Neutrino experiments: Past, Present and Future

Wolfang-Pauli und
die moderne Physik

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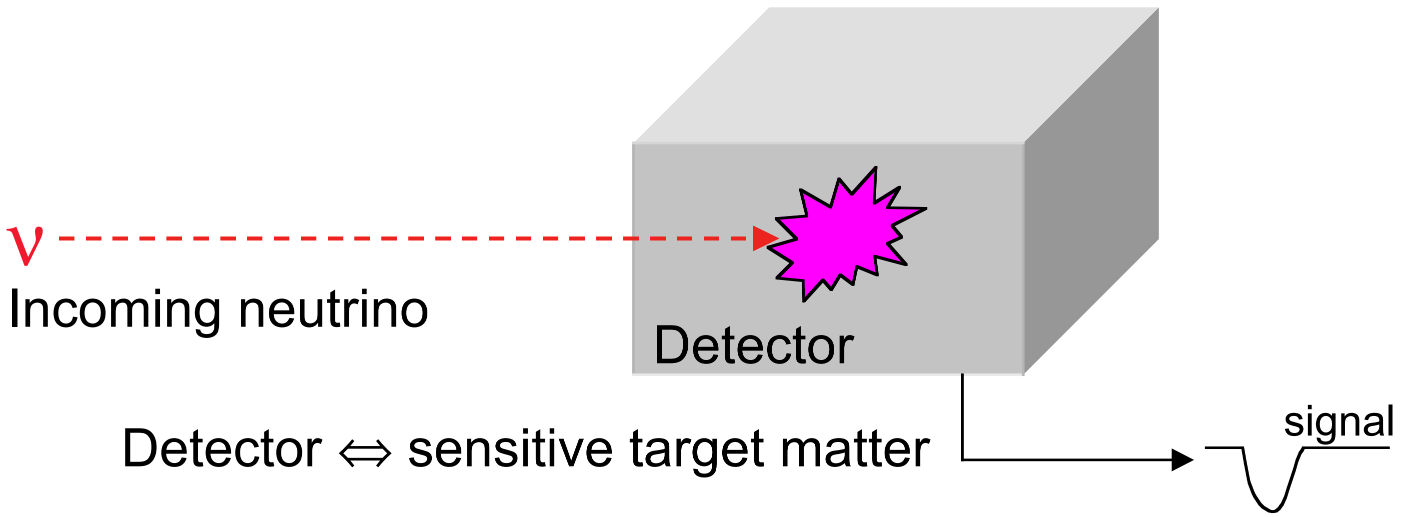
With pictures taken from WWW (CERN)

Neutrino experiments

I will concentrate on experiments that attempt to ***detect*** *neutrinos through their* ***interactions with matter***

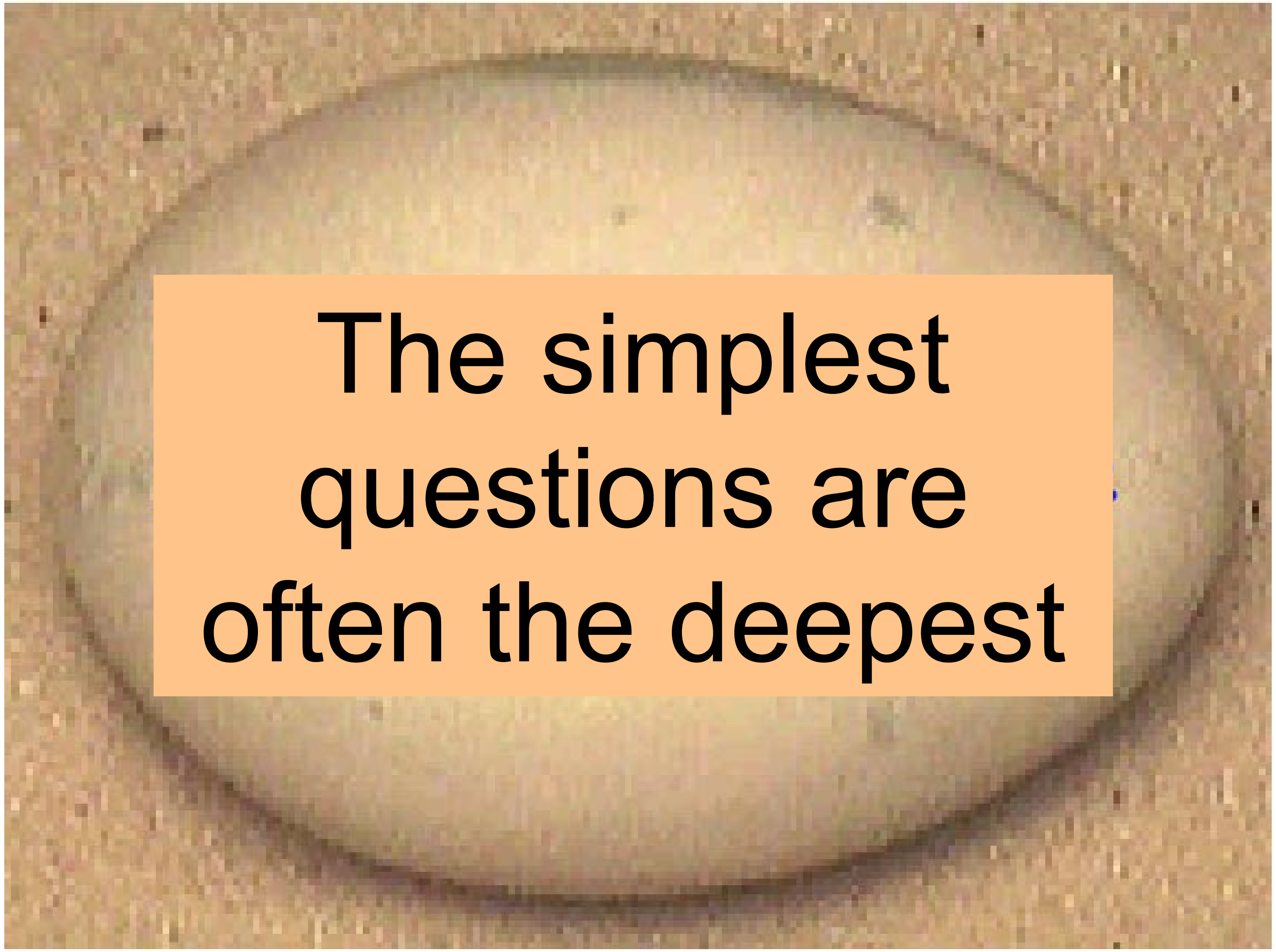


Detector ⇔ sensitive target matter

Not covered:

ν-experiments ***involving neutrinos****, i.e. parity violation, neutrino helicity, direct neutrino mass searches, double beta decays,...*

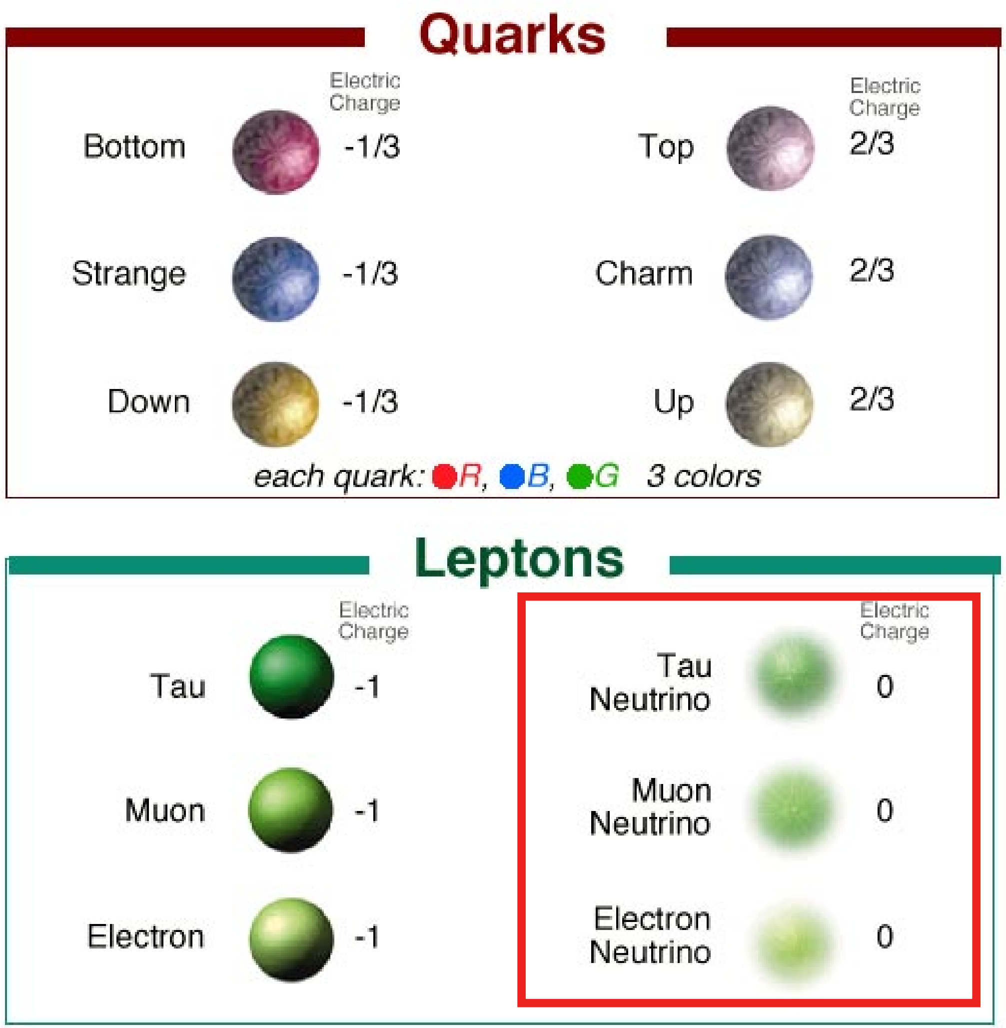
Foreword



Example: what is a neutrino?

Basic constituents of matter

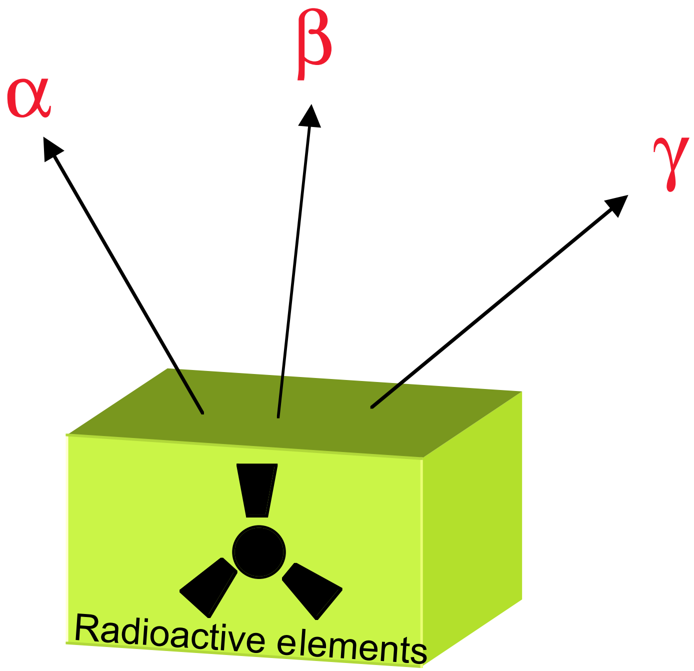
Elementary fermions



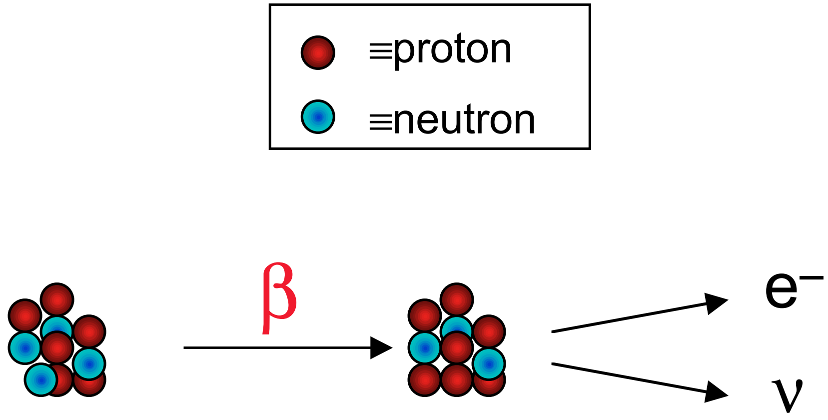
neutrinos

Elementary ≡ no internal structure, does not possess excited states

Neutrinos are emitted in β−decays...



Discovery natural radioactivity, Becquerel 1896



$$^{60}Co \rightarrow {}^{60}Ni + e^{-} + \nu$$

with underlying process:

$$n \rightarrow p + e^{-} + \nu$$

$$d(ud) \rightarrow u(ud) + e^{-} + \nu$$

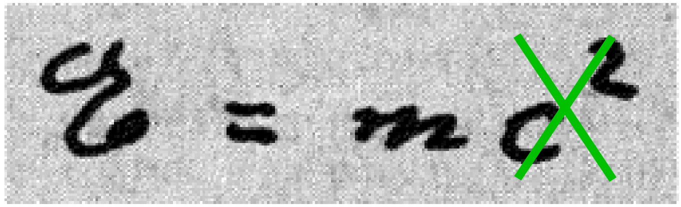
(Quark model, 1964)

... more generally in weak decays

Neutrinos are only sensitive to the weak (and gravitational) forces

$$n \rightarrow p + e^{-} + \nu$$

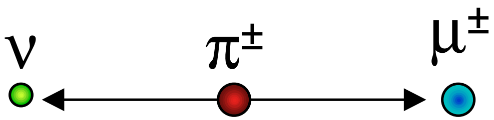
Einstein, 1905



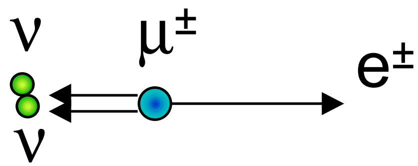
energy ⇄ **matter**

"nothing is created, nothing is destroyed"

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu$$



$$\mu^{\pm} \rightarrow e^{\pm} + \nu + \nu$$



The intrinsic properties

Neutrino is hard to detect

still mostly a mystery!

Electric charge	0
Angular momentum (“spin”)	1/2
Chirality	Appears 100% left-handed
Interactions	Only weak
Rest mass	?
Lifetime	?
Anomalous magnetic moment	?
Intrinsic nature Dirac-Majorana	?

Kinematical analysis of weak decays

Do neutrinos possess a non-vanishing, though small, rest mass or are they massless particles like the photon?

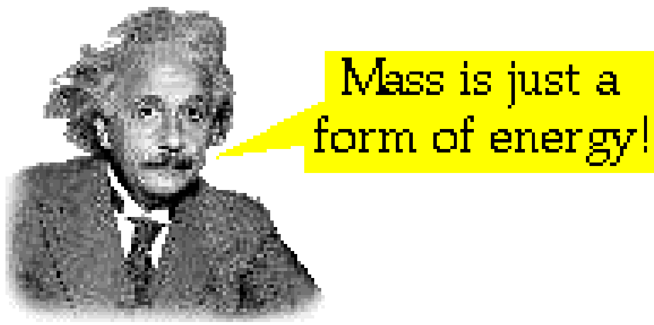
Direct measurement of the neutrino mass by kinematical analysis of weak decays:

$$m_{\nu e} < \approx 5 \ \ eV$$

$$m_{\nu\mu} < 170 \ \ KeV$$

$$m_{\nu\tau} < 18 \ \ MeV$$

(90%C.L.)



$$1 \ \ eV \approx 1.8 \times 10^{-36} kg$$

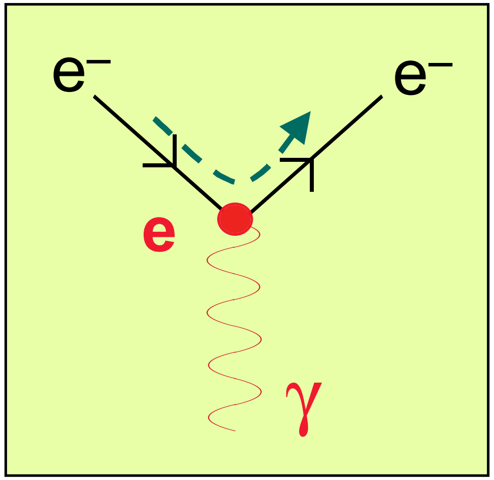
Could not find mass values not consistent with zero...

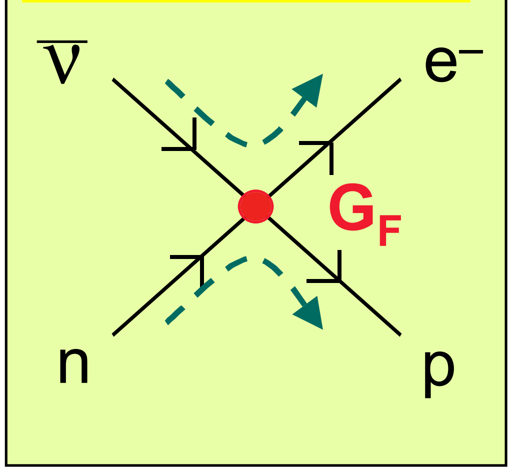
Fermi theory included neutrino hypothesis

Theory of weak interaction based on field currents

$$n \rightarrow p + e^- + \nu$$

$ie\gamma^\mu$





$$G_F\left(\overline{\psi}_p \gamma^\mu \psi_n\right)\left(\overline{\psi}_e \gamma_\mu \psi_\nu\right)$$

Fermi, 1932

Electromagnetic interaction

Weak interaction

Inverse β decay

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

$E_\nu > (m_n - m_p) + m_e \approx 1.8$ MeV

Incoming neutrino

Free proton

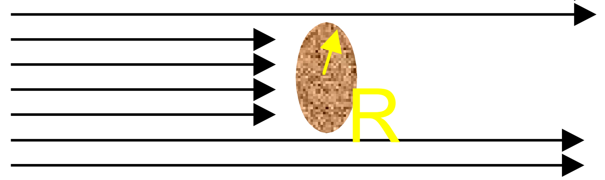
Positron emission

Neutron emission

The "cross-section" σ

$\sigma \equiv$ the apparent area for collisions

e.g. for a disc, $\sigma = \pi R^2$

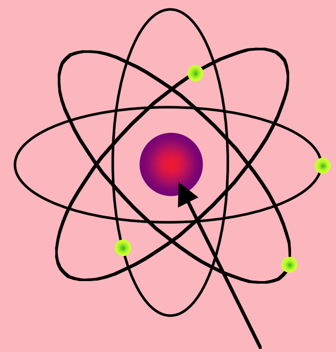


Using Fermi theory:

$$\sigma(\bar{\nu}_e + p \rightarrow e^+ + n) = 10^{-43} \left(\frac{E}{MeV} \right)^2 cm^2$$

Bethe, Peierls

Diameter atom ≈ 10^{-8} cm



Diameter nucleus ≈ 10^{-13} cm

⇒ Extremely small probability to interact with matter

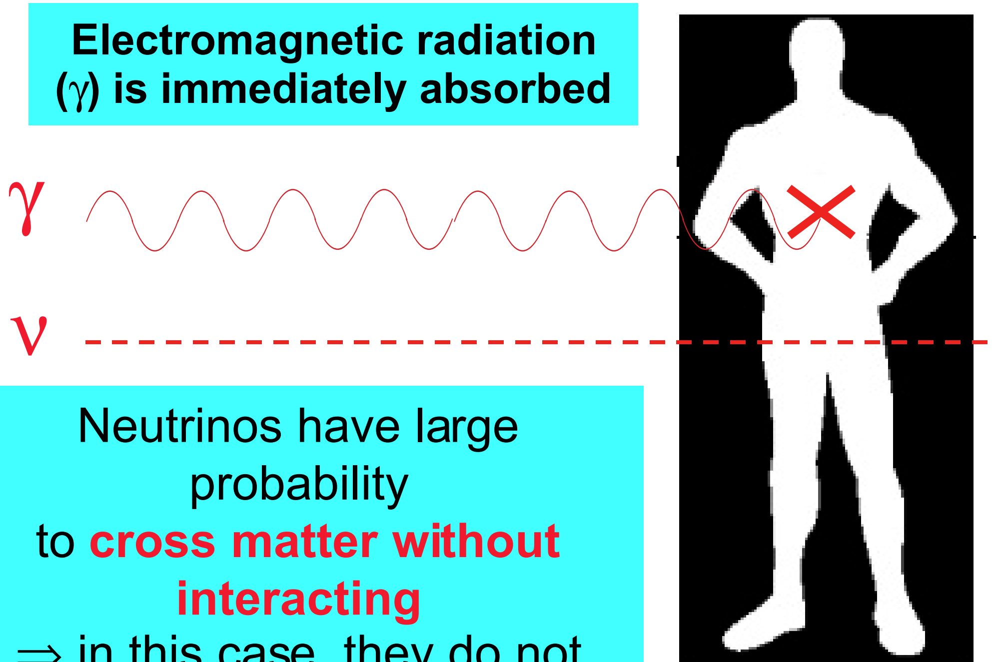
The penetration power

Neutrino radiation is not dangerous!

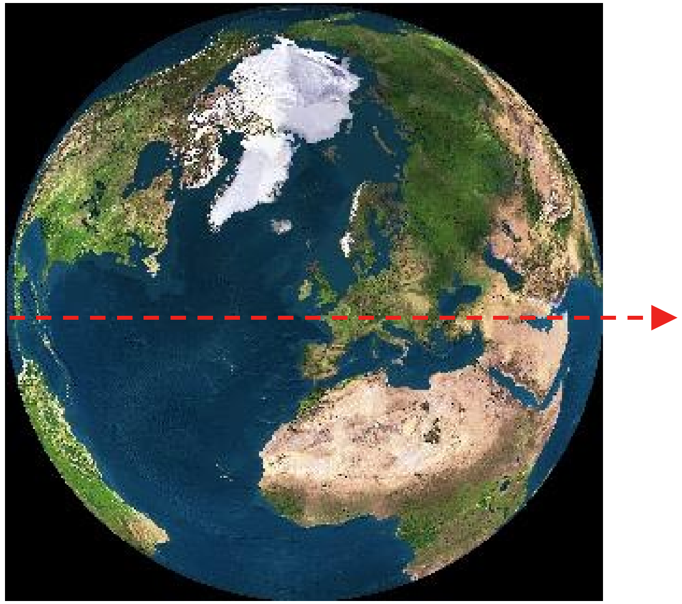
$$\sigma \approx 10^{-43}\,cm^2$$

Mean free path in water:
$\lambda \approx$ 30 light-years

Electromagnetic radiation (γ) is immediately absorbed



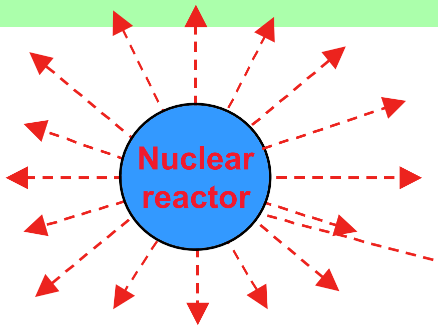
Neutrinos have large probability to **cross matter without interacting**
$\Rightarrow$ in this case, they do not deposit any energy

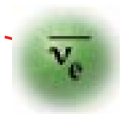


They mostly cross the Earth without interacting!

First direct detection of neutrino (1956)

To have a chance to observe the process requires a very intense anti-neutrino source

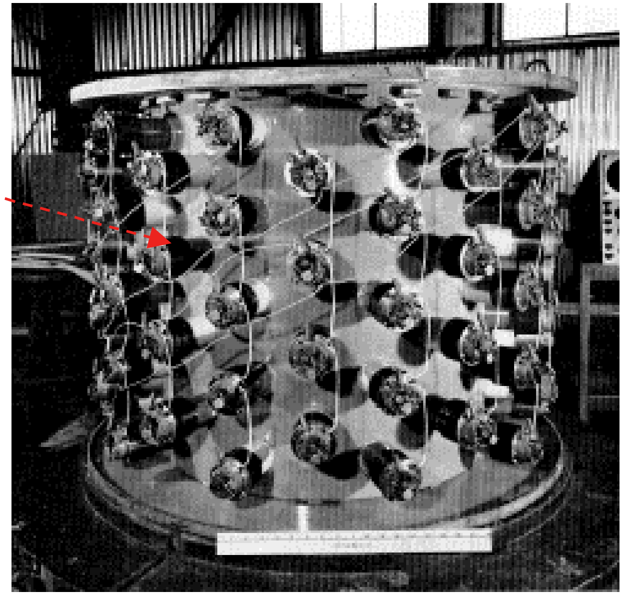




$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\approx 2 \times 10^{20} \times \frac{Power}{GW} \quad \bar{\nu}_e / s$$

Expected rate:
about 3 events per hour !

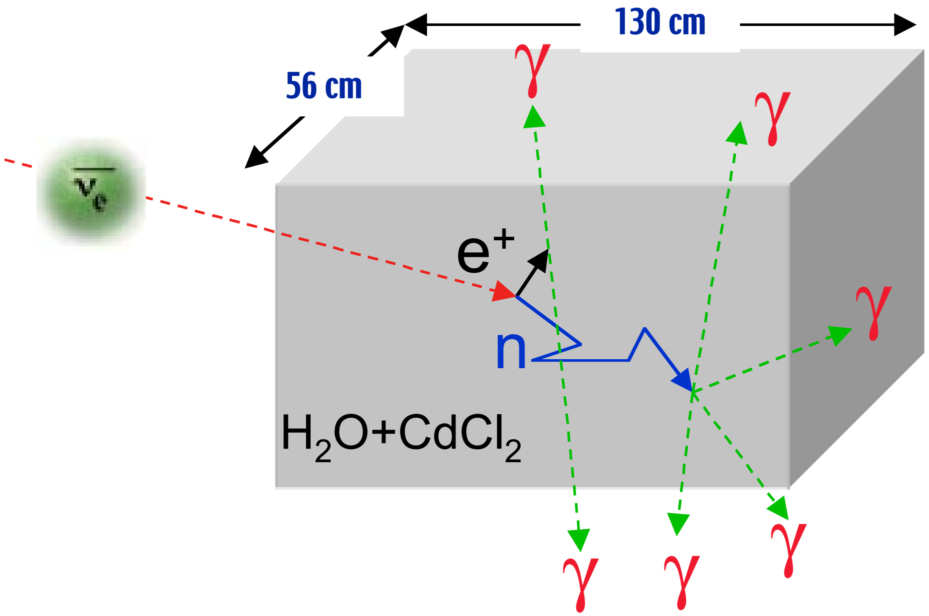


Reines and Cowan experiment located at Savannah River Power Plant (South Carolina, USA)

Need very good event signature to distinguish MeV neutrinos from background (natural radioactivity,etc.)

Reines & Cowan detection technique

Prompt-positron-delayed-neutron correlation technique invented



$$\bar{\nu}_e + p \to e^+ + n$$

$$e^+ + e^- \to \gamma + \gamma$$

Prompt signal:
2x0.51 MeV

$$n + Cd \to Cd^* \to Cd + \gamma' s$$

Delayed signal: ≈9 MeV

Measured rate:
2.88±0.22 counts per hour !
With signal/background ≈ 3/1

$$\sigma = (1.1 \pm 0.3) \times 10^{-43}\, cm^2$$

Reines and Cowan, Science 124 (1956) 103; Phys. Rev. 113 (1959) 273

Lepton “flavors”

Evidence for conserved lepton flavor numbers in all interactions

Neutrino and charged leptons are arranged into “weak doublets”

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

$L_e=$	1	0	0
$L_\mu=$	0	1	0
$L_\tau=$	0	0	1

Explains why radiative decay of muon not seen

$$\mu \not\rightarrow e + \gamma$$

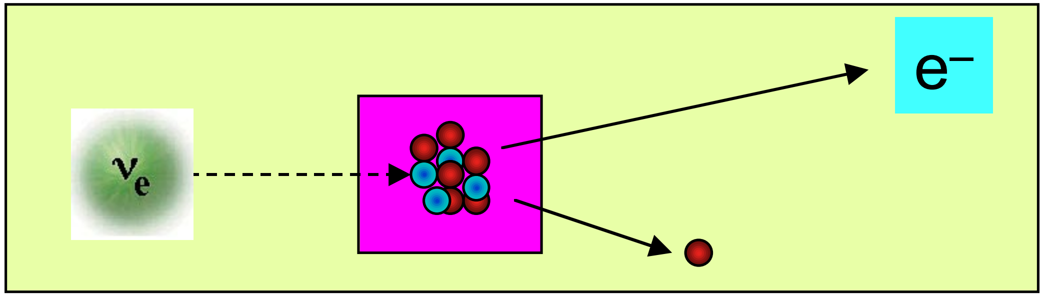
$<\approx 10^{-12}$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \qquad \pi^\pm \rightarrow \mu^\pm + \nu_\mu$$

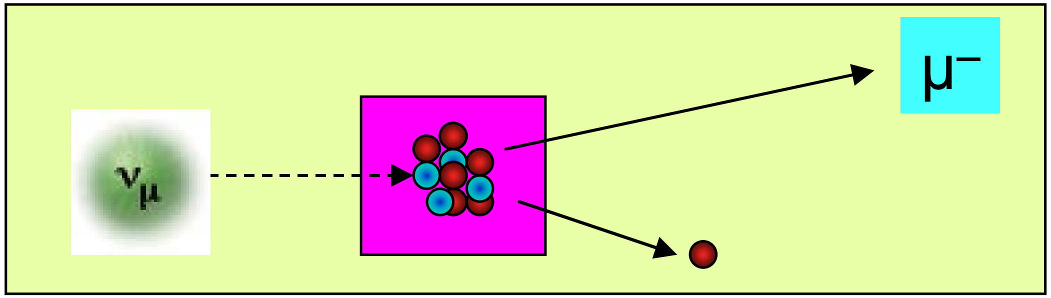
...consequence for interactions

e.g. conserved leptonic flavor in charged current interactions

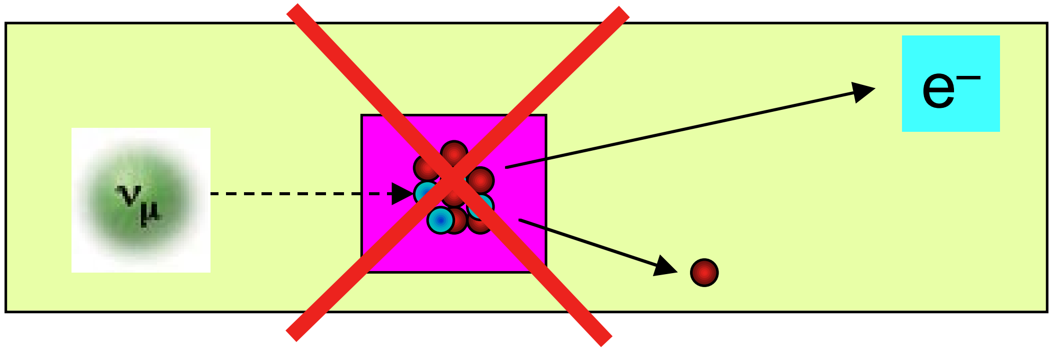
Lee, Yang, Phys. Rev. Lett. 4 (1960) 307



$L_e=$	+1	+1
$L_\mu=$	0	0



$L_e=$	0	0
$L_\mu=$	+1	+1



$L_e=$	0	+1
$L_\mu=$	+1	0

Lepton Flavor Violation (LFV) not allowed!

Study of weak interactions (≈1960)

Lee, Yang

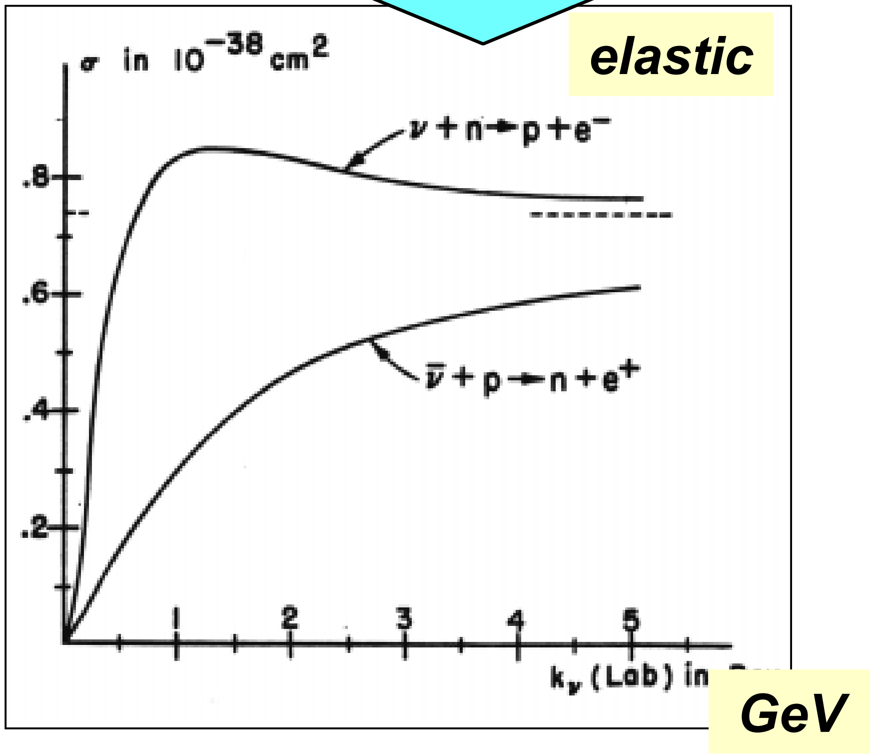
Q: *How can one study weak interactions at high energy?*
A: *with neutrinos!*

Neutrinos were considered to be the best projectiles to study weak interactions, since they only interact weakly
But how many neutrinos would be needed to perform an experiment?

Neutrino energy should be at least a few GeV

Total cross-section increases linearly with neutrino energy!

$\sigma \approx 10^{-38}\ \mathrm{cm}^2$

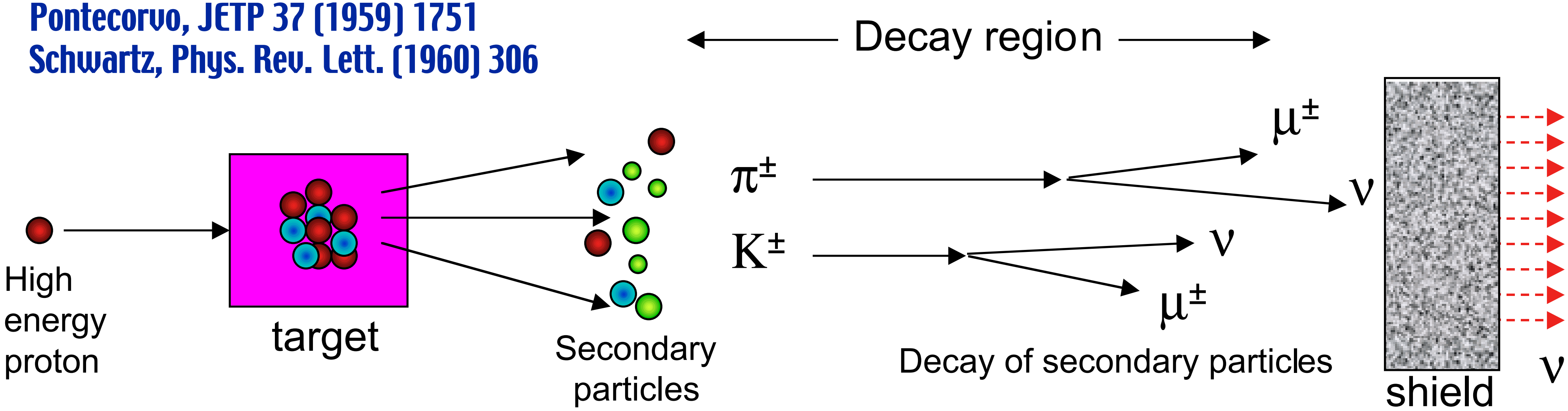


T.D. Lee, C.N. Yang, Phys. Rev. Lett. 4 (1960) 307

Intense high energy neutrino sources (≈1960)

It was realized that high energy accelerators could be used to produce intense high-energy neutrino beams!

Pontecorvo, JETP 37 (1959) 1751
Schwartz, Phys. Rev. Lett. (1960) 306



The birth of "accelerator neutrino physics"...

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

While the technique has been perfected (in particular with the help of magnetic focalizing systems), the basic principle is still the same used today in modern neutrino accelerator experiments

The first accelerator neutrino beam (1962)

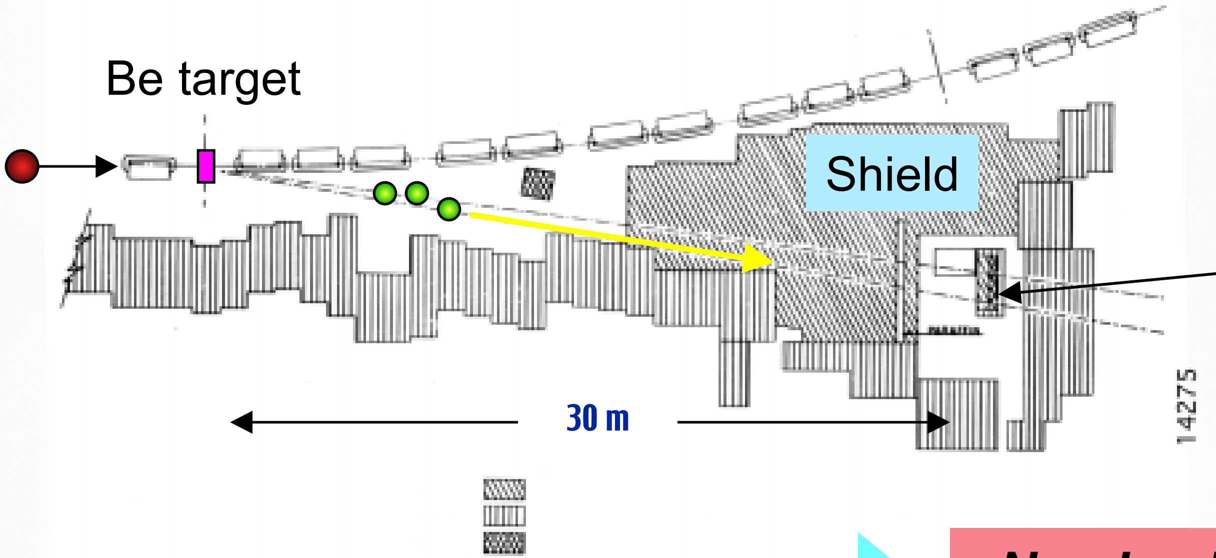
In 1962 at the Brookhaven AGS accelerator

proton energy : 15 GeV

proton intensity: 400’000’000’000 protons/pulse

3000 pulses/day

neutrinos: energy≈1 GeV, mostly ν_μ ?



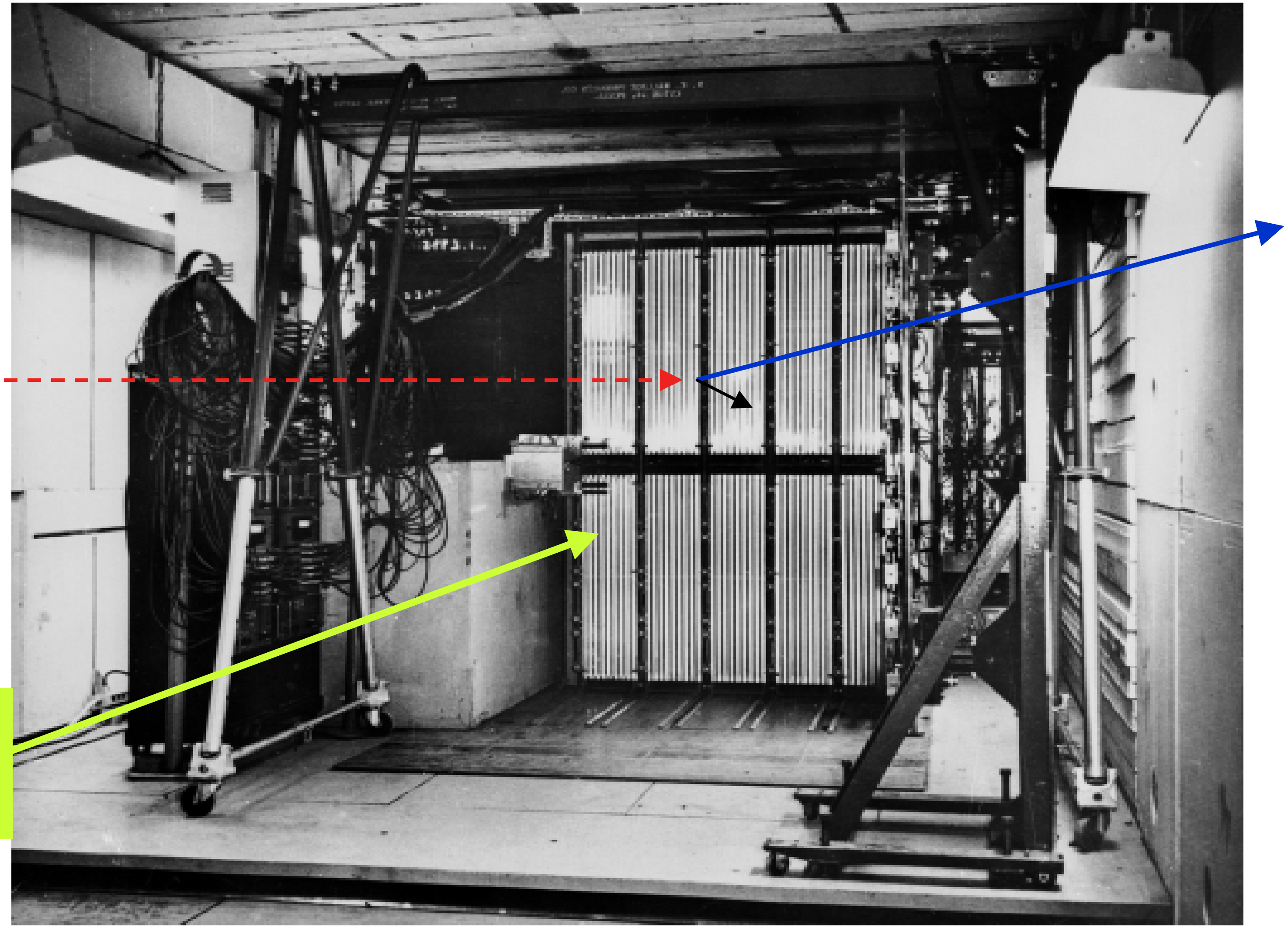
1 neutrino interaction per 1000 kg per day!

Need a detector with large mass able to distinguish electrons from muons !

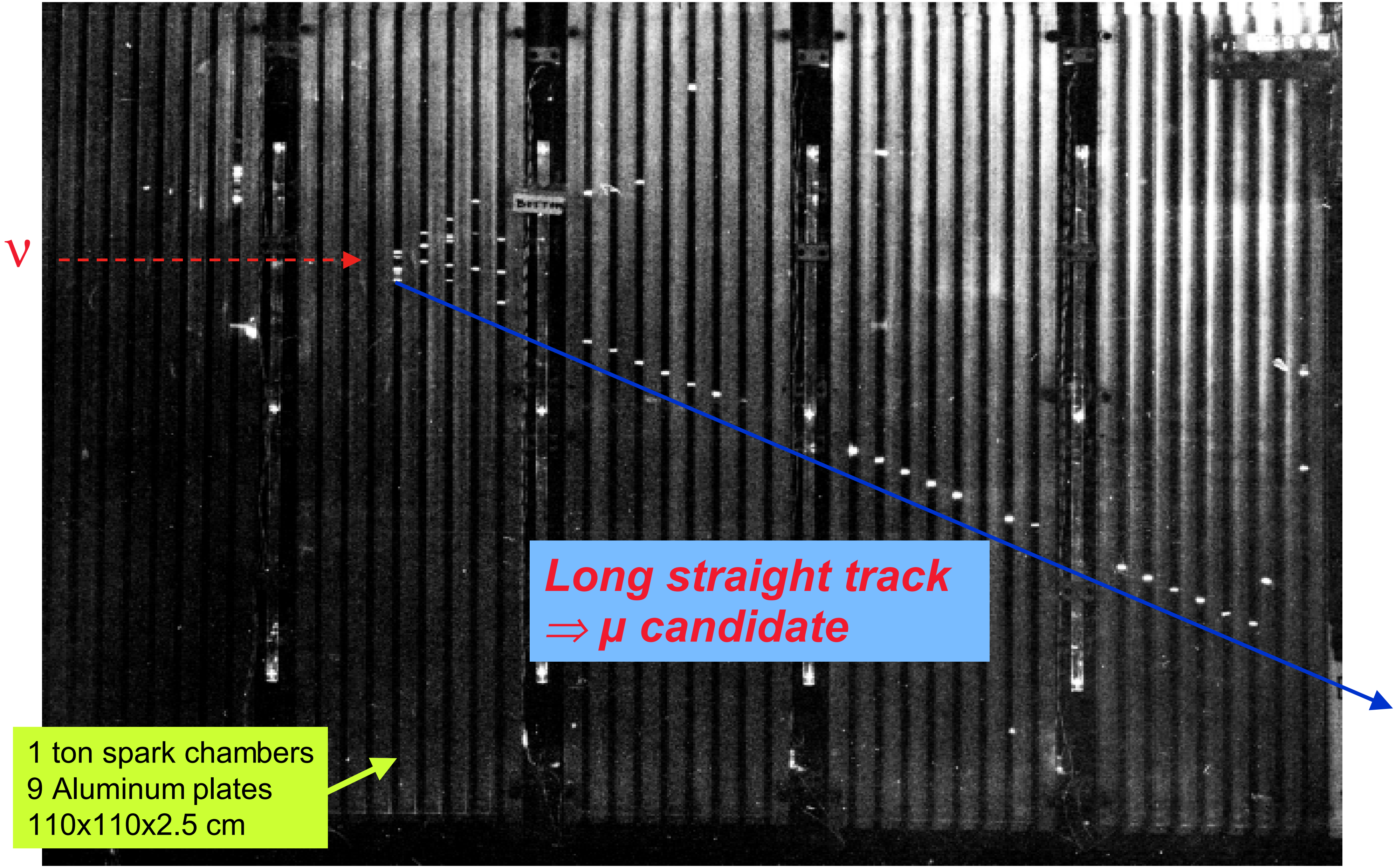
BNL–Columbia experiment (1962)

10 ton "spark chamber" detector

Danby, Gaillard, Goulianos, Lederman, Mistry, Steinberger, Schwartz, Phys. Rev. Lett. 9 (1962) 36

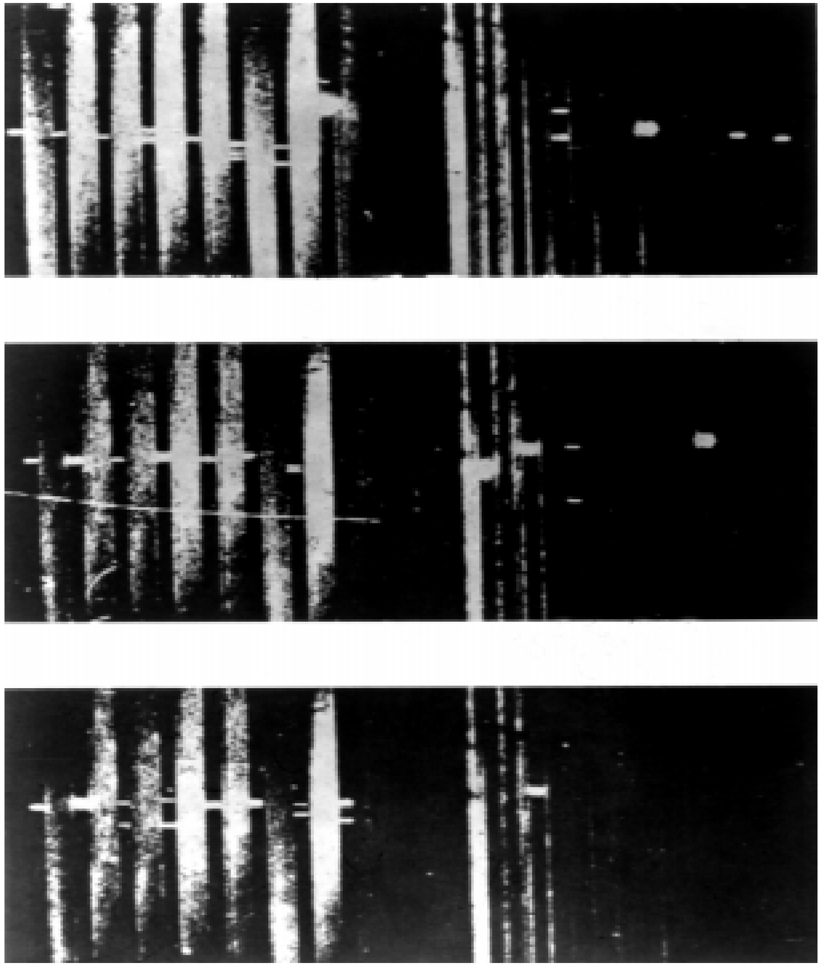


One “muon-like” event in spark chamber



Results from BNL–Columbia experiment

400 MeV electron test beam

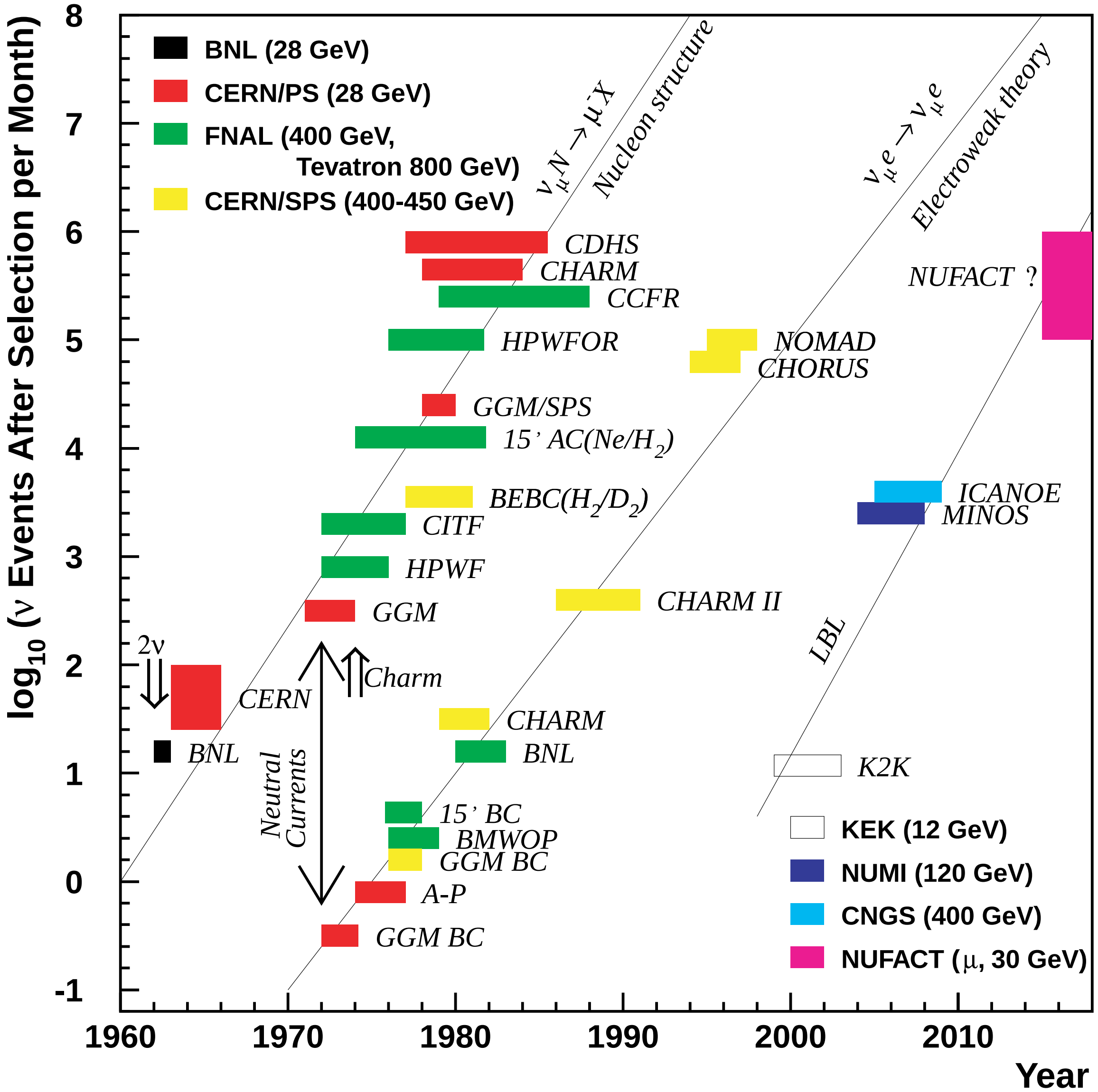


	Number of events
Single tracks	34
Multi tracks	22
"Showers"	**8**

Only 2 are compatible with electrons

$$\nu_e \neq \nu_\mu$$

Accelerator neutrinos



Accelerator neutrino beams have been fundamental in the understanding of the basic properties of matter and interactions!

With the highering of accelerator energies, the number of neutrino interactions studied has increased dramatically over ≈40 years!

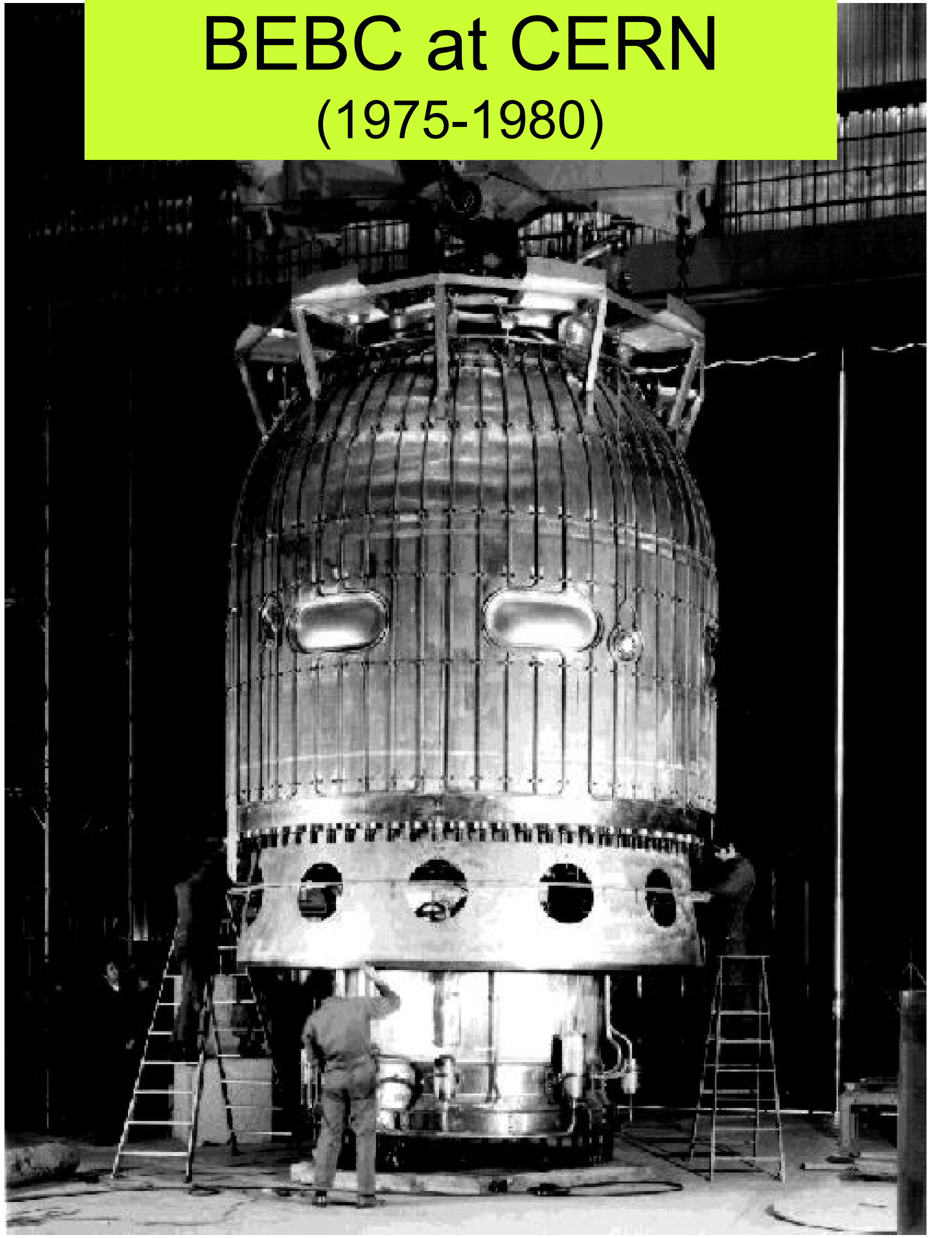
Accelerator neutrino physics

The neutrino has been very successful as a projectile to bombard other pieces of matter for detailed studies of elementary particles

- √ ***Precise tests & measurements of electroweak theory***
- √ ***Study of internal structure of nucleon***
- √ ***Test of Quantum Chromodynamics (QCD)***
- √ ***Measurements of charm quark production***
- √ ***Searches for neutrino oscillations***

Bubble chambers

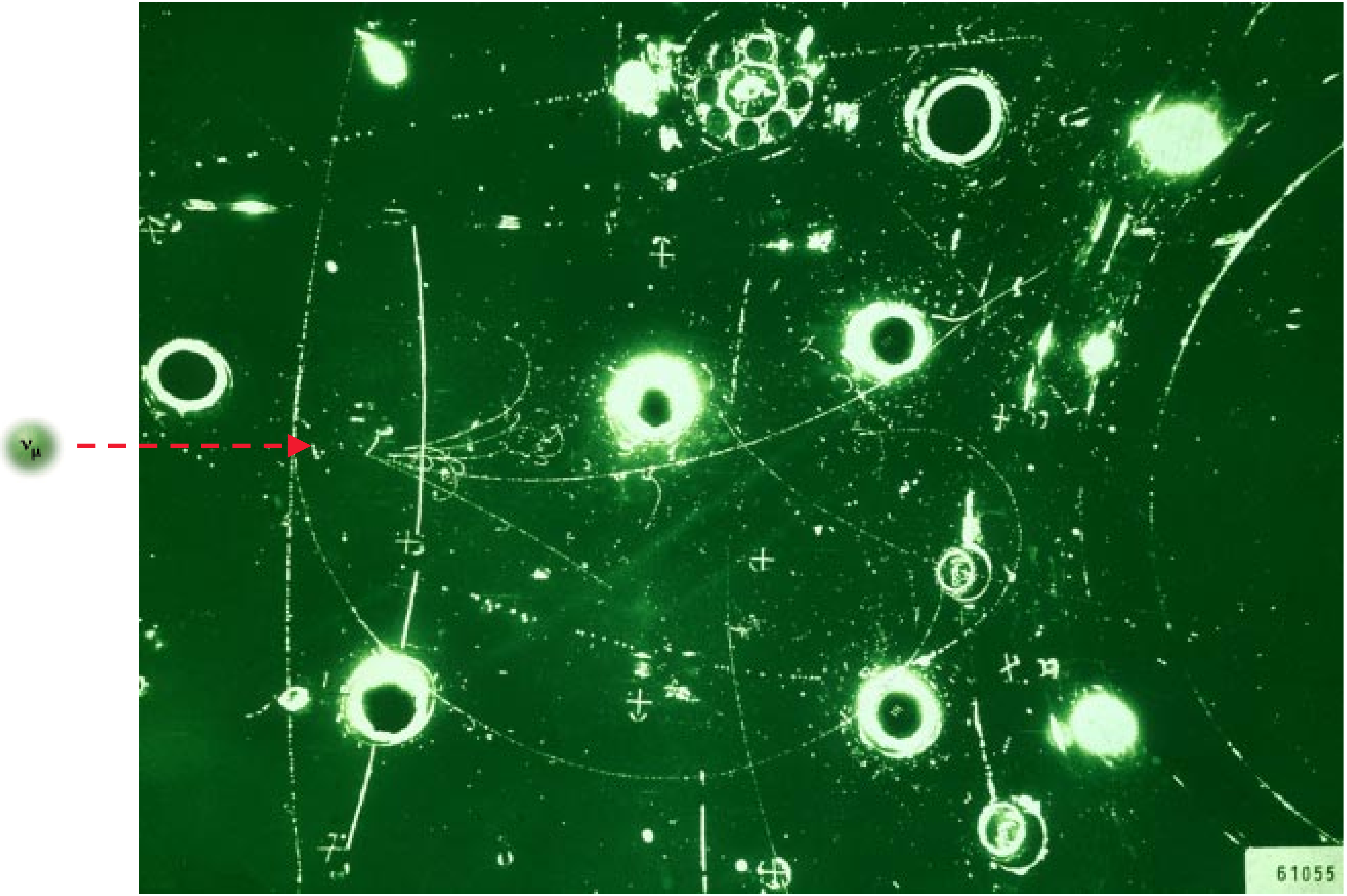
BEBC at CERN
(1975-1980)



Target density ≈ 1.5 g/cm³
+
Excellent event imaging

Bubble chambers have been excellent detectors to study neutrino interactions

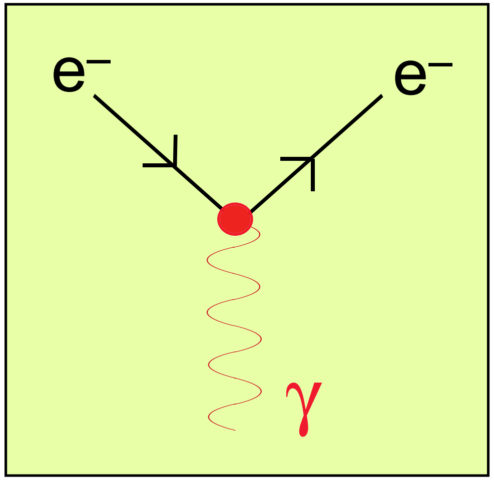
Neutrino event in GGM bubble chamber



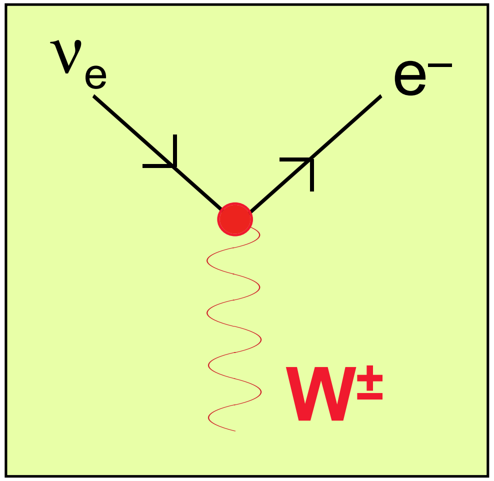
Weak neutral currents (1961–1968)

Neutral currents were predicted by the unified electro-weak interaction theory (today called Standard Model)

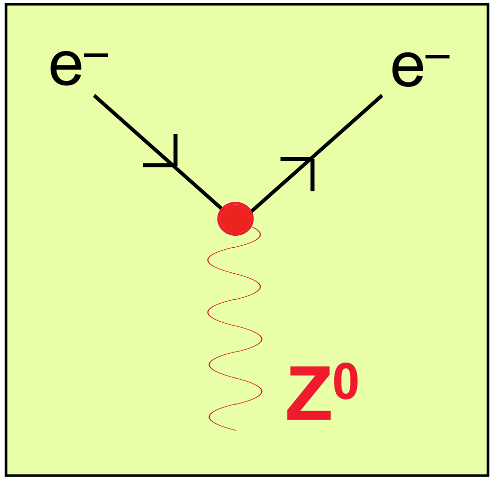
Glashow, NP 22 (1961), 579; Weinberg, PRL 19 (1967) 1264; Salam&Ward PL 13 (1964) 168



Electromagnetic interaction



Charged weak interaction



Neutral weak interaction

Results from Gargamelle Bubble Chamber

GGM bubble chamber at CERN/PS neutrino beam

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

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

Search for single electron events E_e>300MeV, θ_e<5°

	Neutrinos/m^2	Pictures scanned	Estimated background	Observed
ν	2x10^{15}	375000	0.3±0.2	**0**
$\bar{\nu}$	1x10^{15}	360000	**0.03±0.02**	**1**

The excellent imaging properties of bubble chambers provide extremely clean signatures for the searched signal.
It allowed to claim a discovery with only 1 event !

Discovery of neutral currents (1973)

Excellent electron identification

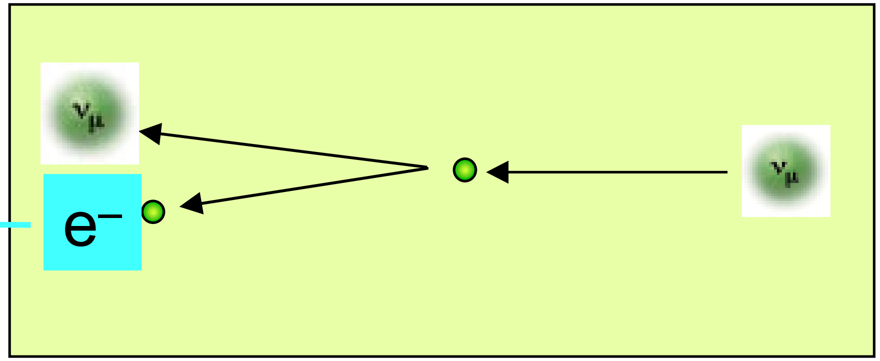
ρ=1.5g/cm^3

Radiation length=11cm

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

E_e=385±100MeV

θ_e=1.4±1.4°



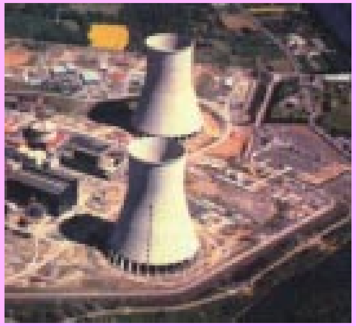
Gargamelle, Phys. Lett. B46 (1973) 121

The “challenging” sources of neutrinos (1970→now)

Apart from the artificial sources, Nature has provided us with “natural” sources of neutrinos

Artificial sources

Accelerators

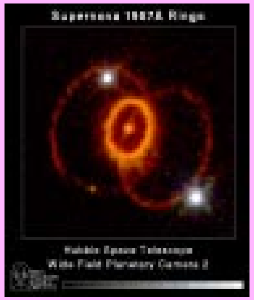


Reactors

Natural sources

Solar

Atmospheric



Supernovae

BigBang

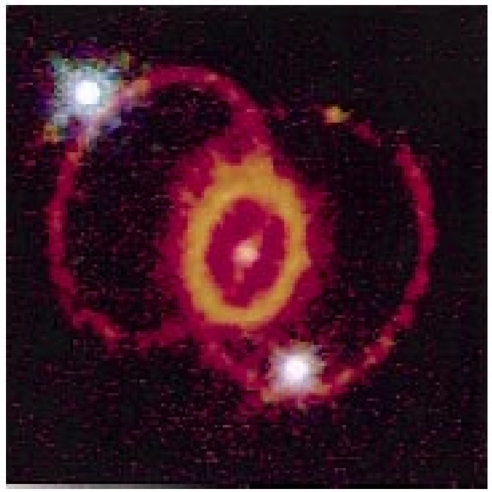
These have all been detected!

Except these! The ultimate challenge?

The most exciting ν-source! SN1987A

The SN1987A supernova before and after its explosion

The extraordinary rings observed in 1994 by the Hubble Space Telescope
(exceptional resolution possible outside the atmosphere)



Neutrinos and supernovae

$L = 1.5\times10^{18}$ km
≈170000 light years

The neutrinos from the SN1987A supernova were convincingly detected on Earth by two experiments!

$\approx 10^{58}$ neutrinos emitted!
$\langle E_\nu \rangle \approx 10$ MeV

	Events
Kamiokande	**12**
IMB	**8**

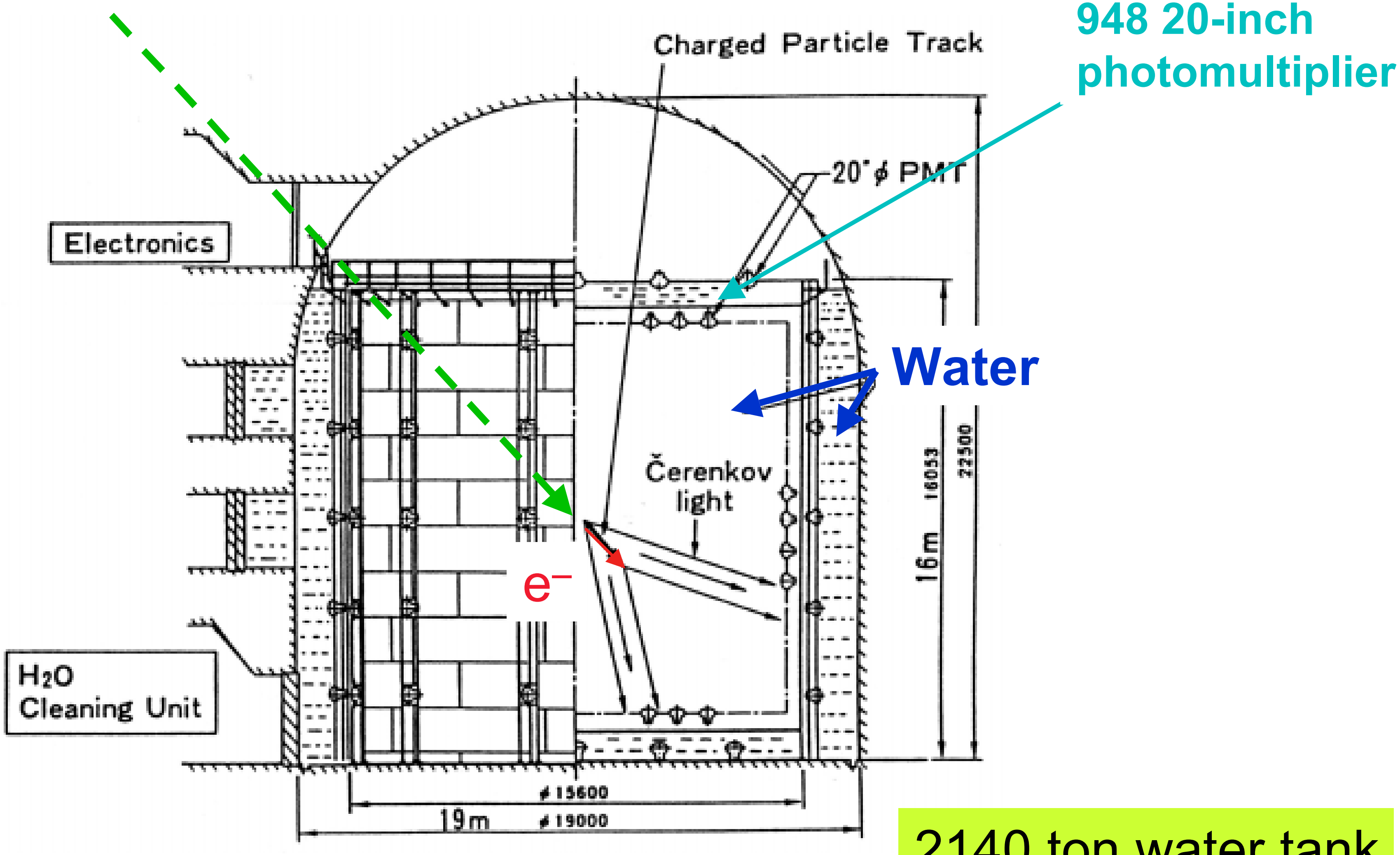
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\nu + e^- \rightarrow \nu + e^-$$

Kamioka Nucleon Decay Experiment (Kamiokande)

Located ≈350km from Tokyo in Kamioka mine ≈1 km underground

Imaging Water Cerenkov Detector

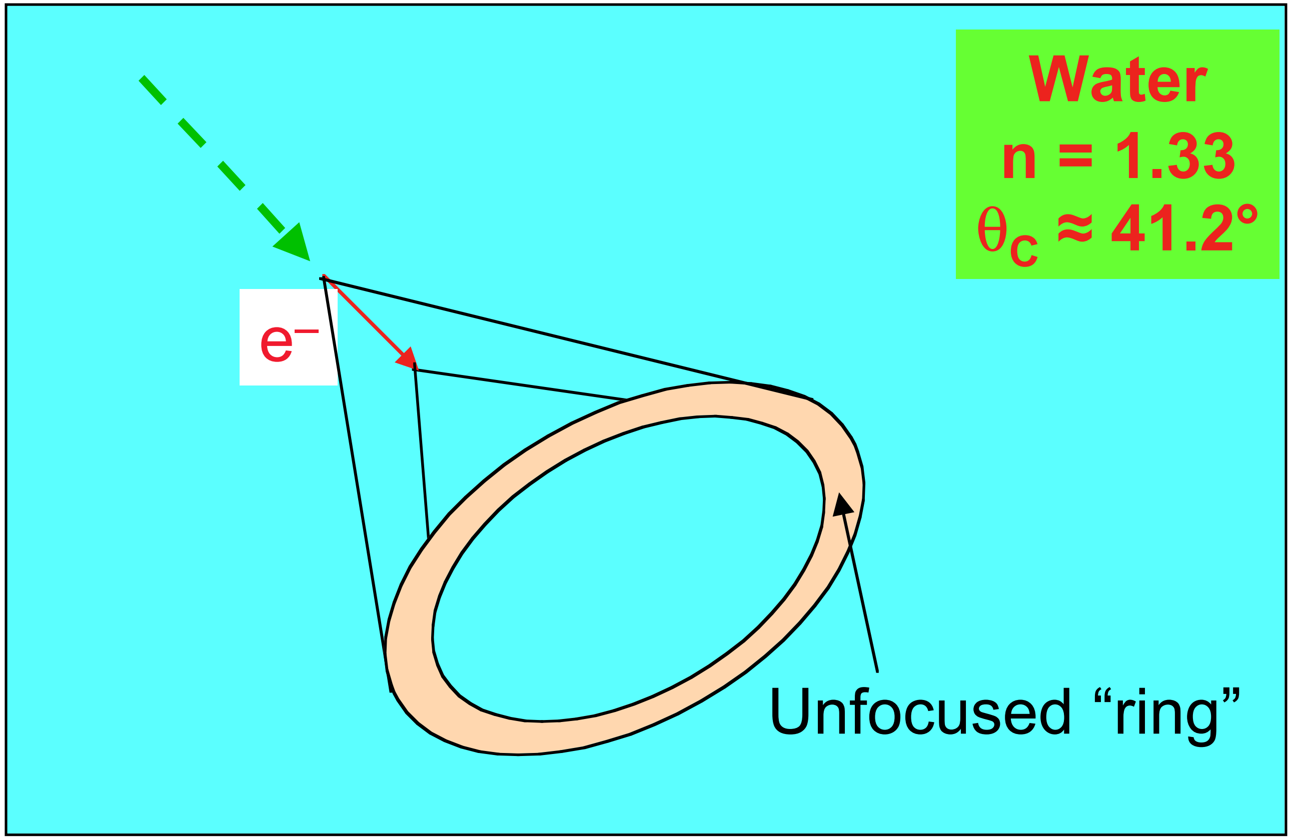


2140 ton water tank

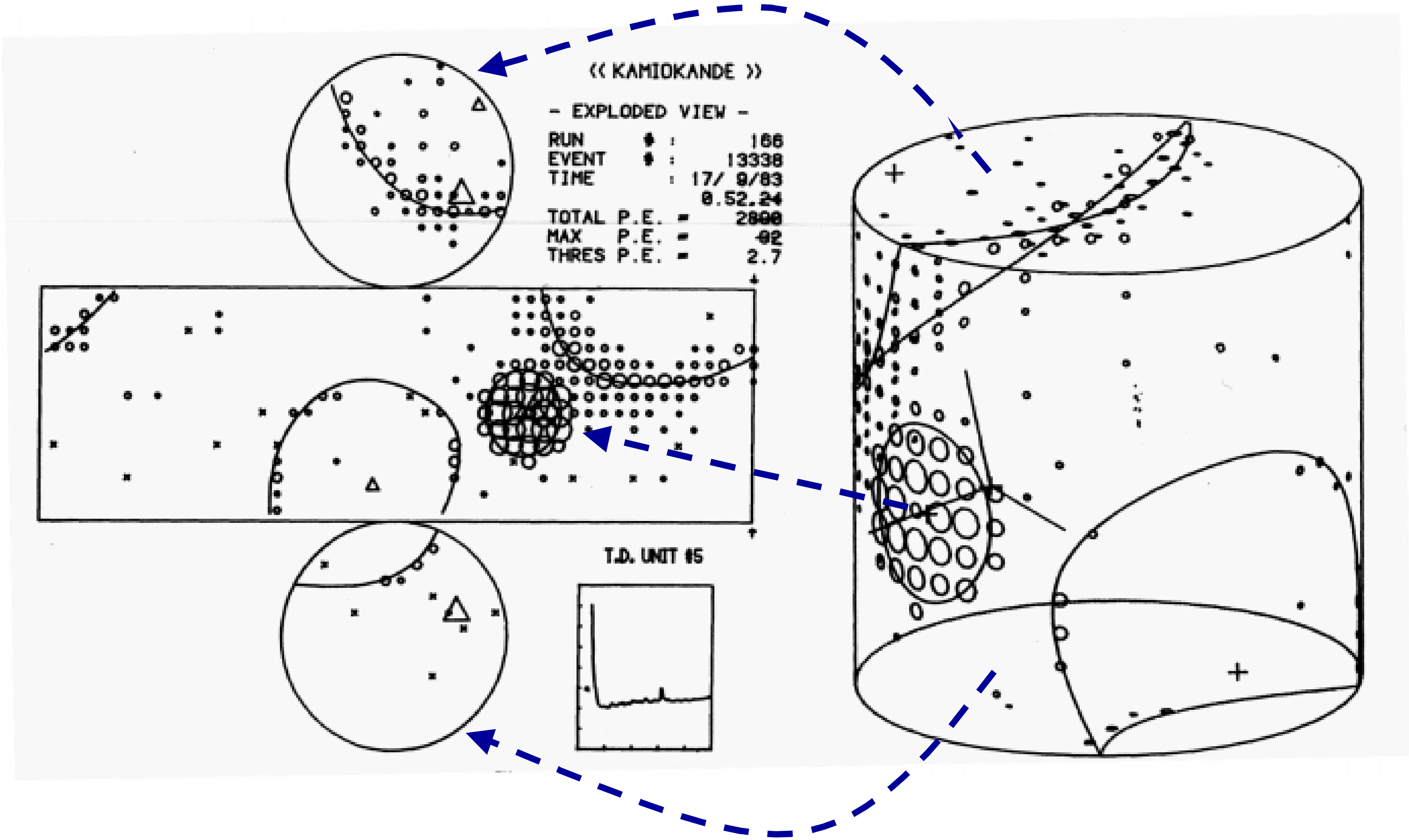
Cerenkov radiation

Radiation emitted by a particle when it travels faster than the speed of light in that medium

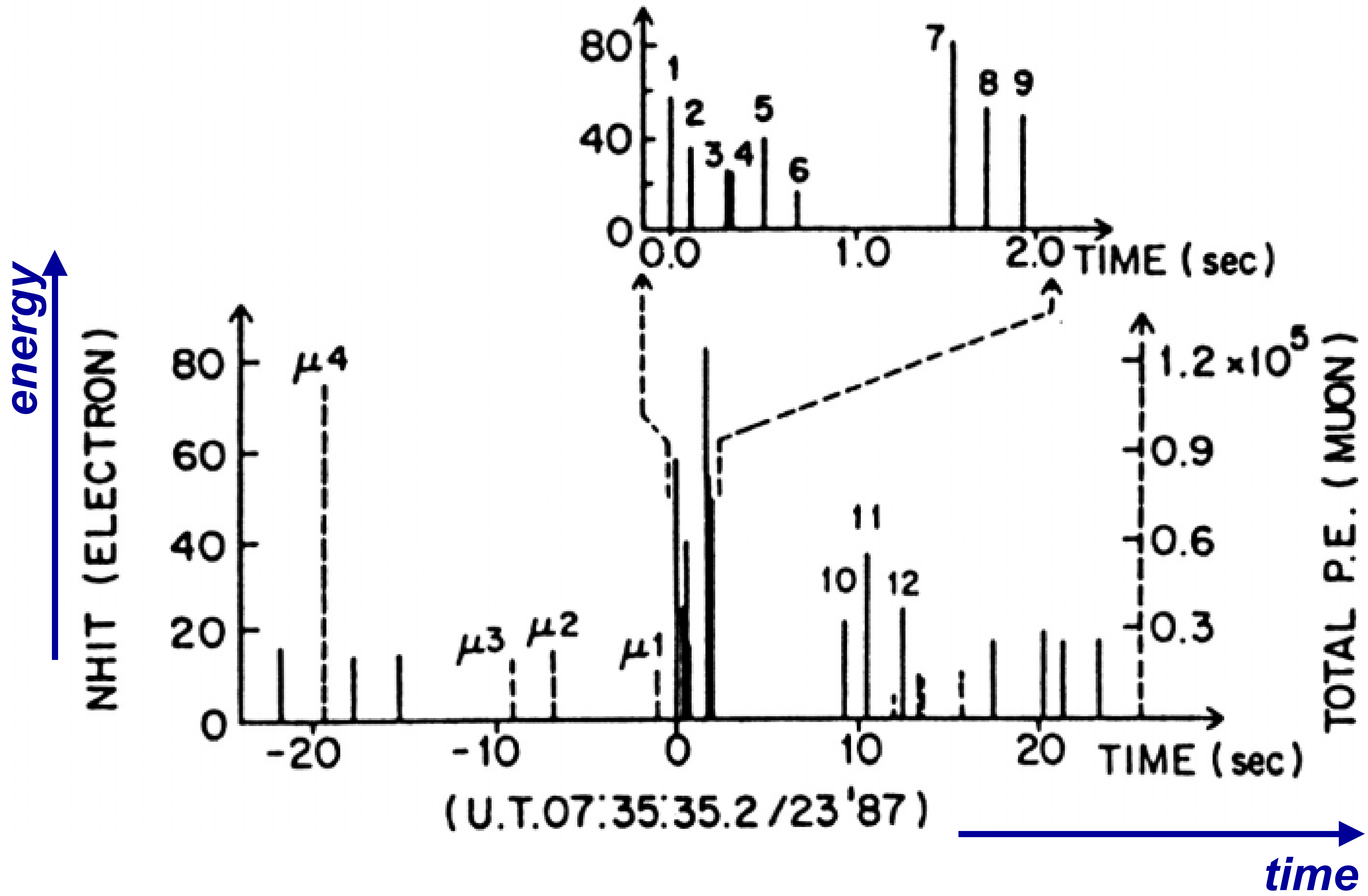
$$\cos\theta_C = 1/\beta n$$



Exploded view of a Kamiokande event



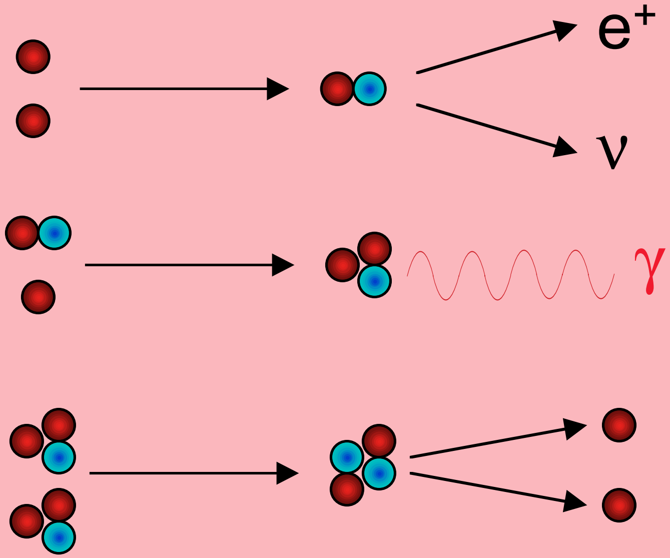
Neutrinos from SN1987A seen in Kamiokande



Solar neutrinos

Stellar energy comes from **NUCLEAR FUSION** in core

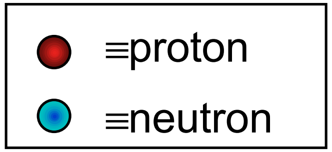
"pp" cycle:

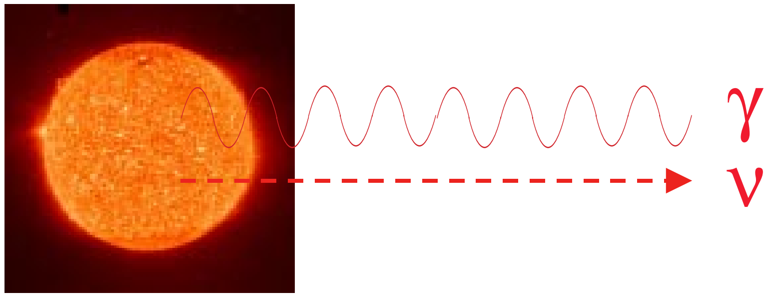


$$p + p \rightarrow D + e^{+} + \nu$$

$$p + D \rightarrow {}^{3}He + \gamma$$

$${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$$





Stars are strong neutrino sources!

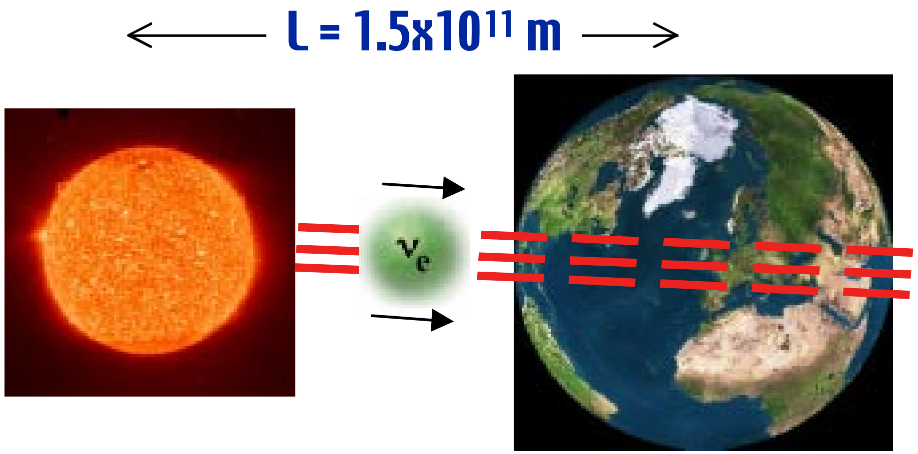
$$\mathbf{4H \rightarrow {}^{4}He + \gamma + \nu}$$

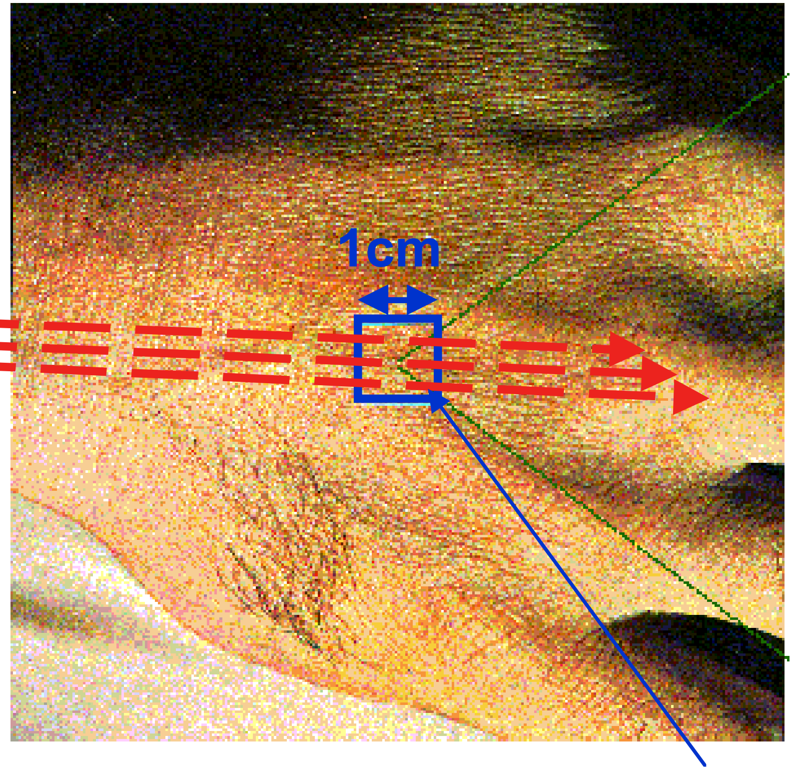
light,heat — neutrinos

Q=26.73 MeV; $\langle E\nu_e \rangle$ = 0.265 MeV

Solar neutrinos

Neutrinos necessarily accompany photons if nuclear fusion is taking place!





Sun in "steady state":

Nuclear energy production⇔ luminosity

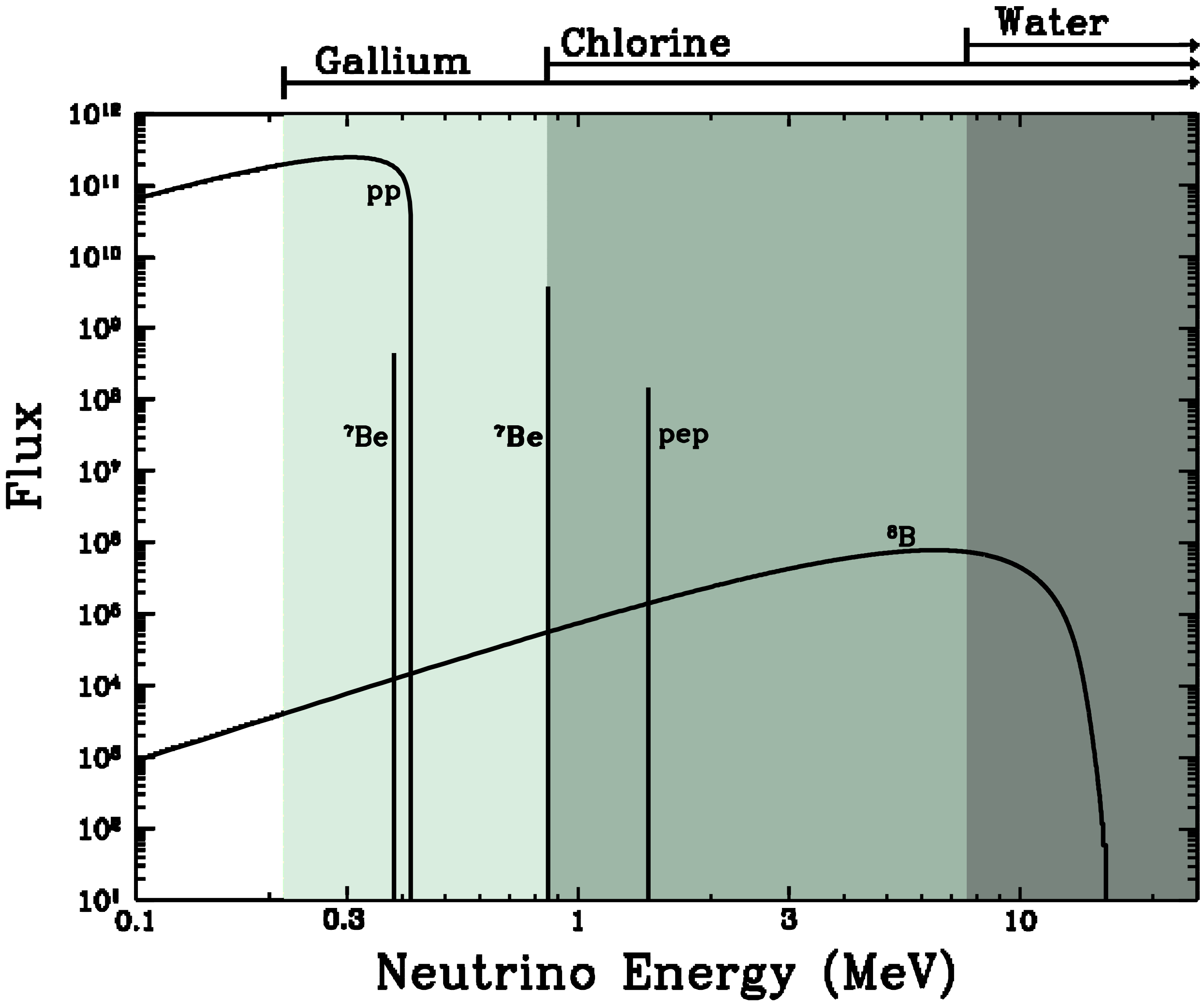
$$\phi_\nu = \frac{2L_\Theta}{Q - 2 < E_{\nu_e} >} \approx 2\times 10^{38}\,\nu / s$$

$$\phi_{Earth} \approx 10^{11} \quad \nu / cm^2 / s$$

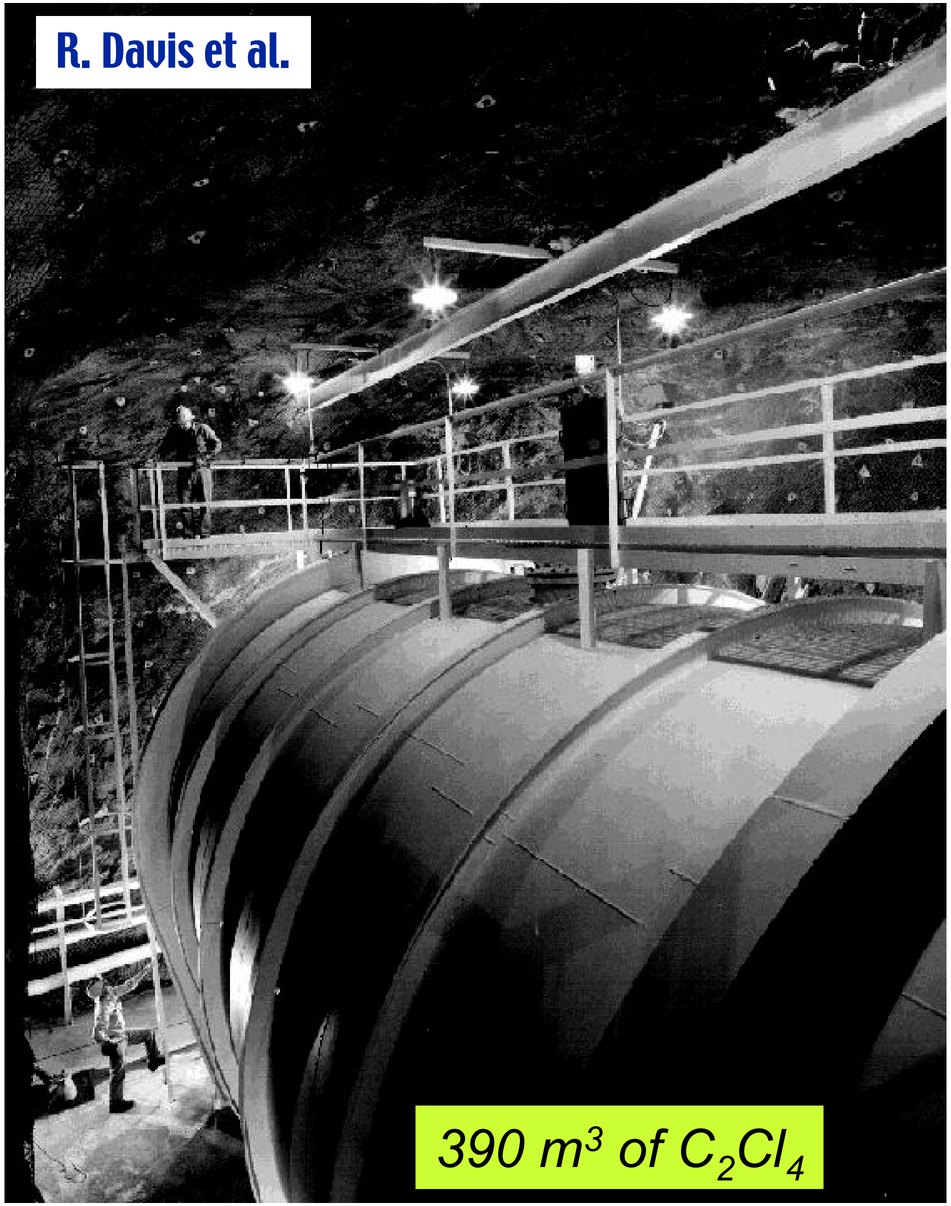
100'000'000'000 ν/s

Day & night!

Predicted solar neutrino spectrum



Chlorine experiment– Homestake Mine



$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

Eν > 814 KeV

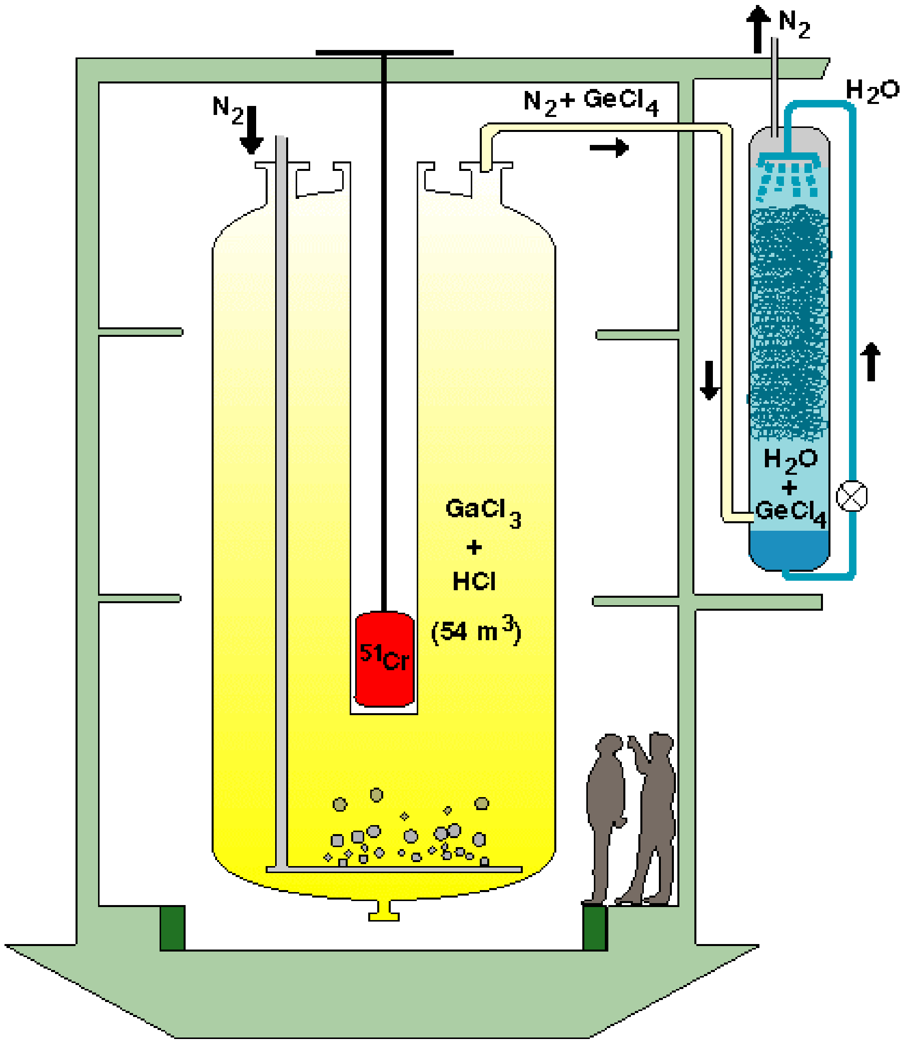
Expected rate: ***9.5±1.4 SNU***

1 SNU≡1 evt/s per 10^{36} target atoms

Expected production:
1.5 Ar nuclei/day

Measured rate: ***2.56±0.22 SNU***
average over 30 years!!!!

GALLEX at Gran Sasso Laboratory (1991–1997)



$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

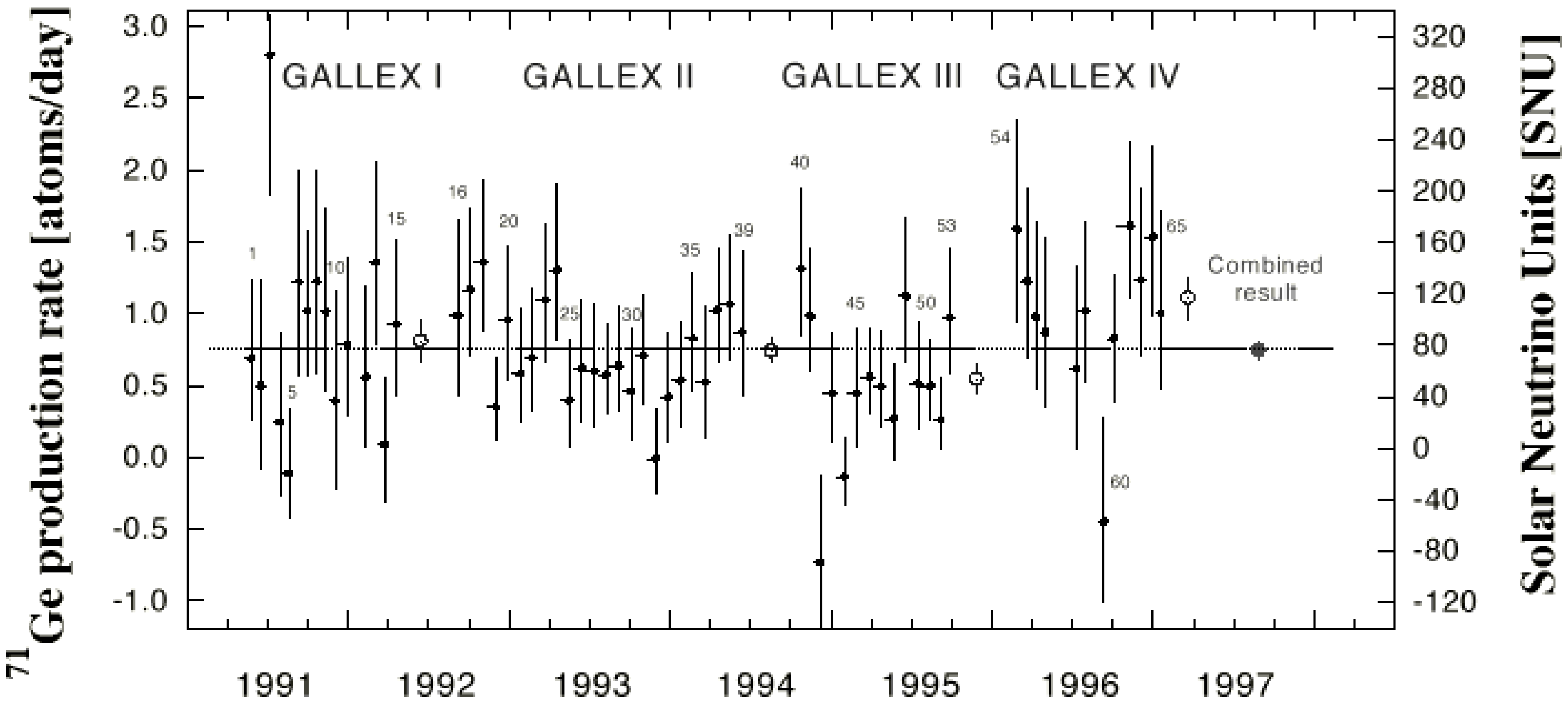
$E_\nu > 233$ KeV

Expected rate: ***137±8 SNU***

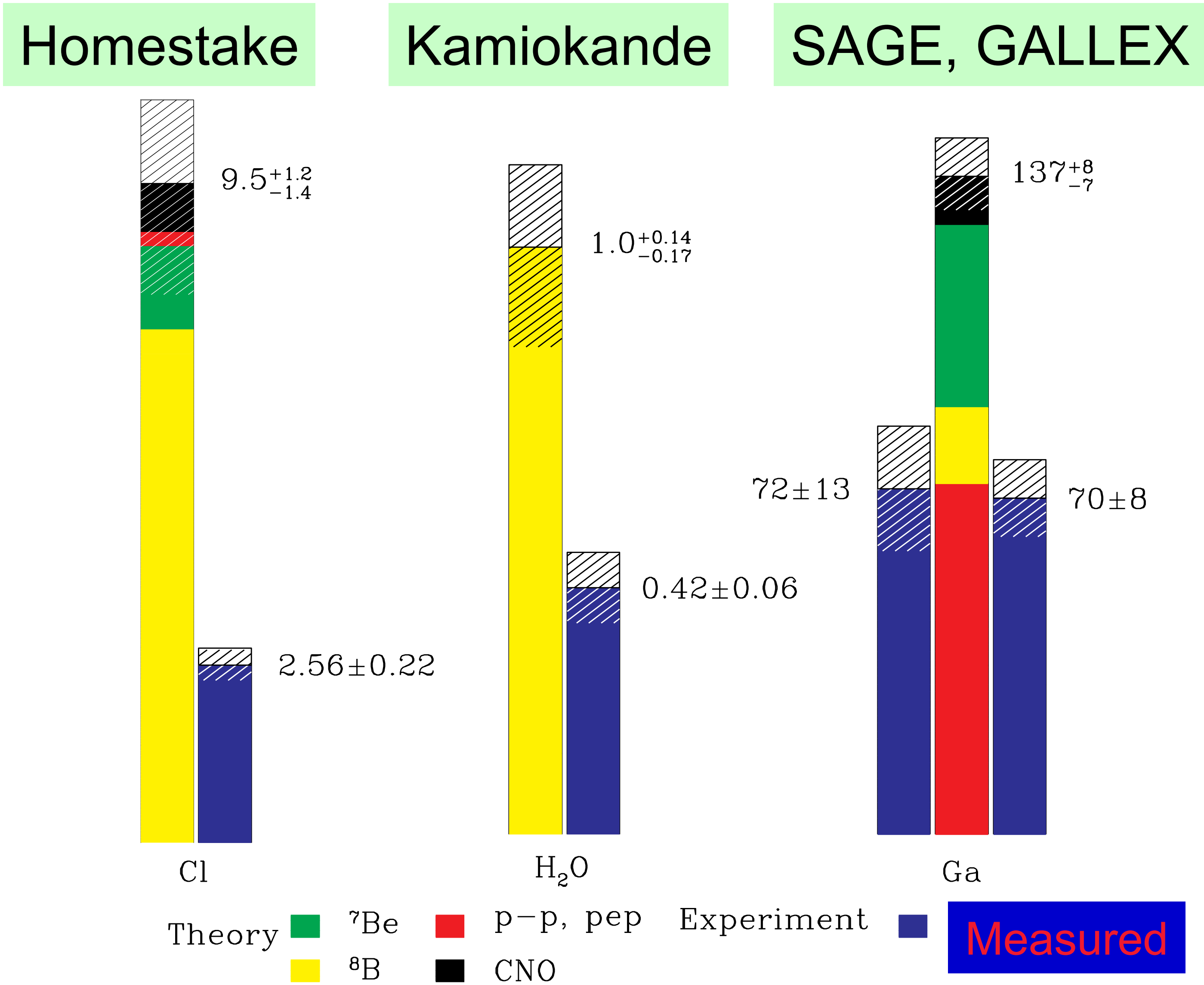
Measured rate: ***70±8 SNU***

Absolute calibration performed

Gallex Observation of the solar neutrino flux



The solar neutrino problems



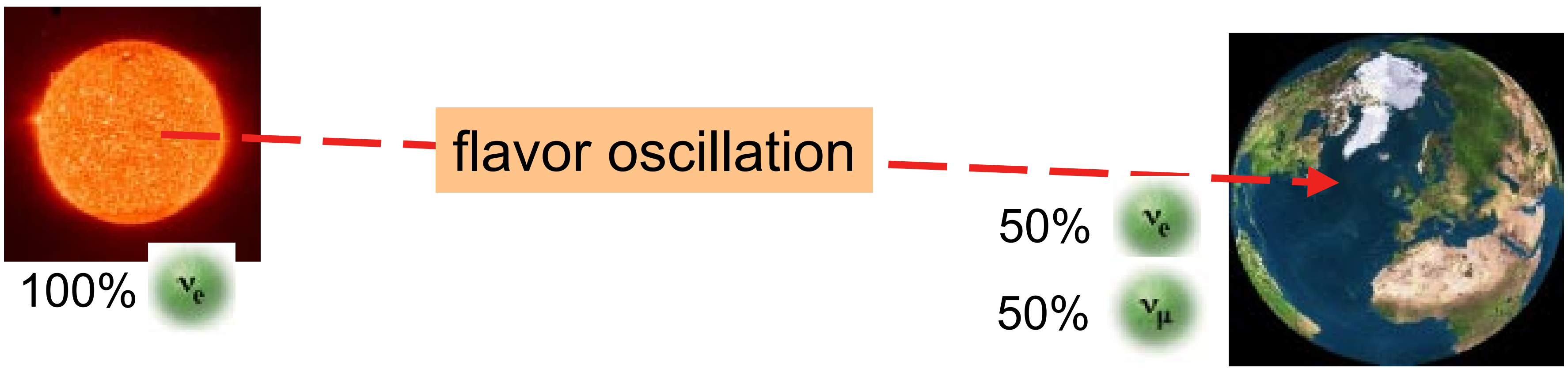
André Rubbia, ETH/Zürich, 14/6/00

New physics?

The solar neutrino deficit came as a total surprise!
the original motivation of the Homestake was to prove the nuclear reaction as the energy production mechanism of stars

The deficit of solar neutrinos can be explained with the help of unaccounted for new physics of flavor oscillation, in which **neutrinos can change flavor identity during their journey in space**
(this phenomenon is known to happen in the quark sector)

Pontecorvo, Gribov (1969)



Lepton sector mixing

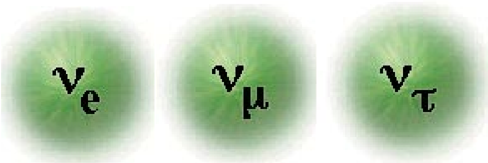
- If neutrinos are massive particles, then it is possible that the **mass eigenstates** and the **weak eigenstates** are not the same:

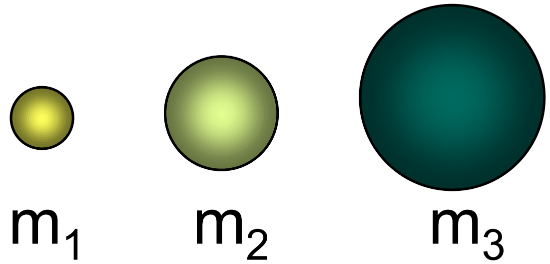
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Weak eigenstates „flavor eigenstates“

3 independent parameters + 1 complex phase

Mass eigenstates

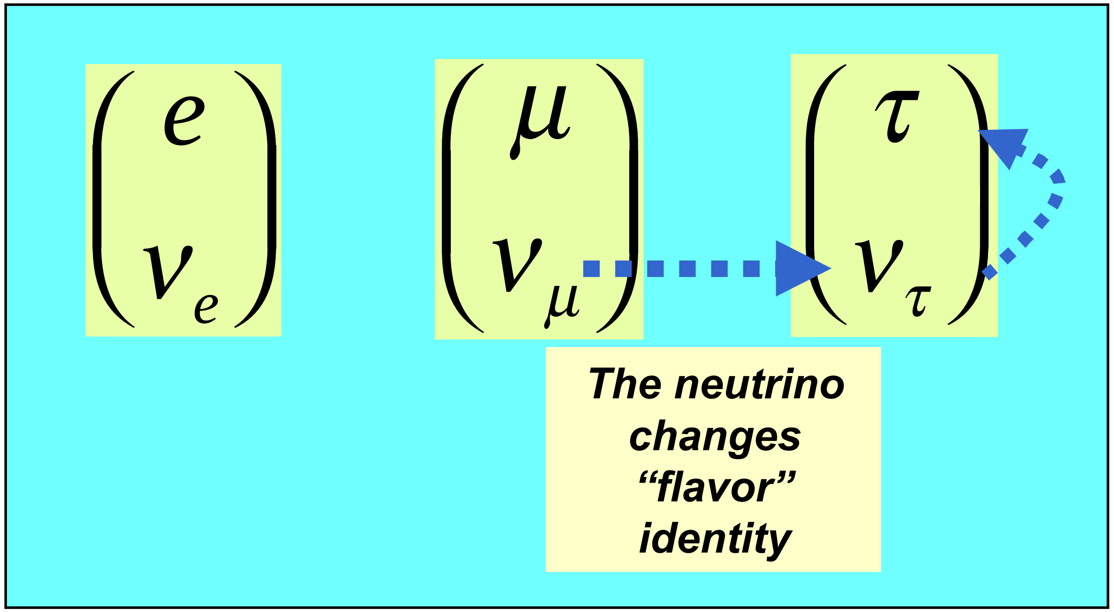




- The analog of the CKM-matrix in the quark sector

…implies neutrino oscillations

- Neutrino oscillation is a quantum mechanical process in which we have oscillating flavor transitions, where a neutrino of one flavor can be detected as a neutrino of a different flavor:



Two necessary conditions:

- ✓ *Not all neutrinos have the same mass*
- ✓ *The neutrino are „mixed"*

In Standard Model, this process does not take place since:

1. neutrinos are massless
2. lepton flavor violation is prohibited

Oscillation probability

- The case with two neutrinos:
  - → A mixing angle: θ
  - → A mass difference:

$$\Delta m^2 = m_2^2 - m_1^2$$

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- The oscillation probability is:

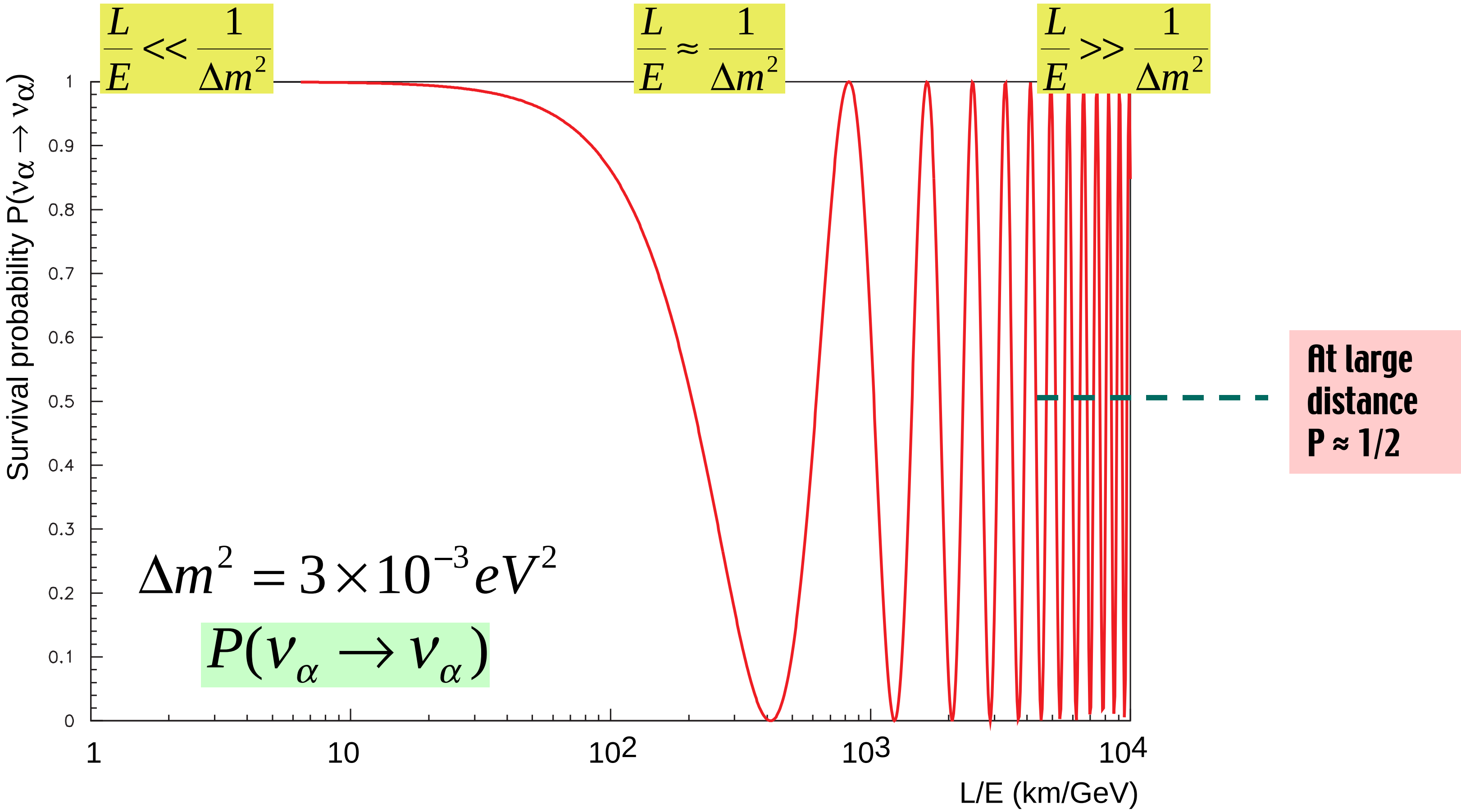
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

where L = distance between source and detector
E = neutrino energy

Neutrino oscillation phenomenology

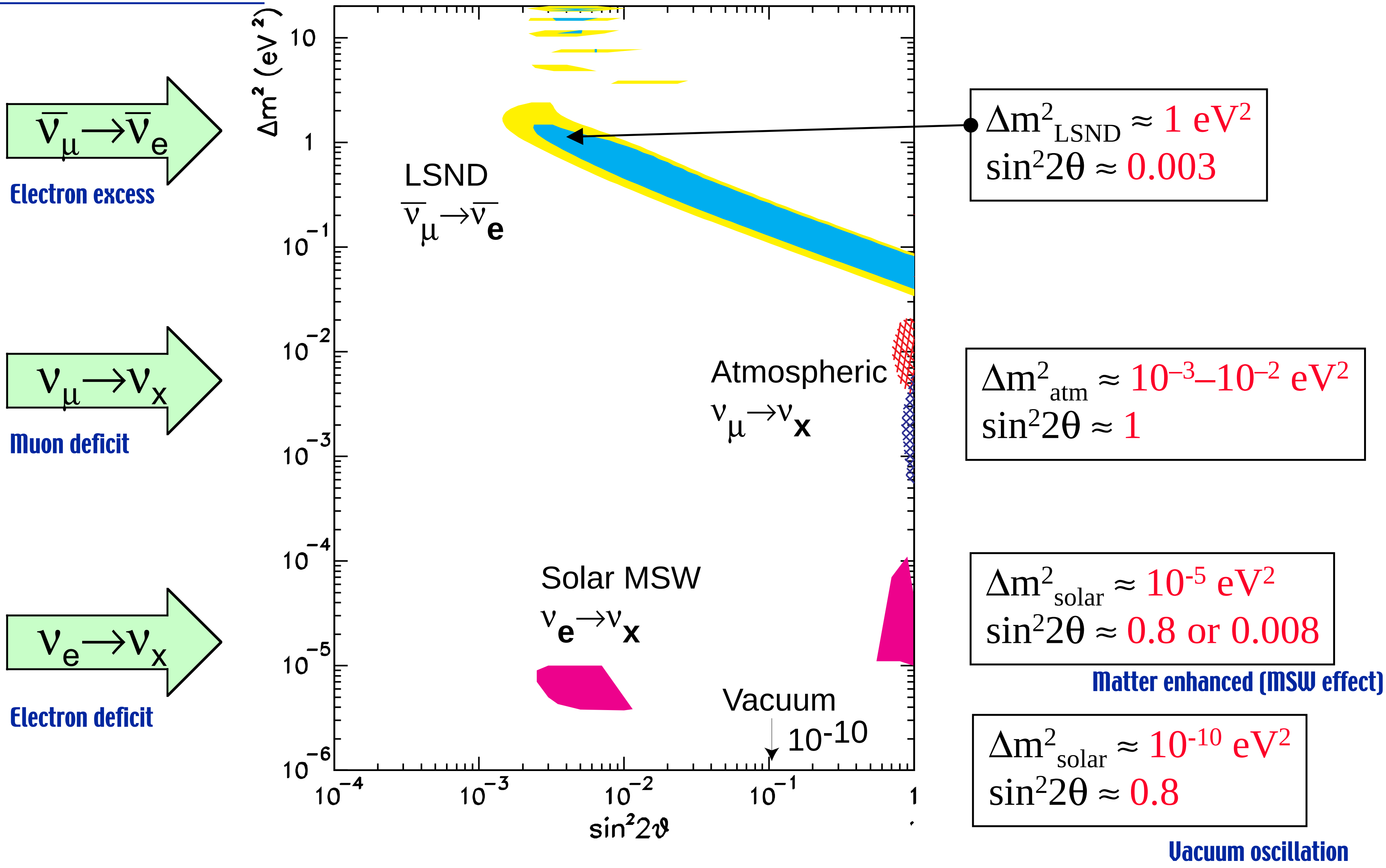
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27 \;\; \Delta m^2_{12} L}{E}\right)$$

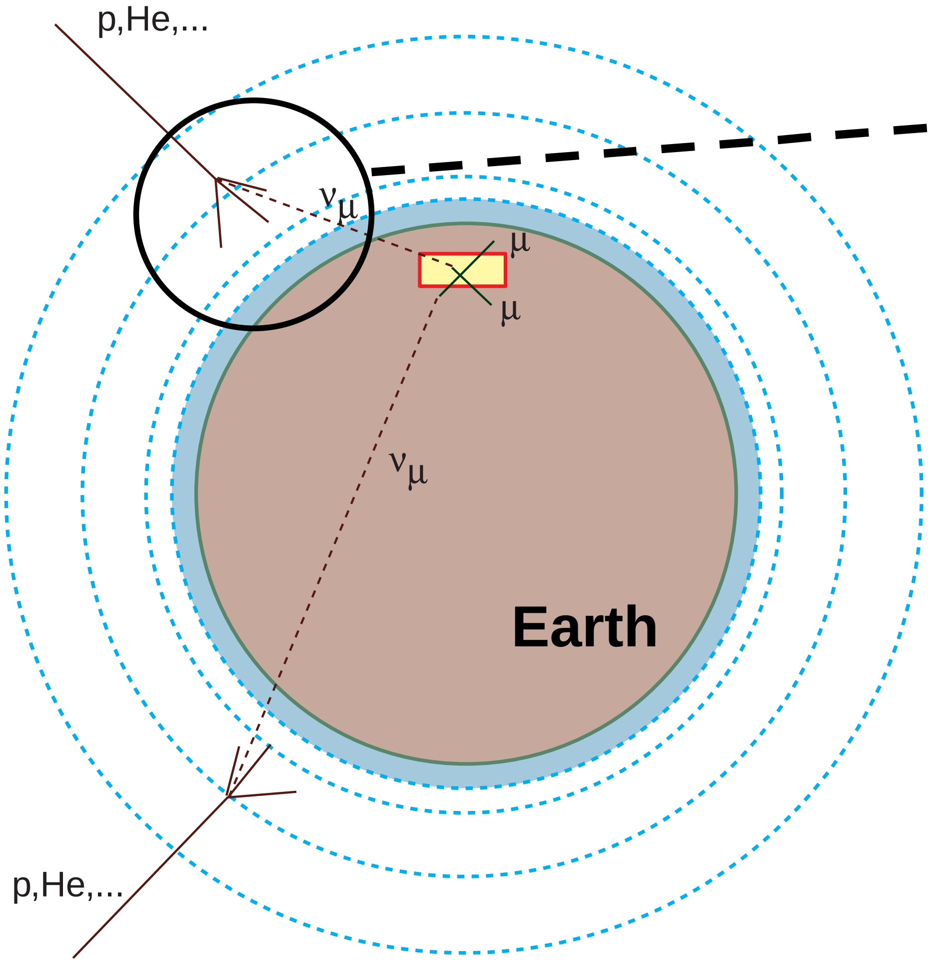


Oscillation map – "allowed regions"

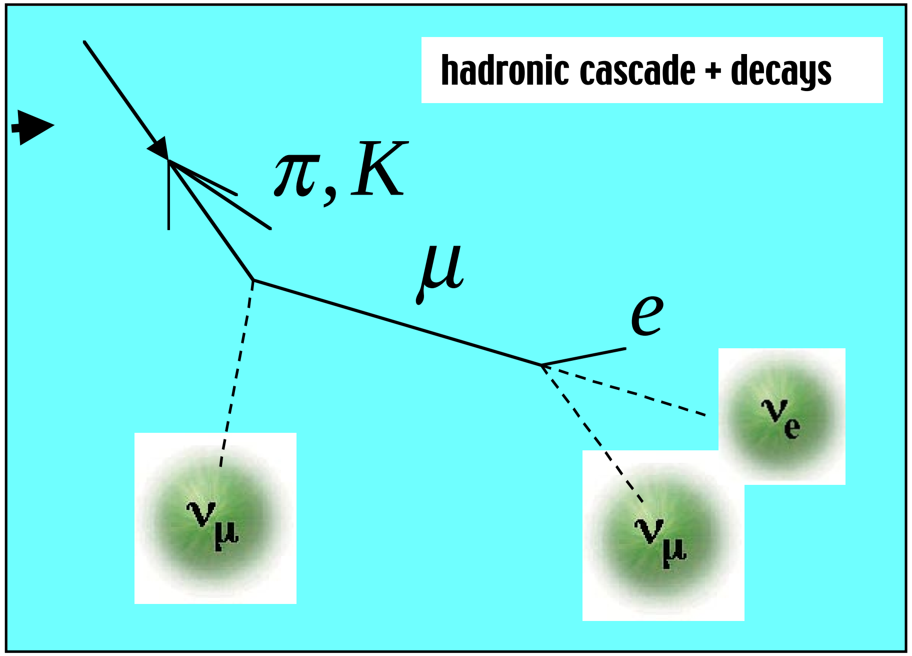
Two-neutrino oscillation



Atmospheric neutrinos



almost isotropic source
(geomagnetic effects)



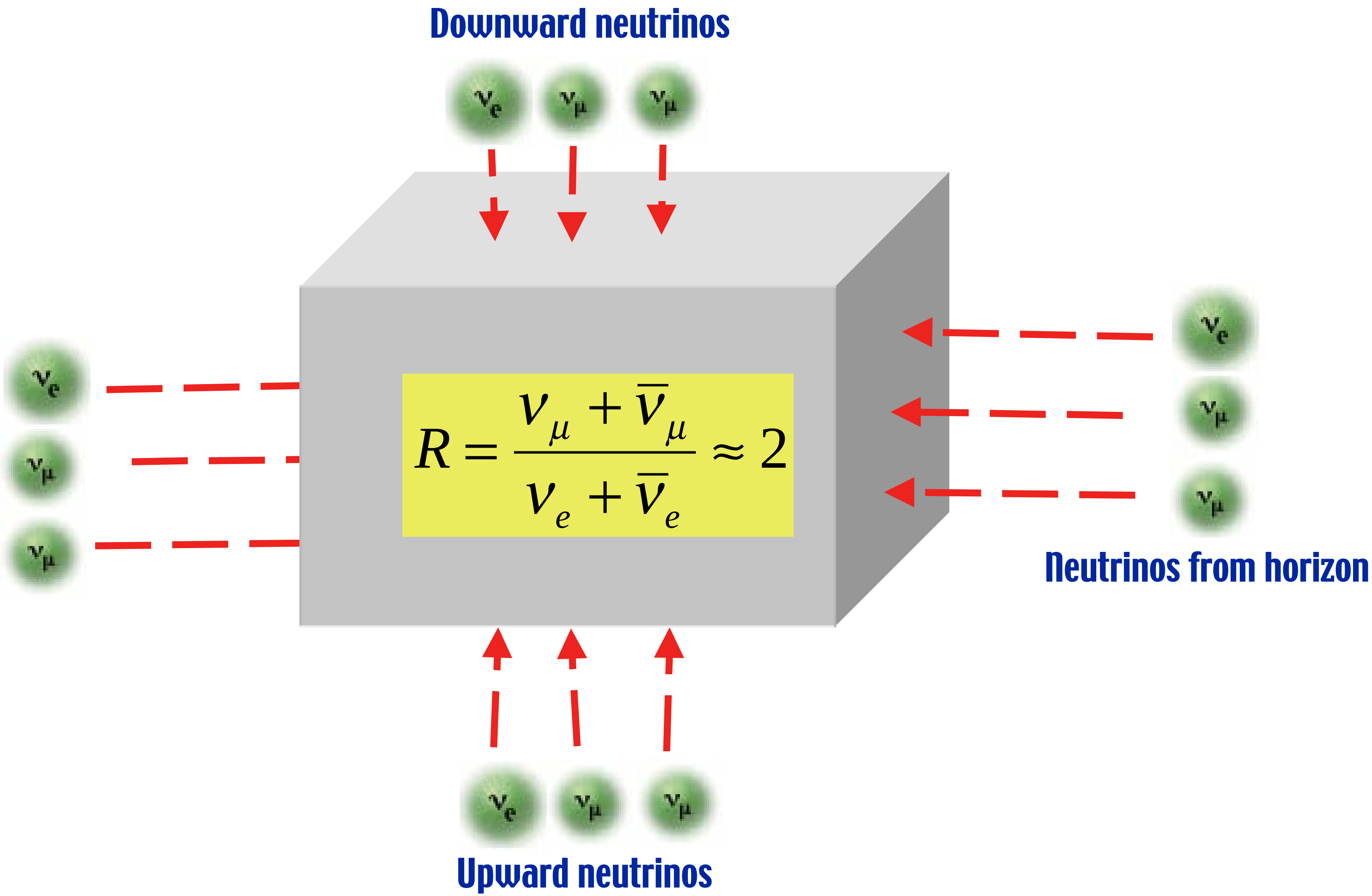
$$R = \frac{\nu_\mu + \overline{\nu}_\mu}{\nu_e + \overline{\nu}_e} \approx 2$$

Predicted ratio of muon to electron neutrinos

Atmospheric neutrino events

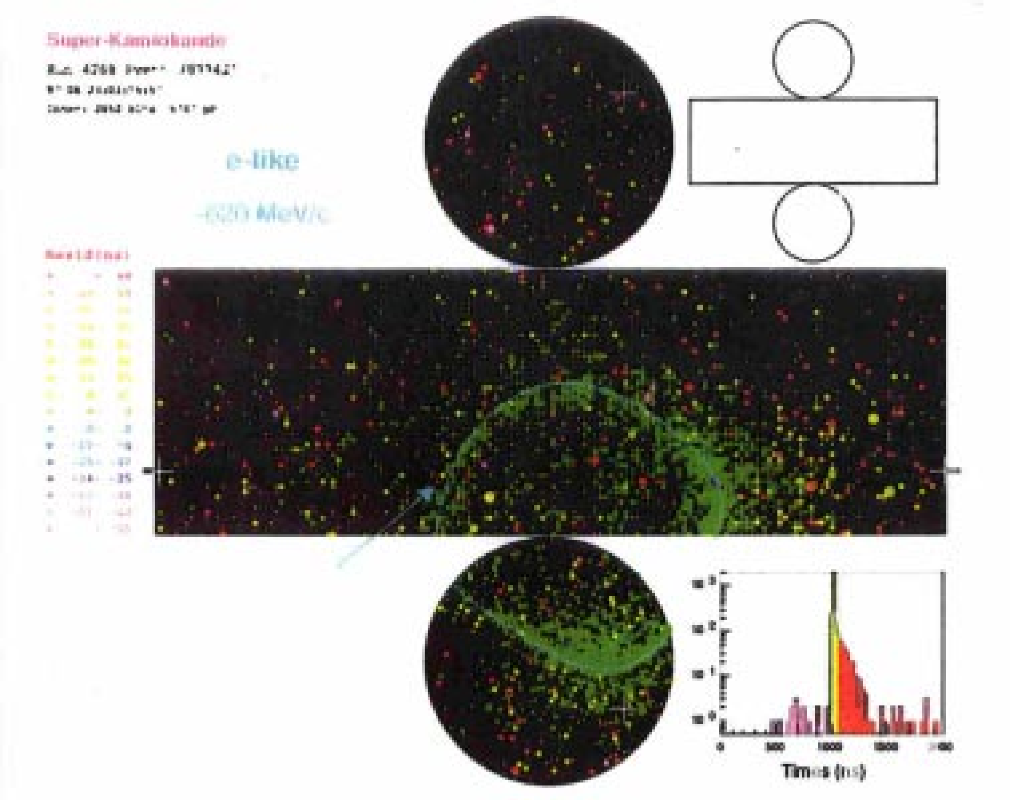
Interactions per year:

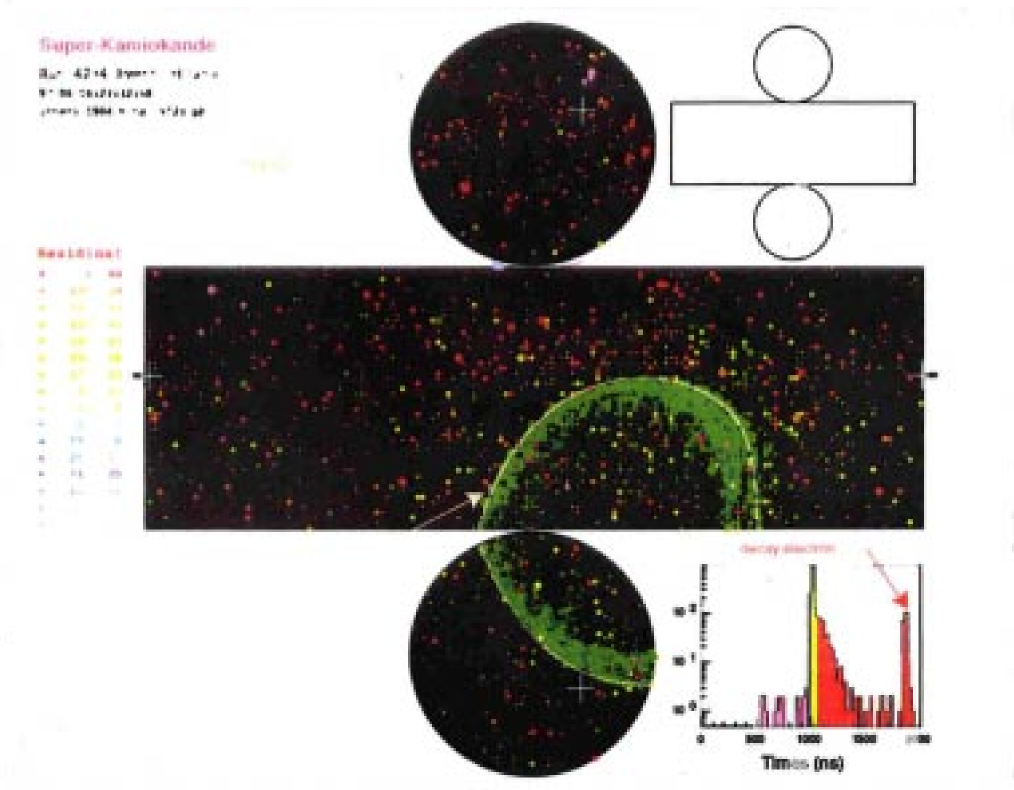
≈200 events per 1000 tons of target



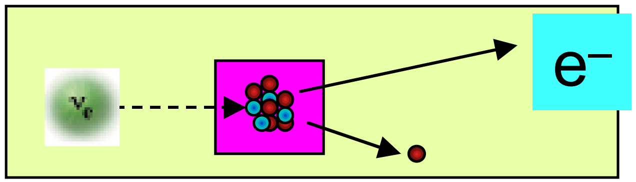
$$R = \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$$

Electron and muon events in Superkamiokande

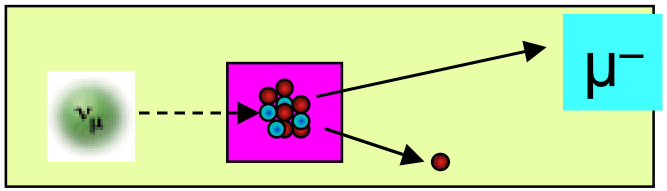




Electron-like event



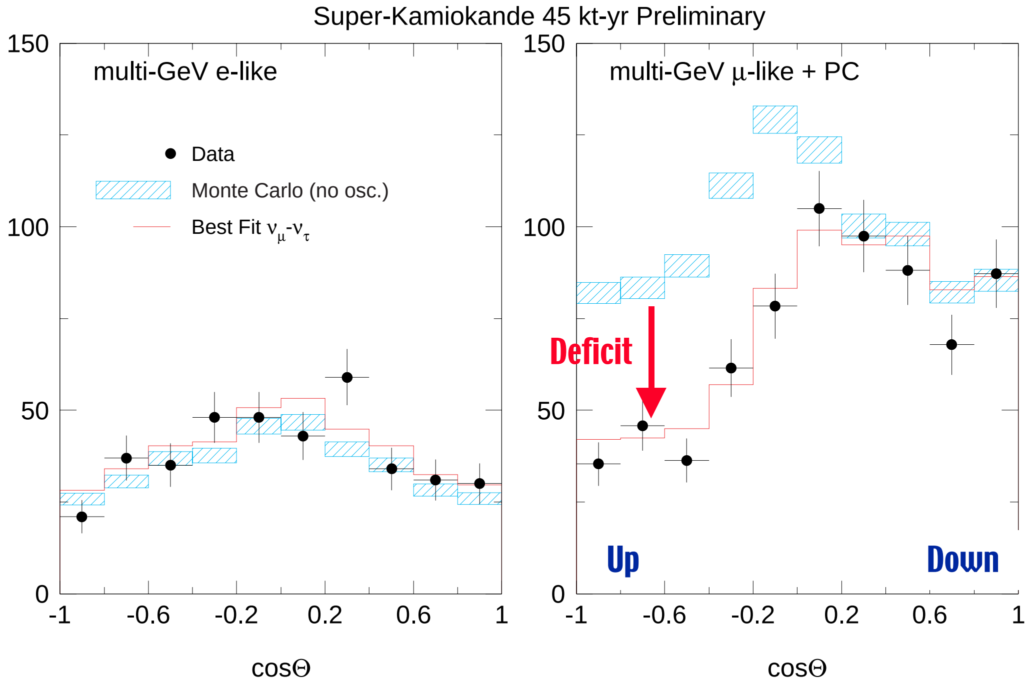
Muon-like event

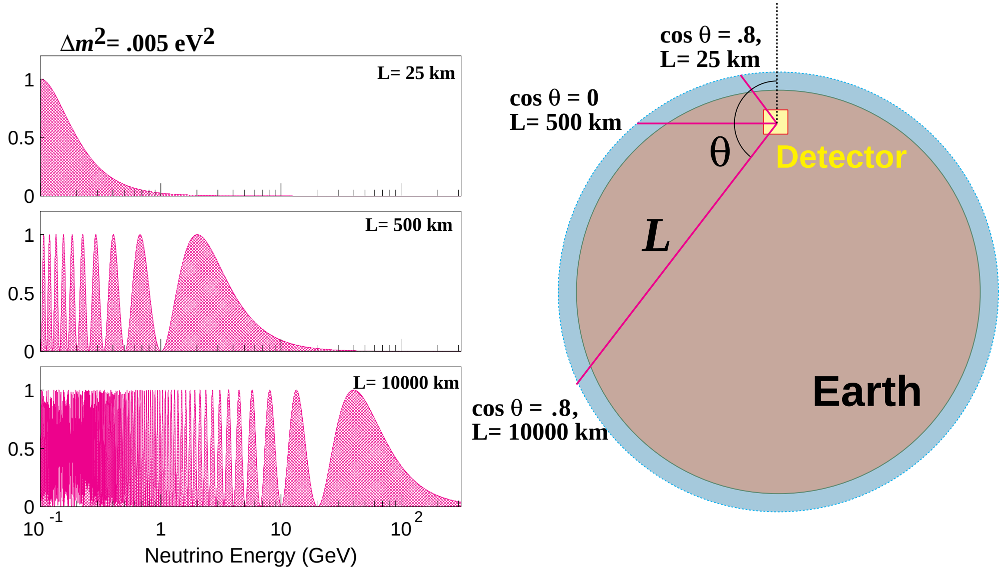


Note: at high energy, the direction & energy of outgoing e/μ is ≈ that of incoming neutrino

Zenith angle distribution

By looking in different zenith angle directions, one can select the neutrino "baseline" L...





$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

(Δm^2 in eV^2, L in km, E in GeV)

⇒ $\nu_\mu \to \nu_\tau$ oscillations?

- ☛ ***ν_μ deficit increases with L***
- ☛ ***no apparent effect with ν_e***

$$U_{\mu 3}^2 = U_{\tau 3}^2 \approx \frac{1}{2}$$

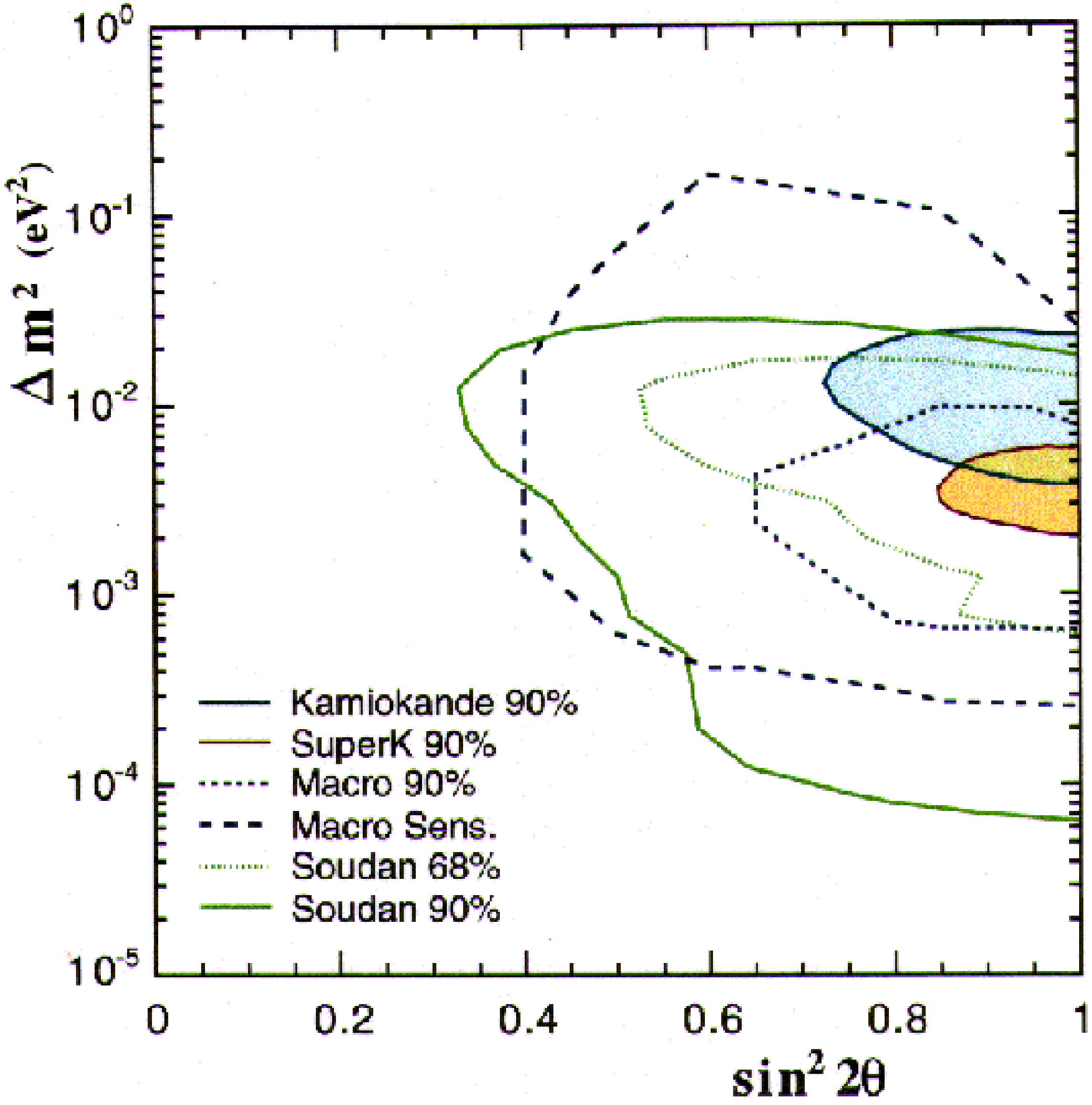
Maximal mixing

$$U_{e3}^2 <\approx 0.05$$

Small mixture allowed

Agreement among atmospheric observations

Two-neutrino oscillation



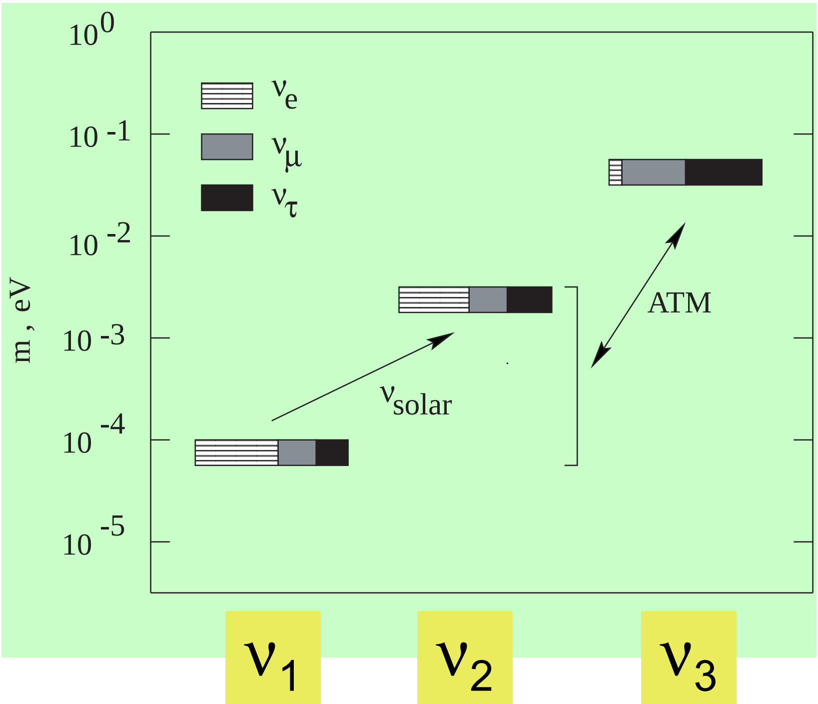
- Effect seen by many experiments in different modes
  - ➜ internal contained, PC events
  - ➜ Stopping/through upward μ
- Consistent with $\nu_\mu \Leftrightarrow \nu_\tau$ maximal mixing with $\Delta m^2 \approx 3\text{x}10^{-3}$ eV^2

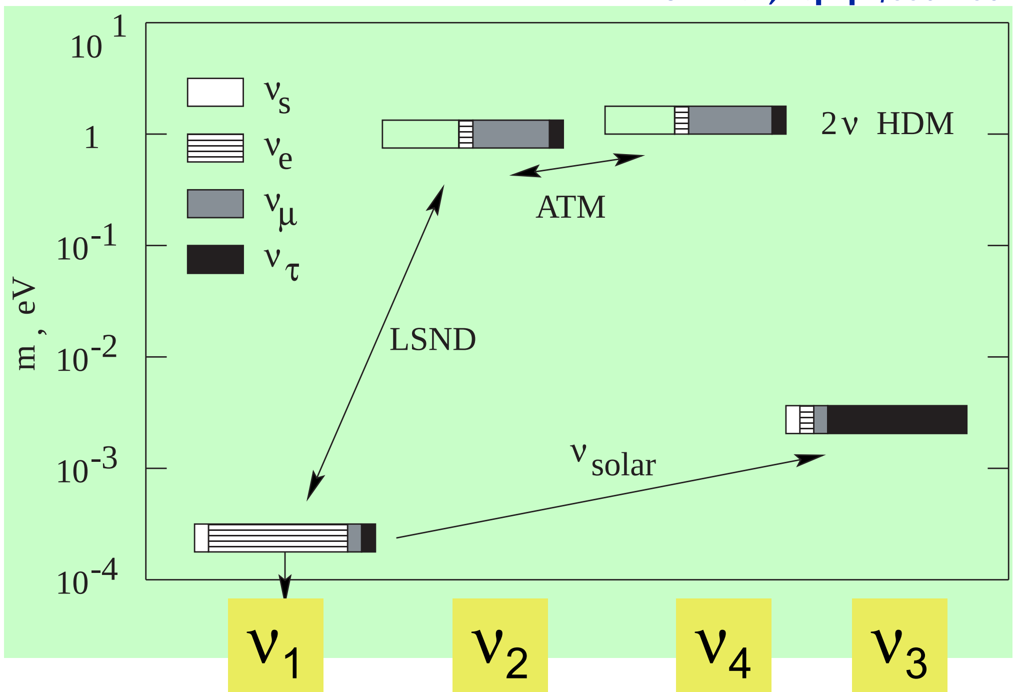
Experiment	Analysis	Δm^2 is ...	$\Delta m^2 (\text{eV})^2$
Kamiokande	R	best fit	1.6×10^{-2}
Kamiokande	up-going μ	best fit	3.2×10^{-2}
Super K	R	best fit	2.2×10^{-3}
Super K	up-going μ	consistent with	2.5×10^{-3}
Soudan II	R	consistent with	$> 10^{-3}$
MACRO	up-going ν	consistent with	5×10^{-3}
MACRO	up-going μ	consistent with	2.5×10^{-3}

Where do we stand with the models?

- The three-flavor mixing **cannot accommodate all experiments**
  - → Only two independent Δm^2 with three neutrinos
  - → 3 distinct Δm^2 regions $\Delta m^2_{solar} << \Delta m^2_{atm} << \Delta m^2_{LSND}$ required to accommodate solar, atmospheric and LSND data requires
  - → transitions involving **"sterile" states** could be occurring as well

Smirnov, hep-ph/9907296



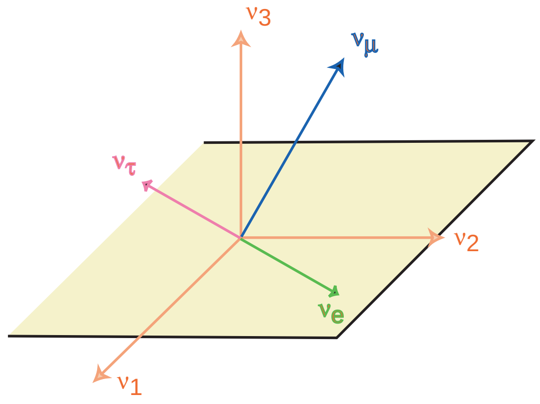


Three flavor mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Weak eigenstates

Mass eigenstates



$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = P_{CP}(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) \pm P_{\not{C}\not{P}}(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta)$$

CP-conserving

$$P_{CP} = \delta_{\alpha\beta} - 4 \sum_{j>k} \mathrm{Re}\, J_{\alpha\beta jk} \sin^2 \Delta_{jk}$$

CP-violating

$$P_{\not{C}\not{P}} = 4 \sum_{j>k} \mathrm{Im}\, J_{\alpha\beta jk} \sin\Delta_{jk} \cos\Delta_{jk}$$

$$J_{\alpha\beta jk} = U_{\alpha k} U^*_{\beta k} U^*_{\alpha j} U_{\beta j}$$

Mixing strength

$$\Delta_{jk} = \frac{1.27 \;\; \Delta m^2_{jk} L}{E}$$

Oscillatory pattern

Δm^2_{jk} in eV^2, L in km, E in GeV

In general, the oscillation pattern may be complicated and involve **a combination of transitions** to ν_e, ν_μ, ν_τ and by symmetry with quark sector **it is natural to expect CP violation** at some level.

Mixing matrix determination

The ultimate understanding of the neutrino phenomenology requires the measurement of the full mixing matrix

3 angles + 1 complex phase

$U_{e3}^2 < 0.05$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Assuming $\Delta m^2_{21} \ll \Delta m^2_{32}$

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \Delta^2{}_{32}$$

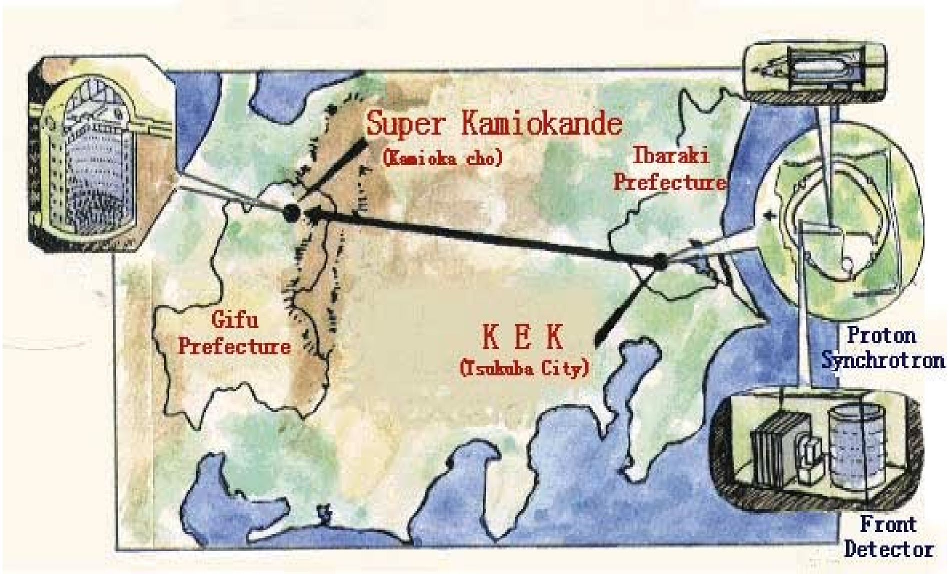
$$P(\nu_\mu \rightarrow \nu_\tau) = \cos^4 \theta_{13} \sin^2 2\theta_{23} \Delta^2{}_{32} \approx \sin^2 2\theta_{23} \Delta^2{}_{32}$$

for $\theta_{13} << 1$

with $\Delta_{32}{}^2 = \sin^2(1.27 \Delta m_{32}{}^2 L / E)$

K2K experiment

- Experiment started in March 1999
  - → Some initial problems with optics system now apparently solved
  - → Beam intensity : 5.5 x 10^{12} ppp
  - → Total integrated (Apr-Nov 99): **7.2 x 10^{18} pots** (goal: 10^{20} pots)
- ***Beam measured with near detectors*** (FD)
  - → 3 different detectors: 1kt H_2O, SCIFI tracker+water, MUC (Fe μ ranger)
  - → Event rate & energy spectrum under study
- ***Extrapolation at far detector*** (SK)



$L = 250$ km
$E_\nu \approx 1$ GeV

stat syst

Expected@SK: 12.1±0.1±1.8
Events seen: 3 events

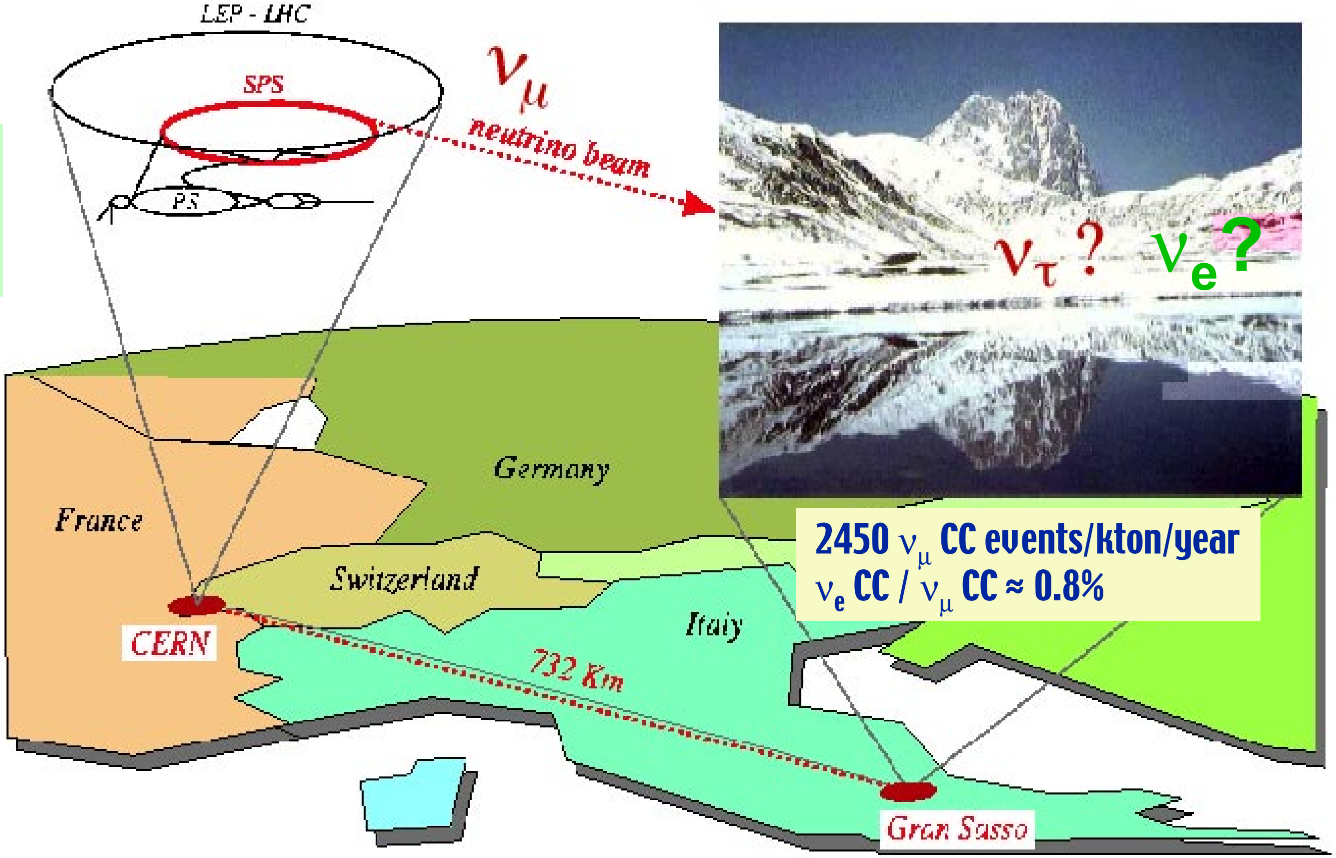
⇒Consistent with a muon disappearance effect!

CNGS neutrino beam

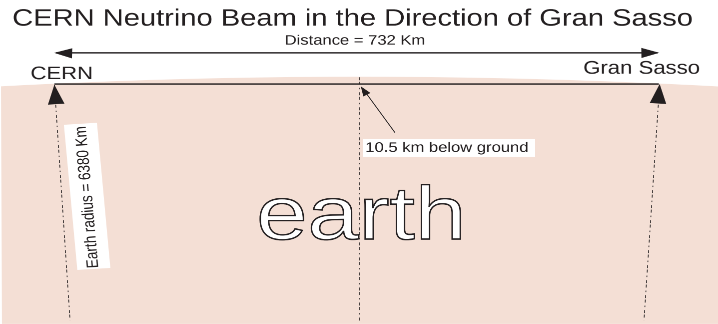
400 GeV protons from CERN/SPS (4.5x10^{19} pots /year "shared"; 7.6x10^{19} pots/year "dedicated")

$L = 732$ km
$E_\nu \approx 17$ GeV

⇒Optimized for tau appearance



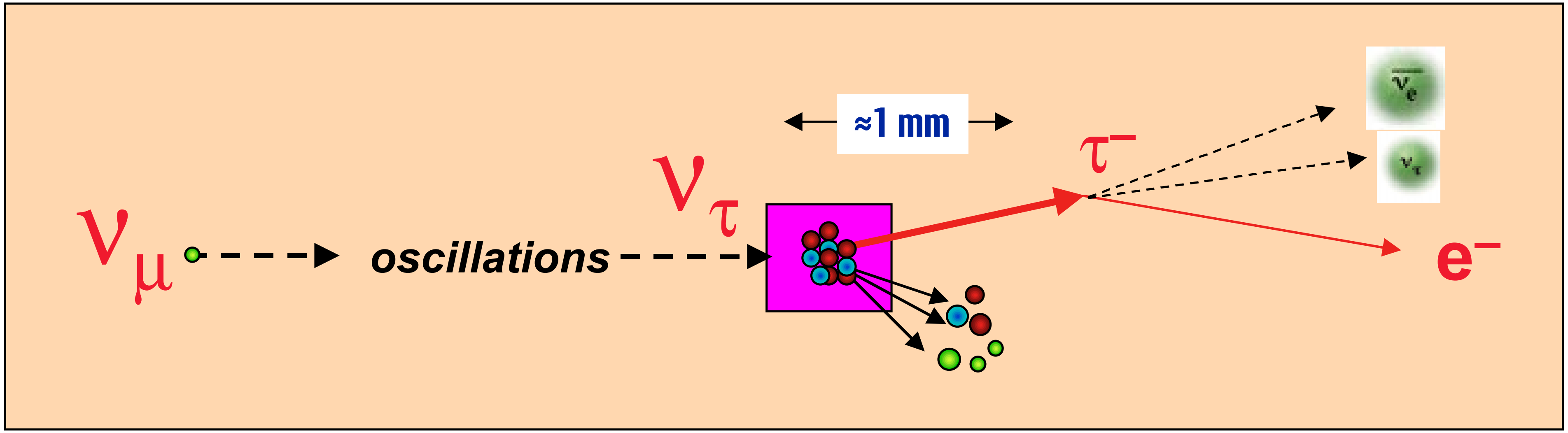
2450 ν_μ CC events/kton/year
ν_e CC / ν_μ CC ≈ 0.8%

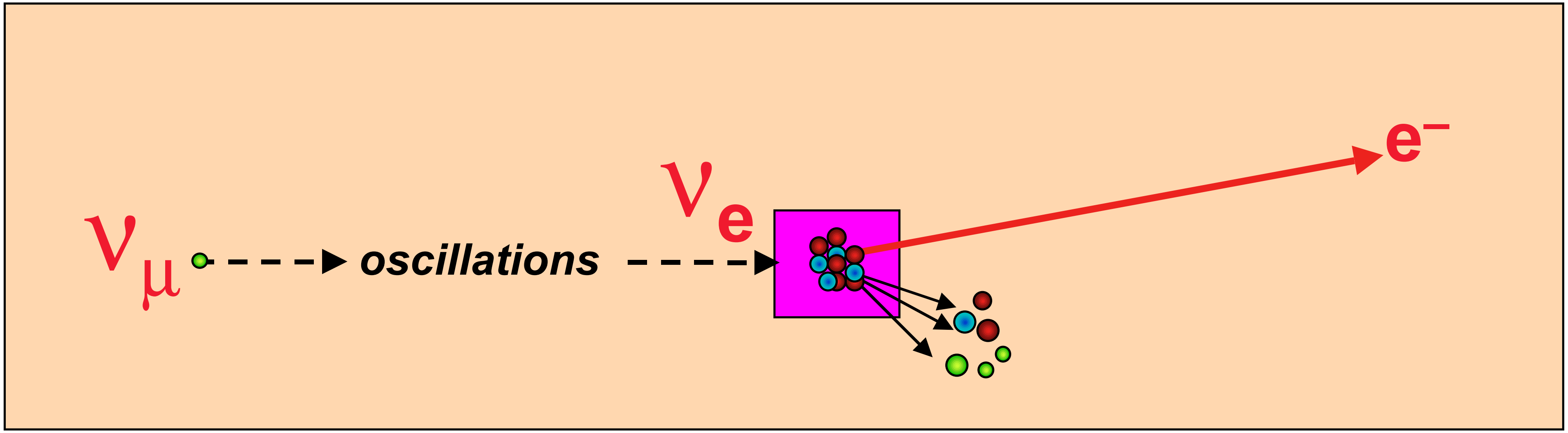


Approved program (Dec 1999)
⇒ beam ready in Spring 2005.

CERN 98-02 - INFN-AE/98-05
CERN-SL/99-034(DI) - INFN/AE-99/05

Detecting neutrino oscillations



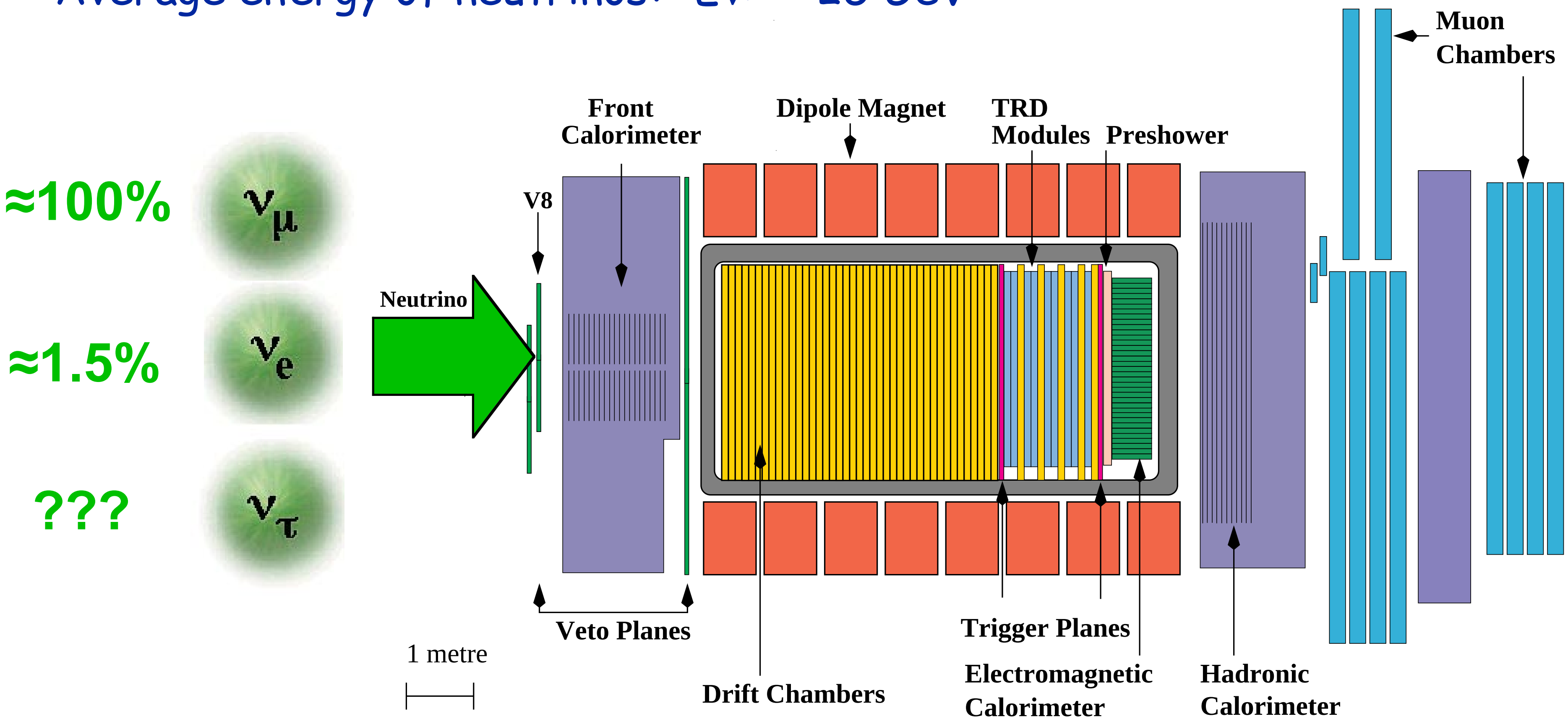


NOMAD Experiment at CERN (1994–1998)

- Dedicated for $\nu_\mu \rightarrow \nu_\tau$ oscillations („Appearance“-Experiment)

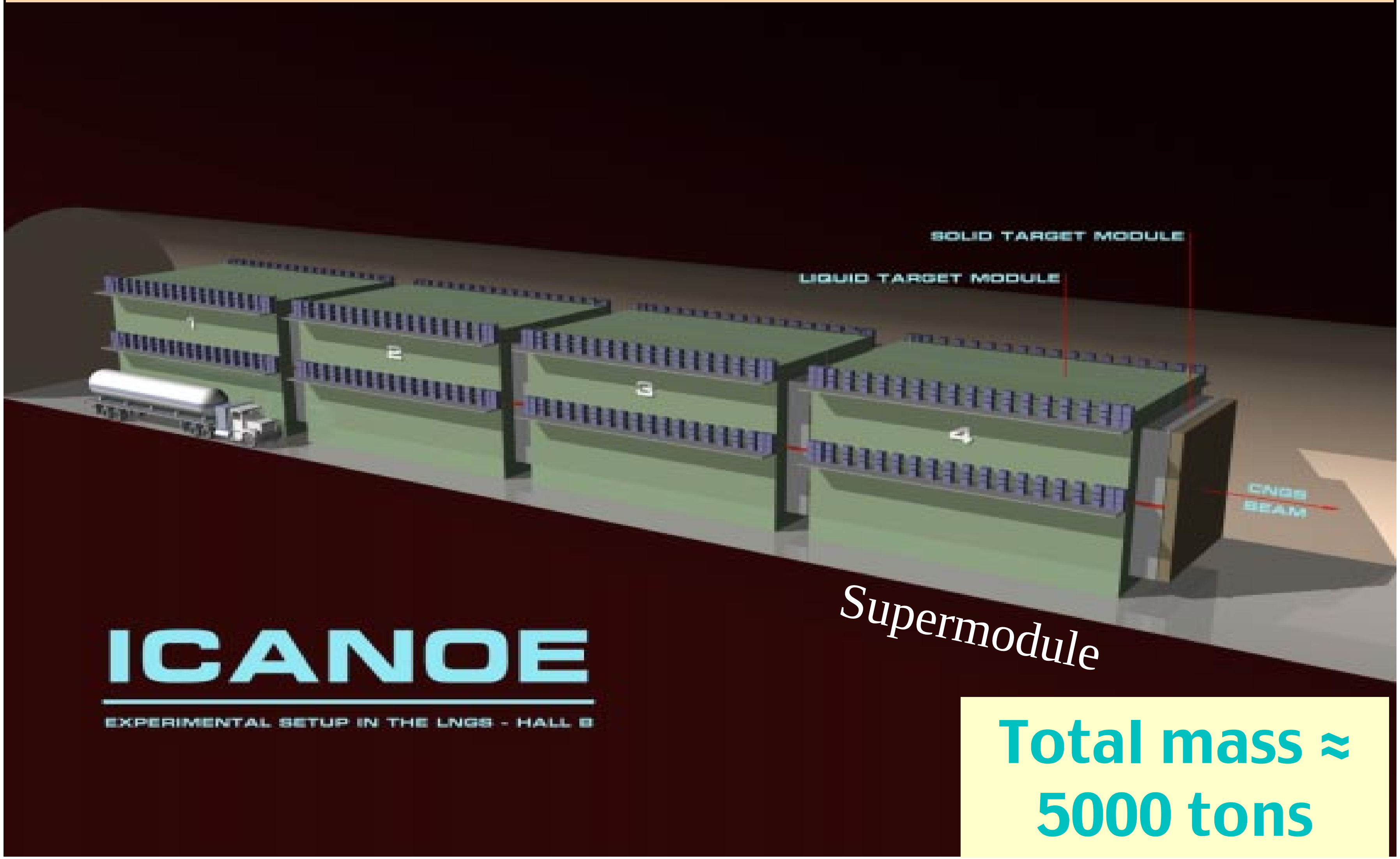
  Distance between source and NOMAD : L = 0.65 km

  Average energy of neutrinos: <Eν> ≈ 25 GeV



Planned ICANOE experiment at LNGS

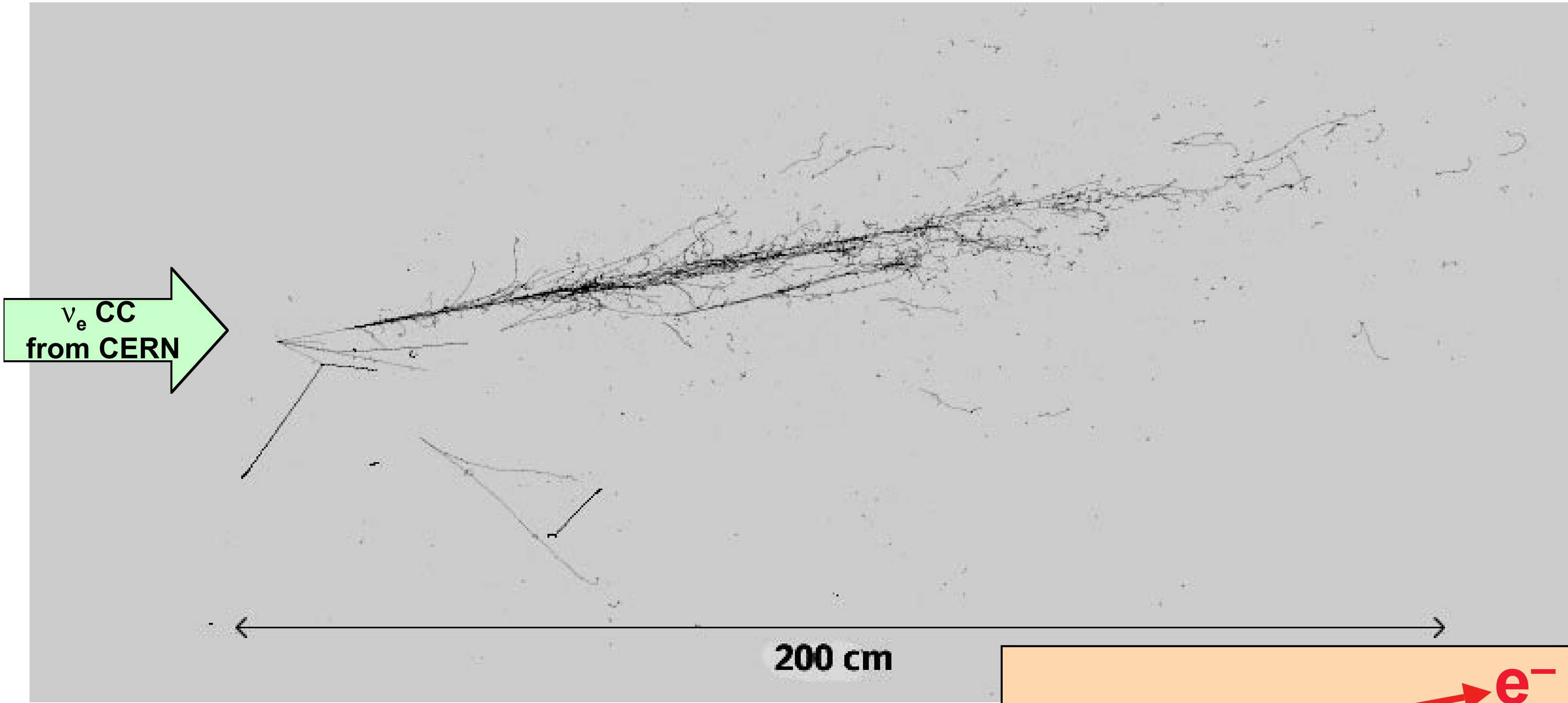
An "electronic bubble chamber" complemented by an external μ-identifier

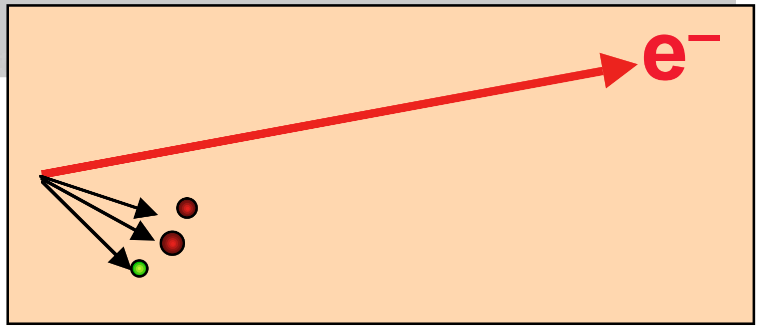


Total mass ≈ 5000 tons

Example of neutrino event (simulated)

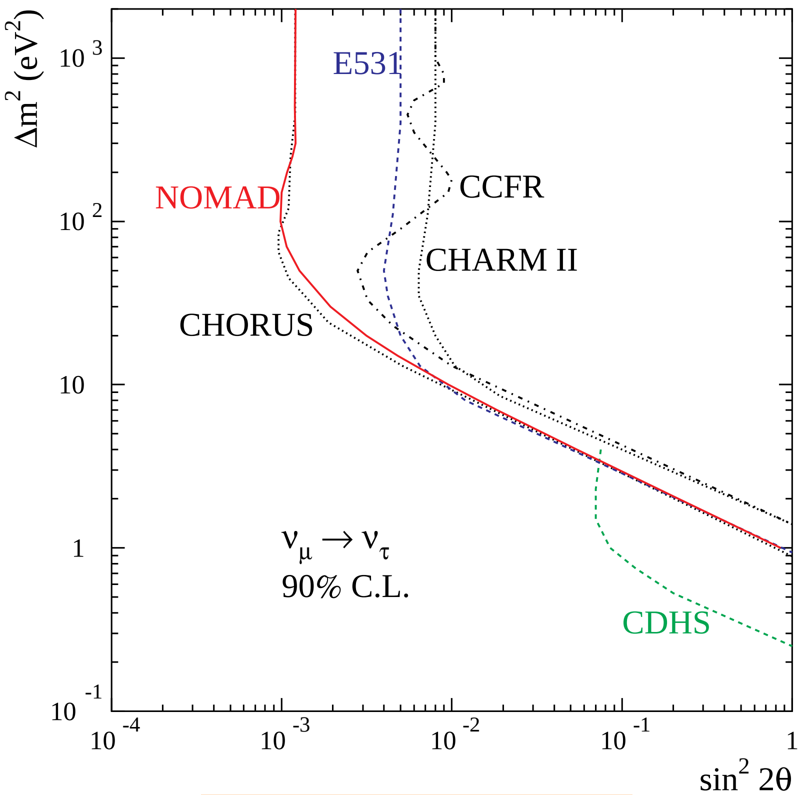
The granularity of a bubble-chamber, with electronic-readout and very large mass





Improving the sensitivity at low masses

NOMAD

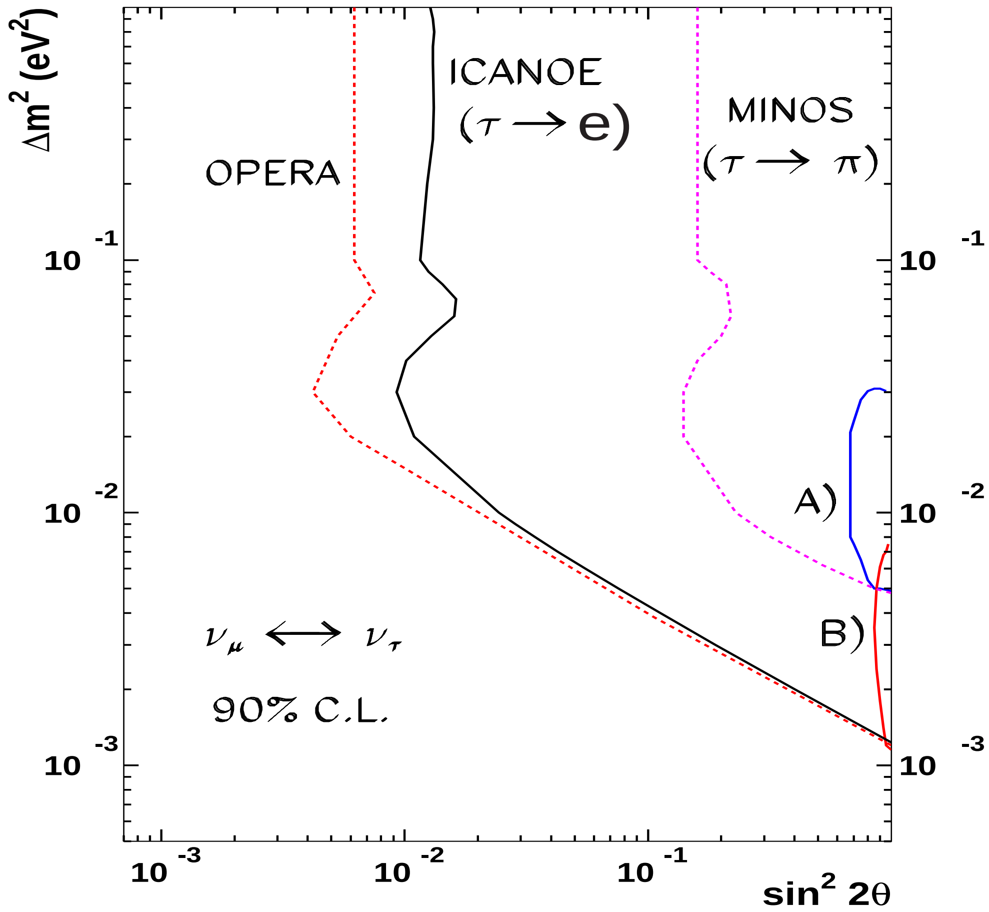


Sensitivity:

$\Delta m^2 \approx 10$ eV^2

ICANOE

4 years

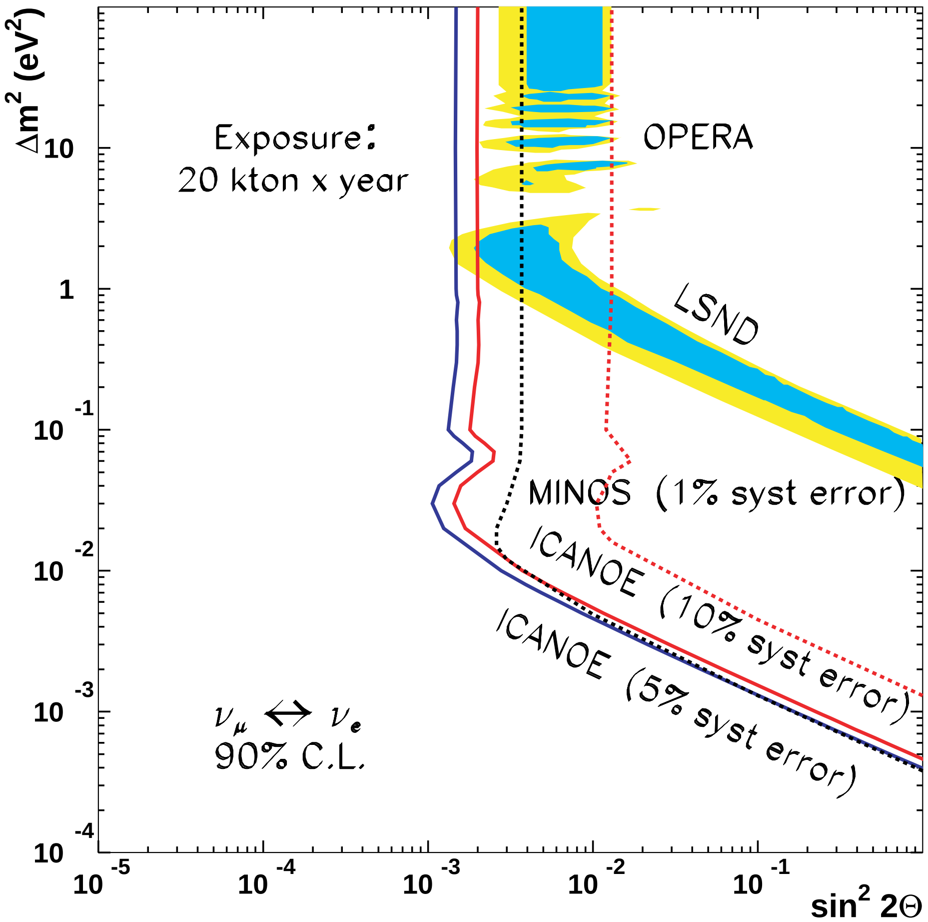


Sensitivity:

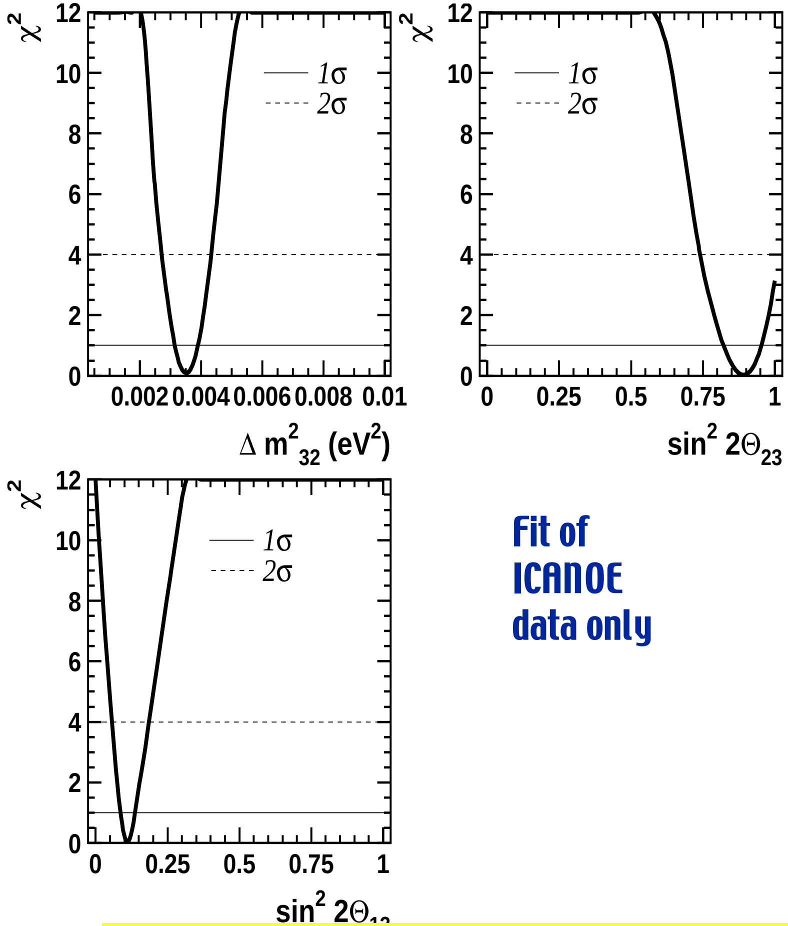
$\Delta m^2 \approx 10^{-3}$ eV^2

Subleading electron oscillation

$\nu_\mu \to \nu_e$



Combining atmospheric and beam data



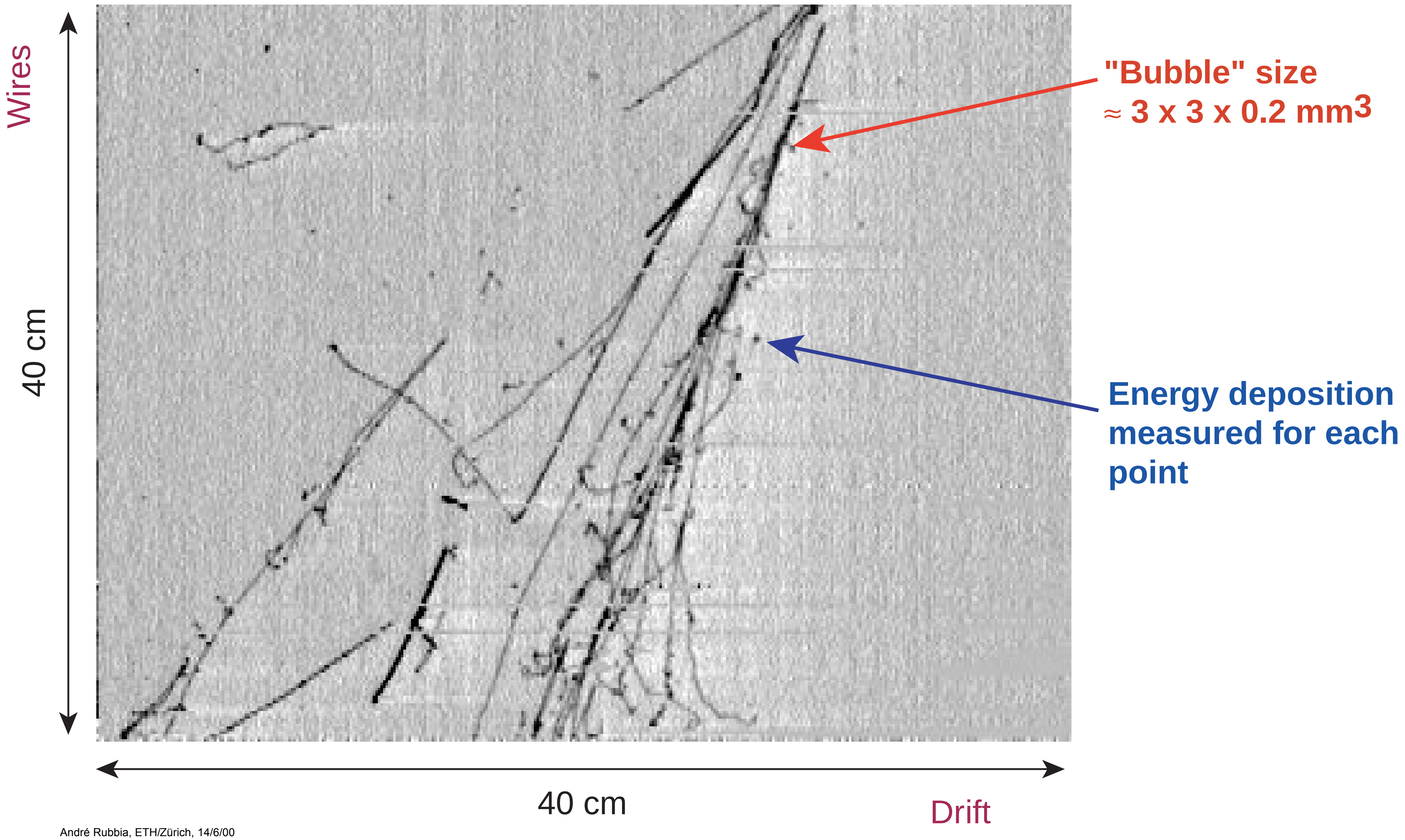
Fit of ICANOE data only

$\sin^2 2\theta_{13} = 0.10 \pm 0.04$

$\Delta m^2_{32} = (3.5 \pm 0.4) \times 10^{-3}\ eV^2$

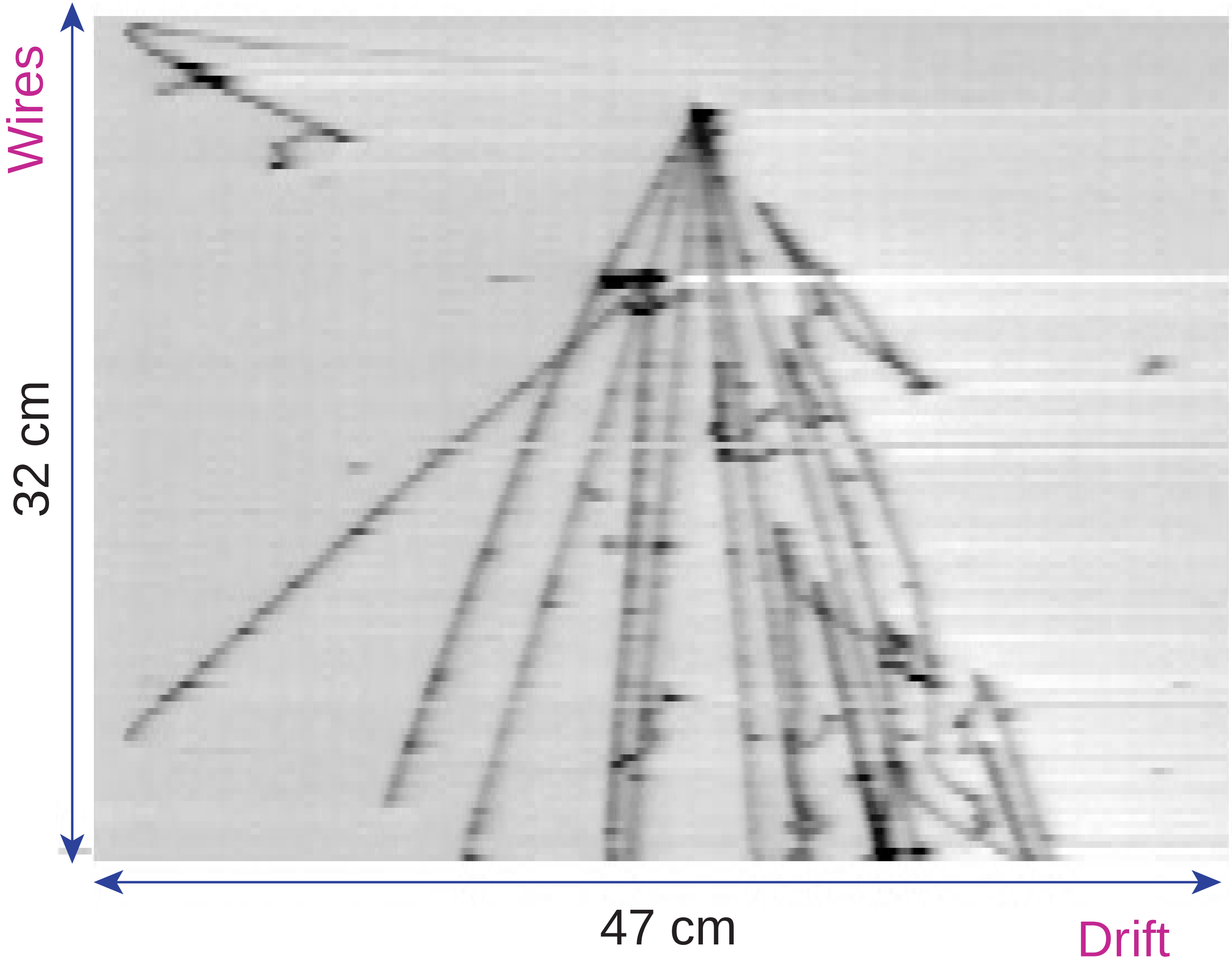
Precision of O(10%) on the oscillation parameters

Cosmic Ray Shower Recorded in the 3 ton Prototype



André Rubbia, ETH/Zürich, 14/6/00

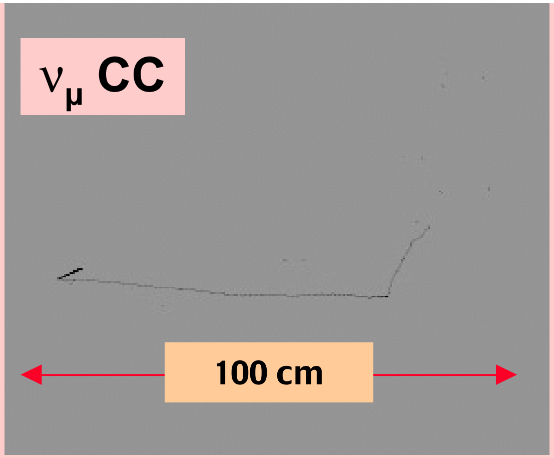
Neutrino Event in the 50 lt Prototype



ICANOE physics program

Looking for rare events:

Atmospheric neutrinos

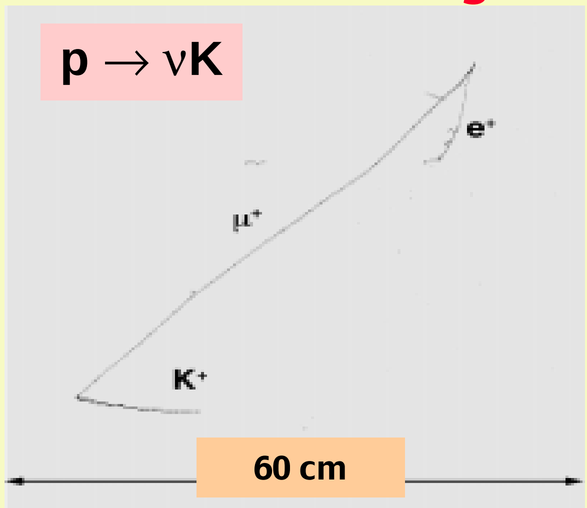


✓Detection of all neutrino flavors, CC & NC modes
✓Study of L/E distributions for e and μ
✓Clean NC/CC
✓Direct tau appearance
✓Upward going muons
✓Very low energy electrons

CERN-NGS

✓Direct tau and electron appearance
✓Muon disappearance

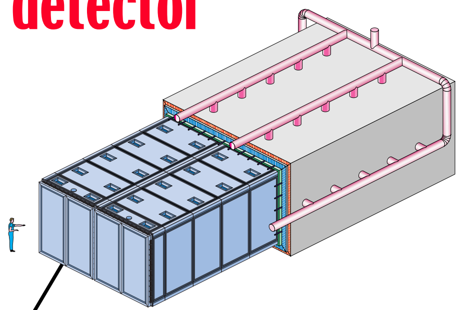
Nucleon decay



✓Background free searches
✓Sensitivity $10^{33} \div 10^{34}$ years

The ICARUS programme

600 ton detector



- ✔currently under construction / assembly in strong cooperation with industry
- ✔will be ready for the first test during summer 2000
- ✔Important milestone for the approval of the ICANOE experiment

15 ton prototype

- ✔Cryogenic test
- ✔LAr purification test
- ✔H.V. & readout test

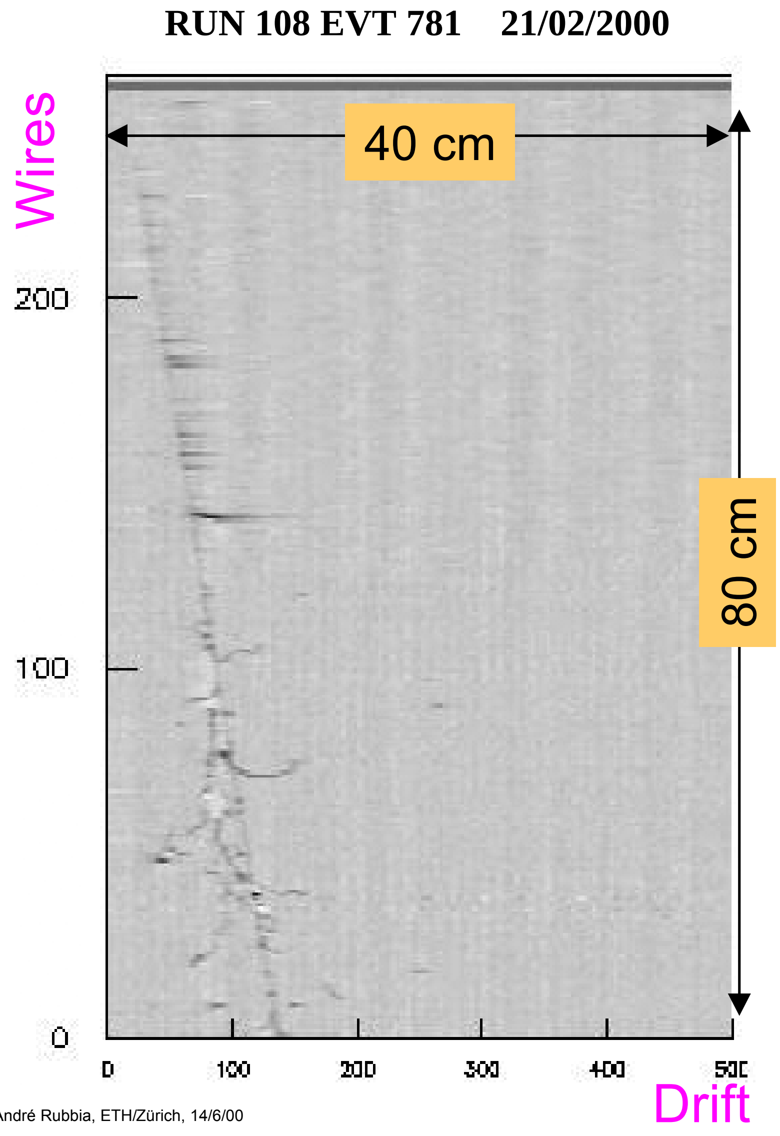
Tracks in 15 ton prototype at LNGS

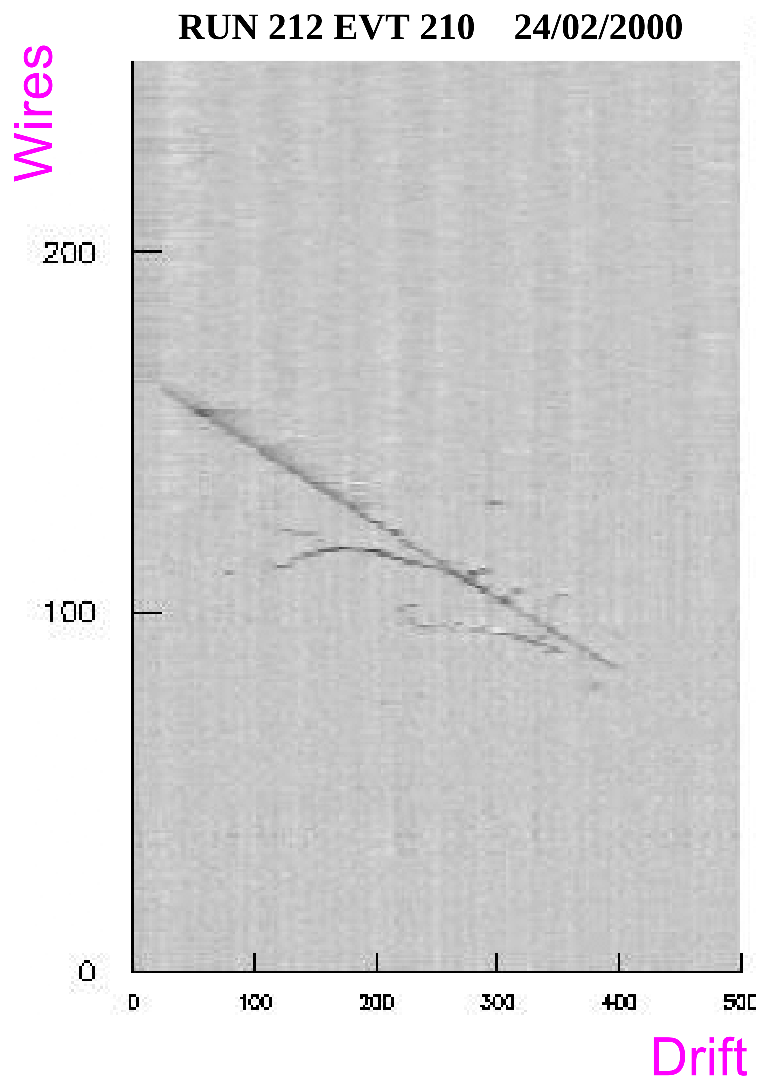
X-ing muon with δ-ray production:

E-field: 300 V/cm

Argon purity: electron lifetime

$\langle\tau_{el}\rangle = 1.05 \pm 0.30$ ms





Beyond the LBL program ?

NuFact ocation	Distance to Gran Sasso	Mean density
CERN	732 km	2.8 g/cm^3
Canary Islands	2900 km	3.2 g/cm^3
FNAL	7400 km	3.7 g/cm^3
KEK	8815 km	4.0 g/cm^3

See hep/ph-0005007 and references therein