Neutrino-Oscillations

Past, Present and Future

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DESY Seminars
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Current Status: Neutrino Oscillations

Studying Neutrino Oscillations in 3 Experimental Steps

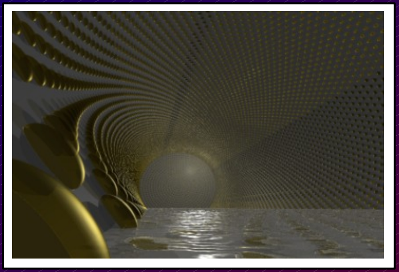
DoubleChooz

Reactor-Neutrinos
Chooz/France

T2K

Long Baseline Beam
Japan

LENA

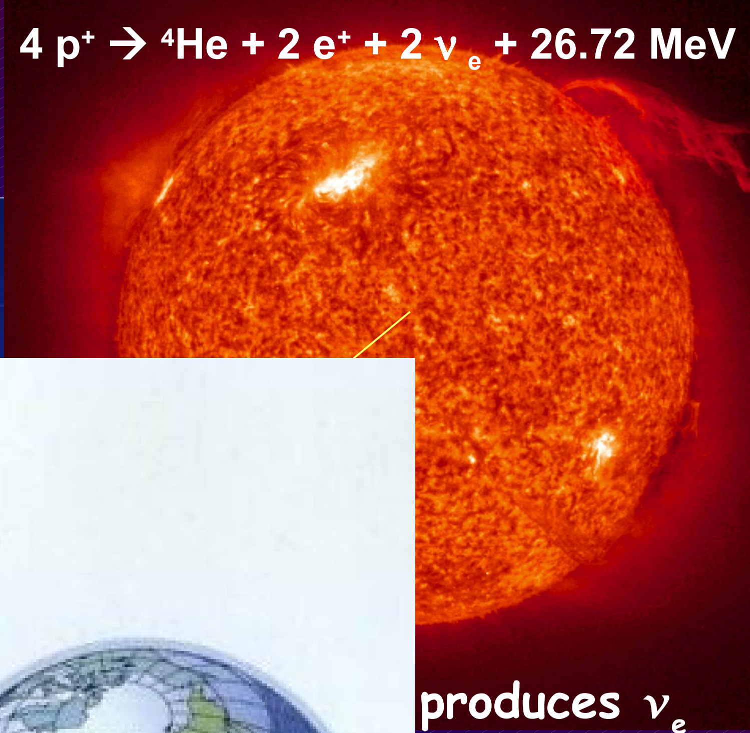


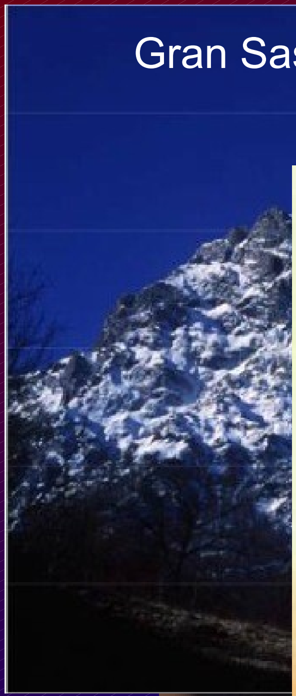
Future European
Neutrino Detector

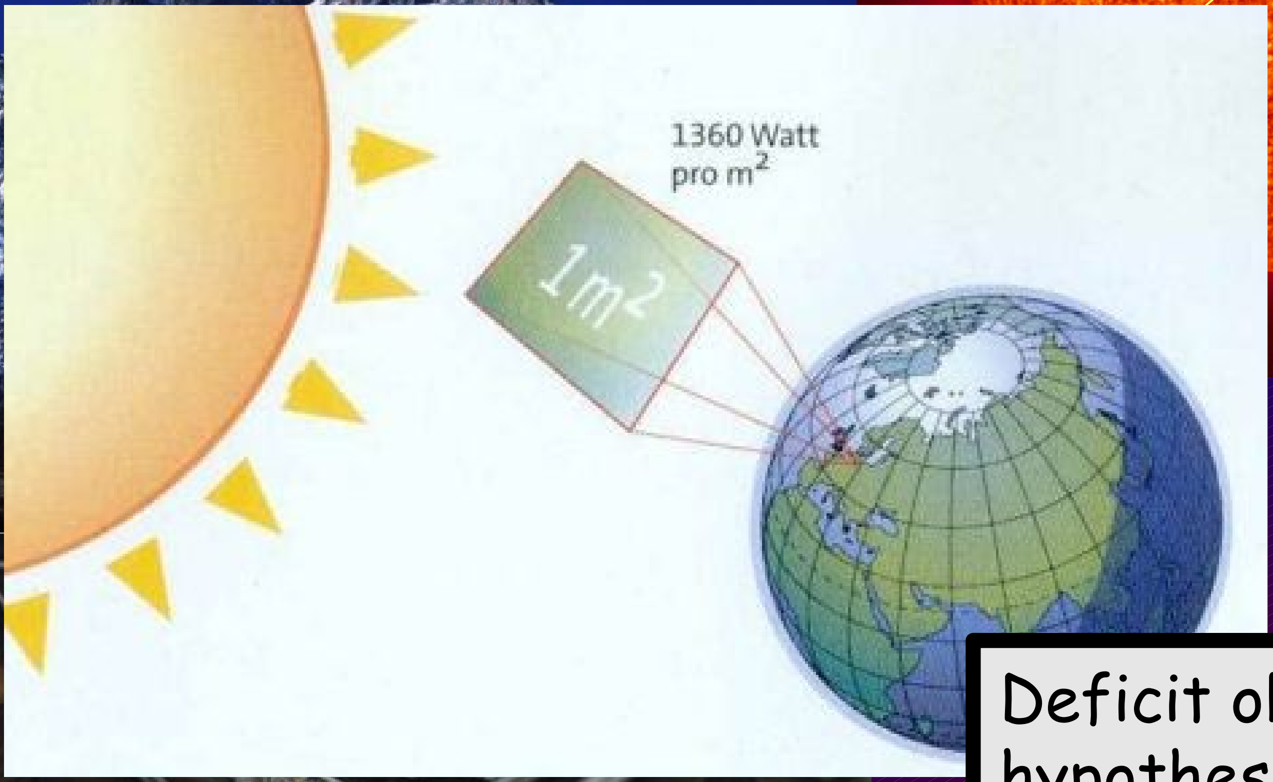
Current Status

Solar Neutrinos

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



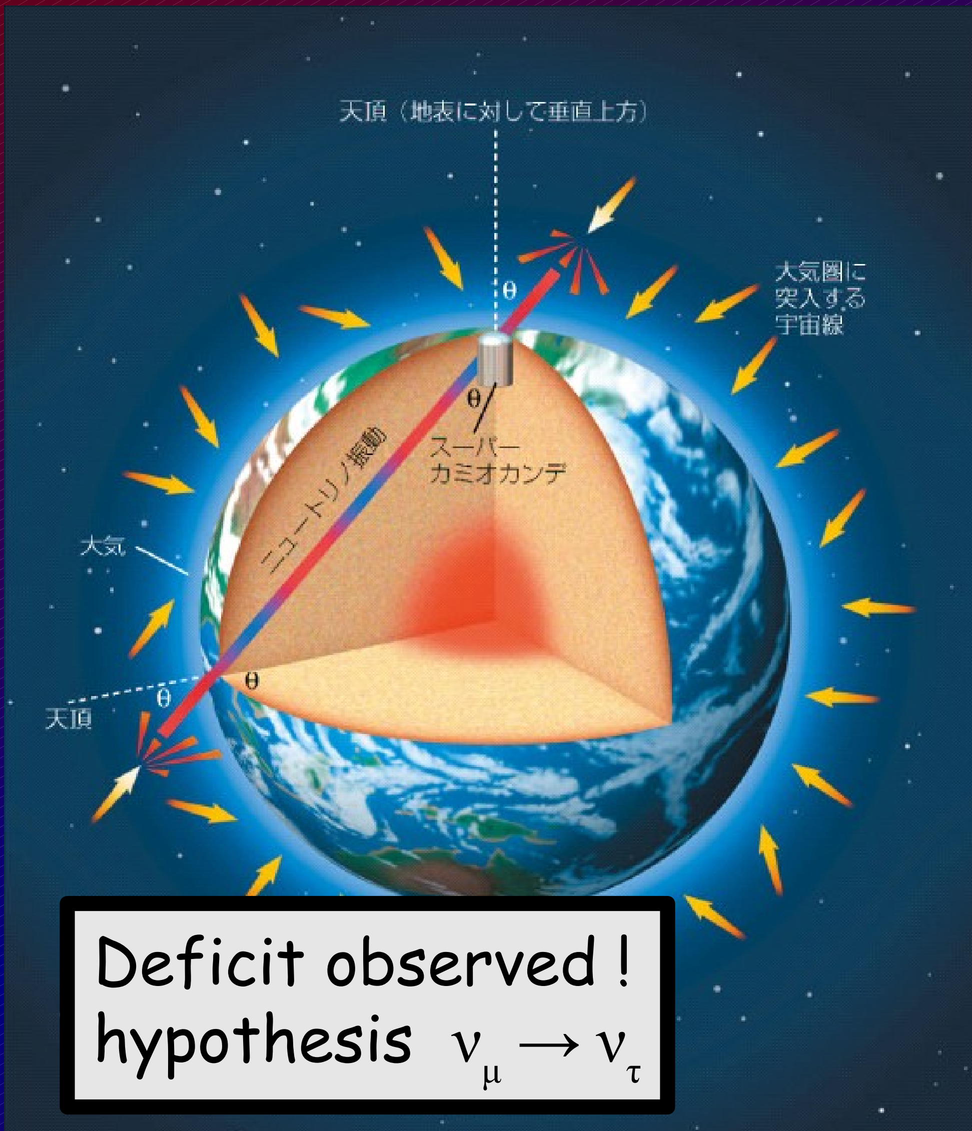




Deficit observed !

hypothesis $\nu_e \rightarrow \nu_\mu$

Atmospheric Neutrinos

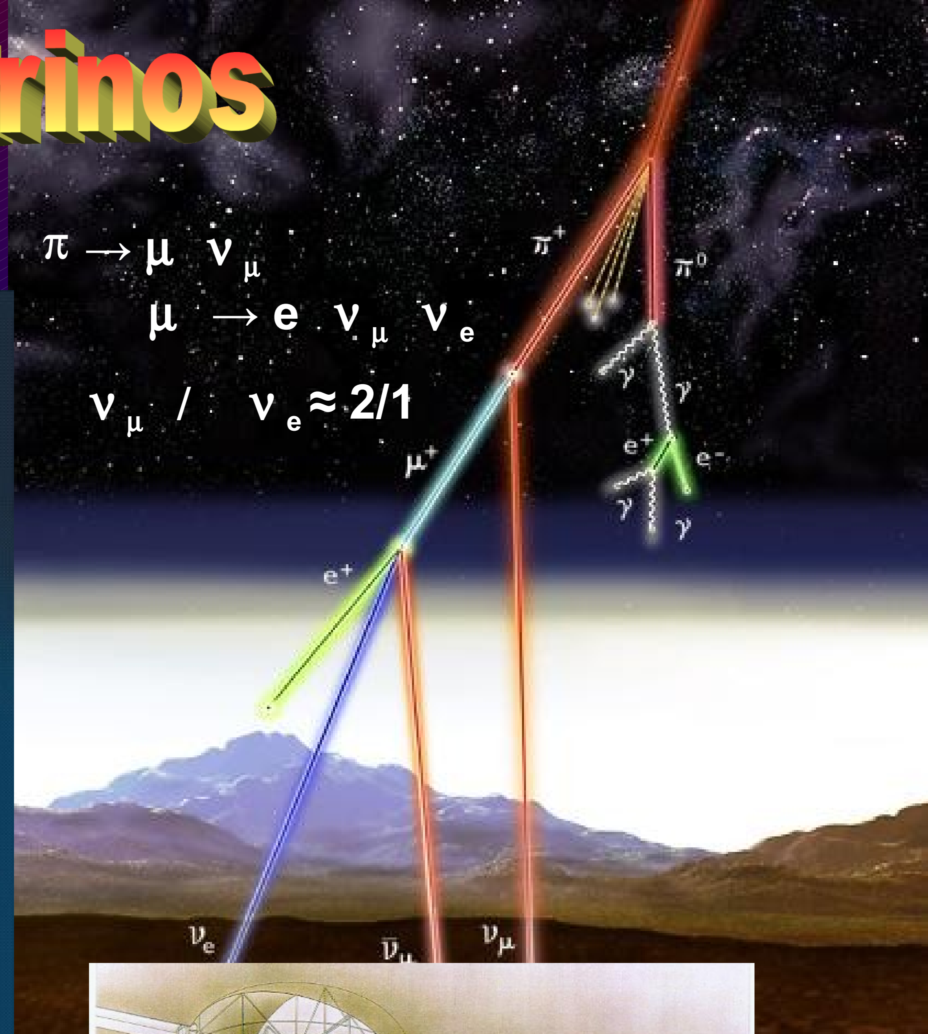


Deficit observed !
hypothesis $\nu_\mu \to \nu_\tau$

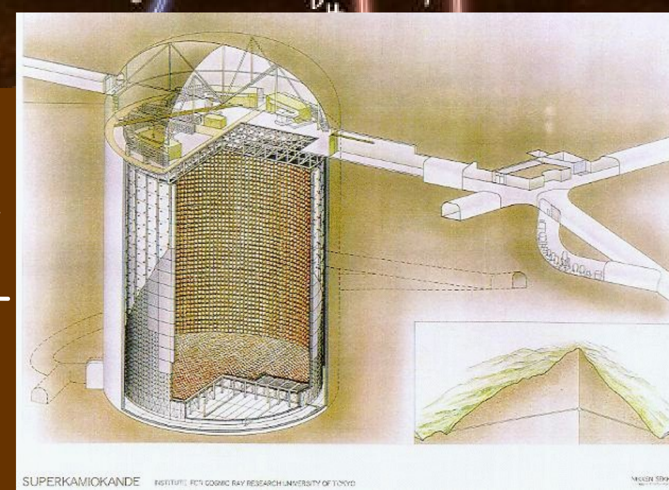
$\pi \to \mu\ \nu_\mu$

$\mu \to e\ \nu_\mu\ \nu_e$

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



Super-K



Neutrino Oscillations

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“ $\theta_{12} \approx 32°$

Pontecorvo-Maki-Nakagawa-Sakata matrix

Neutrino Oscillations

production
through
waek interaction

$$|\nu(x=0)\rangle = \begin{pmatrix} c_1 \\ c_2 \\ c_3 \end{pmatrix}$$

propagation
as
mass eigenstate

$$\nu_i(x) = n_0 \exp\left(i\left(p \cdot x - E\ t\right)\right) \qquad x = c\,t$$

$$E^2 = p^2 + m_i^2$$

$$E \approx p + \frac{m_i^2}{2\ p} \approx p + \frac{m_i^2}{2\ E}$$

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

rel. quantity:
$(m_i^2 - m_j^2)\ L/E$

phase relations change during propagation

detection
through
weak interaction

$$|\nu(x=L)\rangle = \begin{pmatrix} c_1(L) \\ c_2(L) \\ c_3(L) \end{pmatrix}$$

recombine
mass eigenstates

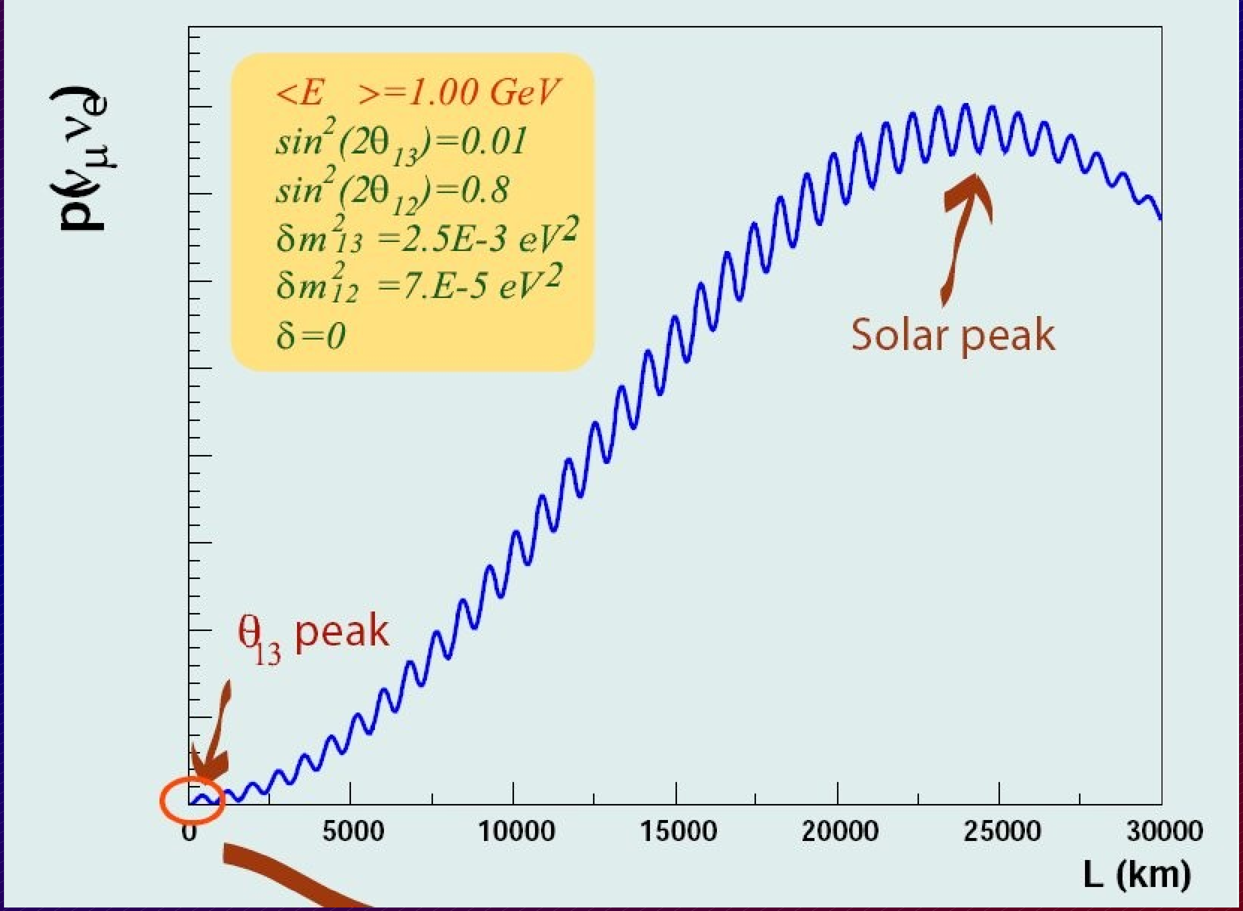
Neutrino Oscillations

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

Two frequencies:

$\Delta m_{12} \rightarrow L_0/E \approx 30.000$ km/GeV

$\Delta m_{13} \approx \Delta m_{23} \rightarrow L_0/E \approx 1.000$ km/GeV



Neutrino Oscillations

Oscillation formula

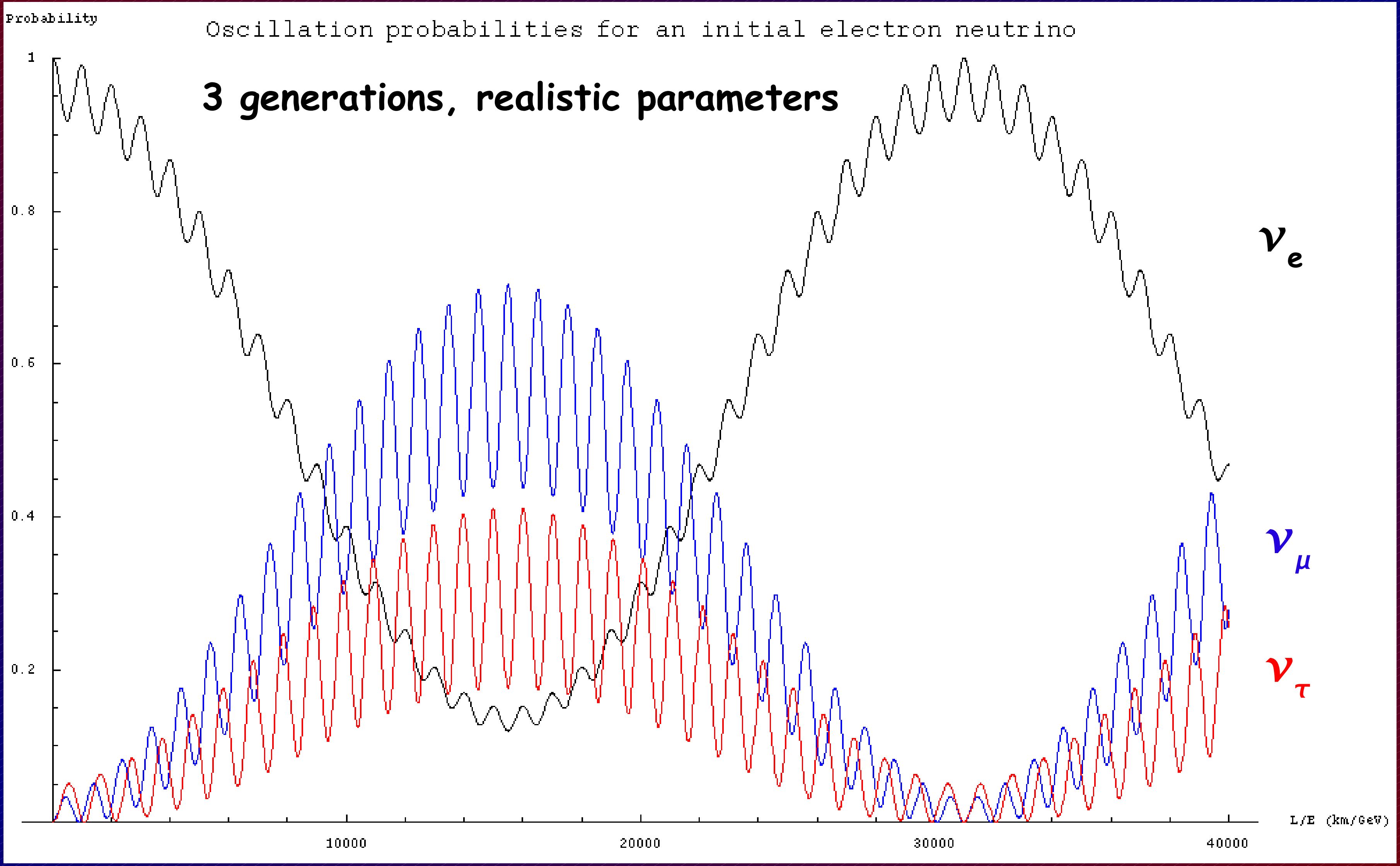
$$P_{\alpha\rightarrow\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j} Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

$$\frac{\Delta m^2 c^3 L}{4\hbar E} = \frac{\text{GeV fm}}{4\hbar c} \times \frac{\Delta m^2}{\text{eV}^2}\frac{L}{\text{km}}\frac{\text{GeV}}{E} \approx 1.267 \times \frac{\Delta m^2}{\text{eV}^2}\frac{L}{\text{km}}\frac{\text{GeV}}{E}$$

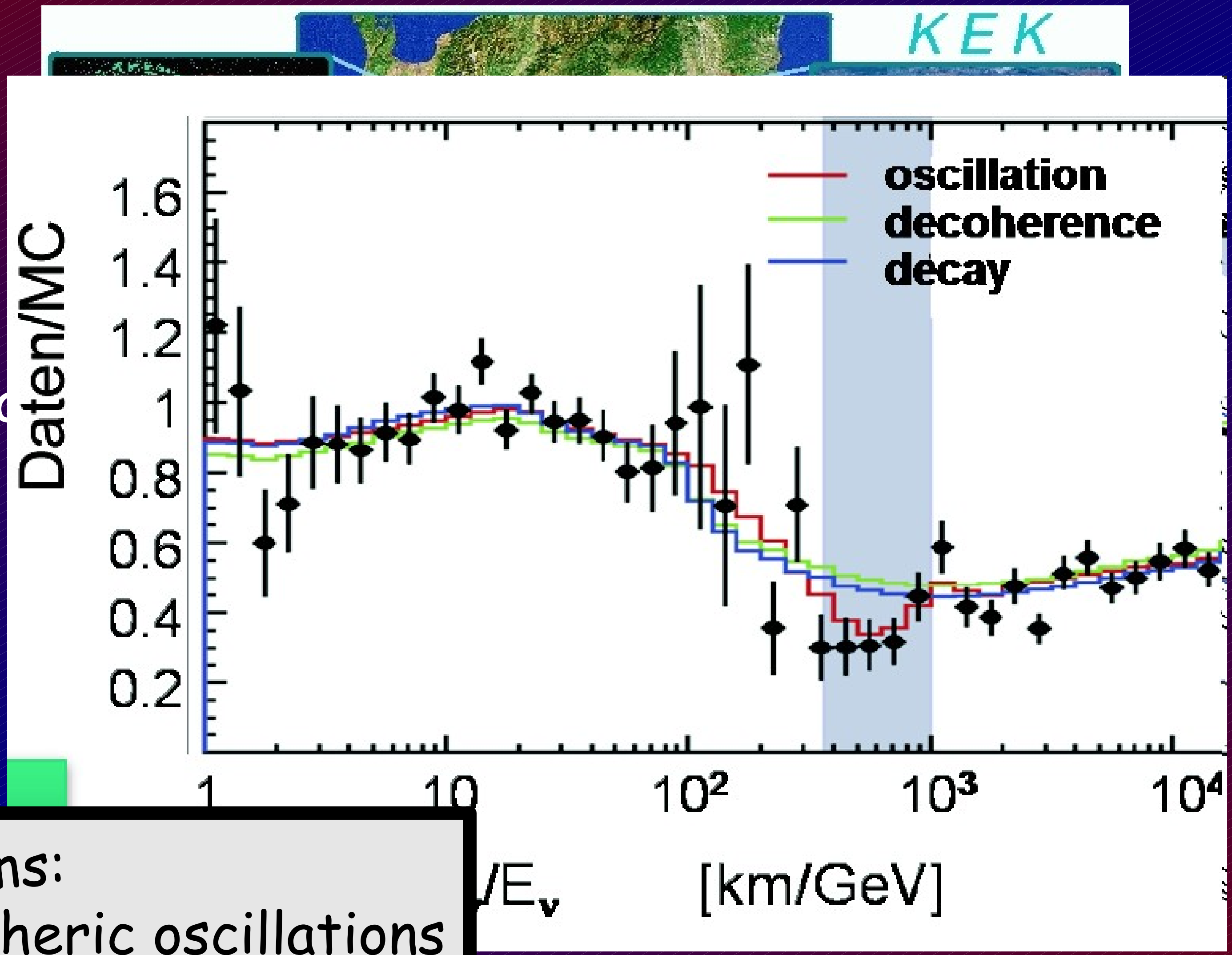
$\Delta m^2_{ij} \equiv m^2_i - m^2_j$ determine oscillation frequency

$U_{\alpha i}$ determine amplitude of oscillation

Neutrino Oscillations

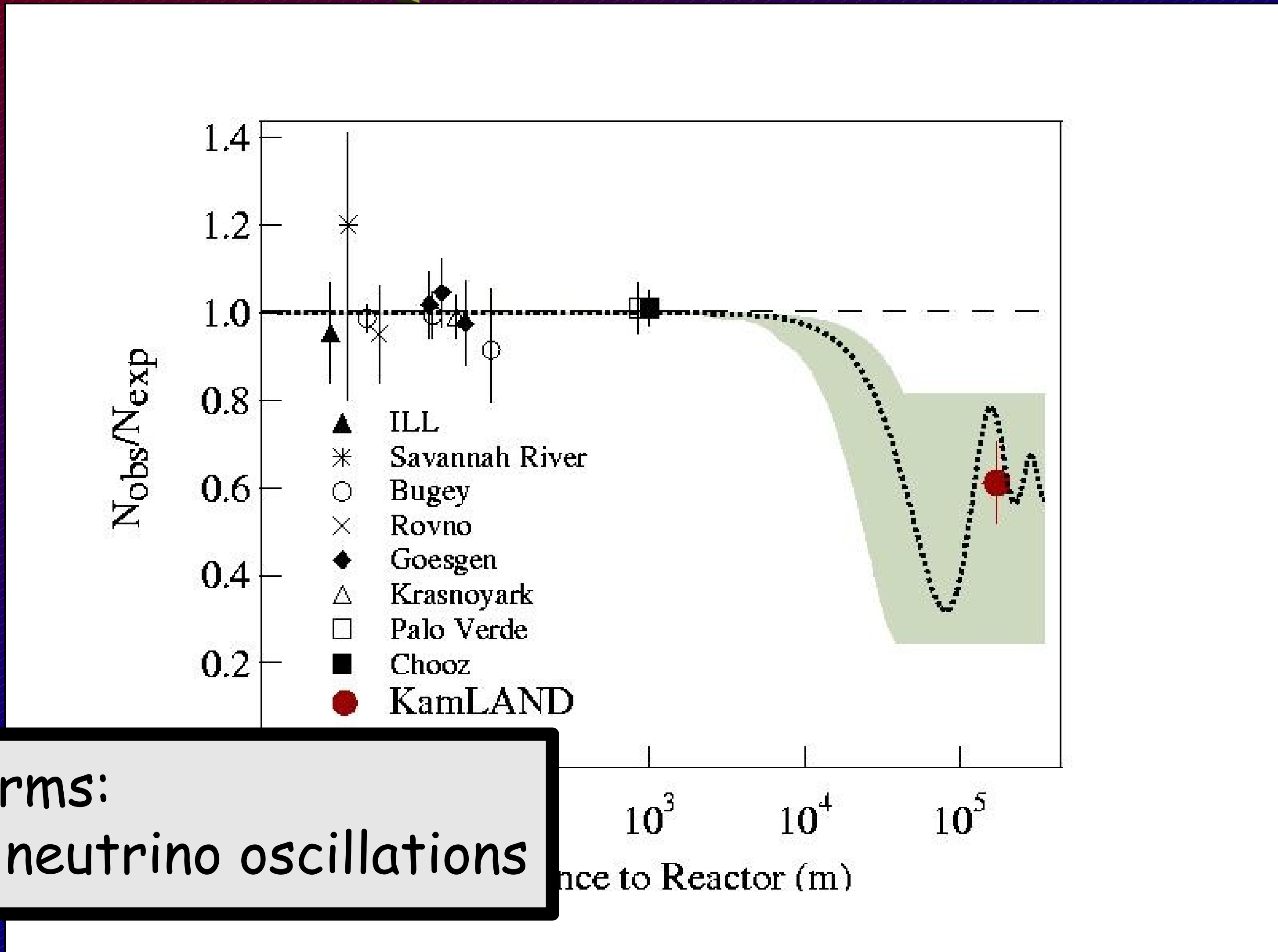


K2K Experiment



Confirms:
atmospheric oscillations

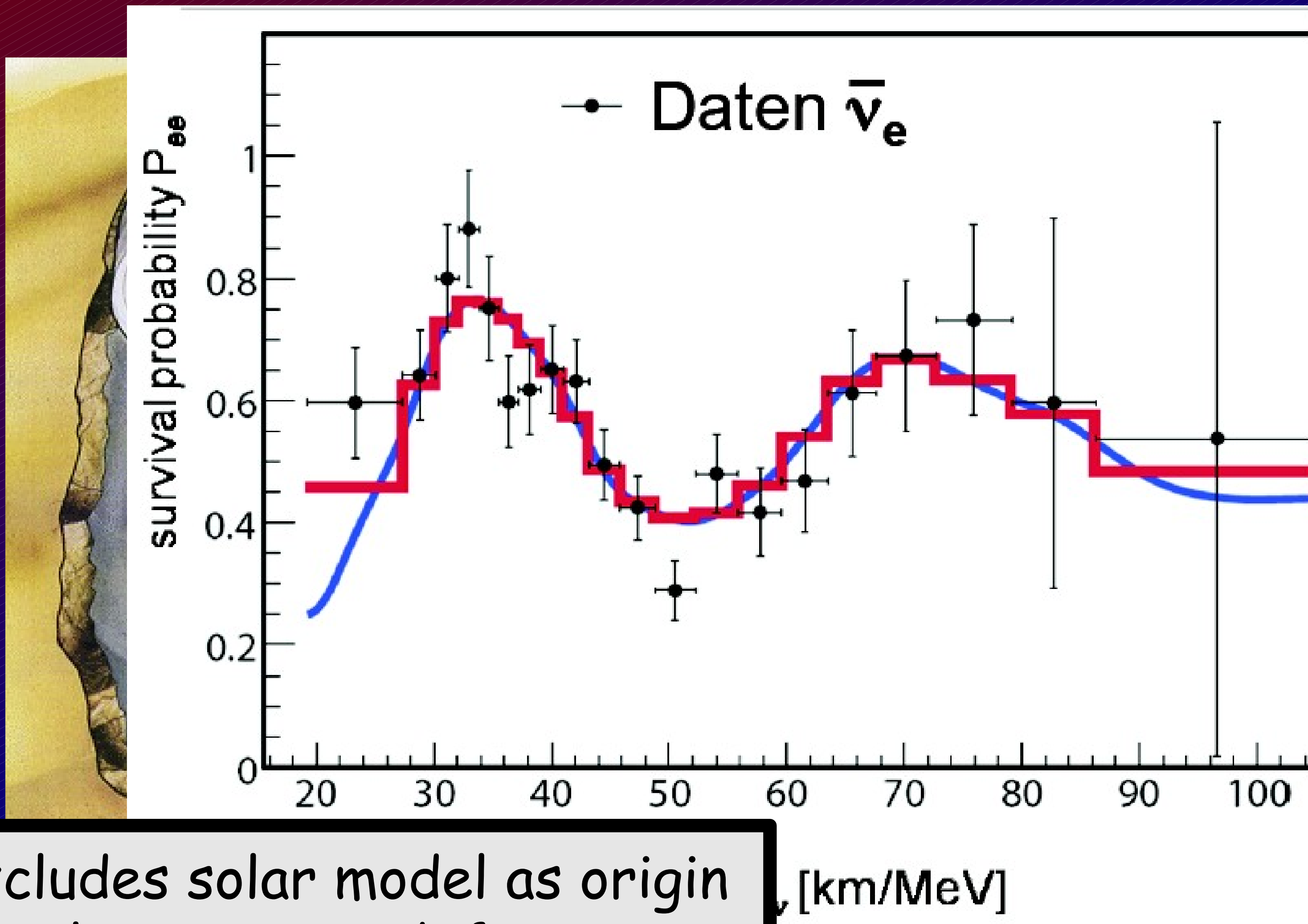
KamLand Experiment



Confirms:
solar neutrino oscillations

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

SNO Experiment



trinos
reactions

$+e^-$

$+\nu_x$

e^-

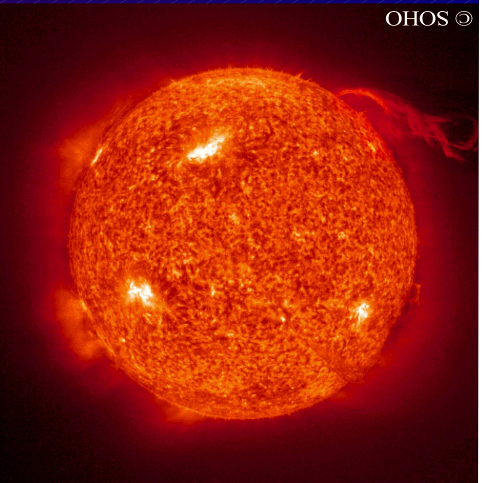
Excludes solar model as origin of solar neutrino deficit

Experiments

Solar Neutrinos

Homestake
Kamiokande
Gallex
Sage
SNO
Borexino

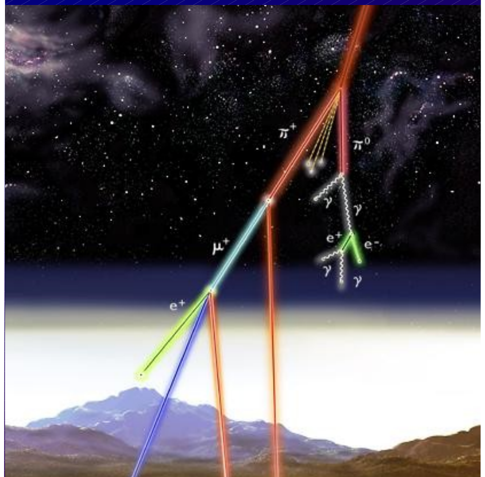
Δm_{solar}



Atmospheric ν

Super-K
Macro

Δm_{atm}



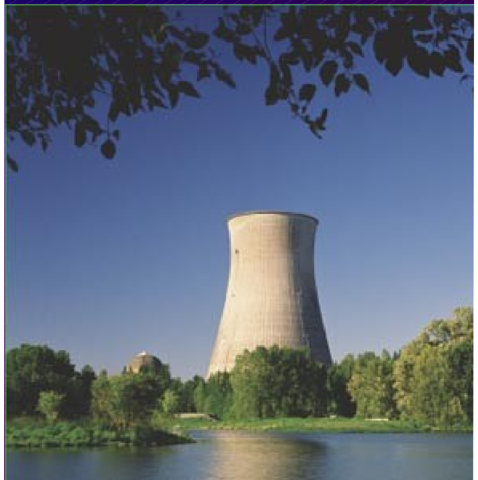
Reactor-Neutrinos

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}

Current Status

Solar Neutrinos	Atmospheric ν	Reactor ν, θ_{13}

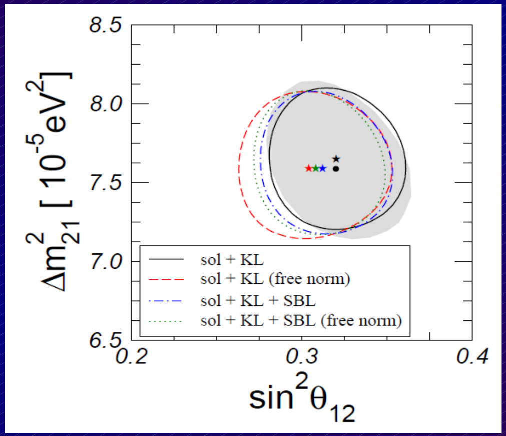
Solar Neutrinos

oscillation observed
- Homestake
- GALLEX
- Super-K

confirmed
- KAMLAND
- SNO

disappearance of ν_e

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



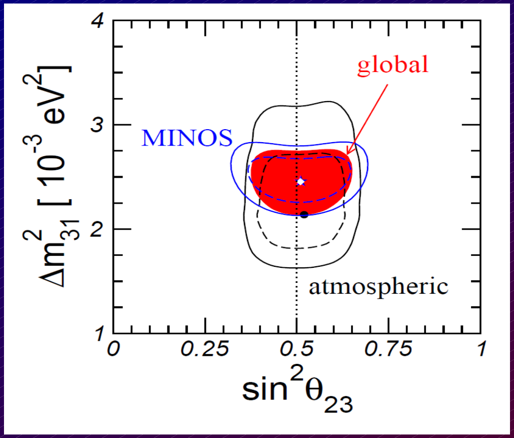
Atmospheric ν

oscillation observed
- Super-K
- MACRO

confirmed
- K2K
- MINOS

disappearance of ν_μ

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



Reactor ν, θ_{13}

no observation yet

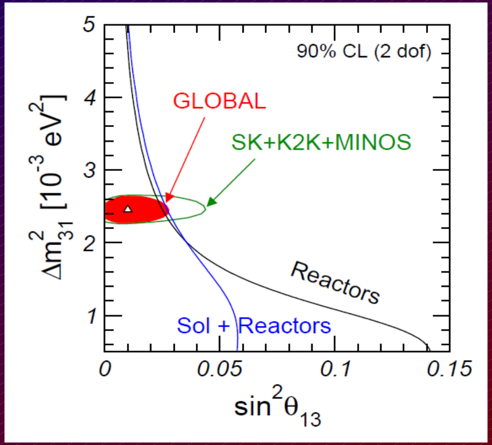
intensive search
- DoubleChooz
- Daya Bay
- RENO

disappearance of $\bar{\nu}_e$

- T2K, MINOS

appearance of ν_e

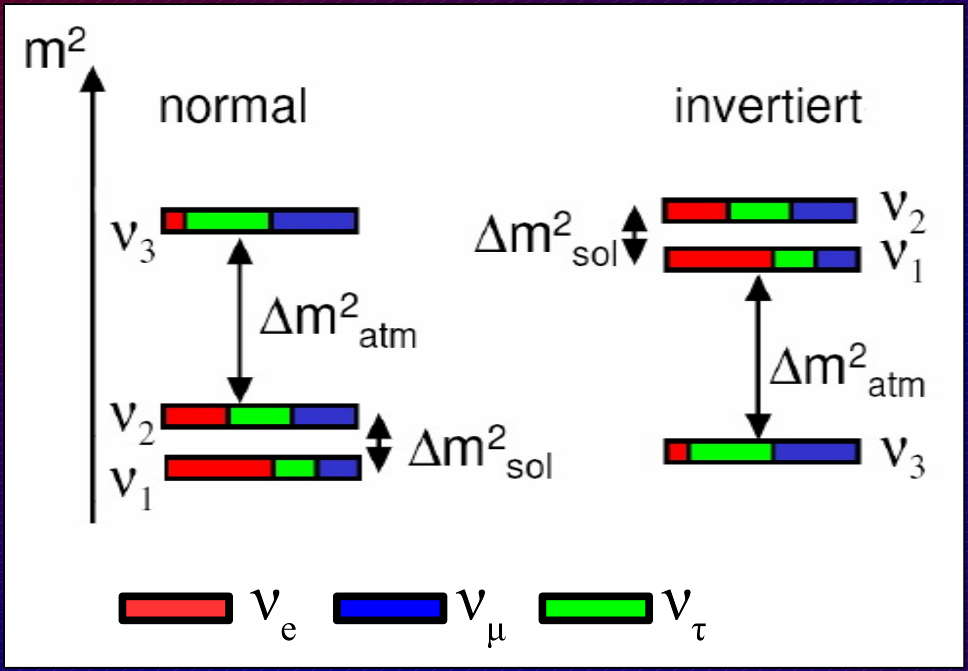
$$\sin^2\theta_{13} = 0.010^{+0.009}_{-0.006}$$



Thomas Schwetz et al., arXiv 1103.0734

(normal hierarchy)

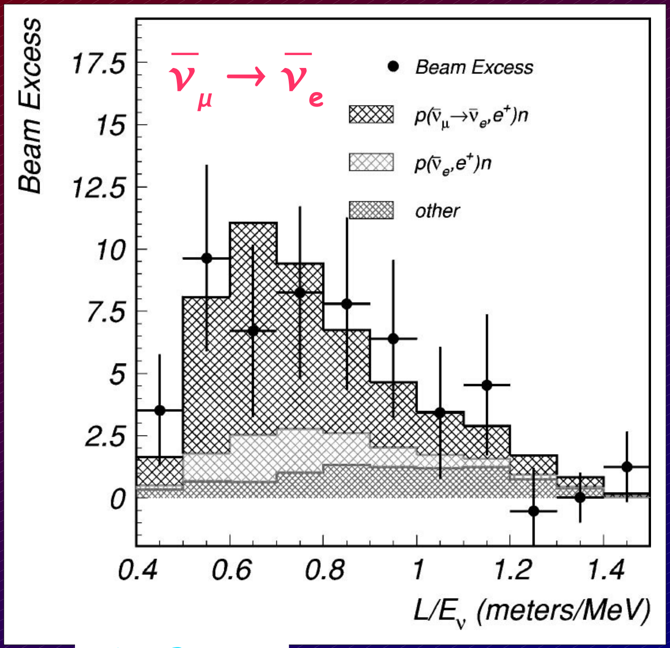
Interpretation

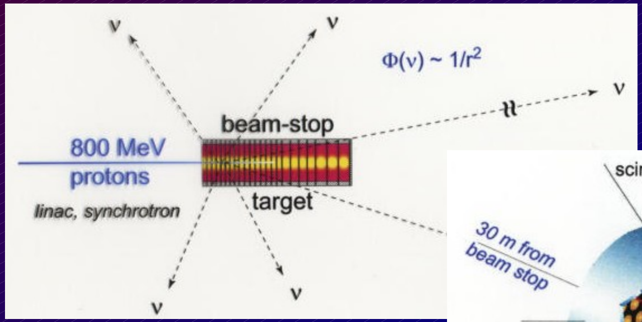


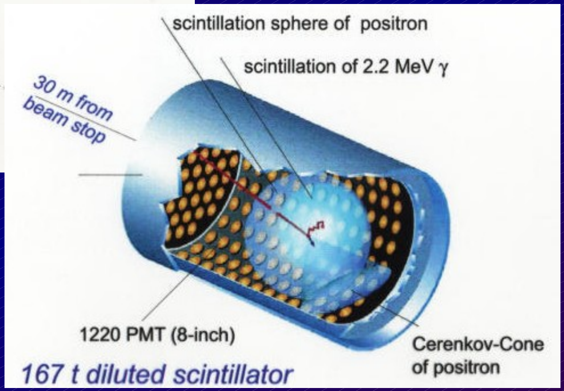
$$
\begin{aligned}
\Delta m_{12}^2 &= 7.24 \dots 7.99\ 10^{-5}\, eV^2 \\
|\Delta m_{13}^2| &= 2.28 \dots 2.64\ 10^{-3}\, eV^2 \\
\sin^2\theta_{12} &= 0.28 \dots 0.35 \\
\sin^2\theta_{23} &= 0.41 \dots 0.61 \\
\sin^2\theta_{13} &= <0.027
\end{aligned}
$$

2-sigma ranges

LSND-Effect



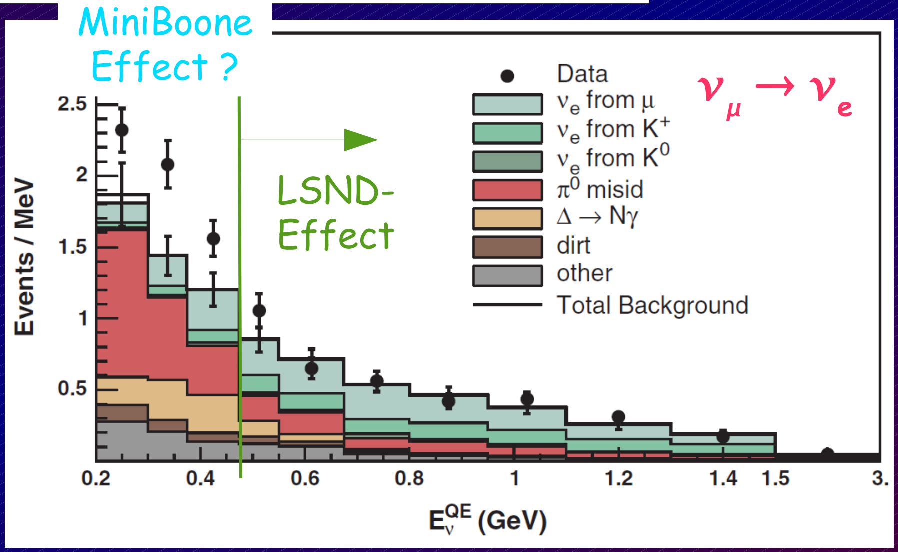




LSND

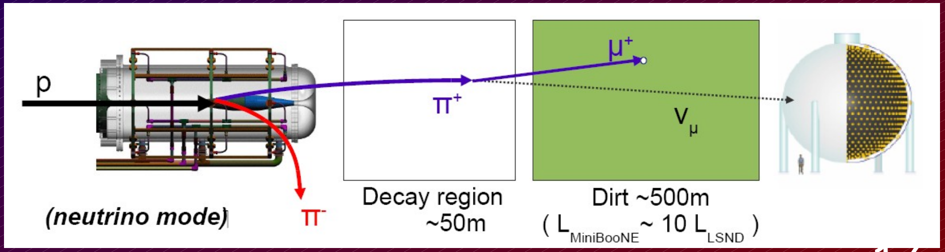
evidence for oscillations
$\Delta m^2 \approx 1\ eV^2$

Liquid Scintillator Neutrino Detector @ Los Alamos

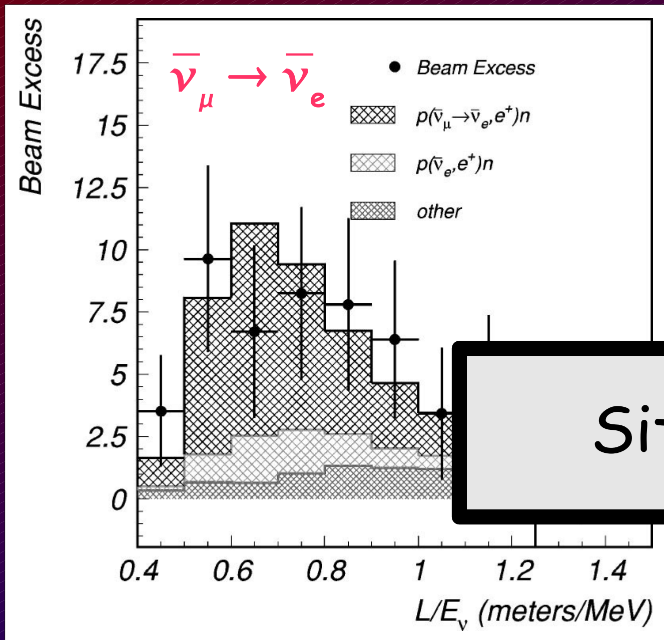


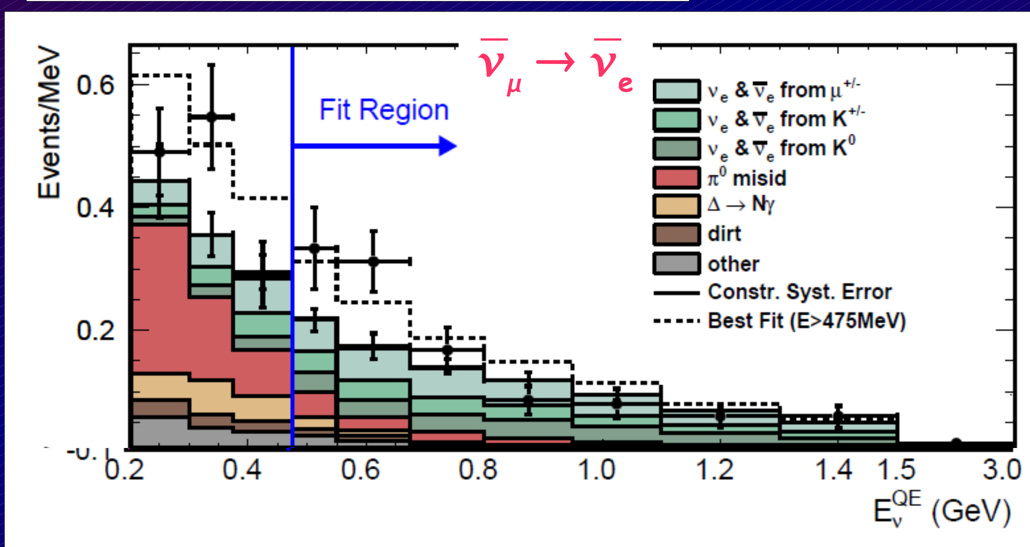
(almost?) excluded by KARMEN

contradicted by MiniBooNE

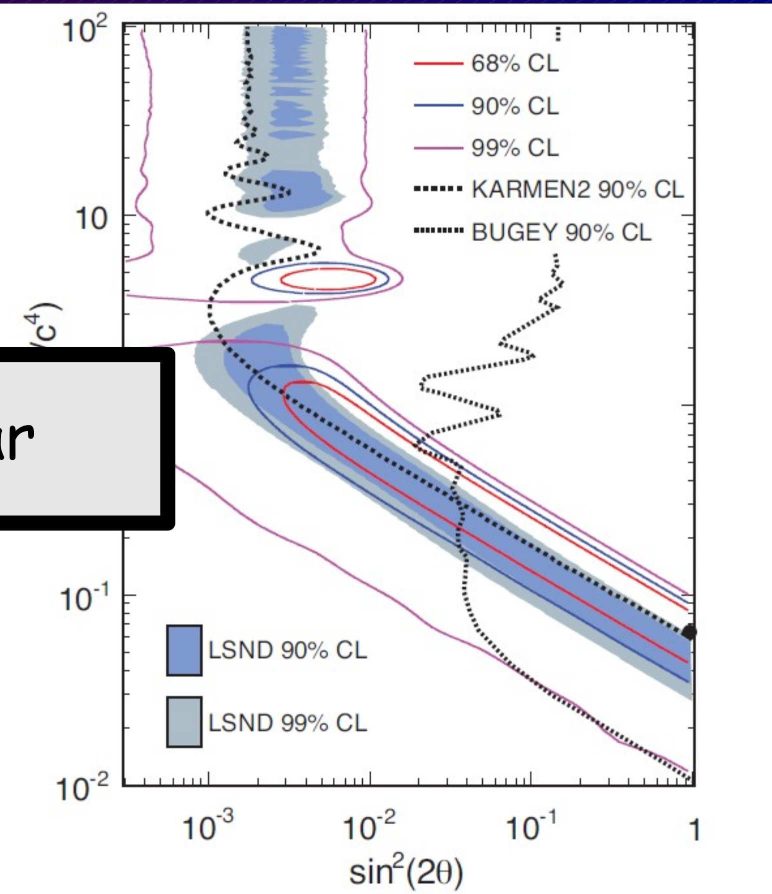


LSND-Effect





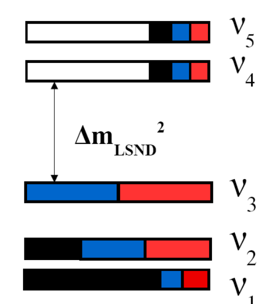
Situation unclear



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

sterile neutrinos

CP-Violation



Minimal extension of the SM

Is it possible to incorporate neutrino oscillations in the SM ?

0. **New phenomena**

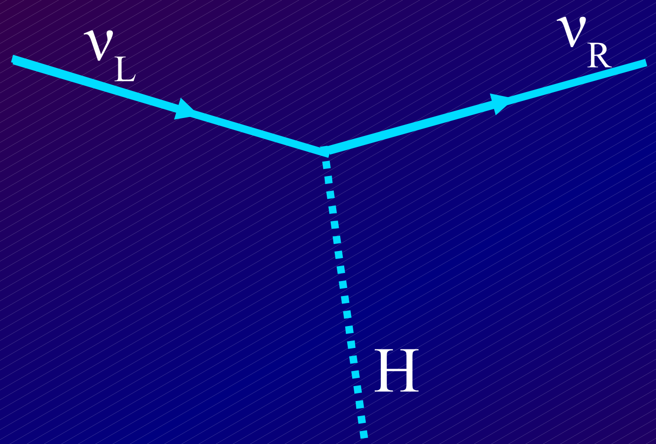
lepton number violation (neutrino oscillations
+ charged lepton decays)

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

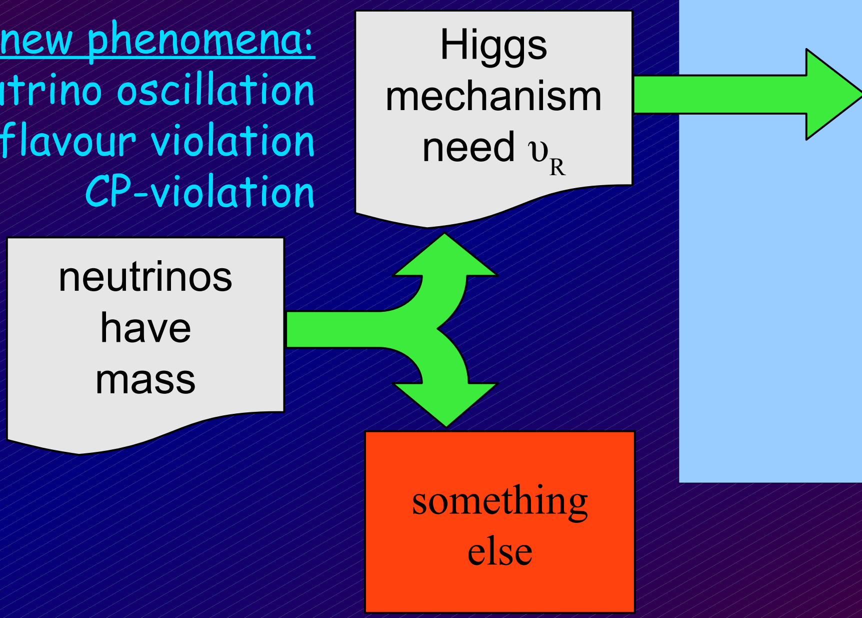
Right- and left-handed neutrino will have different masses

Minimal extension of the SM ?

lepton

new particle:
right-handed neutrino

new phenomena:
neutrino oscillation
lepton flavour violation
CP-violation

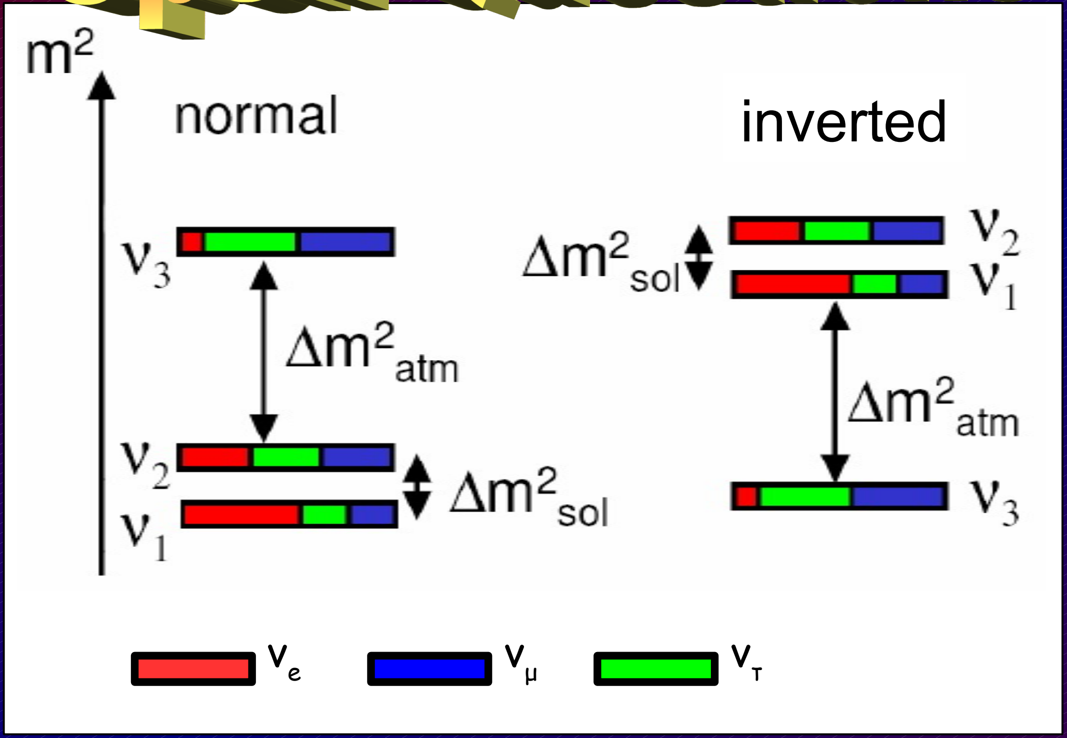


Minimal extension of the SM

Majorana mass terms accidentally zero.

No high-energy extension of the SM (GUT).

Open Questions

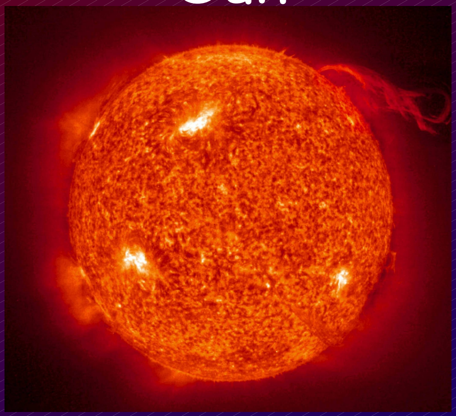


How large is θ_{13} ?	→ experiments started
Precision measurements (θ_{23} maximal ?)	→ next gen. oscillations exp.
Absolute mass scale ?	→ nucl. phys. experiments (KATRIN)
Normal or inverted hierarchie ?	→ next gen. oscillations exp.
Majorana or dirac neutrinos ?	→ double beta decay
CP-violation ?	→ next gen. oscillations exp.

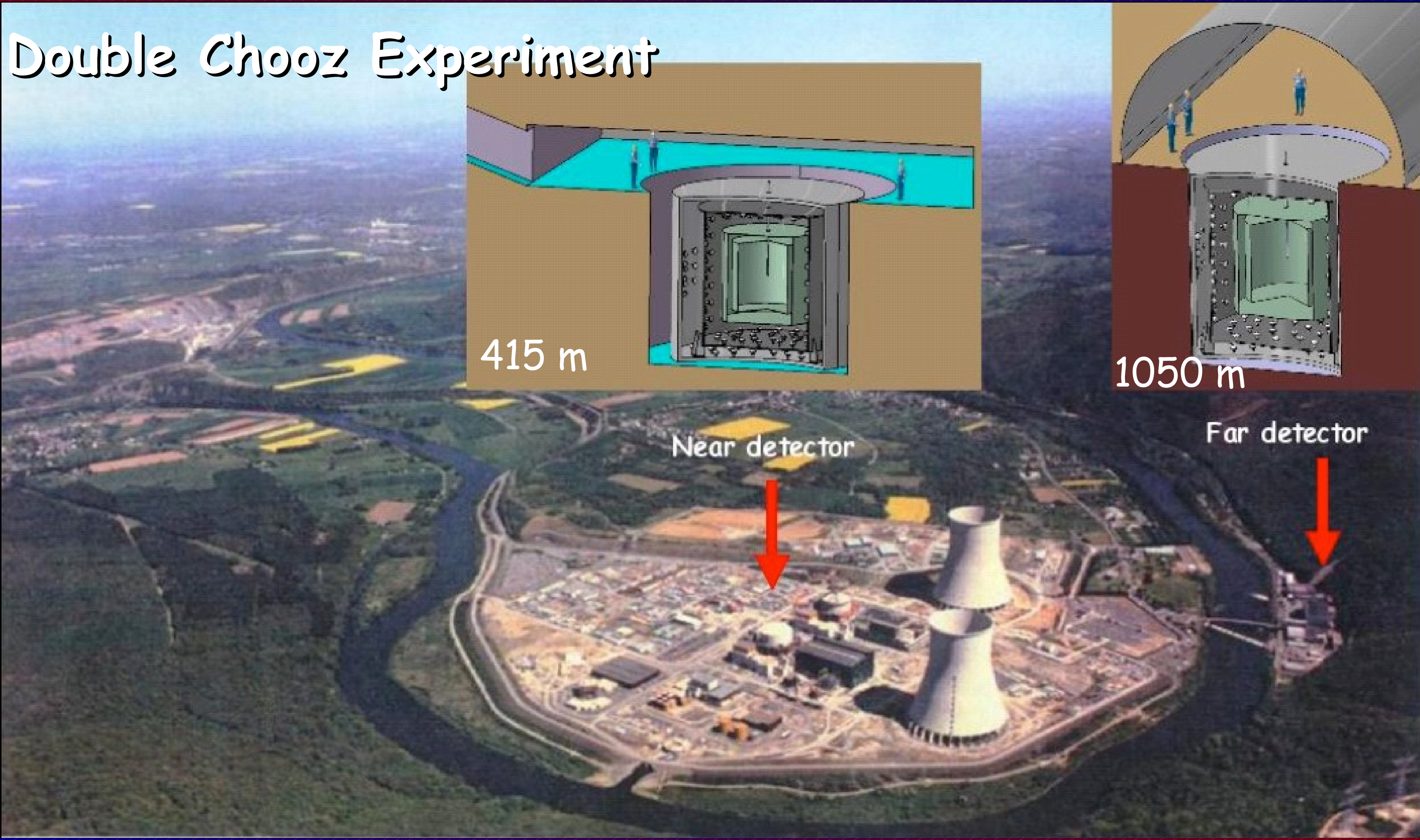
Is the MNS-model correct ?

Double Chooz

Neutrino Sources

Sun	Nuclear Power Plant	Atmospheric Showers	Neutrino Beams
			
0.1 … 10 MeV	1 … 10 MeV	0.1 … 10 GeV	0.1 … 5 GeV
$L_{sol} \approx$ 12 km	$L_{sol} \approx$ 50 km	$L_{sol} \approx$ 15 000 km	$L_{sol} \approx$ 15 000 k
$L_{atm} \approx$ 250 m	$L_{atm} \approx$ 1 km	$L_{atm} \approx$ 250 km	$L_{atm} \approx$ 250 km

Reactor Neutrino Experiment



Neutrino Detection

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

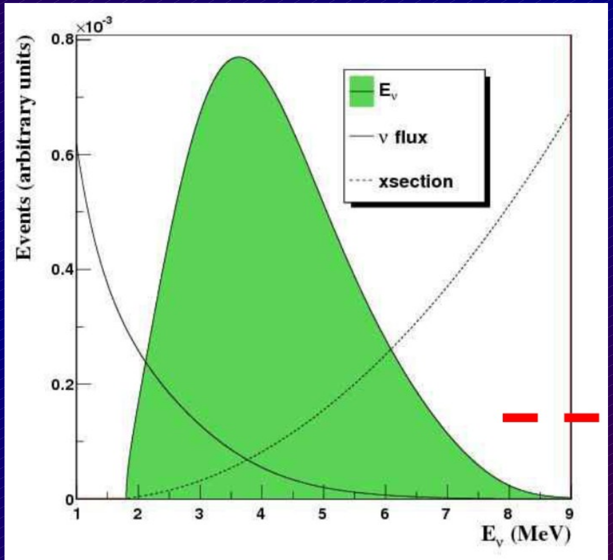
Positron detection:

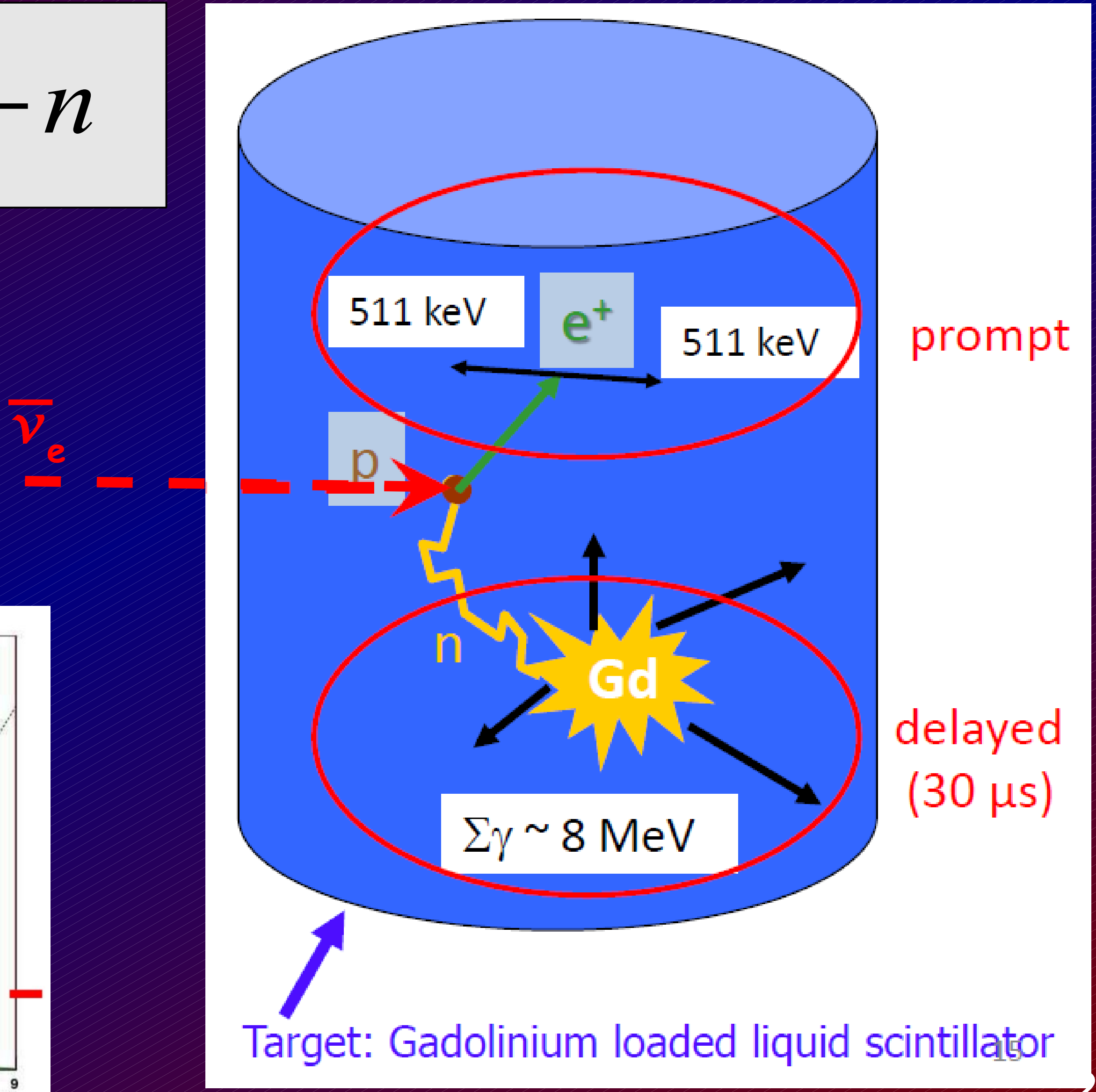
$E_e = E_\nu - Q \rightarrow$ Scint.

$Q = 1.8$ MeV

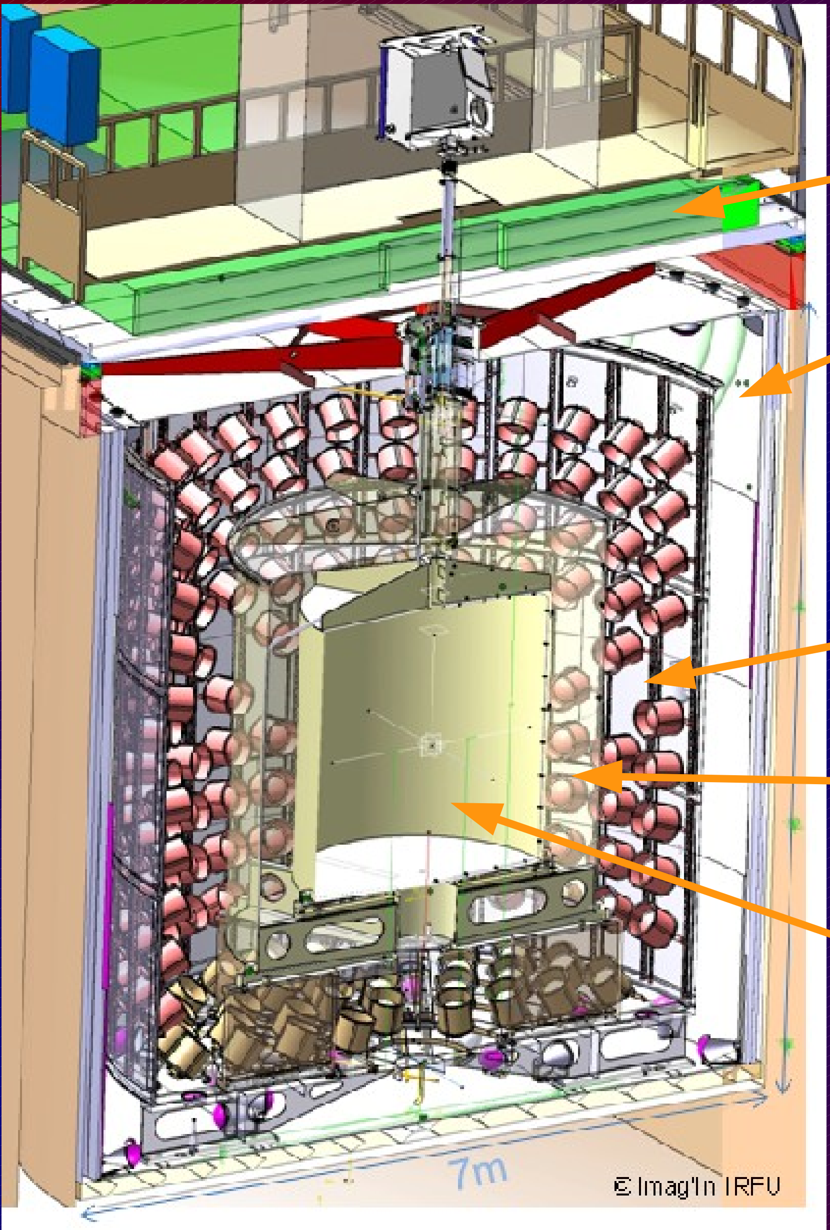
$e^+ \rightarrow \gamma\gamma \rightarrow$ Scint.

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



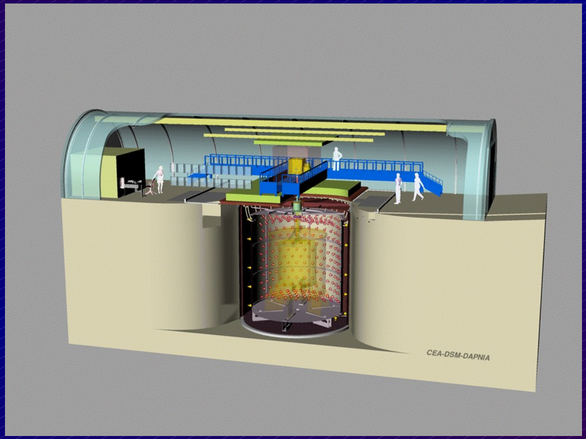


The Detectors



Outer Veto RPC

Inner Veto
mineral oil
scintillator

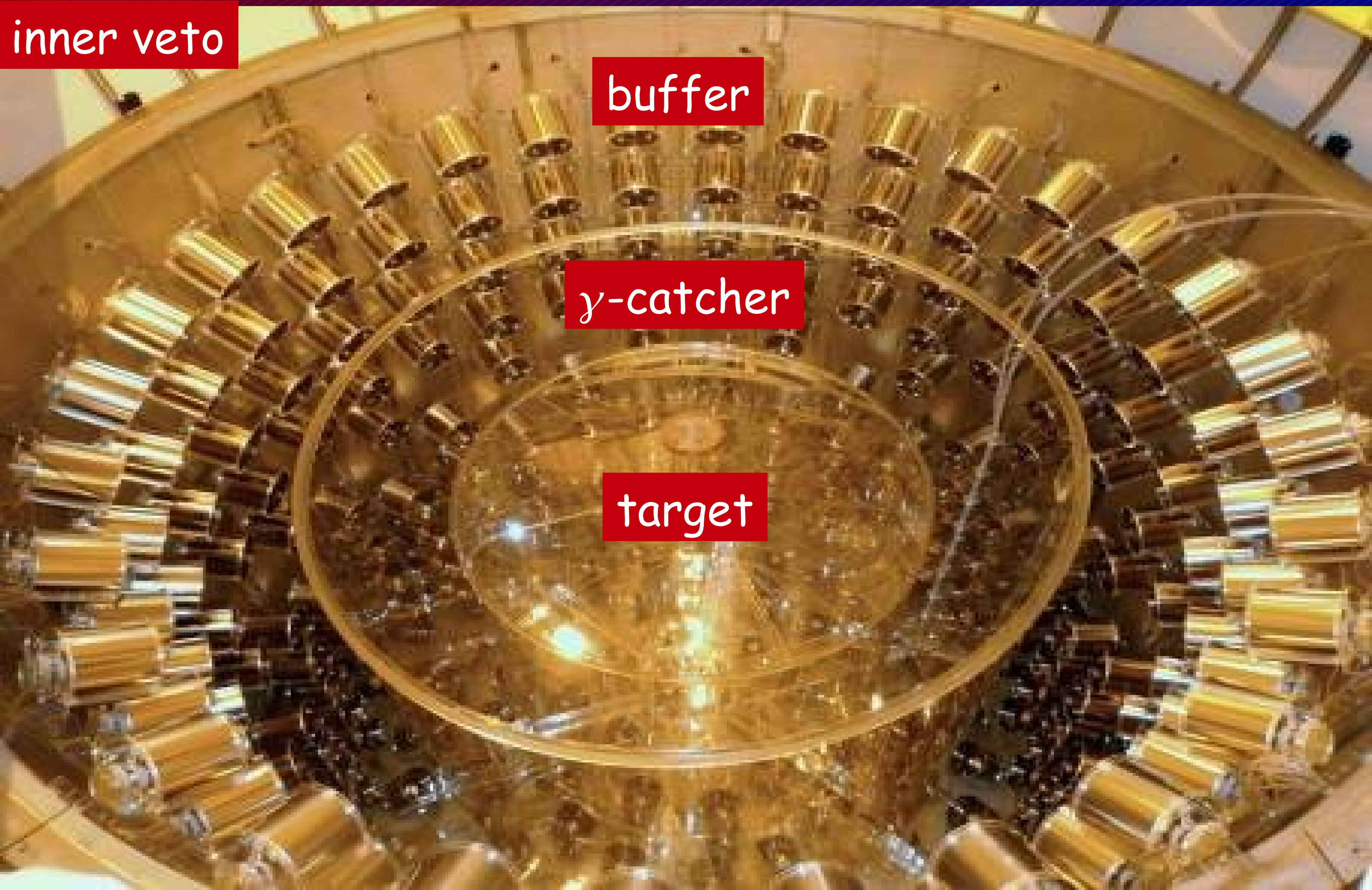


Buffer
mineral oil

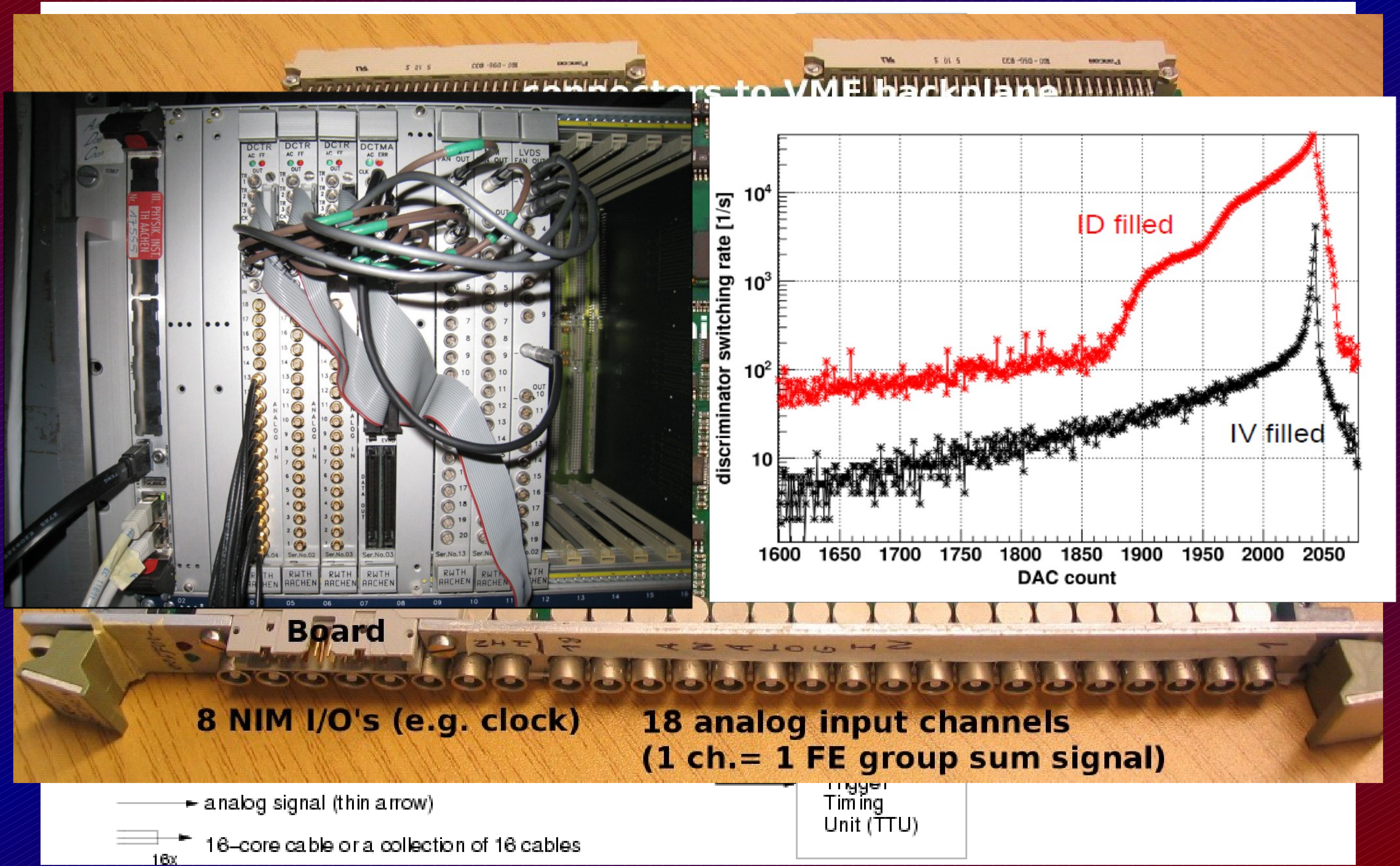
gamma catcher
20% PXE
80% Dodekan

Inner Target
20% PXE
80% Dodekan
0.1% Gd

The Detectors



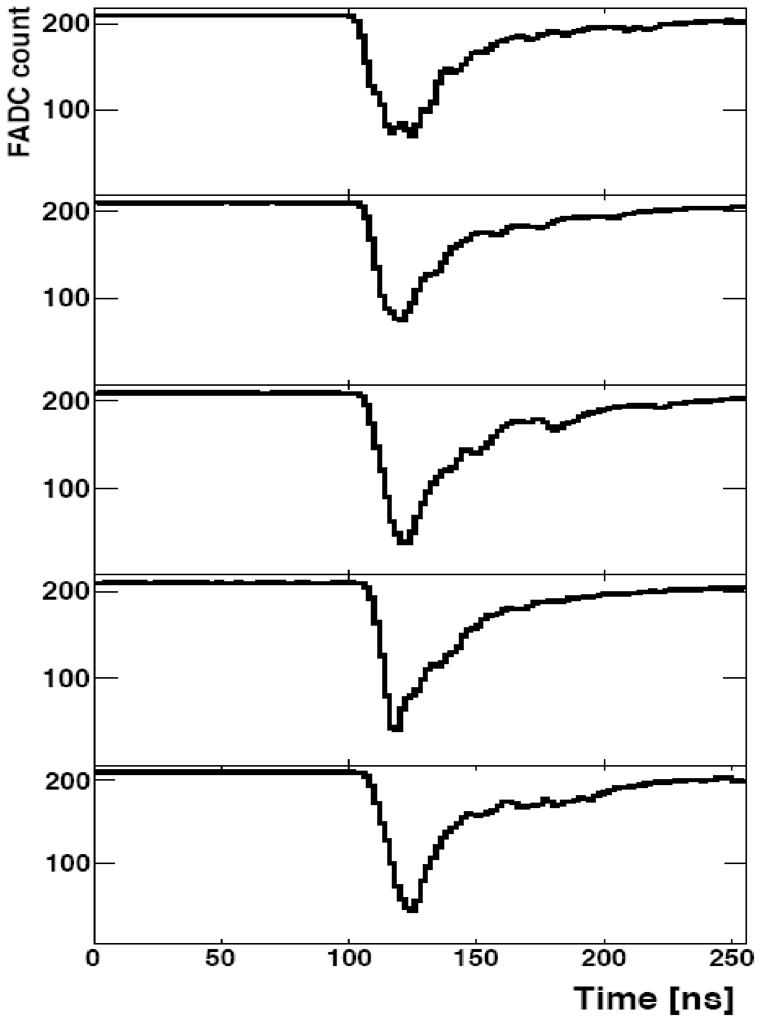
Trigger



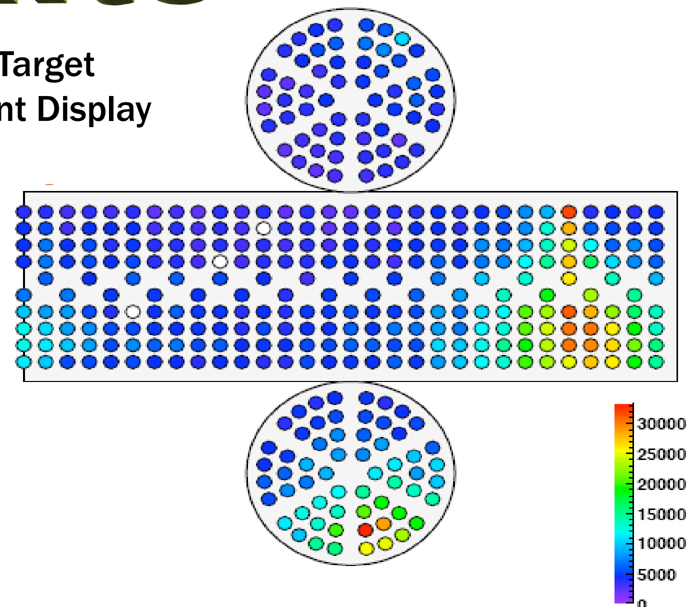
connectors to VME backplane
DCTR
DCTR
DCTR
DCTMA
LVDS
RWTH AACHEN
III. PHYSIK. INST. TH AACHEN
discriminator switching rate [1/s]
10^4
10^3
10^2
10
ID filled
IV filled
1600
1650
1700
1750
1800
1850
1900
1950
2000
2050
DAC count
Board
8 NIM I/O's (e.g. clock)
18 analog input channels
(1 ch.= 1 FE group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

First Events

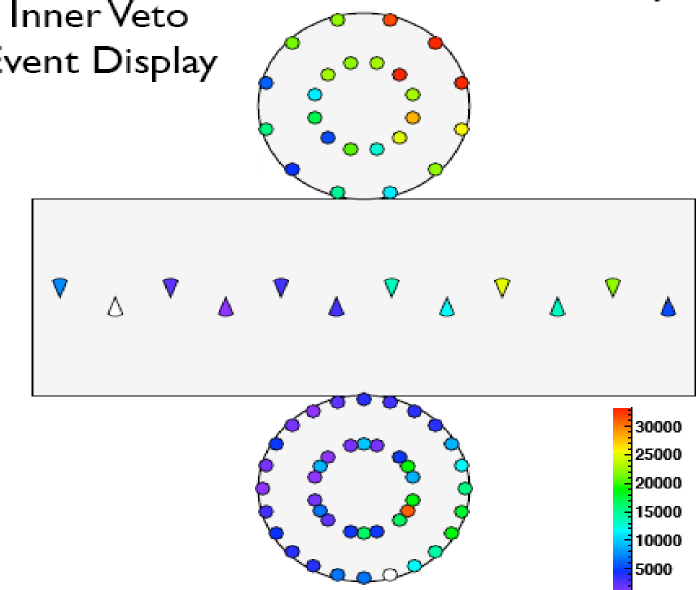
Inner Detector Waveforms



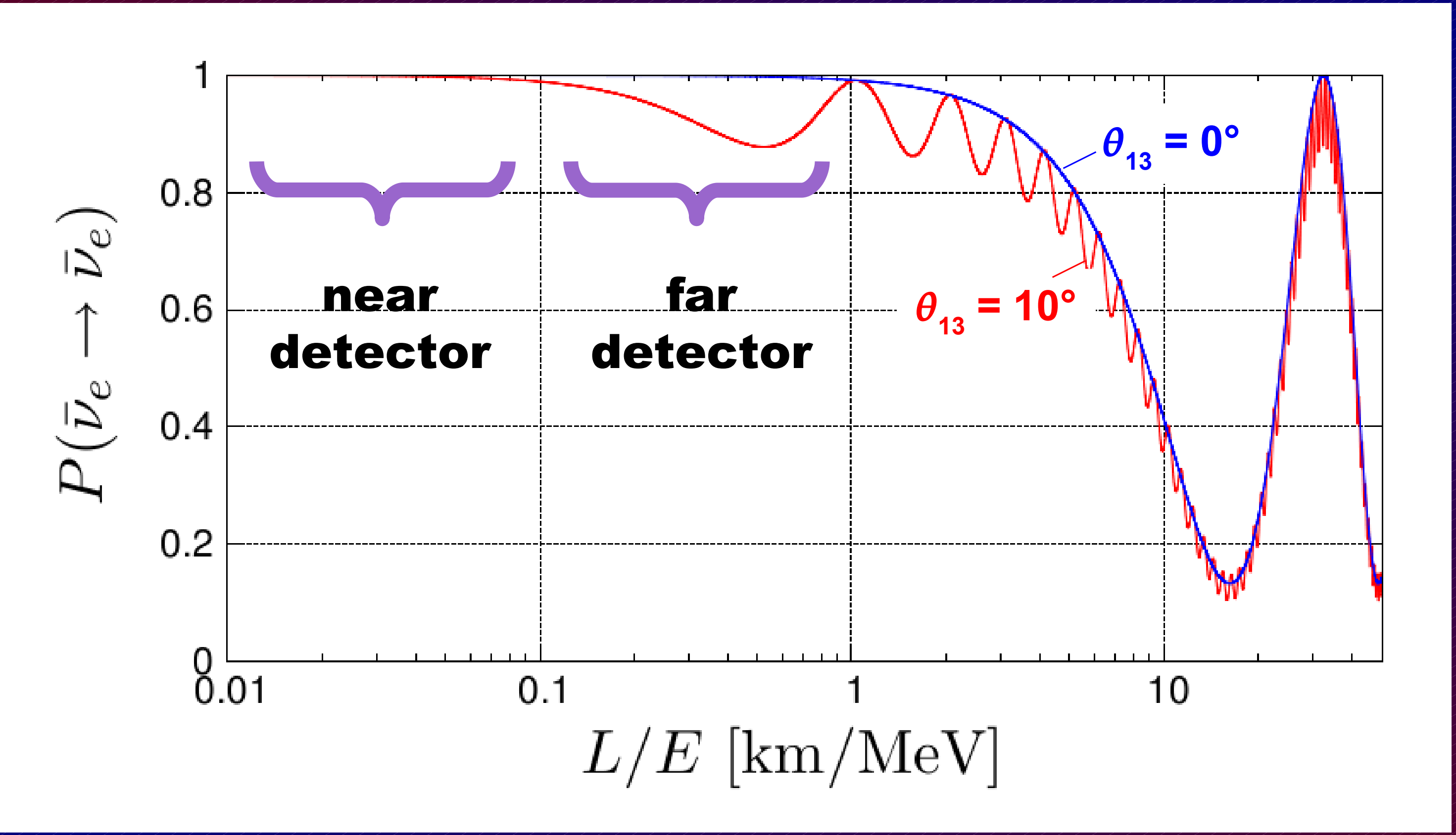
Target Event Display

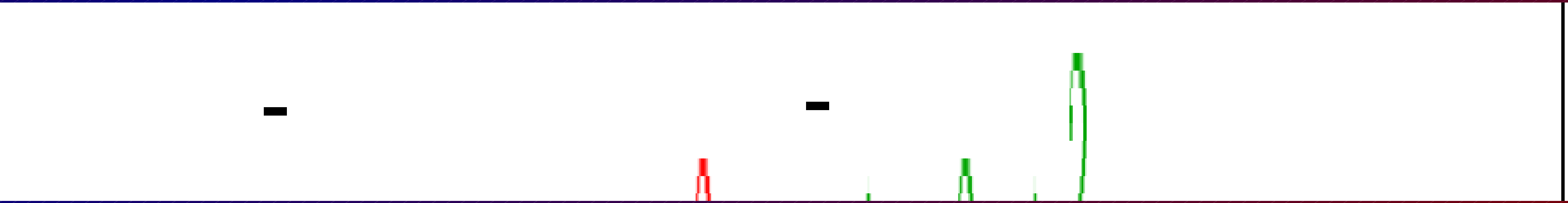


Inner Veto Event Display

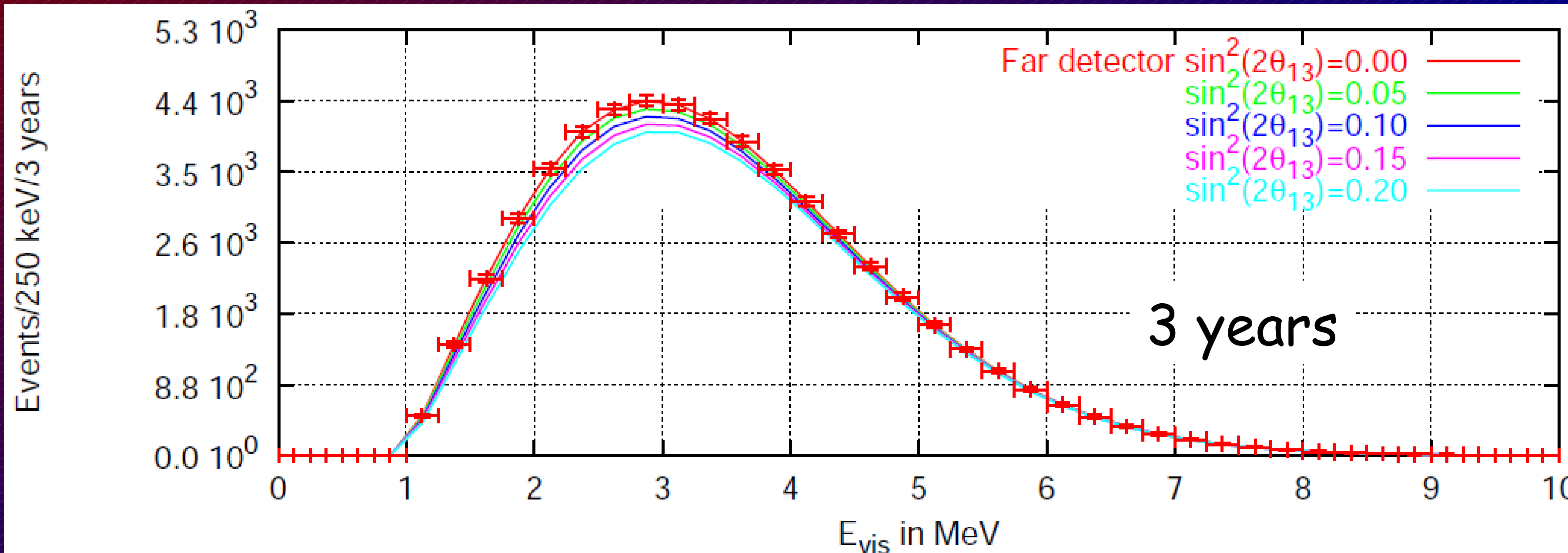


Neutrino Oscillations





Neutrino Oscillations

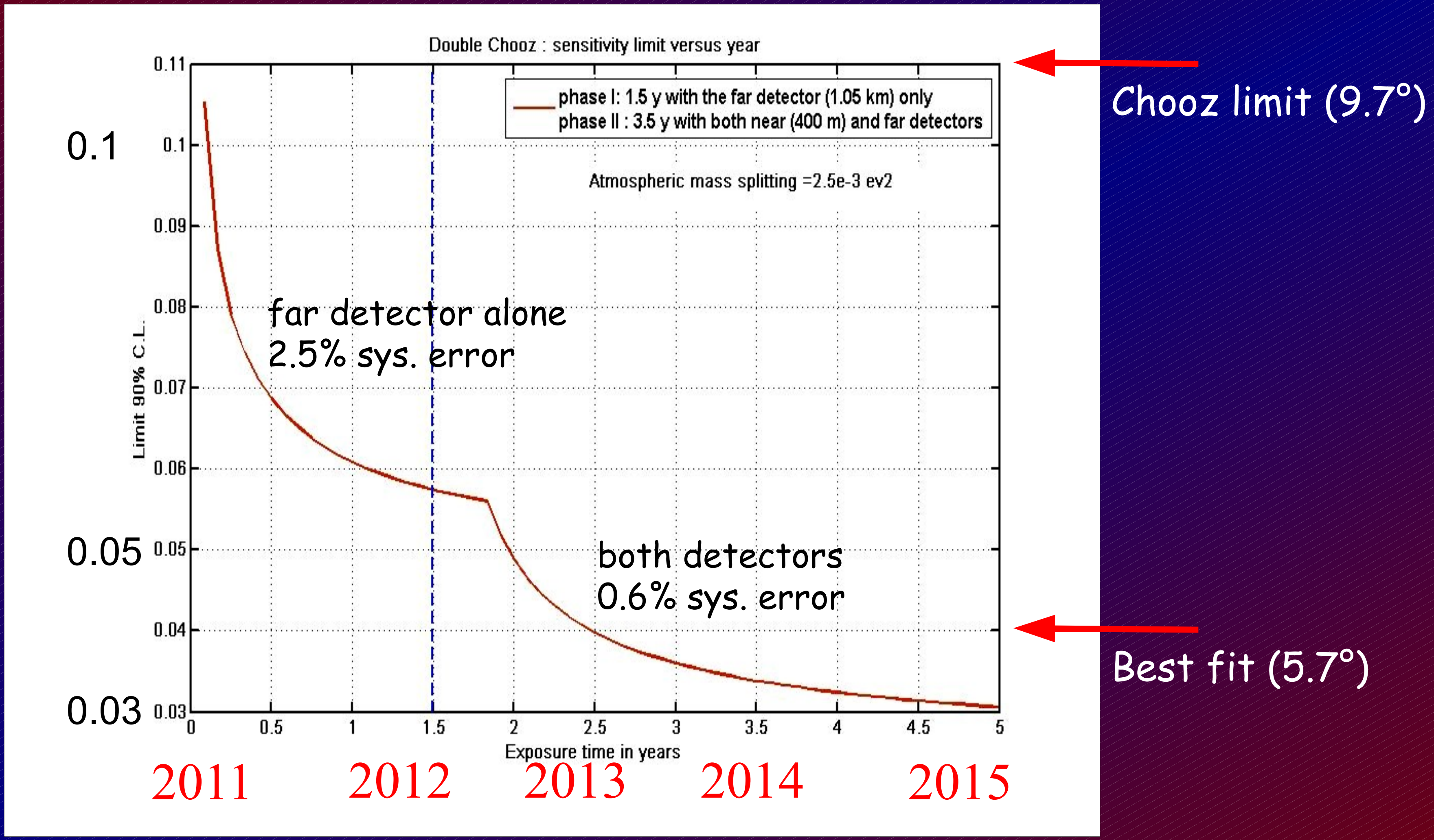


Result of θ_{13} is only a small effect

- high statistics
  - Near detector: ~300/day
  - Far detector ~60/day $\approx$ 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

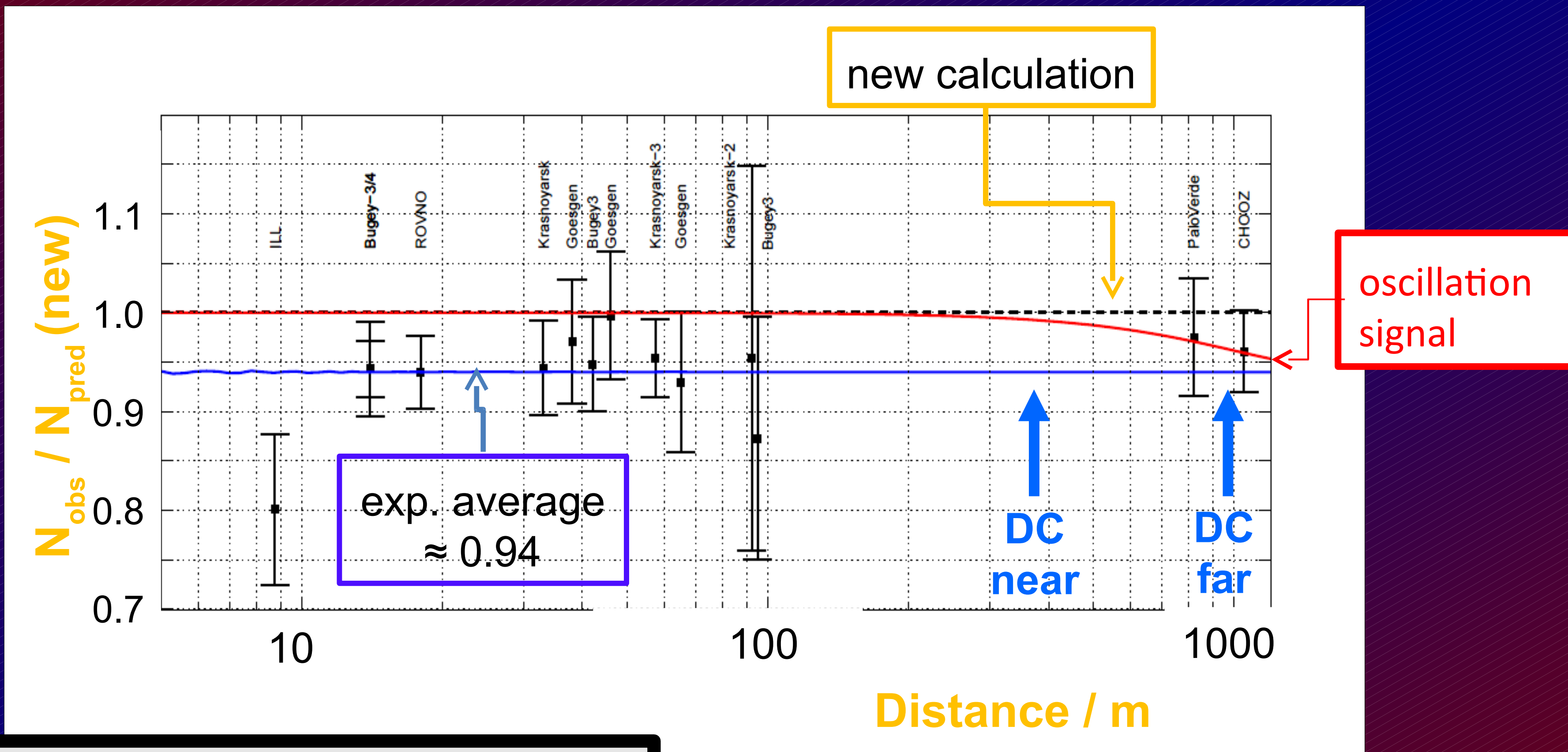
Sensitivity

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



Reactor Neutrino Anomaly ?

New calculation of neutrino flux from reactors

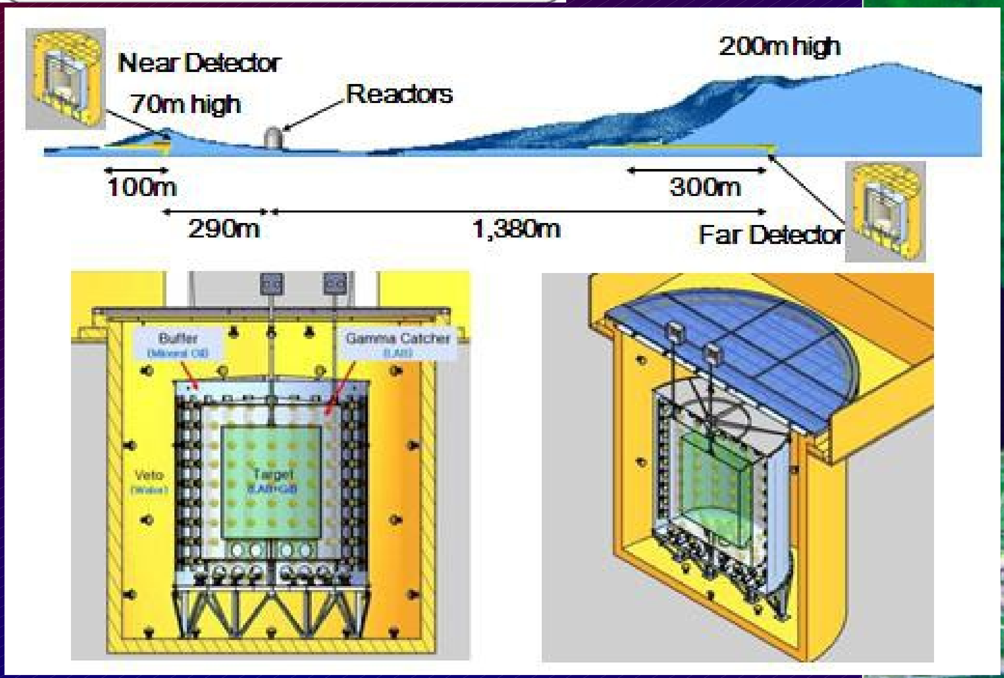


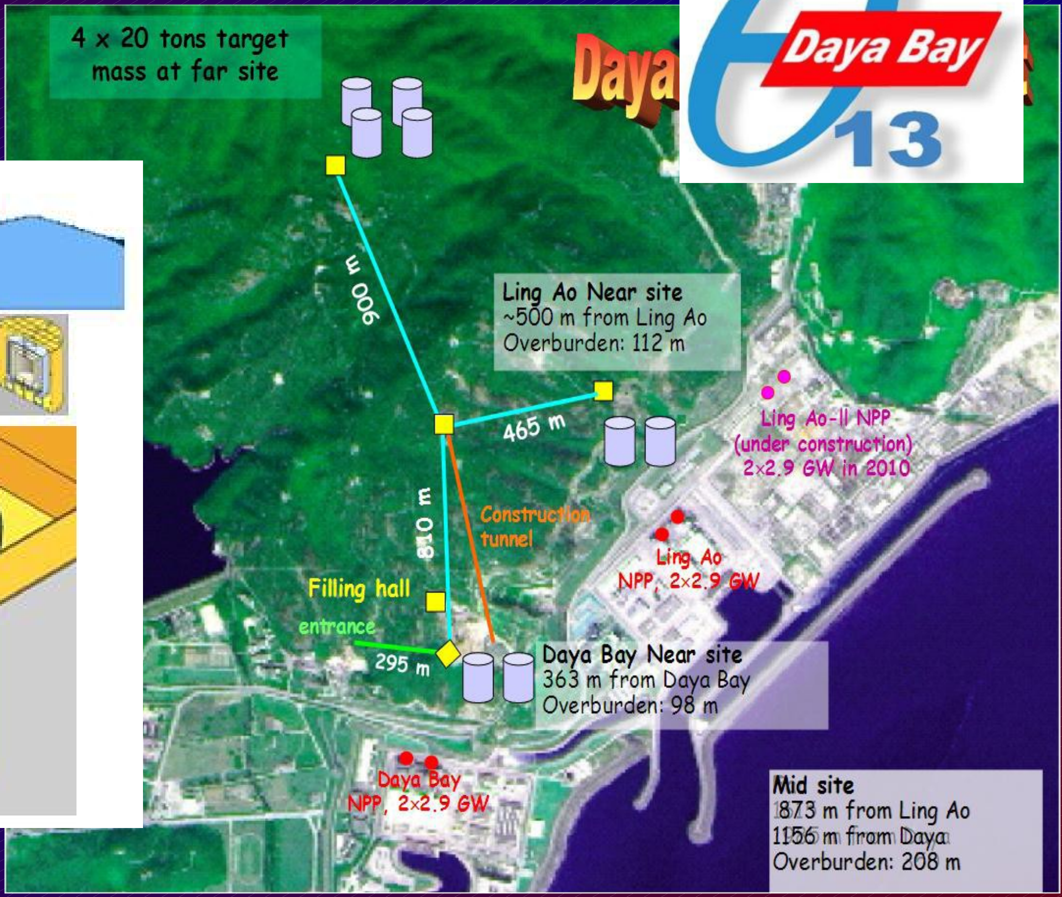
Difficult to interpret as neutrino oscillations

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

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

Reaktor-Experiment





Korea: starts 2011

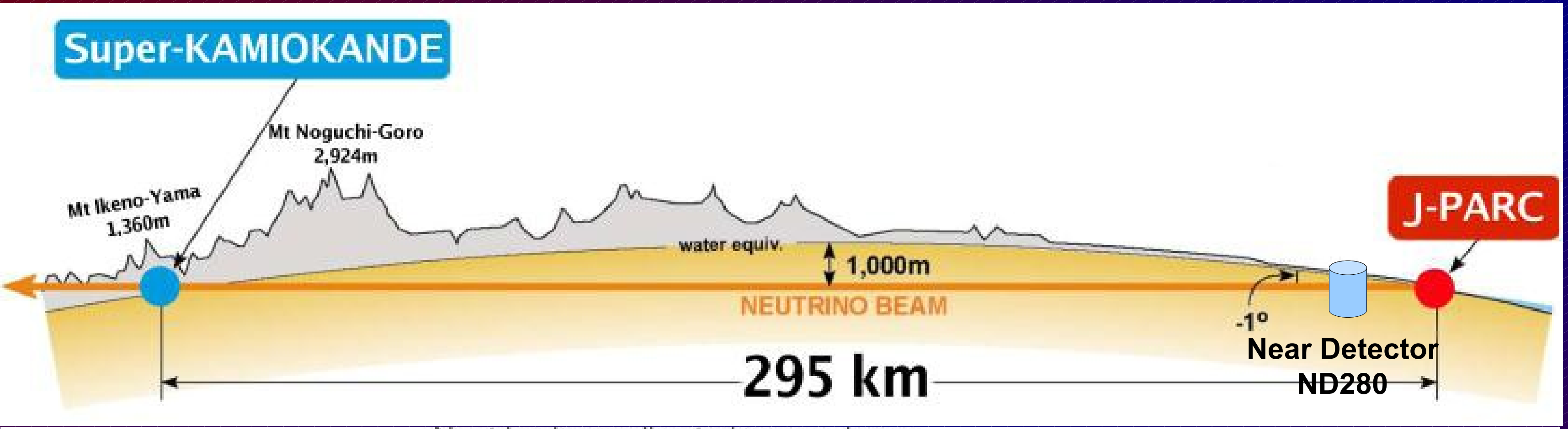
China: starts 2011/12

T2K

The T2K Experiment

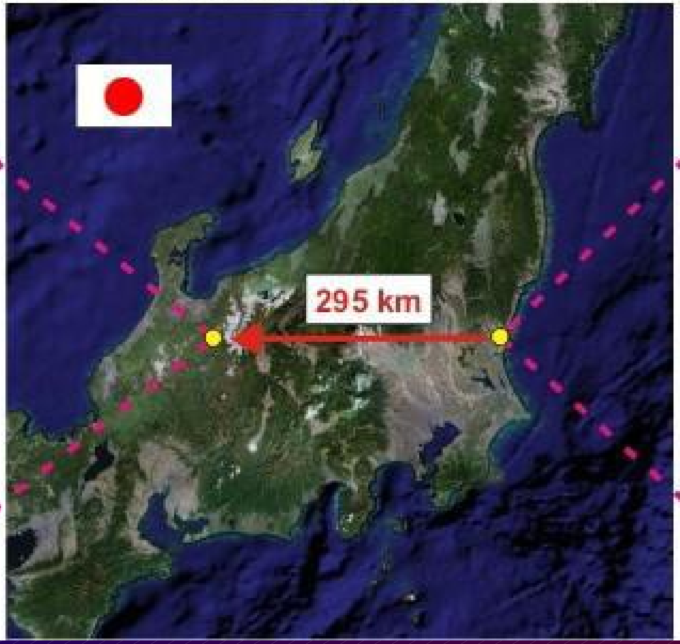
ν_μ-disappearance (Δm^2_{23}, $\sin\theta_{23}$)

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

Tokyo

Earthquake

Some damage on the surface

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

No (vis.) damage underground

Working on recovery plan

Tsunami

J-PARC

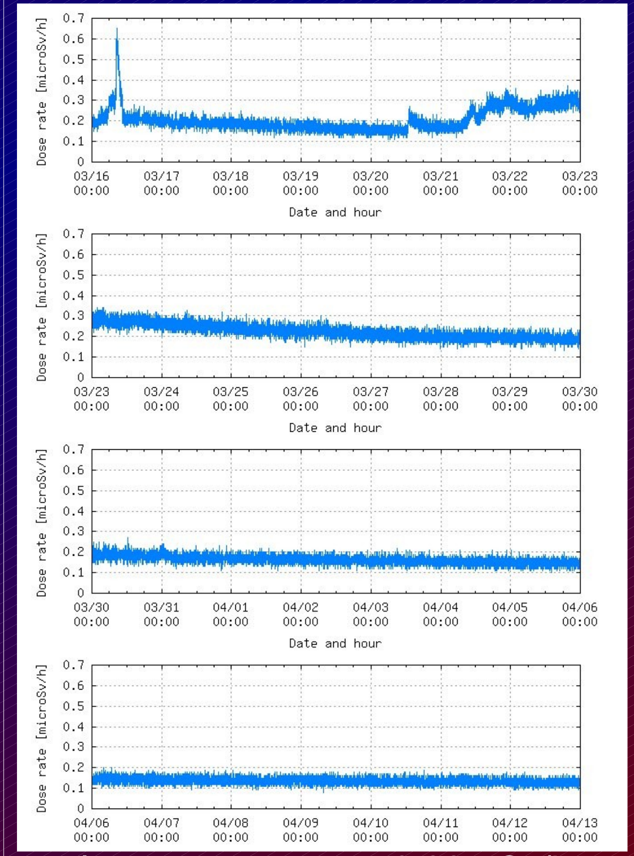
located directly on the beach
≈ 15m above sea level

Tsunami @ J-PARC
≈ 13 m high

No damage!

Reactor Accident

Dose at KEK

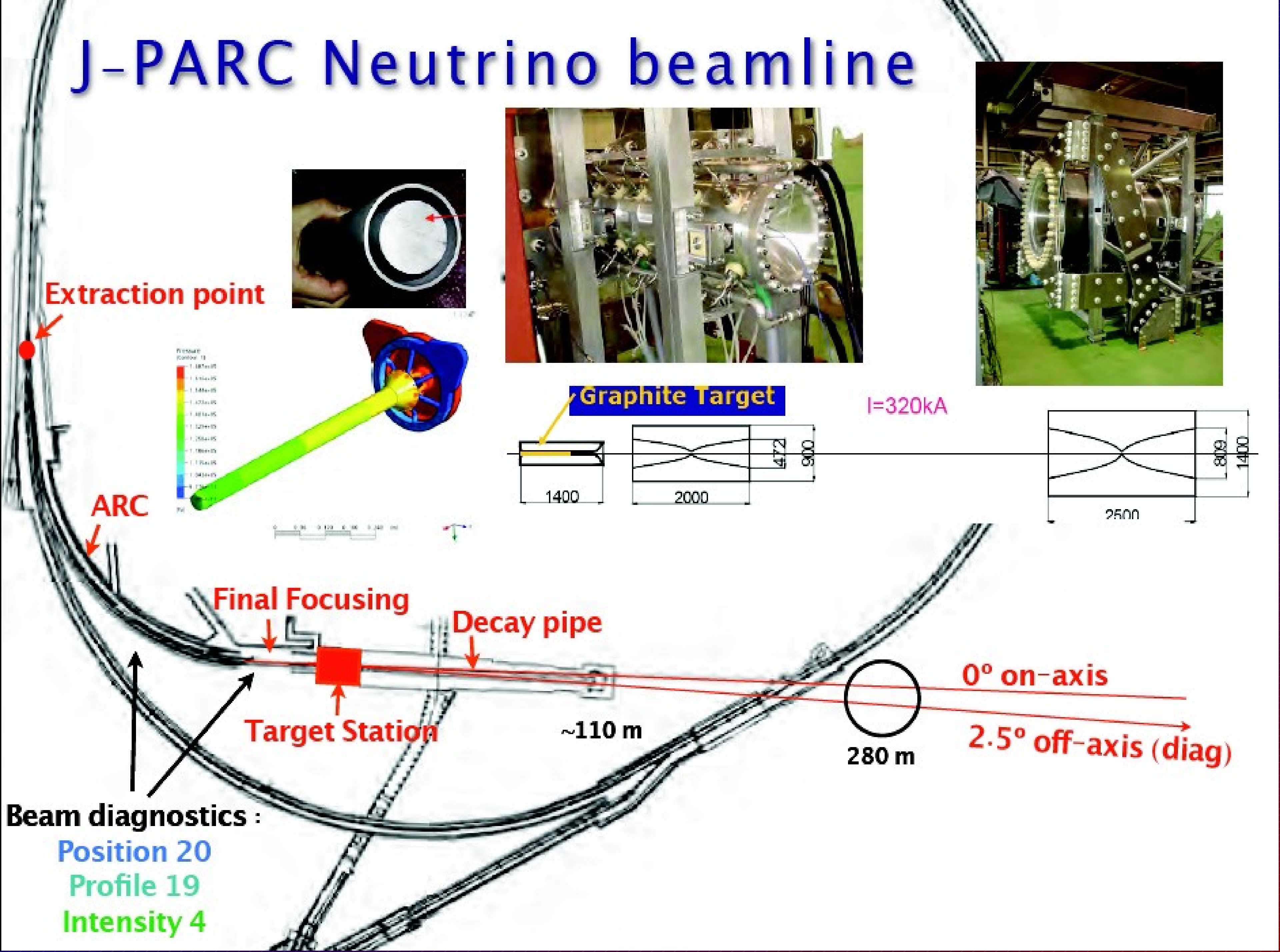


longterm average: 0.08 μSv/h

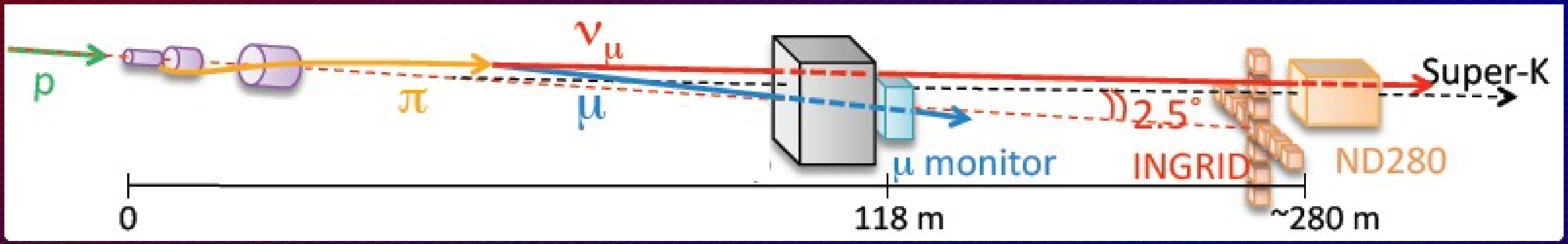
Nothing serious (yet)!

Accelerator Complex

J-PARC Neutrino beamline



Off-Axis Beam



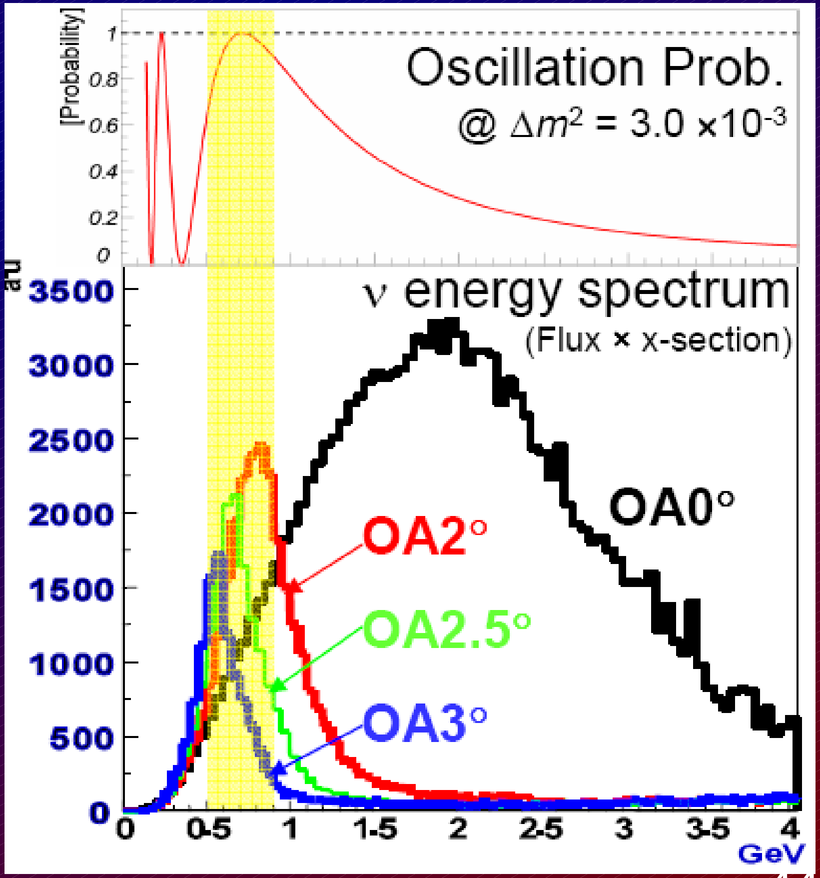
Off-Axis Beam

high intensity at maximum oscillation

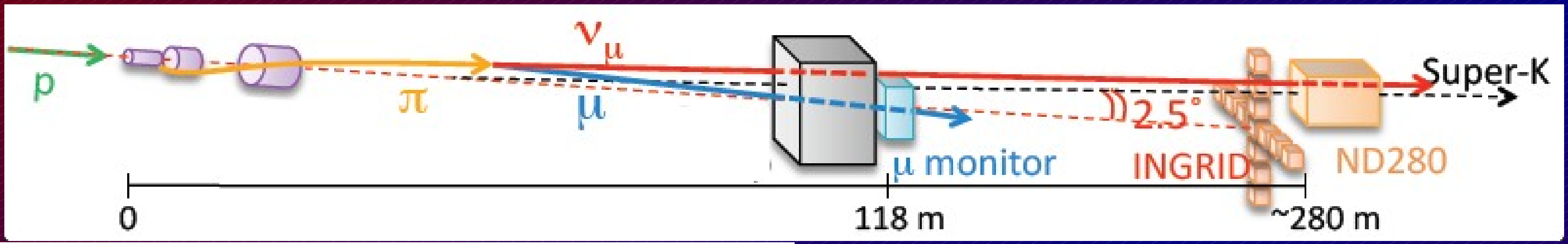
INGRID: on-axis

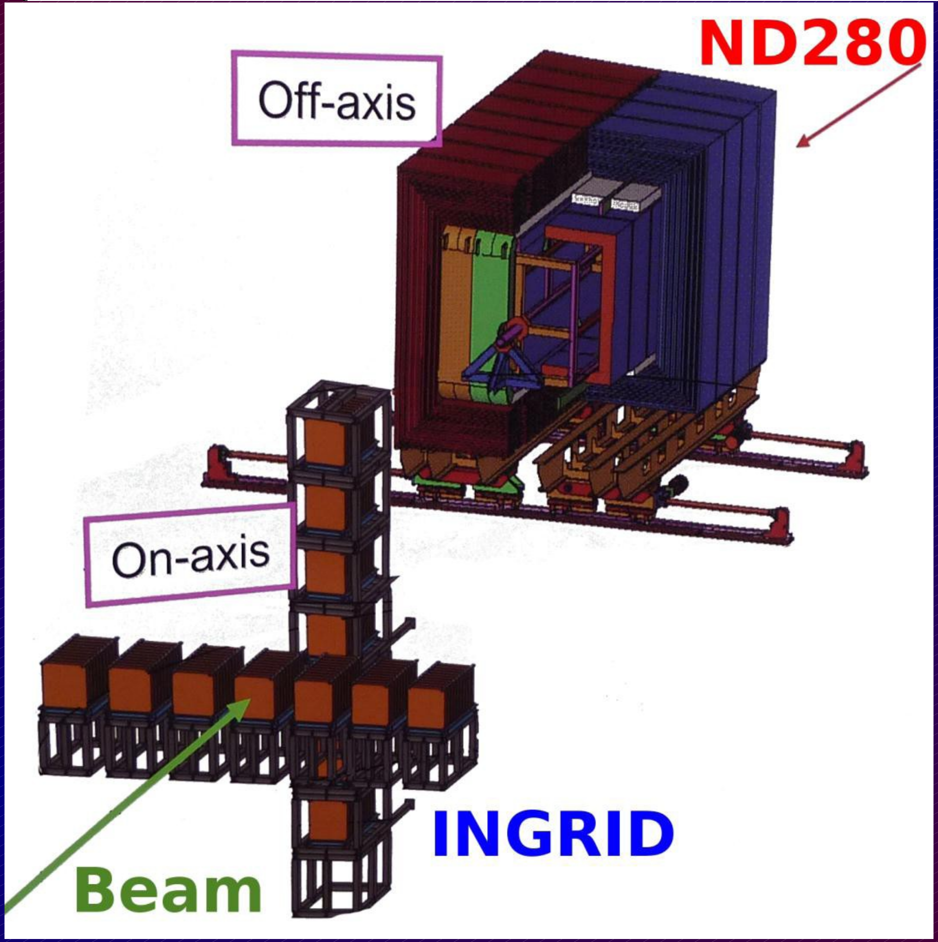
ND280: 2.5° off-axis

SUPER-K: 2.5° off-axis



Near Detectors





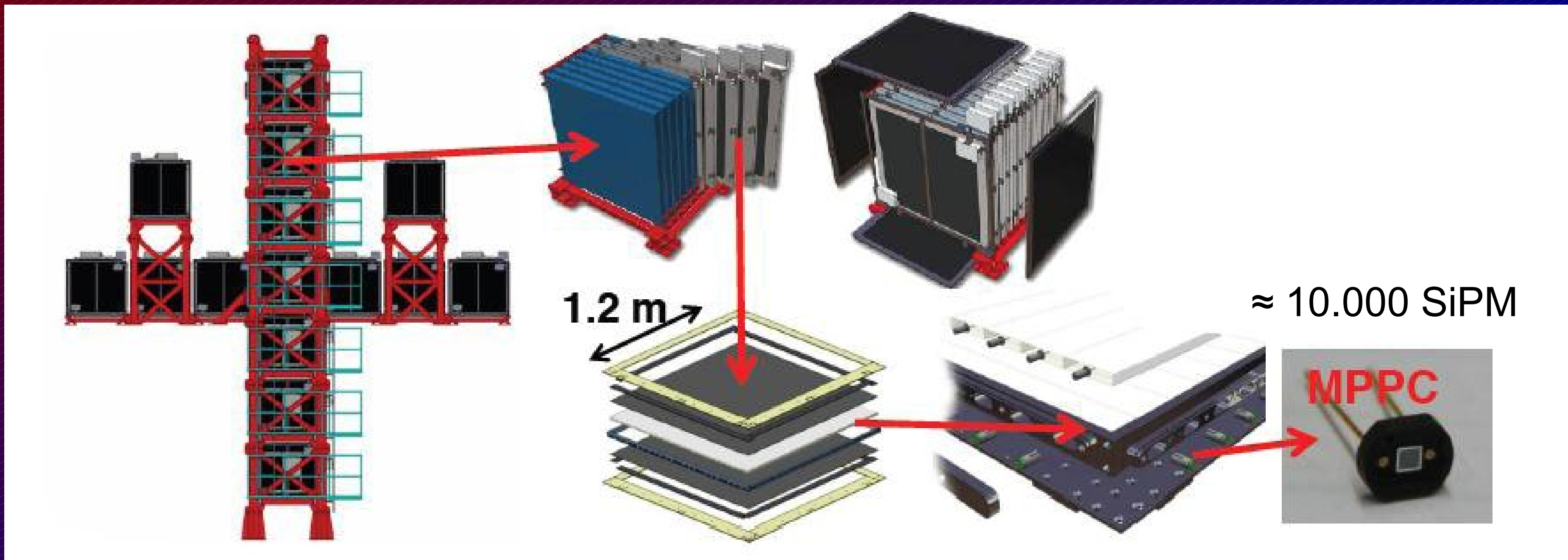
ND280

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

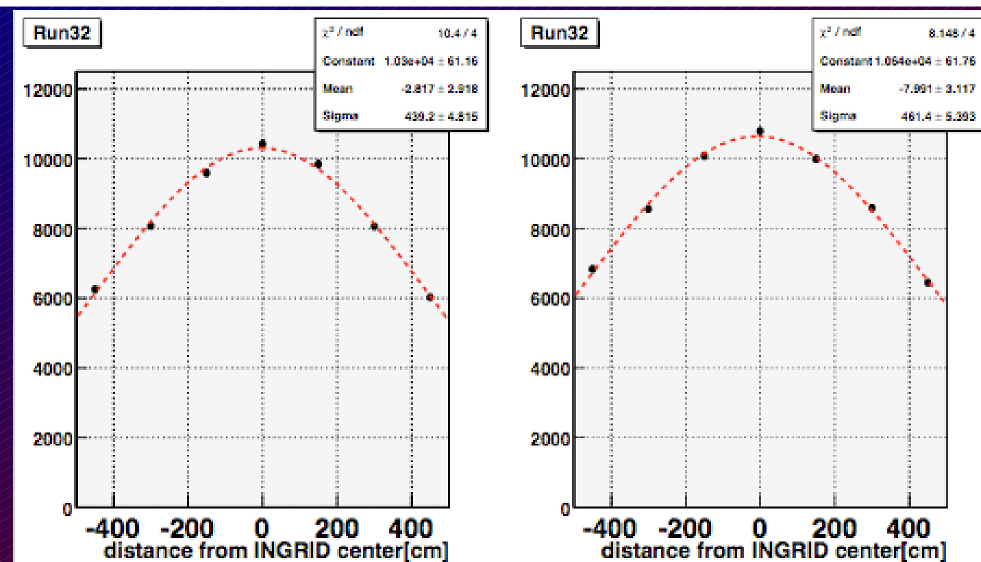
INGRID

- iron/scintillator calorimeter
- beam profile
- bunch timing

Interactive Neutrino GRID



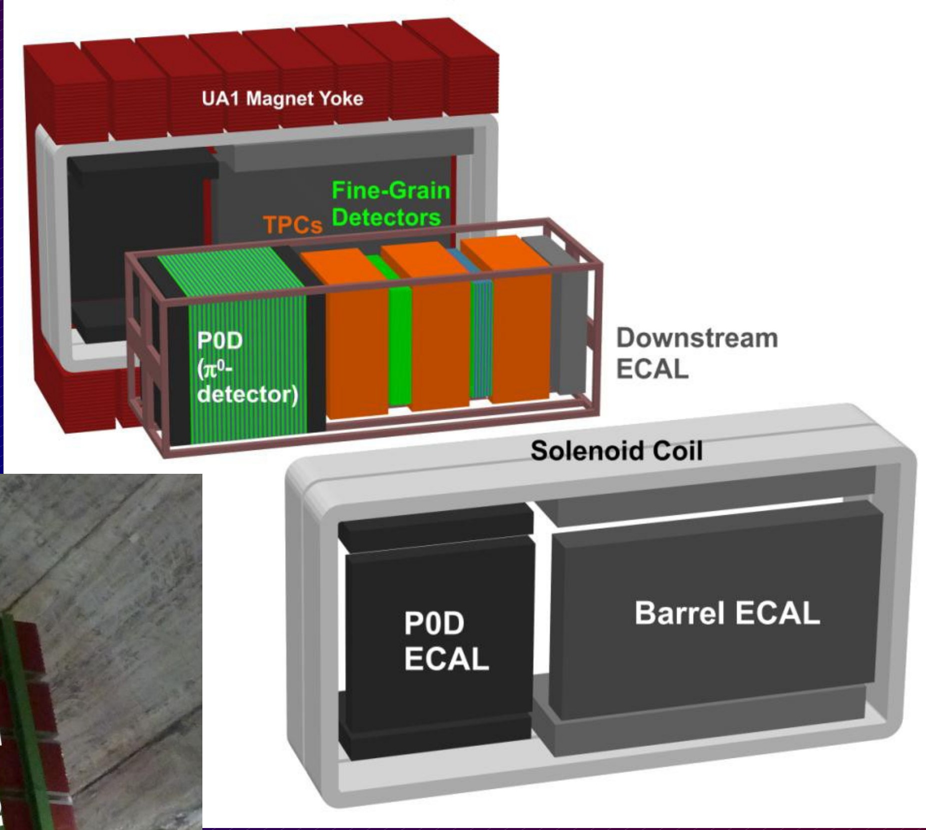
14 iron/scint. modules
X-Y scintillator layers
700 ν interactions/day @ 50 kW
beam direction better: 1 mrad
→ corresponds to 2% change
in flux at Super-K

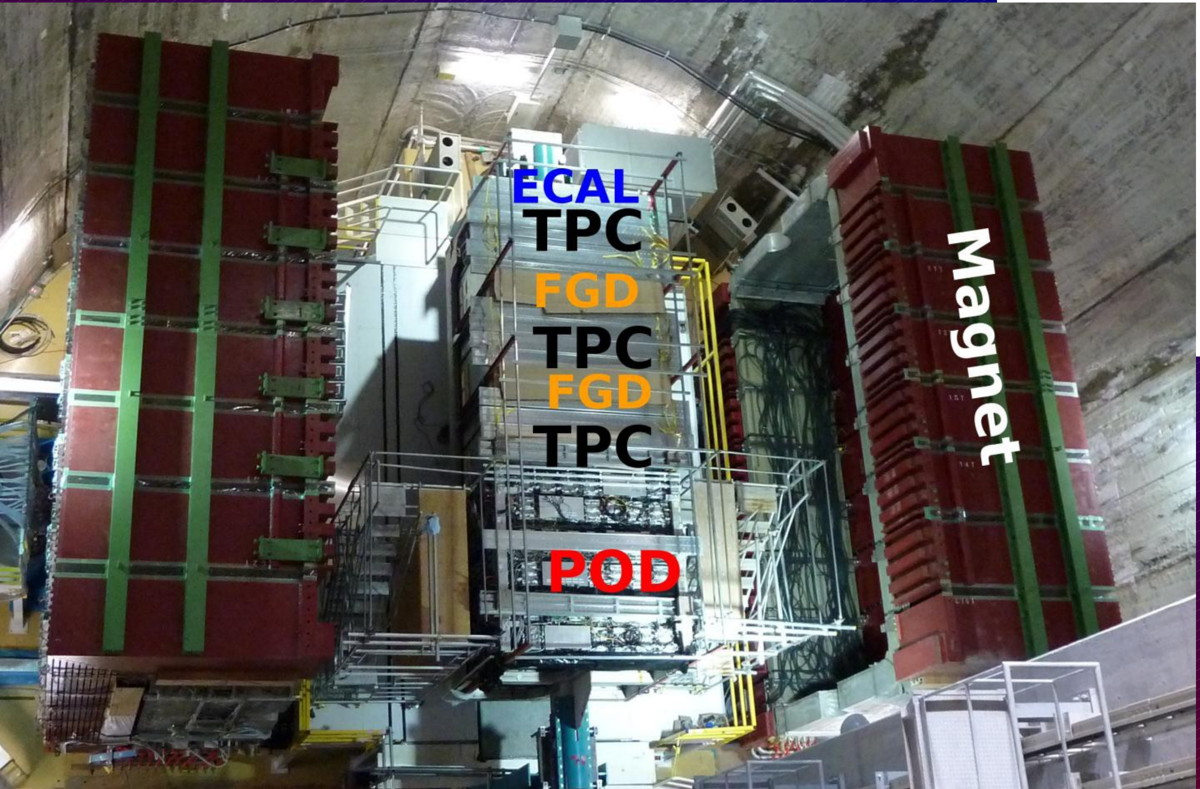


Near Detector ND280

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)

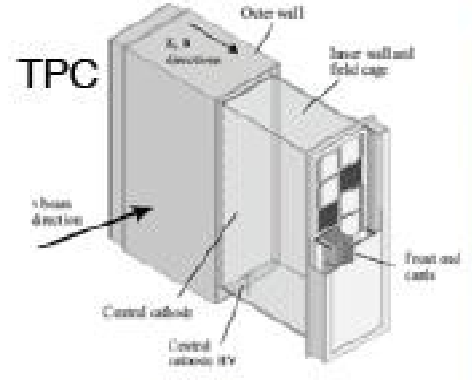


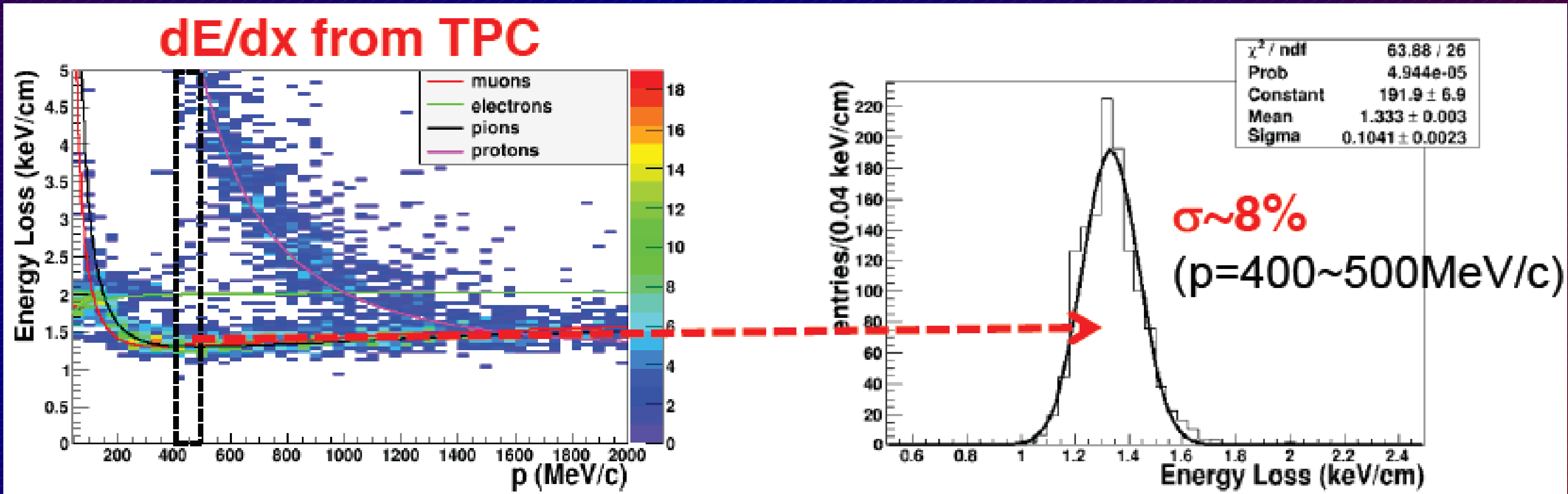


TPC

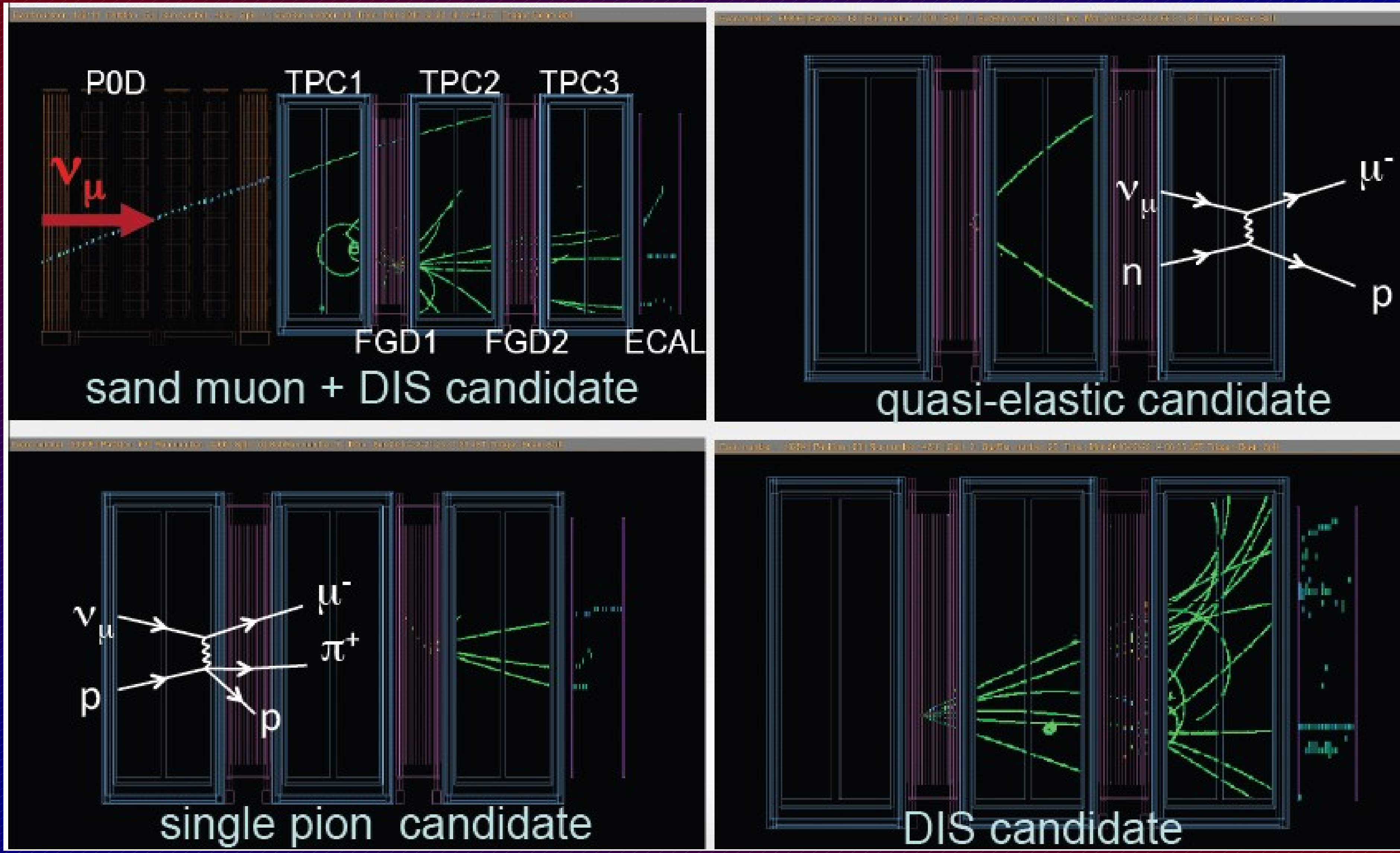
Large TPC

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





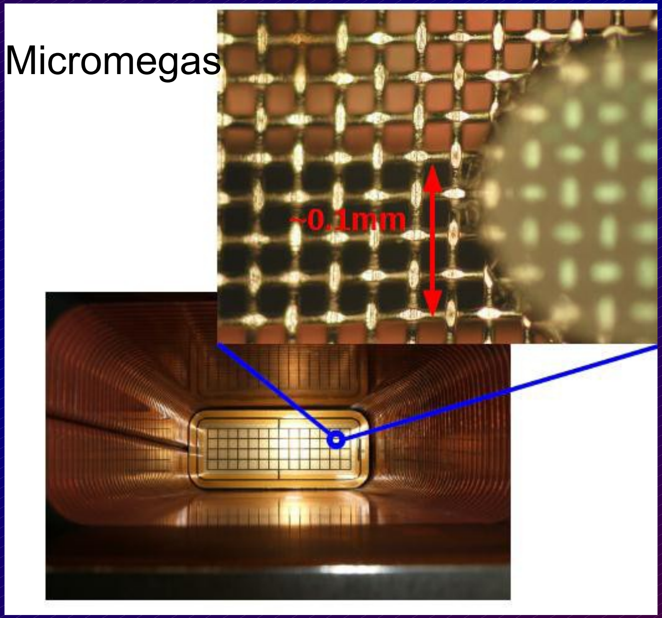
ND280 Event Galery



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

RWTH Aachen: TPC Monitor Chambers

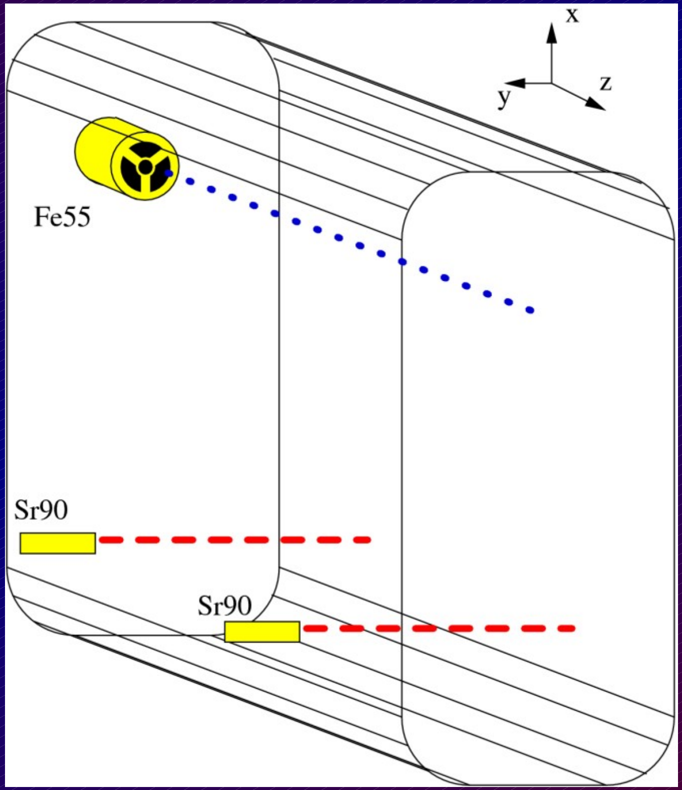


Gain Measurement

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

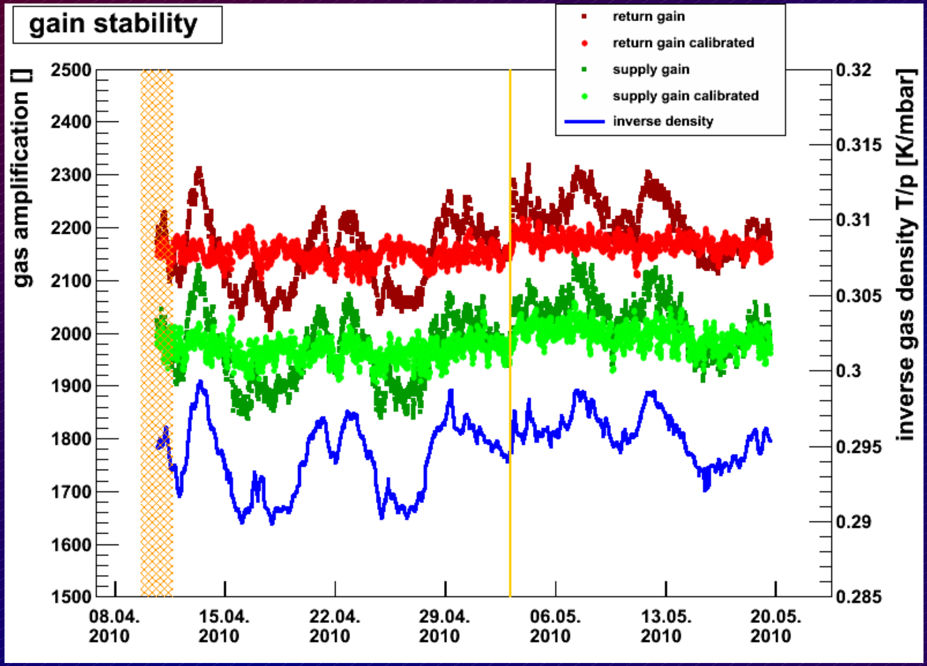
Drift Velocity

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

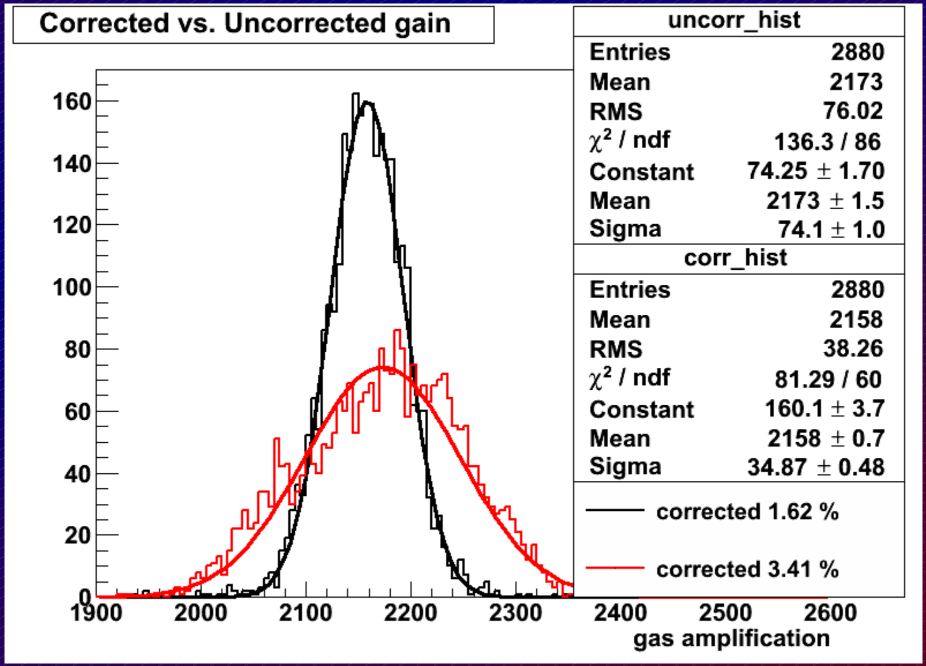


RWTH Aachen: TPC Monitor Chambers

Gain Monitoring



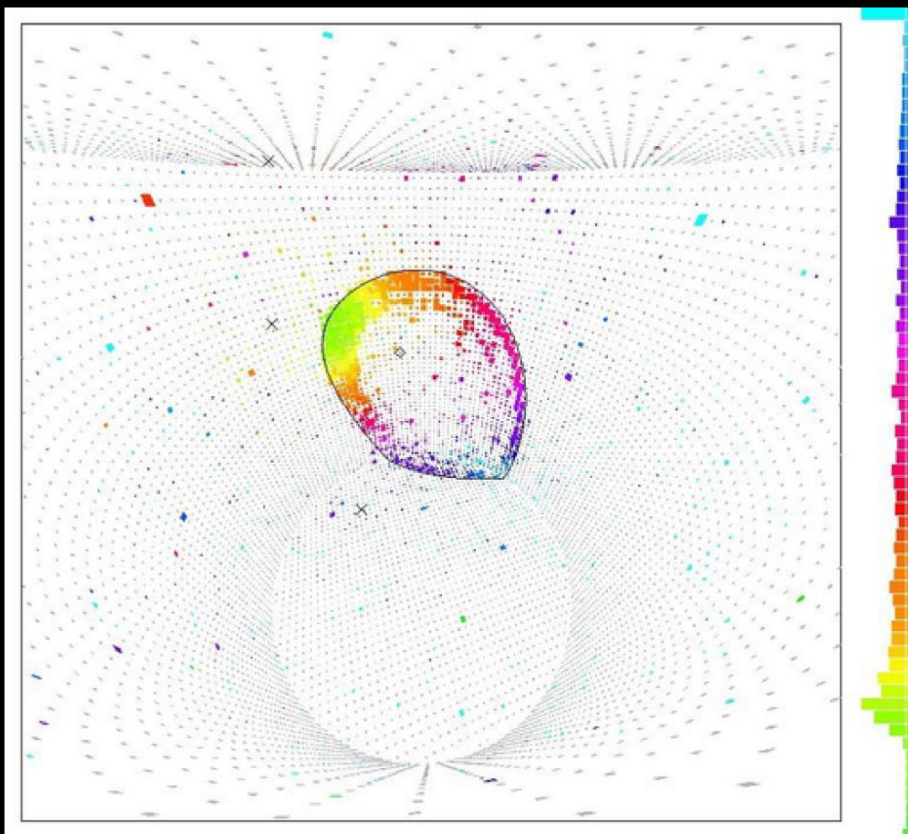
Gain Correction



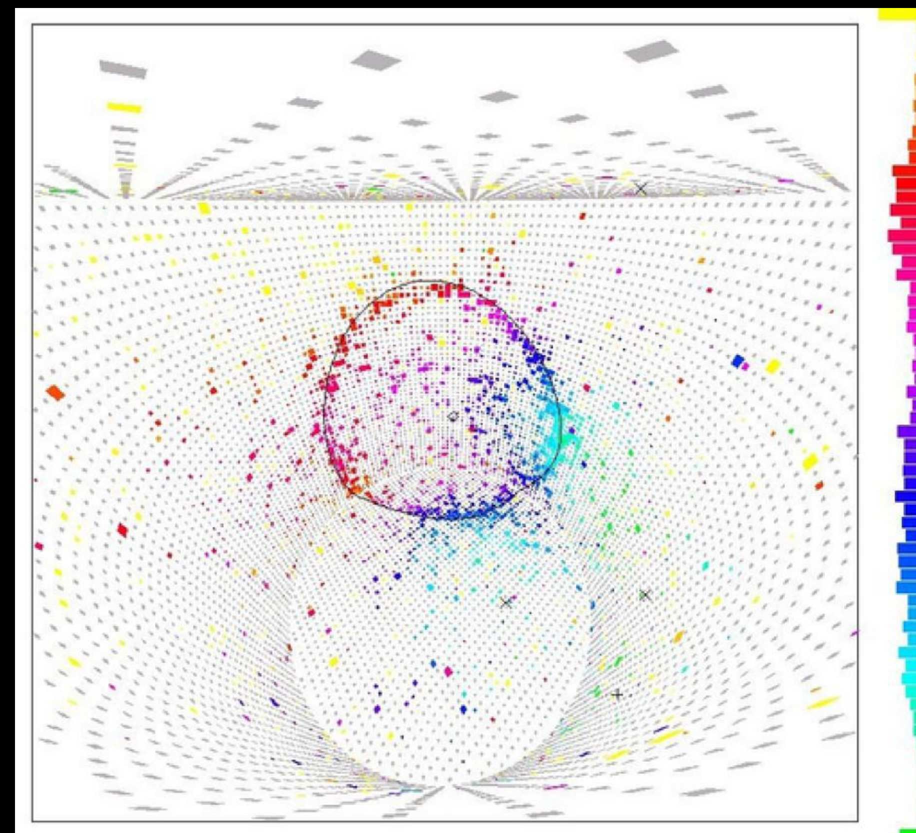
Super-K

50 kt water Čerenkov detector

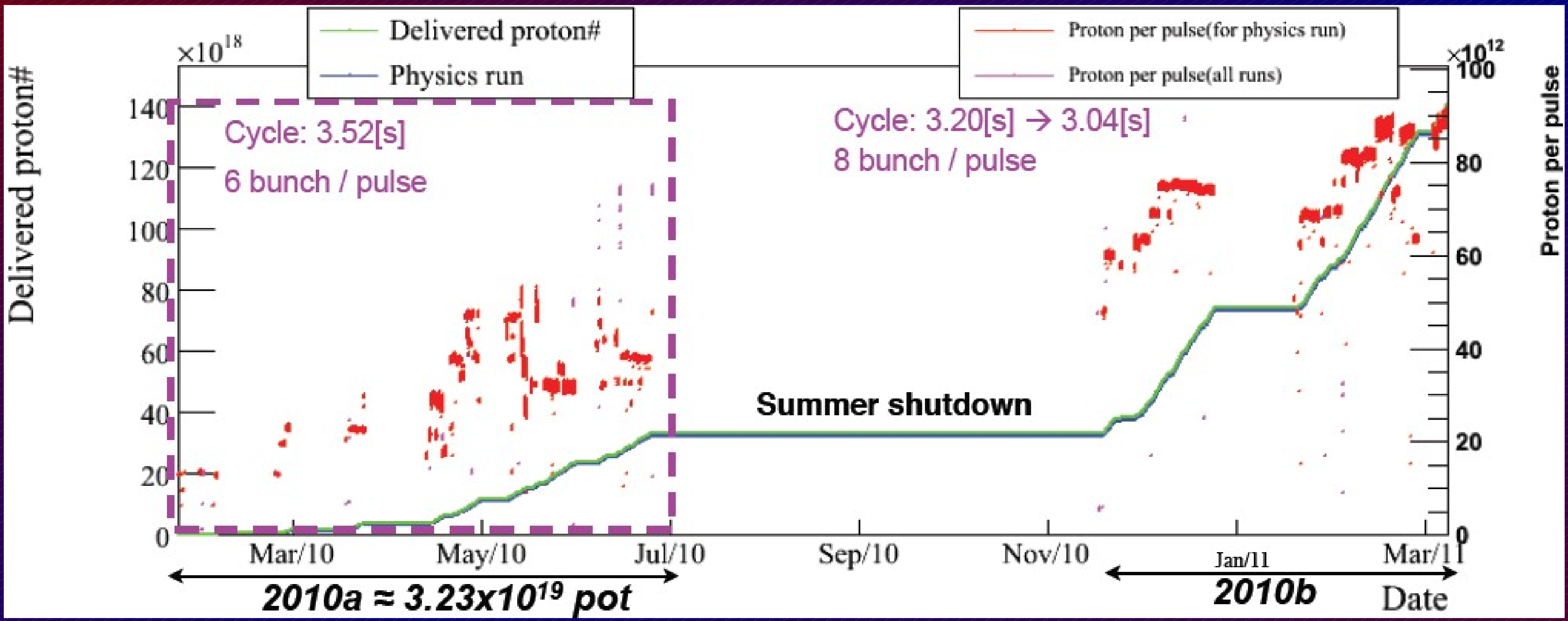
muon-event



electron-event



T2K: Running



Very successfull startup & running

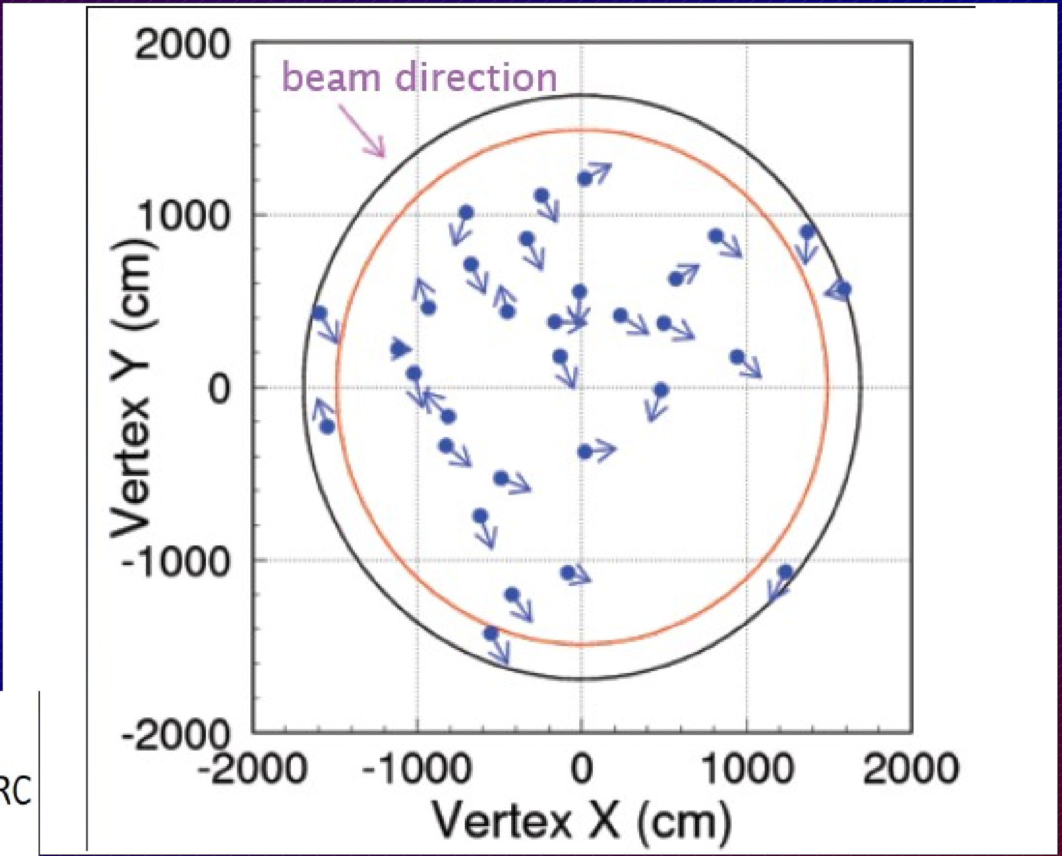
Run 2010a: (Jan. 10 - Jun. 10): 3.23 10^{19} p.o.t. → preliminary results

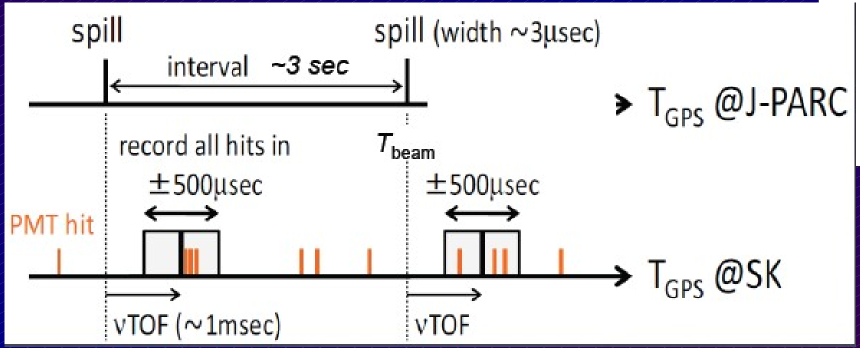
Run 2010b: (Nov. 10 – Mar. 11): 1.45 10^{20} p.o.t. → to be analyzed

(run 2010b terminated by earth quake)

T2K: Timing

- Baseline measurement (Survey)
  - $L = 295{,}335 \pm 7$ m
    → ToF of ν = 985.132 ± 0.02 μsec (≡ νTOF)
  - Expected event timing @ SK (≡T_{SK})
    = Spill timing @ Tokai (≡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





Analysis Overview

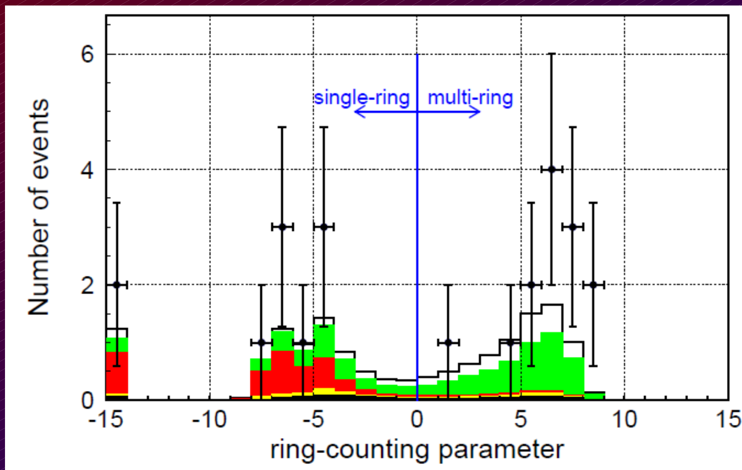
6 Analysis Steps

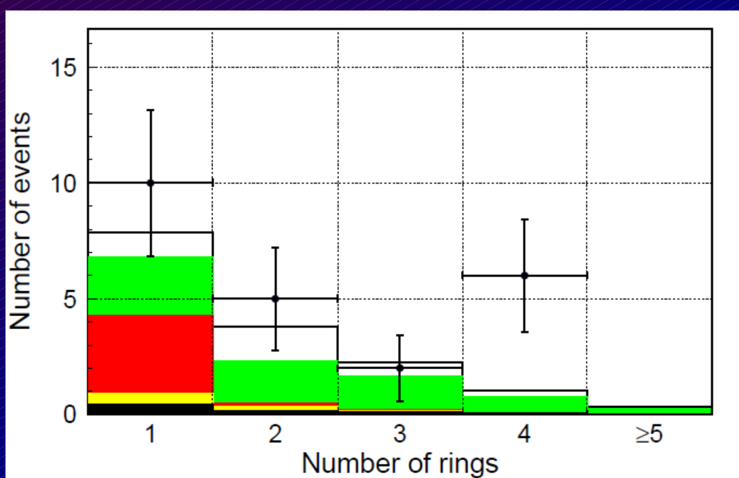
- Beam Intensity Measurement
- Neutrino Beam MC
- ND280 Measurement
- Oscillation
- Neutrino Interaction MC
- Super-K Detector Simulation

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/c	E_ν < 1250 MeV

Event Selection

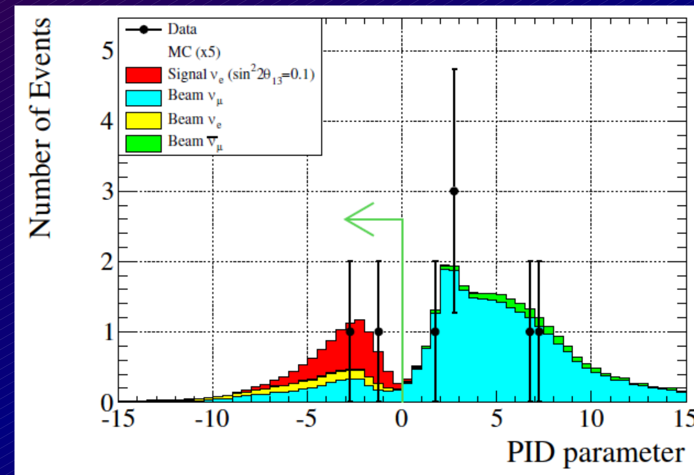
ν_μ-disappearance

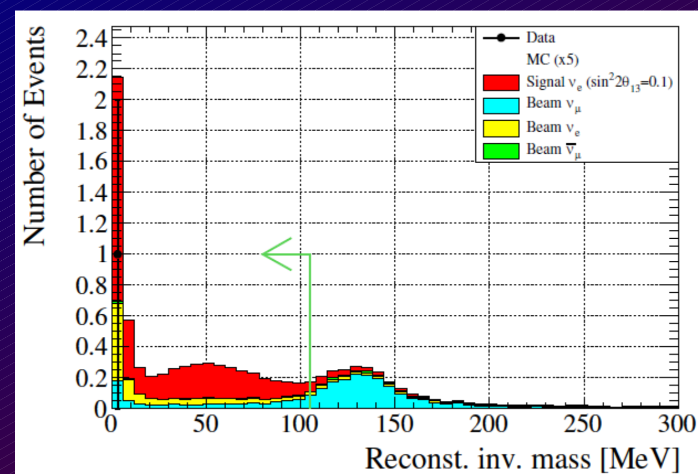




NC $\nu_{\mu,\tau}$
CCnonQE ν_μ
CCQE ν_μ
$\overline{\nu}_\mu$
ν_e

ν_e-appearance





signal ν_e
beam ν_e
$\overline{\nu}_\mu$
ν_μ

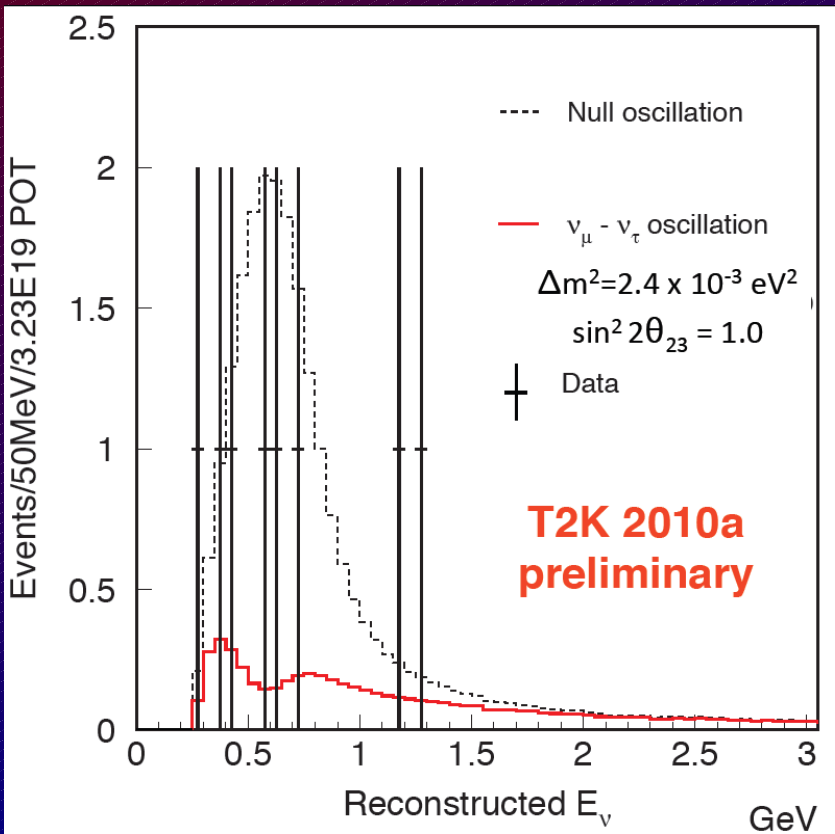
ü ü -disappearance

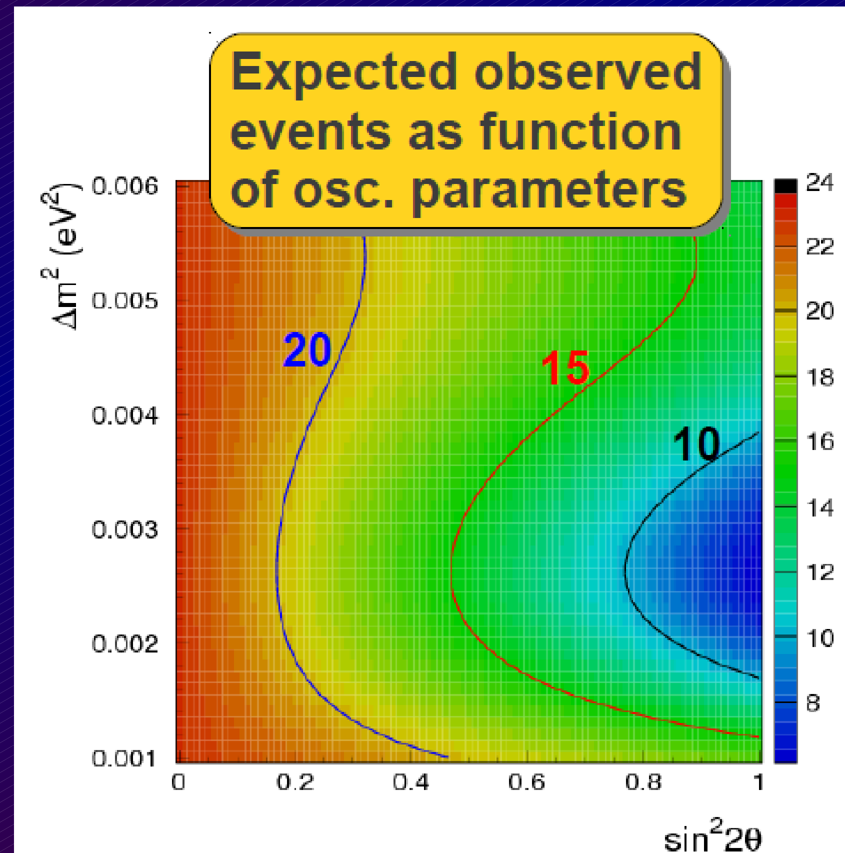
From ±500 μs window around beam spills	Data	MC		BG (12μs window)
		No oscillation	Oscillation $\Delta m^2 = 2.4 \times 10^{-3}$ (eV^2) $\sin^2 2\theta_{23} = 1.0$	
Fully-Contained	**33**	54.5	24.6	0.0094
Fiducial Volume, $E_{vis} > 30$MeV	**23**	36.8	16.7	0.0011
Single-ring μ-like (P_μ>200MeV/c)	**8** (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

ü ü -disappearance

single-ring μ-like: 8 events observed

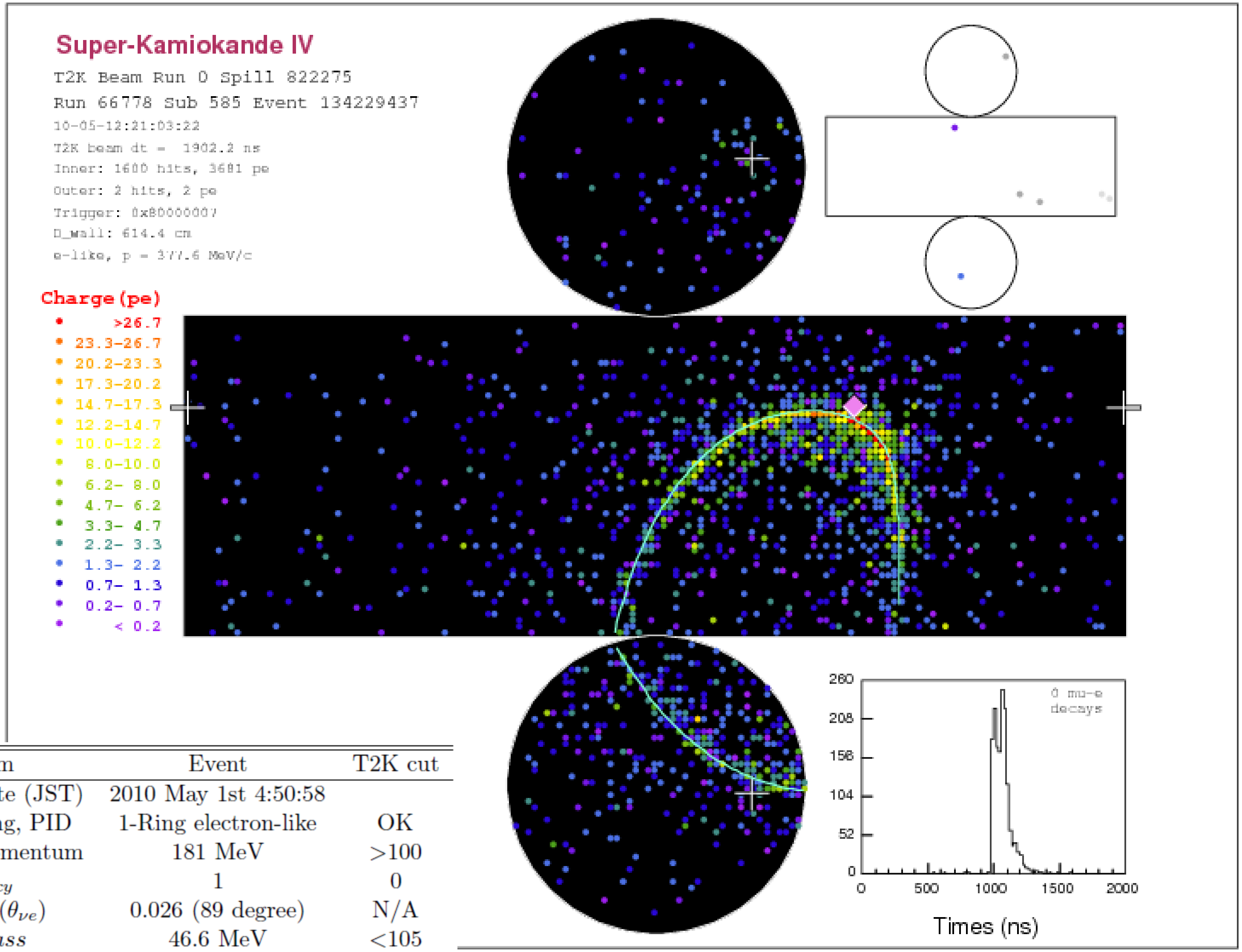




consistent with previous experiments (max. mixing)

ü e-appearance

1 event observed

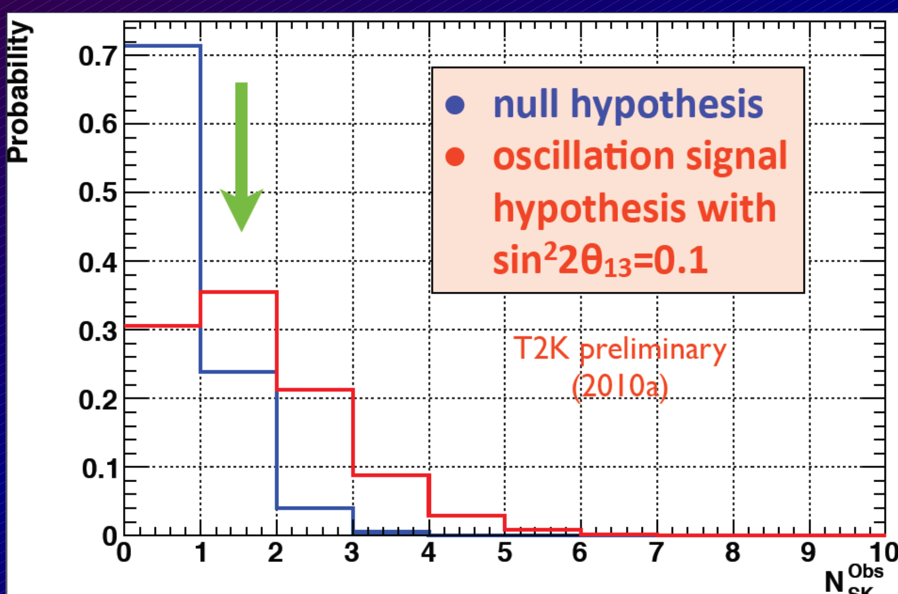


Item	Event	T2K cut
Date (JST)	2010 May 1st 4:50:58	
Ring, PID	1-Ring electron-like	OK
Momentum	181 MeV	>100
N_{dcy}	1	0
$\cos(\theta_{\nu e})$	0.026 (89 degree)	N/A
$Mass$	46.6 MeV	<105
E_{rec}	257 MeV	<1250

ü e-appearance

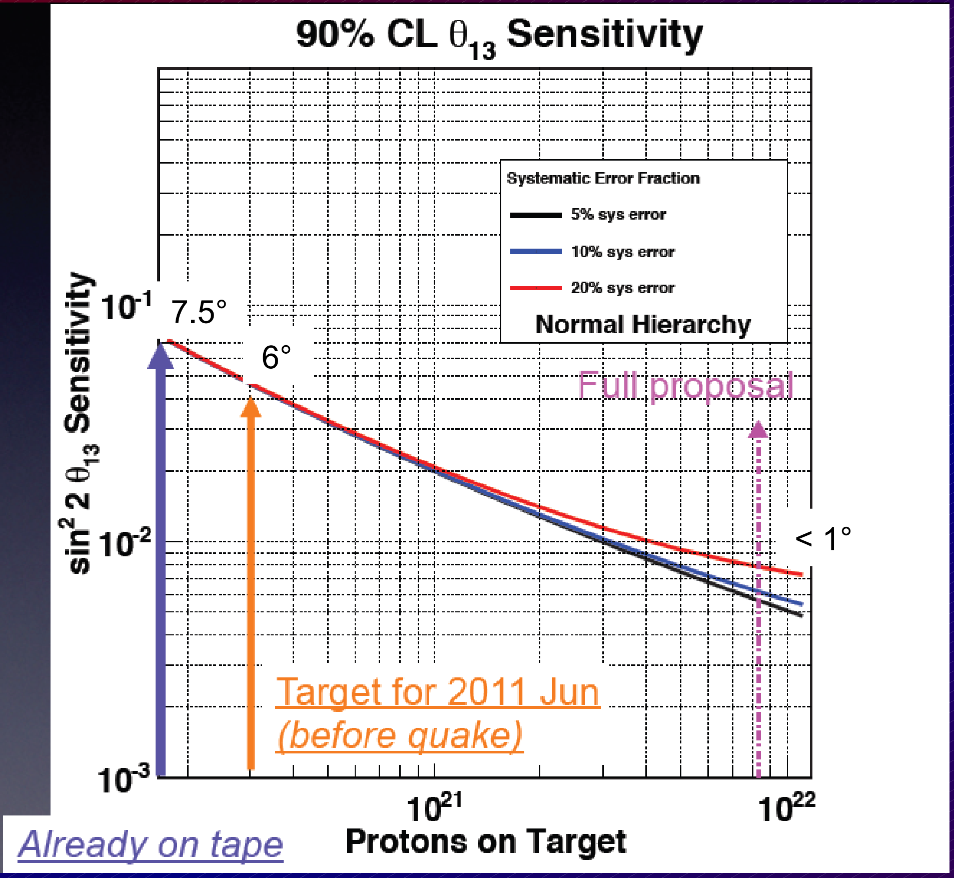
Source	Estimated number
Beam ν_μ (CC+NC)	0.13
Beam $\overline{\nu}_\mu$ (CC+NC)	0.01
Beam ν_e (CC)	0.16
Total background	**0.30 ± 0.07 (syst.)**
Total sig.+background	**1.20 ± 0.23 (syst.)**

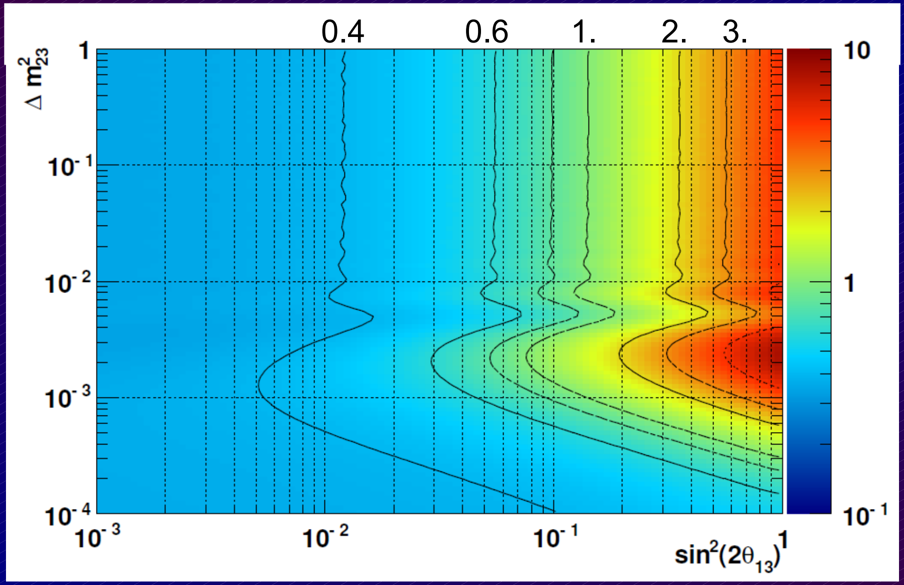
$\Delta m^2_{23}=2.4\cdot10^{-3}eV^2$
$\sin^2 2\theta_{23}=1.0$
$\sin^2 2\theta_{13}=0.1$
$\delta_{CP} = 0$

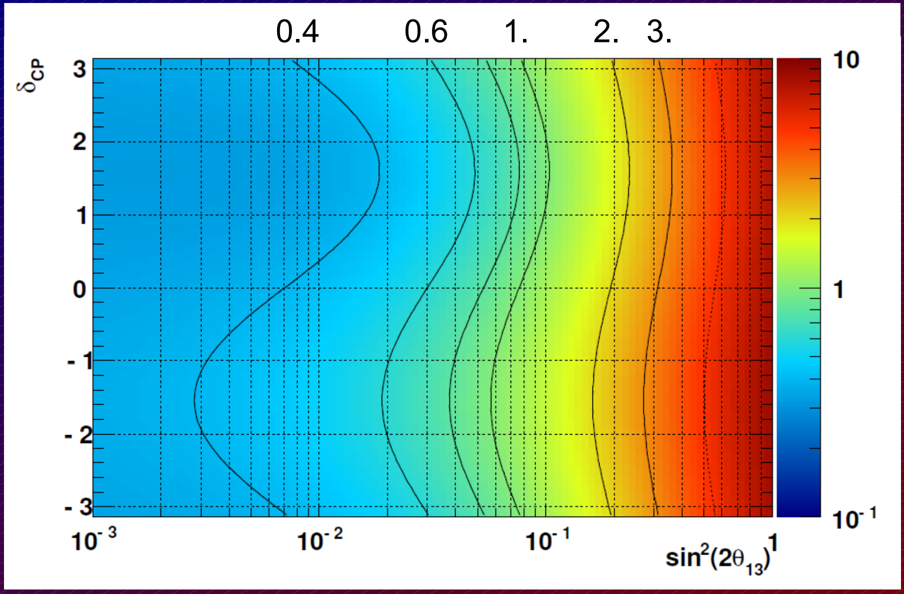


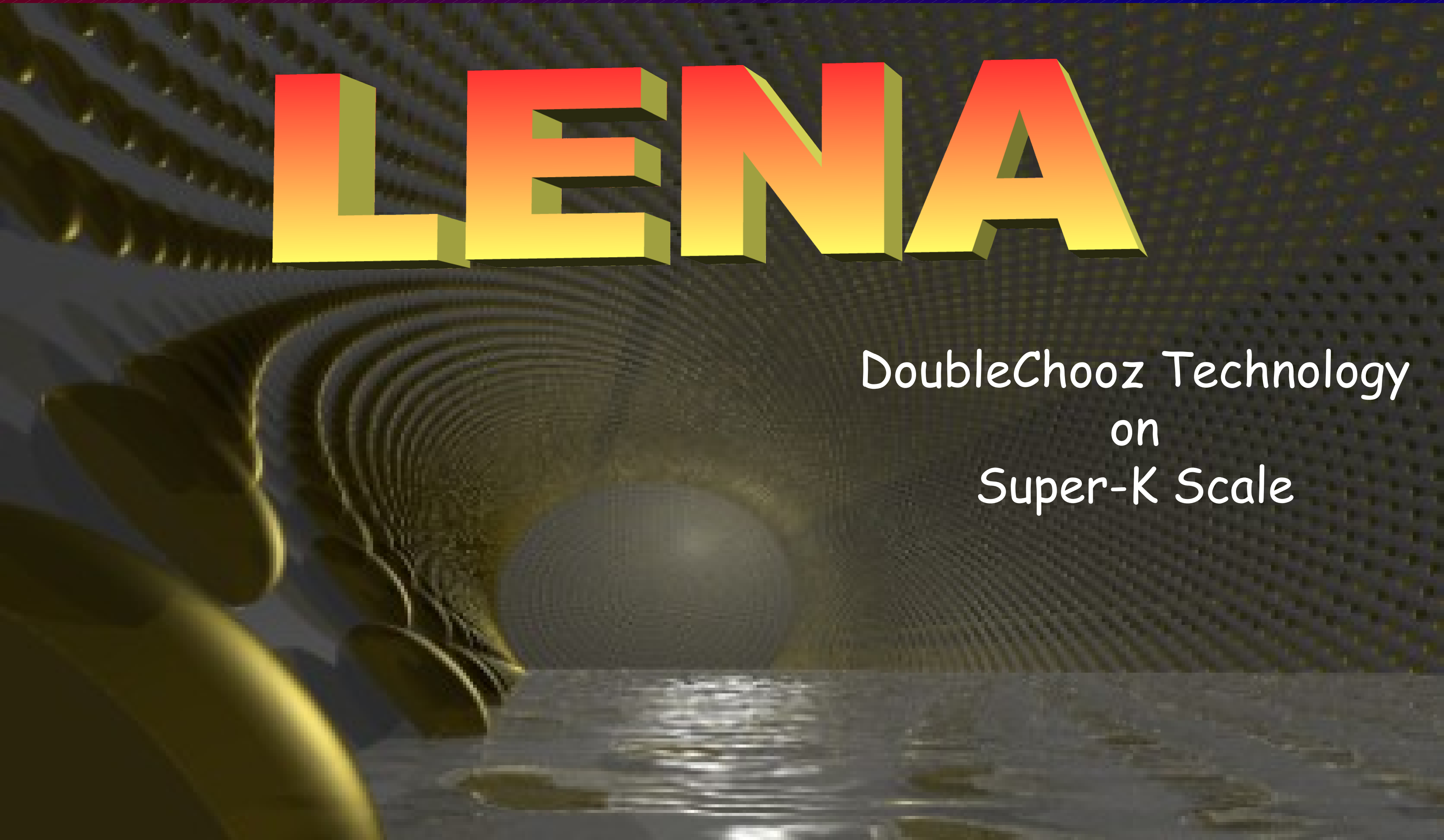
~29% probability to observe >=1 event when expected average = 0.3 event

ü e-appearance

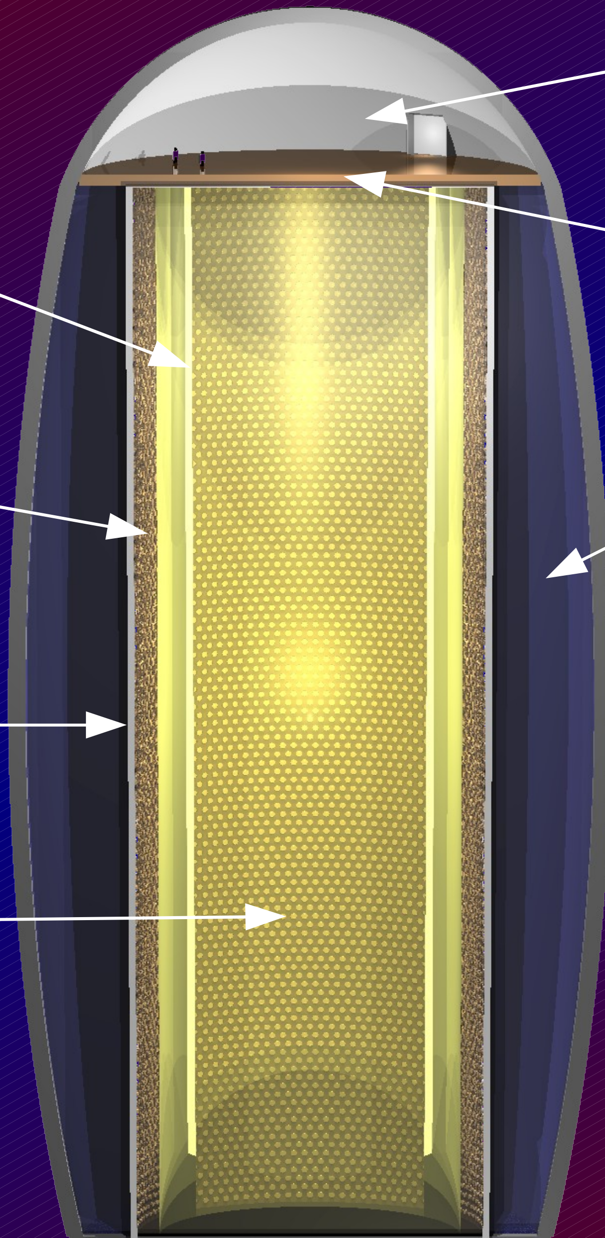







LENA
DoubleChooz Technology
on
Super-K Scale

LENA: Detector



Liquid Scintillator
ca. 50kt LAB

Inner Nylon Vessel
radius: 13m

Buffer Region
inactive, $\Delta r = 2$m
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

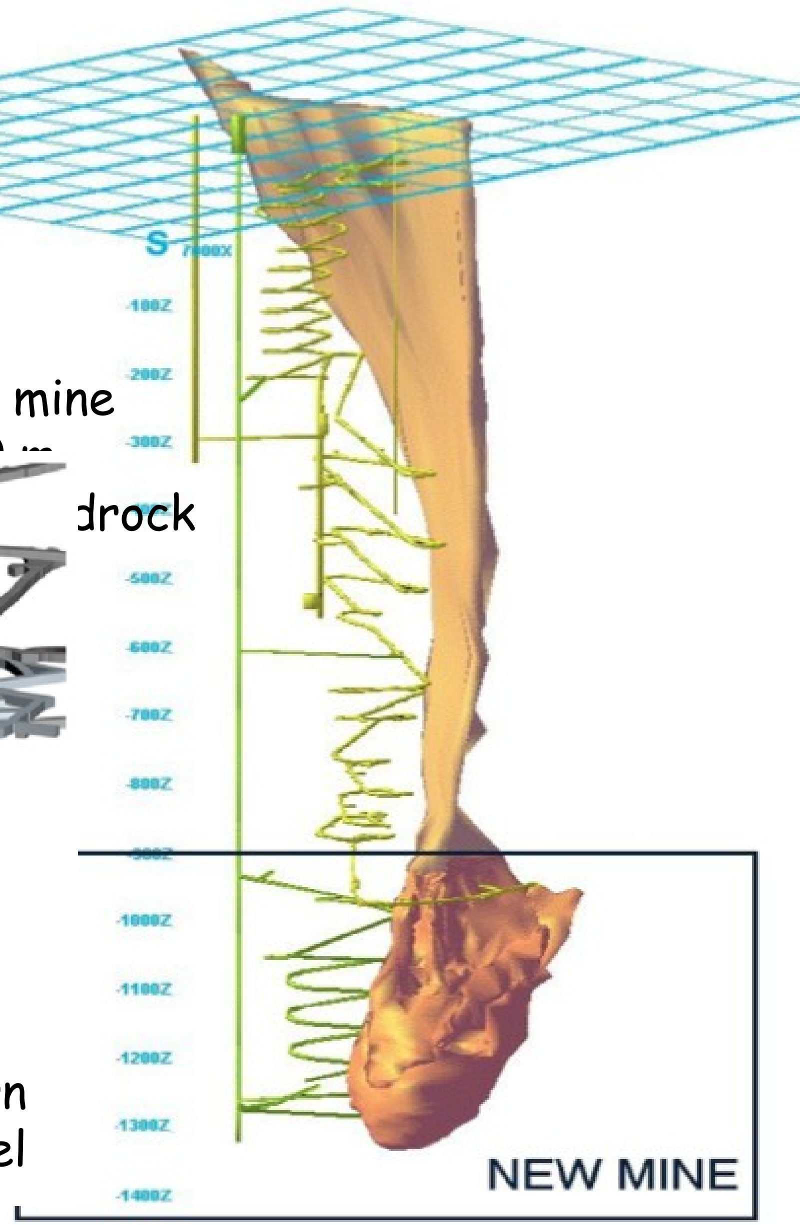
Water Cherenkov Veto
3000 PMTs, $\Delta r > 2$m
fast neutron shield
inclined muons

Egg-Shaped Cavern
about 105 m3

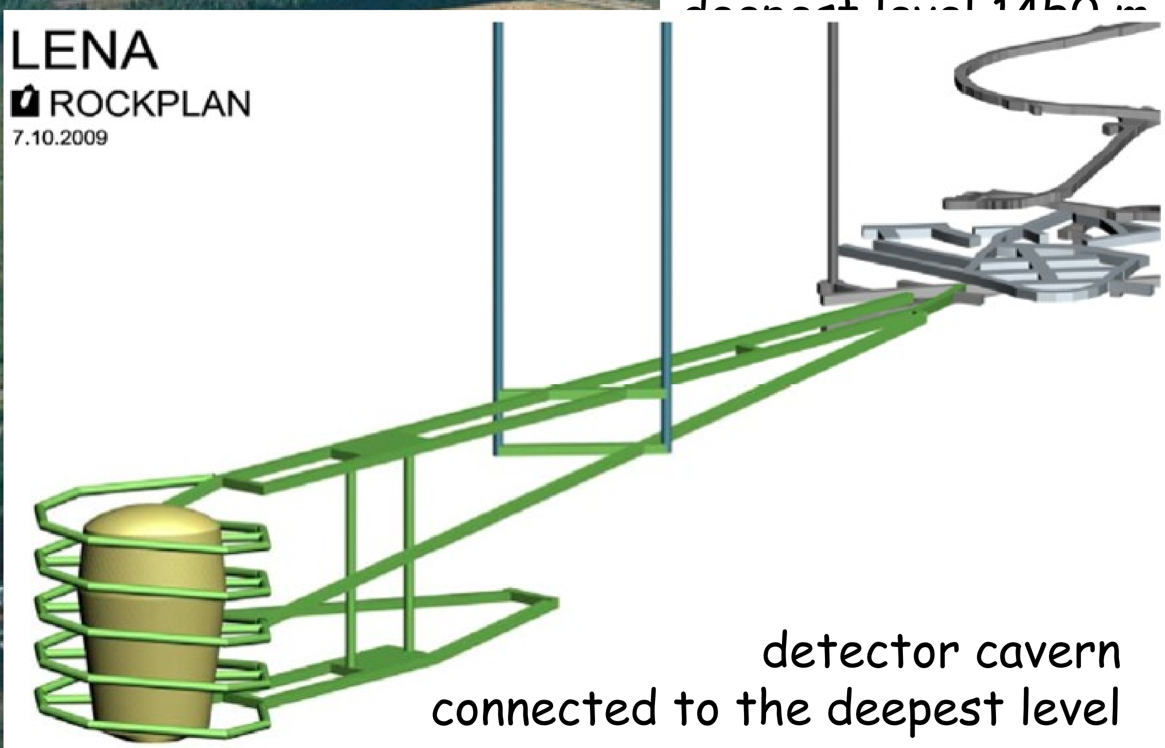
Rock Overburden
at least 4000 mwe

LENA: Location

Phyäsalmi Mine – Central Finland



active copper/zinc mine



detector cavern
connected to the deepest level

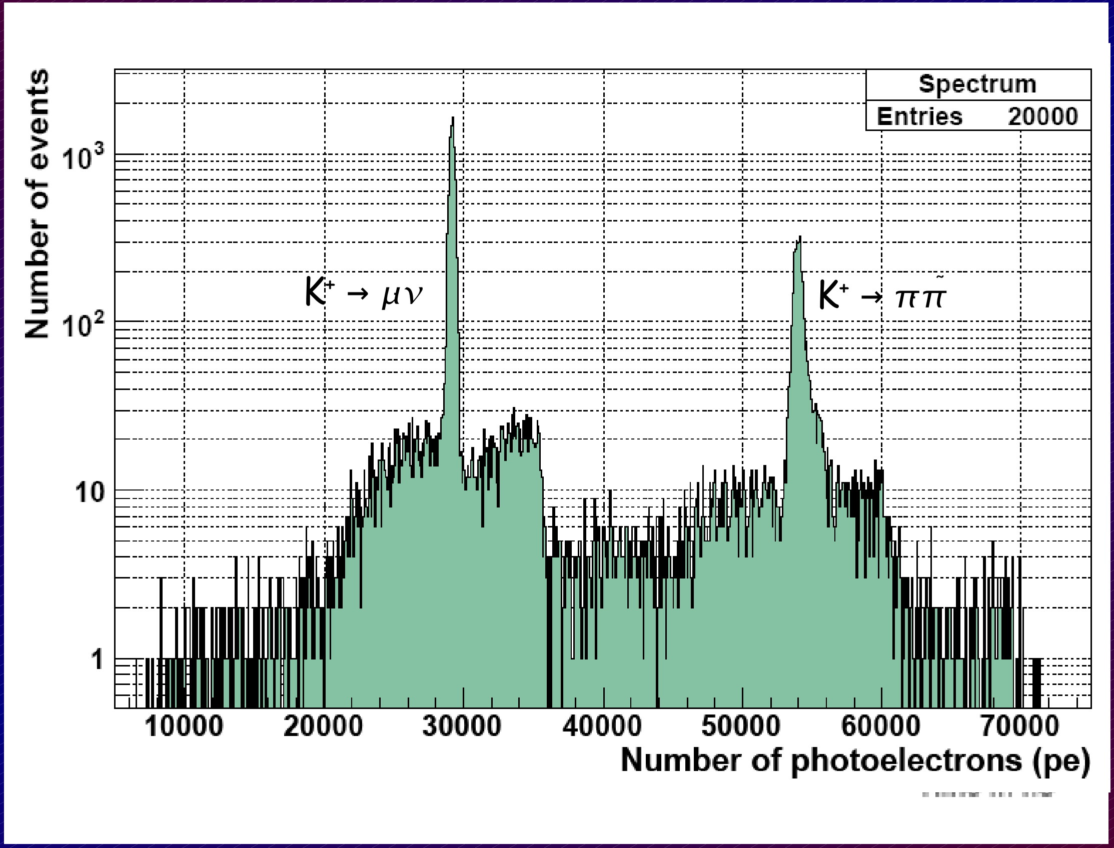
Physics Summary

- 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

$p^+ \rightarrow e^+ \pi^0$ ≈ 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

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

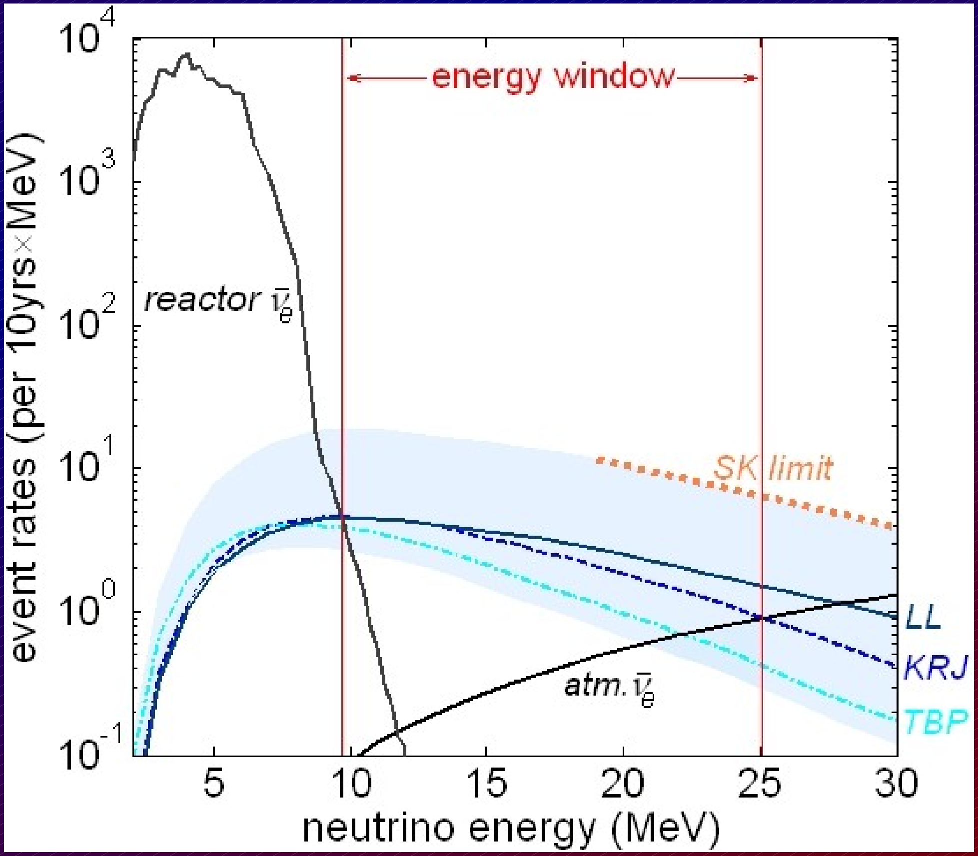
Excellent background rejection

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

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

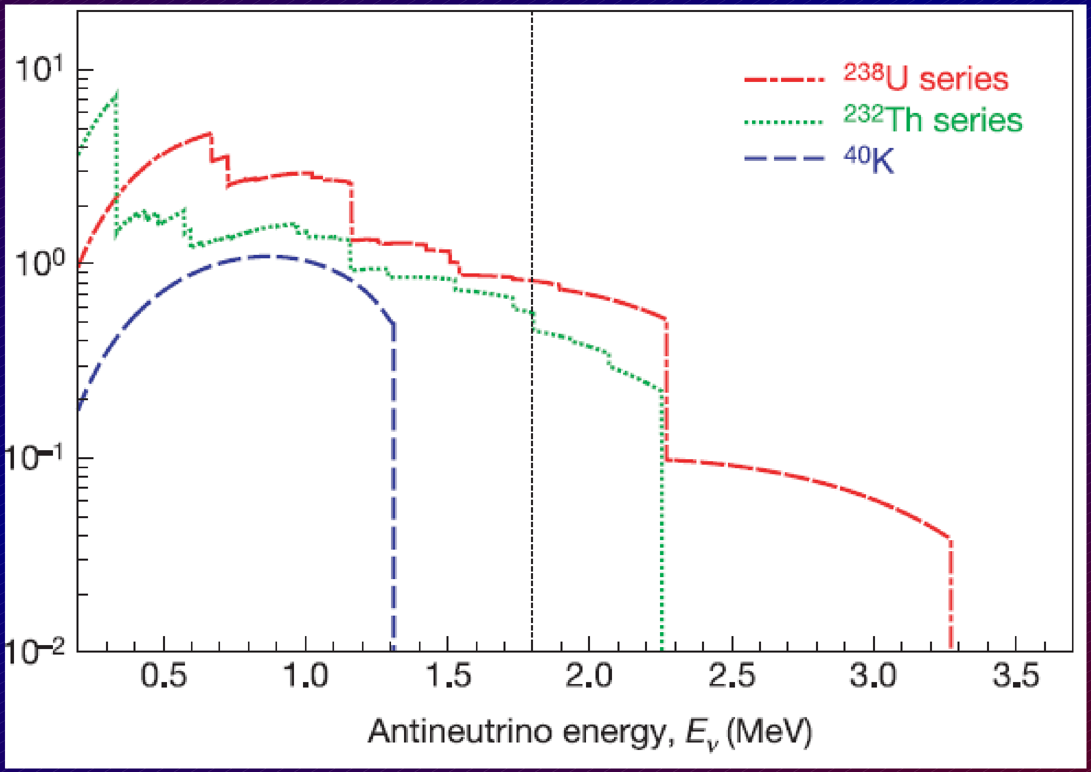
Low reactor flux

→ 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

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

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

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

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

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

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

CP violation is a genuine 3-flavour effect

Jarlskog's determinant $J = c_{12} s_{12} c_{23} s_{23} c_{13}^2 s_{13} s_\delta = (1 - s_{12}^2)^{1/2} (1 - s_{23}^2)^{1/2} (1 - s_{13}^2) s_{12} s_{23} s_{13} s_\delta$

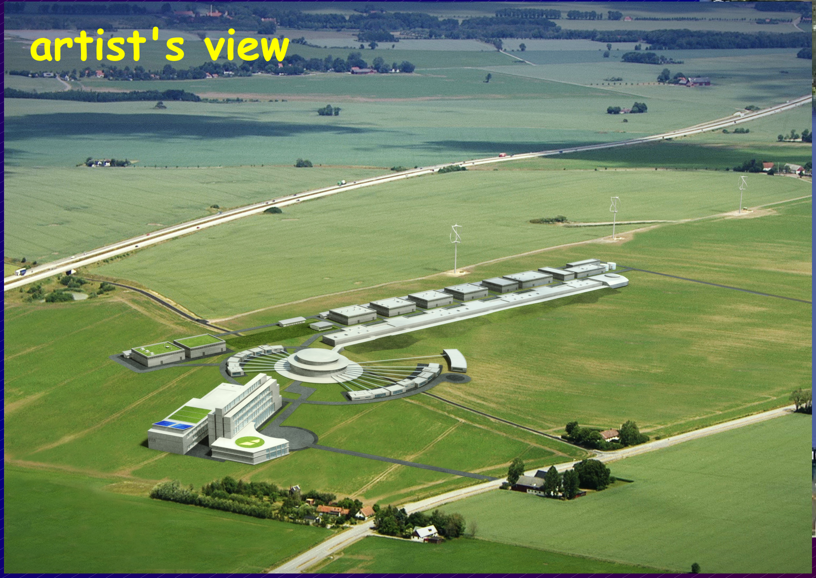
Quarks: 4 10^{-5} Neutrinos: 0.028 $\sin\delta$

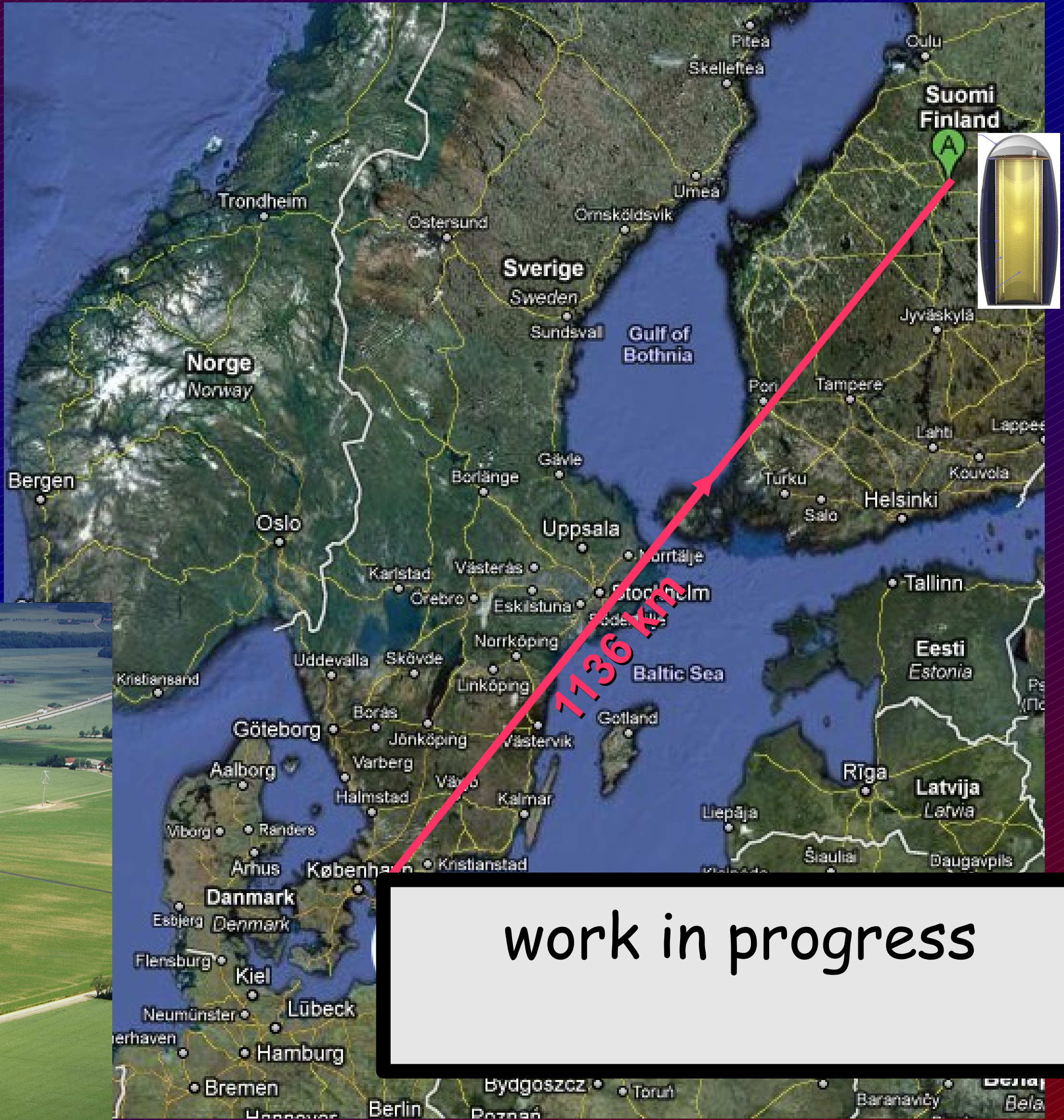
Conventional Neutrino Beam

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

Increase Energy
FFAG x3 … 5

Neutrino Target





work in progress

Summary

How large is θ_{13} ?

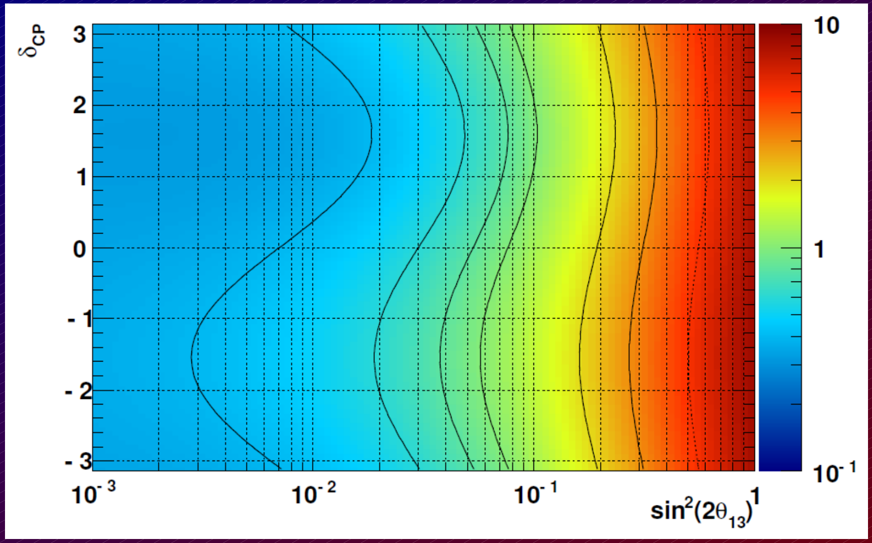
First hint from MINOS (and others) ~ 2σ
T2K: First result ($\frac{1}{4}$ of 2010 data) ~ 1σ
Reactor Experiments just started

Is θ_{23} maximal ?

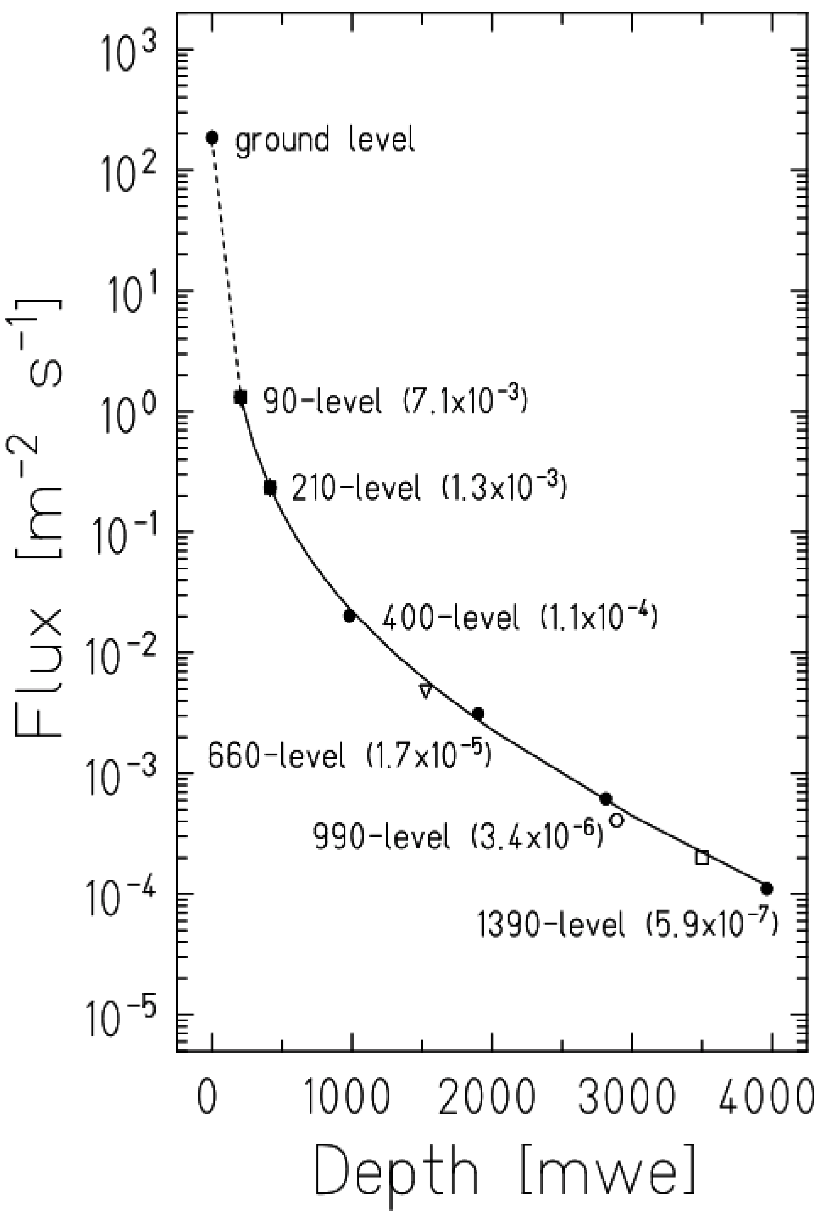
T2K: First result, not competitive yet

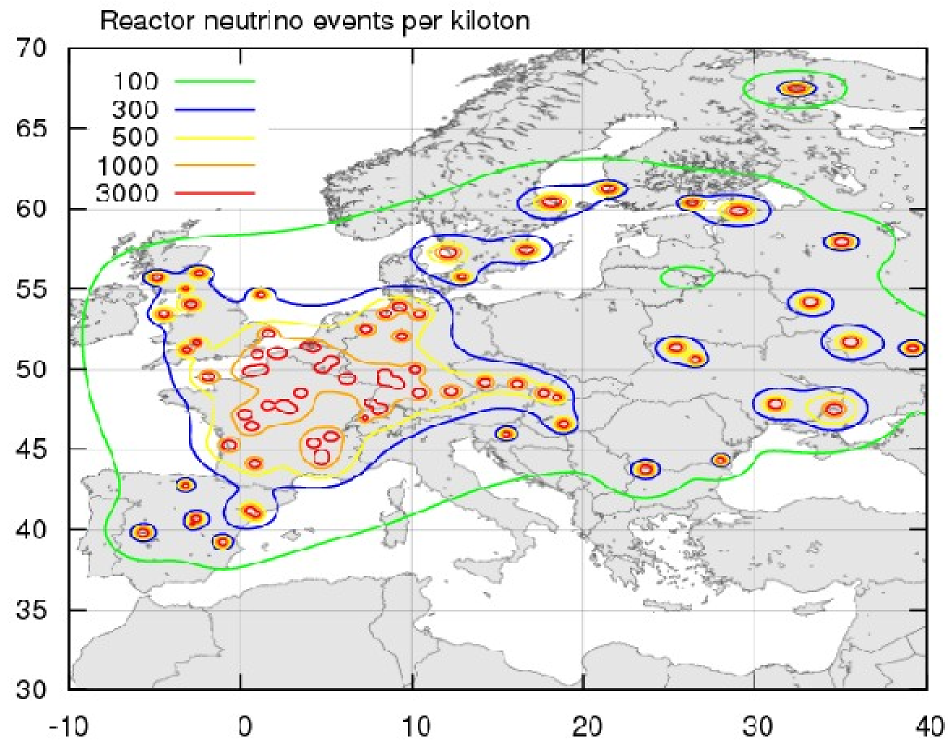
CP-violation ?

Very first shot by MINOS & T2K
Several concepts under investigation
(might not need nu-factory/beta-beam
for some parameter space)



Backup





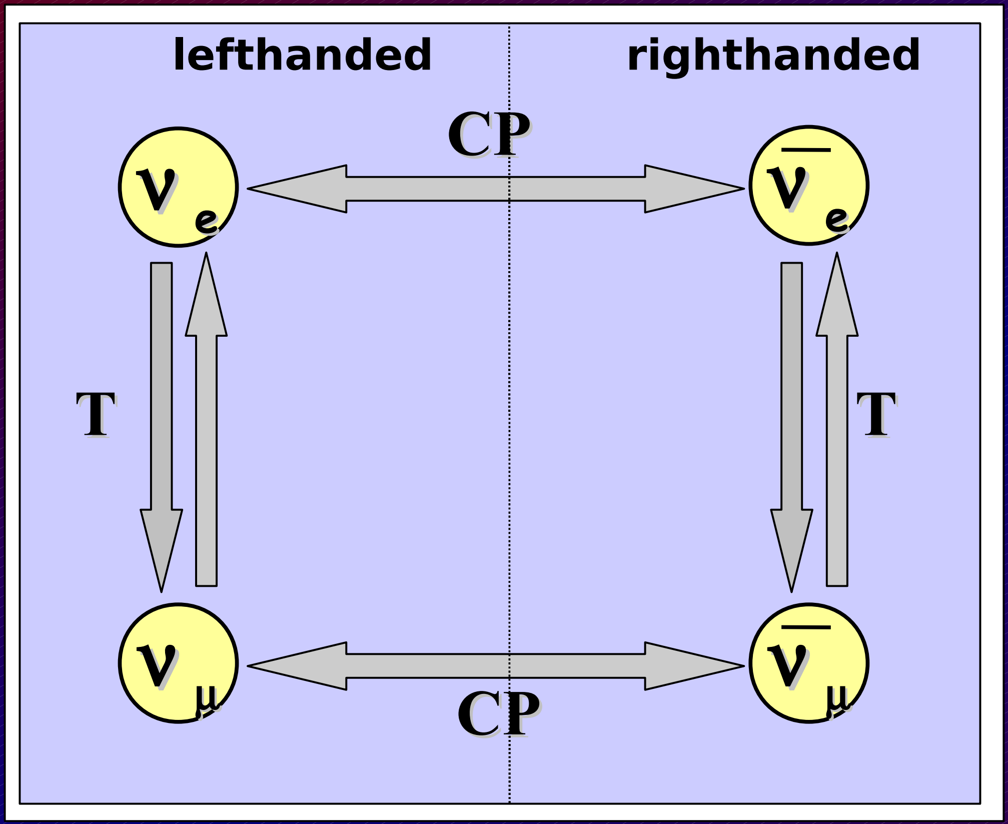
Selection criteria for LENA

- 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:

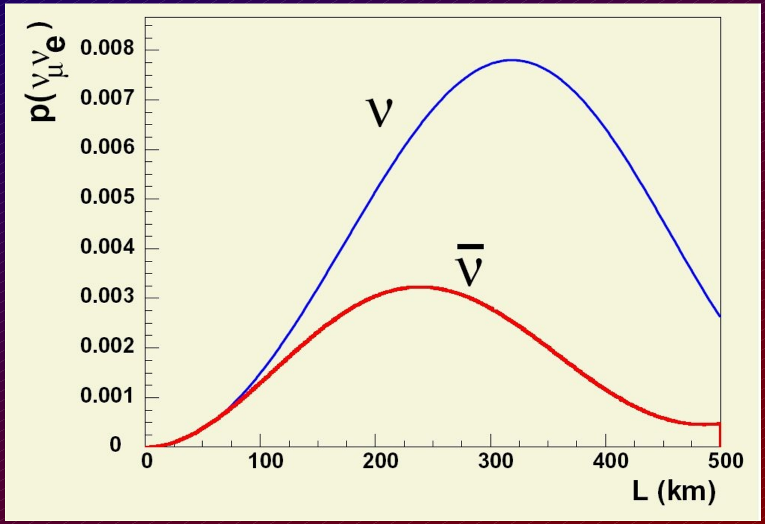
$\nu_e \to \nu_\mu \ / \ \bar{\nu}_e \to \bar{\nu}_\mu$

T-TEST:

$\nu_e \to \nu_\mu \ / \ \nu_\mu \to \nu_e$

CPT-TEST:

$\nu_e \to \nu_\mu \ / \ \bar{\nu}_\mu \to \bar{\nu}_e$



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

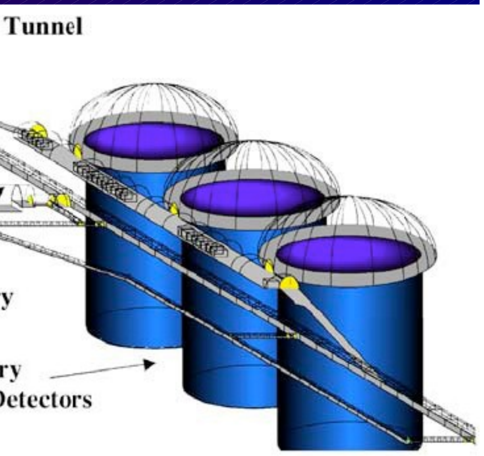
technological challenge
- ion production
- radiation on magnets

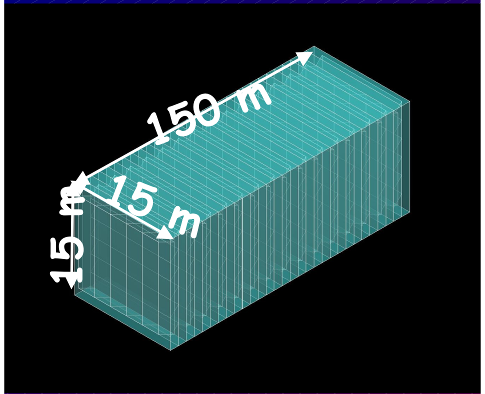
Limitations:
- production of ions

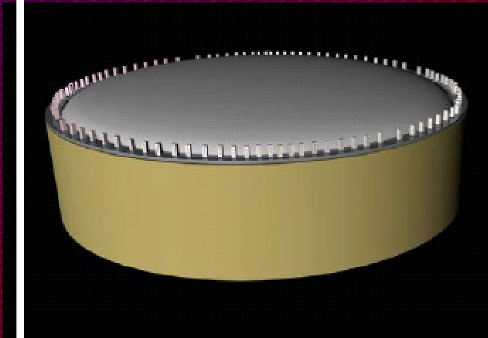
CP-Violation okay

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 restr. information	E_{min} > 10 MeV restr. information	E_{min} ~ 500 keV med. information	E_{min} ~ 10 MeV 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

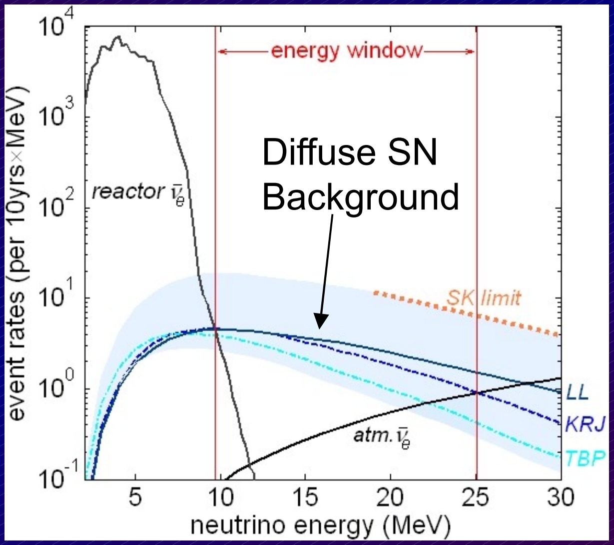
Diffuse Super Nova Background
2 ... 20 ν per year

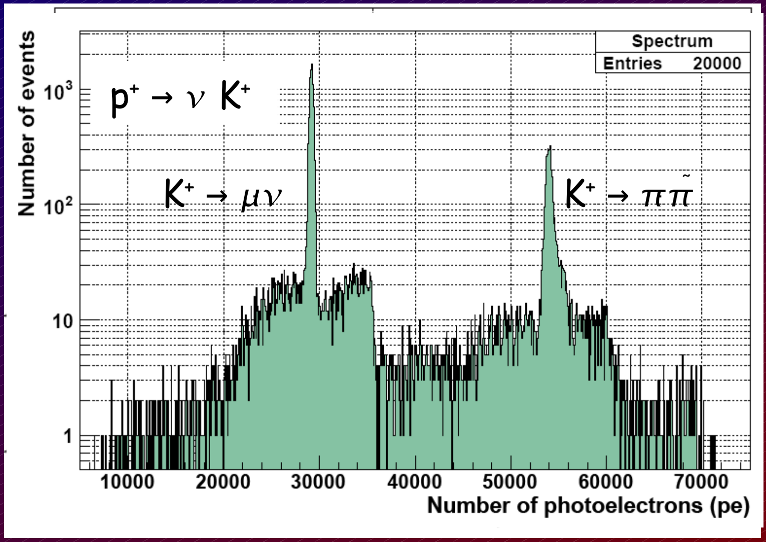
Geo-Neutrinos
~ 3000 ν year → undestand heat release
» & geo chemistry
only possible with LENA

Solar Neutrinos
~ 5000 ν / day   (helio seismology)

Atmospheric Neutrinos
good statistics, promising

CP-Violation (with beam)
covers ~80% of parameter space





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 !

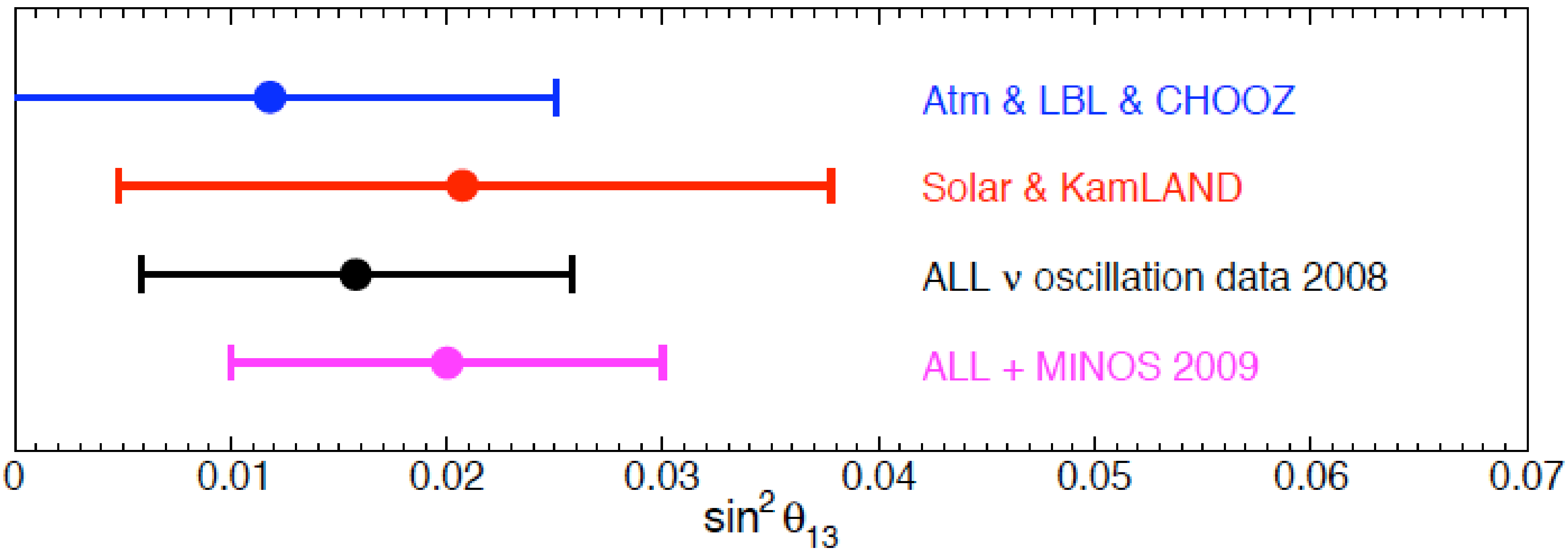
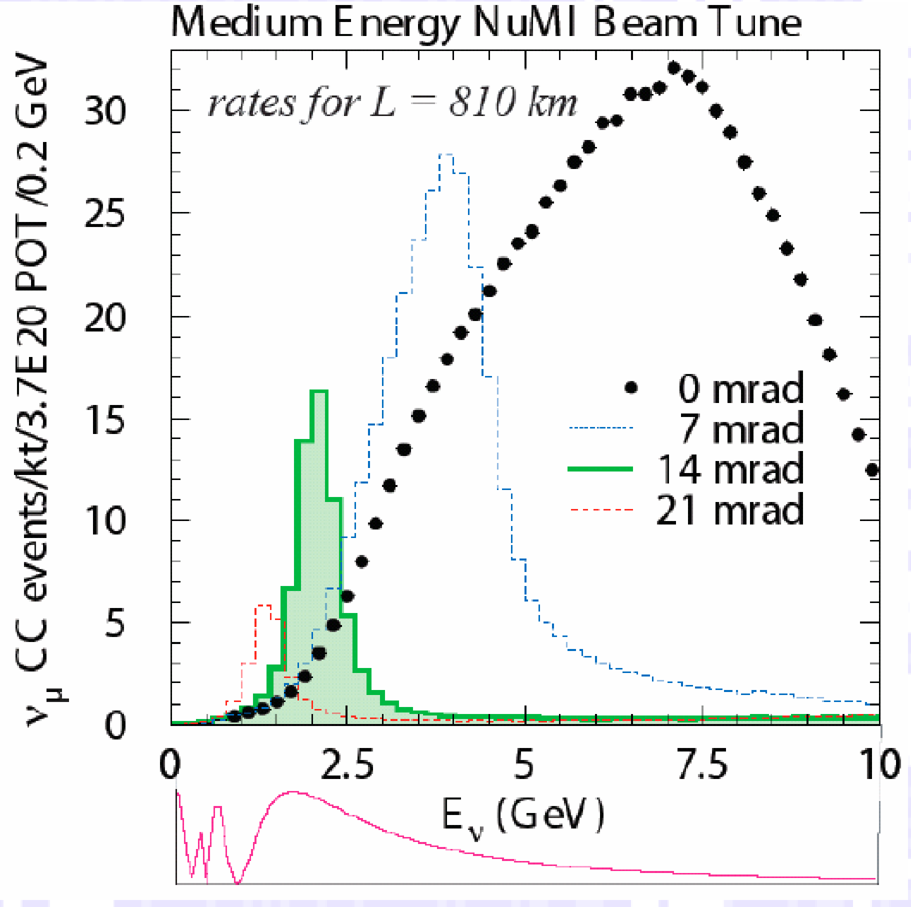


Figure 4: Hints of $\theta_{13} > 0$ from different data sets and combinations: 1σ ranges.



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

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

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

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

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

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