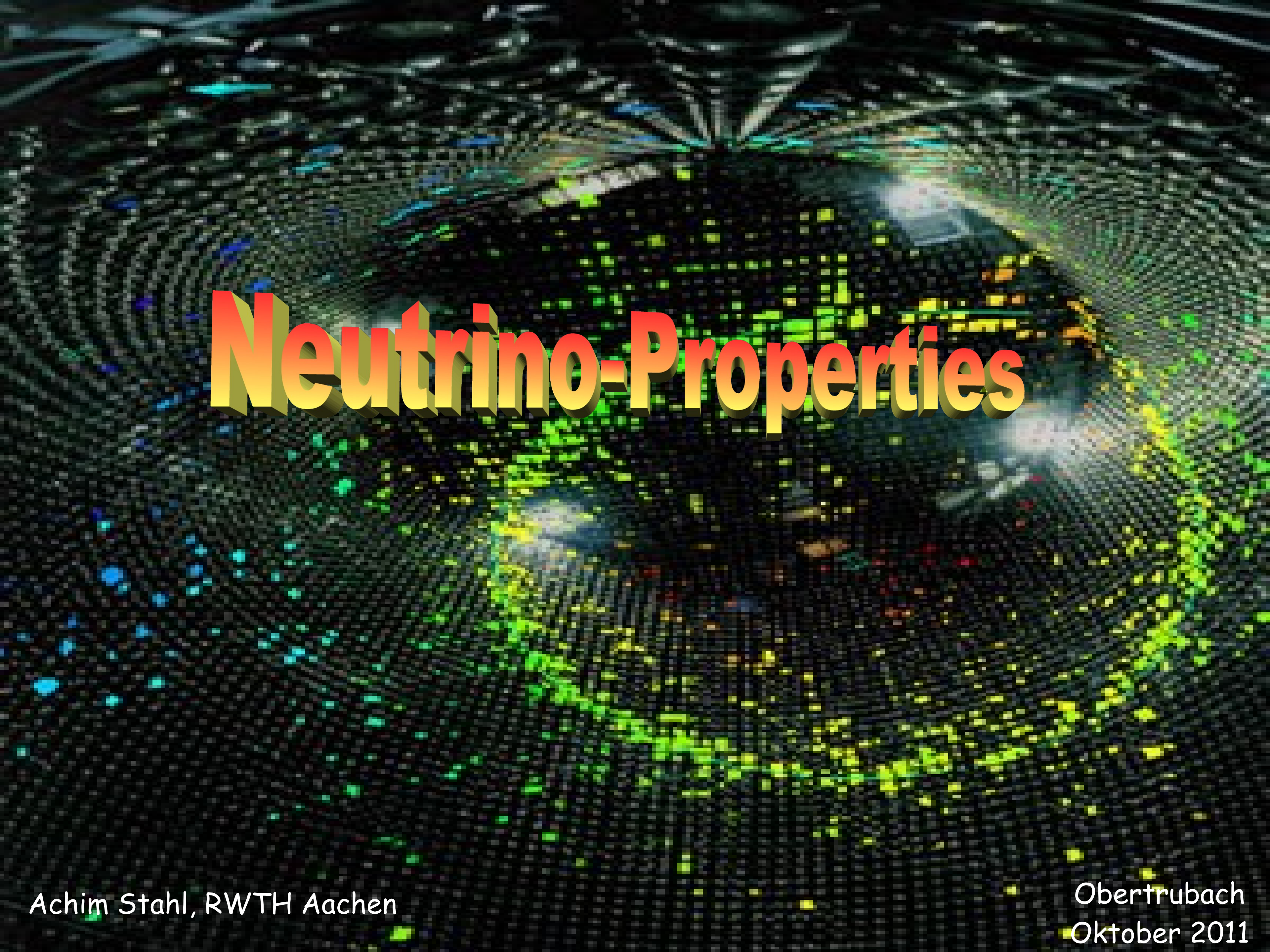


Neutrino-Properties

Achim Stahl, RWTH Aachen

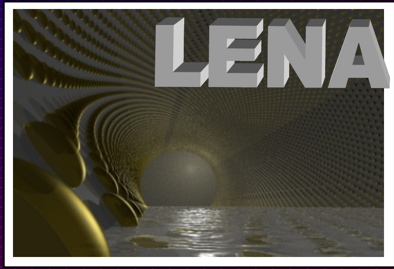
Obertrubach
Oktober 2011

Contents

- History
- ν-mass
- Majorana or Dirac ?
- ν-Oscillations
- CP-violation
- Tachions ?

Reactor-Neutrino Chooz/France

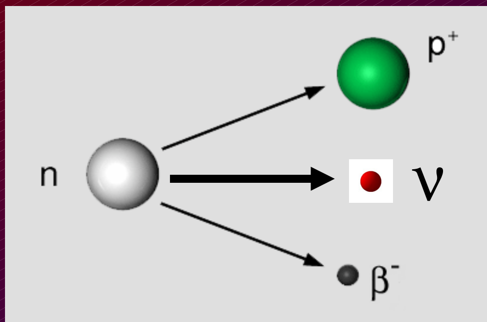
Long Baseline Beam / Japan



Future European ν-Detector

History

Neutrino Hypothesis



Continous β -spectrum ?

Conservation of angular mom. ?

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

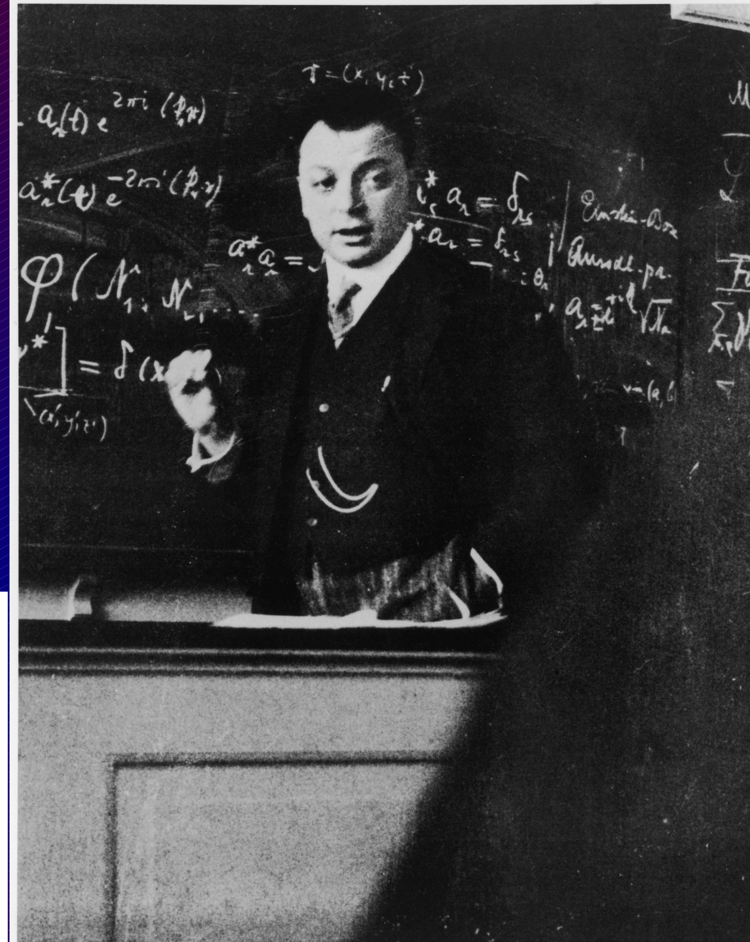
Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.



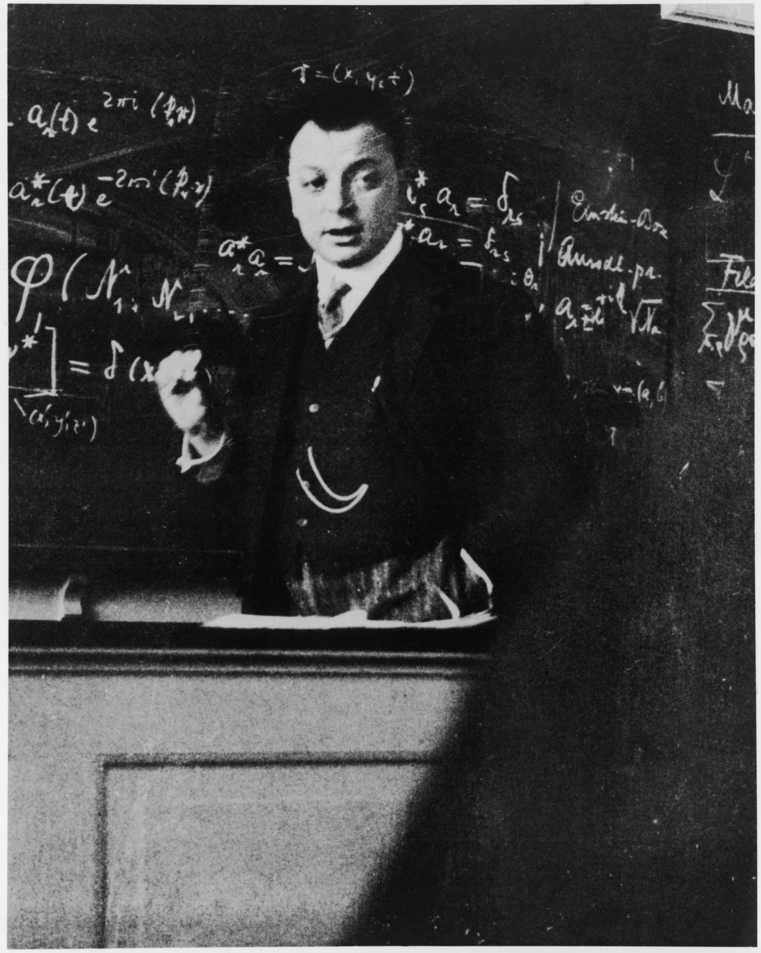
Wolfgang Pauli

1930 1st idea

1932 Fermi calculates spectrum

1933 Publication

Neutrino Hypothese



Pauli später (~1950?) bei einem Besuch am CalTech:

"I have done a terrible thing. I have postulated a particle that cannot be detected." → Poltergeist

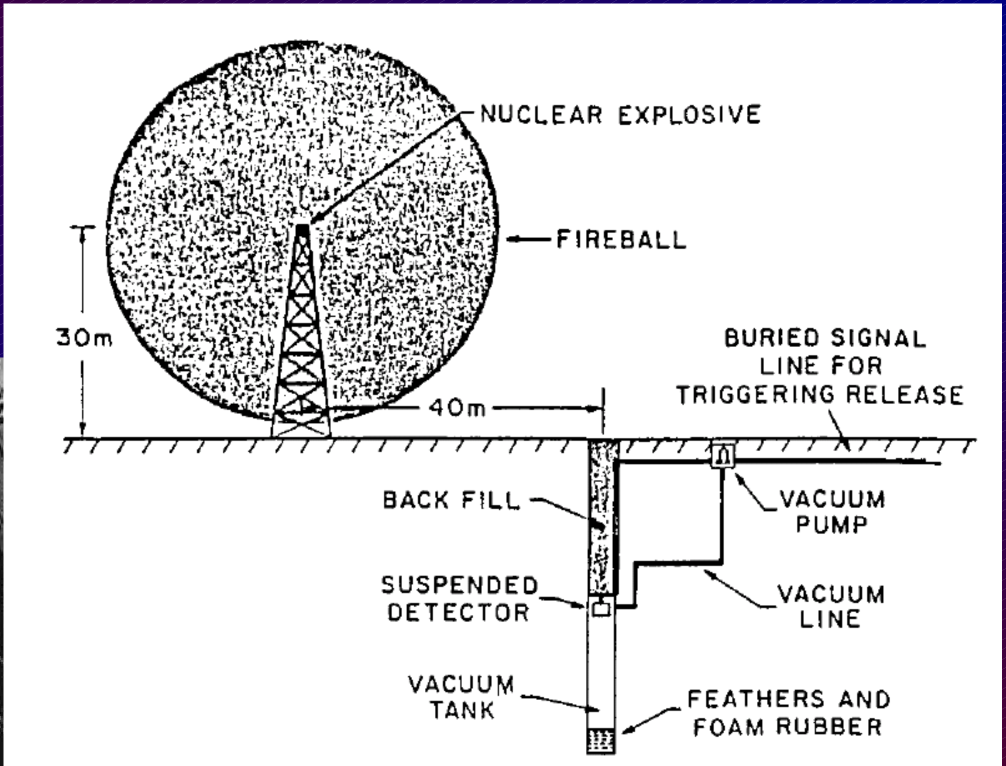
Bethe/Peierls 1934: totaler WQ ≈ 10^{-44} cm^2

⇒ mittlere freie Weglänge in H_2O ≈ 1000 Lichtjahre

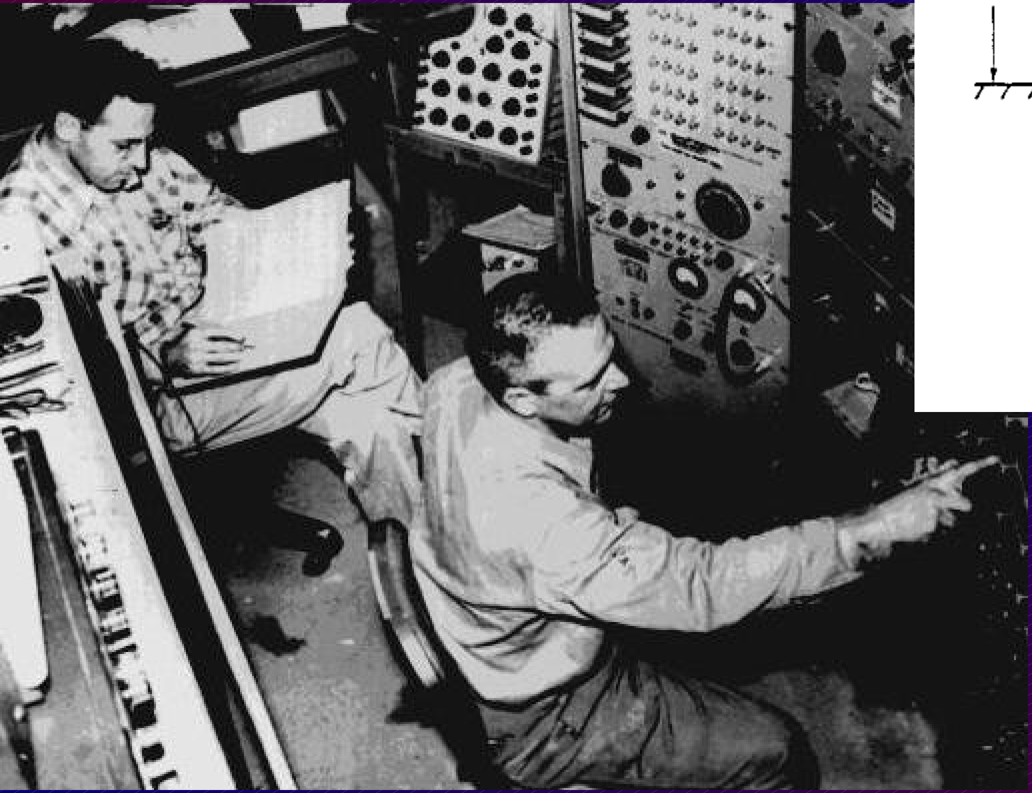
Neutrino Detection

need an intensive neutrino source:

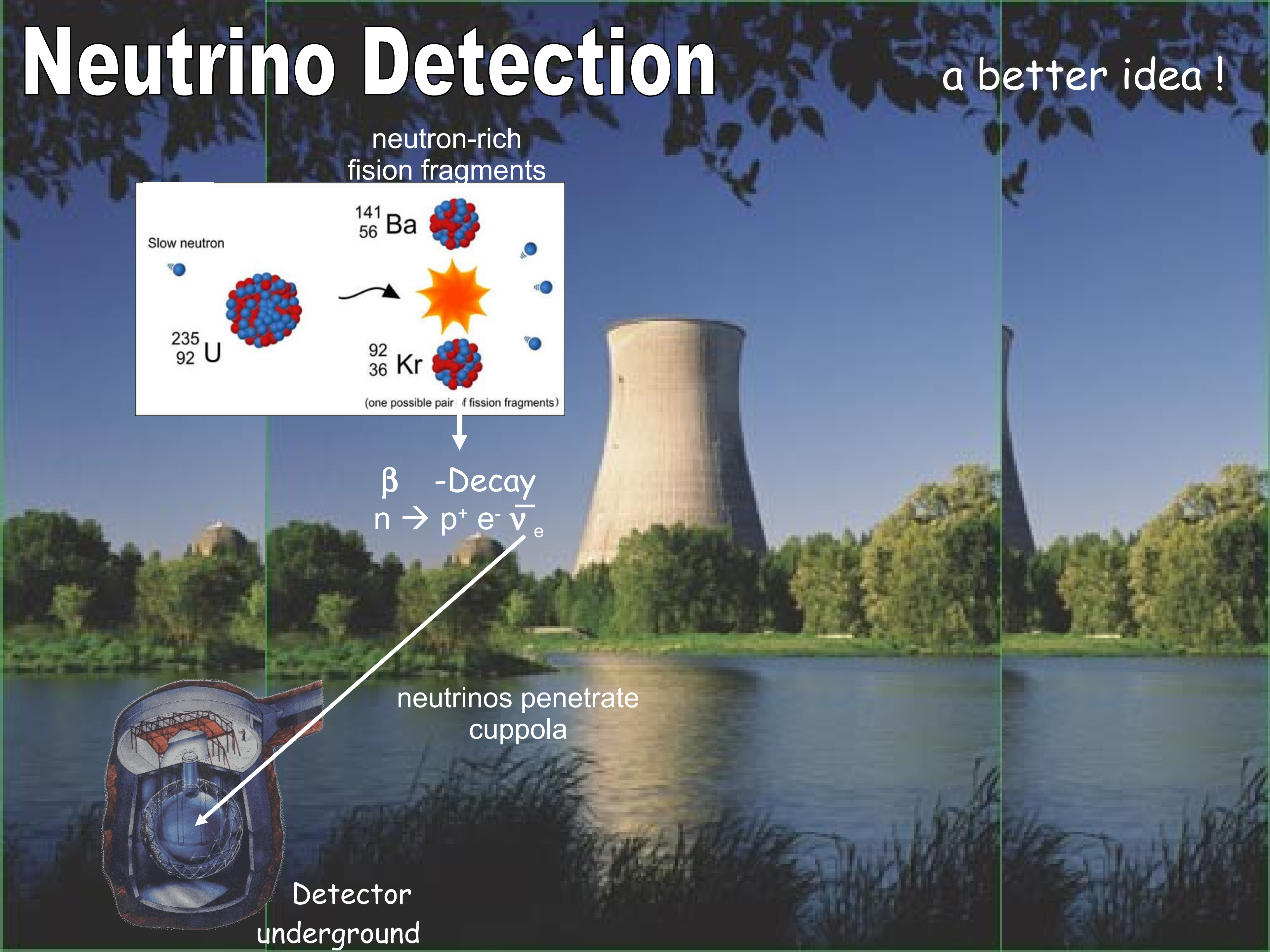
very first idea ~ 1950



Cowan & Reines

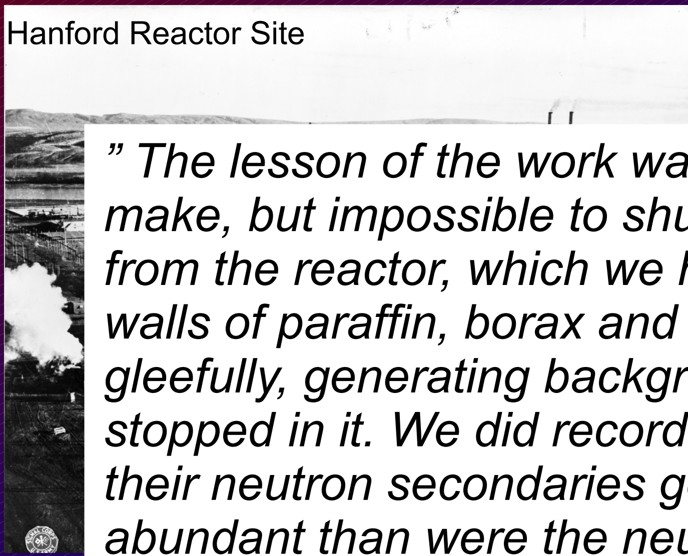


"but detector would be destroyed and with uncertain result"


Neutrino Detection
a better idea !
neutron-rich
fision fragments
Slow neutron
235
92 U
141
56 Ba
92
36 Kr
(one possible pair of fission fragments)
β -Decay
n → p+ e- ν̄ e
neutrinos penetrate
cuppola
Detector
underground

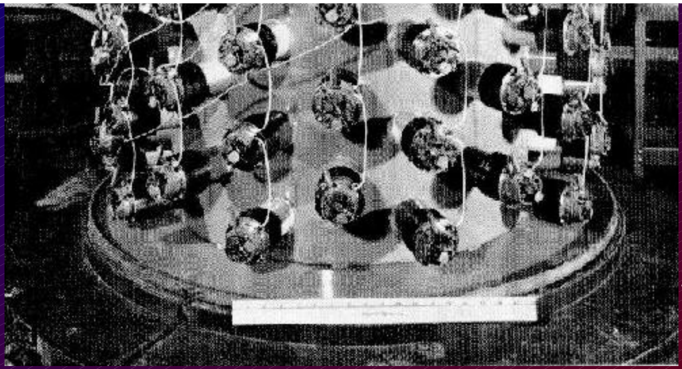
Neutrino Detection

1st attempt: Hanford 1953



" The lesson of the work was clear: It is easy to shield out the noise men make, but impossible to shut out the cosmos. Neutrons and gamma rays from the reactor, which we had feared most, were stopped in our thick walls of paraffin, borax and lead, but the cosmic ray mesons penetrated gleefully, generating backgrounds in our equipment as they passed or stopped in it. We did record neutrino-like signals but the cosmic rays with their neutron secondaries generated in our shields were 10 times more abundant than were the neutrino signals. We felt we had the neutrino by the cottails, but our evidence would not stand up in count."

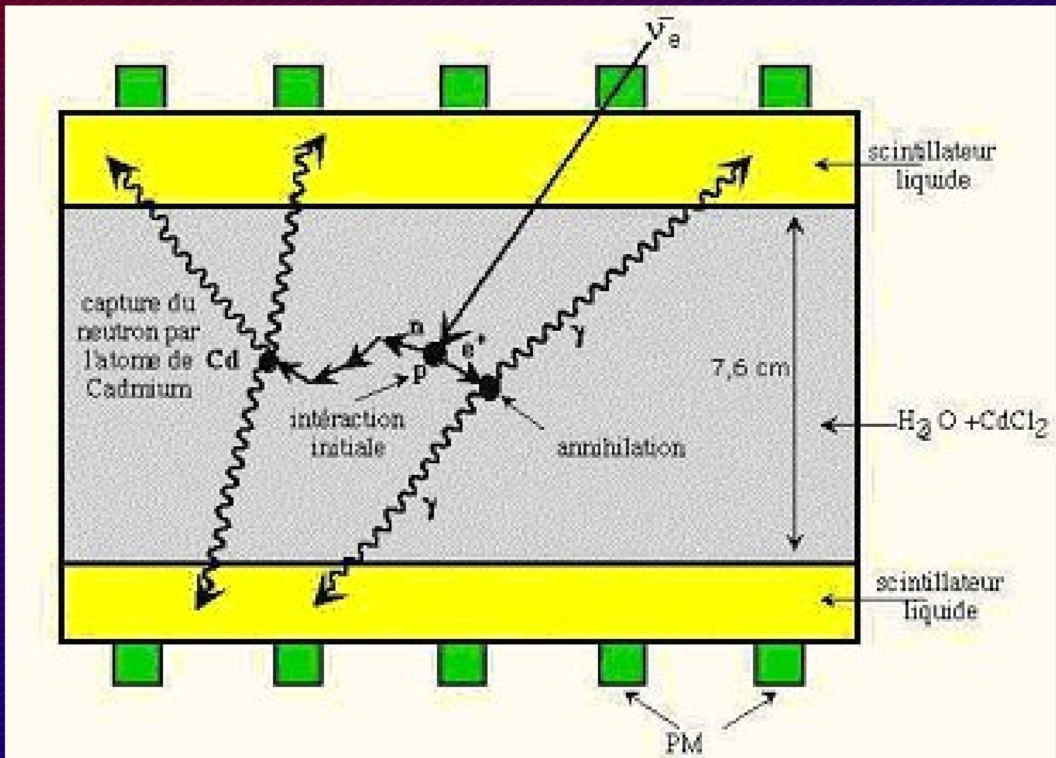
construction camp



Herr Auge
300l scintillator
(90 PMTs)

Neutrino Detection

2^{nd} attempt: Savannah River 1956



method of detection:

inverse β -decay

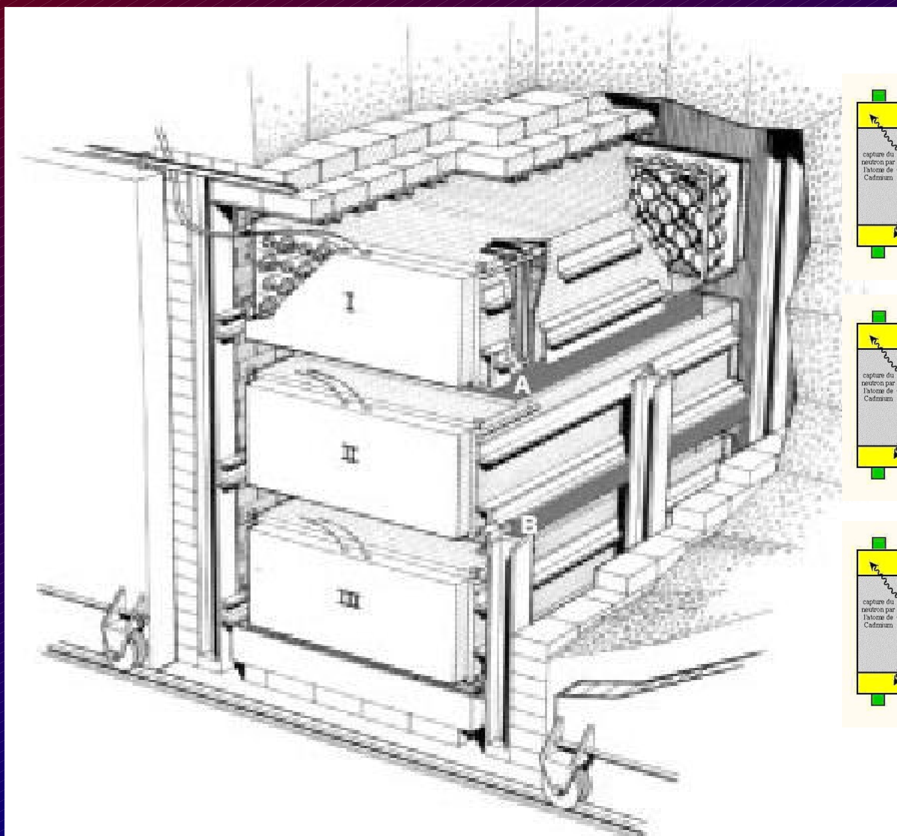
$\bar{\nu}_e + p^+ \rightarrow n\ e^+$

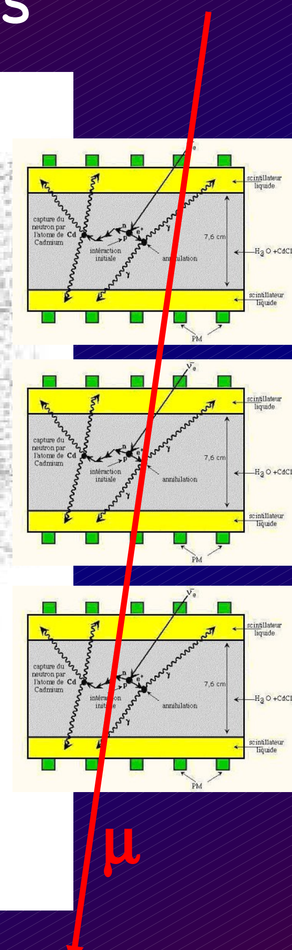
delayed coincidence:

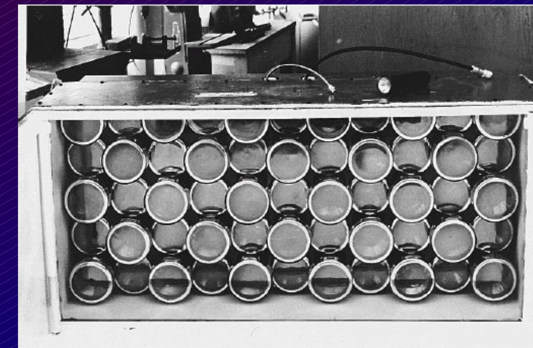
1. e^+ Retardation & Annihilation → $\gamma\ \ \gamma$
2. n Thermalisation & Capture: $n + Cd \rightarrow Cd^* \rightarrow Cd + 3\ \gamma$

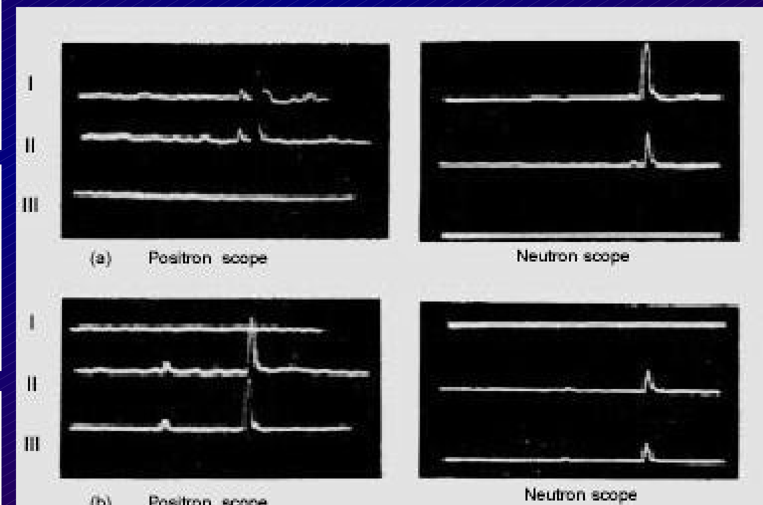
Neutrino Detection

shutting out the cosmos







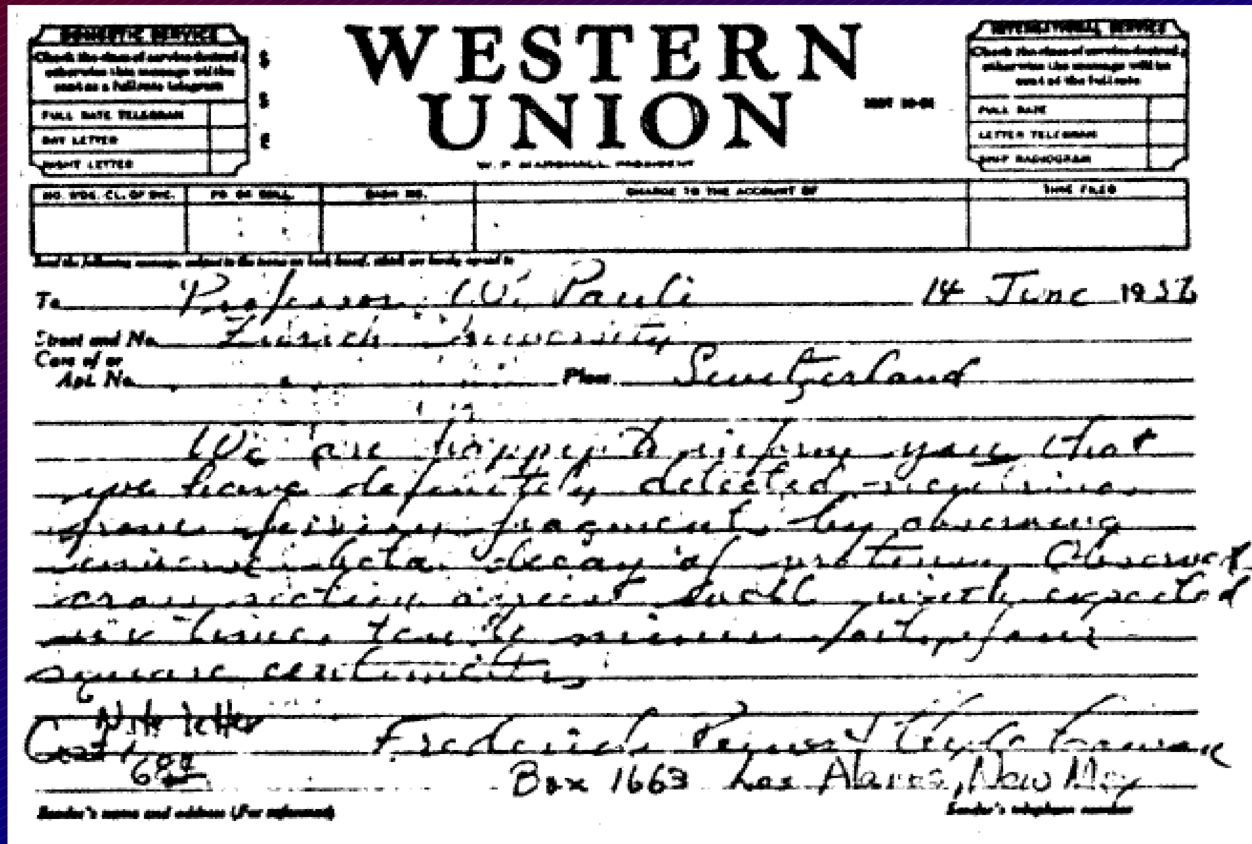


veto-counters reject cosmic myons

+

over-burden shields the detector

Neutrino Detection



WESTERN UNION

To Professor W. Pauli 14 June 1956

Street and No. Zurich University

Place Switzerland

We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters.

Night letter

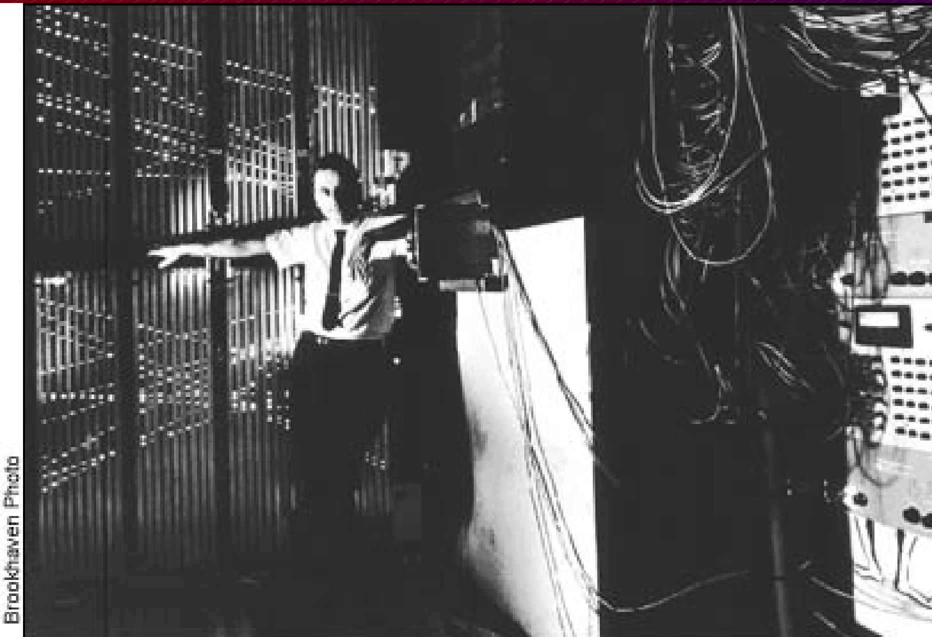
Frederick Reines Clyde Cowan

Box 1663 Los Alamos, New Mex

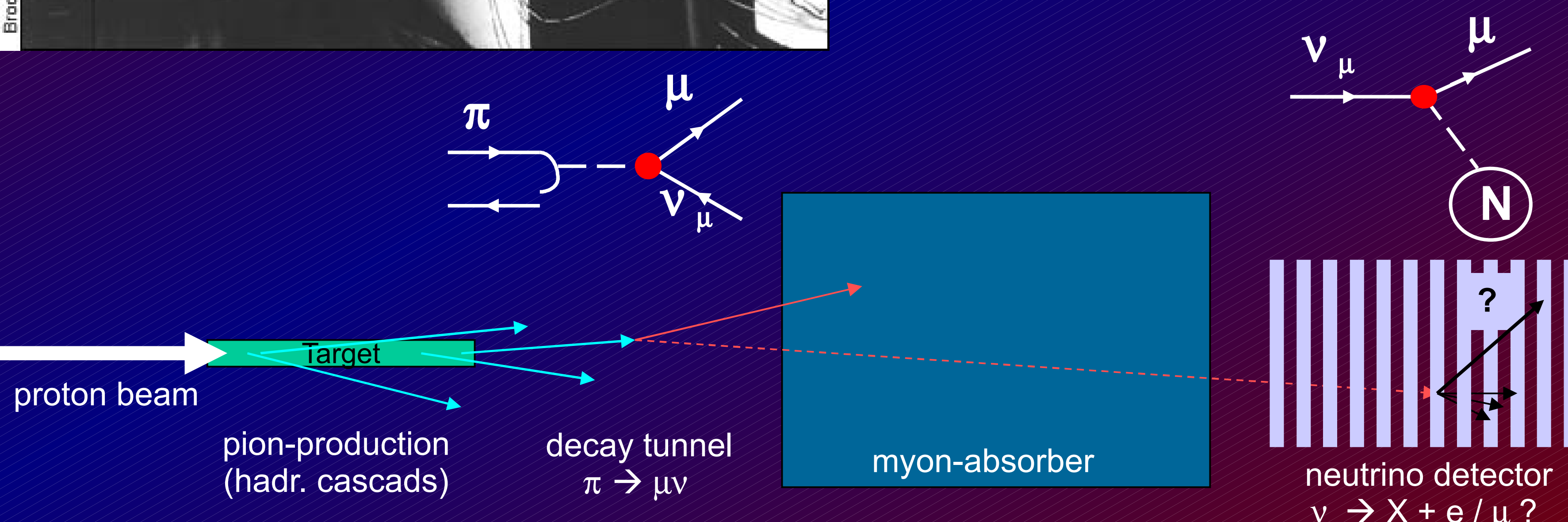
telegram to Pauli
June 1956

We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters.

The Myon-Neutrino



Ledermann Schwartz Steinberger



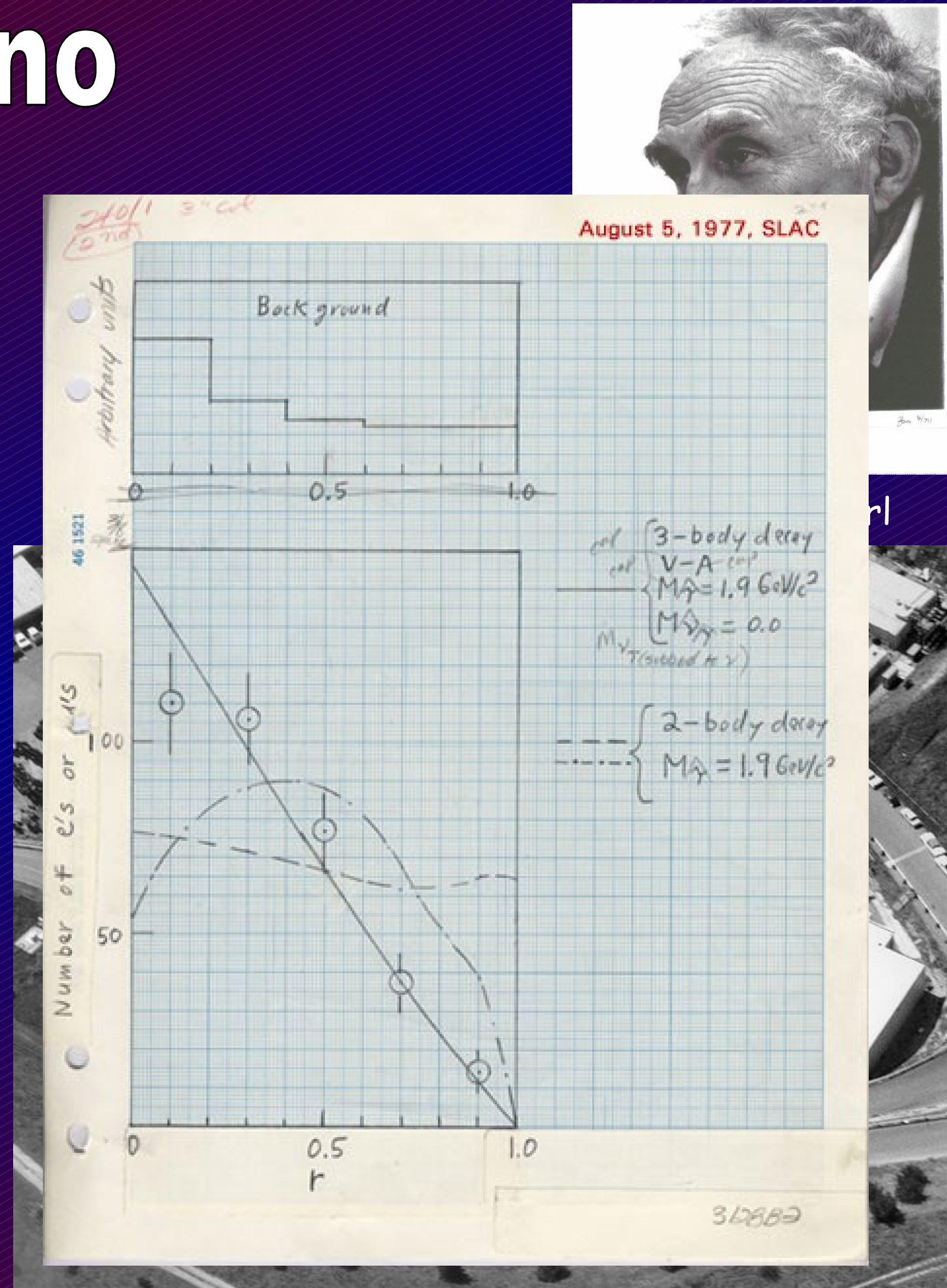
flavour -eigenstates in weak interactions

The Tau-Neutrino

$\tau \rightarrow \mu$ kinematically forbidden
violates E-conservation

$\tau \rightarrow \mu\nu$ 2-body-decay
mono-energetic μ

$\tau \rightarrow \mu\nu\ \nu$ 3-bady-decay
continous spectrum



discovery of the tau-neutrino !

A new neutrino-flavour ?

SPEAR, SLAC

The Tau-Neutrino

$\tau^+ \equiv e^+$

Ortho-Lepton

$\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_e$

$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_e$

$\tau^+ \rightarrow e^+ e^- e^+$

$\tau^+ \equiv e^-$

Para-Lepton

$\tau^+ \rightarrow e^+ \nu_e \nu_e$

$\tau^+ \rightarrow \mu^+ \nu_\mu \nu_e$

$\frac{\nu_e}{\nu_\mu} = \frac{2}{1}$

17,84 %

17,36 %

τ own generation

Sequential Lepton

$\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$

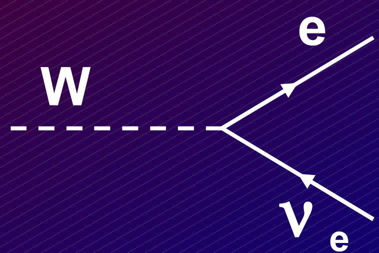
$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$

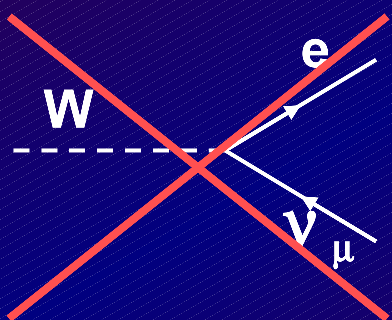
okay

➔ 3 Neutrino-Flavour-Eigenstates: $\nu_e \; \nu_\mu \nu_\tau$

Neutrino-Theory

flavour-eigenstates
in
weak interactions





only
flavour-diagonal
couplings

mass-eigenstates

$$H\,\Psi = E\,\Psi$$

$\rightarrow\ \nu_1\ \nu_2\ \nu_3$

time evolution:

$$\Psi(t) = e^{iEt}\,\Psi(0)$$

$\nu_e \equiv \nu_1$

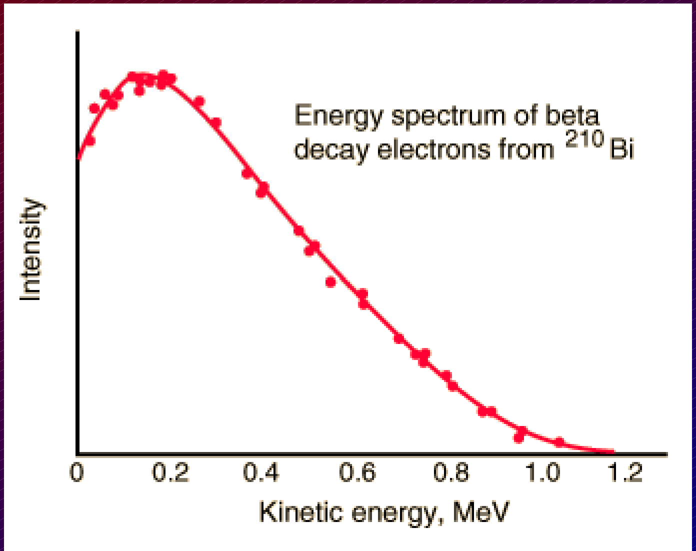
$\nu_\mu \equiv \nu_2$

$\nu_\tau \equiv \nu_3$

?

Neutrino-Mass

Neutrino mass from the endpoint of β-decay spectrum



K_e: kinetic energy of e

Q: energy release in decay

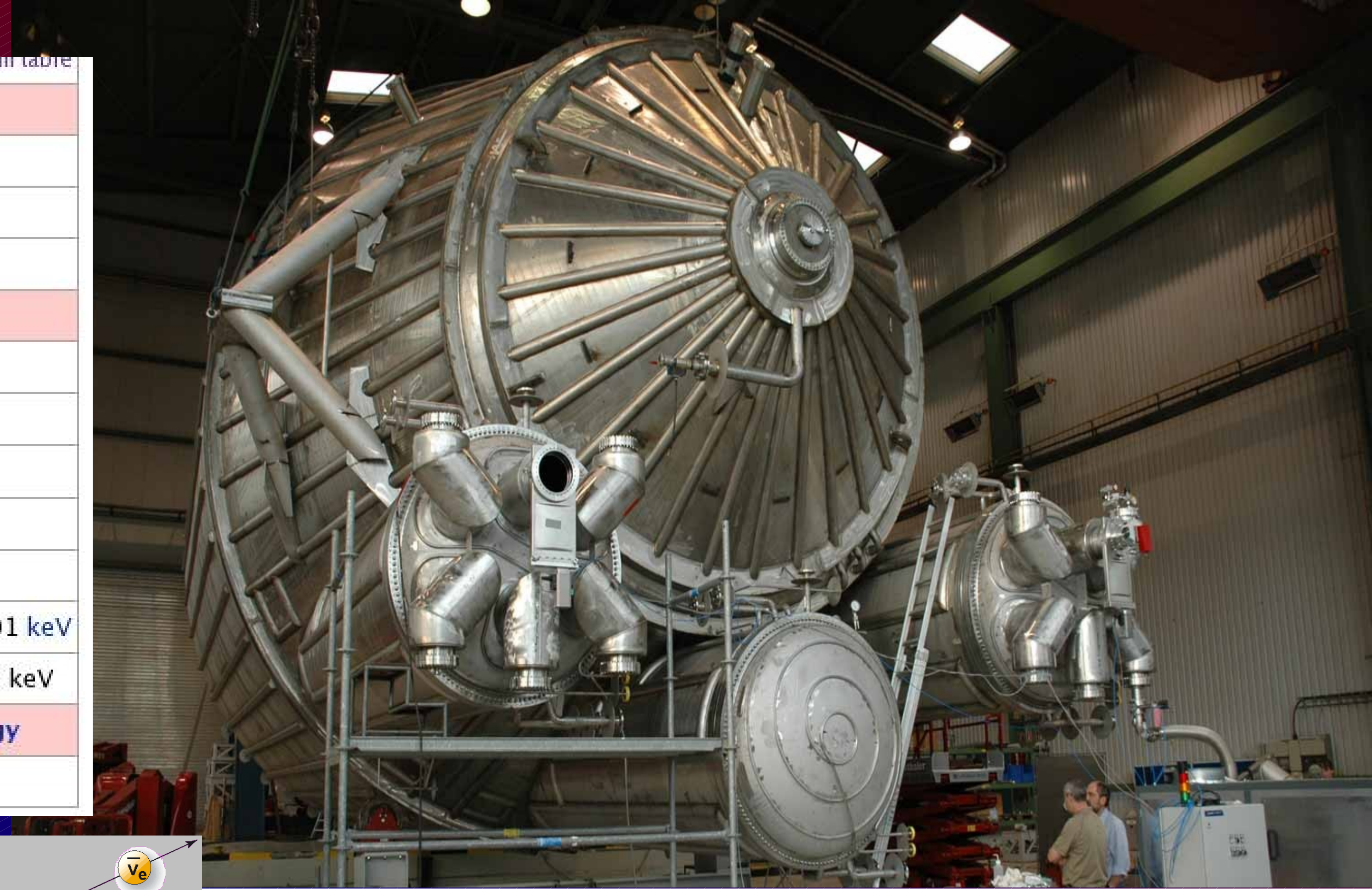
F: matrix element + Coulomb correction

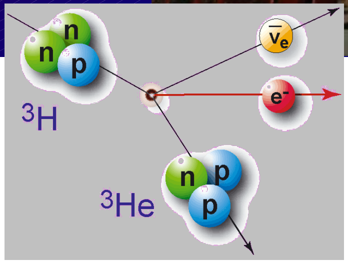
$$N(K_e) = C\sqrt{K_e^2 + 2\,K_e\,m_e c^2}\;(Q - K_e)^2\;(K_e + m_e c^2)\;F(Z', K_e)$$

Problem: Statistics at the endpoint approaches zero!

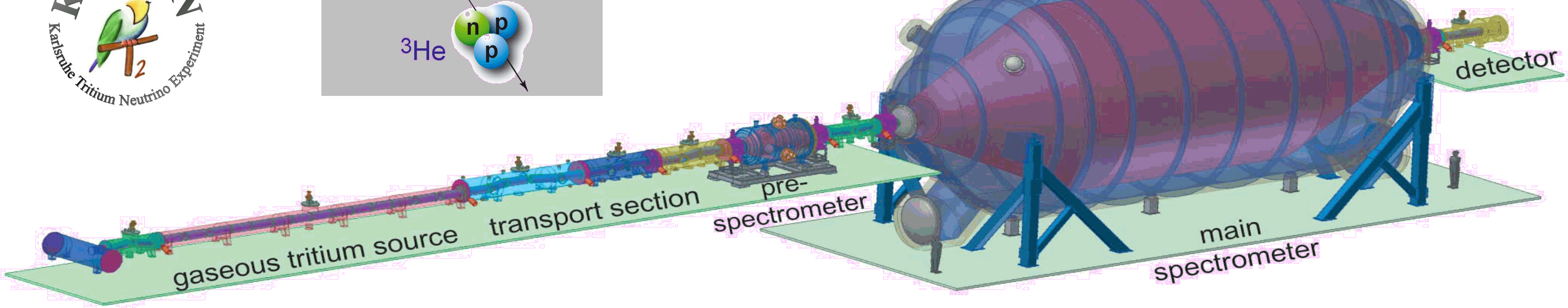
Full table

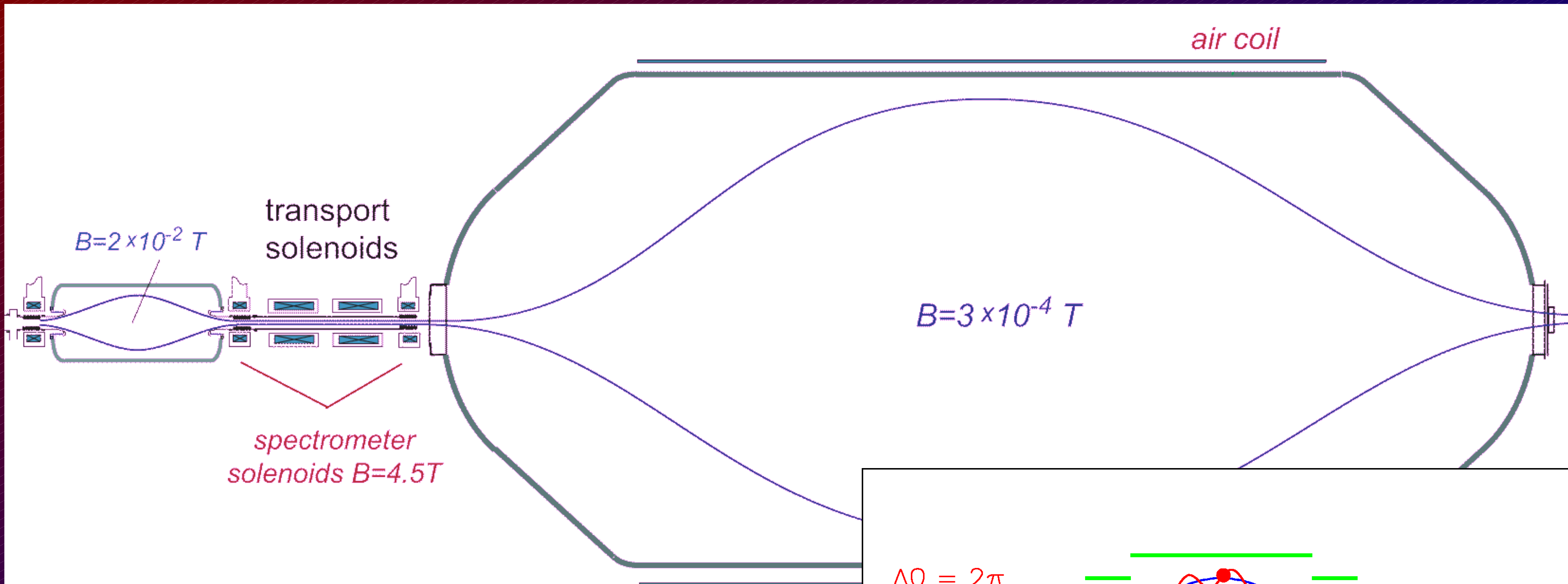
General	
Name, symbol	tritium, triton, ^{3}H
Neutrons	2
Protons	1
Nuclide data	
Natural abundance	trace
Half-life	4500±8 days
Decay products	^{3}He
Isotope mass	3.0160492 u
Spin	1/2+
Excess energy	14949.794± 0.001 keV
Binding energy	8481.821± 0.004 keV
Decay mode	**Decay energy**
Beta emission	0.018590 MeV





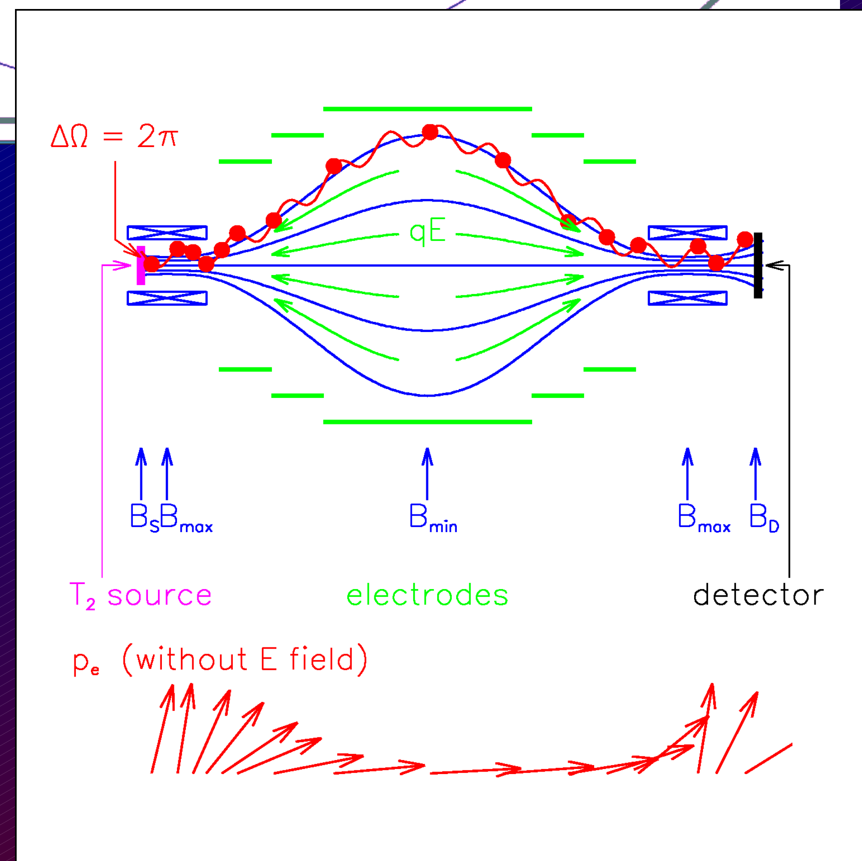
KATRIN
Karlsruhe Tritium Neutrino Experiment





MAC-E filter:
electrostatic potential cuts spectrum in p_z

Magnetic field:
rotates $\vec{p}$ into p_z



How to transport it from Munich to Karlsruhe ?

Leopoldshafen

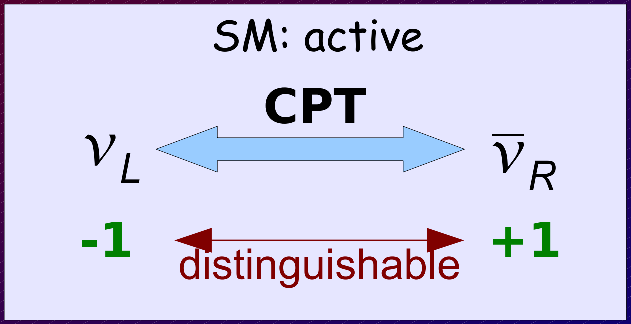
Majorana – Dirac ?

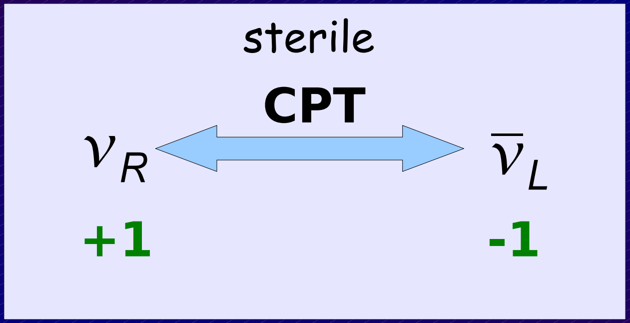
Majorana-Particles: $\pi^0 = 1/\sqrt{2}(u\bar{u} + d\bar{d})$ or γ

invariant under CPT transformation

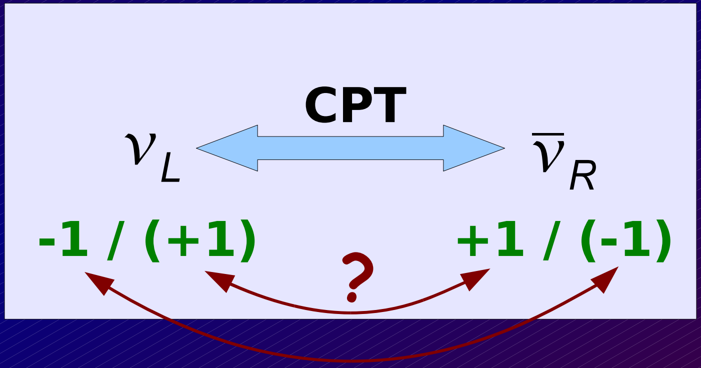
Are neutrinos Majorana particles ?

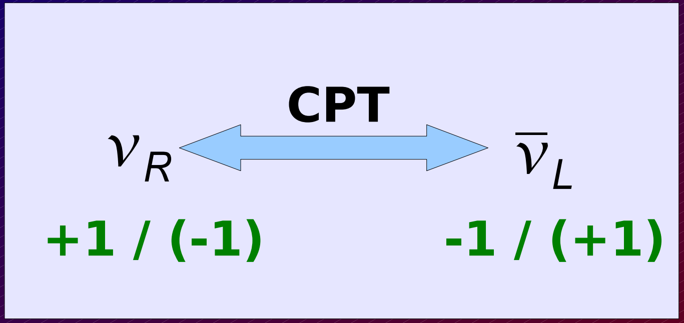
massless neutrinos



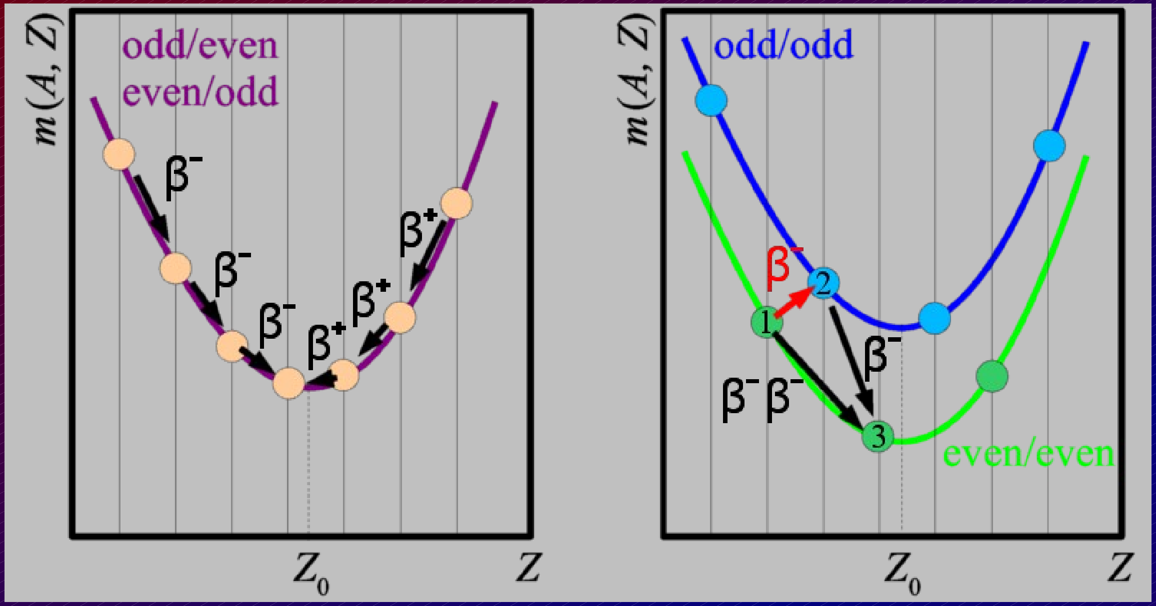


massive neutrinos



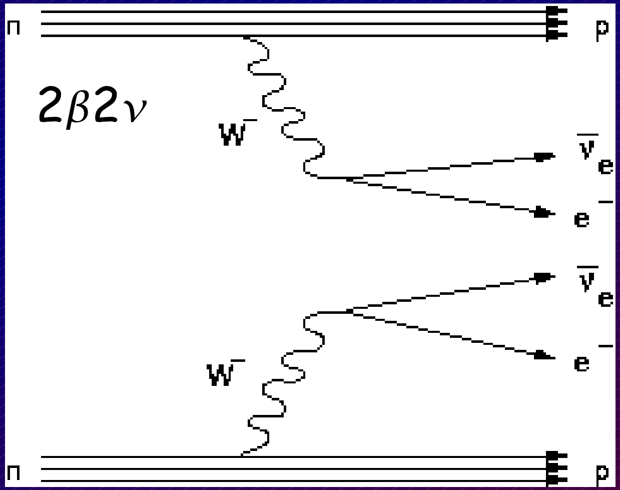


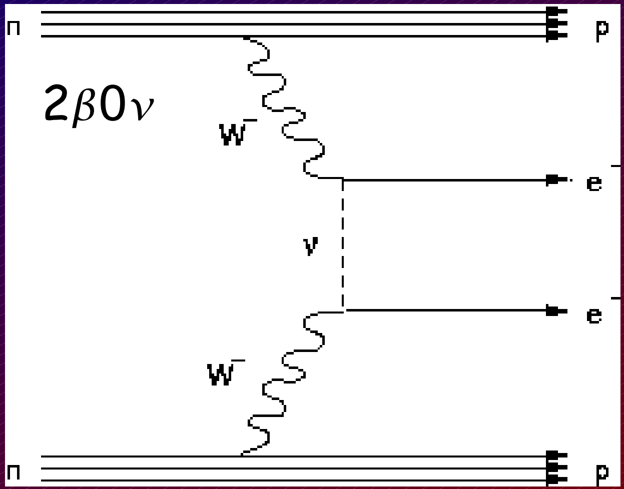
2β - Decay



certain nucleus only decay through a 2β-decay

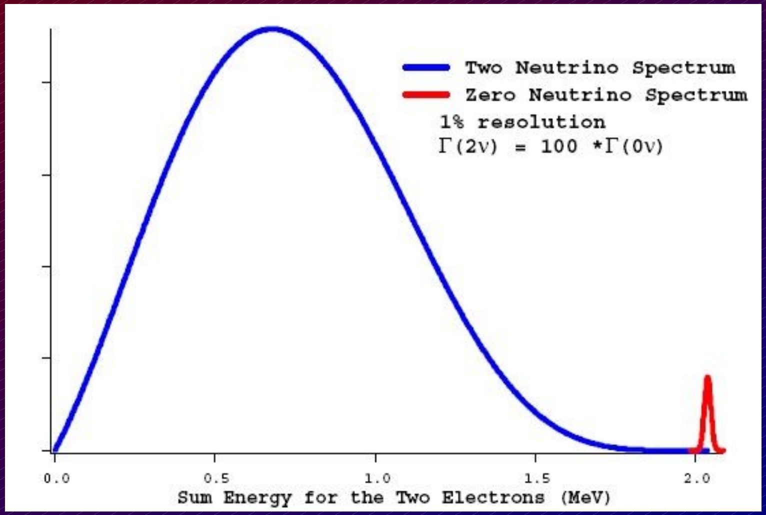
$$(A,Z) \rightarrow (A,Z+2)\ 2\ e^{-}\ 2\ \overline{\nu}_e$$

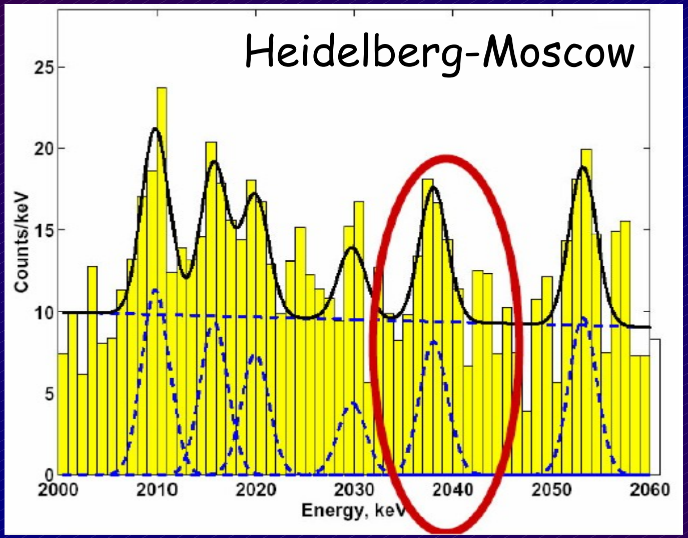


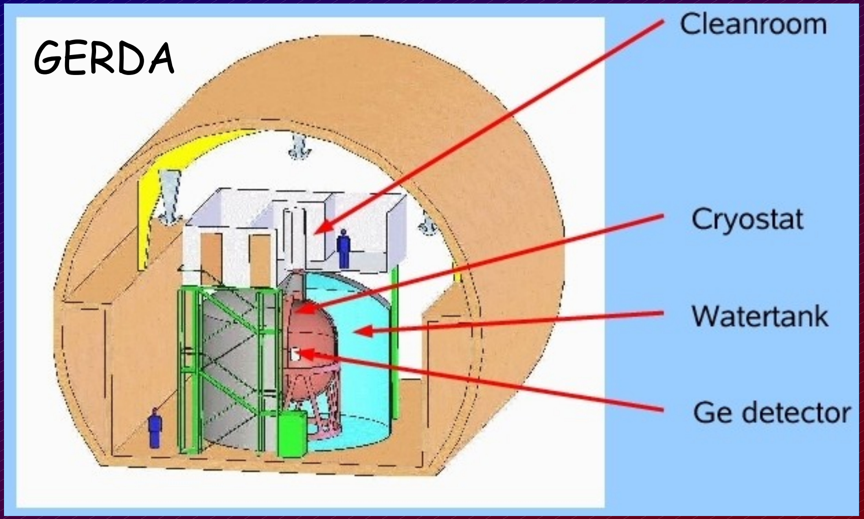


2ß0ü - Decay

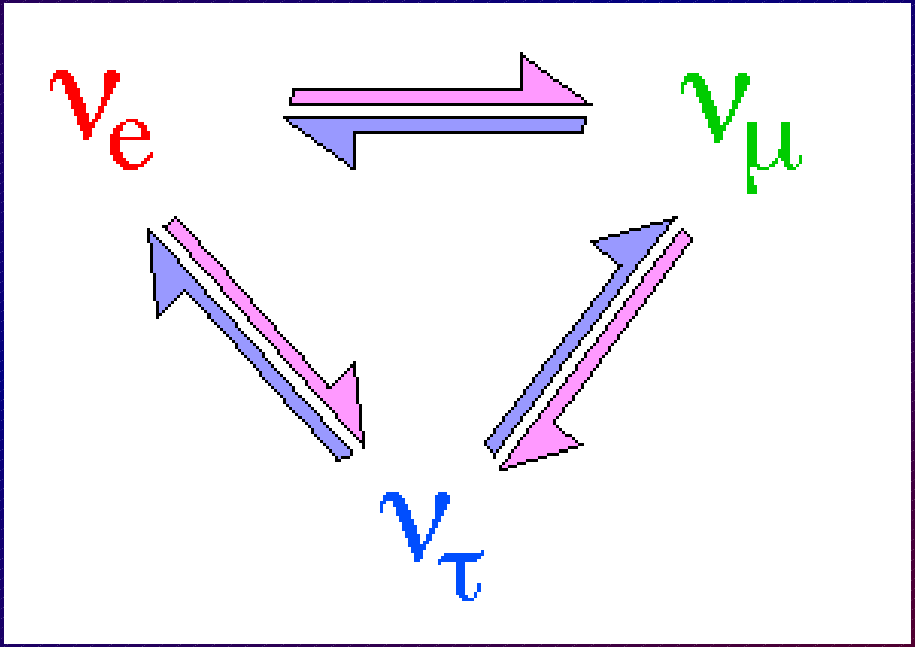
experimental detection:





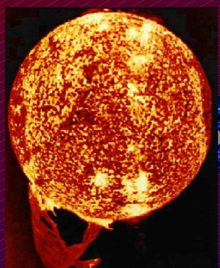


Neutrino-Oscillations



A Neutrino Experiment

SOURCE

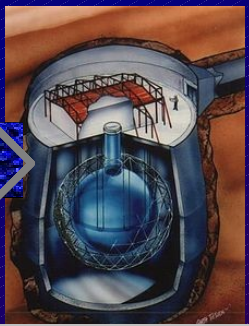


ν production as weak eigenstate

PROPAGATION

ν propagation as mass eigenstate

DETECTION



ν detection as weak eigenstate

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \rightarrow \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \rightarrow \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \longrightarrow \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \rightarrow \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}^{\dagger} \rightarrow \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \rightarrow \text{DETECTION}$$

$$\nu_i(x) = n_0 \exp\left(i\left(p \cdot x - E\,t \right)\right) \approx n_0 \exp\left(-i \frac{m_i^2}{2\,E}\, x \right)$$

i.e. ν_e

i.e. ν_e disappearance

ν_μ appearance

ν_τ appearance

Pontecorvo-Maki-Nakagawa-Sakata matrix

The PMNS-Matrix

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

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\, e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

„atmospheric“ $\theta_{23} \approx 45°$ „reactor“ $\theta_{13} < 10°$ „solar“ $\theta_{12} \approx 32°$

Bruno **P**ontecorvo

Neutrino Oscillations 1957

Zito **M**aki

Masami **N**akagawa

Shoichi **S**akata

Oscillation Matrix 1962

Neutrino Oscillations

Special case: 2 generations

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

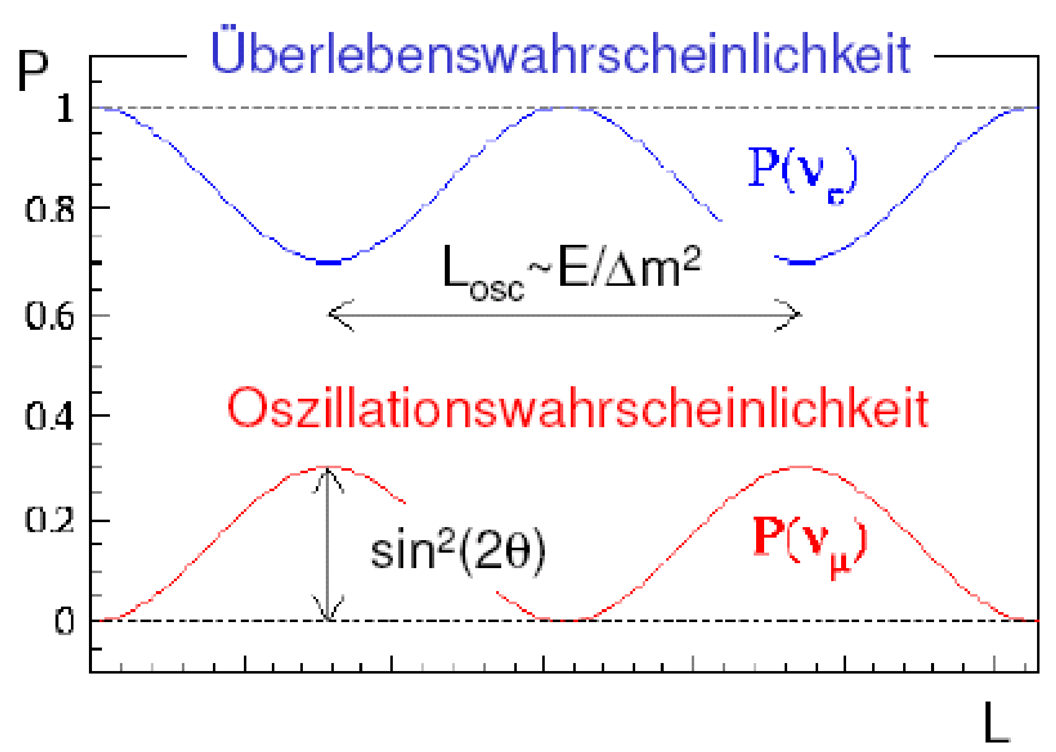
$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Überlebenswahrscheinlichkeit:

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2(2\theta) \cdot \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

Oszillationswahrscheinlichkeit:

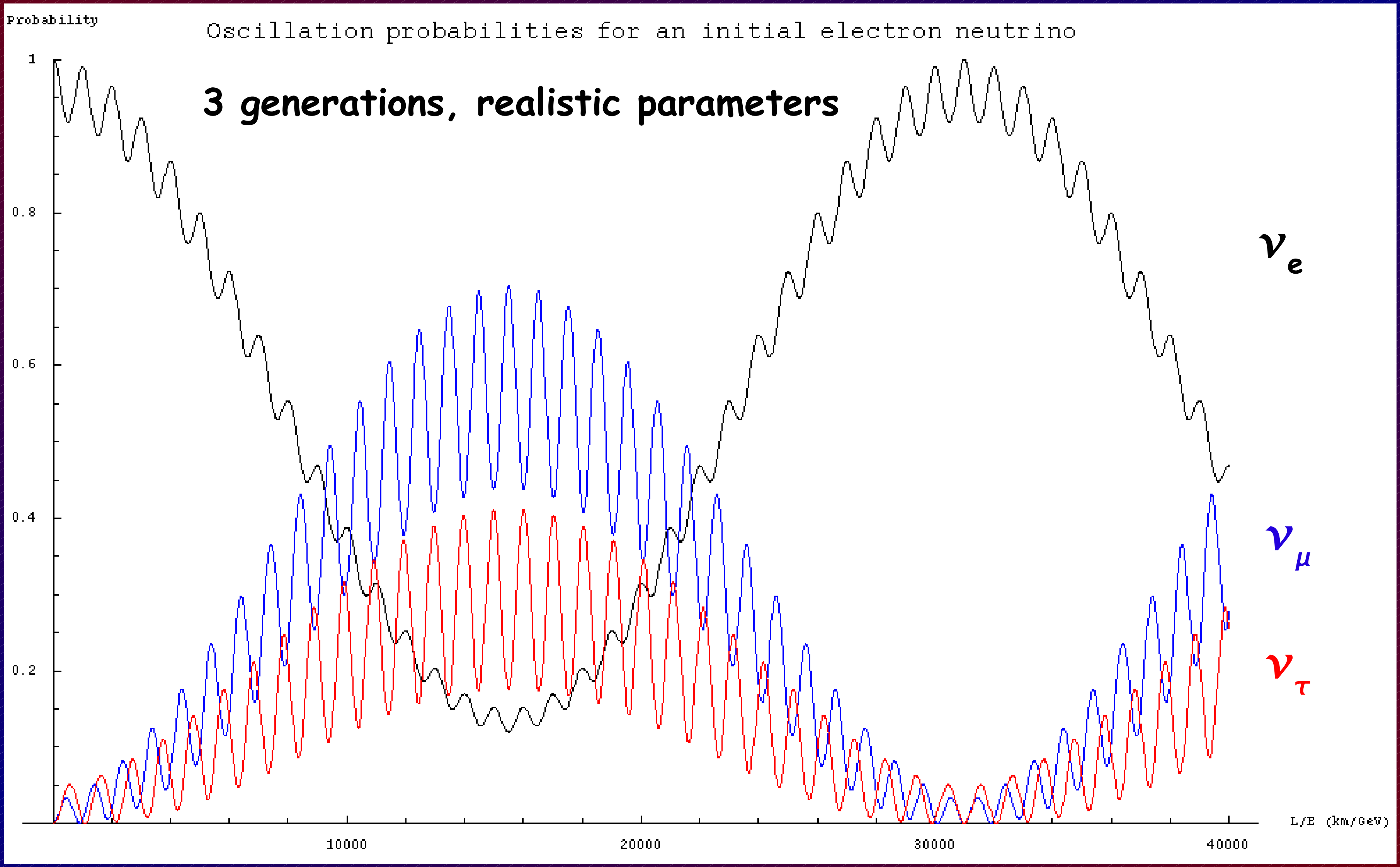
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$



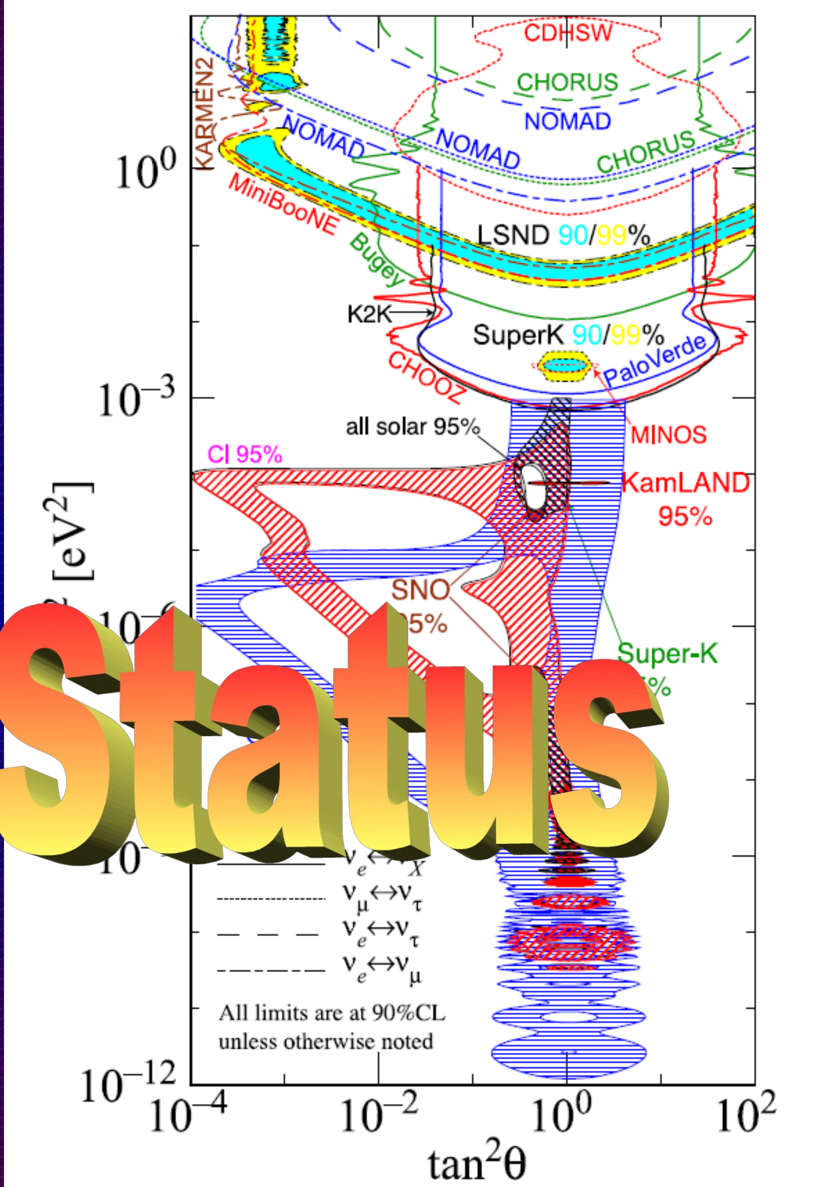
Oszillationslänge

$$L_{osc} = \frac{4\pi E_\nu}{\Delta m^2} = 2.48 \, \frac{E_\nu[\mathrm{MeV}]}{\Delta m^2[\mathrm{eV}^2]} \, \mathrm{m}$$

Neutrino Oscillations

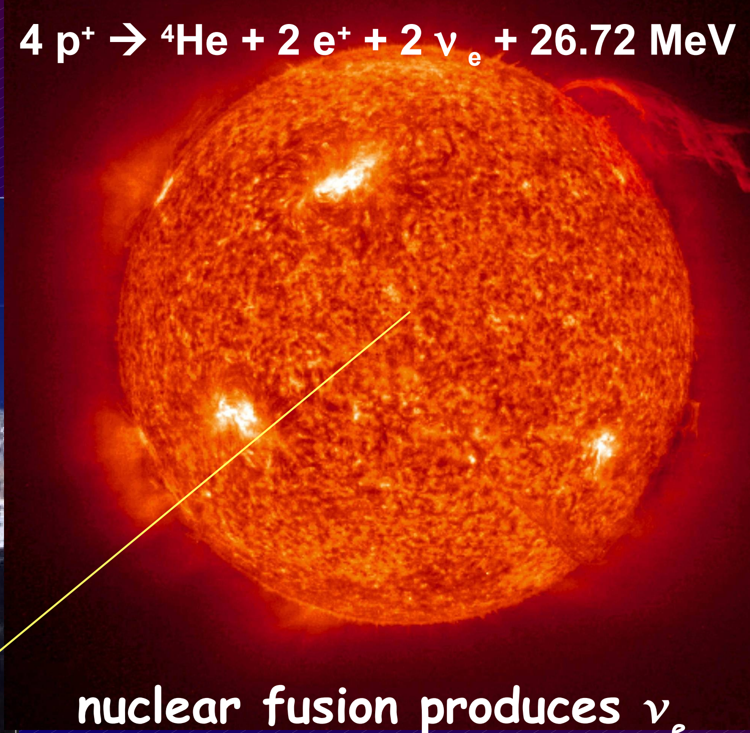


Current Status



Solar Neutrinos

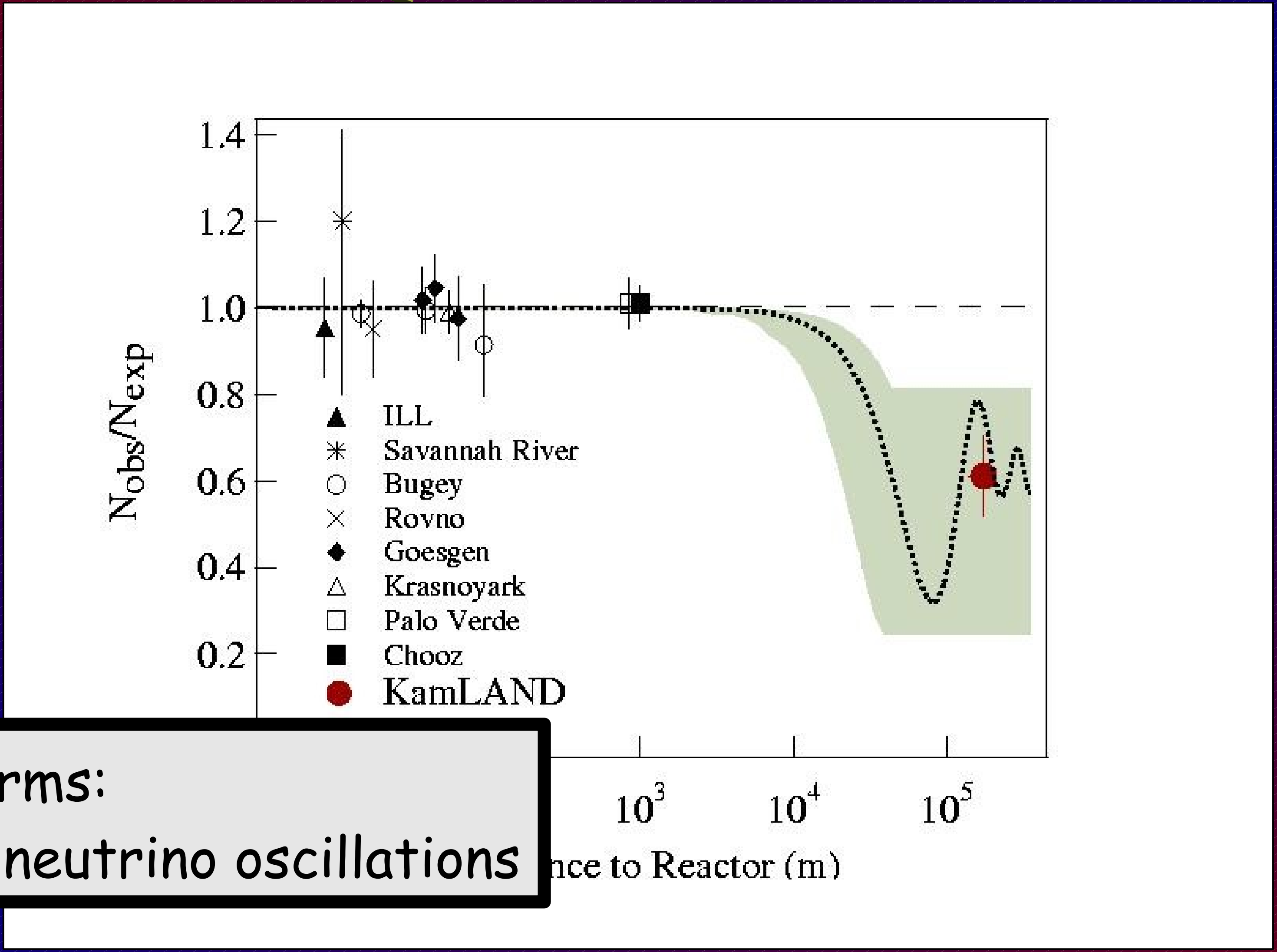
$4\,p^+ \rightarrow {}^4He + 2\,e^+ + 2\,\nu_e + 26.72\ MeV$



Deficit observed !

hypothesis $\nu_e \rightarrow \nu_\mu$

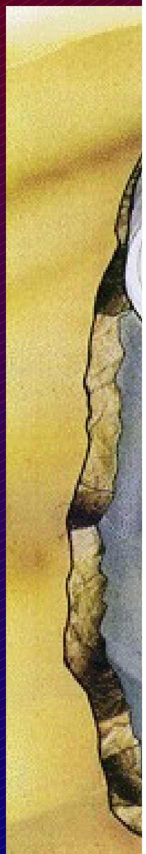
KamLand Experiment

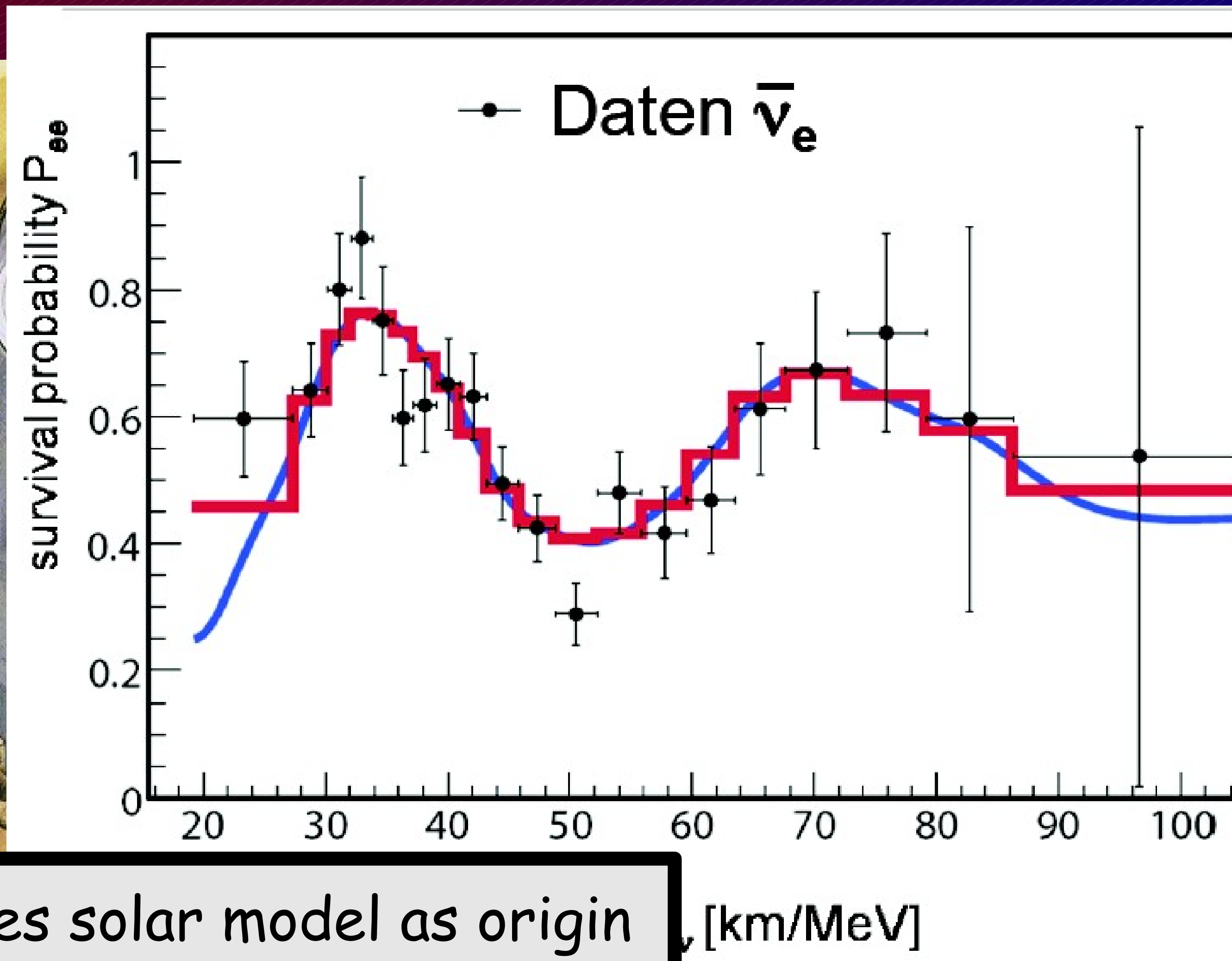


Confirms:
solar neutrino oscillations

Observes $\overline{\nu}_e$ from 55 nuclear power stations in Japan

SNO Experiment





trinos

reactions

+e -

ν x

e -

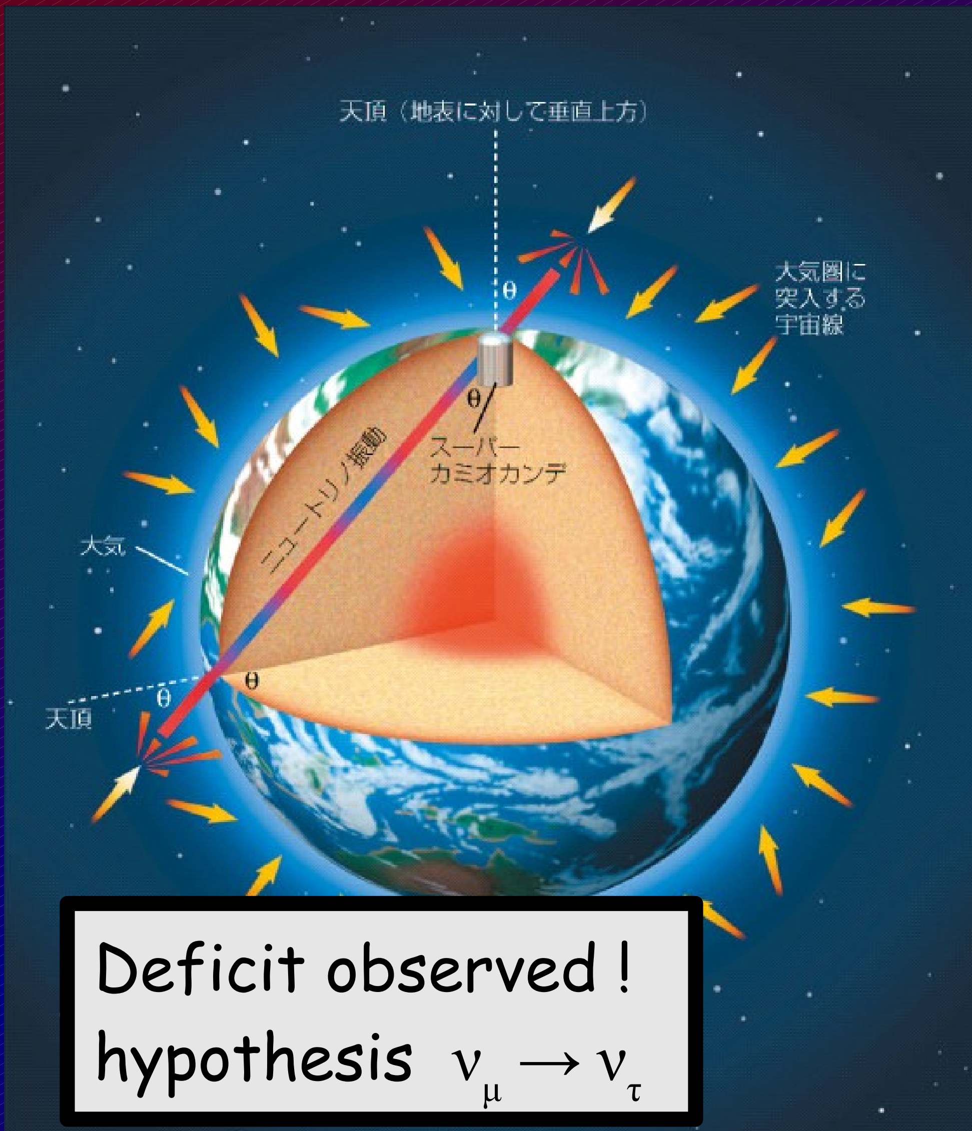
Excludes solar model as origin of solar neutrino deficit

Atmospheric Neutrinos

$\pi \rightarrow \mu \ \nu_\mu$

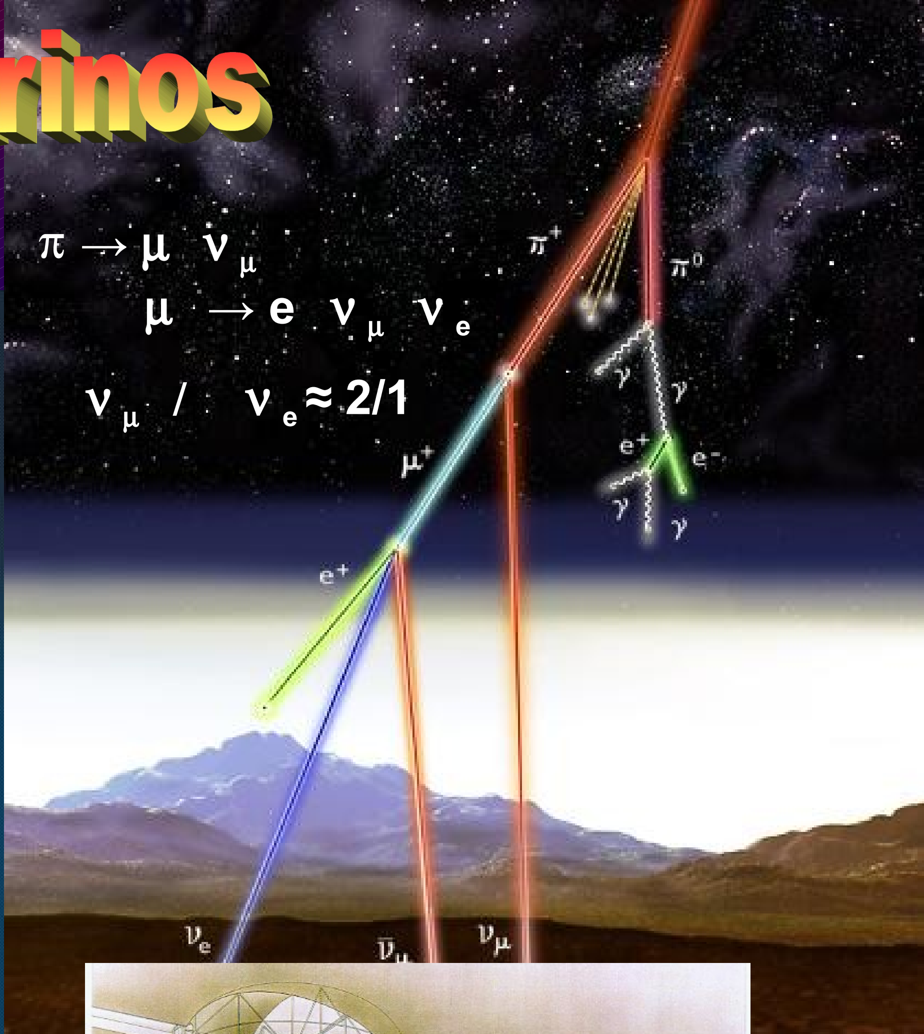
$\mu \rightarrow e \ \nu_\mu \ \nu_e$

$\nu_\mu \ / \ \nu_e \approx 2/1$

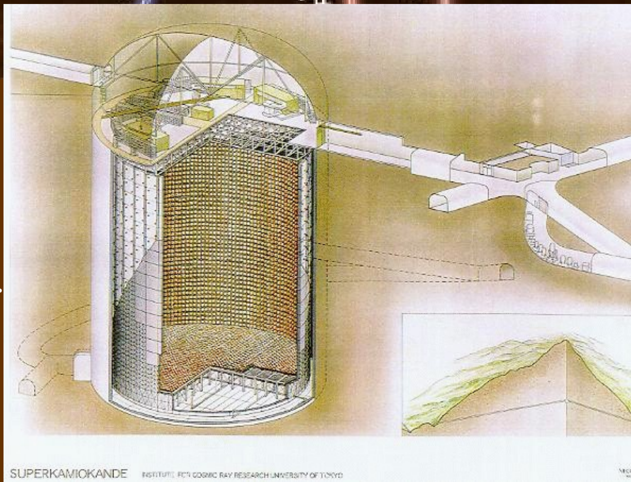


Deficit observed !

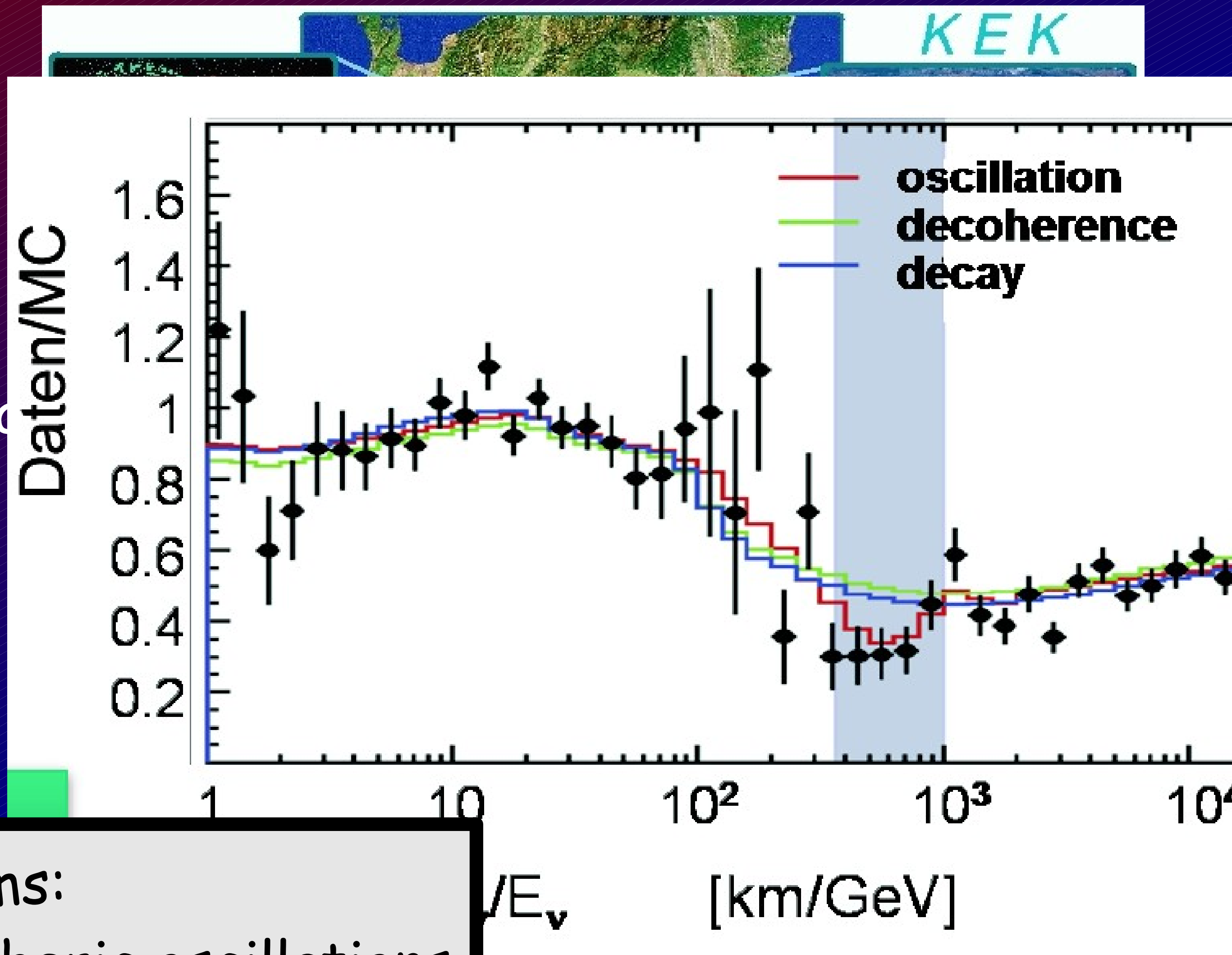
hypothesis $\nu_\mu \rightarrow \nu_\tau$



Super-K



K2K Experiment



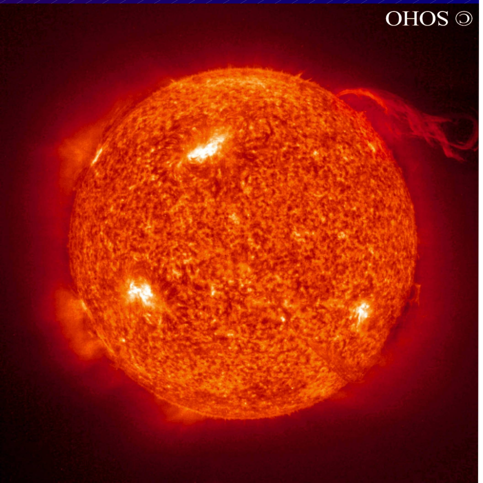
Confirms:
atmospheric oscillations

Experiments

Solar Neutrinos

Homestake
Kamiokande
Gallex
Sage
SNO
Borexino

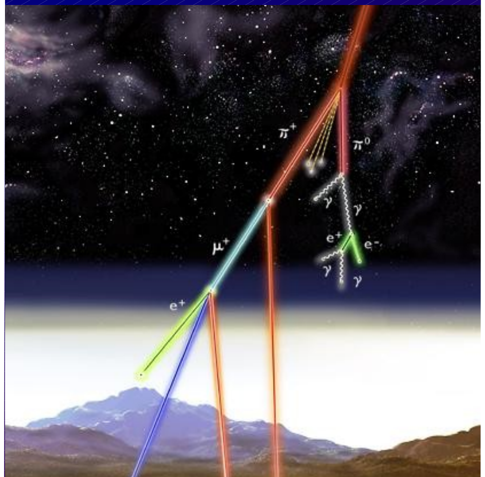
Δm_{solar}



Atmospheric ν

Super-K
Macro

Δm_{atm}



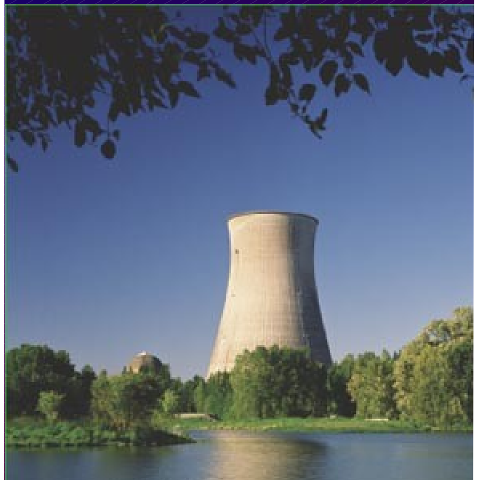
Reactor-Neutrinos

Chooz
DoubleChooz
Daya Bay
Reno

Δm_{atm}

KamLand

Δm_{solar}



Accelerator-ν

Chorus
Nomad
Karmen
LSND
MiniBoone

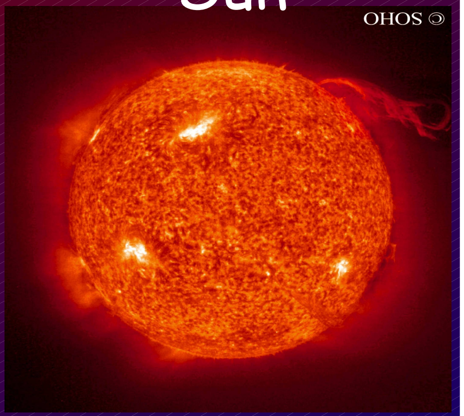
short L
no sig. (?)

K2K
Minos
Opera
T2K
Noνa

long L
Δm_{atm}

Neutrino Sources

Sun



0.1 … 10 MeV

$L_{sol} \approx 12$ km

$L_{atm} \approx 250$ m

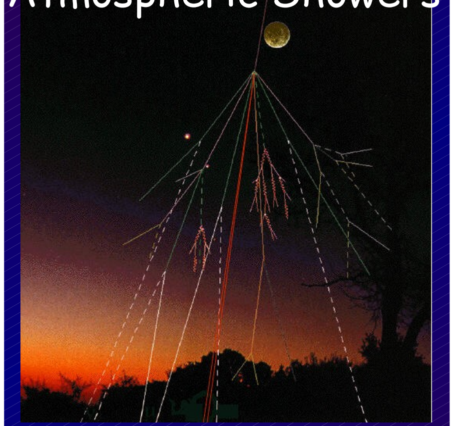
Nuclear Power Plant

1 … 10 MeV

$L_{sol} \approx 50$ km

$L_{atm} \approx 1$ km

Atmospheric Showers



0.1 … 10 GeV

$L_{sol} \approx 15\,000$ km

$L_{atm} \approx 250$ km

Neutrino Beams

0.1 … 5 GeV

$L_{sol} \approx 15\,000$ km

$L_{atm} \approx 250$ km

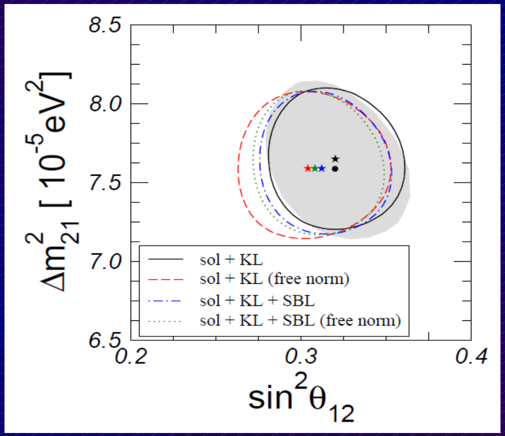
Current Status

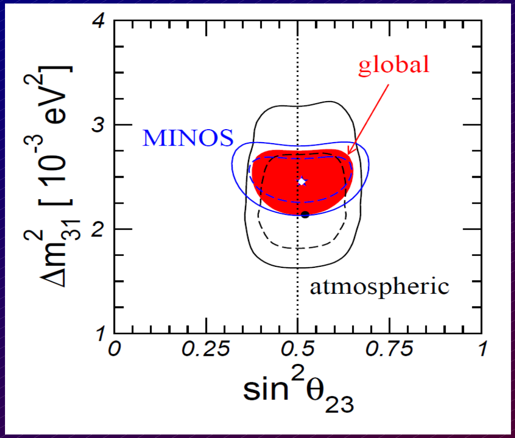
Solar Neutrinos	Atmospheric ν	Reactor ν, θ_{13}
oscillation observed Homestake GALLEX Super-K	oscillation observed Super-K MACRO	no observation yet intensive search DoubleChooz Daya Bay RENO
confirmed KAMLAND SNO	confirmed K2K MINOS	disappearance of $\overline{\nu}_e$ T2K, MINOS
disappearance of ν_e	disappearance of ν_μ	appearance of ν_e

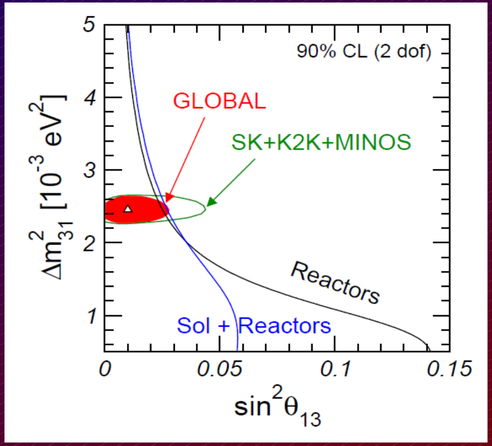
$$|\Delta m^2_{21}| = \left(7.59^{+0.20}_{-0.18}\right) 10^{-5}\ eV^2$$
$$\sin^2\theta_{12} = 0.312^{+0.017}_{-0.015}$$

$$|\Delta m^2_{31}| = \left(2.45 \pm 0.09\right) 10^{-3}\ eV^2$$
$$\sin^2\theta_{23} = 0.51 \pm 0.06$$

$$\sin^2\theta_{13} = 0.010^{+0.009}_{-0.006}$$



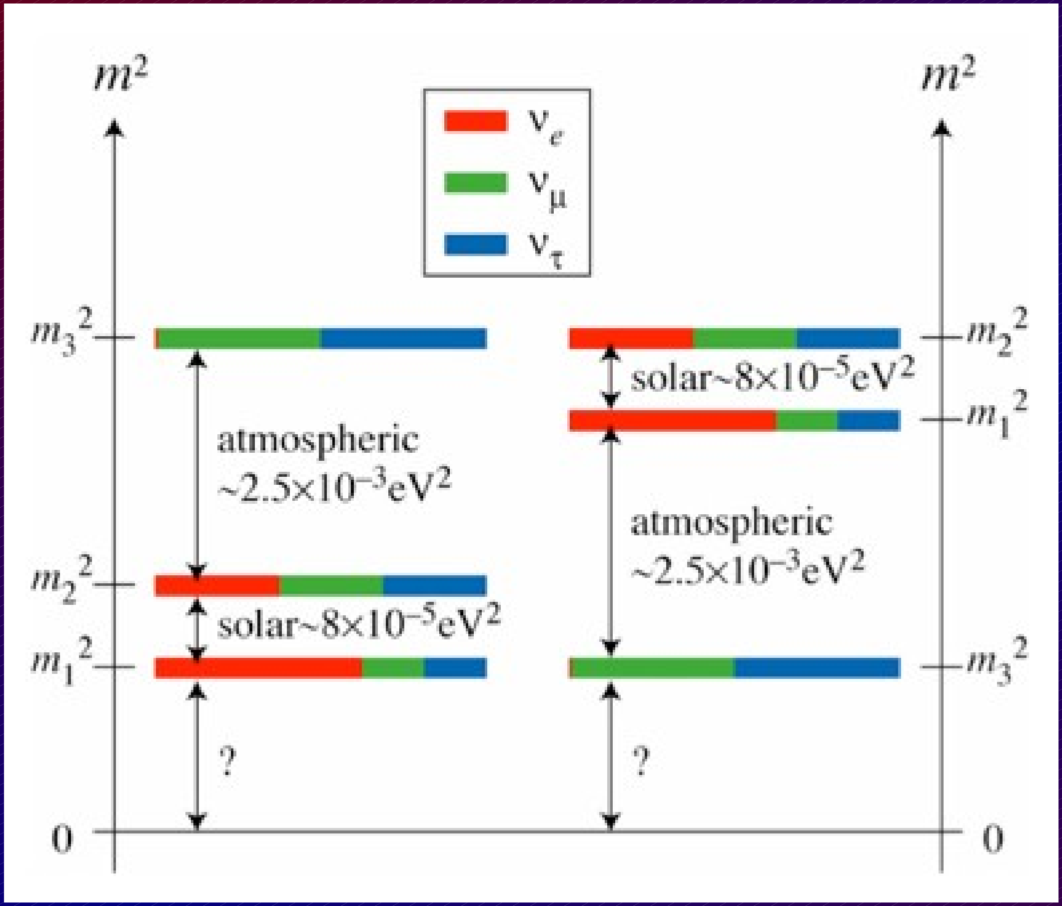




Thomas Schwetz et al., arXiv 1103.0734

(normal hierarchy)

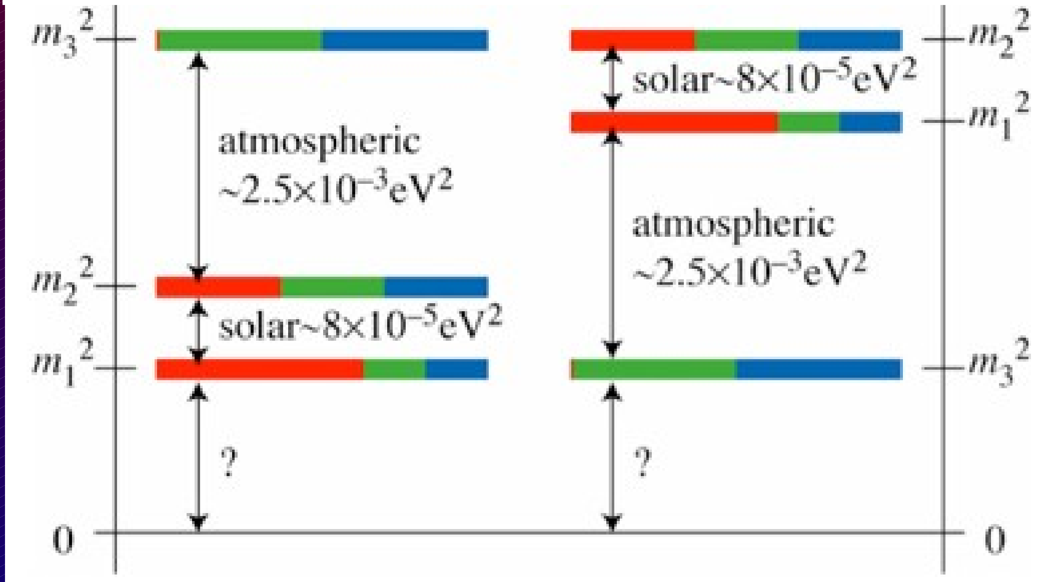
Interpretation



$$
\begin{aligned}
\Delta m_{12}^2 &= 7.24\ldots7.99\ 10^{-5}\,eV^2 \\
|\Delta m_{13}^2| &= 2.28\ldots2.64\ 10^{-3}\,eV^2 \\
\sin^2\theta_{12} &= 0.28\ldots0.35 \\
\sin^2\theta_{23} &= 0.41\ldots0.61 \\
\sin^2\theta_{13} &= <0.027
\end{aligned}
$$

2-sigma ranges

Open Questions



How large is θ_{13} ? → experiments started

Precision measurements (θ_{23} maximal ?) → next gen. oscillations exp.

Absolute mass scale ? → nucl. phys. experiments (KATRIN)

Normal or inverted hierarchie ? → next gen. oscillations exp.

Majorana or dirac neutrinos ? → double beta decay

CP-violation ? → next gen. oscillations exp.

Is the MNS-model correct ?

Minimal extension of the SM

Is it possible to incorporate neutrino oscillations in the SM ?

0. **New phenomena**

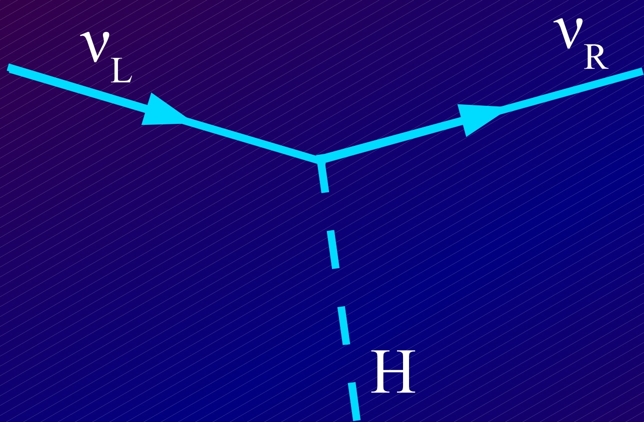
lepton flavour violation (neutrino oscillations
+ charged lepton decays)

potentially CP violation in the lepton sector

Minimal extension of the SM

Is it possible to incorporate neutrino oscillations in the SM ?

1. **Neutrinos have mass** (at least 2 out of 3 states)



Higgs-mechanism

$$\langle \overline{\Psi(\nu_L)} | 1 | \Psi(\nu_R) \rangle$$

$$= \langle \overline{½(1-\gamma_5)\Psi(\nu)} ½(1+\gamma_5)\Psi(\nu) \rangle$$

$$= \langle \overline{\Psi(\nu)} ¼(1+\gamma_5)(1+\gamma_5)\Psi(\nu) \rangle$$

need new particles:
right-handed neutrinos

Minimal extension of the SM

Is it possible to incorporate neutrino oscillations in the SM ?

2. **Majorana Masses**

Right-handed neutrinos are very special

- electric charge = 0
- no colour
- weak isospin = 0

υ_R and $\bar{\upsilon}_L$ have the same quantum numbers

Are they identical? Are they Majorana particles?

→ at tree level: introduce majorana mass term ?

→ loop corrections: generate majorana masses or forbidden by a new symmetrie

Minimal extension of the SM

Is it possible to incorporate neutrino oscillations in the SM ?

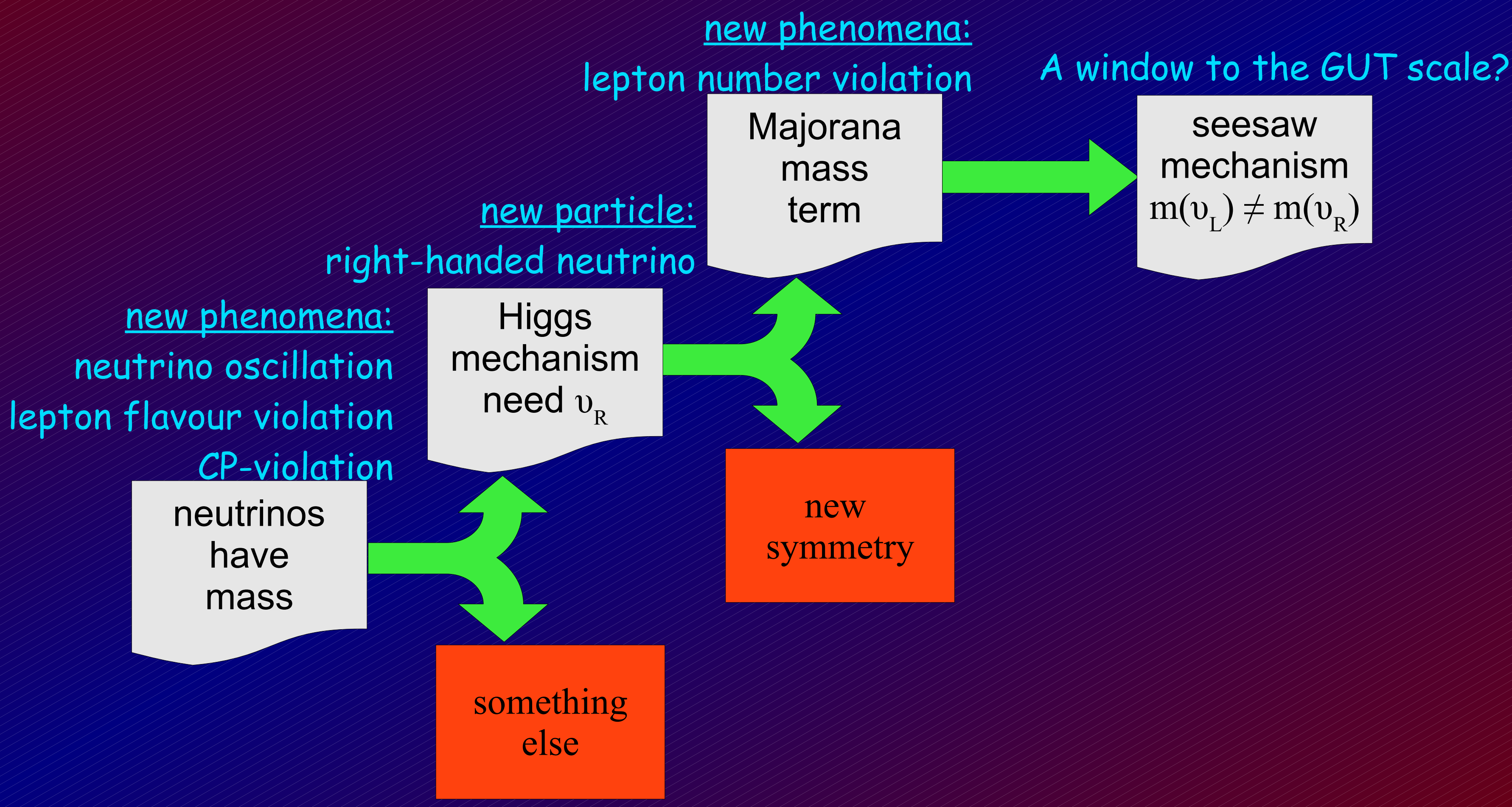
3. **Seesaw mechanism**

If there are dirac and majorana mass terms

diagnonalize mass matrix to find eigenstates

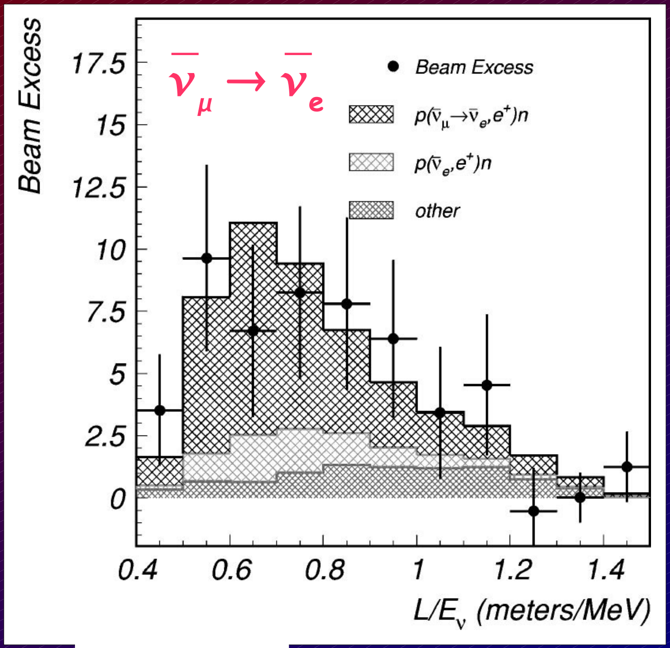
Right- and left-handed neutrino will have different masses

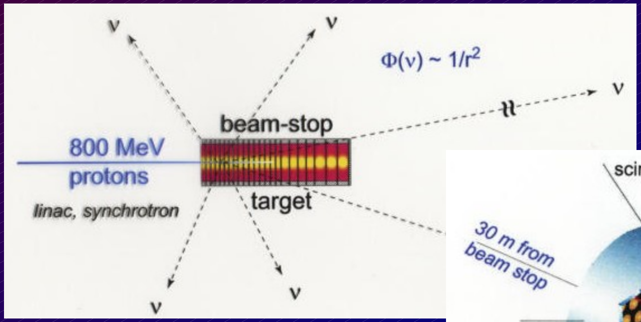
Minimal extension of the SM ?

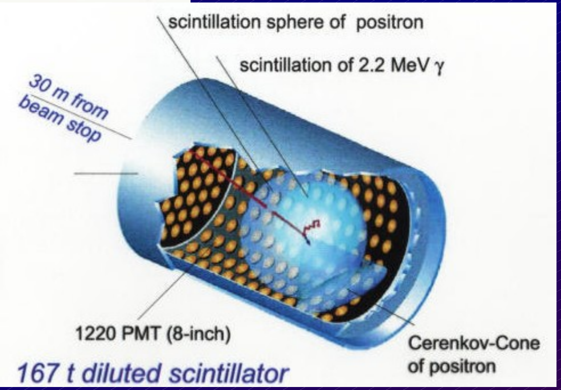


The LSND Effect

LSND-Effect







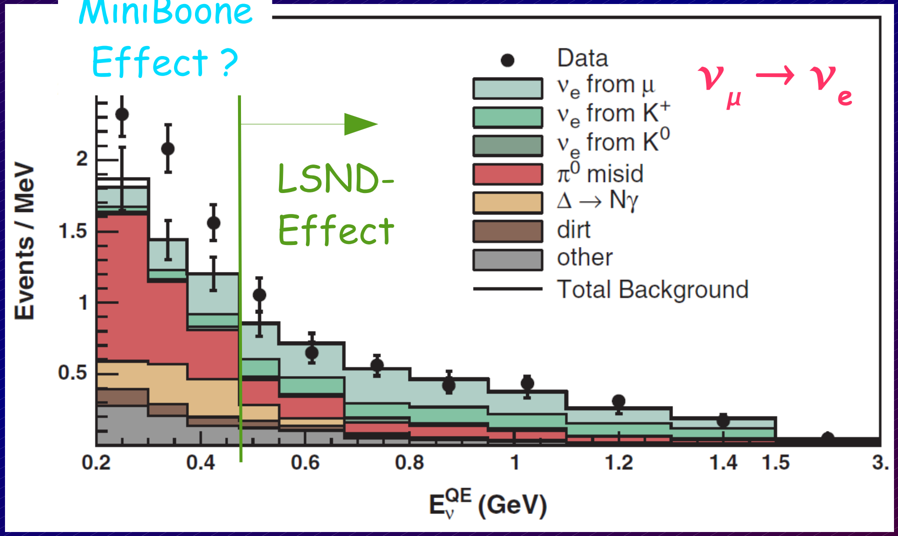
LSND

evidence for oscillations

$\Delta m^2 \approx 1\ eV^2$

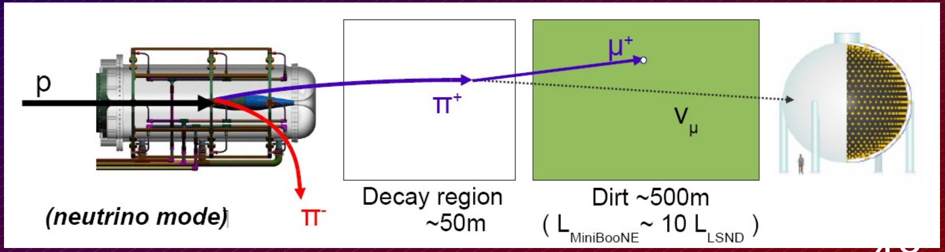
Liquid Scintillator Neutrino Detector @ Los Alamos

MiniBoone Effect ?

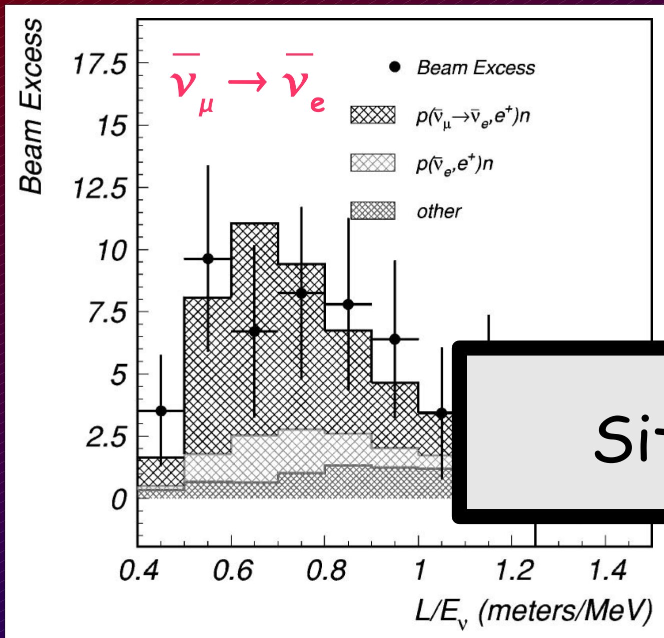


(almost?) excluded by KARMEN

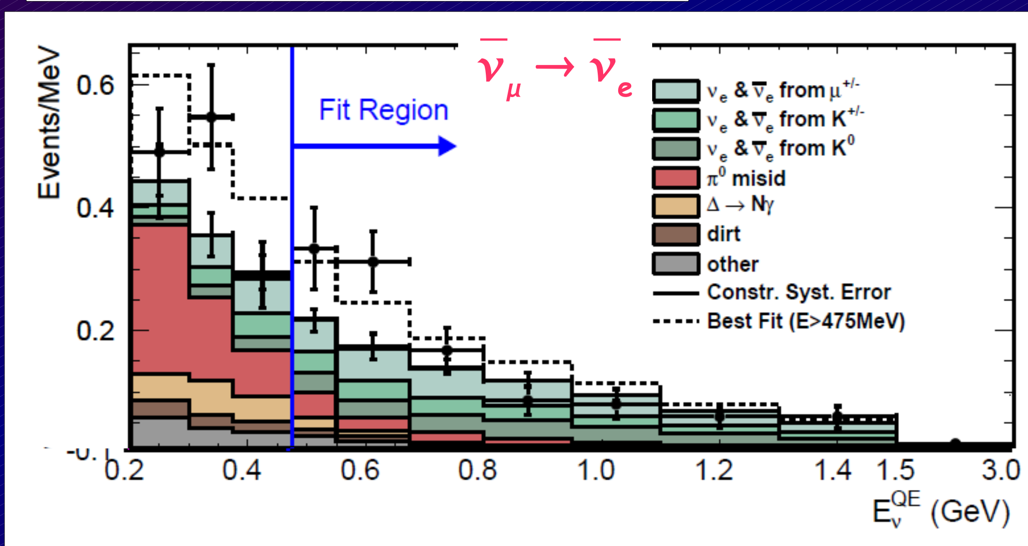
contradicted by MiniBooNE

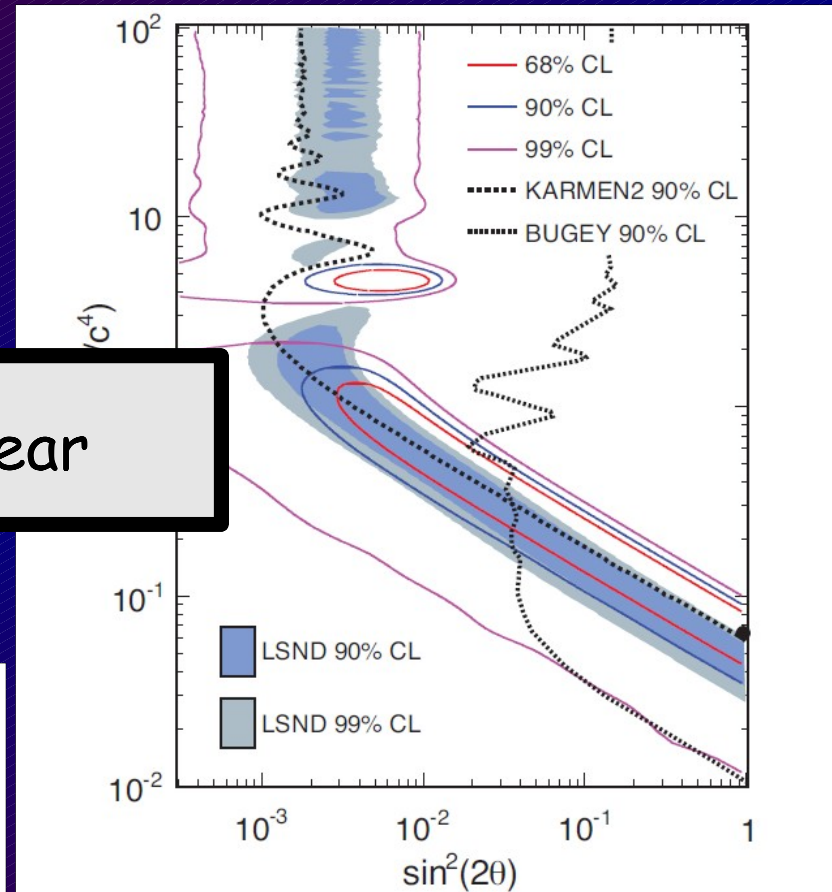


LSND-Effect



Situation unclear

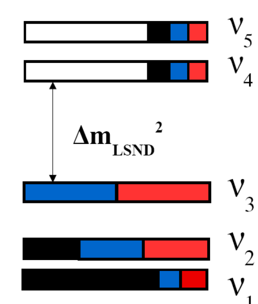




$\Delta m^2 \approx 1\ eV^2$

sterile neutrinos

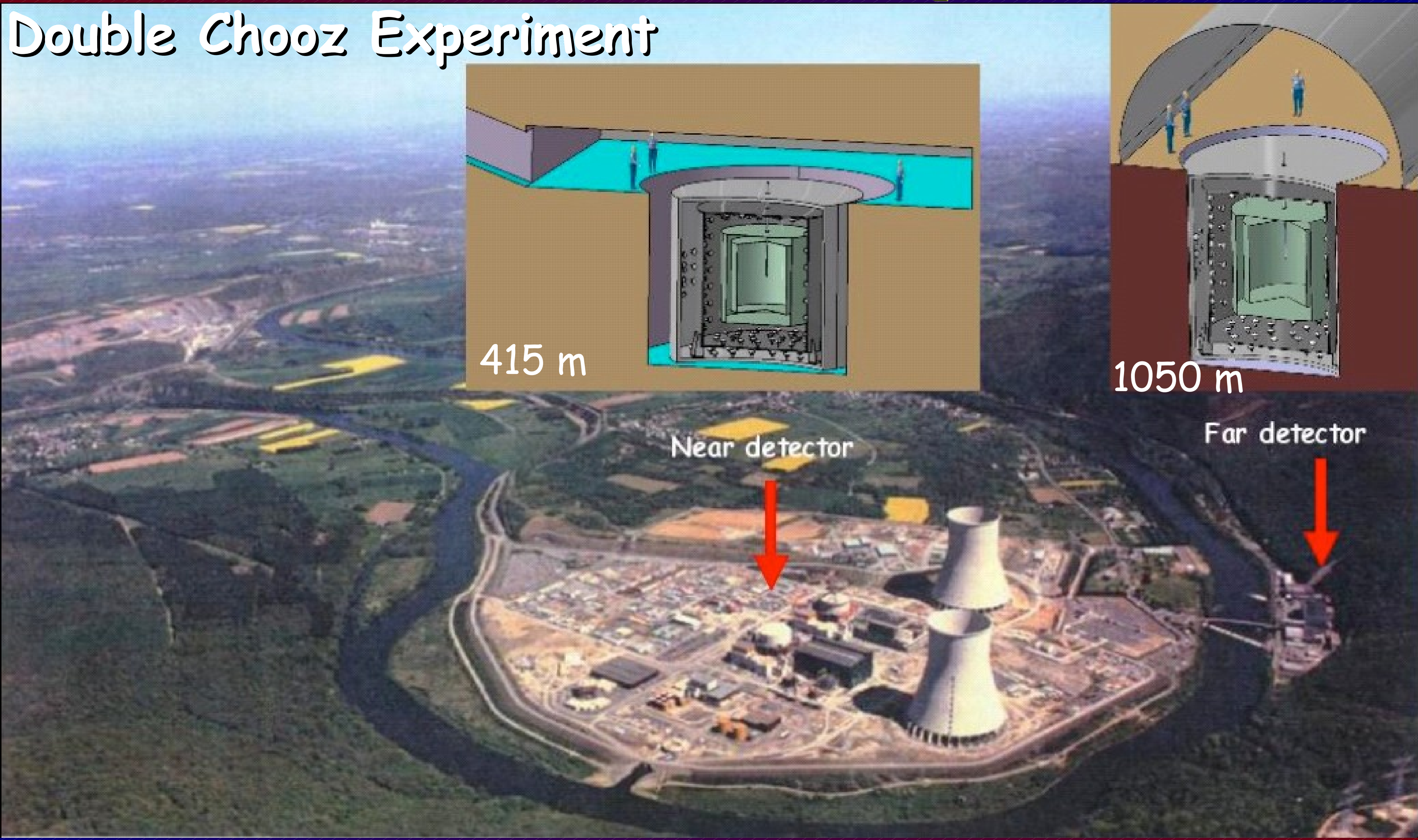
CP-Violation



Double Chooz

Kraftwerk Chooz
Maas-Schleife in den Ardennen

Reactor Neutrino Experiment



Neutrino Detection

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

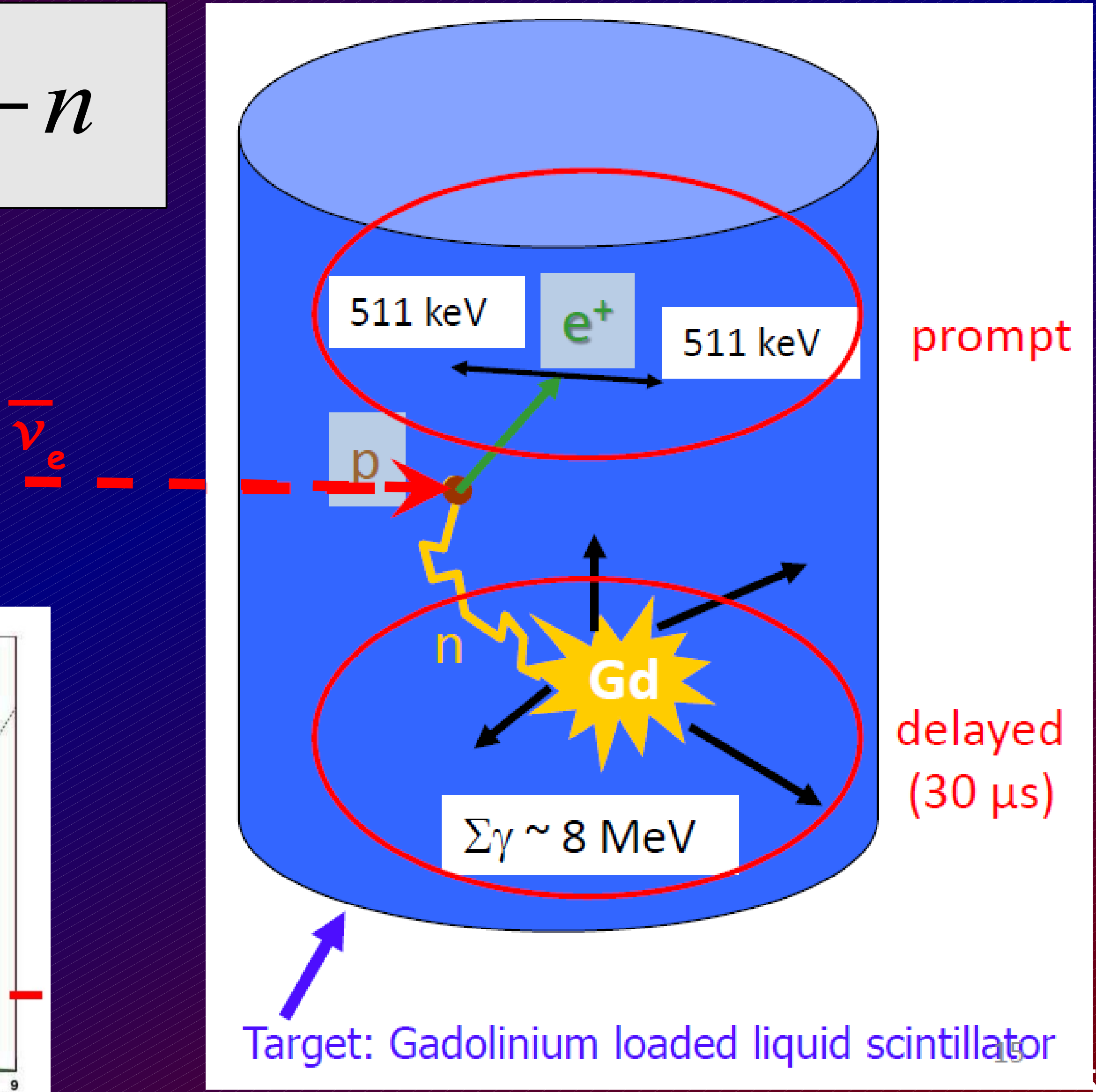
Positron detection:

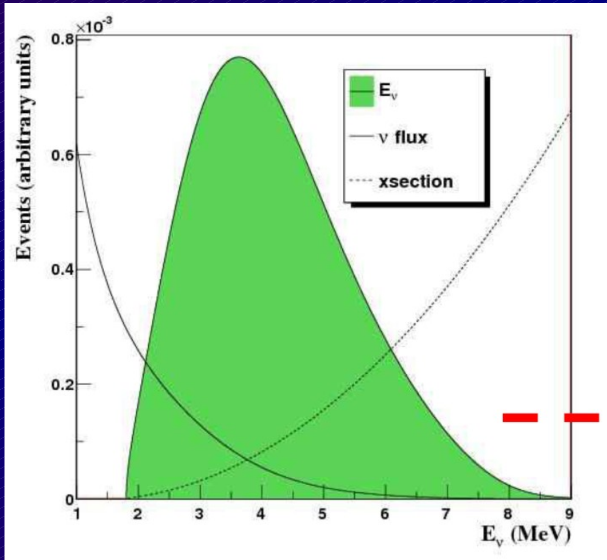
$E_e = E_\nu - Q \rightarrow$ Scint.

$Q = 1.8$ MeV

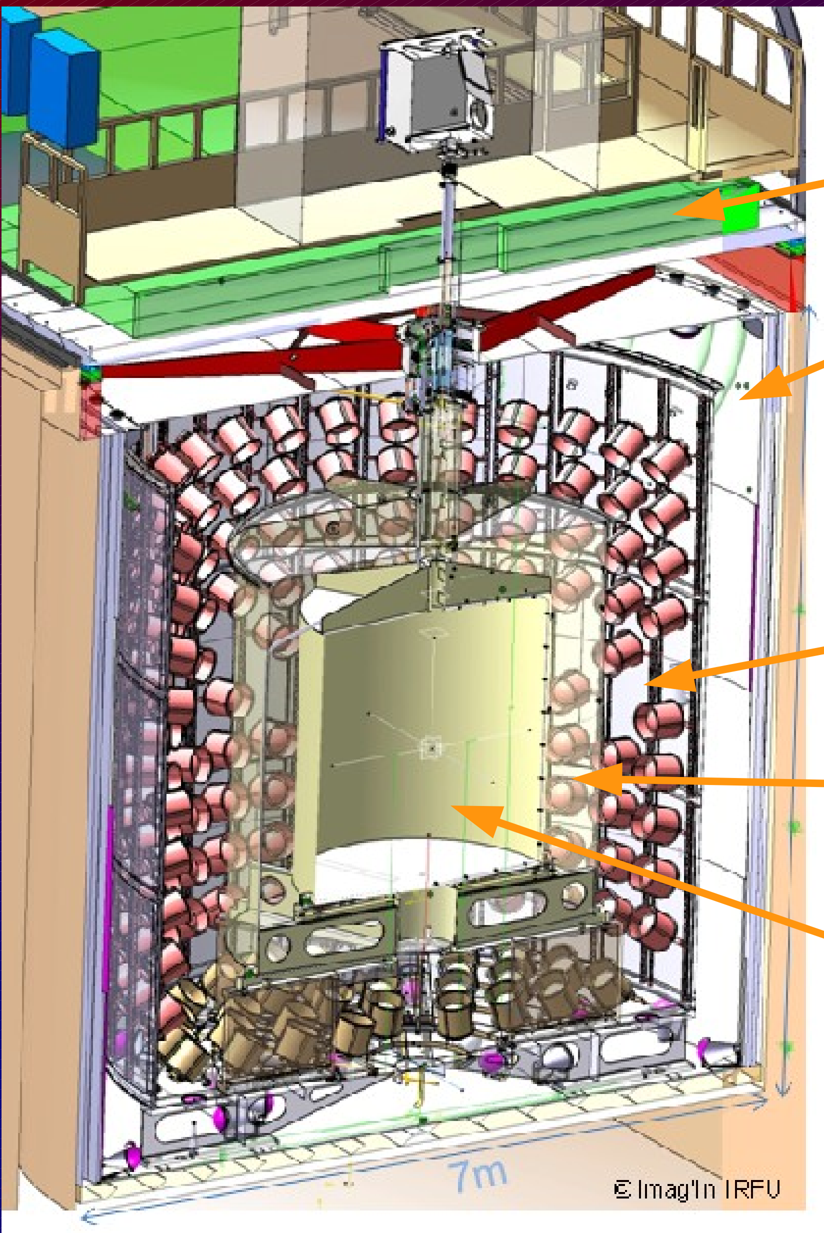
$e^+ \rightarrow \gamma\gamma \rightarrow$ Scint.

$E_{prompt} = E_\nu +$ const.



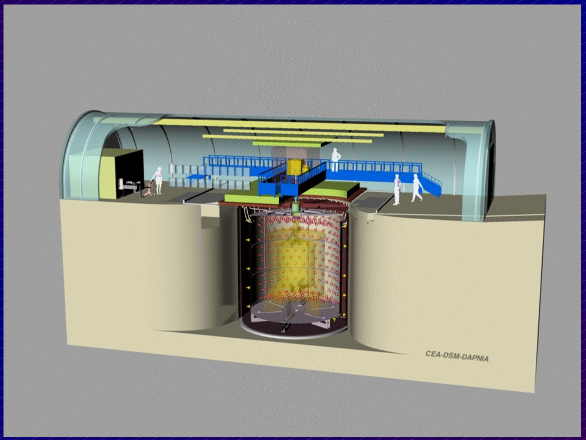


The Detectors



Outer Veto RPC

Inner Veto
mineral oil
scintillator

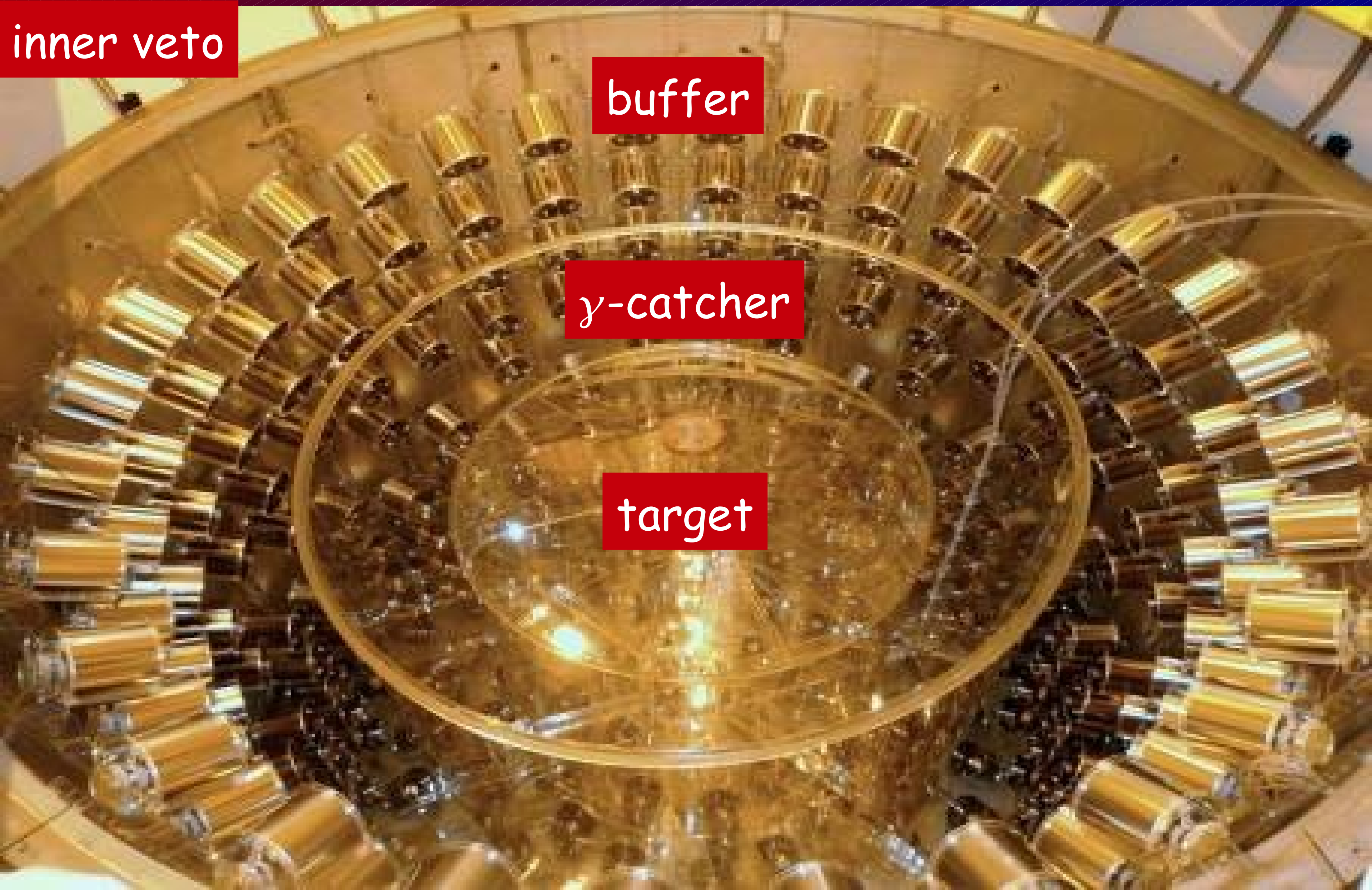


Buffer
mineral oil

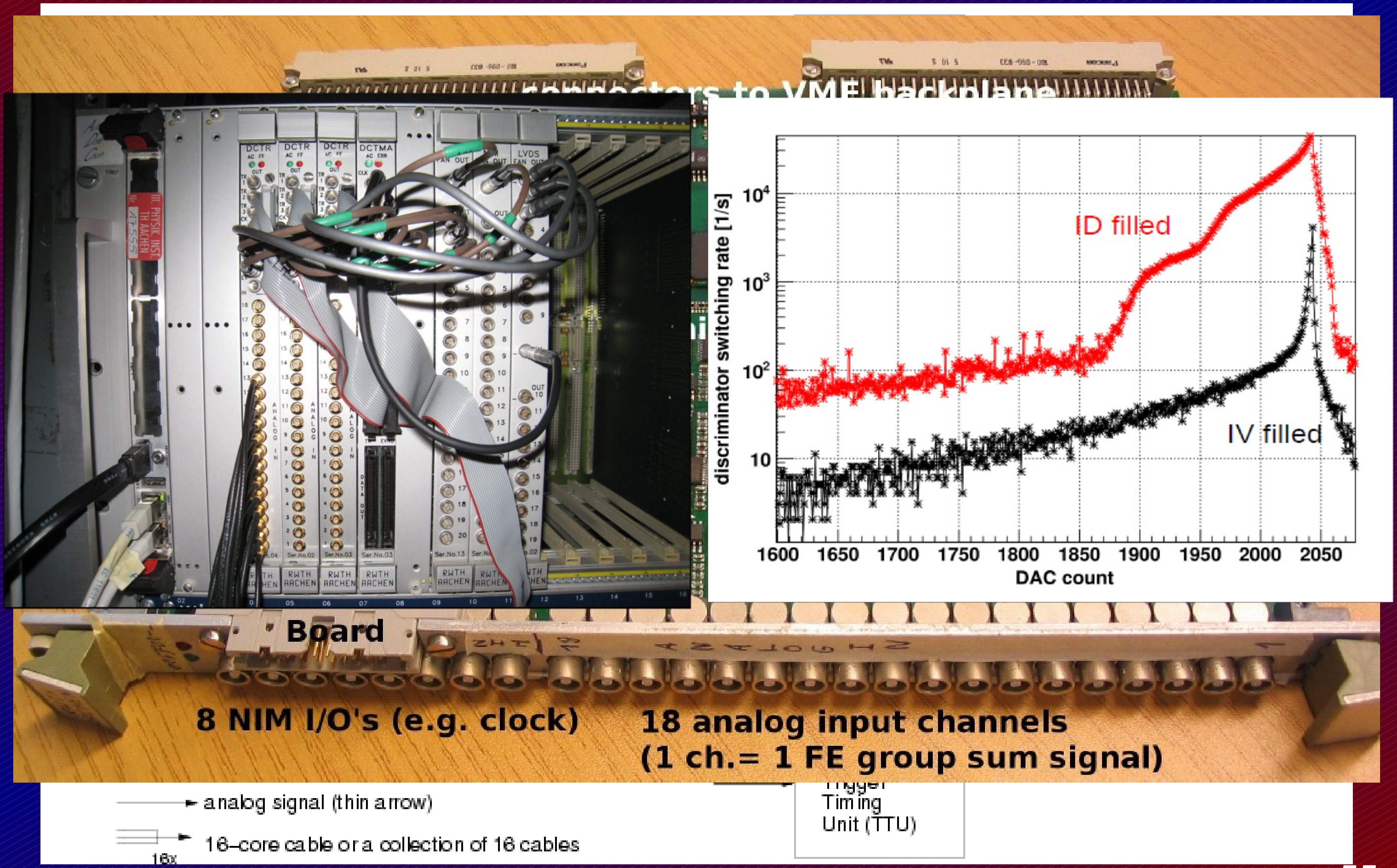
gamma catcher
20% PXE
80% Dodekan

Inner Target
20% PXE
80% Dodekan
0.1% Gd

The Detectors



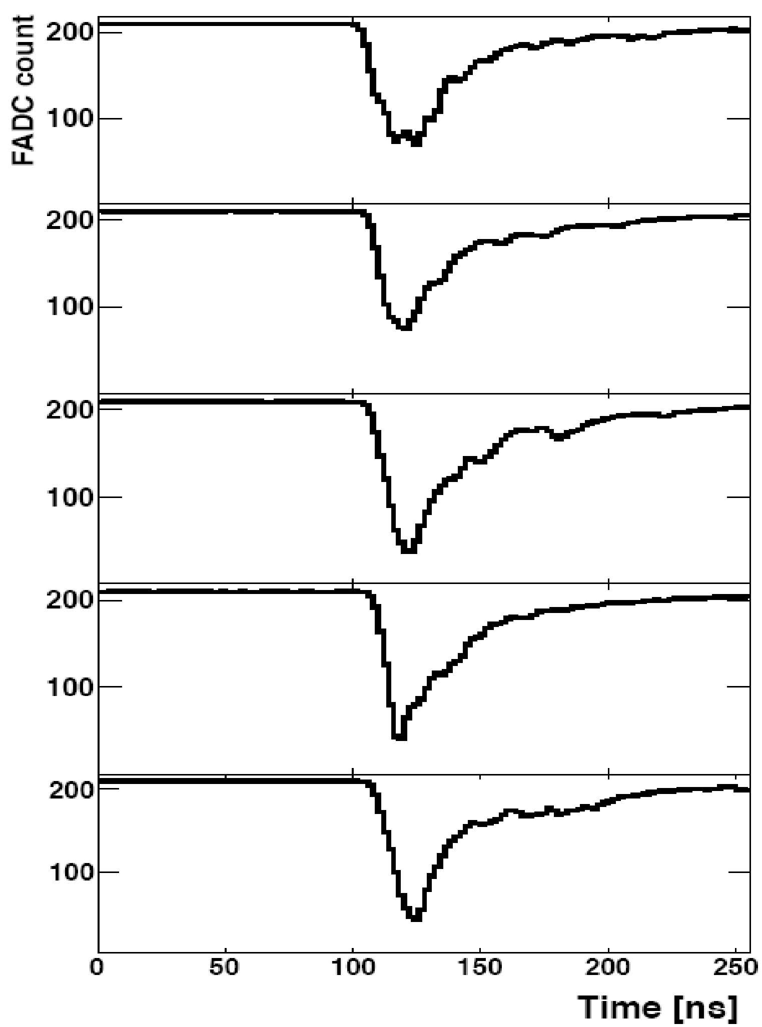
Trigger



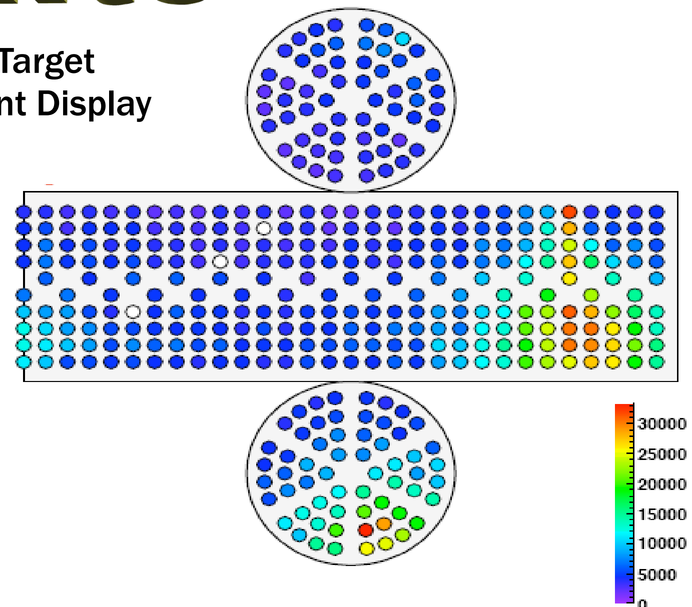
Board
8 NIM I/O's (e.g. clock)
18 analog input channels
(1 ch.= 1 FE group sum signal)
DCTR
DCTMA
LVDS
ANALOG IN
DATA OUT
RWTH AACHEN
III. PHYSIK. INST. TH AACHEN
discriminator switching rate [1/s]
DAC count
ID filled
IV filled
10
10^2
10^3
10^4
1600
1650
1700
1750
1800
1850
1900
1950
2000
2050
analog signal (thin arrow)
16-core cable or a collection of 16 cables
16x
Timing
Unit (TTU)

First Events

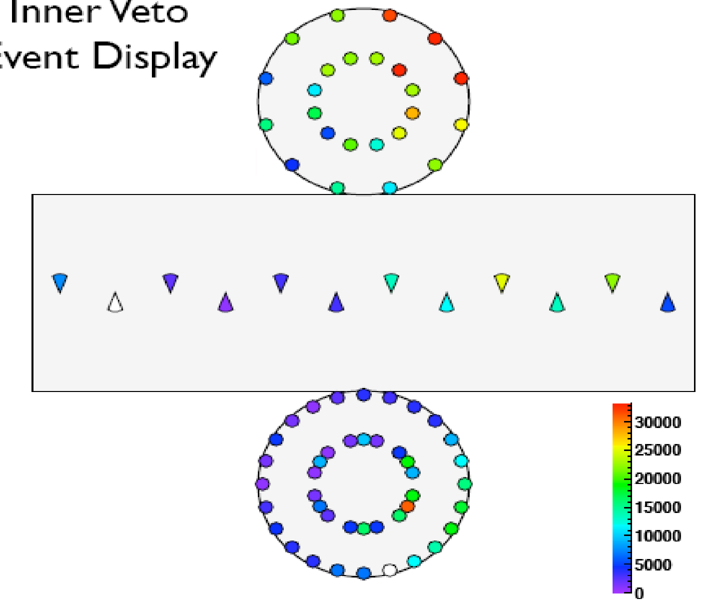
Inner Detector Waveforms



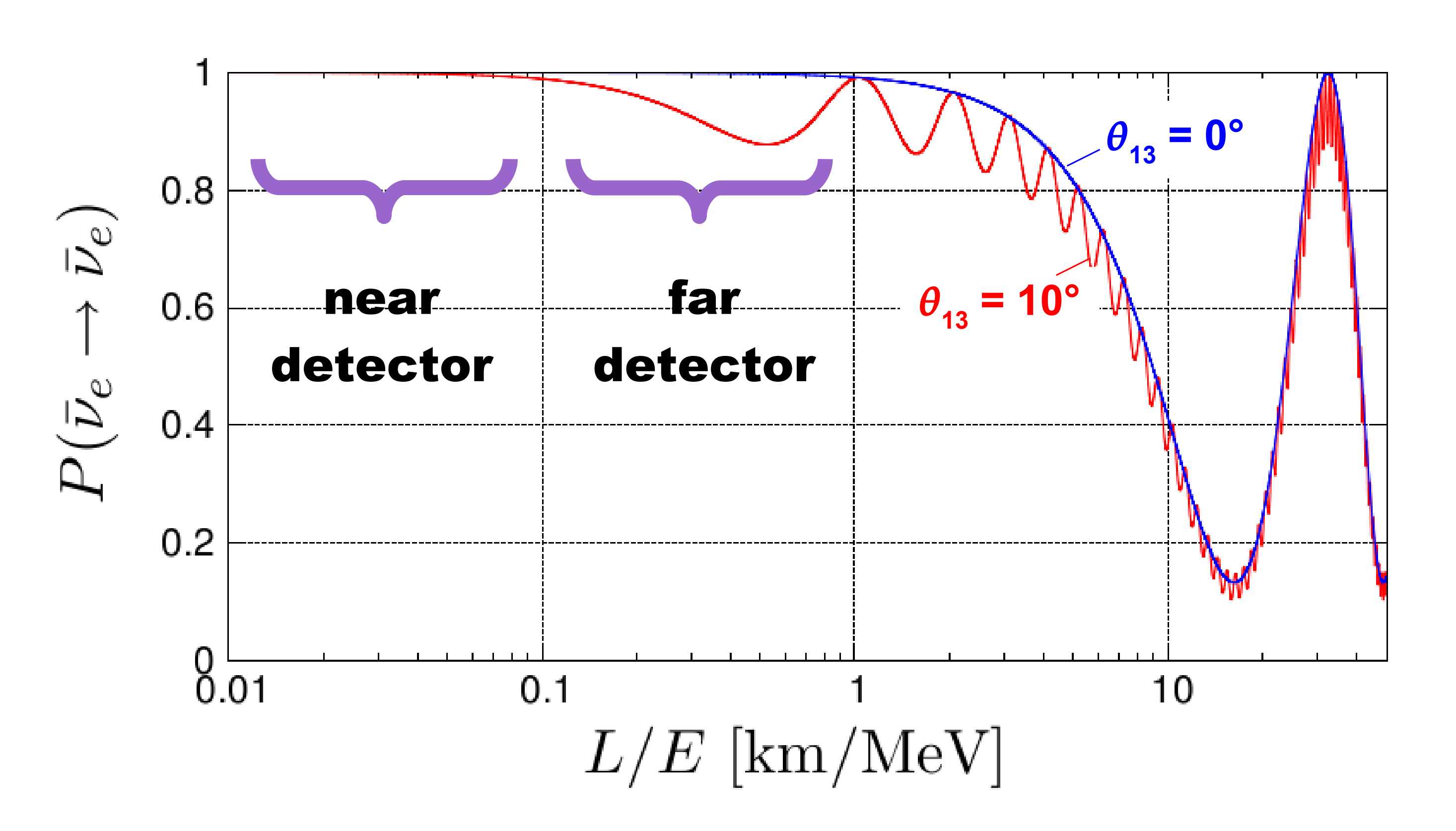
Target
Event Display



Inner Veto
Event Display

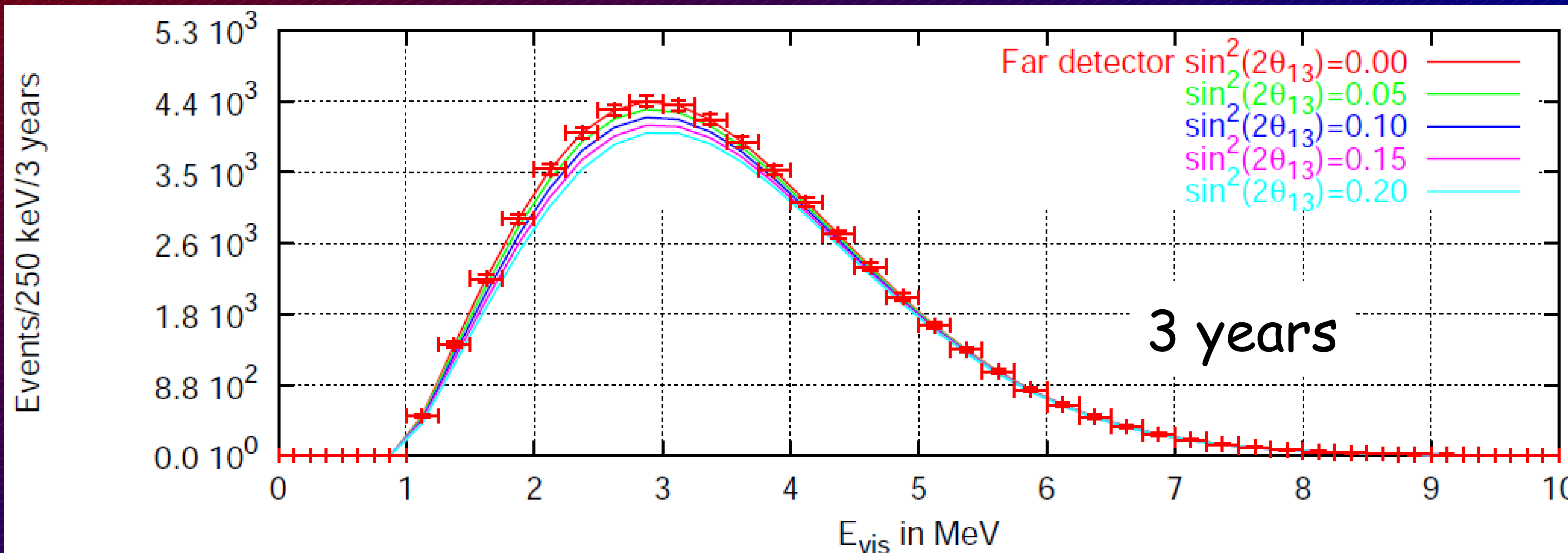


Neutrino Oscillations



- -

Neutrino Oscillations

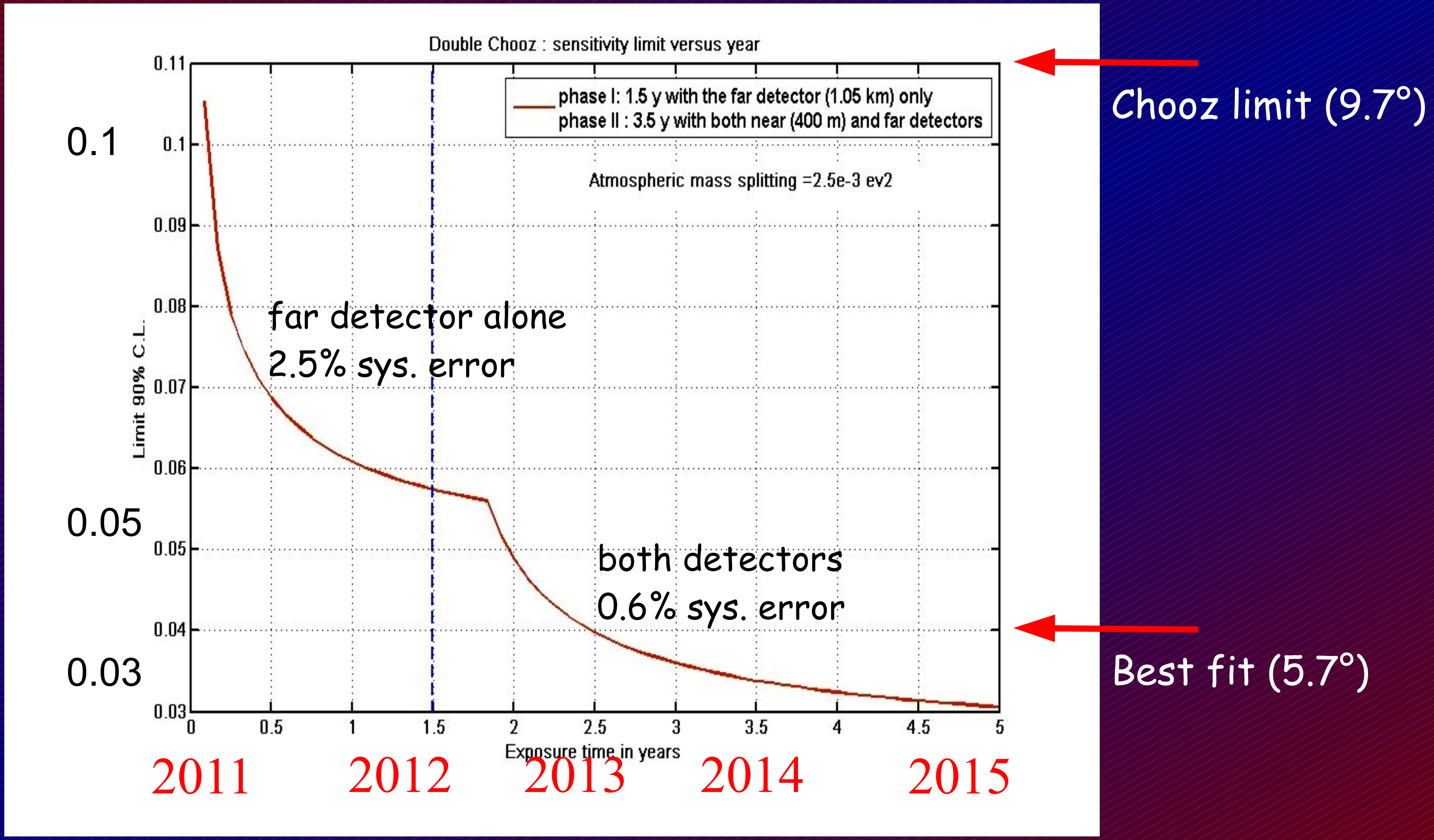


Result of θ_{13} is only a small effect

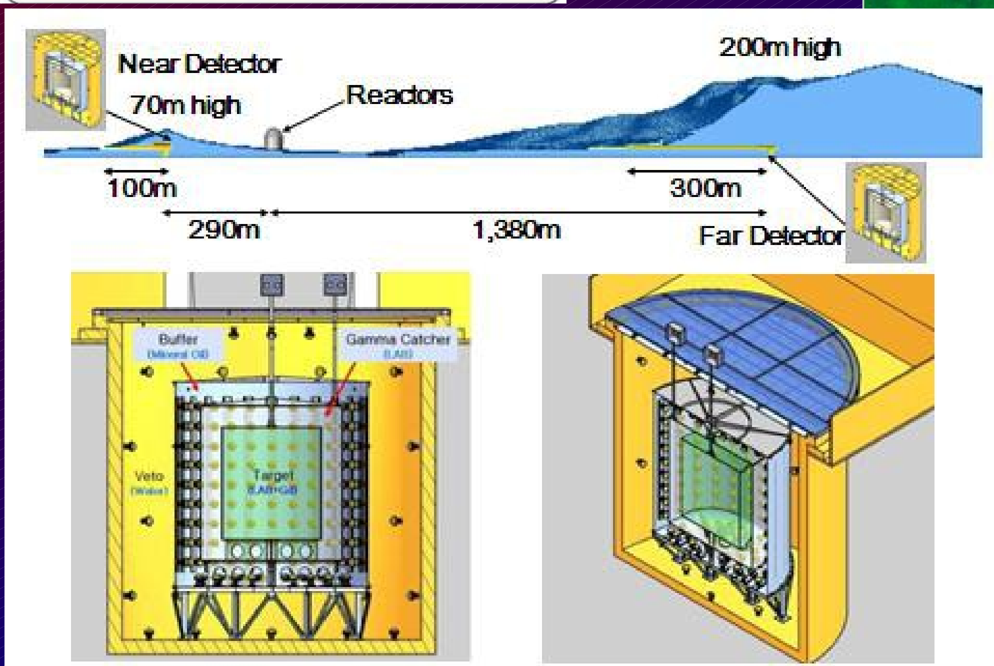
- high statistics
  - Near detector: ~300/day
  - Far detector ~60/day ≈ 50.000 events in 3 years
- requires absolute event rate prediction
  - Previously calculated from thermal power
  - Two identical detectors: systematic error of the normalisation cancels

Sensitivity

limit on $\sin^2 2\theta_{13}$ (90% c.l.)



Reactor-Experiment

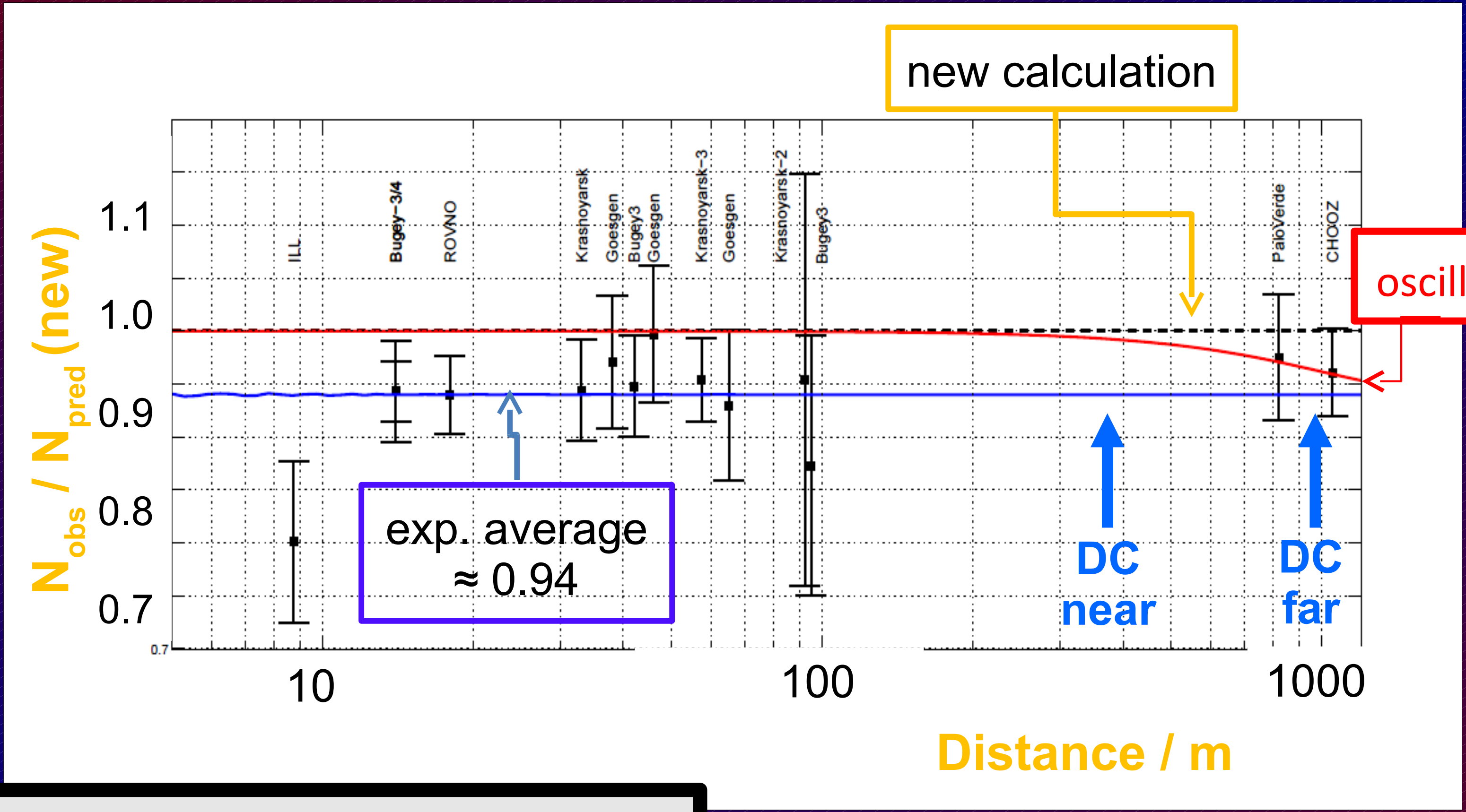


Korea: starts 2011

China: starts 2011/12

Reactor Neutrino Anomaly ?

New calculation of neutrino flux from reactors



Neutrino Oscillations ?

L < 10m → $\Delta m^2 \approx 1\ eV^2$

T. A. Mueller *et al.*, arXiv:1101.2663 [hep-ex].

G. Mention *et al.*, 1101.2755 [hep-ex].

Reactor Anomaly Tests

Several Proposals to test
short range oscillations

CERN proposal
Carlo Rubbia

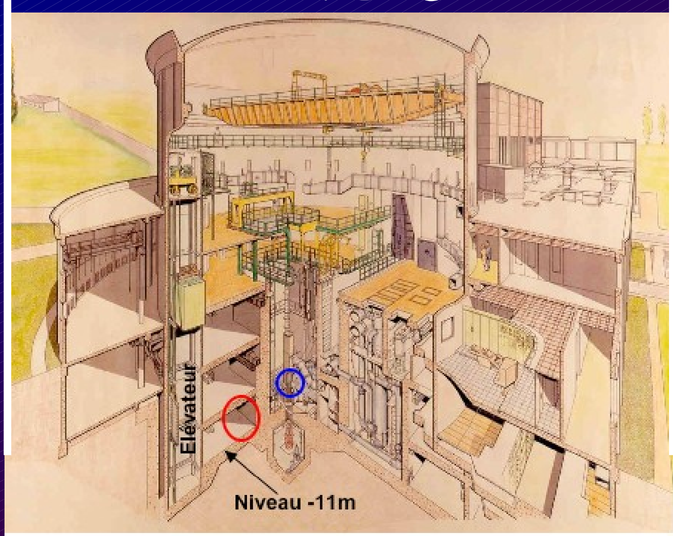
higher E

SPS wide band beam
to ICARUS @ CERN

NUCIFER
small detector for
non-proliferation

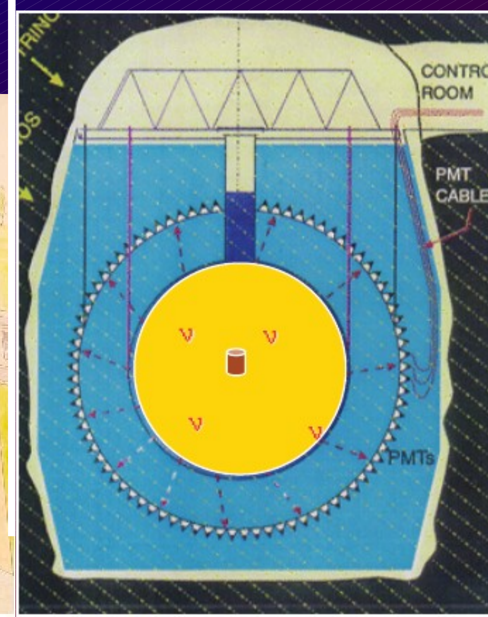
smaller L

sketch NUCIFER@OSIRIS



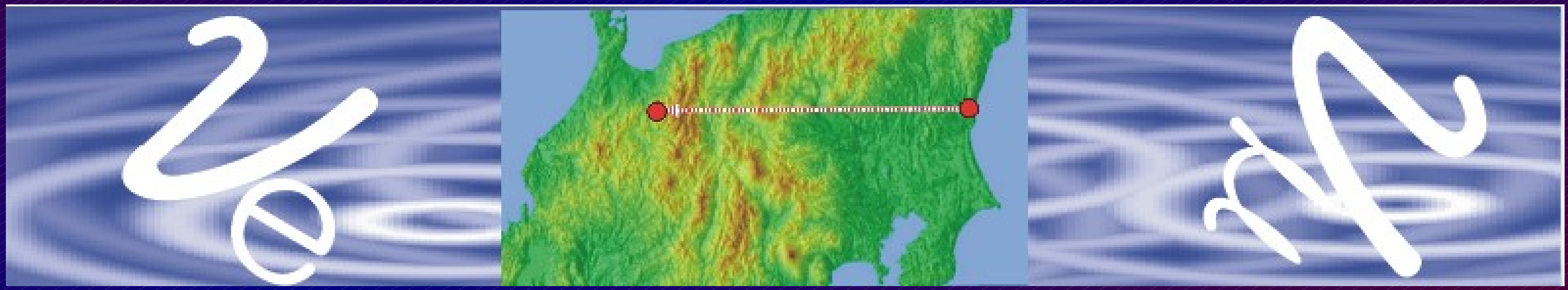
KAMLAND (or others)
Radioactive source inside
large ν-detector

smaller L



^{37}Ar
SNO+

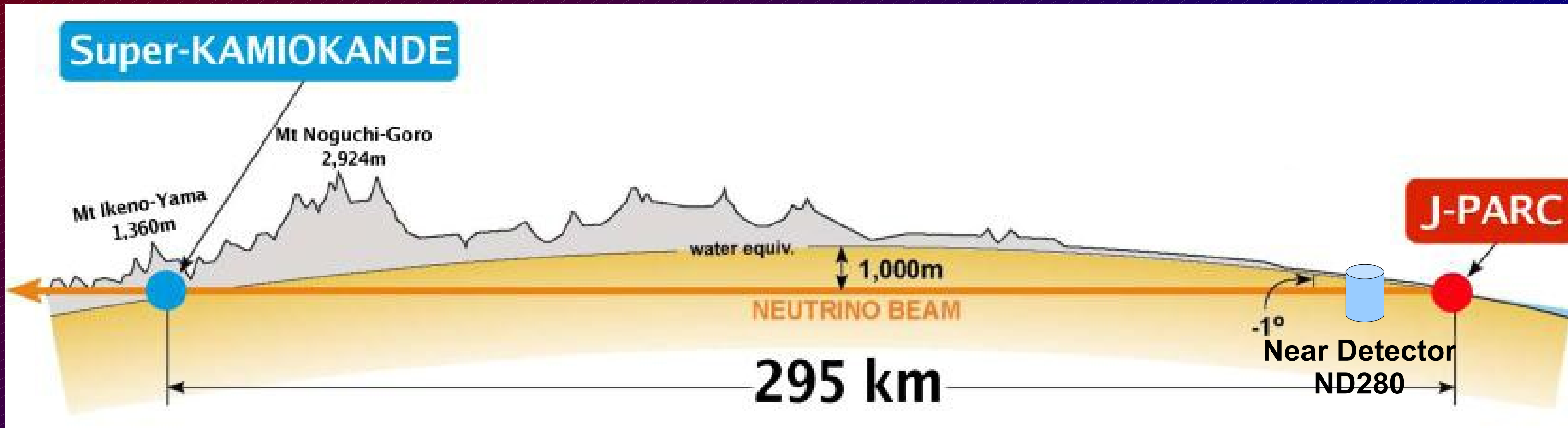
T2K



The T2K Experiment

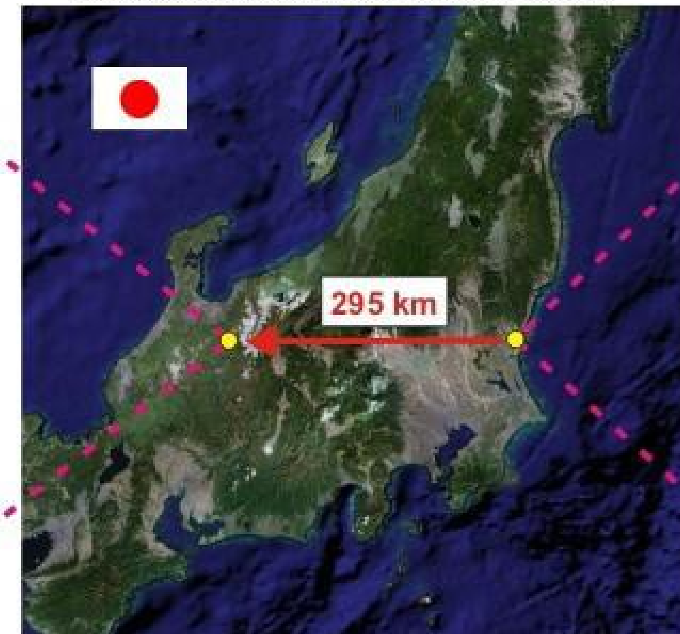
ν_μ-disappearance (Δm^2_{23}, $\sin\theta_{23}$)

ν_e-appearance ($\sin\theta_{13}$)



Super Kamiokande
50,000 tons of water
10,000 phototubes

Neutrino beam directed across Japan



Tokai accelerator complex and location of near detector (ND280)

Japan: March 11th, 2011

Japan experienced very severe earthquake on March 11th 2011 at 14:46 JST. J-PARC facility suffered damages for some extent. There are no reports of casualties and all staff, graduate students, and foreign visitors have been located and as of evening Sunday March 13th all T2K members have been evacuated from Tokai area.

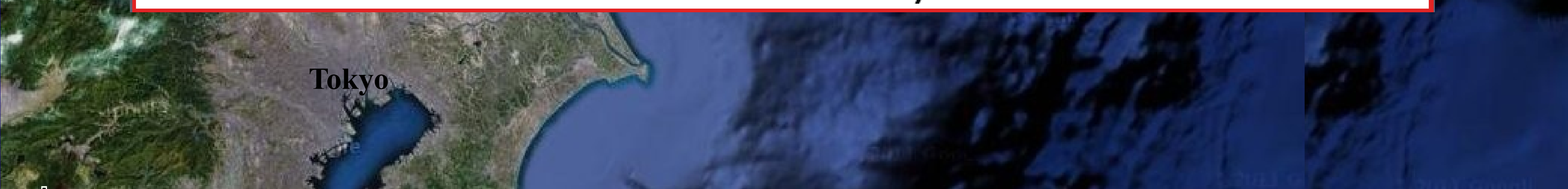
Fortunately enough, the Tsunami tidal wave did not hit J-PARC. We will start the investigation of the facilities. We will update the announcement as we learn the detail of the entire damage.

Our present priority is to restore life-supporting infrastructure such as electricity, water supply and gas at J-PARC. It may take some time, but we promise the full recovery of the J-PARC accelerator and T2K experiment in the near future.

I thank you for the messages of solidarity and sympathy.

Director of the Institute of Particle and Nuclear Studies, KEK
Koichiro Nishikawa

Spokesperson of the T2K experiment
Takashi Kobayashi



Earthquake

Some damage on the surface

(mainly streets,
a few buildings,
power station to linac)

No (vis.) damage undergrou

Working on recovery plan

Tsunami

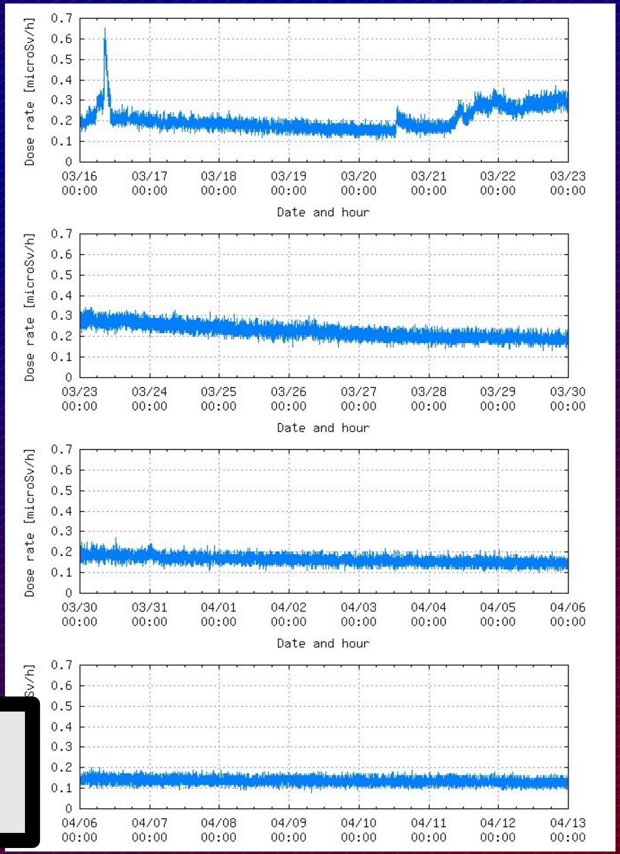
J-PARC

located directly on the beach
≈ 15m above sea level

No damage!

Reactor Accident

Dose at KEK



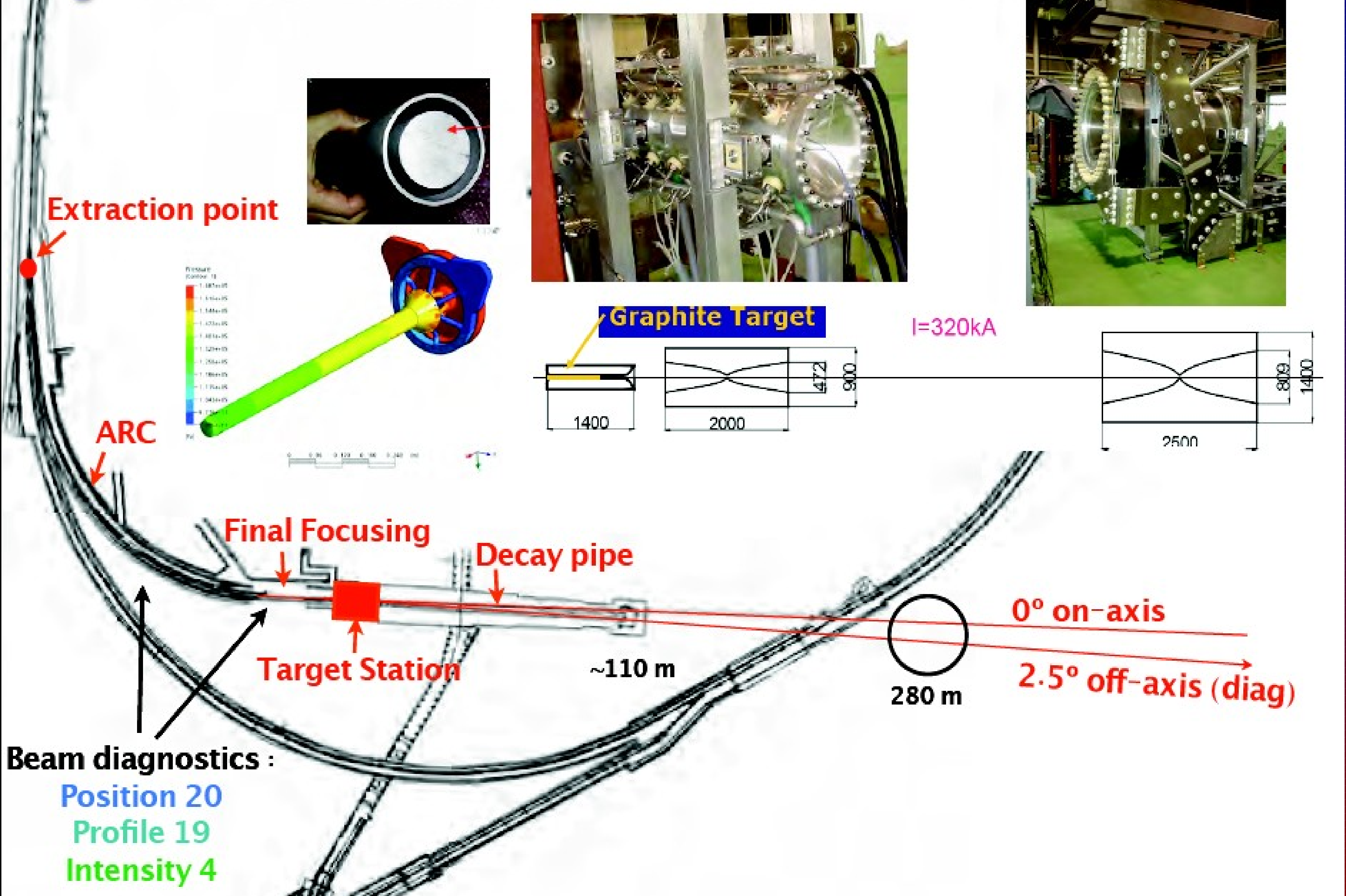
longterm average: 0.08 μSv/h

Nothing serious (yet)!

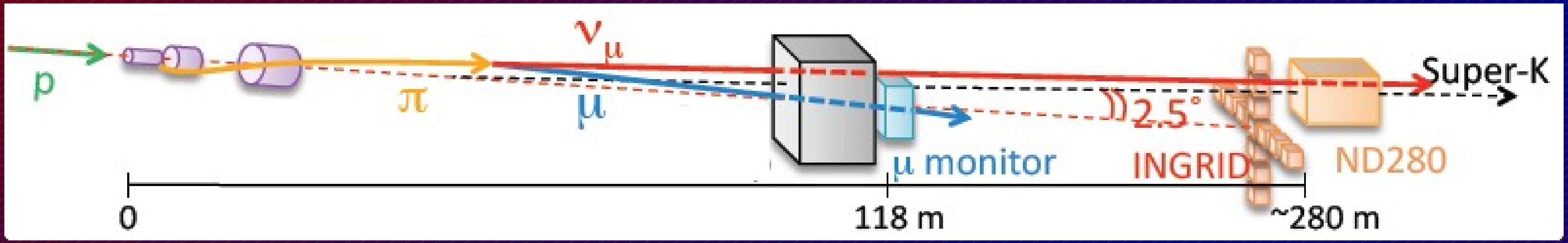
Restart in December


Accelerator Complex
October 2006
Synchrotron
30 (50) GeV
ν_μ-beam
RCS
3 GeV
Linac
181 MeV
J-PARC: Japanese Proton Accelerator Research Complex

J-PARC Neutrino beamline



Off – Axis Beam



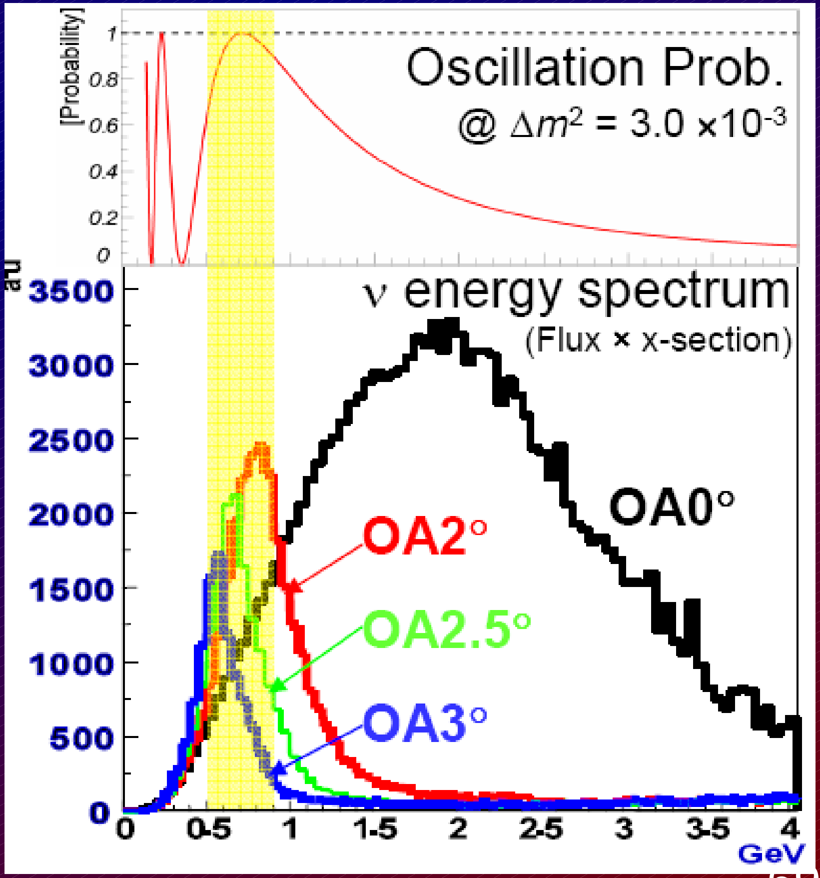
Off-Axis Beam

high intensity at maximum oscillation

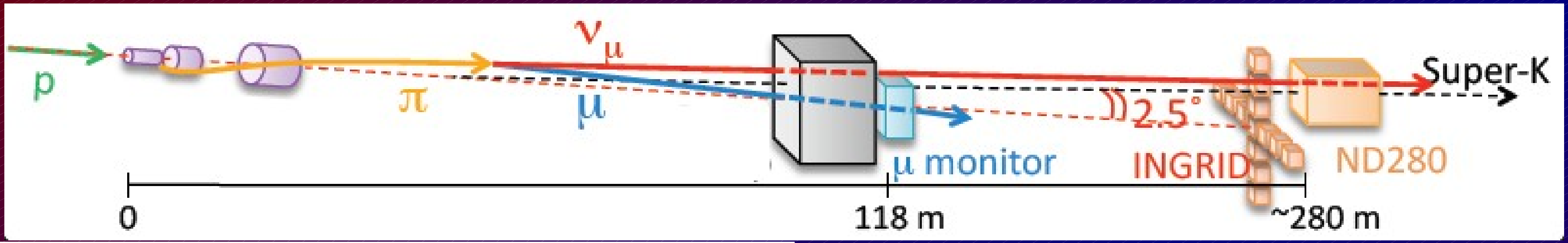
INGRID: on-axis

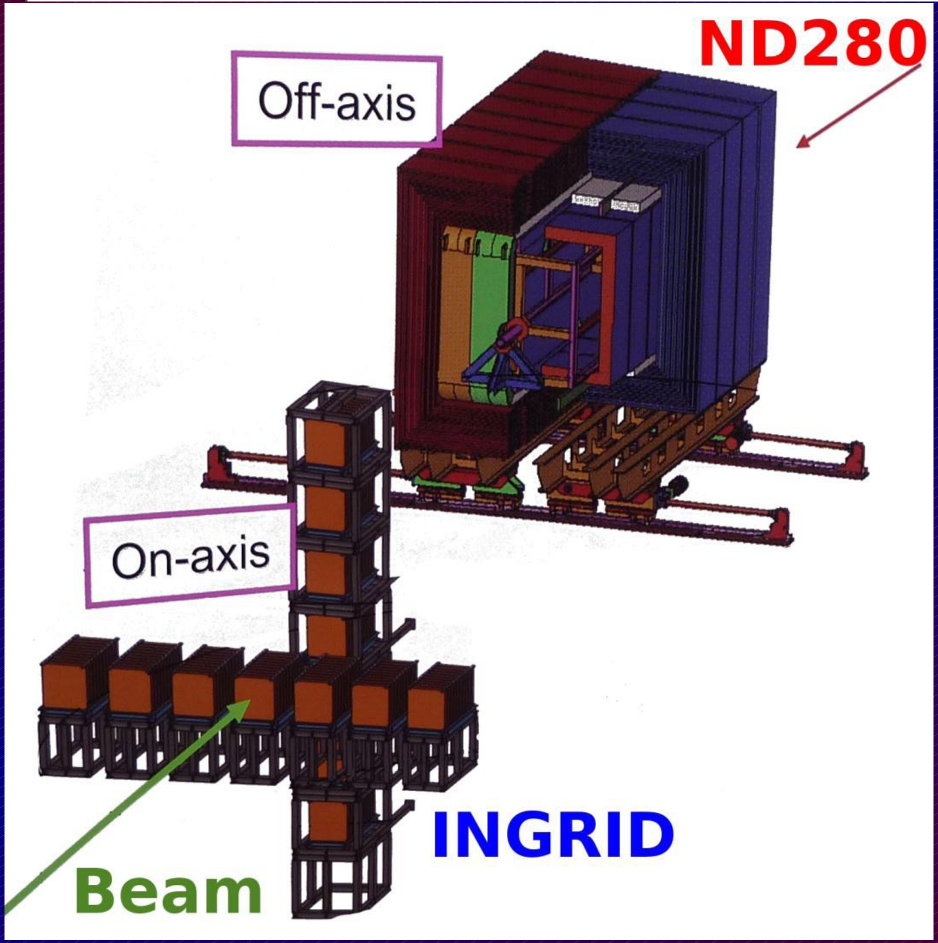
ND280: 2.5° off-axis

SUPER-K: 2.5° off-axis



Near Detectors





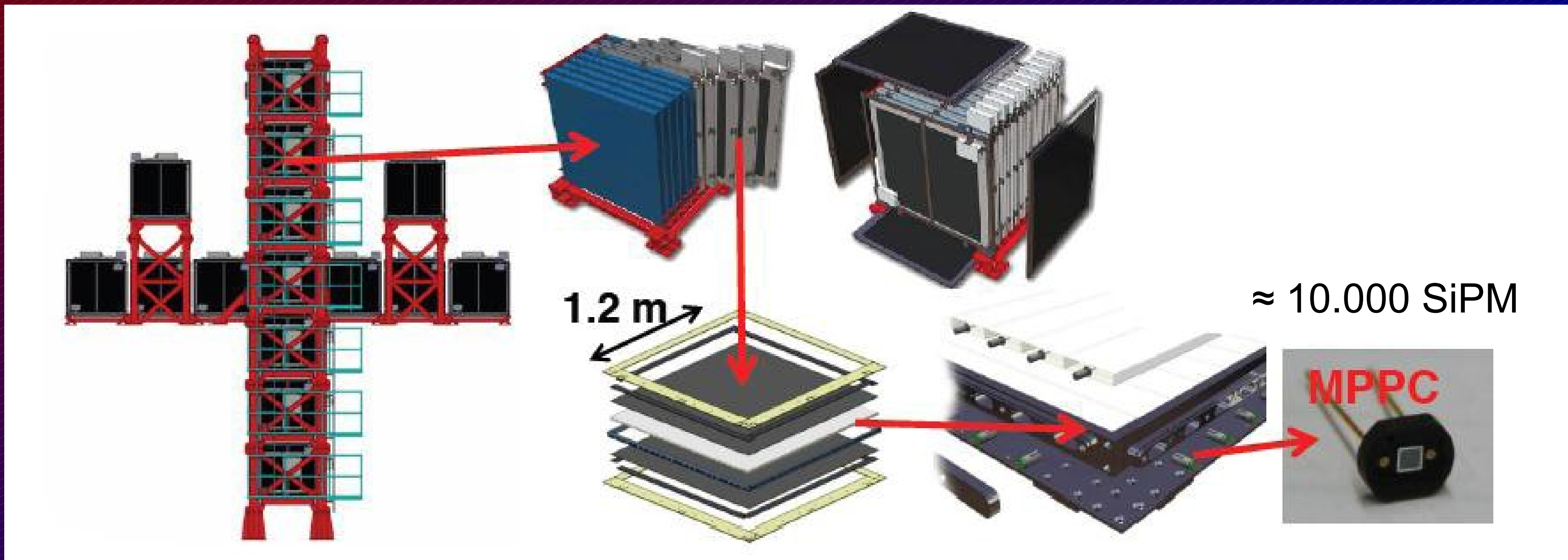
ND280

- tracker/calorimeter in 0.2T field
- beam composition (ν_e background)
- neutrino flux / cross sections

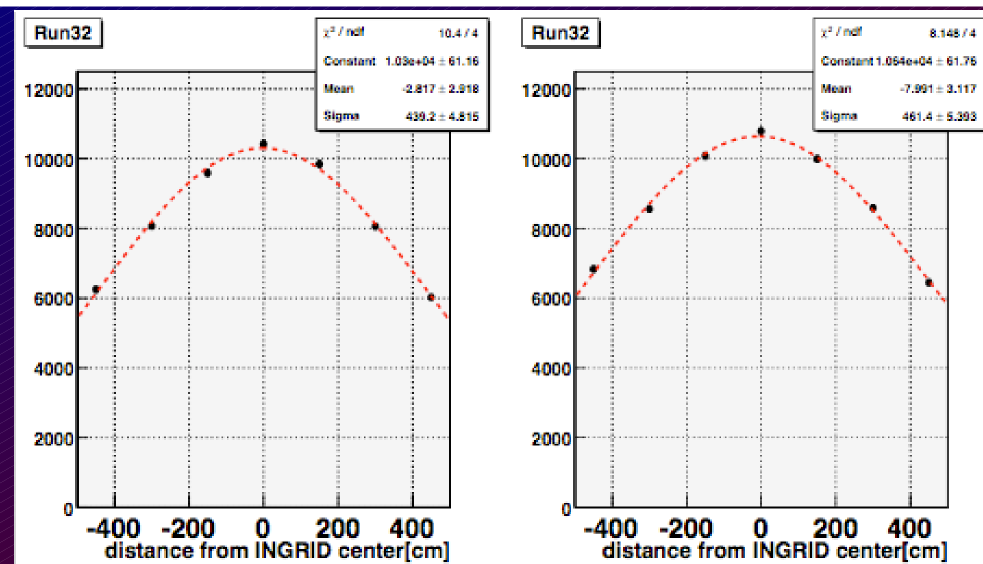
INGRID

- iron/scintillator calorimeter
- beam profile
- bunch timing

Interactive Neutrino GRID



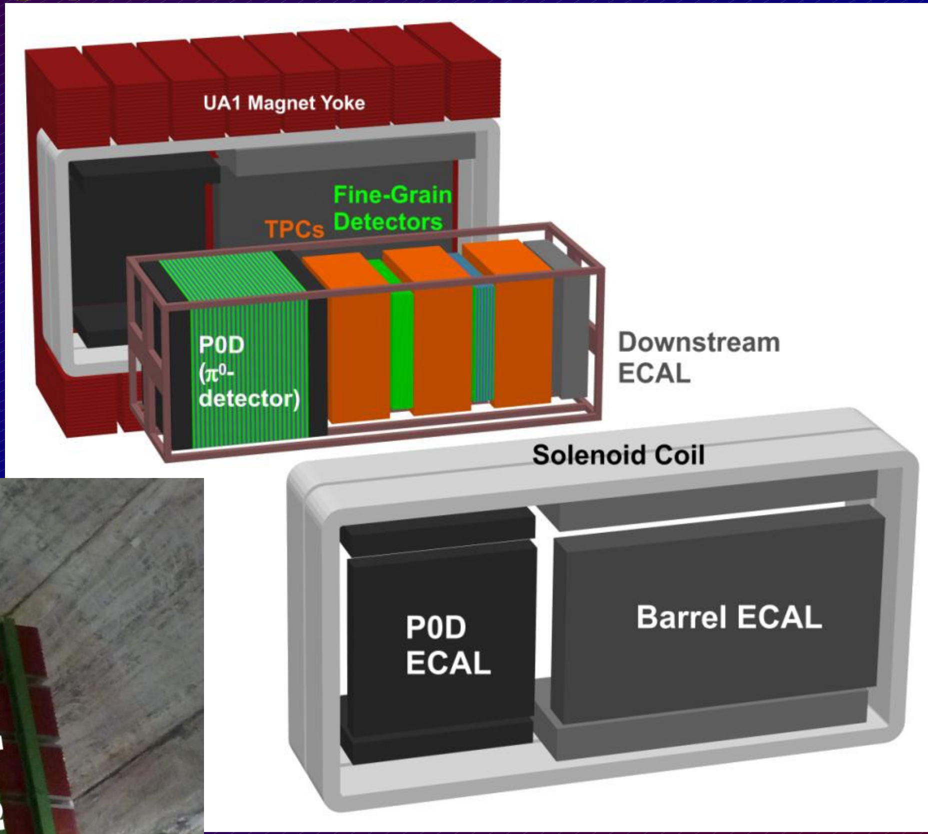
14 iron/scint. modules
X-Y scintillator layers
700 ν interactions/day @ 50 kW
beam direction better: 1 mrad
→ corresponds to 2% change
in flux at Super-K

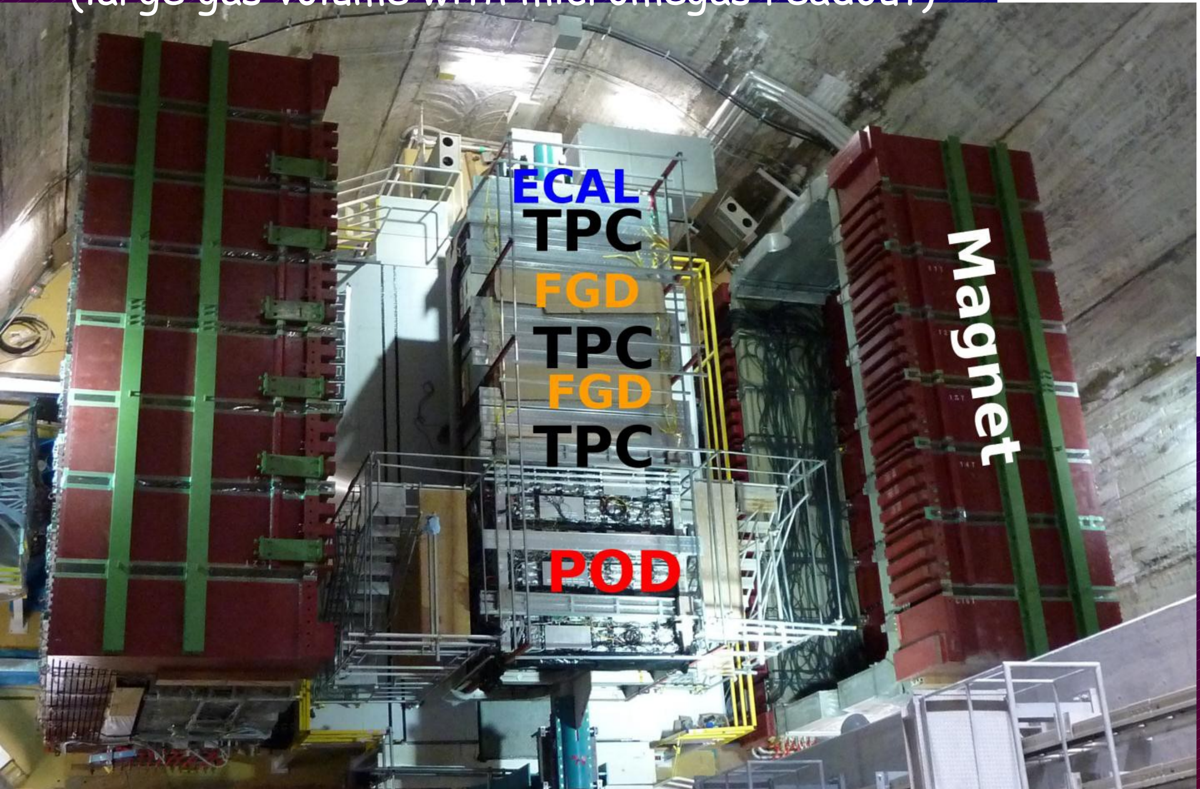


Near Detector ND280

Inside 0.2 T UA1/NOMAD magnet:

- The π^0 detector P0D (lead/water/scintillators)
- Barrel and downstream ECAL
- Fine Grain Detectors FGD (water/scintillators)
- Time Projection Chambers TPC
  (large gas volume with micromegas readout)

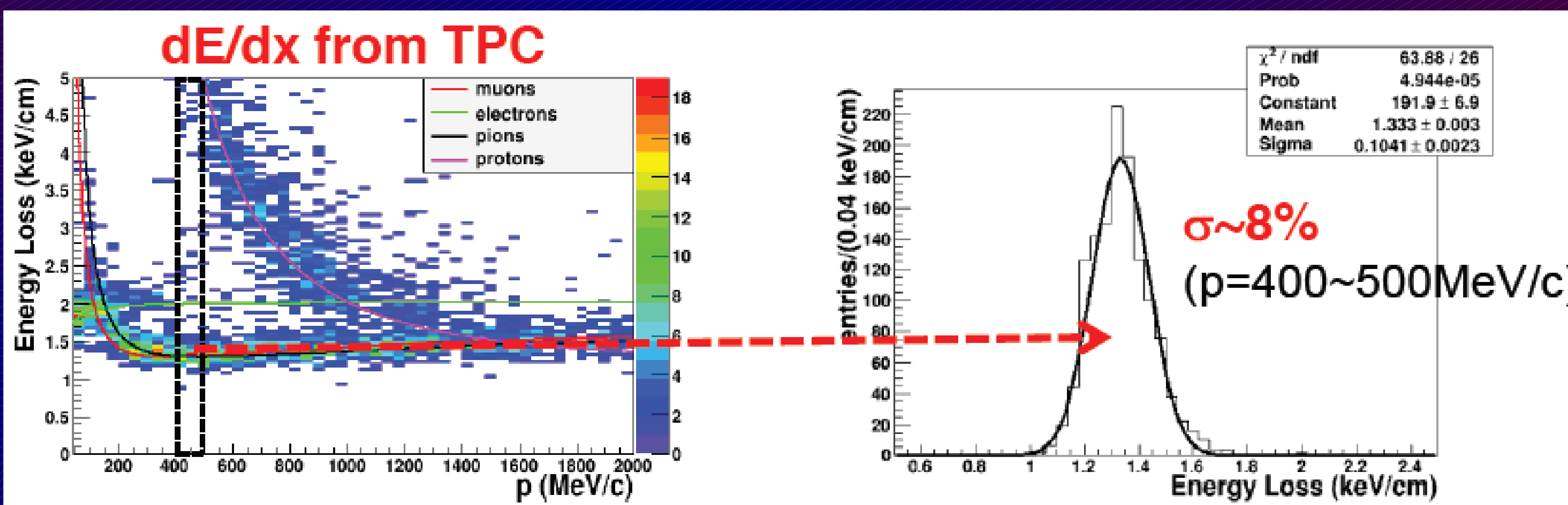




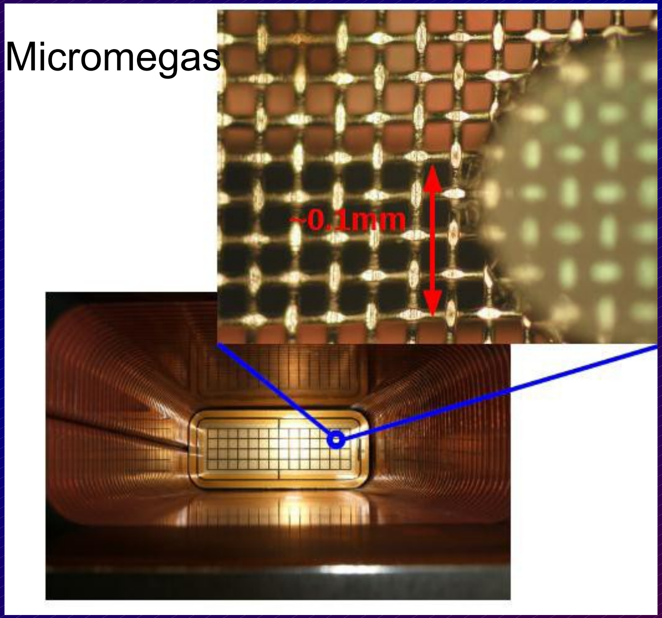
TPC

Large TPC

- 3 modules
- Micromegas read out
- Sens. volume 180 x 200 x 70 cm
- Precise assembly and alignment
- 124,000 channels



RWTH Aachen: TPC Monitor Chambers

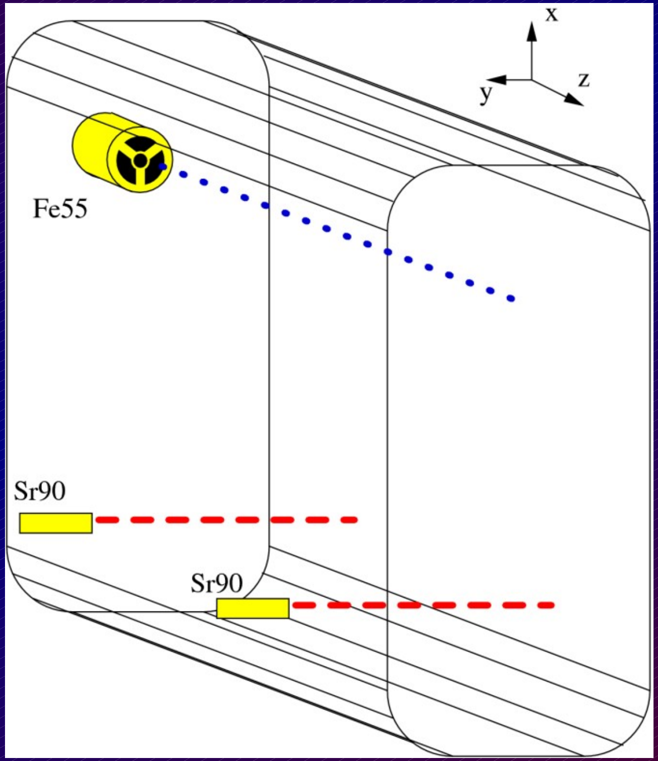


Gain Measurement

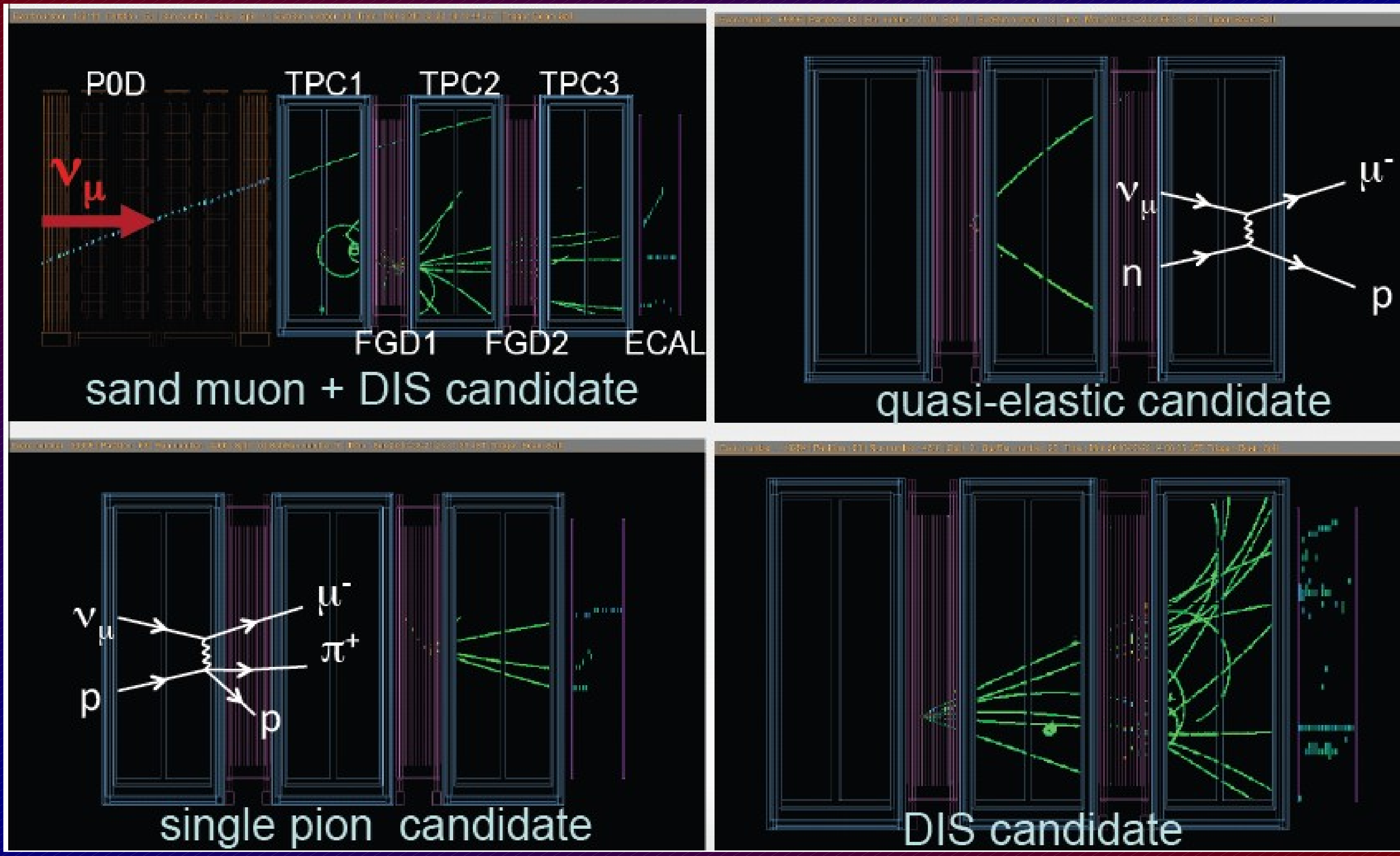
^{55}Fe-source: produces fixed number of primary electrons
→ measure charge on micromegas

Drift Velocity

2 x ^{90}Sr-sources: produce tracks at fixed distance
→ measure time difference

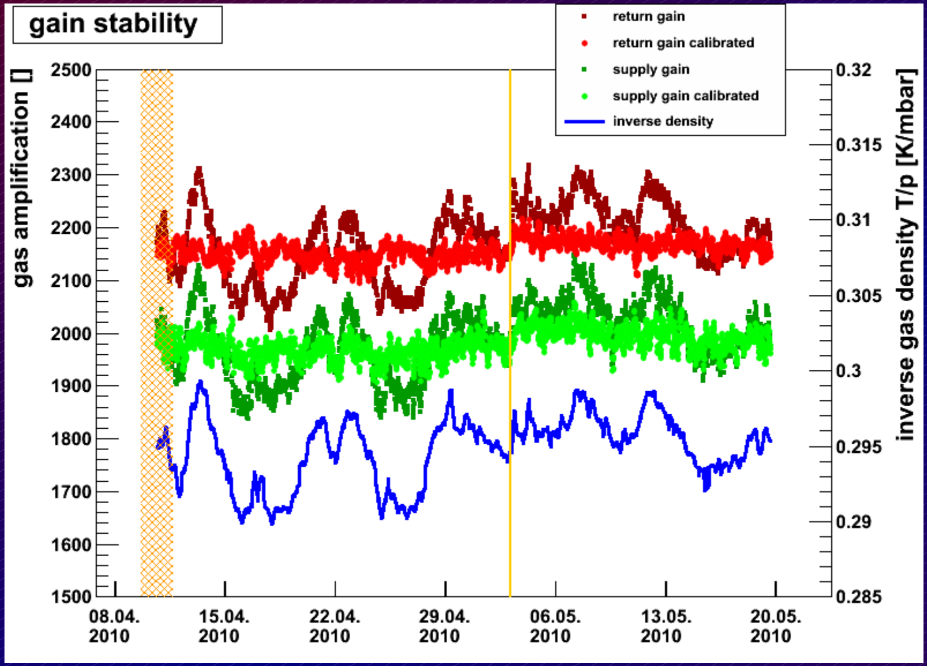


ND280 Event Galery

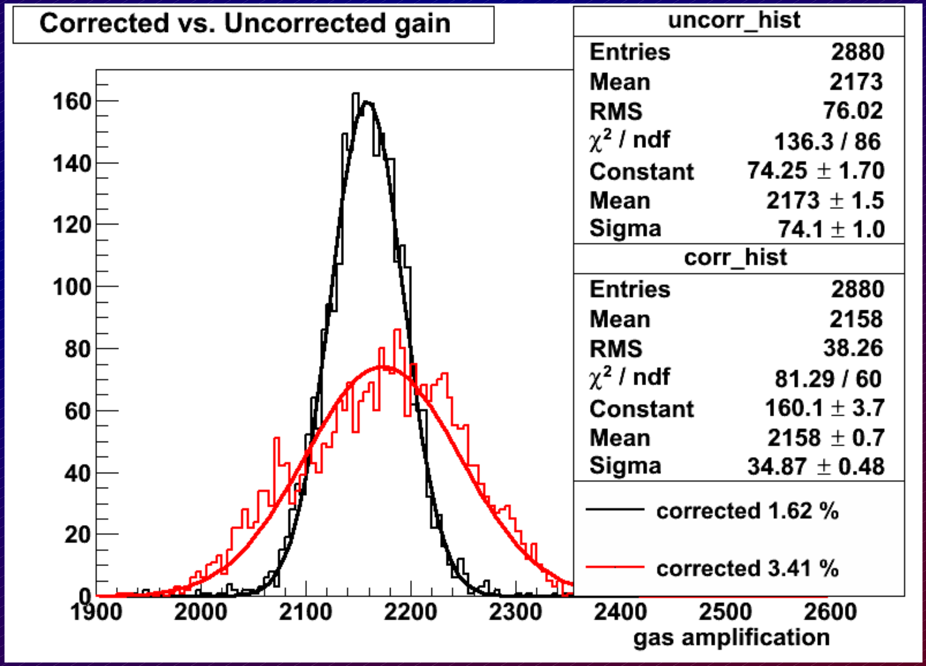


RWTH Aachen: TPC Monitor Chambers

Gain Monitoring



Gain Correction



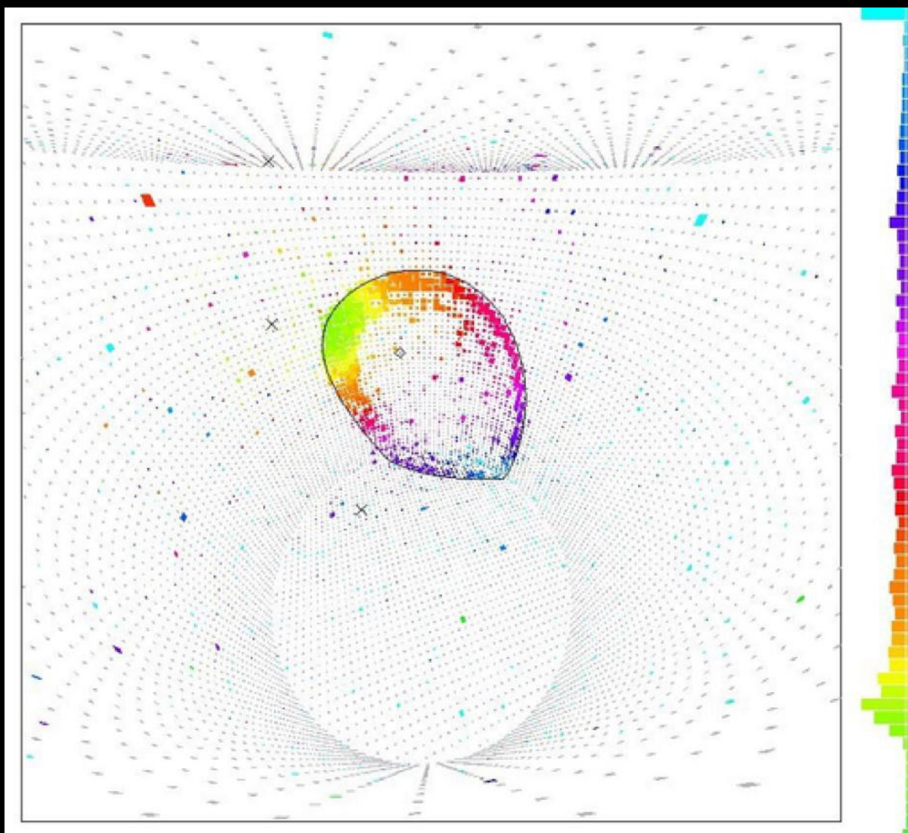
RWTH Aachen: Magnet Moving System

opening/closing of 600t UA1 magnet yokes
design+production+installation of rail system
adaptation of HERA-B guide rollers to carriage
Re-use of HERA hydraulic movers

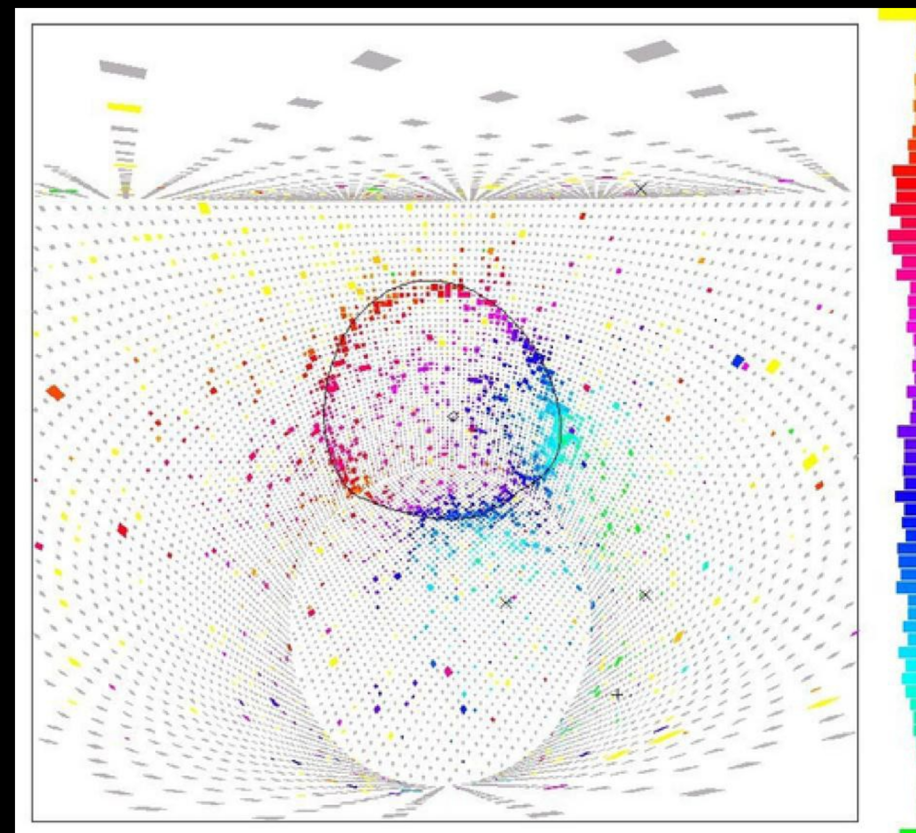
Super-K

50 kt water Čerenkov detector

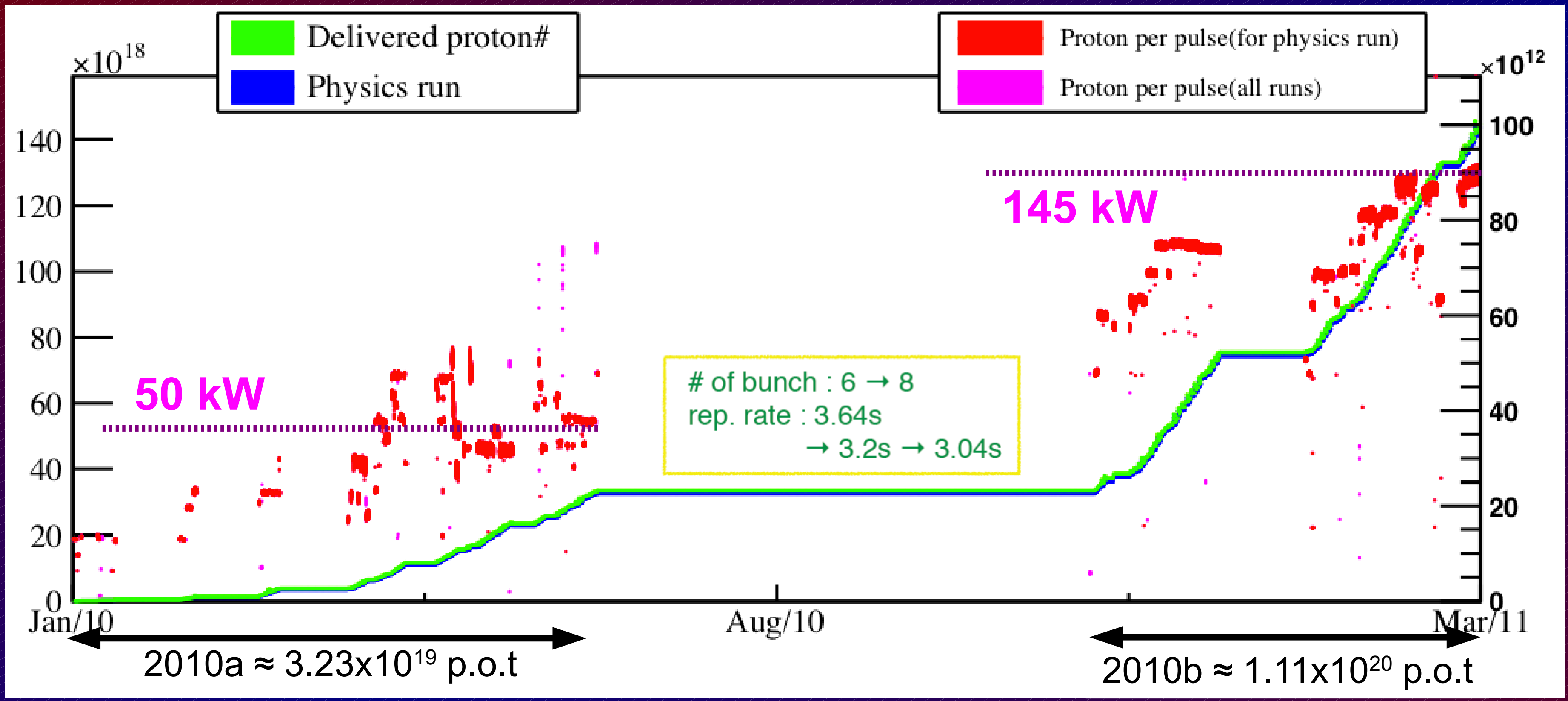
muon-event



electron-event



T2K: Running



Very successfull startup & running

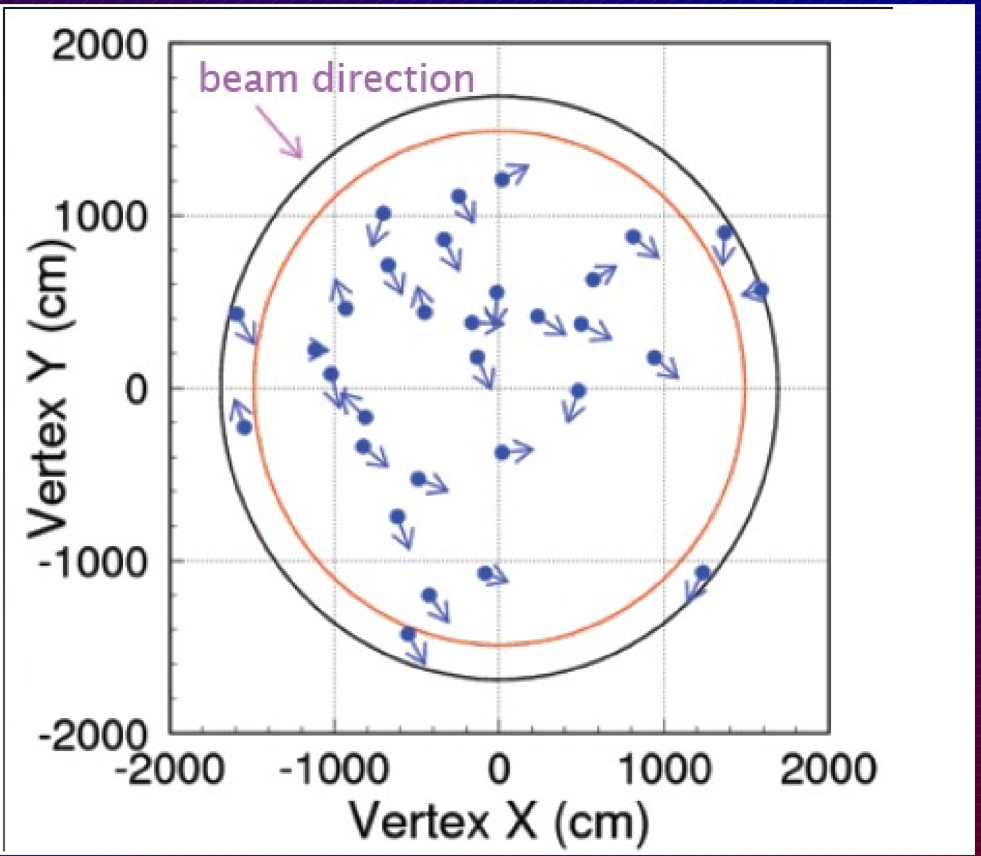
Run 2010b terminated by earth quake

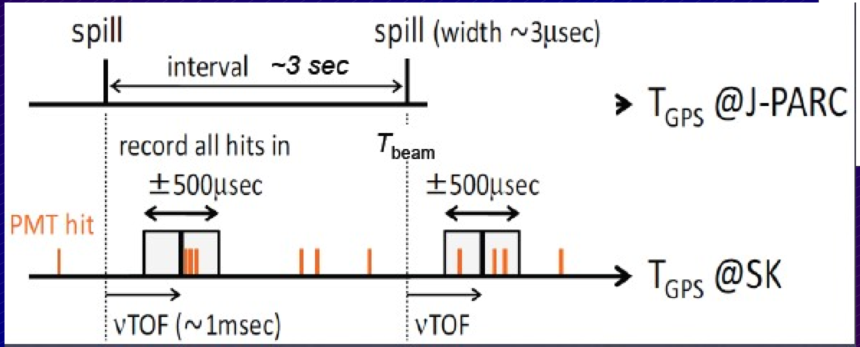
ν_μ: Preliminary results 2010a

ν_e: Results 2010a + 2010b

T2K: Timing

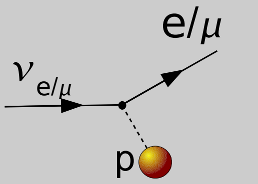
- Baseline measurement (Survey)
  - $L = 295{,}335 \pm 7$ m
    → ToF of $\nu = 985.132 \pm 0.02$ μsec ($\equiv \nu$TOF)
  - Expected event timing @ SK ($\equiv T_{SK}$)
    = Spill timing @ Tokai ($\equiv T_{beam}$) + νTOF.
- DAQ synchronization
  - SK signals in ±500μs timing window are recorded as "T2K beam events".
  - Stability of GPS is checked by comparing 2 GPS hardware and atomic clock.
    → Require |GPS1-GPS2| < 200nsec



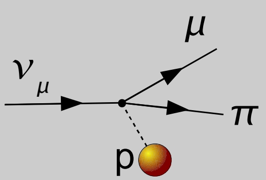


Event Selection

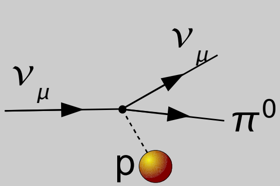
CCQE
(signal)



CC1π
(bgd)



NC1π
(bgd)

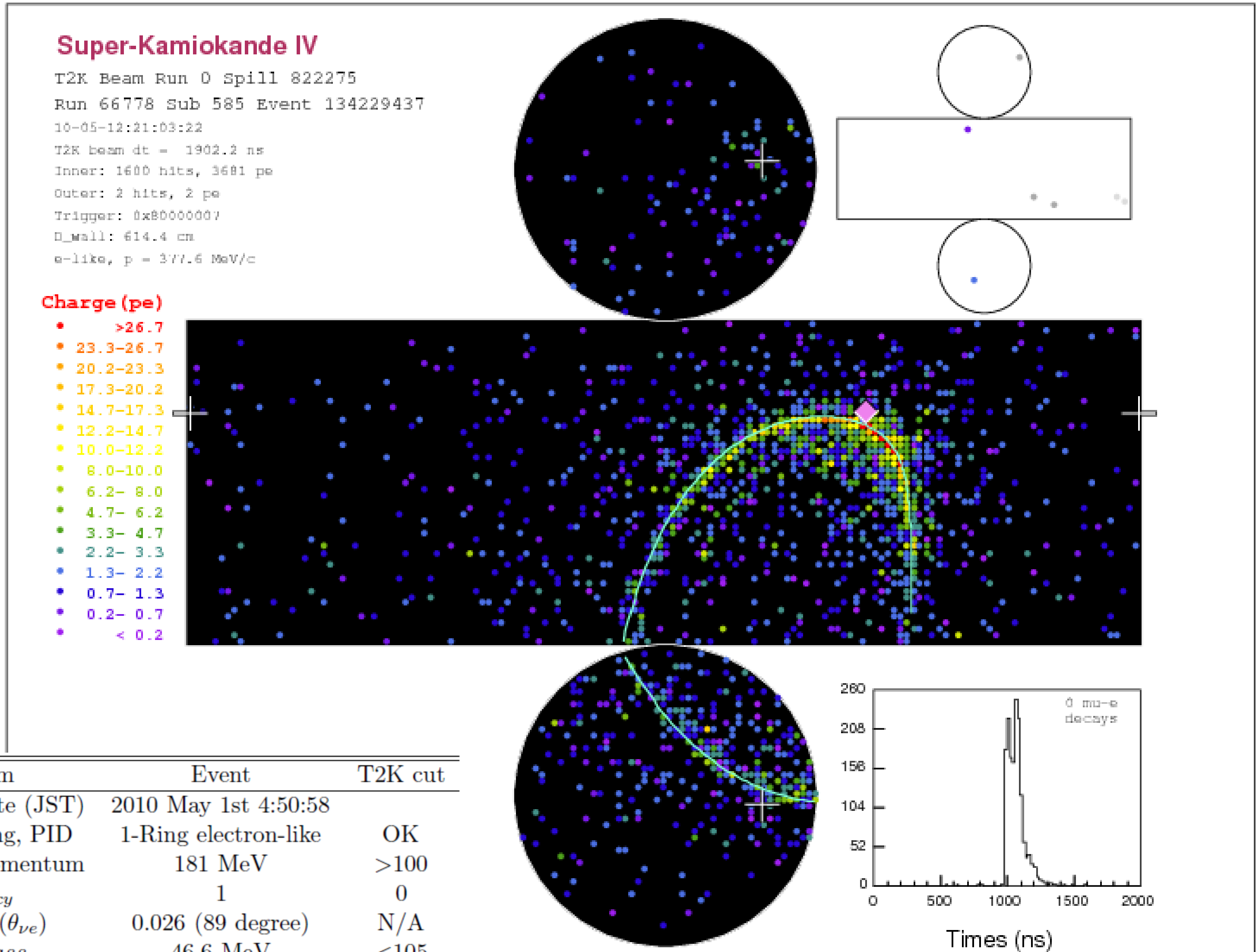


ν_μ-disappearance	ν_e-appearance
fully contained in fiducial volume	
E_{vis} > 30 MeV	E_{vis} > 100 MeV
number of rings = 1	
μ-like	e-like
	no-decay electron
	π^0 hypothesis < 105 MeV
p_μ > 200 MeV	E_ν < 1250 MeV

blind analysis
selection optimized on Monte Carlo

ü e-appearance

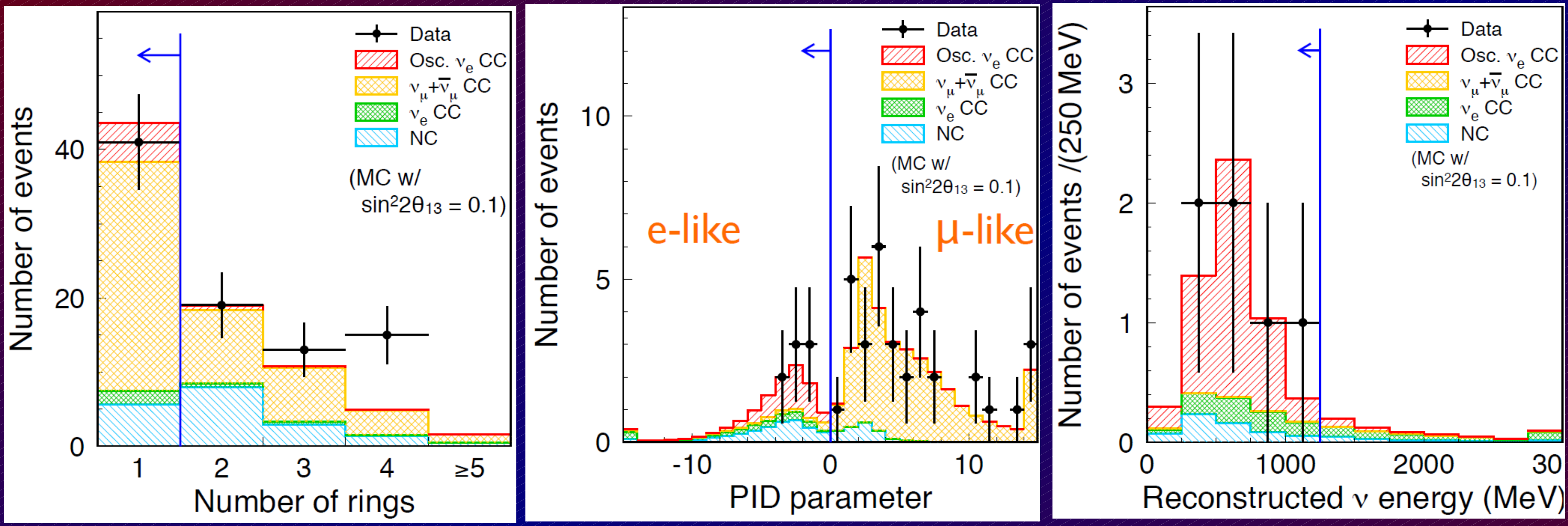
first event observed



Item	Event	T2K cut
Date (JST)	2010 May 1st 4:50:58	
Ring, PID	1-Ring electron-like	OK
Momentum	181 MeV	>100
N_{dcy}	1	0
$\cos(\theta_{\nu e})$	0.026 (89 degree)	N/A
$Mass$	46.6 MeV	<105
E_{rec}	257 MeV	<1250

Event Selection

examples from ν_e-appearance



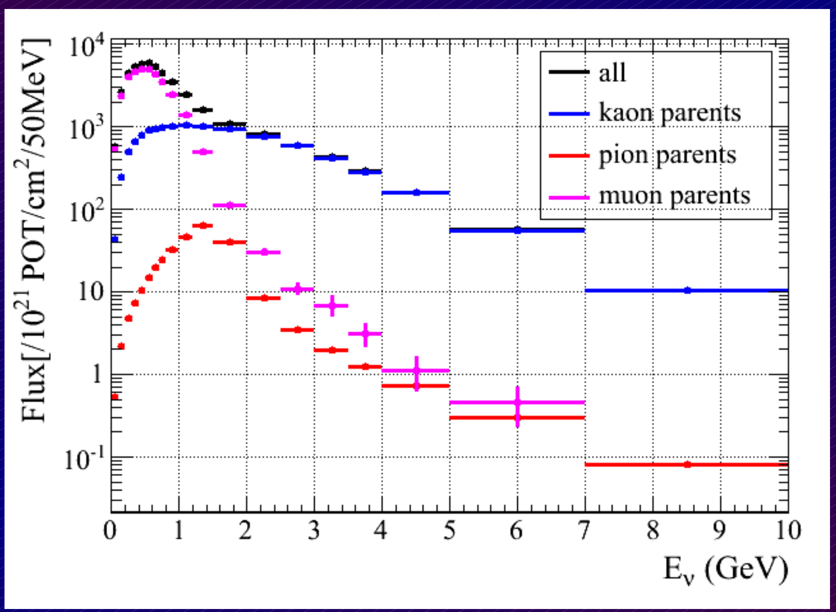
6 candidate events remain after all cuts !!

(N^{exp} = 1.5 ± 0.3 at $\sin^2 2\theta_{13}$=0)

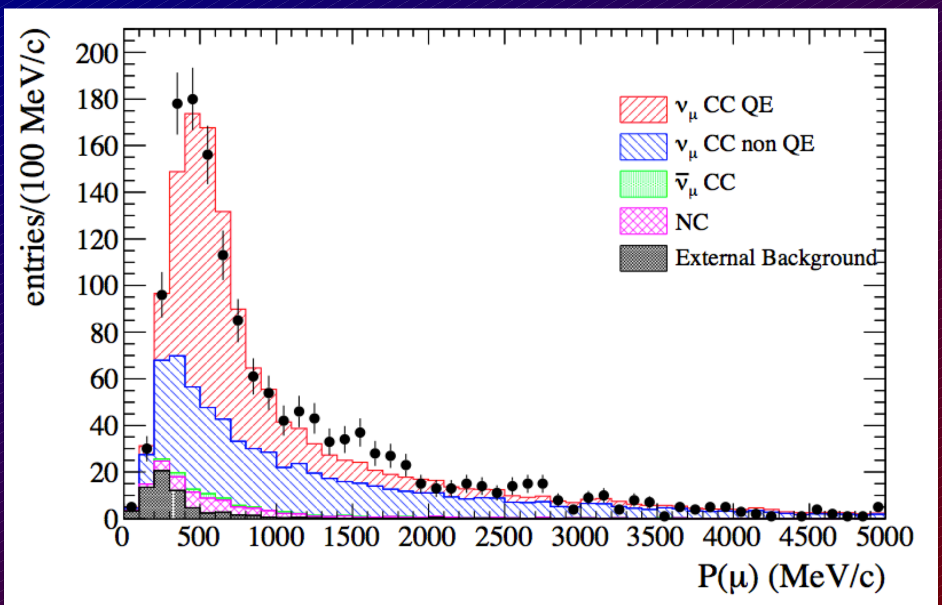
Flux Prediction

$$N_{SK}^{exp} = R_{ND}^{\mu,\,Data} \times \frac{N_{SK}^{MC}}{R_{ND}^{\mu,\,MC}}$$

- Protons-on-target: Beam Intensity Measurement
- ν-flux at source: Neutrino Beam MC
- verification: ND280 Measurement
- ν-flux at Super-K: Oscillations (globes)
- Neutrino Interactions: ν-cross sections
- Super-K response: Detector Simulation



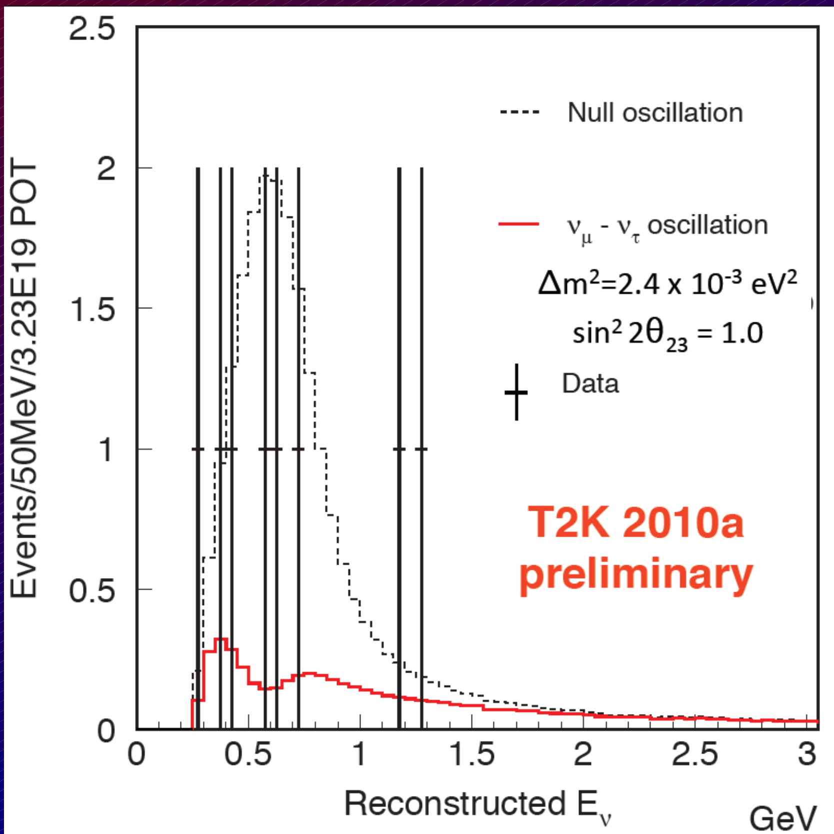
ν_e-flux at Super-K

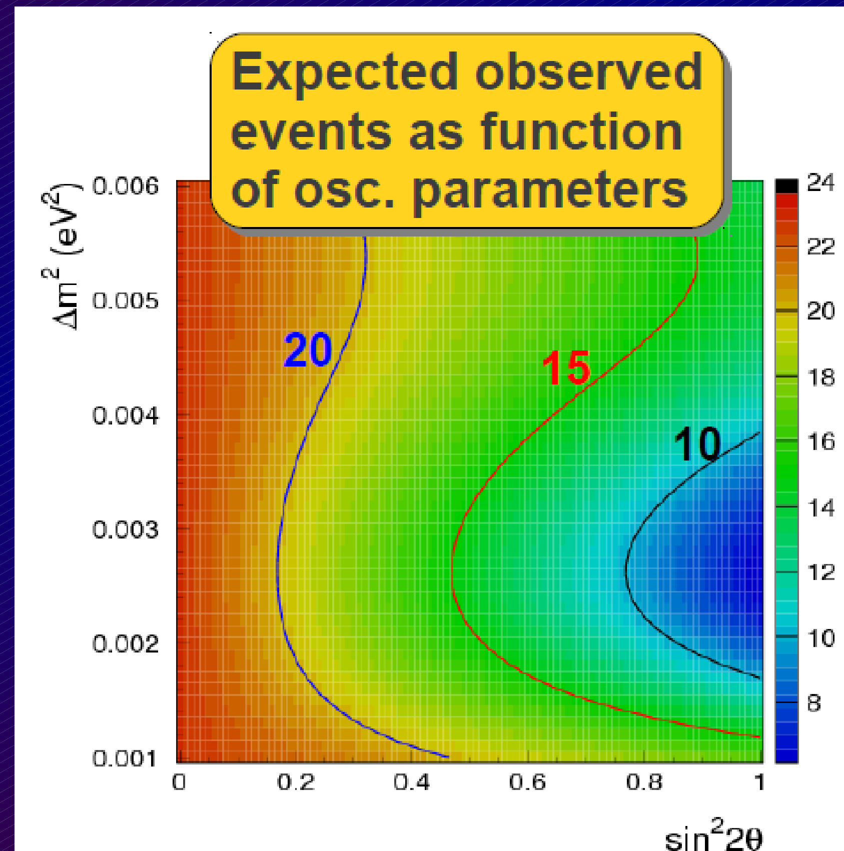


ν_μ-measurement with ND280

ü ü -disappearance

single-ring μ-like: 8 events observed





consistent with previous experiments (max. mixing)

ü ü -disappearance

From ±500 μs window around beam spills	Data	MC: No oscillation	MC: Oscillation $\Delta m^2 = 2.4 \times 10^{-3}$ (eV^2) $\sin^2 2\theta_{23} = 1.0$	BG (12μs window)
Fully-Contained	33	54.5	24.6	0.0094
Fiducial Volume, $E_{vis} > 30MeV$	23	36.8	16.7	0.0011
Single-ring μ-like (P_μ>200MeV/c)	8 (8)	24.6 (24.5 ±3.9)	7.2 (7.1 ±1.3)	-
Single-ring e-like (P_e>100MeV/c)	2 (2)	1.9 (1.5 ±0.7)	1.5 (1.3 ±0.6)	-
Multi-ring	13	10.2	8.0	-

clear evidence for ν_μ disappearance

consistent with maximal mixing

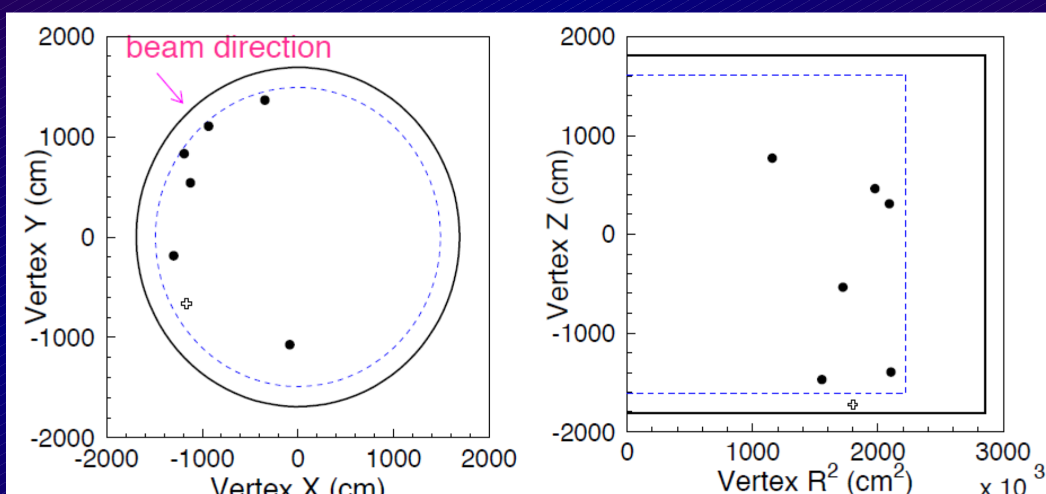
ü e-appearance

Summary of systematic uncertainties on $N^{exp}_{SK\ total.}$ for $\sin^2 2\theta_{13}$=0 and 0.1

Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) Beam flux	$\pm 8.5\%$	$\pm 8.5\%$
(2) ν int. cross section	$\pm 14.0\%$	$\pm 10.5\%$
(3) Near detector	$^{+5.6}_{-5.2}\%$	$^{+5.6}_{-5.2}\%$
(4) Far detector	$\pm 14.7\%$	$\pm 9.4\%$
(5) Near det. statistics	$\pm 2.7\%$	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$	$^{+17.6}_{-17.5}\%$

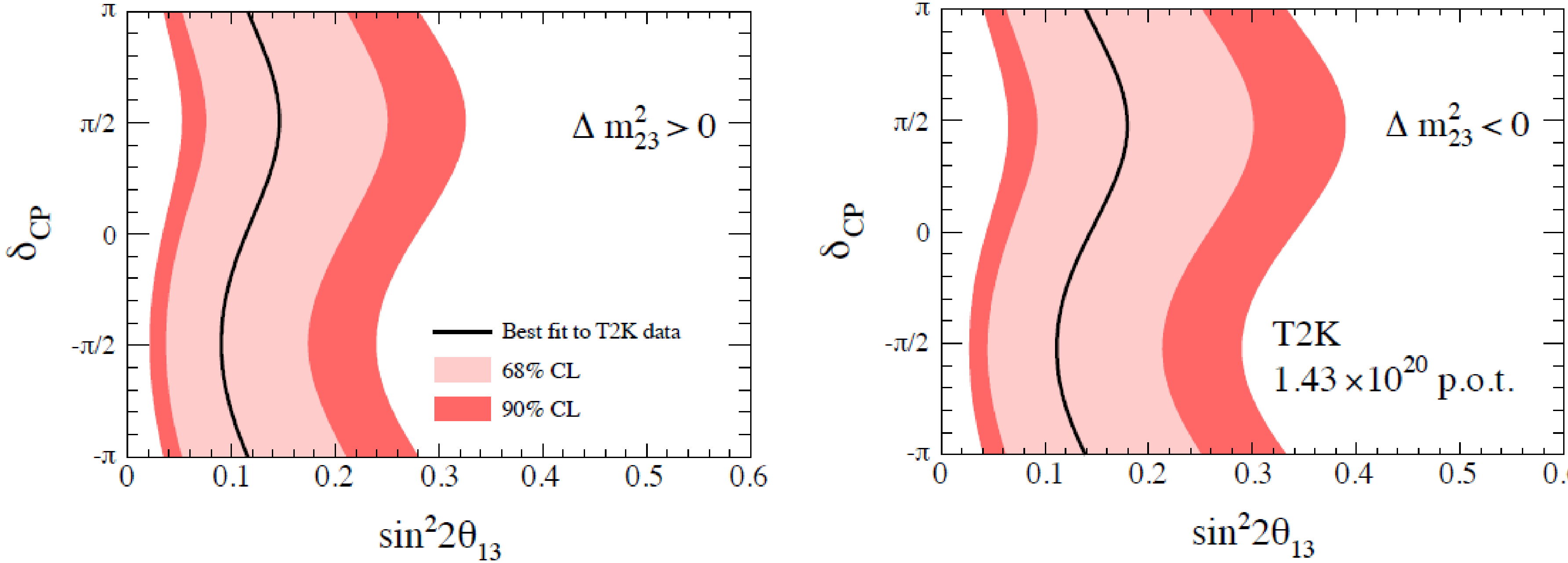
cf.
$\sin^2 2\theta_{13}$=0:
#sig = 0.1 #bkg = 1.4

$\sin^2 2\theta_{13}$=0.1:
#sig = 4.1 #bkg = 1.3



ü e-appearance

(assuming Δm^2_{23}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1)



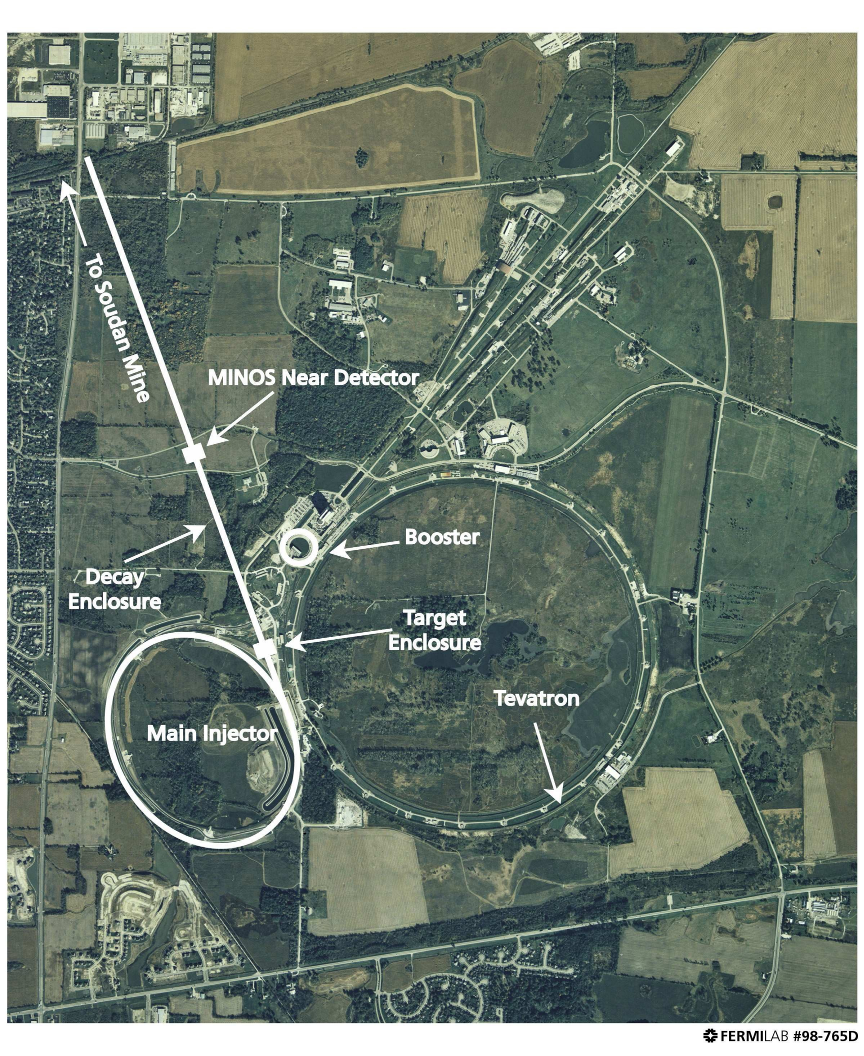
90% C.L. interval & Best fit point (assuming Δm^2_{23}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1, δ_{CP}=0)

$0.03 < \sin^2 2\theta_{13} < 0.28$ — **$0.04 < \sin^2 2\theta_{13} < 0.34$**

$\sin^2 2\theta_{13} = 0.11$ — **$\sin^2 2\theta_{13} = 0.14$**

MINOS

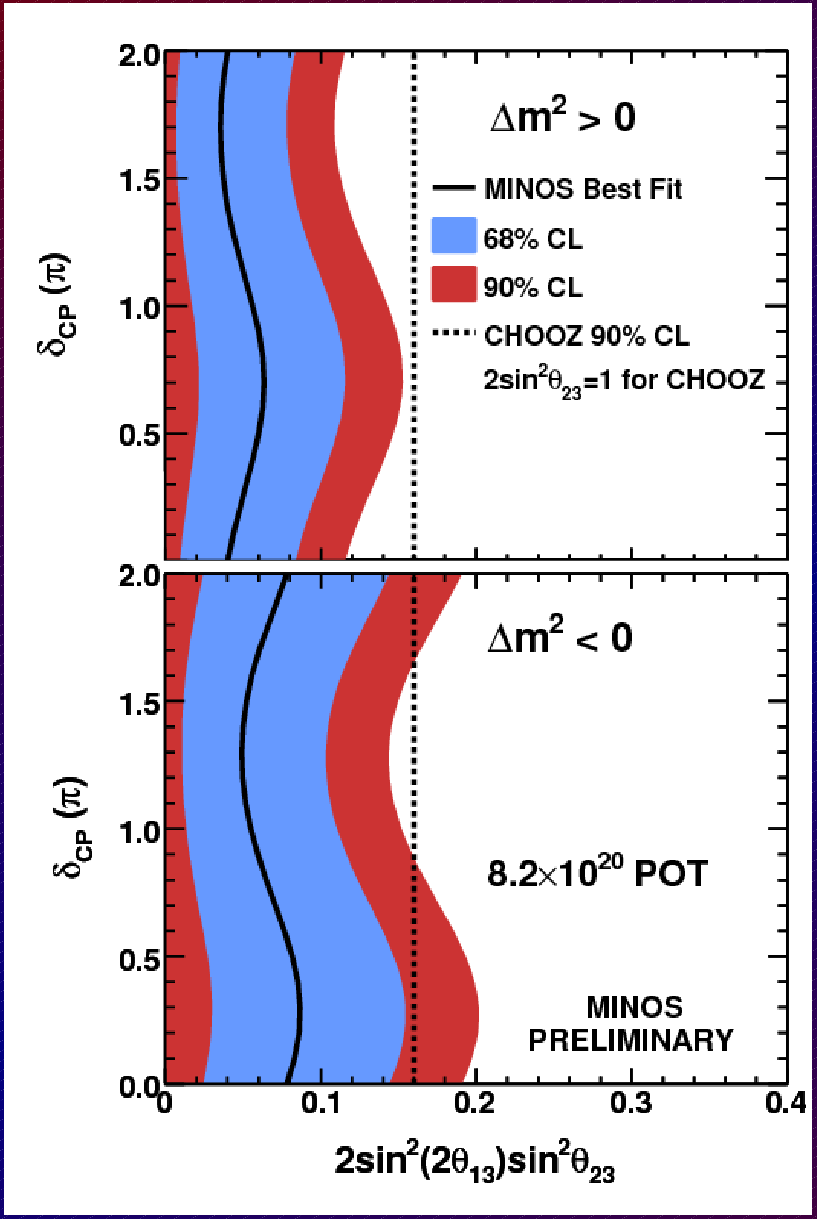
TASD: Totally Active Scintillator Detector

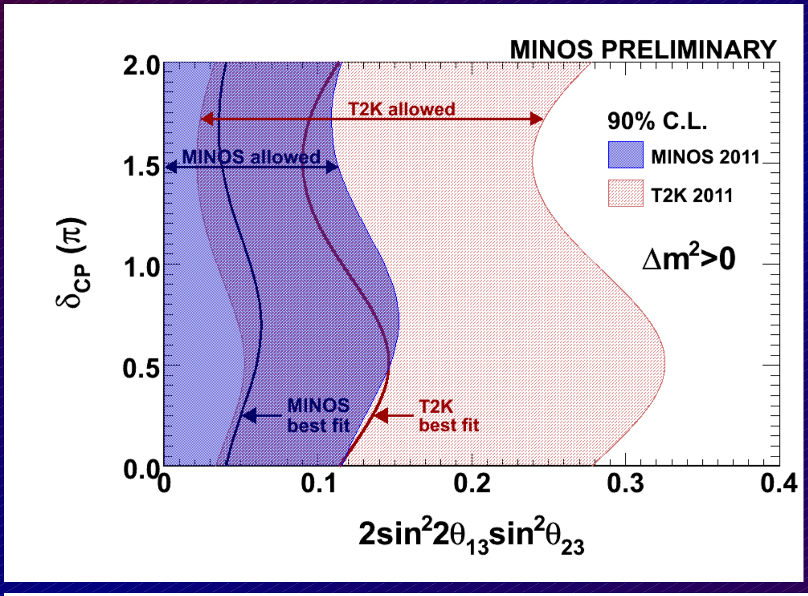


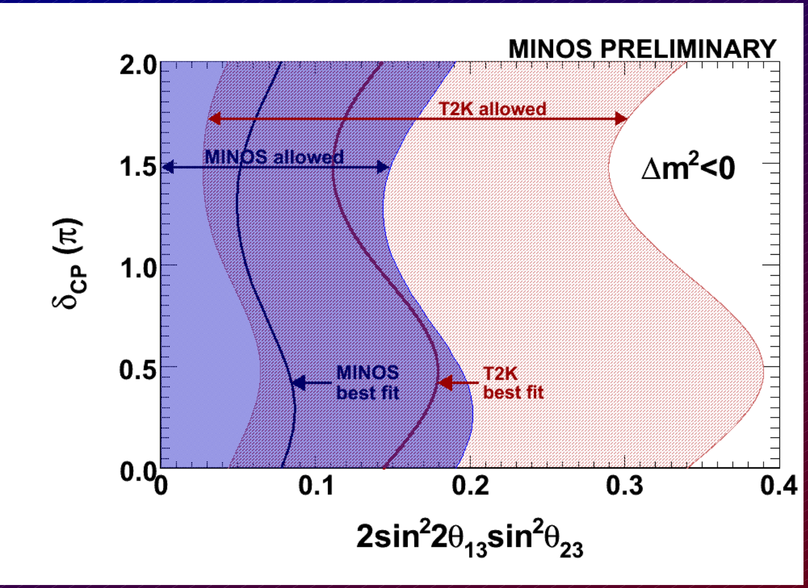
NuMI-Beam: Nu from Main Injector

Result: MINOS + T2K

MINOS





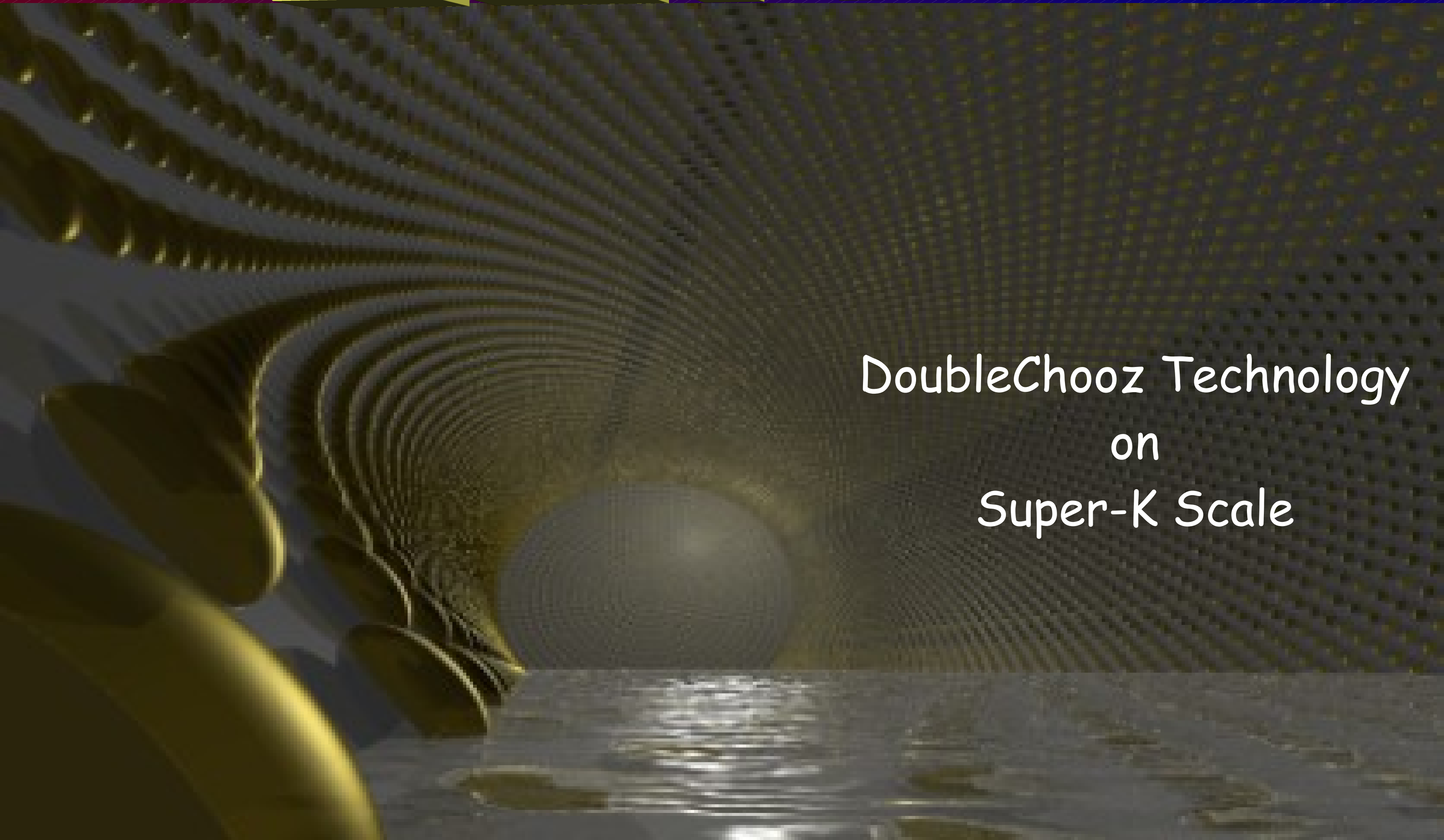


θ_{13} = 0 excluded with

MINOS: 89% probability

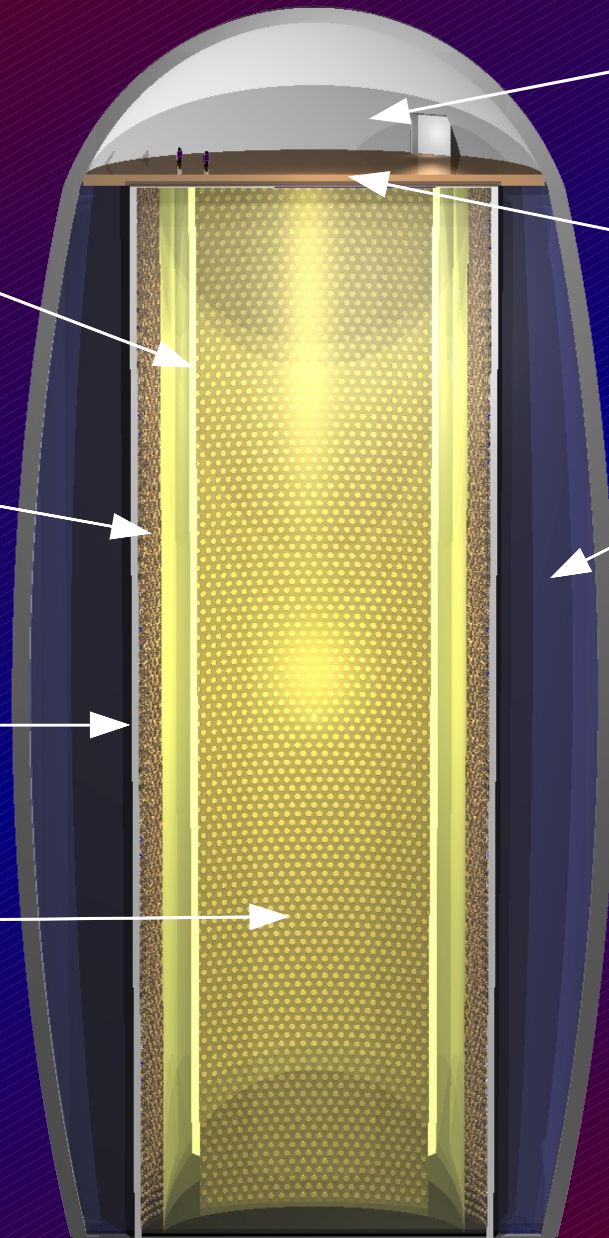
T2K: 99% probability

LENA



DoubleChooz Technology
on
Super-K Scale

LENA: Detector



Liquid Scintillator
ca. 50kt LAB

Inner Nylon Vessel
radius: 13m

Buffer Region
inactive, Δ r = 2m
ca. 20kt LAB

Steel Tank
r = 15m, h = 100m

50,000 8"-PMTs
Winston cones
optical coverage: 30%

Electronics Hall
dome of 15m height

Top Muon Veto
scintillator panels/RPCs
vertical muon tracking

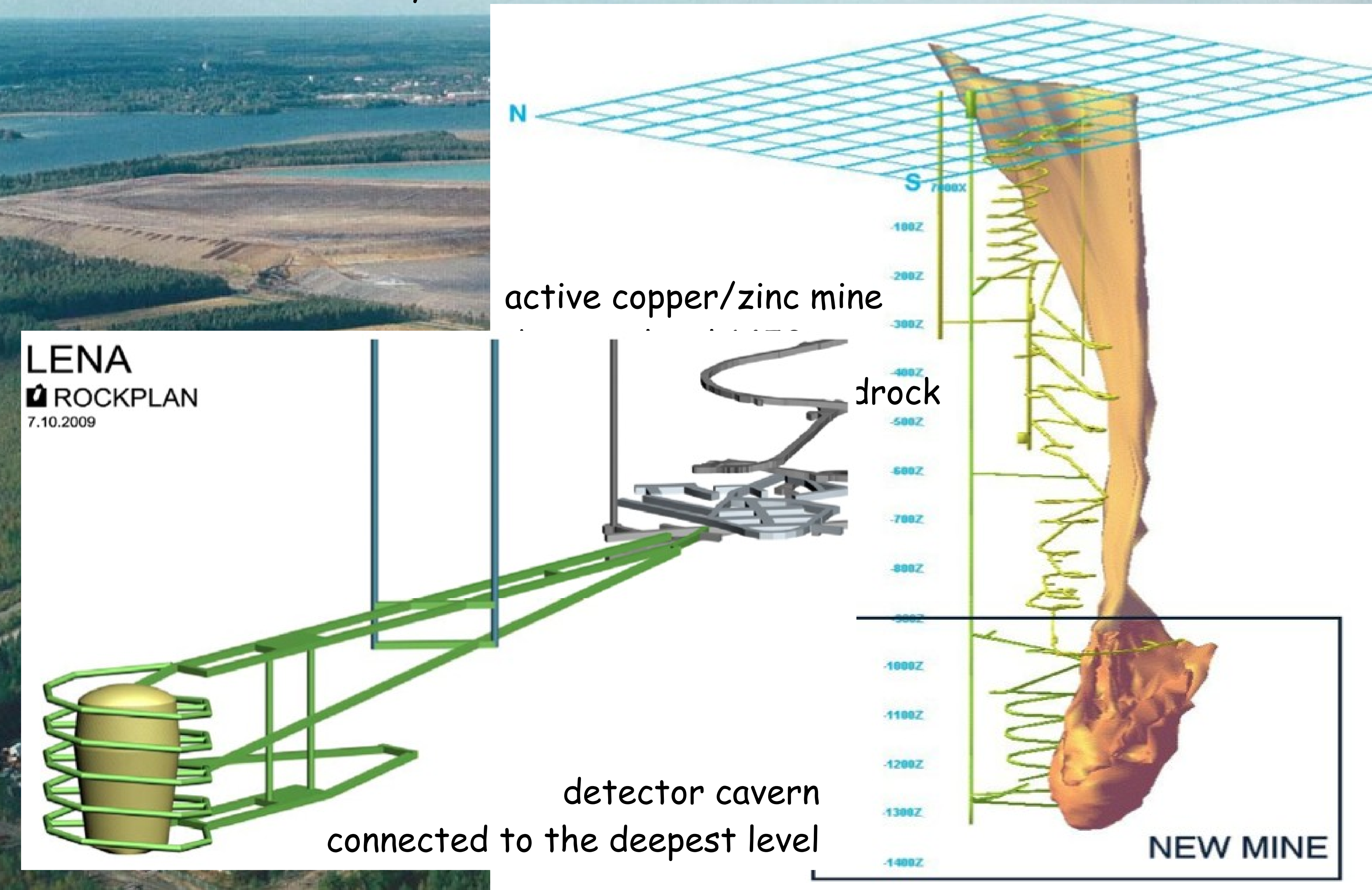
Water Cherenkov Veto
3000 PMTs, Δ r > 2m
fast neutron shield
inclined muons

Egg-Shaped Cavern
about 105 m3

Rock Overburden
at least 4000 mwe

LENA: Location

Phyäsalmi Mine – Central Finland



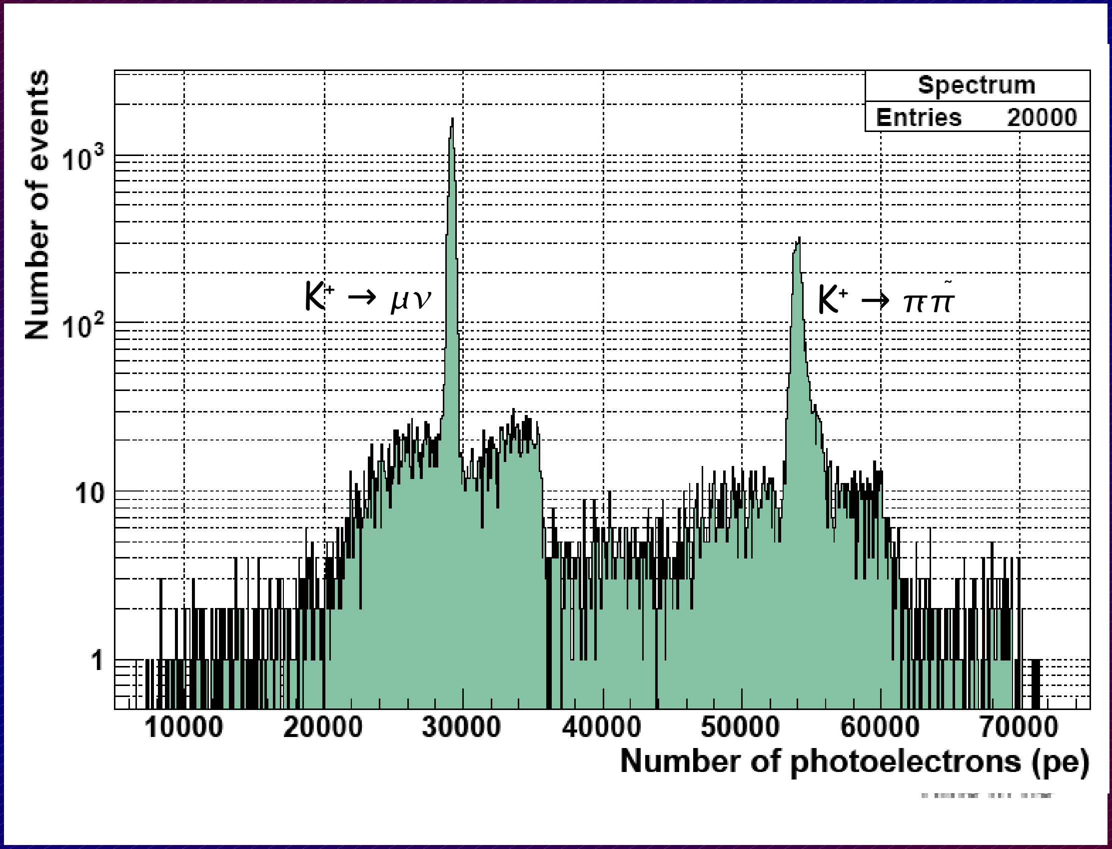
Physics Summary

- Proton Decay
- Galactic Supernova Burst
- Diffuse Supernova Neutrino Background
- Long baseline neutrino oscillations
- Solar Neutrinos
- Geo neutrinos
- Atmospheric neutrinos
- Dark Matter indirect search
- Neutrino oscillometry

Physics: Proton Decay

$p^+ \rightarrow e^+ \pi^0 \approx 10^{33}$ years (current limit: 5.4 10^{33} y)

$p^+ \rightarrow K^+ \nu$ 5 10^{34} years (current limit: 2.3 10^{33} y)



$p^+ \rightarrow K^+ \nu$

1. K-signal
2. delayed coincidence

   $K \rightarrow \mu\nu$ (68%)

   $K \rightarrow 2\pi$ / 3π (31%)

T. Marrodan et al.,
Phys. Rev. D72, 075014 (2005)

Physics: Super Nova Background

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

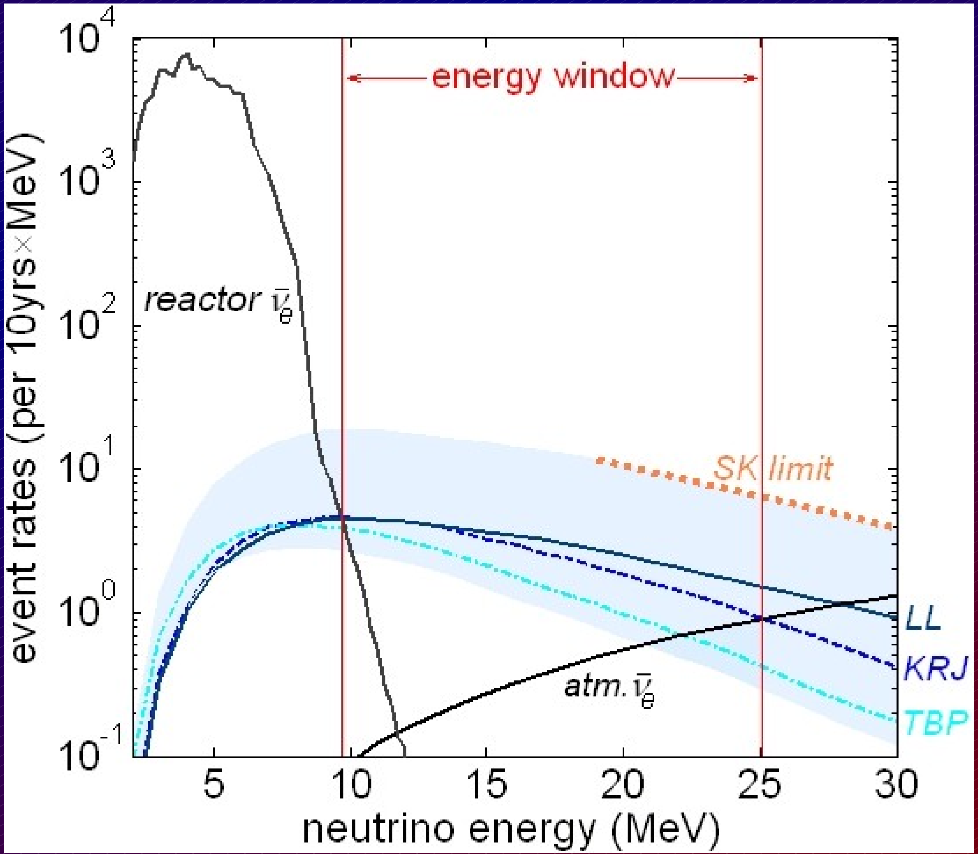
Excellent background rejection

Energy window 10 … 30 MeV

High efficiency (100% within 50kt)

Expect 2 … 20 events / year

(model dependent)



M. Wurm et al., Phys.Rev.D 75 (2007) 023007

Physics: Geo Neutrinos

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

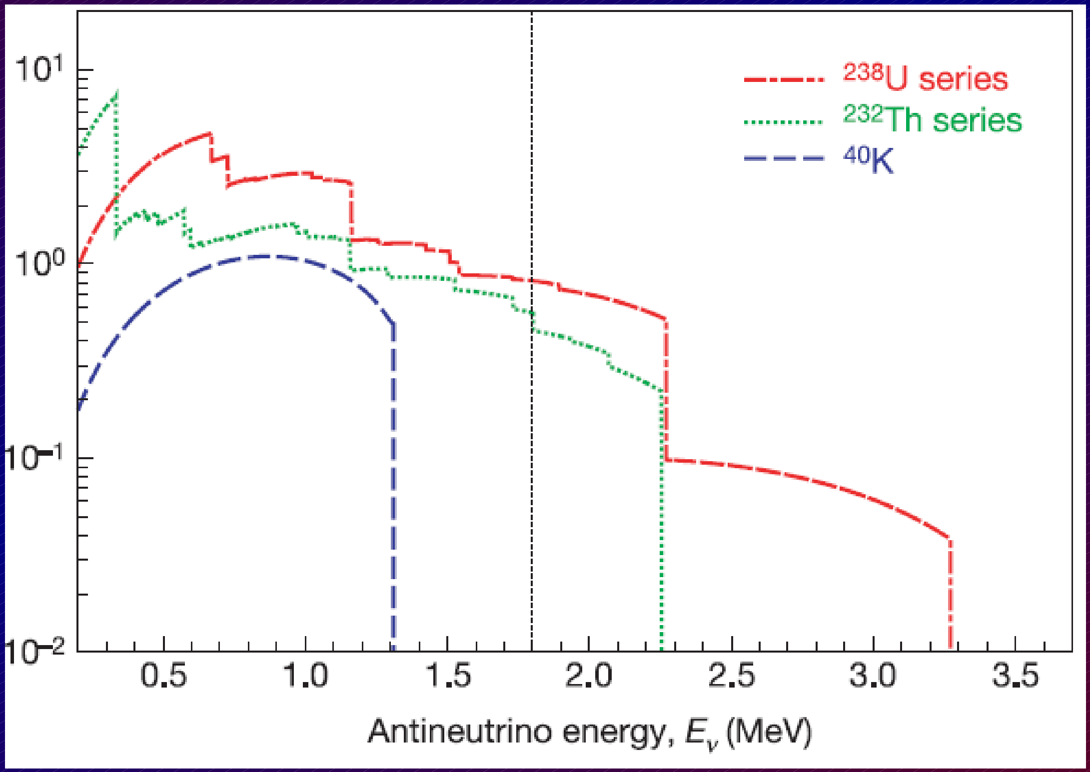
Low reactor flux

→ good signal/background

Expect ≈ 1500 events/year

Separation of U / Th

Test of geological models



K. Hochmuth et al., Astropart.Phys. 27 (2007) 21-29

CP-Violation

Bruno Pontecorvo 1957

production as **weak eigenstate** → propagation as **mass eigenstate** → detection as **weak eigenstate**

z.B. ν_e — ν_1, ν_2, ν_3 — ν_e disappearence, ν_μ appearence, ν_τ appearence

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

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\, e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

„atmospheric“ $\theta_{23} \approx 45°$ „reactor“ $\theta_{13} < 10°$ „solar“ $\theta_{12} < 32°$

Pontecorvo-Maki-Nakagawa-Sakata matrix

CP Violation

$P(\overline{\nu}_\mu \to \overline{\nu}_e) =$ numerically relevant terms only

$$4\, s_{13}^2\, c_{13}^2 \cdot s_{23}^2 \cdot \sin^2 \frac{\Delta m_{13}^2 L}{4E}$$ θ13

$$+\,8 \cdot c_{13}^2 \cdot s_{12} s_{13} s_{23} \cdot (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cdot \cos\frac{\Delta m_{23}^2 L}{4E} \cdot \sin\frac{\Delta m_{13}^2 L}{4E} \cdot \sin\frac{\Delta m_{12}^2 L}{4E}$$ CP-even

$$\mp\,8 \cdot c_{13}^2 \cdot c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\frac{\Delta m_{23}^2 L}{4E} \cdot \sin\frac{\Delta m_{13}^2 L}{4E} \cdot \sin\frac{\Delta m_{12}^2 L}{4E}$$ CP-odd

$$+\,4\, s_{12}^2\, c_{13}^2 \cdot (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2 c_{12} c_{23} s_{12} s_{13} s_{23} \cos\delta) \cdot \sin\frac{\Delta m_{12}^2 L}{4E}$$ solare Skala

$$\mp\,8 \cdot c_{13}^2 \cdot s_{13}^2 \cdot s_{23}^2 \cdot \cos\frac{\Delta m_{23}^2 L}{4E} \cdot \sin\frac{\Delta m_{13}^2 L}{4E} \cdot \frac{a \cdot L}{4E} (1 - 2 s_{13}^2)$$ Materie-Effekt (CP-odd)

CP violation is a genuine 3-flavour effect

Jarlskog's determinant

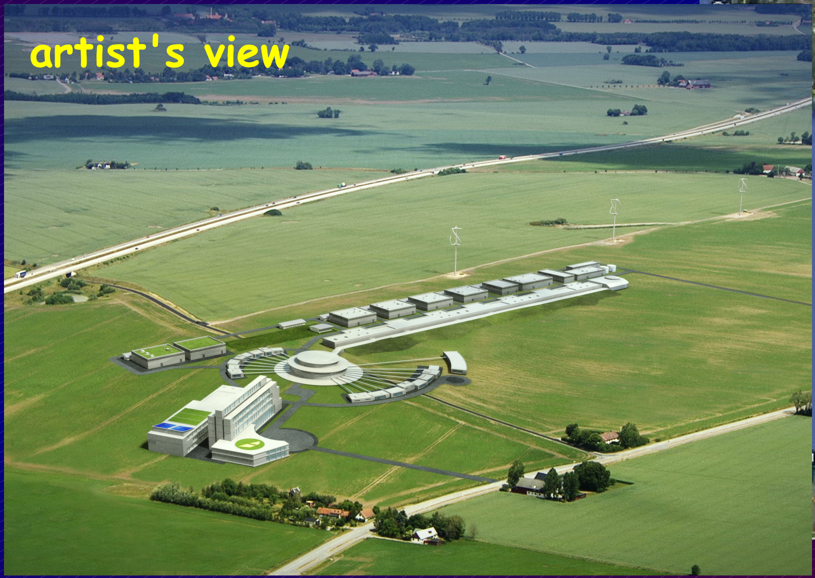
Quarks: 4 10^{-5} Neutrinos: 0.028 sinδ

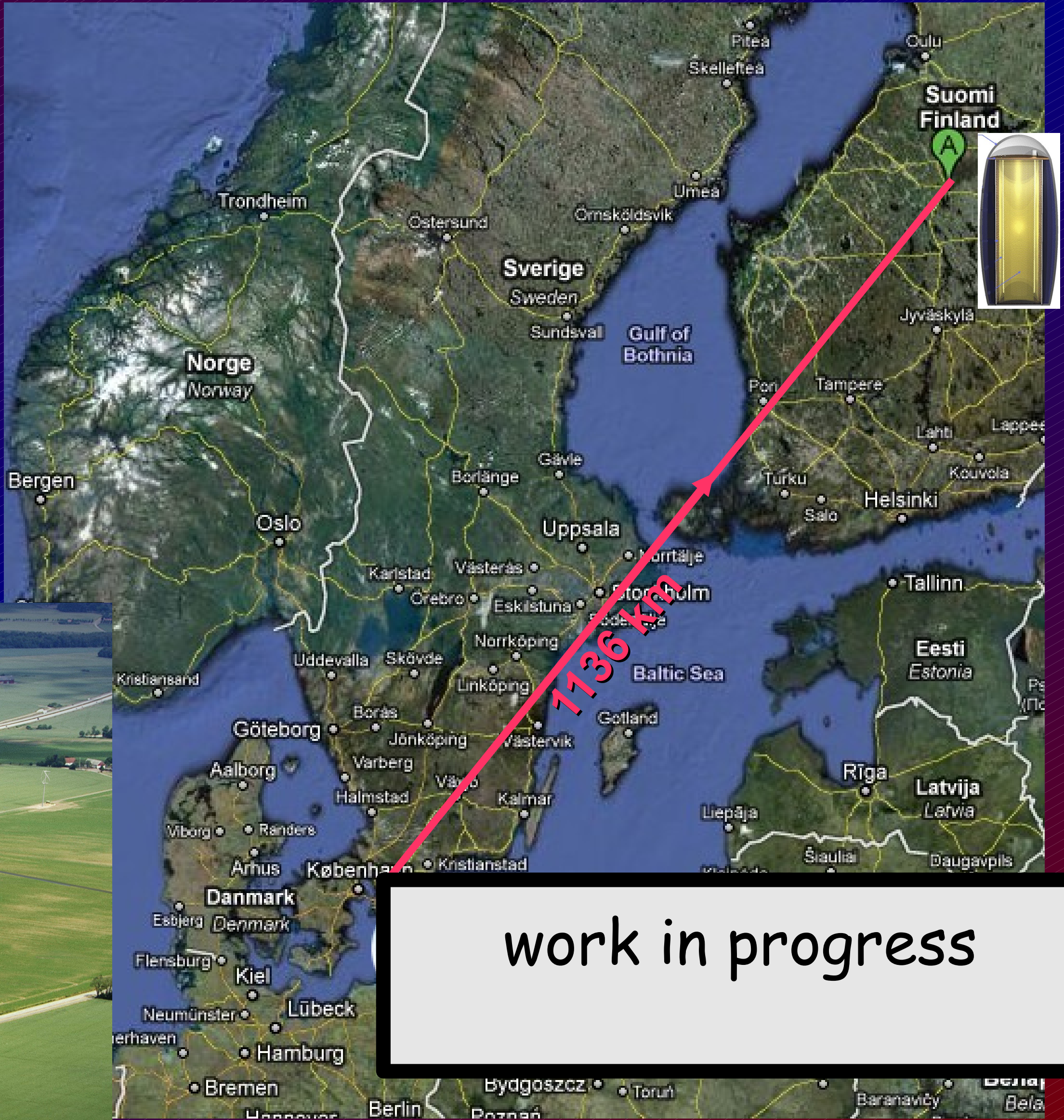
Conventional Neutrino Beam

European Spalation Source
  10 MW p^+ Linac (1.3 GeV)

Increase Energy
  FFAG x3 … 5

Neutrino Target





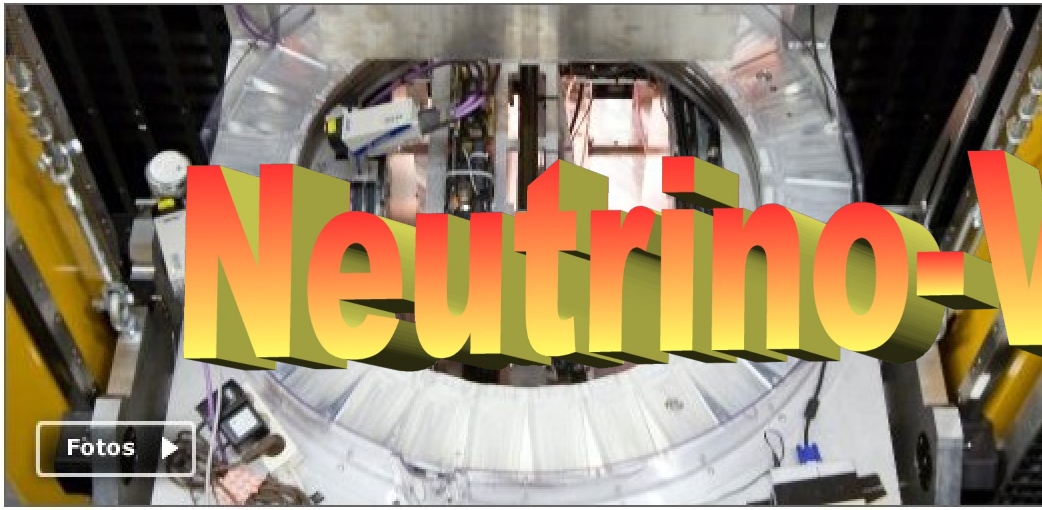
work in progress

Neutrino-Velocity

23.09.2011 Drucken | Senden | Feedback | Merken

Neutrinos schneller als das Licht

Physiker rätseln über rasende Teilchen



Neutrinos schneller als Licht?

Einstein muss zittern

Eine Konstante für die Ewigkeit: die Lichtgeschwindigkeit. Einsteins Relativitätstheorie baut darauf, unser ganzes Weltbild sogar. Physiker h gemessen und festgestellt: Es geht auch schneller - mit Neutrinos. Eine Anomalie?

Von MANFRED LINDINGER

Artikel | Bilder | Lesermeinungen (15)

Die Nachricht kam in der Nacht von Donnerstag auf Freitag in die Welt und schlug ein wie eine Bombe. Eine europäische Forschergruppe habe im italienischen Untergrundlabor Gran Sasso in der Nähe von Rom gemessen

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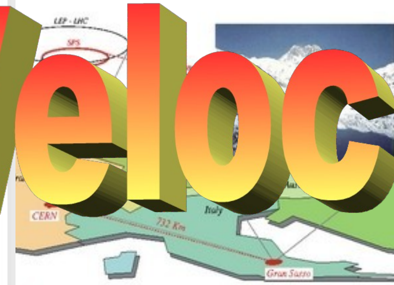
Gefällt mir 123

September 2011 Physik

eutrinos: Schneller als das Licht?

n *Rainer Kayser*

rscher rütteln an einem der wichtigsten Grundpfeiler der Physik



utrinos reisen von einem Teilchen beschleuniger n Cern zu einem Detektor unter dem Gran sso-Massiv in Italien

Cern

Genf (Schweiz) - Ein internationales ...team behauptet, dass Neutrinos ...neller als das Licht bewegen. ...tigt, wäre das ...physikalische ...einem halben ...ssenschaftler haben ...subatomaren ...Beschleuniger am ...m Cern bei Genf zu einer Dete...age im Gran Sasso-Massiv in ...ienischen Abruzzen vermessen. Bewegungen schneller als das Licht sind nach Einsteins Relativitätstheorie verboten.

Ist also die Relativitätstheorie falsch und gerät die moderne Physik ins Wanken?

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NEUTRINOS

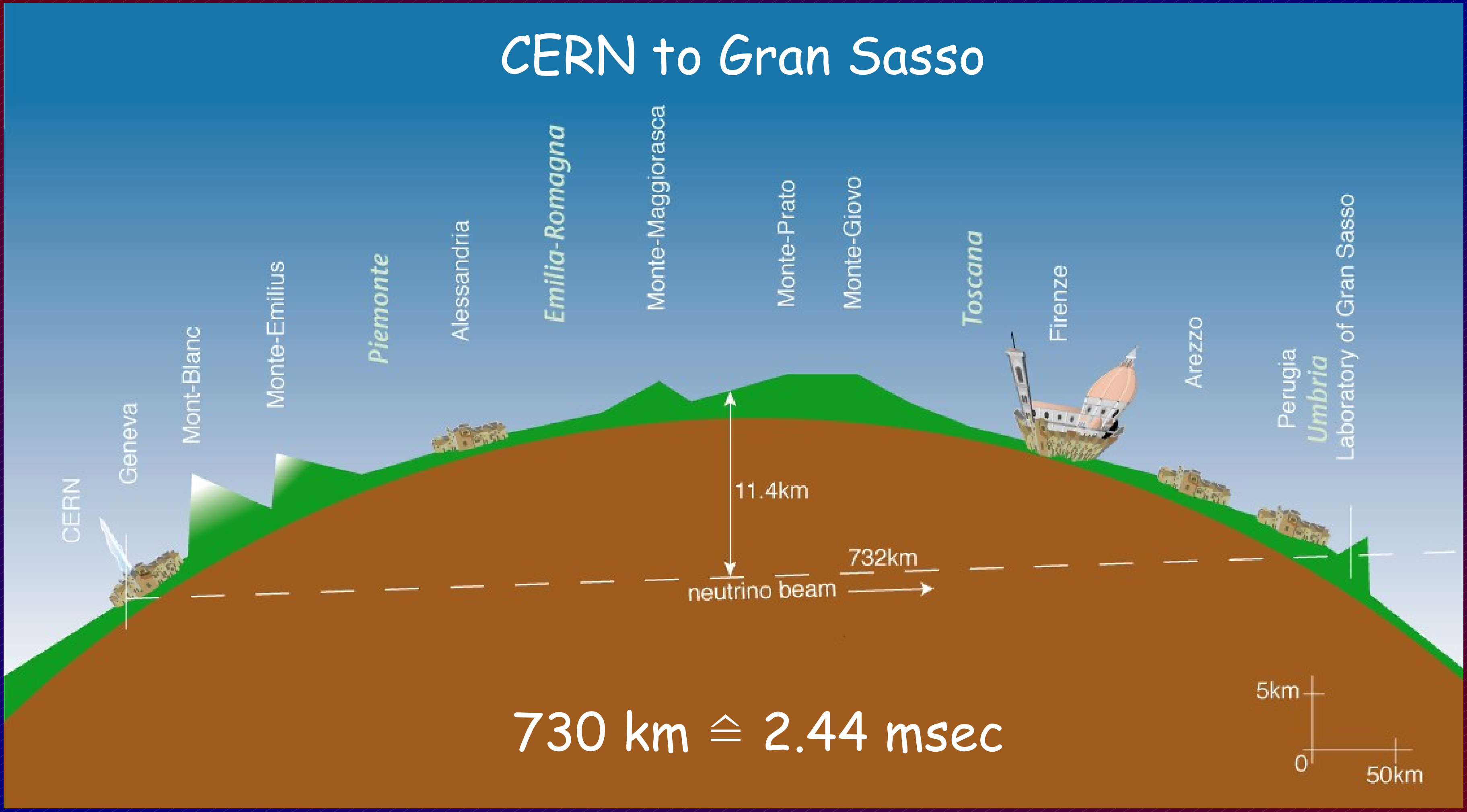
Schneller als das Licht?

Redaktion / Pressemitteilung der Universität Bern
astronews.com
23. September 2011

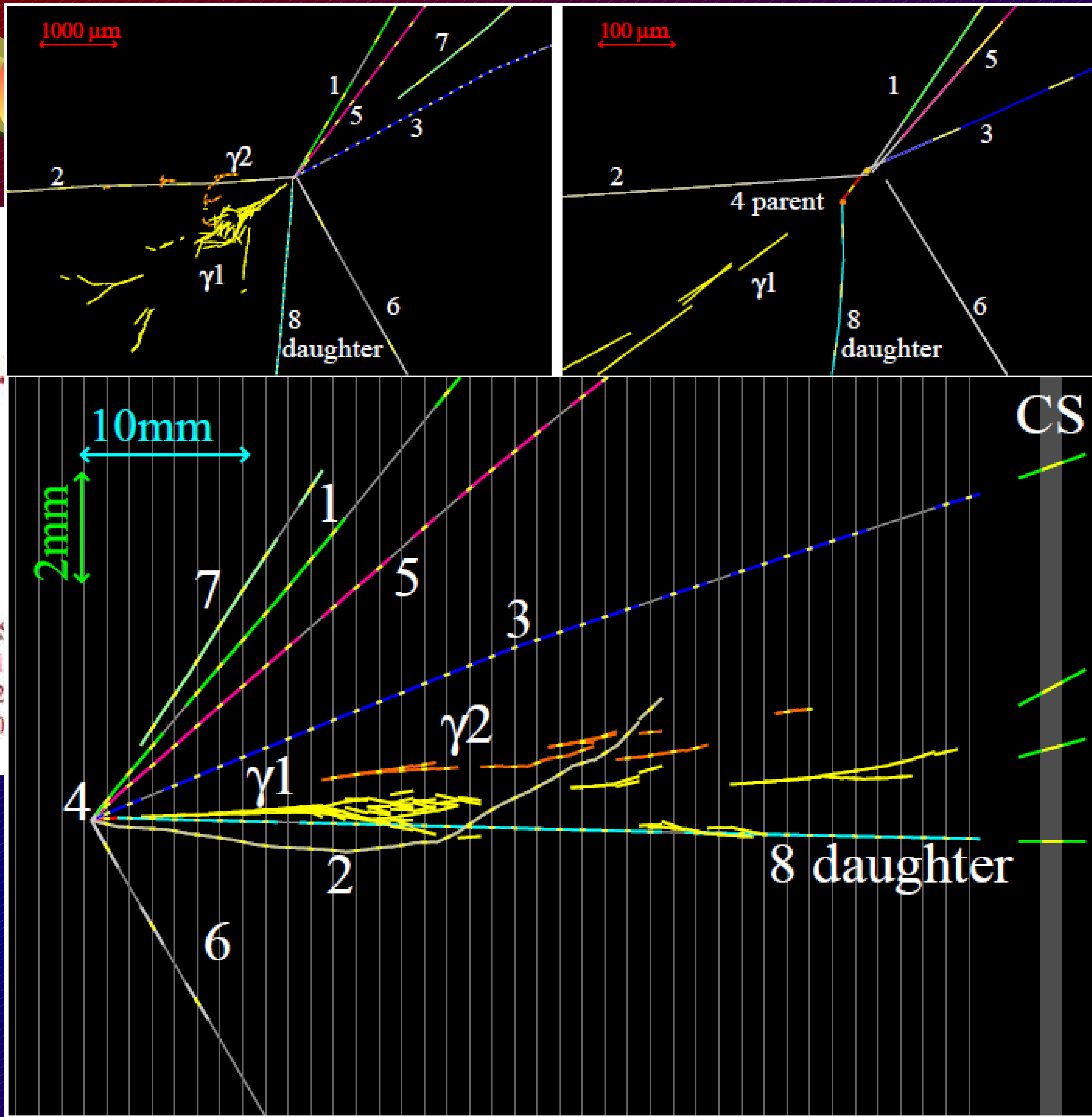
Am Genfer Teilchenlabor CERN wurden Hinweise darauf entdeckt, dass sich Neutrinos schneller bewegen können als das Licht: Die subatomaren Partikel legten eine 730 Kilometer lange Strecke 60 Nanosekunden schneller zurück, als es Licht möglich gewesen wäre. Nun suchen die Wissenschaftlern nach Fehlern bei ihren Messungen, da sich eigentlich nichts schneller bewegen sollte als das Licht.

"Dieses Resultat ist eine komplette Überraschung", urteilt Antonio Ereditato, Professor für Hochenergiephysik an der Universität Bern und Leiter des OPERA-Projekts. Die Verblüffung des

The CNGS Beam



Th

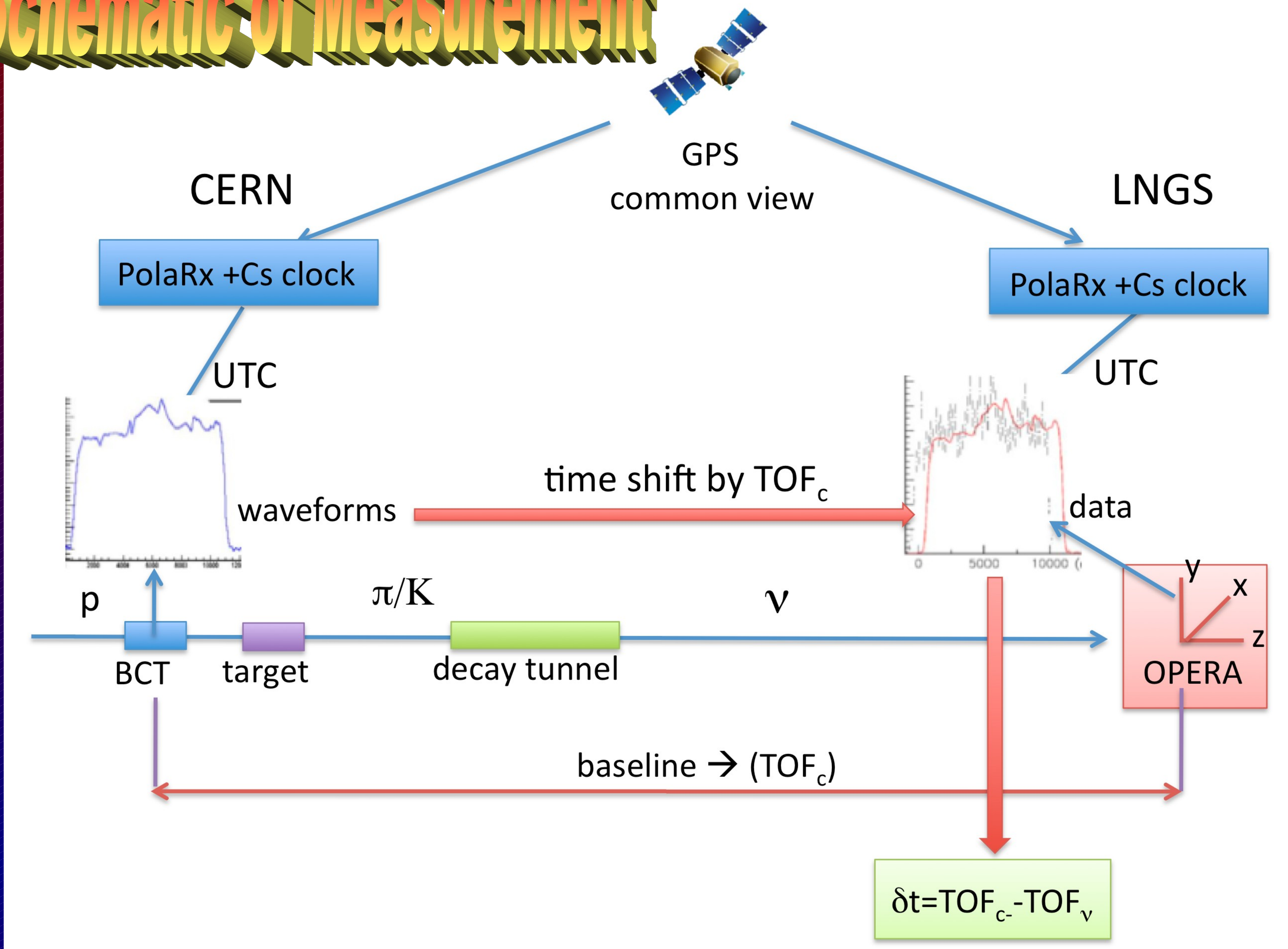


...

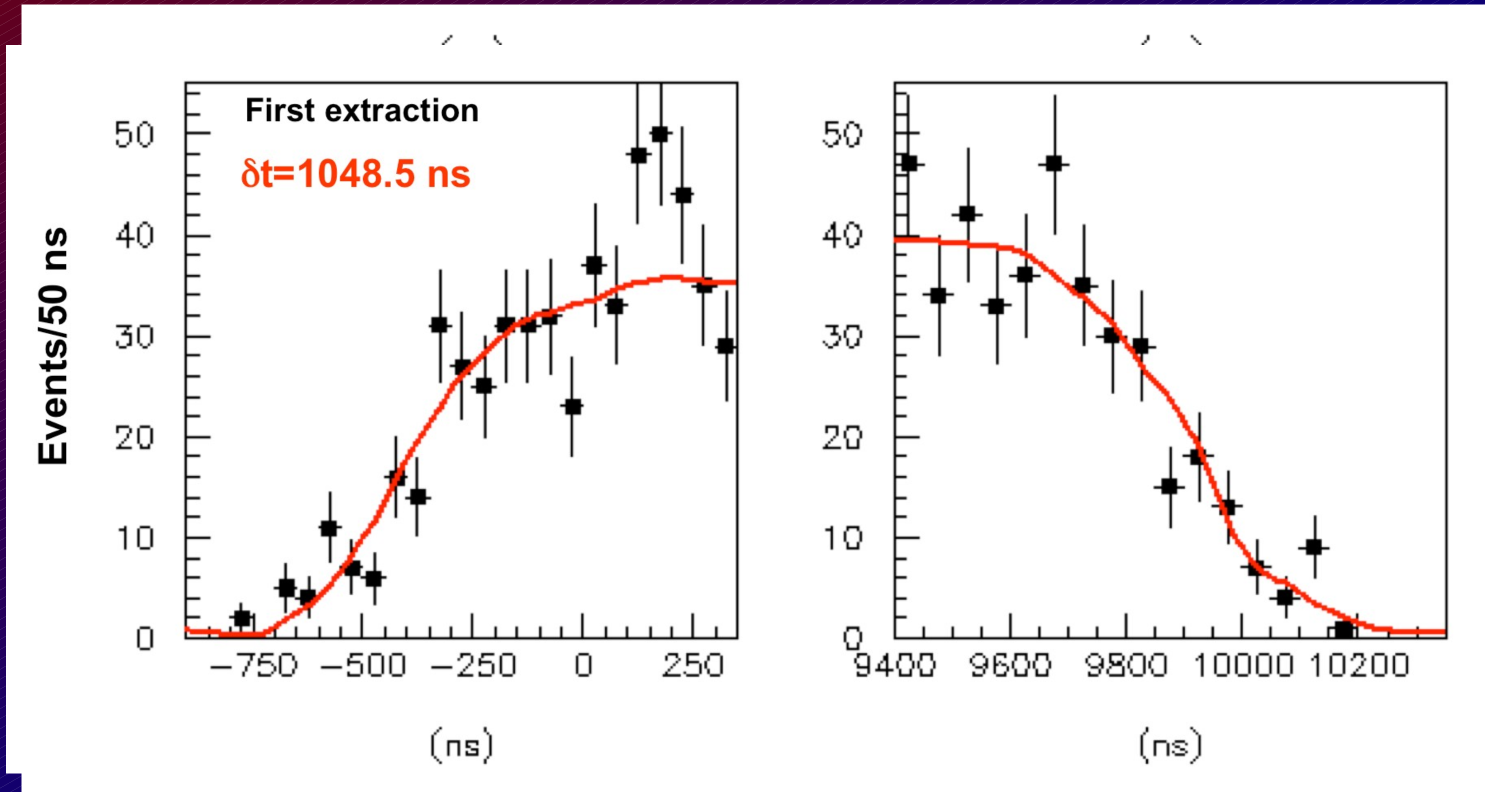
• 2
• 31
• 52
• 20

tection of

Schematic of Measurement



Result



distance: 730534.61 ± 0.20 m

baseline: 2 439 280.9 nsec

δt (TOF_c - TOF_ν): $(60.7 \pm 6.9_{stat} \pm 7.4_{sys})$ nsec

$(v-c) / c$: $(24.8 \pm 2.8_{stat} \pm 3.0_{sys})\ 10^{-6}$

Summary

Is the MNS Modell correct?

Still some problems (LSND, reactor anomaly)

How large is θ_{13} ?

First indication from T2K and MINOS , Reactor Experiments just started

What is the neutrino mass scale?

Waiting for KATRIN. Is it sensitive enough?

Majorana or Dirac ?

Heidelberg-Moscow?? New experiments

CP-violat

Very first sho … n.

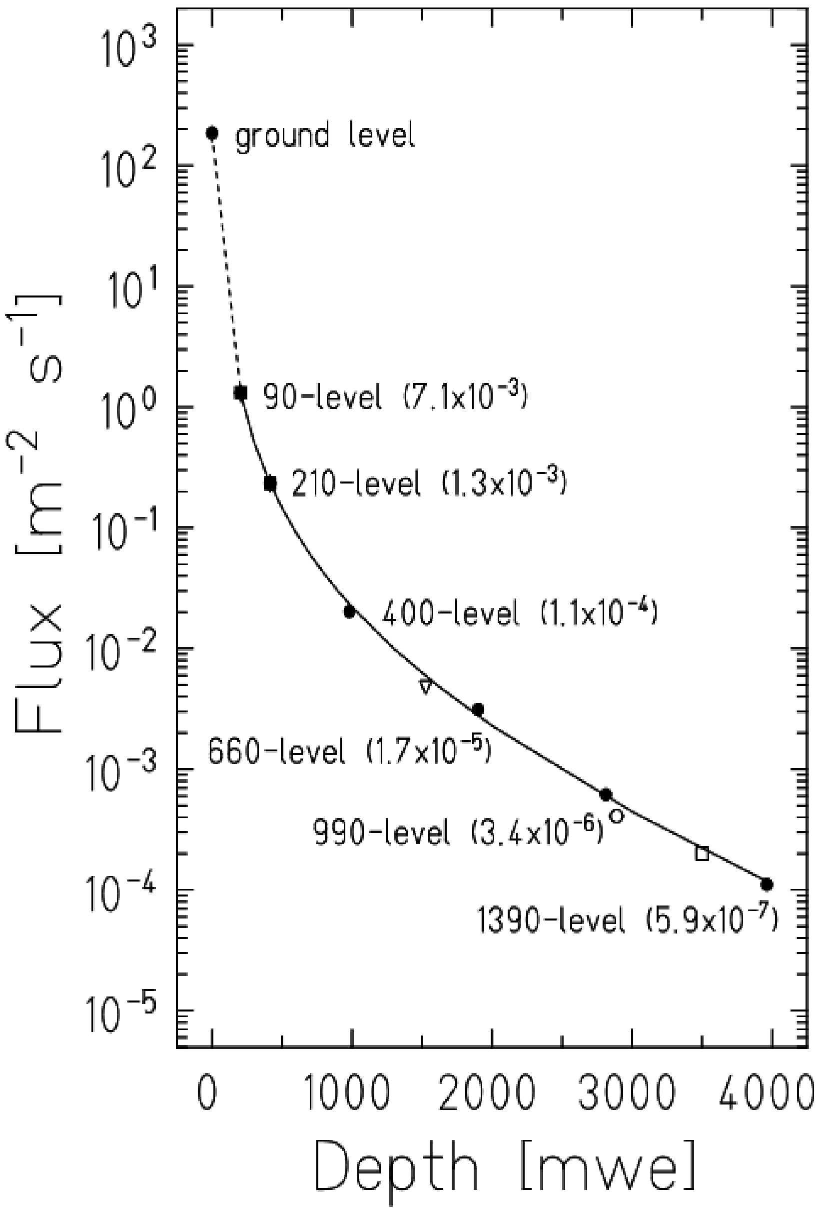
(might not need nu-factory/beta-beam for part of parameter space)

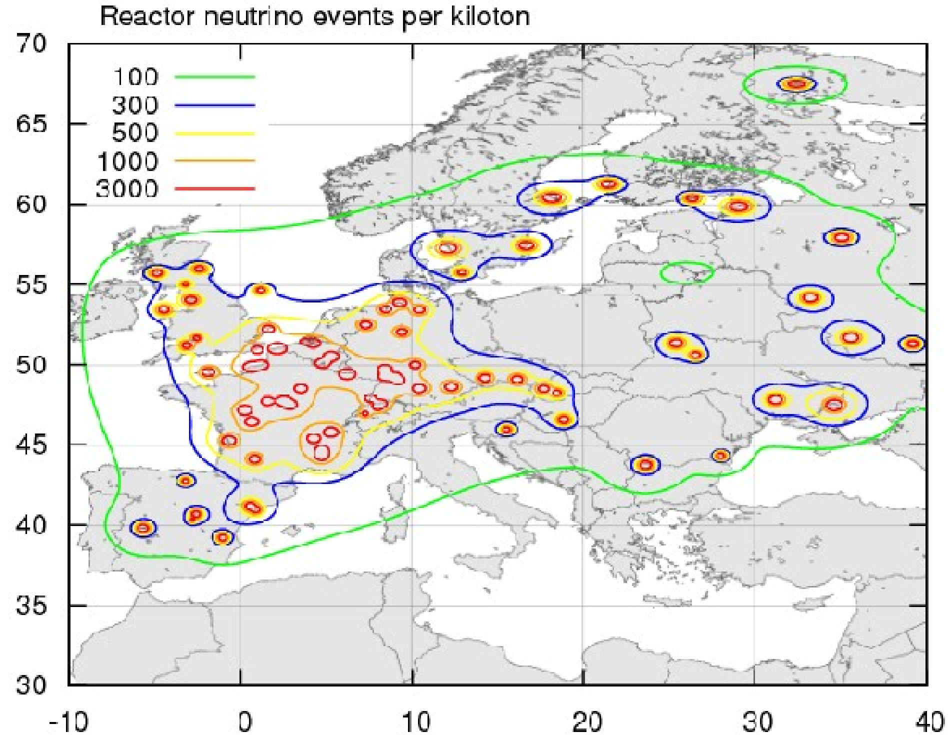
Thanks for Listening

Neutrino Velocity

OPERA correct? Waiting for confirmation (Borexino, T2K, Minos)

Backup





Selection criteria for LENA

feasibility of cavern construction (LAGUNA)

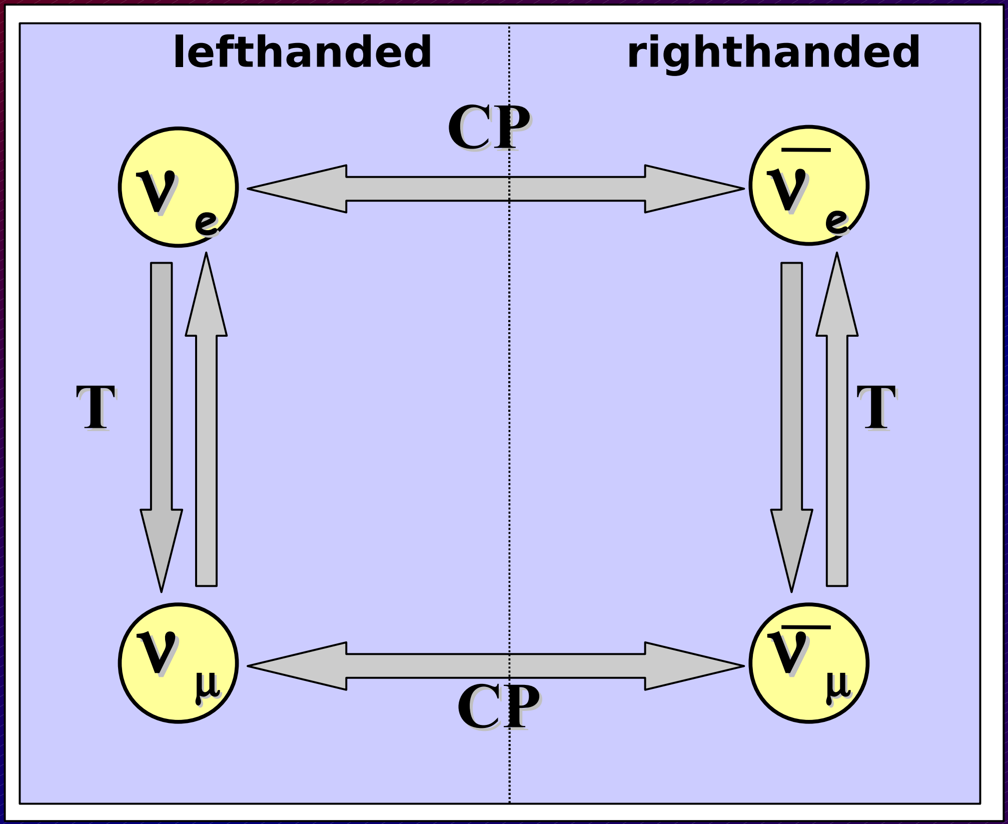
reactor-ν background

depth/cosmic ray shielding

Ž In Europe: Pyhäsalmi or Fréjus

CP-Violation

Testing the discrete symmetries with neutrinos



tau-neutrinos: no practical beam-source

Examples

CP-TEST:

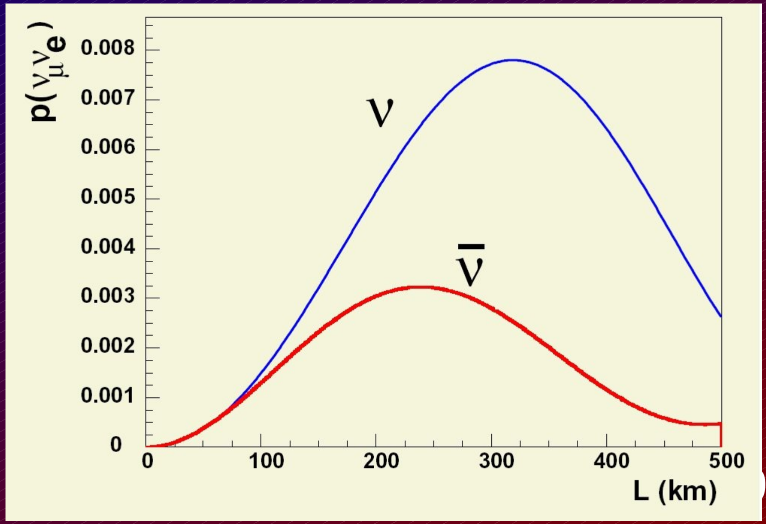
$\nu_e \rightarrow \nu_\mu \quad / \; \bar{\nu}_e \rightarrow \bar{\nu}_\mu$

T-TEST:

$\nu_e \rightarrow \nu_\mu \quad / \; \nu_\mu \rightarrow \nu_e$

CPT-TEST:

$\nu_e \rightarrow \nu_\mu \quad / \; \bar{\nu}_\mu \rightarrow \bar{\nu}_e$



Beam Technologies

Conventional Neutrino-Beam

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

some ν_e background

up to ~ 10 GeV

technologically sound

Limitations:
- background
- target

Neutrino-Factory

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

pure beam
needs magnetic detector
wide energy range

technological challenge
- μ production & capture
- fast acceleration

Limitations:
- power for μ production

CP-Violation okay

Beta-Beams

$$Z \rightarrow Z\text{-}1\ e^+ \nu_e$$
$$Z \rightarrow Z\text{+}1\ e^- \bar{\nu}_e$$

pure beam
only ν_e
MeV … a few GeV

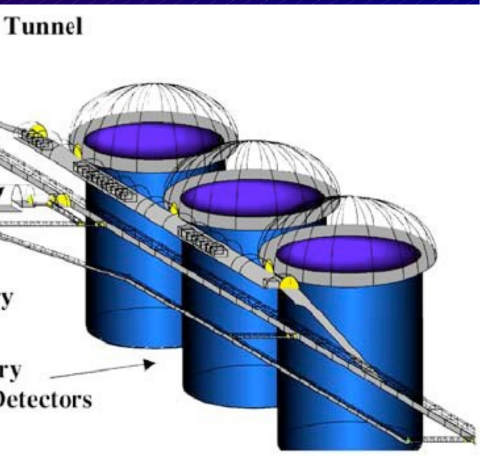
technological challenge
- ion production
- radiation on magnets

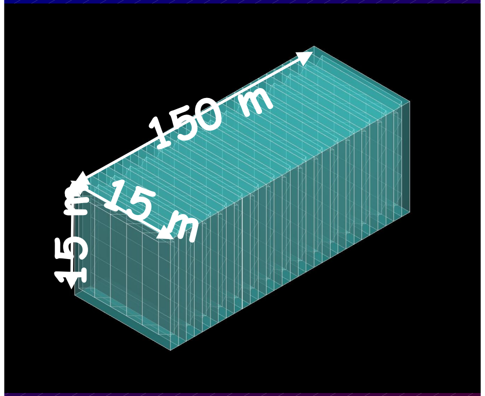
Limitations:
- production of ions

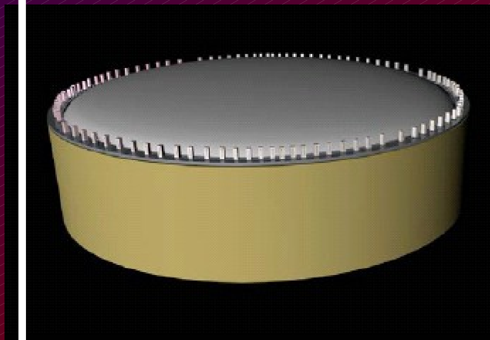
CP-Violation okay

Detectors

Water Čerenkov (MEMPHYS)	Totally Active Scintillator Det.	Liquid Scintillator (LENA)	Liquid Argon TPC (GLACIER)
~ 500 kT	~ 25 kT	~ 50 kT	~ 100 kT
$E_{min} > 10$ MeV	$E_{min} > 10$ MeV	$E_{min} \sim 500$ keV	$E_{min} \sim 10$ MeV
restr. information	restr. information	med. information	max. information
known technology	known technology	known technology	new technology
challenge: huge caverns	challenge: mass production	challenge: big cavern	to be proven







LENA

Physics with LENA

Proton Decay

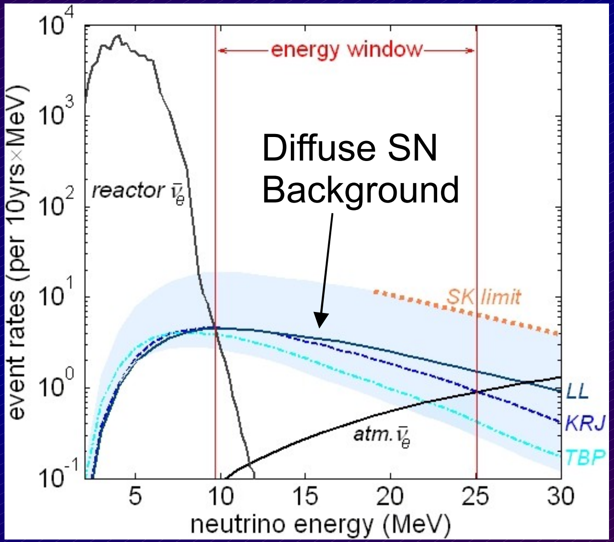
$p^+ \rightarrow \nu K^+$ $\tau > 4\ 10^{34}$ years

Super Nova Detection

glactic center (10 kpc): 15.000 ν

Diffuse Super Nova Background

2 … 20 ν per year

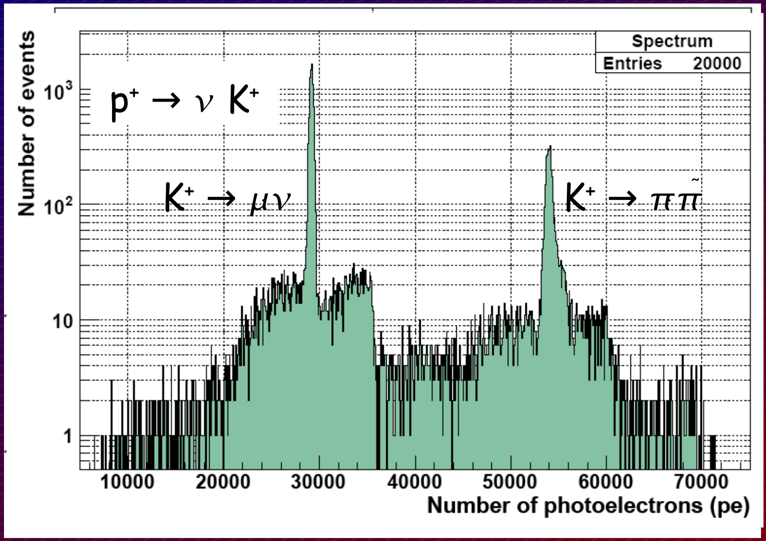


Geo-Neutrinos

~ 3000 ν year → undestand heat release

» & geo chemistry

only possible with LENA



Solar Neutrinos

~ 5000 ν / day   (helio seismology)

Atmospheric Neutrinos

good statistics, promising

CP-Violation (with beam)

Conclusions

Neutrino Revolution during the last decade !

More to come ?

Several interesting new projects

- not yet clear where to go
- open the path to all projects with R&D

LENA is getting ready for first steps

- Get involved !

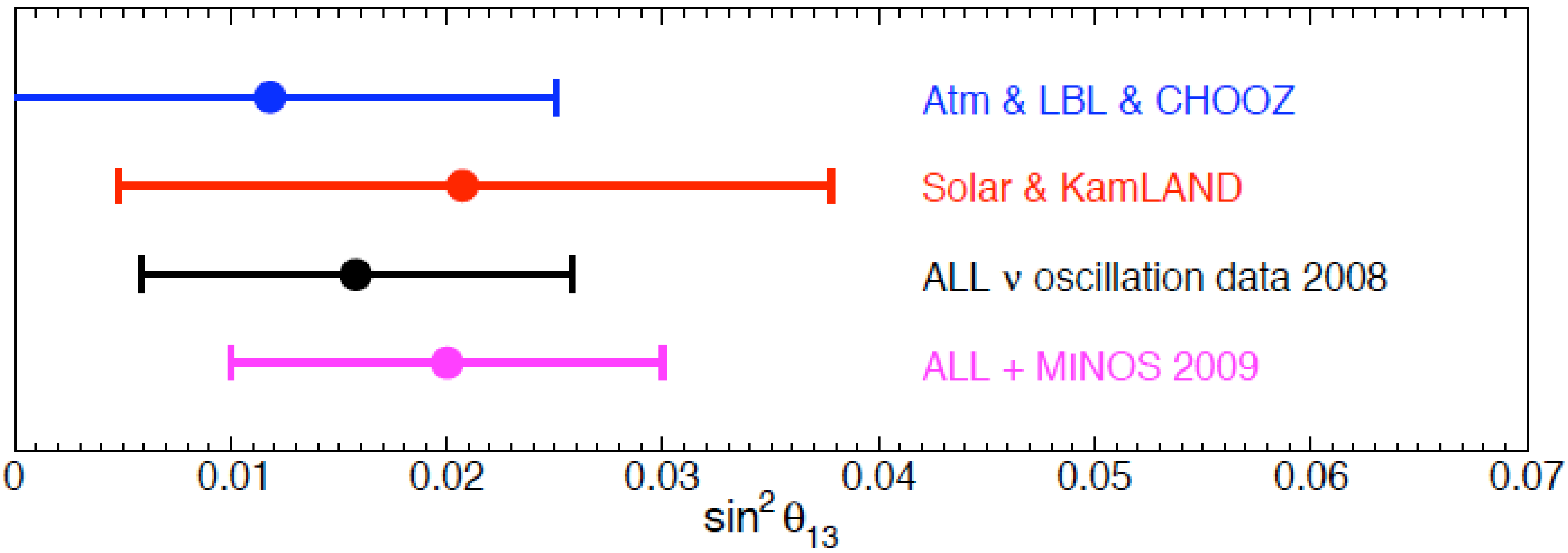
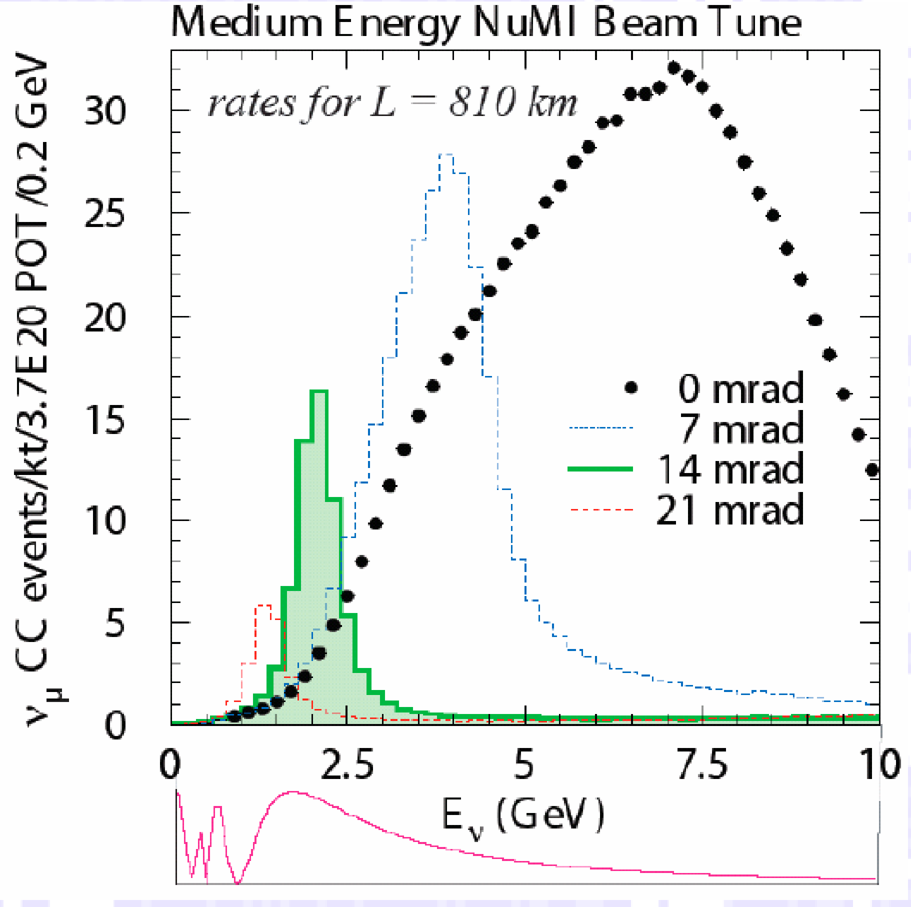


Figure 4: Hints of $\theta_{13} > 0$ from different data sets and combinations: 1σ ranges.



Medium Energy NuMI Beam Tune
rates for L = 810 km
ν_μ CC events/kt/3.7E 20 POT /0.2 GeV
0
5
10
15
20
25
30
0 mrad
7 mrad
14 mrad
21 mrad
0
2.5
5
7.5
10
E_ν (GeV)

Super-K	water Cerencov	50 kt
Nova	TASD	15 kt
LENA	scintillator	50 kT
MINOS	TASD	
OPERA	emulsion	1,25 kt
DoubleChooz	Scintillator	
Glacier	LAr TPC	100 kT
Memphis	Water Cerenkov	500 kT

$$p(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \times \left[1 \pm \frac{2a}{\Delta m_{13}^2}(1 - 2s_{13}^2)\right] \quad \theta_{13} \text{ dri}$$

$$+ 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \quad \text{CPe}$$

$$\mp 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \quad \text{CPodd}$$

$$+ 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta\} \sin \frac{\Delta m_{12}^2 L}{4E} \quad \text{solar driver}$$

$$\mp 8c_{12}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E}(1 - 2s_{13}^2) \quad \text{matter effect (CP odd)}$$