Symposium Summary

Prospects for Neutrino Physics

International Symposium on Neutrino Physics and Beyond
Shenzhen, China
September 26, 2012

Stanley Wojcicki
Stanford University

Topics Discussed

- Status of oscillations
  - Recent Results
  - Phenomenology, Theory
  - Sterile neutrino situation
- Neutrino mass
  - Tritium, cosmology, double beta decay
- Dark matter searches
- Natural sources
  - Solar, geoneutrinos, cosmic rays
- Future
  - Completing the oscillation picture (CP, mass hierarchy, θ_{23})
  - New facilities (accelerators and detectors)

Oscillations: 1998 and 2012

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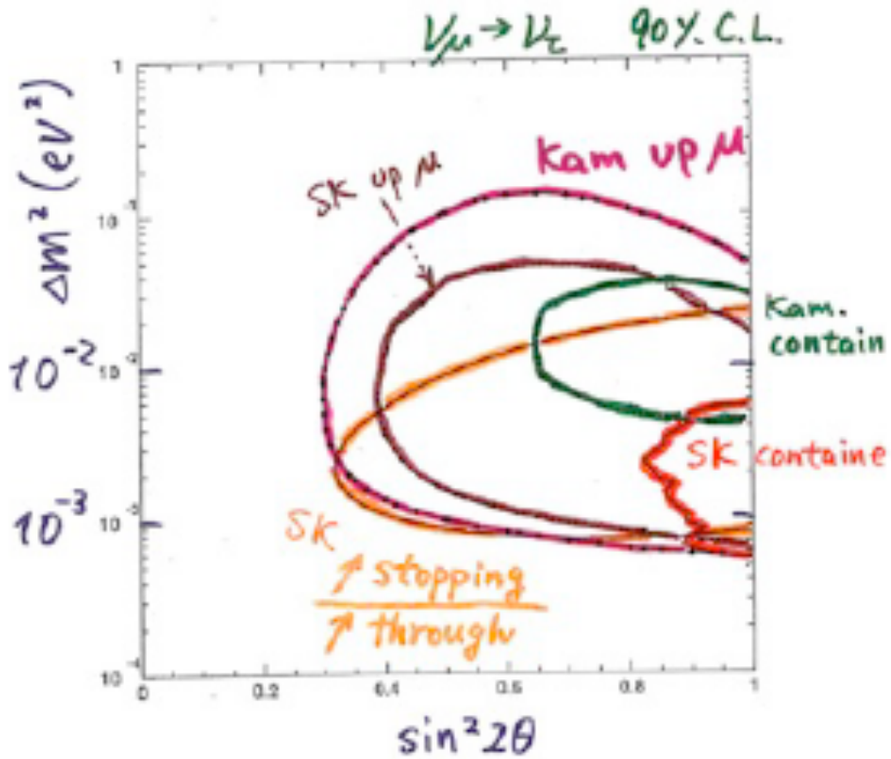
Summary Neutrino1998

Evidence for ν_μ oscillations



- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

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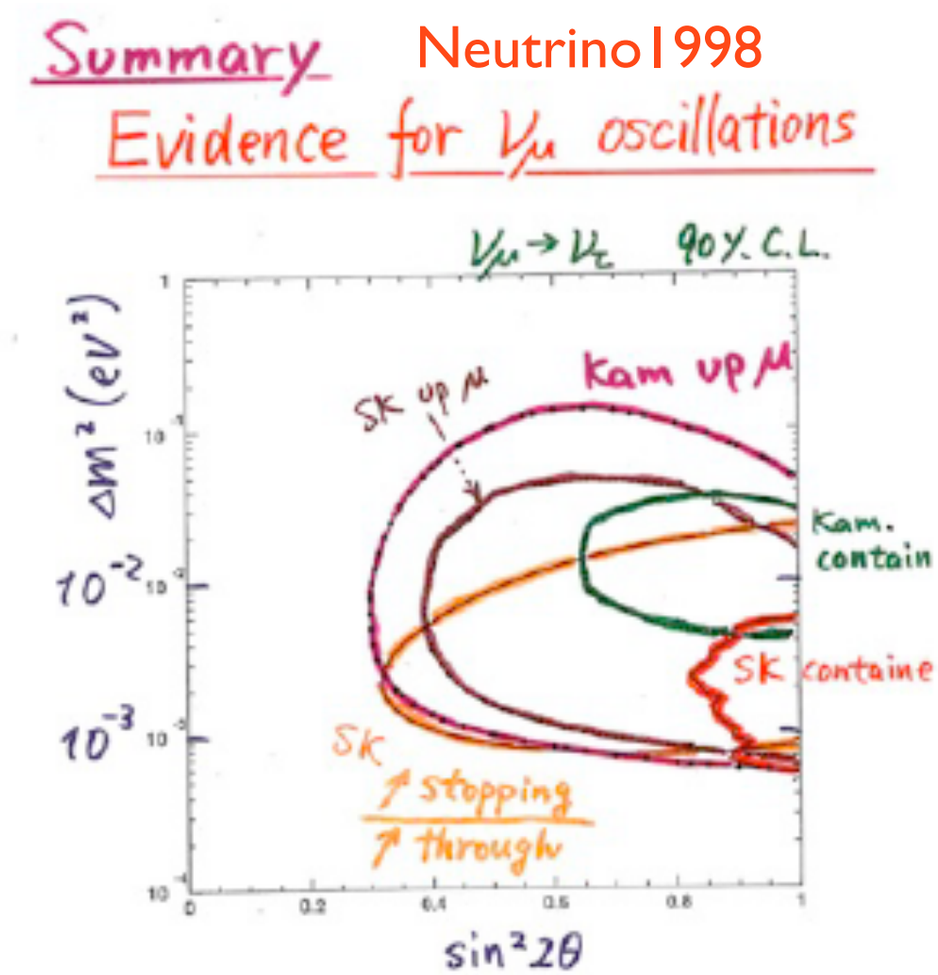

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2012 Status

(from Lisi's 3ν fit)

$$\Delta m^2_{23} = (2.43^{+0.06}_{-0.10}) \times 10^{-3}\ eV^2$$
$$\Delta m^2_{12} = (7.54^{+0.26}_{-0.22}) \times 10^{-5}\ eV^2$$
$$\sin^2\theta_{13} = 0.0242^{+0.0025}_{-0.0025}$$
$$\sin^2\theta_{12} = 0.307^{+0.18}_{-0.16}$$
$$\sin^2\theta_{23} = 0.389^{+0.24}_{-0.21}$$

Fractional 1σ accuracy [defined as 1/6 of ±3σ range]

δm^2	Δm^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
2.6%	3.0%	5.4%	10%	14%

$\theta_{13} \rightarrow$ Second Phase Change

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$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

To complete our knowledge of this current neutrino Standard Model we need to determine mass hierarchy, δ_{CP}, and θ_{23} octant. To achieve this, (global?) 3ν analyses will be needed

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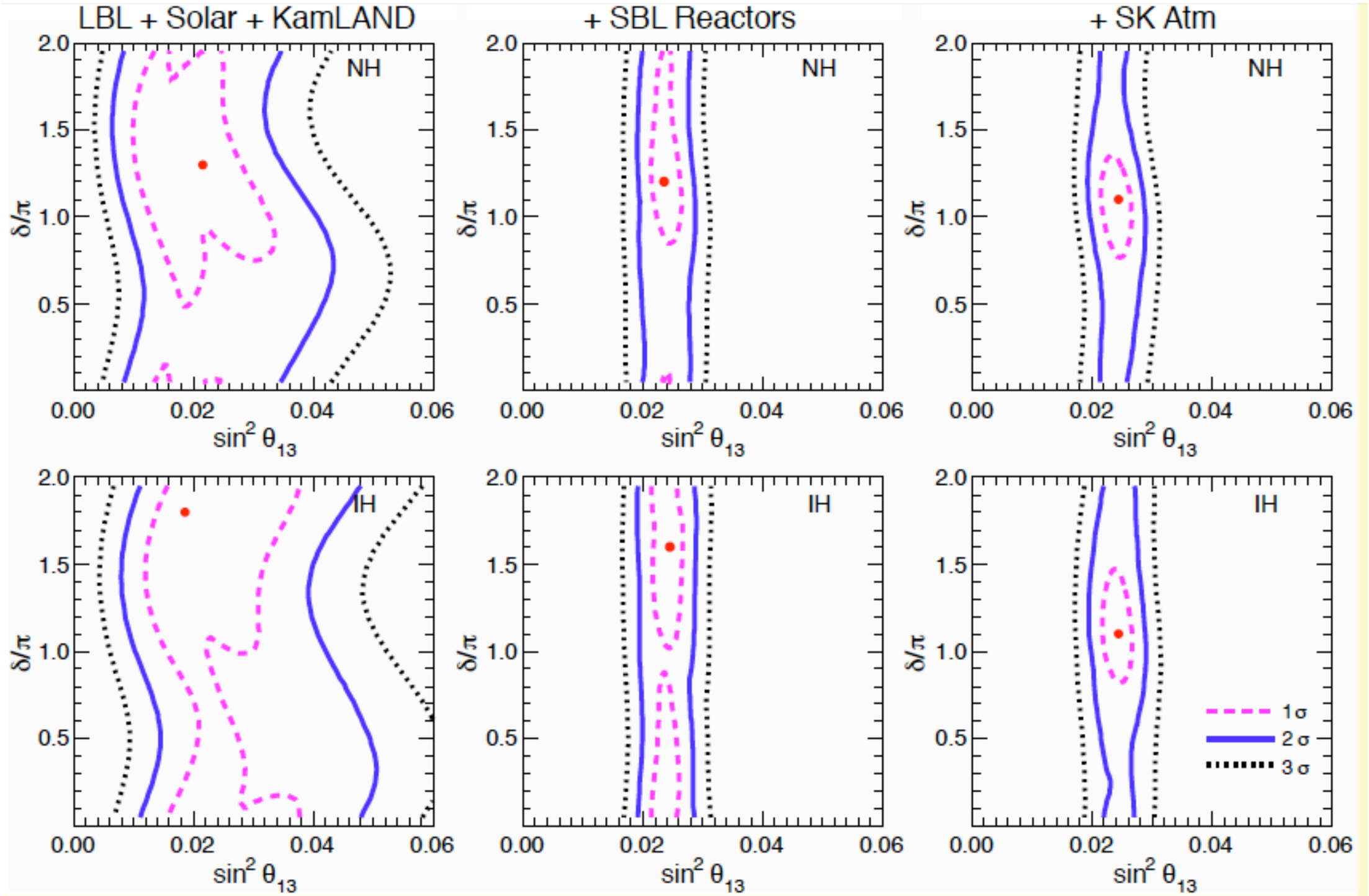
Known, large θ_{13} allows us to define future program

Global Analysis - Example from Lisi



New Results on θ_{13}

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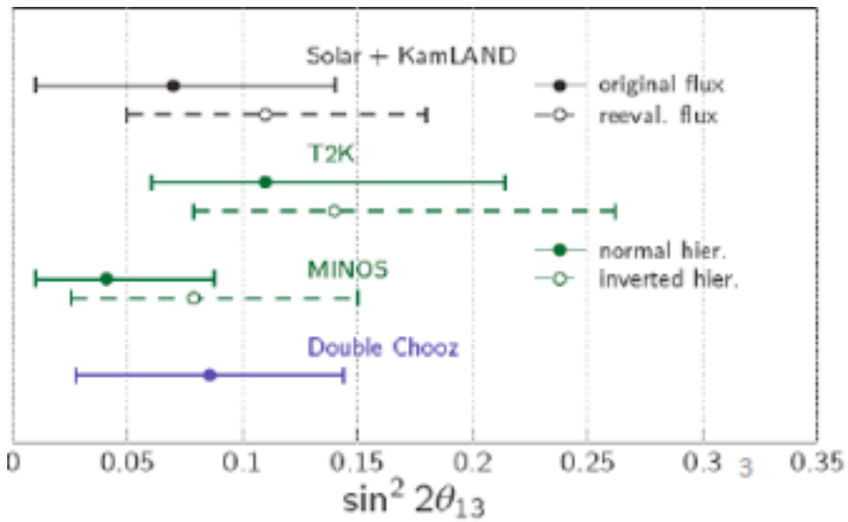

Pre-Daya Bay

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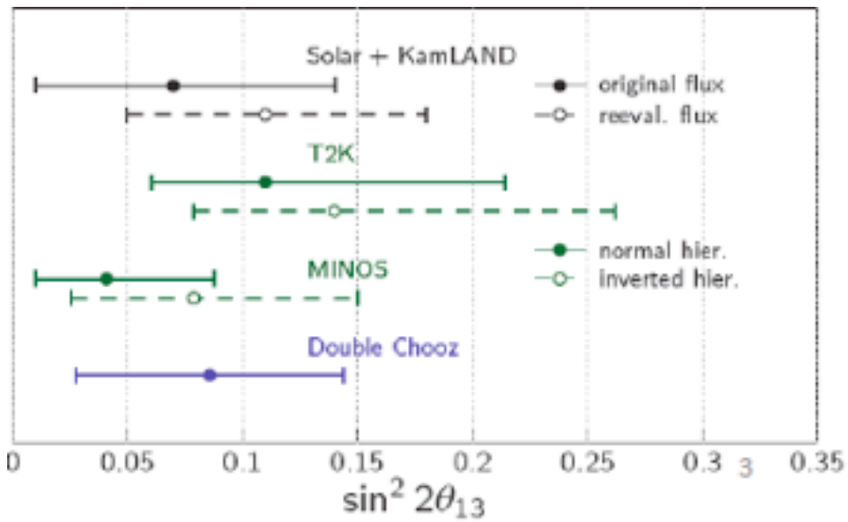

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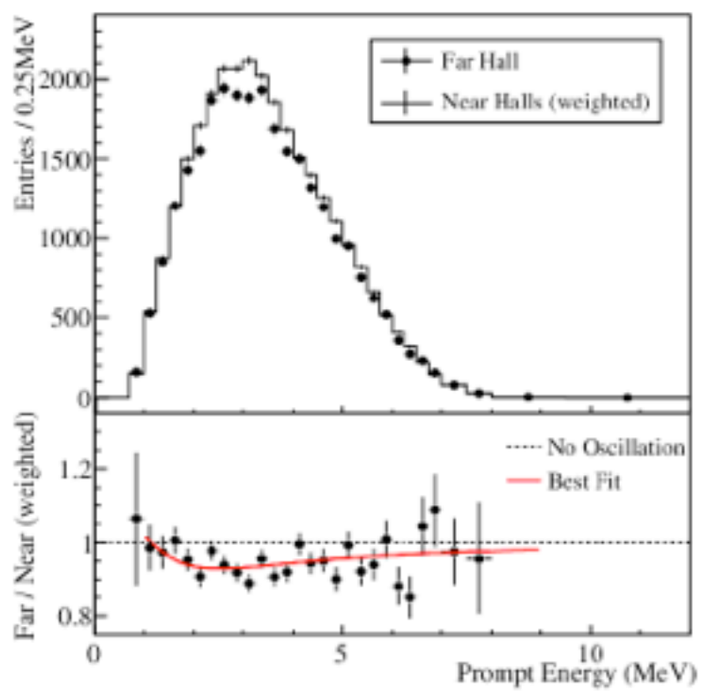
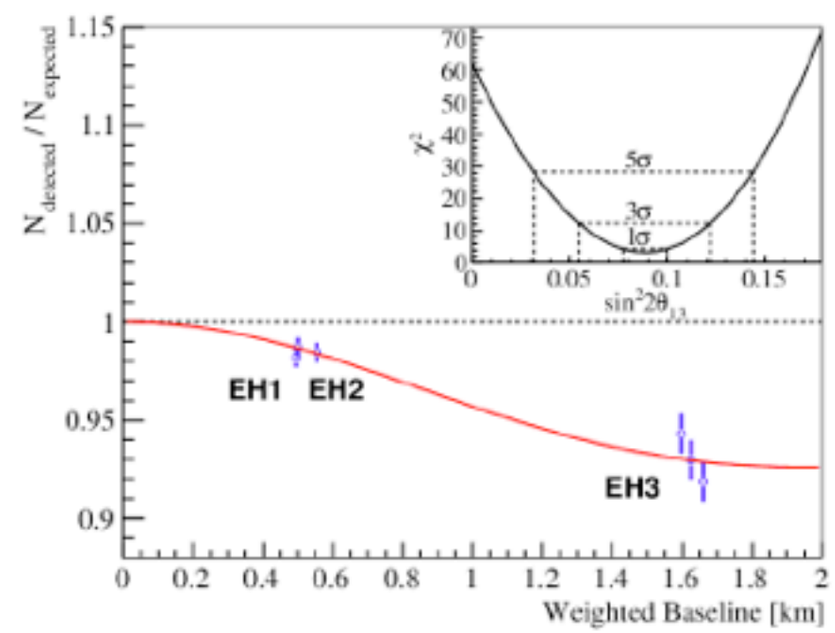
Most Recent Daya Bay Results





R = 0.944 ± 0.007 (stat) ± 0.003 (syst)

$\sin^2 2\theta_{13}$=0.089±0.010(stat)±0.005(syst)

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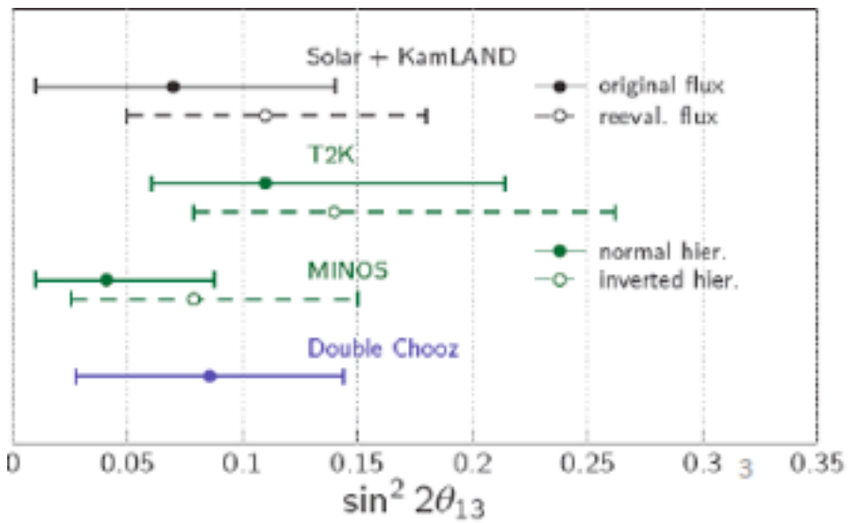

Pre-Daya Bay

Other Recent results

RENO: 0.113±.013±.019

Double-Chooz: 0.109±.03

T2K: $0.094^{+.053}_{-.040}$ (NH)
$0.116^{+.063}_{-.049}$ (IH)

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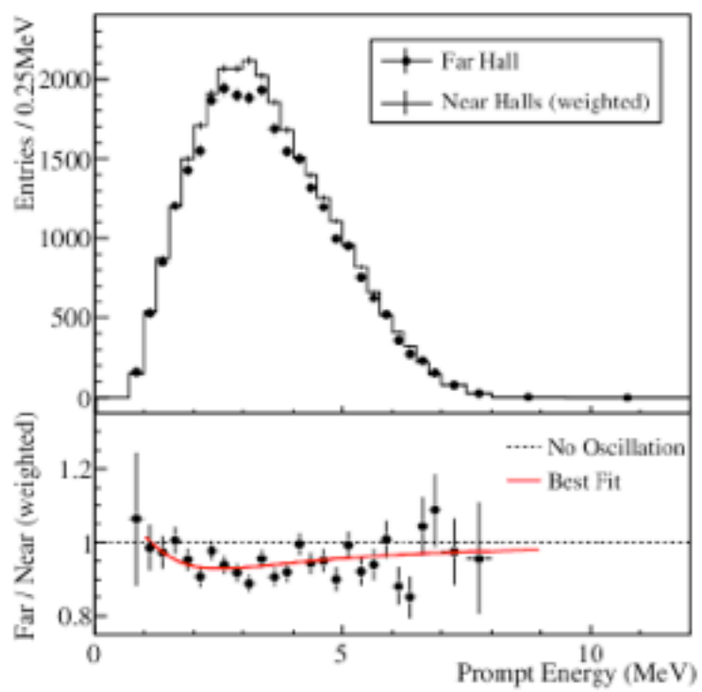

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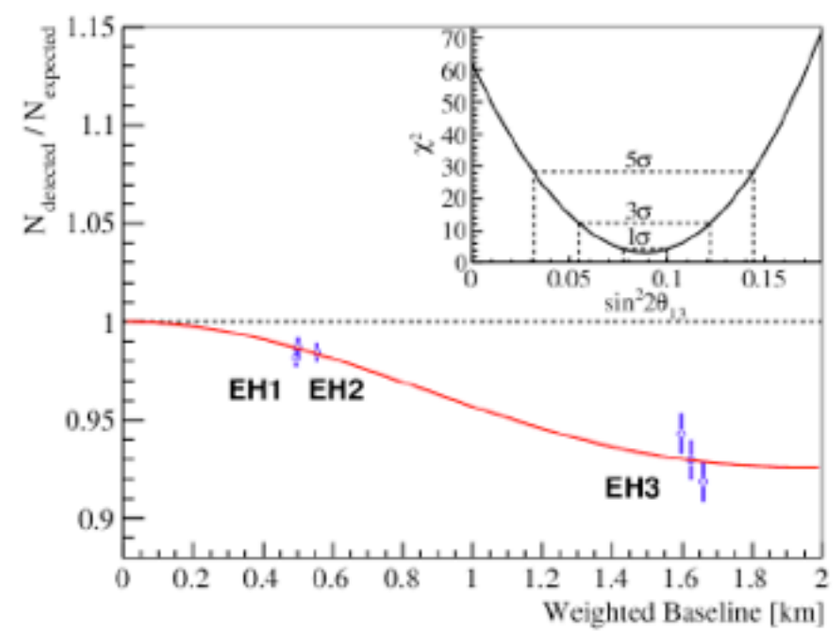

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Atmospheric Sector

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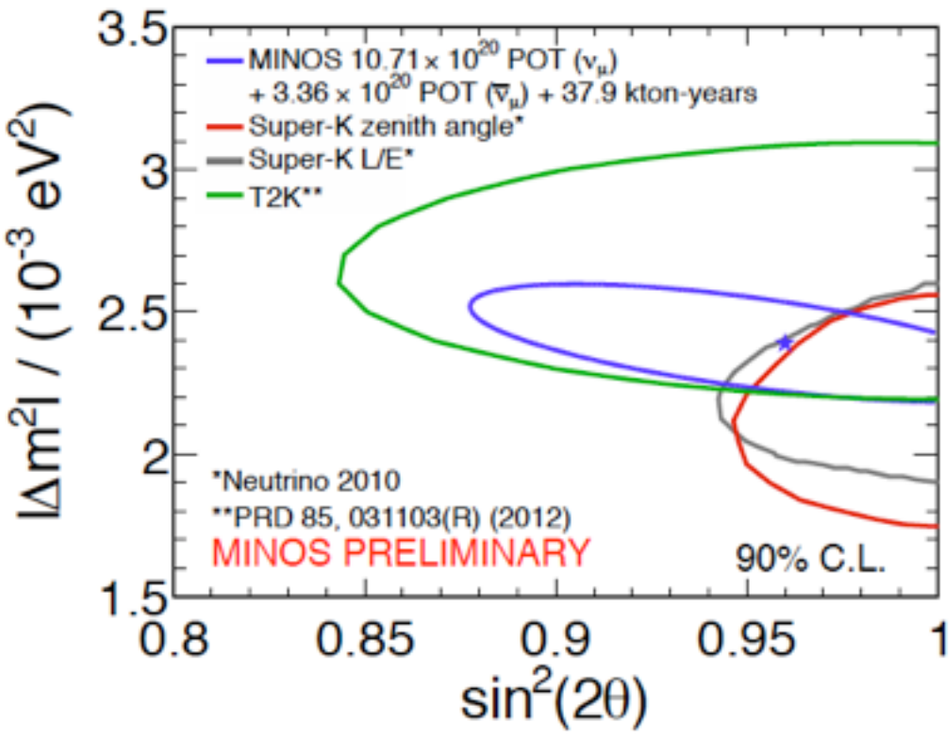
Summary of different analyses
Good agreement



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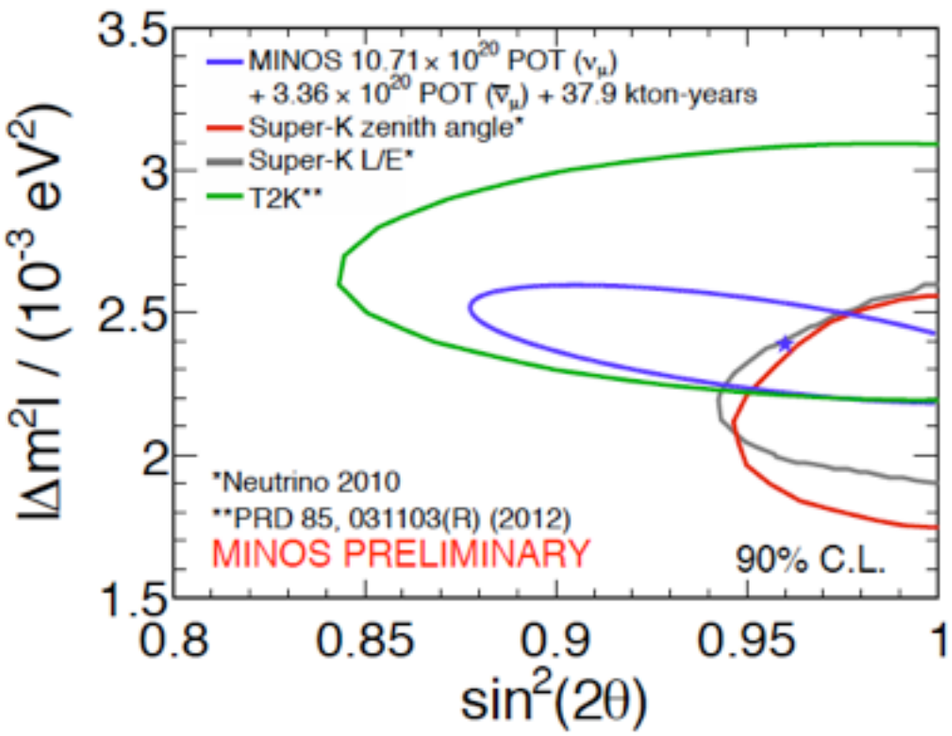

Neutrino Result

$\Delta m^2 = 2.41^{+0.11}_{-0.10} \times 10^{-3}\ eV^2$

$\sin^2(2\theta) = 0.94^{+0.04}_{-0.05}$

Antineutrino Result

$\overline{\Delta m}^2 = 2.60^{+0.28}_{-0.23} \times 10^{-3}\ eV^2$

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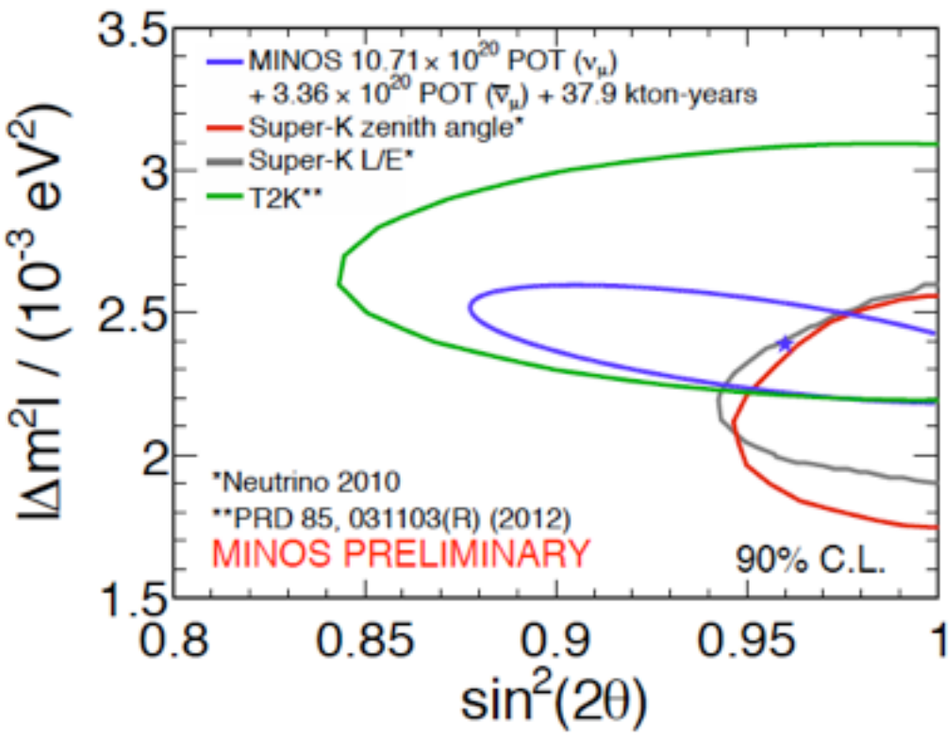

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ν_T's <u>are</u> produced in these oscillations;
OPERA finds expected no of events (2 so far)

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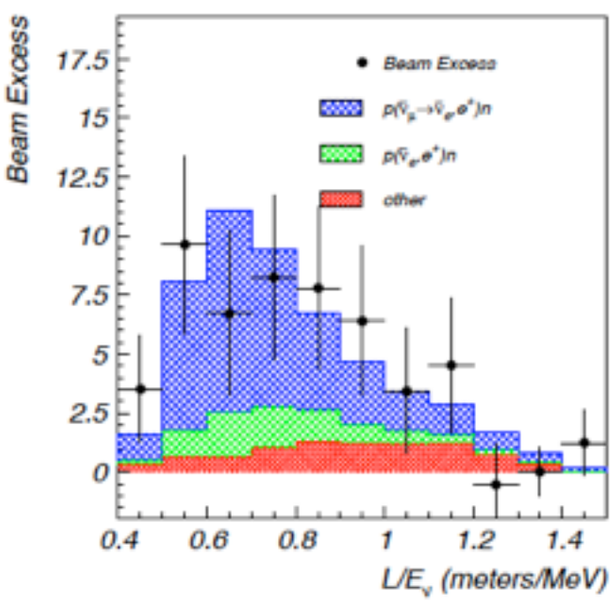
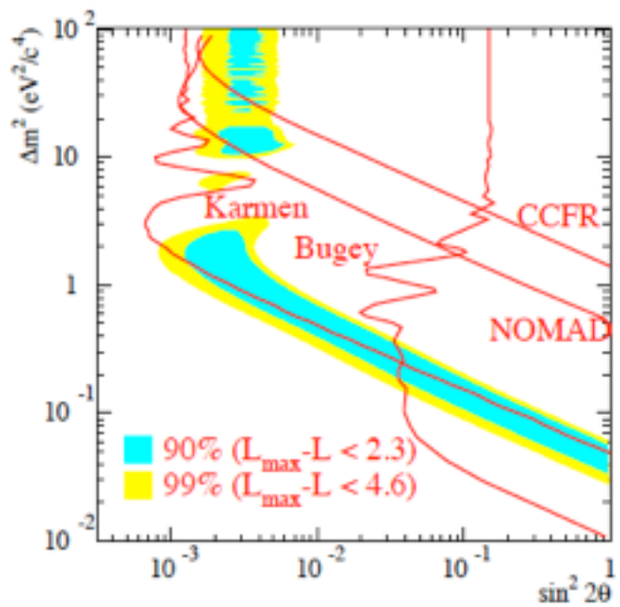
$\bar{\nu}_\mu \to \bar{\nu}_e$ $L \simeq 30$ m $20\ \text{MeV} \leq E \leq 200\ \text{MeV}$





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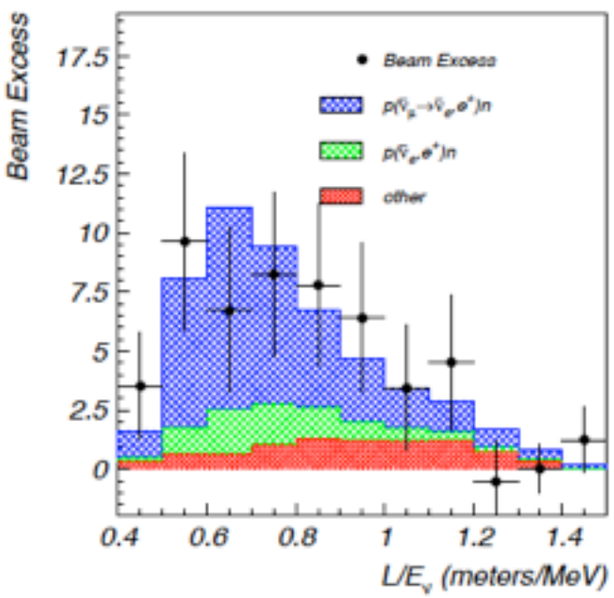
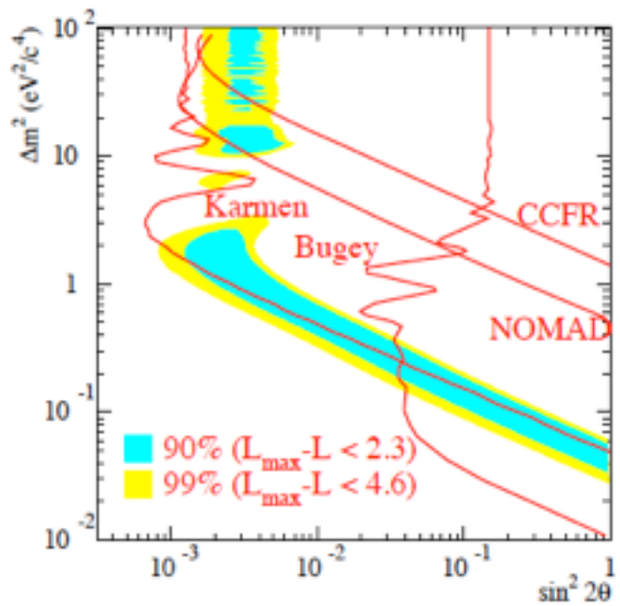
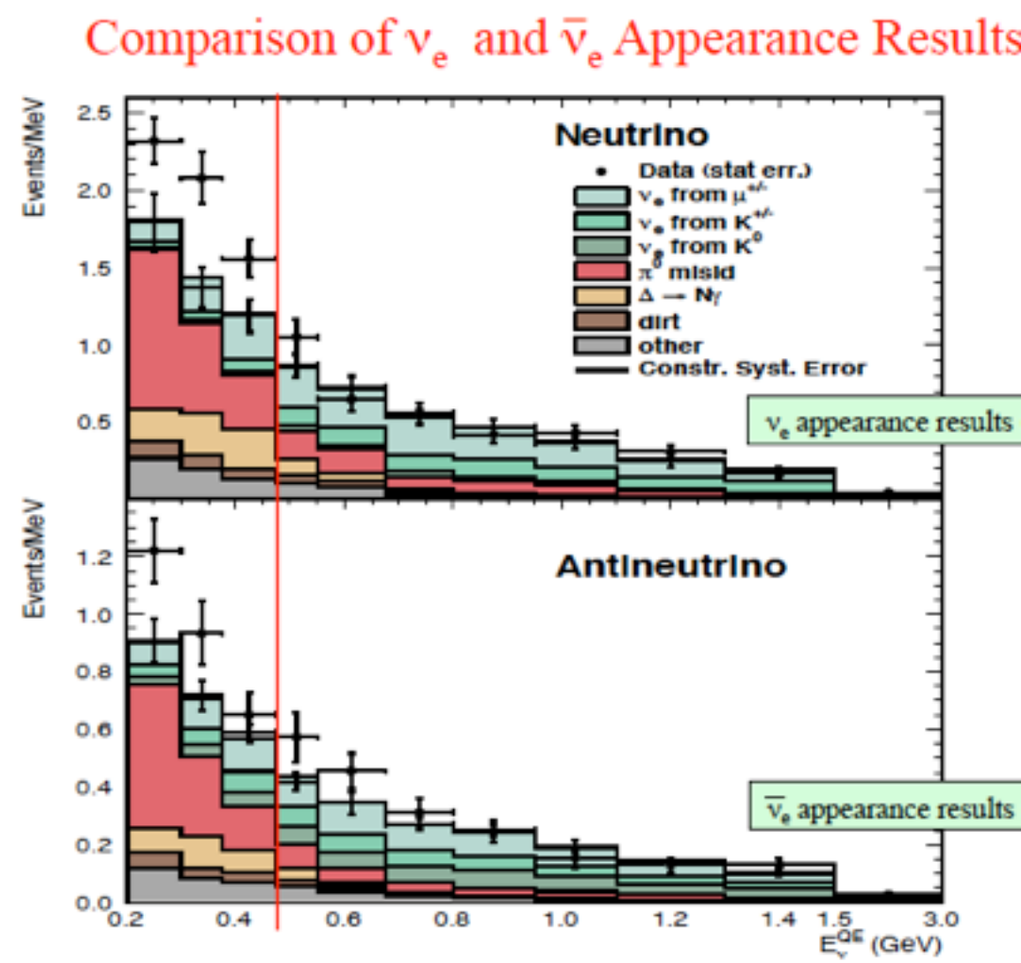




MiniBooNE

L≈540 MeV 200 MeV≤E≤3 GeV



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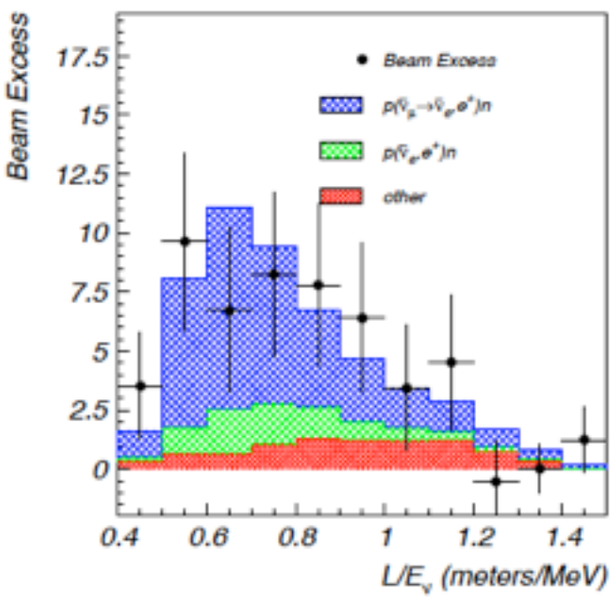

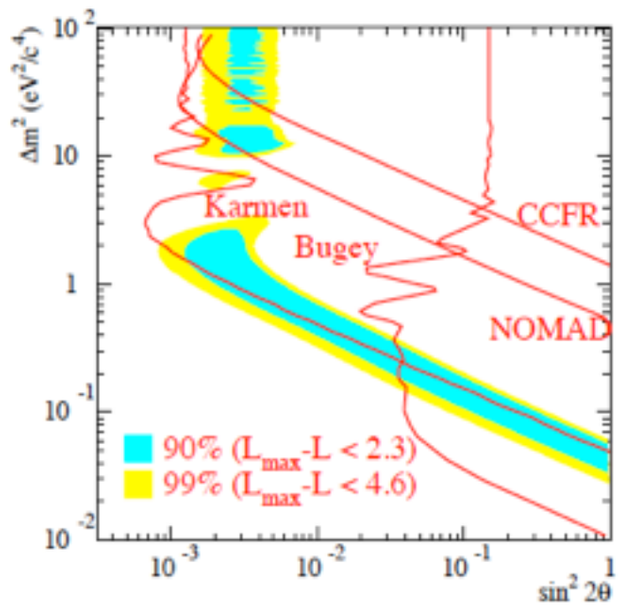

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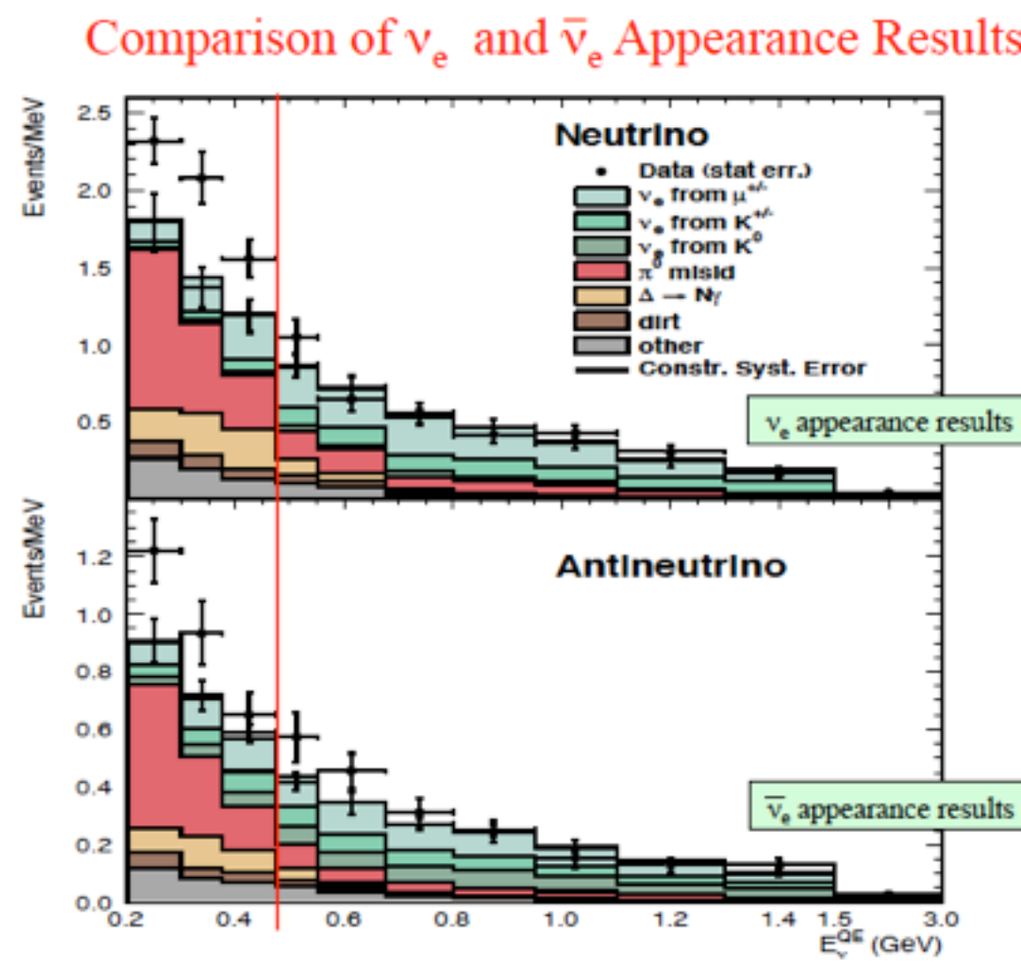

No convincing evidence in MiniBooNE for CP violation

Excess at low energy (E<475MeV) - below LSND region

Marginal support for the LSND effect

Disappearance $\nu_e, \overline{\nu_e}$

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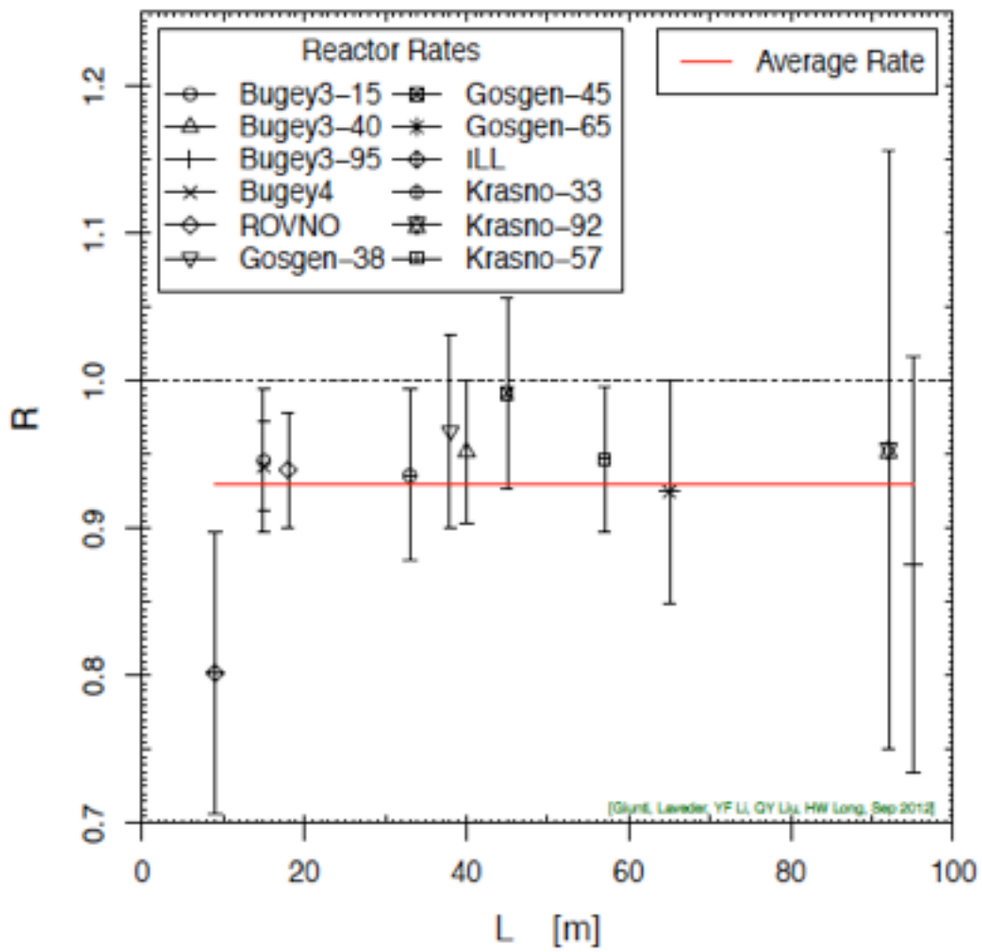
Reactor rate ratios



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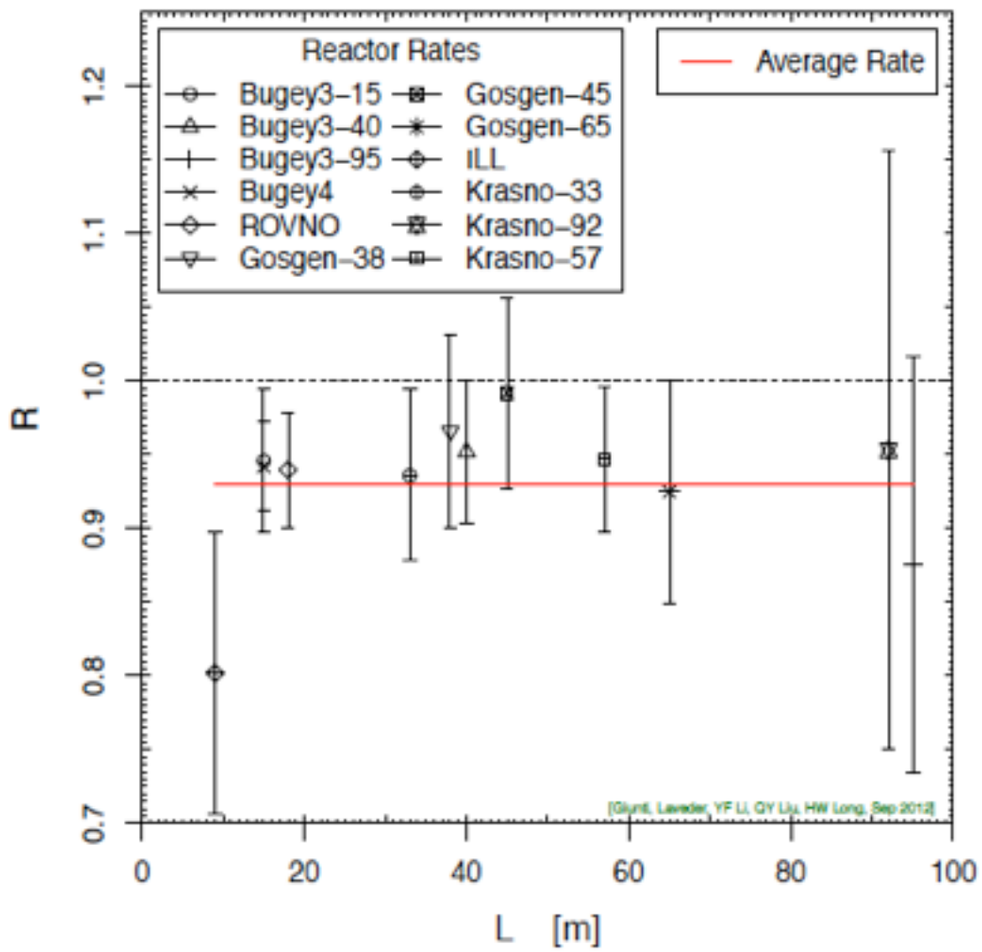

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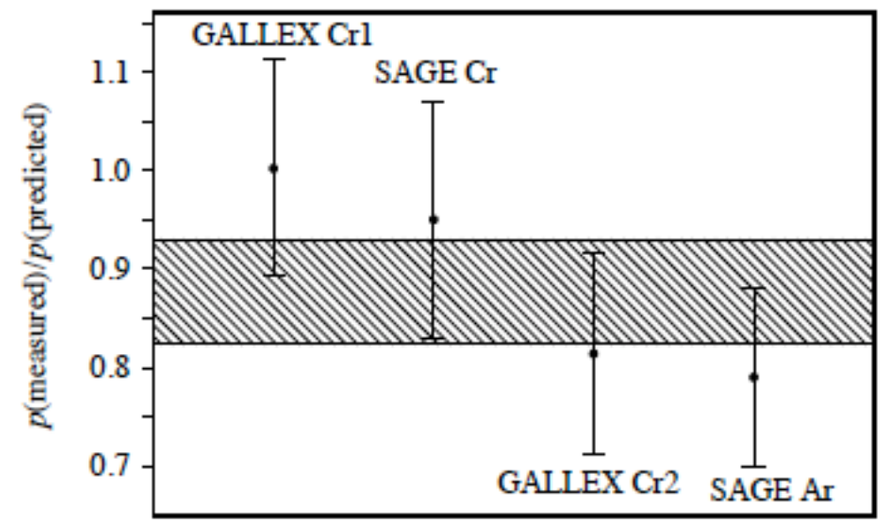

[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

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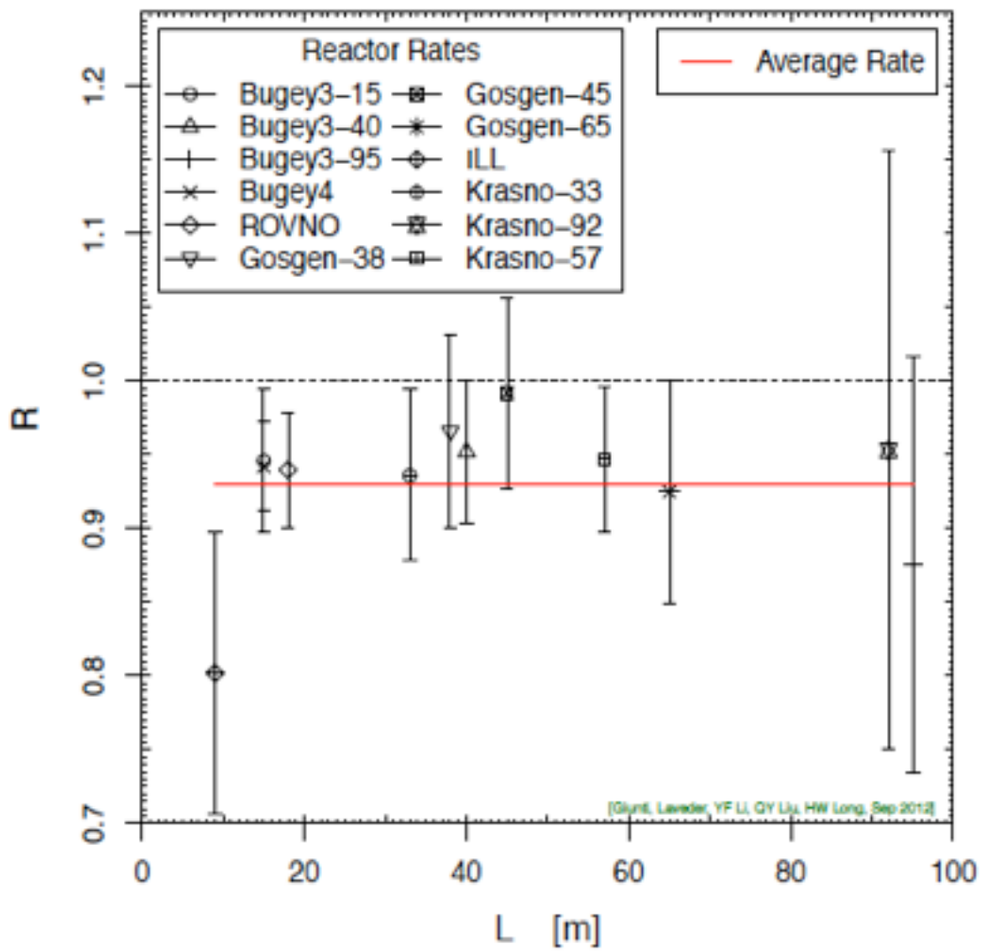

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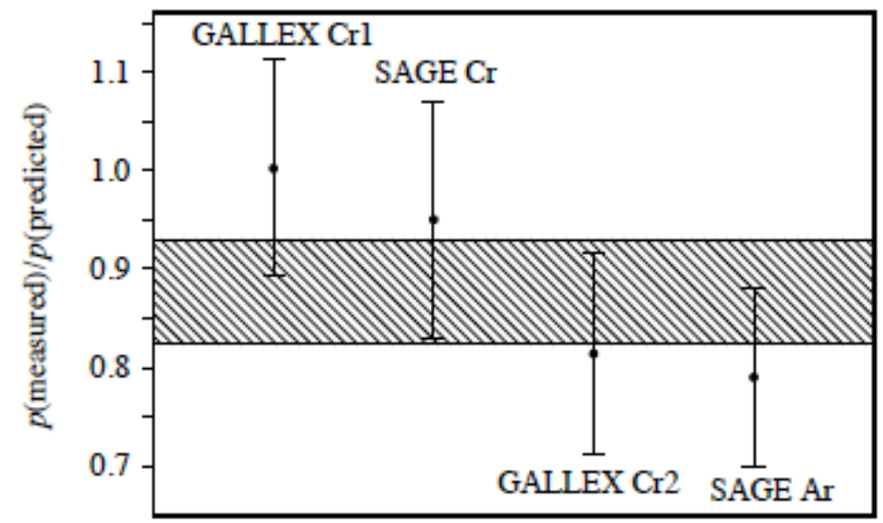

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Several ideas for new very short baseline experiments to explore this anomaly (eg Borexino,DAEδALUS...)

Appearance/Disappearance Tension

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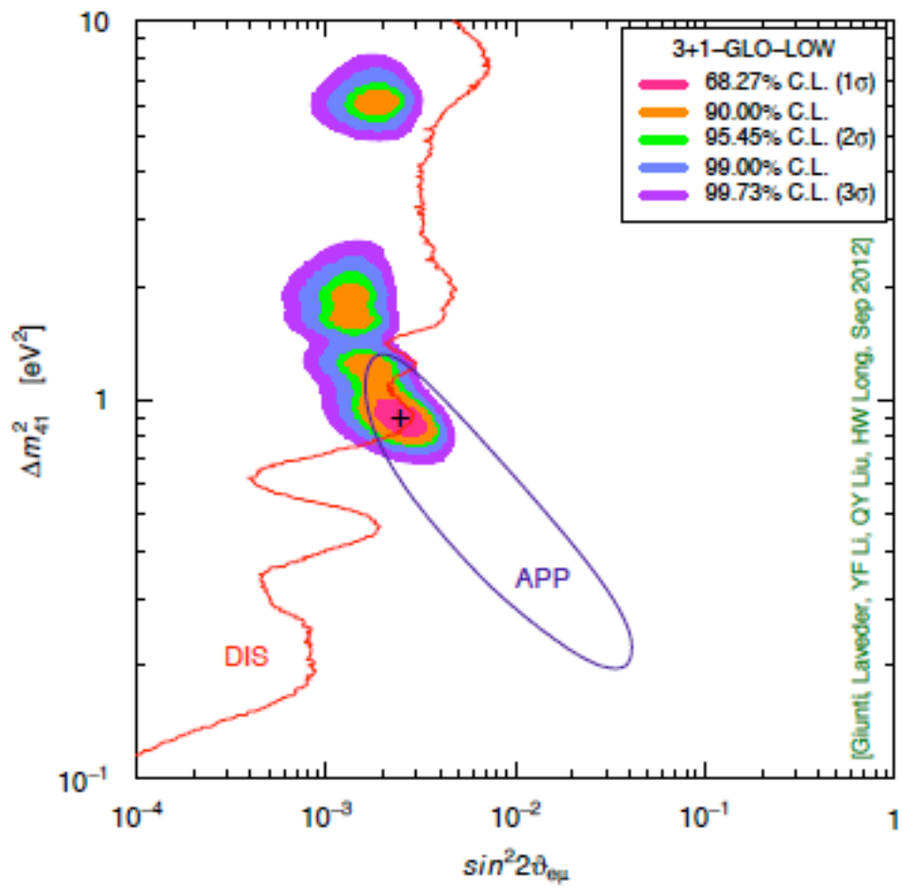
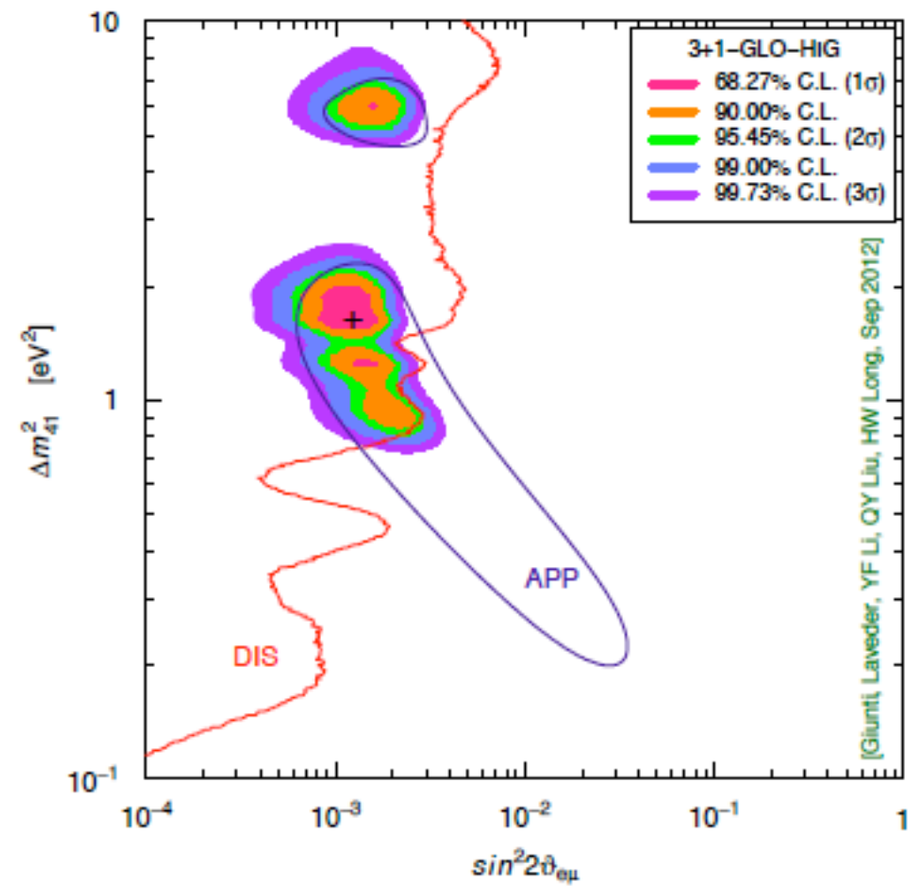
3+1 Global Fit



No Osc. GoF = 0.021%
3+1 GoF = 9.9%
PGoF = 0.01%



No Osc. GoF = 0.87%
3+1 GoF = 32%
PGoF = 0.7%

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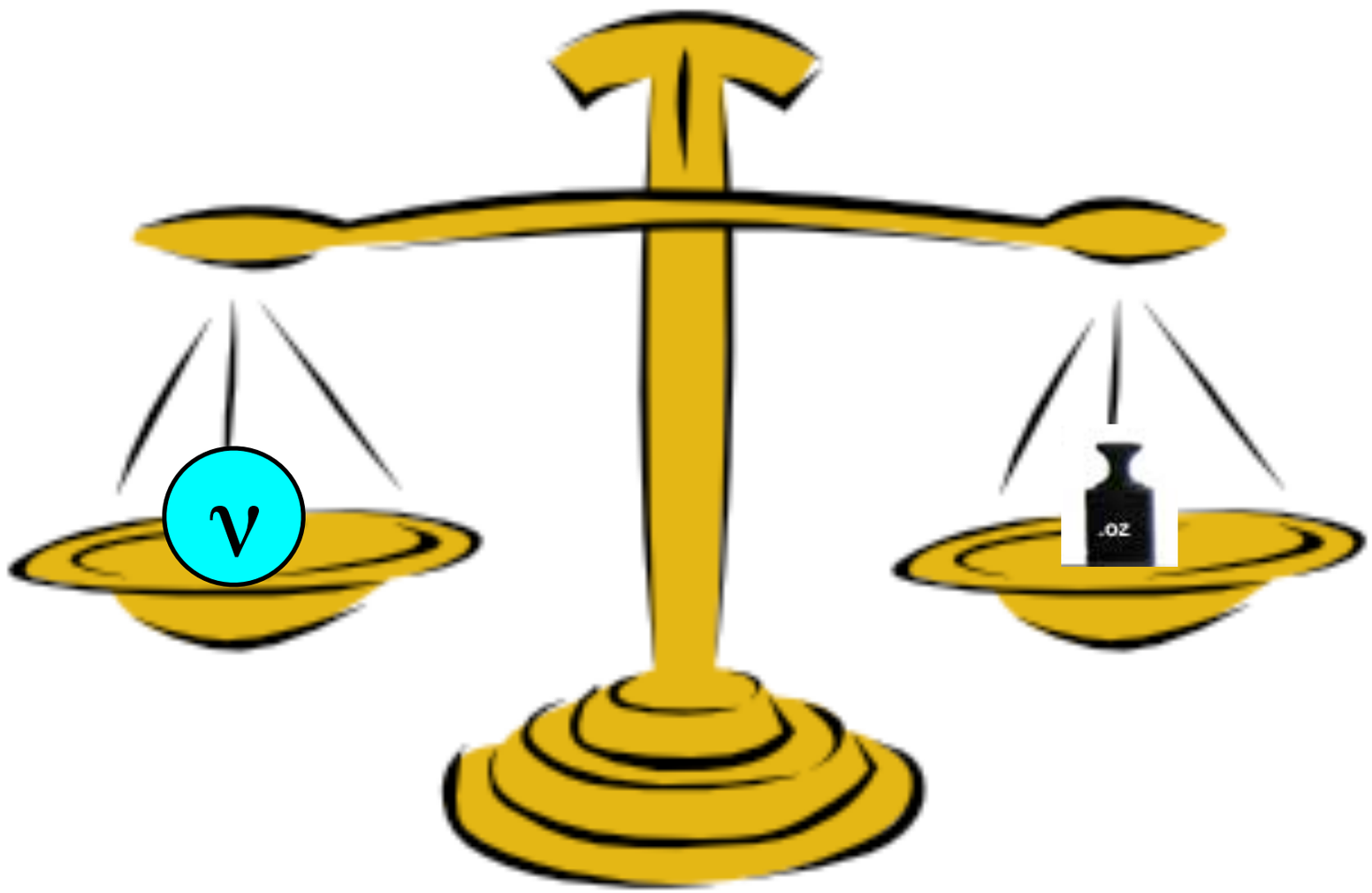
- ✓ Still need to measure the phase δ_{CP}, determine the mass hierarchy and determine the θ_{23} octant
- ✓ LSND anomaly remains unresolved

Neutrino Masses



Methods

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Current limits for the neutrino mass

Cosmology:
- LSS, CMB, …
- model dependent
- status: $\Sigma m_\nu < 0.4$ eV (0.3 – 2.0 eV)
- future sensitivity: 0.1 – 0.6 eV

$$\sum_{j=1}^{3} m_j$$

S. Hannestad et al., *JCAP 08* (2010) 001

Supernova:
- ToF measurement SN 1987A
- status: $m_\nu < 5.7$ eV (PDG 2006)
- future sensitivity: sub-eV ?

neutrino mass measurements

complementary measurements

0νββ-decay:
- eff. Majorana mass
- model dependent (NME)
- cancellation ? (Majorana phase α)
- status: $m_{\beta\beta} = 0.32$ eV ? (K.-K.)
- future sensitivity: 20 – 50 meV

$$\sum_{j=1}^{3} \left|U_{ej}\right|^2 \times e^{i\alpha_j} \times m_j$$

β-decay:
- eff. neutrino mass
- model independent (kinematics)
- status: $m_\beta < 2$ eV (Mainz, Troitsk)
- future sensitivity: 200 meV

$$\sum_{j=1}^{3} \left|U_{ej}\right|^2 \times m_j$$

β - Decay

KATRIN - culmination of several decades of work mainly at Troitsk and Karlsruhe

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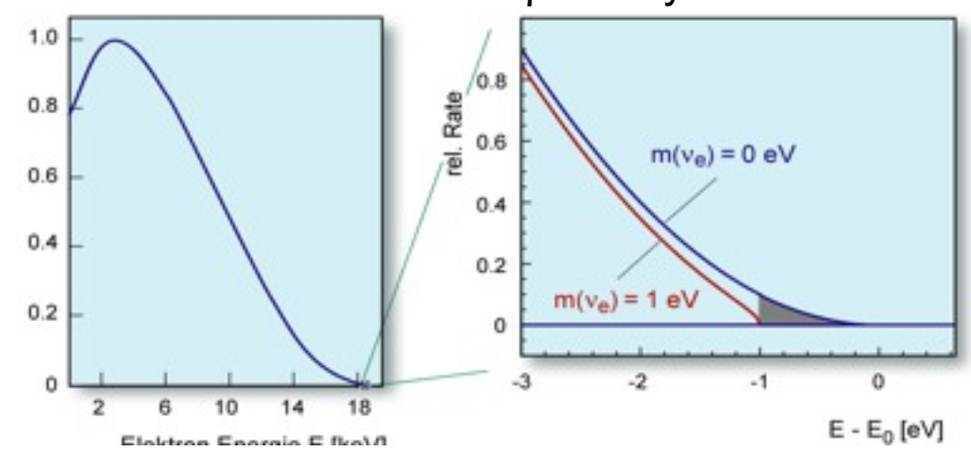

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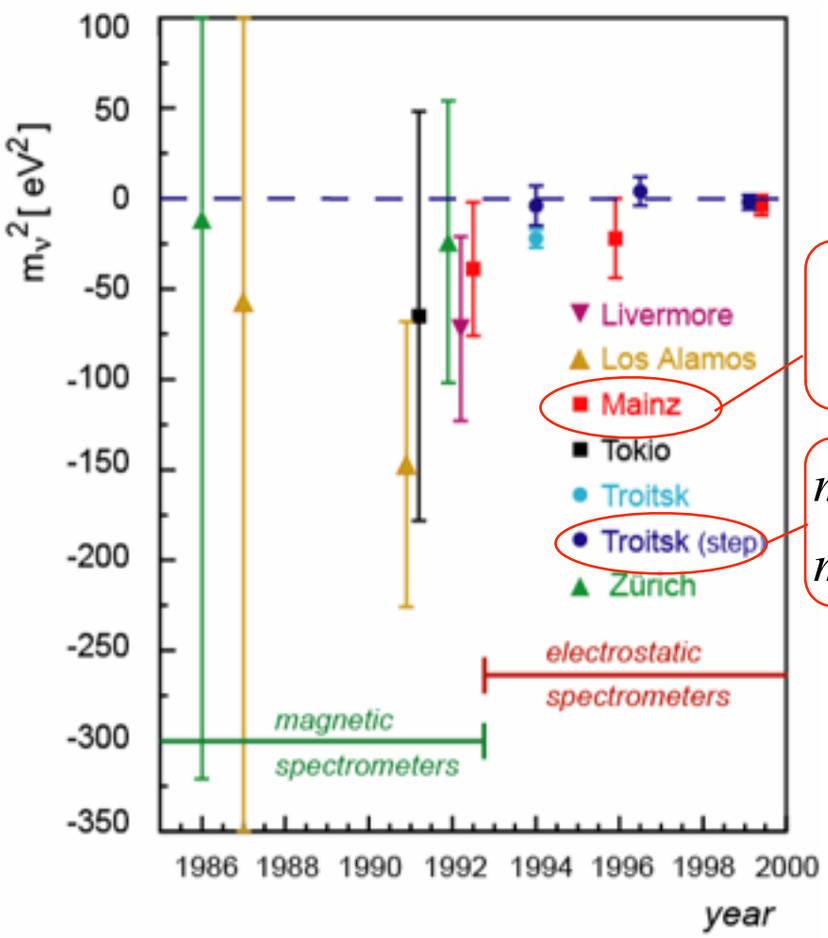

$$m_\nu^2 = -0.6 \pm 2.2_{stat} \pm 2.1_{syst}\,\mathrm{eV}^2$$
$$m_\nu \leq 2.3\,\mathrm{eV}(95\%CL)$$

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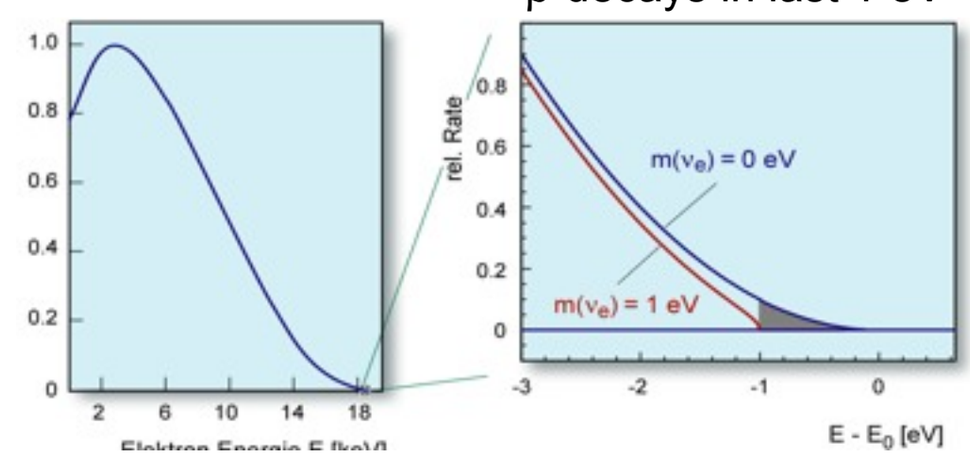

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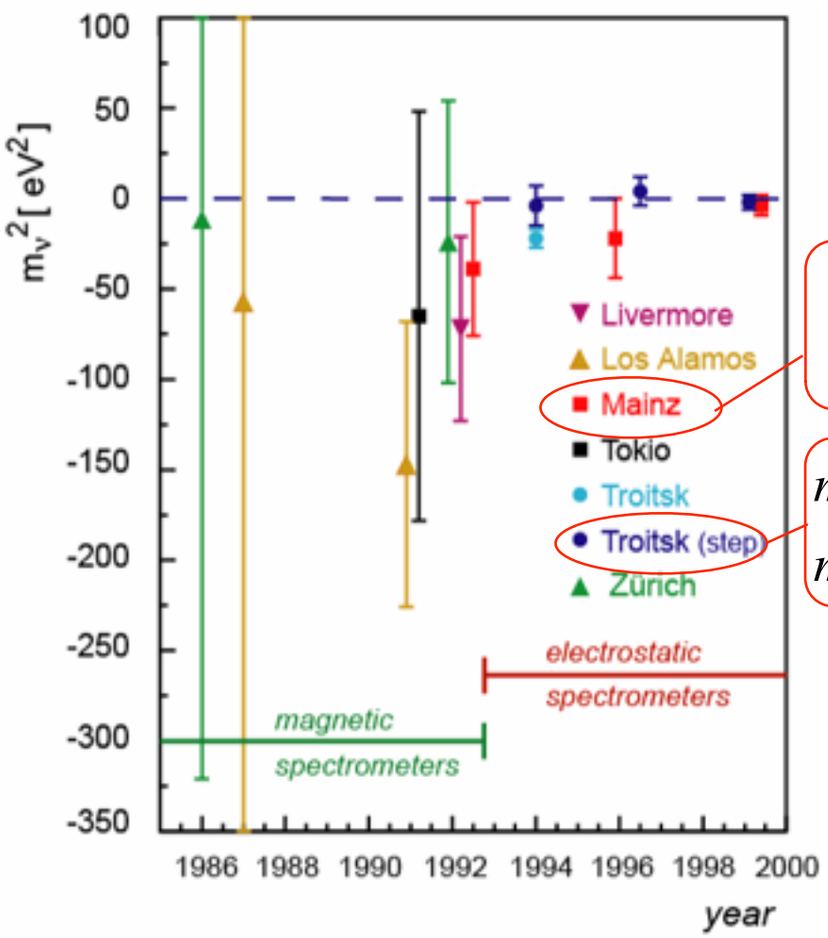

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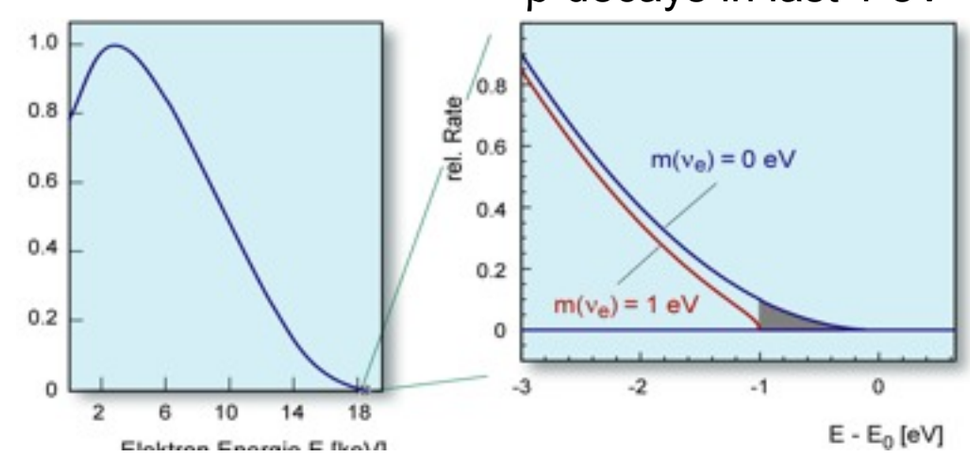

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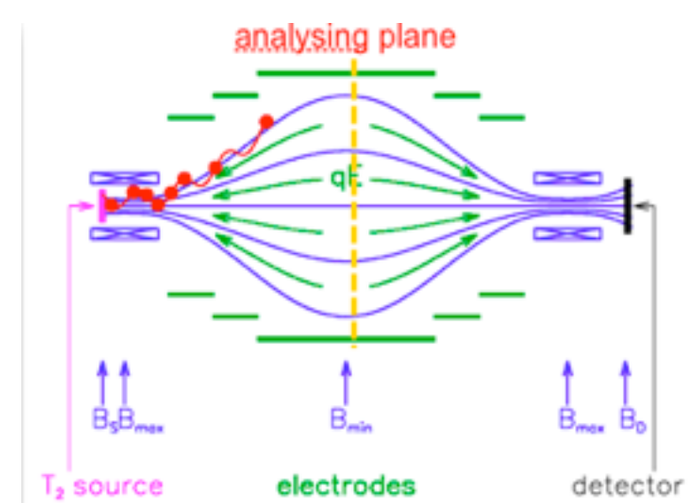

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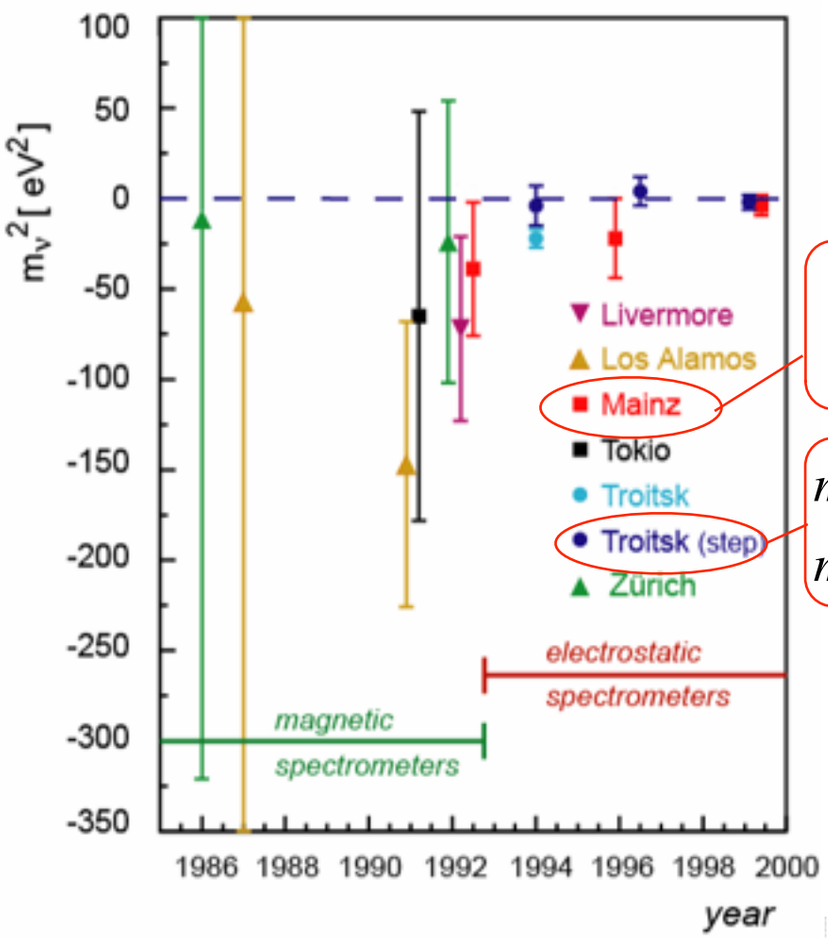

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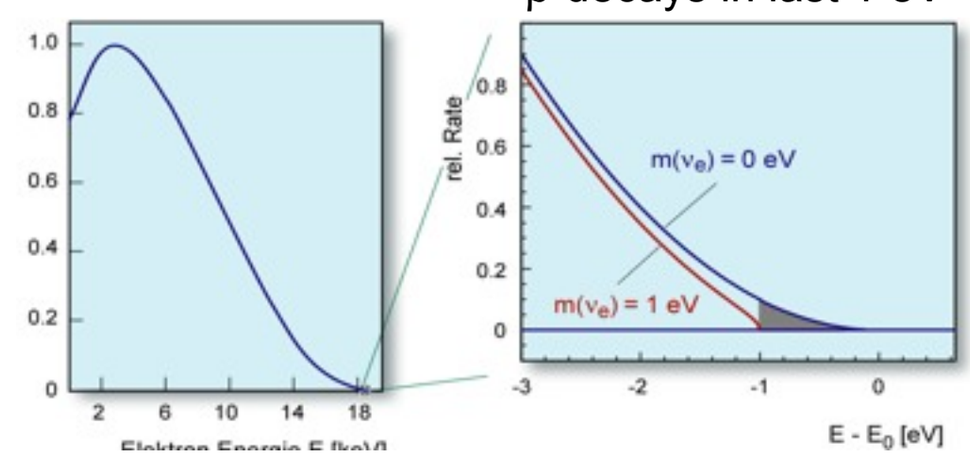

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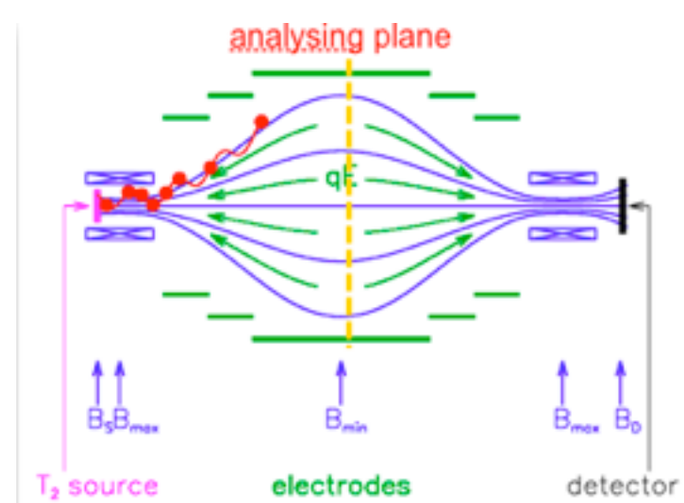

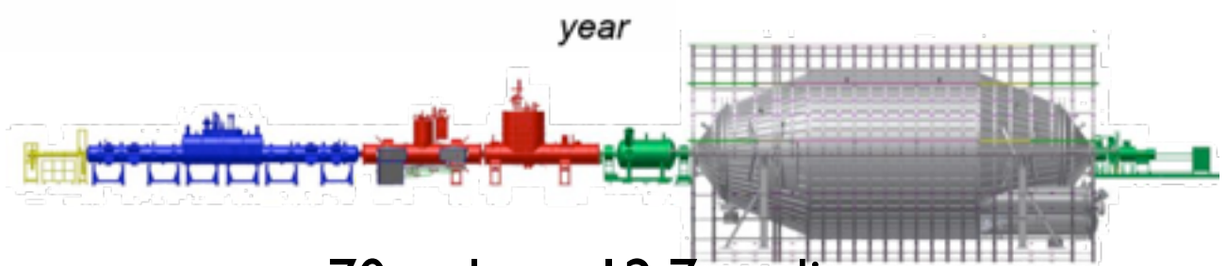

~70 m long, 12.7 m diameter

Katrin Sensitivity, Future

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systematical and statistical errors comparable (3 yrs)
Pretty much impossible to scale it up but some improvement (~x2) might be possible
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Other possible approaches being studied:
^{187}Rhe - calorimetric method (cryogenic bolometer)
E_0=2.47 keV $\tau_{1/2}$ = 48.2 Gy
Project 8 - radio frequency spectroscopy of coherent cyclotron radiation from decay electrons from tritium

Double-Beta Decay - General

from Rodejohann

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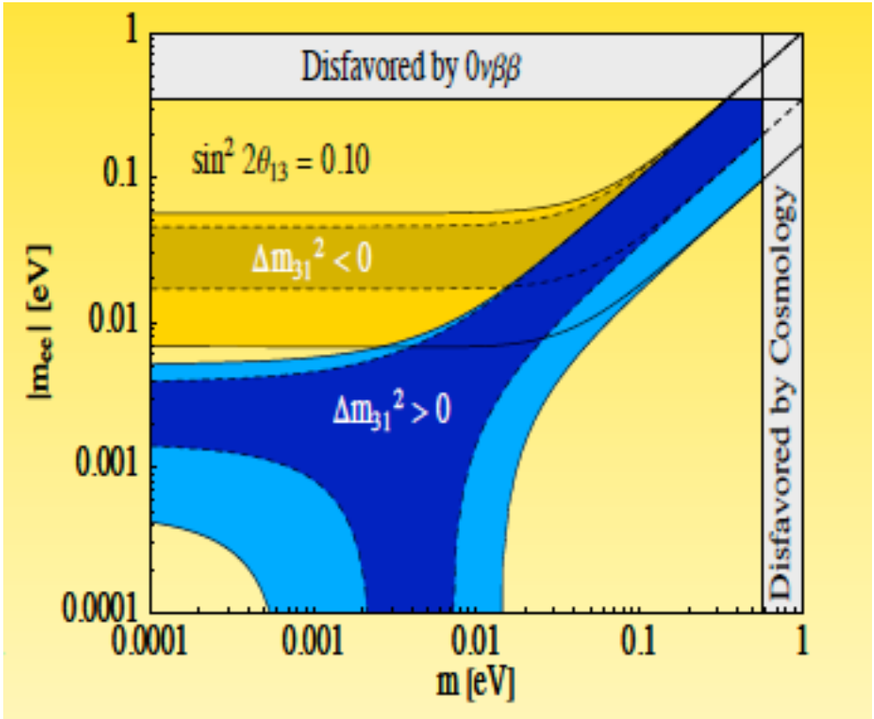

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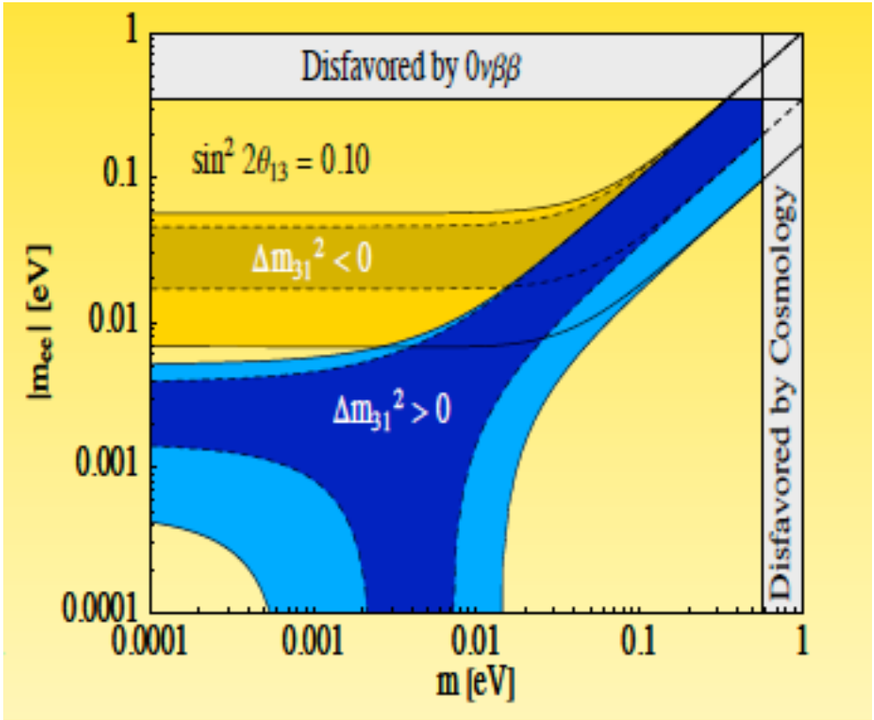

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Dependence of $m_{\beta\beta}$ limit:

W/o background: $m_{\beta\beta} < \text{const}/(MT)^{1/2}$

With background: $m_{\beta\beta} < \text{const}(b\Delta E/MT)^{1/4}$

Double-Beta Decay - Experiments

Experiment	Isotope	Mass of Isotope [kg]	Sensitivity $T^{0\nu}_{1/2}$ [yrs]	Status	Start of data-taking	Sensitivity $\langle m_\nu \rangle$ [eV]
GERDA	^{76}Ge	18	3×10^{25}	running	$\sim$ 2011	0.17-0.42
		40	2×10^{26}	in progress	$\sim$ 2012	0.06-0.16
		1000	6×10^{27}	R&D	$\sim$ 2015	0.012-0.030
CUORE	^{130}Te	200	$6.5 \times 10^{26*}$	in progress	$\sim$ 2013	0.018-0.037
			$2.1 \times 10^{26**}$			0.03-0.066
MAJORANA	^{76}Ge	30-60	$(1-2) \times 10^{26}$	in progress	$\sim$ 2013	0.06-0.16
		1000	6×10^{27}	R&D	$\sim$ 2015	0.012-0.030
EXO	^{136}Xe	200	6.4×10^{25}	running	$\sim$ 2011	0.073-0.18
		1000	8×10^{26}	R&D	$\sim$ 2015	0.02-0.05
SuperNEMO	^{82}Se	100-200	$(1-2) \times 10^{26}$	R&D	$\sim$ 2013-15	0.04-0.096
KamLAND-Zen	^{136}Xe	400	4×10^{26}	running	$\sim$ 2011	0.03-0.07
		1000	10^{27}	R&D	$\sim$ 2013-15	0.02-0.046
SNO+	^{150}Nd	132	1.8×10^{25}	in progress	$\sim$ 2014	0.09-0.18

(with *same* lifetime: ^{150}Nd and ^{100}Mo do best...)

from Rodejohann

Approaching interesting sensitivity; for the future main effort on reducing backgrounds and increasing mass

EXO measurement contradicts the claim of observation of the signal by Klapdor-Kleingrothaus et al.

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The current range of upper limits at the 2σ level on the sum of neutrino masses is: $\sum m_i = 0.47 - 0.71$ eV depending on the specific cosmological model

Dark Matter Searches

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Significant efforts in those direction going on (eg LUCIFER, CsI...)

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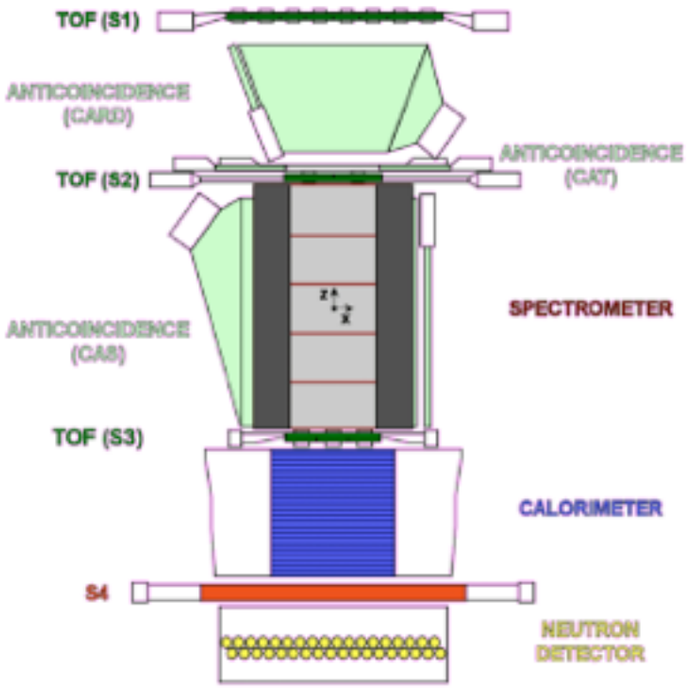

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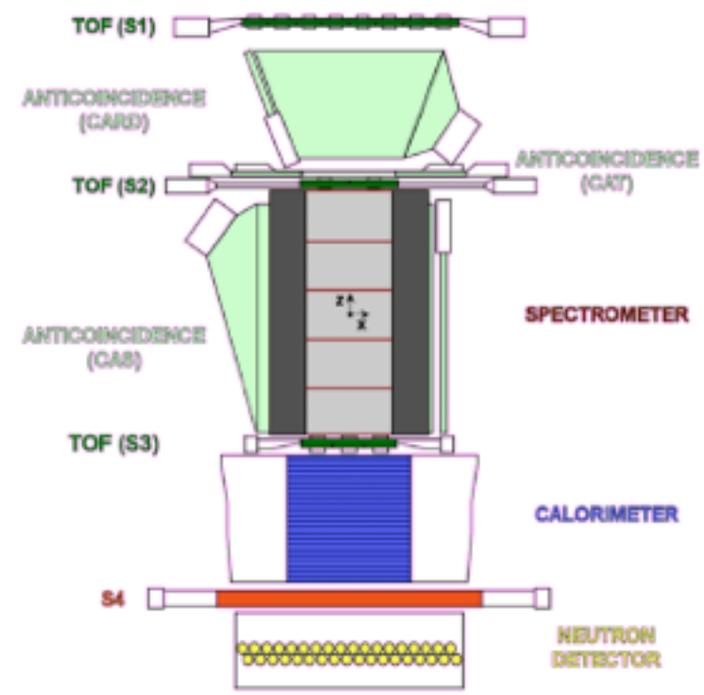

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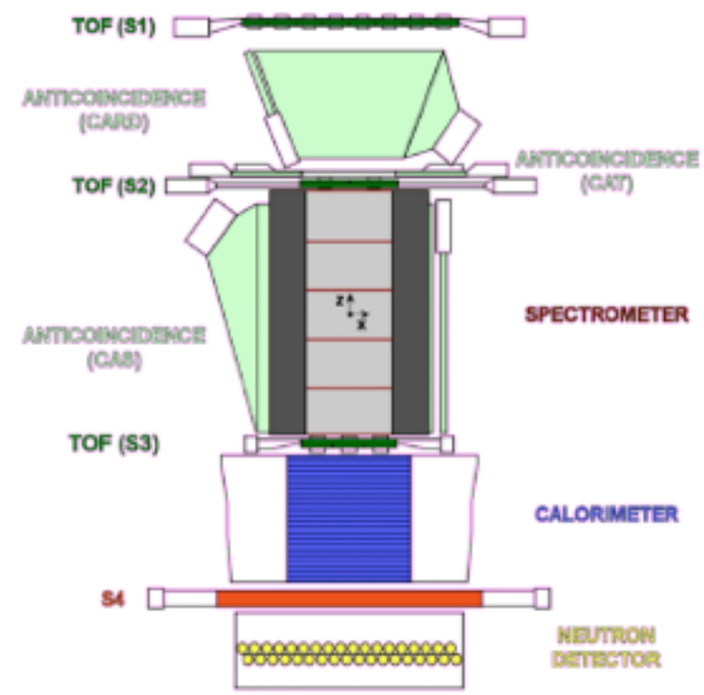

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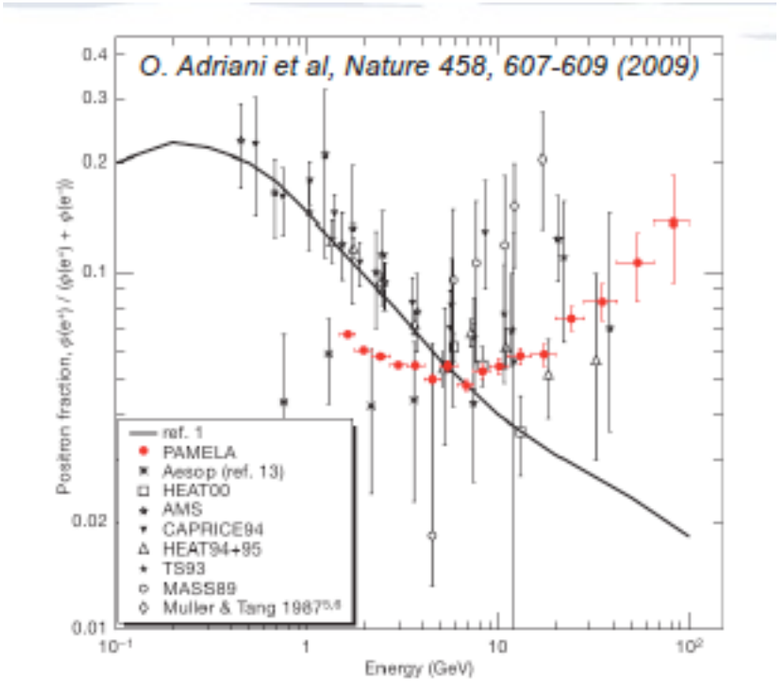

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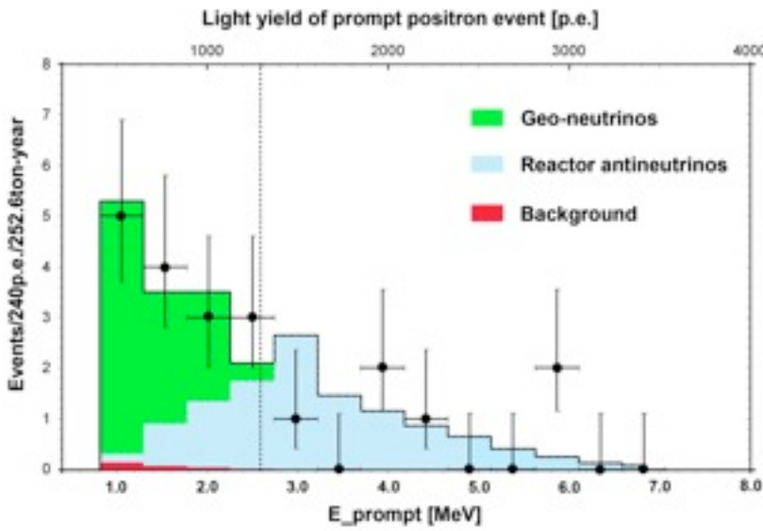

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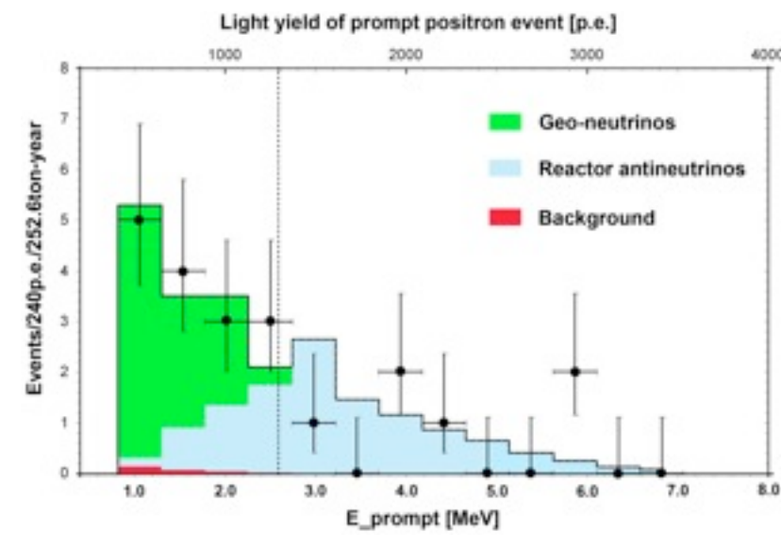

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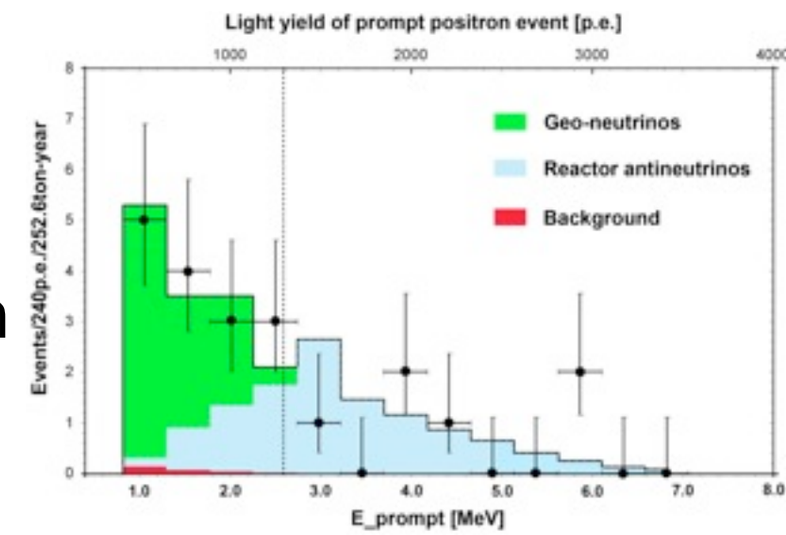

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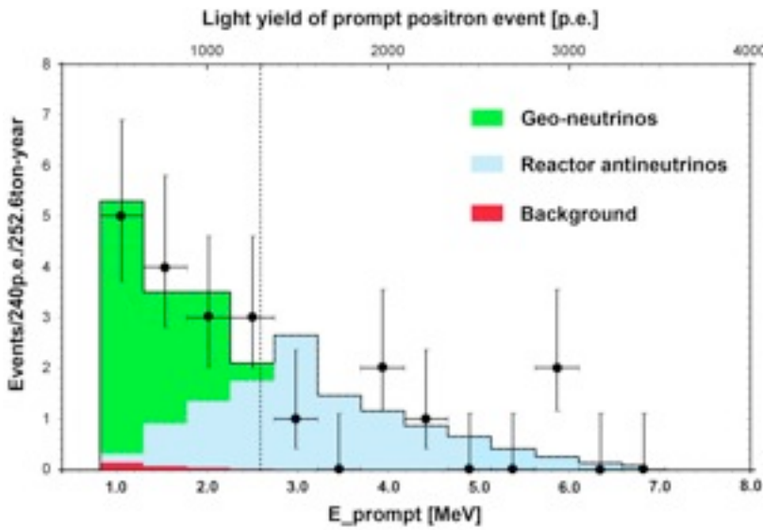

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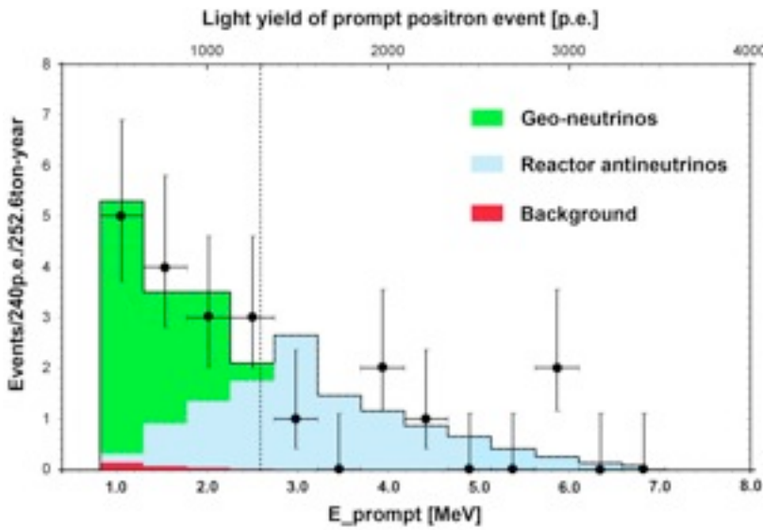

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Cosmology

Impact on cosmological models of neutrino mass scale
Additional light particles (besides 3 active ν's) and their nature

Future Plans, Possibilities

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The major projects that are under consideration with a goal of addressing some or all of these issues are:

New beams: LBNE in US, Laguna (CERN to Finland) in Europe, and T2K beam in Japan to ???

Use of several cyclotrons at different locations to provide well defined antineutrino beams from μ decay (DAEδALUS)

A new large detector for reactor neutrinos with a baseline of ~55-60 km in China

Large magnetized detector in India: INO

Large liquid argon detectors

Location of Different Sites

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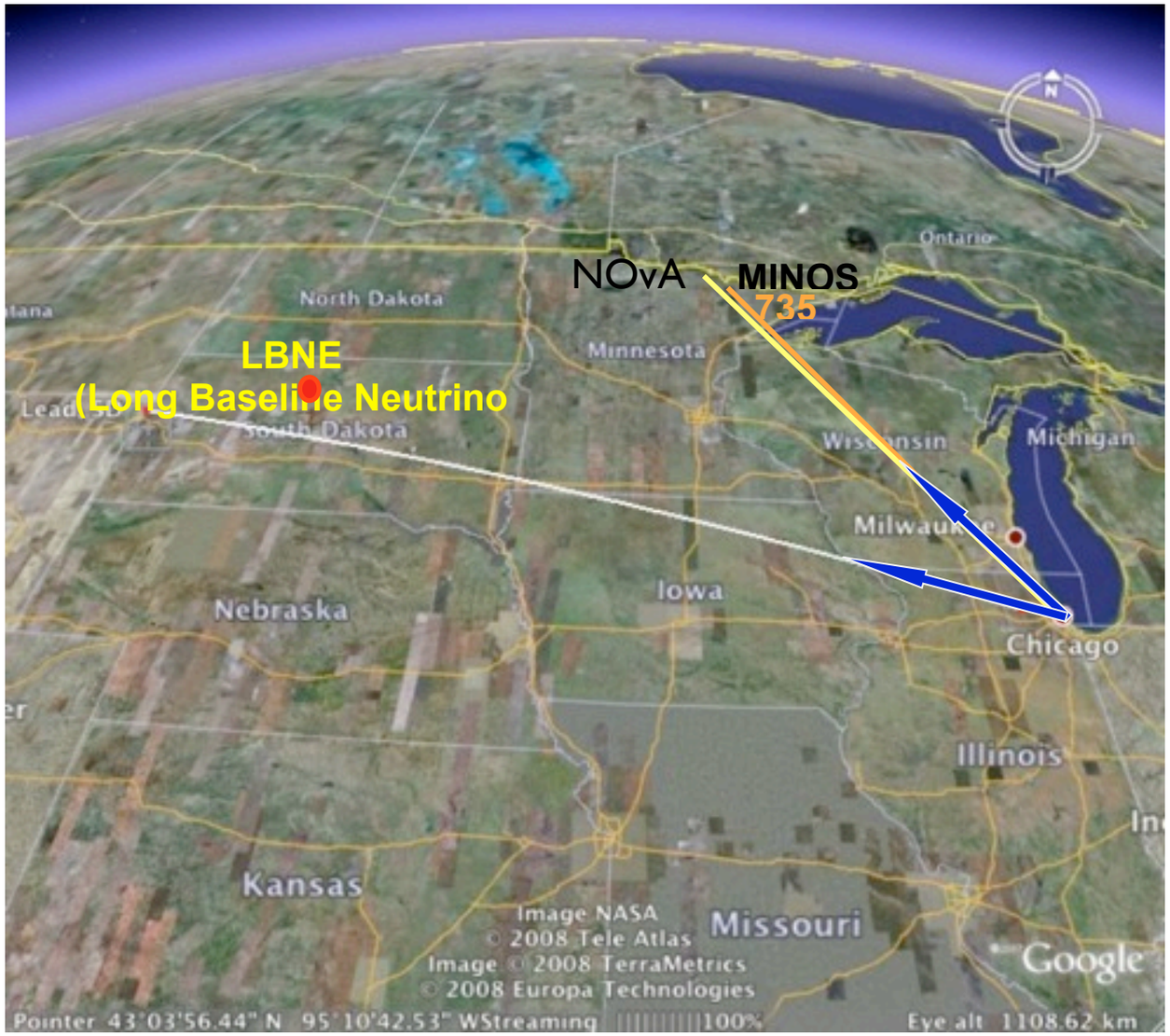

NuMI and LBNE in US

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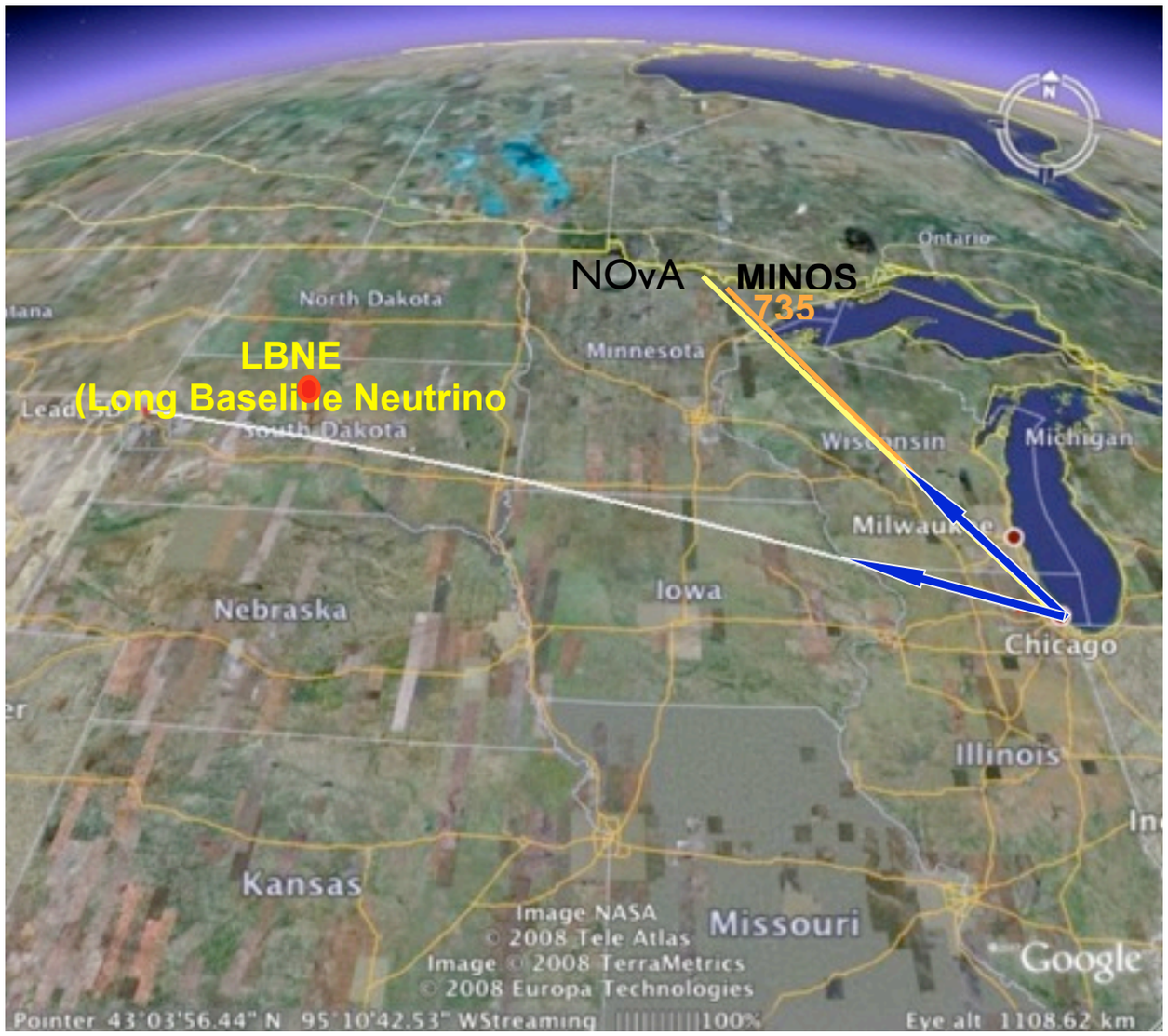

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European site

Graphical Comparison

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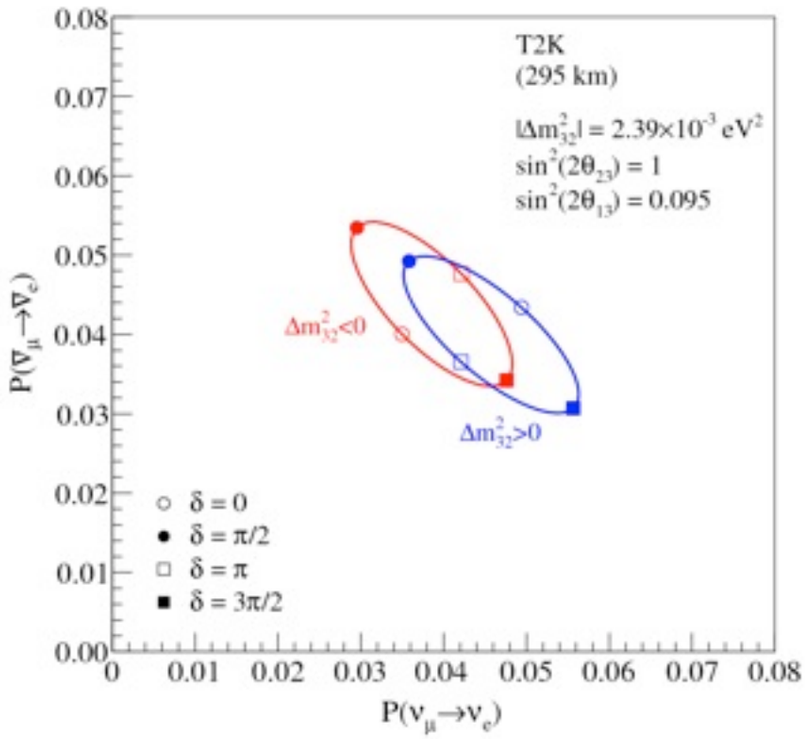

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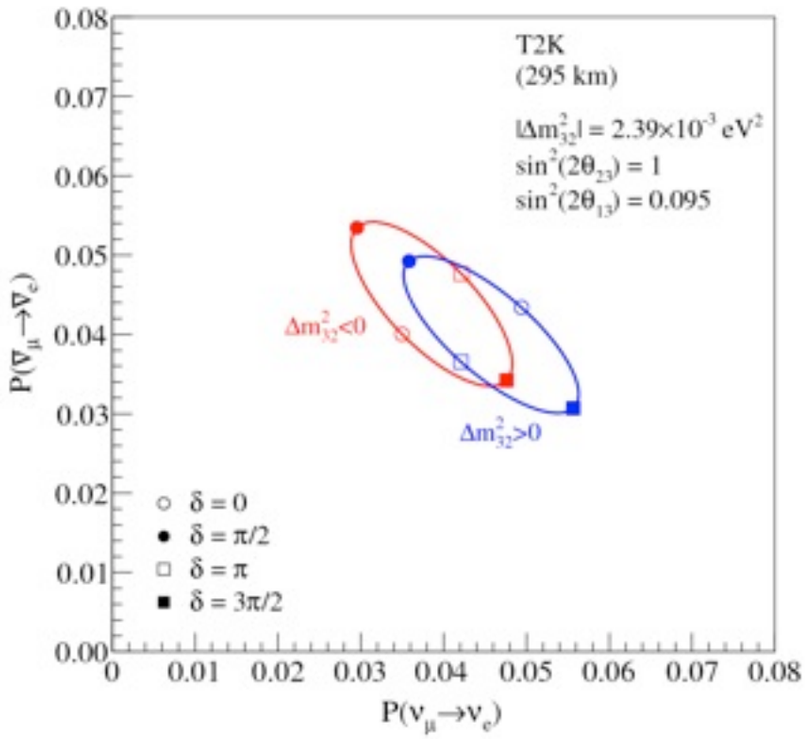

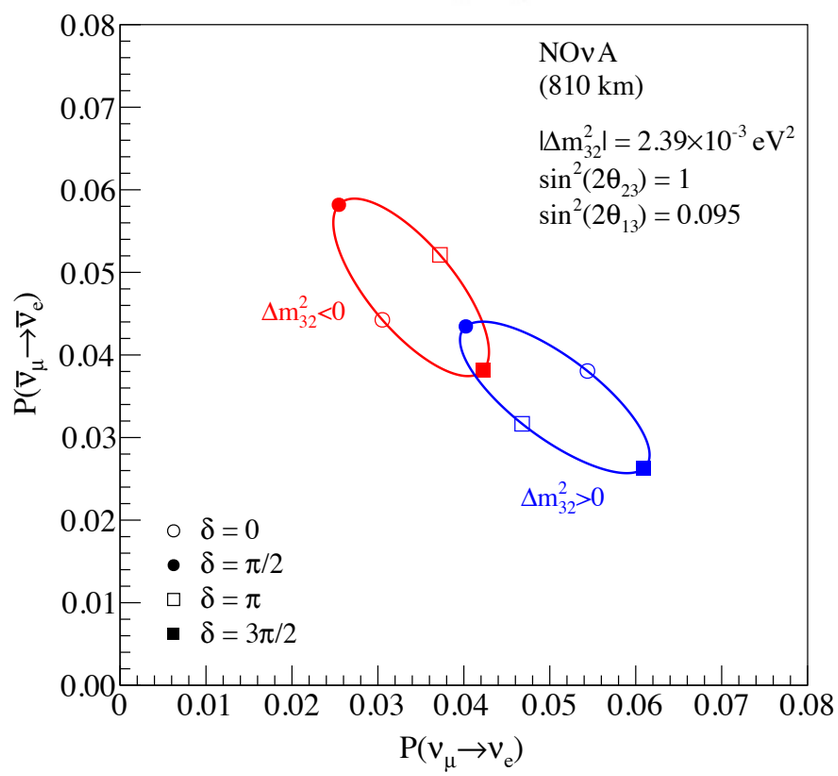

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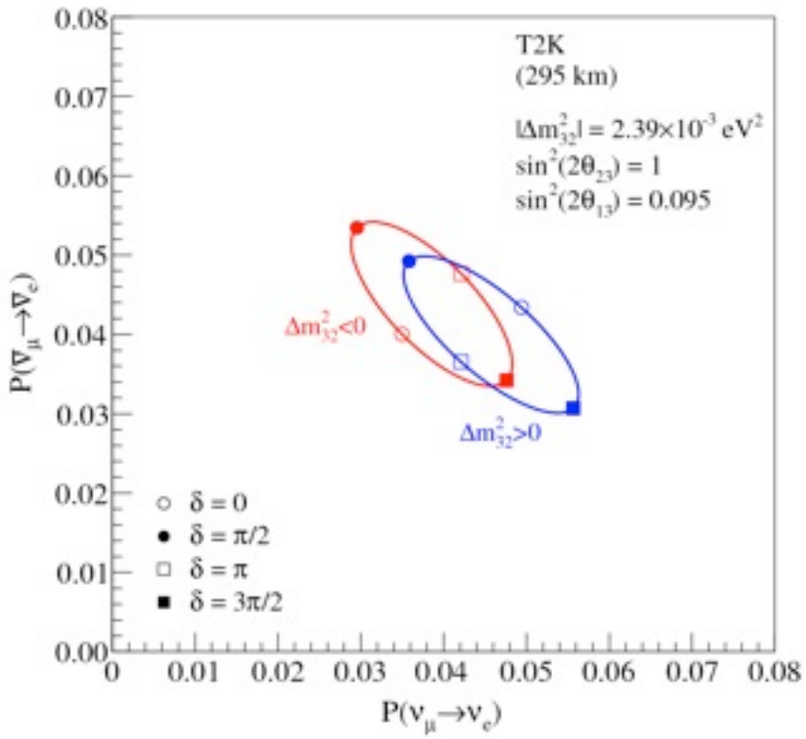

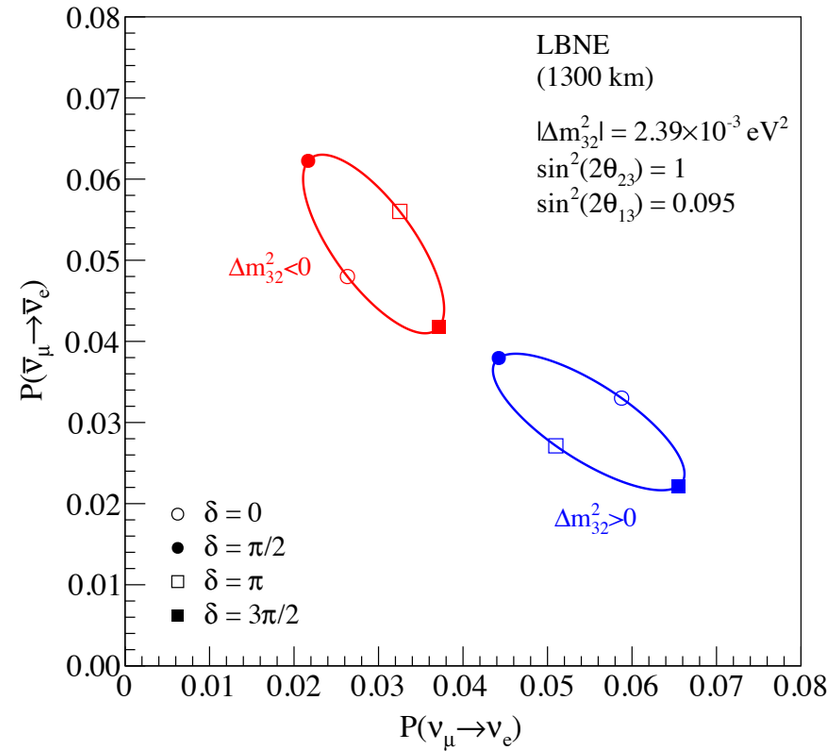

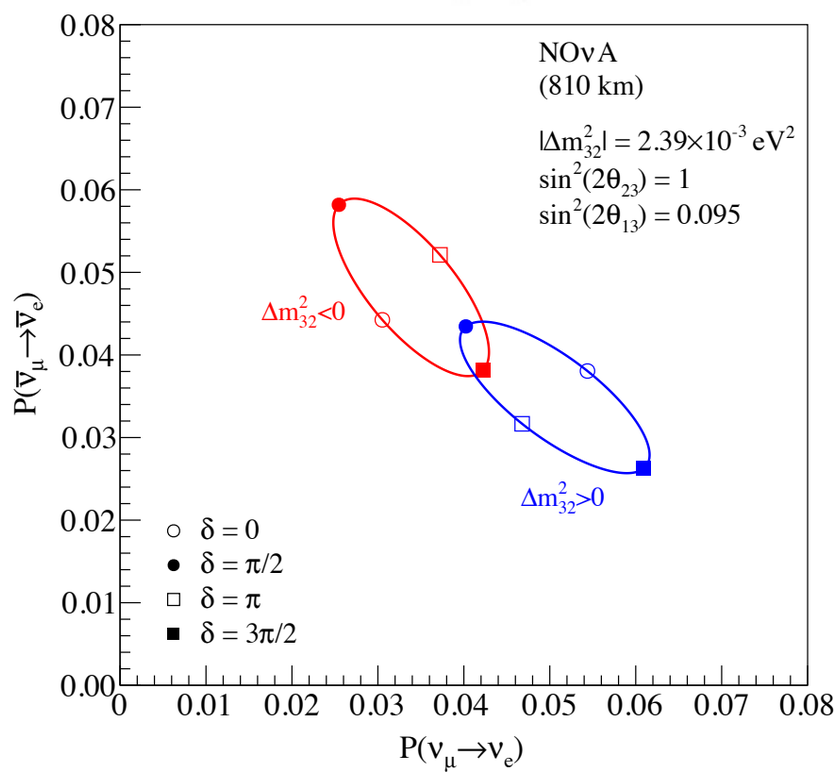

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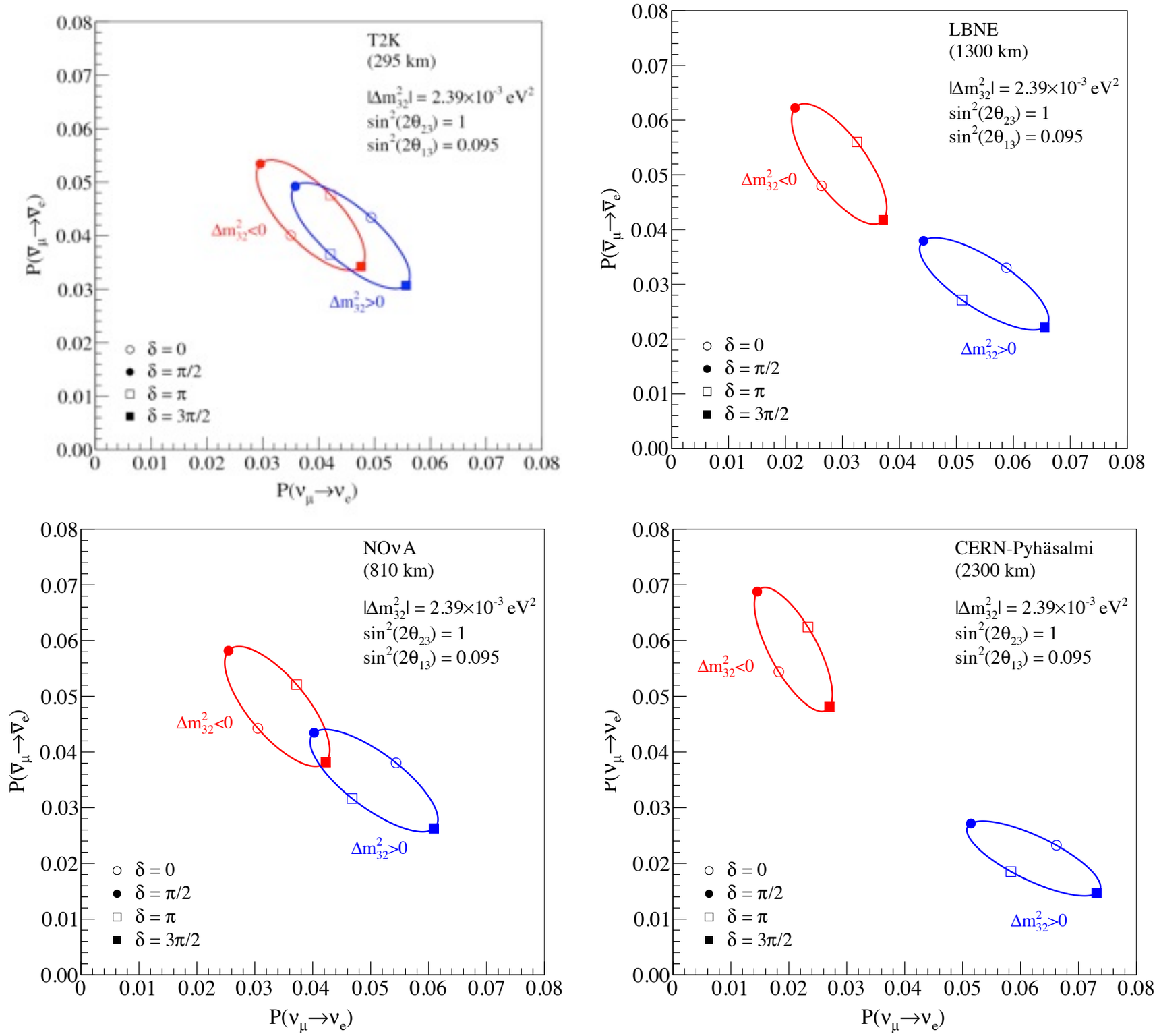


LBNE Beam

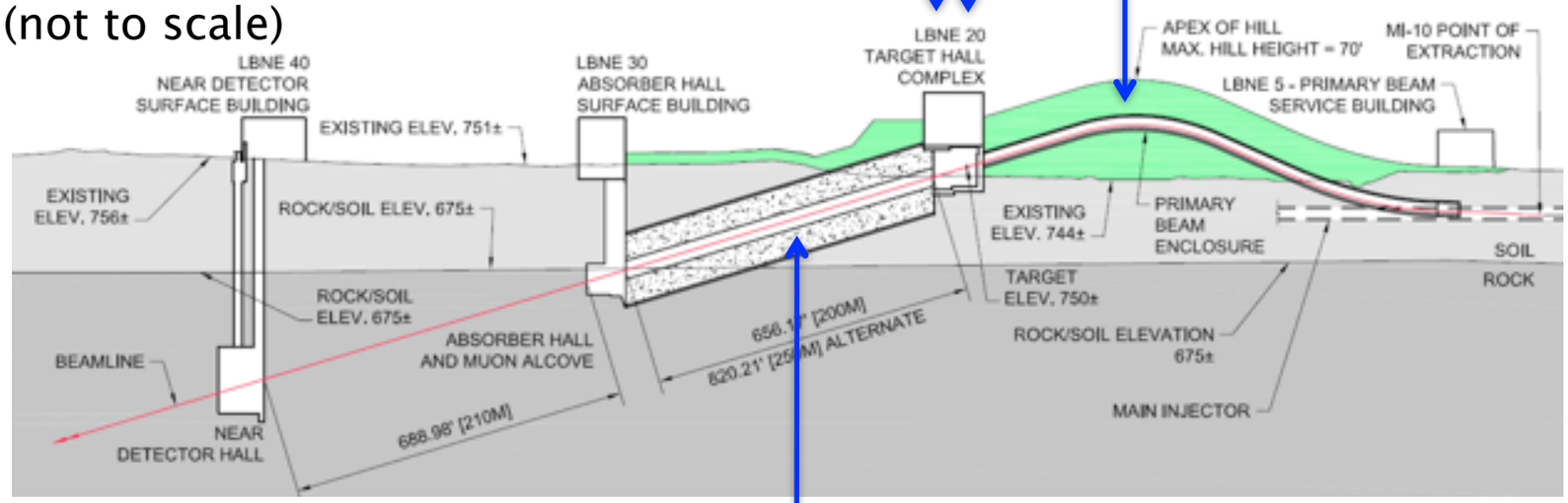
LBNE Beam

Target hall with remote handling in high-radiation environment

Focusing horns for secondary particles

Beam extraction and transport from the Main Injector to target

Beamline to Homestake (not to scale)



Large underground decay pipe (4m x 200m for Homestake ; 2m x 675m for NuMI)

Homestake beamline: much better aquifer protection than the NuMI beamline

LBNE Sensitivities

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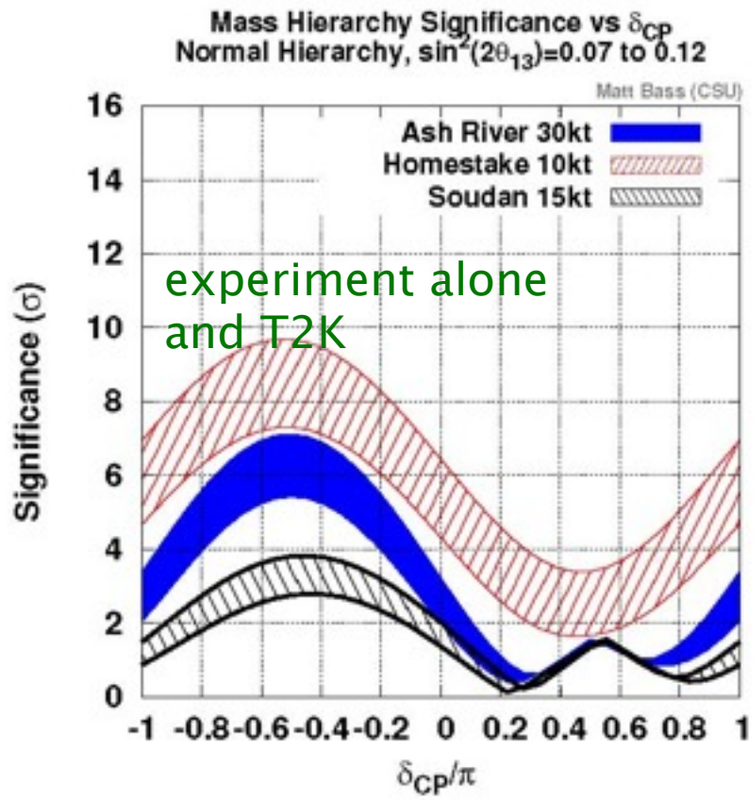

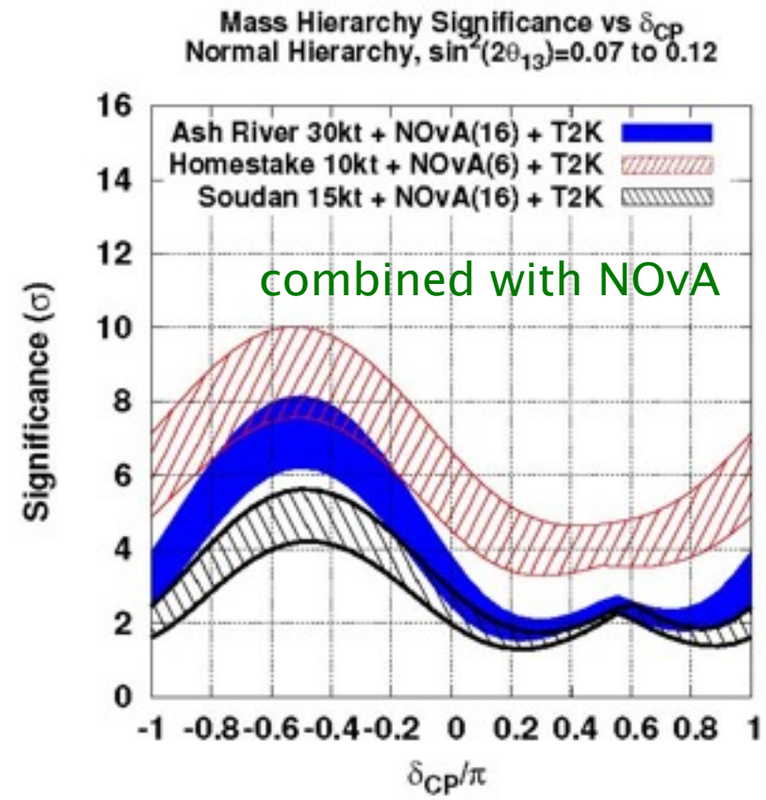

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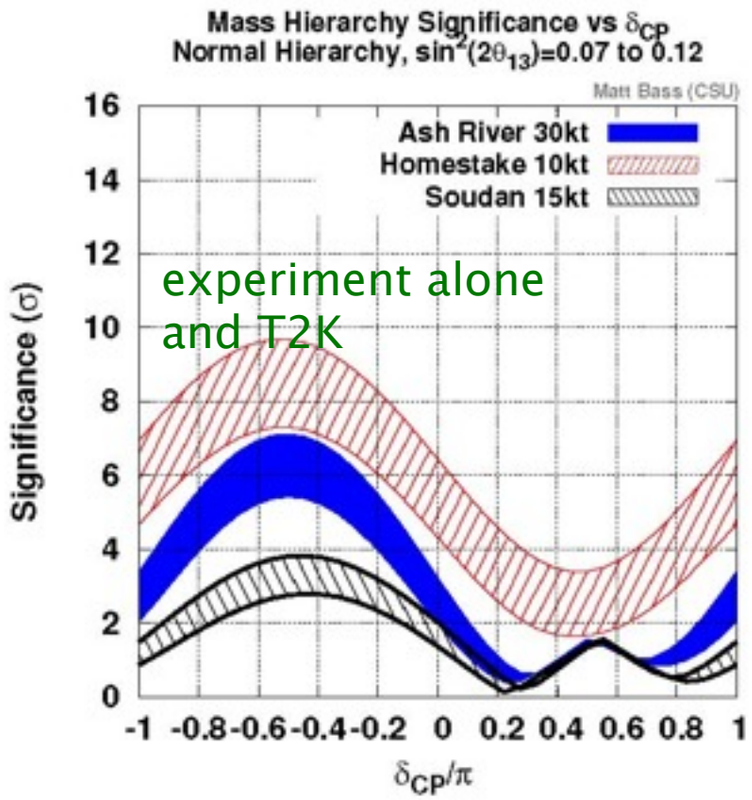

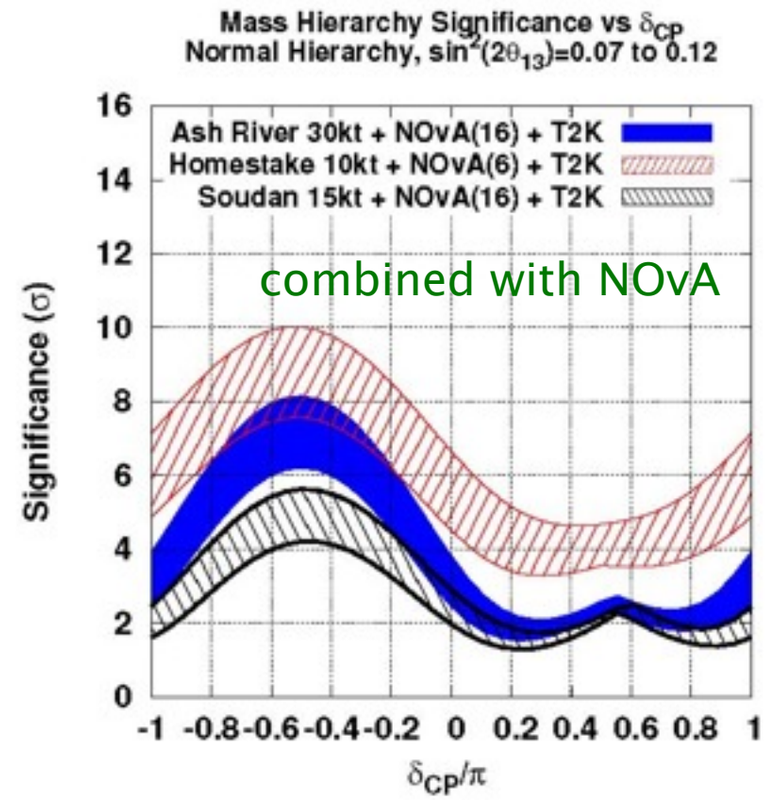

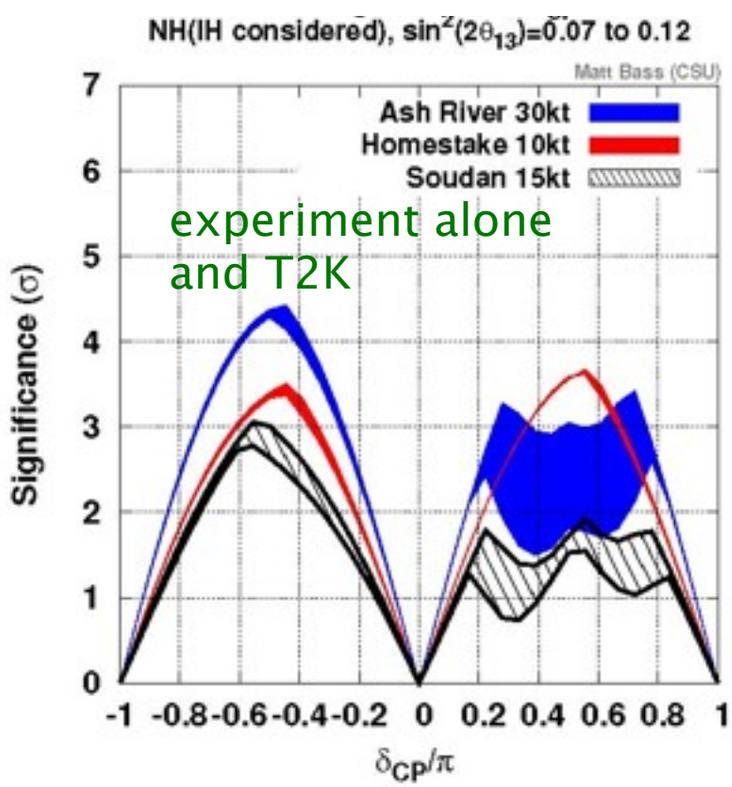

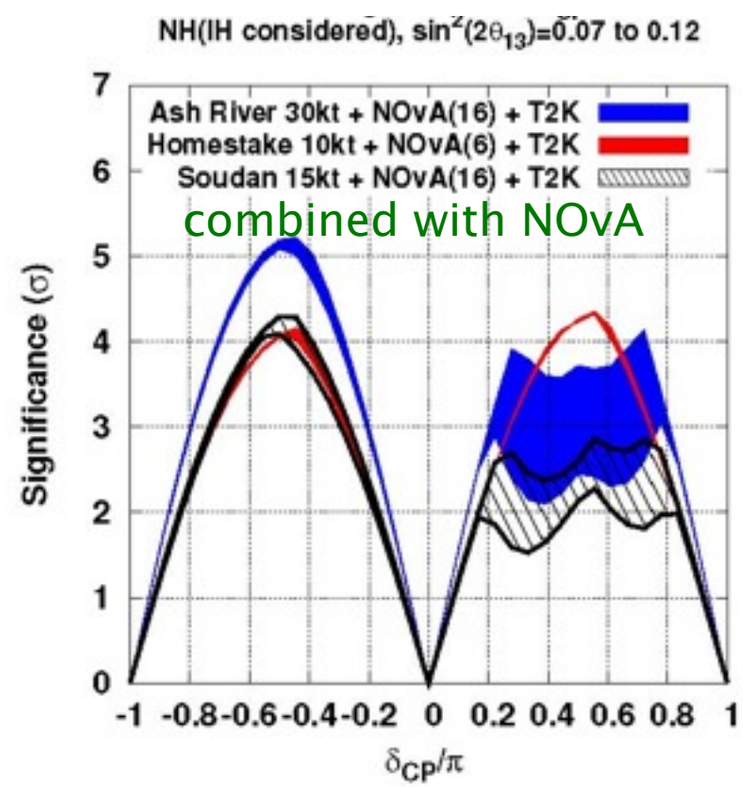

Laguna, LBNO in brief

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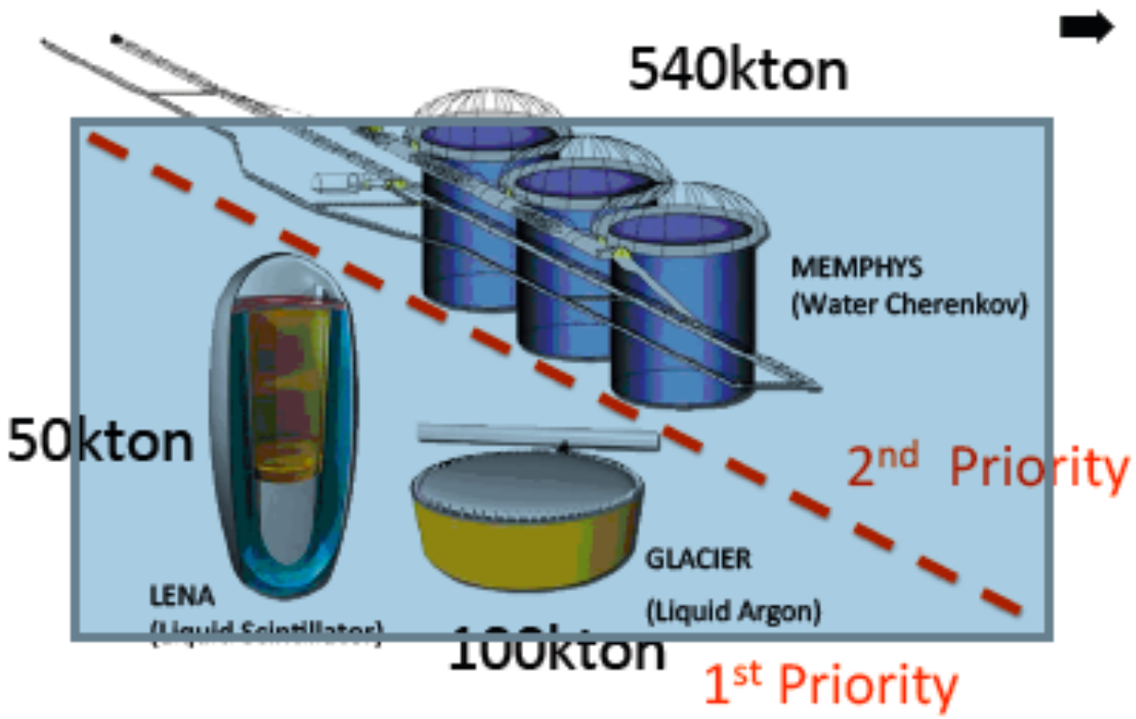

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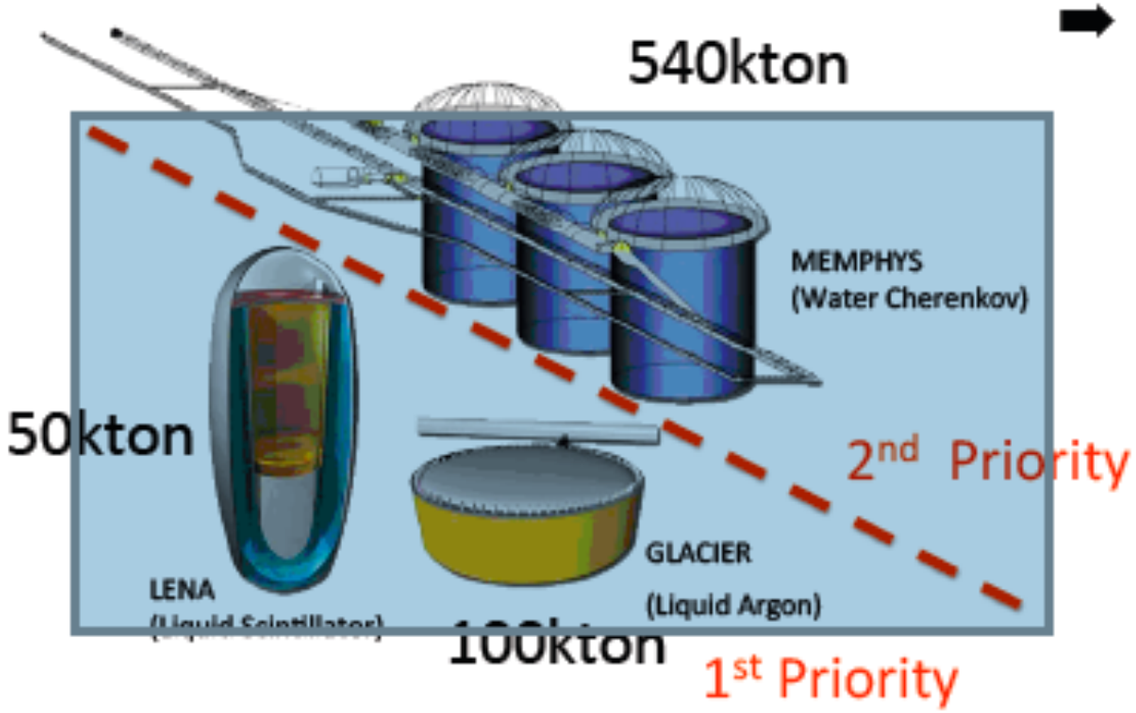

Beam

Fully exploit long baseline neutrino oscillation pattern

⇩

perform L/E analysis over large energy range
(1st and 2nd maxima)

⇩

Wide Band Beam (WBB)

$$E_\nu^{2nd\,max} \gtrsim 0.5\,\mathrm{GeV} \Longrightarrow L \gtrsim 1000\ \mathrm{km}$$

Detector

Better signal efficiency and background rejection
with a comparable mass

⇩

20 kton fine sampling tracking device

and magnetized muon detector

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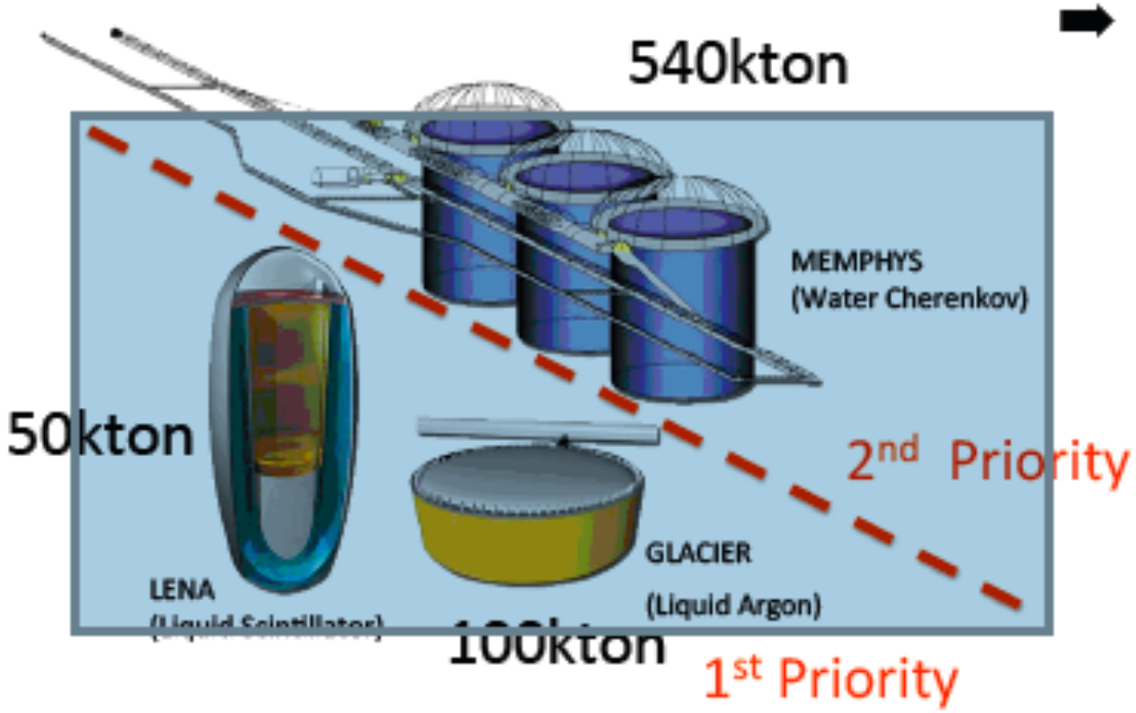

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Hope is for construction i n 2016-2021, physics in 2023

Electron ν's in LBNO

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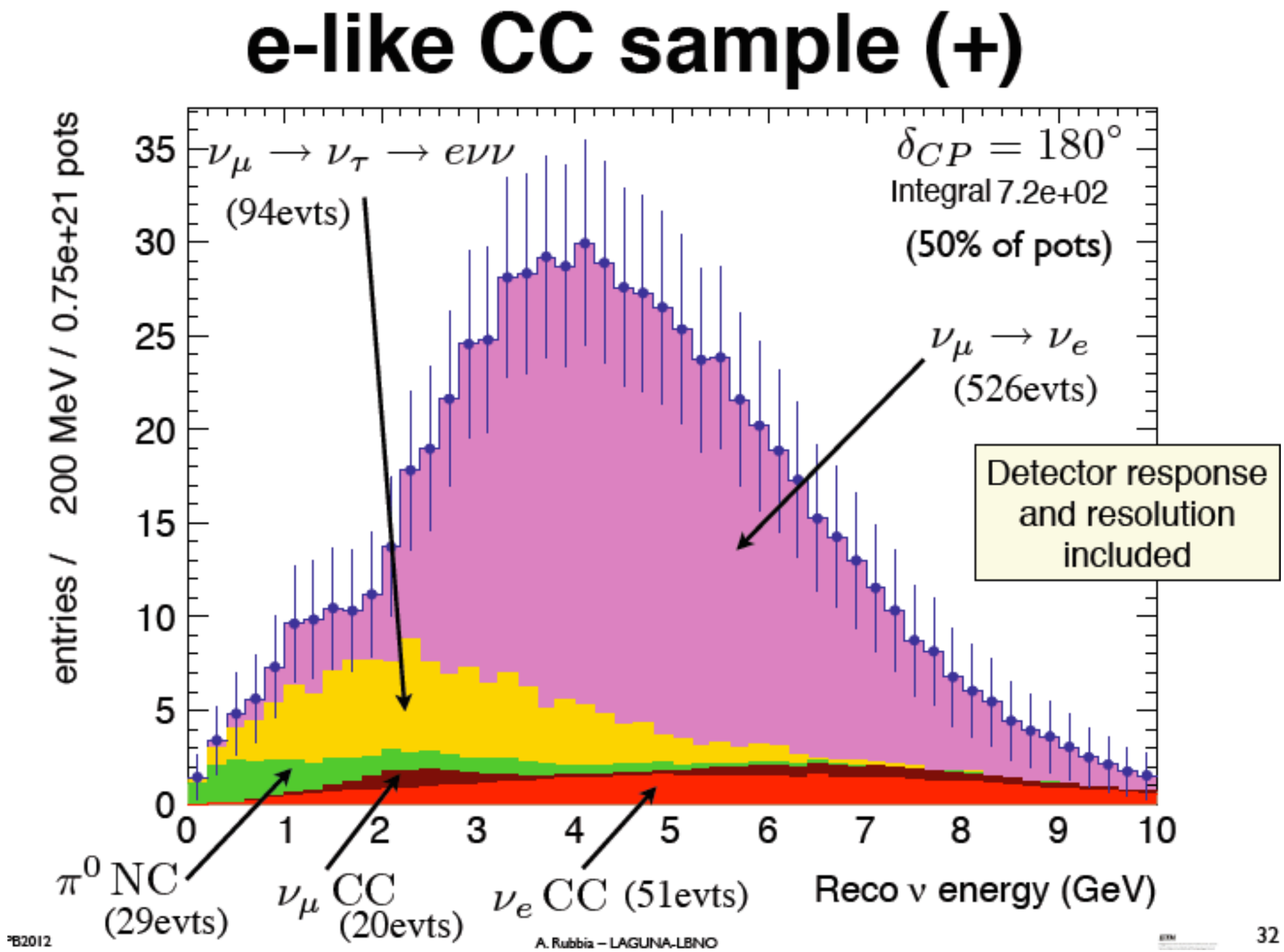
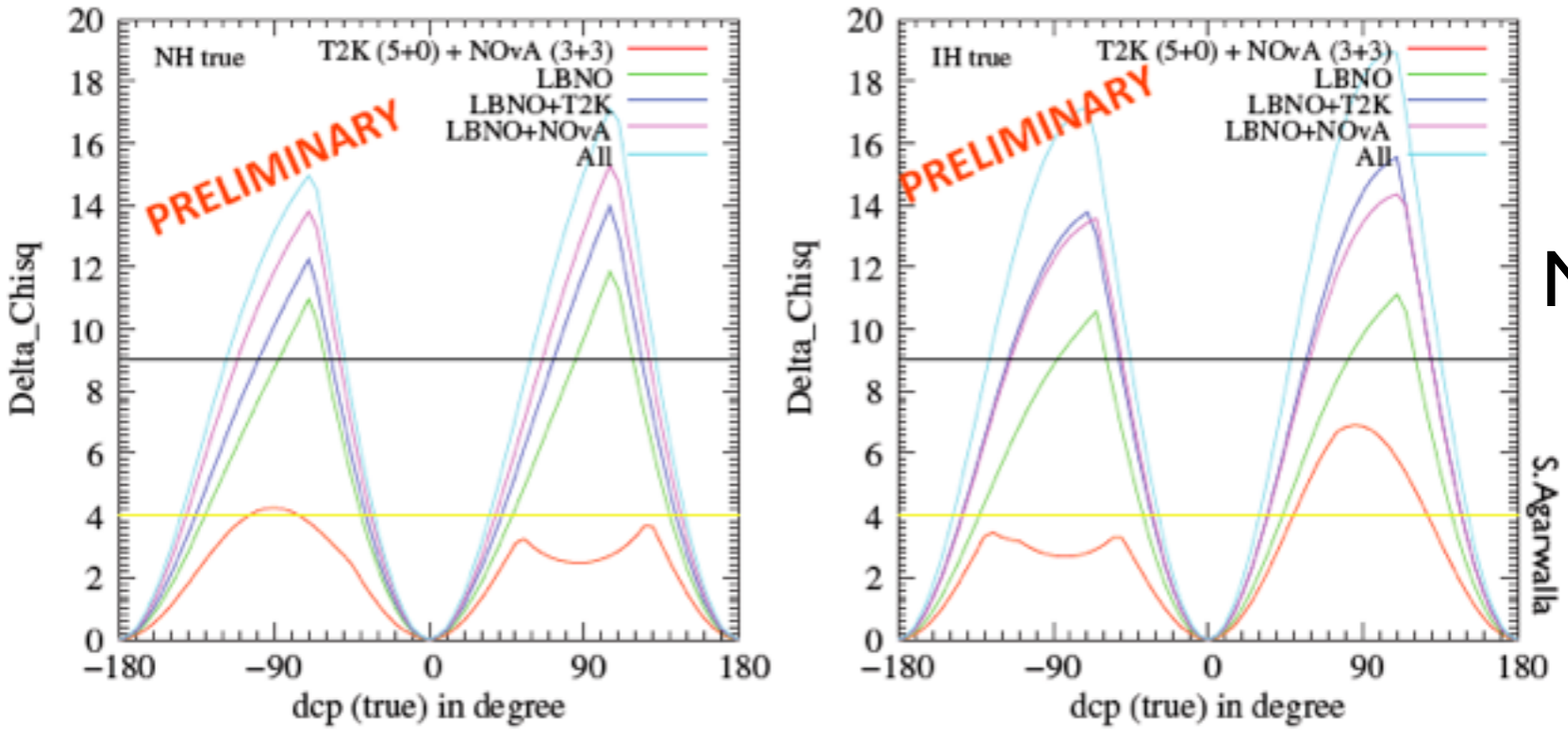


LBNO Sensitivities

Mass hierarchy
comparisons

LBNO Sensitivities

Sensitivity combining T2K(295km), NOvA(810km) and LBNO(2300km)



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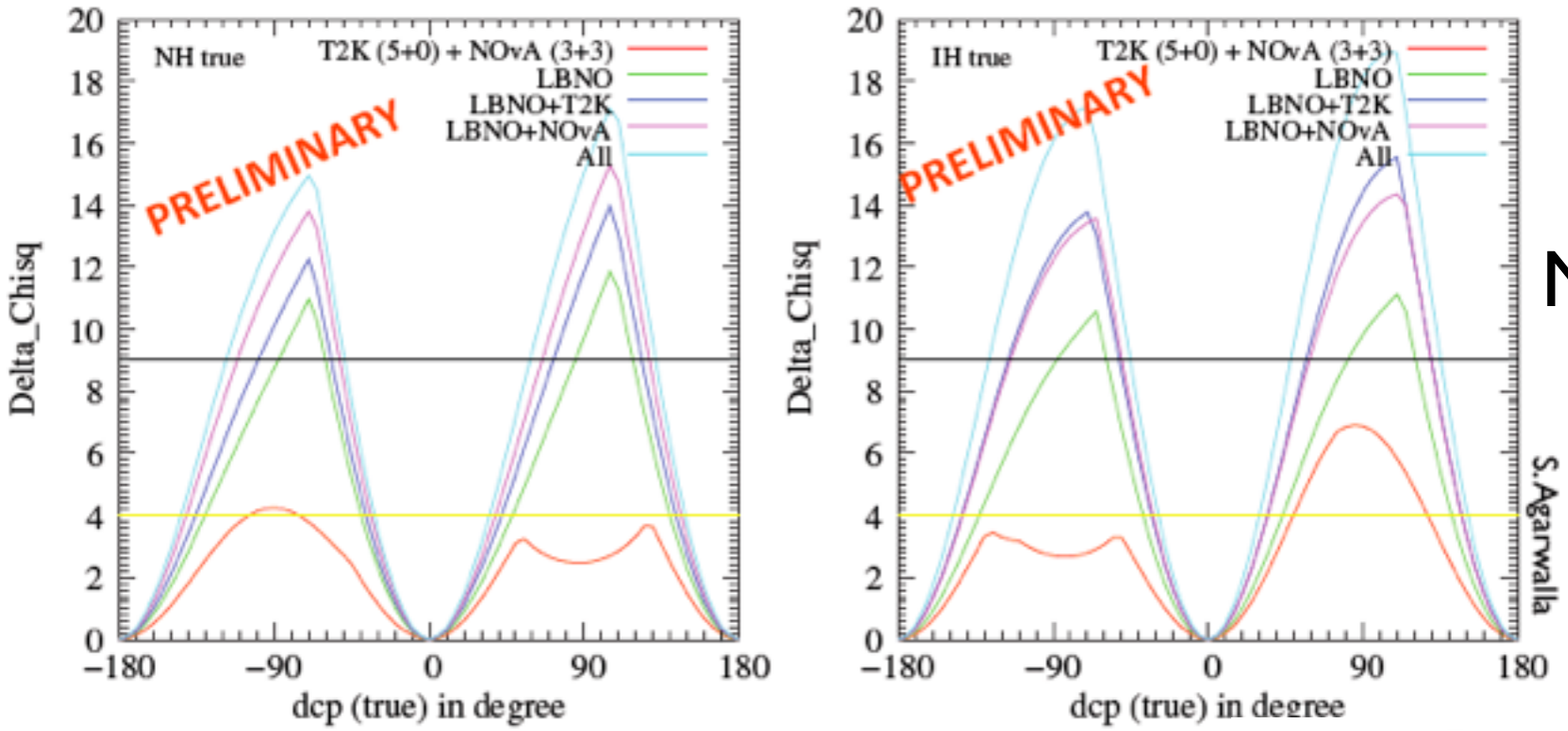
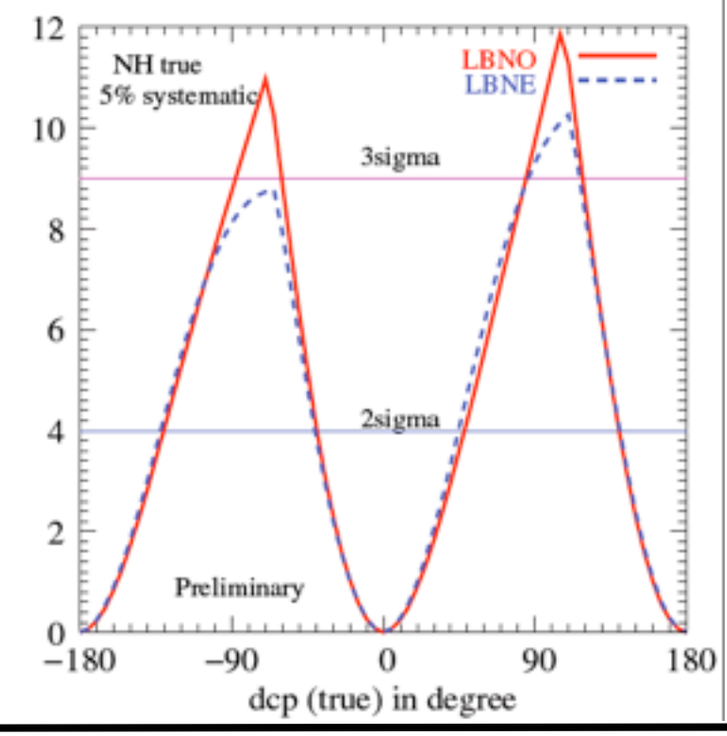


Mass hierarchy comparisons

CPV: LBNE vs LBNO

- Assume same systematic errors for both setups
- LBNE 10 kton @ 1300 km
- LBNO 20kton @ 2300 km



Daya Bay II

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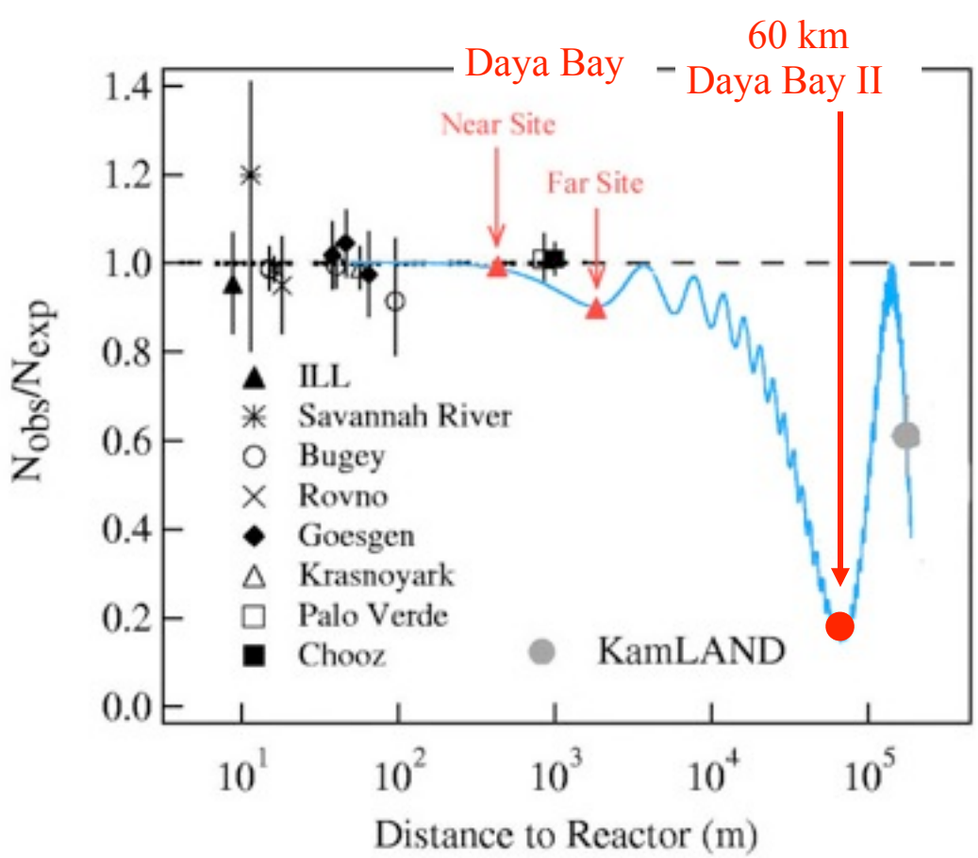

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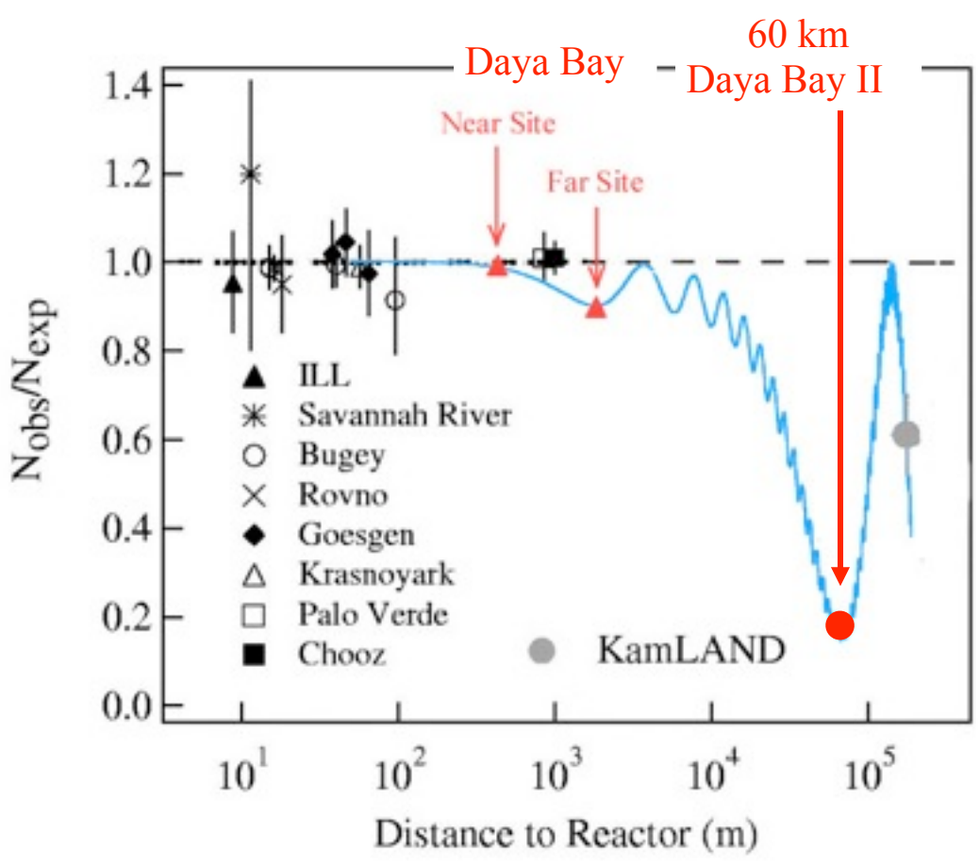
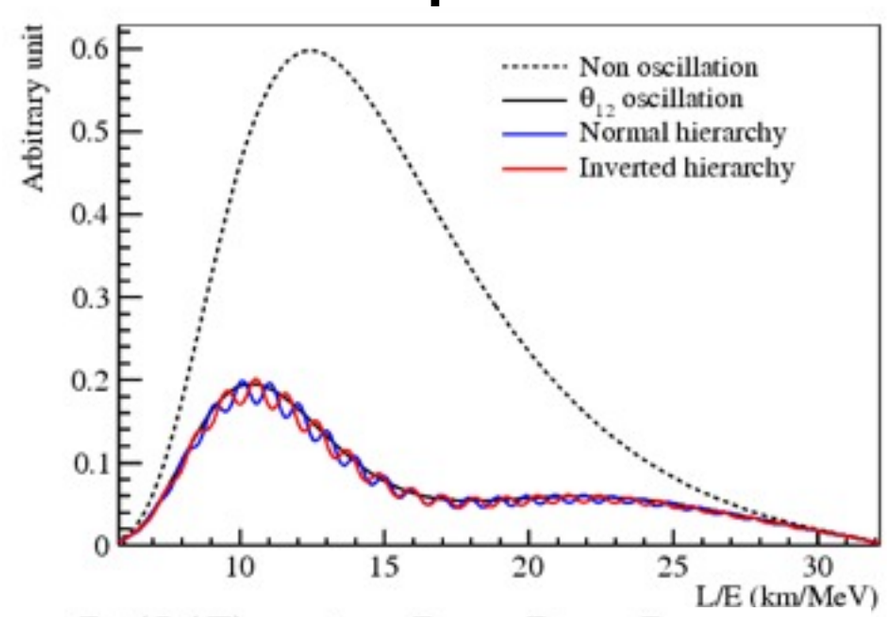
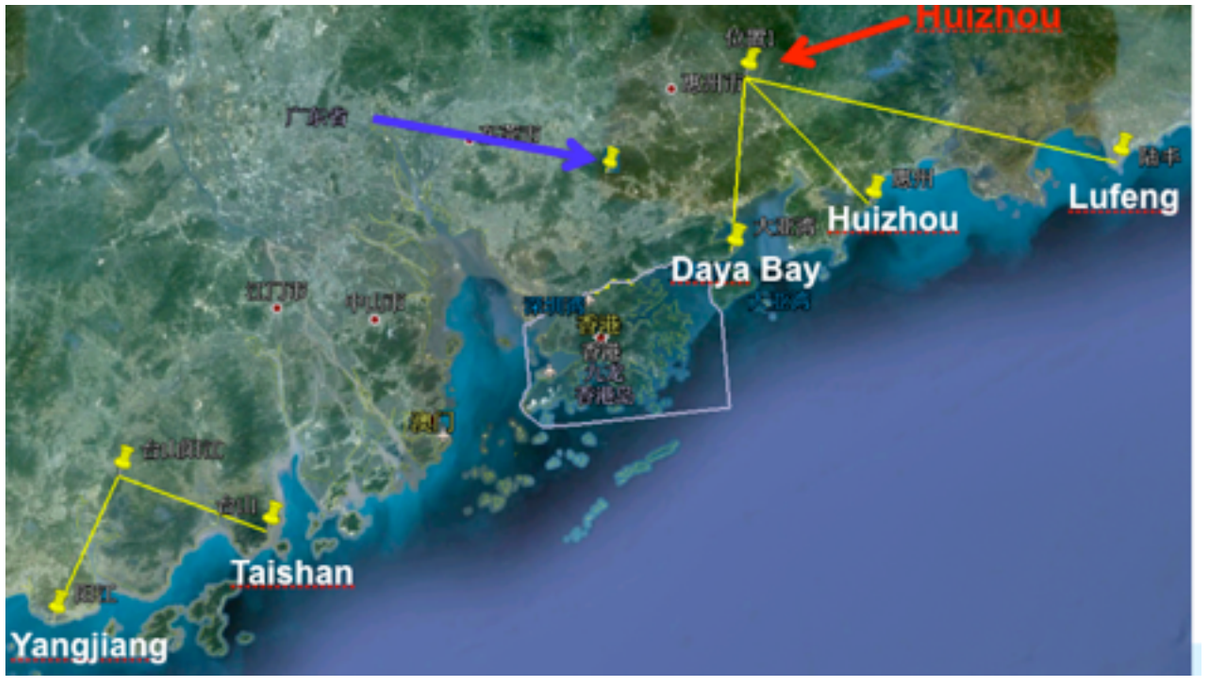




$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$

Daya Bay II - Issues



Is there adequate site?

Sufficient neutrino flux
Avoid "spurious" reactors to wash out the effect
Sufficient overburden

Adequate energy resolution
Understanding energy scale
Long attenuation length in the scintillator
(one design has sphere with diameter=34.5m)
Adequate amount of light
Suppression of backgrounds

Hope is to be ready for construction in 2016-2020

INO Detector

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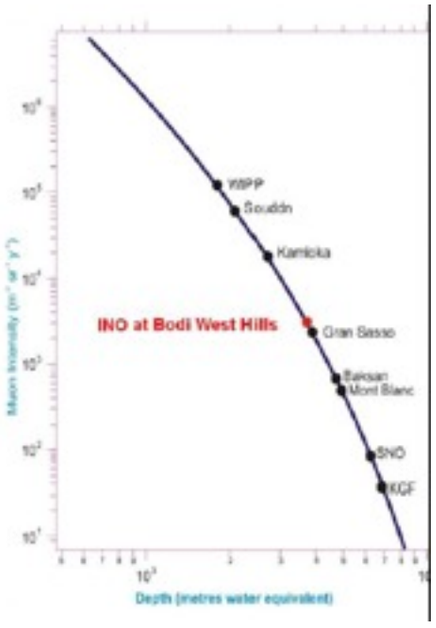

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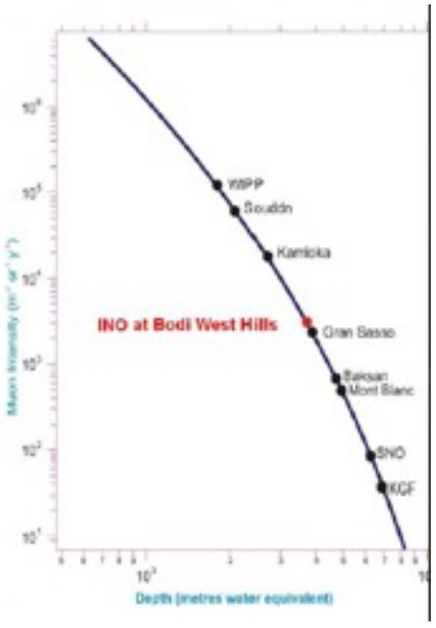

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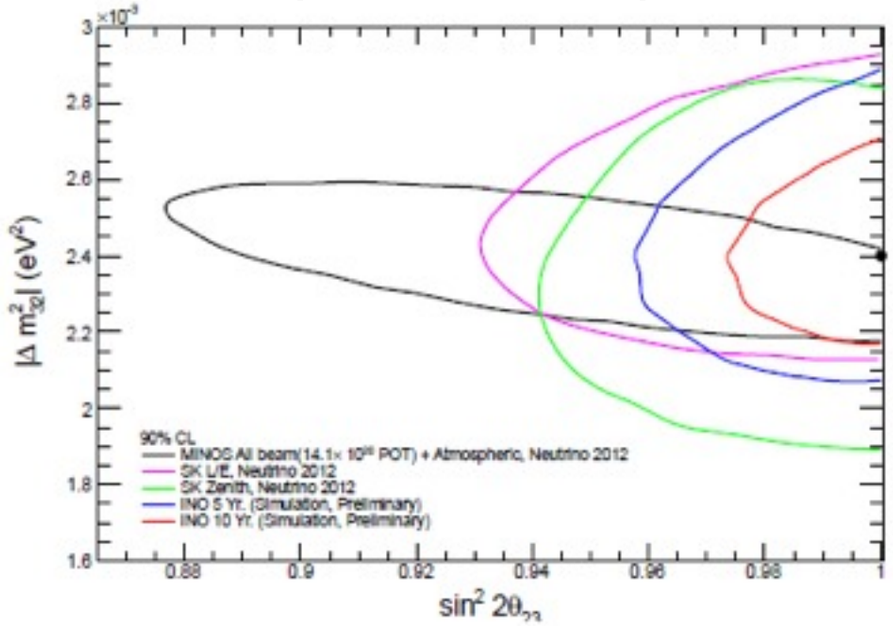
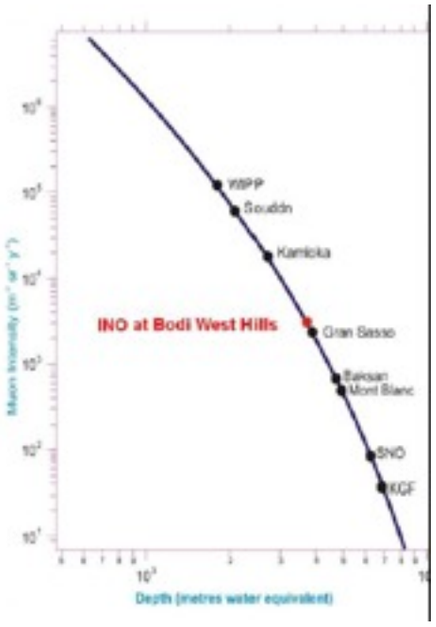
Atmospheric sector potential





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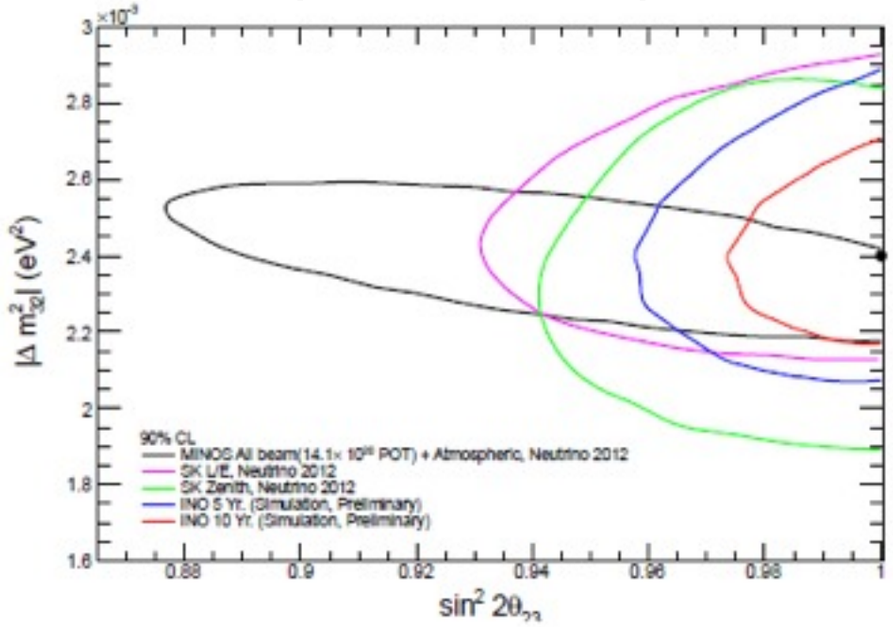

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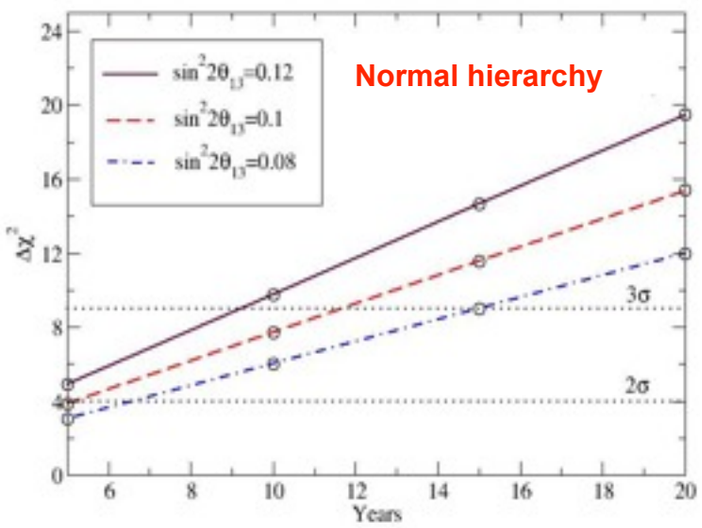

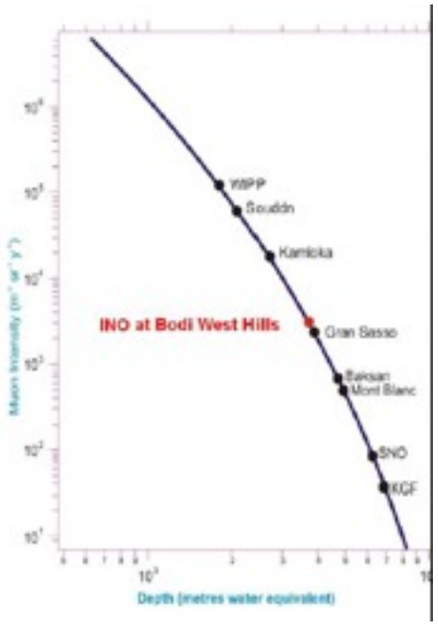

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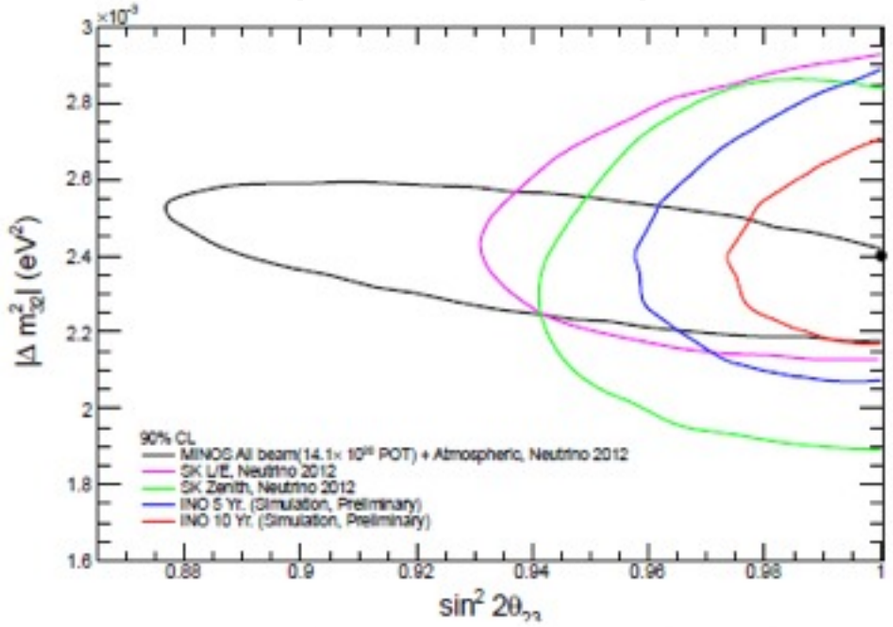

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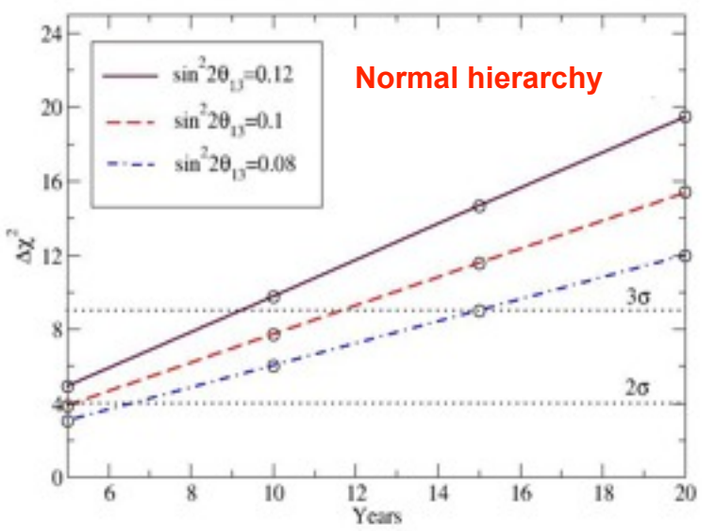

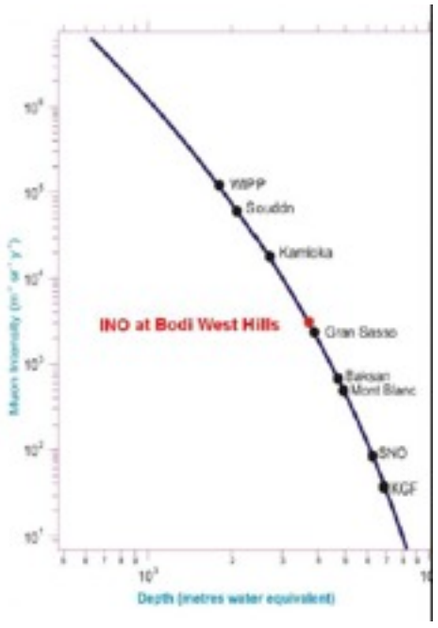

Site is available; commissioning hoped to start in 2017

Neutrino Community

Number of authors on most recent publications from the ongoing experiments - 2145

Duplication - ÷1.5 ??
Did not include in above SuperK, NOvA, SNO+,...

Need to add people working on new detectors, new experiments and theorists

So my guesstimate is 2000-2500 for the whole community

Comparable to ATLAS or CMS

A Look into the Future

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This may well be the golden decade in ν physics

Thank you

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Many thanks to the conference organizers for their warm and sincere hospitality and very efficient organization of the conference

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感谢主办方的热情款待和出色的会议组织

Comparison of Different Ways

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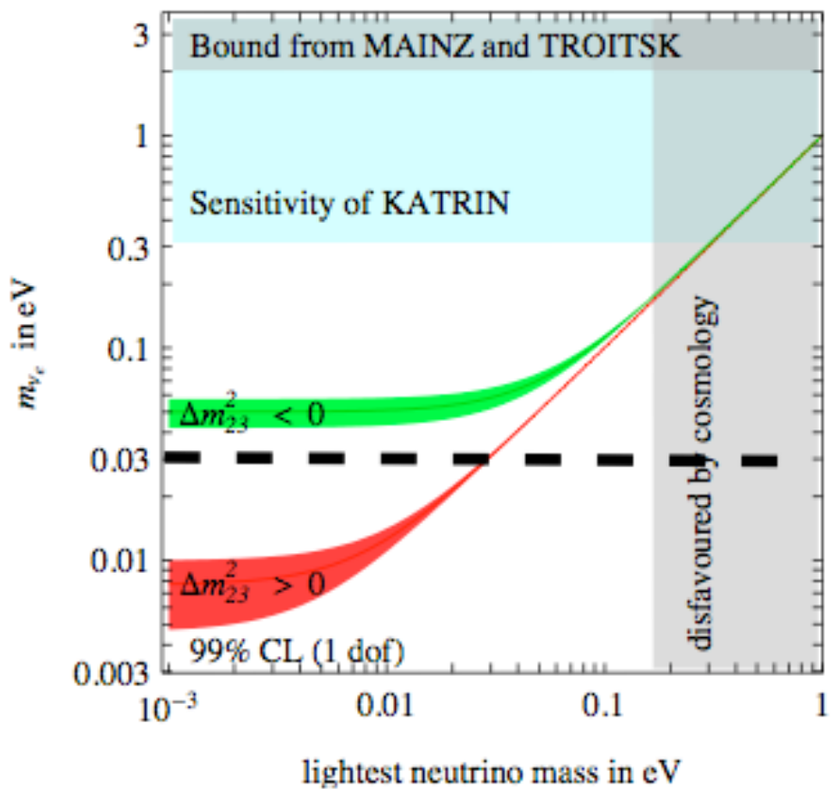

Kinematics of Decay

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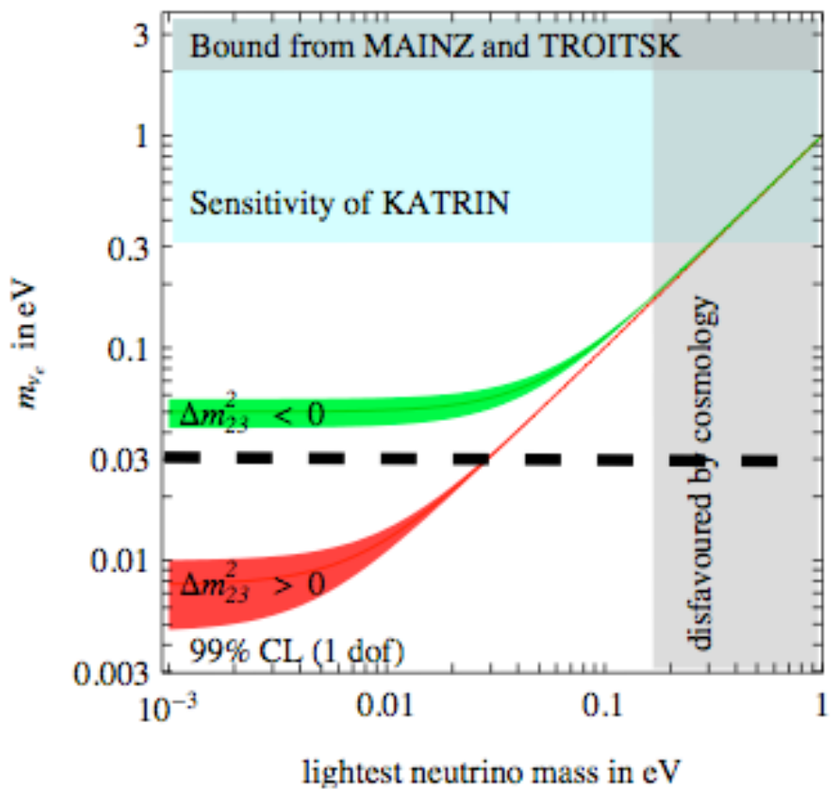

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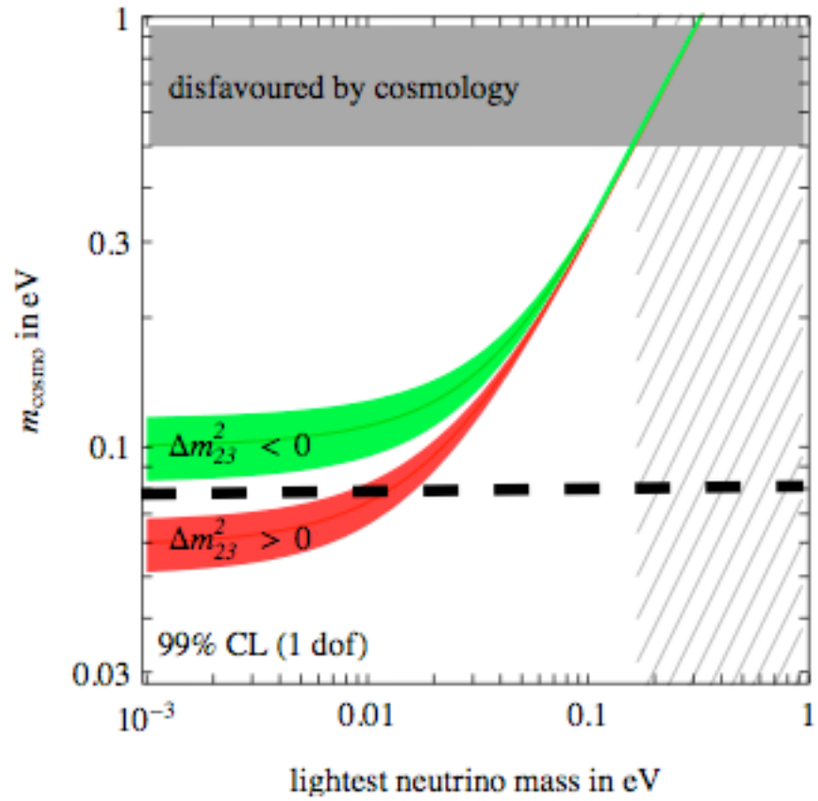

Cosmology

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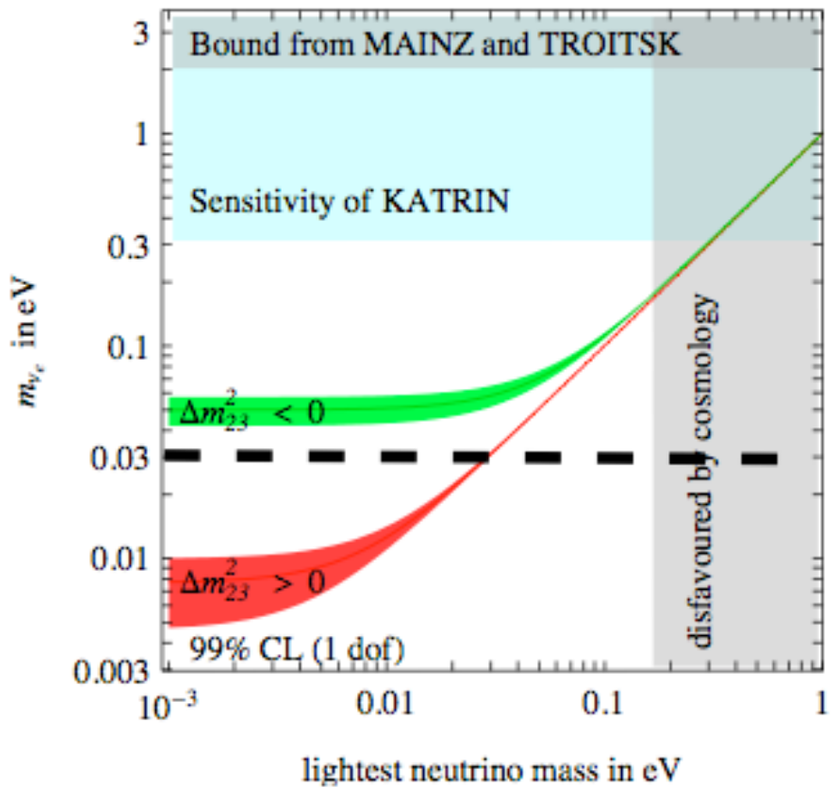

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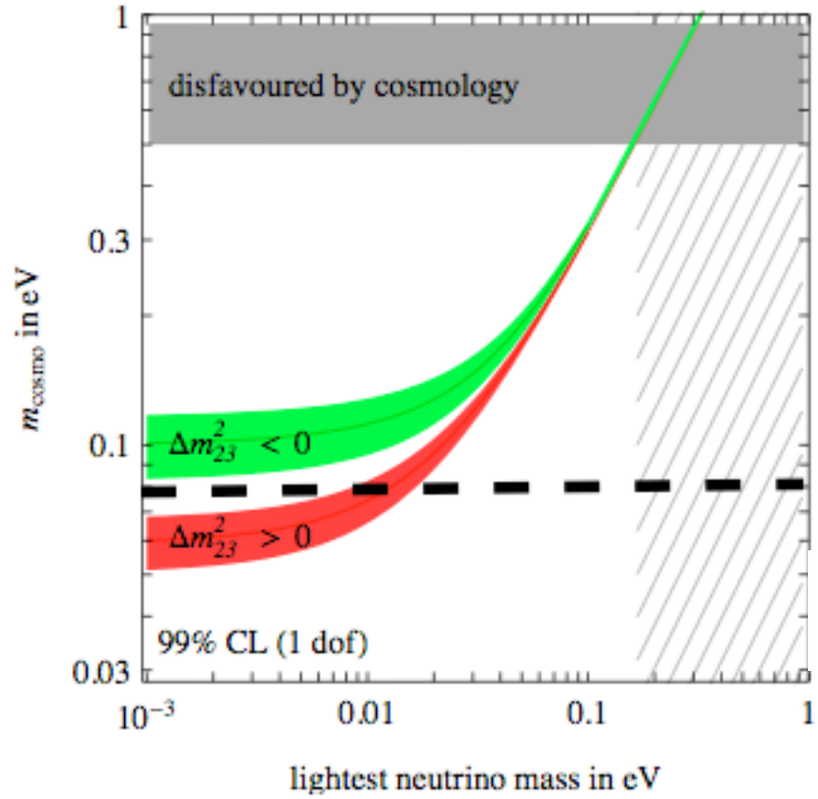

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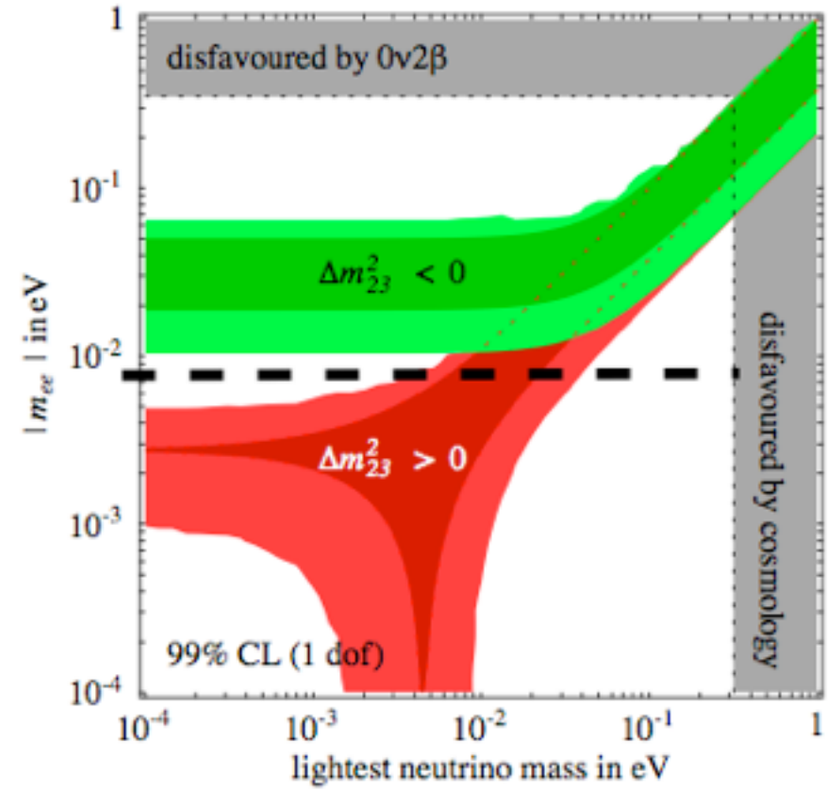
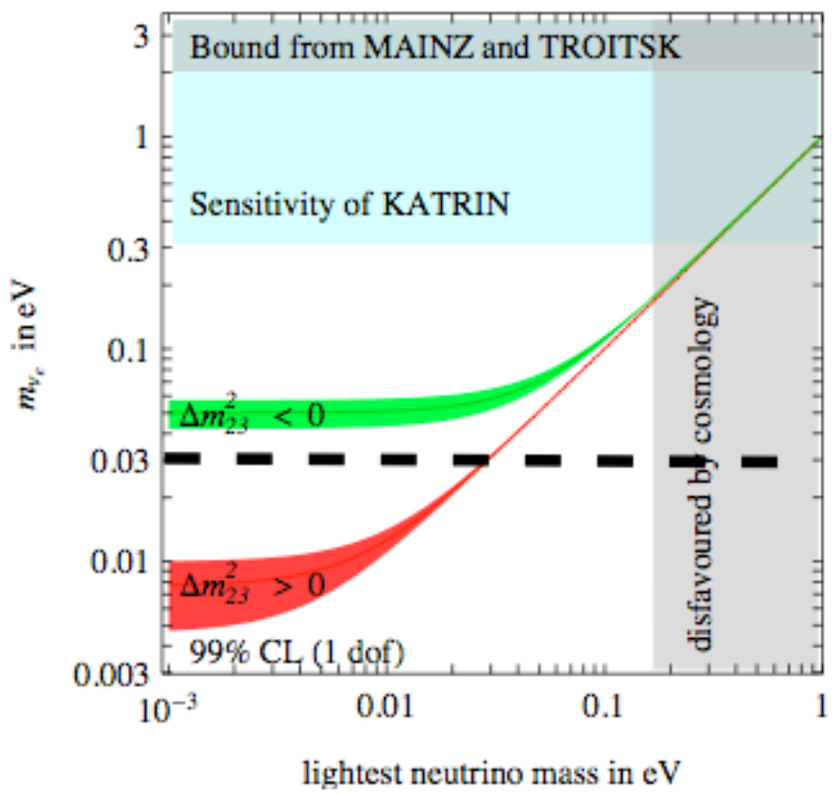


Double Beta Decay

Comparison of Different Ways



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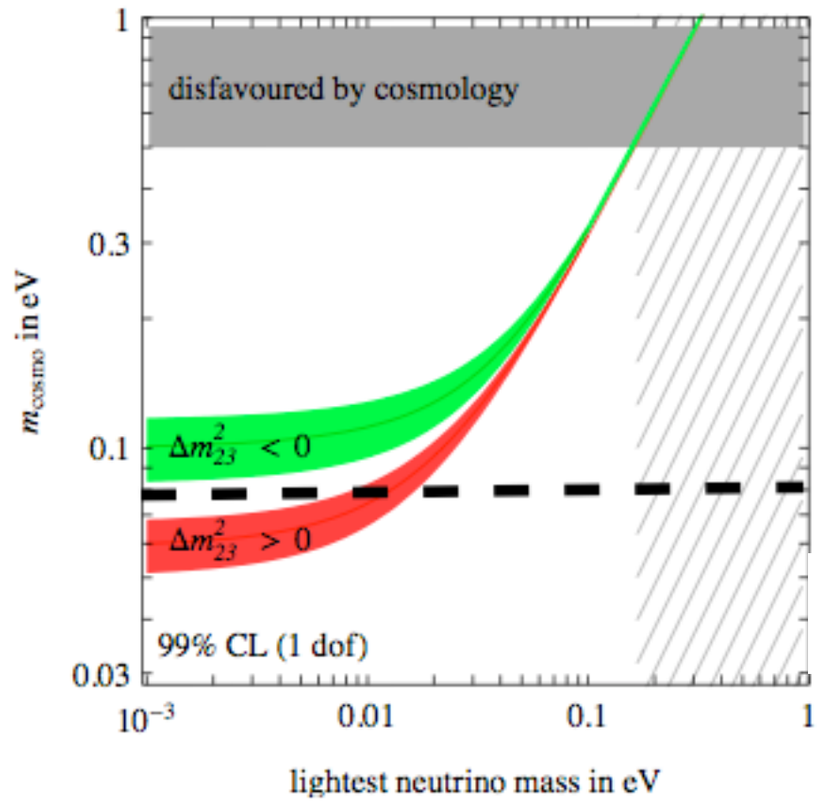
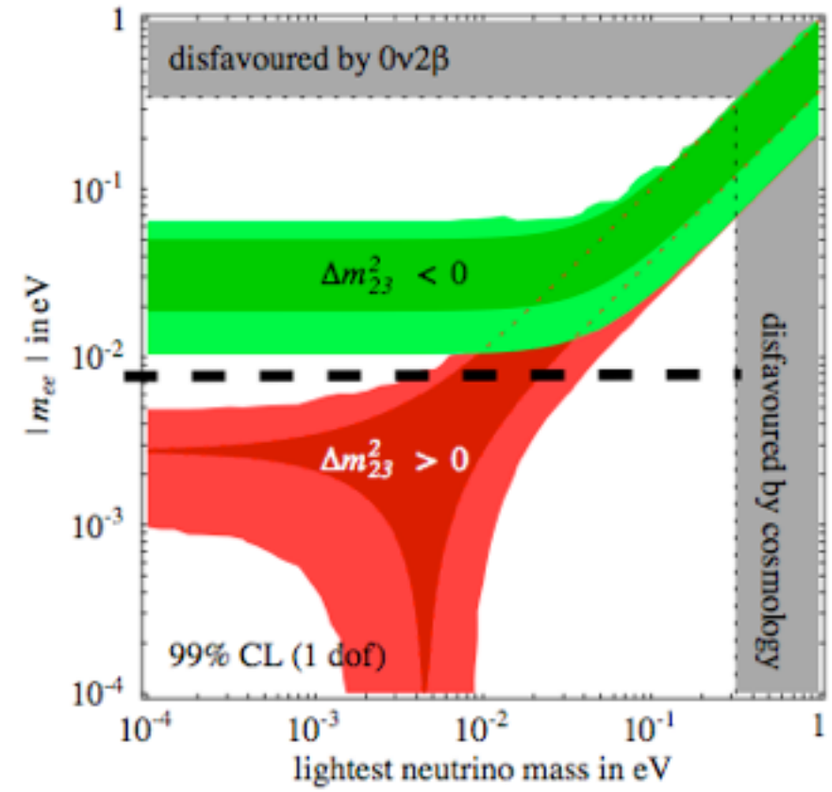


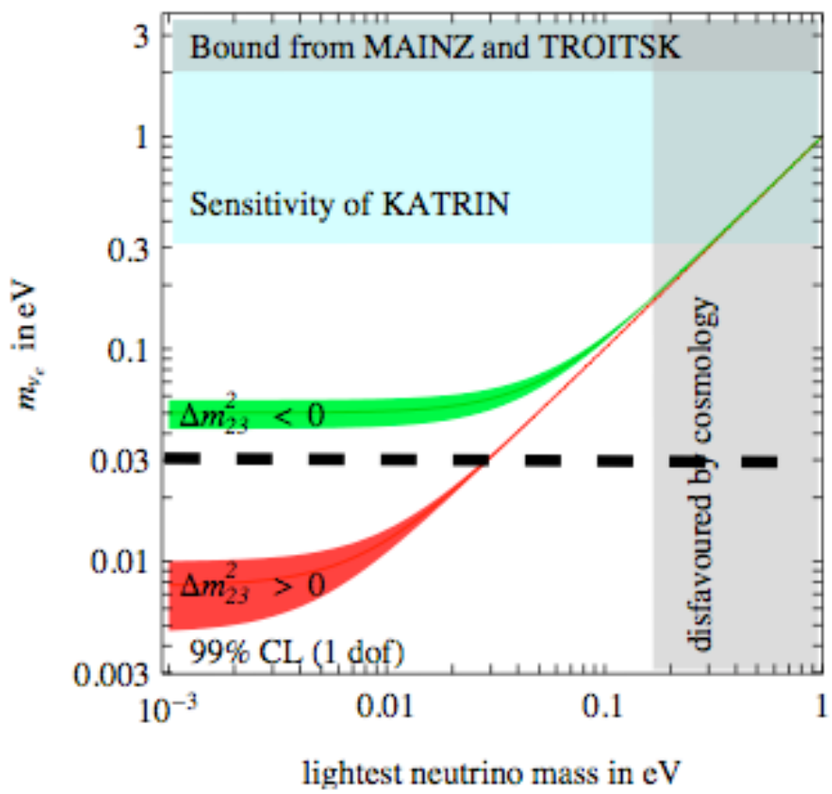
Cosmology



Double Beta Decay

Obviously, we should all hope for inverted hierarchy

Comparison of Different Ways



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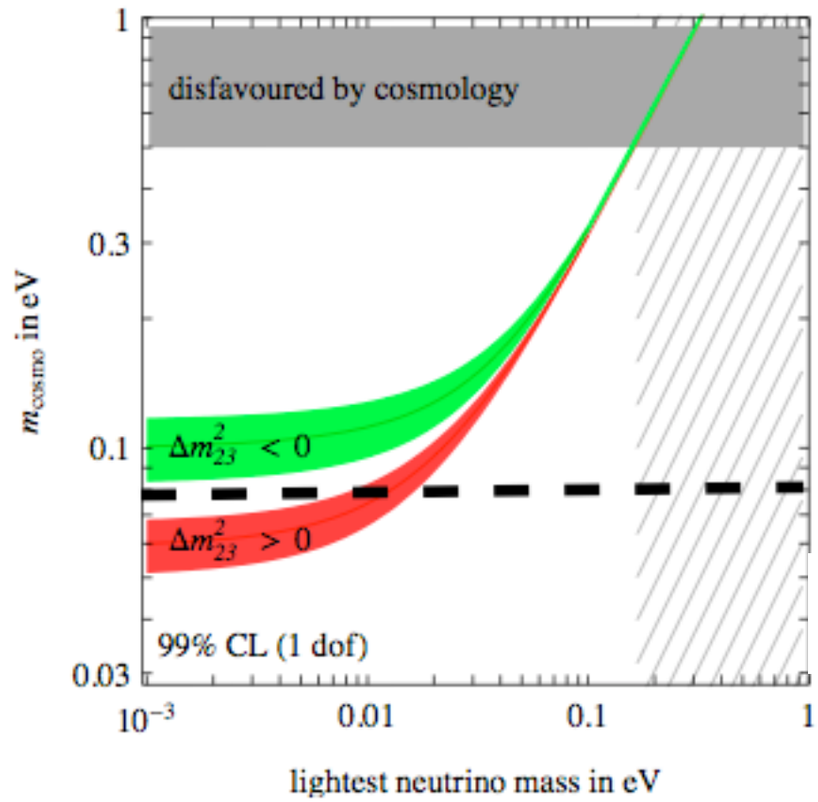
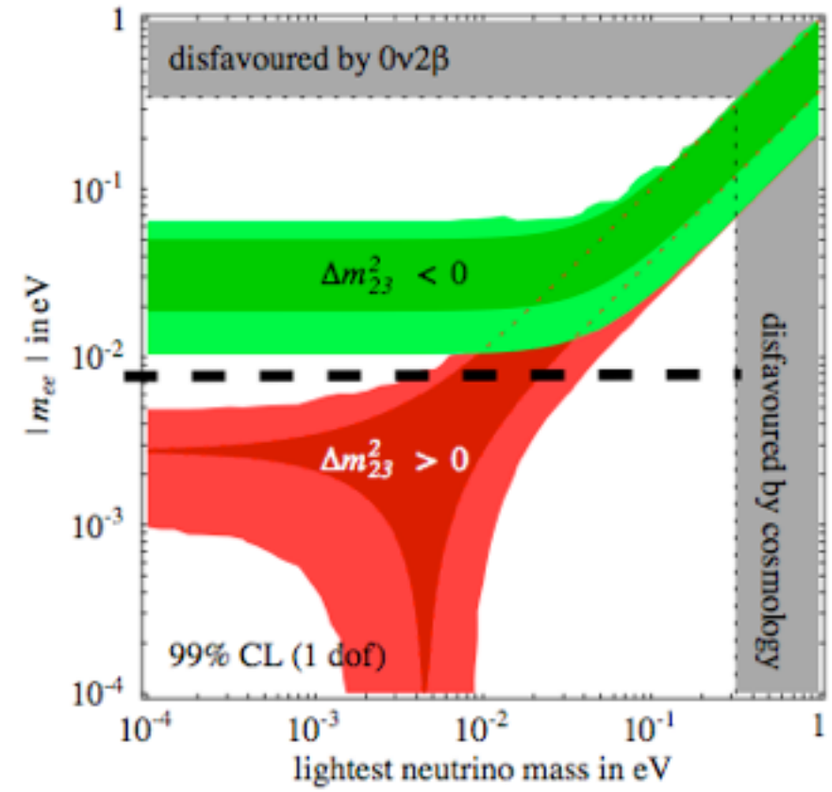


Cosmology

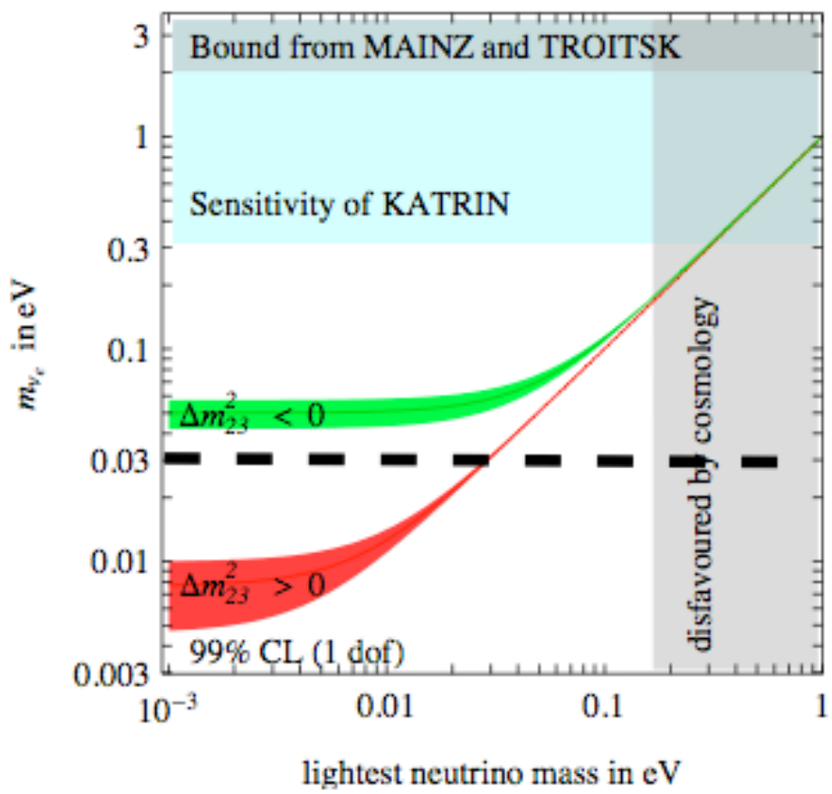


Double Beta Decay

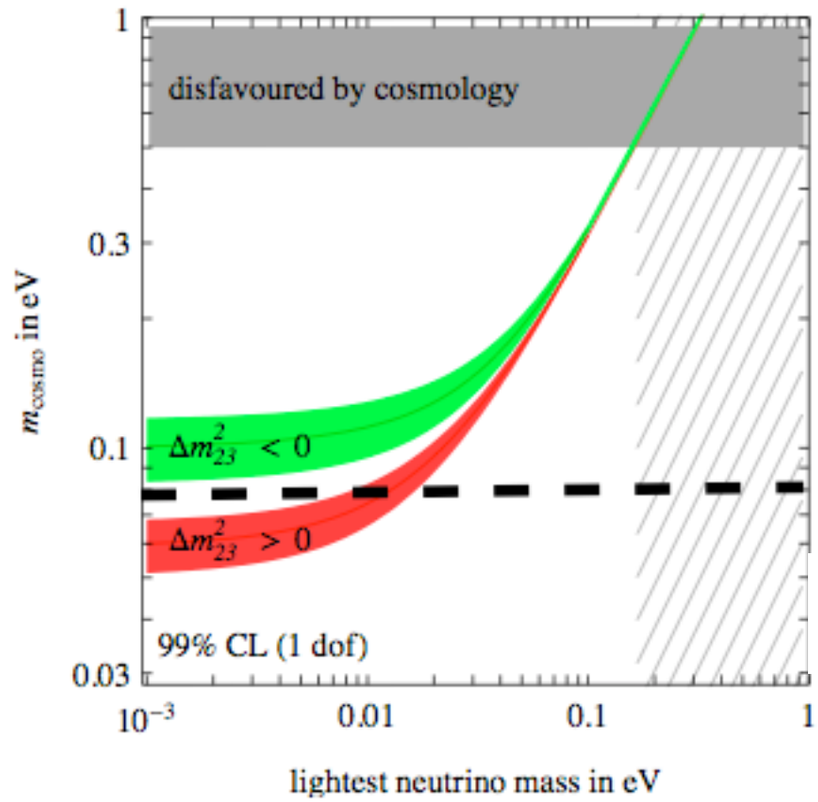
Obviously, we should all hope for inverted hierarchy

The measured mass parameter is different for the three different classes of experiments

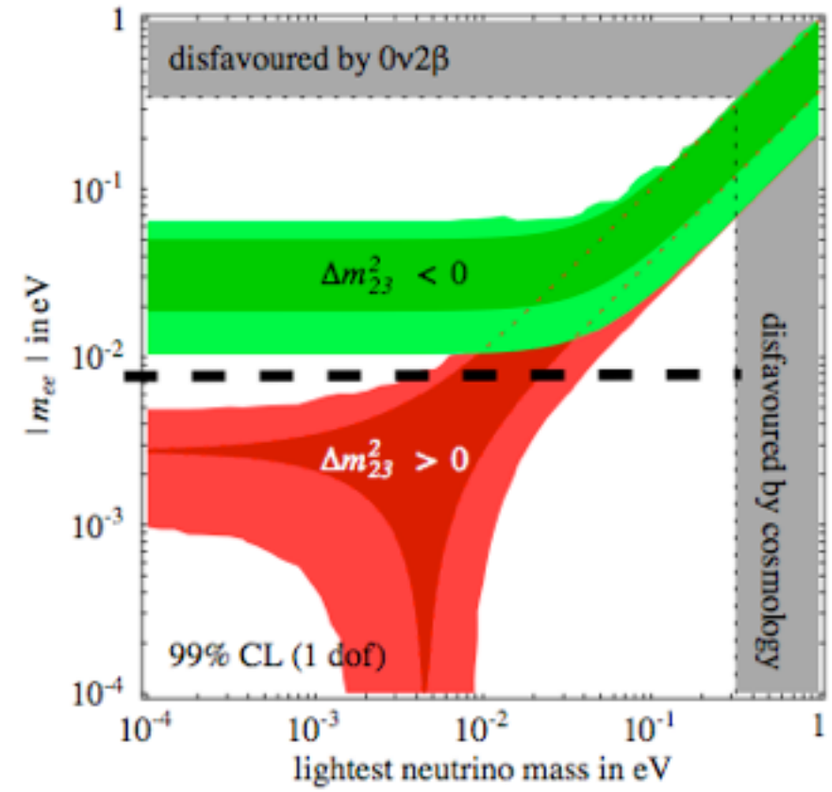
Comparison of Different Ways



Kinematics of Decay



Cosmology



Double Beta Decay

Obviously, we should all hope for inverted hierarchy

The measured mass parameter is different for the three different classes of experiments

The goal is to reach a value which would either exclude inverted hierarchy or obtain a measurement