Super-Kamiokande
Copyright by Paweł Przewłocki

Oscylacje neutrin:

Co już wiemy oraz program na najbliższe lata.

Danuta Kiełczewska, UW&IPJ

- Oscylacje neutrin słonecznych i reaktorowych (małe δm^2)
  - SNO
  - KamLAND
  - Borexino
- Oscylacje neutrin atmosf. i akceleratorowych (duże Δm^2)
  - MINOS
  - MiniBoone
- Co zostaje do zmierzenia za pomocą oscylacji neutrin
- Przyszłe eksperymenty
  - Reaktorowe z kilkoma detektorami
  - Akceleratorowe nowej generacji: T2K i NOvA

Neutrino mixing NOT in Standard Model

IF neutrinos are massive:

States with well defined masses (mass matrix eigenstates):

$$\begin{matrix} e^- & \mu^- & \tau^- \\ \nu_1 & \nu_2 & \nu_3 \end{matrix}$$

$W^\pm$

States participating in weak interactions:

$$\begin{matrix} e^- & \mu^- & \tau^- \\ \nu_e & \nu_\mu & \nu_\tau \end{matrix}$$

Lepton mixing:

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

Neutrino oscillation - 2 flavors

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

mass states: m_1, m_2

mixing angle: ϑ

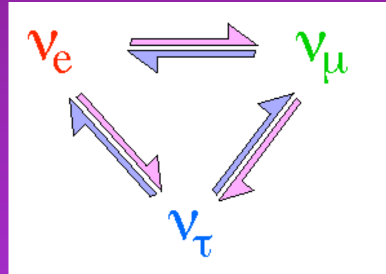
ν_α, ν_β are defined as different proportions of ν_1, ν_2 states

ν_1, ν_2 states have different masses ⇒ different velocities

The ratio $\frac{\nu_1}{\nu_2}$ changes during propagation, hence $\nu_\beta \Leftrightarrow \nu_\alpha$

Oscillation Probability - 3 flavors (part 1)

Per analogy with 2 flavor case the amplitude for the neutrino oscillation:



$$\nu_\alpha \rightarrow \nu_\beta$$

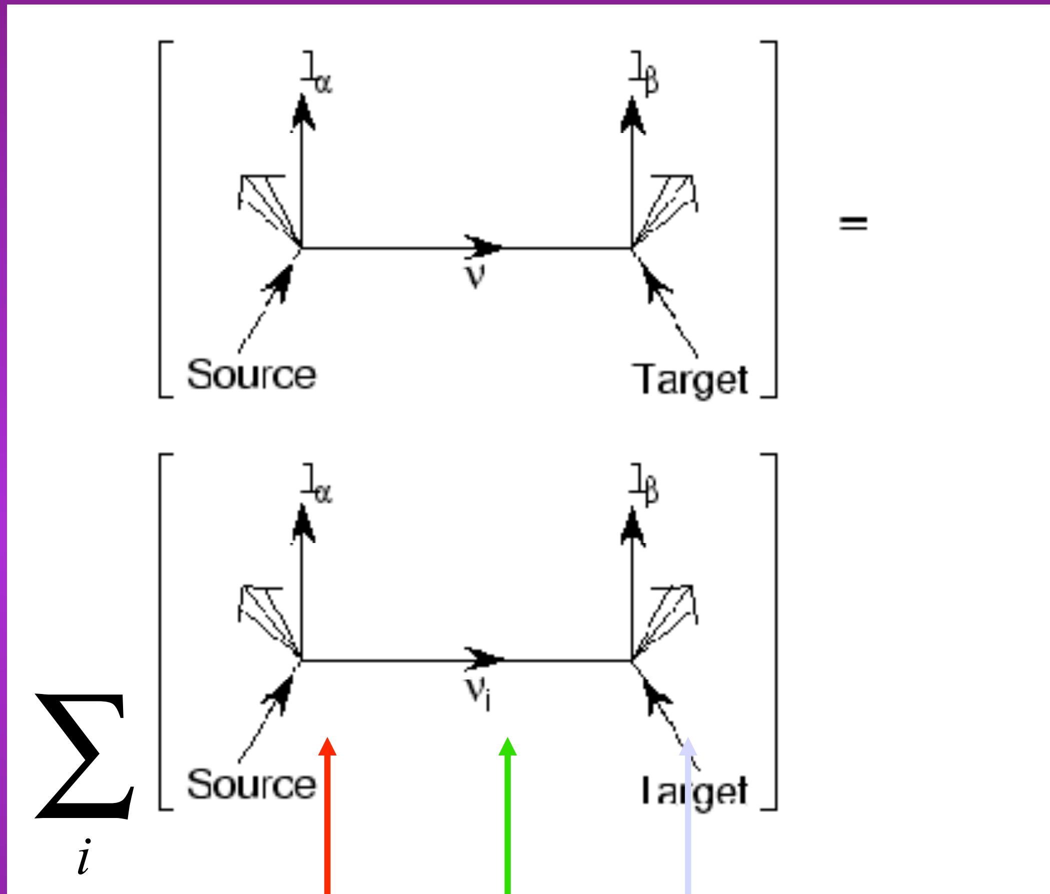
$$A(\nu_\alpha \rightarrow \nu_\beta) = \sum_i \begin{bmatrix} A(\text{neutrino born with flavor } \alpha \text{ is a } \nu_\mathrm{i}) \times \\ A(\nu_i \text{ propagates}) \times \\ \mathrm{A}(\text{when } \nu_\mathrm{i} \text{ interacts it makes flavor } \beta) \end{bmatrix}$$

A denotes an amplitude.

How do Neutrinos Oscillate?

Amplitude

Amplitude



$$\mathcal{A} = \sum_i U^*_{\alpha i} e^{-i\frac{m_i^2}{2E}L} U_{\beta i}$$

Oscillation Probability - 3 flavors

In a general case, with at least one non-zero complex phase:

$$P(\nu_\alpha \to \nu_\beta) = \left|\mathcal{A}(\nu_\alpha \to \nu_\beta)\right|^2$$

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

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

Note here: if $\alpha=\beta$ then the imaginary components disappear

→ CP phase cannot be measured in disappearance experiments

Oscillation Probability - 3 flavors (φ=0)

$$P(\nu_\alpha \xrightarrow{\alpha\neq\beta} \nu_\beta) = -4\sum_{i>j}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{1.27\Delta m^2_{ij}L}{E}\right) =$$

$$= -2\sum_{i=1}^{3}\sum_{j=1,j\neq i}^{3}(U_{\alpha i}U_{\beta i}U_{\alpha j}U_{\beta j})\sin^2\left(\frac{1.27\Delta m^2_{ij}L}{E}\right) =$$

$$= -4\left[\underbrace{U_{\alpha 1}U_{\beta 1}U_{\alpha 2}U_{\beta 2}}_{\mathbf{a_{12}}}\sin^2\left(\frac{1.27\Delta m^2_{12}L}{E}\right) + \underbrace{U_{\alpha 1}U_{\beta 1}U_{\alpha 3}U_{\beta 3}}_{\mathbf{a_{13}}}\sin^2\left(\frac{1.27\Delta m^2_{13}L}{E}\right) + \underbrace{U_{\alpha 2}U_{\beta 2}U_{\alpha 3}U_{\beta 3}}_{\mathbf{a_{23}}}\sin^2\left(\frac{1.27\Delta m^2_{23}L}{E}\right)\right]$$

Oscillation Probability - 3 flavors (ϕ=0)

$$P(\nu_\alpha \to \nu_\beta) = -4\left[a_{12}\sin^2\left(\frac{1.27\Delta m_{12}^2 L}{E}\right) + a_{13}\sin^2\left(\frac{1.27\Delta m_{13}^2 L}{E}\right) + a_{23}\sin^2\left(\frac{1.27\Delta m_{23}^2 L}{E}\right)\right]$$

Let's assume:

$$\Delta m_{13} \approx \Delta m_{23} \equiv \Delta m \qquad \Delta m_{12} \equiv \delta m$$

$$\Delta m \gg \delta m$$

Then we have 2 types of experiments:

Case A – „atmospheric" - small L/E:

$$\sin^2\left(\frac{1.27\delta m^2 L}{E}\right) \approx 0$$

$$P(\nu_\alpha \to \nu_\beta) = -4(a_{13} + a_{23})\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

Case B – „solar" - large L/E

$$\left\langle \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)\right\rangle \approx \frac{1}{2}$$

$$P(\nu_\alpha \to \nu_\beta) = -4\left[a_{12}\sin^2\left(\frac{1.27\delta m^2 L}{E}\right) + 0.5(a_{13} + a_{23})\right]$$

Oscillation probability - 3 flavors (ϕ=0)

$$\Delta m_{13} \approx \Delta m_{23} \equiv \Delta m, \quad \Delta m_{12} \equiv \delta m$$

$\Delta m >> \delta m$

Case A – „atmospheric” - small L/E:

$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

$$P(\nu_e \to \nu_\tau) = \sin^2 2\theta_{13} \cos^2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

Note:
for ϑ_{13}=0
all formulas
are the same
as for 2 flavors

Case B – „solar” - large L/E

$$P(\nu_e \to \nu_{\mu\tau}) = \cos^2\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\delta m^2 L}{E_\nu}\right) + 0.5\sin^2 2\theta_{13}$$

Sensitivity to oscillations

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

	E_ν (MeV)	L (m)	$\Delta m^2 (eV^2)$
Supernovae	<100	$>10^{19}$	$10^{-19} - 10^{-20}$
Solar	<14	10^{11}	10^{-10}
Atmospheric	>100	$10^4 - 10^7$	10^{-4}
Reactor	<10	$<10^6$	10^{-5}
Accelerator with short baseline	>100	10^3	10^{-1}
Accelerator with long baseline	>100	$<10^6$	10^{-3}

More exact formula: $\nu_\mu \leftrightarrow \nu_e$ and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$

By expanding in: $\vartheta_{13},\ \Delta_{12}/\Delta_{23},\ \Delta_{12}/A,\ \Delta_{12}L$ one gets:

$$P(\nu_e \leftrightarrow \nu_\mu) = s_{23}^2 \sin^2 2\vartheta_{13} \left(\frac{\Delta_{23}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp L}{2}\right)$$
$$+ c_{23}^2 \sin^2 2\vartheta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$
$$+ \mathrm{J} \frac{\Delta_{12}}{\mathrm{A}} \frac{\Delta_{23}}{B_\mp} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{B_\mp L}{2}\right) \cos\left(\pm\varphi - \frac{\Delta_{23} L}{2}\right)$$

+ neutrinos
- antineutrinos

solar term

CP violation

L - baseline; $\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E}$

$s_{ij} \equiv \sin\vartheta_{ij}, \quad c_{ij} \equiv \cos\vartheta_{ij}$

$J \equiv \cos\vartheta_{13} \cdot \sin 2\vartheta_{13} \cdot \sin 2\vartheta_{23} \cdot \sin 2\vartheta_{12}$

We will introduce later:

$B_\mp \equiv \left|A \mp \Delta_{23}\right|$

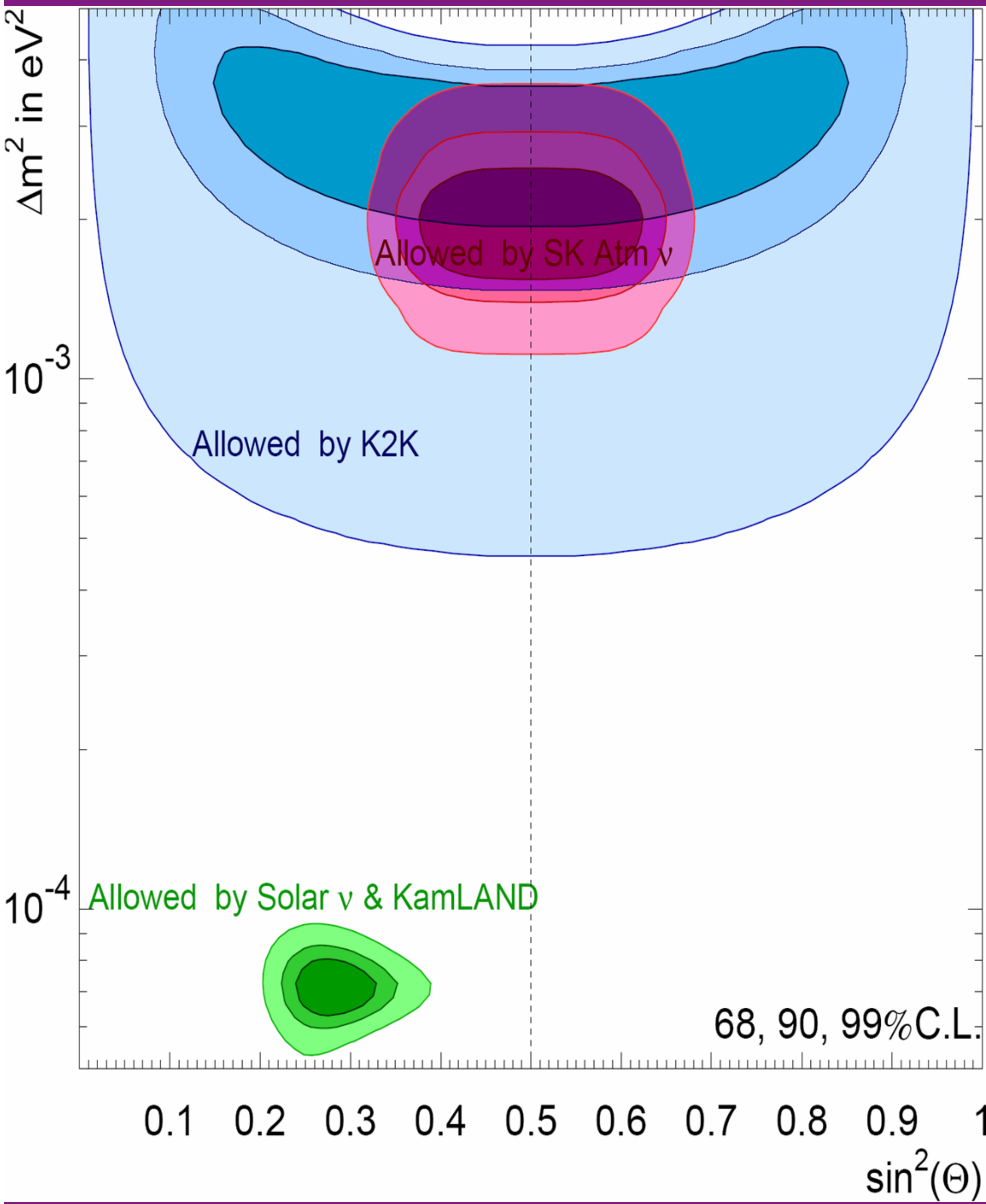
$A \equiv \sqrt{2} G_F n_e(L)$

matter effects
→ sensitivity to mass hierarchy

If LA<<1:

$$P(\bar{\nu}_e \leftrightarrow \bar{\nu}_x) \cong \sin^2 2\vartheta_{13} \sin^2 \vartheta_{23} \sin^2(\Delta_{23})$$

The above formula is necessary for future, more exact studies



First oscillation measurements

were done with natural neutrinos: atmospheric and solar

$$|\Delta m_{23}^2| = (2.5 \pm 0.3) \times 10^{-3} \quad eV^2$$

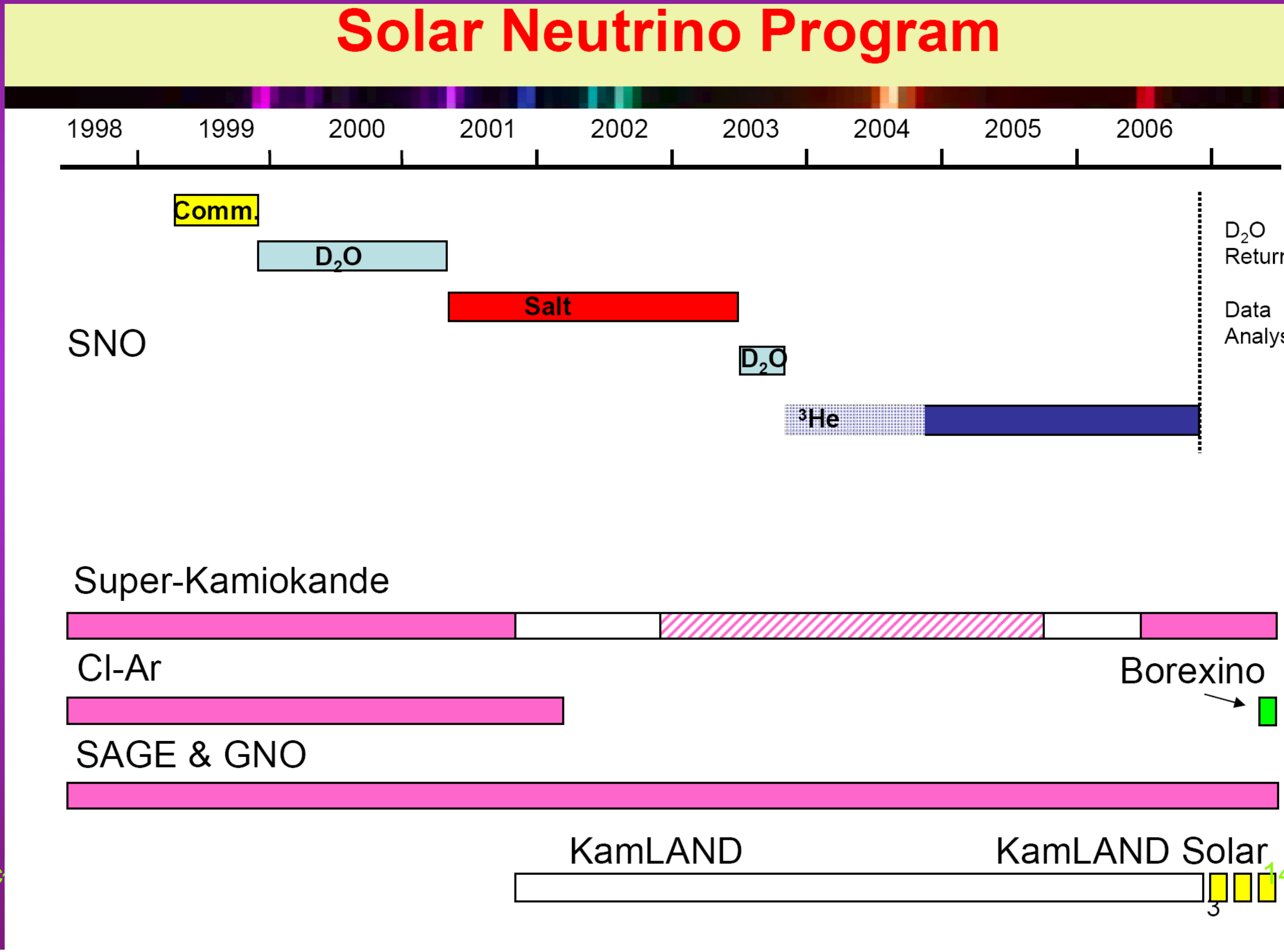
$$\delta m_{12}^2 = (8.0 \pm 0.3) \times 10^{-5} \quad eV^2$$

Mixing:

$$\vartheta_{12} = 33.9^{+2.4}_{-2.2} \text{ deg}$$ NOT max

$$\vartheta_{23} = 45 \pm 8 \text{ deg}$$ max

Completing the oscillation picture at small dm² (solar)



Results from the last SNO phase

SNO

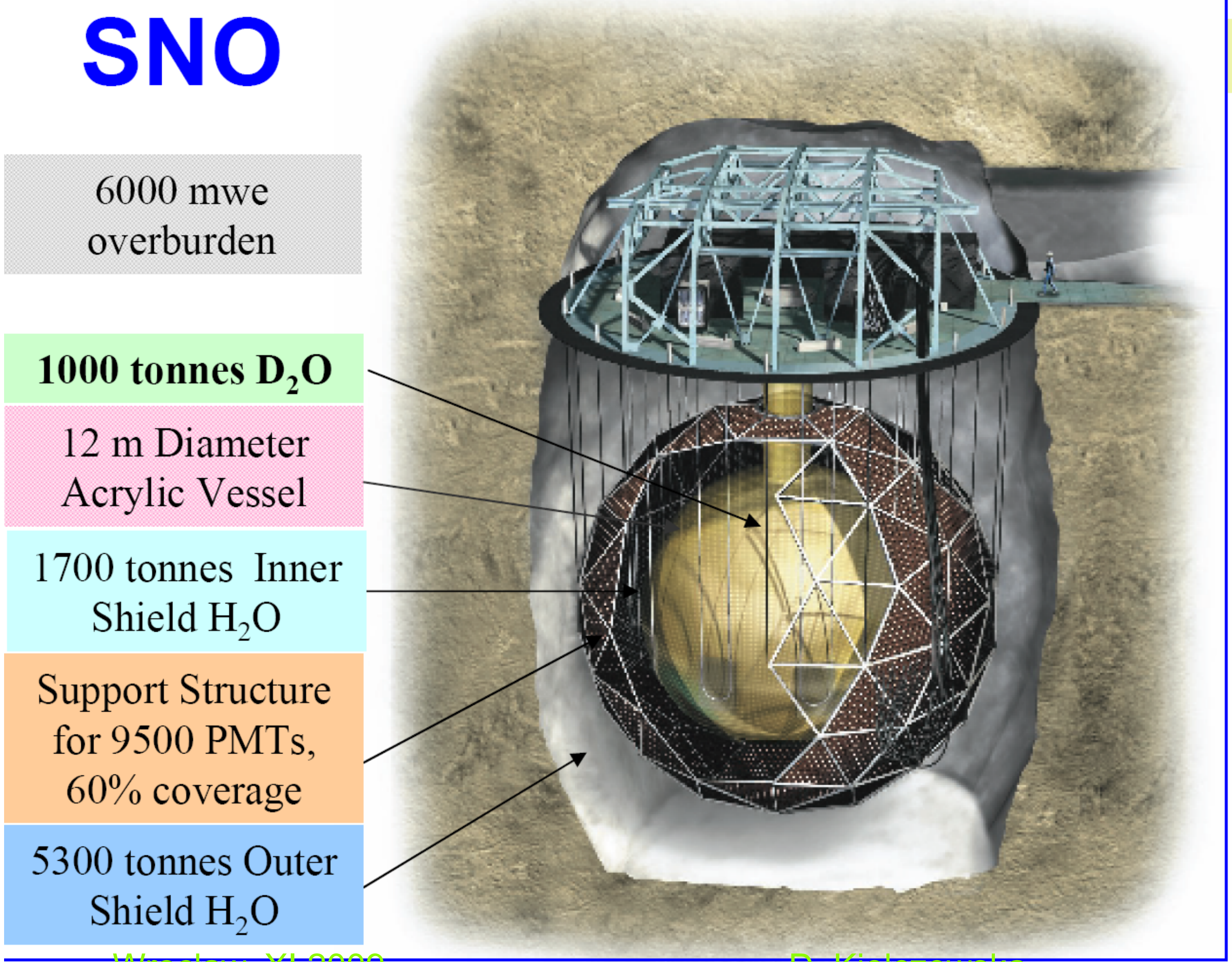


Image courtesy National Geographic

3 Reactions:

$\nu_x + e^- \rightarrow \nu_x + e^-$ ES

$\nu_e + d \rightarrow p + p + e^-$ CC

$\nu_x + d \rightarrow p + n + \nu_x$ NC

3 neutron detection methods:

$n + d \rightarrow t + \gamma + 6.25$ MeV

$n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma + 8.6$ MeV

$n + {}^{3}He \rightarrow p + t + 0.76$ MeV

Neutron counters

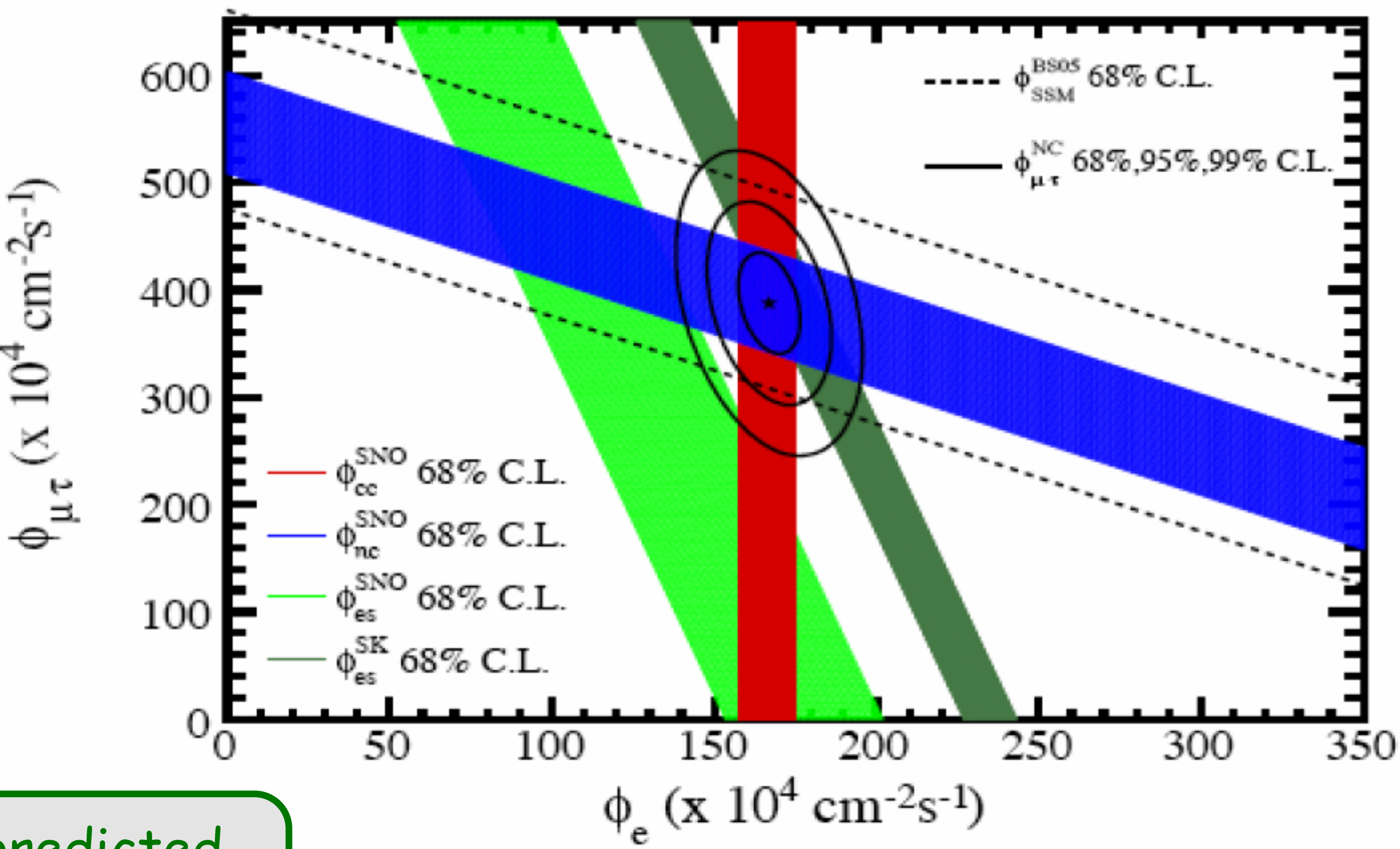
Results from SNO NCD Phase & Super-K

Preliminary

Fluxes

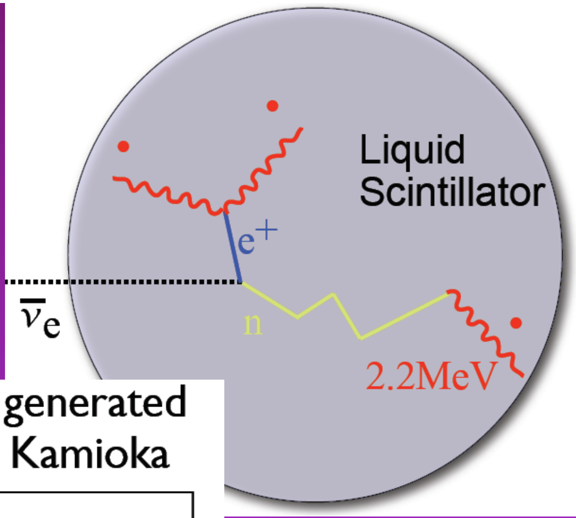
$(10^4\ cm^{-2}\ s^{-1})$

ν_e:	167(9)
ν_{ES}:	177(26)
ν_{total}:	554(48)
ν_{SSM}:	569(91)

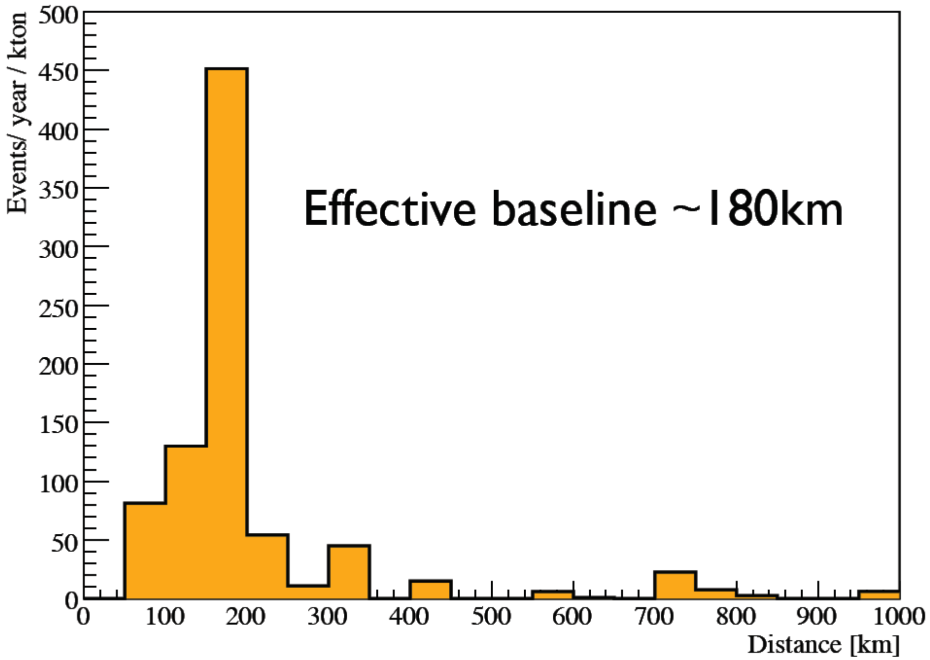


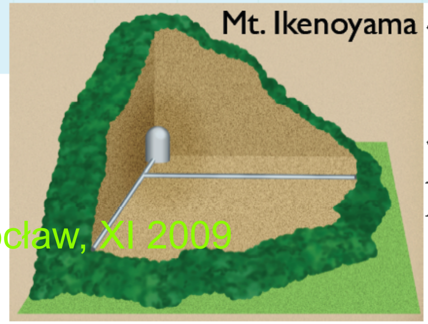
All the neutrinos predicted by SSM have been observed by NC reaction

Kamland – recent results



70 GW (7% of world total) is generated at 130-220 km distance from Kamioka

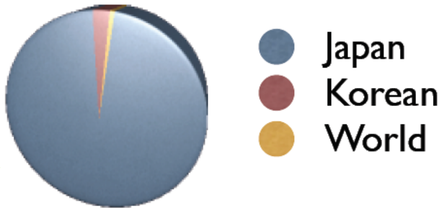




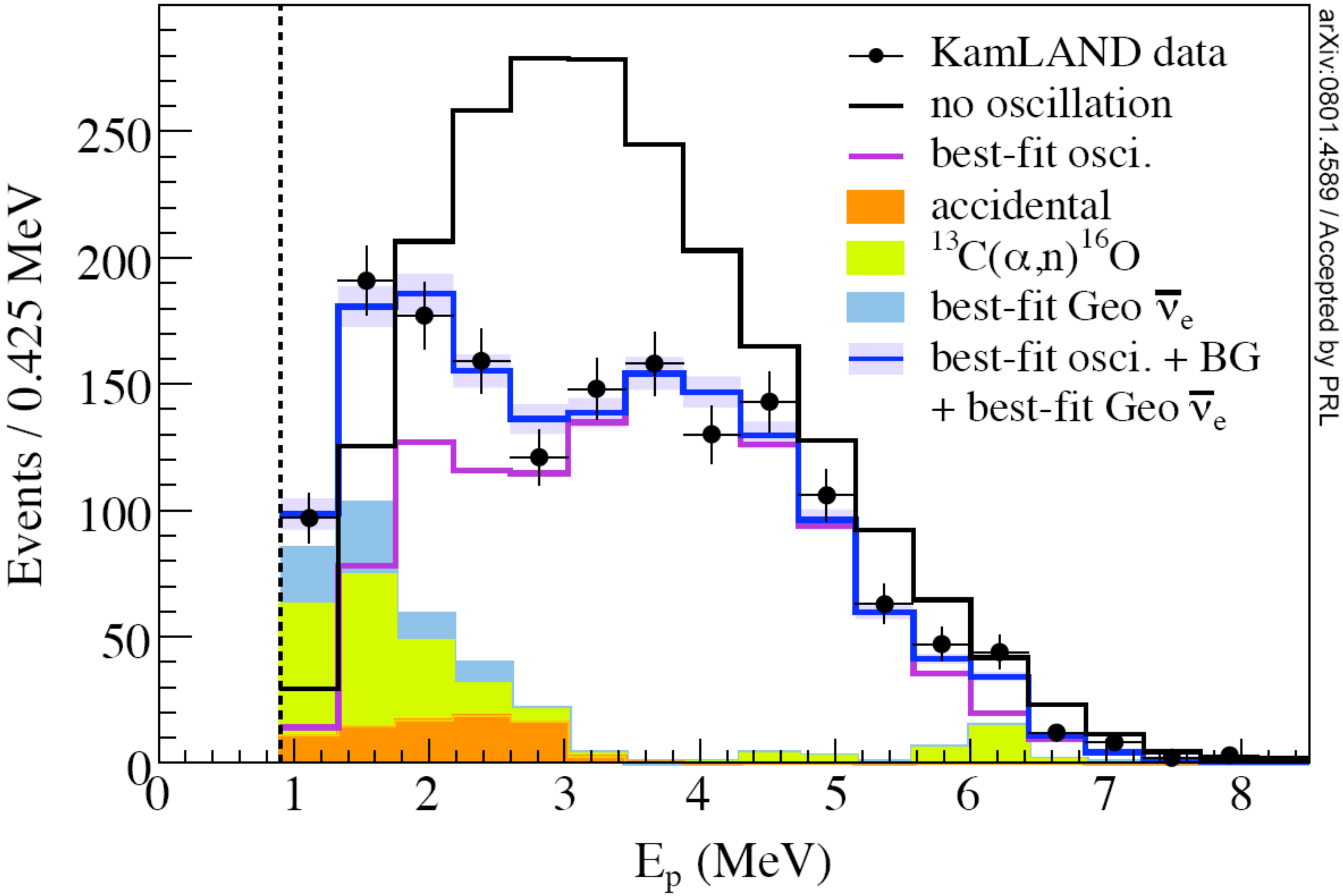
1000m rock
= 2700 mwe

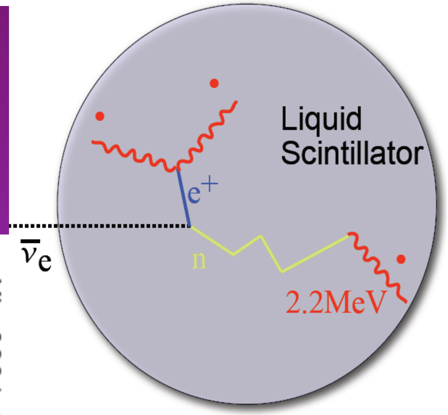
long. 137° 18' 43.495"
lat. 36° 25' 35.562"
alt. 358 m

Reactor neutrino flux:
~6×10^6 cm^{-2}s^{-1}



Kamland - Energy spectrum

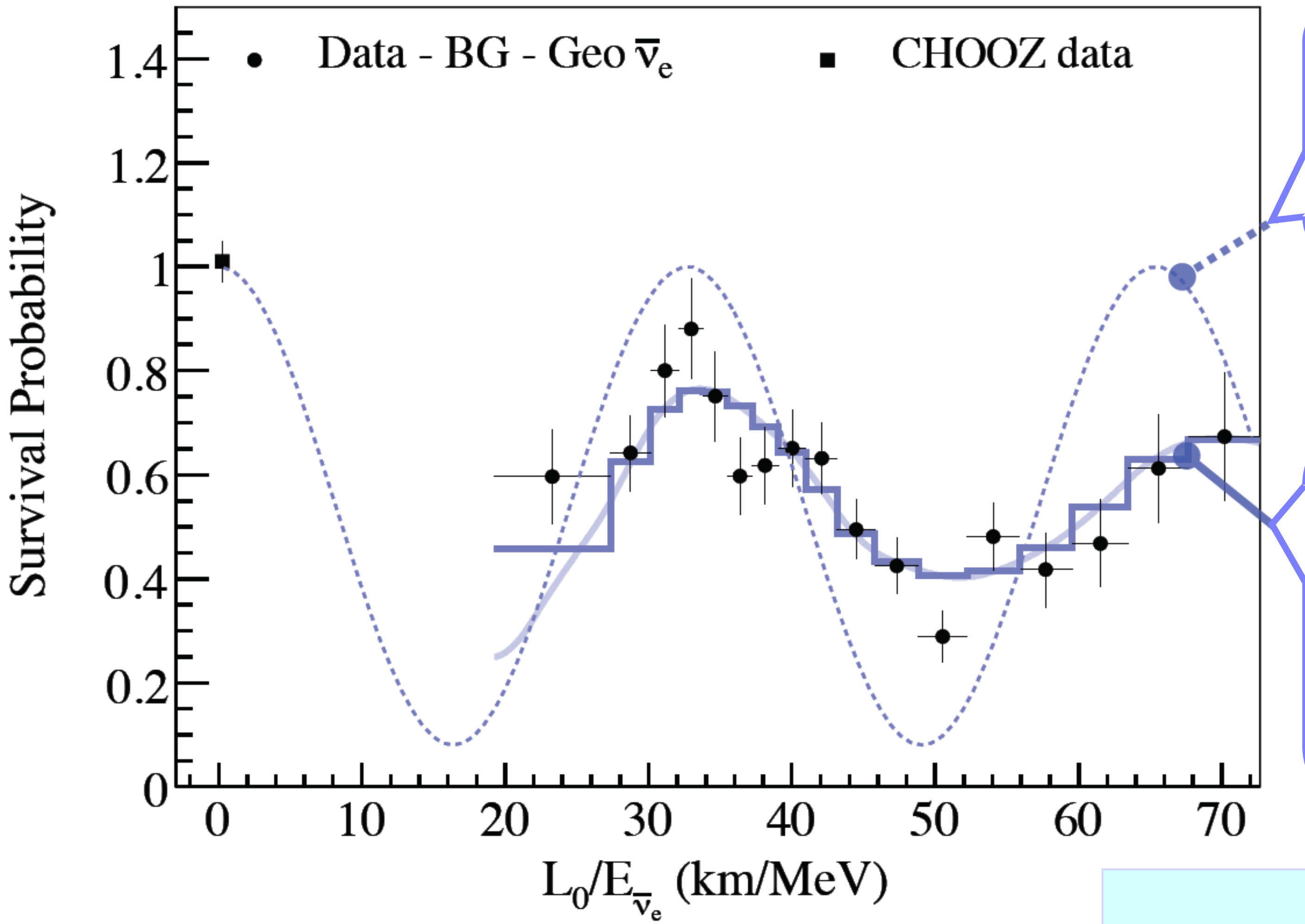




From Mar 2002 to May 2007.
i.e 1491 live days, 2881 ton-year exposure

Fit to scaled no-oscillation spectrum excluded at 5.1σ

Kamland – oscillation signature

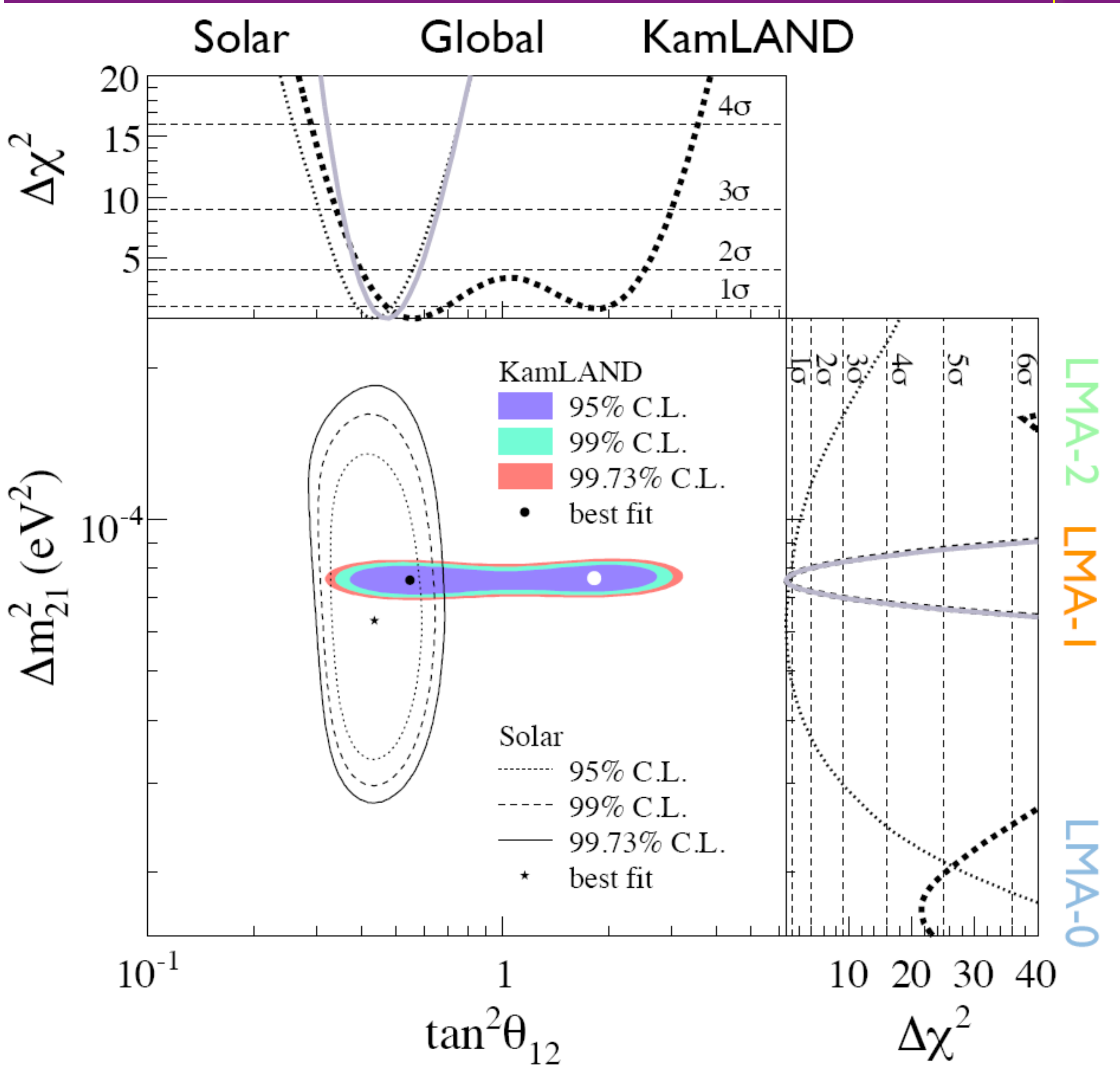


Oscillation pattern for mono-energetic, at one baseline

Best-fit oscillation accounting for energy spectrum and reactor distribution

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = \sin^2 2\vartheta \sin^2 \frac{1,27\delta m^2 L}{E_\nu}$$

Kamland - oscillation parameters



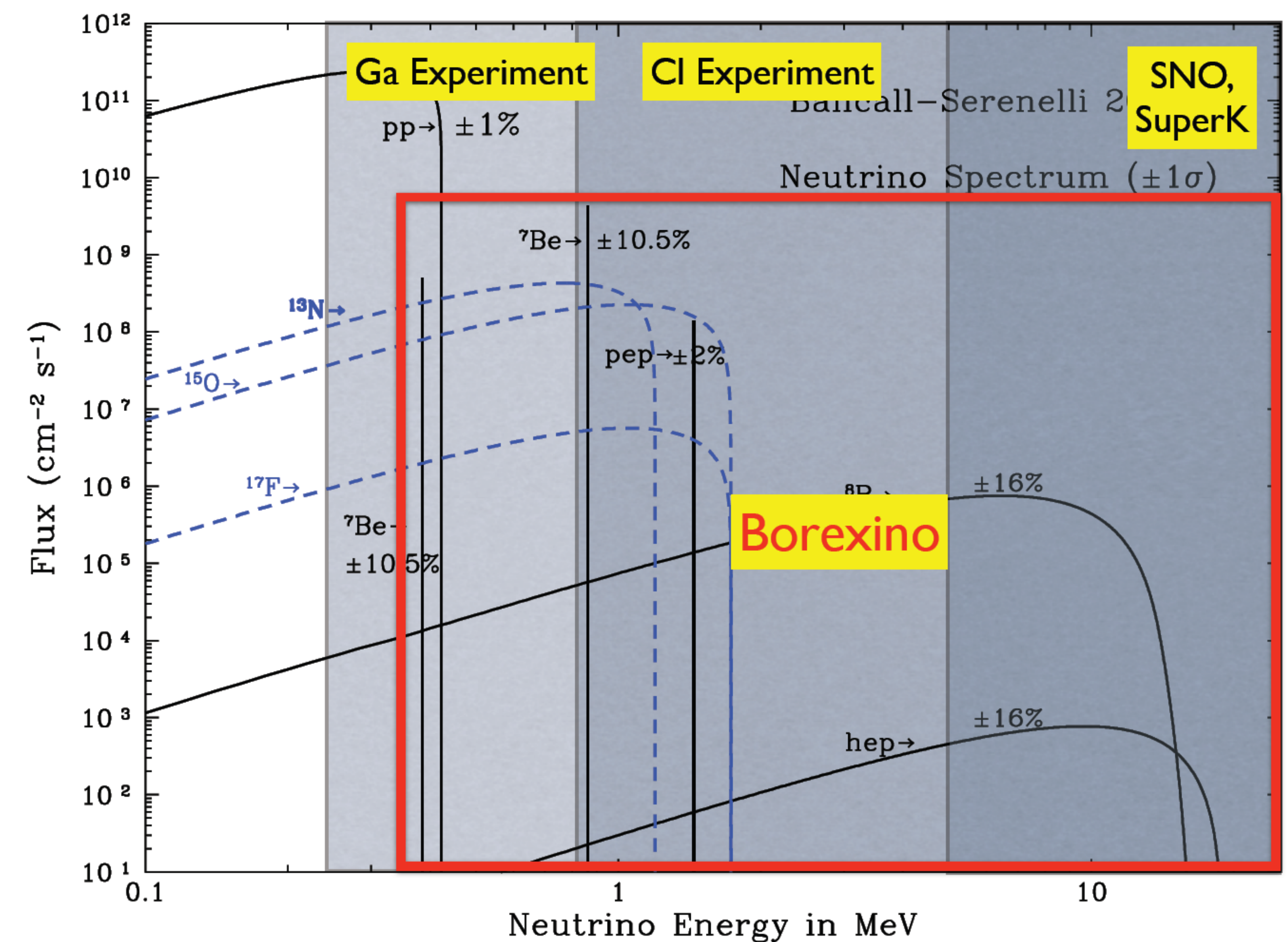
Kamland:

$$\bar{\nu}_e \rightarrow \bar{\nu}_x$$

Solar

$$\nu_e \rightarrow \nu_{\mu\tau}$$

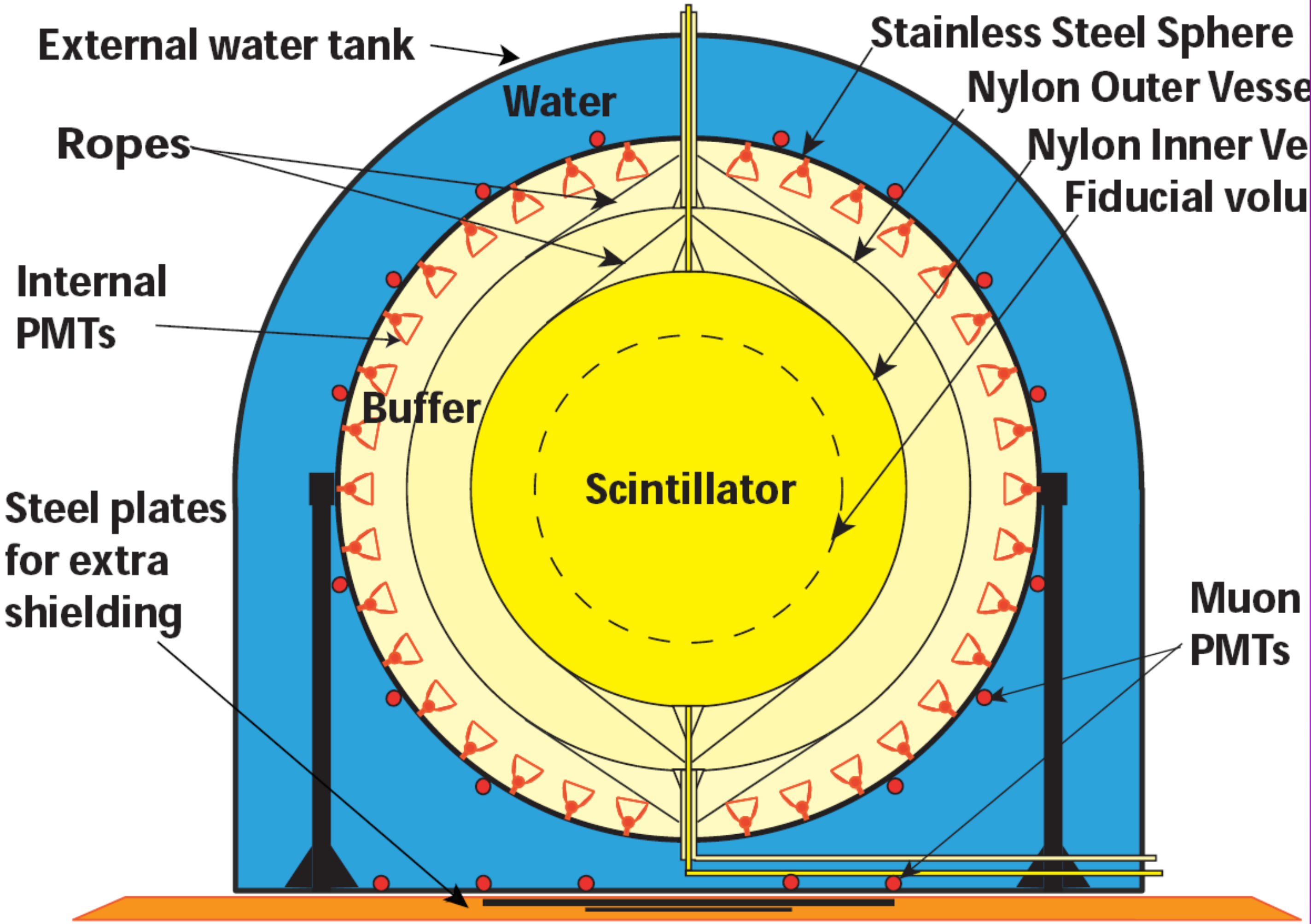
Borexino probes low energies



- real time
- energy reconstruction

Borexino detector

$\nu_x e^- \rightarrow \nu_x e^-$

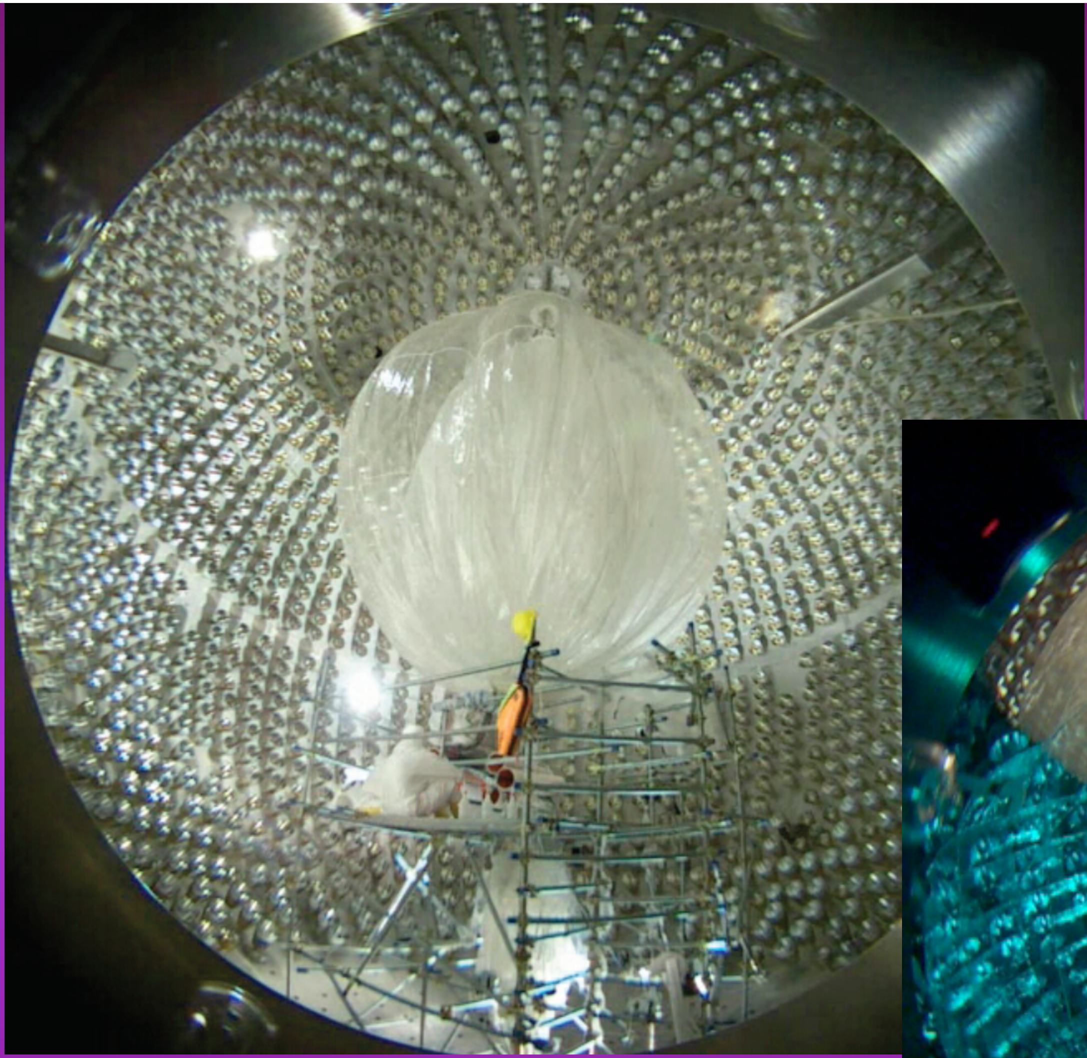


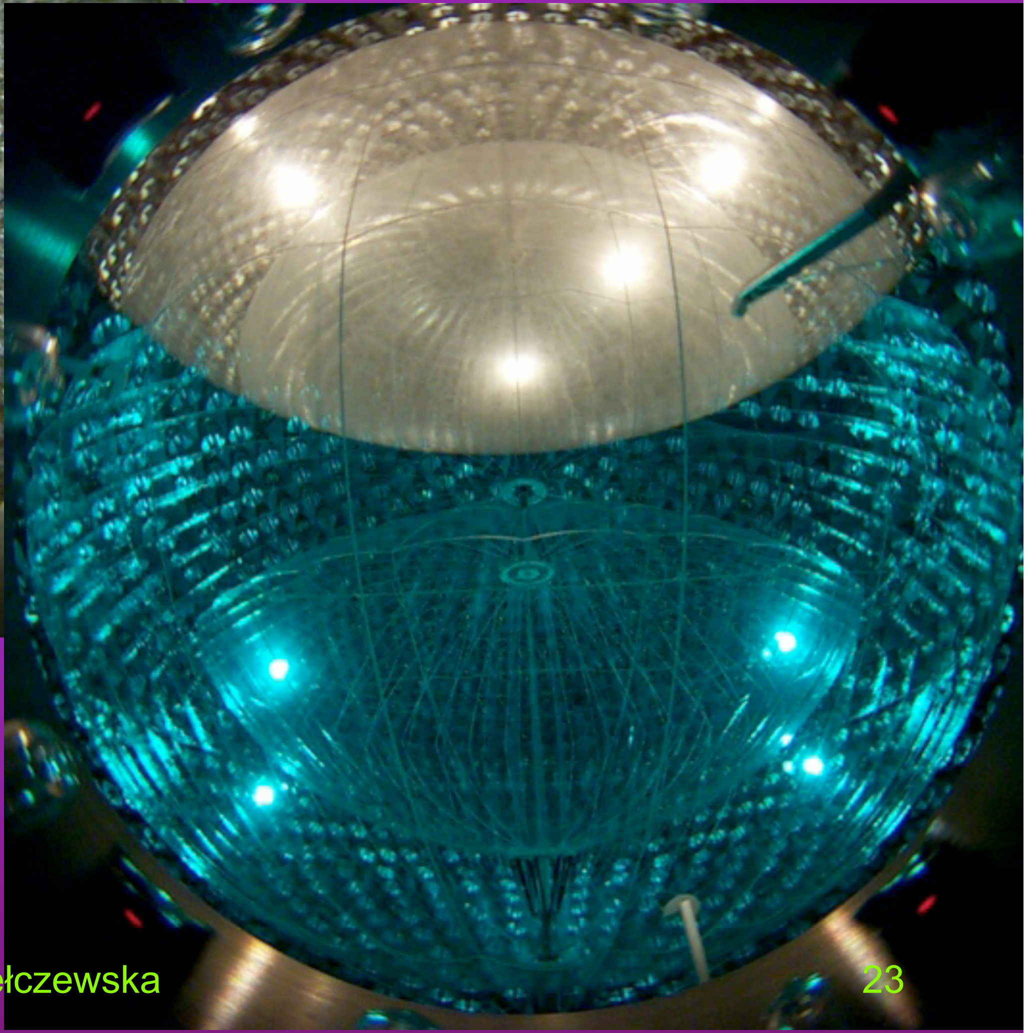
Located in LNGS - 3800 m.w.e. against cosmic rays

- 278 tons of scintillator
- 4.25m radius
- Experiment requires extreme purity from all radioactive contaminants

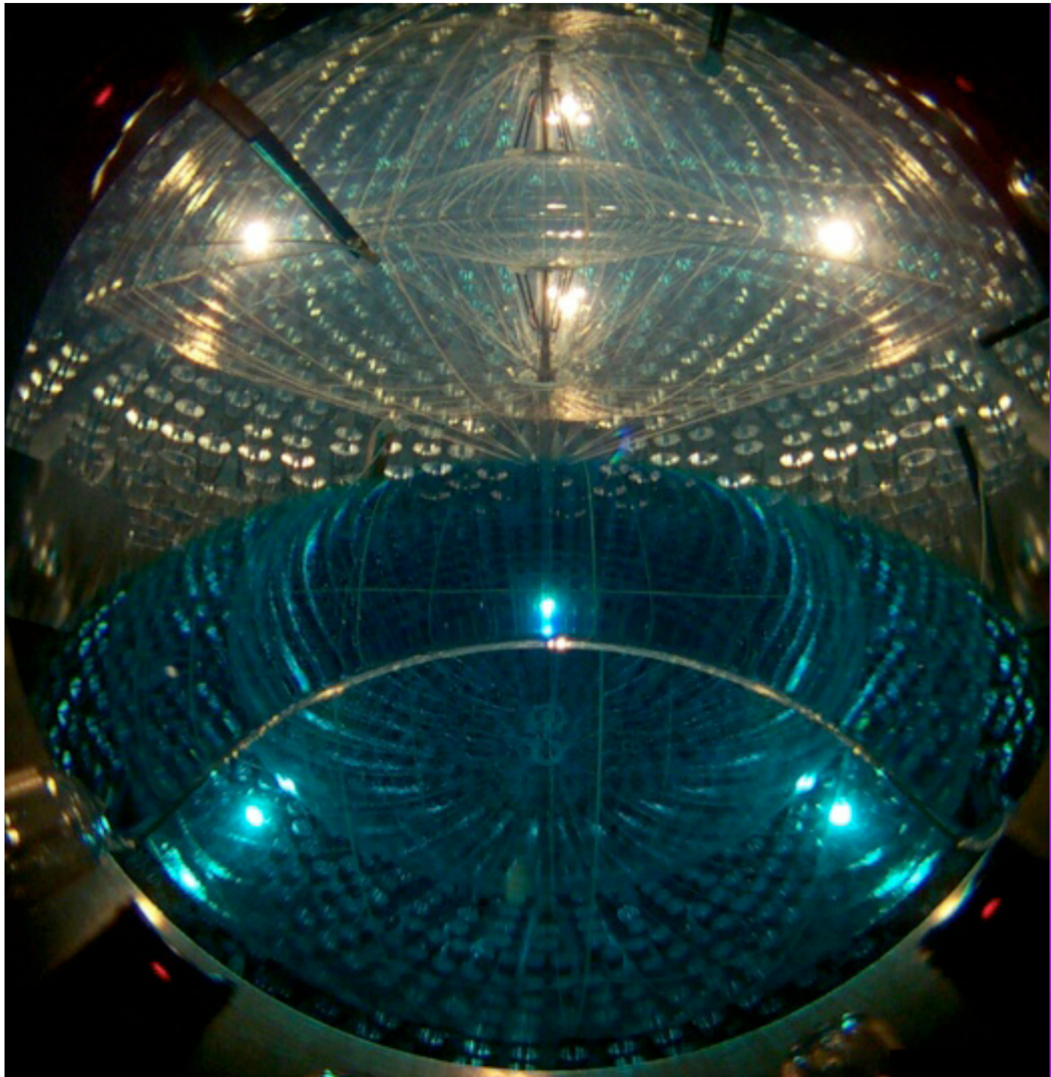
To explore:
- the vacuum-matter transition: untested feature of MSW-LMA solution
- possibly sensitive to new physics
- CNO neutrinos

Borexino detector

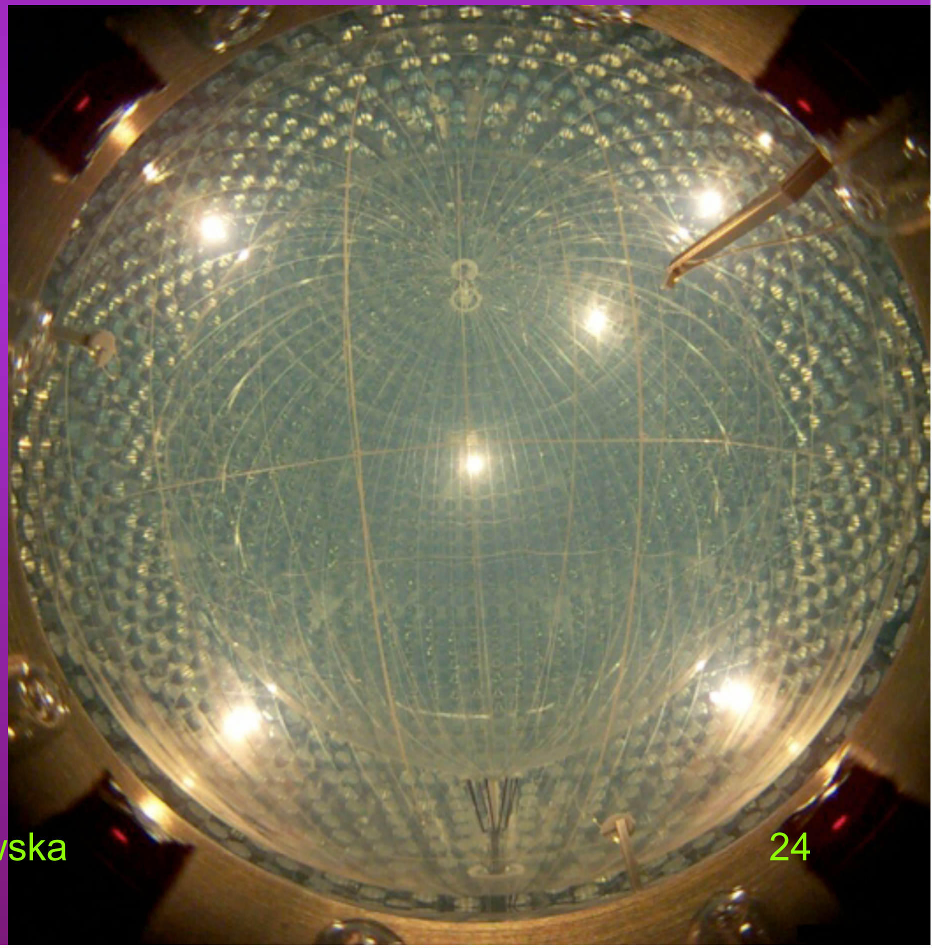




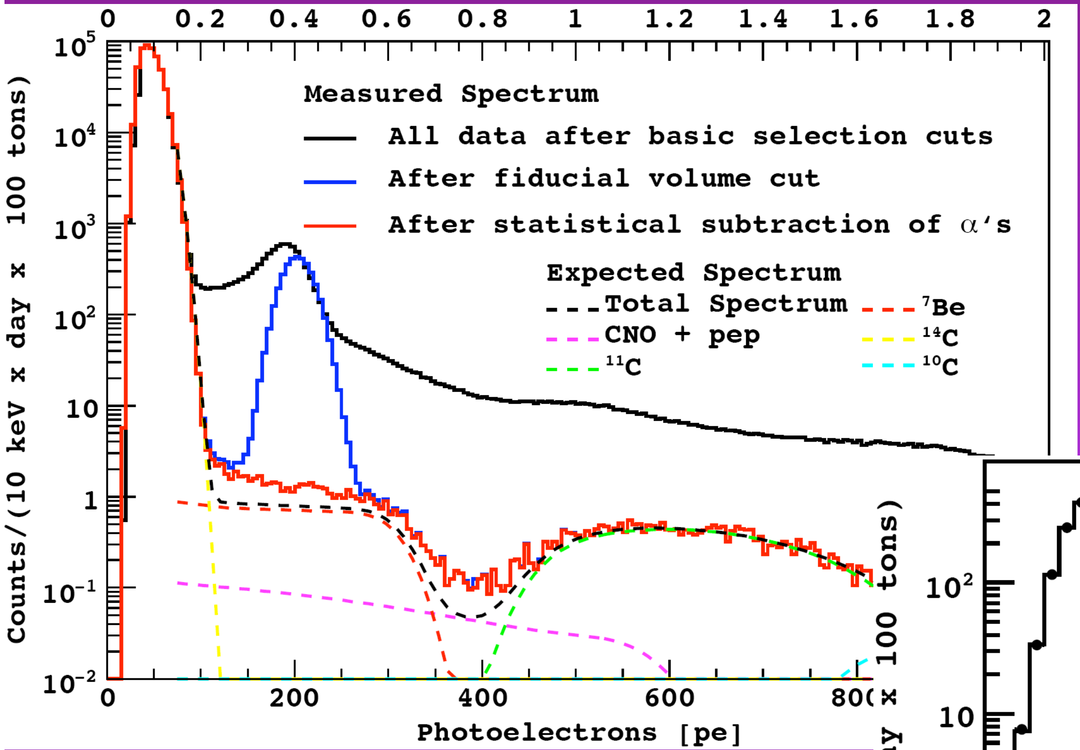
From PL: M. Wójcik et al. UJ



Borexino detector



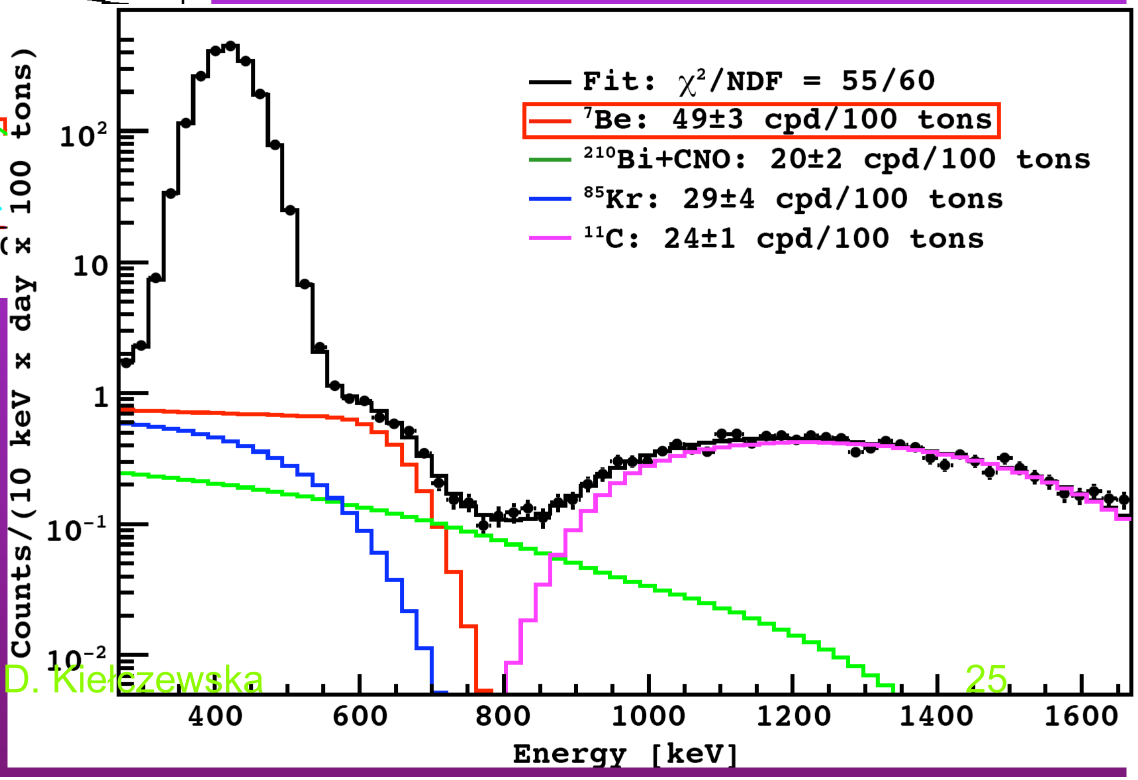
Borexino results after 192 days



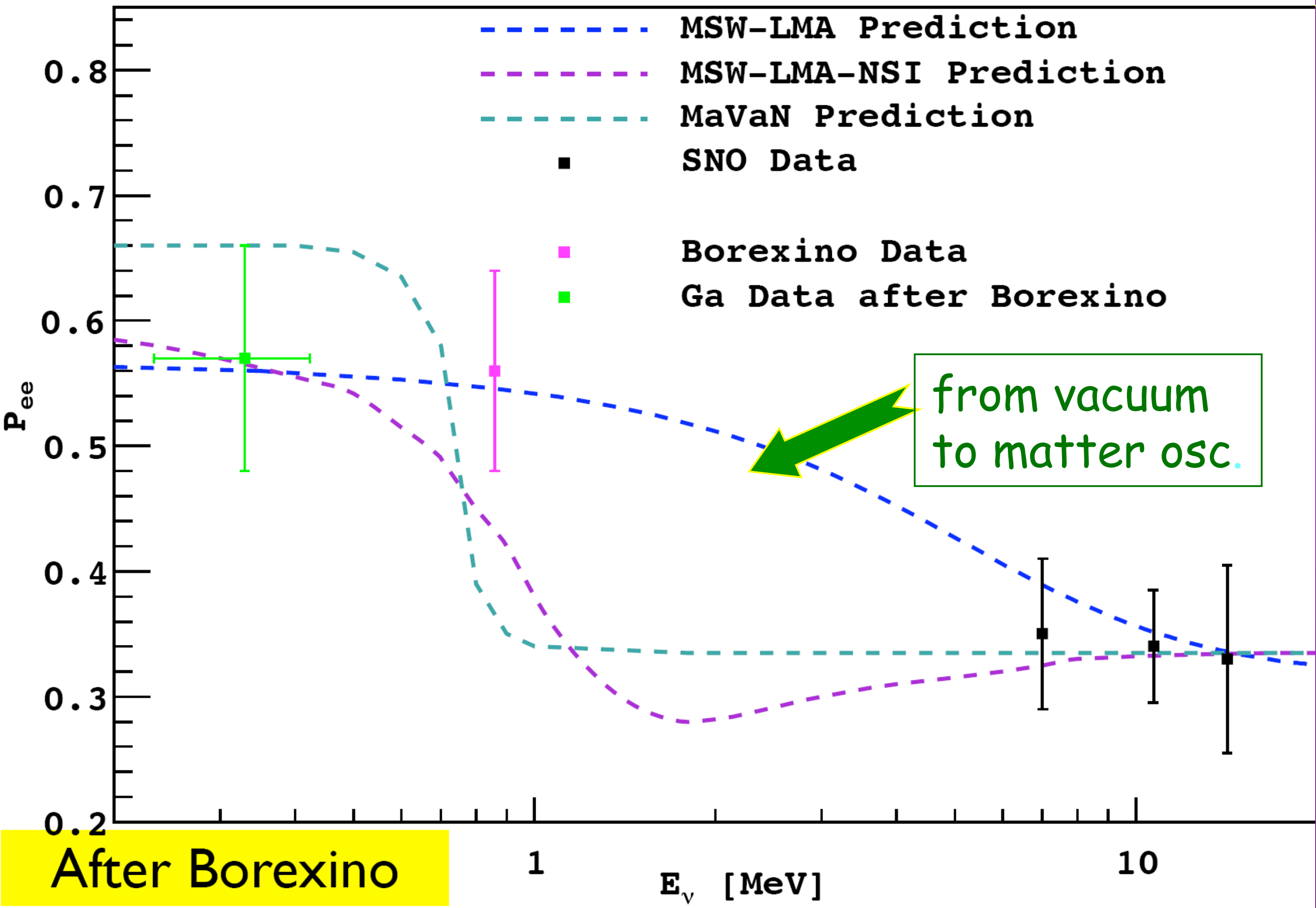
^{7}Be neutrinos:

Measured:
49±3stat±4syst cpd/100 tons

Expected w/o oscill:
75±4 cpd/100 tons



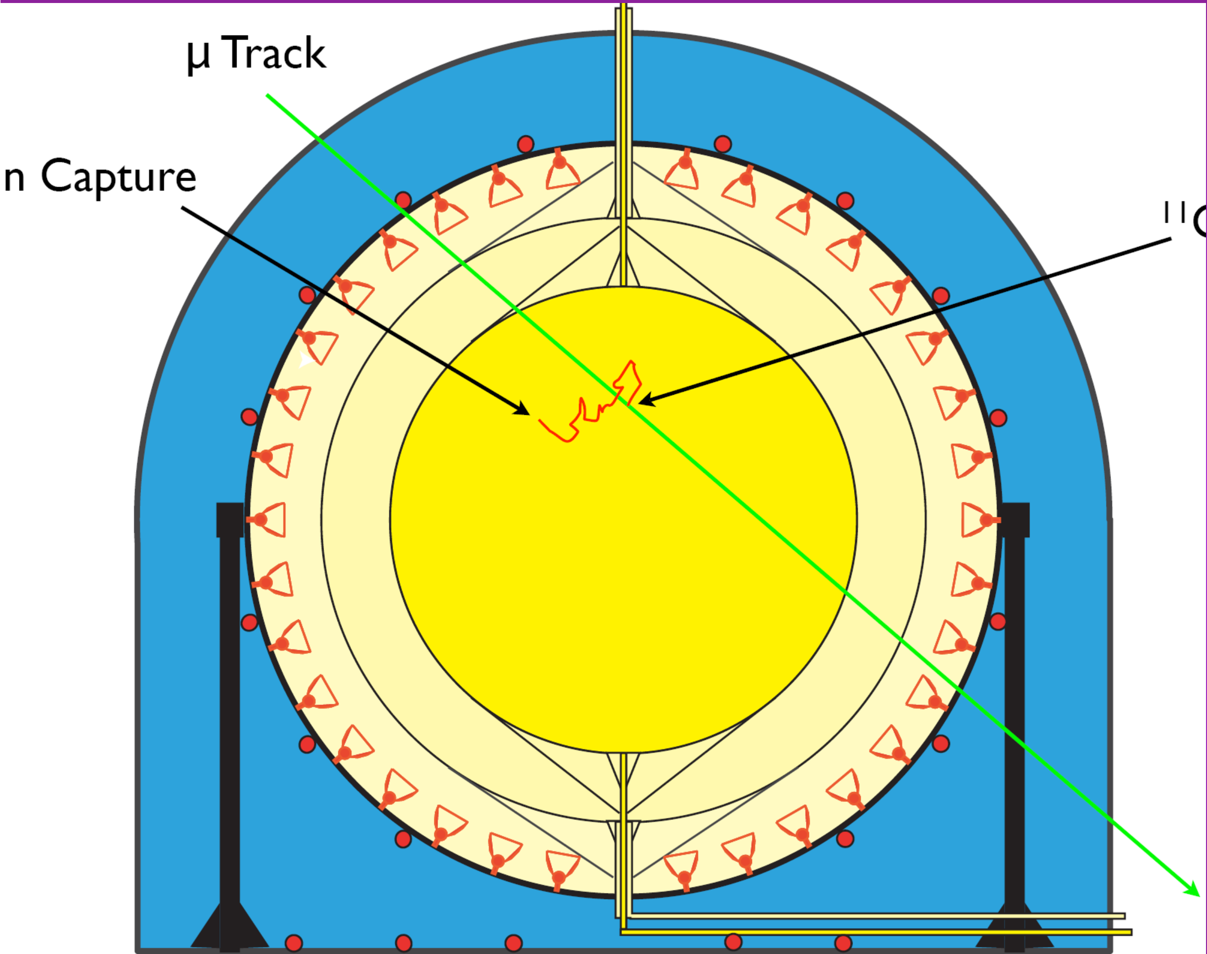
Borexino (192 days) – solar neutrino survival probability



After Borexino

No oscillations hypothesis (Pee=1) excluded at 4σ C.L.

Borexino – ^{11}C background



Measuring 25 cpd/100 tons of ^{11}C
Major background for CNO and *pep*
CNO: 5 cpd/100 tons
pep: 2 cpd/100 tons
Long-lived isotope (30 min mean life)
Simple coincidence with muon impractical (dead time kills!)
Neutron must be emitted together with ^{11}C
Tag in coincidence with muon and neutron capture (300 μs, 2.2 MeV γ-ray)

Borexino – electron neutrino magnetic moment

$$\left(\frac{d\sigma}{dT}\right)_W = \frac{2G_F^2 m_e}{\pi}\left[g_L^2 + g_R^2\left(1-\frac{T}{E_\nu}\right)^2 - g_L g_R \frac{m_e T}{E_\nu^2}\right]$$

EM current affects cross section σ

Spectral shape sensitive to μ_ν

Sensitivity enhanced at low energies ($\sigma \approx 1/T$)

$$\left(\frac{d\sigma}{dT}\right)_{EM} = \mu_\nu^2 \frac{\pi\alpha_{em}^2}{m_e^2}\left(\frac{1}{T}-\frac{1}{E_\nu}\right)$$

Estimate	Method	90% C.L. 10^{-11} μ_B
SuperK	^8B	<11
Montanino et al.	^7Be	<8.4
GEMMA	Reactor	<5.8
Borexino	^7Be	<5.4

All results from solar and reactor experiments (large L/E) seem to be consistently described by

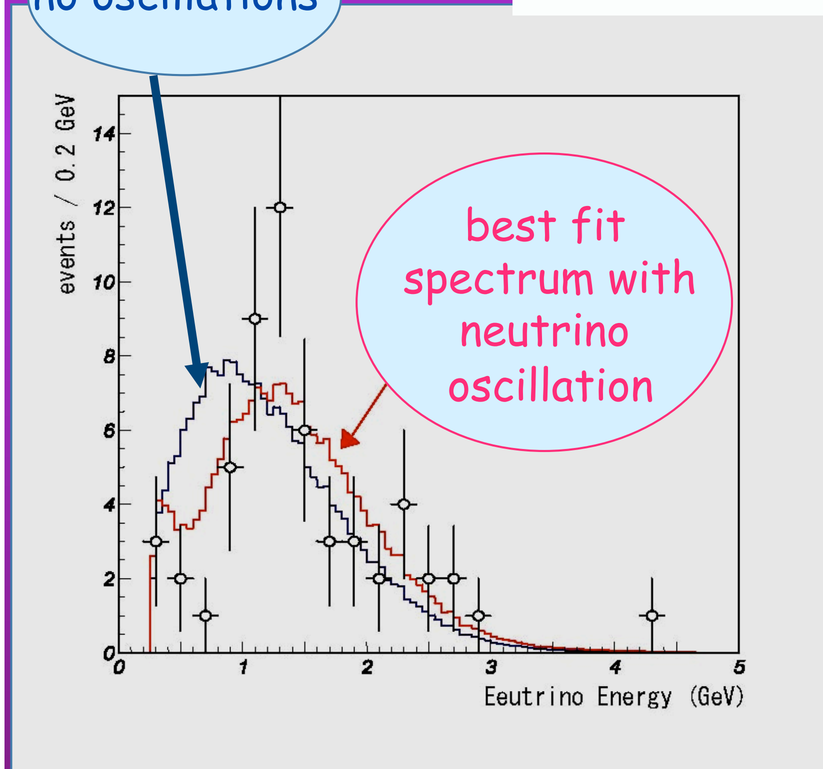
$$\nu_e \rightarrow \nu_{\mu\tau}$$

Let's switch to
atmospheric and long-baseline domain:
smaller L/E and larger Δm^2

where $\nu_\mu \rightarrow \nu_\tau$ dominates

Observation of ν_μ oscillation in K2K
(KEK to Kamioka) 1999-2004

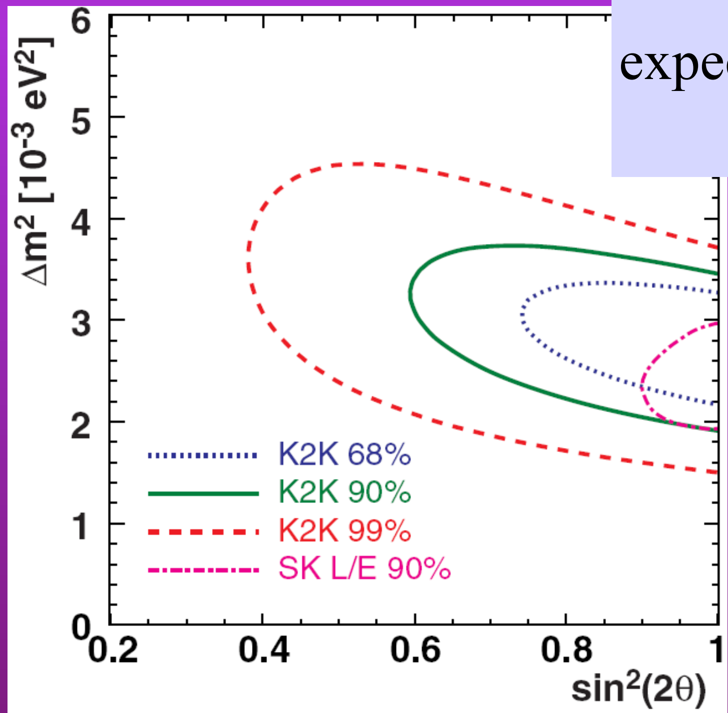
UW & **IPJ**



observed : 107 events

expected : 151^{+12}_{-10} events

103.8 for

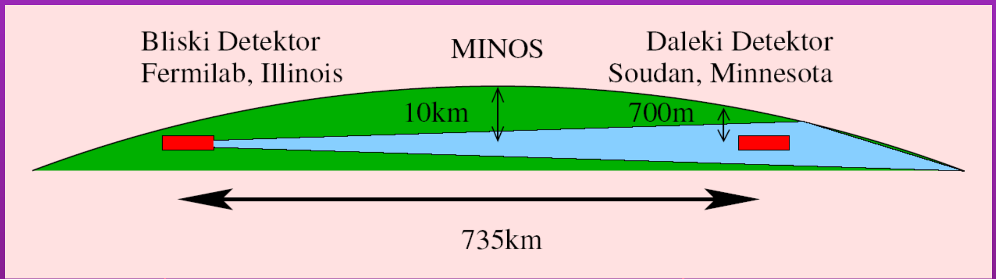


oscil. parameters consistent with atmosph. neutrinos

MINOS
(Main Injector Neutrino Oscillation Search)

K. Grzelak from
Warsaw University

- Two detectors
- Iron (magnetized) - scintillator sampling calorimeter
- ND 980tons @1km, FD 5400tons @730km
- Far detector fully operational since 2003



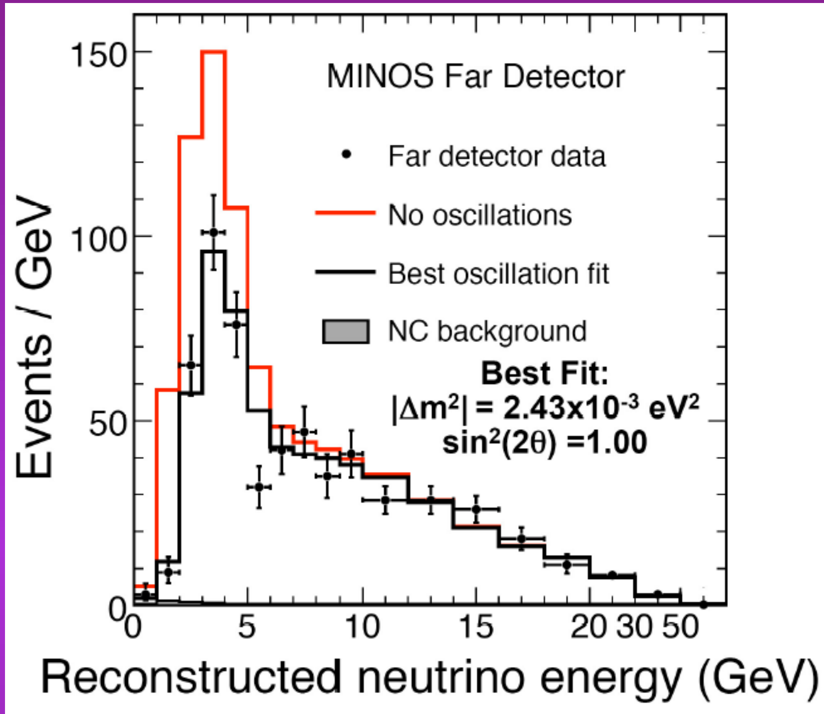
Near detector

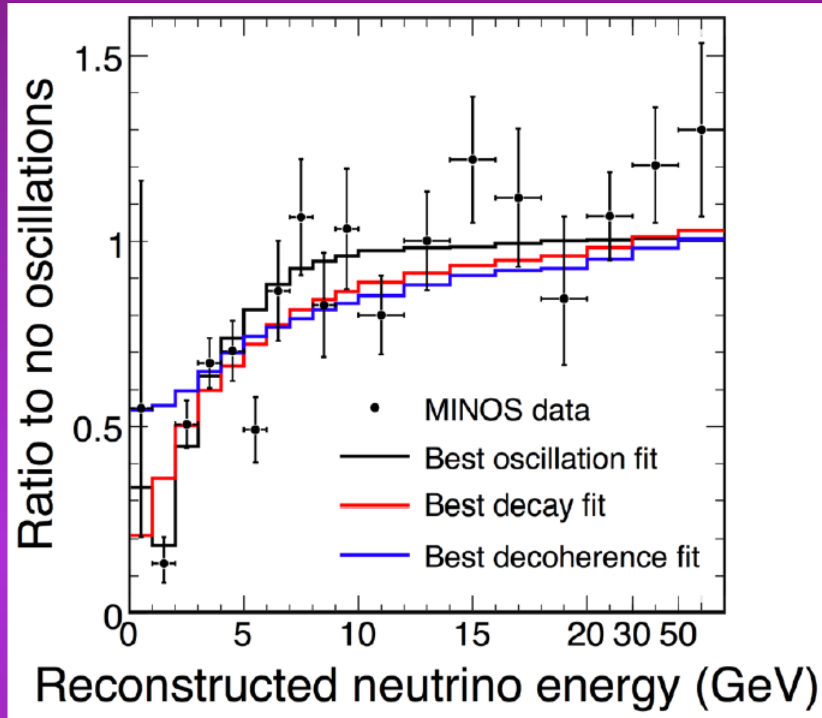
Far detector

Far Detector

Minos results: CC events

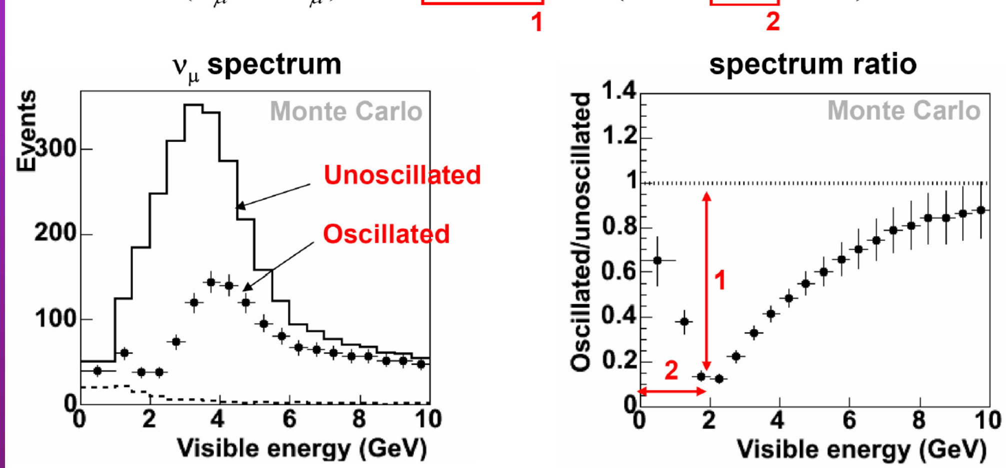
848 events observed
3.36×10^{20} pot





MC guide to interpretation:

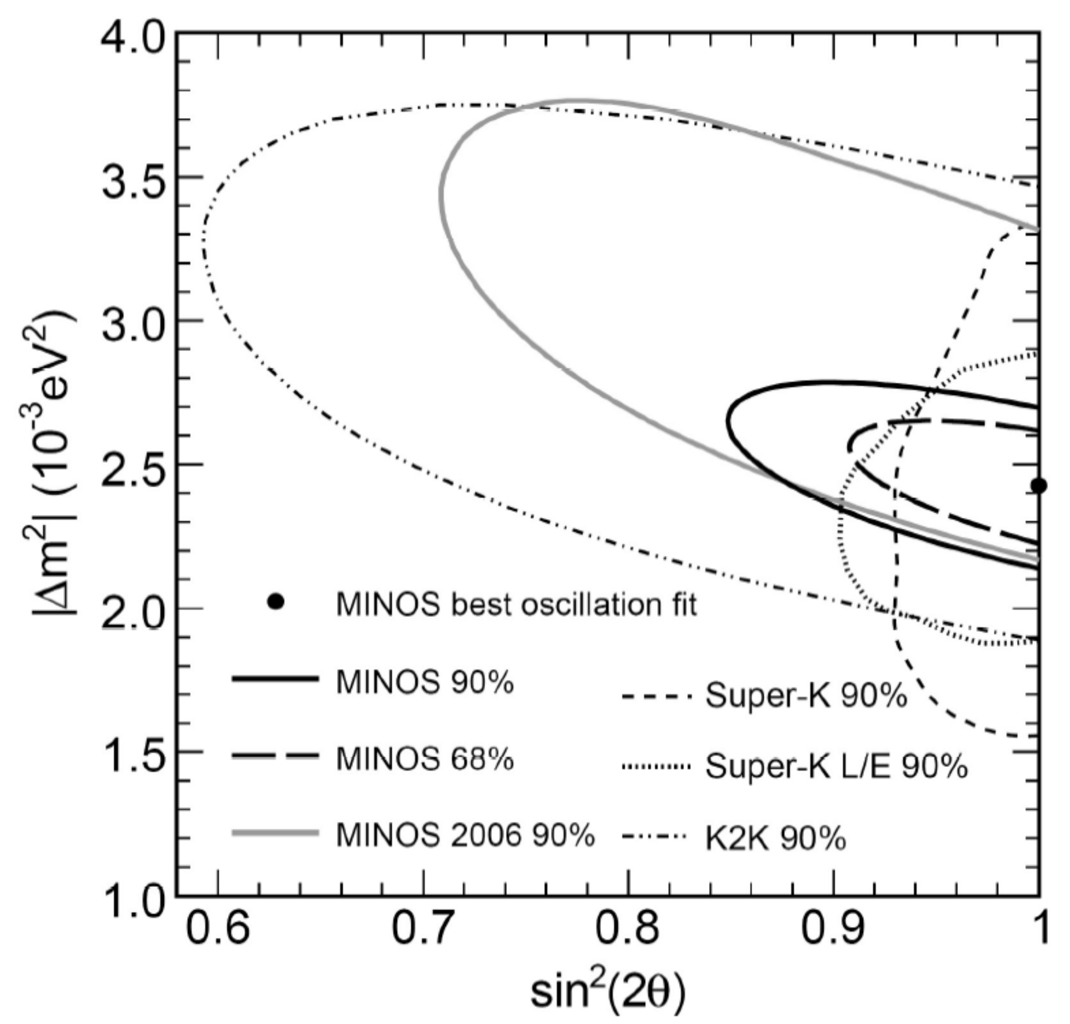
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267 \Delta m^2 L / E)$$



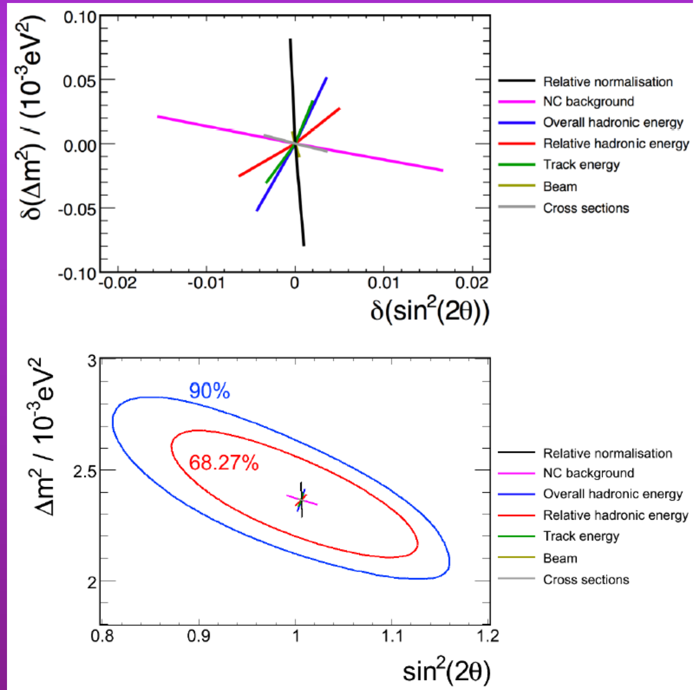
Minos results

848 events observed
3.36×10^{20} pot

$\nu_\mu \rightarrow \nu_x$



Consistent results from:
- Super-K
- K2K
- MINOS

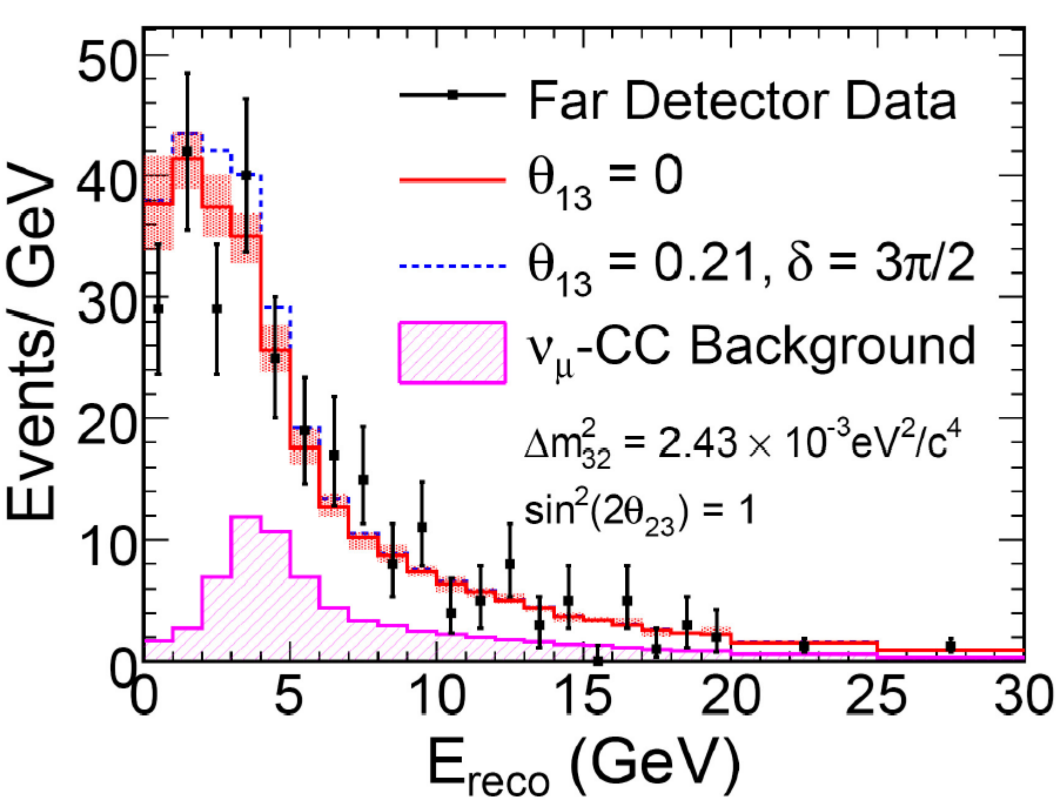


still limited by statistics

Minos results - NC data

3.36×10^{20} pot

Search for: $\nu_\mu \rightarrow \nu_{sterile}$



$$R \equiv \frac{N_{Data} - B_{CC}}{S_{NC}}$$

B_{CC}: przewidywane tło od wszystkich oddziaływań CC
S_{NC}: przewidywany sygnał NC

E_{reco}(GeV)	N_{Data}	S_{NC}	$B_{CC}^{\nu_\mu}$	$B_{CC}^{\nu_\tau}$	$B_{CC}^{\nu_e}$
0-3	100	101.1	11.2	1.0	1.8 (9.3)
3-120	191	98.0	64.2	3.5	11.8 (24.6)

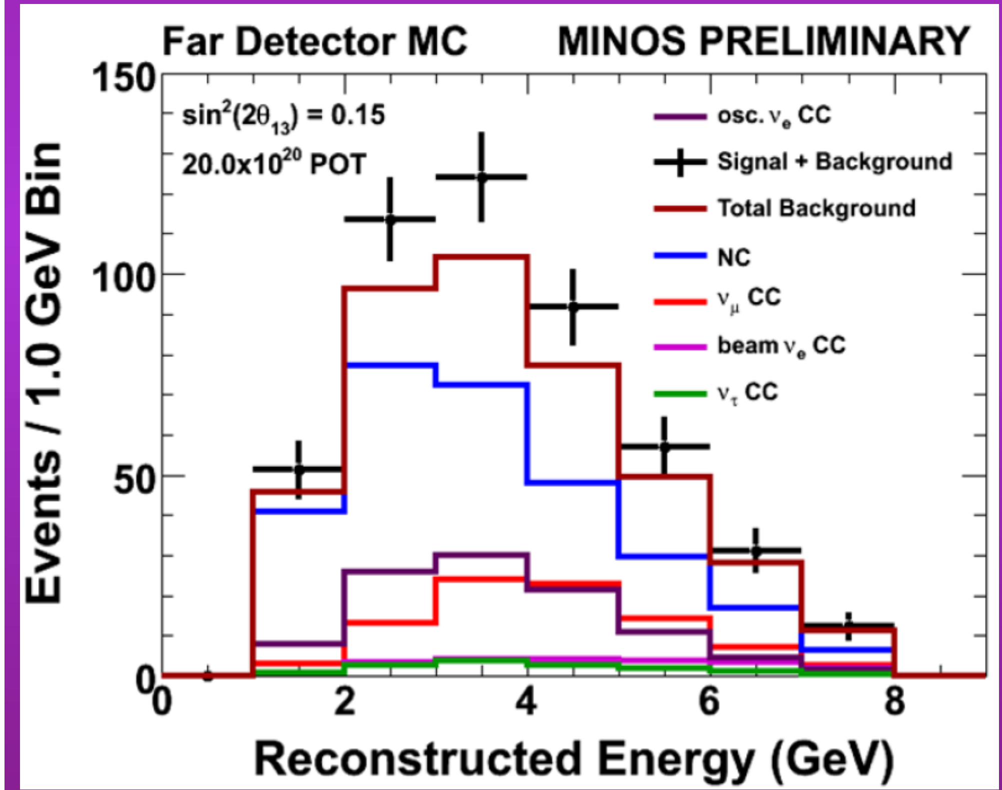
0-3	R=0.85 $\pm$ 0.10 $\pm$ 0.07	(0.78 $\pm$ 0.10 $\pm$ 0.07)
3-120	R=1.14 $\pm$ 0.14 $\pm$ 0.10	(1.02 $\pm$ 0.14 $\pm$ 0.10)
0-120	R=0.99 $\pm$ 0.99 $\pm$ 0.07	(0.90 $\pm$ 0.09 $\pm$ 0.08)

No sign of: $\nu_\mu \rightarrow \nu_{sterile}$

MINOS outlook

Search for: $\nu_\mu \rightarrow \nu_e$

Expected for 20×10^{20} pot:



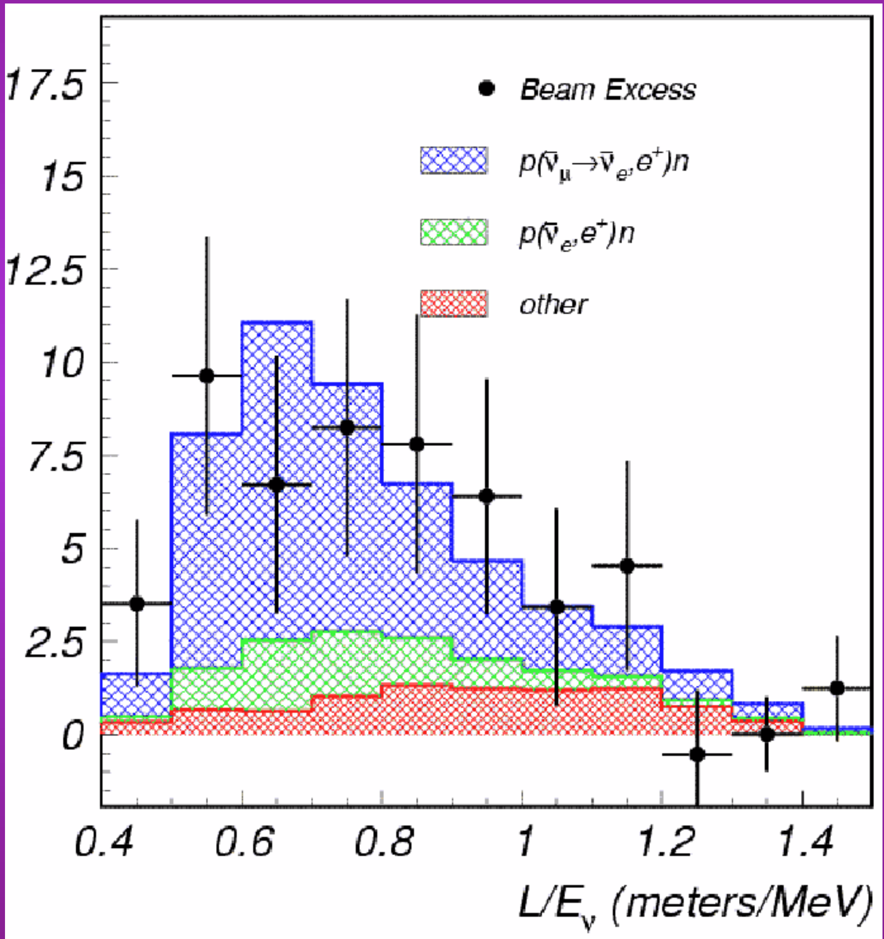
Dla 3.25×10^{20}pot dla limitu CHOOZ oczekiwanych jest 12 przypadków sygnału i 42 przypadki tła

Do chwili obecnej zebrane ponad 5×10^{20} pot. Do najbliższego zamknięcia akceleratora na początku kwietnia 2009 oczekiwane jest 6.5×10^{20} pot

Obecnie oficjalny koniec zbierania danych w 2010 roku, ale planuje się przedłużenie ($\bar{\nu}_\mu$!)

LSND oscillations ??

$\nu_\mu \rightarrow \nu_e$



LSND found an excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam

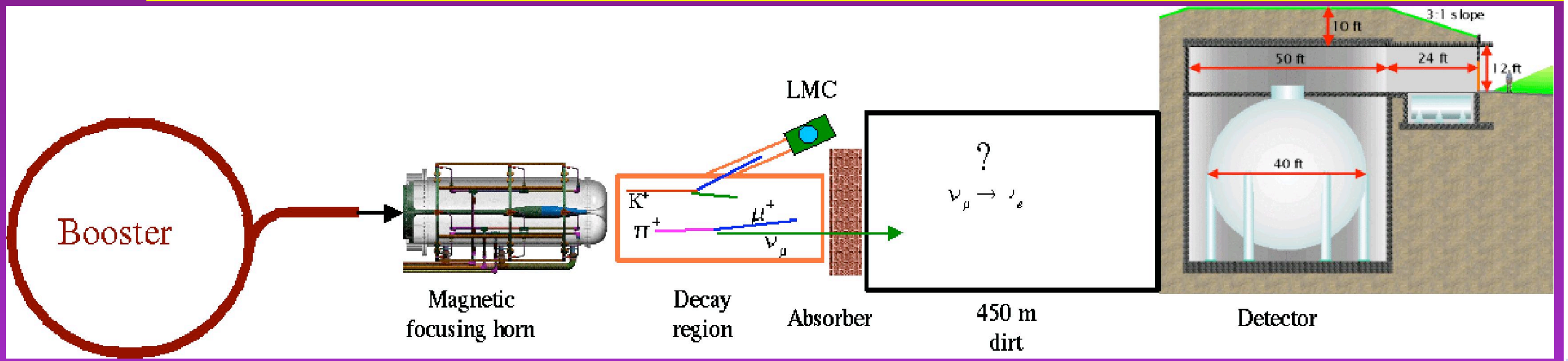
Excess: $87.9 \pm 22.4 \pm 6.0$ (3.8σ)

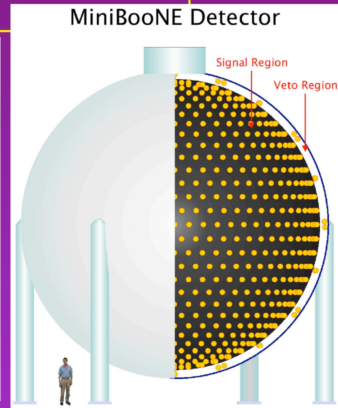
A less significant excess of ν_e was also found in ν_m beam.

To check LSND one should preserve L/D:

LSND 0.03 km/0.05 GeV
MiniBoone 0.5 km/0.8 GeV

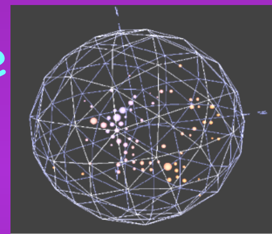
MiniBooNE (2002~) (Fermilab)





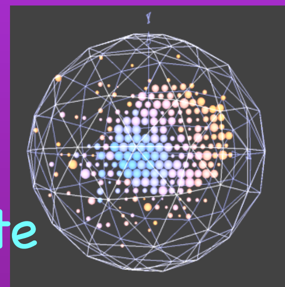
To check $\nu_\mu \rightarrow \nu_e$ at $\Delta m^2 \sim 1 eV^2$ (LSND)

Michel e from μ decay

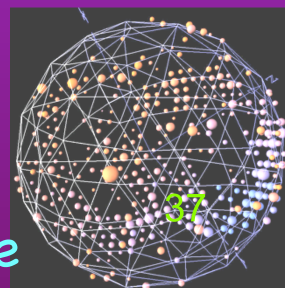


- 8 GeV proton beam (Be target)
  - E_n~700 MeV, L~541m (L/E~0.77)

- Mineral Oil Cherenkov Detector
  - 800 tons, 12 m diameter sphere
  - 1280 eight-inch PMT's
  - 240 PMT for VETO.
  - 611,000 ν events.



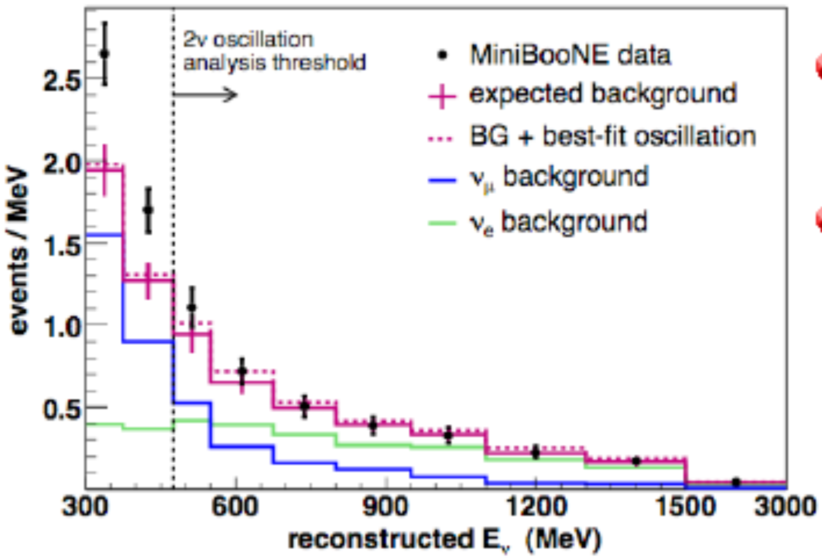
ν_e candidate



π^0 candidate

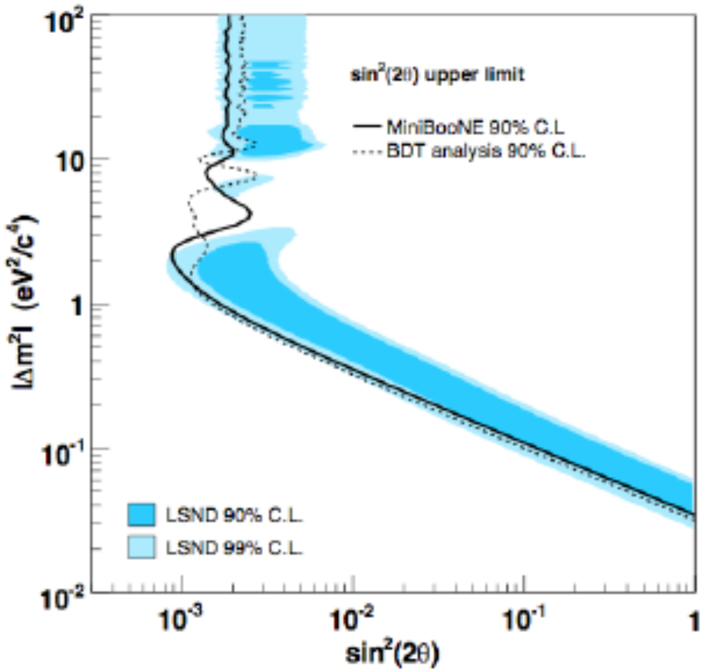
MiniBoone results – Aug 2008

Data/fit result after blind analysis complete...



- No sign of an excess in the analysis region (where the LSND signal is expected for the 2ν mixing hypothesis)
- Visible excess at low E

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



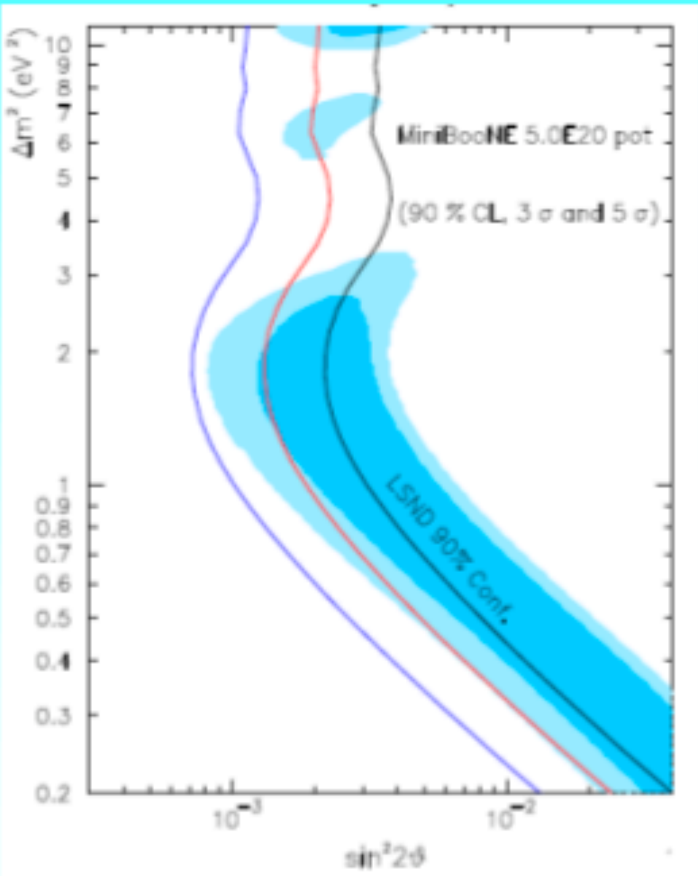
- What does it all mean? There are a few possibilities...
  - Some problem with LSND, e.g. mis-estimated background?
  - Difference between neutrinos and antineutrinos?
  - The physics causing the excess in LSND doesn't scale with L/E?
    - Low E excess in MB related?

Chris Polly, Fermilab W&C, 1 Aug 2008

MINIBOONE

MiniBooNe will most definitely check the LSND result in terms of neutrino oscillations - and see whether this so far inscrutable stone guest is the messenger of god's wrath over neutrino physics or something else

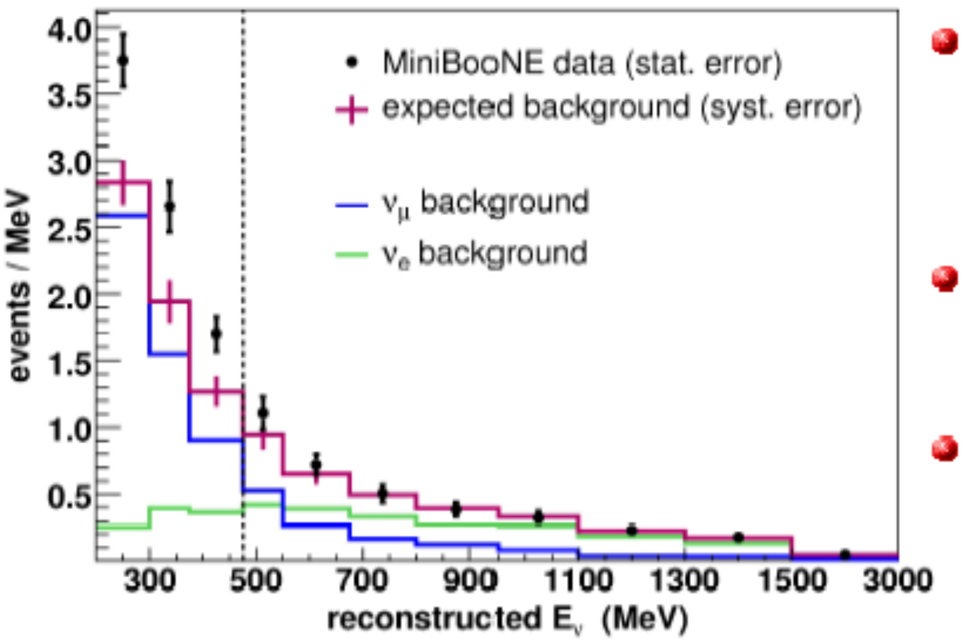
MiniBooNE is designed to have the same L/E of LSND (~0.6 km/GeV) with different L and different E, and also completely different systematic errors and experimental challenges



FULL STATISTIC FOR FIRST OSCILLATION RESULT (5.7E20 POT) COLLECTED BY JAN '06

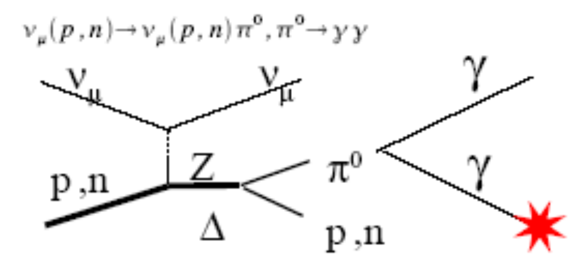
A. Curioni - Yale U.

Extending the analysis to lower energies



- Original excess quoted in initial oscillation PRL 98, 231801 (2007)
  - 475–1250 MeV, 22 ± 40, 0.6σ
  - 300–475 MeV, 96 ± 26, 3.7σ
- In summer 2007 extended analysis down to 200 MeV
  - 200–300 MeV, 92 ± 37, 2.5σ
- Combined significance with proper systematic correlations
  - 200–475 MeV, 188 ± 54, 3.5σ

Only hadronic process found to contribute significantly:

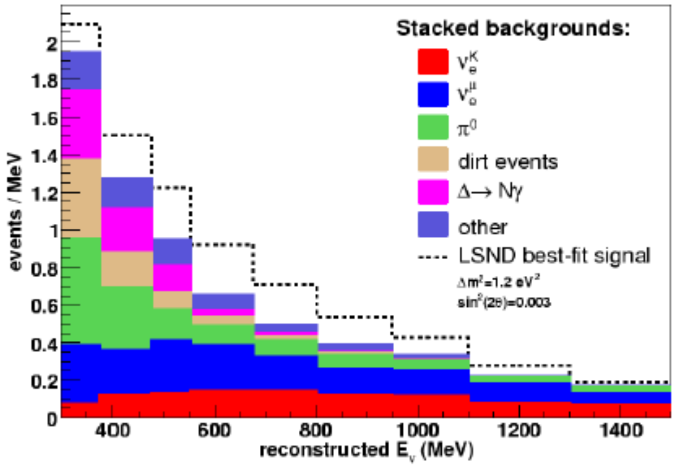


Photonuclear interactions

- Absent in GEANT3
- Can delete a γ in a NC pi0 interactions, thus creating a single e–like ring

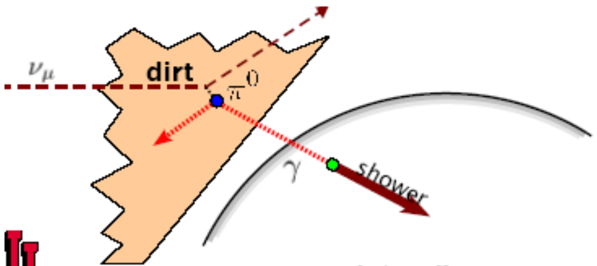
MiniBoone - backgrounds

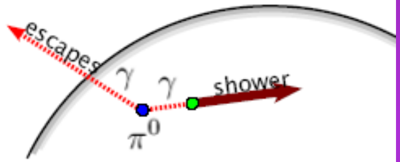
TBL Analysis: Expected event totals



475 MeV - 1250 MeV	
ν_e^K	94
ν_e^μ	132
π^0	62
dirt	17
$\Delta \to N\gamma$	20
other	33
total	358

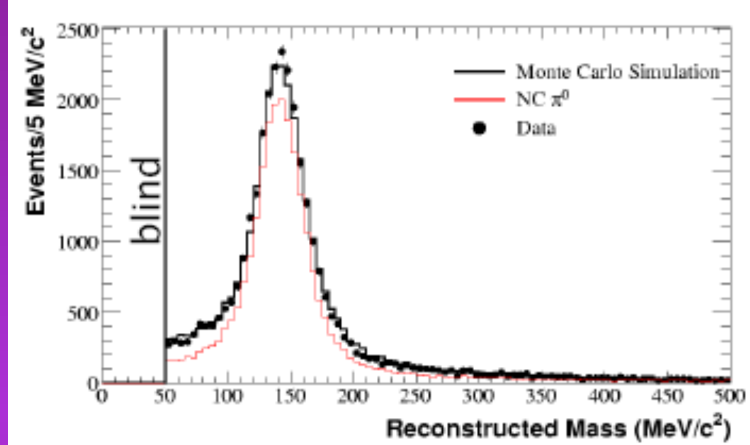
LSND best-fit $\nu_\mu \to \nu_e$ 126



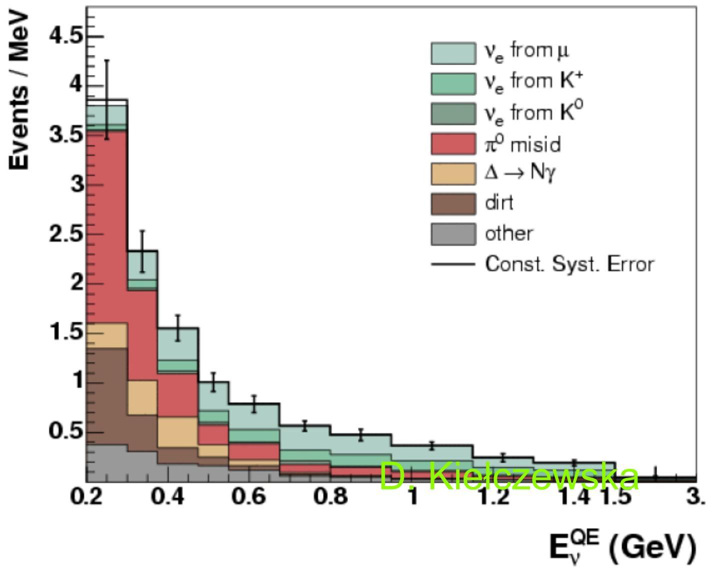


Chris Polly, I

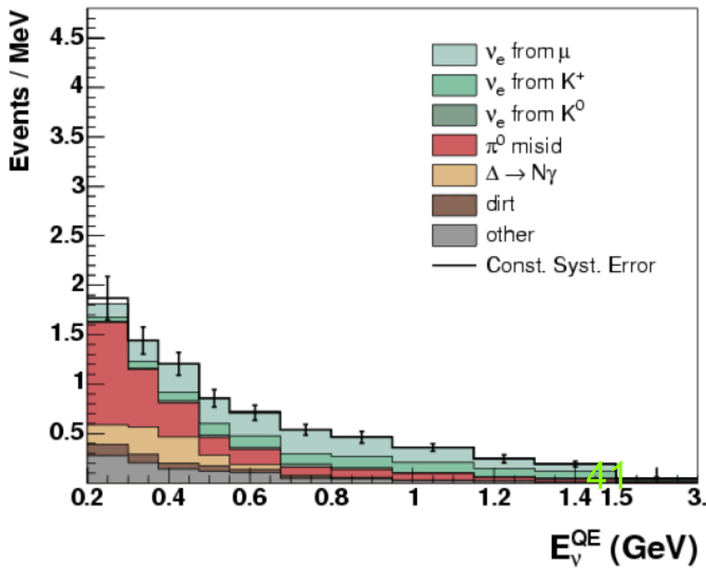
Separating e from p^0



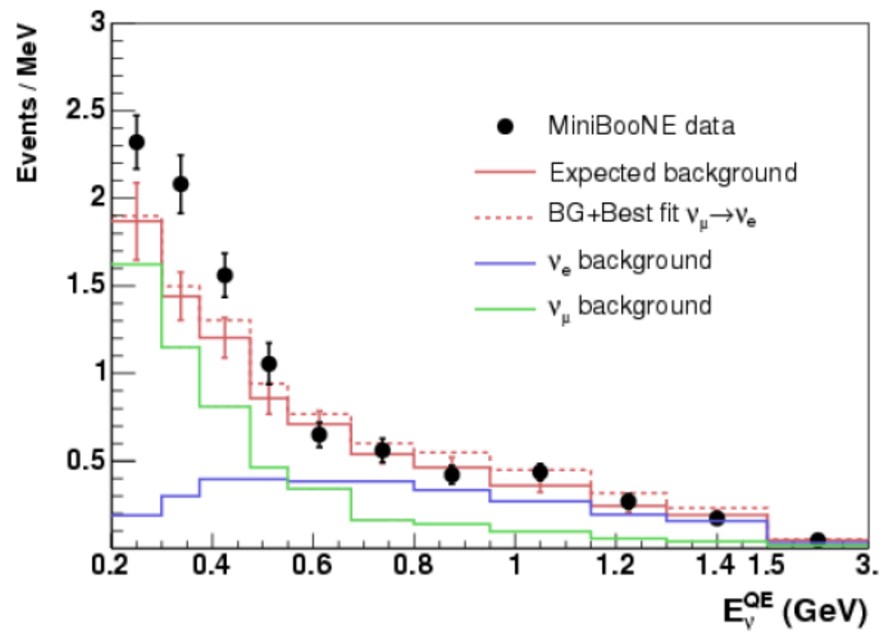
No DIRT cuts

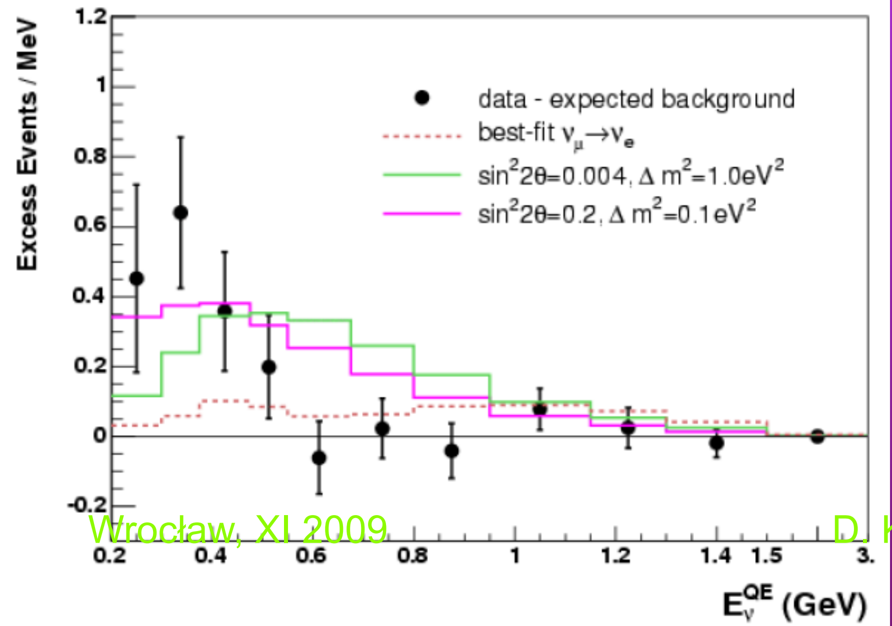


With DIRT Cuts



MiniBoone – extend 2 n fit to low E





	E_ν>475 MeV	E_ν>200 MeV
Null fit χ^2 (prob.):	9.1(91%)	22.0(28%)
Best fit χ^2 (prob.):	7.2(93%)	18.3(37%)

- Adding 3 bins to fit causes chi^2 to increase by 11 (expected 3)
- Can see the problem...the best 2ν fit that can be found does not describe the low E excess.

After a review of all backgrounds and errors with emphasis st low E:

- no change to the analysis > 475 MeV
- the excess at low E is still >3s and remains a mystery

MiniBoone - summary

MiniBoone rules out at 98% cl the LSND result interpreted as $\nu_\mu \to \nu_e$

Now they are running antineutrinos to check $\bar{\nu}_\mu \to \bar{\nu}_e$

This leaves us with only 2 experimentally found mass differences

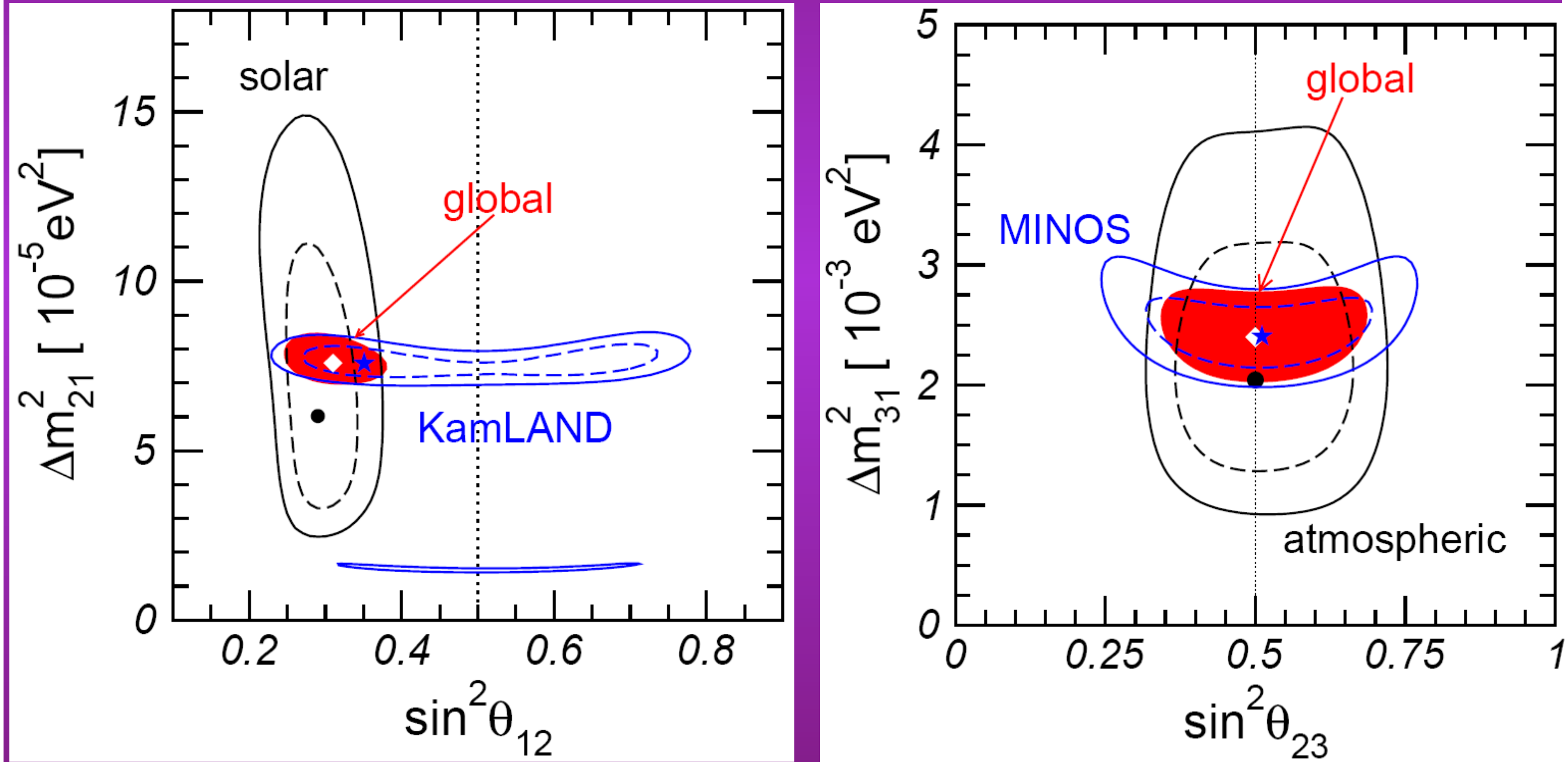
↓

3 mass states

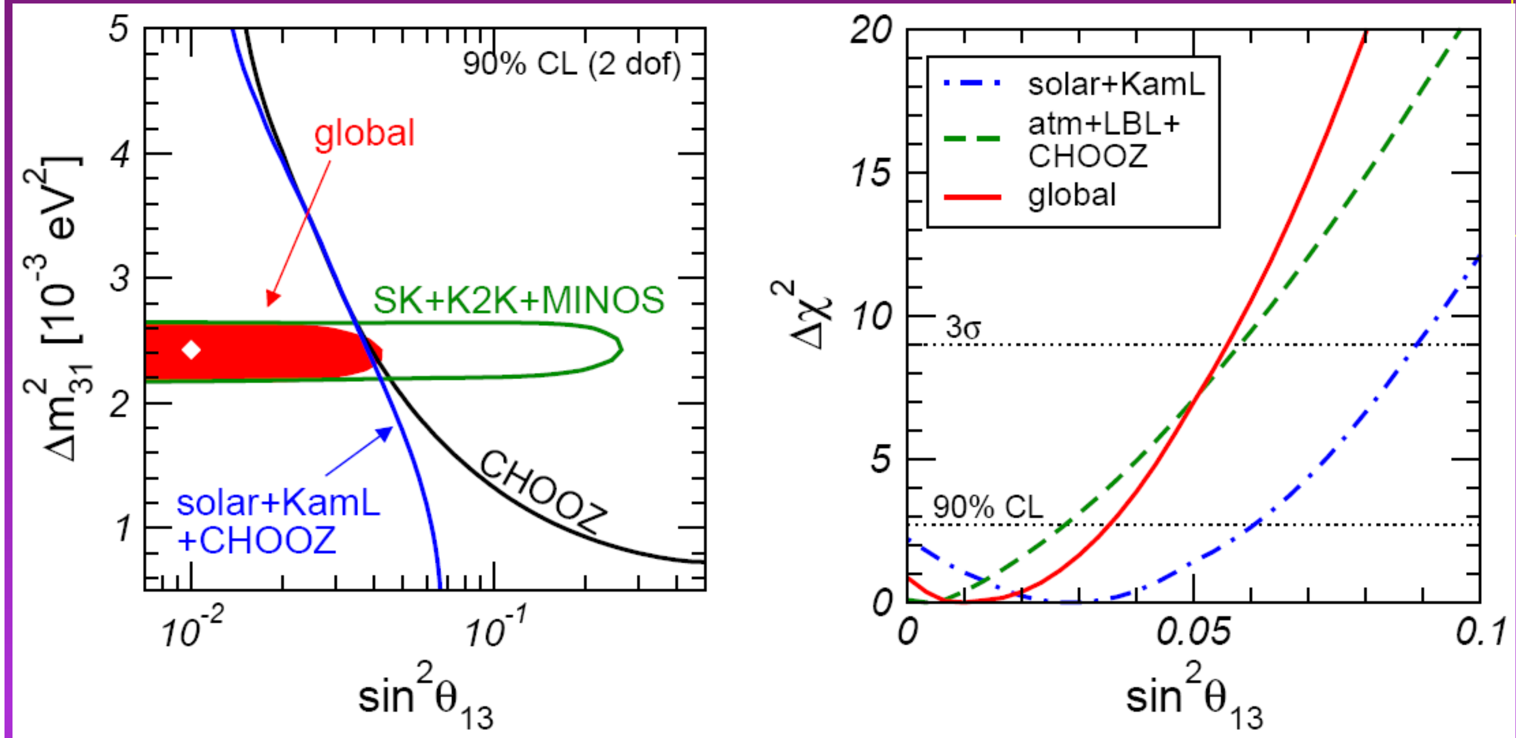
Global analysis

on the basis of the data presented at Nu2008

T. Schwetz, M. Tortola and J.W.F. Valle, arXiv:0808.2016



Global analysis

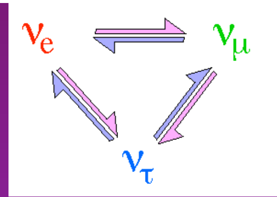


on the basis of the data at Nu2008

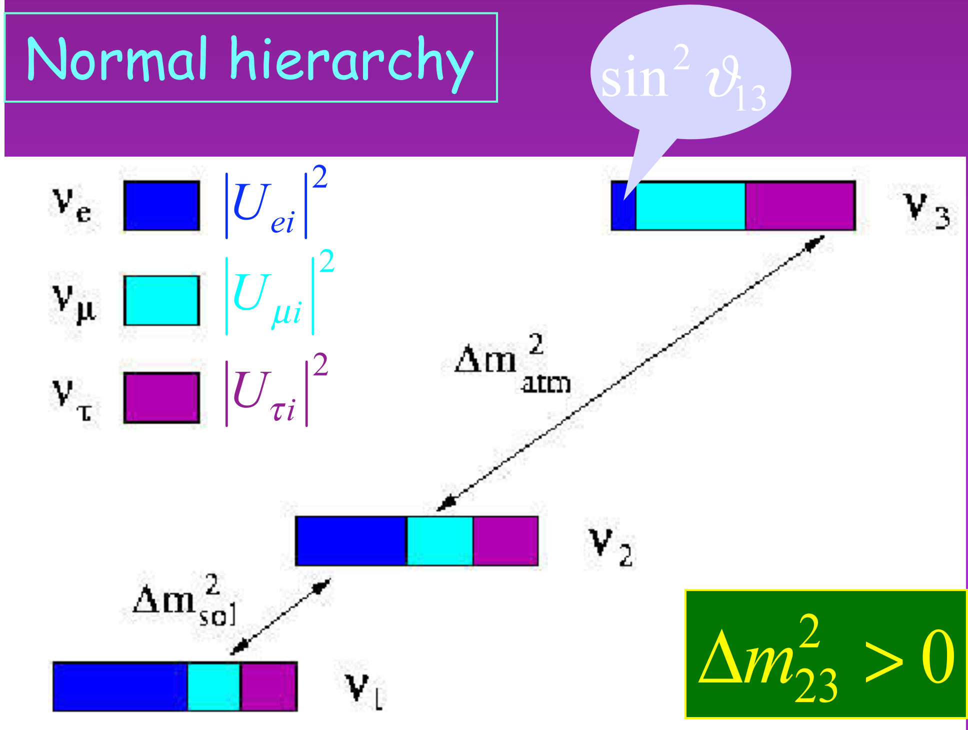
T. Schwetz et al. arXiv:0808.2016

parameter	best fit	2σ	3σ
Δm^2_{21} [10^{-5}eV^2]	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2]	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056
$\sin^2 2\vartheta_{13}$	0.04	<0.15	

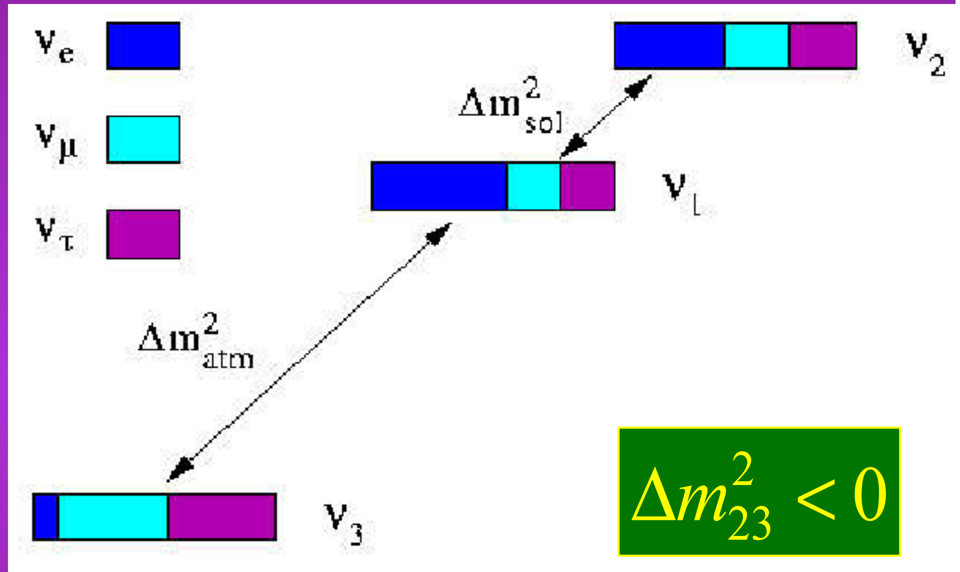
Status of: Neutrino masses



Normal hierarchy



Reversed hierarchy



Already measured:

$$\left|\Delta m^2_{23}\right| = (2.4 \pm 0.1)\times 10^{-3}\ \text{eV}^2$$

$$\Delta m^2_{21} = (7.6 \pm 0.2)\times 10^{-5}\ \text{eV}^2$$

To be measured:

$$\text{sgn}(\Delta m^2_{23})$$

And improve precision of:

$$\left|\Delta m^2_{23}\right|$$

Co już wiemy o neutrinach?

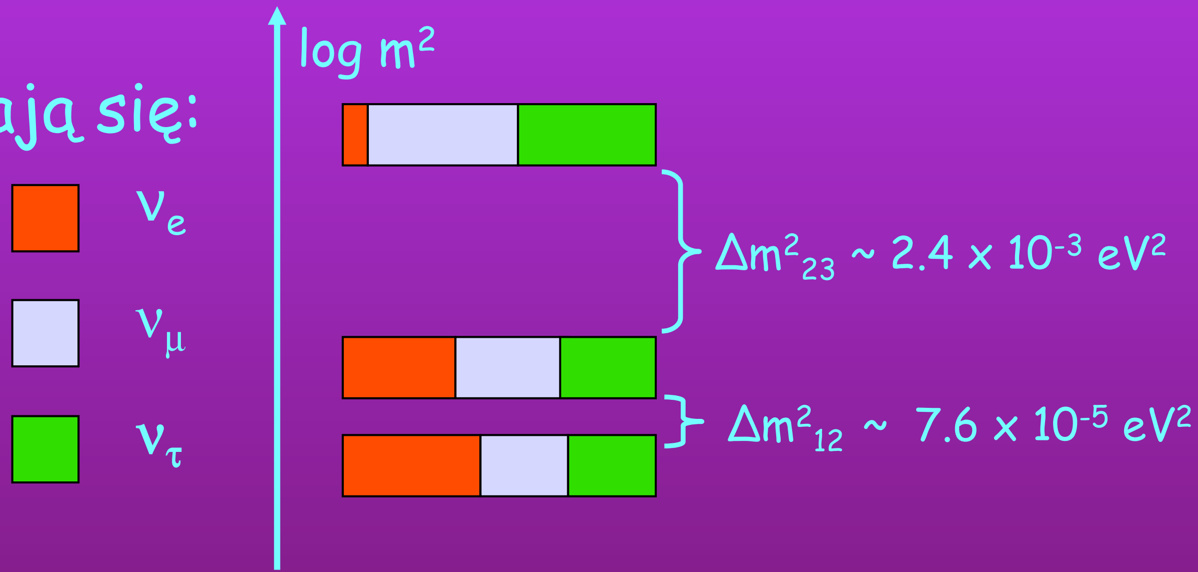
- Neutrina mają masę: $$40\ \text{meV} < \sum_{i=1}^{3} m_i < 2\ \text{eV}$$

→ znaczący wkład do bilansu energii Wszechświata

$$\Omega_\nu \geq \sum_{i=1}^{3} m_i / 93h^2 \approx 0.001$$

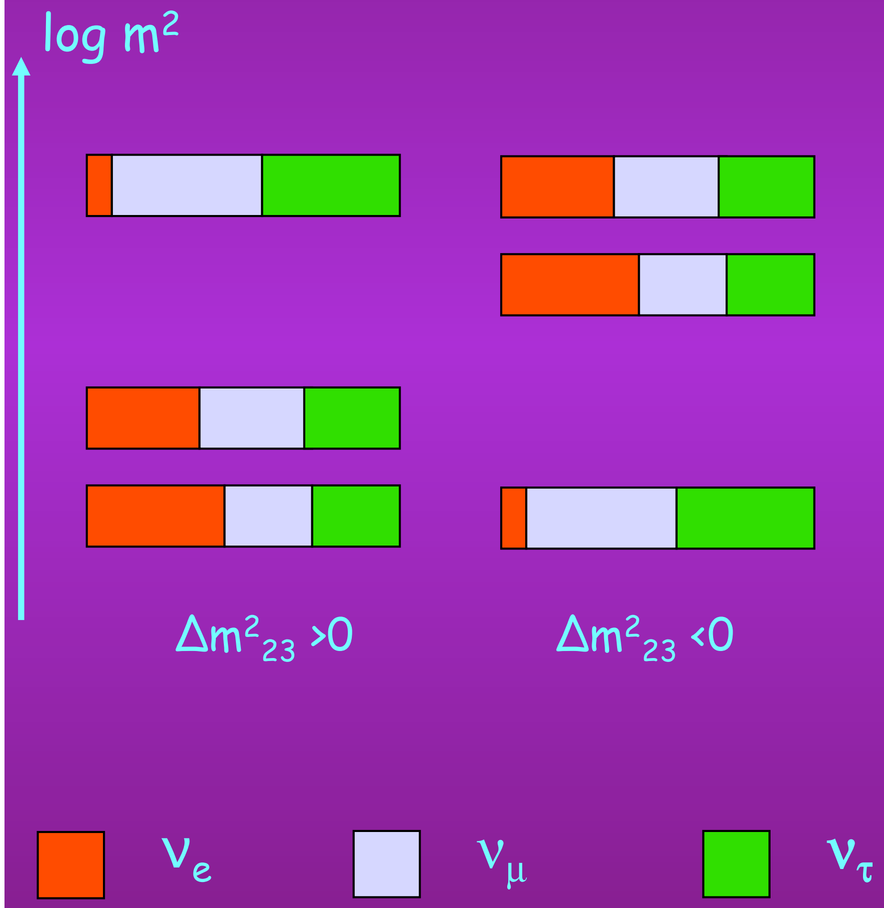
- Neutrina mieszają się:

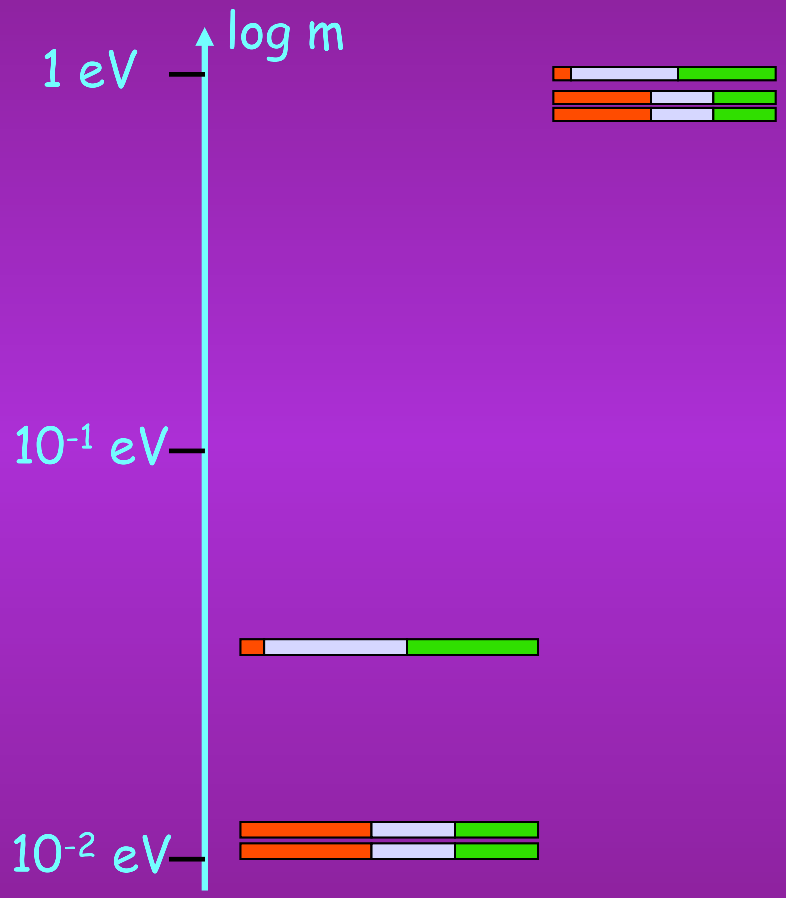
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} e^{i\alpha_1/2}\nu_1 \\ e^{i\alpha_2/2}\nu_2 \\ \nu_3 \end{pmatrix}$$



Jaka jest hierarchia mas?

Jaka skala?





Co wiemy o macierzy mieszania?

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \cdot e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

słoneczne | atmosferyczne | 0νββ

$\sin^2 2\vartheta_{23} = 1.02 \pm 0.04 \quad (37^\circ\text{-}53^\circ)$ - czy jest maksymalny? Która ćwiartka?

$\sin^2 2\vartheta_{12} = 0.84 + 0.03 \quad (\vartheta_{12} = 33^\circ)$

$\sin^2 2\vartheta_{13} < 0.14$ at 90% c.l. $(\vartheta_{13} < 10^\circ)$ - czy zero?

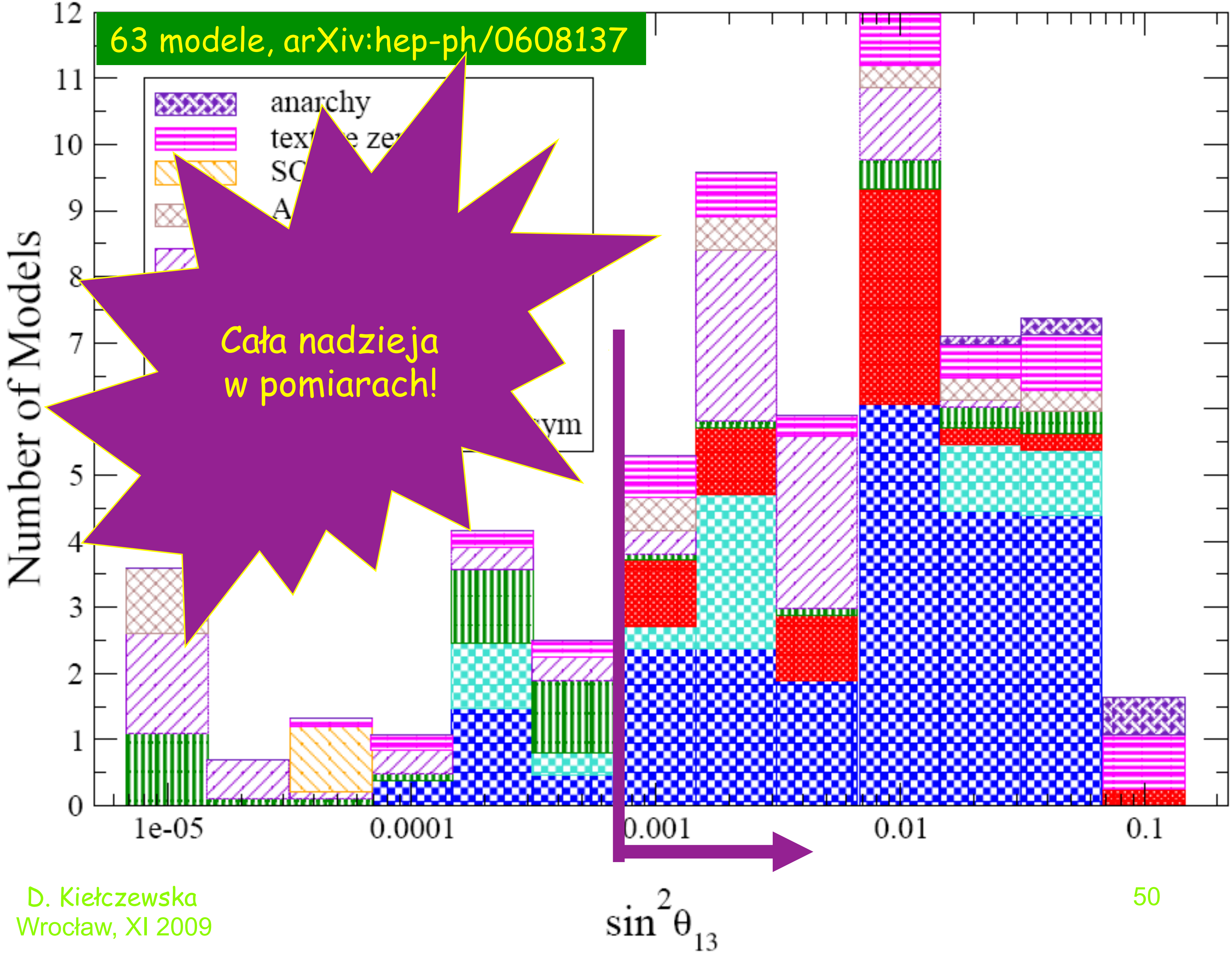
Trzeba zmierzyć:

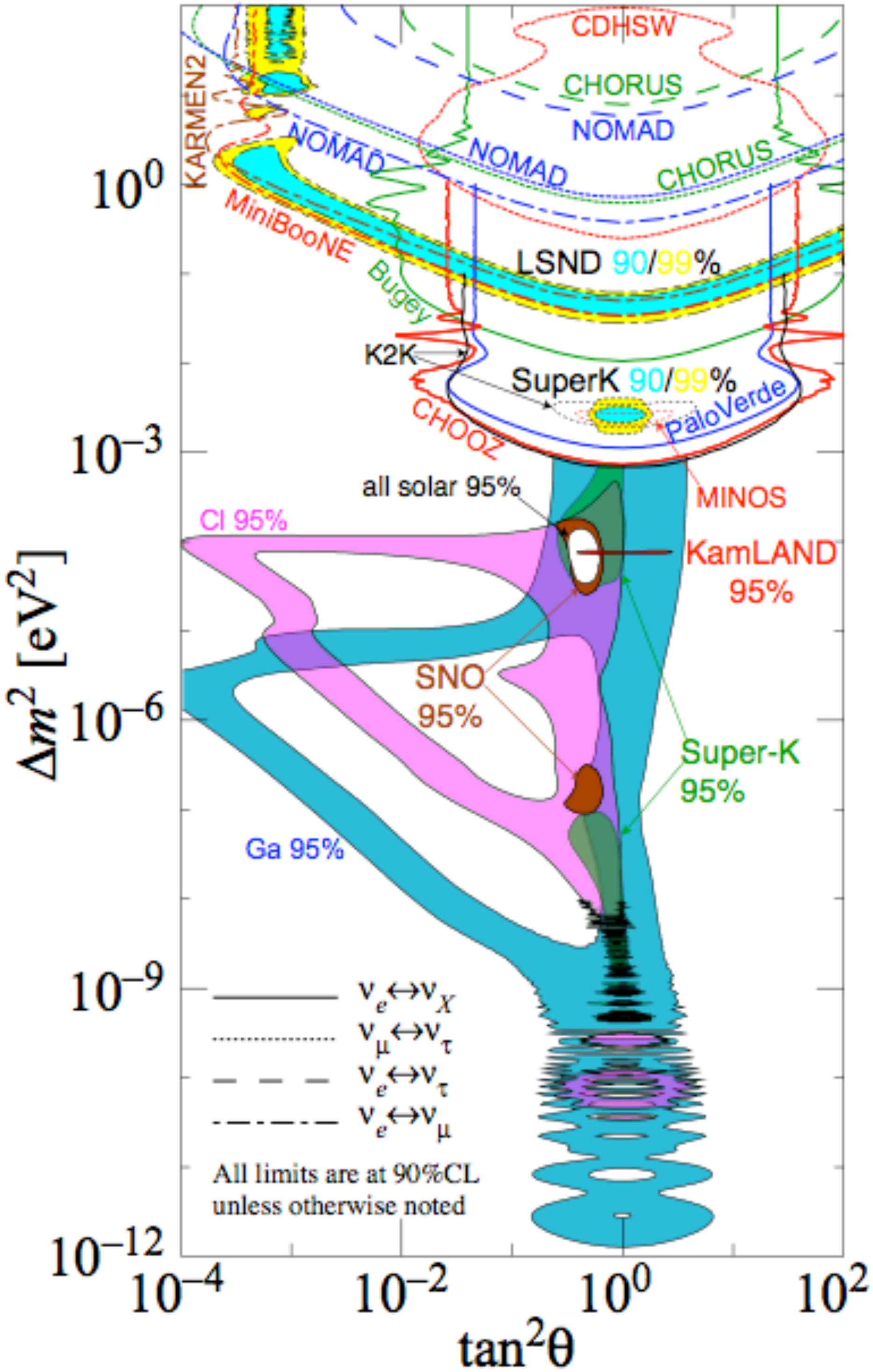
ϑ_{23} <- dokładniej

ϑ_{13}

δ

A czego się oczekuje?


63 modele, arXiv:hep-ph/0608137
Cała nadzieja
w pomiarach!
anarchy
Number of Models
0
1
2
3
4
5
7
8
9
10
11
12
1e-05
0.0001
0.001
0.01
0.1
sin$^2\theta_{13}$



Eksperymenty neutrinowe pierwszej generacji

Nie stwierdzono oscylacji - za małe L/E

„atmosf."

„słoneczne"

$$P_{vac}(\nu_\alpha \to \nu_\beta) = \sin^2 2\vartheta \cdot \sin^2 \frac{1.27\,\Delta m_{ij}^2 \cdot L}{E}$$

Particle Data Group, 2008

http://pdg.lbl.gov/2008/reviews/rpp2008-rev-neutrino-mixing.pdf/

lczewska ϑ_{23}

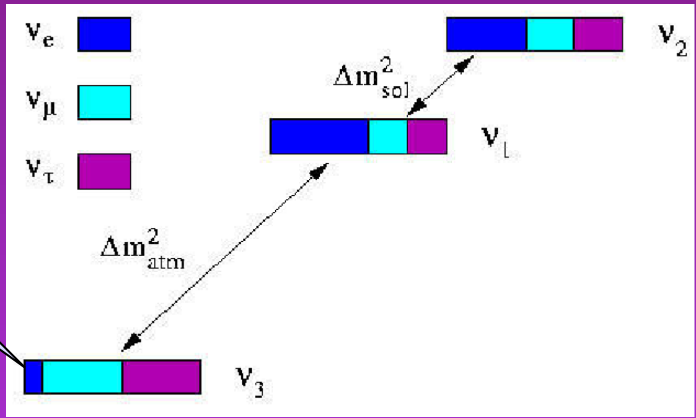
Dotychczasowe pomiary oscylacji

Dla neutrin słonecznych
i reaktorowych przy dużych L/E
(KamLand) dominują: $\nu_e \to \nu_{\mu\tau}$ ⟹ $\delta m^2_{12}, \quad \vartheta_{12}$

Dla neutrin atmosferycznych
i akceleratorowych przy
(stosunkowo) małych L/E
(K2K, MINOS, OPERA, T2K)
dominują: $\nu_\mu \to \nu_\tau$ ⟹ $\delta m^2_{23} \approx \delta m^2_{13}, \quad \vartheta_{23}$

How to measure ϑ_{13}

$\sin^2 \vartheta_{13}$



We need:

- an experiment sensitive to Δm^2_{atm}
  i.e. L/E ~500 km/GeV
- involving ν_e or $\bar{\nu}_e$

- Reactor $\bar{\nu}_e \rightarrow \bar{\nu}_e$ disappearance

e.g. Chooz - the best current limit: $\sin^2 2\vartheta_{13} < 0.14$ for $\Delta m^2_{13} = 0.025\ \mathrm{eV}^2$

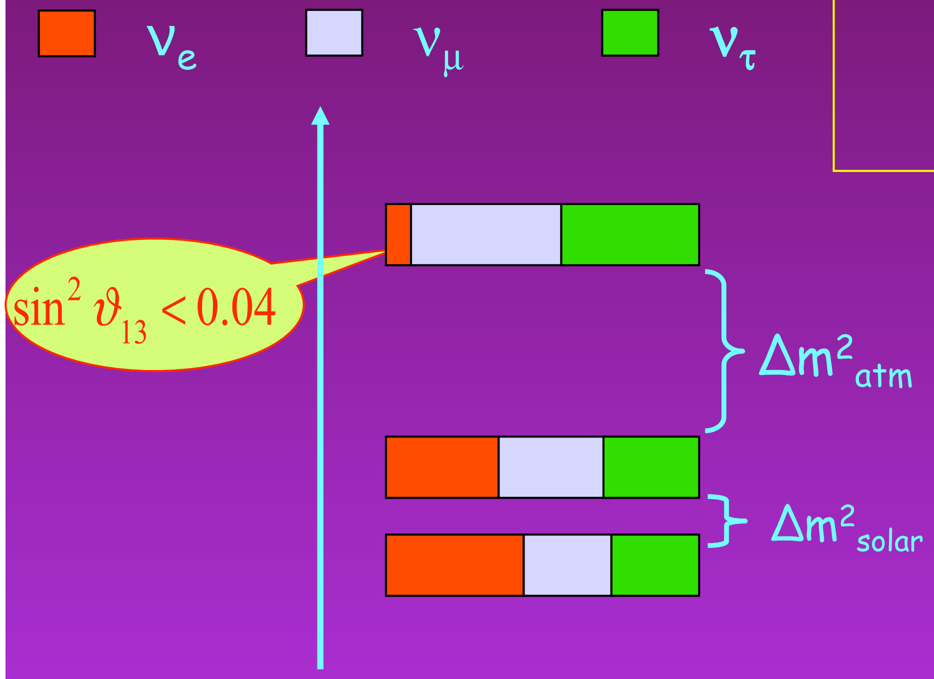
- Accelerator $\nu_\mu \rightarrow \nu_e$ appearance

$$P_{vac}(\nu_\mu \rightarrow \nu_e) \sim \sin^2 2\vartheta_{13} \cdot \sin^2 \vartheta_{23} \cdot \sin^2 \frac{1.27\Delta m^2_{13} \cdot L}{E}$$

at one of the prob. max: $P_{vac}(\nu_\mu \rightarrow \nu_e) = \frac{1}{2}\sin^2 2\vartheta_{13}$

Sensitivity to
a signal of a few%
is needed

Jak mierzyć ϑ_{13}



Potrzebujemy:

- eksperymentu o L/E odpowiadającego Δm^2_{atm}
- przejście od/do ν_e or $\bar{\nu}_e$
- dużej precyzji (kilku procent)

❖ Reactor $\bar{\nu}_e \to \bar{\nu}_e$ disappearance → ϑ_{13}

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\vartheta_{13} \cdot \sin^2 \frac{1.27\Delta m^2_{13} \cdot L}{E}$$

❖ Accelerator $\nu_\mu \to \nu_e$ appearance → ϑ_{13} hierarchia mas łamanie CP

$$P_{vac}(\nu_\mu \to \nu_e) = \sin^2 2\vartheta_{13} \cdot \sin^2 \vartheta_{23} \cdot \sin^2 \frac{1.27\Delta m^2_{13} \cdot L}{E} + f(\delta_{CP}, \mathrm{sgn}(\Delta m^2_{13}))$$

CP violation

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin^2 \Delta_{ij}$$

$$\pm 2\sum_{i>j} \mathrm{Im}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin 2\Delta_{ij}$$

$$\Delta_{ij} \equiv \frac{1.27\,\Delta m^2_{ij} L}{E_\nu}$$

- for neutrinos
+ for antineutrinos

CP violation can be observed only in appearance experiments because :

$$\mathrm{Im}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) = 0$$
$$\text{for} \quad \alpha = \beta$$

How to measure $\text{sgn}(\Delta m^2_{32})$

Matter effects: due to a difference in interactions of $\nu\ (\bar{\nu})$ of different flavors with electrons:

$$\Delta V = \sqrt{2}\, G_F\, n_e$$

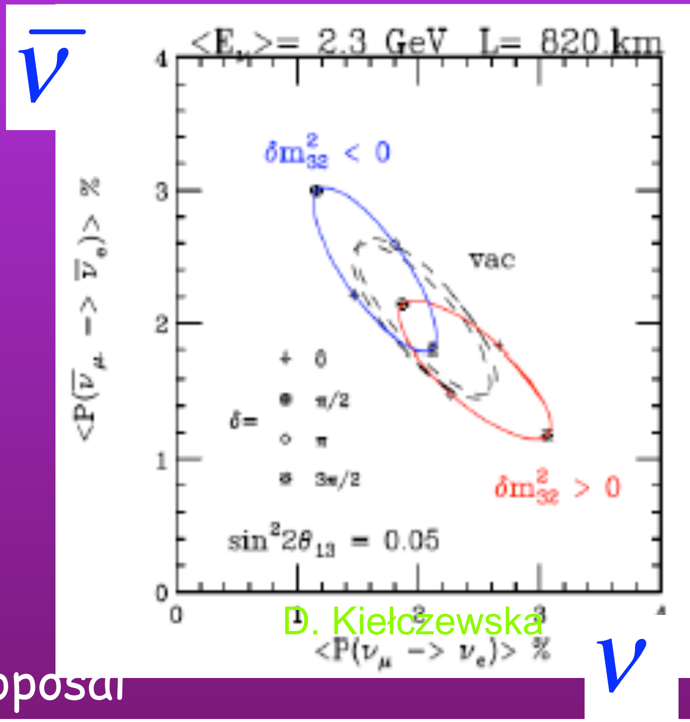
$$\delta m^2 \Rightarrow \delta m^2 \pm \frac{2E(\Delta V)}{\cos 2\vartheta}$$

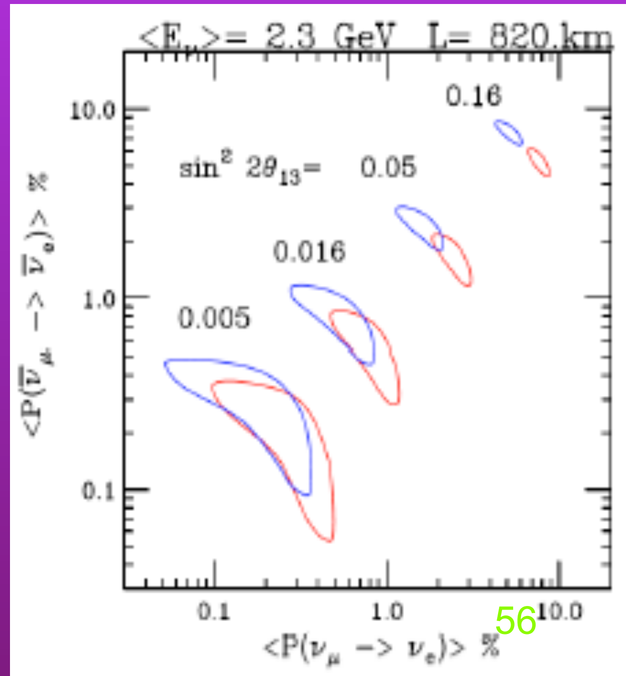
different sign for ν and $\bar{\nu}$

Good news: matter effects are sensitive to $\text{sgn}(\Delta m^2_{32})$

Bad news:
matter effects can mimic CP violation in vacuum

Note:
matter effects grow with energy





from „Nona" proposal

Golden channels: $\nu_\mu \leftrightarrow \nu_e$ and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$

By expanding in: $\vartheta_{13},\ \Delta_{12}/\Delta_{23},\ \Delta_{12}/A,\ \Delta_{12}L$ one gets:

+ neutrinos
- antineutrinos

$$P(\nu_e \leftrightarrow \nu_\mu) = s_{23}^2 \sin^2 2\vartheta_{13} \left(\frac{\Delta_{23}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp L}{2}\right)$$

$$+ c_{23}^2 \sin^2 2\vartheta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$

solar term

$$+J \frac{\Delta_{12}}{A} \frac{\Delta_{23}}{B_\mp} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{B_\mp L}{2}\right) \cos\left(\pm\delta - \frac{\Delta_{23}L}{2}\right)$$

CP violation

L - baseline; $\Delta_{ij} \equiv \dfrac{\Delta m_{ij}^2}{2E}$

hopefully not too small ϑ_{13}

$s_{ij} \equiv \sin\vartheta_{ij},\quad c_{ij} \equiv \cos\vartheta_{ij}$

$J \equiv \cos\vartheta_{13} \cdot \sin 2\vartheta_{13} \cdot \sin 2\vartheta_{23} \cdot \sin 2\vartheta_{12}$

$B_\mp \equiv |A \mp \Delta_{23}|$

$A \equiv \sqrt{2} G_F n_e(L)$

matter effects
→ sensitivity to mass hierarchy

For reactor exp. LA<<1 i.e :

$$P(\bar{\nu}_e \leftrightarrow \bar{\nu}_x) \cong \sin^2 2\vartheta_{13} \sin^2 \vartheta_{23} \sin^2(\Delta_{23})$$

No ambiguity: independent of δ and mass hierarchy

How to measure…(cont.)

Reactor experiments which have relatively short baselines and very low energies will measure:

$\sin^2 2\vartheta_{13}$ down to ~0.01

but not:

$\delta, \quad sgn(\Delta m^2_{13}), \quad nor \ \Delta m^2_{13}, \quad \sin^2 2\vartheta_{23}$

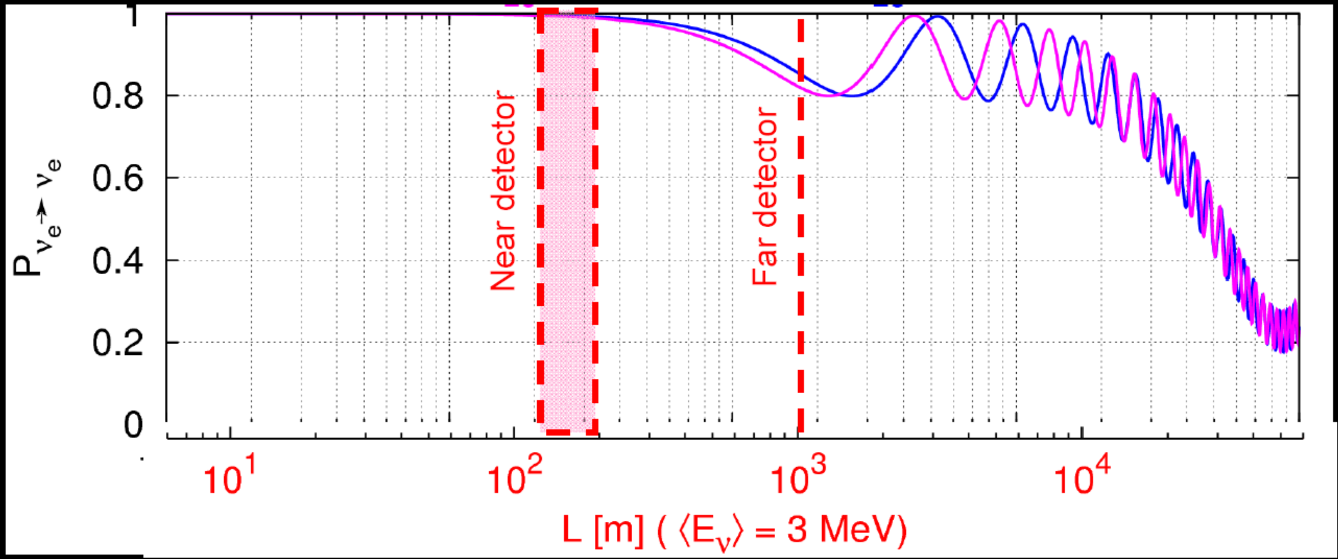
A number of different sites for reactor experiments are considered:
- Brasil, China, France (Double Chooz), Japan (KASKA), Russia, Taiwan and USA (Braidwood…)

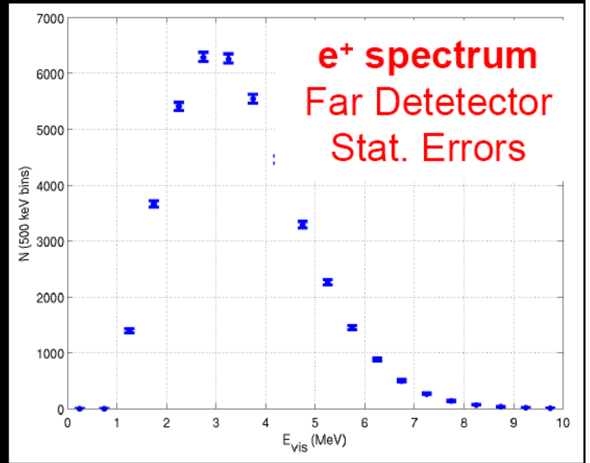
Complementary to accelerator experiments

Double-Chooz The - new - concept

Europe, USA, Japan

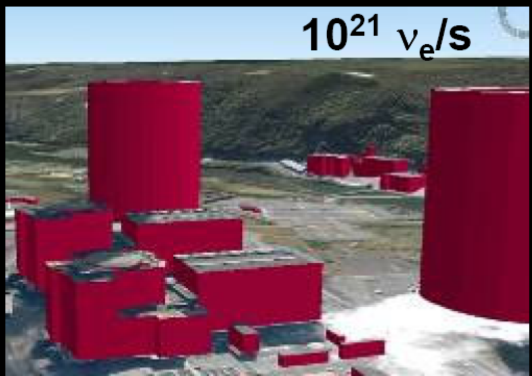
$P(\nu_e \to \nu_e) = 1-\sin^2(2\theta_{13})\sin^2(\Delta m^2_{31}L/4E)$



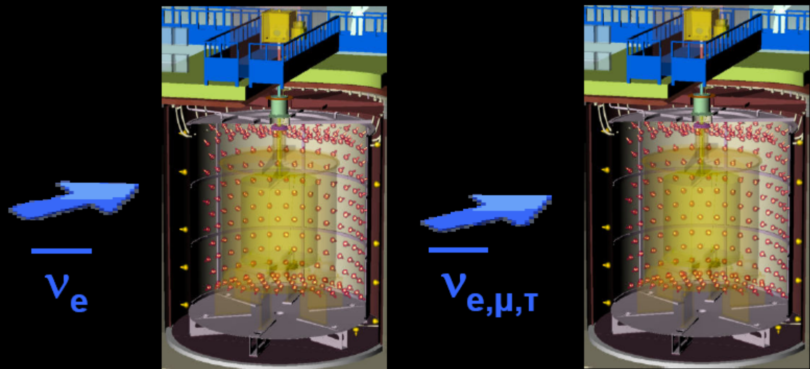


$\Delta m^2_{atm} = 3.0\ 10^{-3}\ eV^2$

$\sin^2(2\theta_{13})=0.12$



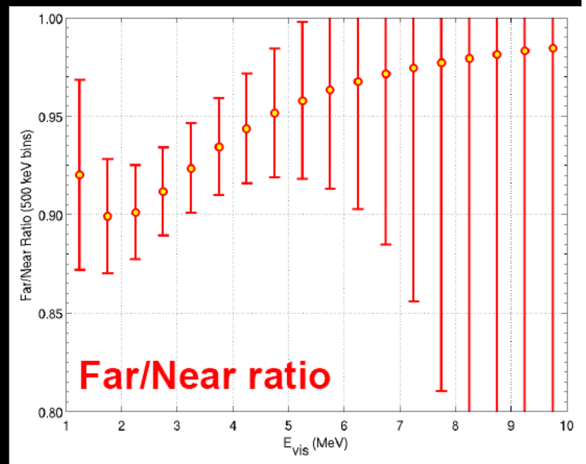
Chooz Nuclear Power Station
2 cores of 4.27 GW_{th} each
Ardellier et. al, hep-ex/0405032



Near detector
400 m

Far detector
1050 m

T. Lasserre 26/05/2008



Conclusions & outlook

- Double Chooz Far integration Started in May 08

- First goal: measurement of θ_{13}

  - *2008-09 → Far Detector construction & integration*
  - *Middle 09 → Start of phase I : Far 1 km detector alone*
    $\sin^2(2\theta_{13}) < 0.06$ after 1,5 year (90% C.L.) if no-oscillation
  - *2008-10 → Near Lab Escavation & Near Detector Integration*
  - *2011 → Start of phase II : Both near and far detectors*
    $\sin^2(2\theta_{13}) < 0.03$ after 3 years (90% C.L.) if no-oscillation

- Faisability study on non proliferation with Double Chooz near detector ongoing (See N. Bowden's Talk)

Daya Bay Collaboration

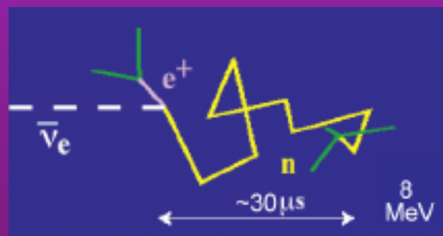
„ASIA" (=China, Taiwan) – 18 inst.
US – 14 inst; Europe (Russia, Czech Rep) – 3 inst

The Daya Bay Nuclear Power Complex

- 12th most powerful in the world (11.6 GW_{th})
- One of the top five most powerful by 2011 (17.4 GW_{th})
- Adjacent to mountain, easy to construct tunnels to reach underground labs with sufficient overburden to suppress cosmic rays

3 GWth generates
6 x 10^{20} $\bar{\nu}_e$ per sec

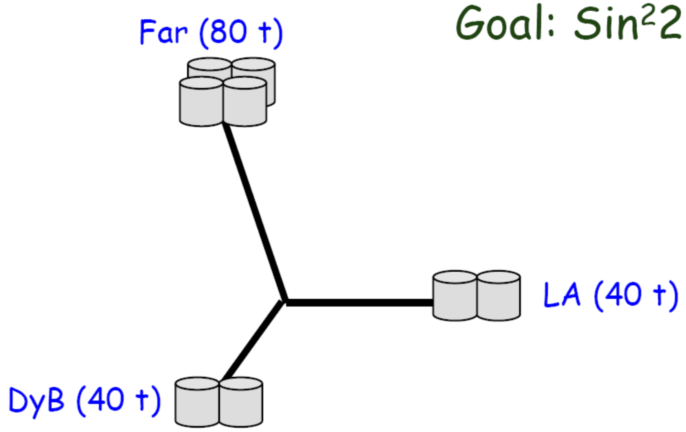
Detection:



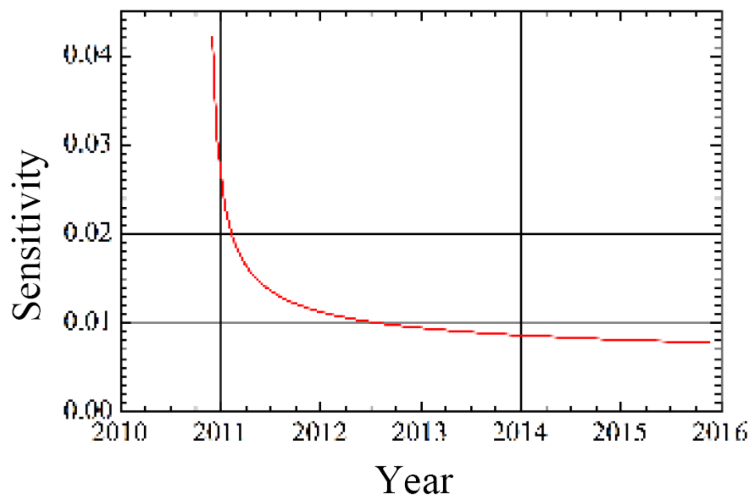
with Gd

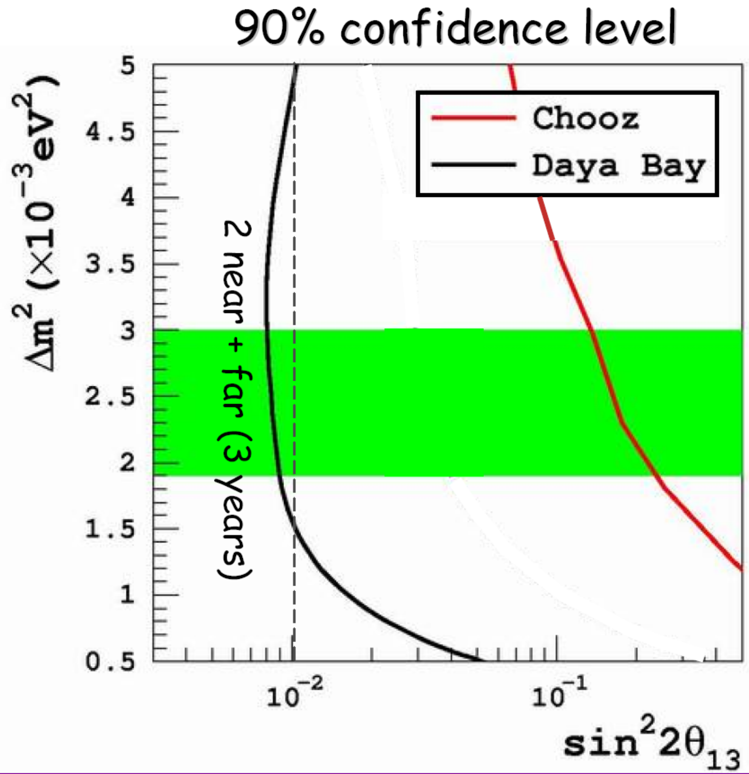
Sensitivity of Daya Bay

Goal: $\sin^2 2\theta_{13} < 0.01$



- Use rate and spectral shape
- input relative detector syst. error of 0.38%/detector



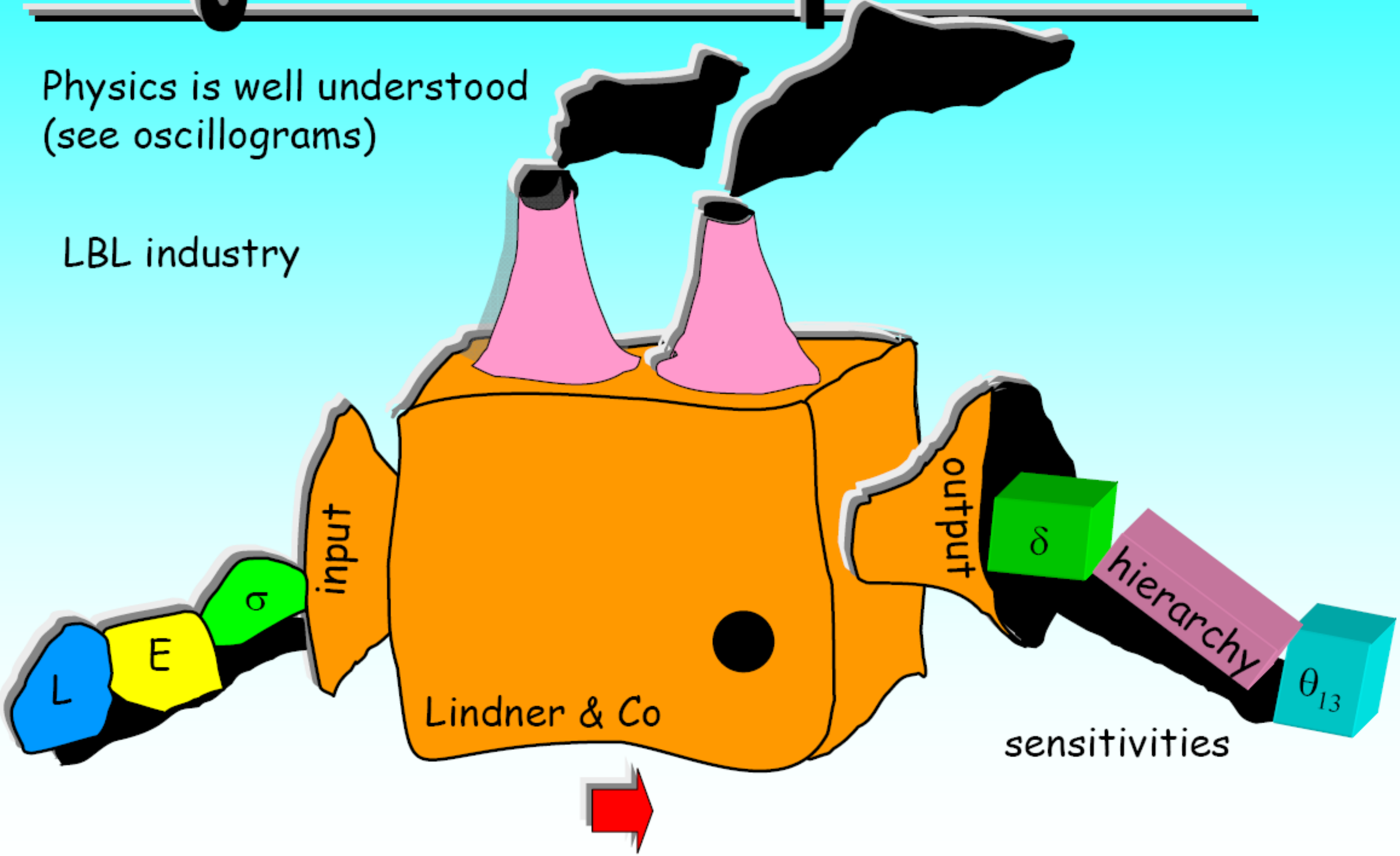


	Daya Bay Near	Ling Ao Near	Far Hall
Baseline (m)	363	481 from Ling Ao 526 from Ling Ao II	1985 from Daya Bay 1615 from Ling Ao
Overburden (m)	98	112	350

Long baseline experiments

Physics is well understood
(see oscillograms)

LBL industry



Program for long-baseline experiments (next ~10-15 years)

Measurement	Method	Experiments	Why?
$\lvert\Delta m^2_{32}\rvert$	ν_μ disapp.	Minos	Better precision for further studies
ϑ_{23}	as above	T2K, Nova	Max. mixing (a symmetry? or which octant
ϑ_{13}	ν_e appear.	Minos, T2K, Nova	=0 ? A symmetry? Essential for
	$\bar{\nu}_e$ disapp.	Reactor	Hierarchy and CP
Hierarchy ~~CP~~	$\bar{\nu}_e$ vs ν_e appearance	T2KK, Super-Nova, „BNL"	Unification, Leptogenesis, Ω_ν
$\nu_\mu \to \nu_\tau$	τ appear.	OPERA	To check oscil. scenario

Akceleratorowe eksperymenty drugiej generacji

- Silne źródła neutrin
- Wiązki „off axis"

	T2K	Nova
site	Japan	USA
beam	od 1/04/2009	NuMi (upgraded)
E_ν (peak)	0.76 GeV	2.22 GeV
distance	295 km	812 km
Far detector	Super-Kamiokande	to be built
of mass (FV)	22.5 kton	14 kton

Owing to higher energy and larger distance, NOvA will have a three-fold bigger matter effect.
Combining the NOvA and T2K results will facilitate the separation of CP from matter effects.

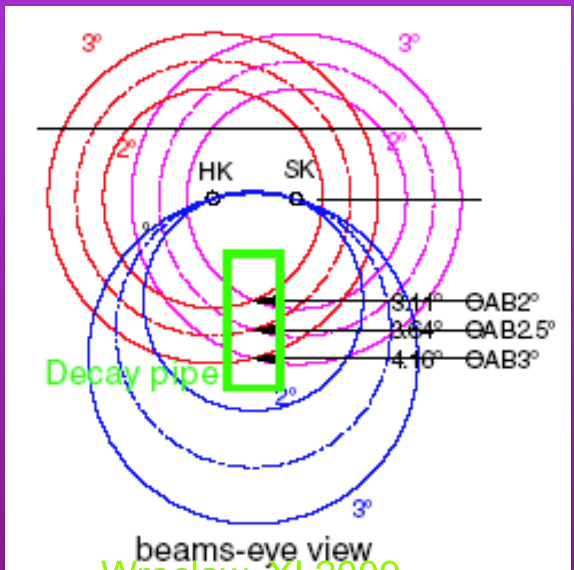
T2K
(Tokai to Kamioka)

J-PARC accel.
PS:
T2K I: 0.75 MW
at 50 (30) GeV
(20xK2K)

12 Countries

Canada, France, Germany, Italy, Japan, Korea, Poland, Russia, Spain, Switzerland, UK, USA

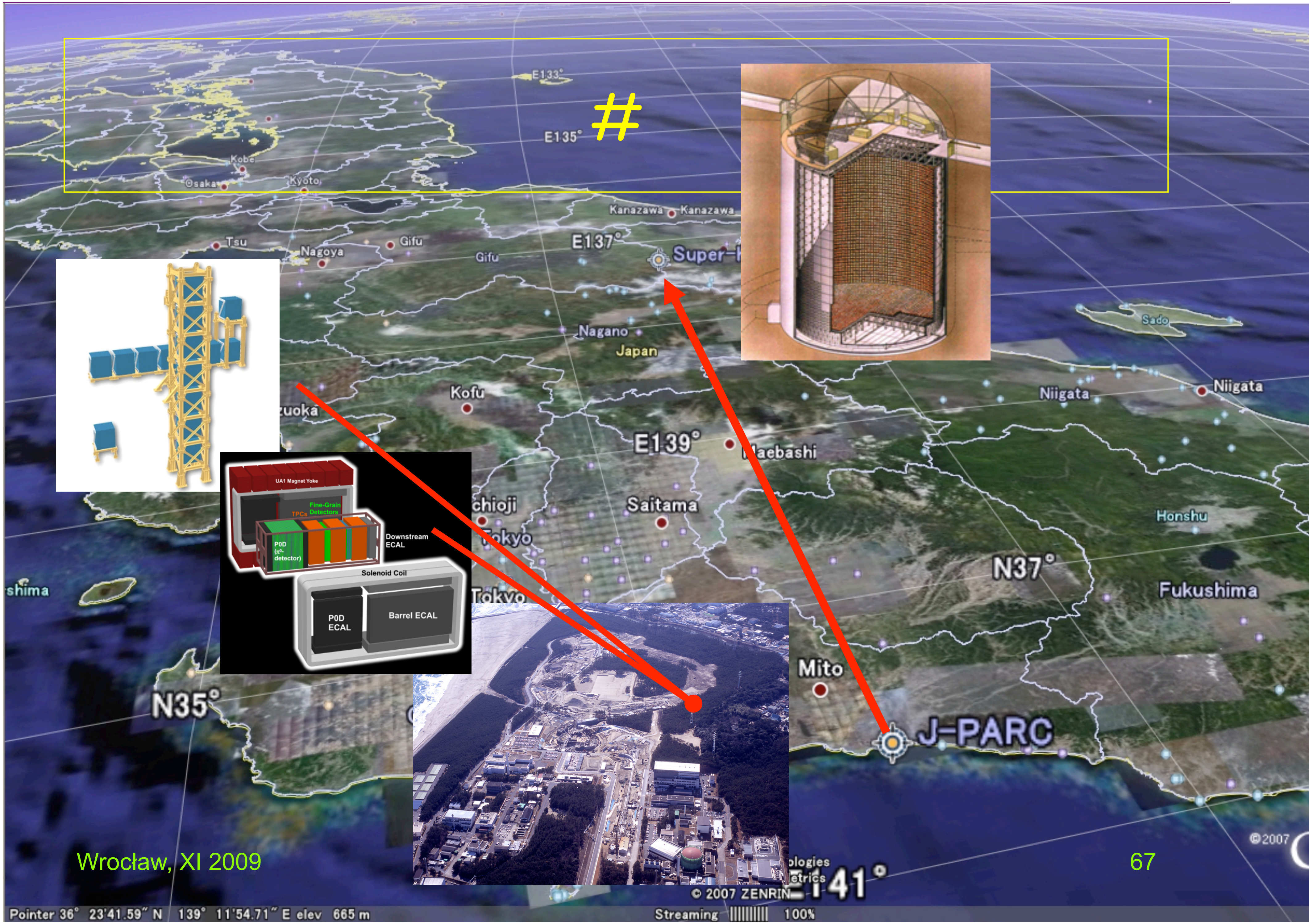
60 Institutions, 300 Ph.D. members



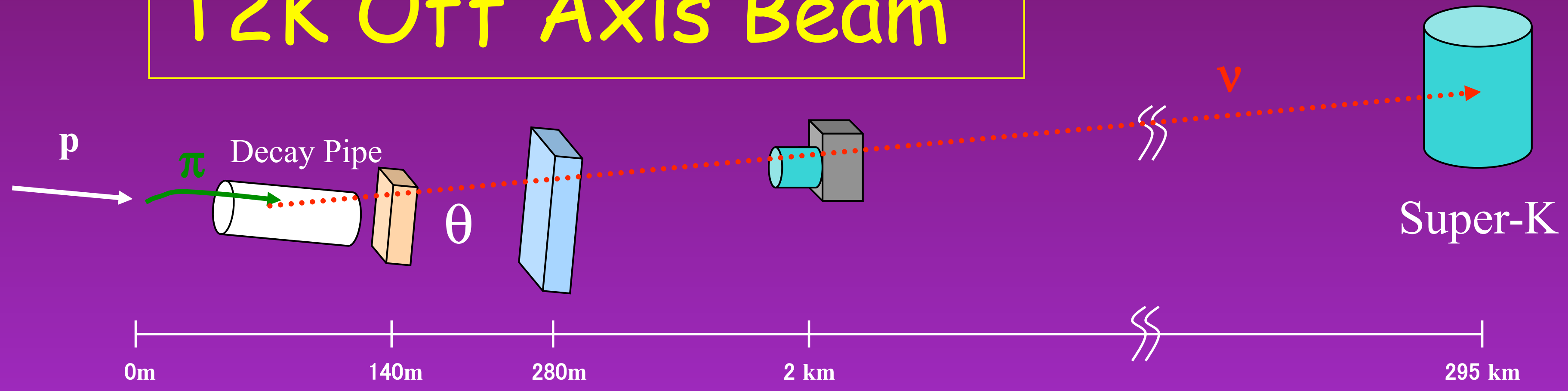
beam designed
for both:
phase I
and phase II:
4 MW @
Hyper-Kamiok.
and Korea

Z Polski około 30 osób z:
- IFJ Kraków
- IPJ Warszawa
- Politechnika Warszawska
- Uniwersytet Śląski
- Uniwersytet Warszawski
- Uniwersytet Wrocławski

Data taking starts in 2009


E133°
E135°
#
Osaka
Kobe
Kyoto
Kanazawa
Kanazawa
Tsu
Nagoya
Gifu
Gifu
E137°
Super-K
Nagano
Japan
Kofu
E139°
Maebashi
Sado
Niigata
Niigata
Honshu
Saitama
Tokyo
Tokyo
N37°
Fukushima
Mito
J-PARC
N35°
UA1 Magnet Yoke
Fine-Grain Detectors
TPCs
P0D (π^0-detector)
Downstream ECAL
Solenoid Coil
P0D ECAL
Barrel ECAL
© 2007 ZENRIN
E141°
©2007
Pointer 36° 23'41.59" N 139° 11'54.71" E elev 665 m
Streaming 100%

T2K Off Axis Beam

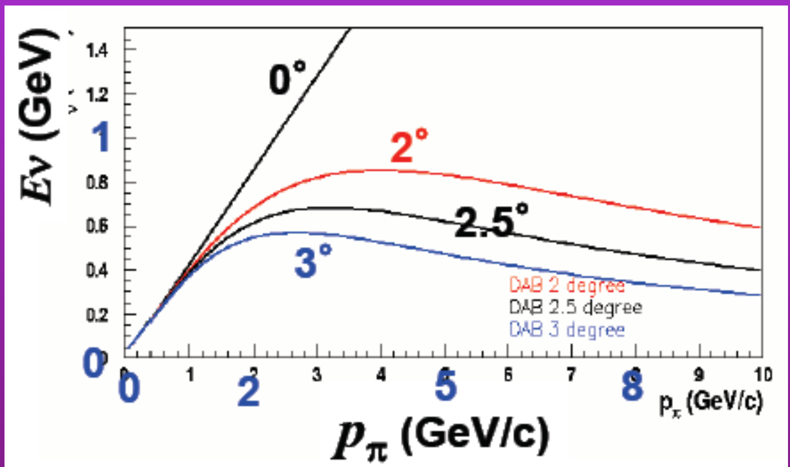


- Muon monitors @ ~140m
- First front detector @280m
- Second front detector @ ~2km
- Far detector @ 295km
  - Super-Kamiokande

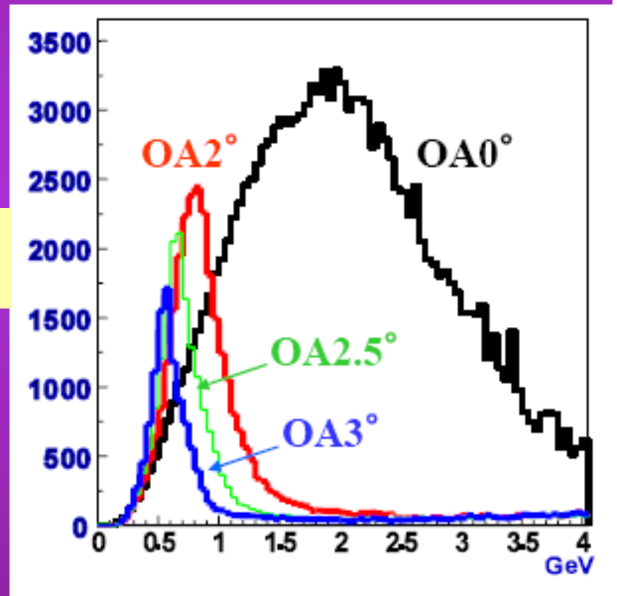
Kinematics of π decay

$$E_\nu = \frac{0.43 \cdot E_\pi}{1+\gamma^2\theta^2}$$

Tunable at oscillation max

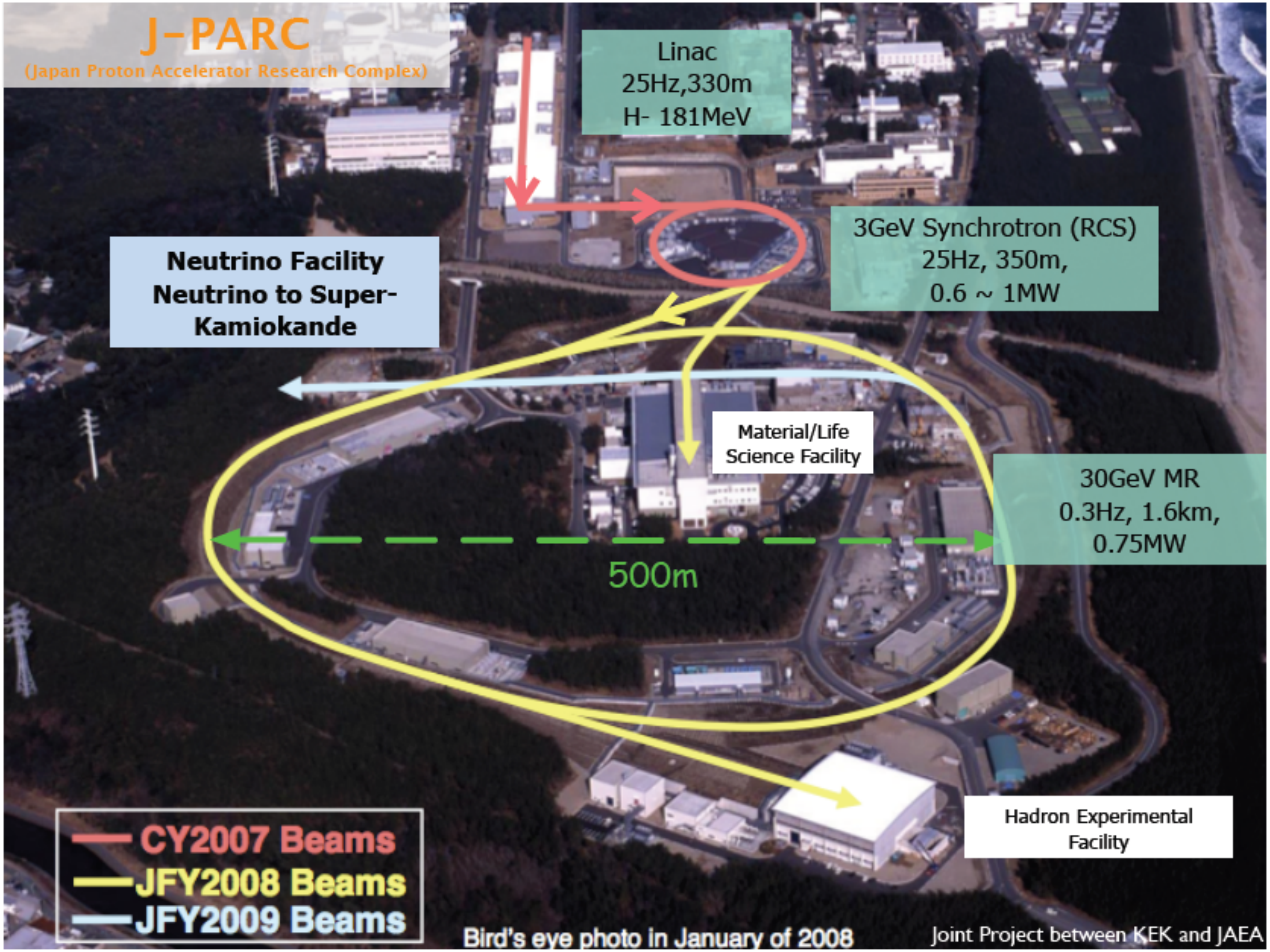


Quasi monochromatic beam

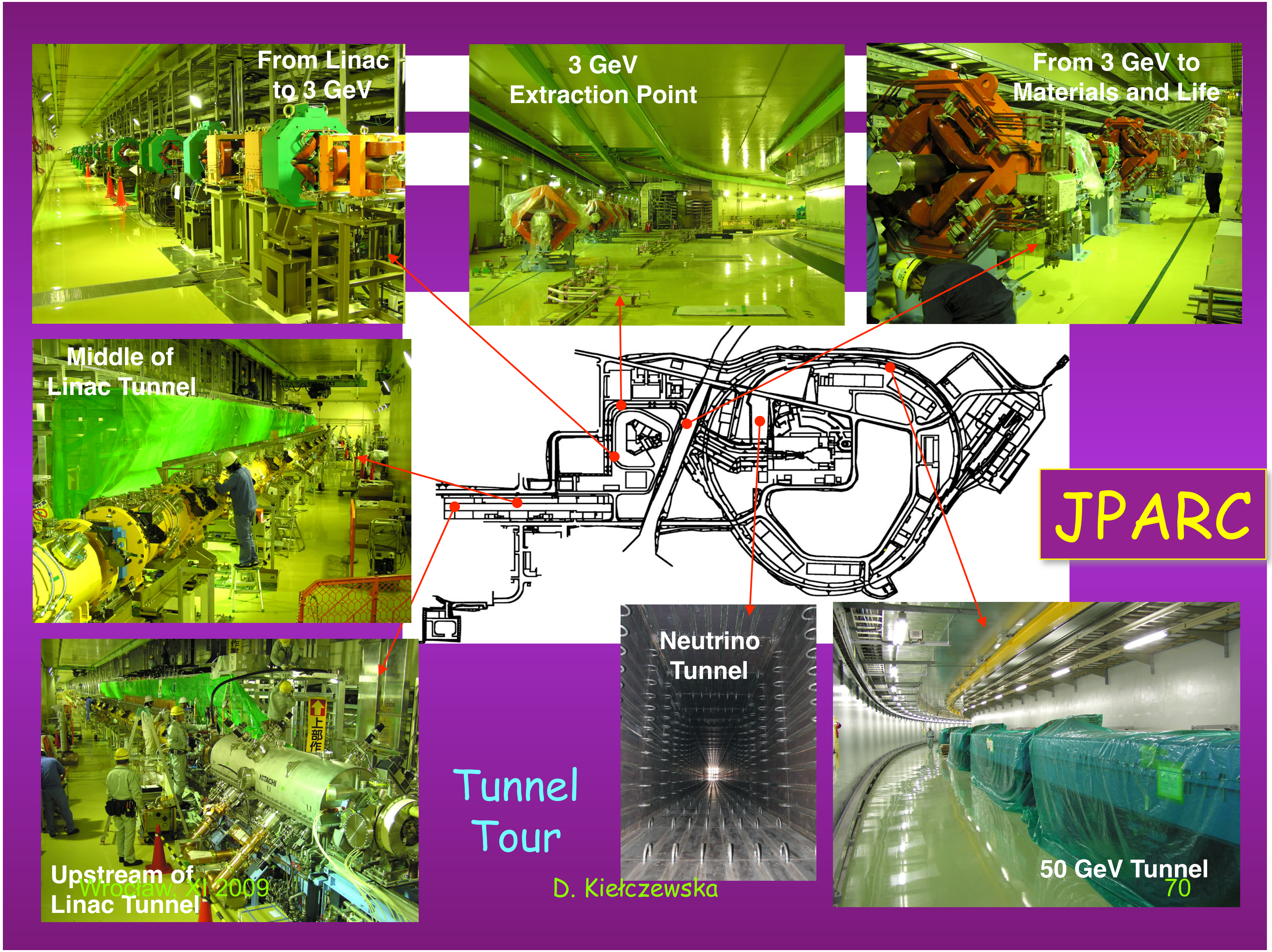


Neutrino energy

Reduced tail at high ν energies helps to reduce background due to π^0 production

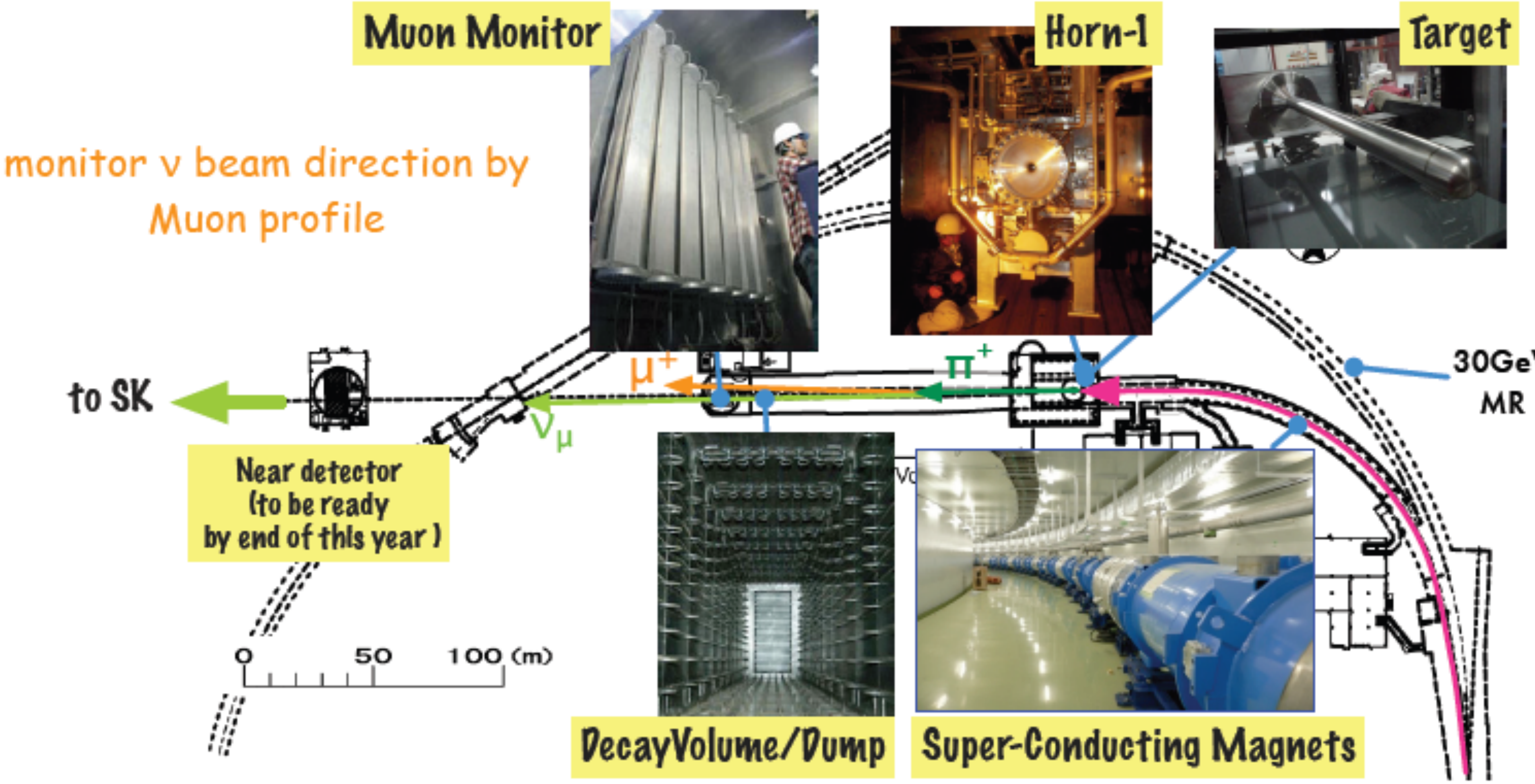


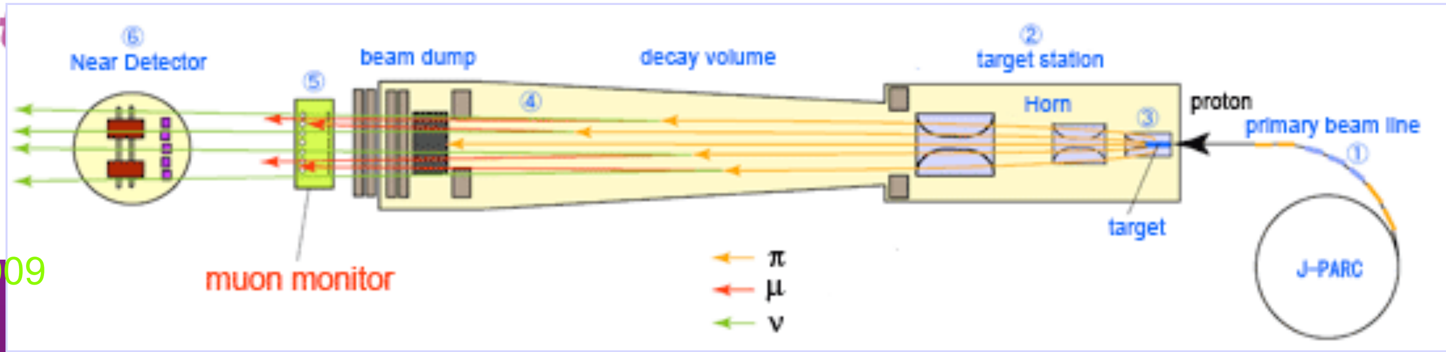
J-PARC
(Japan Proton Accelerator Research Complex)
Linac
25Hz,330m
H- 181MeV
3GeV Synchrotron (RCS)
25Hz, 350m,
0.6 ~ 1MW
Neutrino Facility
Neutrino to Super-Kamiokande
Material/Life Science Facility
30GeV MR
0.3Hz, 1.6km,
0.75MW
500m
Hadron Experimental Facility
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008
Joint Project between KEK and JAEA


From Linac
to 3 GeV
3 GeV
Extraction Point
From 3 GeV to
Materials and Life
Middle of
Linac Tunnel
JPARC
Neutrino
Tunnel
Tunnel
Tour
Upstream of
Linac Tunnel
50 GeV Tunnel

T2K Neutrino Beam-line

- Completed the beam-line construction [2004~2009, 5 years]
  (Horn-2,3 to be installed in this summer)

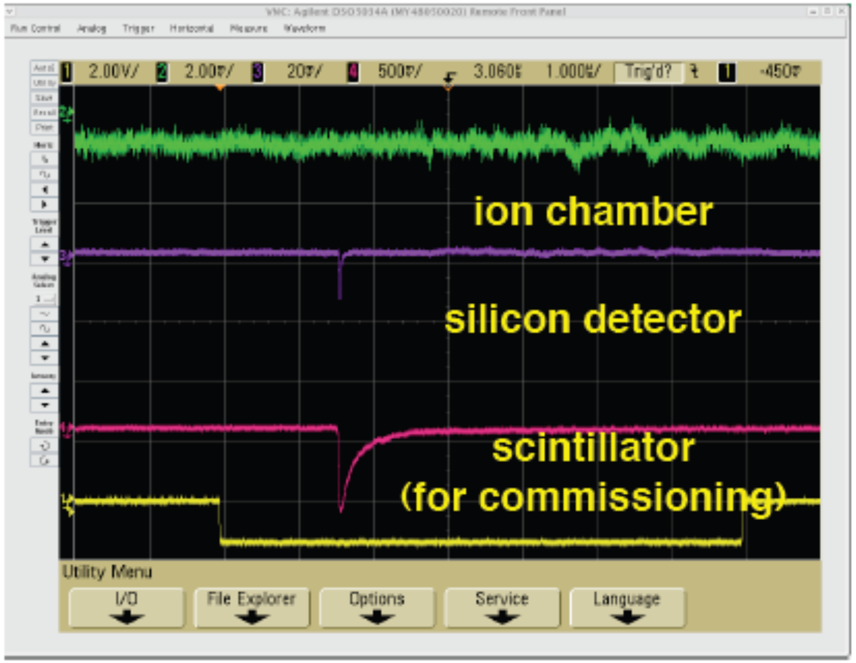




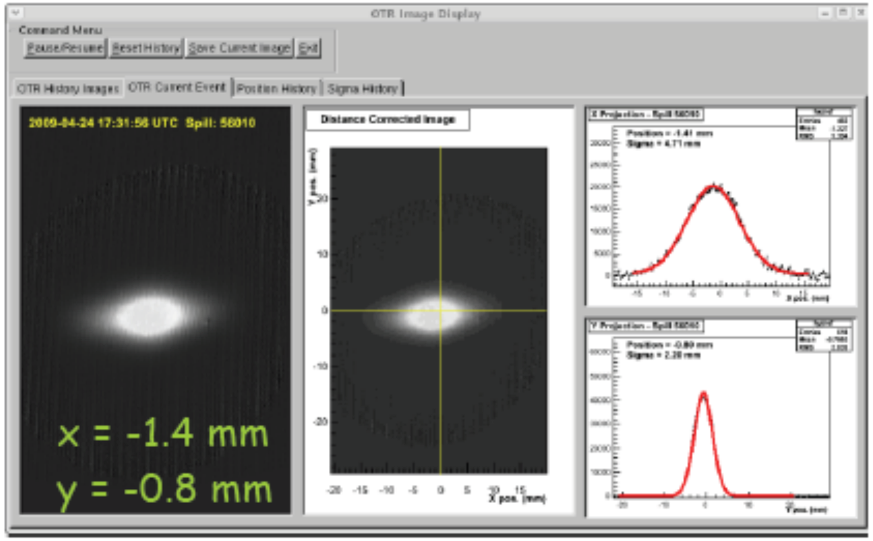
T2K neutrino beam-line starts operation

(First beam in Apr/23/2009)

Muon monitor signal
at 1st shot after SC turned on

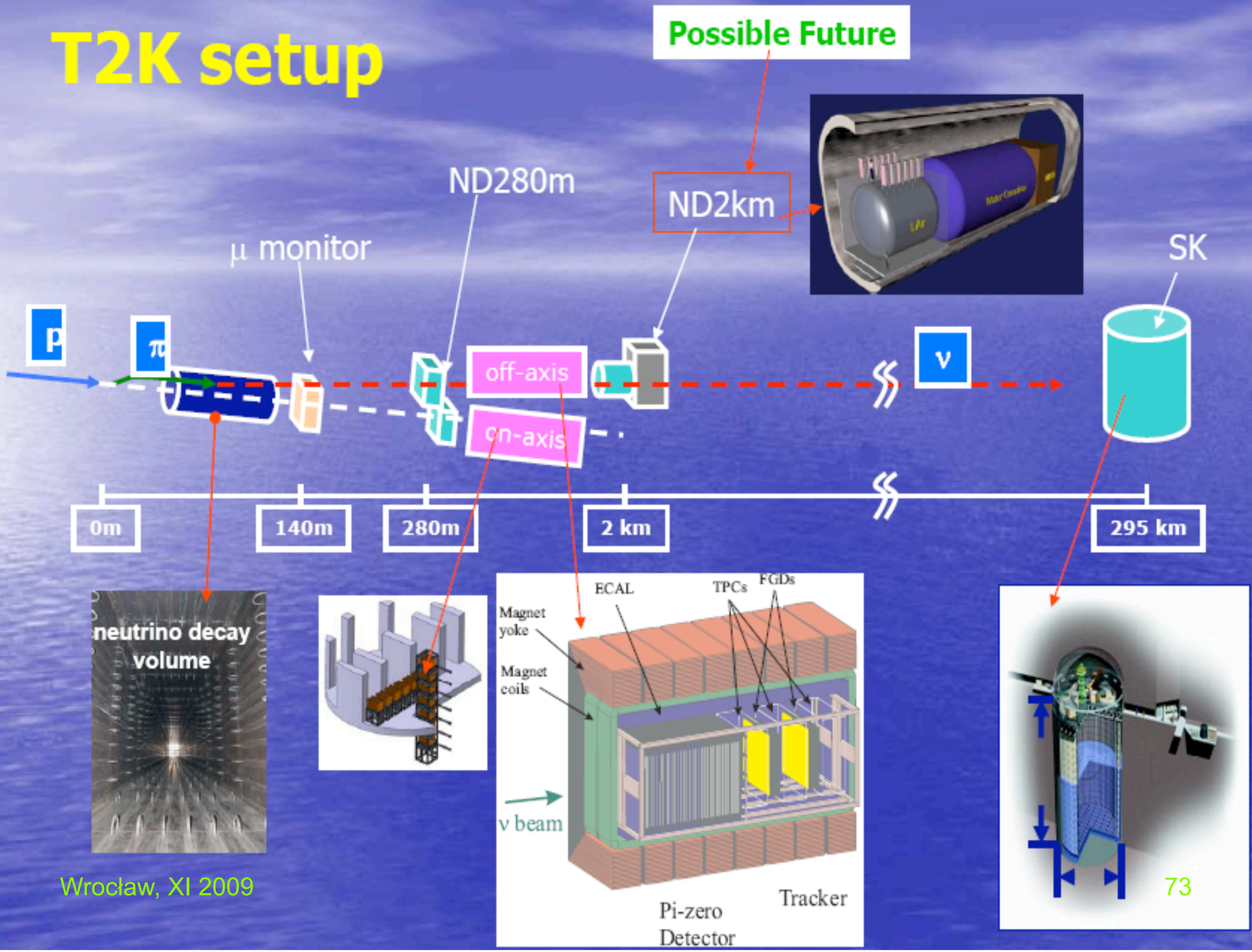


proton profile just in front of the target
after 9 shots beam tuning
(fluorescence plate)



We successfully started to produce neutrino beam

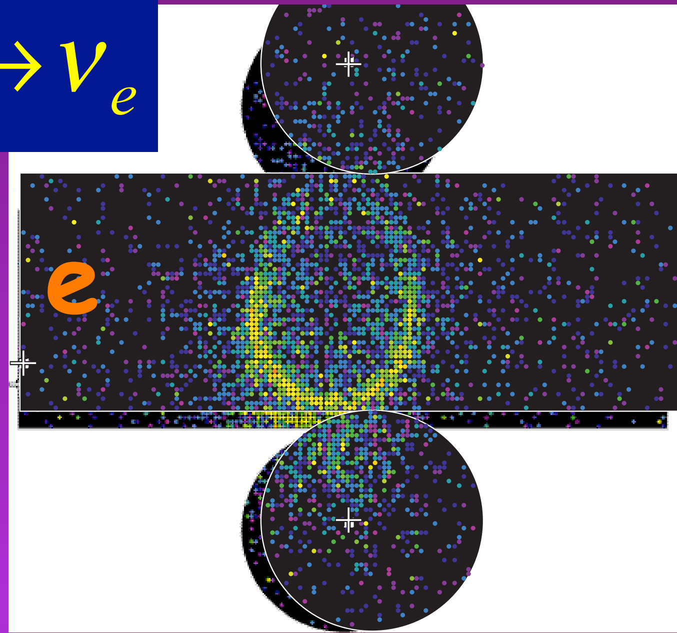
T2K setup



Possible Future
ND280m
ND2km
μ monitor
SK
p
π
ν
off-axis
on-axis
0m
140m
280m
2 km
295 km
neutrino decay volume
ECAL
TPCs
FGDs
Magnet yoke
Magnet coils
ν beam
Tracker
Pi-zero Detector

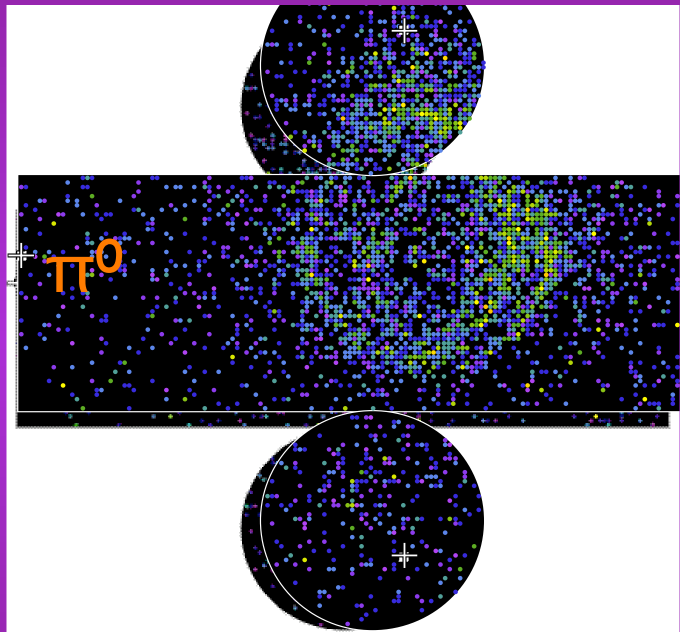
Poszukiwany sygnał w Super Kamiokande:

$\nu_\mu \rightarrow \nu_e$



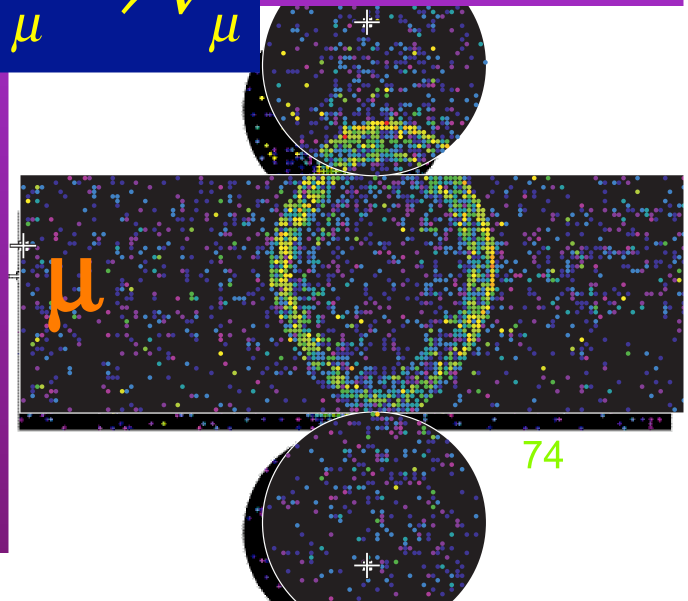
Tło od oddziaływań:

$$\nu_\mu N \rightarrow \nu_\mu N \pi^0$$



Również w wiązce jest domieszka ν_e - około 0.4% ν_μ

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



Detektor Super Kamiokande dobrze zbadany. Z dużą efektywnością rozróżnia elektrony, miony i niskoenerget. π^0

T2K – search for $\nu_\mu \rightarrow \nu_e$

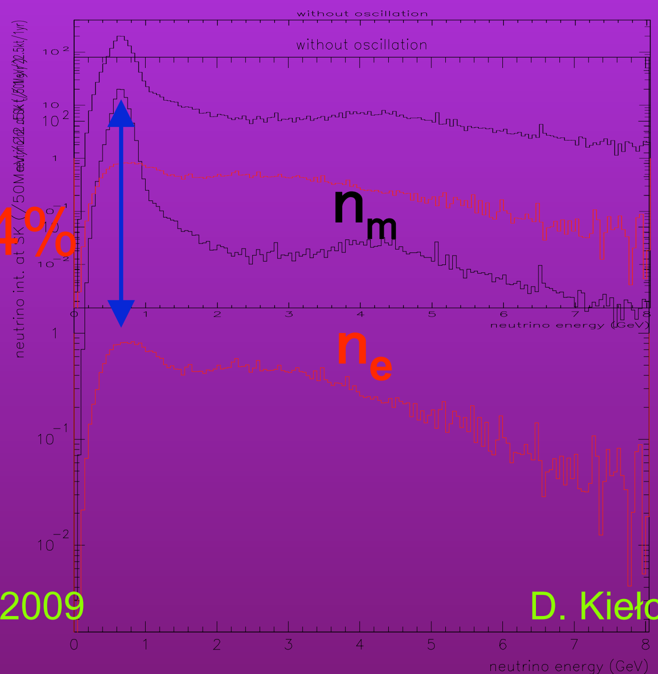
In Super-K detector:

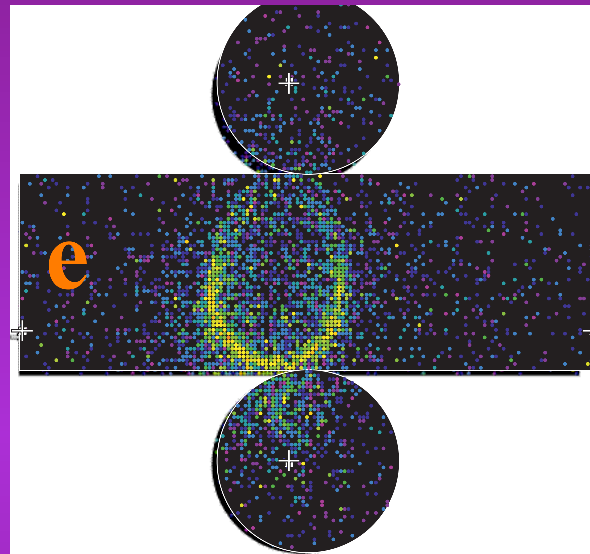
Signal:

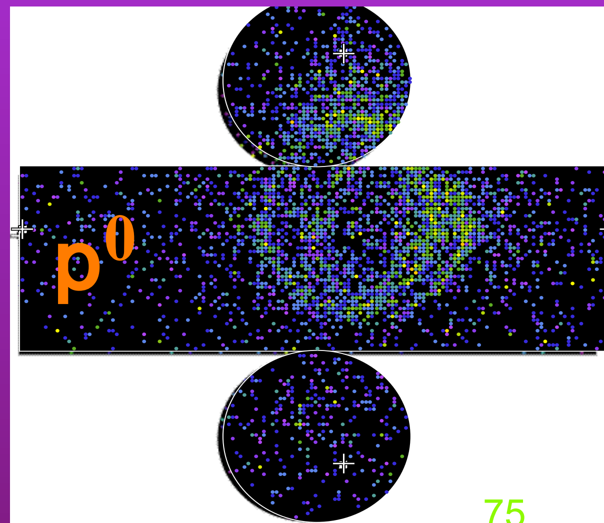
- 1ring e-like event (CC QE sample)

Background:

- beam n_e contamination (0.4% of n_m)
- mis-reconstructed p^0 events (produced by n_m)



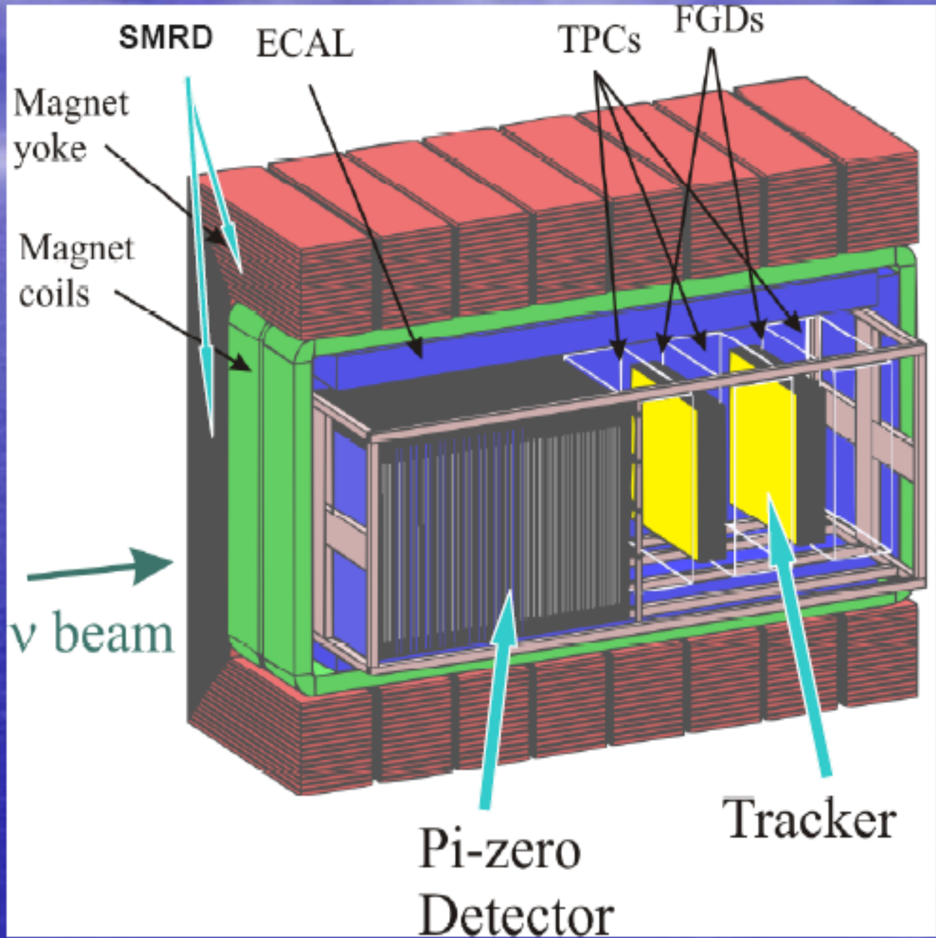


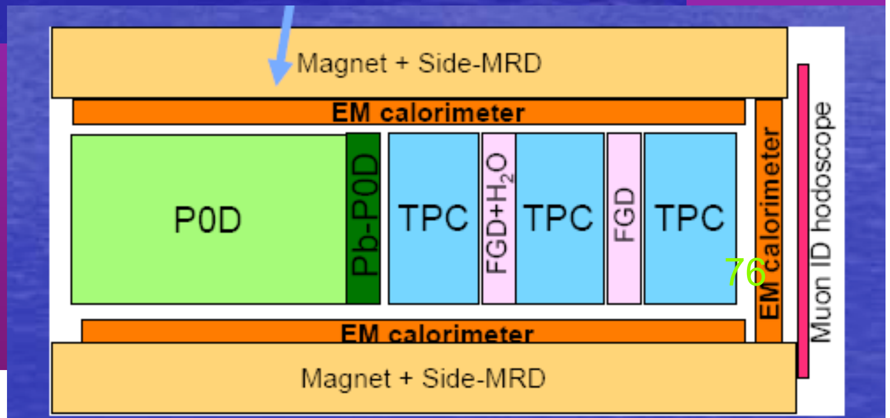


ND280m off-axis detector

Conceptual design

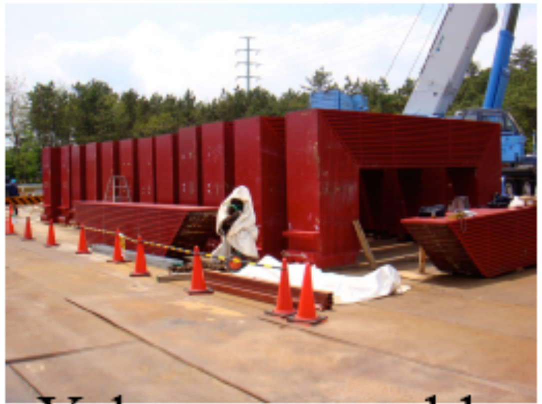
- UA1 magnet
  0.2 T
  inner volume:
  3.5×3.6×7.0 m³
- Pi-Zero optimized for π^0 from NC
- Tracker optimized for CC studies
- surrounded by ECAL and Side Muon Range Detector





Installation at ND280 (Apr-Jun 08)

Yokes installation
(open position)



Yoke re-assembly

Coils installation

Grupy polskie współodpowiedzialne za detektor SMRD

SMRD

Magnet yoke: 17 mm air gaps between iron plates
SMRD: 6 layers of the gaps instrumented with scintillator slabs
- about 4000 slabs
- S-type configuration for fiber readout
- both-end readout using multi-pixel Si APD's

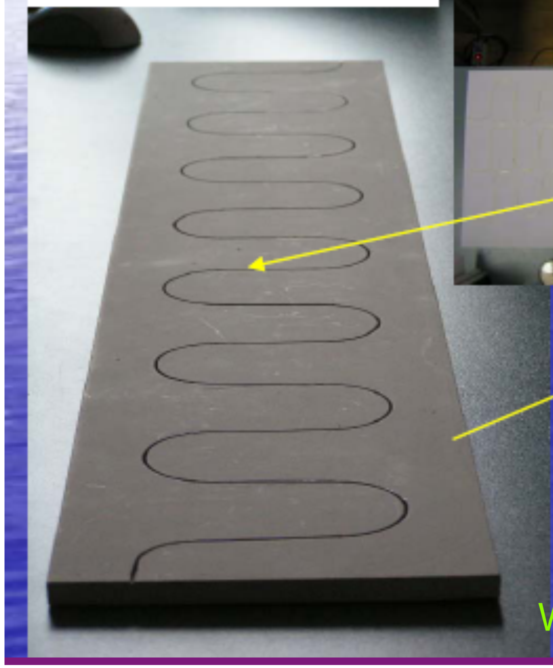
Sci Slab:
Length = ~ 87 cm
Width = ~ 18 cm
Thickmess = 10 mm

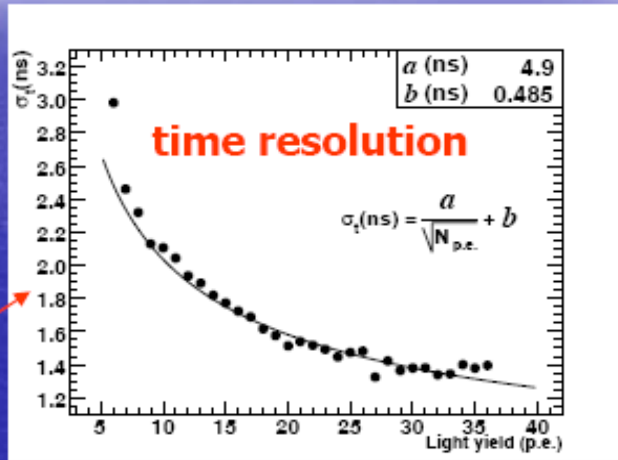
S-shape grooves
Depth 4 mm
Length ~ 2.5 m

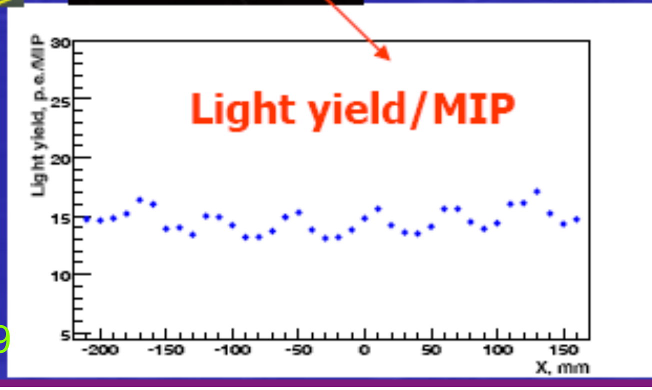
Y11, double clad,
1 mm diameter

Beam test with 1.4 GeV/c pions

Light yield	15-20 p.e.
Timing (σ_t)	1.5 – 2.0 ns
space resolution	10-11 cm
efficiency (MIP)	> 99%

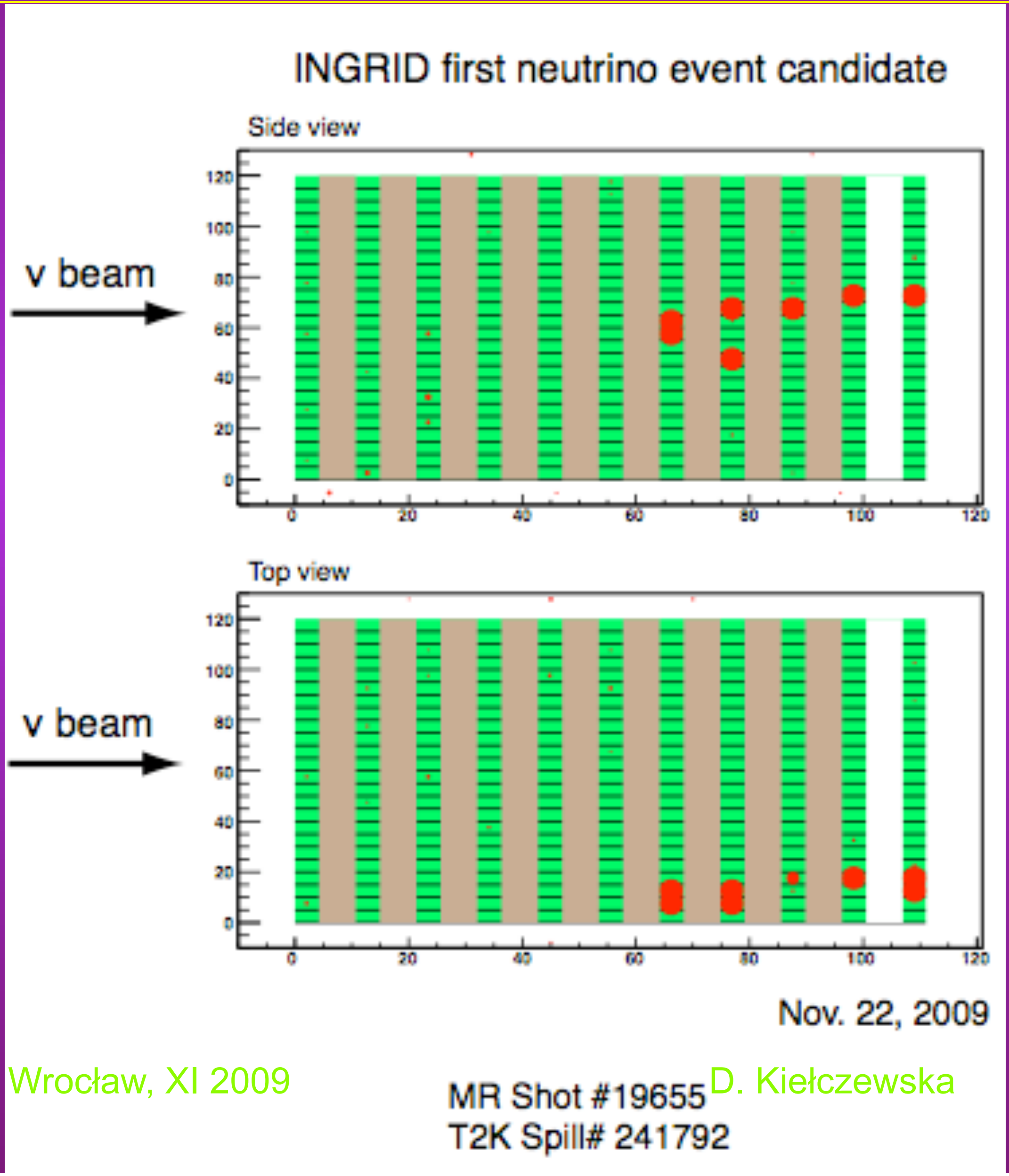






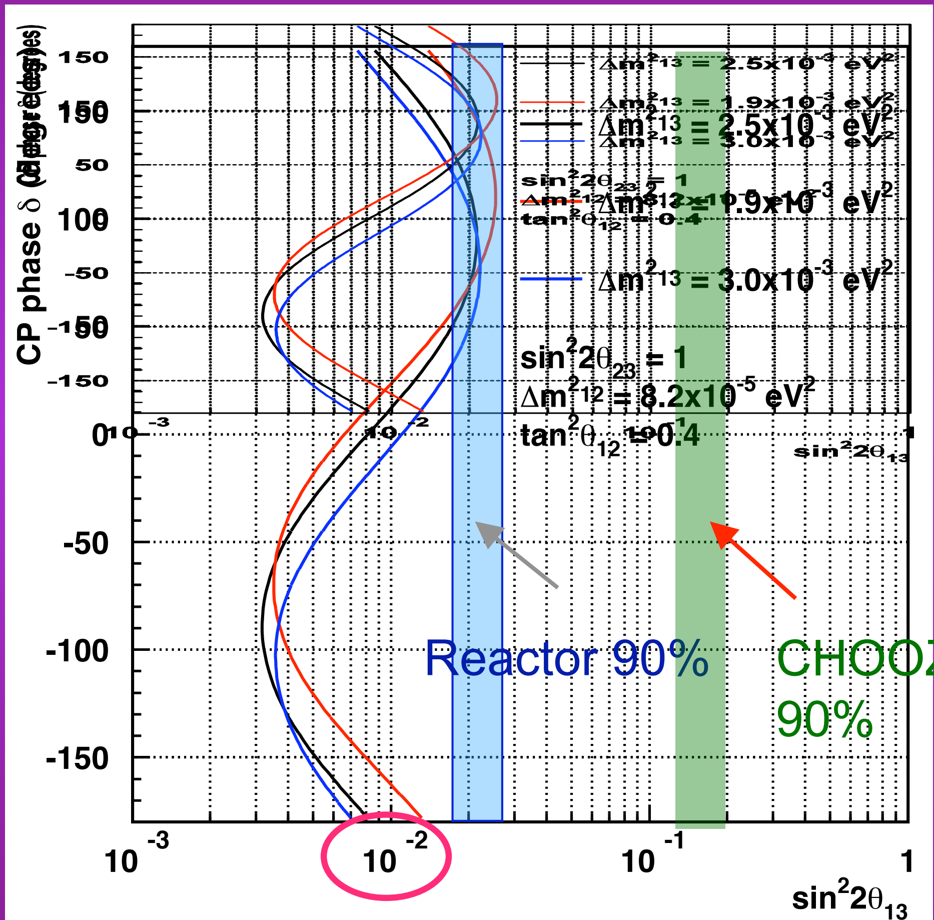
Zakończyliśmy instalację modułów w lipcu 2009

First neutrino event in ND280 (INGRID)

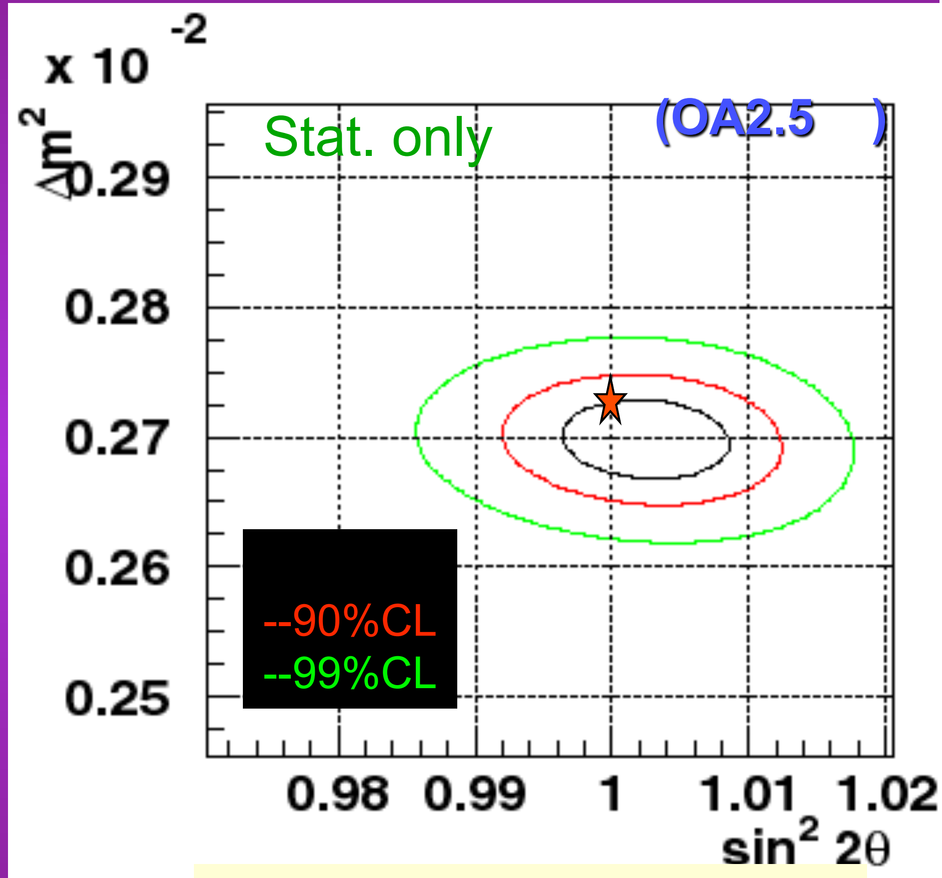


T2K Sensitivities

ν_e appearance



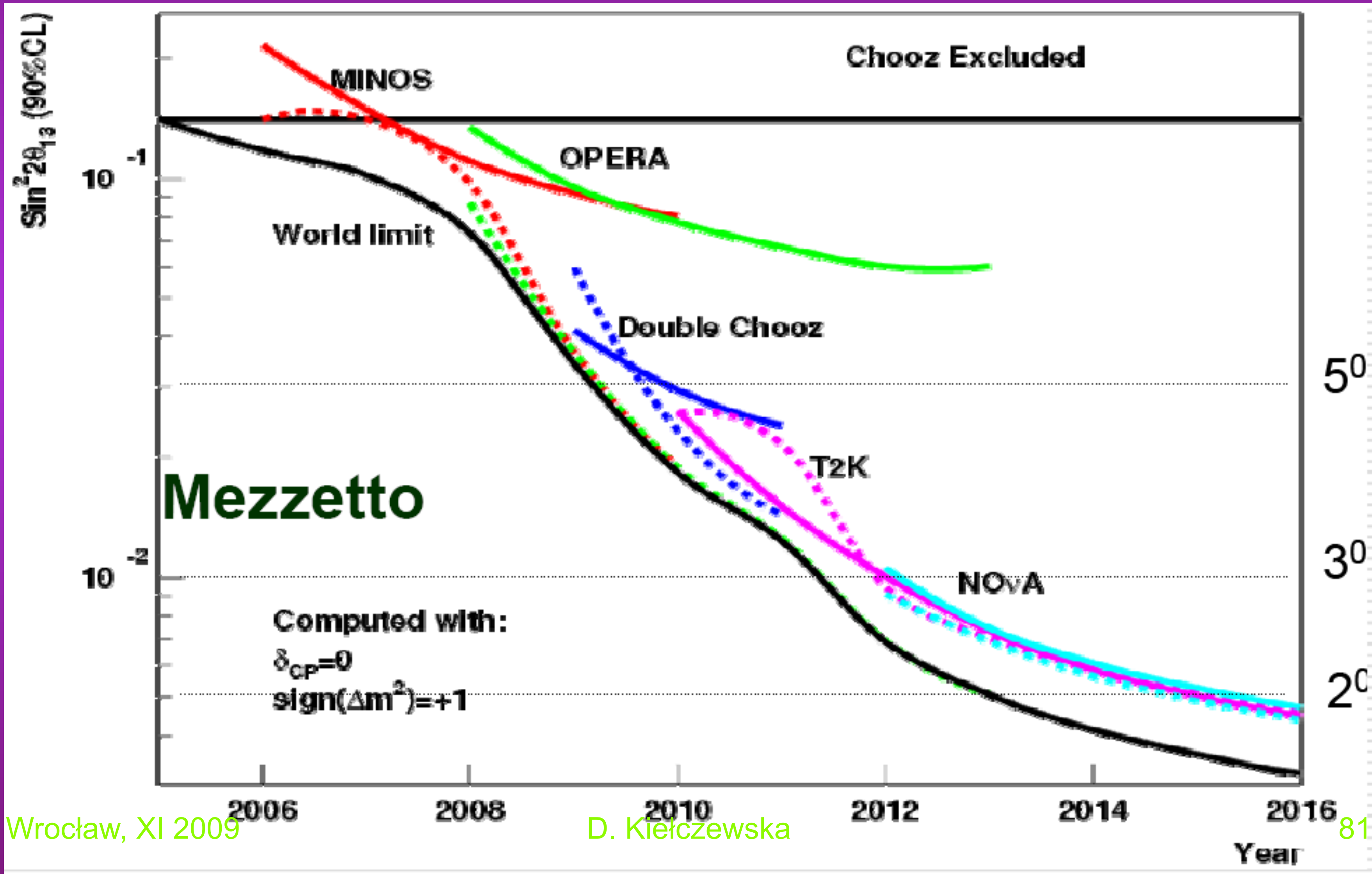
ν_μ disappearance



Goal
$d(\sin^2 2q_{23})\sim 0.01$
$d(\Delta m_{23}{}^2)\sim<1\times10^{-4}$

>10 times improvement above *CHOOZ*

Sensitivities to ϑ_{13}



T2K Sensitivities

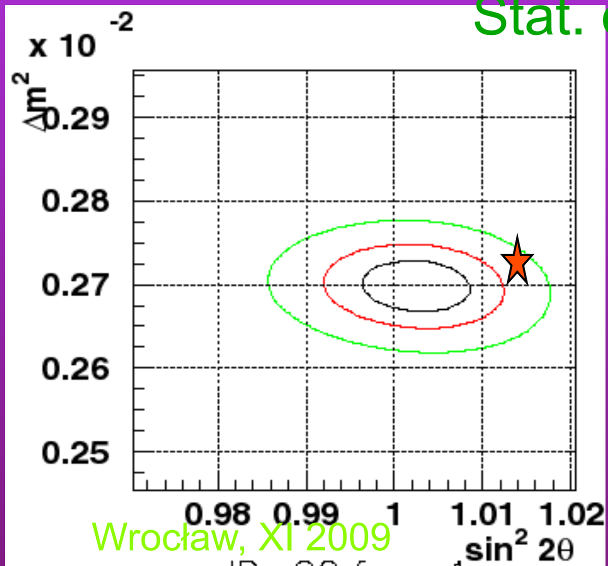
ν_μ disappearance

Current precision:

parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

T. Schwetz et al.
arXiv:0808.2016

Stat. only



--90%CL
--99%CL

Goal

$\delta(\sin^2 2\theta_{23})\sim 0.01$

$\delta(\Delta m_{23}^2)\sim<1\times10^{-4}$ eV^2

NOνA

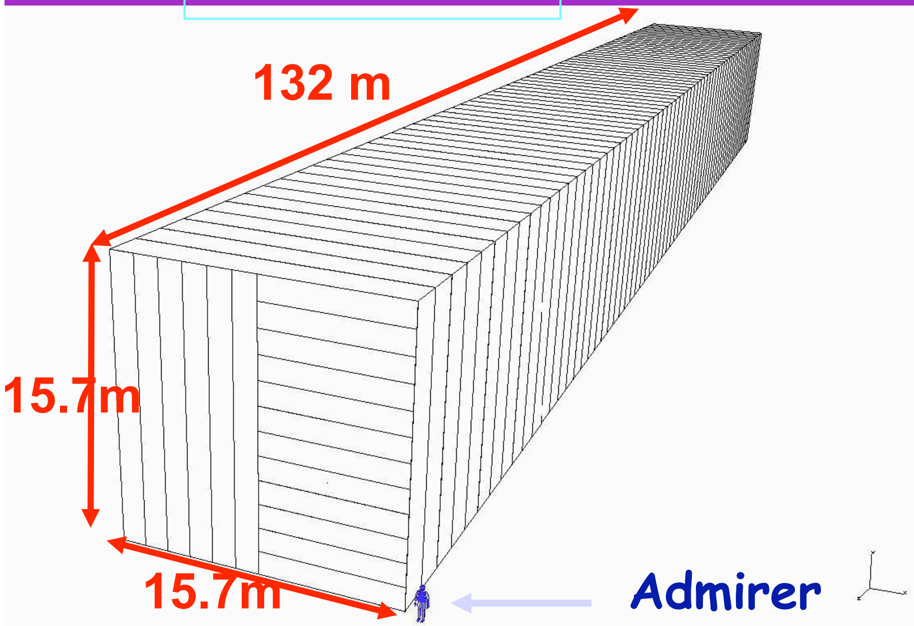
6 countries:
Brasil, France, Greece, Russia, UK, USA
27 Institutions

- Upgraded NuMi beam in Fermilab
  1 MW after 2012

- Far Detector at a distance of 810 km
  - 14 mrad off-axis
  - Liquid scintillator in 14000 PVC extrusions (about 14 kt)
  - 24% effic. for n_e detection
  - start of construction in 2010

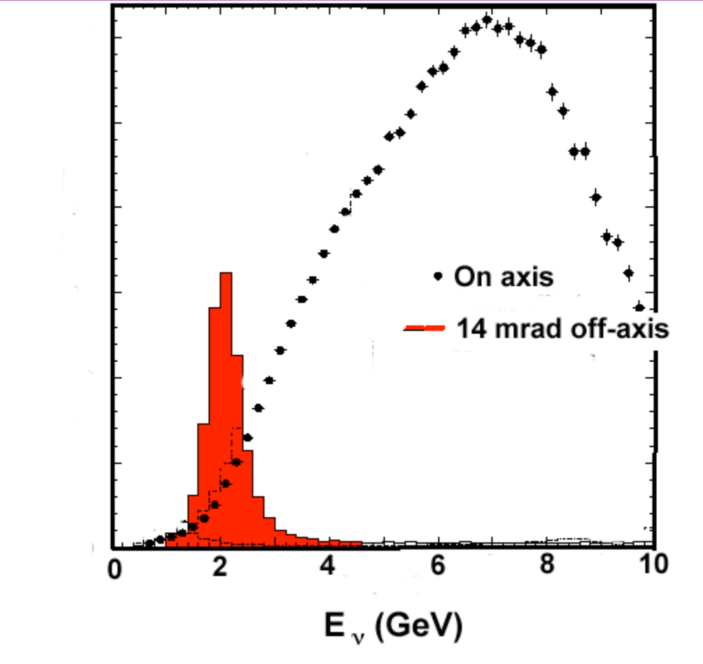
- Near detector will be built in MINOS access tunnel (moveable to sample different background)

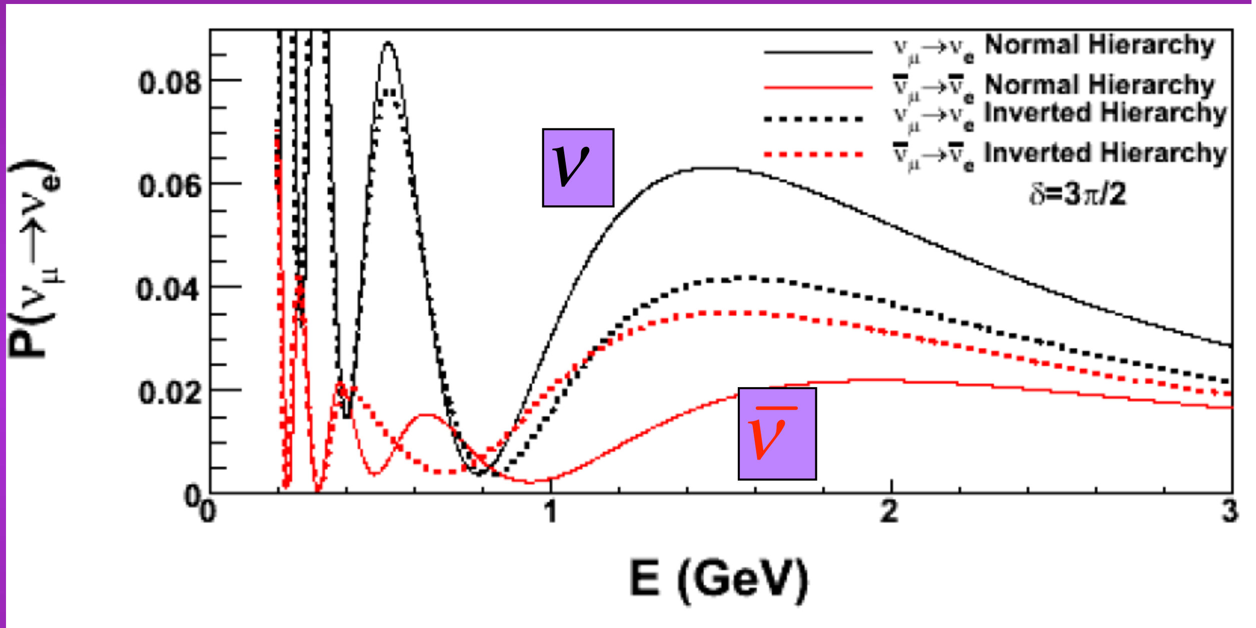
Far detector



NOνA

- Baseline: 810 km
- <E$_n$> 2.22 GeV





Dotted lines for inverted hierarchy

- Thanks to a longer baseline and higher energy Nova has better sensitivity to matter effects and mass hierarchy than T2K
- Nova and T2K are complementary: comparing results allow to disentangle true CP effects from matter effects

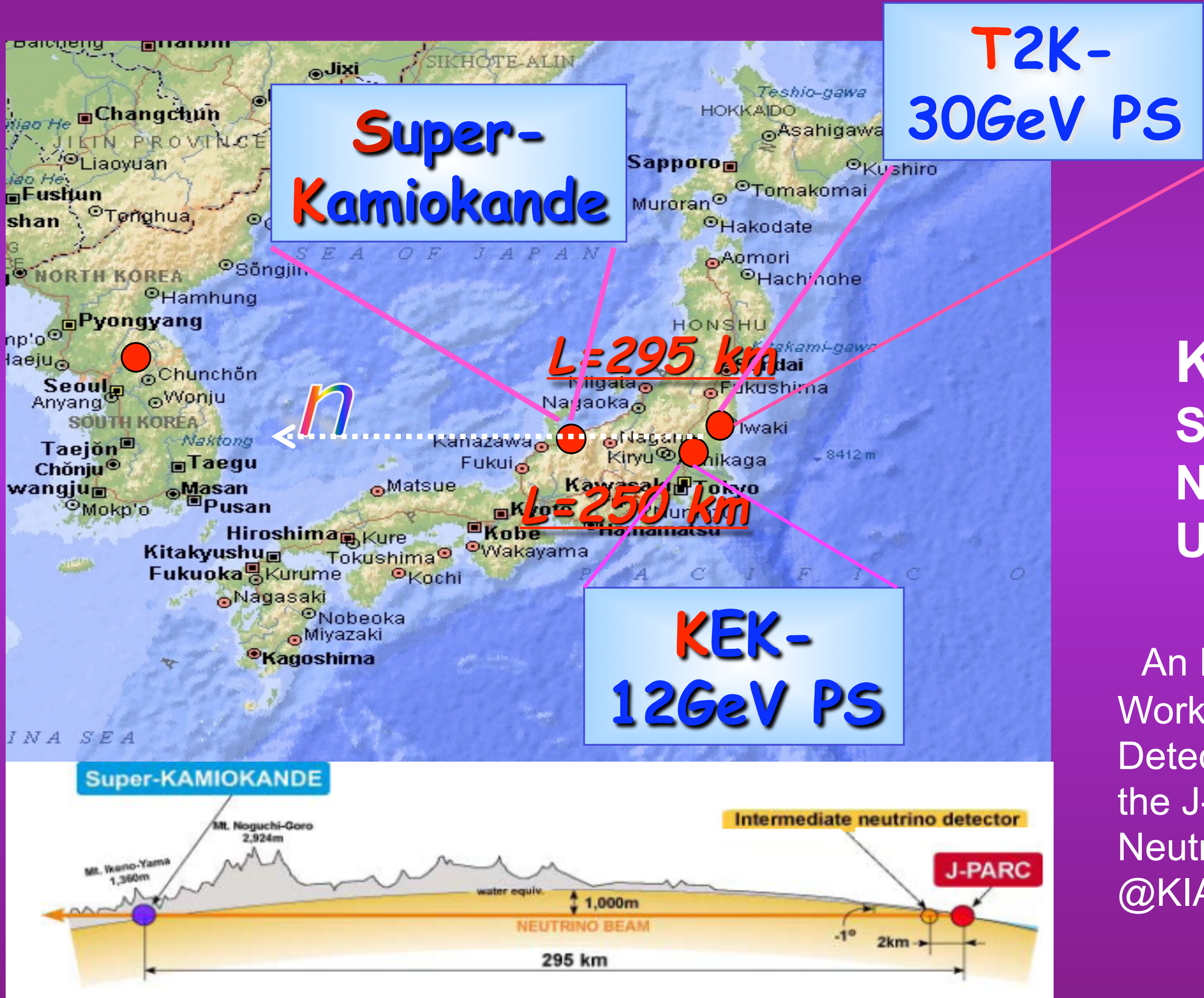
New ideas for CPV sensitivity

Need to solve the problem:
CP violating solution can be confused with CP conserving one due to unknown mass hierarchy

- T2KK – Japan to Korea experiment
  - two detectors on the same beam (J-PARC 4MW)
    (identical detectors: FV=0.27Mton, water Cher.)
  - spectrum analysis (the same beam spectra)
  - 4 years ν + 4 years $\bar{\nu}_\mu$ (if $\sin^2 2\vartheta_{13} > 0.03\ (0.055)$ at $2\sigma\ (3\sigma)$)
- Super-NOvA
  - 2 detectors at the same (L/E) (but different baseline and different off axis angle and thus different spectra)

Minakata & Nunokawa, Phys. Lett. B 413, 369 (1997)
Ishitsuka, Kajita, Minakata, Nunokawa, hep-ph/0504026
Mena et al., hep-ph/0504015, hep-ph/0510182

T2K - faza 2



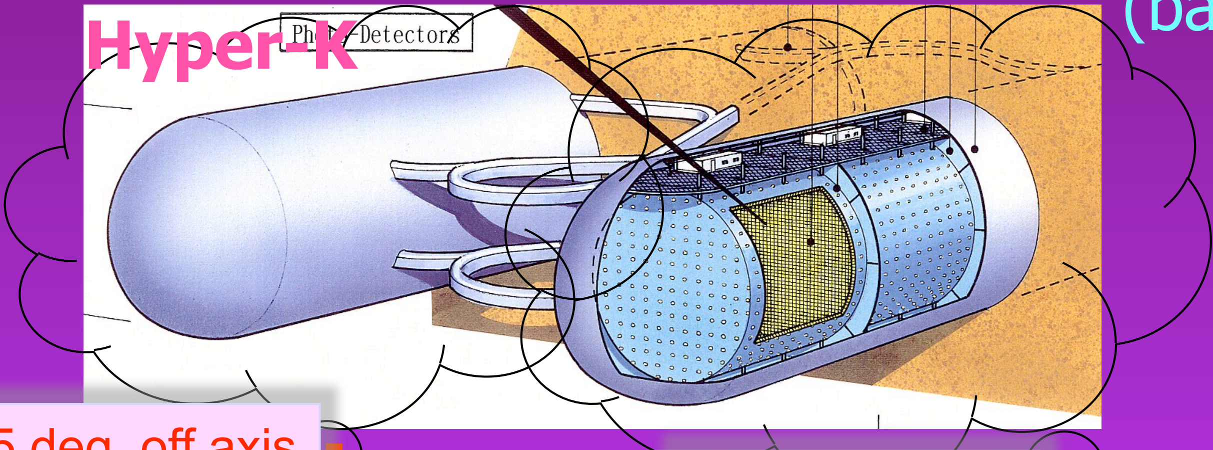
KK Joo
Seoul National University

An International Workshop on a Far Detector in Korea for the J-PARC Neutrino Beam @KIAS

2005/11/18

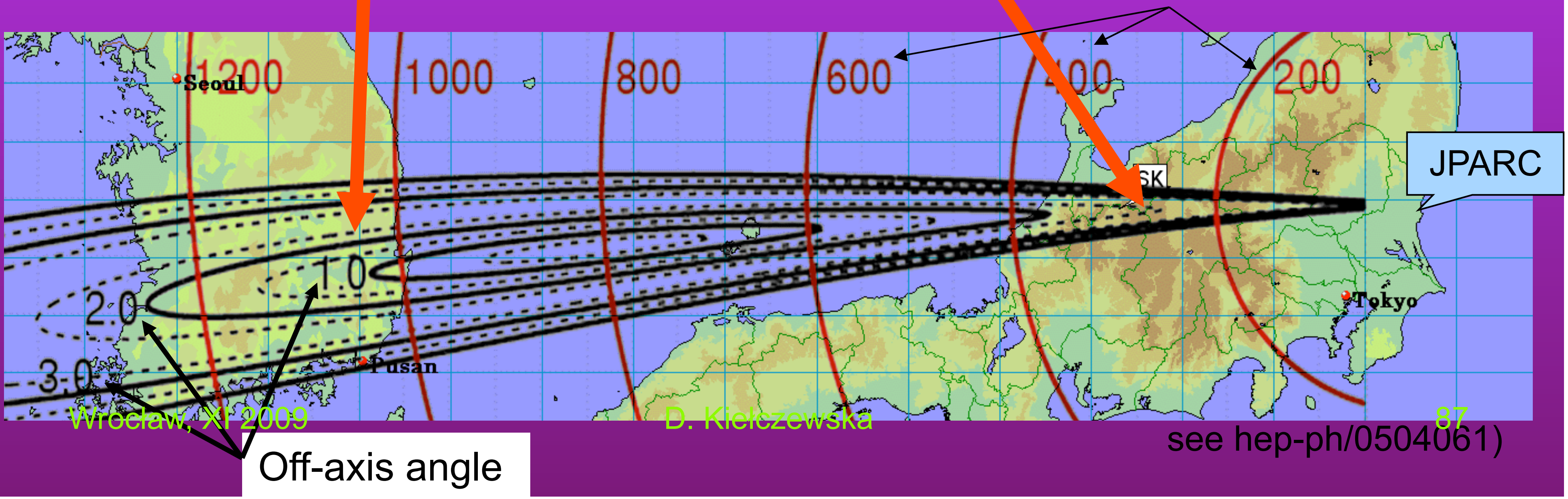
T2K2-Korea?

The second detector in Korea at the 2nd osc. maximum (baseline ~1050km)

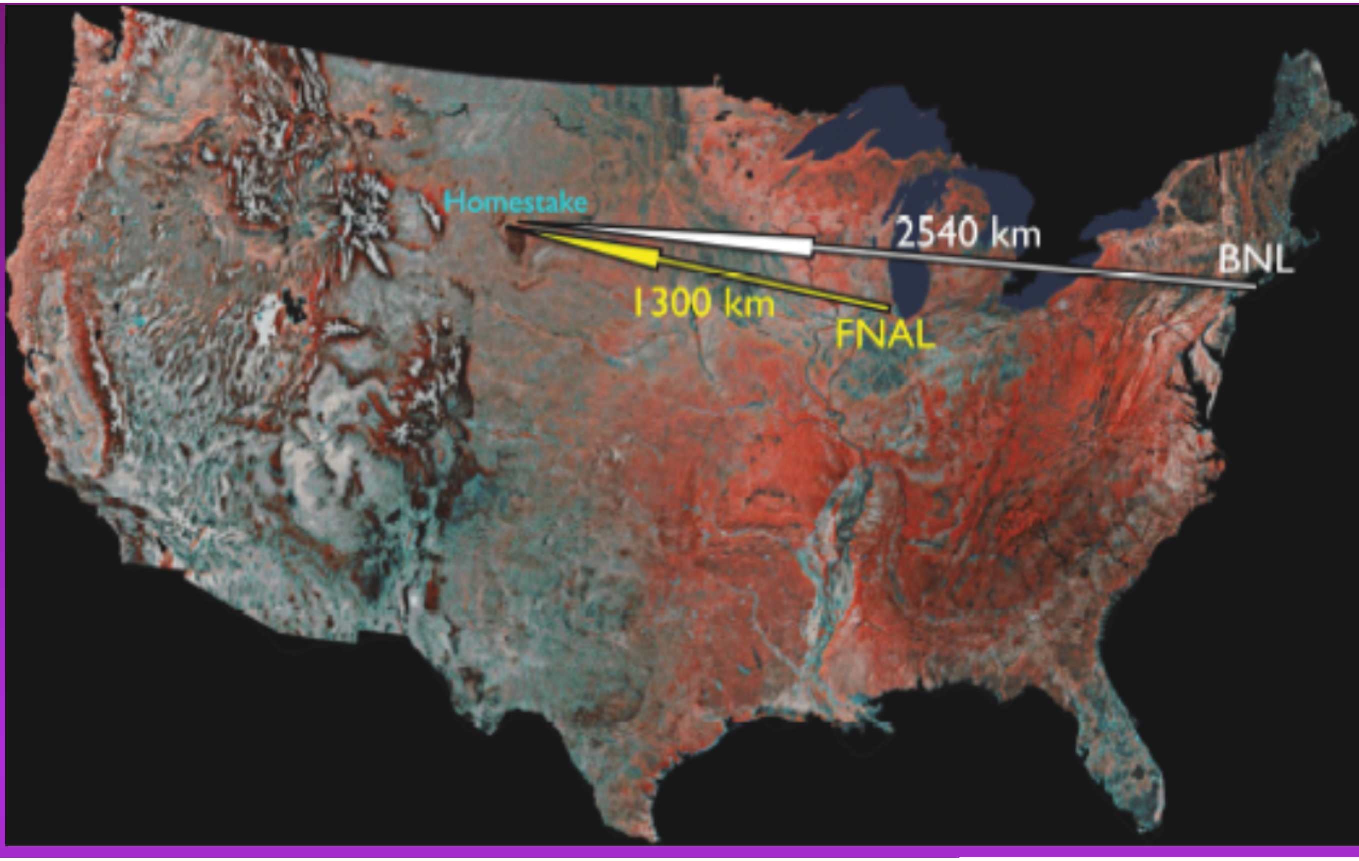


2.5 deg. off axis

2.5 deg. off axis

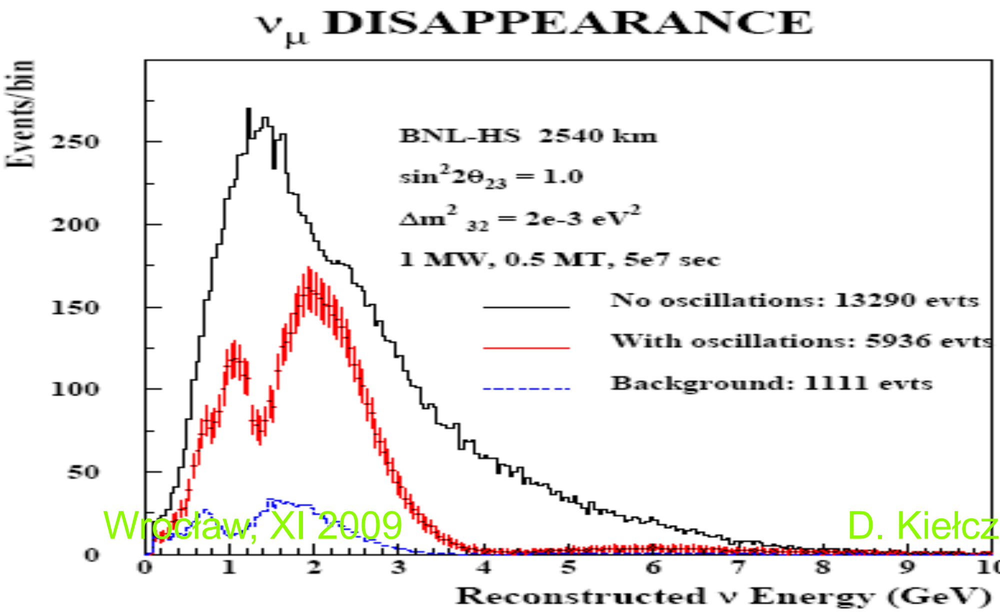


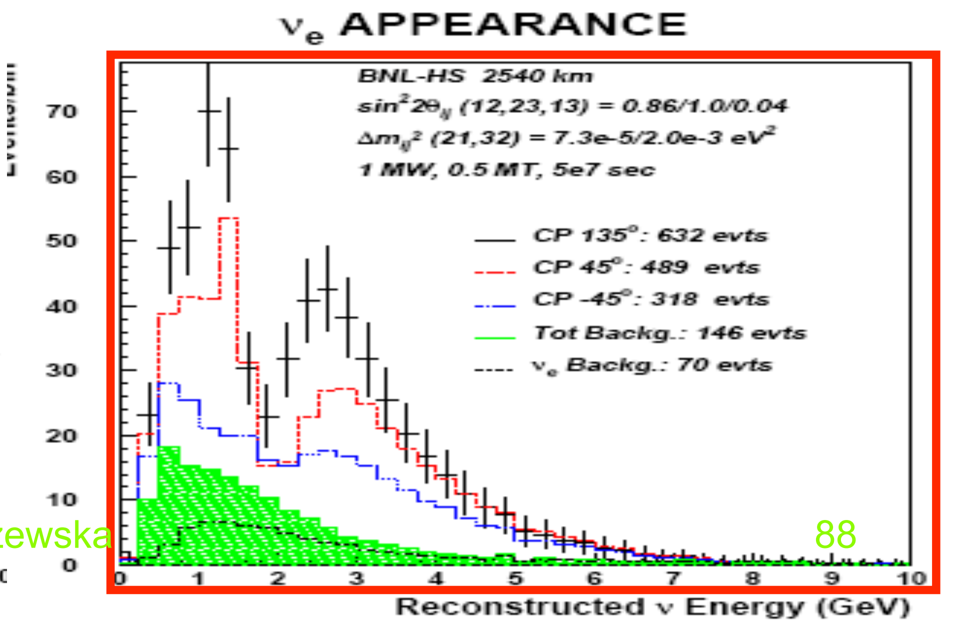
see hep-ph/0504061)



Very Long Baseline

DUSEL
- underground lab in Homestake
- 500 kt detector





Podsumowanie

W poszukiwaniu ukrytych symetrii chcemy:

- ❖ Zmierzyć precyzyjnie ϑ_{23} – czy jest dokładnie 45° ?
- ❖ Zmierzyć precyzyjnie ϑ_{13} – czy jest dokładnie 0° ?

- ❖ Badać symetrię CP w sektorze leptonowym (Leptogeneza??).

W tym celu musimy:

- ➢ zmierzyć najpierw ϑ_{13}
- ➢ ustalić hierarchię mas neutrin (normalna czy odwrócona)

Konieczne różne eksperymenty:

- Faza pierwsza: T2K , NOvA, reactor experiments (ϑ_{13})
- Faza druga δ_{CP}

T2K wkrótce zaczyna zbierać dane

Summary

In a search for underlying symmetries we need to

- ❖ Measure more precisely ϑ_{23} – is it 45^o ?
- ❖ Measure more precisely ϑ_{13} – is it 0^o ?
- ❖ Study CP symmetry

For that we must:

- ➢ measure ϑ_{13} in order to design a roadmap for searches of CPV
- ➢ determine the neutrino mass spectrum hierarchy (normal or inverted)

From the experimental point of view:

Various approaches are needed to resolve degeneracies:

- First phase: T2K , NOvA, reactor experiments (ϑ_{13})
- Second phase δ_{CP}

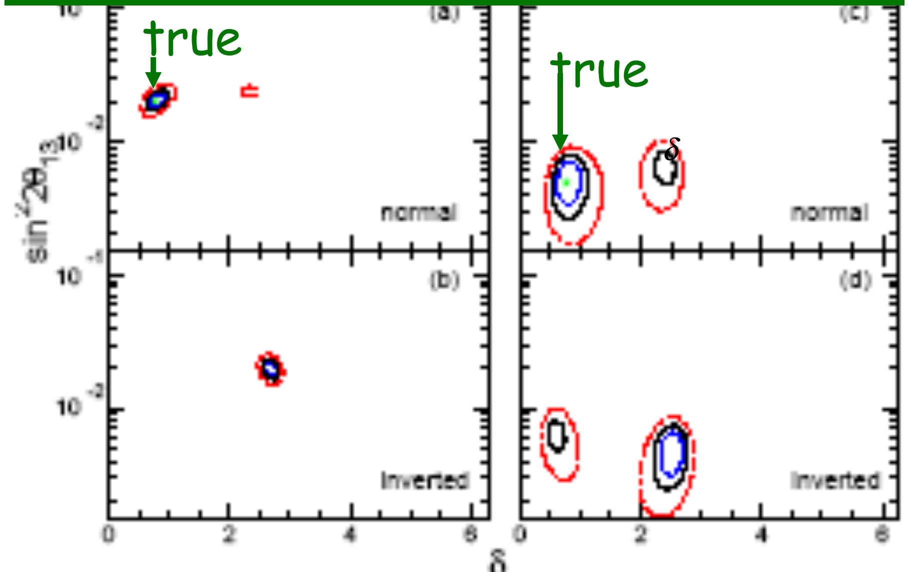
T2K: Japan to Korea

Nova: 2 large off-axis detectors

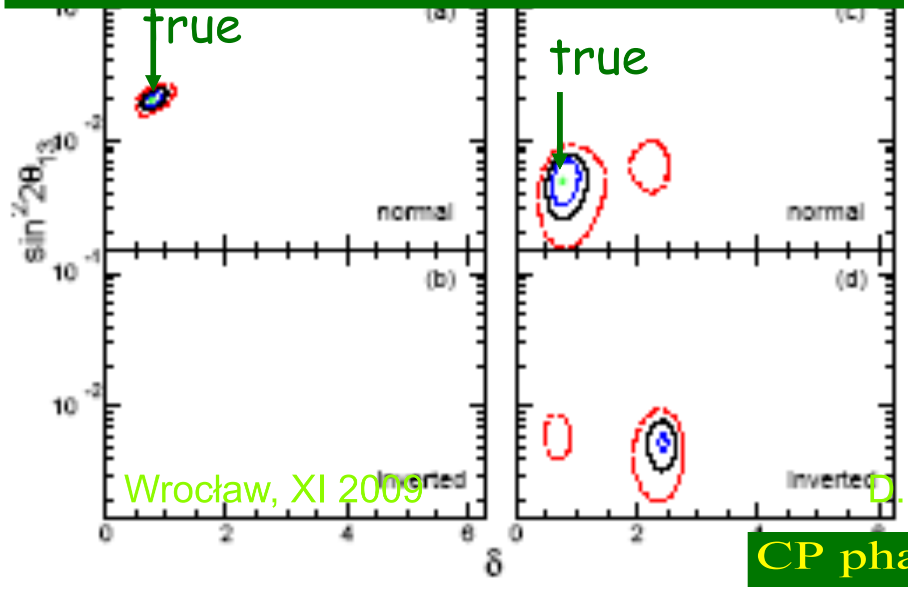
hep-ph/0504026

J2K – 2 identical detectors

1 detector of 0.54 Mton in Kamioka



2 detect. of 0.27 Mton (Kamioka &Korea)



CP phase δ

How to lift 4-fold degeneracies in: CP phase δ and sign(Δm^2_{13})

Analysis of data expected after 8 years total of 4MW beam: ν and $\bar{\nu}$

The contours crrespondto different c.l. solutions

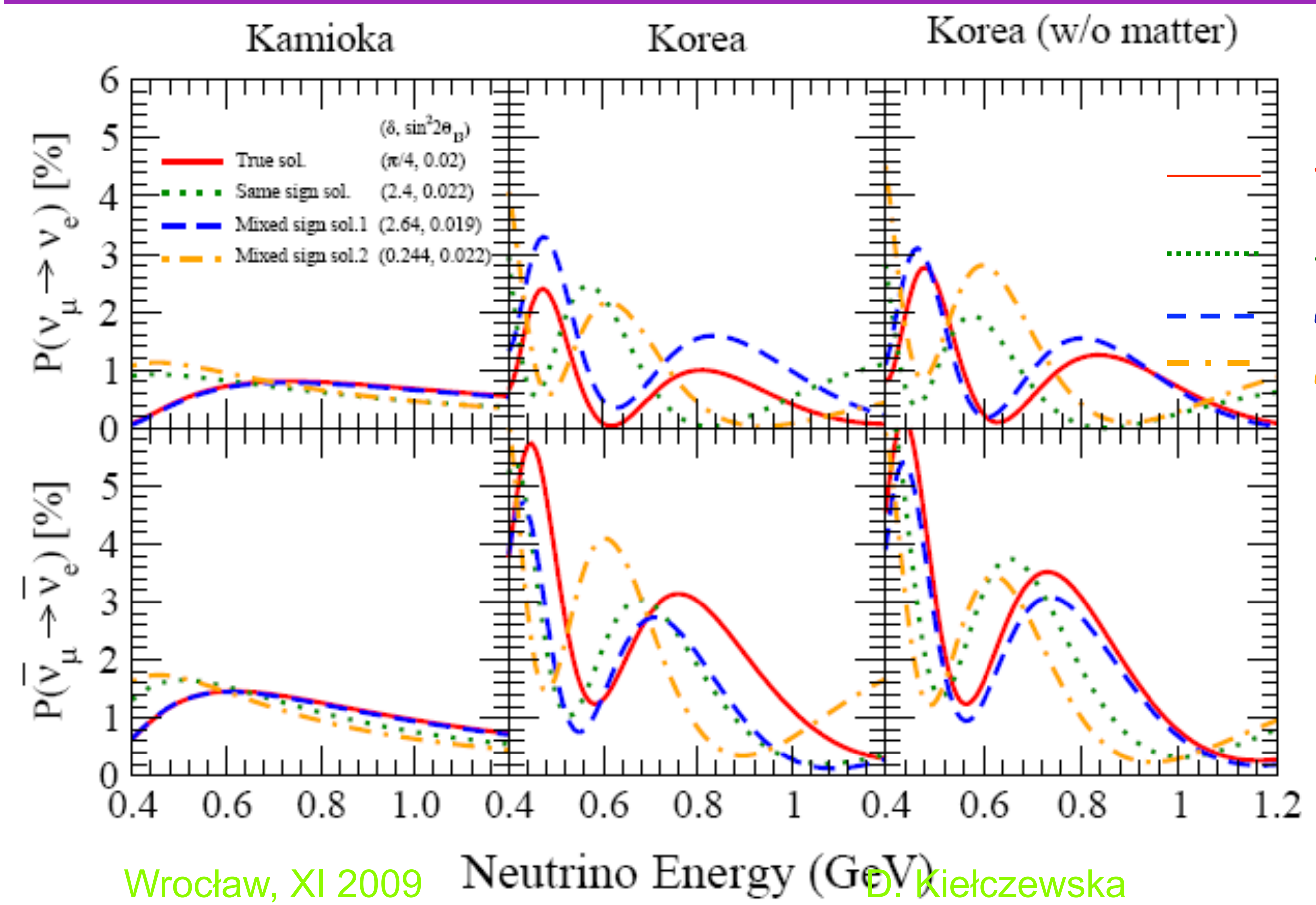
With 2 detectors

Assumed set of parameters	Result
Left panels: $\delta = \frac{\pi}{4},\ \sin^2 2\vartheta_{13} = 0.02,\ \Delta m^2_{13} > 0$	only true solution found
Right panels: $\delta = \frac{\pi}{4},\ \sin^2 2\vartheta_{13} = 0.005,\ \Delta m^2_{13} > 0$	some degeneracy remains

This is due to spectrum analysis

J2K – 2 identical detectors

- When going to the second max the rates alone not a solution because although CPV effect gets larger the matter effects stay approx the same
- However the spectrum modification is very sensitive to sign(Dm^2)



$(\delta, \sin^2 2\vartheta_{13})$

True solution	(p/4, 0.02)
Same sign sol.	(2.4, 0.022)
Mixed sign sol.1	(2.54, 0.019)
Mixed sign sol.2	(0.244, 0.022)

From the rate only analysis at SK one gets only 1 degenerate solution with the above parameters.

hep-ph/0504026

Very long baseline scenario (BNL proposal)

N~1/L²

$$\sin\Delta_{12} = \sin\frac{1.27\Delta m^2_{12}L}{E} \sim L$$

$$P(\nu_\mu \to \nu_e) =$$

$$4s^2_{23}s^2_{13}c^2_{13}\sin^2\Delta_{13}$$

N_e~1/L²

$$+8s_{12}s_{23}s_{13}c^2_{13}(c_{12}c_{23}\cos\delta - s_{12}s_{23}s_{13})\sin\Delta_{13}\sin\Delta_{12}\cos\Delta_{23}$$

$$-8s_{12}s_{23}s_{13}c_{12}c_{23}c^2_{13}\sin\delta\sin\Delta_{13}\sin\Delta_{12}\sin\Delta_{23}$$

N_e~1/L

$$+4s^2_{12}c^2_{13}(c^2_{12}c^2_{23} + s^2_{23}s^2_{13}c^2_{13} - 2s_{12}s_{23}s_{13}c_{12}c_{23}\cos\delta)\sin^2\Delta_{12}$$

$$-8s^2_{13}s^2_{23}c^2_{13}(1-2s^2_{13})\frac{\alpha L}{4E}\sin\Delta_{13}\cos\Delta_{23}$$

$$A \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq \frac{\sin 2\vartheta_{12}}{\sin\vartheta_{13}}\frac{\Delta m^2_{12}L}{4E_\nu}\sin\delta$$

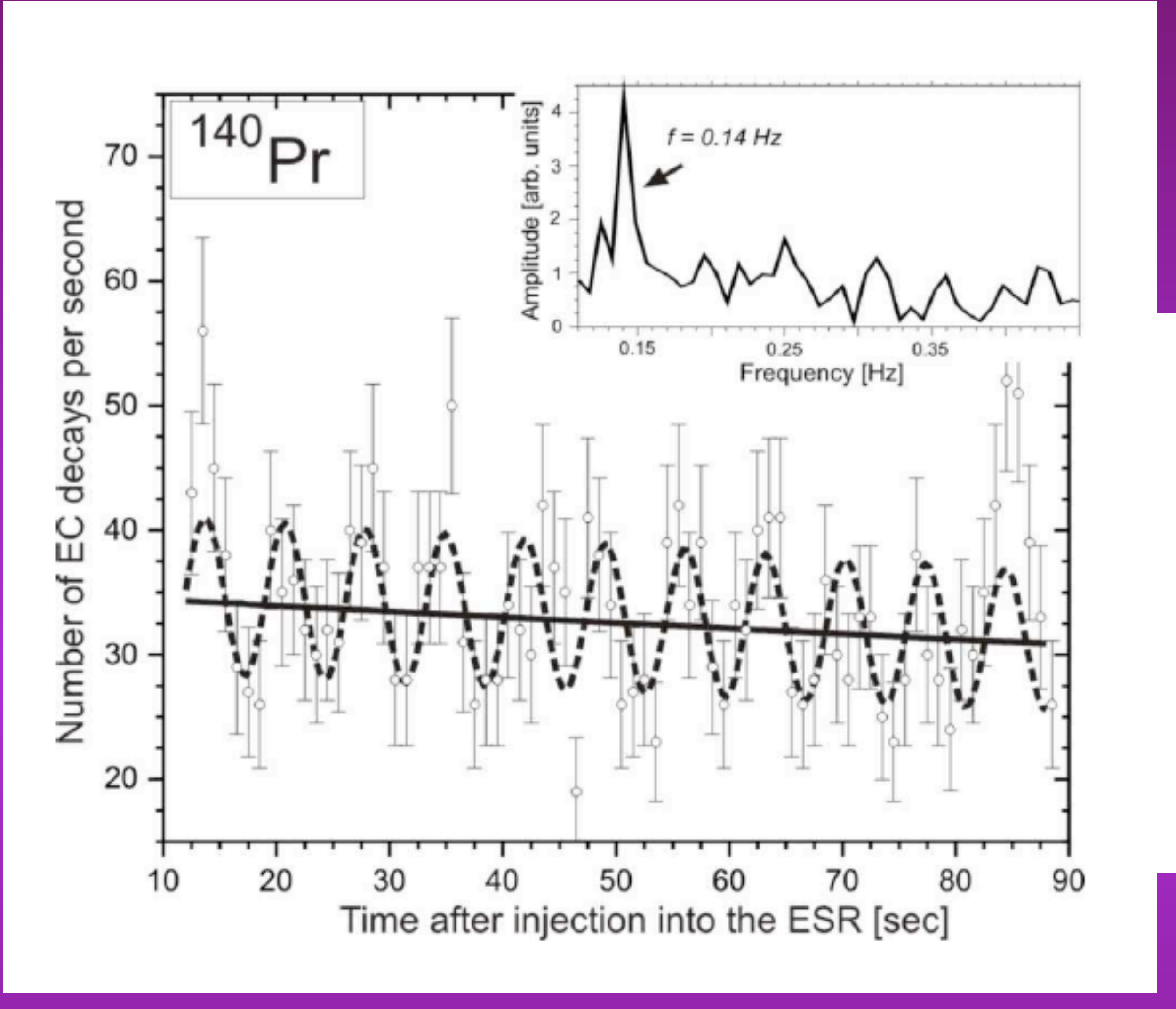
→ Some like very long baselines

w/out matter effects and smaller terms

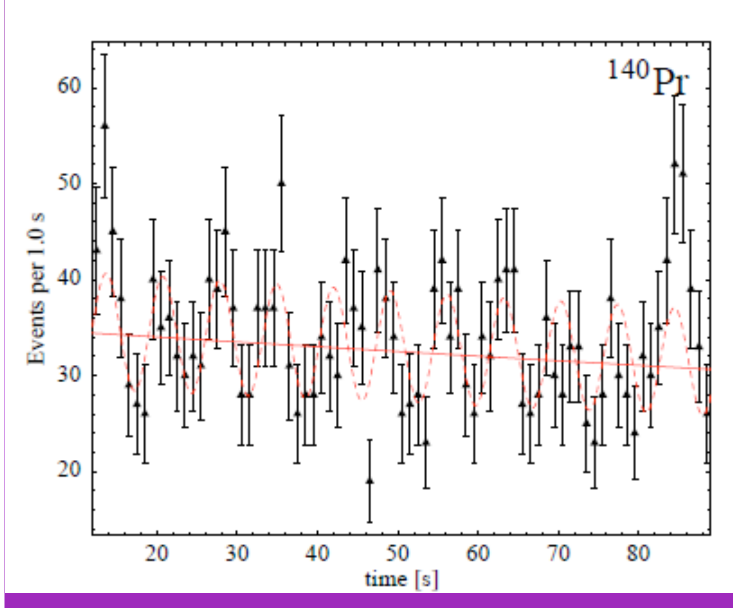
Intelligent Design of Neutrino Parameters?
(after A. Friedman)

- The optimum choice for Dm^2_{23}?
  Such as to give full oscillation in the middle of the range of possible distances that atmospheric n's travel to get to the detector
  - done, $Dm^2_{23} = 2.5 \times 10^{-3}$ eV^2
- The optimum choice for $sinq_{23}$?
  Big enough so that oscillations could be seen easily - done, q_{23} ~ p/4
- The optimum choice for Dm^2_{12}?
  Such as to give transition from vacuum to matter oscillations in the middle of solar energy spectrum - done, $Dm^2_{12} = 8.2 \times 10^{-5}$ eV^2
- The optimum choice for $sinq_{12}$?
  Big enough for oscillations to be seen in KamLAND - done, ~0.8
- The optimum choice for $sinq_{13}$?
  Sm

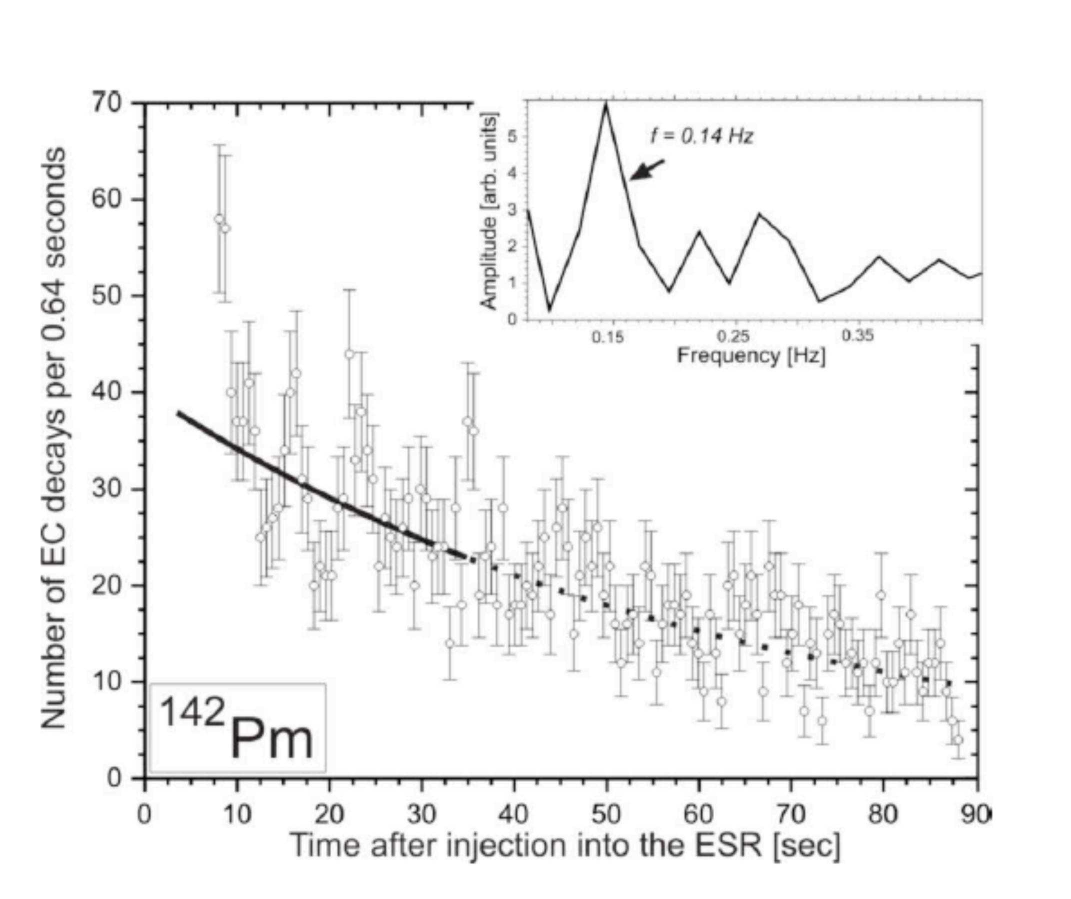
But the acid test - will q_{13} be big enough to see CP violation and determine mass hierarchy?

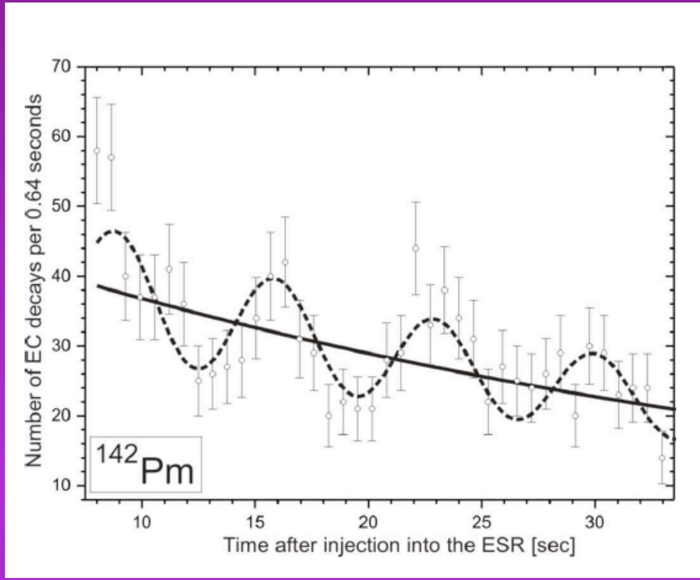


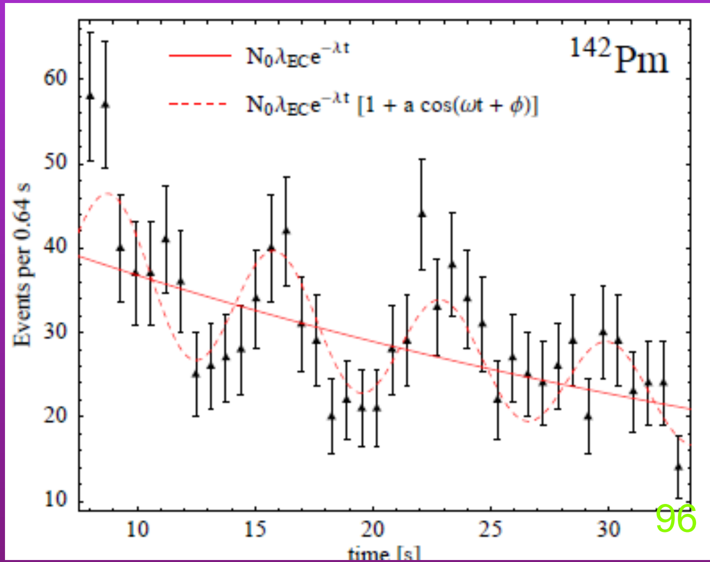
^{140}Pr
f = 0.14 Hz
Amplitude [arb. units]
Frequency [Hz]
Number of EC decays per second
Time after injection into the ESR [sec]



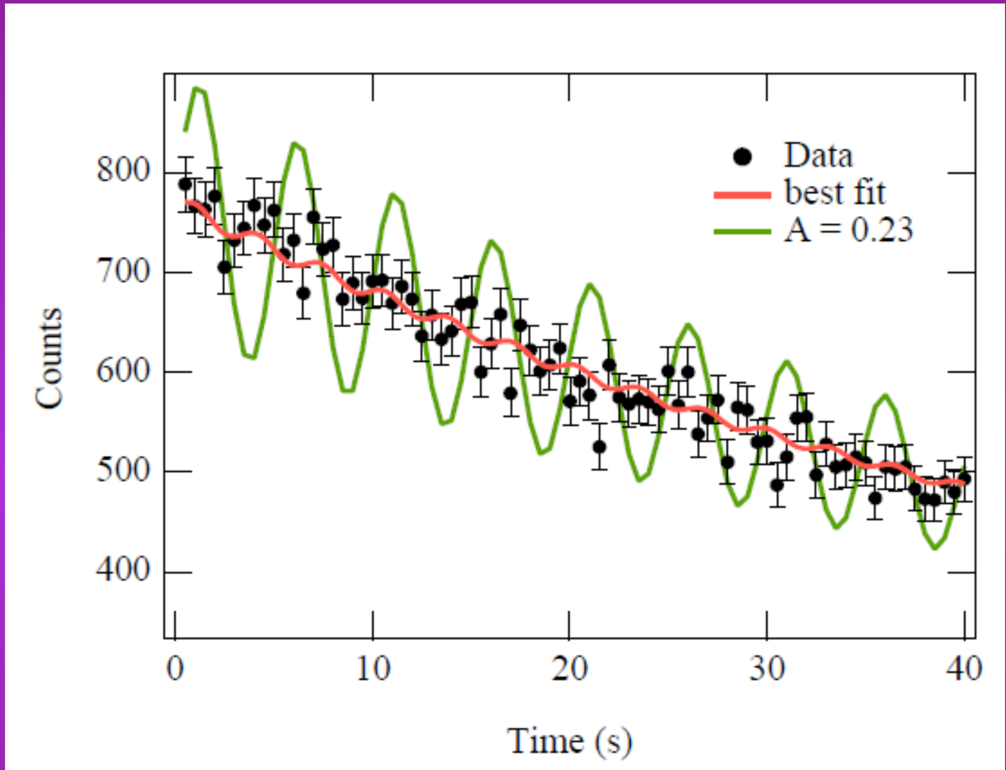
^{140}Pr
Events per 1.0 s
time [s]


Number of EC decays per 0.64 seconds
Time after injection into the ESR [sec]
^{142}Pm
Amplitude [arb. units]
Frequency [Hz]
f = 0.14 Hz


Number of EC decays per 0.64 seconds
Time after injection into the ESR [sec]
^{142}Pm


$N_0\lambda_{EC}e^{-\lambda t}$
$N_0\lambda_{EC}e^{-\lambda t}$ [1 + a cos(ωt + ϕ)]
^{142}Pm
Events per 0.64 s
time [s]

Od tego czasu ponad 20 prac („teoretycznych") i 2 dośw.

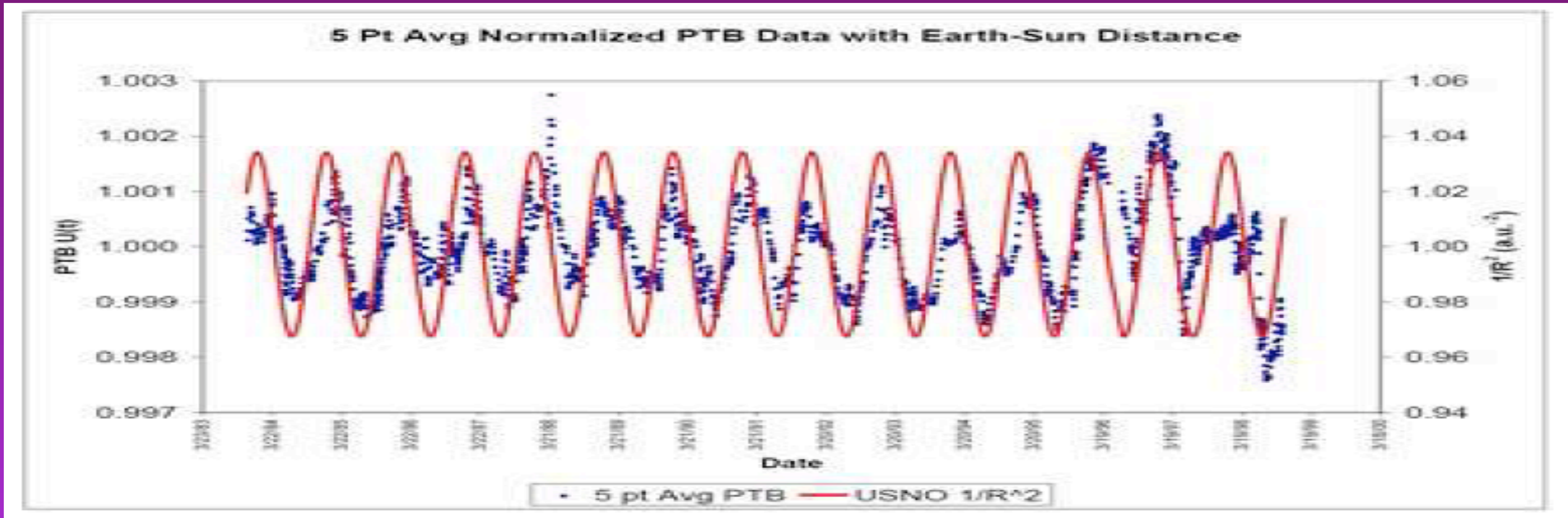


0807.0649
(w Berkeley)

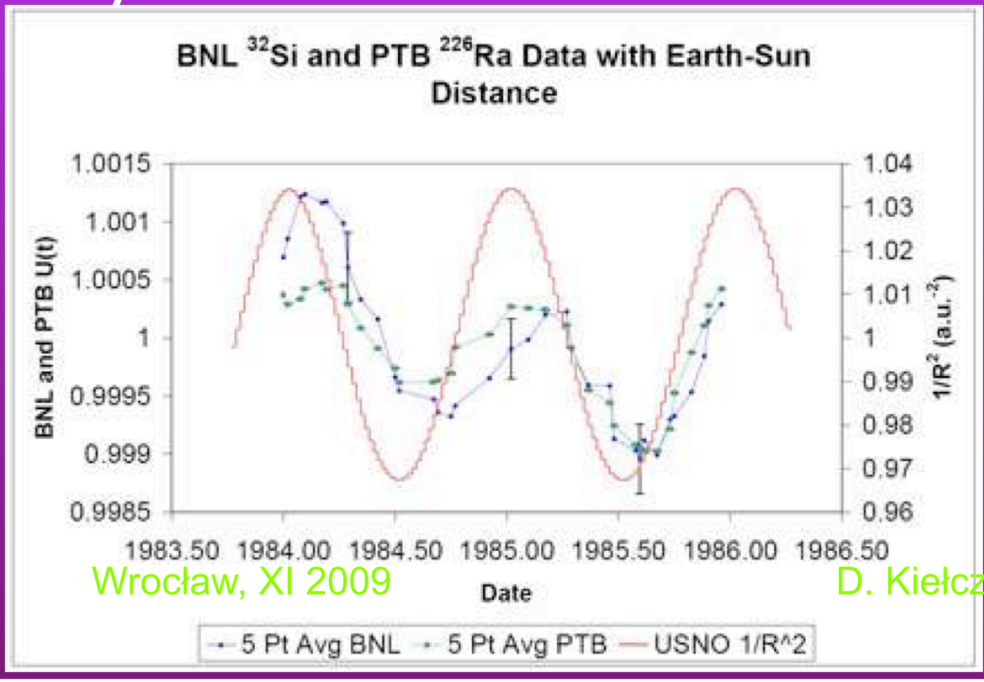
^{142}Pm – kanał EC

Krytyka autorów z GSI: rozpad w ośrodku (3 ciała)

Teoretyczne: kilku fizyków niem. i austr. (+ H. Lipkin) usiłuje przekonać wszystkich pozostałych, że mieszanie neutrin jest w stanie wywołać oscylacje w EC.



Aktywność ^{226}Ra (rozpad alfa) mierzona przez 15 lat w Physikalisch-Technische Bundesandstalt (PTB) w Niemczech

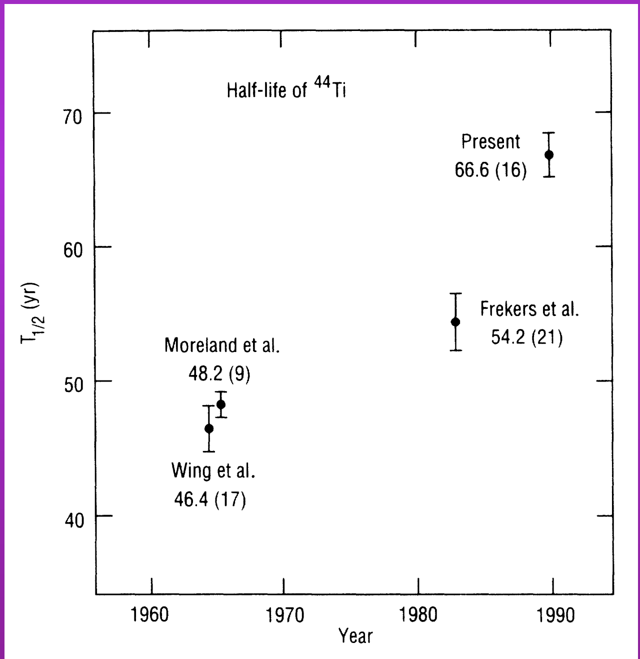


H. Siegert, H. Schrader, and U. Schötzig, Appl. Radiat. Isot. **49**, 1397 (1998).

Autorzy:

Istnienie takich efektów może wyjaśnić rozbieżności w wielkościach czasów życia mierzonych w różnych czasach (np. ^{32}Si, ^{44}Ti, ^{137}Cs).

– może aktywność izotopu zależy od odległości od Słońca, czy jego aktywności.



D. E. Alburger and G. Harbottle, Phys. Rev. C **41**, 2321 (1990).

I. Ahmad et al., Phys. Rev. Lett. **80**, 2550 (1998).

59.2 ± 0.6 yr (1σ error)

^{44}Ti ważny dla datowania meteorytów

Horror dla datowania!