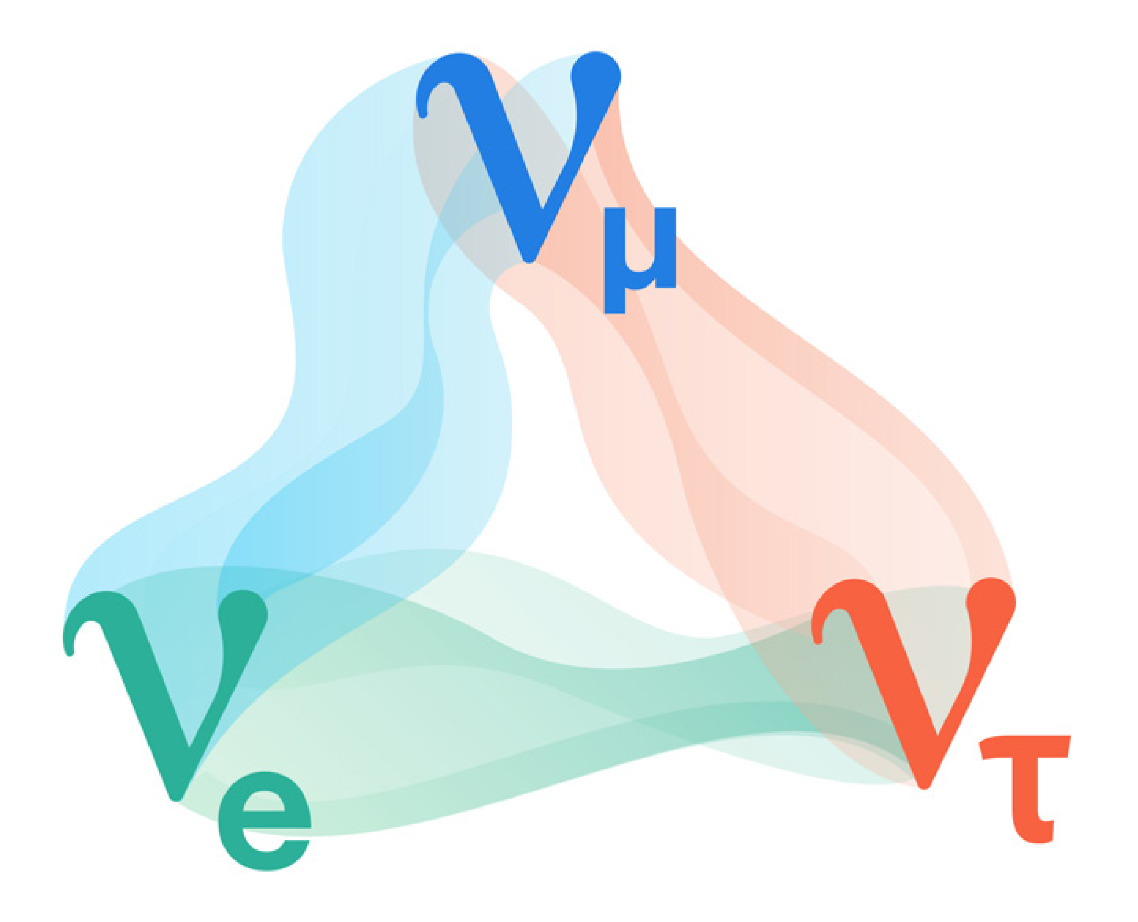
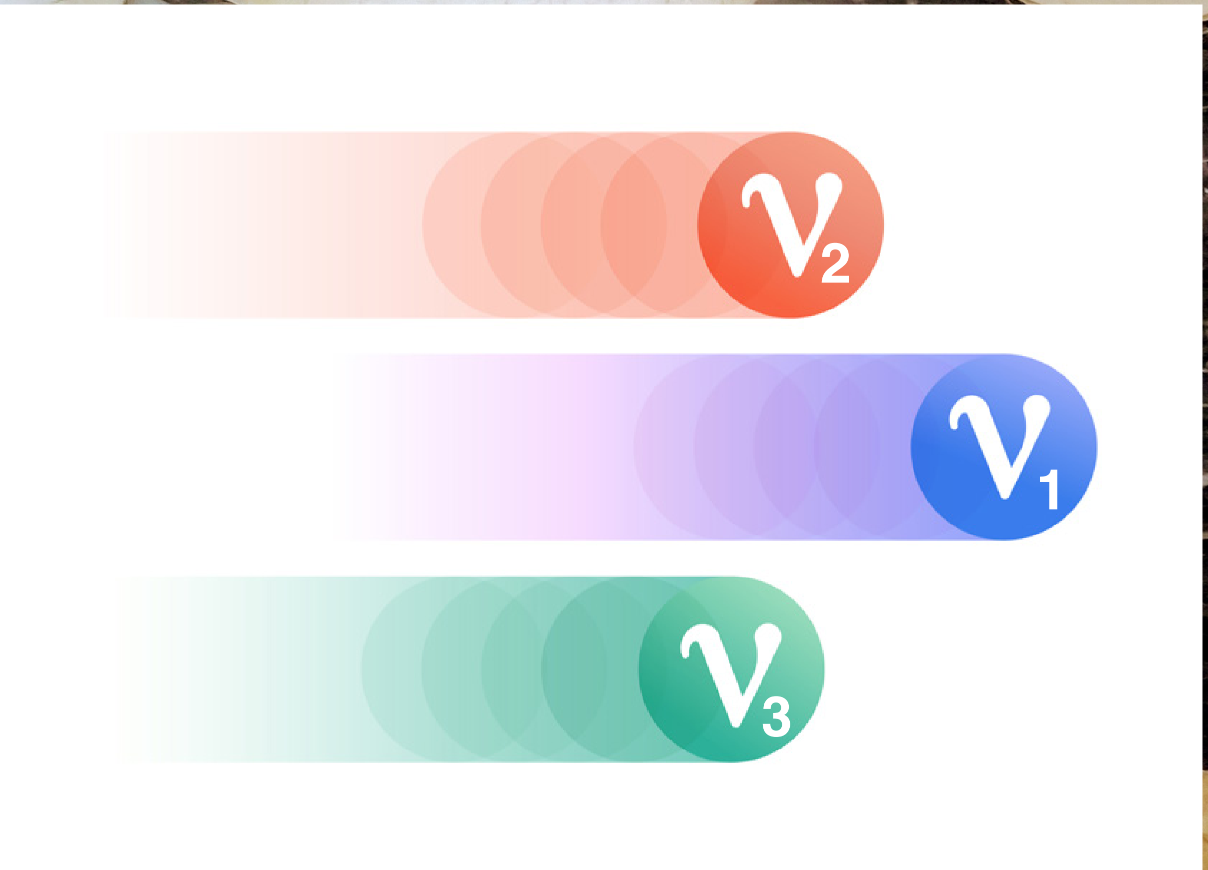
“ Δm^2_{21} Measurements and Tensions”

Stephen Parke
Fermilab
orcid #: 0000-0003-2028-6782

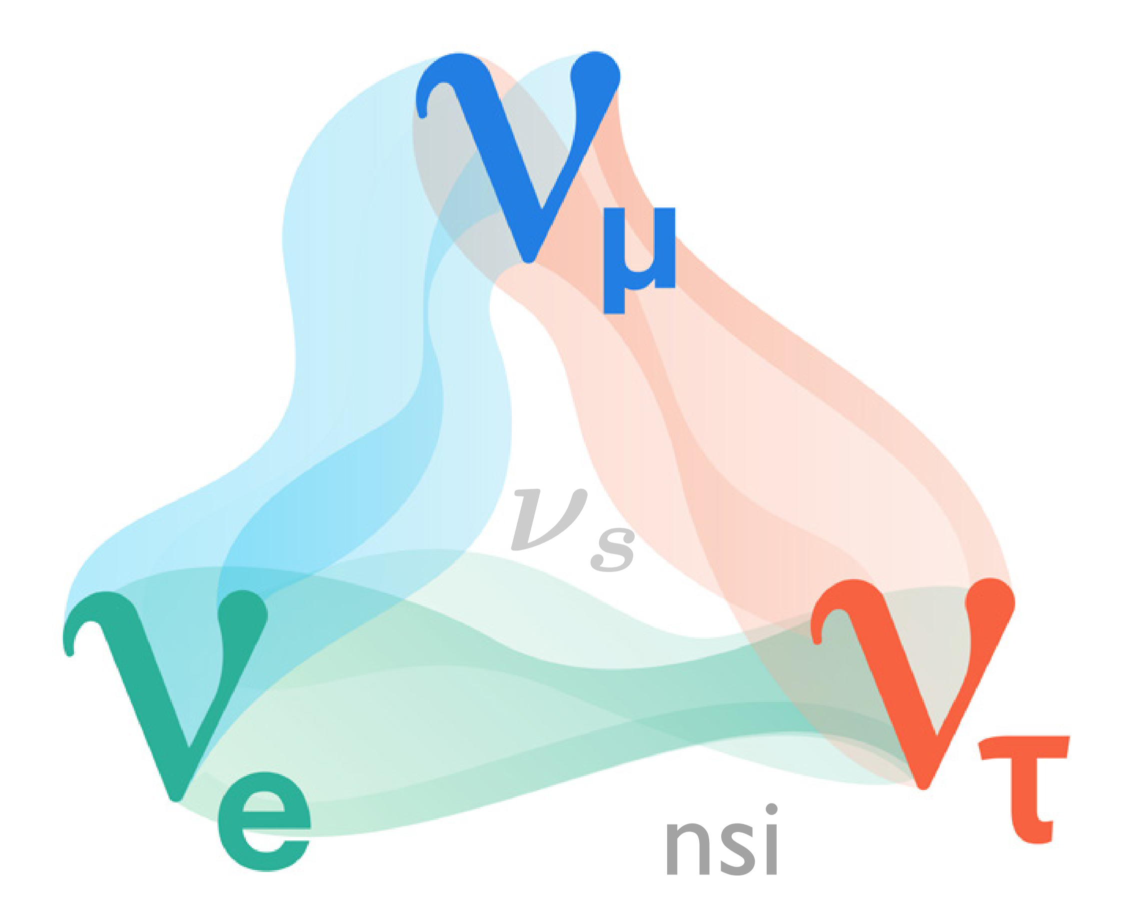


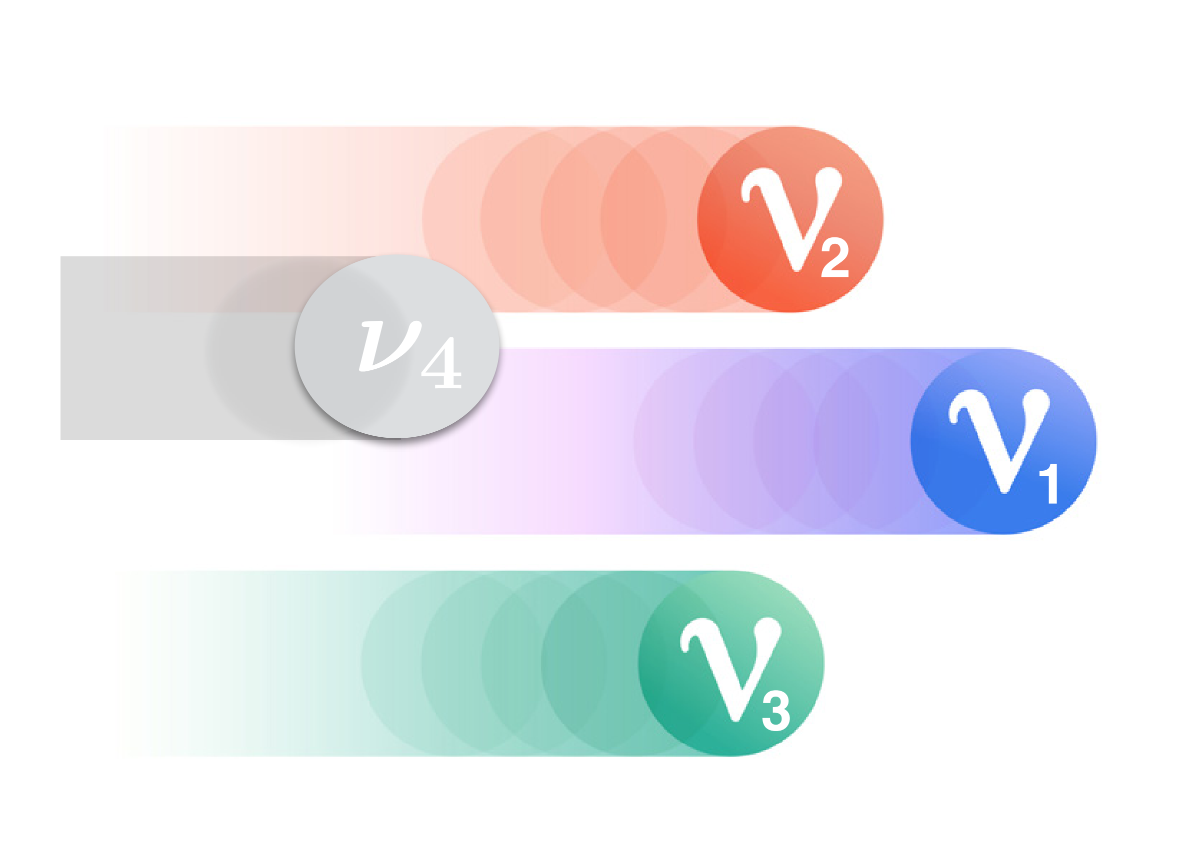


S.H. Seo and SP
arXiv:1808.09150

“ Δm^2_{21} Measurements and Tensions”

Stephen Parke
Fermilab
orcid #: 0000-0003-2028-6782





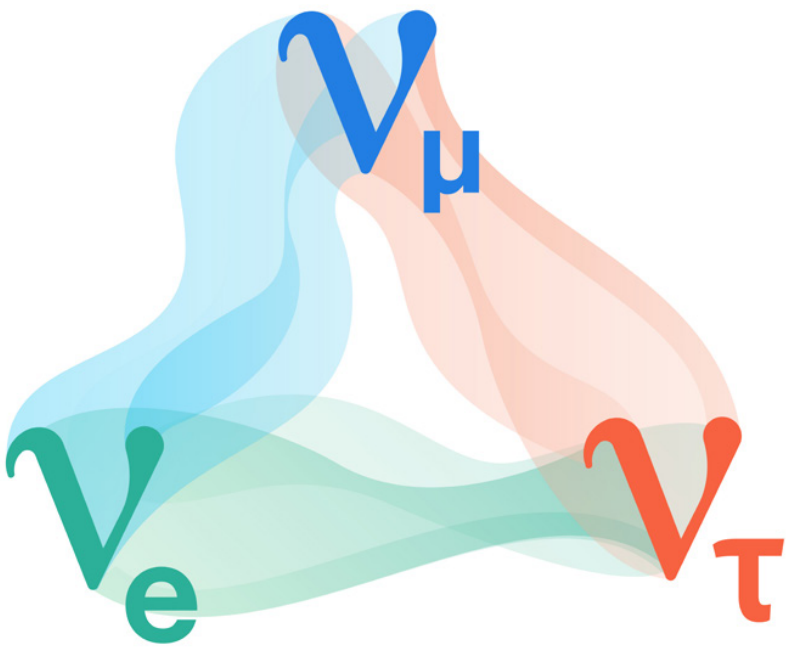
S.H. Seo and SP
arXiv:1808.09150

Outline:

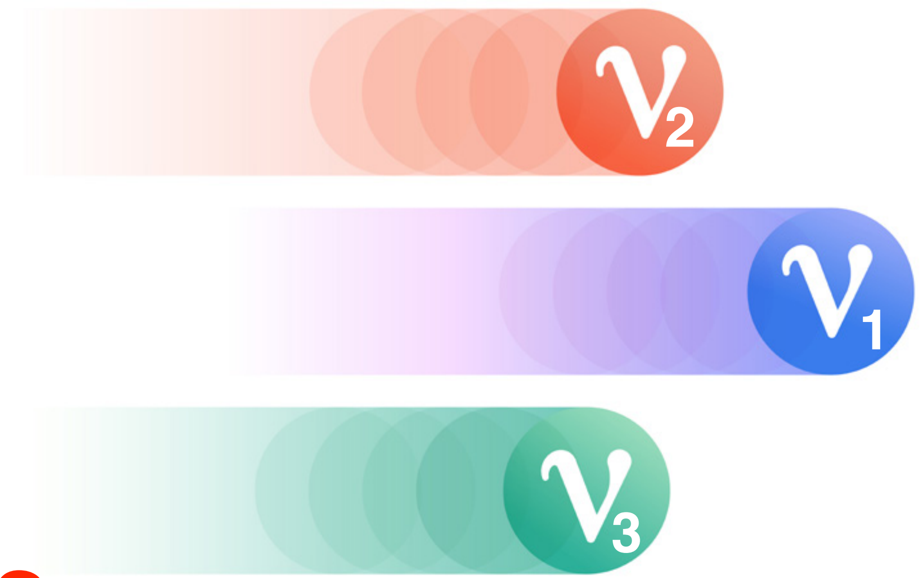
- Current Status
- Effect on other measurements !!!
- Previous Measurements of Delta m^2_21 (SK/SNO, KamLAND)
- Future (JUNO-2025)
- Near Future (Daya Bay & RENO - now !)
- Summary & Conclusion

Interactions:

simple | complicated



=U



unitary matrix ?

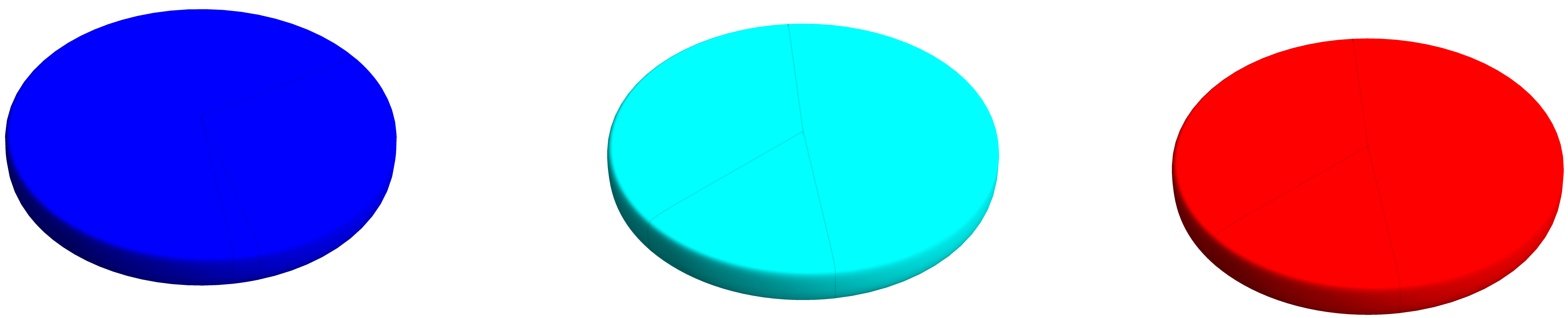
complicated | simple

masses ?

Propagation:

Neutrino Flavor or Interaction States:

$W^+ \to e^+\nu_e$ $W^+ \to \mu^+\nu_\mu$ $W^+ \to \tau^+\nu_\tau$



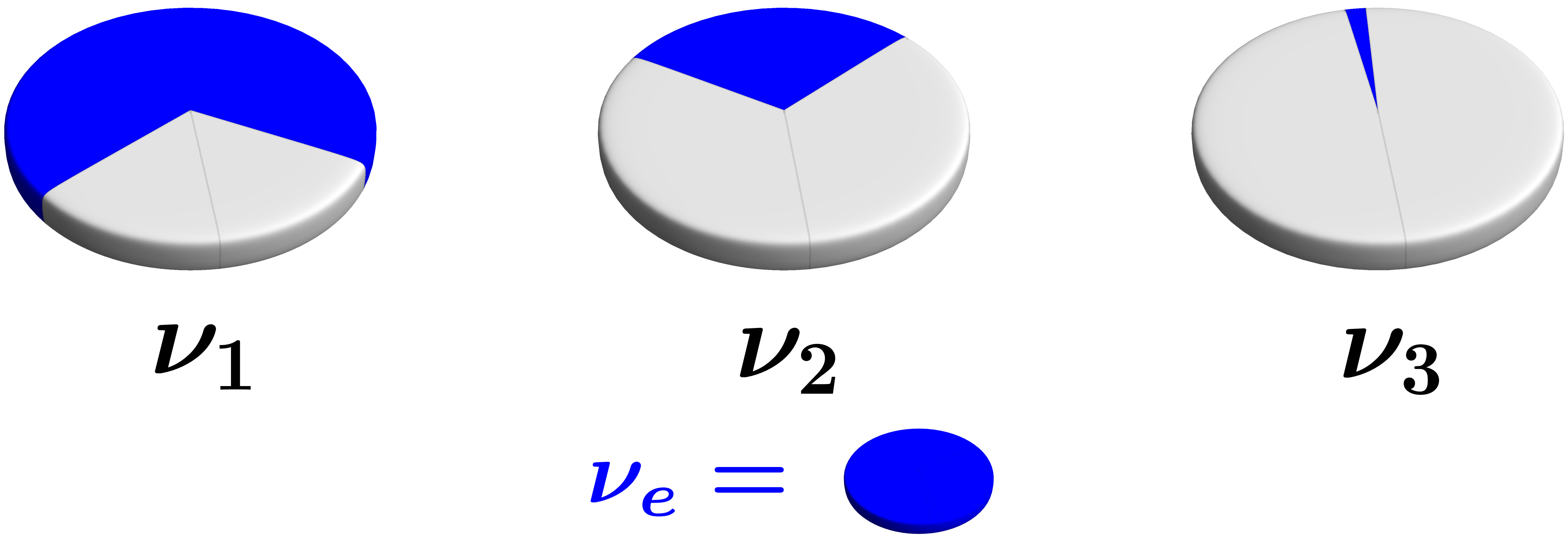
ν_e ν_μ ν_τ

provided $L/E \ll \mathbf{0.5}$ km/MeV $= \mathbf{500}$ km/GeV !!!

"Proper Age" $\tau_\nu = \mathbf{0.15}\ \text{psec} \left(\frac{L/E}{\mathbf{0.5}\,\text{km/MeV}}\right) \left(\frac{m_\nu}{0.1\,\text{eV}}\right)$

Neutrino Mass EigenStates or Propagation States:

$$\text{Propagator } \nu_j \to \nu_k \;=\; \delta_{jk}\, e^{-i\left(\frac{m_j^2 L}{2E_\nu}\right)}$$



$$\Delta m^2_{21} \sim 7.5 \times 10^{-5}\ \text{eV}^2$$

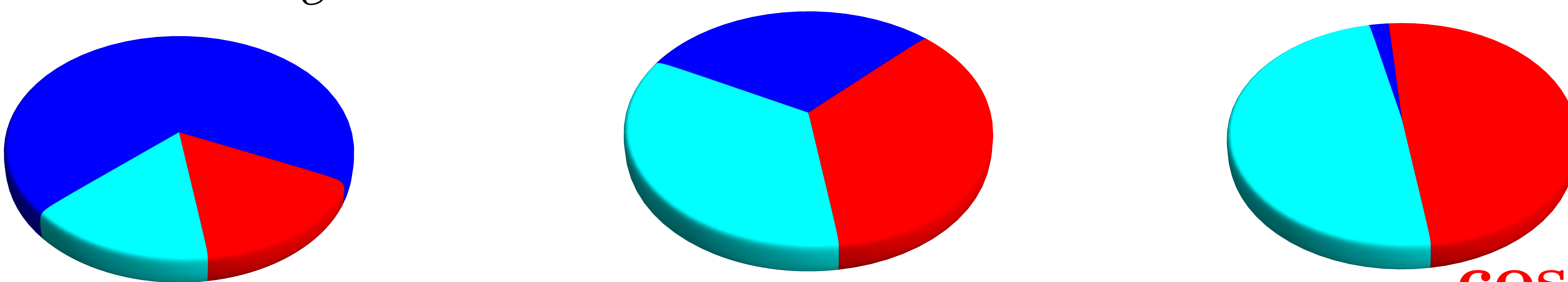
$$|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \sim 2.5 \times 10^{-3}\ \text{eV}^2$$

Neutrino Mass EigenStates or Propagation States:

ν_1 most ν_e

ν_2 $\sin^2\theta_{12}$

ν_3 $\sin^2\theta_{13}$ least ν_e



$\cos^2\theta_{23}$

δ, θ_{23} δ, θ_{23} θ_{23}

$\nu_e =$

Solar Exp, SNO
KamiLAND
Daya Bay, RENO, …

$\nu_\mu =$

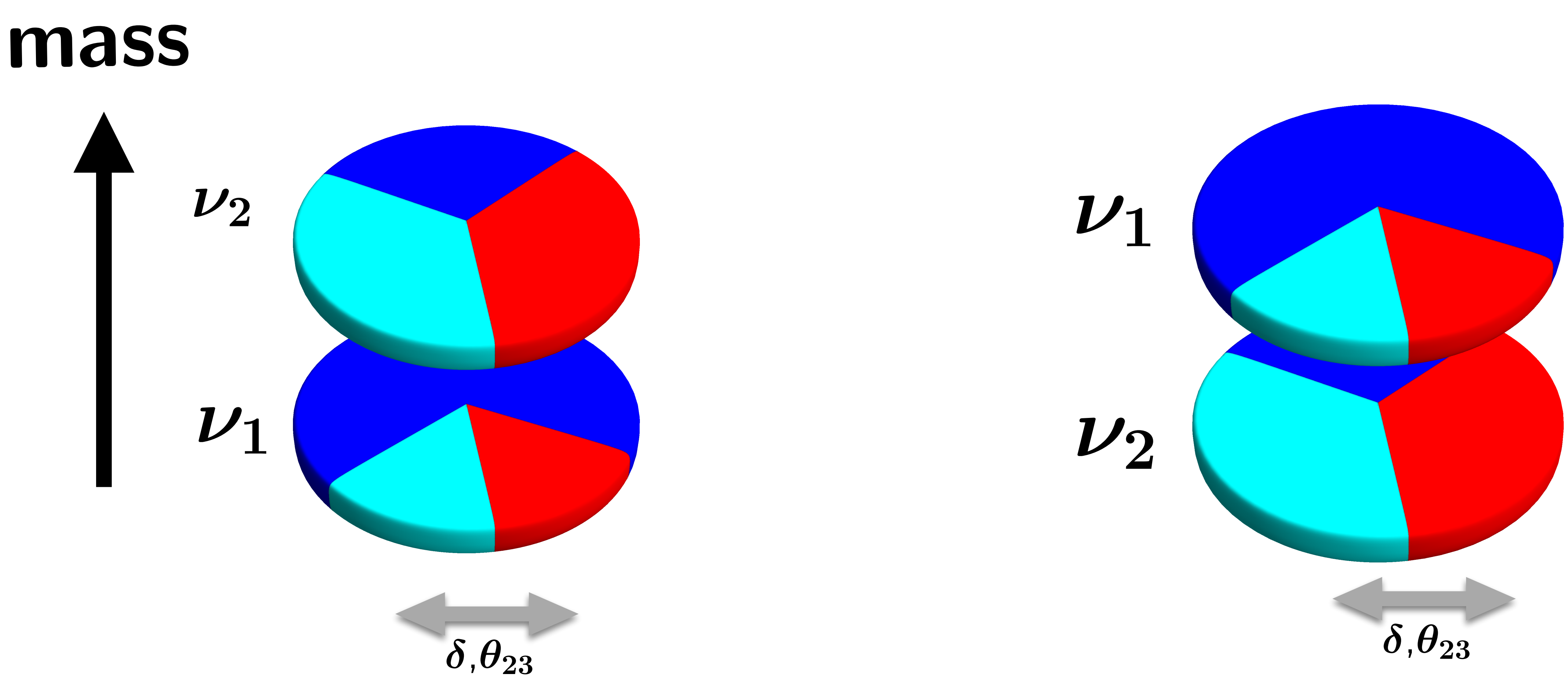
SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

$\nu_\tau =$

Unitarity
SK, Opera
ICECUBE ?

ν_1, ν_2 Mass Ordering:

–solar mass ordering



$|\Delta m^2_{21}| = |m^2_2 - m^2_1| = 7.5 \times 10^{-5}\ \mathrm{eV}^2$

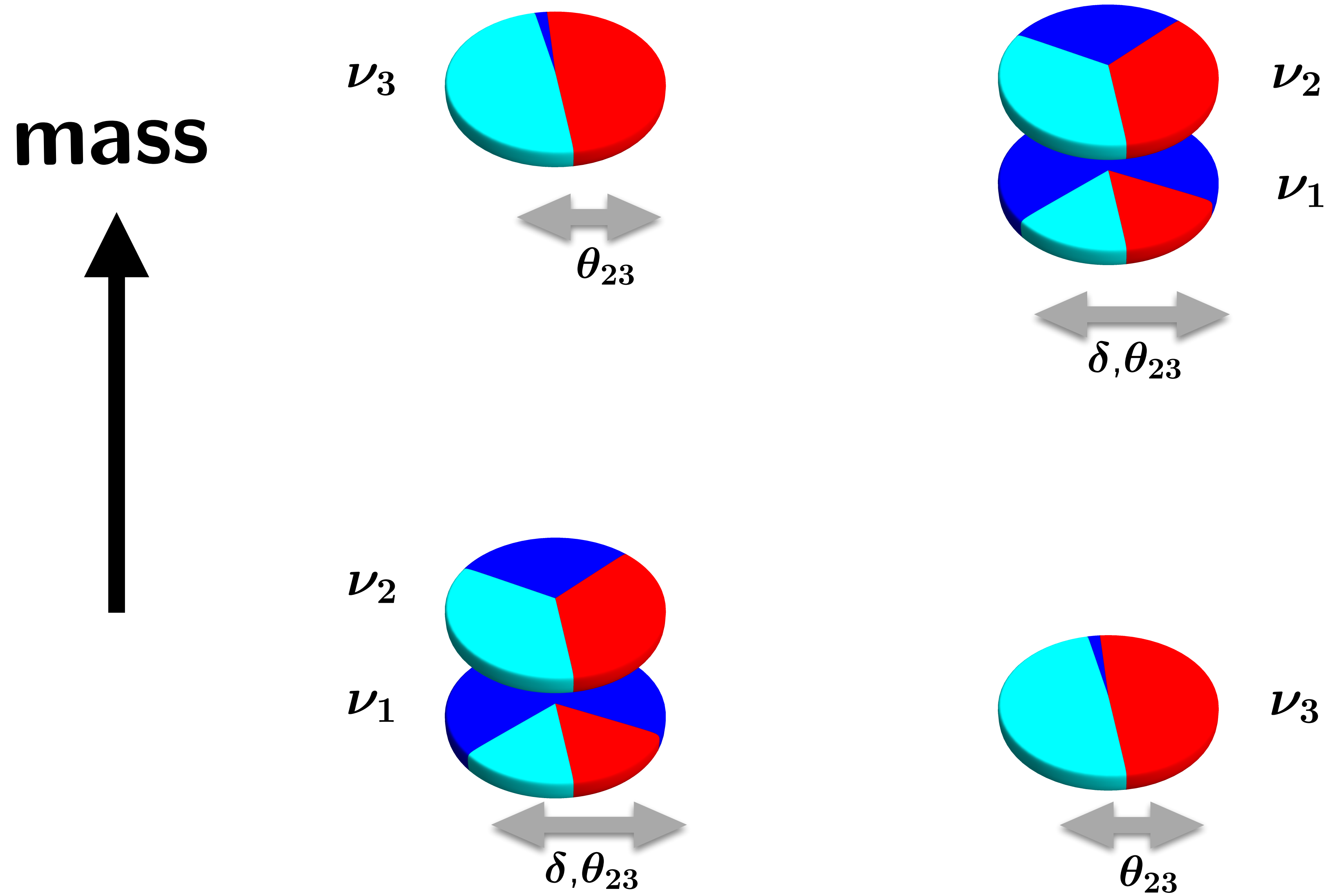
$L/E = 15\ \mathrm{km/MeV} = 15,000\ \mathrm{km/GeV}$

SNO $m_2 > m_1$

$\nu_e =$ (blue) $\nu_\mu =$ (cyan) $\nu_\tau =$ (red)

$\nu_3, \; \nu_1/\nu_2$ Mass Ordering:

–atmospheric mass ordering



$$\sin^2\theta_{12} \sim \frac{1}{3}$$

$$\sin^2\theta_{23} \sim \frac{1}{2}$$

$$\sin^2\theta_{13} \sim 0.02$$

$$0 \leq \delta < 2\pi$$

$$|\Delta m^2_{31}| = |m^2_3 - m^2_1| = 2.5 \times 10^{-3}\ \mathrm{eV}^2$$

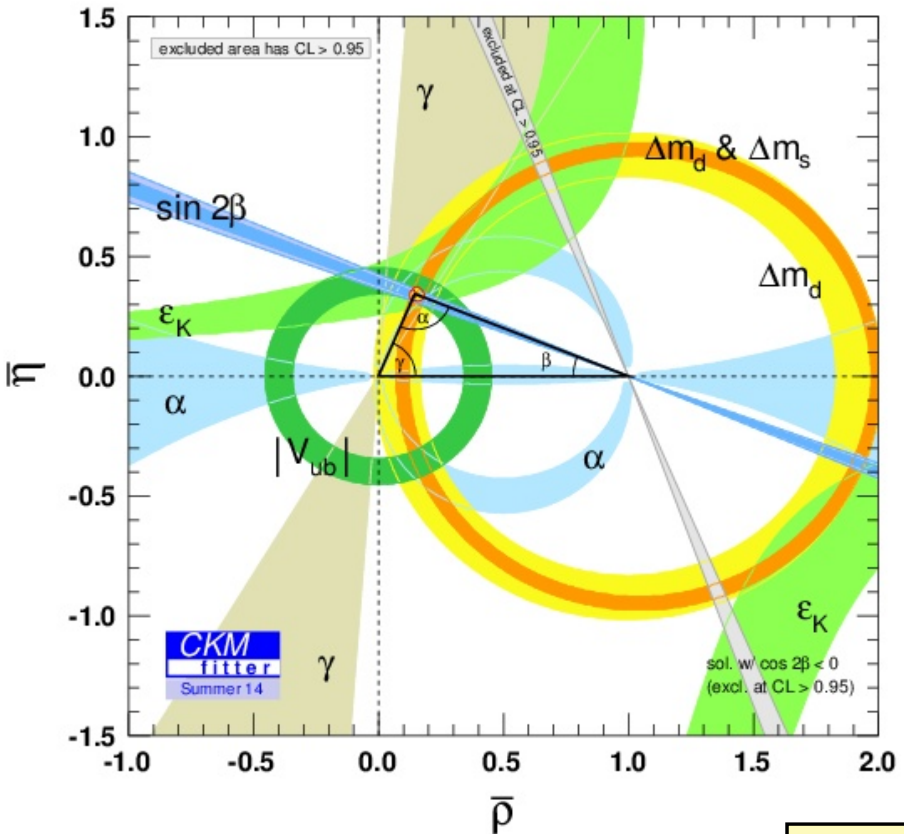
$$L/E = 0.5\ \mathrm{km/MeV} = 500\ \mathrm{km/GeV}$$

Unknown: NOνA, JUNO, ICECUBE, DUNE, T2HKK....

quarks

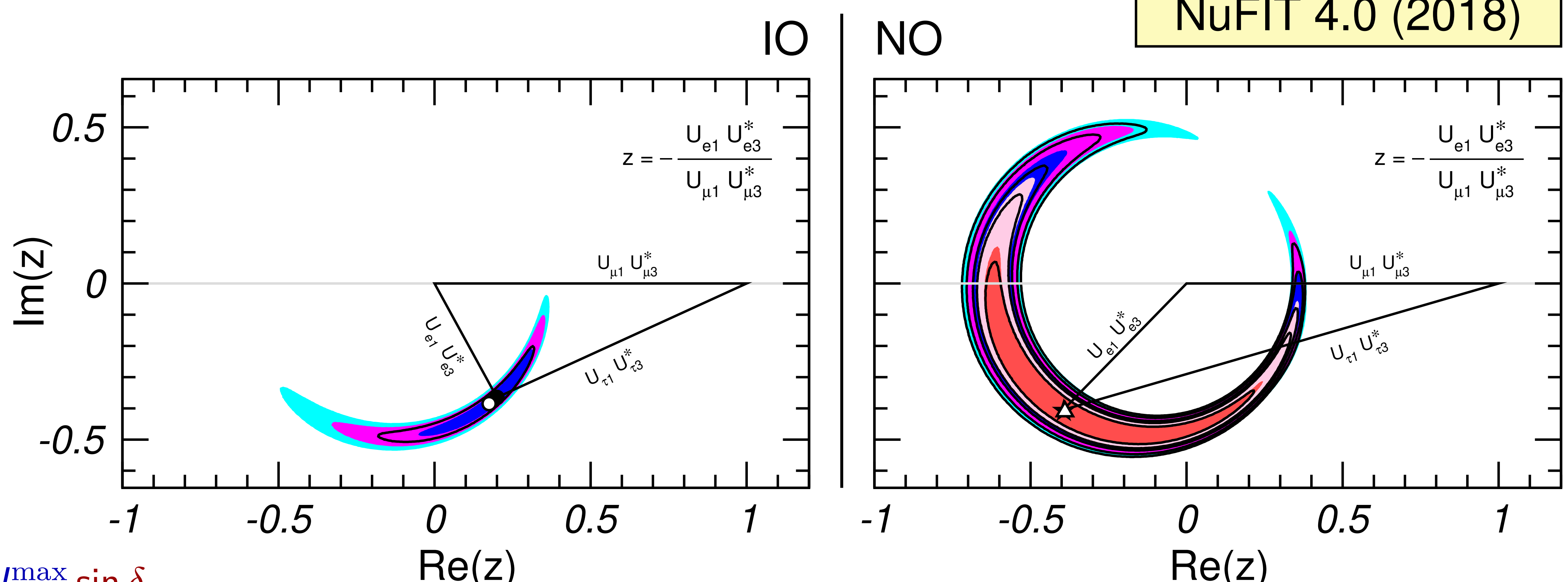
$$J_{CP}^{\text{quarks}} = (3.18 \pm 0.15) \times 10^{-5}$$

Unitarity *NOT* assumed



neutrinos

NuFIT 4.0 (2018)



$J \equiv J^{\max} \sin\delta$

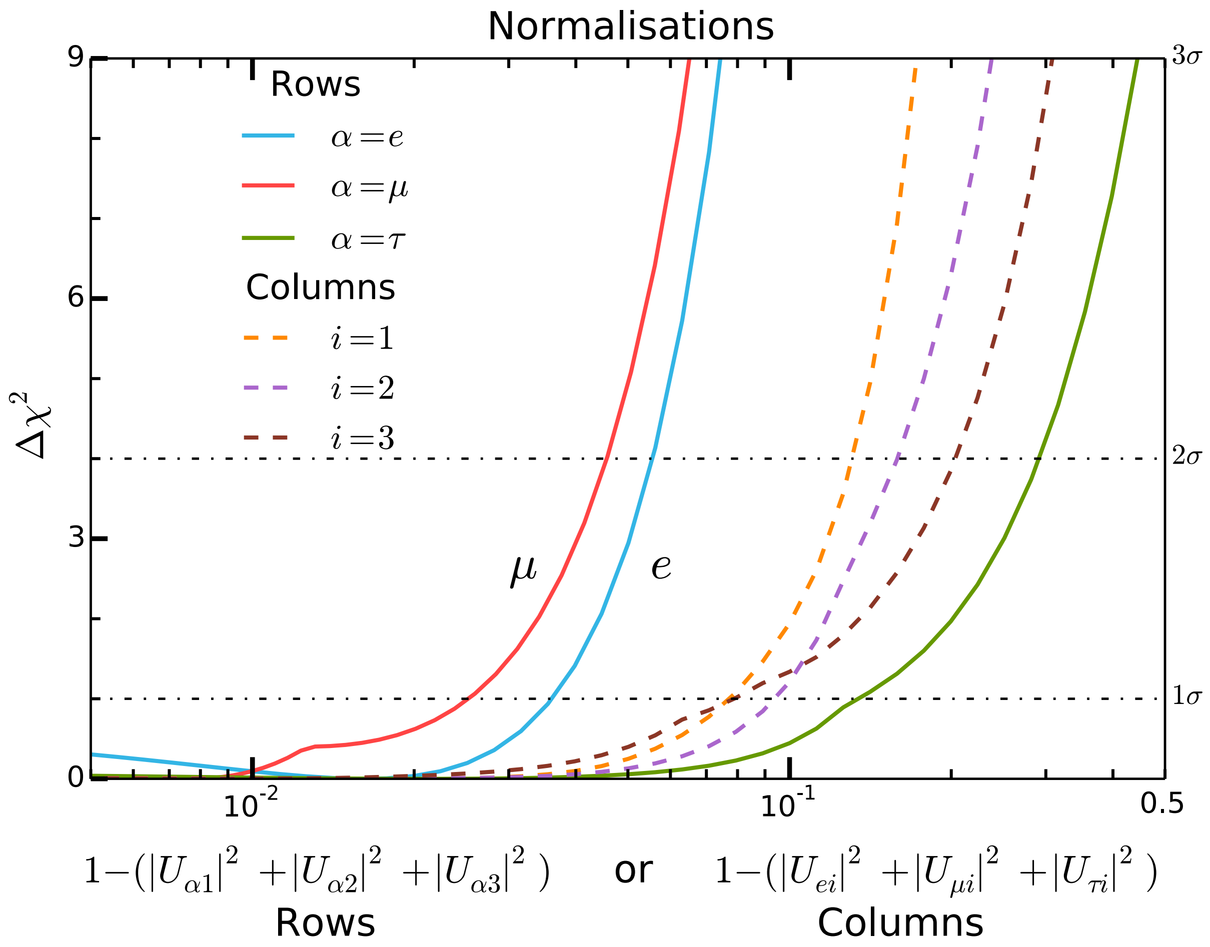
$$J_{CP}^{\max} = 0.0333 \pm 0.0006\,(\pm 0.0019) \text{ at } 1\sigma\ (3\sigma)$$

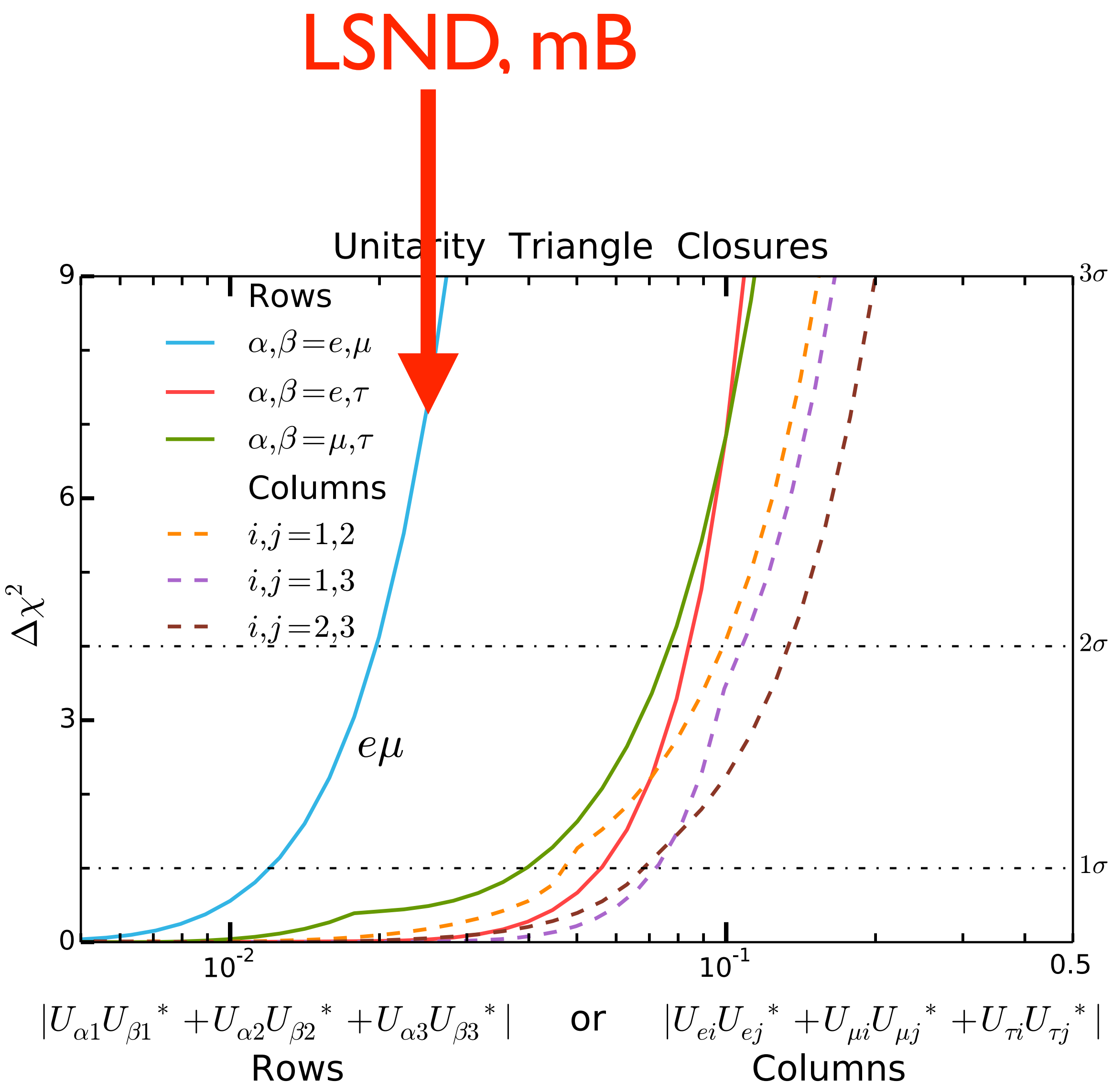
Unitarity *Is* assumed

Unitarity ???

NeuTel 2015

6 row/column plus 6 triangle conditions

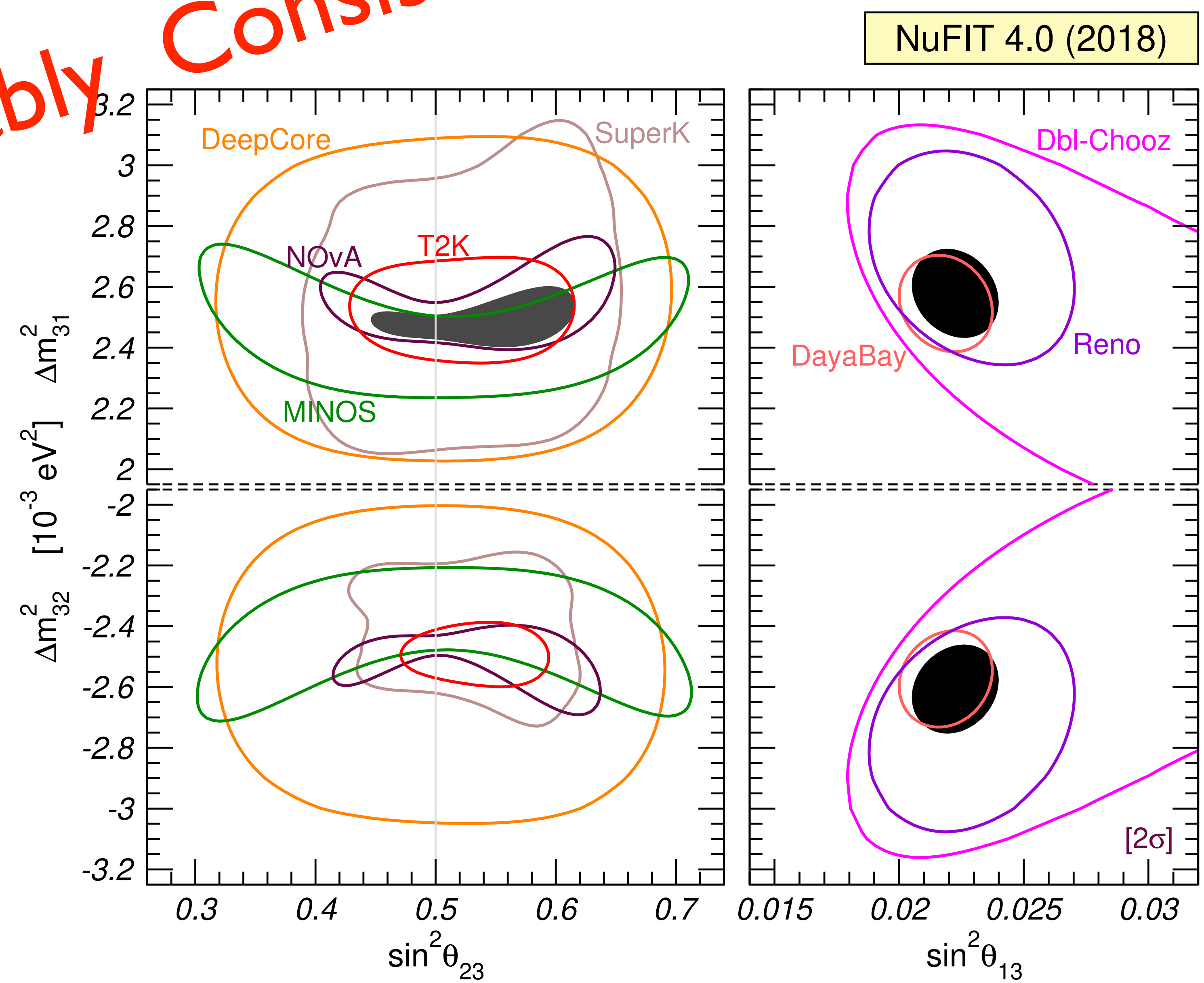




2 row and 1 triangle, independent of ν_τ

Δm^2_{atm} v $\sin^2\theta_{23}$ $(\sin^2\theta_{13})$ consistency ?

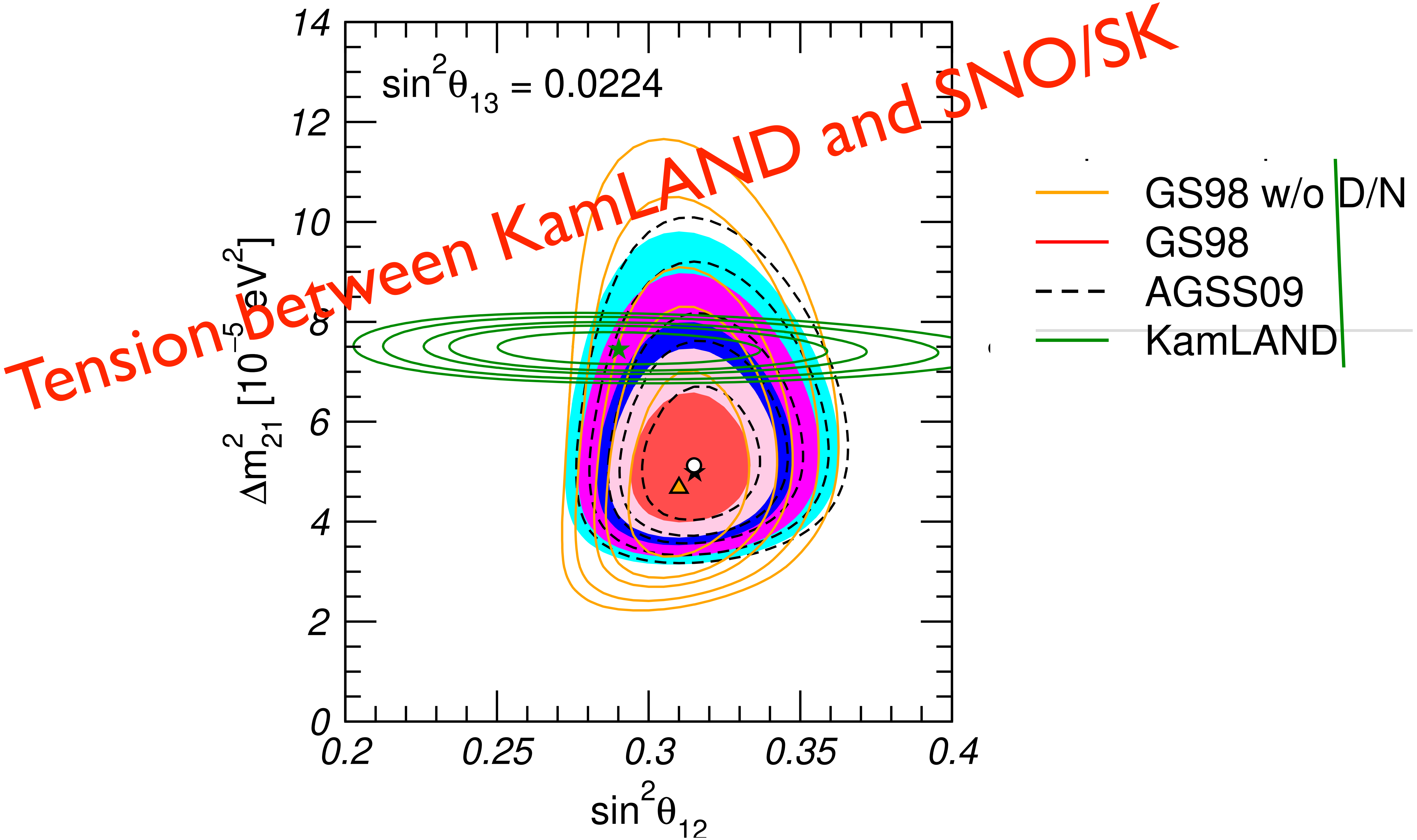
Reasonably Consistent



$$4|U_{\mu3}|^2(1-|U_{\mu3}|^2)$$

$$|U_{\mu3}|^2 = c_{13}^2\sin^2\theta_{23}$$

Δm^2_{21} v $\sin^2\theta_{12}$ consistency ?



1σ, 90%, 2σ, 99%, 3σ CL for 2 dof)

Why do we care about Δm^2_{21}

CP Violation:

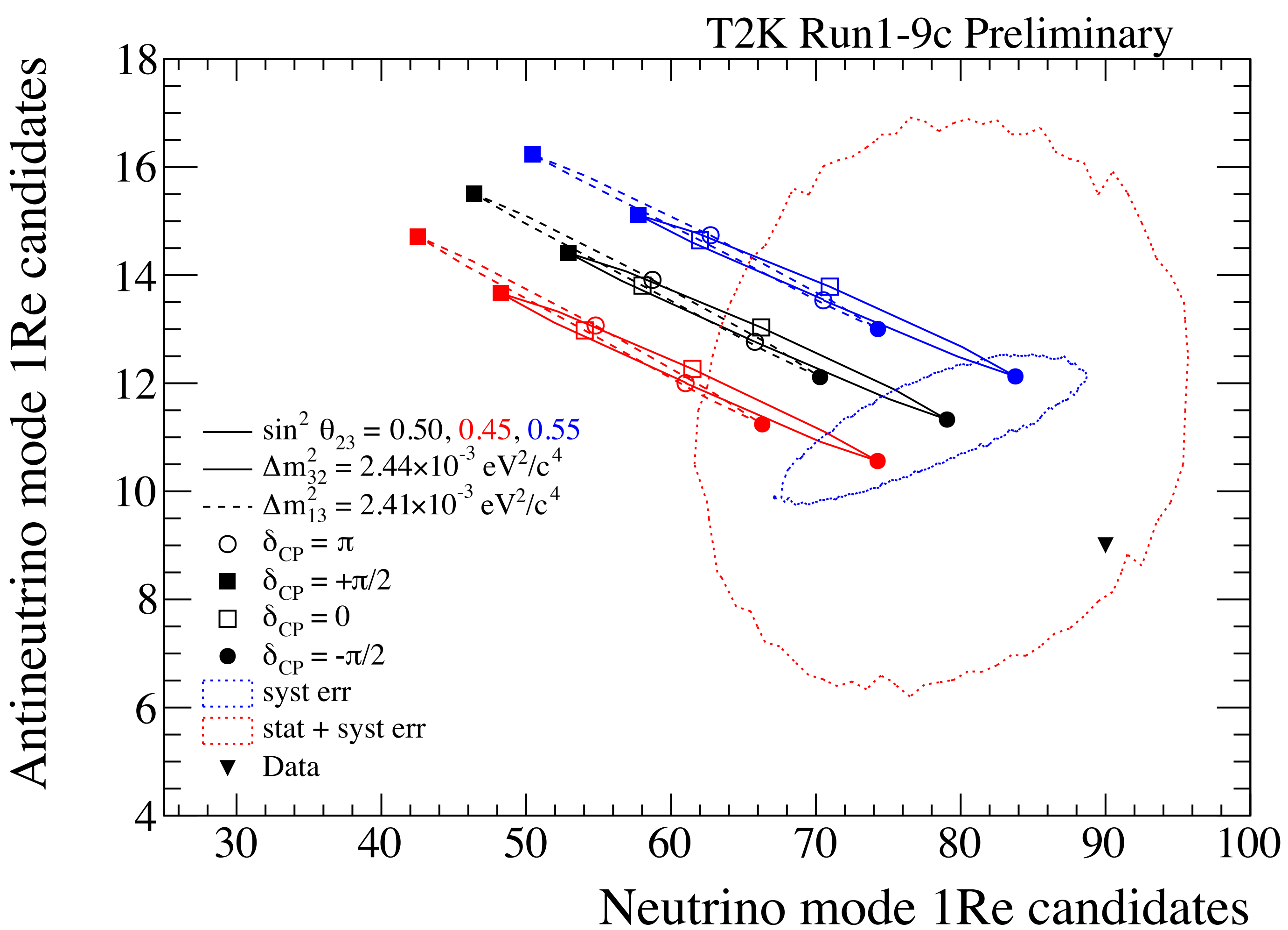
At oscillation maximum in vacuum:

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) - P(\nu_\mu \to \nu_e) \approx \pi J \left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right)$$

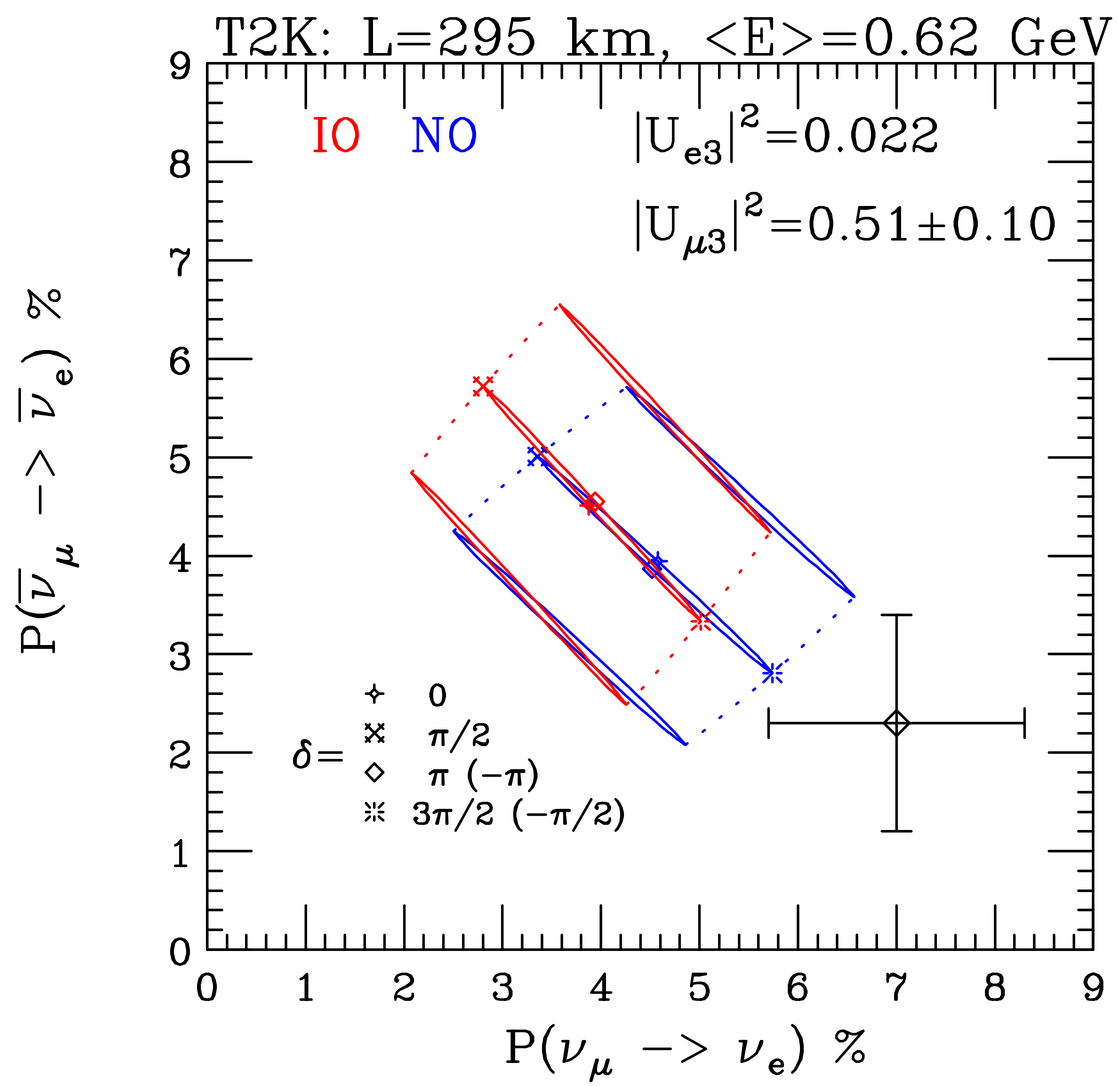
where J is Jarlskog Invariant (1985):

$$J = \sin 2\theta_{12} \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{23} \sin\delta \approx 0.3 \sin\delta$$

T2K



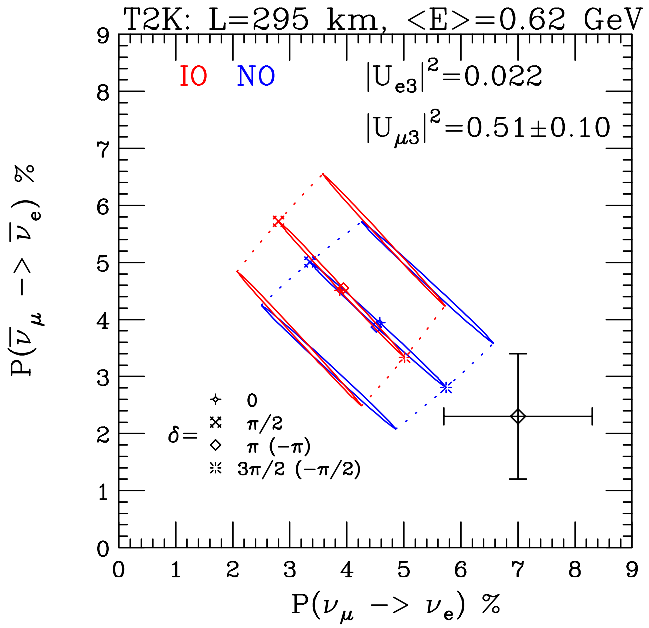
bi-event:



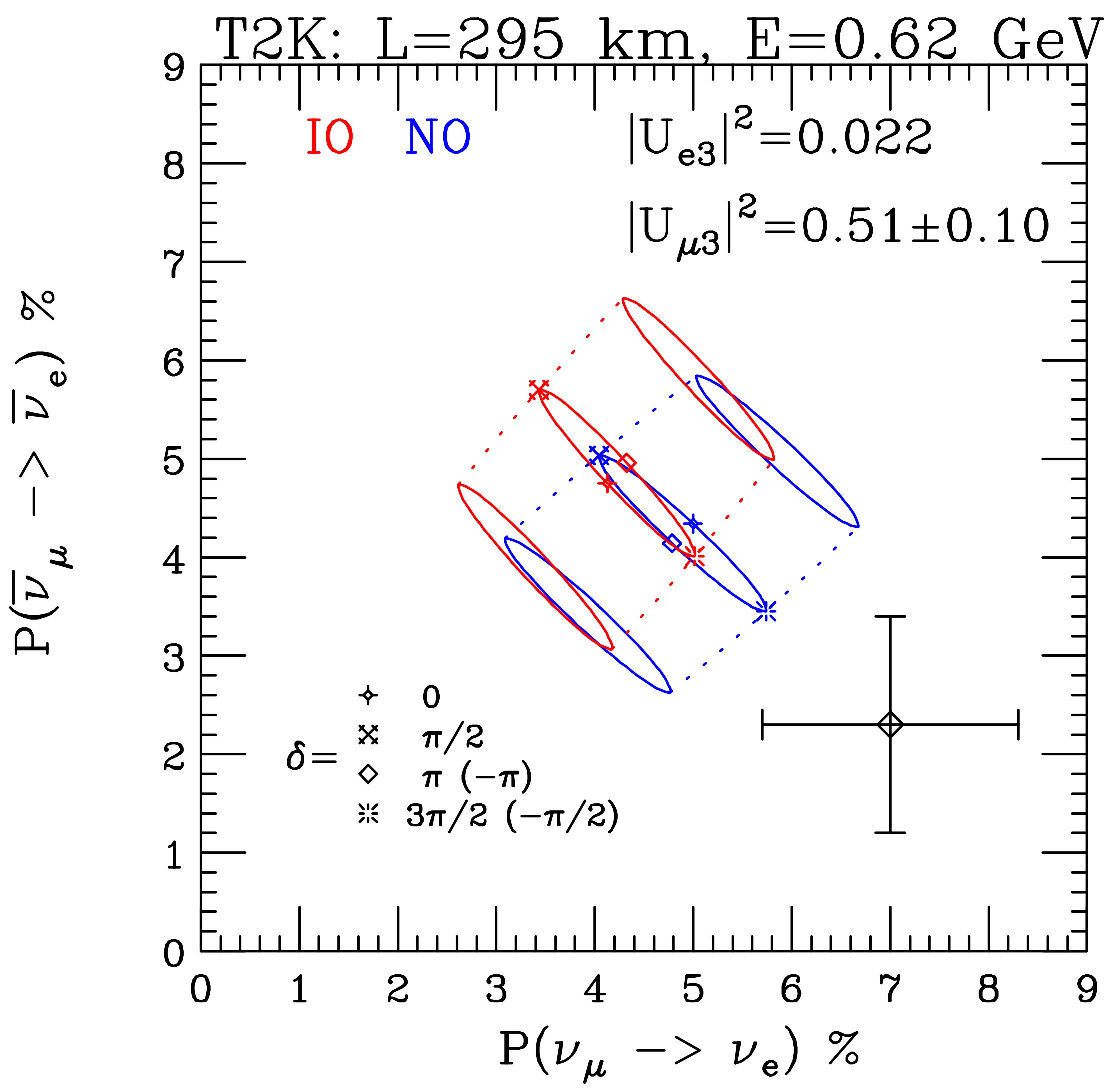
bi-probability:

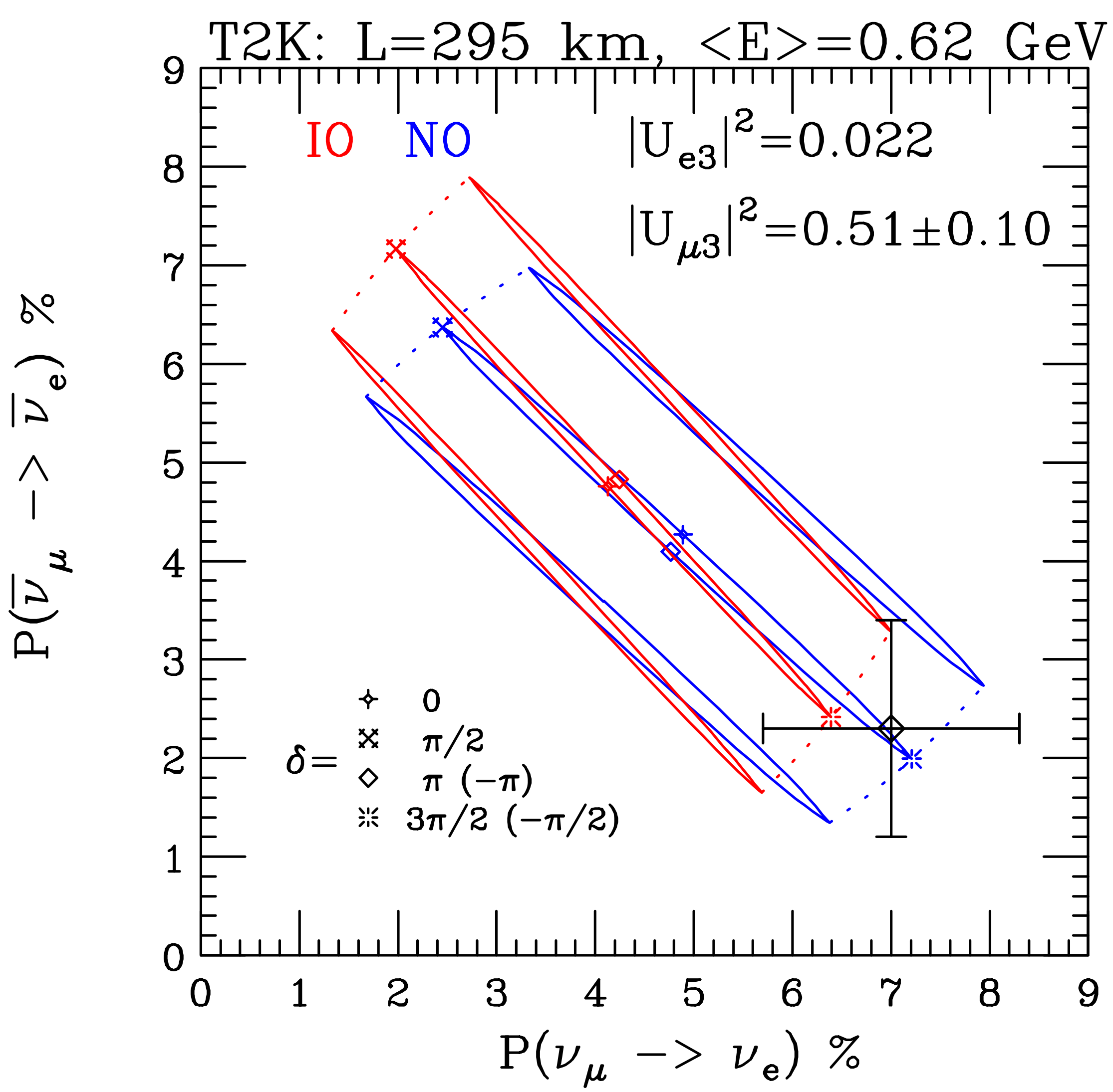
Varying:

Δm^2_{21}



KamLAND



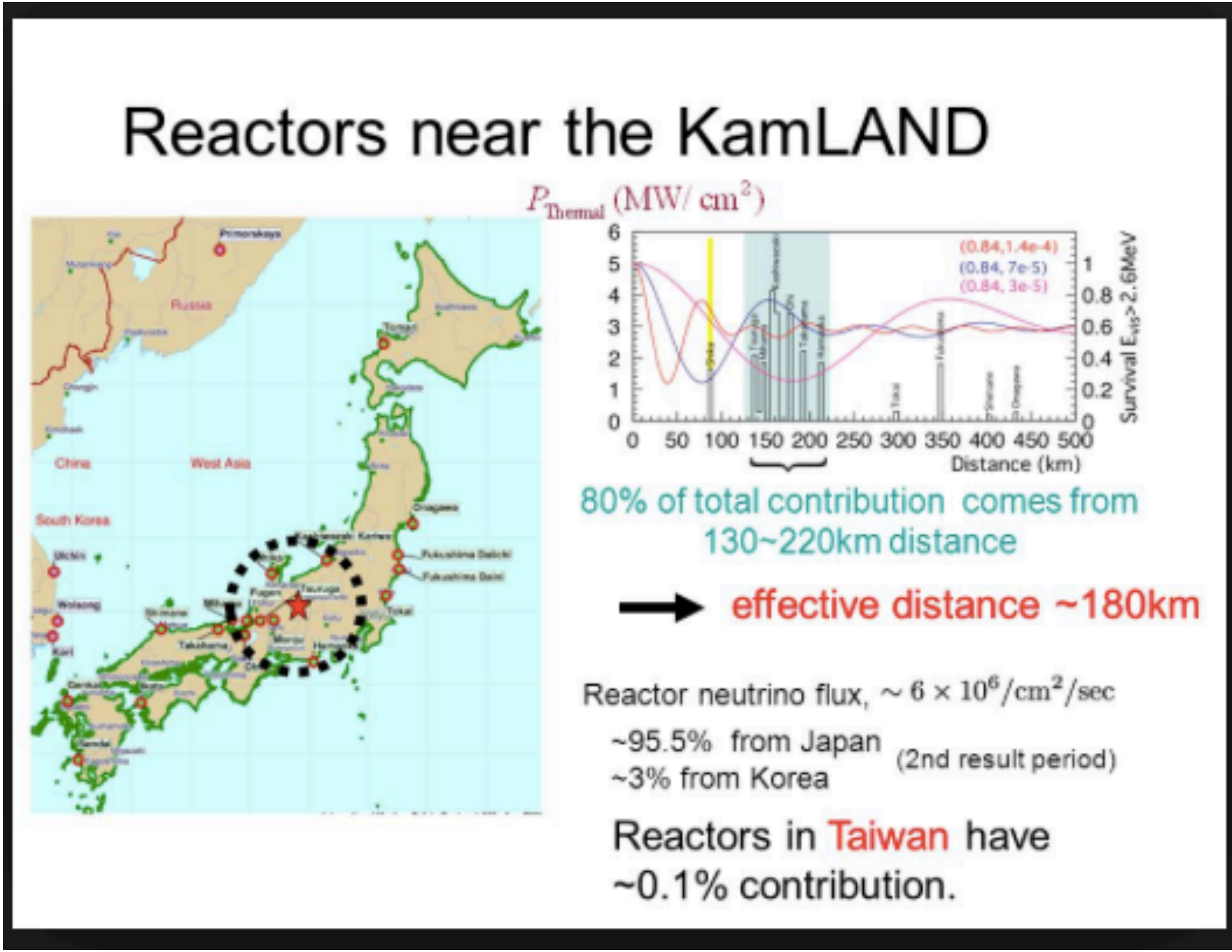


SK/SNO

2 x KamLAND

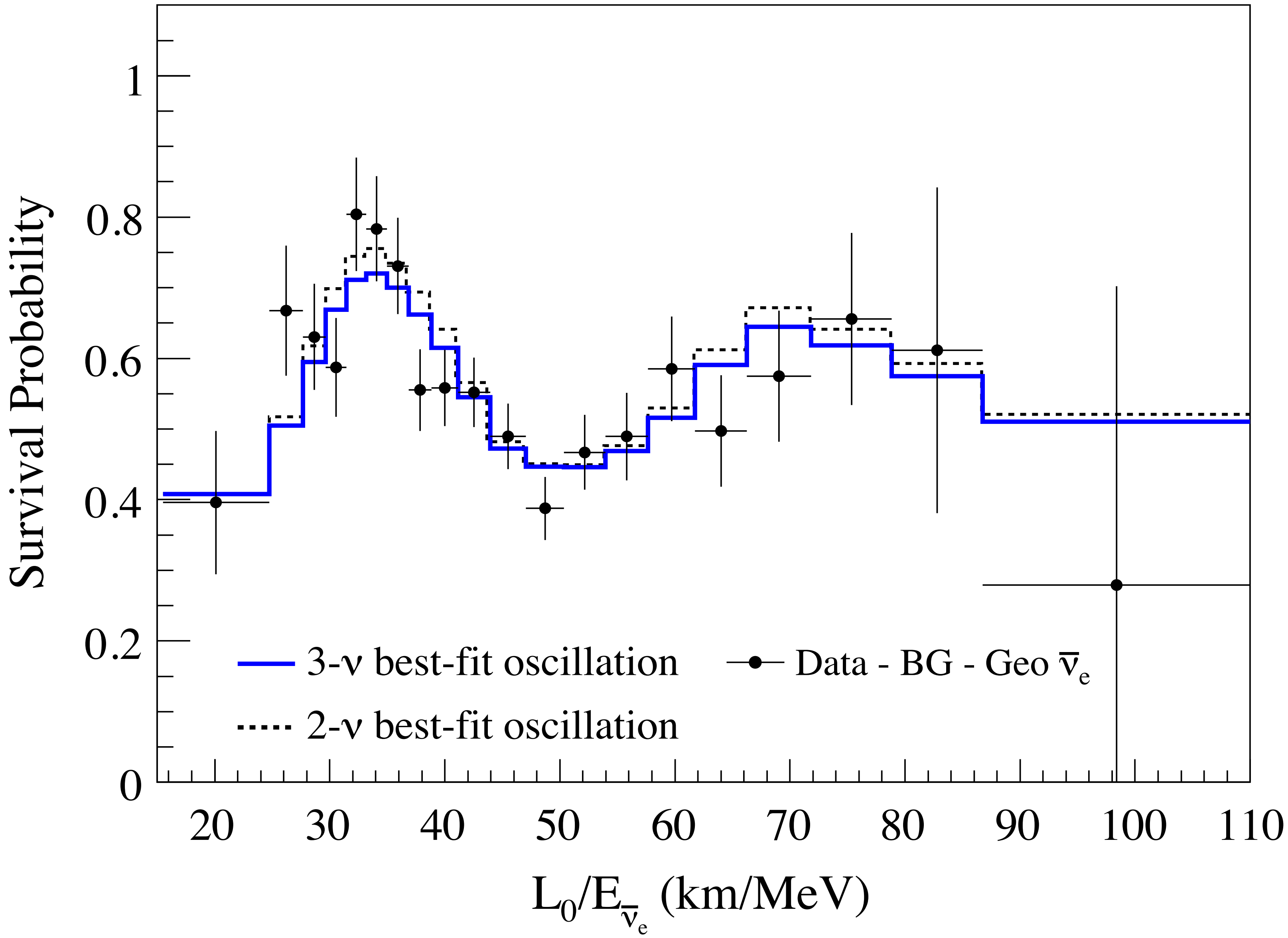
How do we measure Δm^2_{21}

KamLAND:



Reactors near the KamLAND
$P_{Thermal}$ (MW/ cm²)
(0.84,1.4e-4)
(0.84, 7e-5)
(0.84, 3e-5)
0 50 100 150 200 250 300 350 400 450 500
Distance (km)
Survival E_{vis}>2.6MeV
Russia
China
South Korea
80% of total contribution comes from
130~220km distance
effective distance ~180km
Reactor neutrino flux, $\sim 6 \times 10^6/cm^2/sec$
~95.5% from Japan
~3% from Korea
(2nd result period)
Reactors in Taiwan have
~0.1% contribution.

KamLAND:



Vacuum: averaged osc

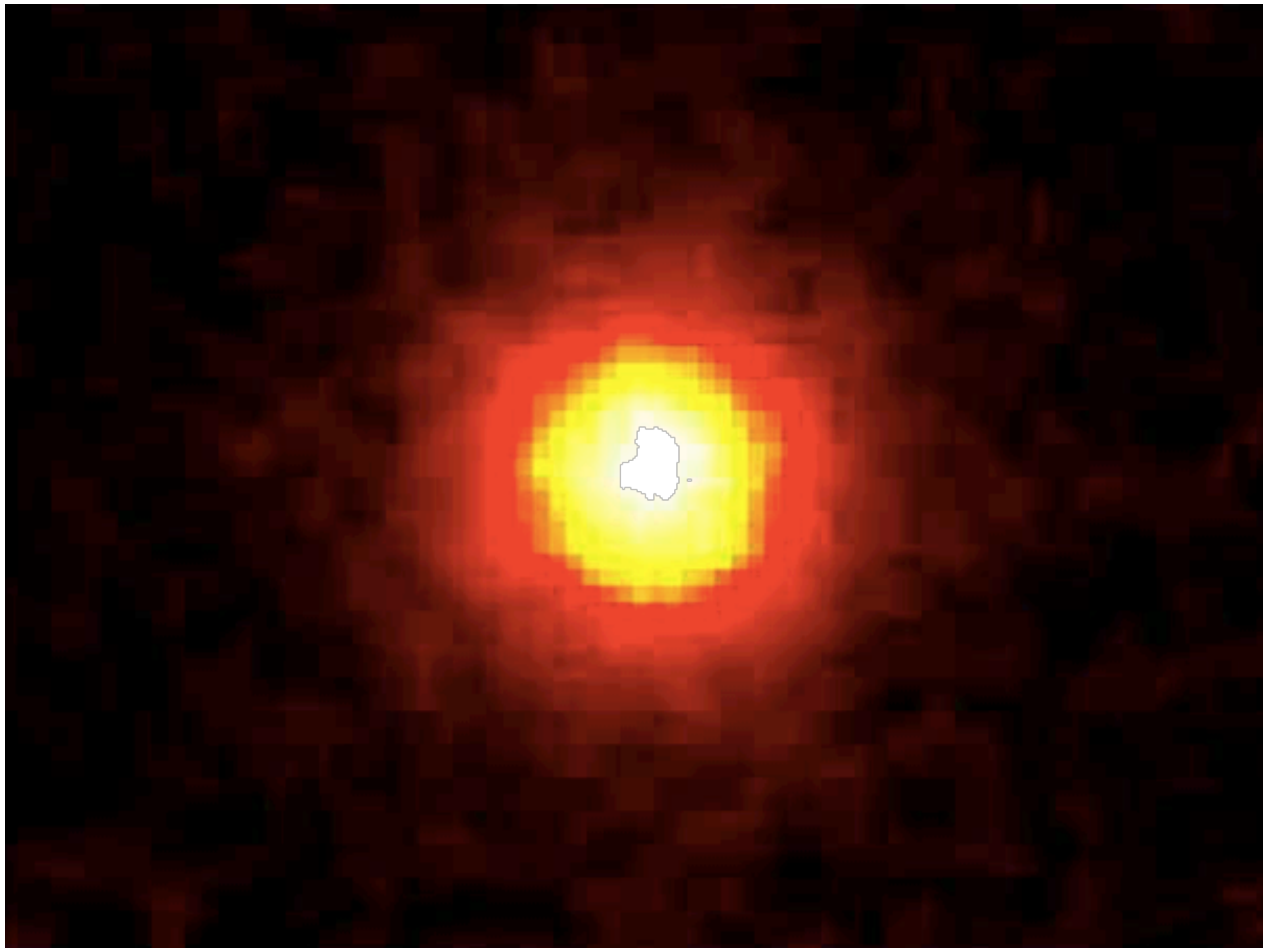
$\sim$ 68% ν_1

$\sim$ 30% ν_2

$\sim$ 2% ν_3

$$\Delta m^2_{21} = 7.50\,^{+0.20}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2,$$

SuperK

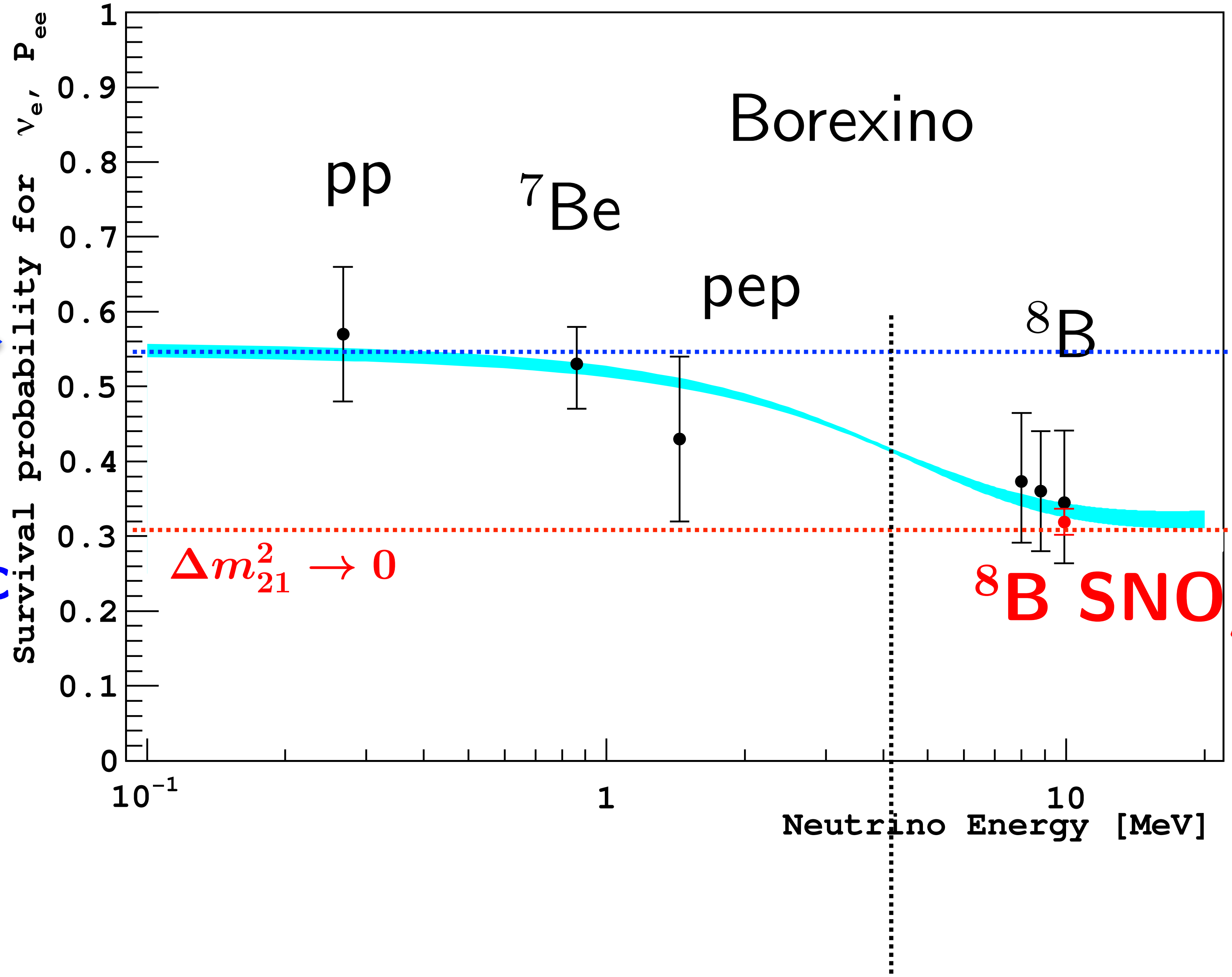


$$\nu_? + e \longrightarrow \nu + e$$

Which "type" of Neutrino dominates this image ?

it's not nu_e !

Solar Neutrinos:



$\Delta m^2_{21} \to \infty$

Vacuum:
averaged osc
$\sim 68\%\ \nu_1$
$\sim 30\%\ \nu_2$
$\sim\ 2\%\ \nu_3$

^{8}**B SNO/SK**

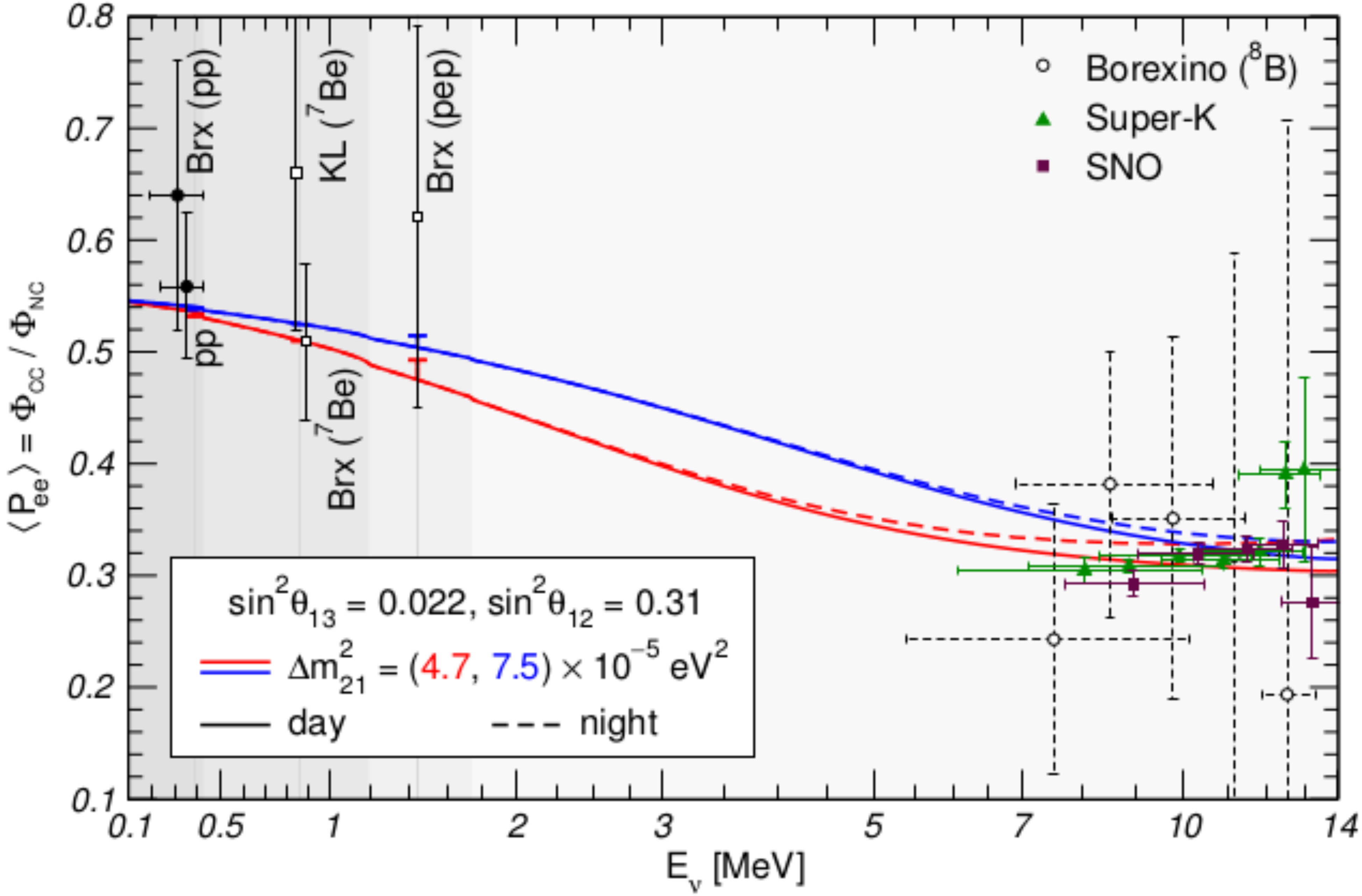
MSW:
$> 90\%\ \nu_2$

matter effect

$$E_\nu = (\,\#\,)\Delta m^2_{21} \cos 2\theta_{12} / (\cos^2\theta_{13} 2\sqrt{2} G_F N_e)$$

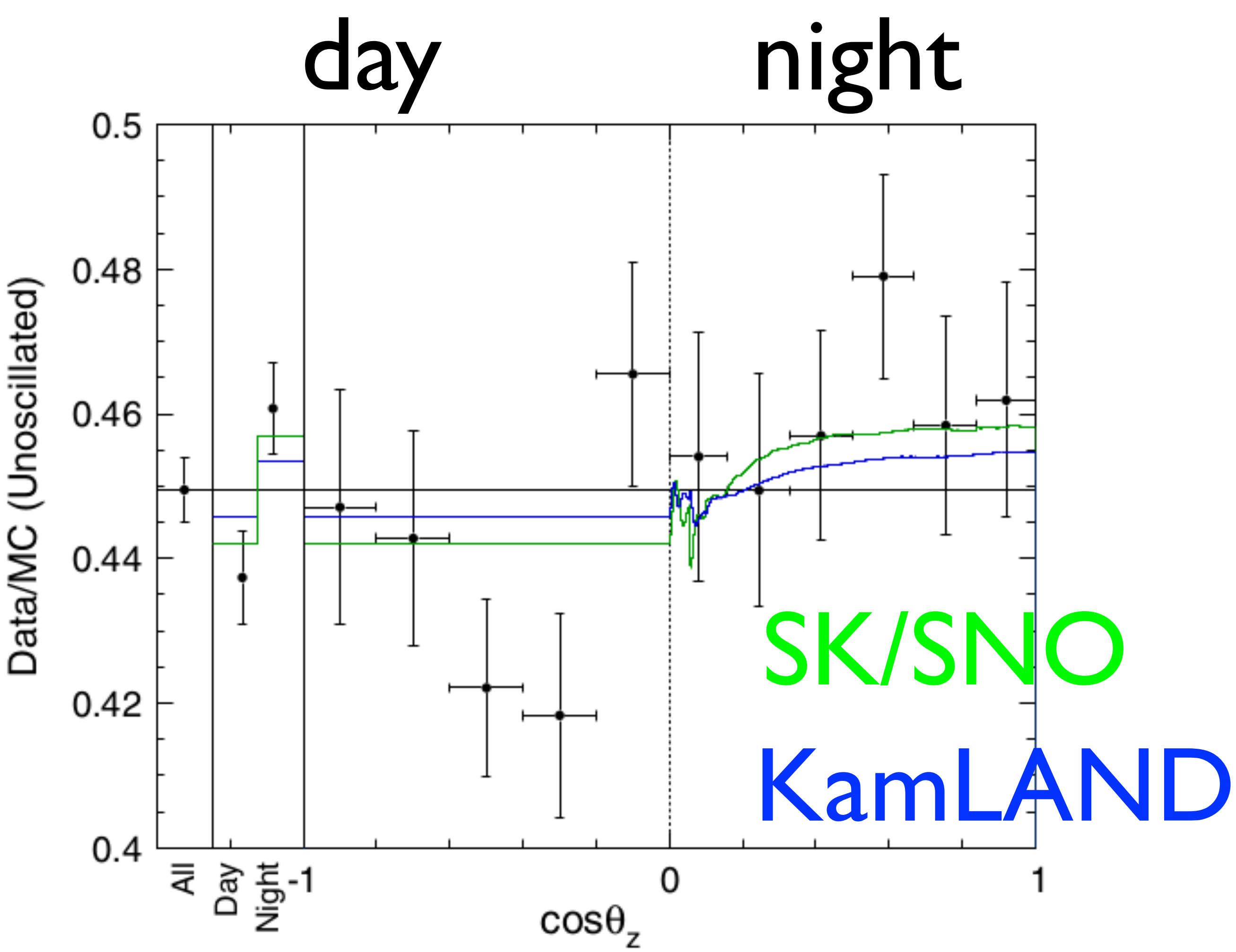
Large Δm^2_{21} implies large E_ν at transition between Vac. and Matter dominated

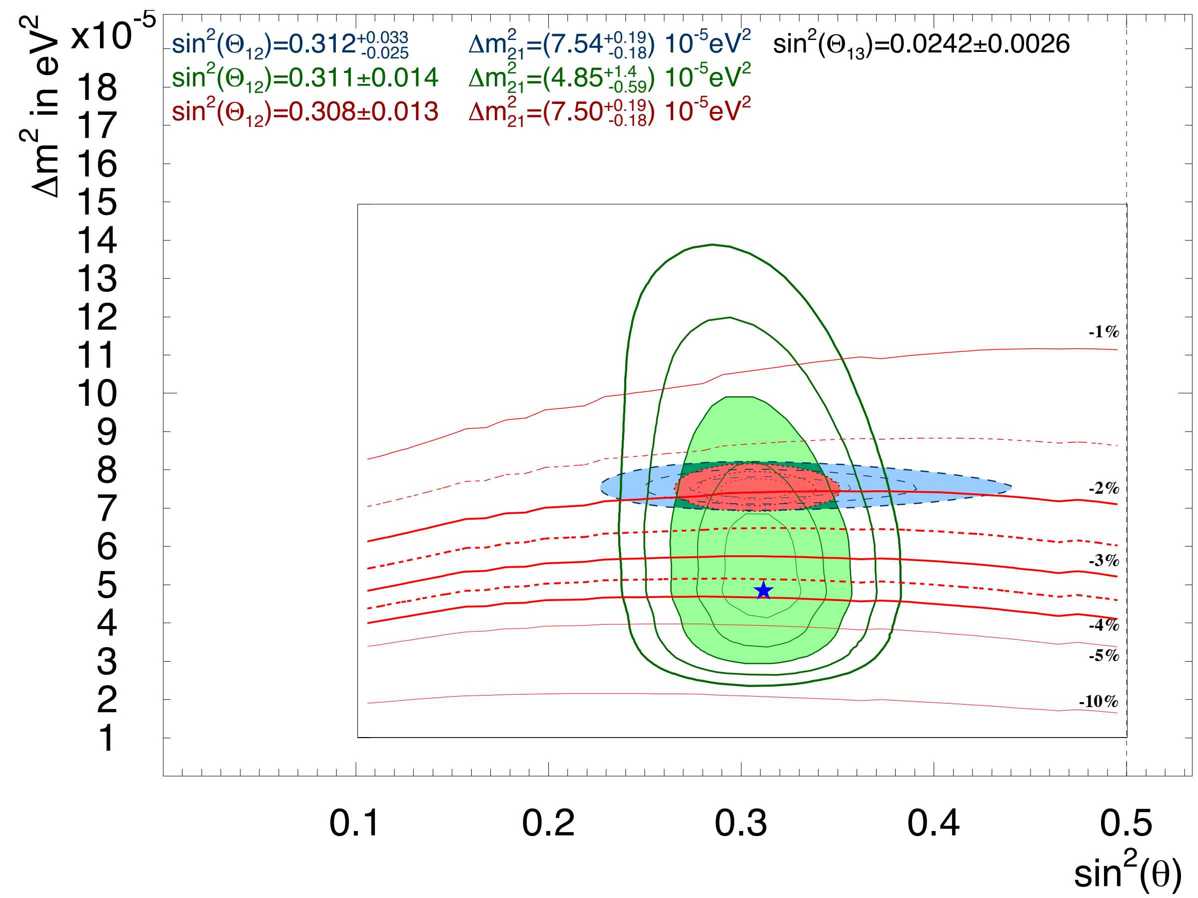
Lack of observation of upturn at low E



Eur.Phys.J. A52 (2016) no.4, 87

D/N asymmetry





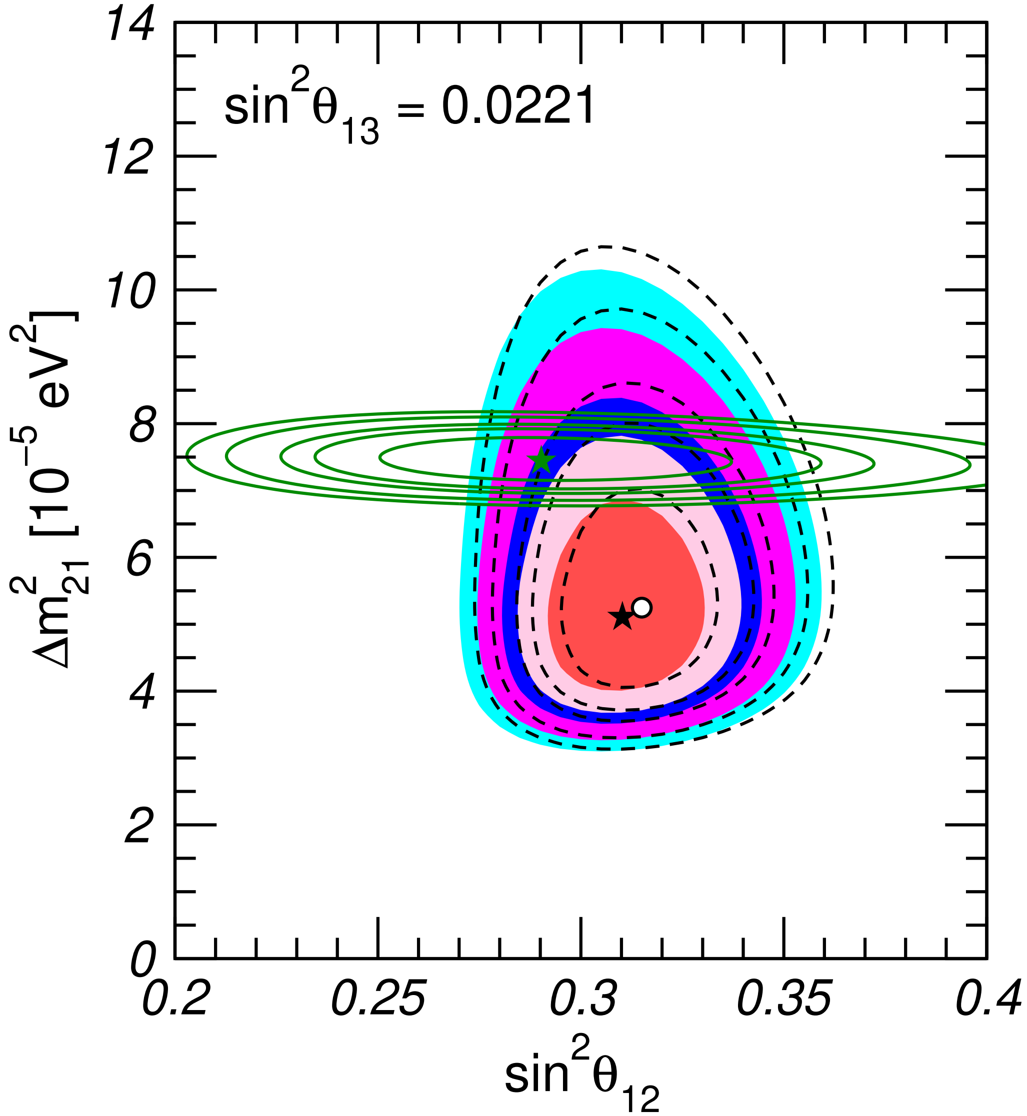
Phys. Rev. D94, 052010 (2016)

$$(D - N)/(D + N) = (\,\#\,)(\cos^2\theta_{13} 2\sqrt{2} G_F N_e^{\oplus})/\Delta m^2_{21} \cos 2\theta_{12}$$

Smaller Δm^2_{21} implies large D/N Asym.

Tension between KamLAND and SNO/SK

Nu-fit



KamLAND

$$\Delta m^2_{21} = 7.50\,^{+0.20}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2,$$

SK/SNO

$$\Delta m^2_{21} = 5.1\,^{+1.3}_{-1.0} \times 10^{-5}\ \mathrm{eV}^2,$$

Borexino covers both, see Vissani's talk and 1709.05813

BSM explanations:

Steriles

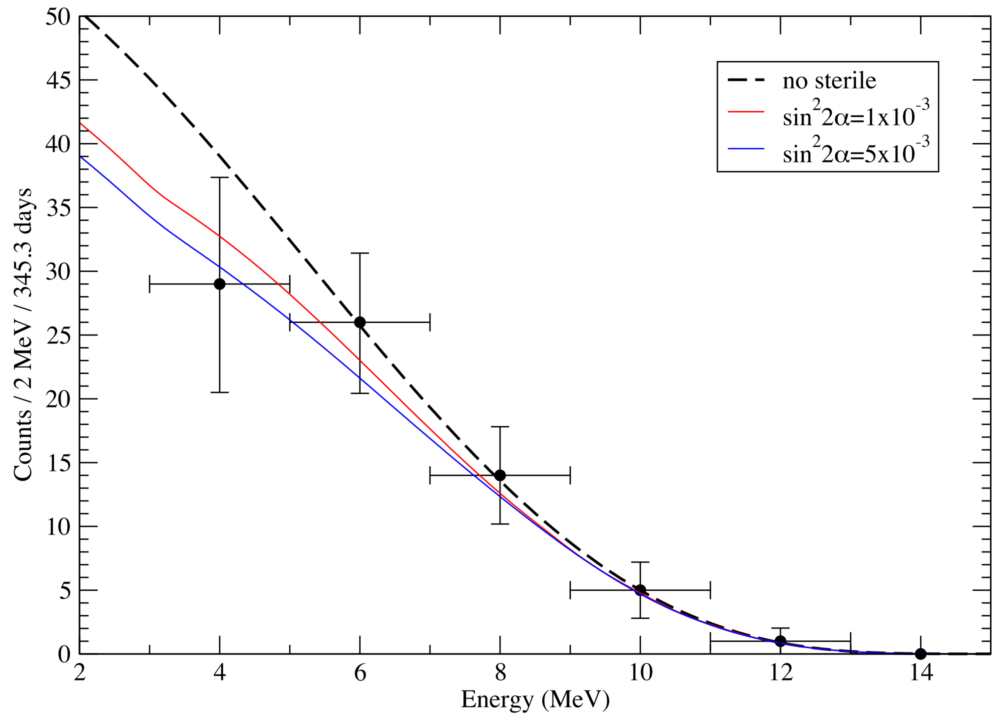
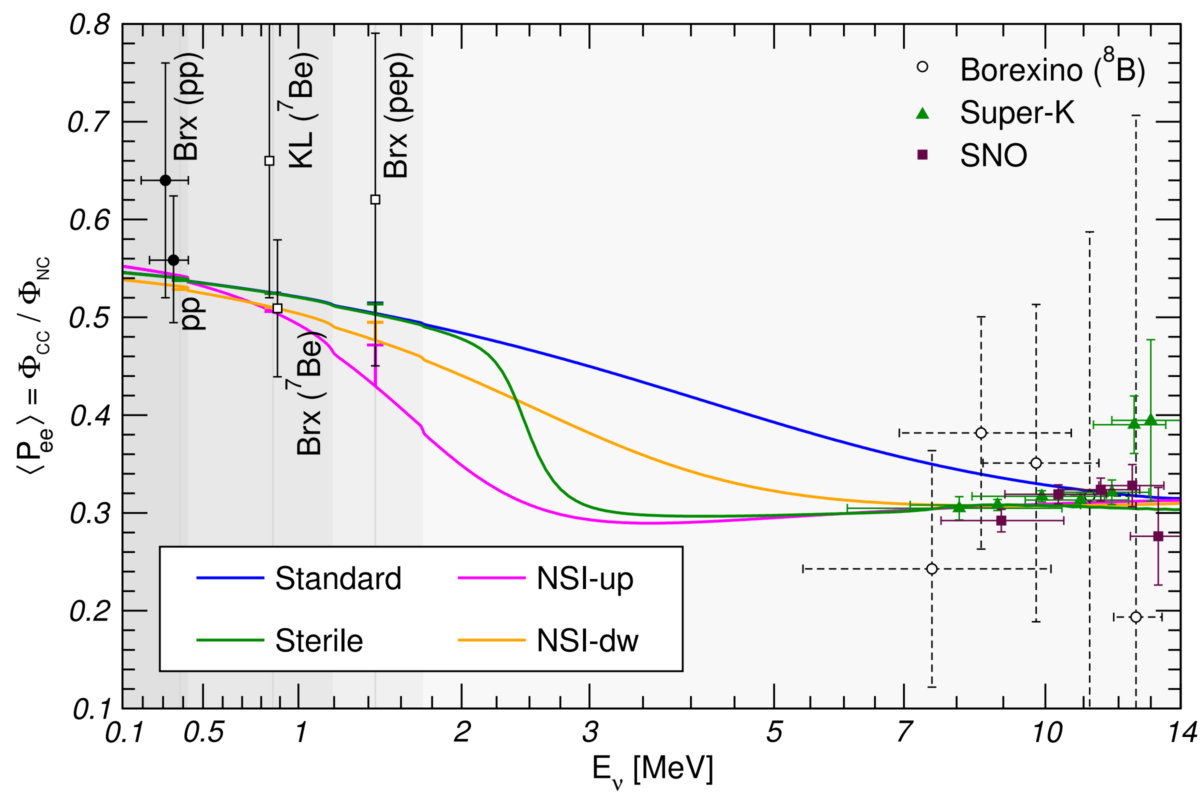


Figure 12: Prediction for $B-$neutrino spectrum at Borexino versus with experimental data [16]. The neutrino parameters and solar model are the same as in fig. 8.

de Holanda + Smirnov
1012.5627

vector NSI's



Maltoni + Smirnov
1507.05287

BSM conti:

Scalar NSI

Ge + SP 1812.08376

3

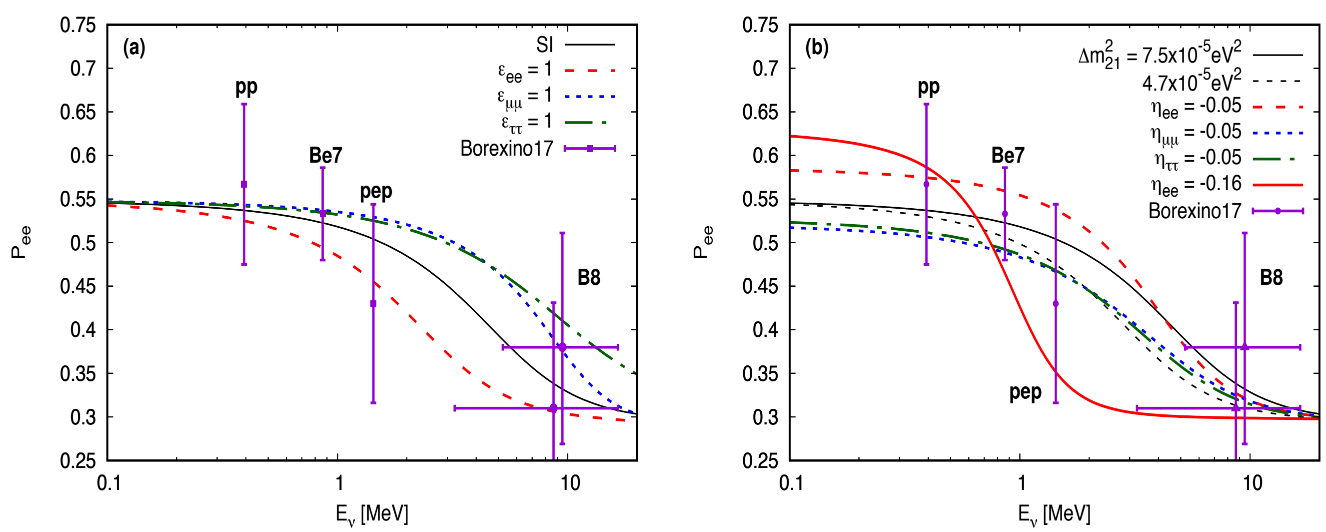
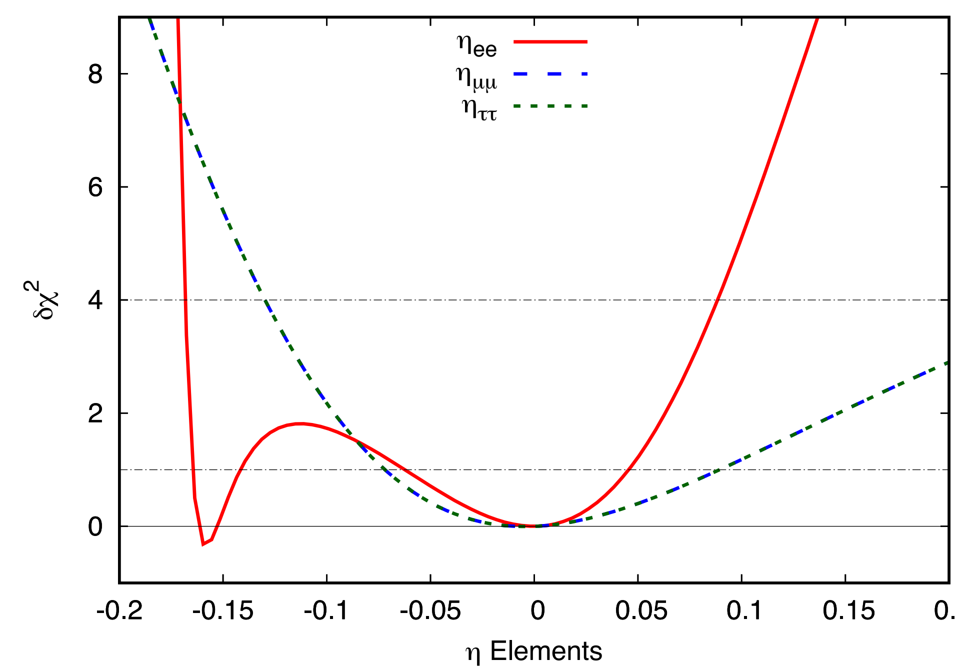


FIG. 2. The solar neutrino convertion probabilities with (a) the vector and (b) the scalar NSIs, together with the Borexino measurement [39] of the *pp*, ^{7}Be, and *pep* fluxes.



best fit at non-zero scalar NSIs

$\nu_e \to \nu_e$ and $\bar{\nu}_e \to \bar{\nu}_e$

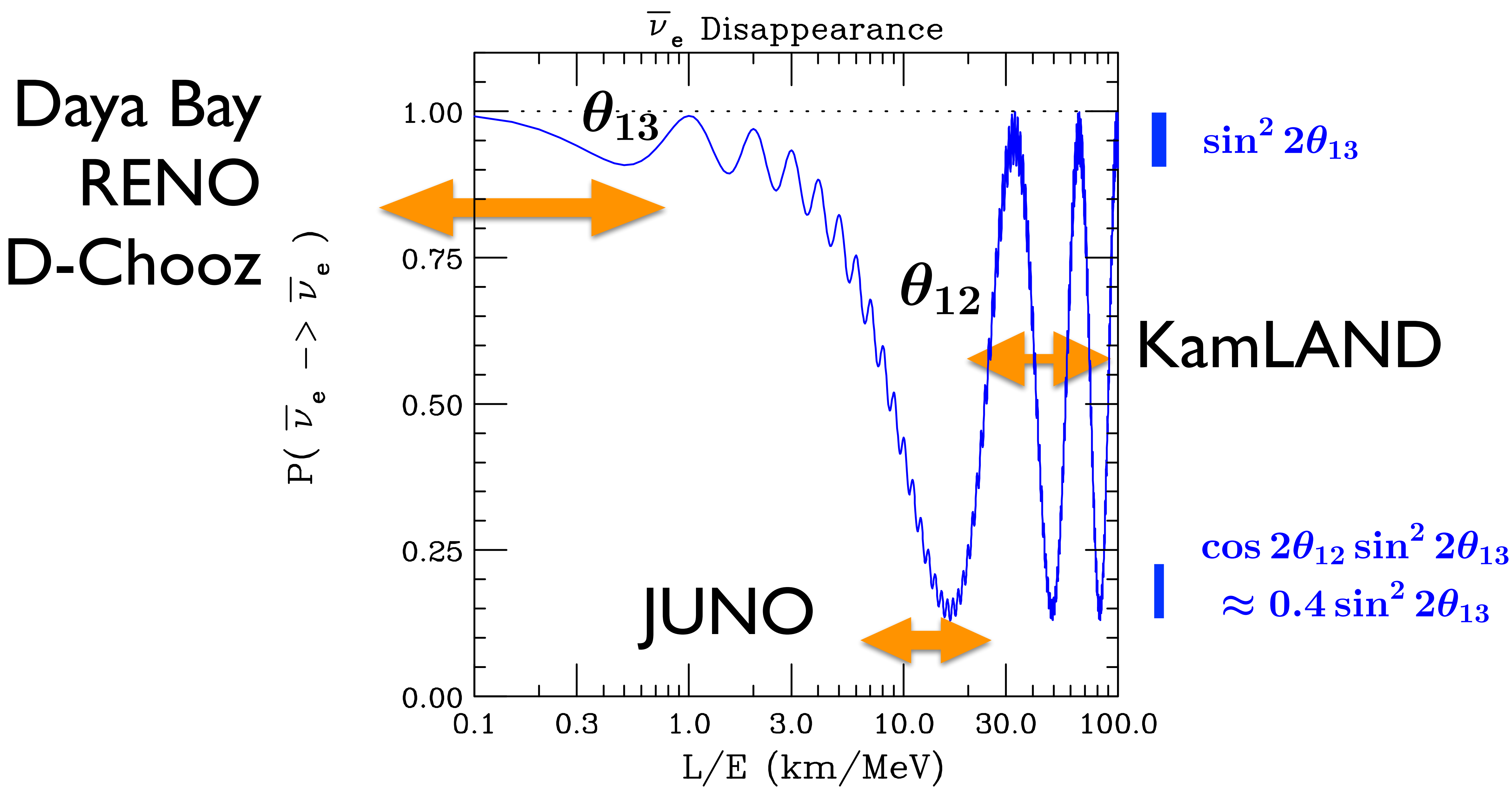
REACTOR NEUTRINOS:

kinematic phase:

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

REACTOR NEUTRINOS:

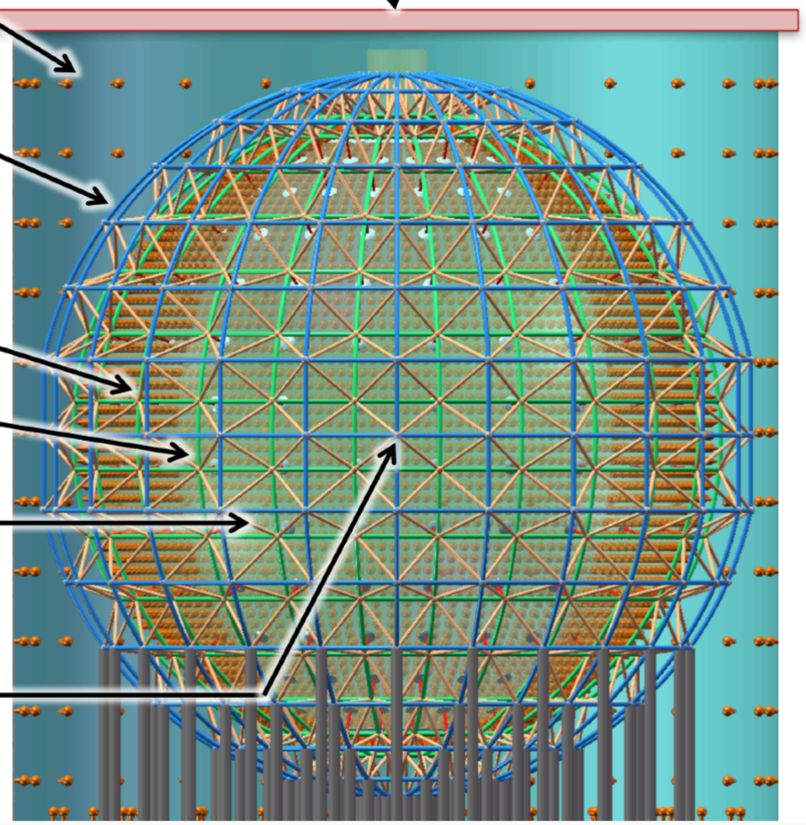
$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$$



JUNO
circa 2025

JUNO

LS Detectors	Daya Bay	Borexino	KamLAND	JUNO
Target Mass	**20 t x 8**	**300 t**	**1 kt**	**20 kt**



Similar in concept to previous LS experiments, but much LARGER

In fact, JUNO will be the largest liquid scintillator (LS) detector so far in history!

JUNO precision ~2025

$$\sin^2\theta_{12},\ \Delta m^2_{21} \text{ and } |\Delta m^2_{ee}|$$

0.5%

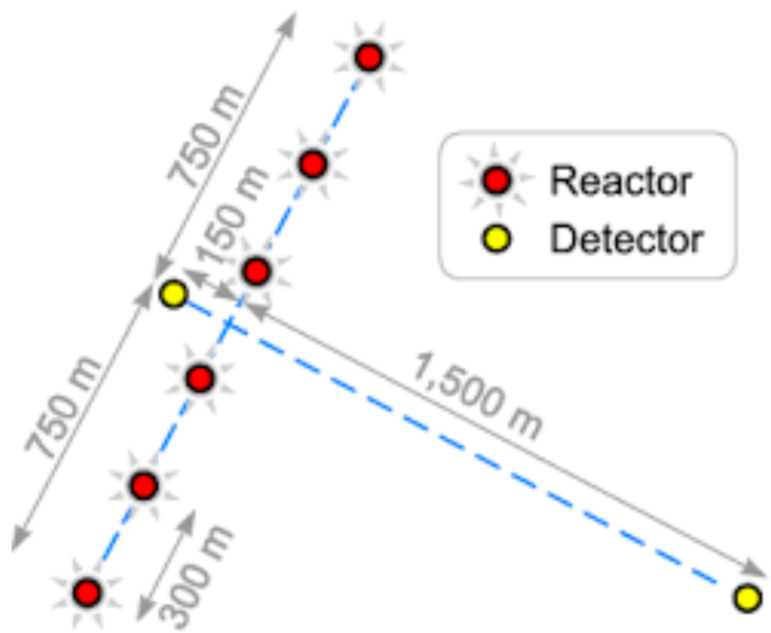
	Nominal	+ B2B (1%)	+ BG	+ EL (1%)	+ NL (1%)
$\sin^2\theta_{12}$	0.54%	0.60%	0.62%	0.64%	0.67%
Δm^2_{21}	0.24%	0.27%	0.29%	0.44%	0.59%
$\|\Delta m^2_{ee}\|$	0.27%	0.31%	0.31%	0.35%	0.44%

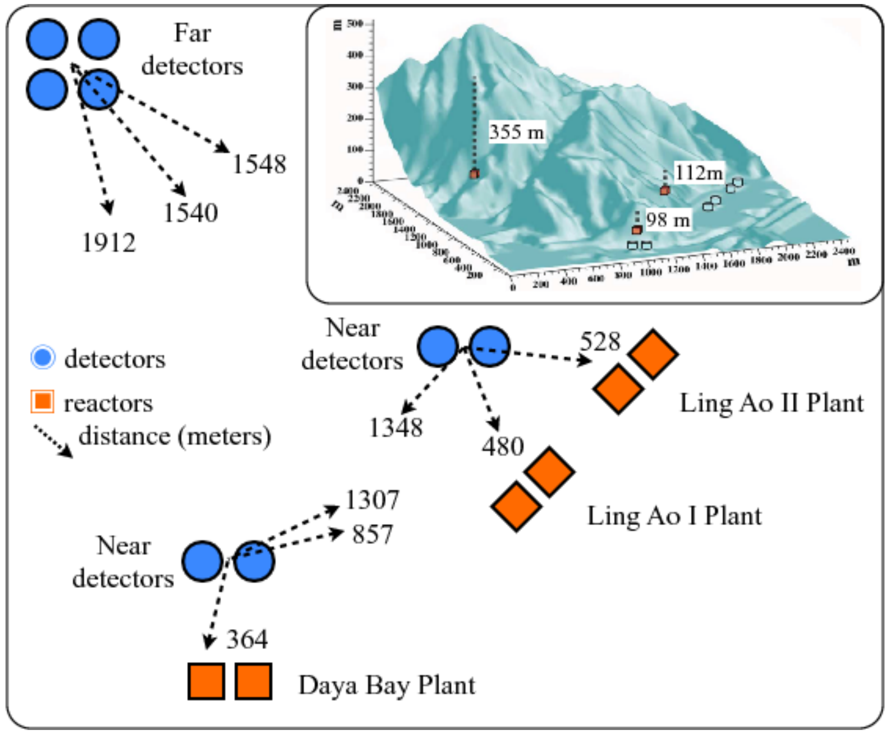
Table 3-2: Precision of $\sin^2\theta_{12}$, Δm^2_{21} and $|\Delta m^2_{ee}|$ from the nominal setup to those including additional systematic uncertainties. The systematics are added one by one from left to right.

$$\Delta m^2_{ee}(\text{NPZ}) \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

Δm^2_{ee} is the only atmospheric Δm^2 that JUNO can measured UNIQUELY, until mass ordering is determined.

Reactor θ_{13} Experiments

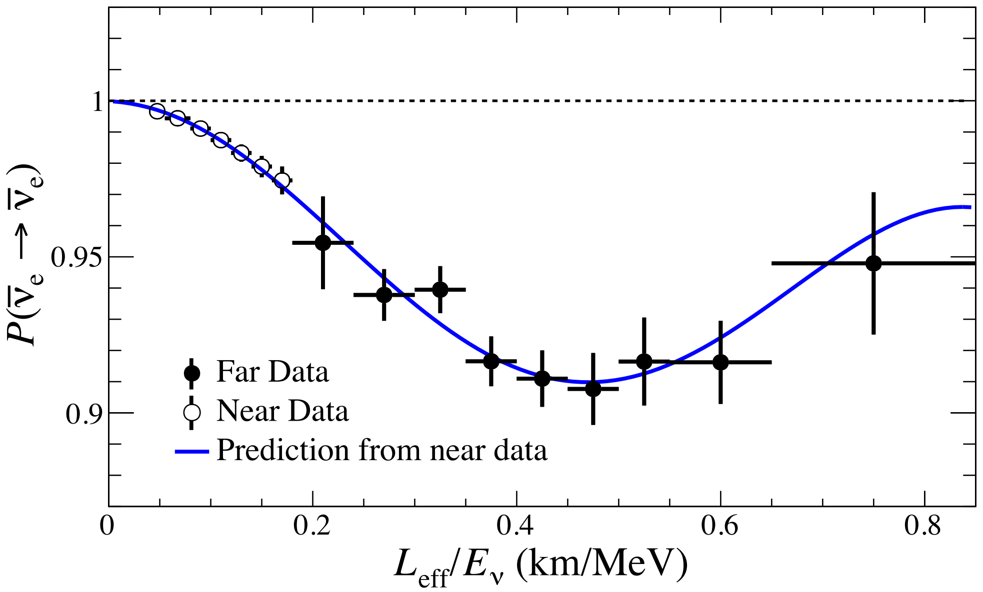


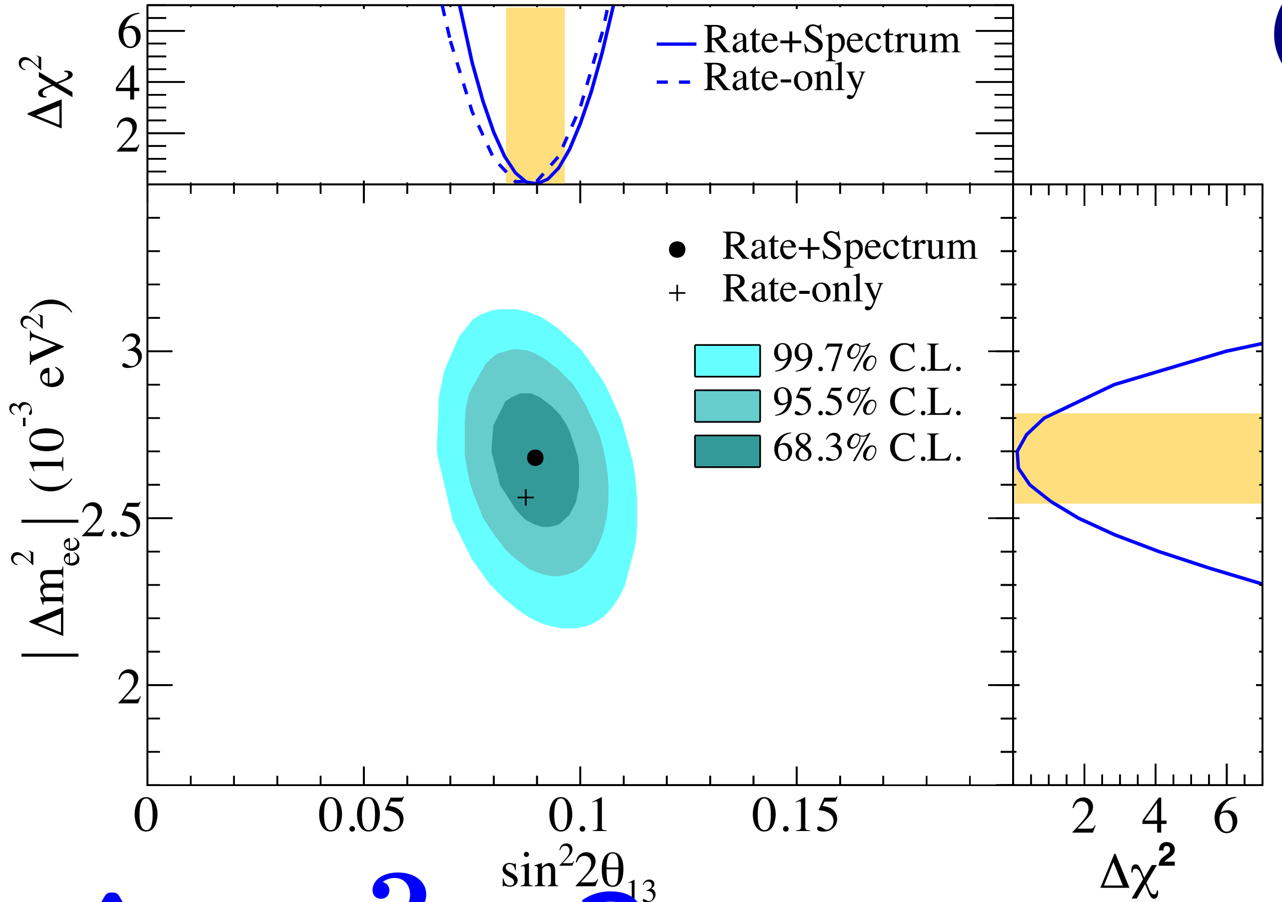


RENO

Daya Bay

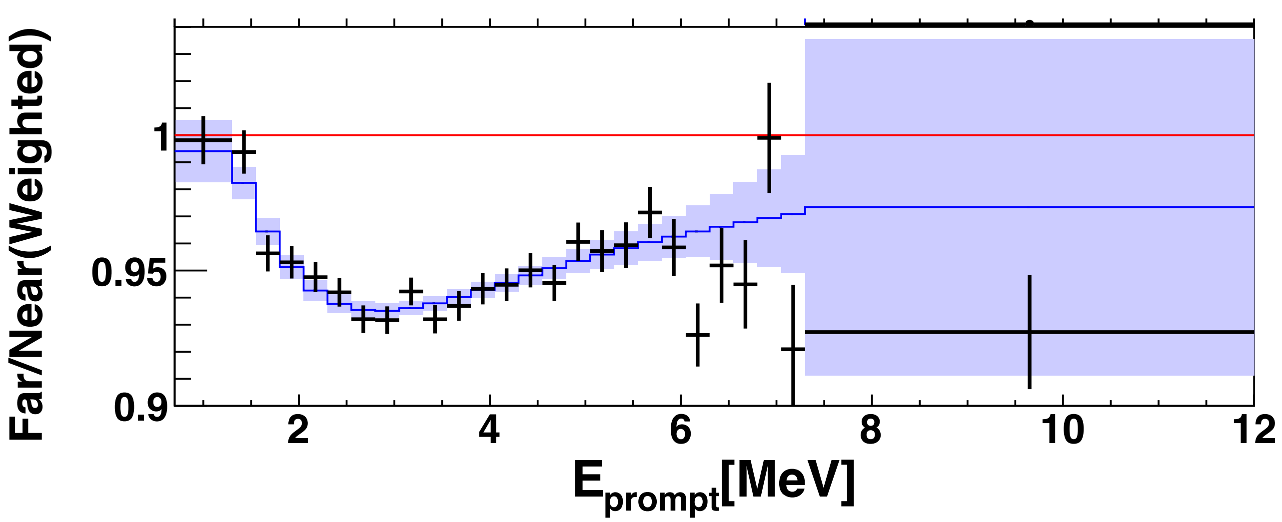
RENO 2200 days

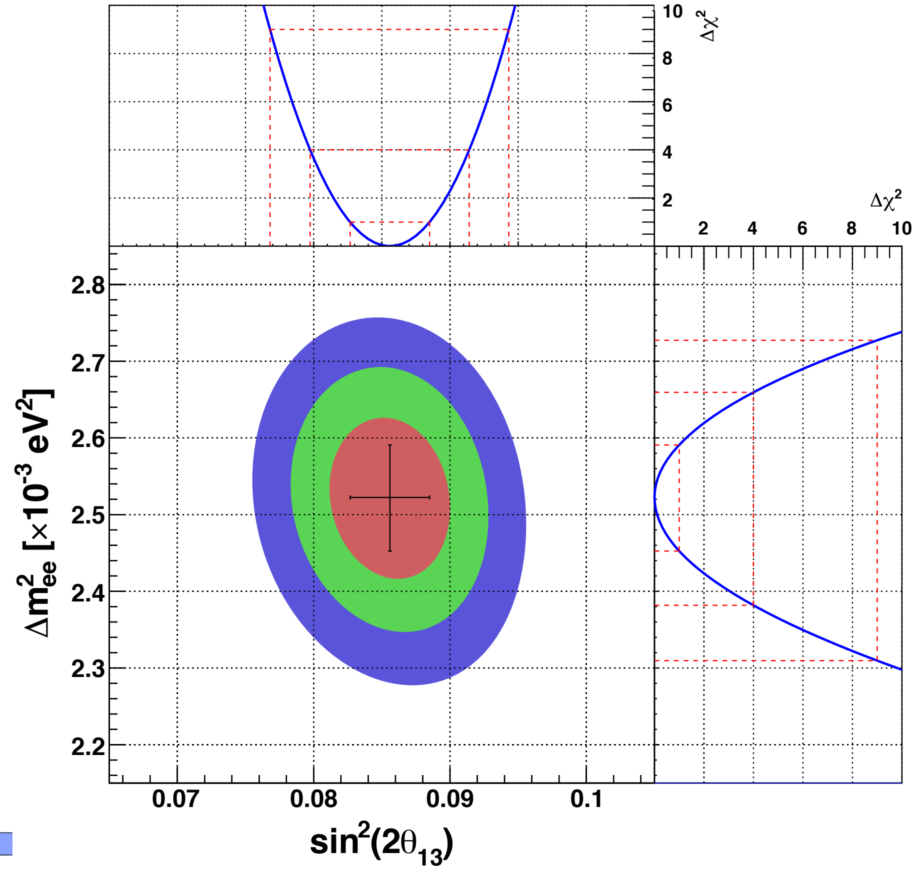




What is Δm^2_{ee} ?

Daya Bay 1958 days





~3%

Survival Probability:

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

$$1 - P_{ee} \approx (\cos^2\theta_{13}\ \sin 2\theta_{12}\,\Delta_{21})^2 + \sin^2 2\theta_{13}\sin^2\Delta_{ee}$$

$\sin\Delta_{21} \approx \Delta_{21}$ as $\Delta_{21} \ll \pi/6$

$\sin^2\Delta_{ee} \approx \cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}$

What makes a good Δm^2_{ee} ?

(not in PDG !)

- good approx. for L/E < 1 km/MeV
- Simply related to Δm^2_{31} and Δm^2_{32}
- Independent of L/E or "proper age" of the neutrino

"Δm^2_{ee} Saga"

$$\Delta m^2_{ee}(\text{NPZ}) \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

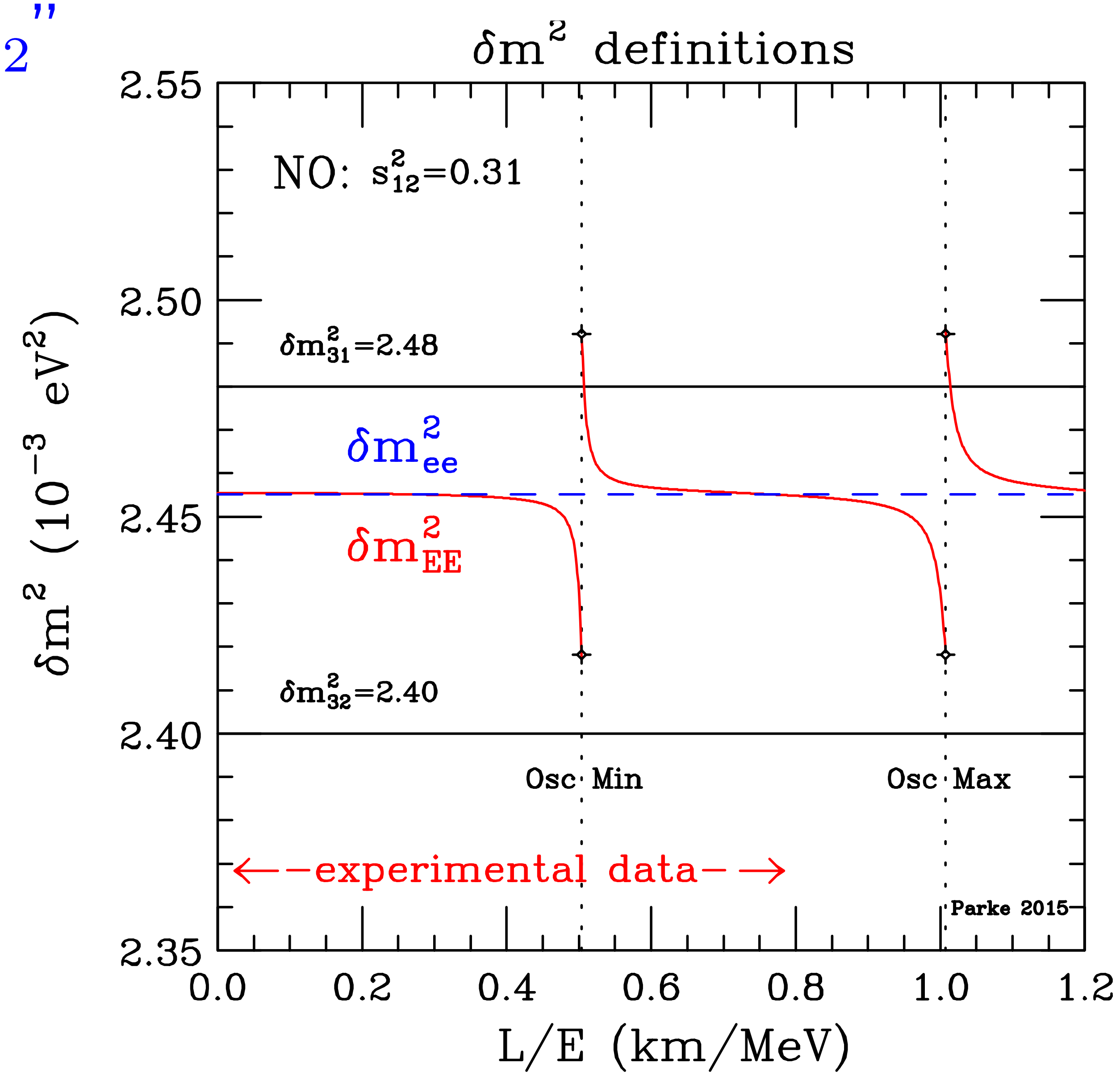
hep-ph/0503283

$$= \Delta m^2_{31} - \sin^2\theta_{12}\Delta m^2_{21} = \Delta m^2_{32} + \cos^2\theta_{12}\Delta m^2_{21}$$

10^{-4}

"ν_e average of Δm^2_{31} and Δm^2_{32}"

used by RENO



1310.6732, 1505.03456v1

exact

$$\Delta m^2_{ee}(\text{DB1}) \equiv \left(\frac{4E}{L}\right)\arcsin\sqrt{\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta m^2_{32}}$$

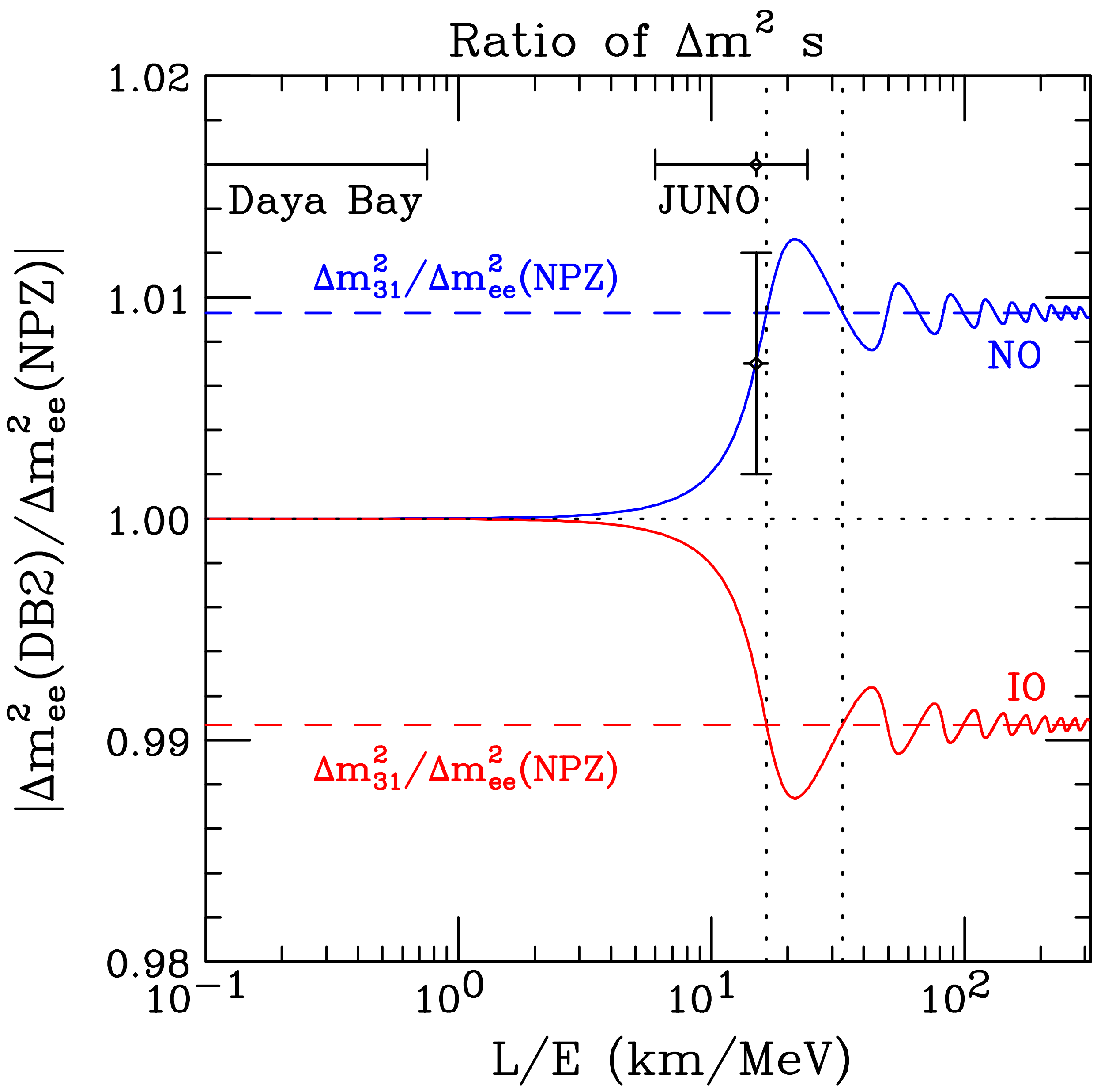
“Δm^2_{ee} Saga”

$$\Delta m^2_{ee}(\text{DB2}) \equiv \Delta m^2_{32} + \left(\frac{2E}{L}\right) \arctan\left(\frac{\sin 2\Delta_{21}}{\cos 2\Delta_{21} + \tan^2\theta_{12}}\right)$$

10^{-4}

1505.03456v2,1809.02261

for Daya Bay $\approx \cos^2\theta_{12}\Delta m^2_{21}$



1903.00148

Can Short Baseline Reactor Neutrinos say anything about

$$\Delta m^2_{21}$$

S.H. Seo and SP arXiv:1808.09150

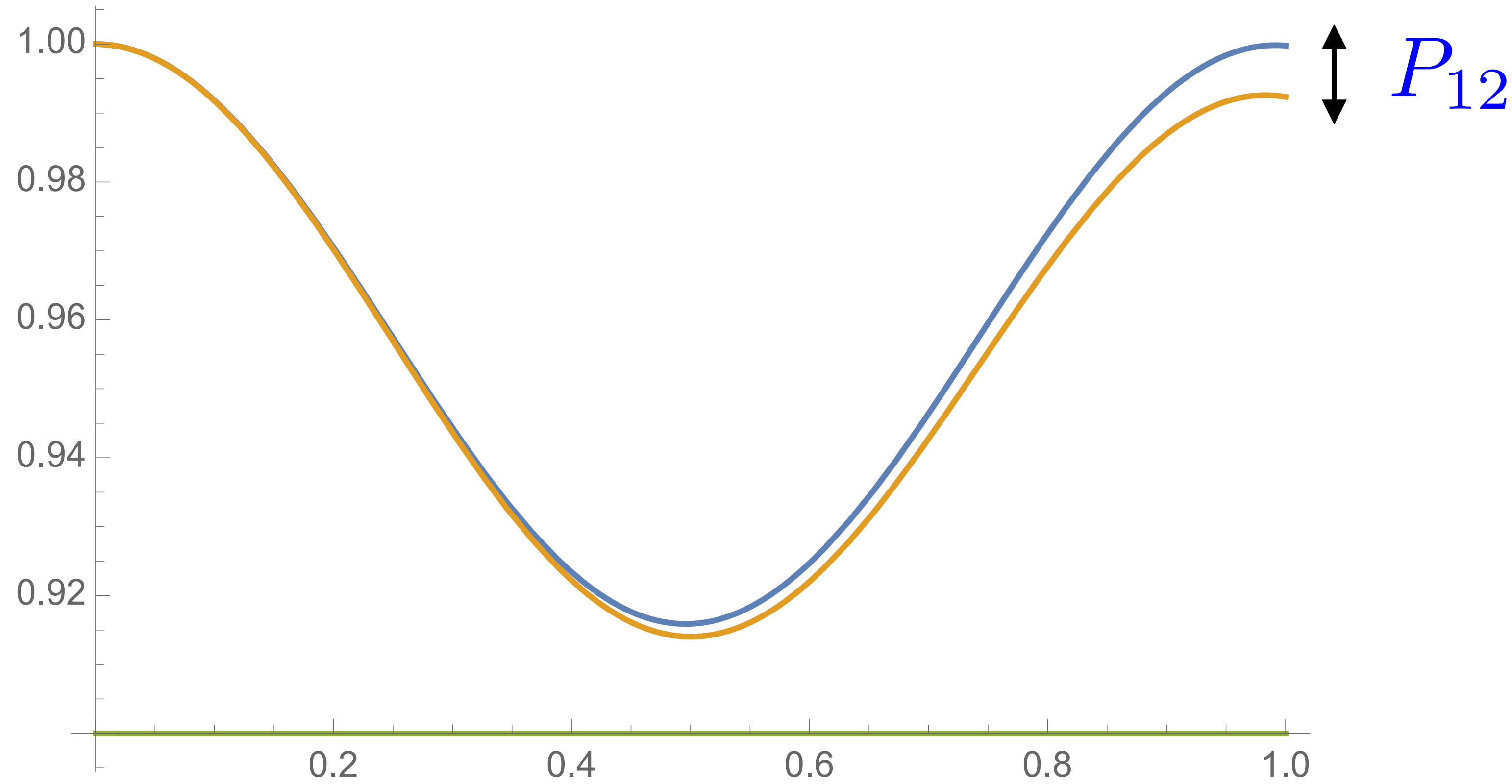
$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$$

$$P_{ee} = 1 - P_{13} - P_{12}$$

$$P_{13} = \sin^2 2\theta_{13} \sin^2 \Delta_{ee}$$ (< 0.1)

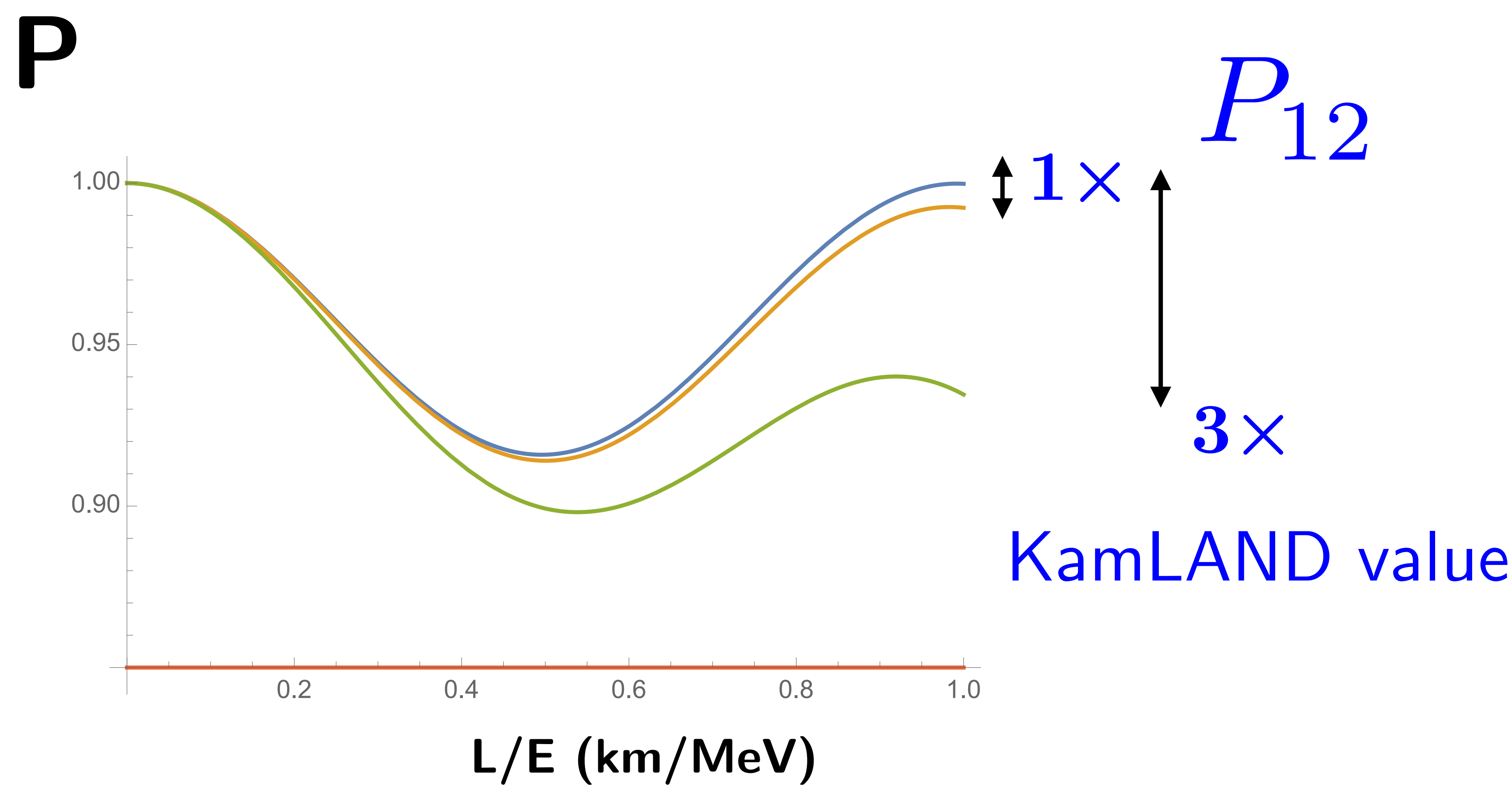
$$P_{12} = (\cos^2 \theta_{13} \, \sin 2\theta_{12} \, \Delta_{21})^2$$ (< 0.01)

P



L/E (km/MeV)

Dependence on Solar Parameters:

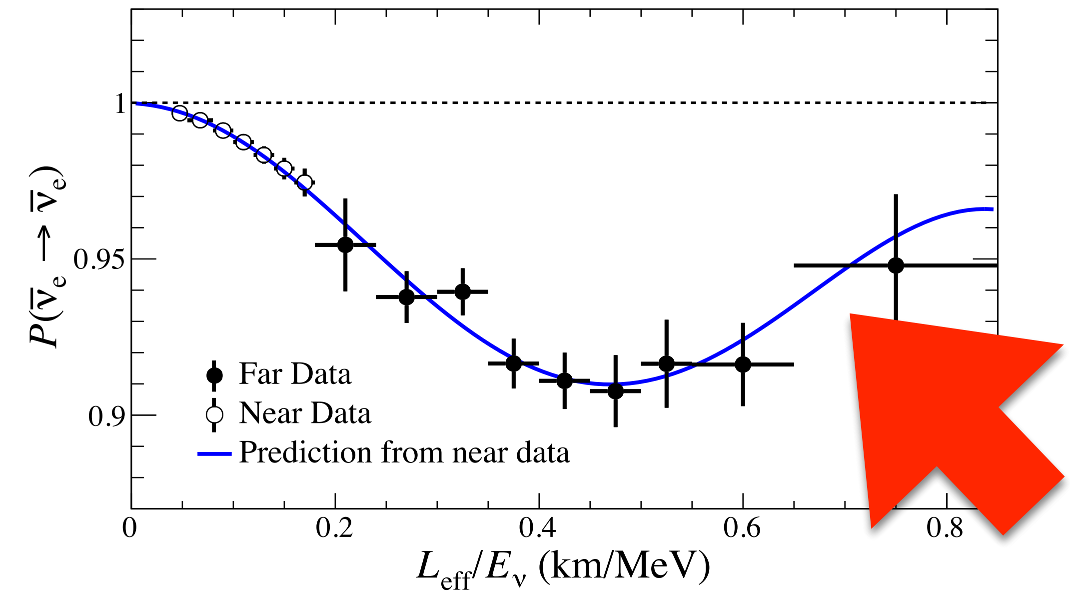


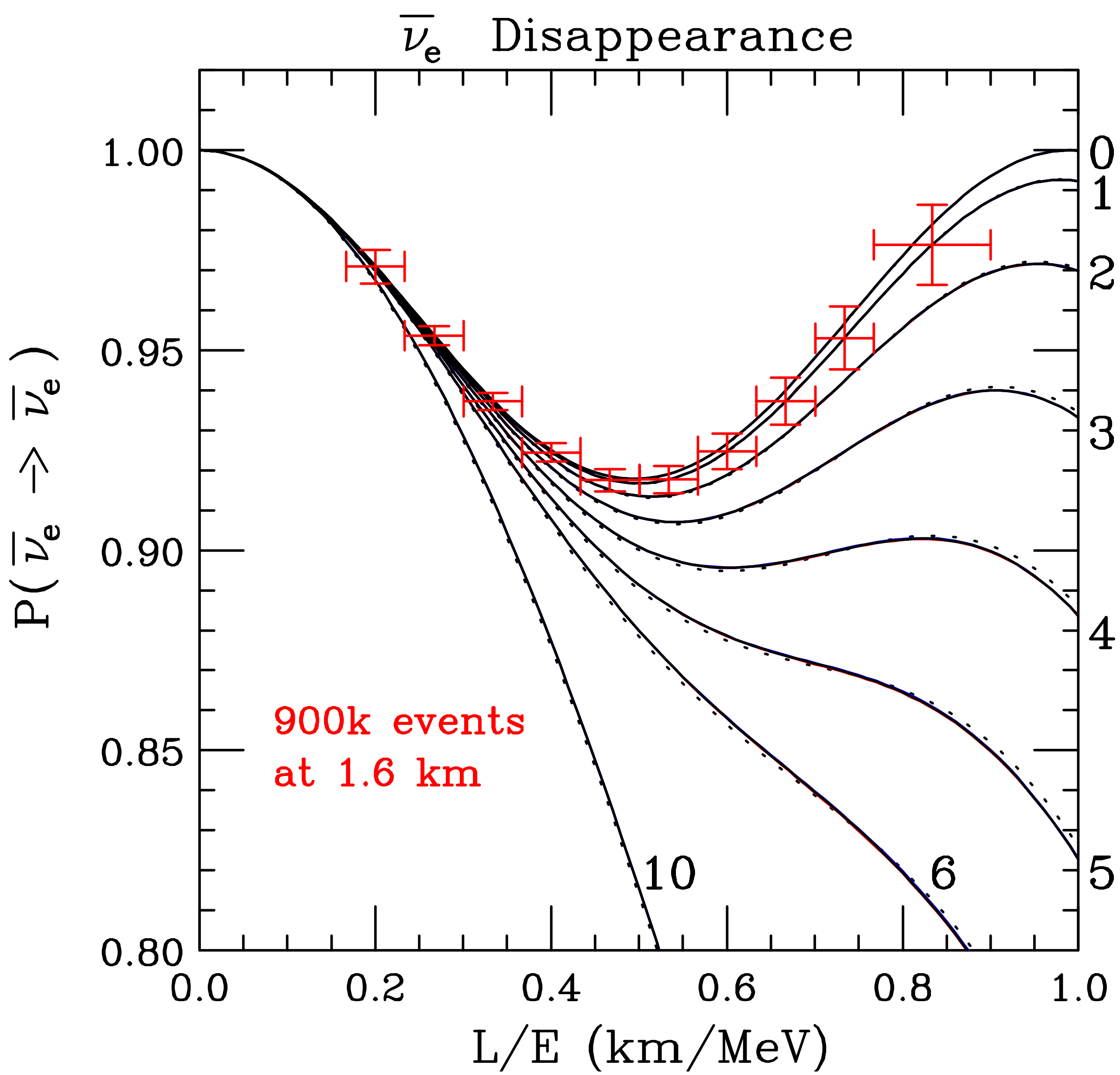
$$P_{13} \approx 0.08 \sin^2\left(\frac{\pi}{2}\left(\frac{L/E}{0.5\,\mathrm{km/MeV}}\right)\right)$$

$$P_{12} \approx 0.002 \left(\frac{L/E}{0.5\,\mathrm{km/MeV}}\right)^2 \left(\frac{\Delta m^2_{21}}{7.5 \times 10^{-5}\,\mathrm{eV}^2}\right)^2$$

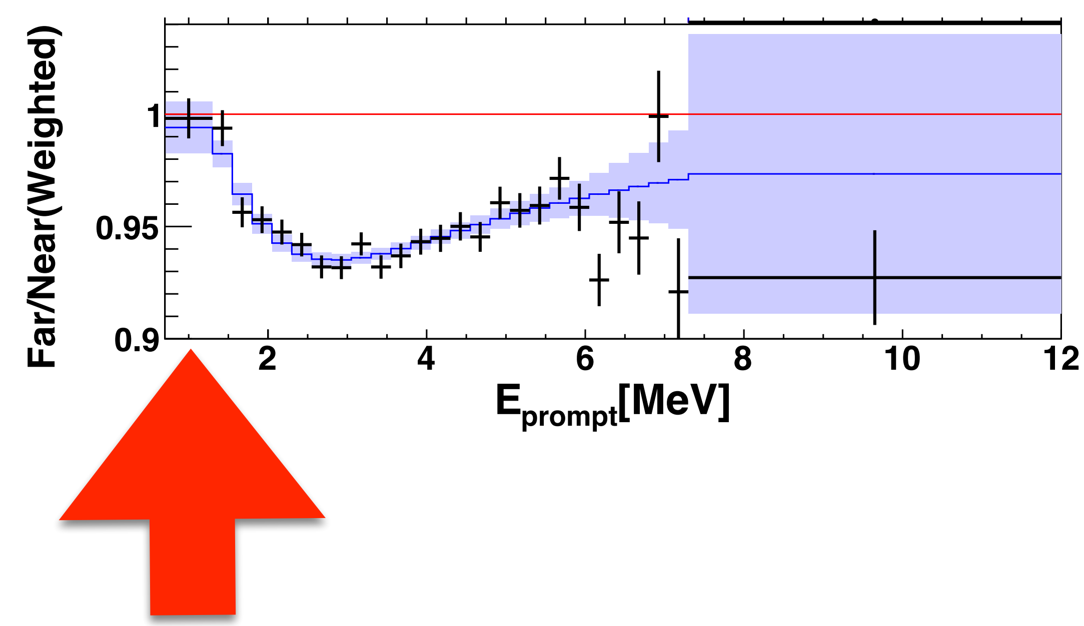
If Δm^2_{21} is 3 times bigger, P_{12} is 9 times larger !

RENO





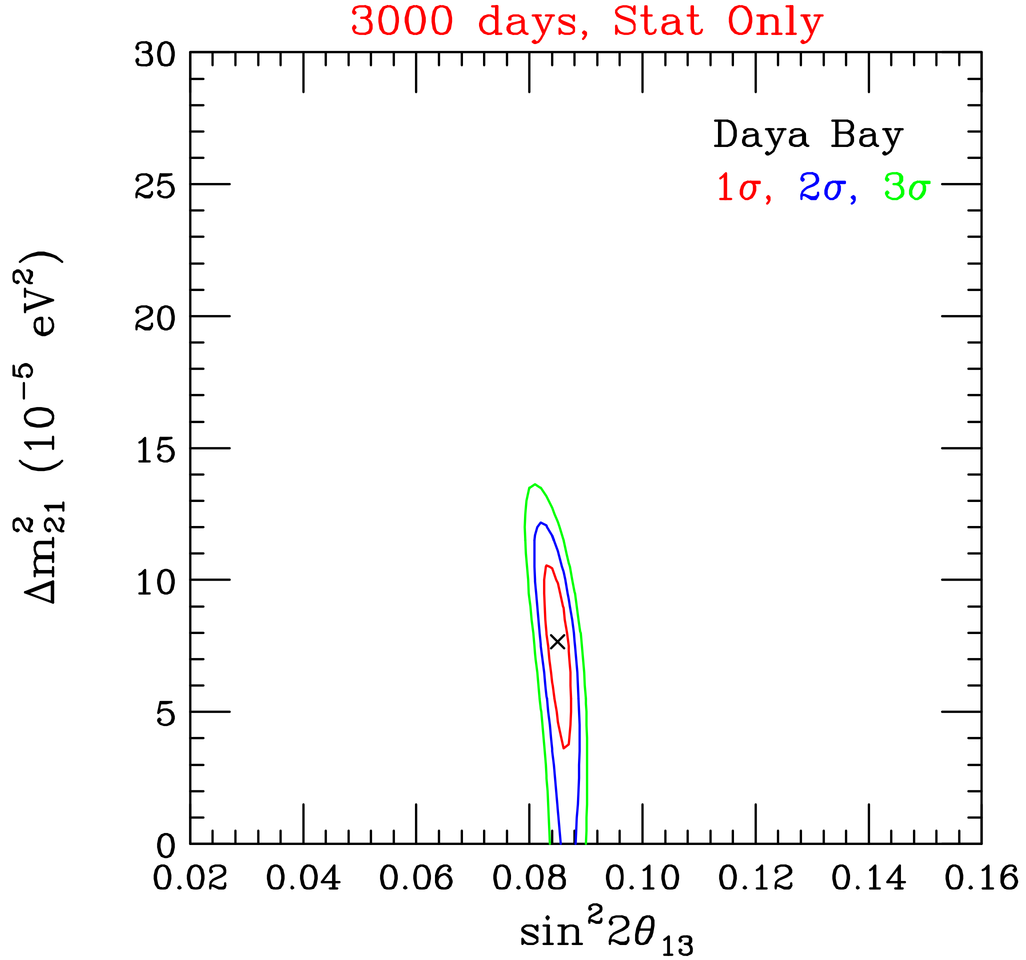
Daya Bay

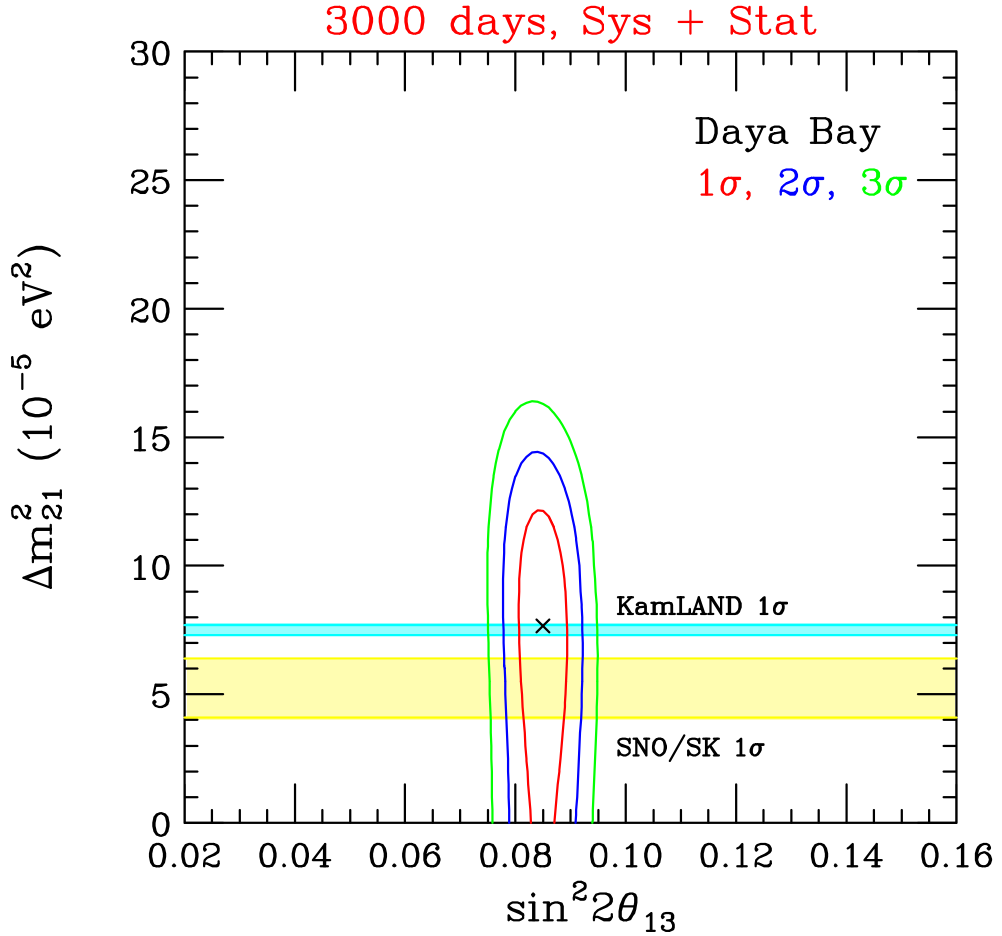


1 - 10 KamLAND

$$\Delta m^2_{21}$$

Simulation: Daya Bay



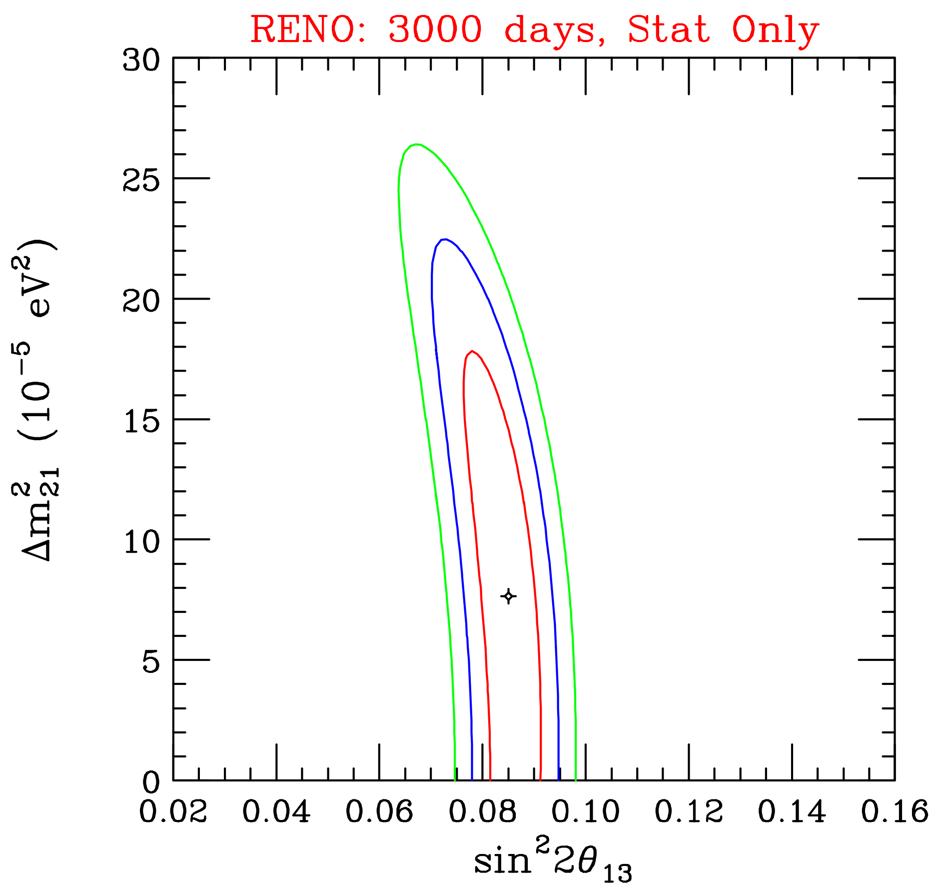


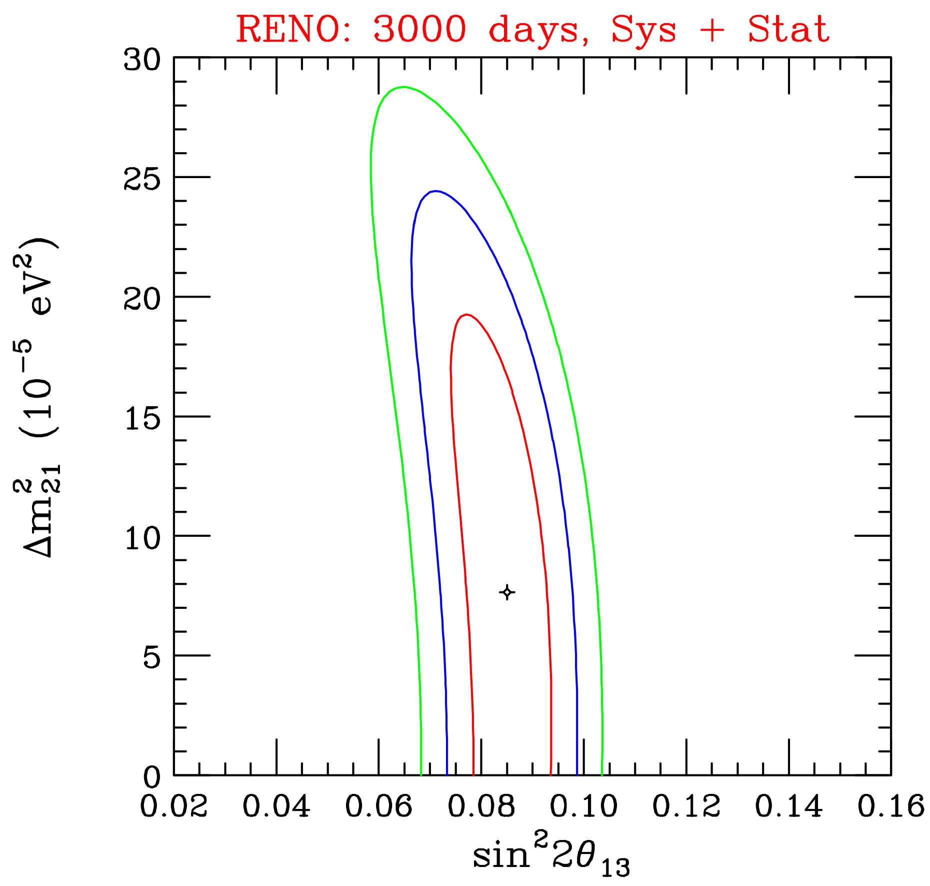
Limit expected about twice KamLAND

$L/E \sim 0.5$ km/MeV compared to KamLAND $L/E \sim 50$ km/MeV

T2K is at 0.5 km/MeV

Simulation: RENO





Limit expected about three times KamLAND

Reinterpretation !

Daya Bay
Sterile Neutrino Search

1607.01174
621 days

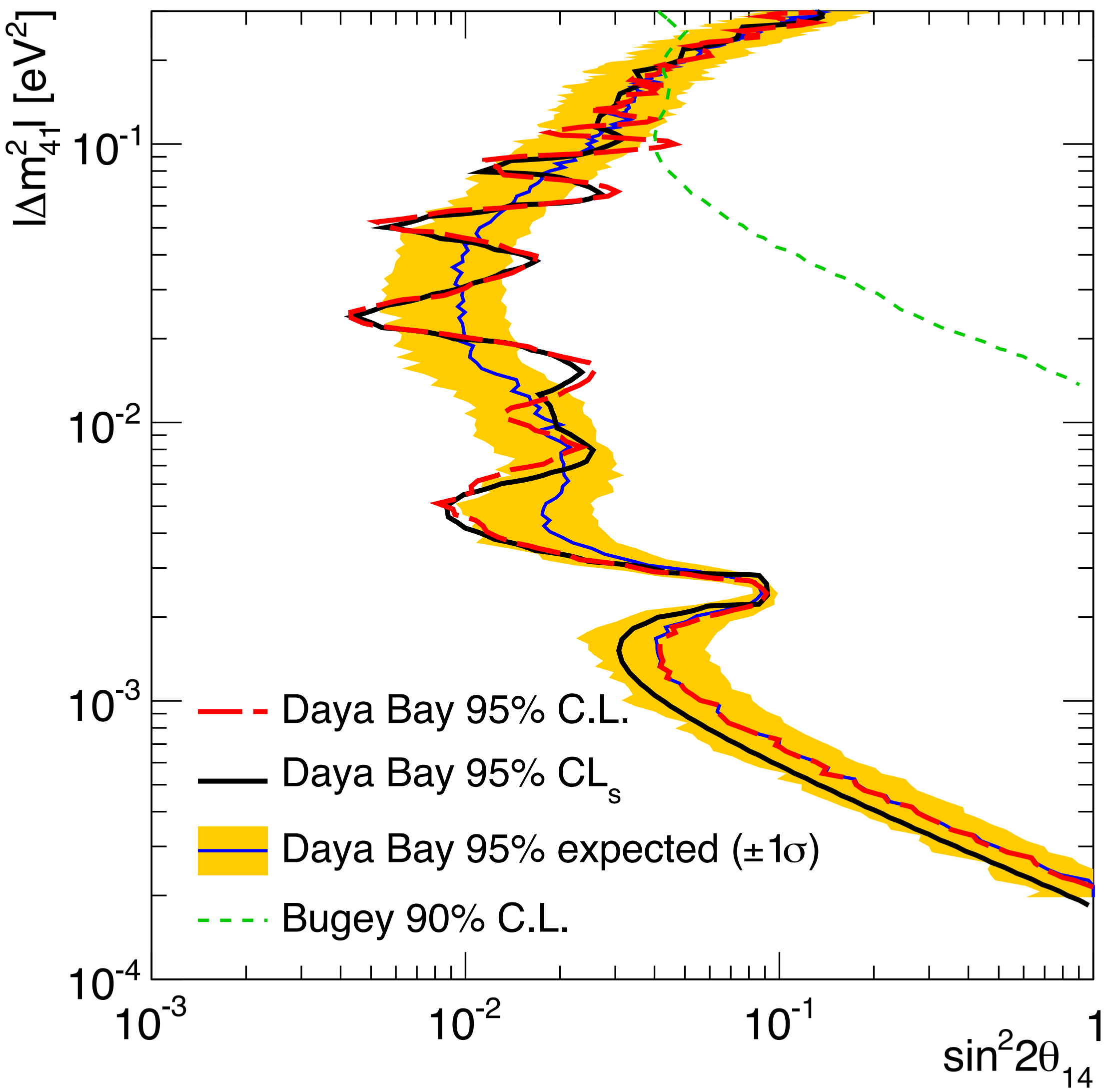
$$1 - P_{ee} \approx \sin^2 2\theta_{12} \sin^2 \Delta_{ee} + \sin^2 \theta_{14} \sin^2 \Delta_{41} + \cos^4 \theta_{13} \sin^2 \theta_{12} \sin^2 \Delta_{21}$$

not important unless

$\Delta m^2_{41} \approx \Delta m^2_{21}$

12% effect on Δm^2_{41}

@ 1.5×10^{-4} eV^2



$3\times$

KamLAND value

Neutrino Propagation in Matter - 3 flavors

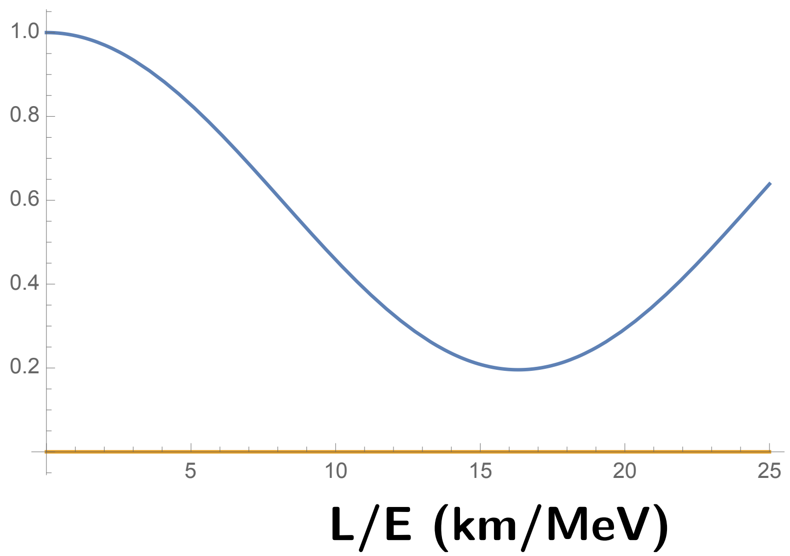
Wolfenstein Matter Potential $a \equiv 2\sqrt{2} G_F N_e E_\nu$

cubic eqn for 3 flavors !

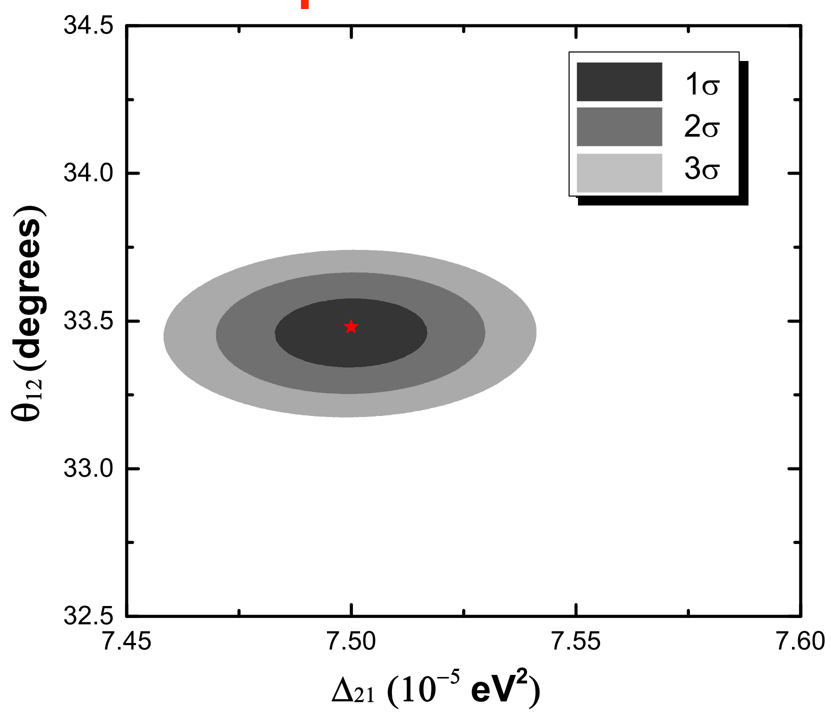
Matter Effects in JUNO

Li, Wang, Xing 1605.00900

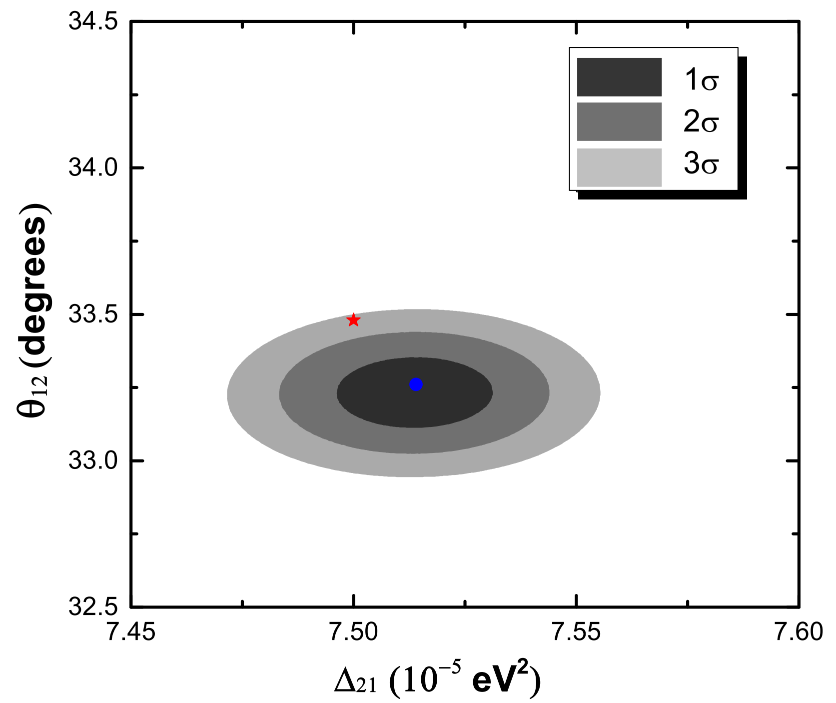
$1 - P_{12}$



Matter Input/Matter Fit



Matter Input/Vacuum Fit

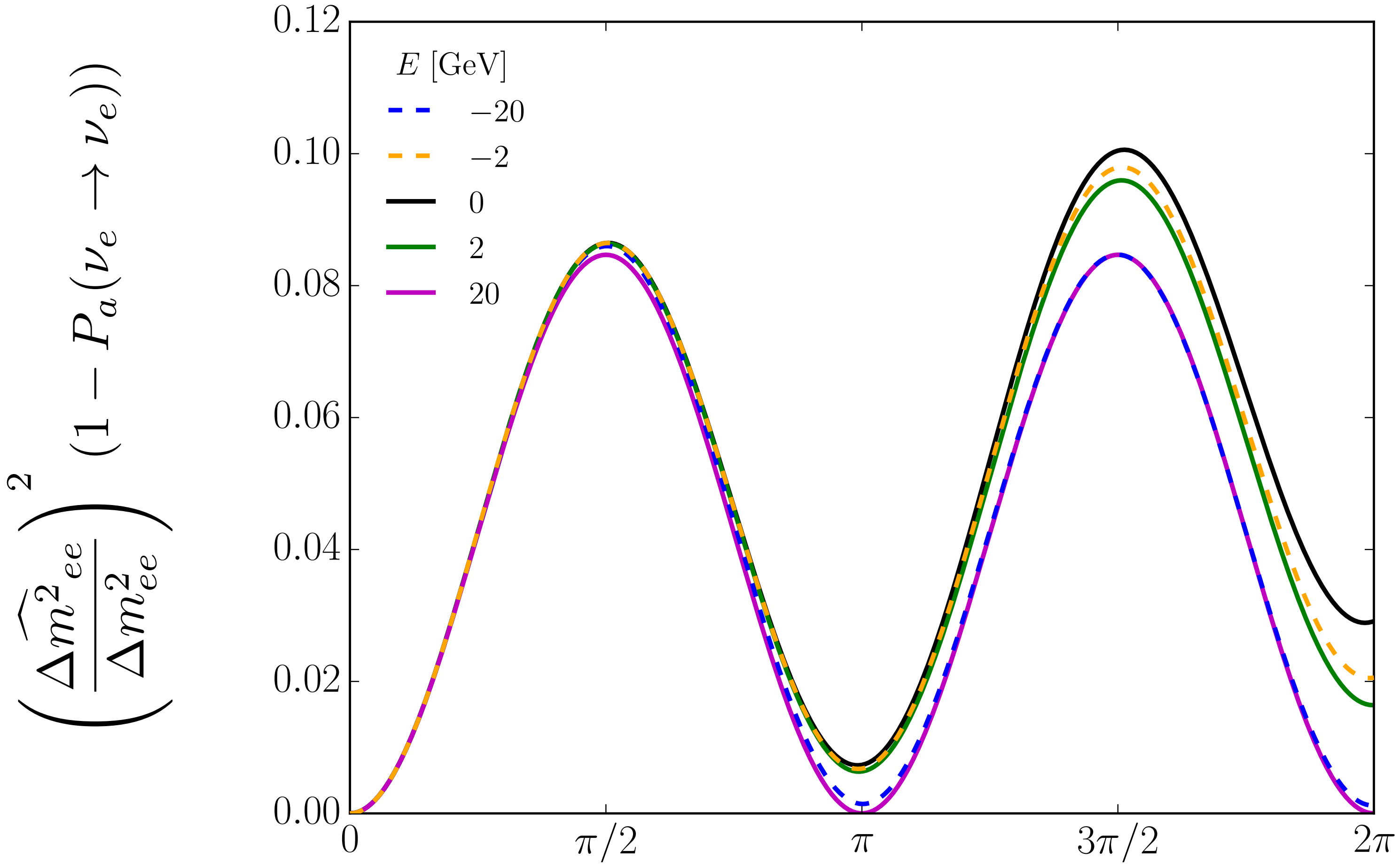


Shift 1σ in Δm^2_{21} and 3σ in θ_{12}

$\nu_e \rightarrow \nu_e$

$$P_a(\nu_e \to \nu_e) \approx 1 - \sin^2 2\theta_{13} \left(\frac{\Delta m^2_{ee}}{\widehat{\Delta m^2}_{ee}} \right)^2 \sin^2 \widehat{\Delta}_{ee} \,, \qquad \widehat{\Delta}_{ee} \equiv \widehat{\Delta m^2}_{ee} L/(4E) \,,$$

$$\widehat{\Delta m^2}_{ee} \approx \Delta m^2_{ee} \sqrt{(\cos 2\theta_{13} - a/\Delta m^2_{ee})^2 + \sin^2 2\theta_{13}} \,,$$



$$|\widehat{\Delta}_{ee}|$$

Denton, SP 1808.09453

Jarlskog Invariant in Matter:

Denton, SP 1902.07185

$$\widehat{J} \approx \frac{J}{\mathcal{S}_{\odot}\,\mathcal{S}_{\rm atm}} \quad \begin{cases} \mathcal{S}_{\rm atm} = \sqrt{(\cos 2\theta_{13} - a/\Delta m^2_{ee})^2 + \sin^2 2\theta_{13}} \\ \mathcal{S}_{\odot} = \sqrt{(\cos 2\theta_{12} - c^2_{13}a/\Delta m^2_{21})^2 + \sin^2 2\theta_{12}} \end{cases}$$

two flavor resonance factors !

~~$\mathcal{O}(s^2_{13})$ and/or $\mathcal{O}(\frac{\Delta m^2_{21}}{\Delta m^2_{ee}})$ 2-3%~~

$\mathcal{O}(s^2_{13}\cos 2\theta_{12}\frac{\Delta m^2_{21}}{\Delta m^2_{ee}})$ 0.04%

for any value of the matter potential "a"

Summary:

- There is a tension between the Solar (SK/SNO) and long baseline reactor (KamLAND) measurements of the Delta m^2_21 ! Are there issues with either measurement ? New Physics ? ....

- Delta m^2_21 is important for the measurement of CP violation by T2K, NOvA, T2HK(K), DUNE, ...

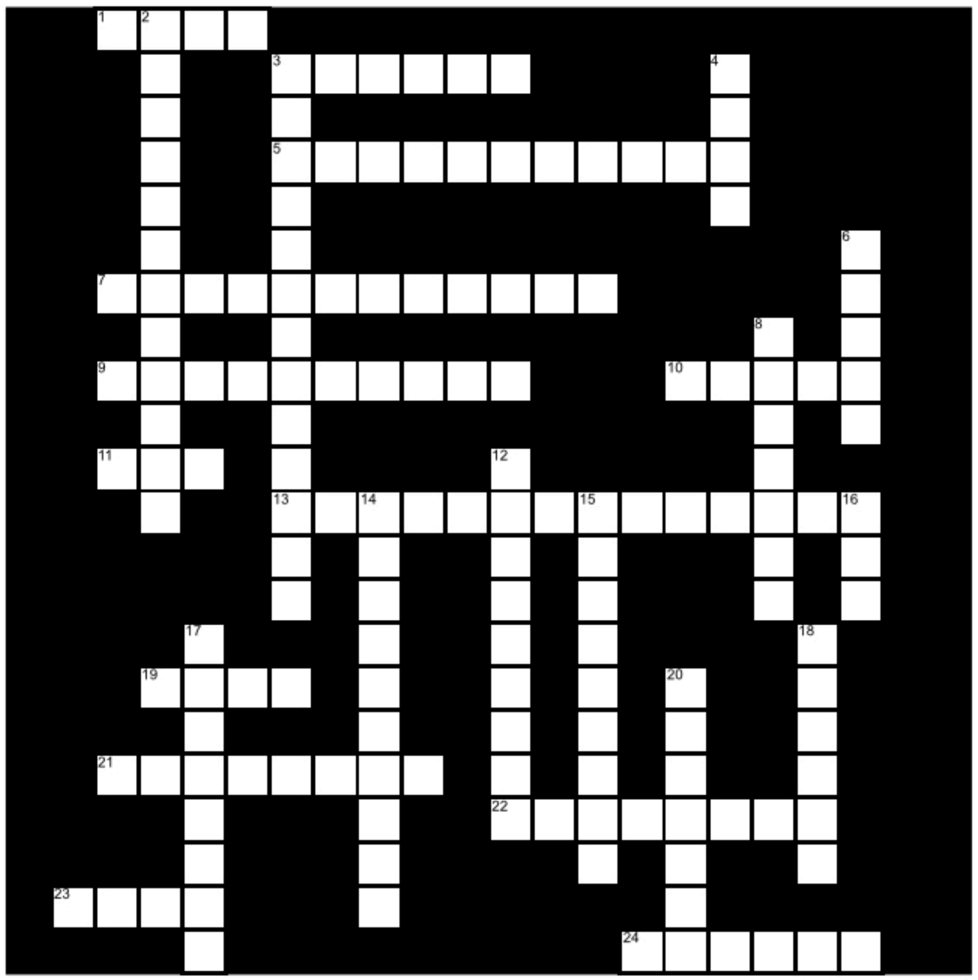
- for electron neutrino disappearance, in vaccum and in matter, the concept of an effective Delta m^2, Delta m^2_ee, is useful for the shape analysis: (Daya Bay has caused confusion on this concept. PDG of no help.) Δm^2_{ee} is ν_e average of Δm^2_{31} and Δm^2_{32}

- Short baseline reactor experiments, Daya Bay and RENO, can constrain Delta m^2_21 at twice the KamLAND value. This can be preformed NOW !

S.H. Seo and SP arXiv:1808.09150

Neutrino Crossword

Neutrino Puzzle



Across

1 When Potassium 40 decays does it emit neutrinos or antineutrinos ?

3 In 1966 a popular book on neutrinos was written by

5 How many neutrinos, in log base 10, does the Sun emit per second ?

7 What important effect did Wolfenstein discover in 1978 ?

9 What percentage of the energy from a Supernova is released in neutrinos ?

10 Neutrinos from Decay of this element have been observed

11 Solar Neutrino Unit

13 Why are neutrino nucleon cross sections so challenging to calculate ?

19 Neutrino Propagation states

21 What distinguishes a neutrino from and antineutrino ?

22 Little neutral one

23 What happens to oscillation length if Planck's constant goes to zero ?

24 If neutrinos are Majorana which number symmetry is violated ?

Down

2 Quantum mechanical interference of the mass eigenstate leads to ...

3 What do reactors emit ?

4 Why Pauli did not go to the scientific meeting where his invention of the neutrino was announced ?

6 When crossing a high energy neutrino beam is it better to cross in front or behind a concrete wall ?

8 Powers Nuclear Reactors

12 Who gave the SuperK atmospheric neutrino talk at Neutrino 1998

14 Why is |U_e1|^2 larger than |U_e2|^2 or |U_e3|^2 ?

15 The Argon in earth's atmosphere comes from decay of which element ?

16 Which experiment "nailed" the solar neutrino anomaly ?

17 The invariant that controls the size of CP violation was invented/discovered by this woman physicist

18 Neutrino Interaction States

20 Zombie neutrinos

npc.fnal.gov/question/

Fermilab

Neutrino Question • Neutrino Physics Center