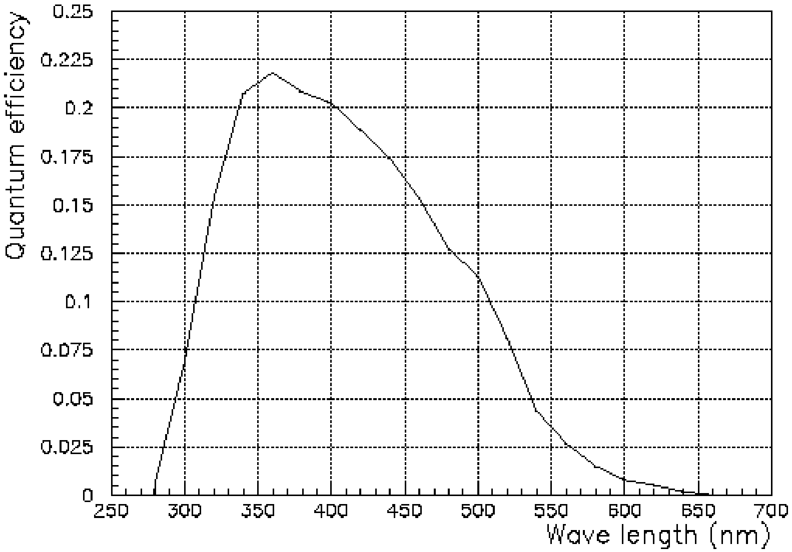
Question 5: Evaluate the number of Cherenkov photons in water in the λ=300-600 nm interval for a relativistic single charged particle





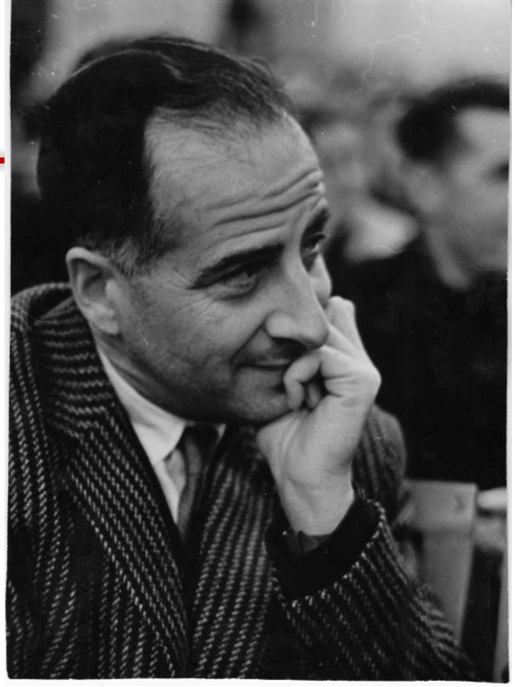
The PMTs


(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo



- **Quantum efficiency (Q.e.)**= probability that an incoming photon of a given wavelength produces a signal

The discovery of neutrino masses



- **Neutrino are massless in the Standard Model**
- **Lepton flavour is strictly conserved in SM**
- Idea of neutrinos being massive was first suggested by B. Pontecorvo, from proposal of neutrino oscillations

$|\nu_e>$, $|\nu_\mu>$, $|\nu_\tau>$ =Weak Interactions (WI) eigenstats

$|\nu^1>$, $|\nu^2>$, $|\nu^3>$ =Mass (Hamiltonian) eigenstats

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = V_{\mathrm{PNMS}} \begin{pmatrix} \nu^1 \\ \nu^2 \\ \nu^3 \end{pmatrix}$$

The Pontecorvo-Maki-Nakagawa-Sakata matrix

- **We are here**

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric and accelerator
$\theta_{23} \approx 50°$
$\left|\Delta m^2_{32}\right| \sim 2.5 \times 10^{-3}\mathrm{eV}^2$

Reactor and accelerator
$\theta_{13} \approx 8°$
Accelerator only: $\delta_{CP} = ?$

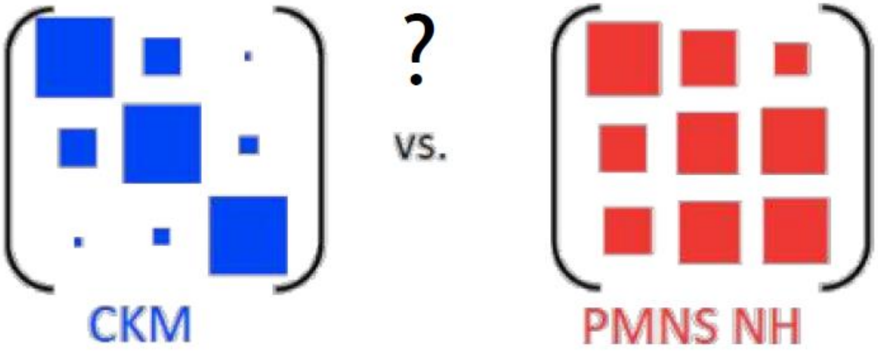
Solar and reactor
$\theta_{12} \approx 34°$
$\Delta m^2_{12} \sim 7.5 \times 10^{-5}\mathrm{eV}^2$

$0\nu\beta\beta$ experiments

Normal hierarchy

Inverted hierar

Quark sector

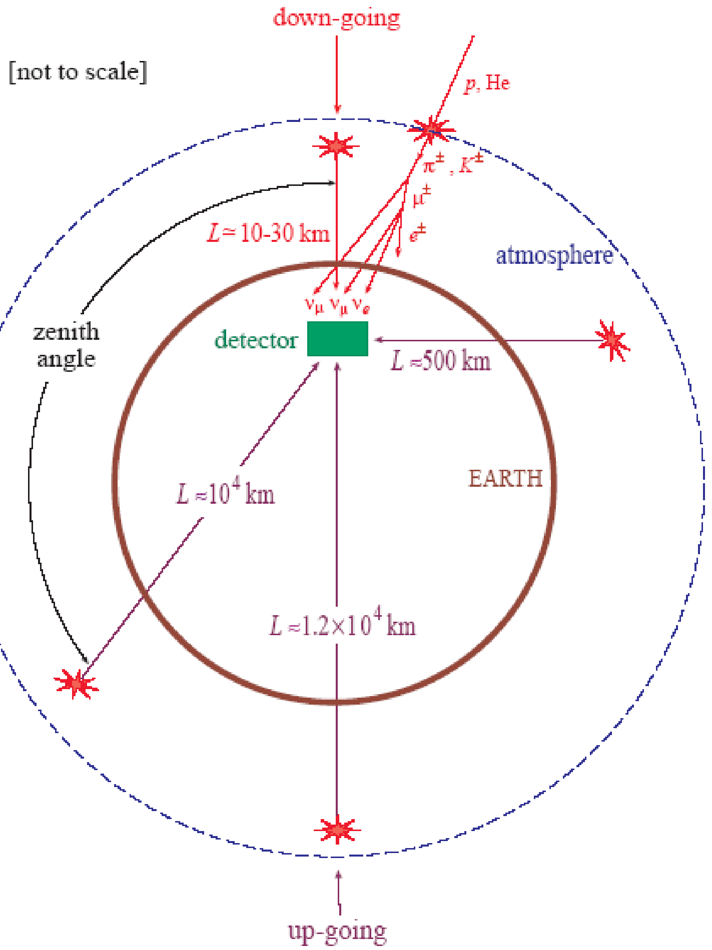


Lepton sector

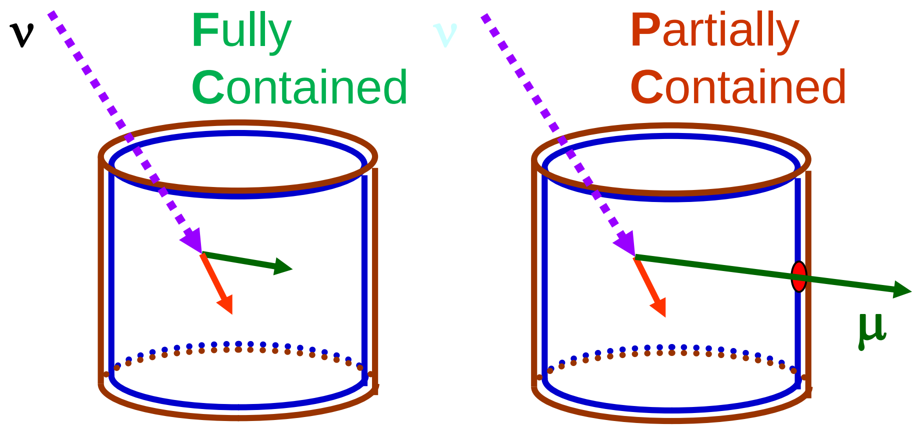
…with atmospheric neutrinos

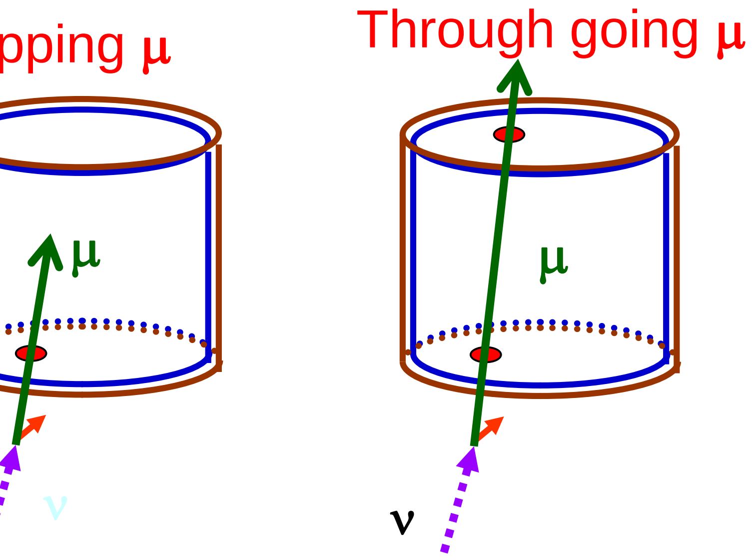
$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\vartheta_{23} \sin^2\left[1.27 \frac{\Delta m^2_{23}\, L}{E_\nu}\right]$$

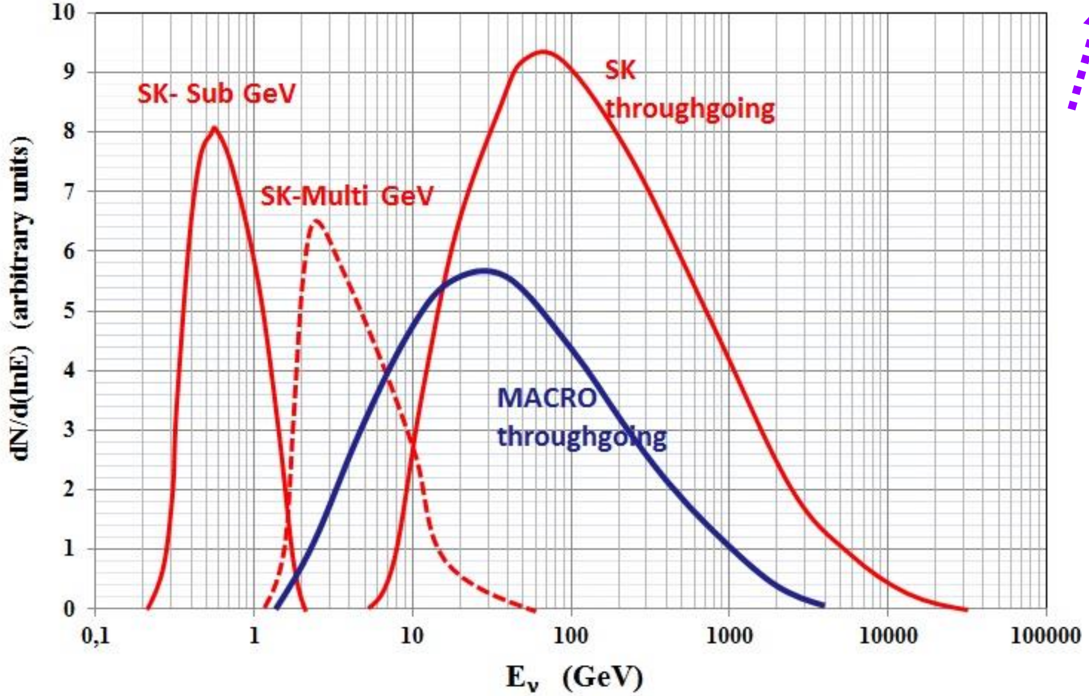
- $\boldsymbol{\Delta m^2_{23}, \vartheta_{23}}$ → from Nature;
- $\boldsymbol{E_\nu}$ = experimental parameter (energy distribution of neutrino giving a particular configuration of events)
- $\boldsymbol{L}$ = experimental parameter (neutrino path length from production to interaction)



ν energy/direction: event topology

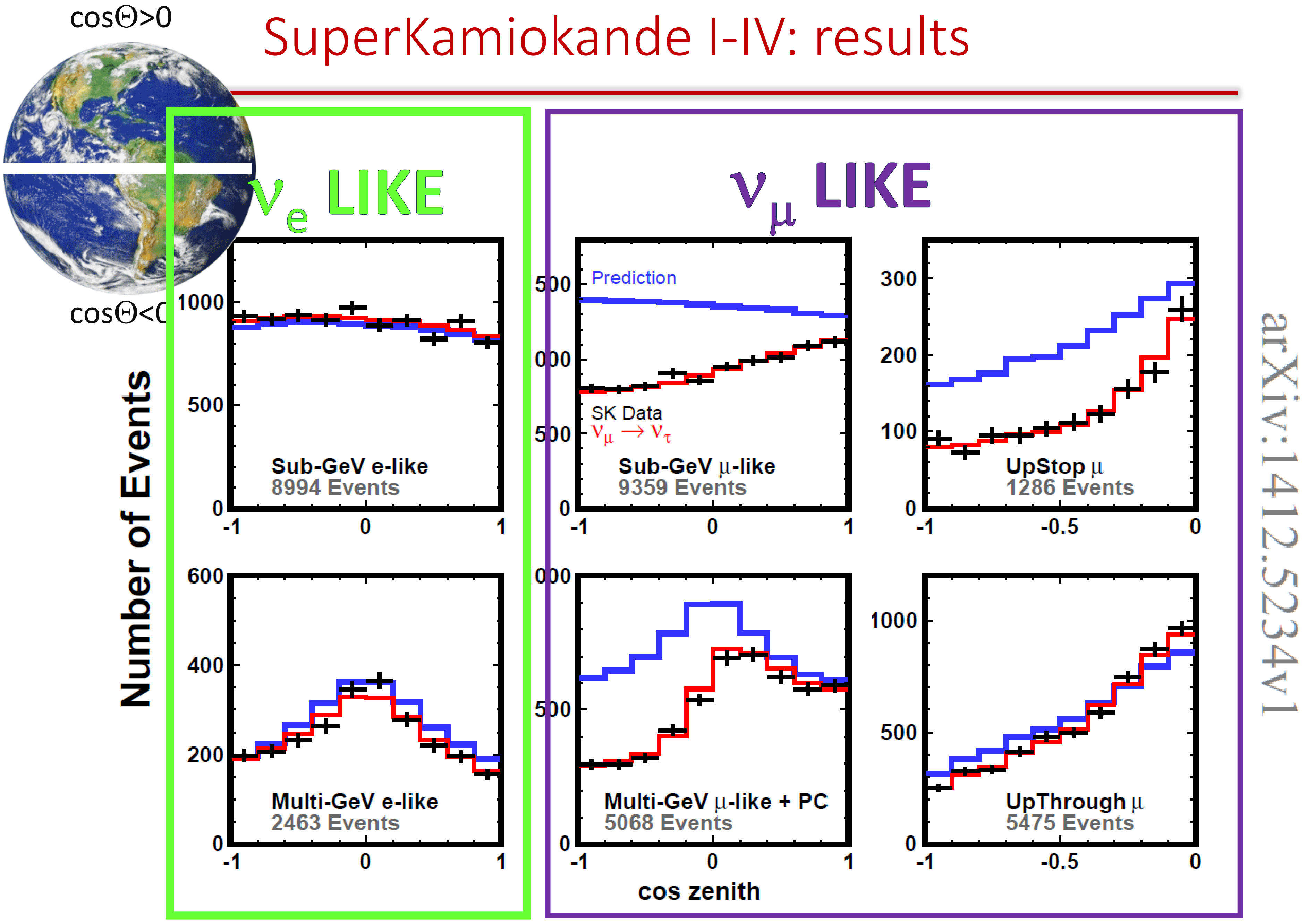




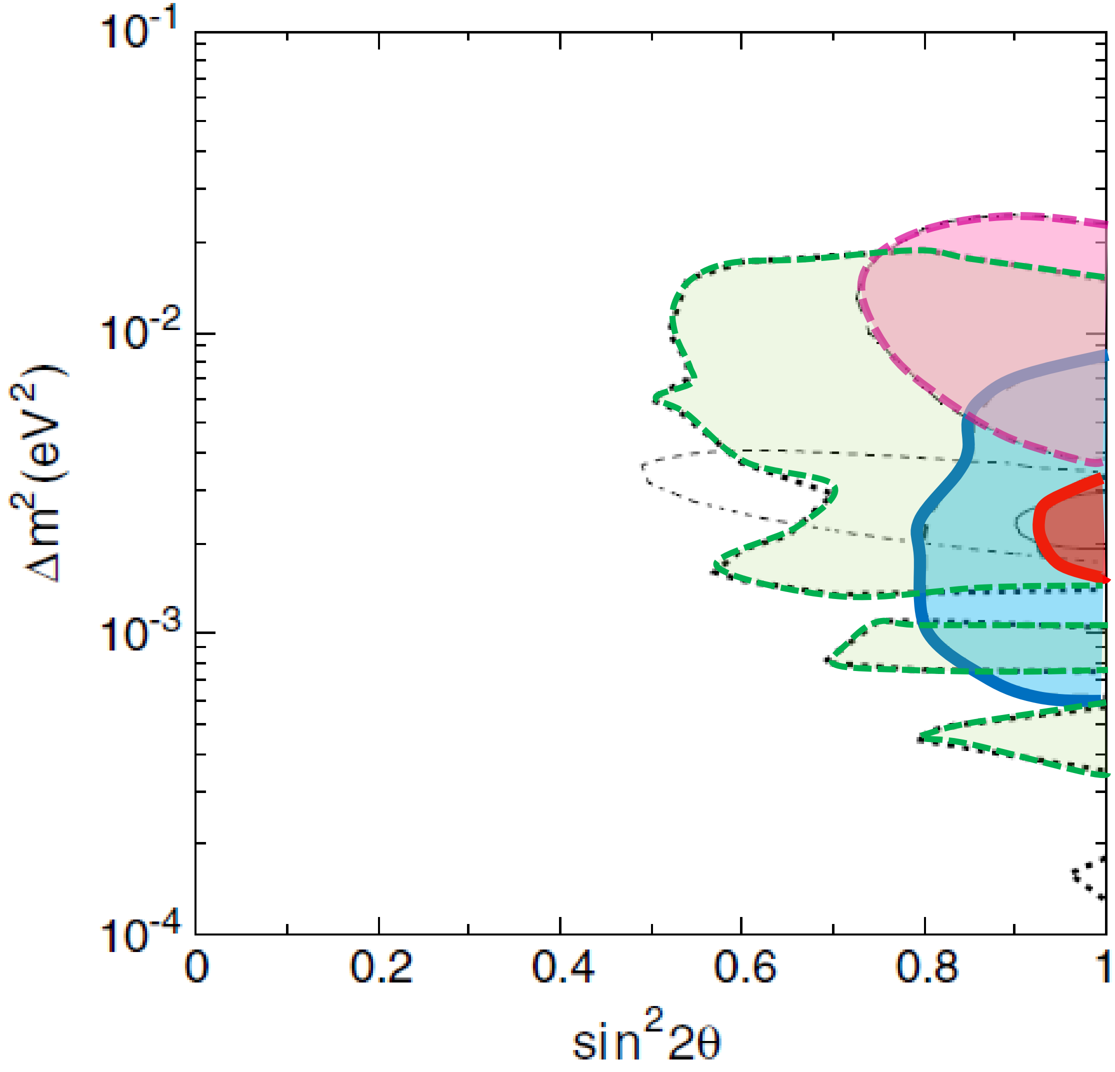


Energy spectrum (Monte Carlo) of atmospheric ν seen with different event topologies (Super-Kamiokande, MACRO)

SuperKamiokande I-IV: results



Discovery of neutrino oscillations



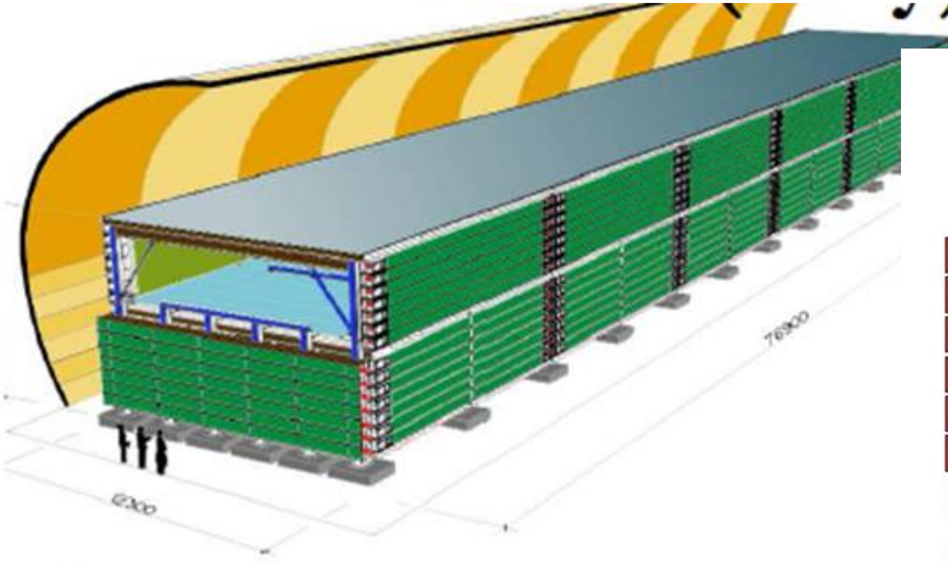
SuperKamiokande

Kamiokande

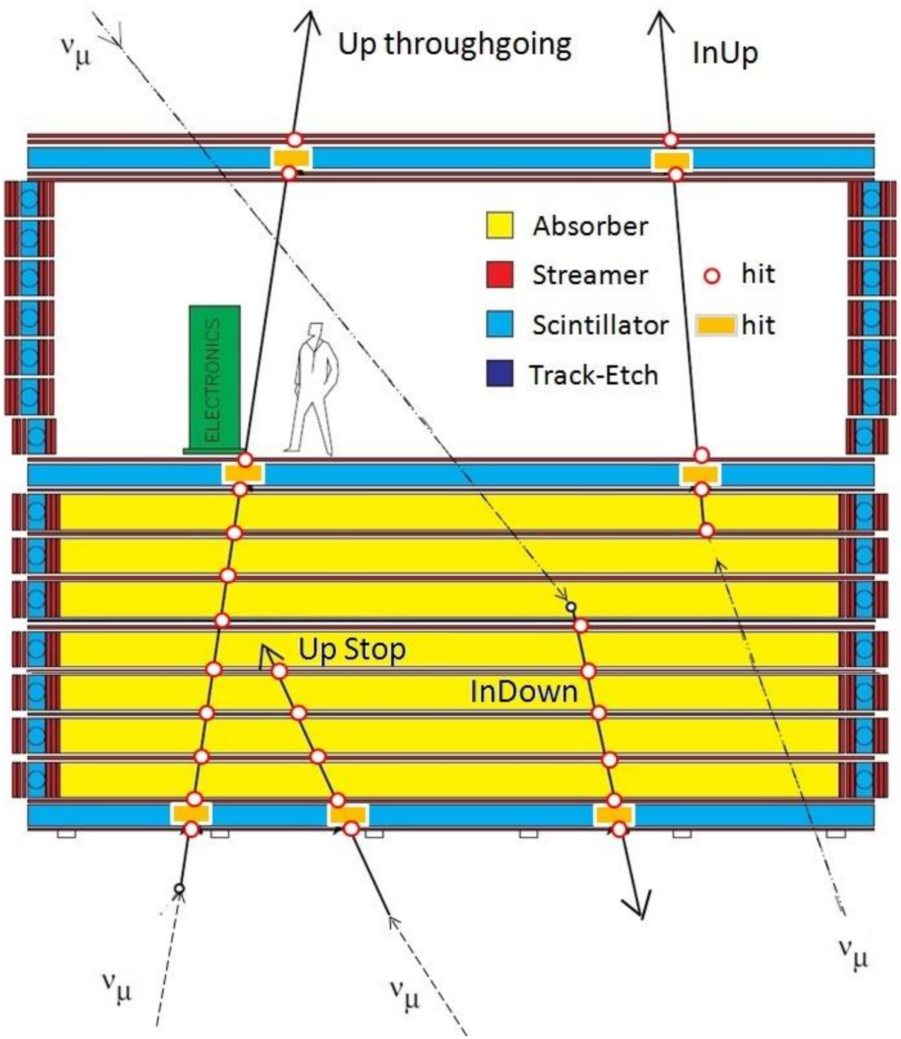
MACRO

Soudan 2

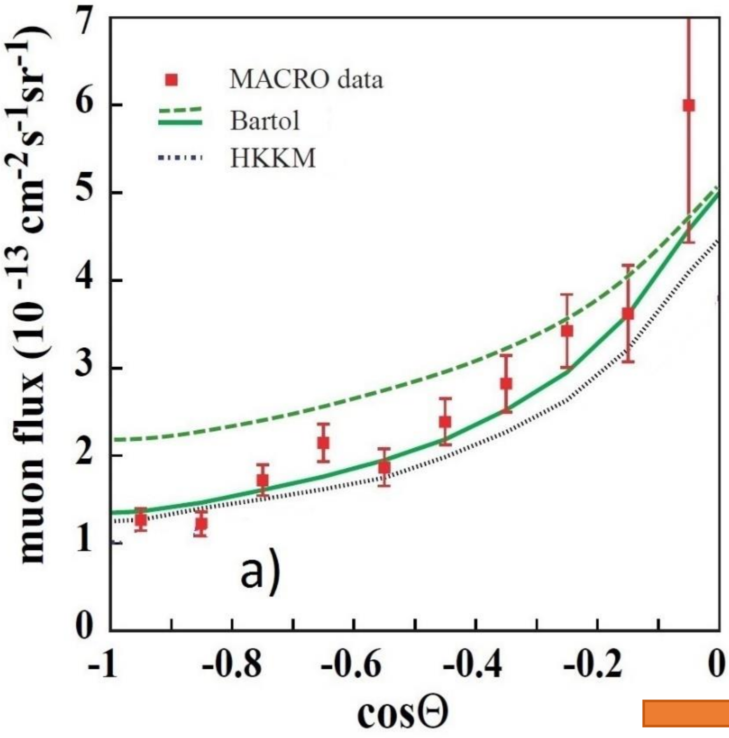
MACRO@ LNGS

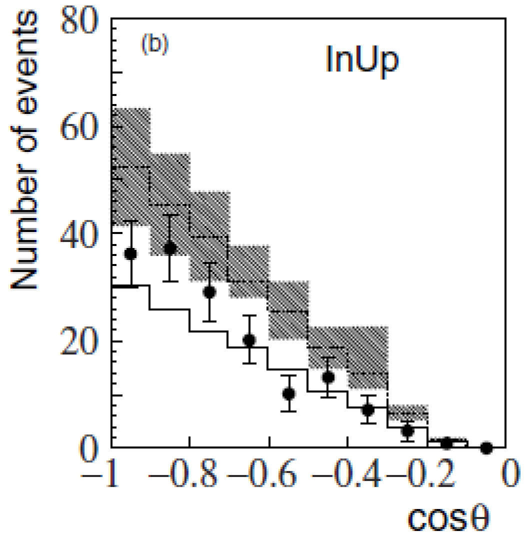


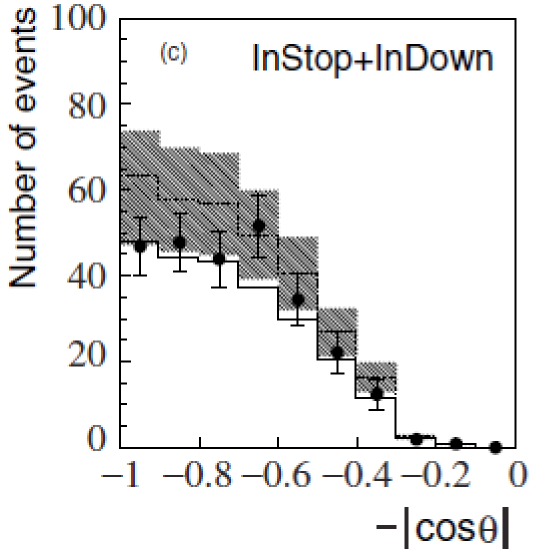
- ***Liquid scintillator counters***, (3 planes) for the measurement of **time** and **dE/dx**.
- ***Streamer tubes*** (14 planes), for the measurement of the track position (<1°);
- Detector mass: 5.3 kton
- 1 Up going muons ~ 10^6 downgoing muons
- Different neutrino topologies



The MACRO neutrino deficits

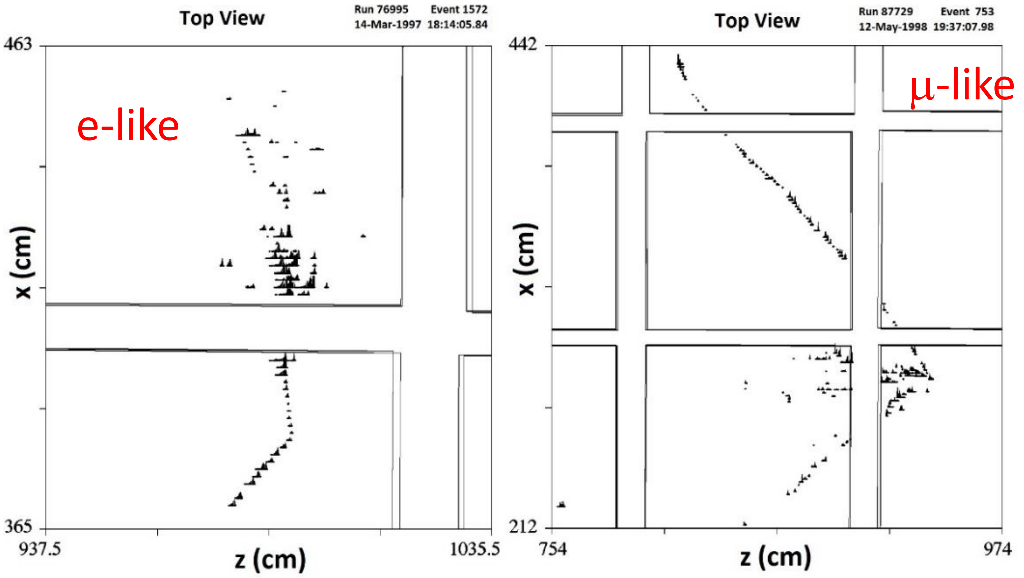




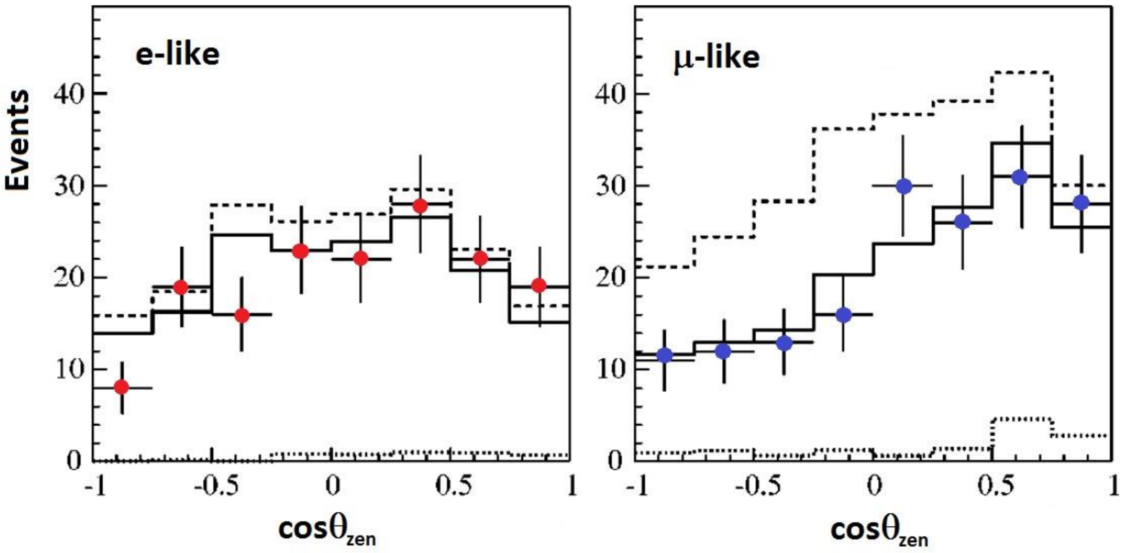


- Completely different topology w.r.t. SK
- Different experimental technique
- Deformation of the angular distribution w.r.t. expectation
- Missing events from the vertical direction
- Interpretation: oscillations
- The same oscillation parameters!

The Soudan II neutrino deficit

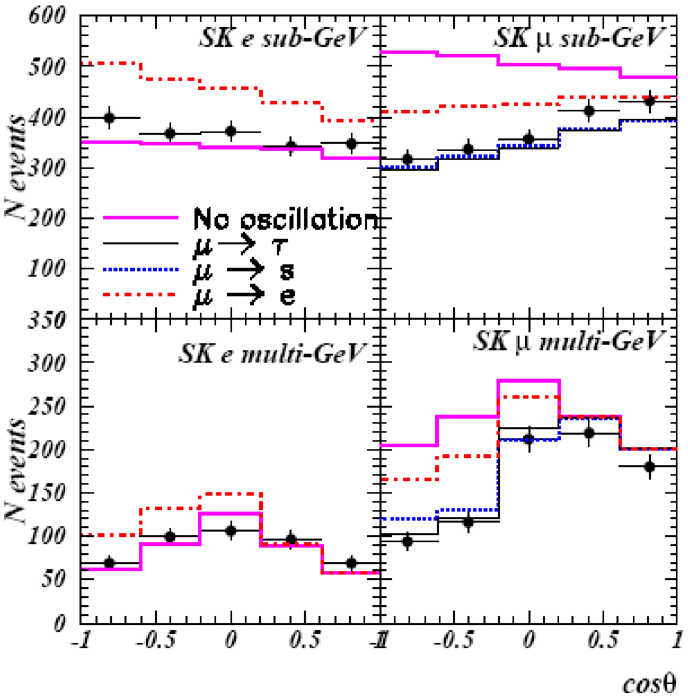


- Iron tracking calorimeter
- 770 t fiducial mass
- Active from 1989 to 2001 in the Soudan Mine (USA)
- (P)contained events
- μ-like deficit from below

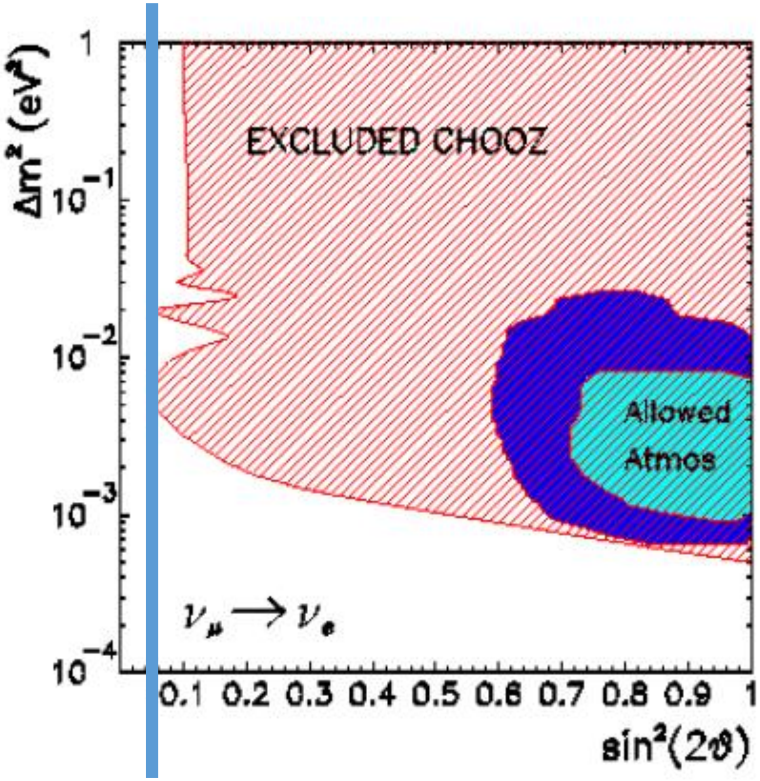


Why not $\nu_\mu \to \nu_e$?

- i.e., through the ϑ_{13} angle of the PMNS matrix



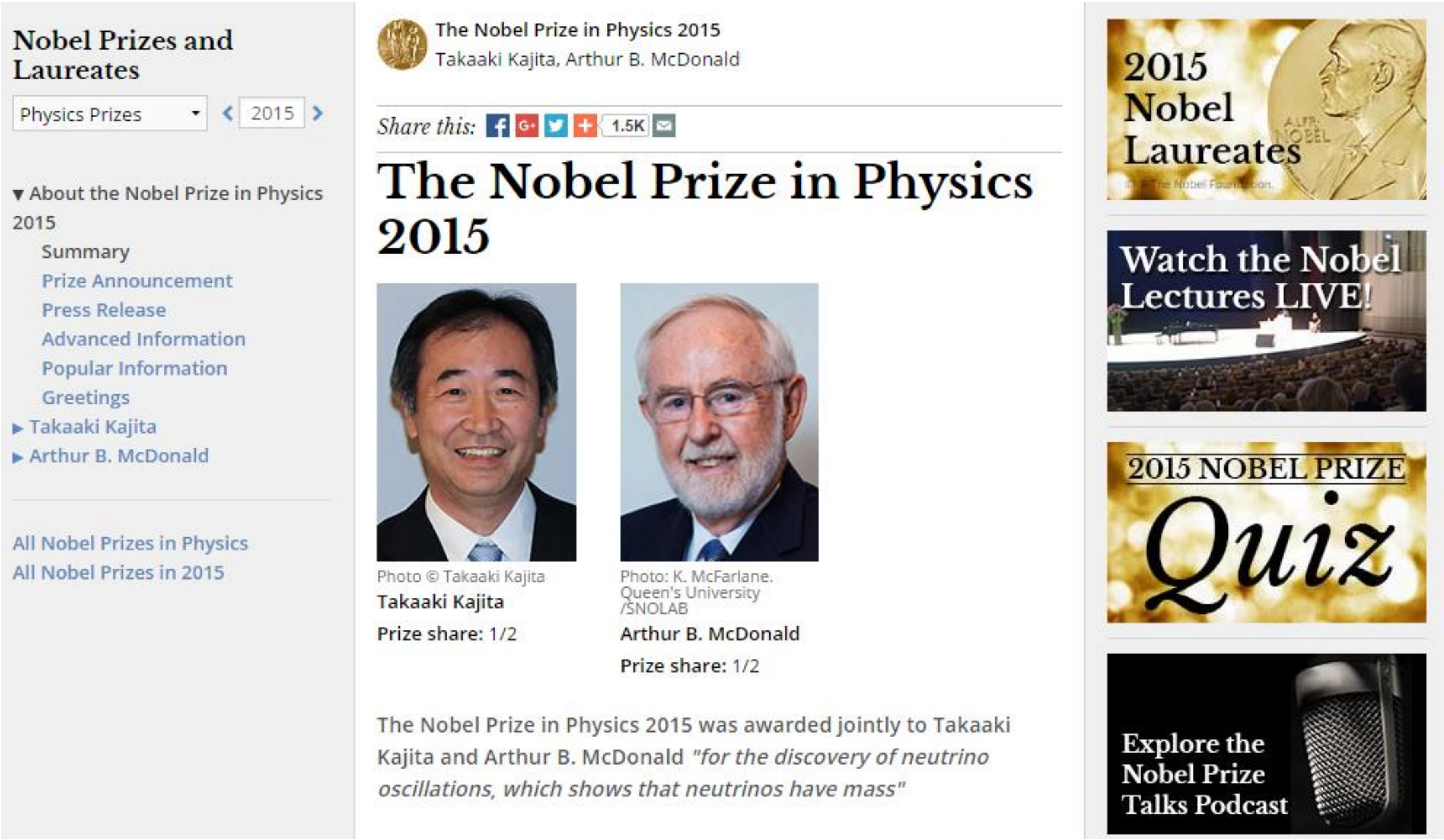
Apollonio et al., CHOOZ Coll., Phys.Lett.B466 (1999) 415



PDG value:

0.095±0.010

The 2015 Nobel Prize



▾ About the Nobel Prize in Physics 2015

- Summary
- Prize Announcement
- Press Release
- Advanced Information
- Popular Information
- Greetings

▸ Takaaki Kajita

▸ Arthur B. McDonald

All Nobel Prizes in Physics
All Nobel Prizes in 2015

The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

The Nobel Prize in Physics 2015

Photo © Takaaki Kajita
Takaaki Kajita
Prize share: 1/2

Photo: K. McFarlane. Queen's University /SNOLAB
Arthur B. McDonald
Prize share: 1/2

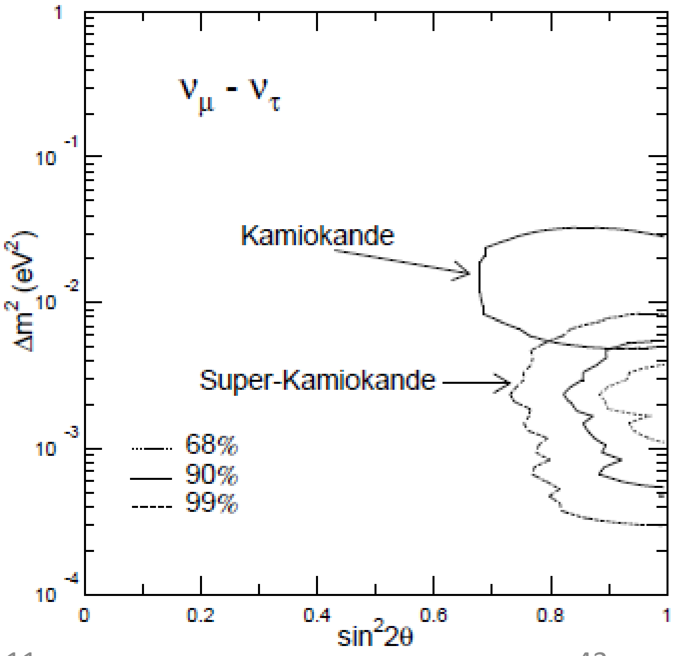
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

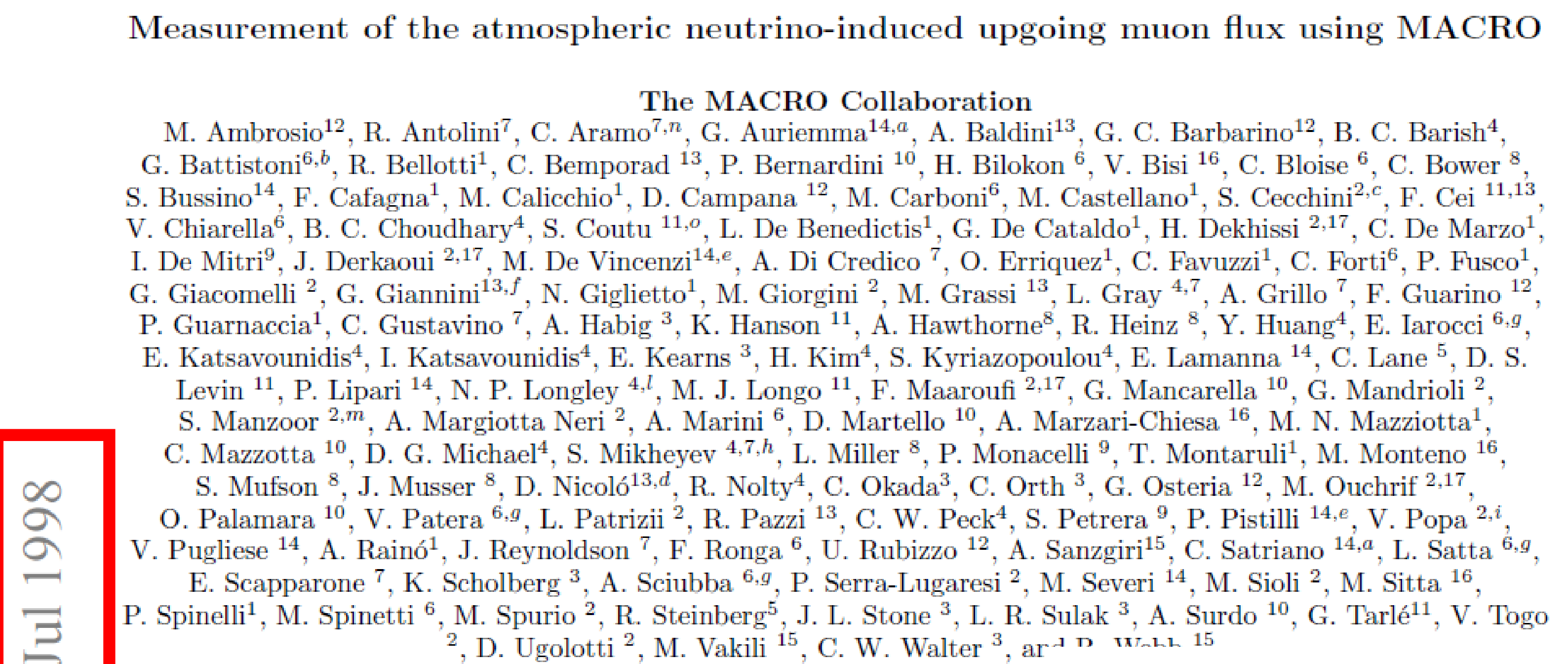
Evidence for oscillation of atmospheric neutrinos

The Super-Kamiokande Collaboration

Y.Fukuda[a], T.Hayakawa[a], E.Ichihara[a], K.Inoue[a], K.Ishihara[a], H.Ishino[a], Y.Itow[a], T.Kajita[a], J.Kameda[a], S.Kasuga[a], K.Kobayashi[a], Y.Kobayashi[a], Y.Koshio[a], M.Miura[a], M.Nakahata[a], S.Nakayama[a], A.Okada[a], K.Okumura[a], N.Sakurai[a], M.Shiozawa[a], Y.Suzuki[a], Y.Takeuchi[a], Y.Totsuka[a], S.Yamada[a], M.Earl[b], A.Habig[b], E.Kearns[b], M.D.Messier[b], K.Scholberg[b], J.L.Stone[b], L.R.Sulak[b], C.W.Walter[b], M.Goldhaber[c], T.Barszczak[d], D.Casper[d], W.Gajewski[d], P.G.Halverson[d,*], J.Hsu[d], W.R.Kropp[d], L.R. Price[d], F.Reines[d], M.Smy[d], H.W.Sobel[d], M.R.Vagins[d], K.S.Ganezer[e], W.E.Keig[e], R.W.Ellsworth[f], S.Tasaka[g], J.W.Flanagan[h,†] A.Kibayashi[h], J.G.Learned[h], S.Matsuno[h], V.J.Stenger[h], D.Takemori[h], T.Ishii[i], J.Kanzaki[i], T.Kobayashi[i], S.Mine[i], K.Nakamura[i], K.Nishikawa[i], Y.Oyama[i], A.Sakai[i], M.Sakuda[i], O.Sasaki[i], S.Echigo[j], M.Kohama[j], A.T.Suzuki[j], T.J.Haines[k,d] E.Blaufuss[l], B.K.Kim[l], R.Sanford[l], R.Svoboda[l], M.L.Chen[m], Z.Conner[m,‡] J.A.Goodman[m], G.W.Sullivan[m], J.Hill[n], C.K.Jung[n], K.Martens[n], C.Mauger[n], C.McGrew[n], E.Sharkey[n], B.Viren[n], C.Yanagisawa[n], W.Doki[o], K.Miyano[o], H.Okazawa[o], C.Saji[o], M.Takahata[o], Y.Nagashima[p], M.Takita[p], T.Yamaguchi[p], M.Yoshida[p], S.B.Kim[q], M.Etoh[r], K.Fujita[r], A.Hasegawa[r], T.Hasegawa[r], S.Hatakeyama[r], T.Iwamoto[r], M.Koga[r], T.Maruyama[r], H.Ogawa[r], J.Shirai[r], A.Suzuki[r], F.Tsushima[r], M.Koshiba[s], M.Nemoto[t], K.Nishijima[t], T.Futagami[u], Y.Hayato[u,§], Y.Kanaya[u], K.Kaneyuki[u], Y.Watanabe[u], D.Kielczewska[v,d], R.A.Doyle[w], J.S.George[w], A.L.Stachyra[w], L.L.Wai[w,**], R.J.Wilkes[w], K.K.Young[w]

[a] *Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo 188*
[b] *Department of Physics, Boston University, Boston, MA 02215, U*
[c] *Physics Department, Brookhaven National Laboratory, Upton, NY 1197*
[d] *Department of Physics and Astronomy, University of California, Irvine, Irvine, CA*
[e] *Department of Physics, California State University, Dominguez Hills, Carson,*
[f] *Department of Physics, George Mason University, Fairfax, VA 22030,*
[g] *Department of Physics, Gifu University, Gifu, Gifu 501-1193, Jap*
[h] *Department of Physics and Astronomy, University of Hawaii, Honolulu, HI*
[i] *Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization*
305-0801, Japan
[j] *Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Ja*
[k] *Physics Division, P-23, Los Alamos National Laboratory, Los Alamos, NM*
[l] *Department of Physics and Astronomy, Louisiana State University, Baton Rouge,*
[m] *Department of Physics, University of Maryland, College Park, MD 207*
[n] *Department of Physics and Astronomy, State University of New York, Stony Brook,*
[o] *Department of Physics, Niigata University, Niigata, Niigata 950-2181,*
[p] *Department of Physics, Osaka University, Toyonaka, Osaka 560-0043,*
[q] *Department of Physics, Seoul National University, Seoul 151-742, K*
[r] *Department of Physics, Tohoku University, Sendai, Miyagi 980-8578,*
[s] *The University of Tokyo, Tokyo 113-0033, Japan*
[t] *Department of Physics, Tokai University, Hiratsuka, Kanagawa 259-129*
[u] *Department of Physics, Tokyo Institute for Technology, Meguro, Tokyo 152-*
[v] *Institute of Experimental Physics, Warsaw University, 00-681 Warsaw,*
[w] *Department of Physics, University of Washington, Seattle, WA 98195-15*





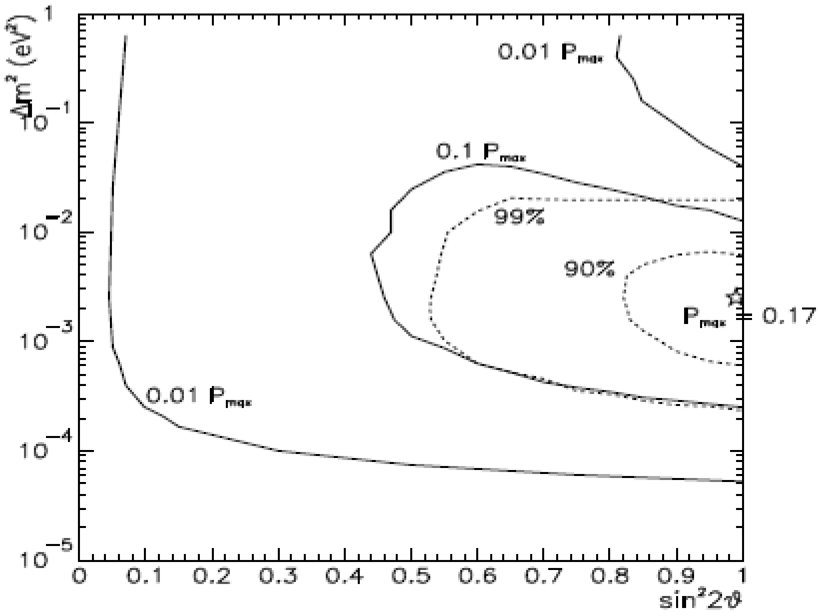
Measurement of the atmospheric neutrino-induced upgoing muon flux using MACRO

The MACRO Collaboration

M. Ambrosio[12], R. Antolini[7], C. Aramo[7,n], G. Auriemma[14,a], A. Baldini[13], G. C. Barbarino[12], B. C. Barish[4], G. Battistoni[6,b], R. Bellotti[1], C. Bemporad [13], P. Bernardini [10], H. Bilokon [6], V. Bisi [16], C. Bloise [6], C. Bower [8], S. Bussino[14], F. Cafagna[1], M. Calicchio[1], D. Campana [12], M. Carboni[6], M. Castellano[1], S. Cecchini[2,c], F. Cei [11,13], V. Chiarella[6], B. C. Choudhary[4], S. Coutu [11,o], L. De Benedictis[1], G. De Cataldo[1], H. Dekhissi [2,17], C. De Marzo[1], I. De Mitri[9], J. Derkaoui [2,17], M. De Vincenzi[14,e], A. Di Credico [7], O. Erriquez[1], C. Favuzzi[1], C. Forti[6], P. Fusco[1], G. Giacomelli [2], G. Giannini[13,f], N. Giglietto[1], M. Giorgini [2], M. Grassi [13], L. Gray [4,7], A. Grillo [7], F. Guarino [12], P. Guarnaccia[1], C. Gustavino [7], A. Habig [3], K. Hanson [11], A. Hawthorne[8], R. Heinz [8], Y. Huang[4], E. Iarocci [6,g], E. Katsavounidis[4], I. Katsavounidis[4], E. Kearns [3], H. Kim[4], S. Kyriazopoulou[4], E. Lamanna [14], C. Lane [5], D. S. Levin [11], P. Lipari [14], N. P. Longley [4,l], M. J. Longo [11], F. Maaroufi [2,17], G. Mancarella [10], G. Mandrioli [2], S. Manzoor [2,m], A. Margiotta Neri [2], A. Marini [6], D. Martello [10], A. Marzari-Chiesa [16], M. N. Mazziotta[1], C. Mazzotta [10], D. G. Michael[4], S. Mikheyev [4,7,h], L. Miller [8], P. Monacelli [9], T. Montaruli[1], M. Monteno [16], S. Mufson [8], J. Musser [8], D. Nicoló[13,d], R. Nolty[4], C. Okada[3], C. Orth [3], G. Osteria [12], M. Ouchrif [2,17], O. Palamara [10], V. Patera [6,g], L. Patrizii [2], R. Pazzi [13], C. W. Peck[4], S. Petrera [9], P. Pistilli [14,e], V. Popa [2,i], V. Pugliese [14], A. Rainó[1], J. Reynoldson [7], F. Ronga [6], U. Rubizzo [12], A. Sanzgiri[15], C. Satriano [14,a], L. Satta [6,g], E. Scapparone [7], K. Scholberg [3], A. Sciubba [6,g], P. Serra-Lugaresi [2], M. Severi [14], M. Sioli [2], M. Sitta [16], P. Spinelli[1], M. Spinetti [6], M. Spurio [2], R. Steinberg[5], J. L. Stone [3], L. R. Sulak [3], A. Surdo [10], G. Tarlé[11], V. Togo [2], D. Ugolotti [2], M. Vakili [15], C. W. Walter [3], and R. Webb [15]

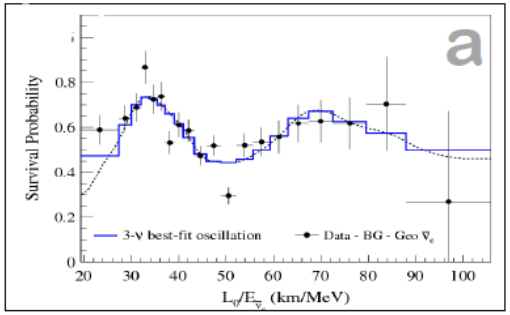
1. Dipartimento di Fisica dell'Università di Bari and INF
2. Dipartimento di Fisica dell'Università di Bologna and INF
3. Physics Department, Boston University, Boston,
4. California Institute of Technology, Pasadena, C.
5. Department of Physics, Drexel University, Philadelph
6. Laboratori Nazionali di Frascati dell'INFN, 00044 Fr
7. Laboratori Nazionali del Gran Sasso dell'INFN, 67010 A
8. Depts. of Physics and of Astronomy, Indiana University, Bl
9. Dipartimento di Fisica dell'Università dell'Aquila and INF
10. Dipartimento di Fisica dell'Università di Lecce and IN
11. Department of Physics, University of Michigan, Ann A
12. Dipartimento di Fisica dell'Università di Napoli and IN
13. Dipartimento di Fisica dell'Università di Pisa and IN
14. Dipartimento di Fisica dell'Università di Roma "La Sapienza"
15. Physics Department, Texas A&M University, College St
16. Dipartimento di Fisica Sperimentale dell'Università di Torino
17. Faculty of Sciences, University Mohamed I, B.P. 4

a Also Università della Basilicata, 85100 Potenz
b Also INFN Milano, 20133 Milano, Italy
c Also Istituto TESRE/CNR, 40129 Bologna,

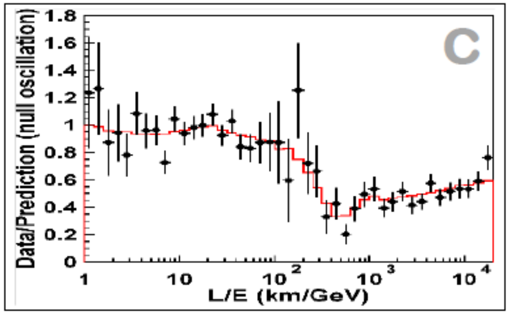


Now and next... [From E. Lisi (INFN-Bari)]

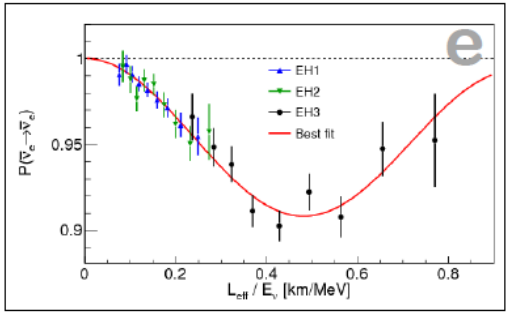
e→e (KamLAND, KL)



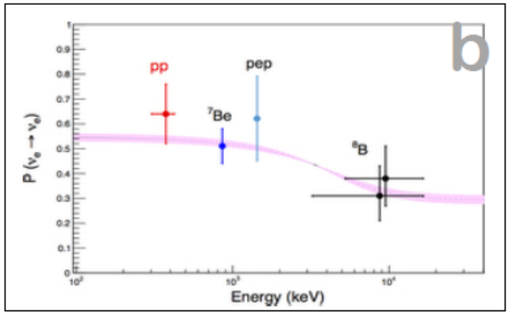
μ→μ (Atmospheric)



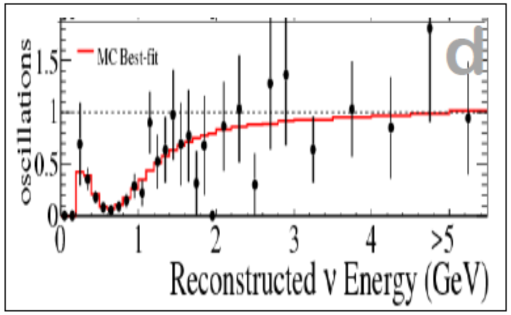
e→e (SBL Reac.)



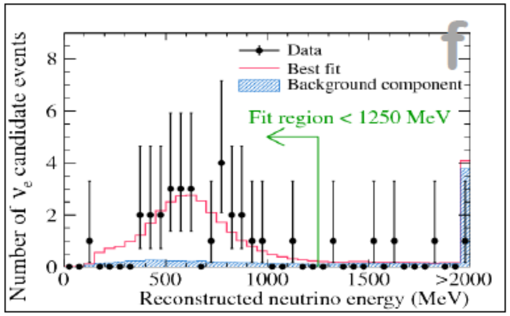
e→e (Solar)



μ→μ (LBL Accel)



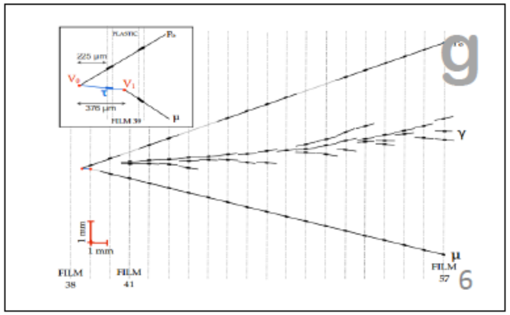
μ→e (LBL Accel)



LBL = Long baseline (few x 100 km); **SBL = short baseline** (~1 km)

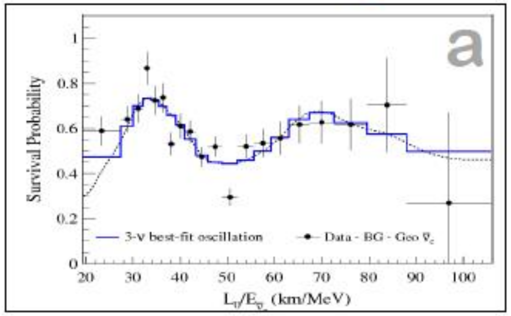
(a) KamLAND reactor [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K LBL accel.; (e) Daya Bay [plot], RENO, Double Chooz SBL reactor; (f) T2K [plot], MINOS, NOvA LBL accel.; (g) OPERA [plot] LBL accel., Super-K and IC-CD atmospheric.

μ→τ (OPERA, SK, DC)

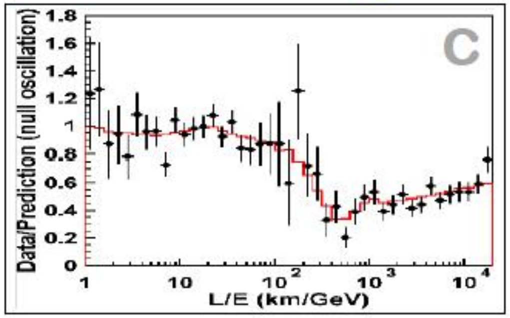


Now and next… [From E. Lisi (INFN-Bari)]

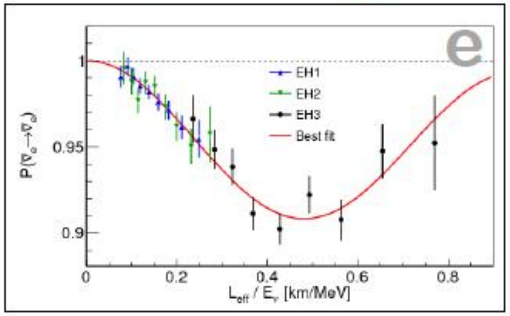
$e \rightarrow e \; (\delta m^2, \theta_{12})$



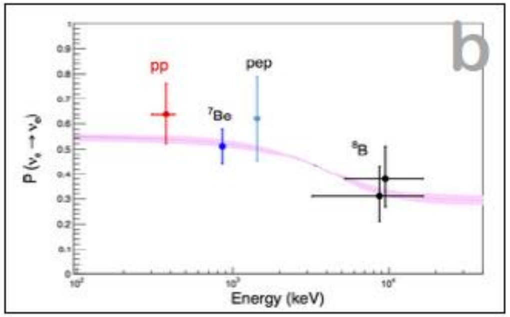
$\mu \rightarrow \mu \; (\Delta m^2, \theta_{23})$



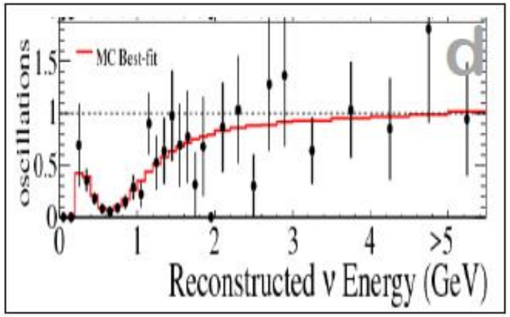
$e \rightarrow e \; (\Delta m^2, \theta_{13})$



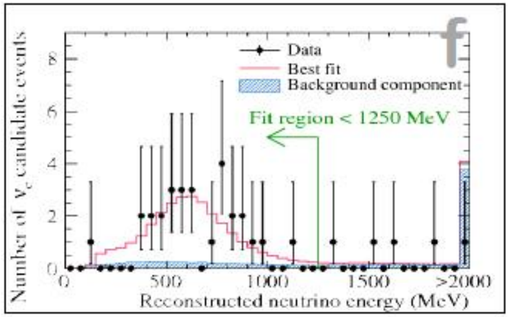
$e \rightarrow e \; (\delta m^2, \theta_{12})$



$\mu \rightarrow \mu \; (\Delta m^2, \theta_{23})$



$\mu \rightarrow e \; (\Delta m^2, \theta_{13}, \theta_{23})$

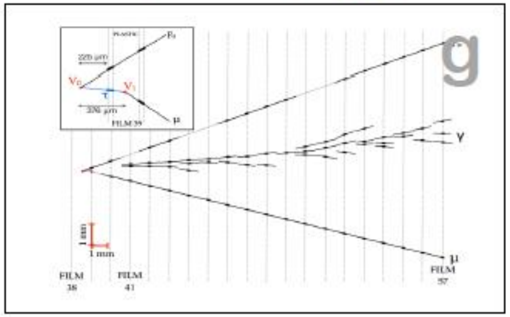


Terra cognita:

$\delta m^2 \quad |\Delta m^2|$

$\theta_{12} \quad \theta_{23} \quad \theta_{13}$

$\mu \rightarrow \tau \; (\Delta m^2, \theta_{23})$



Terra incognita

5 Knowns:

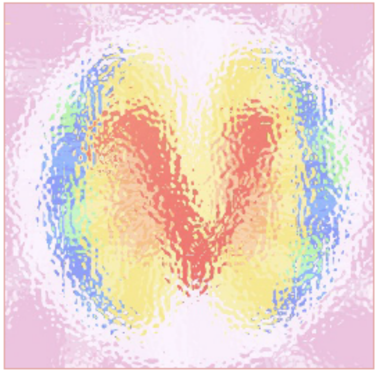
δm^2 ~ 7 x 10^{-5} eV^2

Δm^2 ~ 2 x 10^{-3} eV^2

$\sin^2\theta_{12}$ ~ 0.3

$\sin^2\theta_{23}$ ~ 0.5

$\sin^2\theta_{13}$ ~ 0.02



5 Unknowns:

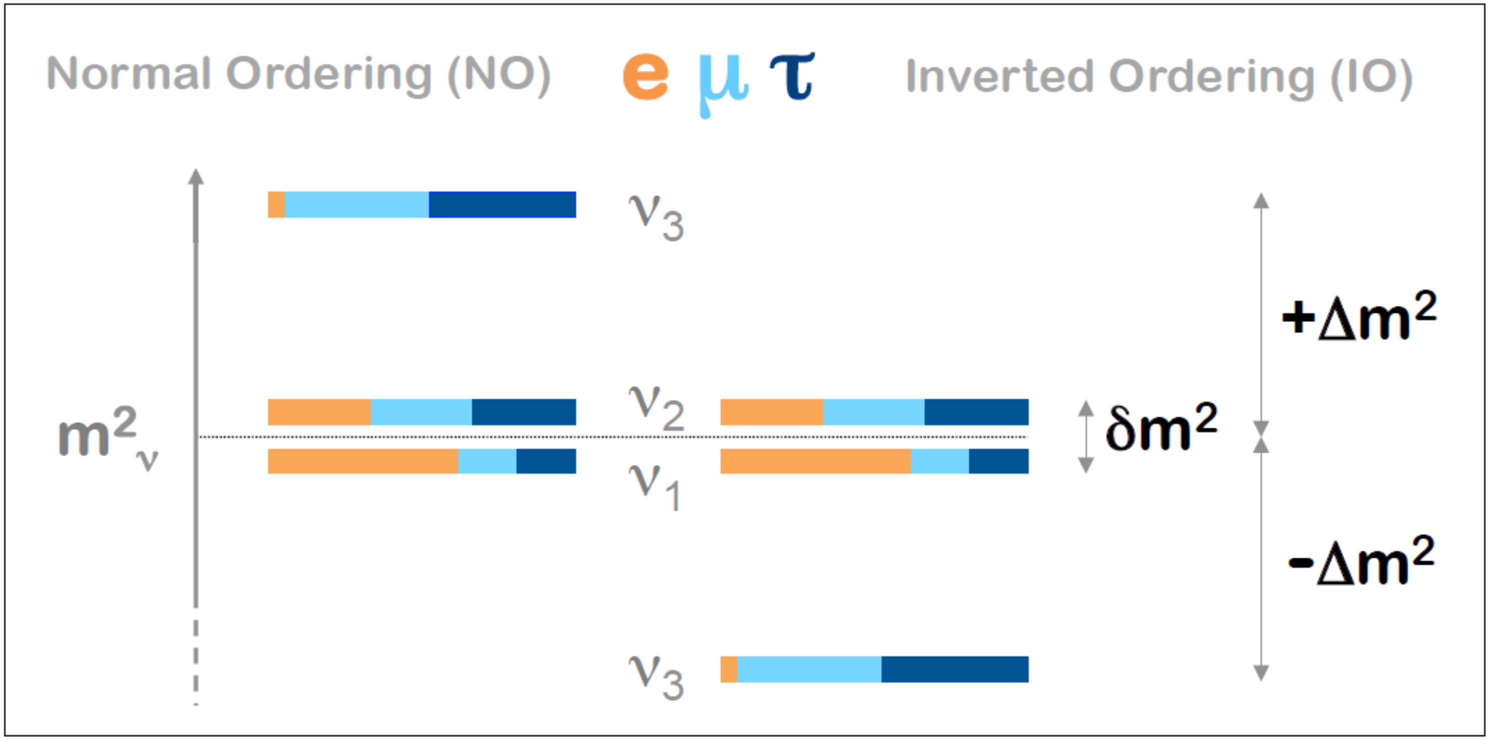
δ = Dirac CPV phase

sign(Δm^2) = ordering

octant(θ_{23})

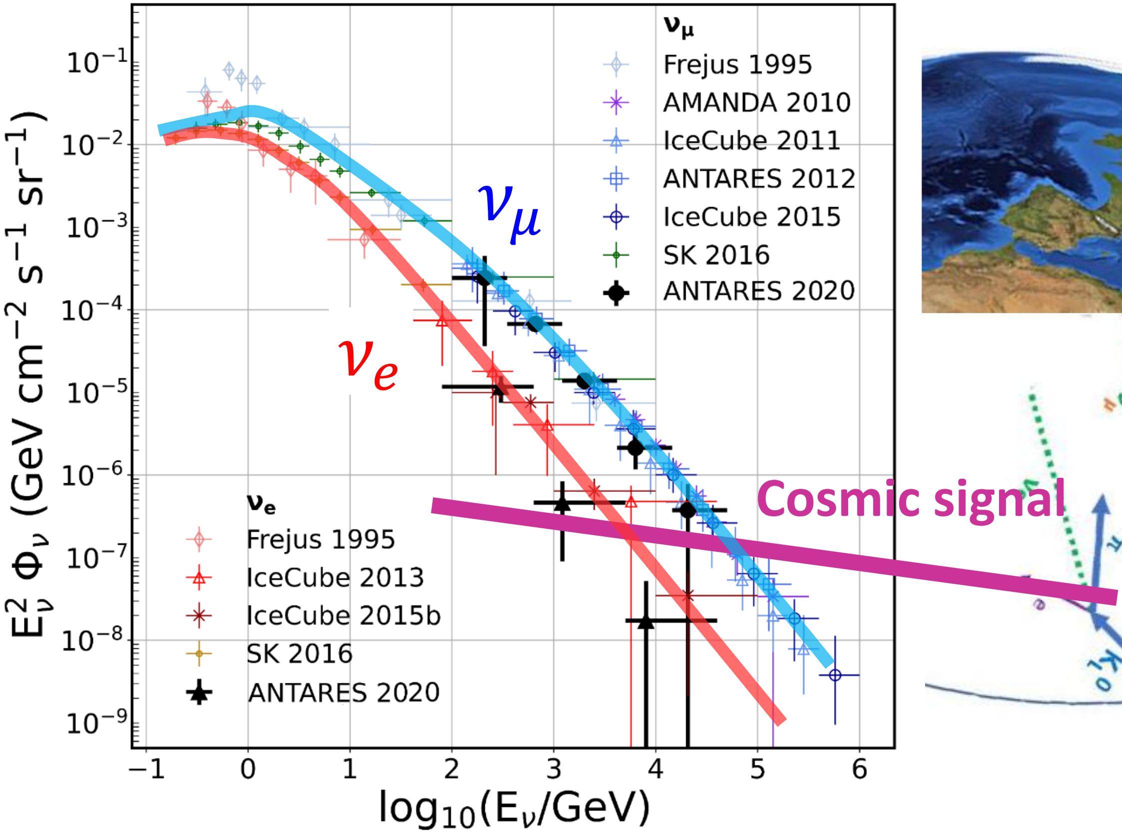
absolute mass scale

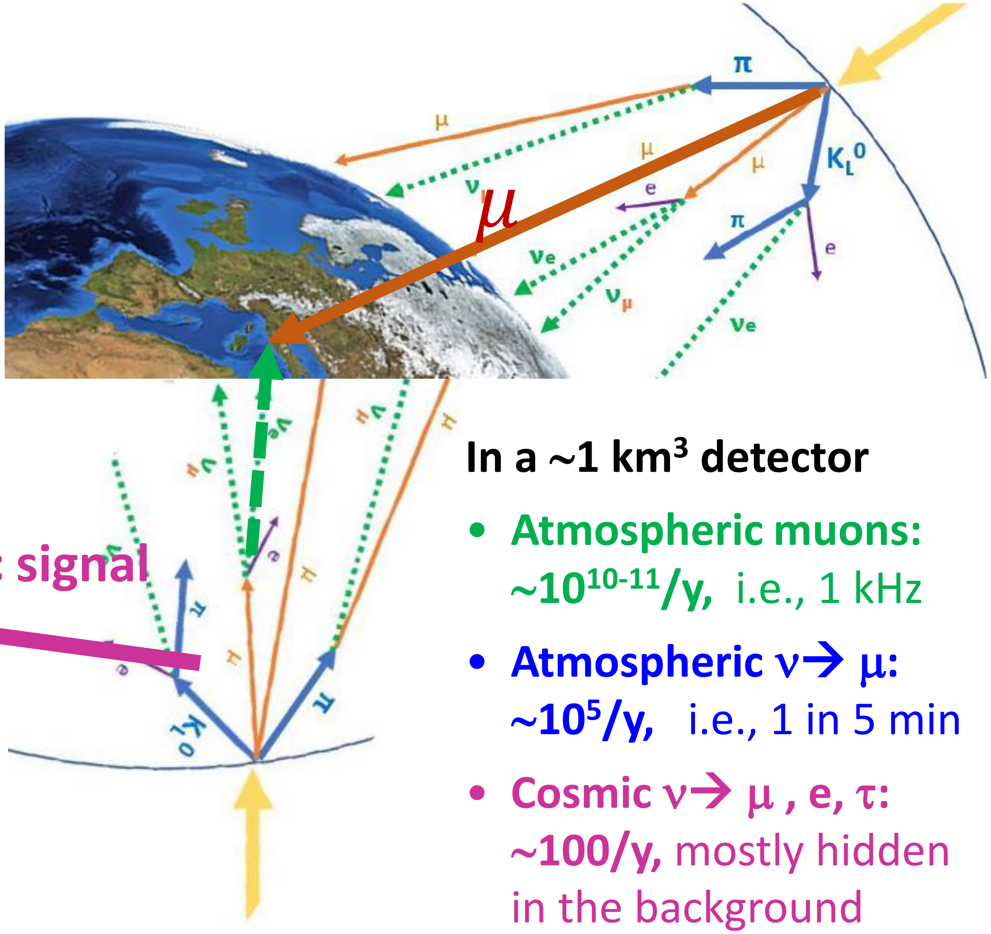
Dirac/Majorana nature



Atmospheric neutrinos: background for cosmic ν

arXiv:2101.12170





In a ~1 km^3 detector

- **Atmospheric muons: ~10^{10-11}/y,** i.e., 1 kHz
- **Atmospheric $\nu\rightarrow\mu$: ~10^5/y,** i.e., 1 in 5 min
- **Cosmic $\nu\rightarrow\mu$, e, τ: ~100/y,** mostly hidden in the background

Solution of question 2)

- The event rate of atmospheric neutrinos can be obtained from Fig. 11.9.
- With a threshold of about 1 GeV, the $\Phi\nu\mu$ (>1 GeV)=0.65 cm^{-2} s^{-1}, and that of $\Phi\nu e$(>1 GeV) a factor of two lower. The neutrino must interact inside the detector to produce a visible event.
- The event rate for T =1 y and for the flavor i= μ;e is given by

$$N_{\nu_i} = \Phi_{\nu_i}(>1\mathrm{GeV}) \cdot \sigma_\nu \cdot N_T \cdot T \ ,$$

- $\sigma_\nu = \sigma_o$E is the neutrino cross-section. After averaging over neutrinos and aninu's, we have $\sigma_o \approx 0.5\ 10^{-38}$ cm^2/GeV
- NT = 6×10^{32} nucleons/ton is the number of target nucleons in 1 tonl,
- T = 3:15 107 s is the number of seconds in 1 year.
- Thus, inserting the numerical values, we obtain

$$N_{\nu_\mu} = 66 \text{ kton/y} \quad ; \quad N_{\nu_e} = 34 \text{ kton/y} \ .$$

Solution of question 3)

- At low energy, neutrinos exceed antineutrinos due to the fact that CR protons are more aboundant than neutrons
- Above few hundreds GeV, neutrinos from K decay are more abundant than from pions. Thus, **conservation of the strangeness (S) and baryon (B) quantum numbers** are responsible for the difference
- Consider the production of charged kaons from pp interactions:
  - K^+ (B=0, S=1) is produced in association with Λ (B=1, S=-1);
  - K^- (B=0, S=-1) requires at least one associated baryon (B=1) **and** an additional strange meson (S=1).
- K^+ are generated much more frequently than K^- because of the associated production with the Λ.

Solution of question 5)

- In water (n=1.33) for z=1 and β=1 the number of photons for energy interval and unit path length is:

$$\frac{d^2N}{dxdE} = \frac{z^2\alpha}{\hbar c}\sin^2\vartheta_c .$$

- With: $\cos\vartheta_c = (1/n) = 0.75 \rightarrow \vartheta_c = 42^o$
- The Δλ=(600-300) nm corresponds to ΔE=2 eV, thus

$$\frac{d^2N}{dx} = \frac{(1/137)}{(197\mathrm{MeV\ fm})}\cdot\Delta E\cdot\sin^2\vartheta_c = \frac{2\mathrm{eV}\times(0.67)^2}{27\cdot10^3\times10^6\mathrm{eV}\times10^{-13}\mathrm{cm}} = \frac{330}{\mathrm{cm}}$$