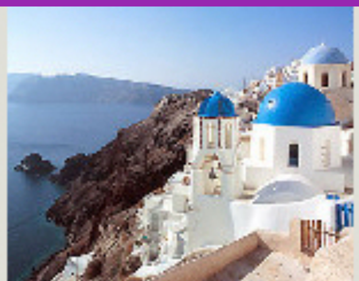
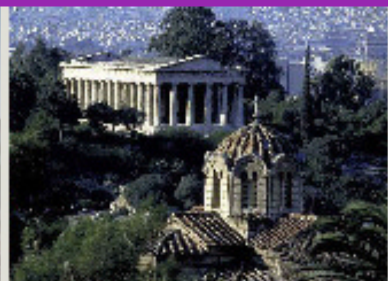
Neutrino 2010
Ateny, 14-19 VI

455 uczestników
w tym 9 z PL

1. Mieszanie ν i oscylacje
2. Mieszanie ν i masy
3. Oddziaływania ν
4. Wiązki i źródła ν
5. Przyszłe detektory i eksperymenty (częściowo)
6. Astrofizyczne i kosmologiczne ν

Tylko sesje plenarne
oraz sesja plakatowa
(P. Mijakowski,
M. Posiadała,
J. Sobczyk)

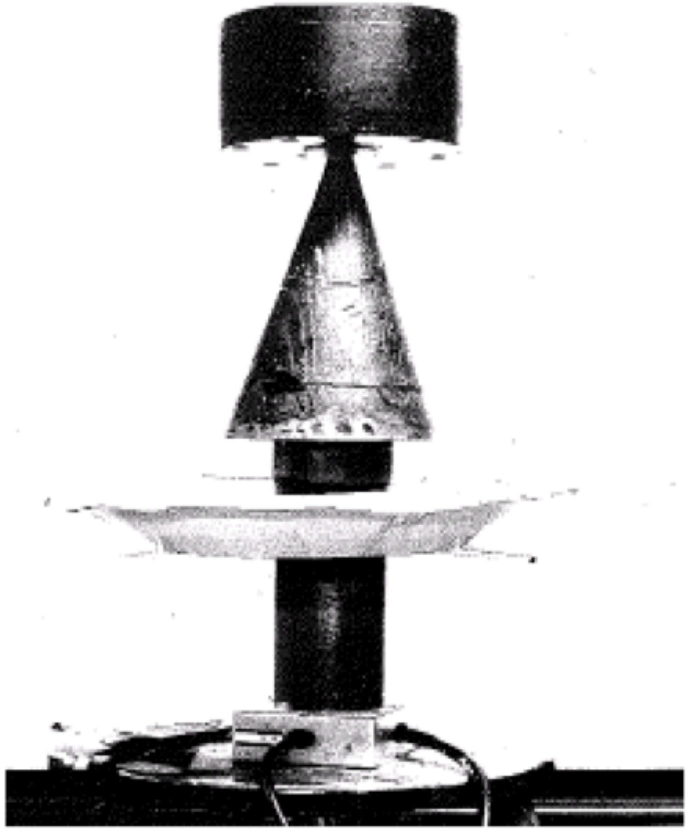



Wybrane tematy

- Oscylacje neutrin słonecznych i reaktorowych (małe δm^2)
  - wyniki globalnej analizy dotychczasowych pomiarów
  - Borexino
- Oscylacje neutrin atmosf. i akceleratorowych (duże Δm^2)
  - MINOS
  - MiniBoone

  } zagadki
- Poszukiwanie ϑ_{13}
  - Wyniki analizy 3-zapachowej dotychczasowych pomiarów
  - Nowe eksperymenty (T2K, Nova, reaktorowe)
- Podsumowania

The Goldhaber-Grodzins-Sunyar Experiment

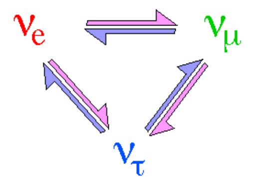


1956

Equipment	2k
3 guys 2 wks	1k
TOTAL	3k

2010

Proj. Mgmt.	500k
Fire suppr.	300k
Hazmat	100k
Training	100k
Equipment	2k
3 guys 2 wks	free
TOTAL	1002k



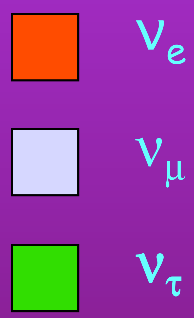
Co już wiemy o neutrinach?

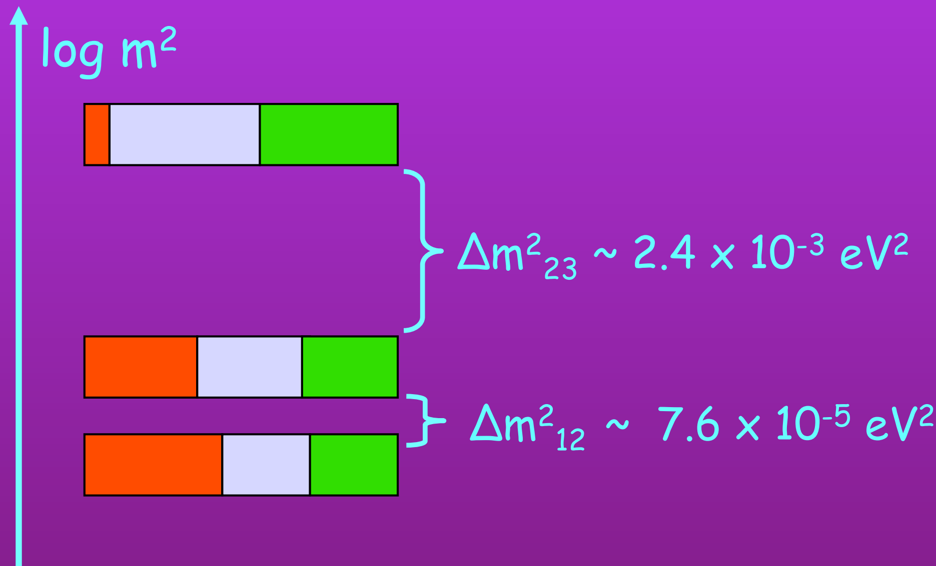
- Neutrina mają masę: $$40\ \text{meV} < \sum_{i=1}^{3} m_i < 2\ \text{eV}$$

→ znaczący wkład do bilansu energii Wszechświata $$\Omega_\nu \geq \sum_{i=1}^{3} m_i / 93h^2 \approx 0.001$$

- Neutrina mieszają się:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$





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 | $0\nu\beta\beta$

$\sin^2 2\vartheta_{23} = 1.02 \pm 0.04 \quad (37^{\circ}\text{-}53^{\circ})$ - 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

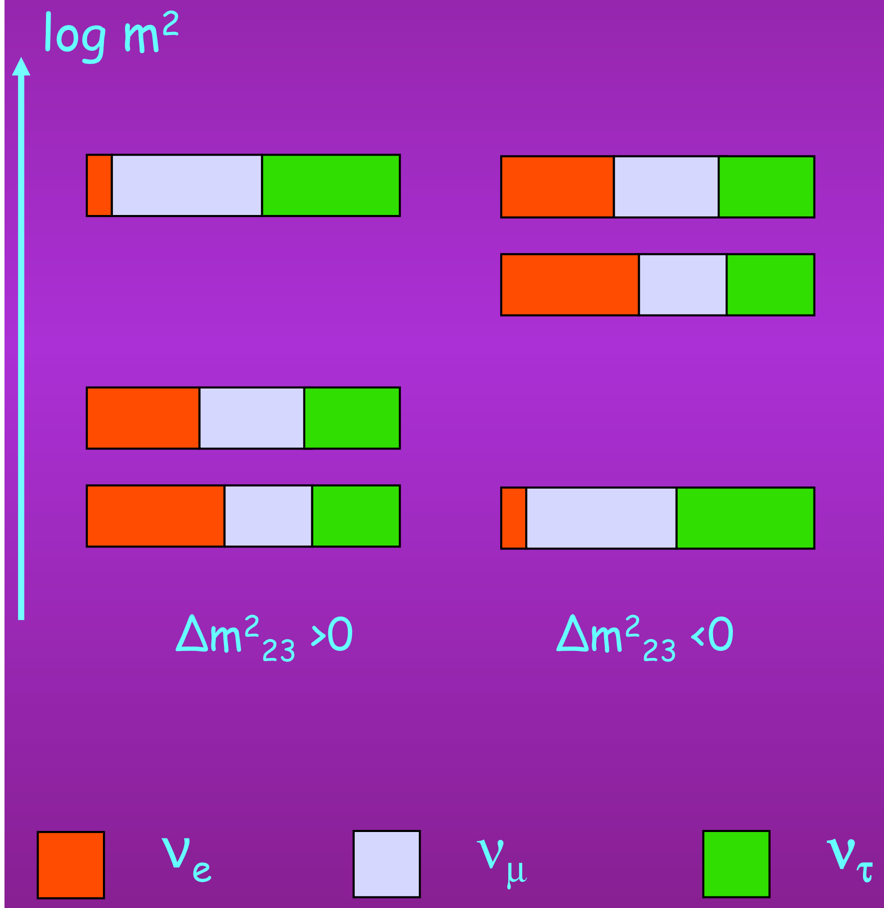
→ ϑ_{13}

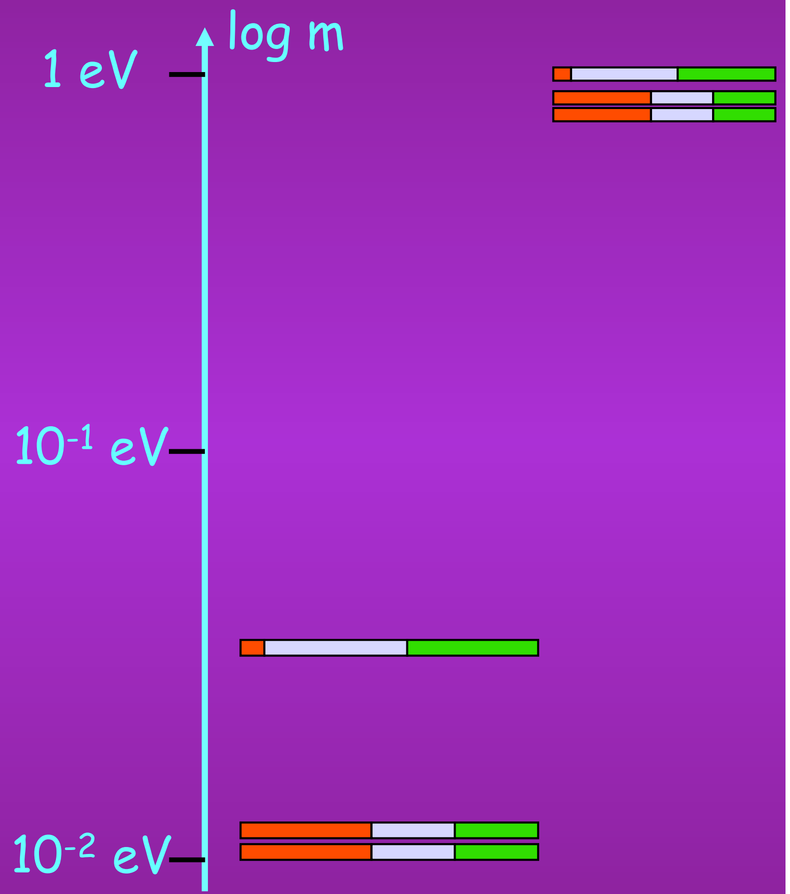
→ δ

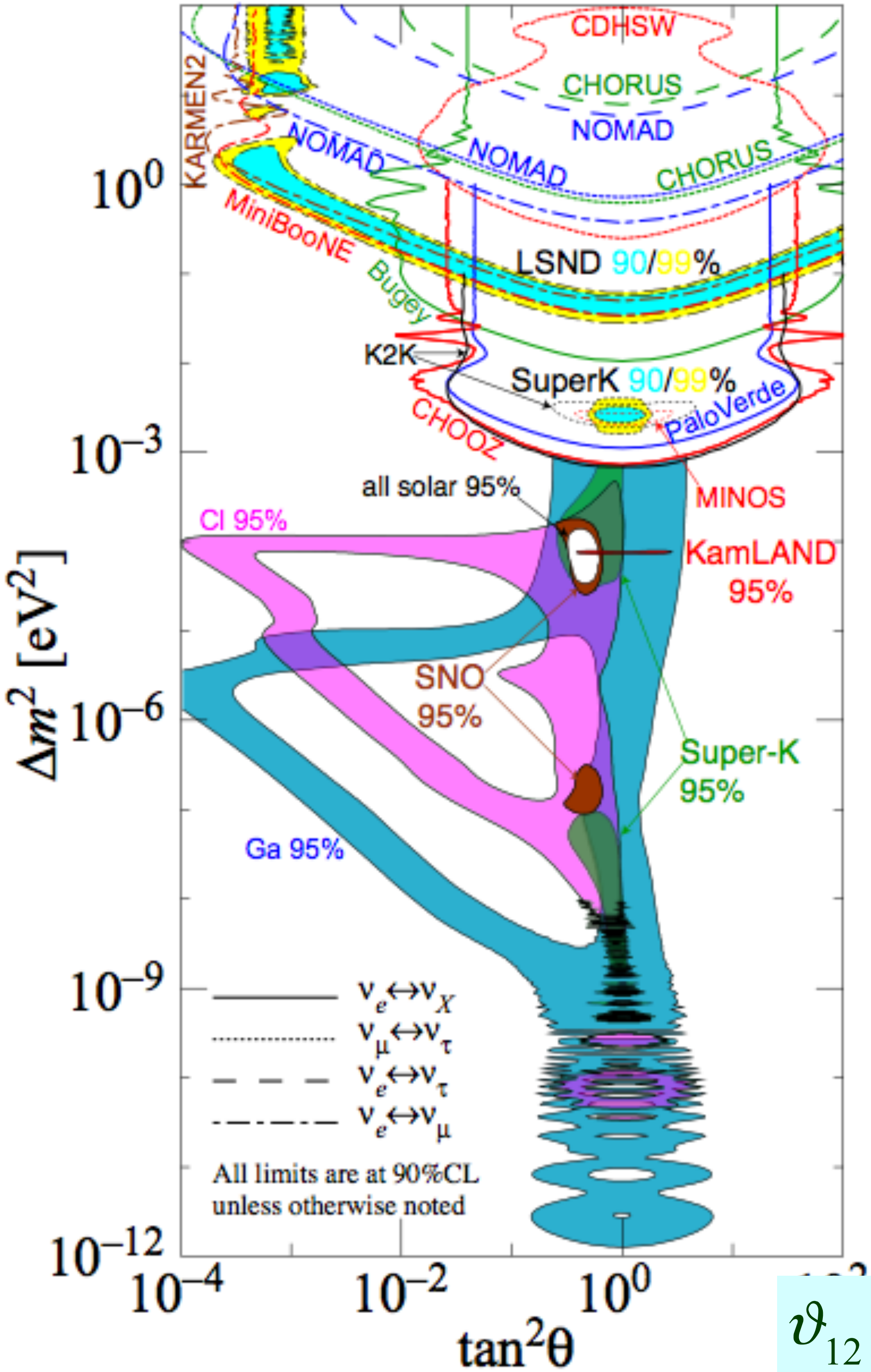
D. Kiełczewska
Nu2010

Jaka jest hierarchia mas?

Jaka skala?







ϑ_{12} or ϑ_{23}

Nie stwierdzono oscylacji - za małe L/E

Eksperymenty neutrinowe pierwszej generacji

„atmosf."

„słoneczne"

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

Particle Data Group, 2008

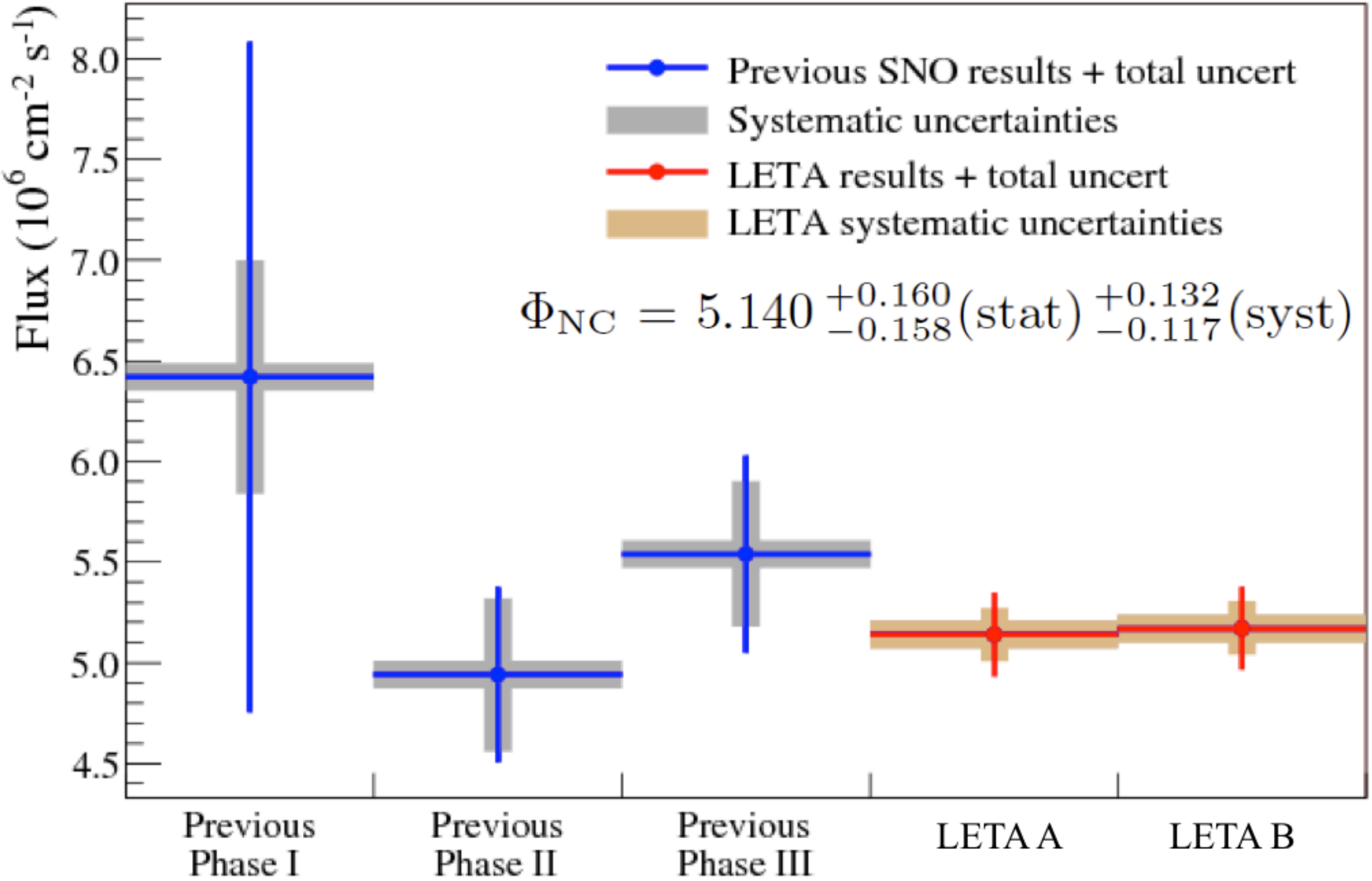
http://pdg.lbl.gov/2008/reviews/rpp2008-rev-neutrino-mixing.pdf/

Dotychczasowe pomiary oscylacji

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

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

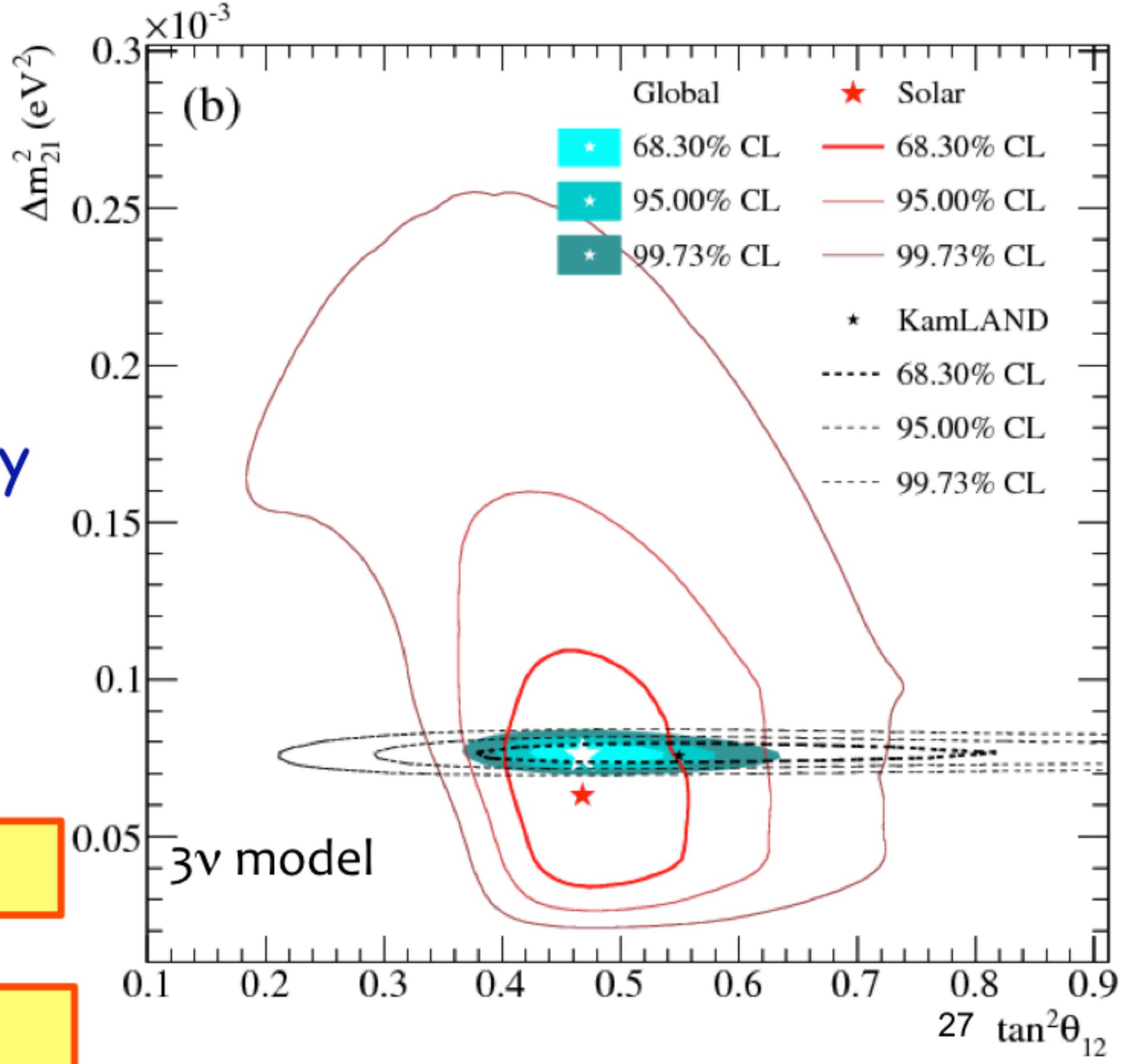
SNO ^{8}B Flux Result



Solar + KamLAND 3-flavor Overlay

LETA paper 2009:
LETA joint-phase fit
+ Phase III
+ all solar expts
+ KamLAND

3-flavor fit/overlay
-> Pointed out by
many authors

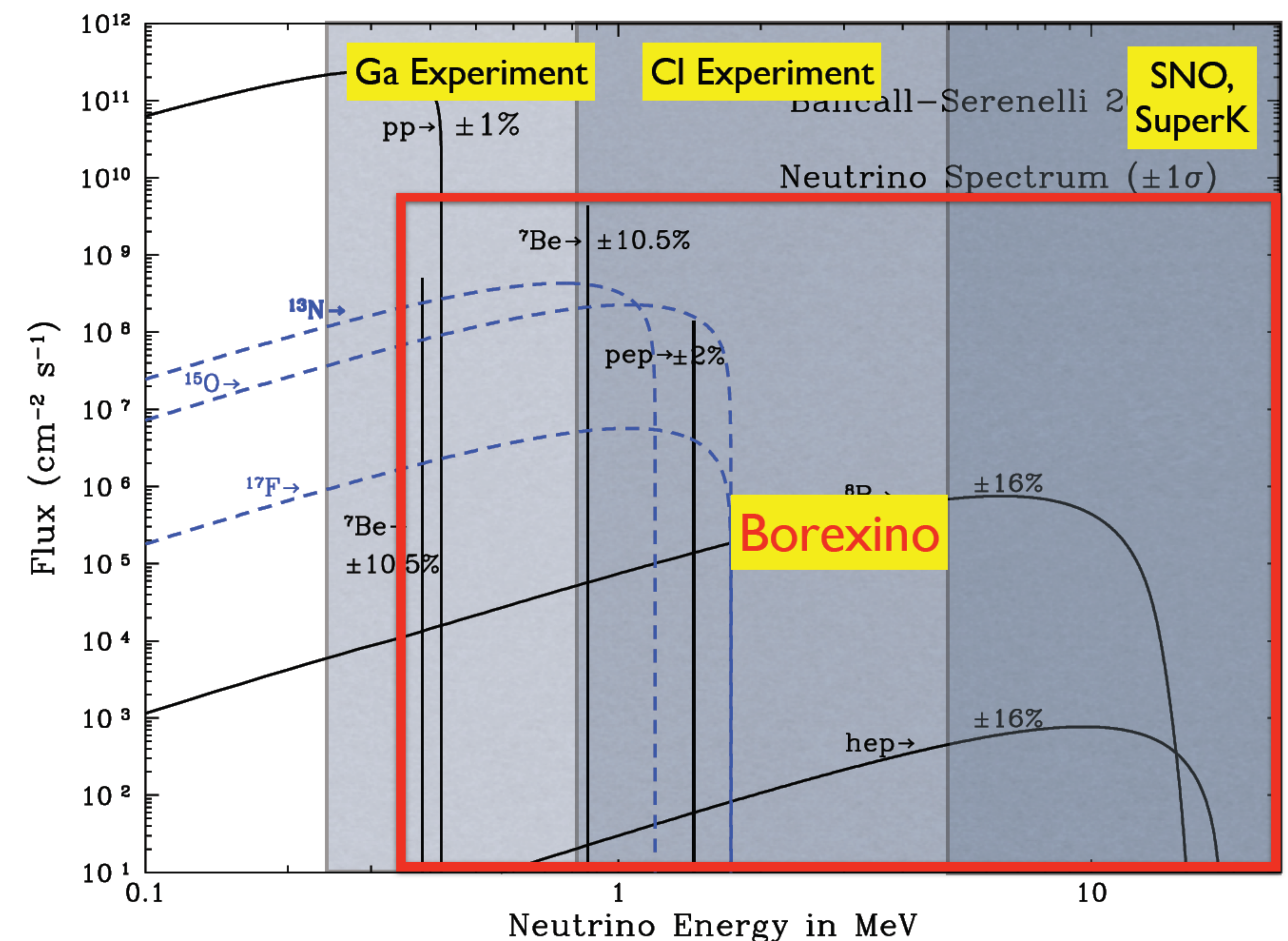


Best-fit:

$\sin^2\theta_{13}=2.00^{+2.09}_{-1.63}\times 10^{-2}$

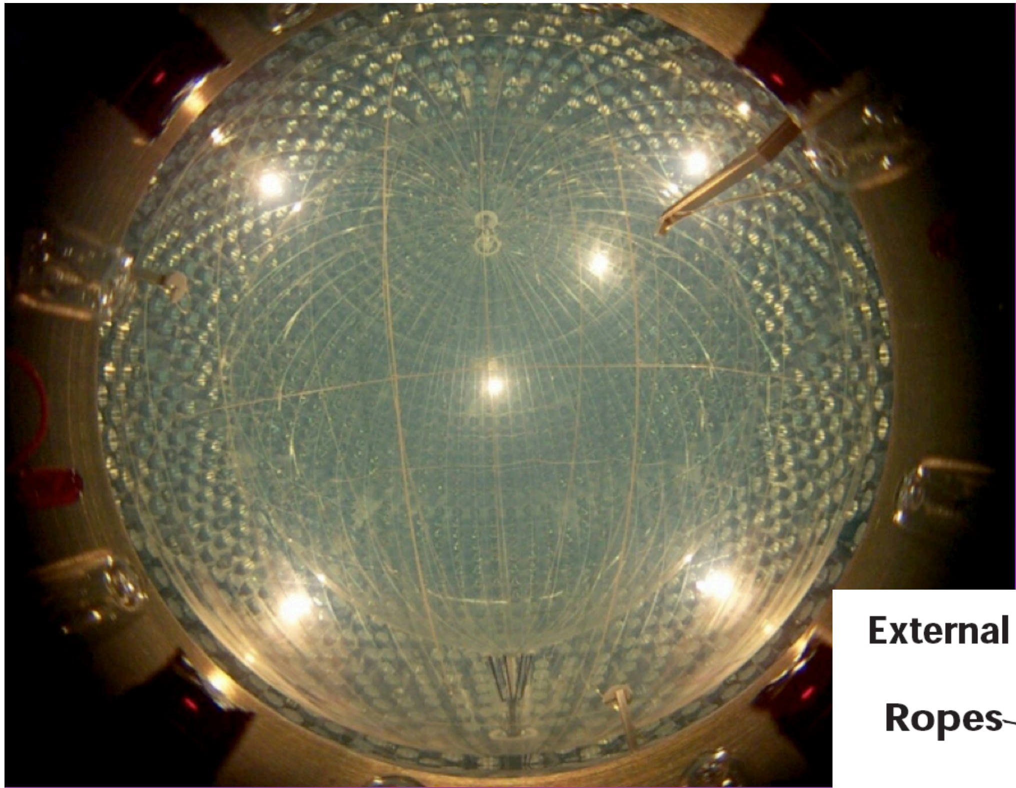
$\sin^2\theta_{13} < 0.057$ (95% C.L.)

Borexino probes low energies

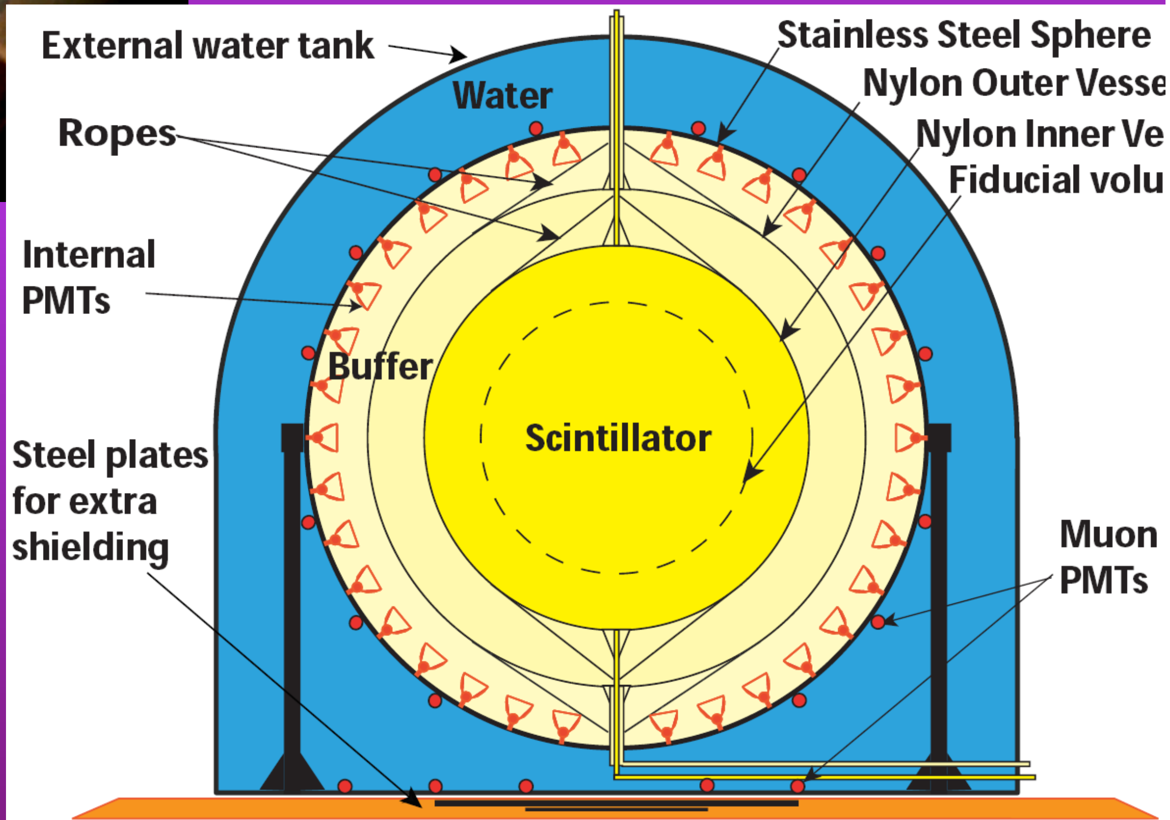


- real time
- energy reconstruction

Borexino detector



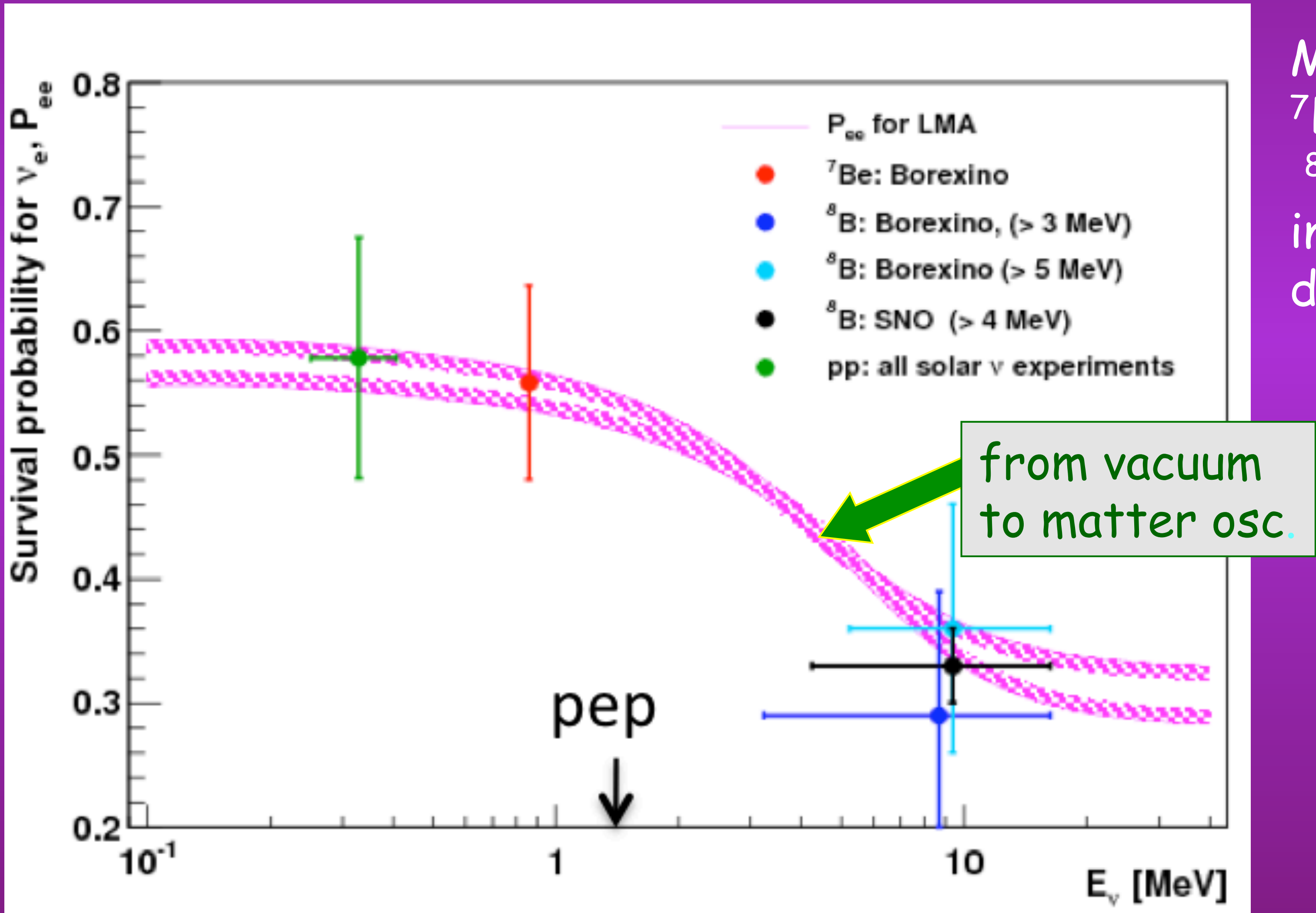
- 278 tons of scintillator
- 4.25m radius



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

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

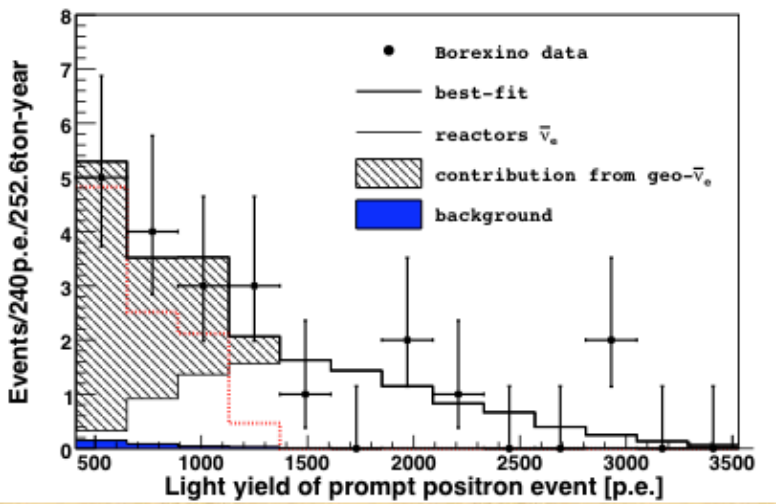
Borexino (487.7 days) – solar neutrino survival probability



Measurement of ^{7}Be (vac.) and ^{8}B (matter) in the same detector

Borexino antineutrinos <3 MeV

Geo-neutrino Results



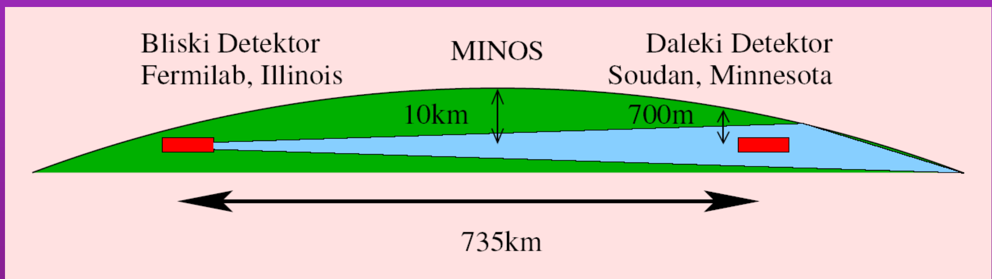
Source	Geo–$\bar{\nu}_e$ Rate [events/(100 ton·yr)]
Borexino	$3.9^{+1.6}_{-1.3}$
BSE [16]	$2.5^{+0.3}_{-0.5}$
BSE [30]	2.5 ± 0.2
BSE [5]	3.6
Max. Radiogenic Earth	3.9
Min. Radiogenic Earth	1.6

- About 10 geo-events seen in exposure of 252.6 ton-yr.
- Background is very low.
- Reactor rate requires neutrino oscillations.
  - Non-oscillations ruled out with 99.6% CL.
- Result consistent with Bulk Silicate Earth model calculations.
- Error consistent with Radioactivity could produce all internal heat of earth.

MINOS
(Main Injector Neutrino Oscillation Search)

K. Grzelak

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

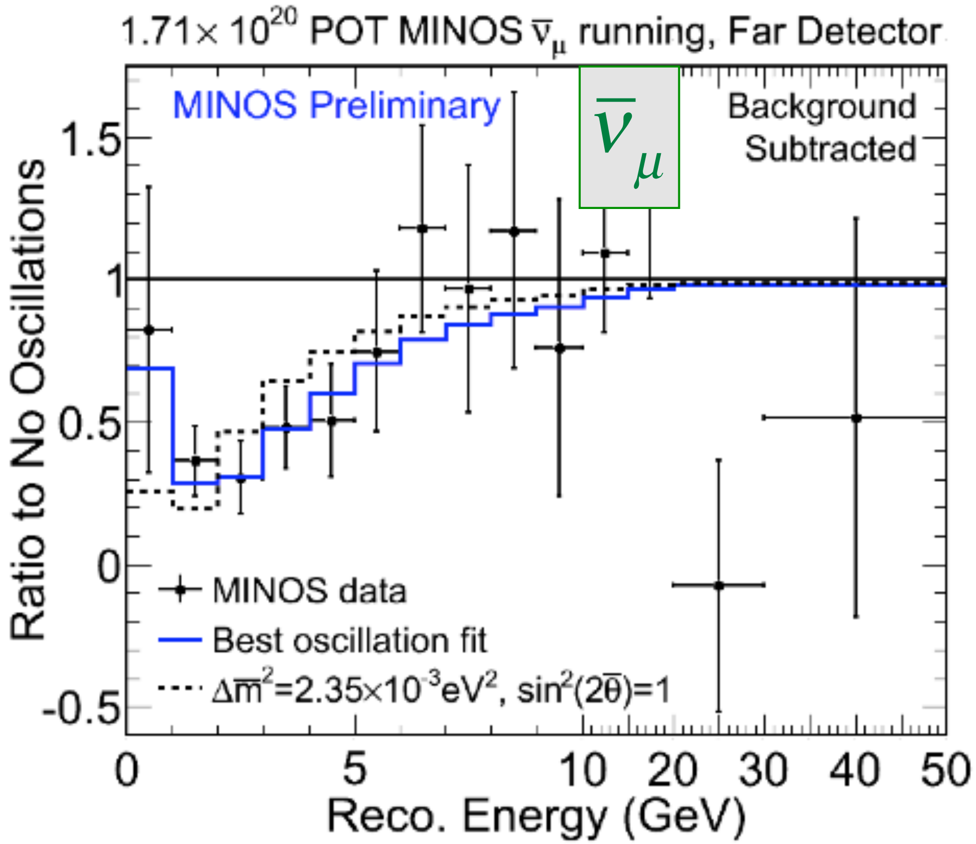


Near detector

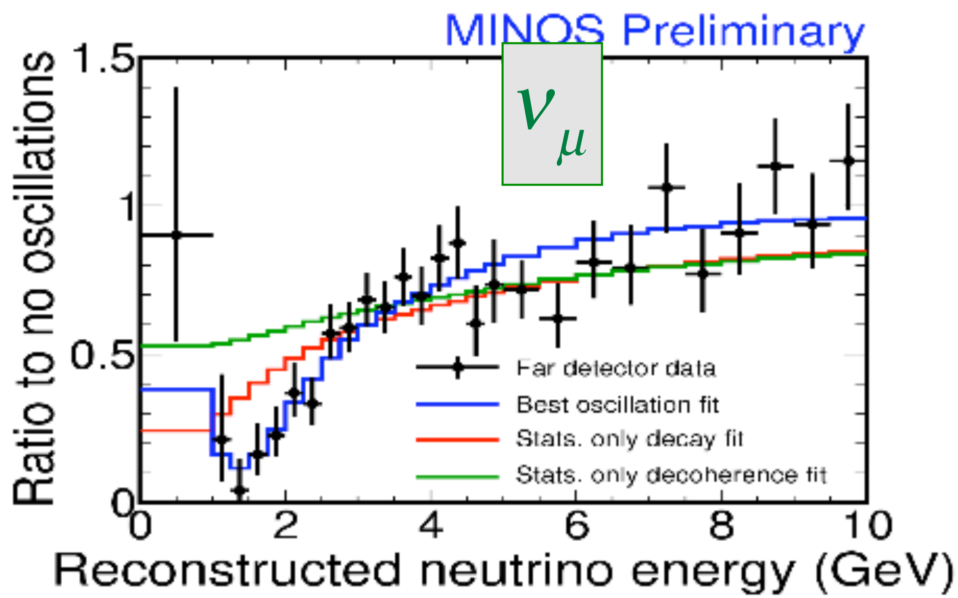
Far detector

Far Detector

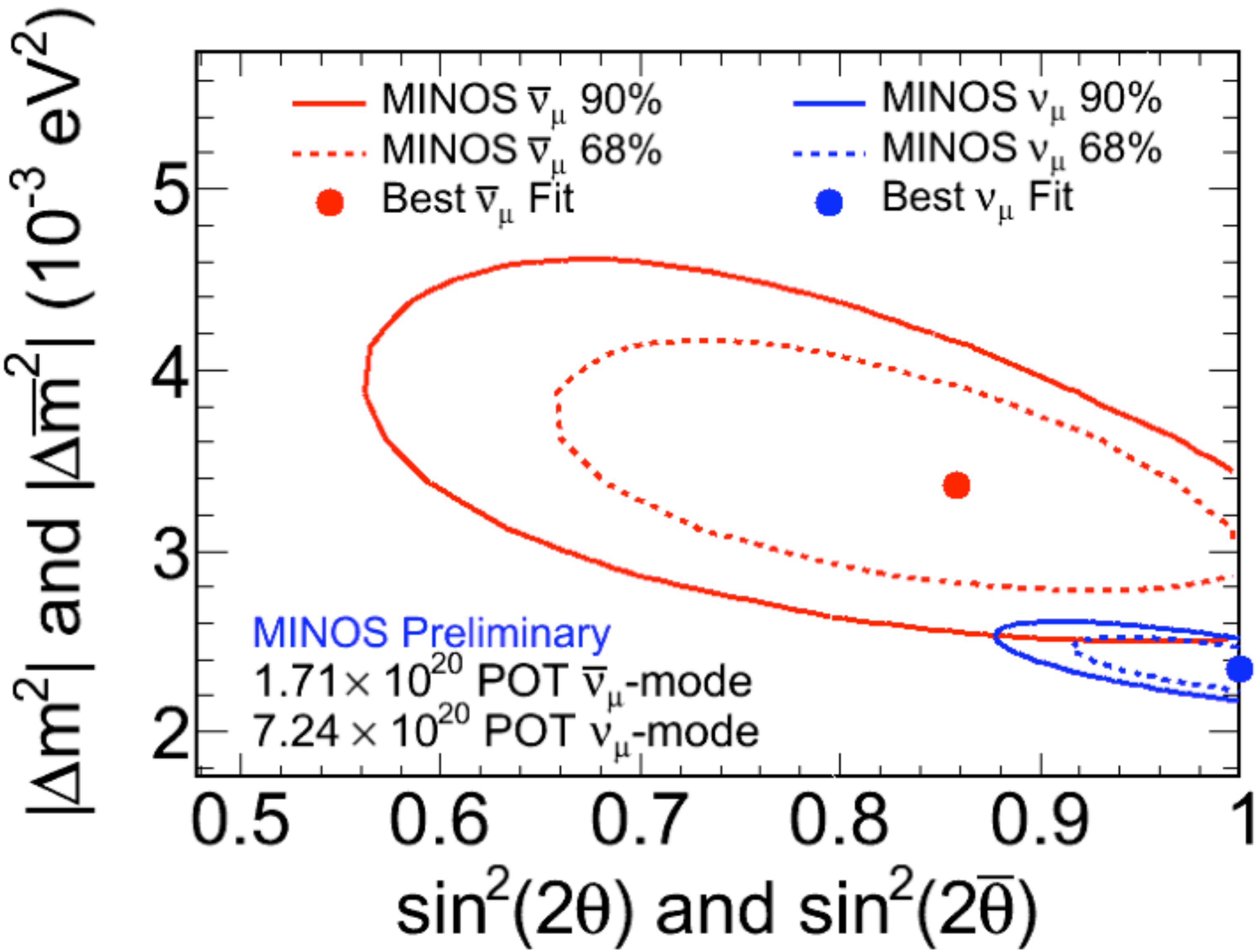
MINOS ν_μ vs $\bar{\nu}_\mu$ disappearance



7.2x10^20 POT



MINOS ν_μ vs $\bar{\nu}_\mu$ disappearance



MINOS $\nu_\mu \rightarrow \nu_e$

P. Vahle, NU2010

ν_e Appearance Results

for $\delta_{CP} = 0, \sin^2(2\theta_{23}) = 1,$

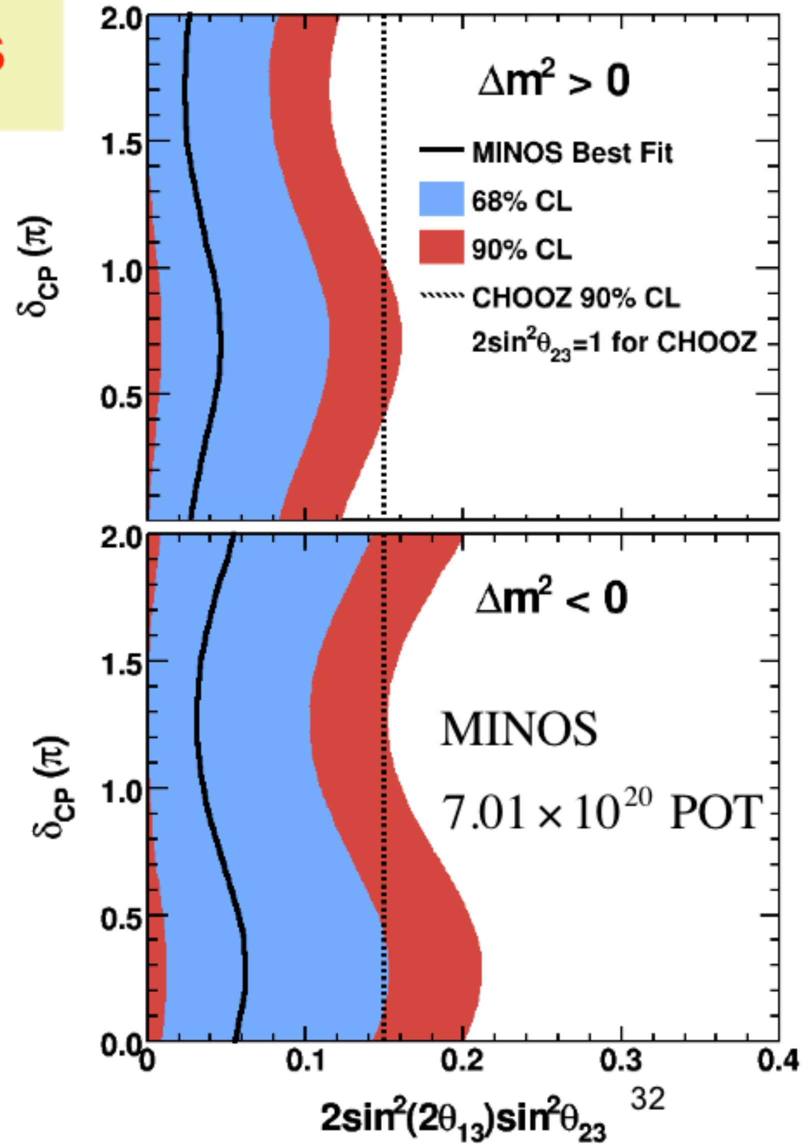
$|\Delta m^2_{32}| = 2.43 \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2(2\theta_{13}) < 0.12$ normal hierarchy

$\sin^2(2\theta_{13}) < 0.20$ inverted hierarchy

at 90% C.L.

arXiv:1006.0996v1 [hep-ex]



Summary

- With $7\text{x}10^{20}$ POT of neutrino beam, MINOS finds
  - muon-neutrinos disappear

$$|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\text{eV}^2,$$
$$\sin^2(2\theta) > 0.91\ (90\%\ \text{C.L.})$$

  - NC event rate is not diminished

$$f_s < 0.22\,(0.40)\ \text{at}\ 90\%\ \text{C.L.}$$

  - electron-neutrino appearance is limited

$$\sin^2(2\theta_{13}) < 0.12\ (0.20)\ \text{at}\ 90\%\ \text{C.L.}$$

- With $1.71\text{x}10^{20}$ POT of anti-neutrino beam
  - muon anti-neutrinos also disappear with

$$|\overline{\Delta m^2}| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\,\text{eV}^2,$$
$$\sin^2(2\overline{\theta}) = 0.86 \pm 0.11$$

  - we look forward to more anti-neutrino beam!

MINOS ν_μ vs $\bar{\nu}_\mu$ disappearance

What can this be?

- CPT violation? Probably not.
- Just statistics? Combining the data will probably produce a decent χ^2. But that is a weak test. Is there a parametric hypothesis?
- *"Within standard neutrino mixing, disappearance probabilities for neutrinos and antineutrinos are identical, by CPT conservation!"* (G. Karagiorgi). However, not true when matter is present.
- Could this mean that θ_{13} is showing up??

3-flavor, with matter, expanded

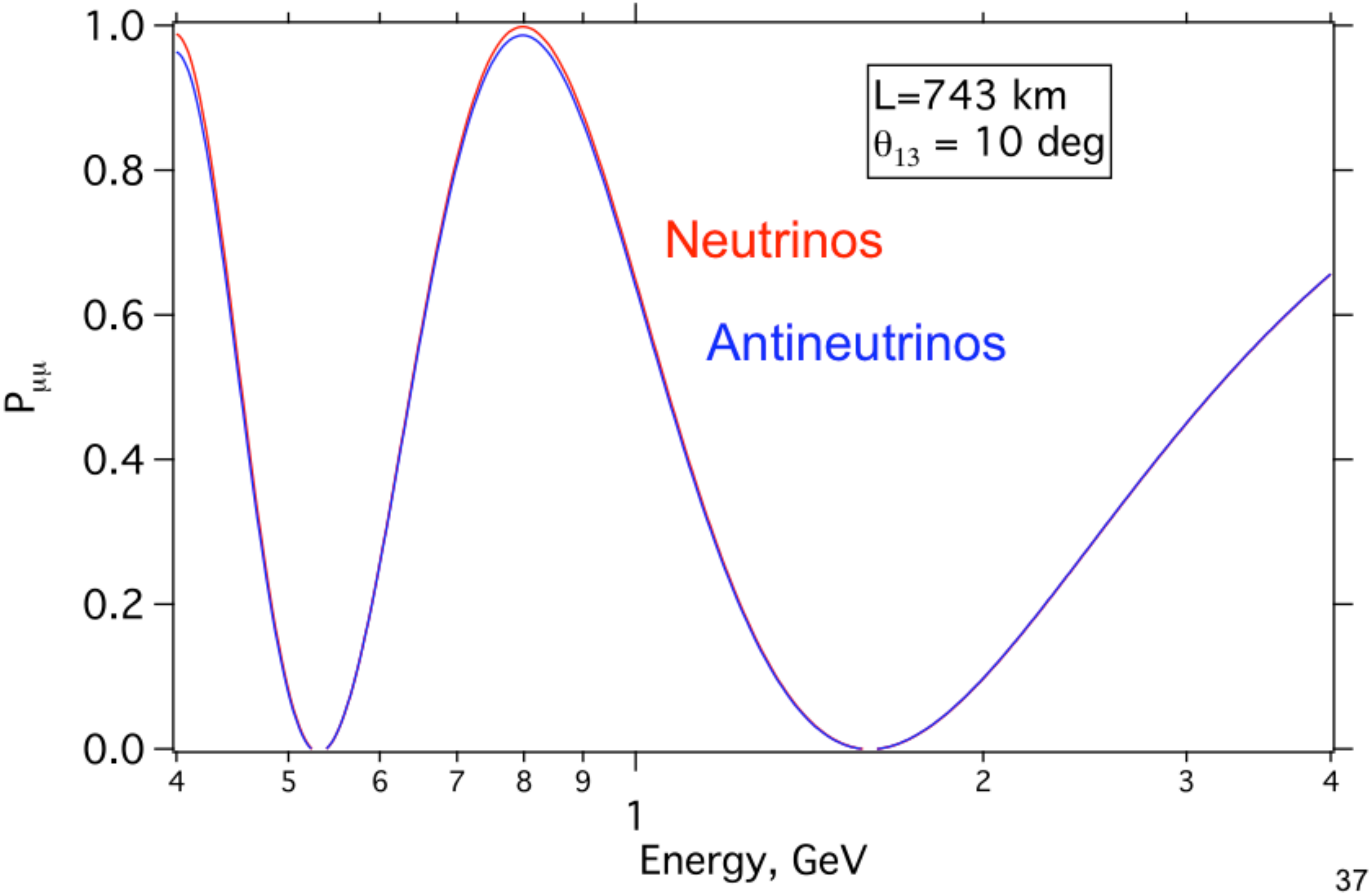
$$
\begin{aligned}
P_{\mu\mu} = 1 &- \sin^2 2\theta_{23} \sin^2 \Delta + \alpha\, c_{12}^2 \sin^2 2\theta_{23}\, \Delta \sin 2\Delta - \\
&- \alpha^2 \sin^2 2\theta_{12}\, c_{23}^2 \frac{\sin^2 A\Delta}{A^2} - \alpha^2 c_{12}^4 \sin^2 2\theta_{23}\, \Delta^2 \cos 2\Delta + \\
&+ \frac{1}{2A} \alpha^2 \sin^2 2\theta_{12} \sin^2 2\theta_{23} \left(\sin\Delta \frac{\sin A\Delta}{A} \cos(A-1)\Delta - \frac{\Delta}{2} \sin 2\Delta \right) - \\
&- 4\, s_{13}^2\, s_{23}^2 \frac{\sin^2 (A-1)\Delta}{(A-1)^2} - \\
&- \frac{2}{A-1} s_{13}^2 \sin^2 2\theta_{23} \left(\sin\Delta \cos A\Delta \frac{\sin(A-1)\Delta}{A-1} - \frac{A}{2}\Delta \sin 2\Delta \right) - \\
&- 2\,\alpha\, s_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\delta_{CP} \cos\Delta \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} + \\
&+ \frac{2}{A-1} \alpha\, s_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos 2\theta_{23} \cos\delta_{CP} \sin\Delta \times \\
&\times \left(A \sin\Delta - \frac{\sin A\Delta}{A} \cos(A-1)\Delta \right),
\end{aligned}
$$

$$\alpha \equiv \frac{\Delta m_{12}^2}{\Delta m_{13}^2} \qquad \Delta \equiv \frac{\Delta m_{13}^2}{4E}$$

$$A \equiv \frac{2EV}{\Delta m_{13}^2} \qquad V = \pm\sqrt{2} G_F N_e$$

E. Akhmedov et al. JHEP04 (2004) 078

No difference apparent here



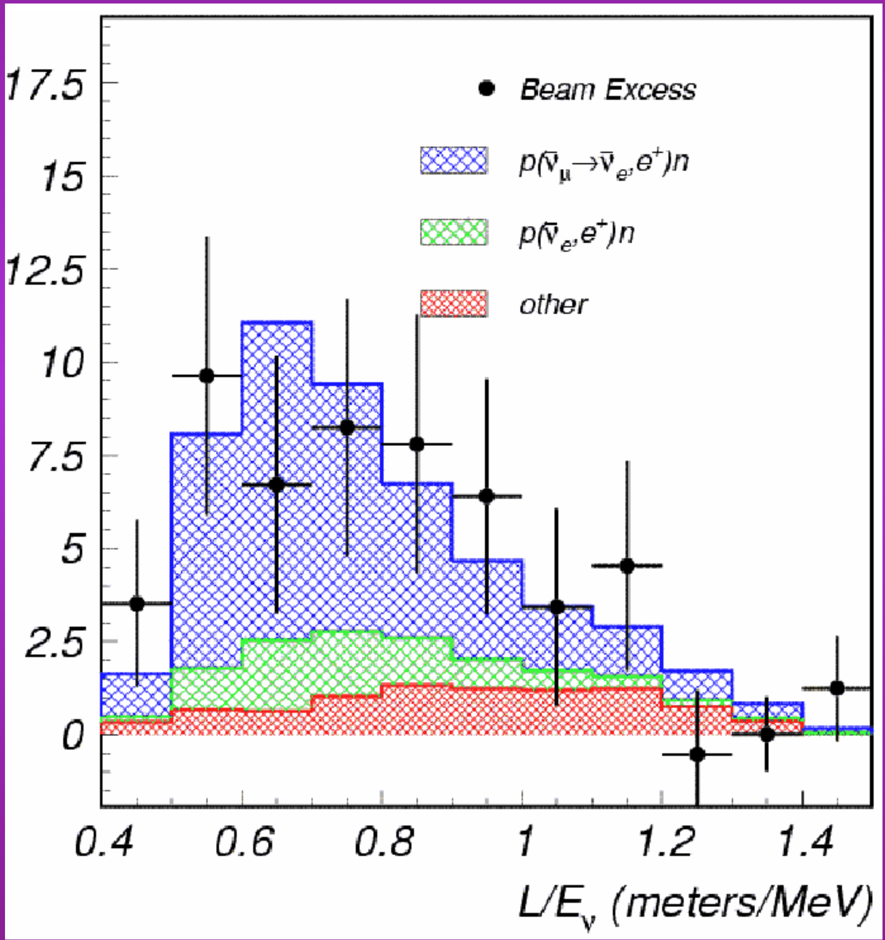
37

(But don't believe a calculation done the day before!)

Zagadka LSND - MiniBoone

Czy poza trzema neutrinami MS są jeszcze neutrina sterylne ??

LSND oscillations ?? $\bar{\nu}_\mu \to \bar{\nu}_e$



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

Excess: 87.9 ± 22.4 ± 6.0 (3.8σ)

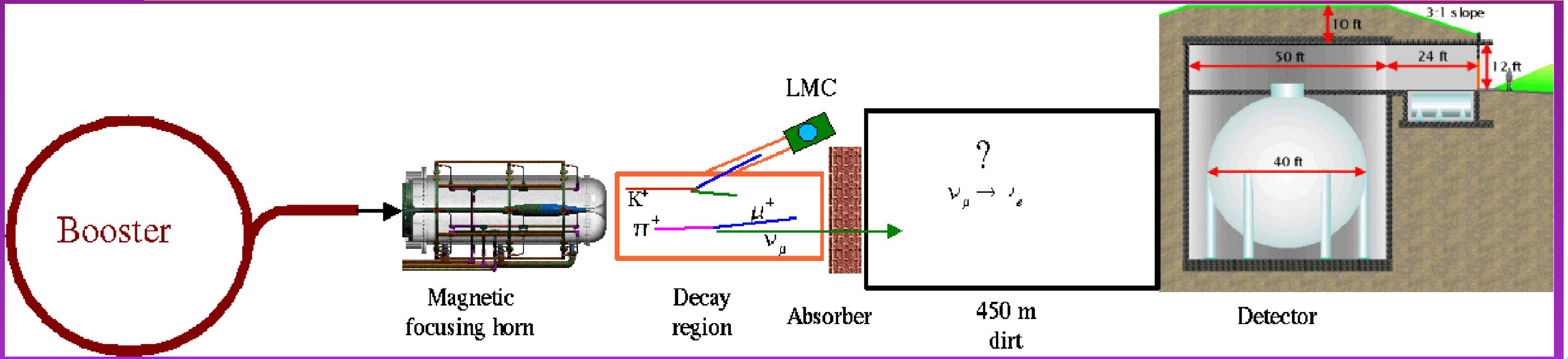
A less significant excess of ν_e was also found in ν_μ beam.

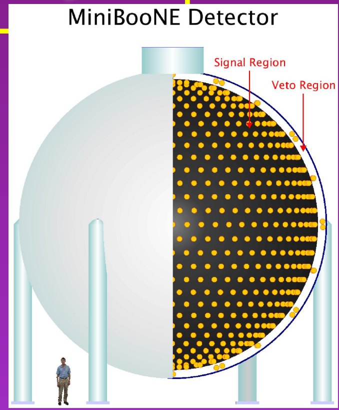
To check LSND one should preserve L/D:

LSND 0.03 km/0.05 GeV

MiniBoone 0.5 km/0.8 GeV

MiniBooNE (2002~) (Fermilab)

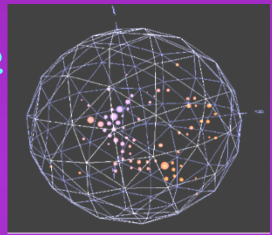




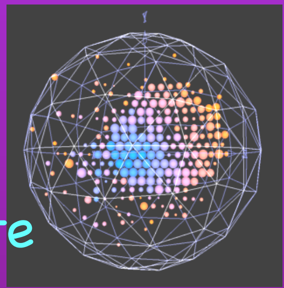
To check $\nu_\mu \to \nu_e$ at $\Delta m^2 \sim 1eV^2$ (LSND)

- 8 GeV proton beam (Be target)
  - E_ν~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.

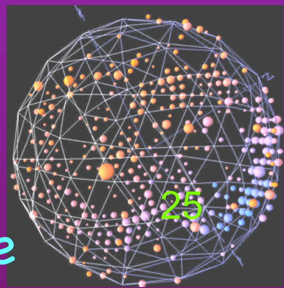
Michel e from μ decay



ν_e candidate



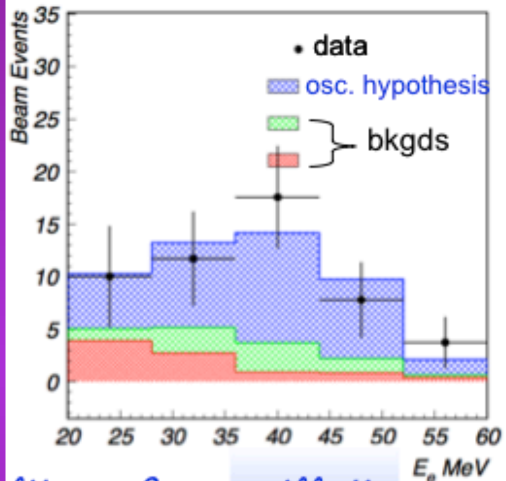
π^0 candidate



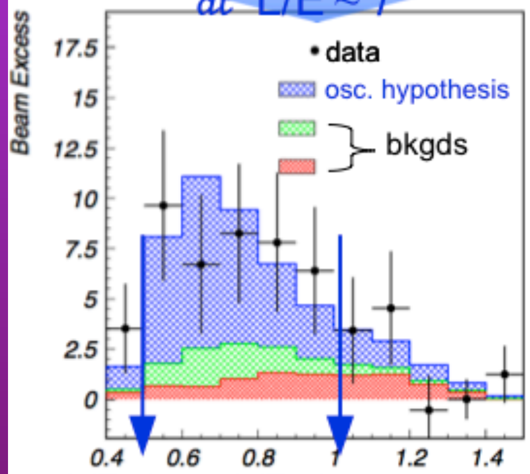
Excess signatures from LSND and MiniBooNE

LSND $\bar{\nu}_\mu$

3.8 σ excess of $\bar{\nu}_e$
in a $\bar{\nu}_\mu$-dominated beam
from μ^+ decay at rest

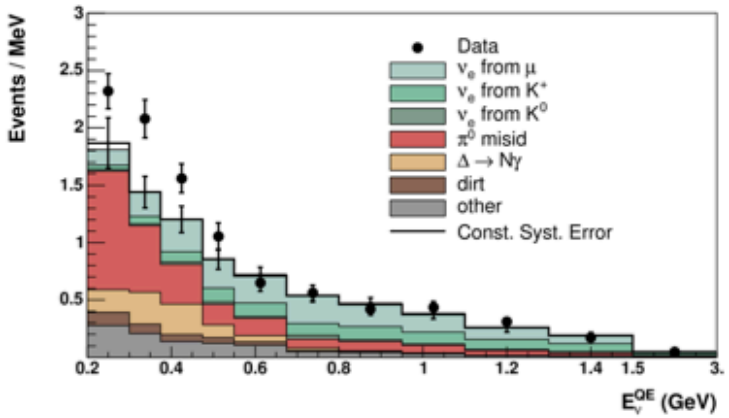


fits a 2-ν oscillation interpretation at L/E ~ 1

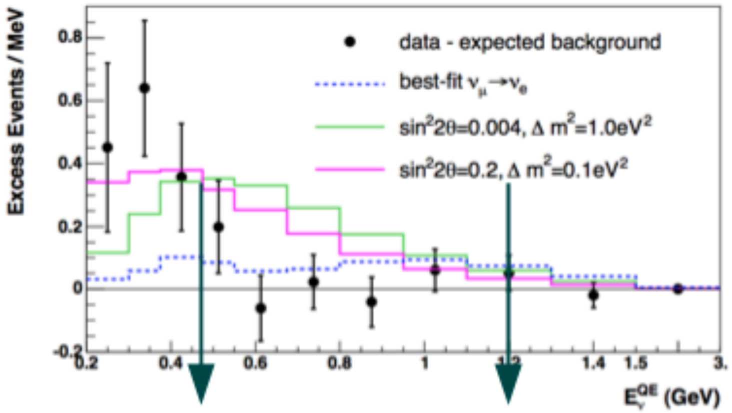


MiniBooNE neutrino mode ν_μ

3.0 σ excess of ν_e
in a ν_μ-dominated beam
from π^+ decay in flight



shows up at a slightly different L/E *compared to* LSND



Rozkłady energii dla przyp. typu „e-like"
dla hipotezy:

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

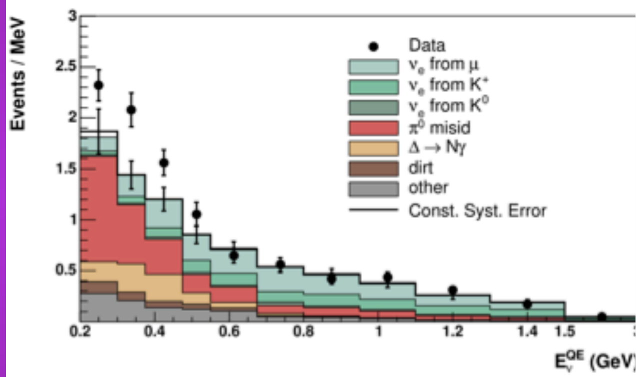
„Official oscillation region": >475 MeV

G. Karagiorgi, NU2010

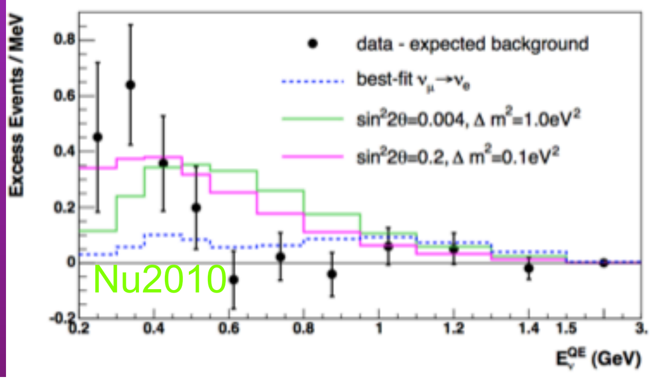
MiniBoone - wiązka $\bar{\nu}_\mu$

MiniBooNE neutrino mode
3.0 σ excess of ν_e
in a ν_μ-dominated beam
from π^+ decay in flight

ν_μ

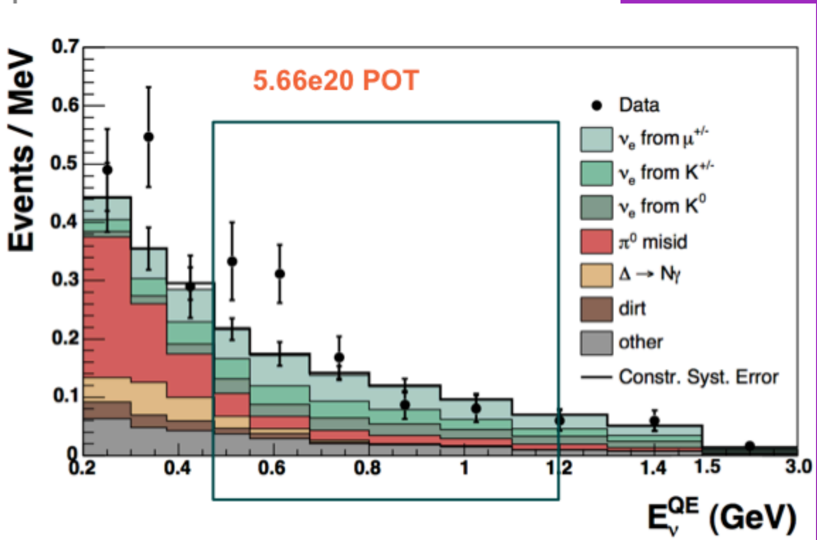


and is too sharply peaked at low energy to accommodate 2-ν oscillation interpretation



MiniBooNE antineutrino mode
no significant* excess of $\bar{\nu}_e$
in a $\bar{\nu}_\mu$-dominated beam
from π^- decay in flight (*low stats)

$\bar{\nu}_\mu$



and no significant excess at low energy

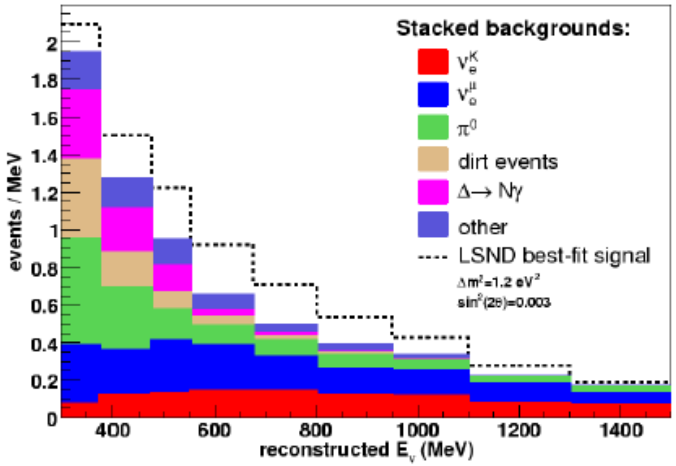
Nu2010

7

G. Karagiorgi, NU2010

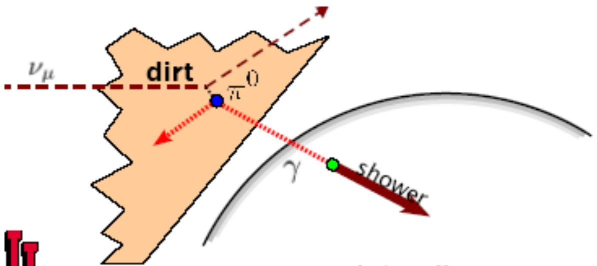
MiniBoone - backgrounds

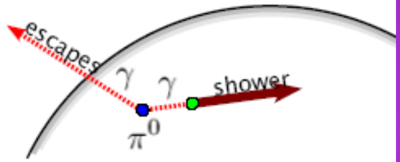
TBL Analysis: Expected event totals



475 MeV - 1250 MeV	
ν_e^K	94
ν_e^μ	132
π^0	62
dirt	17
Δ→Nγ	20
other	33
total	358

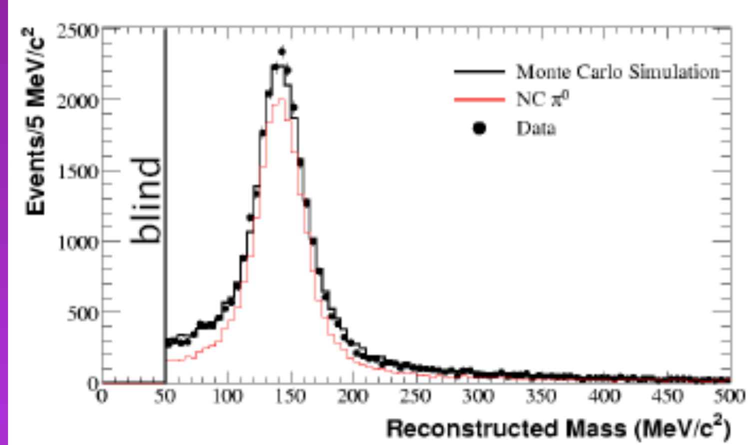
LSND best-fit $\nu_\mu \rightarrow \nu_e$ 126



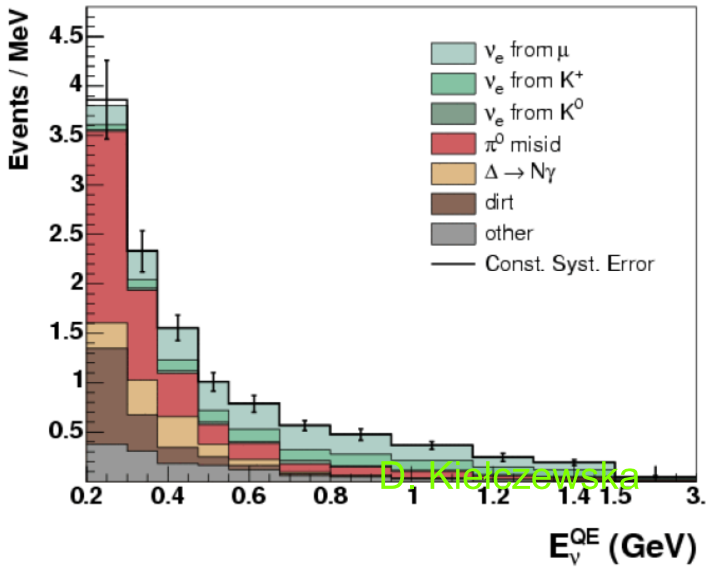


Chris Polly, I

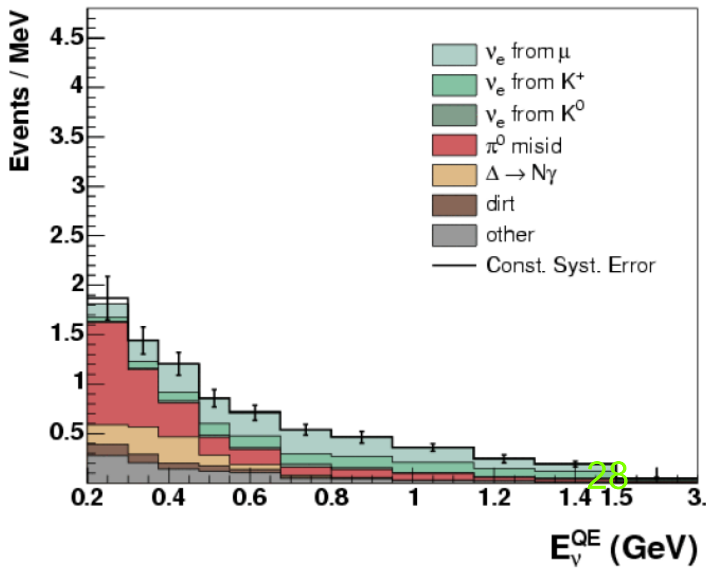
Separating e from π^0



No DIRT cuts



With DIRT Cuts

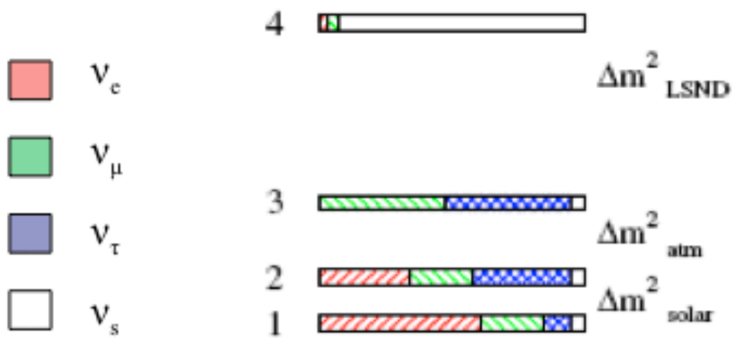


Light sterile neutrino oscillations: Are they still viable?

G. Karagiorgi
NU2010

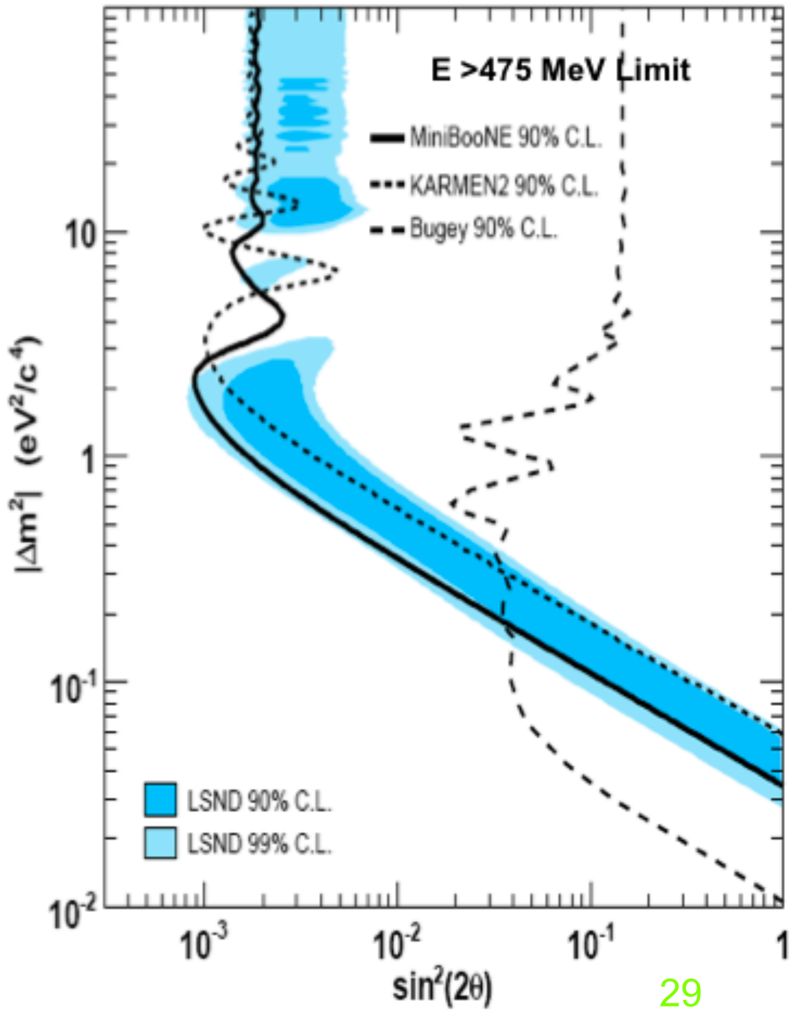
MiniBooNE's lack of excess above 475 MeV in **neutrino mode** rules out:

3 active + 1 sterile neutrinos (3+1)



approximated as two-neutrino oscillations →

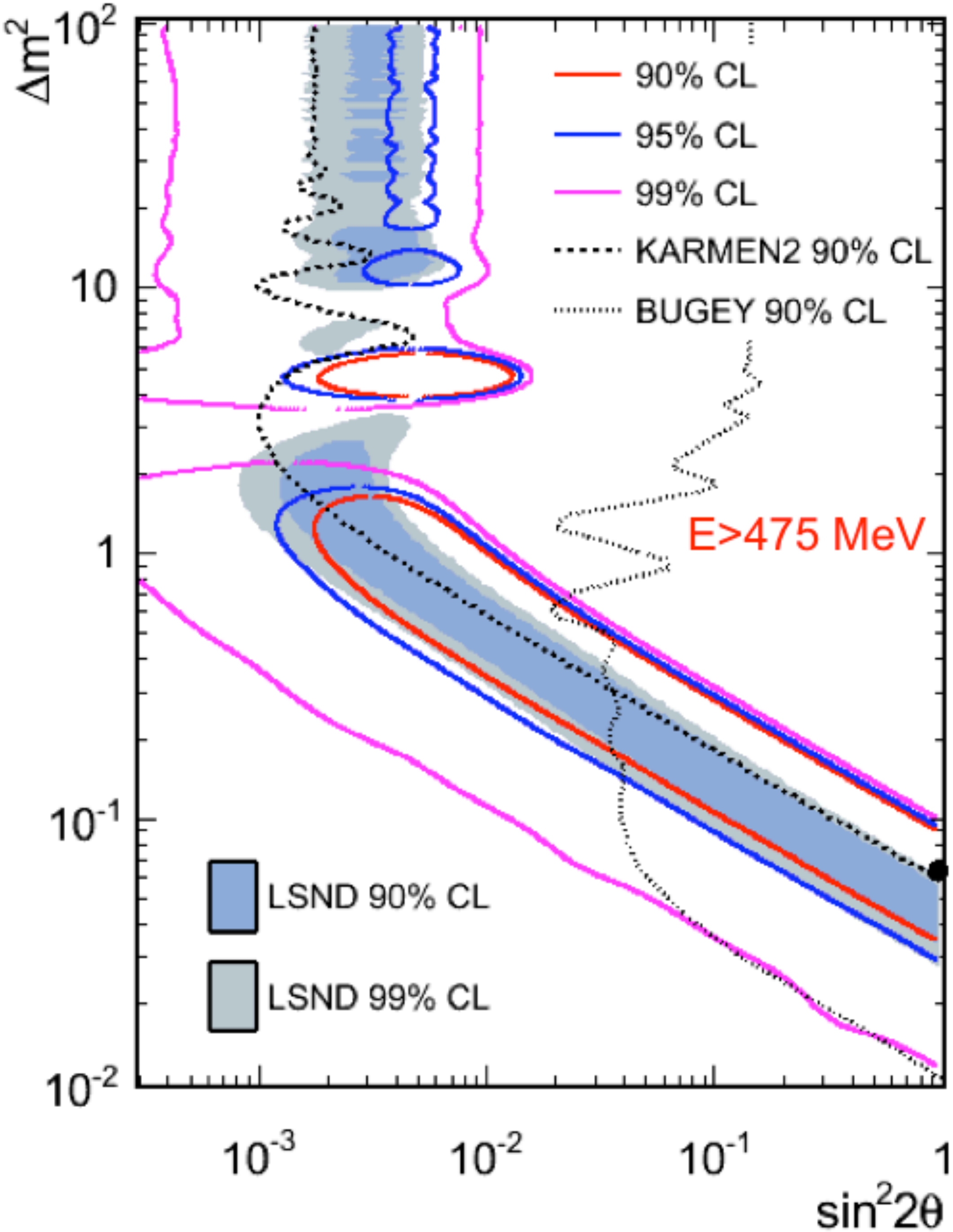
$$P(\nu_\mu \rightarrow \nu_e) = \underbrace{\sin^2 2\theta}_{4\,|U_{e4}|^2\,|U_{\mu 4}|^2} \sin^2(1.27\, \underbrace{\Delta m^2}_{\Delta m^2_{41} \sim \Delta m^2_{LSND}}\, L[m]/E[MeV])$$



(implying neutrino and antineutrino oscillation probabilities must be identical)

Updated Antineutrino mode MB results for E>475 MeV
(official oscillation region)

- Results for **5.66E20 POT**
- Maximum likelihood fit.
- Null excluded at 99.4% with respect to the two neutrino oscillation fit.
- Best Fit Point
  $(\Delta m^2, \sin^2 2\theta)$ =
  (0.064 eV^2, 0.96)
  χ^2/NDF= 16.4/12.6
  $P(\chi^2)$= 20.5%
- Results to be published.



Global fits to sterile neutrino oscillations: (3+1)

G. Karagiorgi
NU2010

Status of (3+1) sterile neutrino oscillation hypothesis:

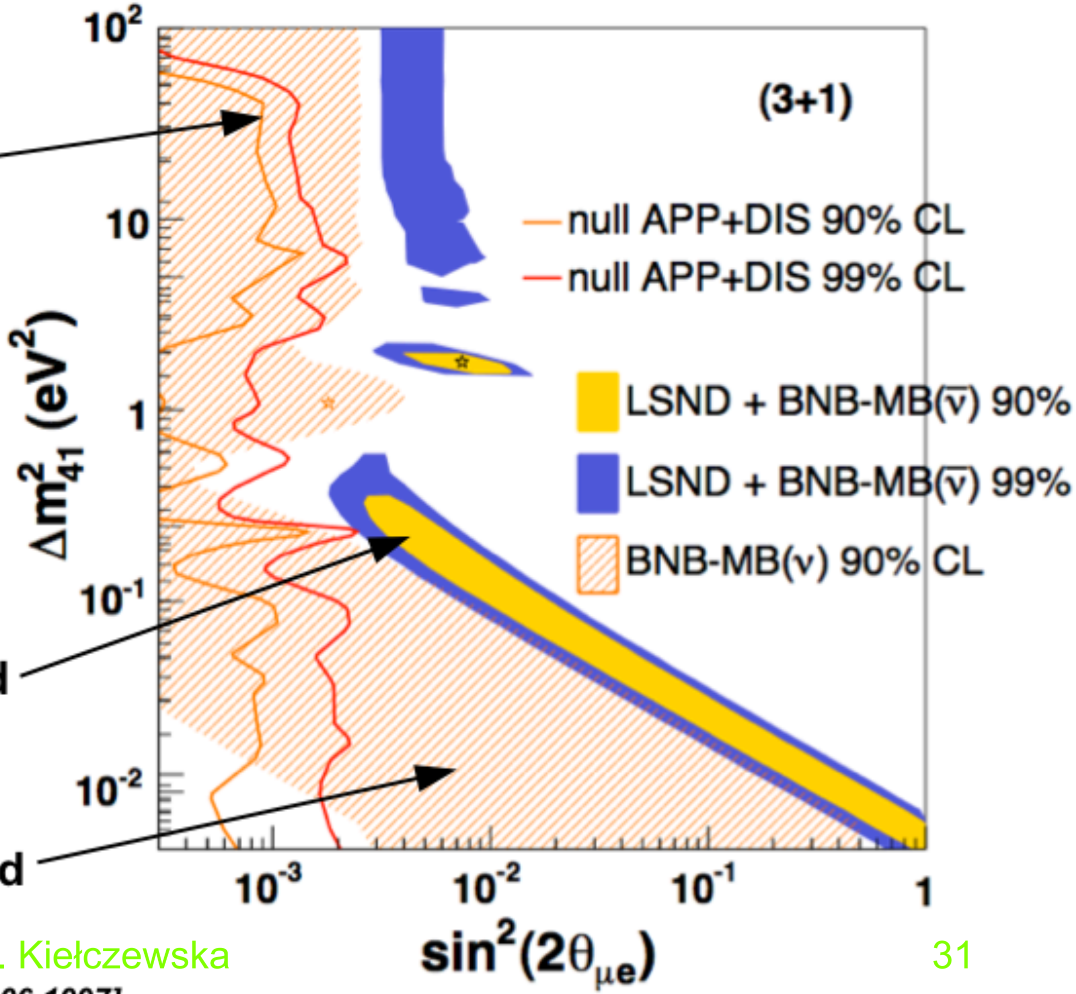
All short-baseline and atmospheric experimental results are highly incompatible: 0.11%

Combined **exclusion limits from null** atmospheric ν_μ disappearance and null short-baseline experiments:

- Bugey and Chooz: $\bar{\nu}_e$ disappearance
- CCFR, CDHS: ν_μ disappearance
- NOMAD, NuMI-MiniBooNE $\nu_\mu \rightarrow \nu_e$ appearance
- KARMEN: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance

Joint **LSND+MiniBooNE($\bar{\nu}$) allowed**

MiniBooNE(ν) allowed



Results based on analysis of PRD 80,073001 (2009) [arXiv:0906.1997]

Interpretacja wyników MiniBoone

Implications of new antineutrino results from MiniBooNE

Preliminary

New antineutrino results from MiniBooNE support conclusions in previous sterile neutrino fits:

In a (3+1) fit, antineutrino experiments are still compatible at 20% (from 30%), and still strongly exclude the no oscillations hypothesis.

Compatibility among **all datasets (SBL+atm)** decreases further:

0.11% → **0.04%**	in a (3+1) hypothesis
7% → **3%**	in a (3+2) CPV hypothesis

G. Karagiorgi
NU2010

MiniBooNE's summary

- The MiniBooNE ν_e and $\bar{\nu}_e$ appearance picture starting to emerge is the following:
  1) **Neutrino Mode**:
     a) E < 475 MeV: An unexplained 3σ electron-like excess.
     b) E > 475 MeV: A two neutrino fit is inconsistent with LSND at the 90% CL.
  2) **Anti-neutrino Mode**:
     a) E < 475 MeV: A small 1.3σ electron-like excess.
     b) E > 475 MeV: An excess that is 3.0% consistent with null. Two neutrino oscillation fits consistent with LSND at 99.4% CL relative to null.
- **Clearly we need more statistics!**
  – MiniBooNE is running to double antineutrino data set for a total of ~10×10^{20} POT.
  – If signal continues at current rate, statistical error will be ~4σ and two neutrino best fit will be >3σ.

H. Robertson

NOW what?

If your experiment needs better statistics, you need a better experiment.

-- Sir Ernest Rutherford

Fine, but Rutherford isn't paying the bills. The experiment exists and needs more antineutrino running on MiniBooNE. Maybe it IS just statistics?

There are opportunities with ICARUS, the near detectors at T2K, and with a new proposal for gallium by V. Gavrin, to address the anomalies.

H. Robertson

E. Lisi:

A persistent -but evolving- anomaly: LSND/MiniBooNE

ν_S oscillation interpr.: remains difficult after last results [G. Karagiorgi]

3ν? No!

3+1? Not a good fit*

3+2? Not a good fit*

*Analysis reveals tension between different datasets:
Low/high E, ν/antiv, appearance/disappear., SBL/atm…
Can be mitigated by selective choice/adjustment of data sets/errors, and/or by exotic new physics (CPTV?)

No obvious "single" theor. explanation. Possibly: several underlying effects of different origin (including cross sections)

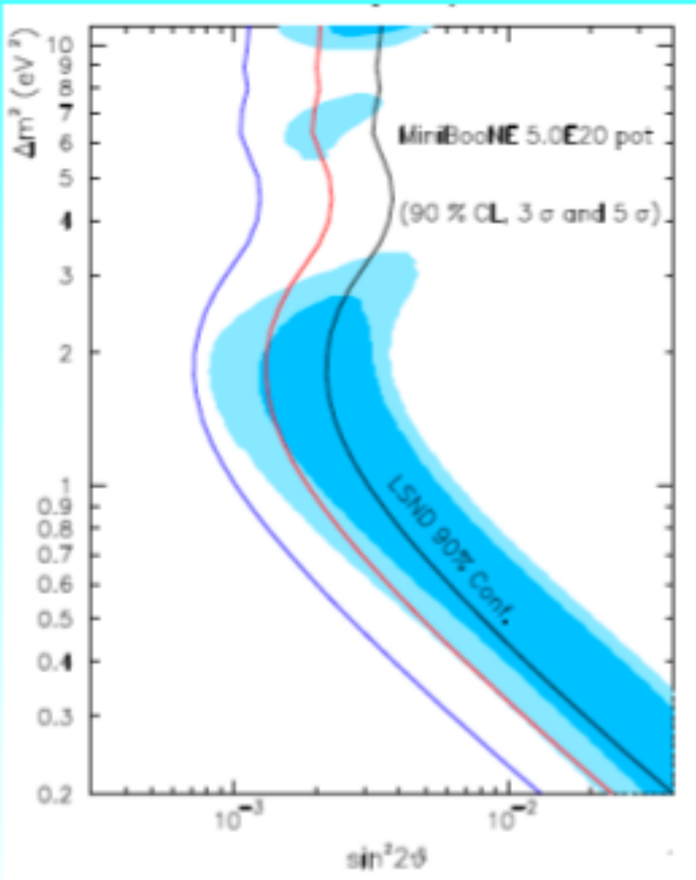
Further experimental tests underway/proposed [Van deWater] [Guglielmi] …

Note: If exotic new physics → "same L/E" tests may not be enough.

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.

Wyniki analiz 3-zapachowych oraz ϑ_{13}

How are we doing?

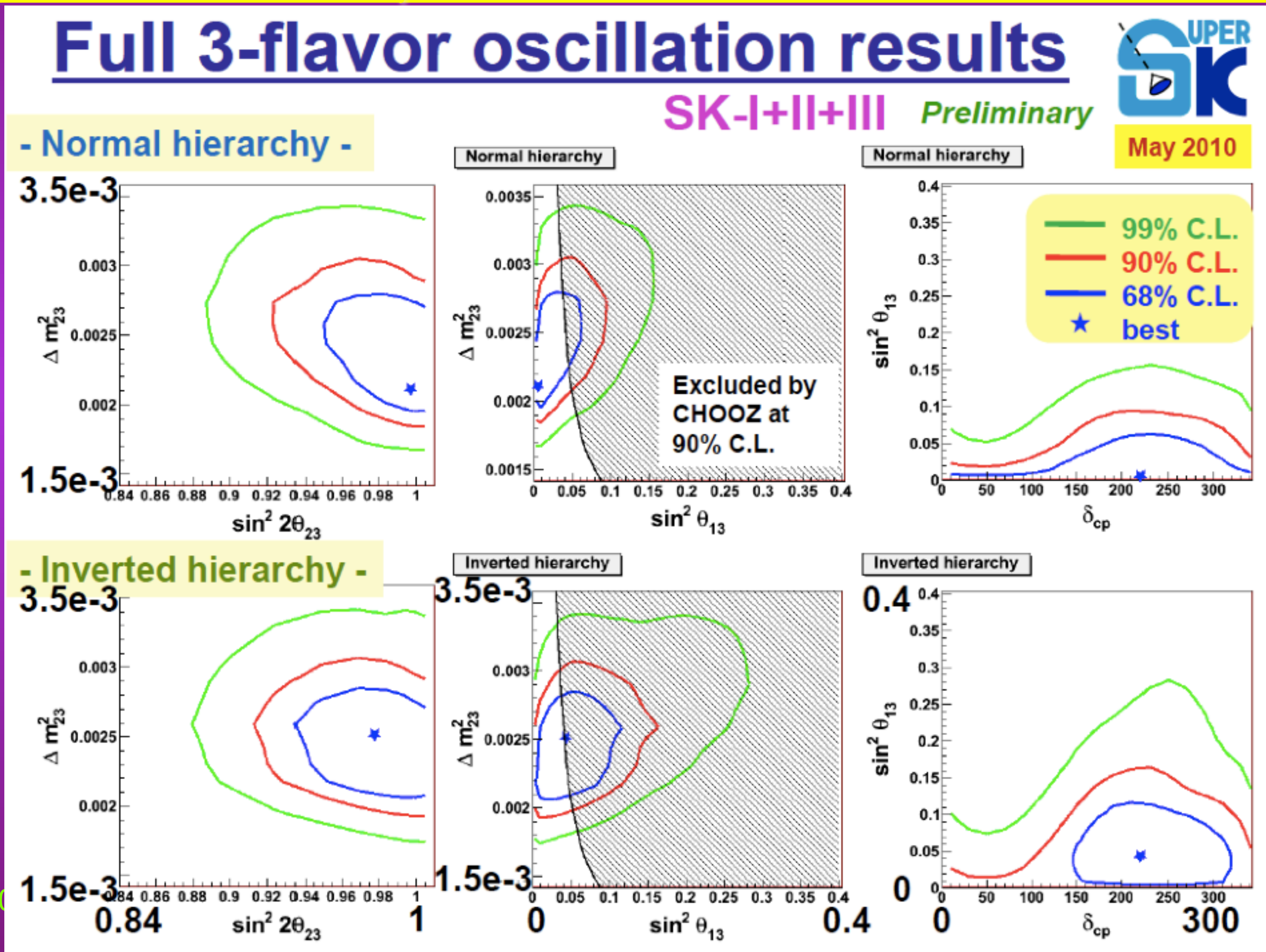
parameter	best-fit$^{+1\sigma}_{-1\sigma}$	2σ	3σ
Δm^2_{21} $[10^{-5}$ eV$^2]$	$7.59^{+0.23}_{-0.18}$	$7.22 - 8.03$	$7.03 - 8.27$
$\|\Delta m^2_{31}\|$ $[10^{-3}$ eV$^2]$	$2.40^{+0.12}_{-0.11}$	$2.18 - 2.64$	$2.07 - 2.75$
$\sin^2\theta_{12}$	$0.318^{+0.019}_{-0.016}$	$0.29 - 0.36$	$0.27 - 0.38$
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	$0.39 - 0.63$	$0.36 - 0.67$
$\sin^2\theta_{13}$	$0.013^{+0.013}_{-0.009}$	≤ 0.039	≤ 0.053

Schwetz, Tortola, Valle, 0808.2016v3 (Feb 2010)

…and: Surprises!

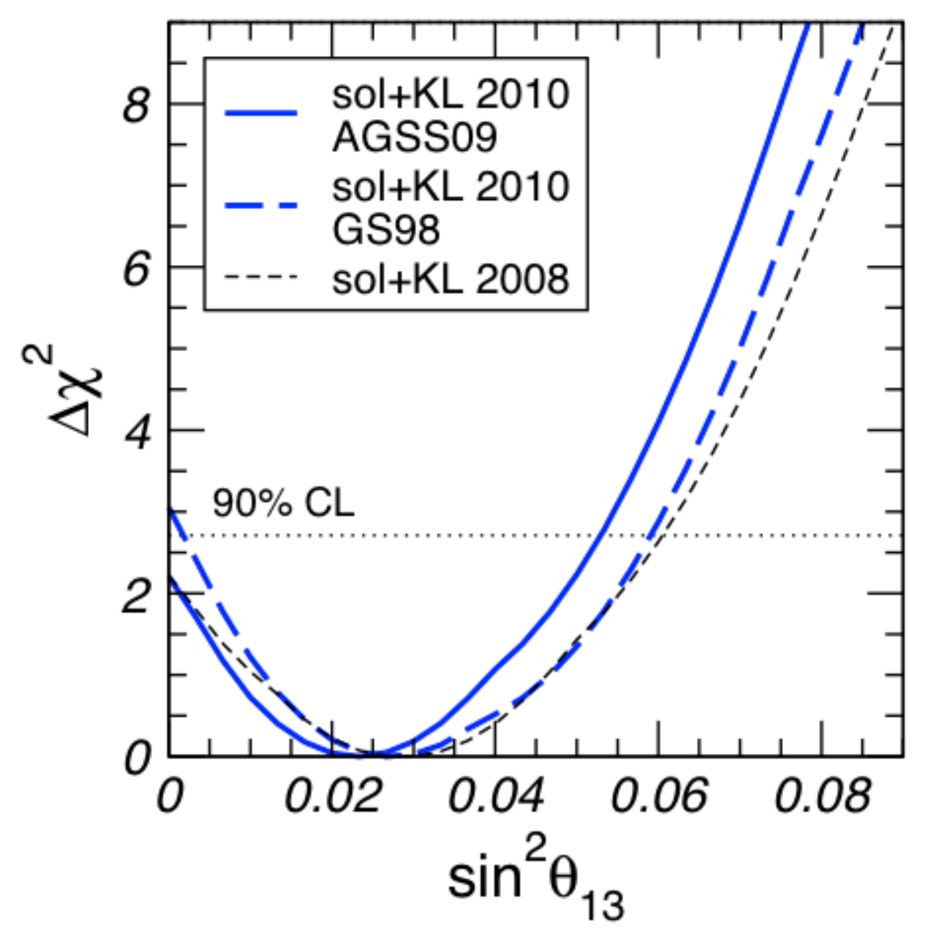
W. Rodejohann

Neutrina atmosferyczne -Super-Kamiokande

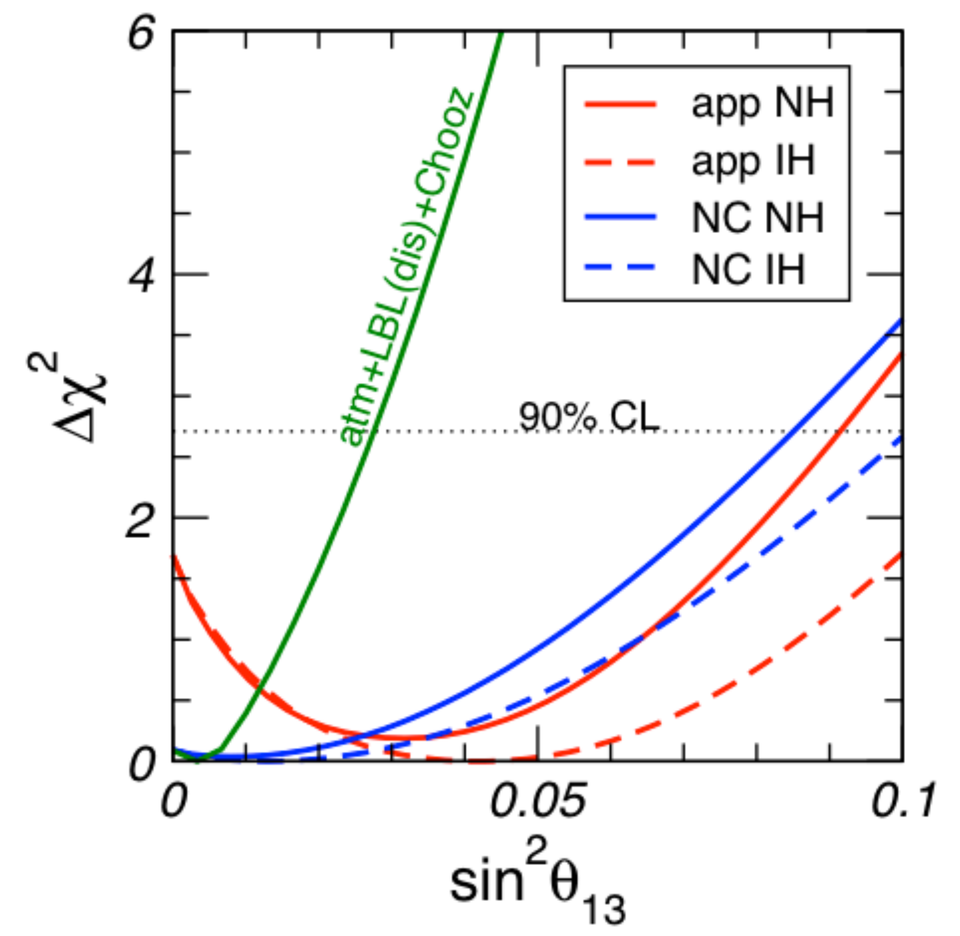


Analiza globalna: ϑ_{13}

Słoneczne & KamLand



MINOS vs atmosf & inne LBL



M. Mezzetto and T. Schwetz, arXiv:1003.5800

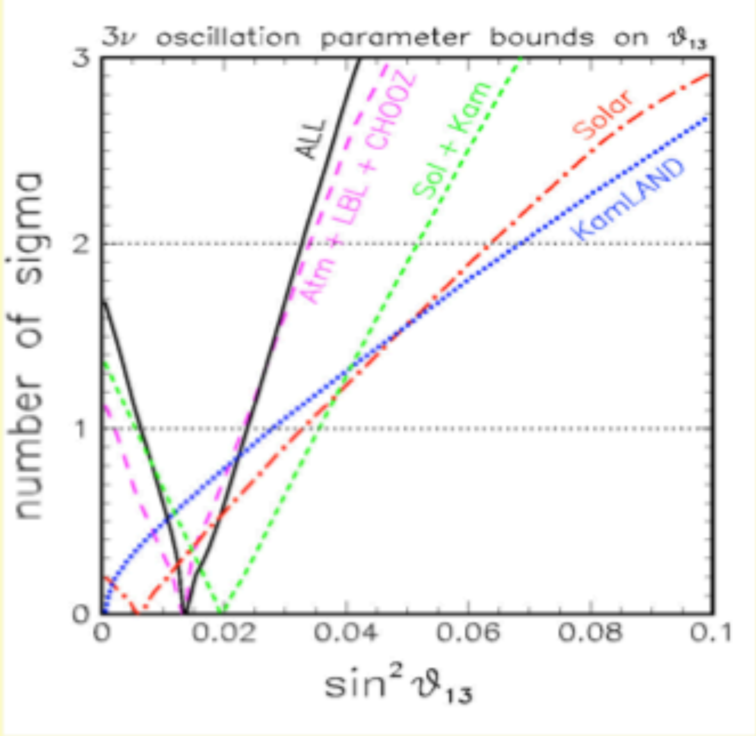
Analiza globalna (E. Lisi): ϑ_{13}

STATUS just before ν 2010… Our preliminary 2010 update*
(including MINOS app./disapp., SK-I+II+III atm, new Gallium, SNO-LETA, new SSMs):

$\sin^2\theta_{13}$: best fit 0.013; 1.7σ "hint"

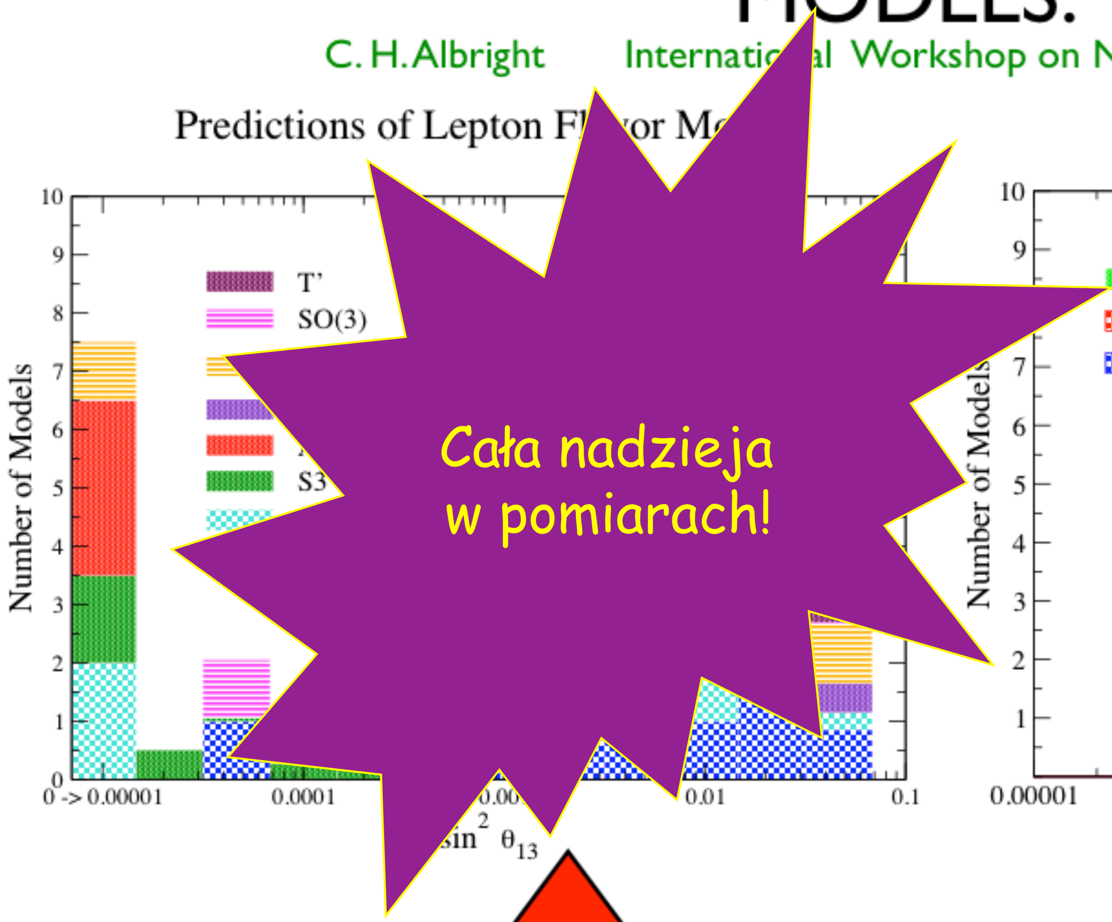
This analysis is not only preliminary, but already obsolete… It needs to be revised after **new results from MINOS (disapp), Super-K,…,** as presented at this meeting!

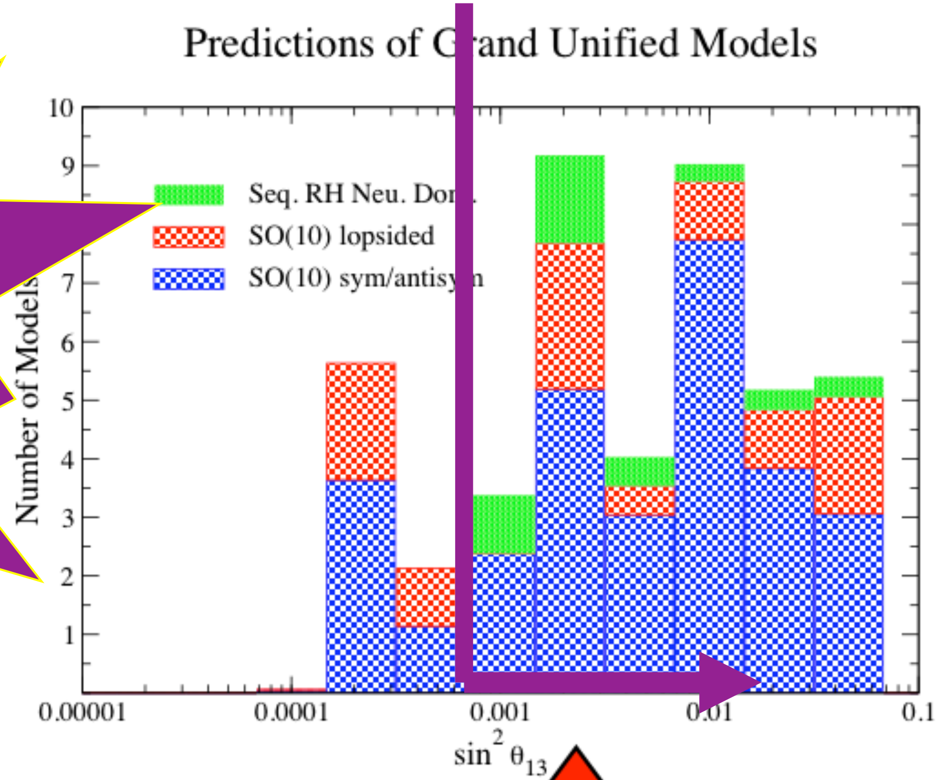
*Fogli, EL, Marrone, Palazzo, Rotunno



MODELS:

C. H. Albright   International Workshop on Neutrino Telescopes   March 10-13, 2009



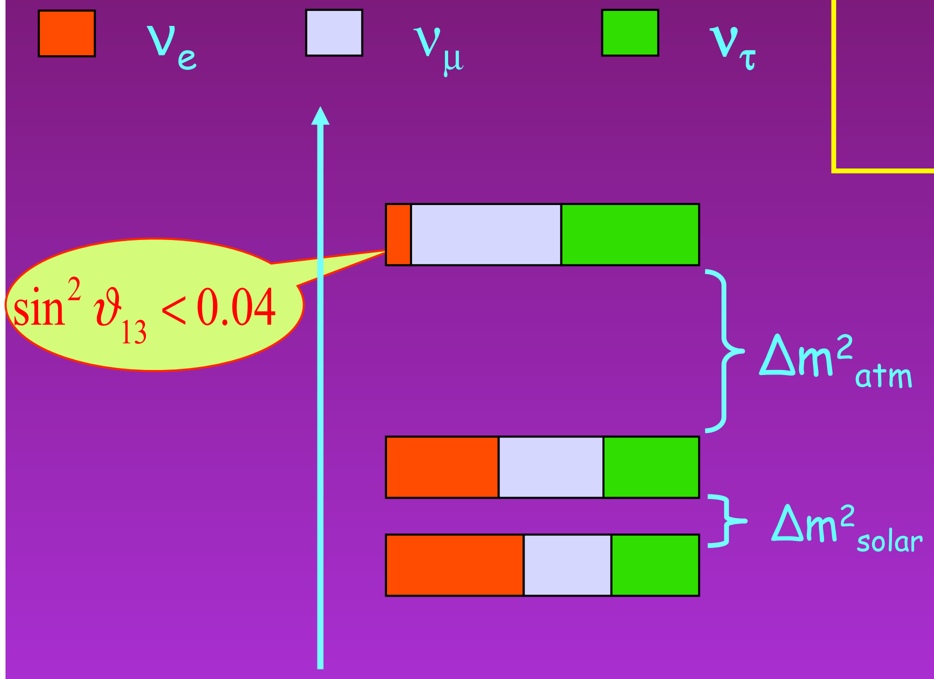


How do we distinguish Models with the same $\sin^2\theta_{13}$?

By relationships with other parameters:
e.g. $\theta_{12} - \theta_{13}\cos(\delta) = \sqrt{1/3}$
but there are many such examples.

This will require precision measurements of
$\sin^2\theta_{13}, \sin^2\theta_{12}, \sin^2\theta_{23}$ and δ_{CP}

Jak mierzyć ϑ_{13}



Potrzebujemy:

- eksperymentu o L/E odpowiadającym Δm^2_{atm}
- przejście od/do ν_e or $\bar{\nu}_e$
- dużej precyzji (sygnał - kilka 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

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

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

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

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

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

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

matter effects → sensitivity to mass hierarchy

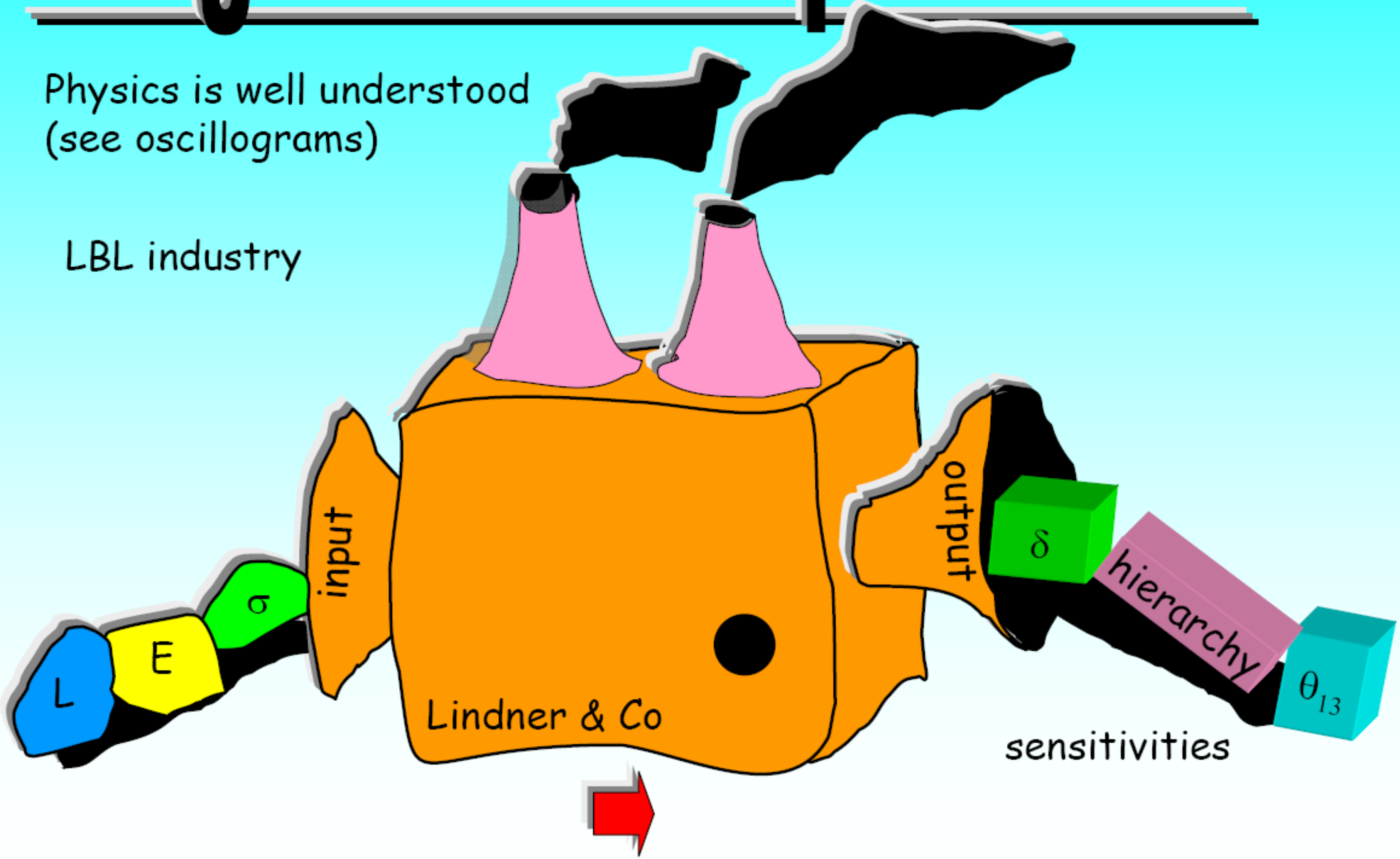
If LA<<1 (reactor exper.):

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

Long baseline experiments

Physics is well understood
(see oscillograms)

LBL industry



sensitivities

Akceleratorowe eksperymenty drugiej generacji

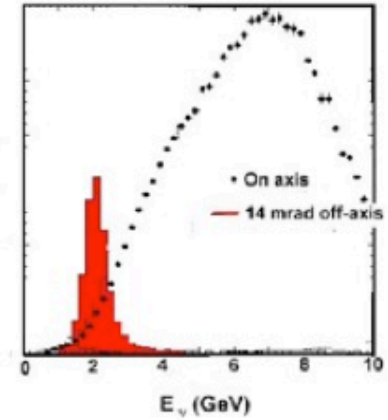
- Silne źródła neutrin
- Wiązki „off axis"

	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.

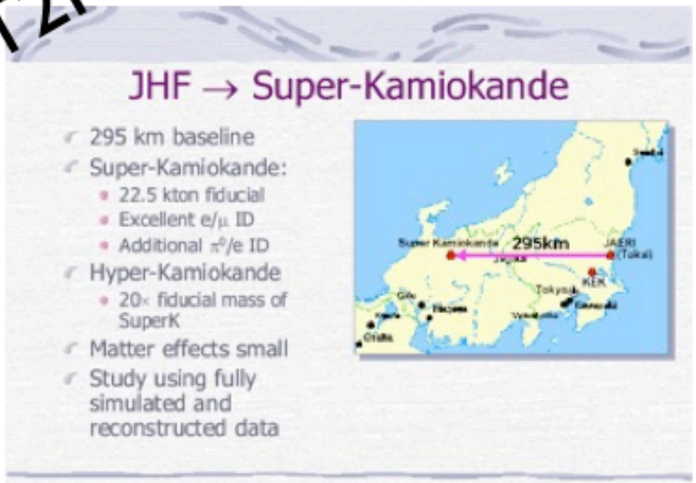
Off-Axis Beams:

BNL 1994



π^0 suppression

T2K



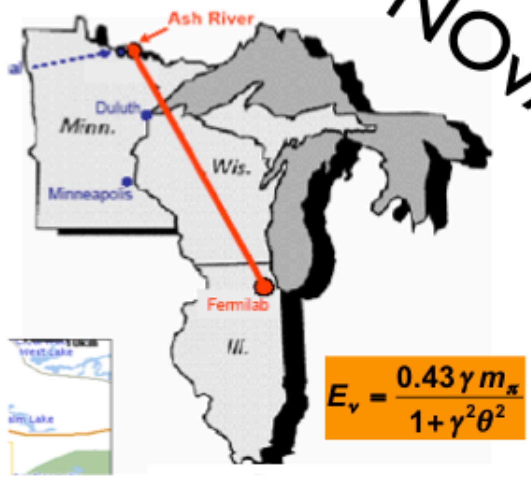
L=295 km and

Energy at Vac. Osc. Max. (vom)

$$E_{vom} = 0.6\ GeV \left\{ \frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2} \right\}$$

0.75 upgrade to 4 MW

NOvA



L=700 - 1000 km and

Energy near 2 GeV

$$E_{vom} = 1.8\ GeV \left\{ \frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2} \right\} \times \left\{ \frac{L}{820\ km} \right\}$$

0.4 upgrade to 2 MW

T2K (Tokai to Kamioka)

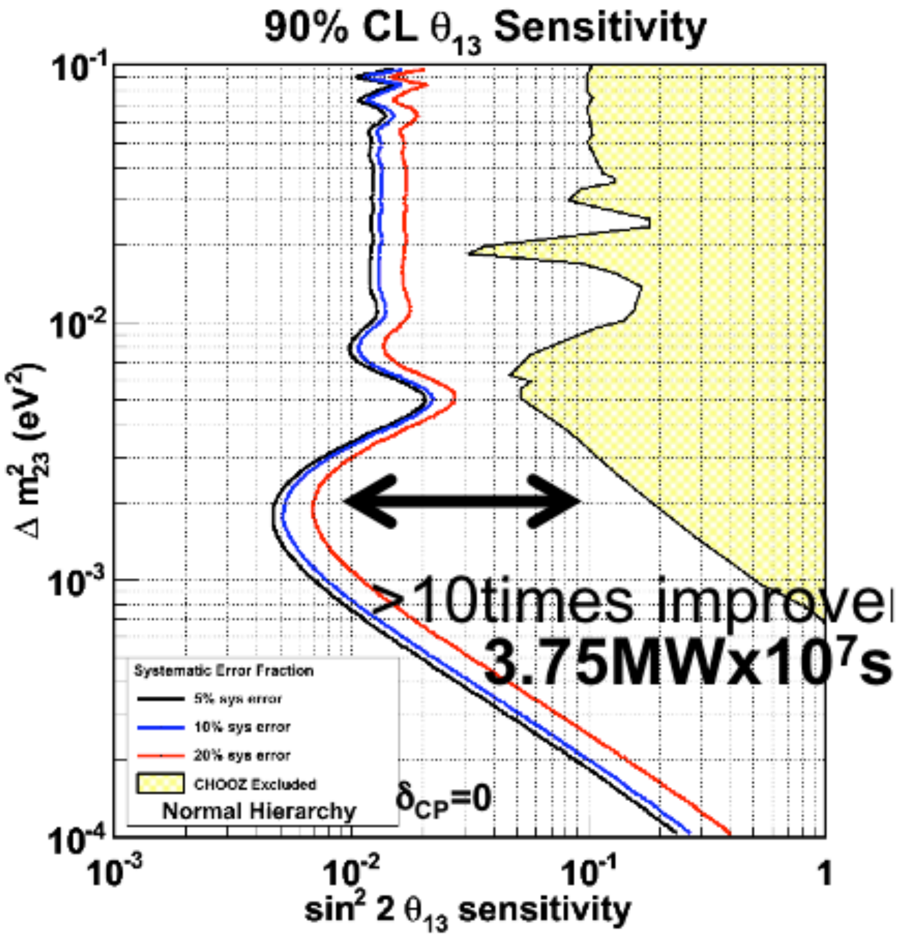
T. Kobayashi

Ponad 30 przyp. skorelowanych z wiązką zaobserwowano od lutego do czerwca 2010 w Super-Kamiokande.

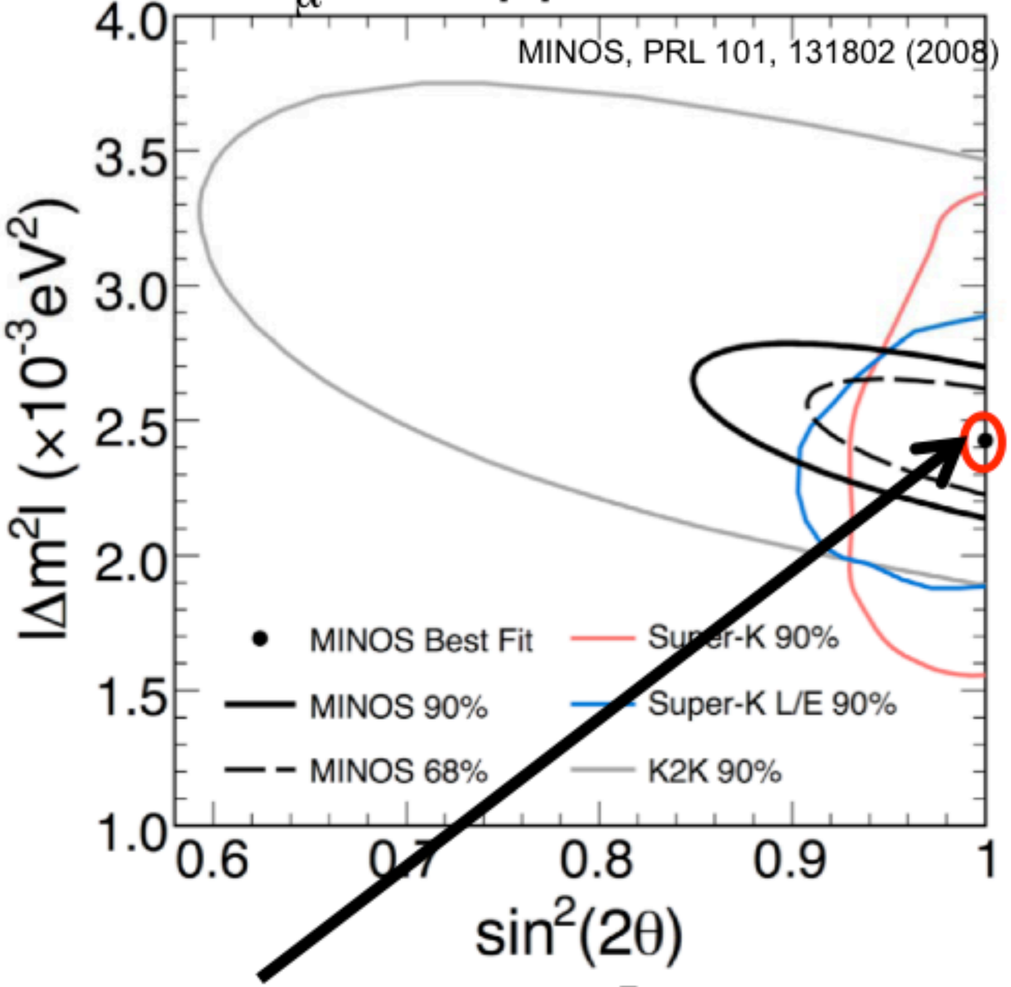
→ Specjalne seminarium na początku 2011
Paweł Przewłocki

Expected Sensitivity of T2K

ν_μ◊ν_e appearance



ν_μ disappearance

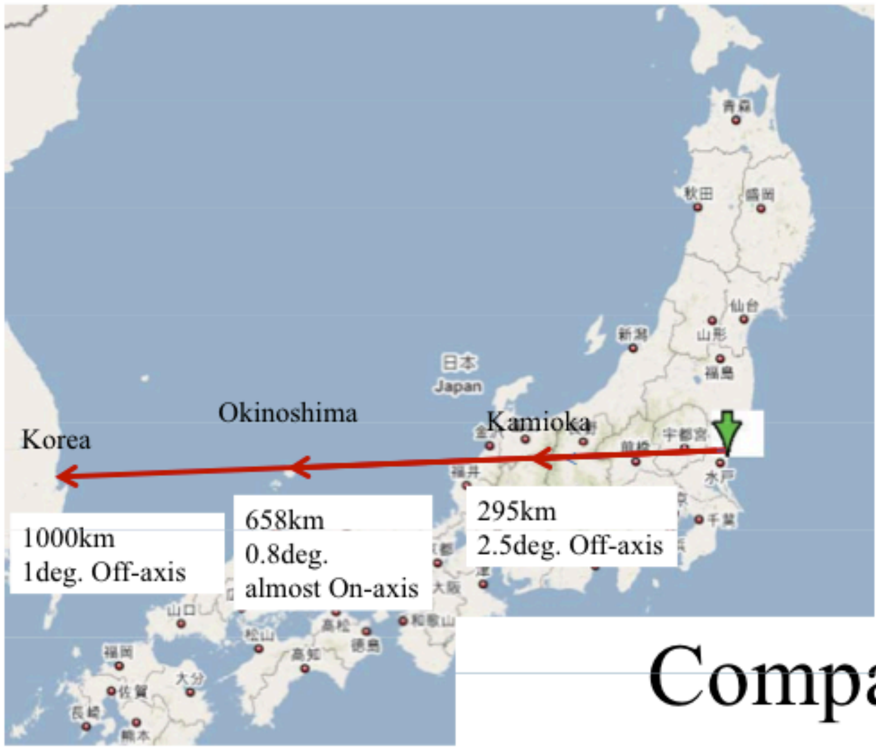


Goal @ 3.75MWx10^{7}s:

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

$\delta(\Delta m^2_{23}) < 1\times10^{-4}$ [eV^2]

Three Possible Scenario Studied at NP08 Workshop



Comparison of Each Scenario

	Scenario 1 Okinoshima	Scenario 2 Kamioka	Scenario 3 Kamioka Korea
Baseline(km)	660	295	295 & 1000
Off-Axis Angle(°)	0.8(almost on-axis)	2.5	2.5 1
Method	ν_e Spectrum Shape	Ratio between ν_e $\bar{\nu}_e$	Ratio between 1st 2nd Max Ratio between ν_e $\bar{\nu}_e$
Beam	5Years ν_{μ}, then Decide Next	2.2 Years ν_{μ}, 7.8 Years $\bar{\nu}_{\mu}$,	5 Years ν_{μ}, 5 Years $\bar{\nu}_{\mu}$,
Detector Tech.	Liq. Ar TPC	Water Cherenkov	Water Cherenkov
Detector Mass (kt)	100	2×270	270+270

NOνA

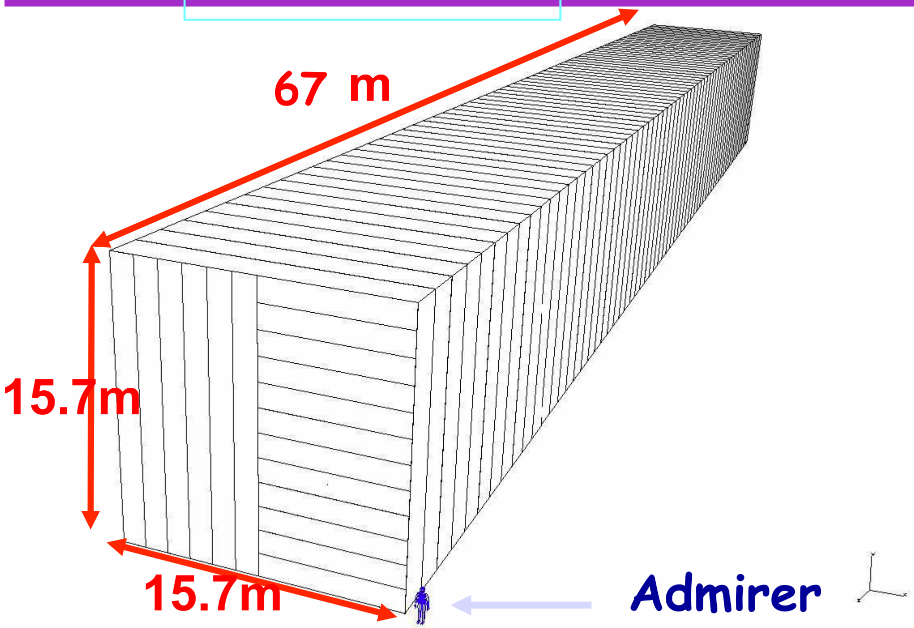
6 countries:
Brasil, France, Greece, Russia, UK, USA
27 Institutions

- Upgraded NuMi beam in Fermilab
  0.7 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 ν_e detection
  - start of construction in 2010

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

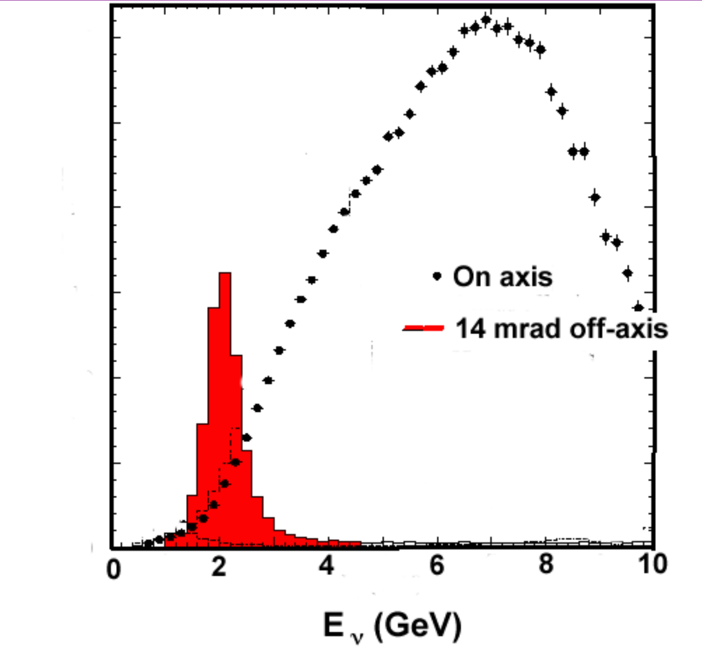
Far detector

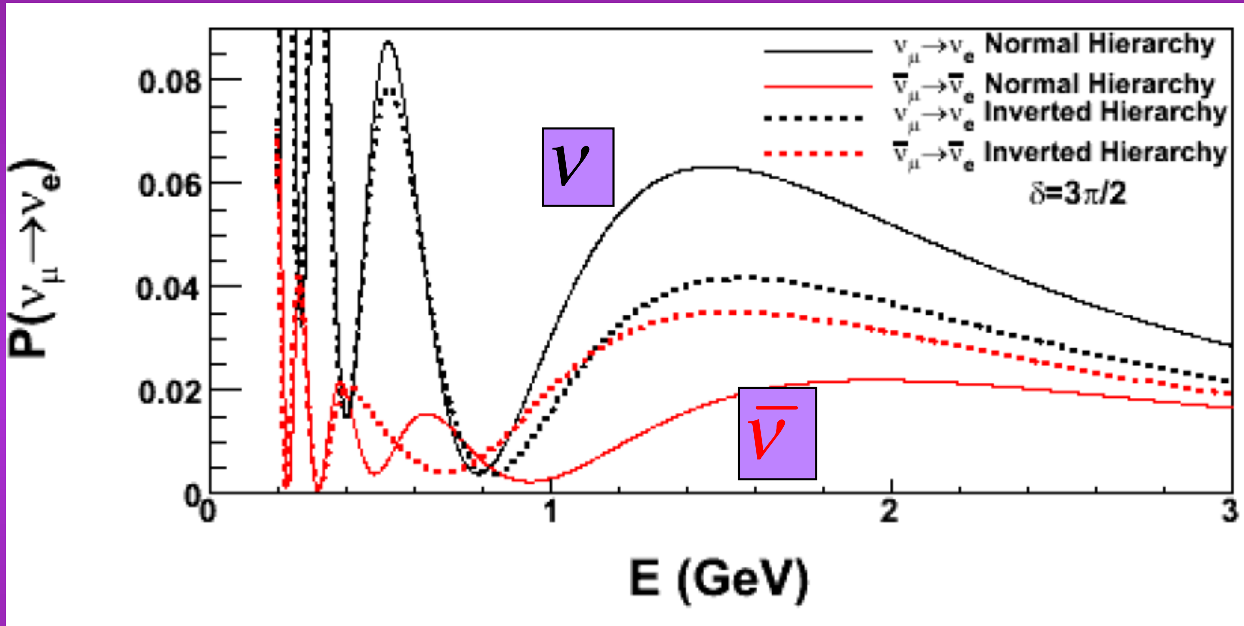


D. Kiełczewska

NOνA

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



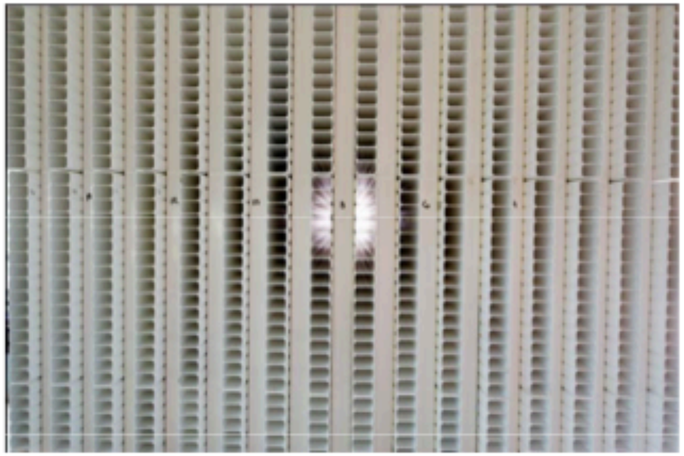


Dotted lines for inverted hierarchy

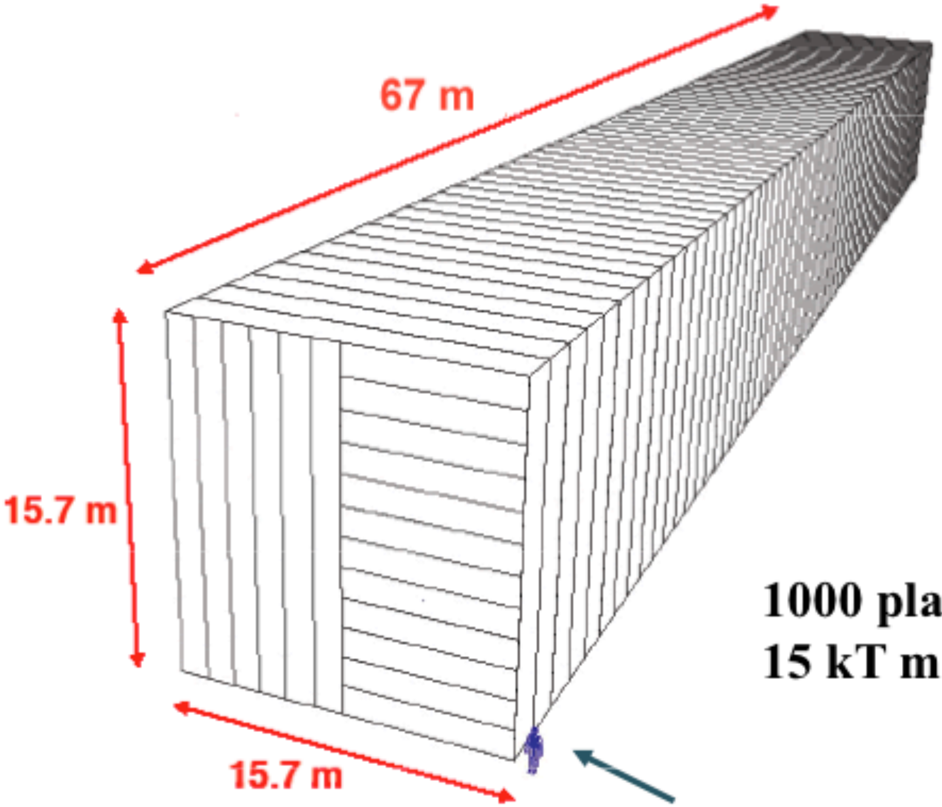
- ➢Thanks to a longer baseline and higher energy Nova has better sensitivity to matter effects and mass hierarchy than T2K
- ➢Nova and T2K are complementary: comparing results allow to disentangle true CP effects from matter effects

Far Detector

- Cells are in 16-cell PVC extrusion.
- Glue 2 extrusions together to make a 32 cell module.
- 12 modules make up a plane.
- Planes alternate horizontal and vertical.

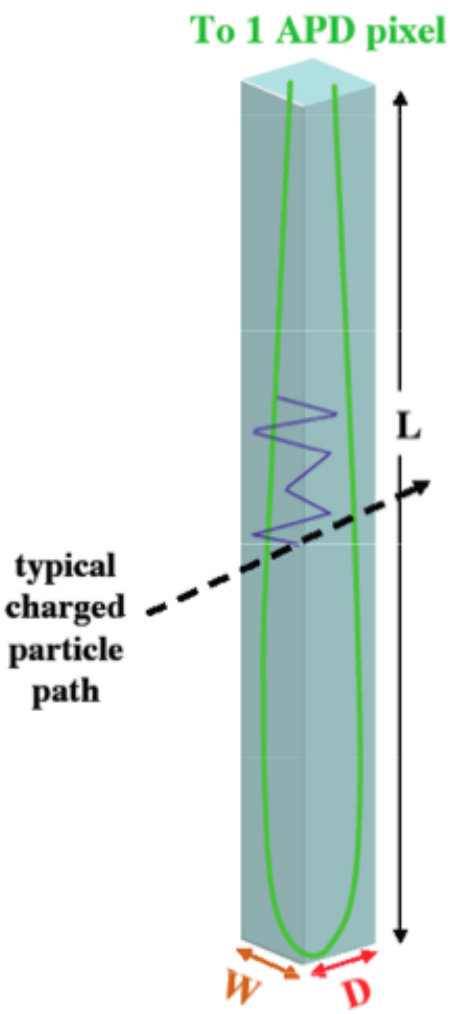


Extrusion cells



1000 planes , 380,000 channels
15 kT mass (~85% fudicial)

NOvA Detector Element



Liquid scintillator in a cell

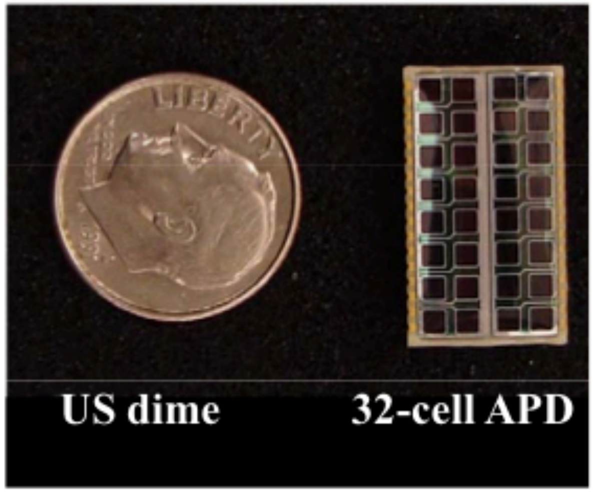
- 4 cm wide, 6 cm deep, 15.7 m long.
- Cell from highly reflective PVC.
- 32 cells in a PVC module.

Light collected by U-shaped wavelength-shifting fiber.

- 0.7 mm diameter.
- Both ends go into a pixel of a 32-pixel avalanche photodiode (APD).

APD quantum efficiency of 85%.

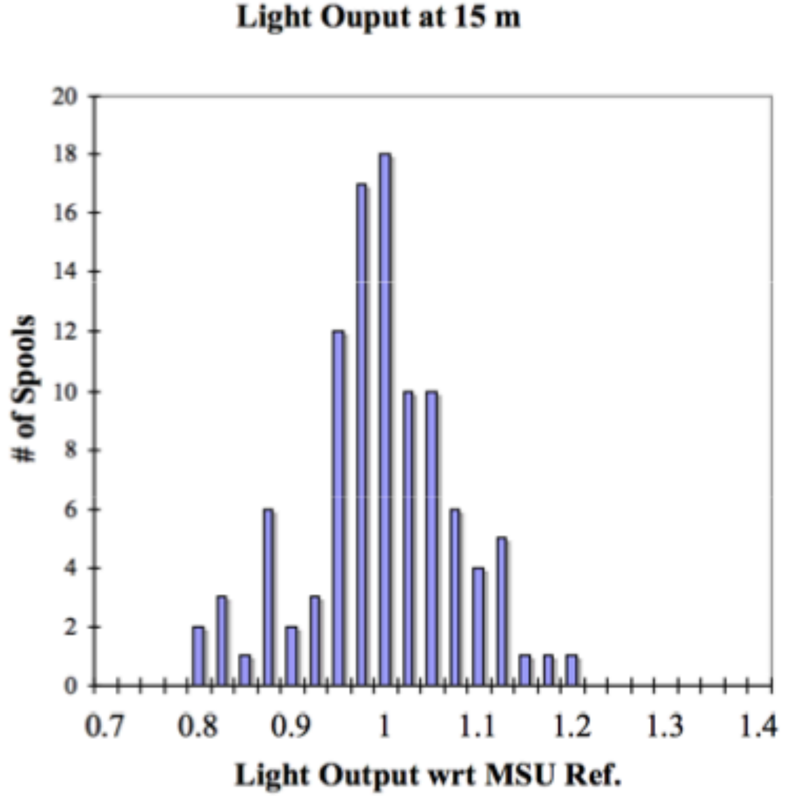
- Gain of 100.
- Cooled to -15°C.

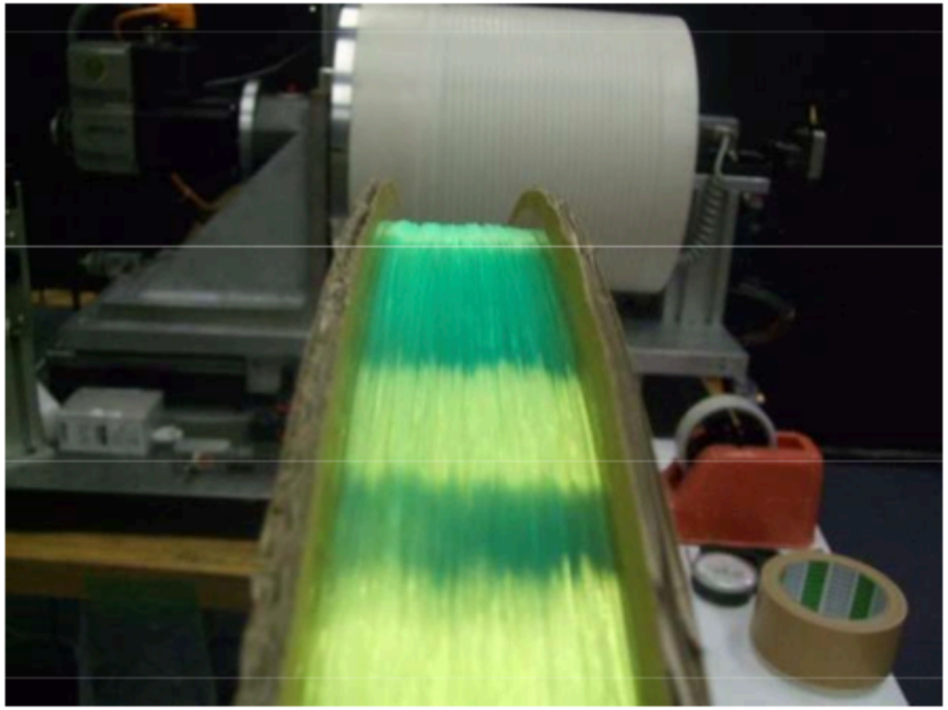


Fiber

Need ~ 12,000 km of 0.7 mm diameter wavelength shifting fiber from Kuraray
So far ~10% received and tested

K27 dye @ 300 ppm, S-type





Michigan State

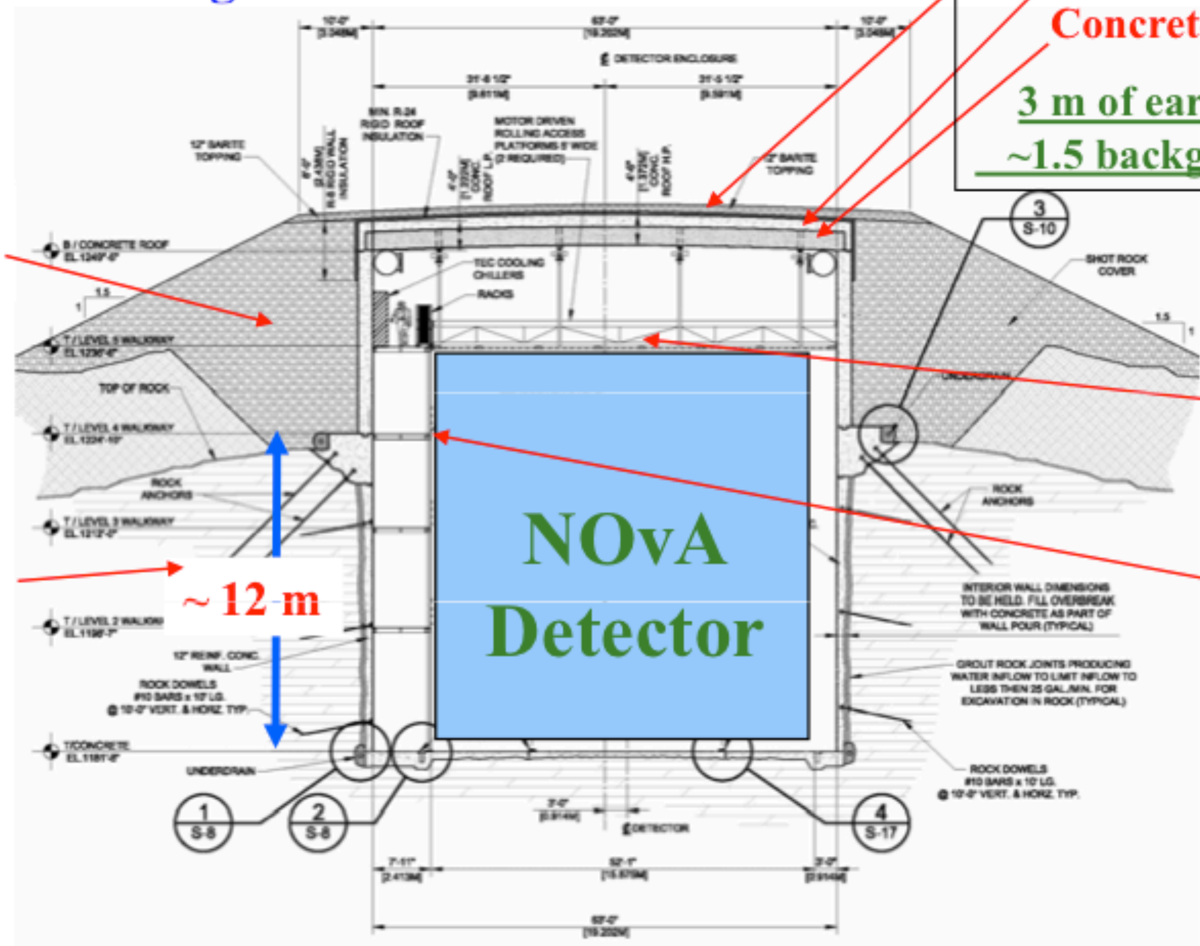
Far Detector Hall

Cross section as seen by the neutrino beam
19 m wide x 22 m high

15 cm barite
Cast Concrete
Concrete Planks

3 m of earth equivalent
~1.5 background event in 6 yrs

Excavated granite



Rolling access bridges

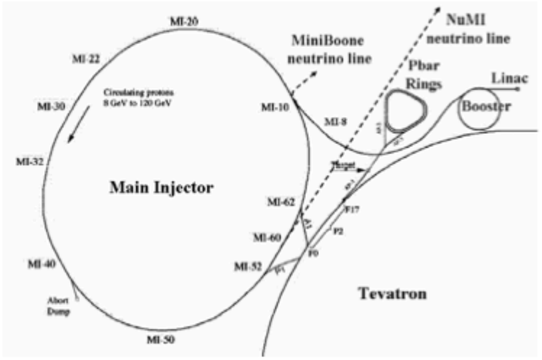
Solid granite (bathtub for 100% secondary containment)

4 catwalks, electronics on top catwalk

Nova – daleki detektor

NUMI Beam to 700 kW

- Changes to the FNAL Accelerator complex to
  - Recycler from pbar to proton ring
    - Injection and extraction lines – need bigger aperture
    - Associated kickers and instrumentation
    - 53 MHz RF – for slip stacking
  - Shorten MI cycle to 1.33 seconds
    - RF upgrades
    - Power Supply upgrades
  - NuMI target station to 700 kW
    - Target
    - Horns
- On course for shutdown Mar 2012
  - Changeover shutdown: 6 Dec 2011
    - 53 MHz RF task critical path
  - Installation shutdown Mar 2012 - Feb 2013



Fermilab

Schedule

NDOS operational	Winter 2010
Far detector building complete	Winter 2010
Start of far detector assembly	Fall 2011
Start of long shutdown for NuMI upgrades (determined by Collider run)	Fall 2011
First 2.5 kT operational	Winter 2011/12
Full far detector operational	Spring 2013

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

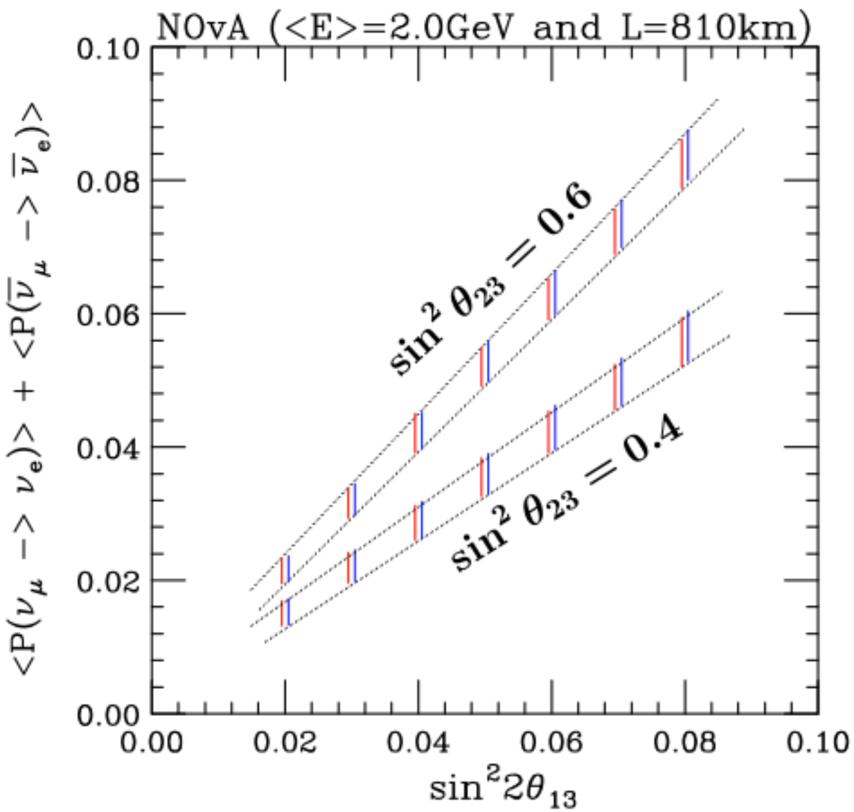
At Vac. Osc. Max. ($\Delta_{31} = \frac{\pi}{2}$)

$$P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e) \approx 2\sin^2\theta_{23}\sin^2 2\theta_{13} \quad + \quad \mathcal{O}[(aL)\sin\delta]$$

directly comparable to reactor

$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) = \sin^2 2\theta_{13}$$

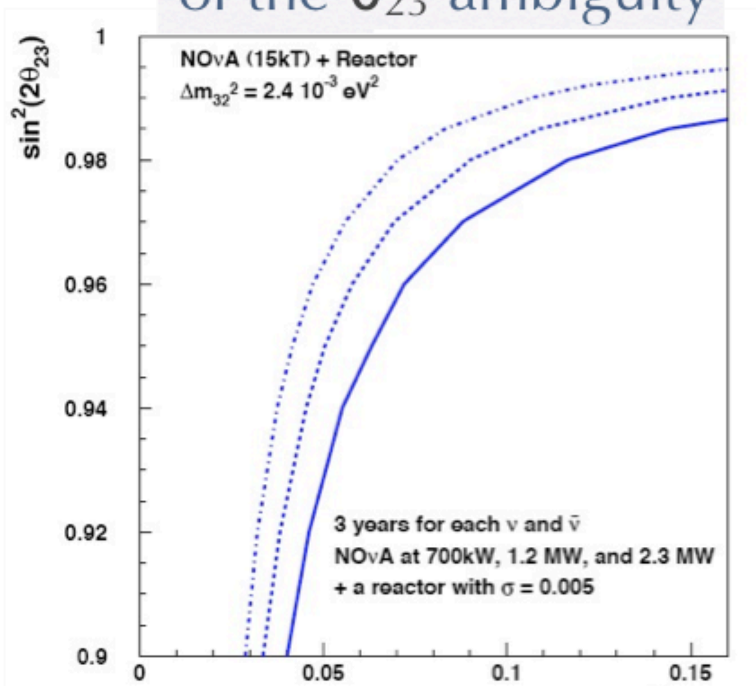
NOvA



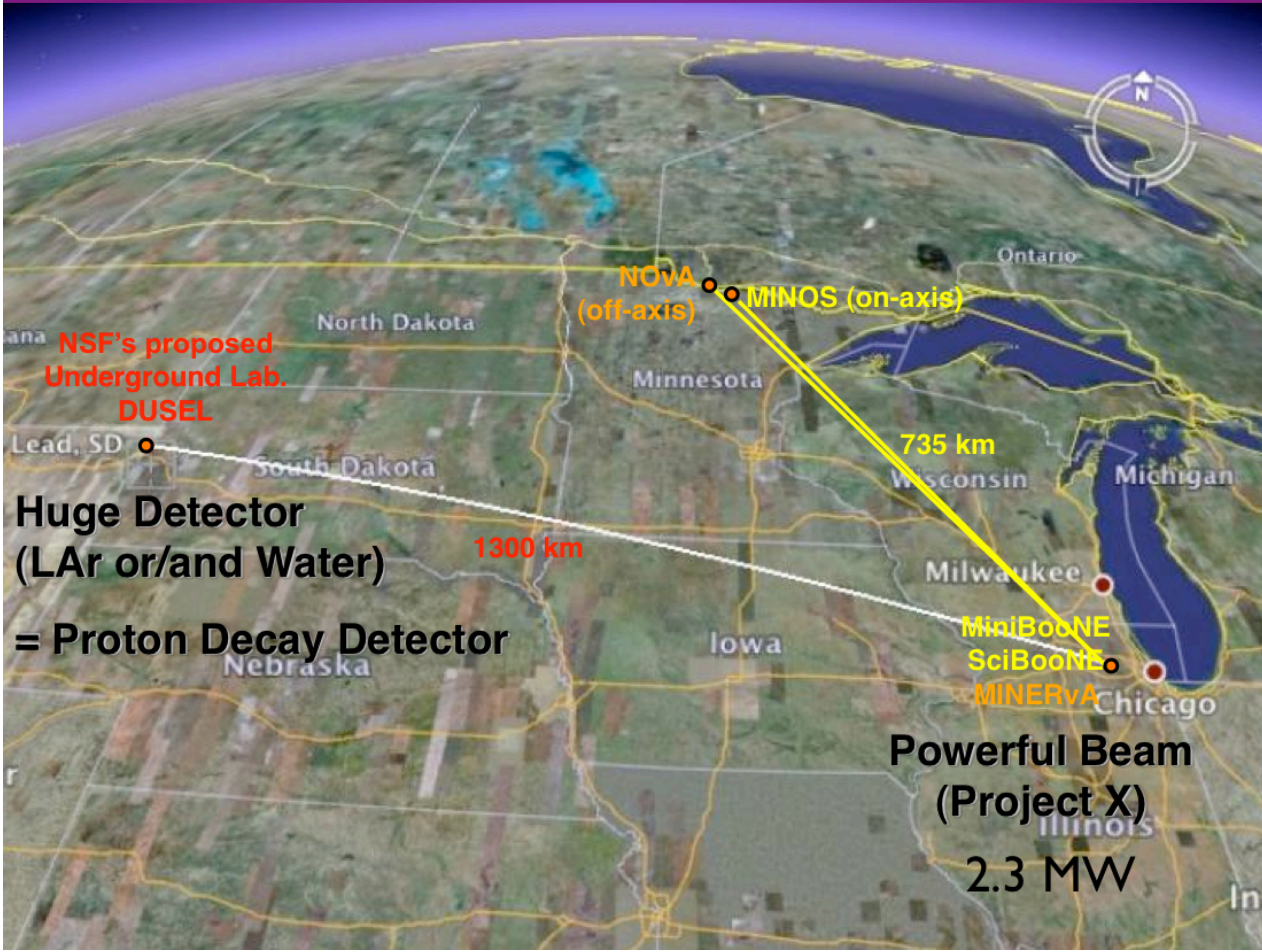
For $\sin^2 2\theta_{23} = 0.96$
thus $\sin^2\theta_{23} = 0.4$ or 0.6

(4*0.4*0.6=0.96)

95% CL Resolution of the θ_{23} ambiguity



T2K could also do this, if they ran $\bar{\nu}_\mu$



NOvA
(off-axis)
MINOS (on-axis)
Ontario
North Dakota
NSF's proposed
Underground Lab.
DUSEL
Minnesota
Lead, SD
South Dakota
735 km
Wisconsin
Michigan
Huge Detector
(LAr or/and Water)
1300 km
Milwaukee
= Proton Decay Detector
Iowa
Nebraska
MiniBooNE
SciBooNE
MINERvA
Chicago
Powerful Beam
(Project X)
Illinois
2.3 MW

Eksperymenty reaktorowe - wyznaczanie ϑ_{13}

θ_{13} from Reactor Disappearance

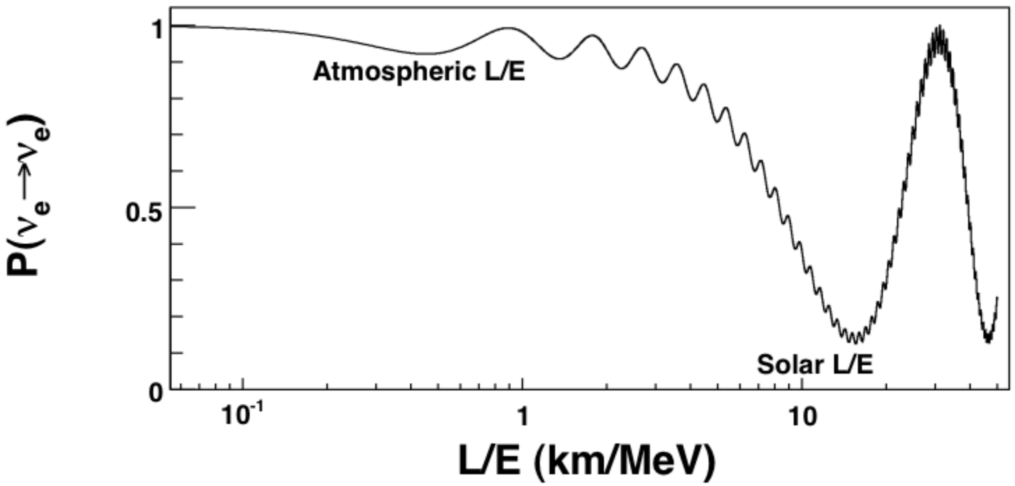
kinematic phase:

$$\Delta_{ij} \equiv \frac{\delta m^2_{ij} L}{4E}$$

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\delta m^2_{ee} L}{4E}\right) - \mathcal{O}(\Delta_{21})^2$$

where $\delta m^2_{ee} = \cos^2\theta_{12}|\delta m^2_{31}| + \sin^2\theta_{12}|\delta m^2_{32}|$

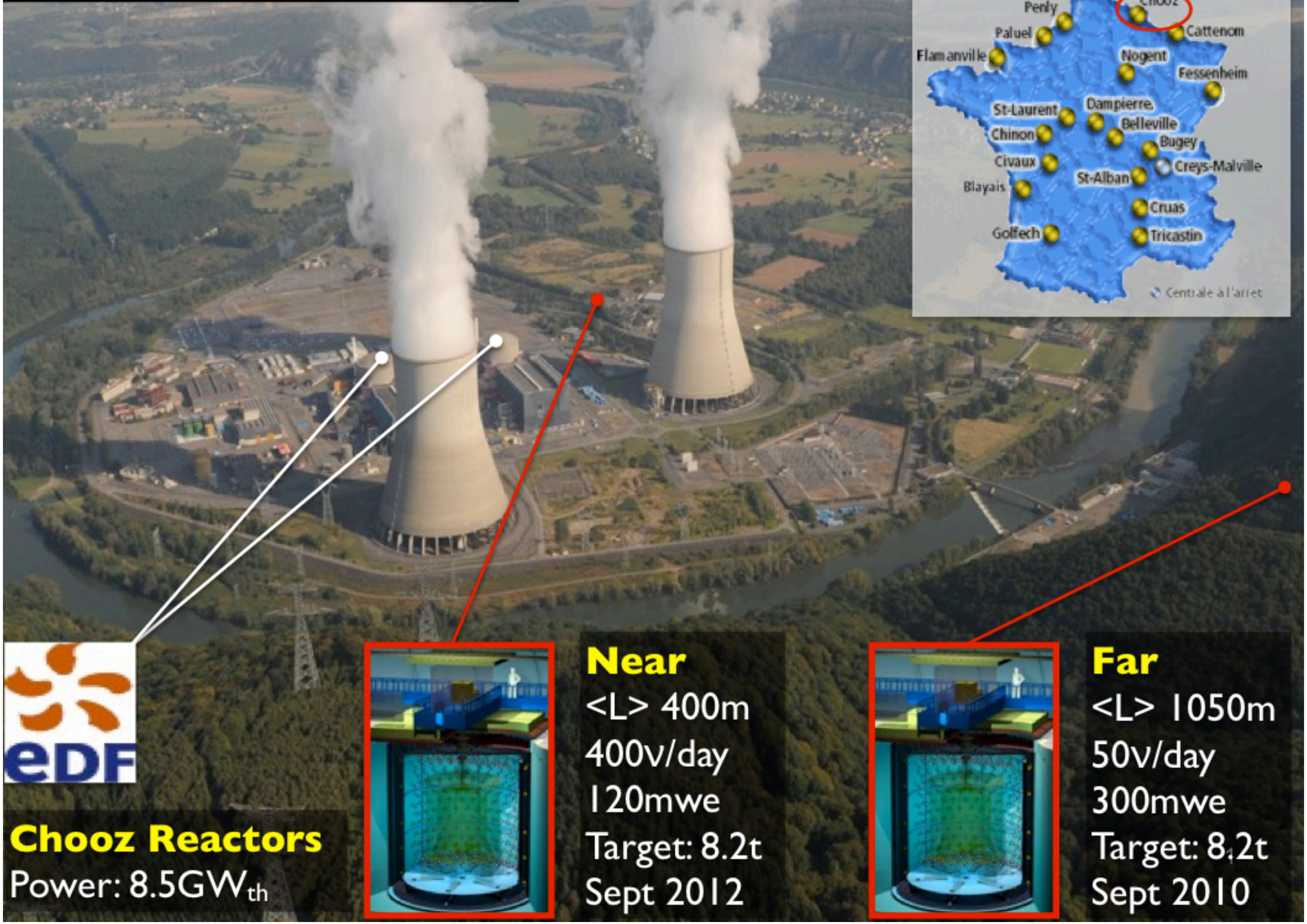
ν_e weight average of $|\delta m^2_{31}|$ and $|\delta m^2_{32}|$



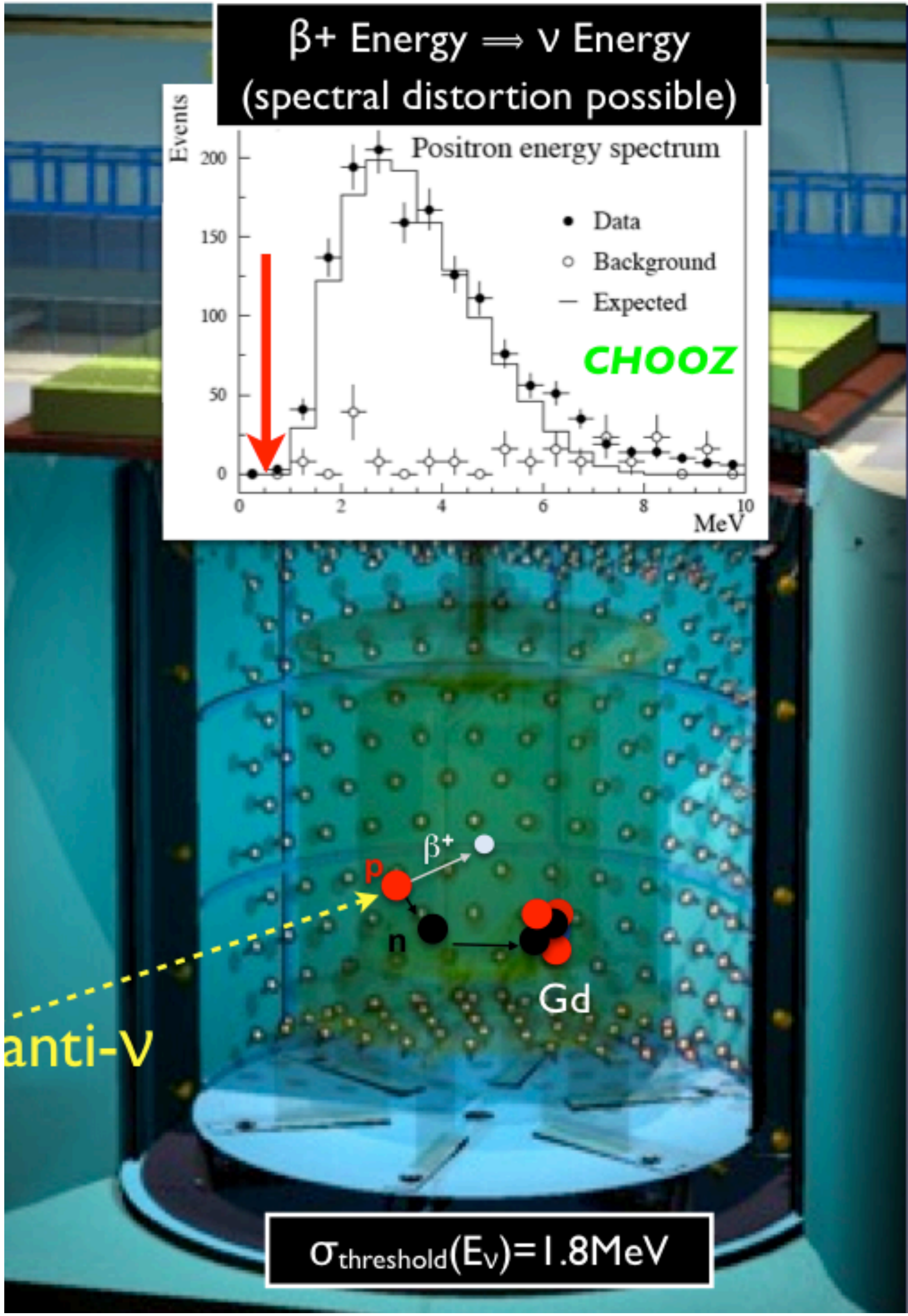
Pure measurement of $\sin^2\theta_{13}$!!!

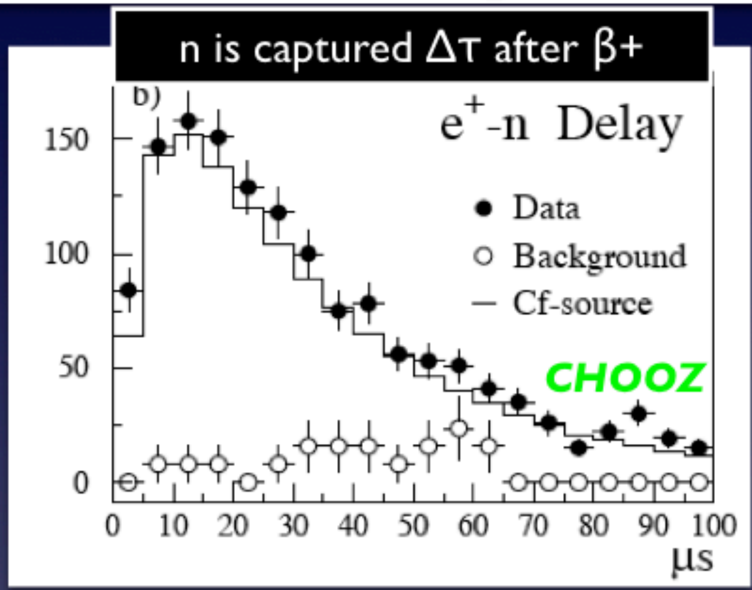
the ν_e component of ν_3

Experimental Setup…

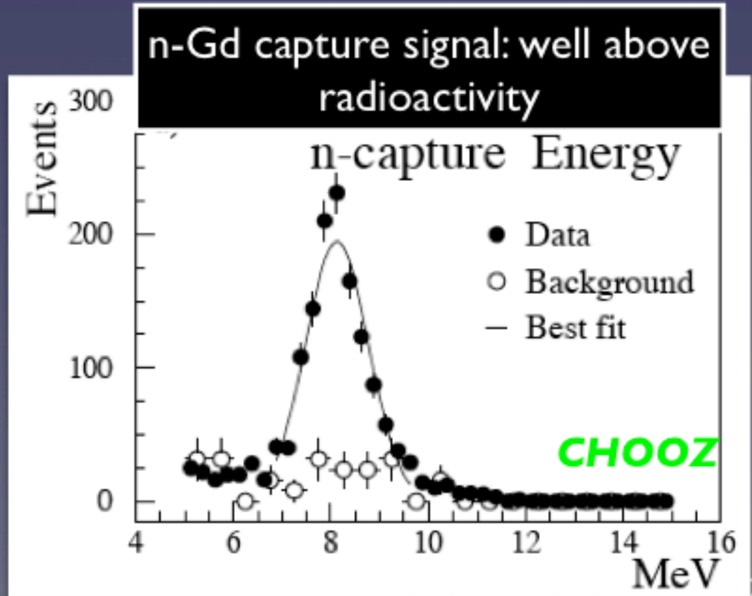


inverse-β reaction





Coincidence Δτ depends on Gd concentration
⟹ excellent BG rejection mechanism



Apollonio et al (CHOOZ) hep-ex/0301017

- **Double Chooz FD is about to start data taking**…
  - FD construction ⟹ finished!
  - FD first lights ⟹ achieved last week ("dry" detector)
  - FD filling ⟹ about to start (in a few weeks)
  - FD first scintillation lights ⟹ during filling data-taking
  - FD commissioning ⟹ **running from September!!!**
  - FD publication on θ_{13} ⟹ soon!
- DC can obtain CHOOZ worth of **signal** data <2 months of running
  - **$\sin^2(2\theta_{13}) \leq 0.054$ 90%CL** with FD only (about 1.5years of data)
  - **$\sin^2(2\theta_{13}) \leq 0.030$ 90%CL** with ND (about 3years of data)
- Near Detector digging end of the Nov.2010 ⟹ running by 2012!!

Daya Bay Collaboration

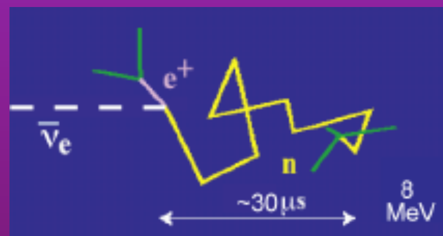
„ASIA" (=China & Taiwan) – 19 inst.
US – 16 inst; Europe (Russia, Czech Rep) – 3 inst

The Daya Bay Nuclear Power Complex in Shenzhen

- 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 GW generates
6 x $10^{20}\ \overline{\nu}_e$ per sec

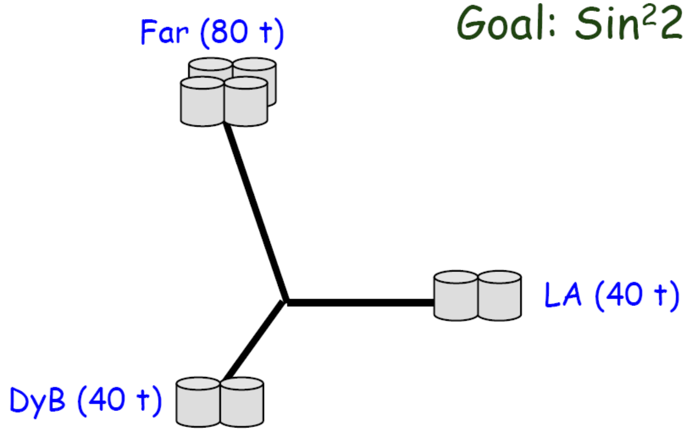
Detection:



with Gd

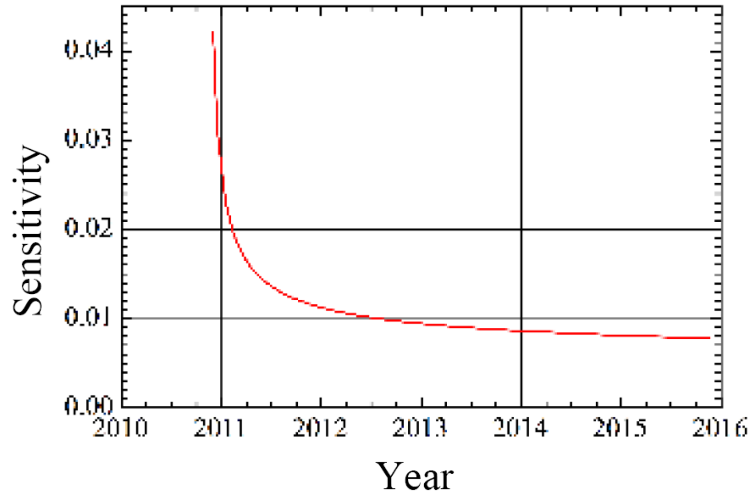
Sensitivity of Daya Bay

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

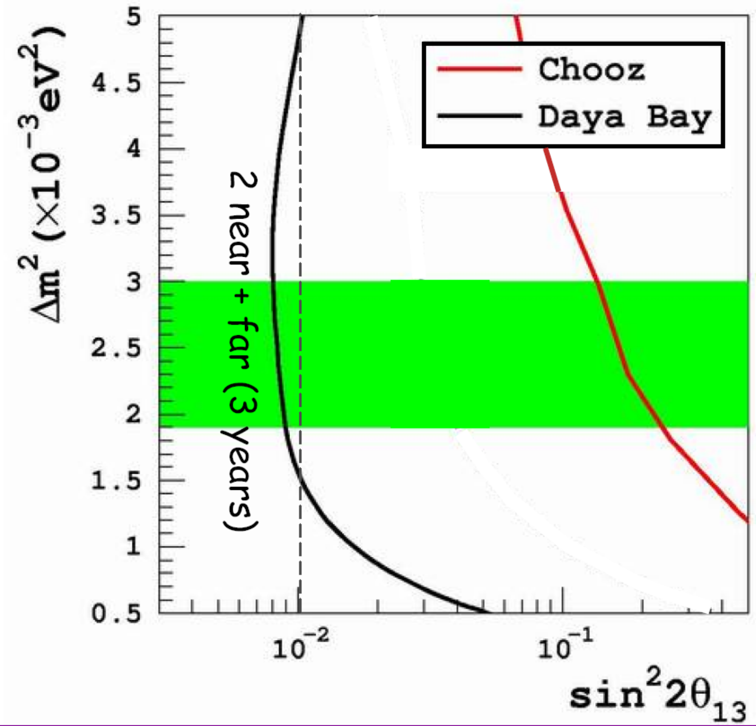


- Use rate and spectral shape
- input relative detector syst. error of 0.38%/detector

Stan NU2010:
1.5 detektora



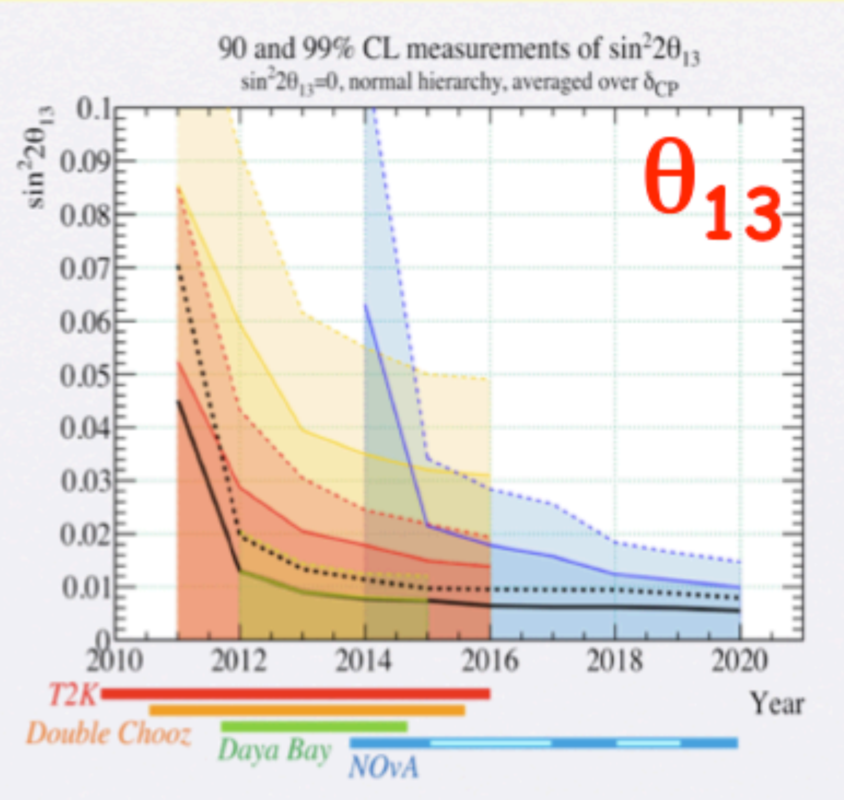
90% confidence level



	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

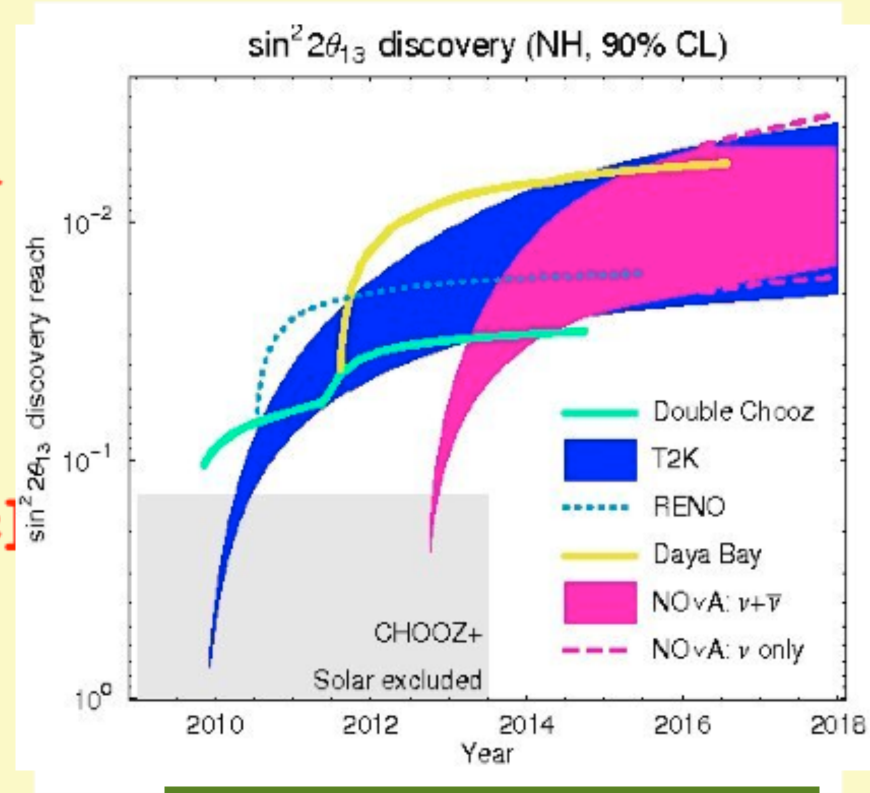
E. Lisi

Prospects: Theory of 3ν oscillations (matter effects, degeneracies, …) under control → Phenomenology can provide realistic sensitivity estimates and optimizations for given SBL & LBL set-up and syst. error budget.



→

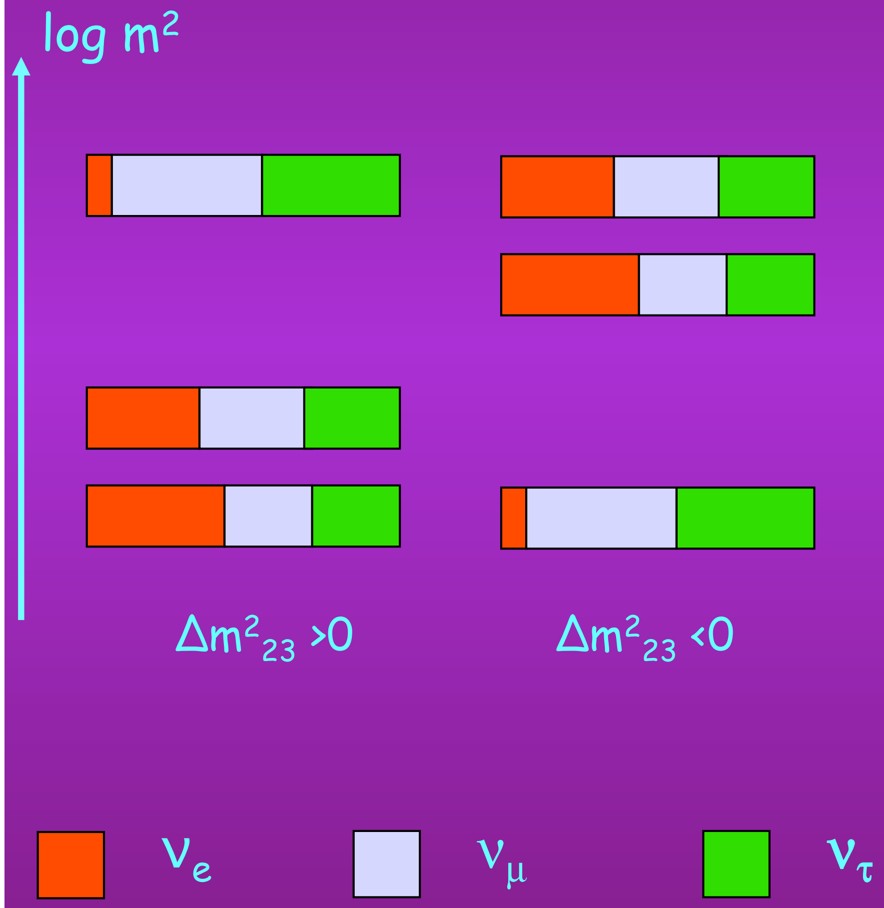
[S. Parke] + many other talks



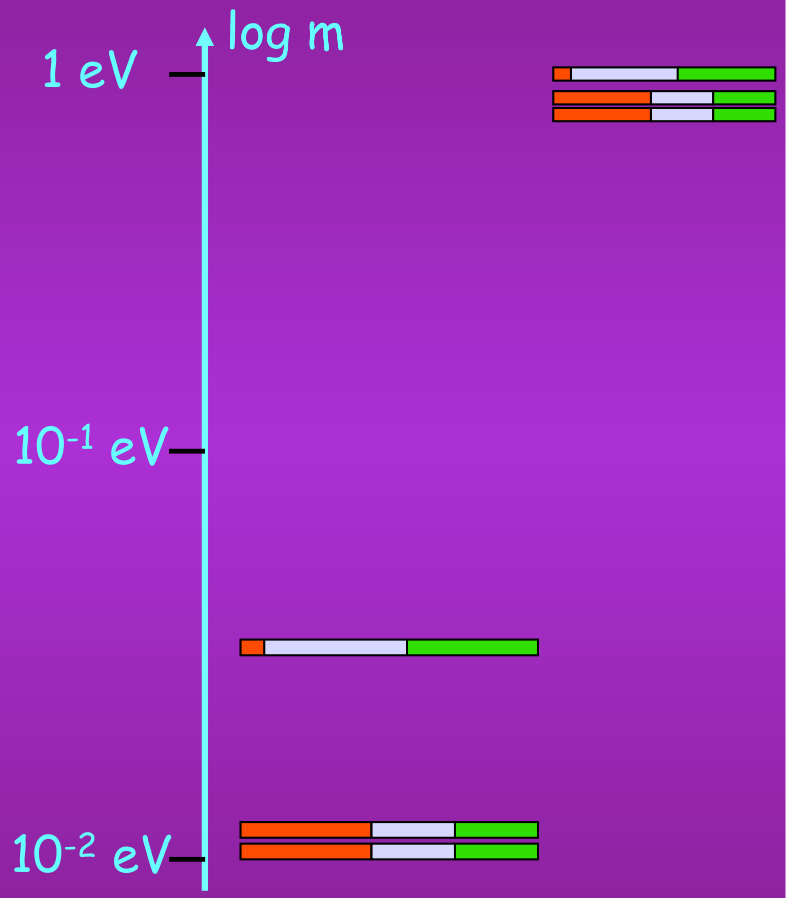
FUTURE
Huber, Lindner, Schwetz, Winter, 2009

Masy neutrin

Jaka jest hierarchia mas?



Jaka skala?



2. Neutrino mixing and masses: (m_β, $m_{\beta\beta}$, Σ)

1) Single β decay: $m^2_i \neq 0$ alters the spectrum tail. Sensitive* to the so-called "effective mass of electron neutrino":

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

[Simkovic]

2) Double 0νββ decay: Iff $m^2_i \neq 0$ and ν=anti-ν (Majorana). Sensitive* to the "effective Majorana mass" (and related phases):

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

[Valle]
[Rodejohann]
[Simkovic]
[Mohapatra]

3) Cosmology: $m^2_i \neq 0$ alters large scale structure formation within standard cosmology constrained by CMB+other data. Measures*:

$$\Sigma = m_1 + m_2 + m_3$$

[Wong]

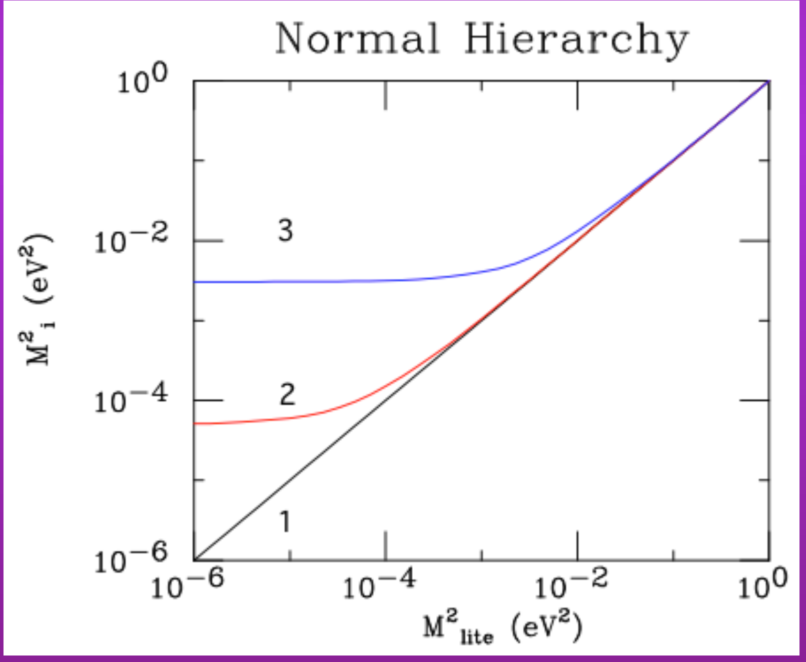
Masy neutrin

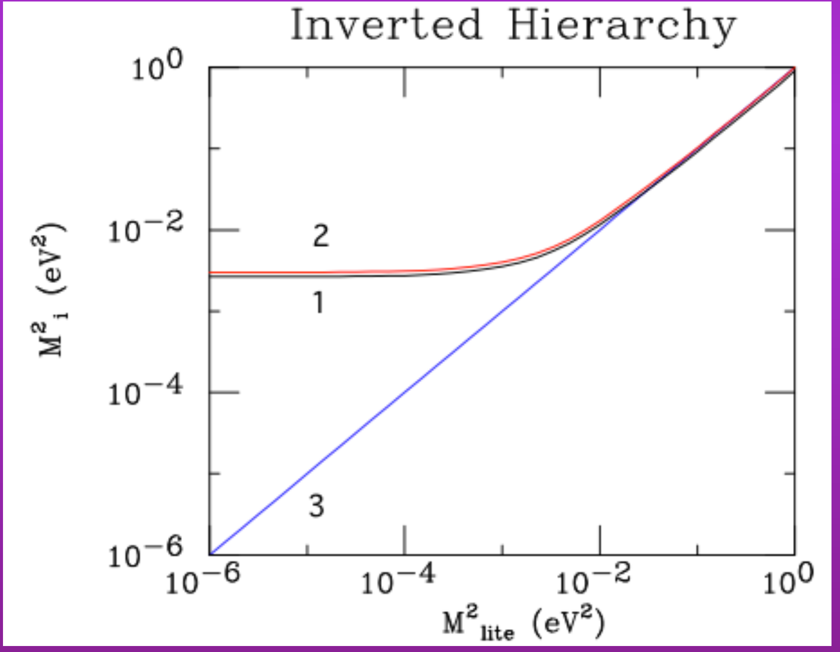
Z oscylacji:

$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2$$

$$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2$$

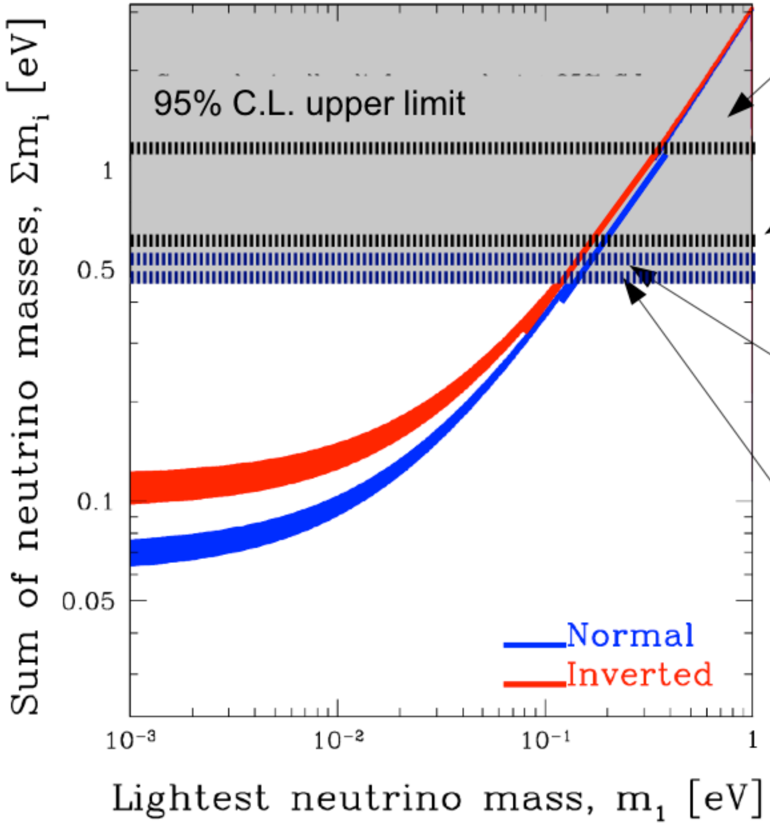
- Σm_i >55 meV
- m_β wyznacza wszystkie masy

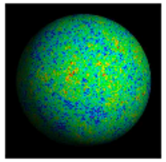




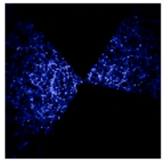
Masa^2 najlżejszego neutrina (eV^2)

Present status...

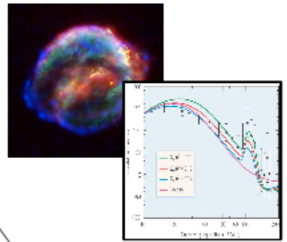




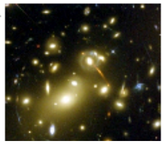
WMAP7 only
Komatsu et al. 2010



WMAP7+Galaxy clustering
Hannestad, Mirizzi, Raffelt & Y[3]W 2010



WMAP5+Galaxy +SN+HST
Reid et al. 2009
(extended models)



WMAP5+Weak lensing
Tereno et al. 2008
Ichiki et al. 2008

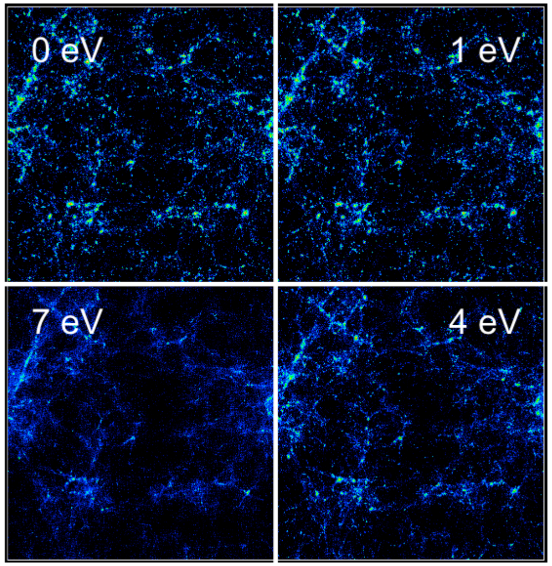
Ograniczenie na sumę mas z kosmologii

Nu2010

- The free-streaming effects of massive neutrinos are best observed in the large-scale structure distribution (e.g., galaxy distribution).

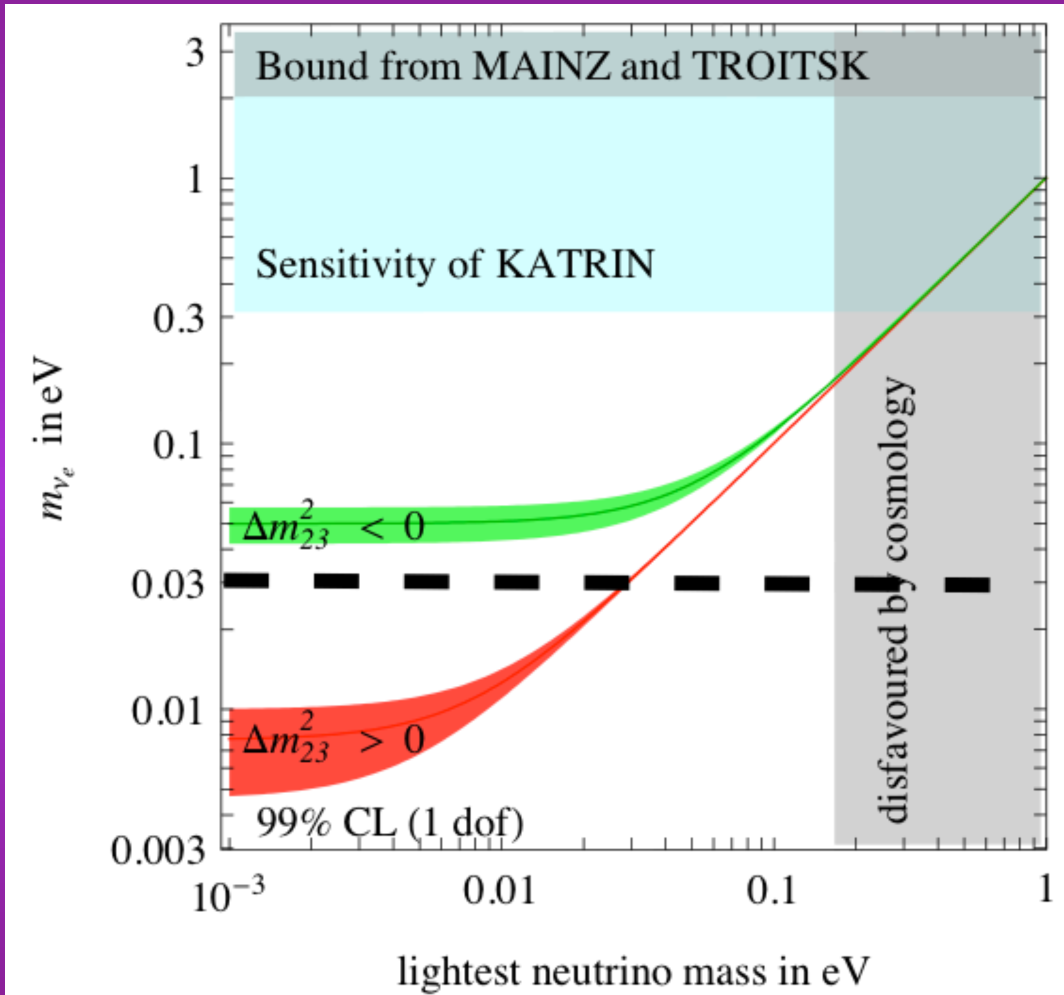
→ **Suppression** of structure formation on small scales.

→ Heavier neutrino = more suppression.



Mixed CHDM N-body simulation, Ma 1996

Efektywna masa z rozpadu β



Pomiar niezależny od modeli.

Czułość Katrin:

After 3 years data (5y realtime):

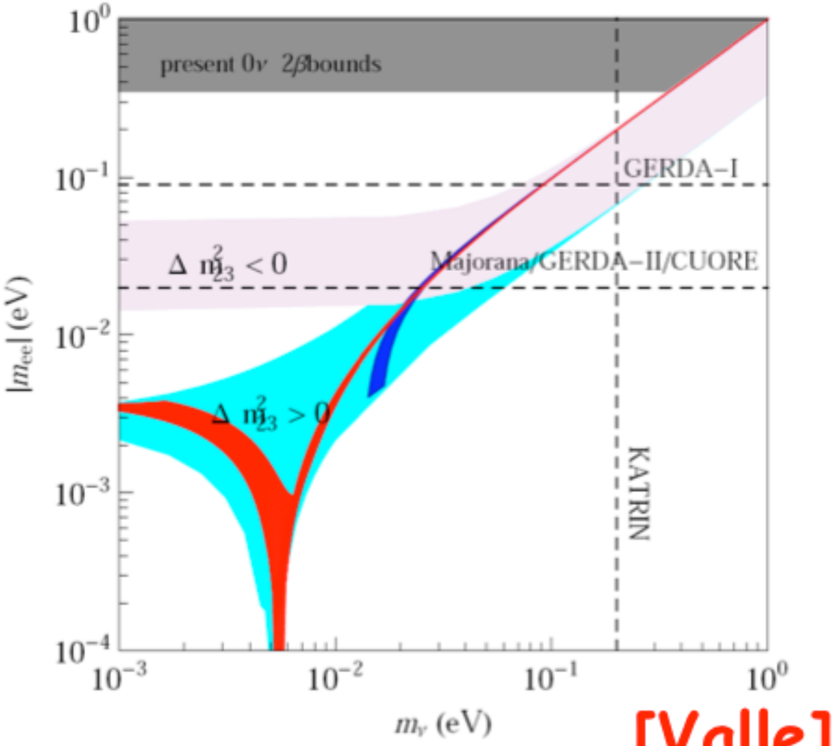
discovery potential
m(ν) = 0.35 eV (5σ)

sensitivity (90% CL)
m(ν) < 0.2 eV

Thomas Thummler

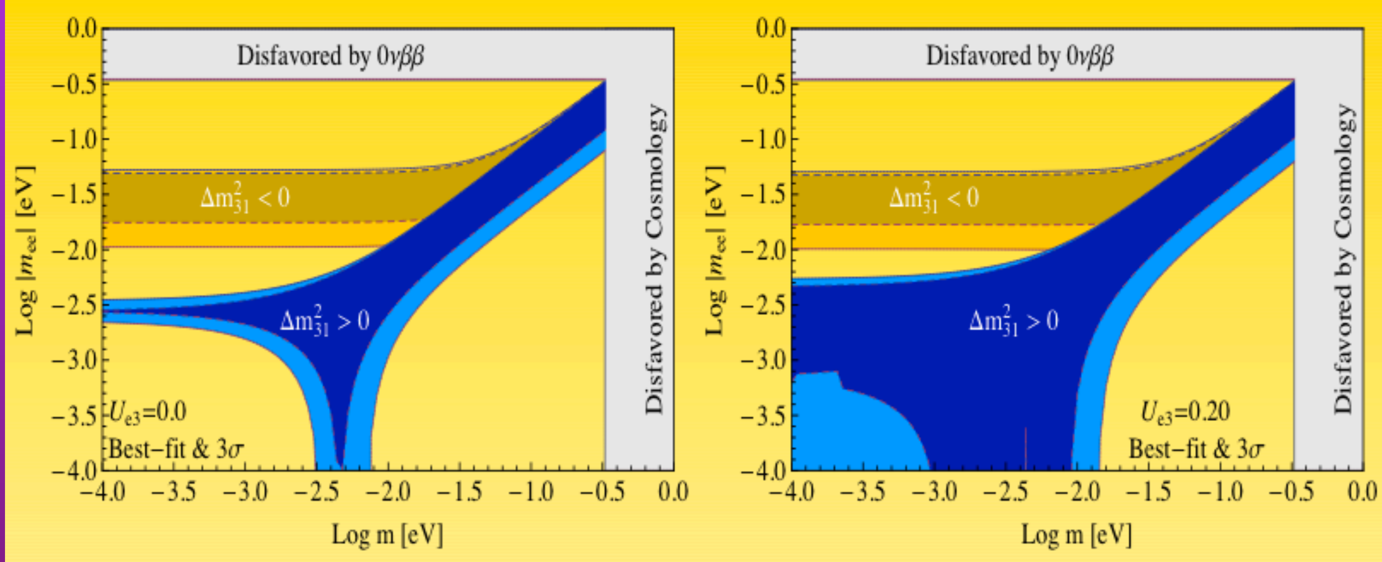
Similarly, if Tritium decay exp. (Hyper-Katrin) could exclude $m_{\nu_e} > \frac{1}{30}\ eV$, then Normal Hierarchy.

Efektywna masa $m_{\beta\beta}$ z rozpadów $2\beta 0\nu$



[Valle]

W. Rodejohann



Note: importance of U_{e3}

Nu2010

Workshop NEU2012

28 Sep 2010

Towards a European Roadmap?

S. Pascoli

1- "**Short-baseline program**" for:
Detector R&D,
Target tests,
cross sections measurement,
sterile neutrino searches

2010 - 2020

2- "**Long baseline superbeam**" program:
CNGS upgrade,
SPS beam to LAGUNA sites (e.g. Umbria, Frejus, Phyasalmi),
SPL to Frejus (EUROnu)

2015 - 2025

3- "**Long baseline ultimate beams**"
Betabeam
Neutrino factory (low or high energy).

2020 - 2030

Podsumowanie

- Różnice δm_{sol} i Δm_{atm} znane z dokł. 3% i 5%
- Kąty mieszania ϑ_{12} i ϑ_{23} z dokł. 6% i 14%
- Borexino potwierdza model MSW; ponadto obserwuje geoneutrina
- Tymczasem $\vartheta_{13}=0$ w granicach błędów
- Bogaty program pomiaru ϑ_{13} już rozpoczęty (T2K), wkrótce zacznie zbieranie danych Double-Chooz, potem Daya-Bay i Nova

Zagadki

MINOS: możliwa różnica w oscylacjach $\nu_\mu \rightarrow \nu_x$ i $\bar{\nu}_\mu \rightarrow \bar{\nu}_x$

MiniBoone: w wiązce $\bar{\nu}_\mu$ możliwy sygnał konsystentny z obserwacjami LSND, niewidoczny w wiązce ν_μ

Zanim ogłosimy łamanie CPT: więcej statystyki i pomiarów oddz. neutrin

CP

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

T $\Updownarrow$ CPT across diagonals $\Updownarrow$ T

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

CP

- First Row: Superbeams where ν_e contamination $\sim$1 %
- Second Row: ν-Factory or β-Beams, no beam contamination

However

for ν-Factory: Distinguish μ^+ from μ^- at 10^{-4}

for β-Beam: Distinguish μ from e in Water Cerenkov or LAr

INTERNATIONAL UNDERGROUND LABORATORIES (Present and Planned)