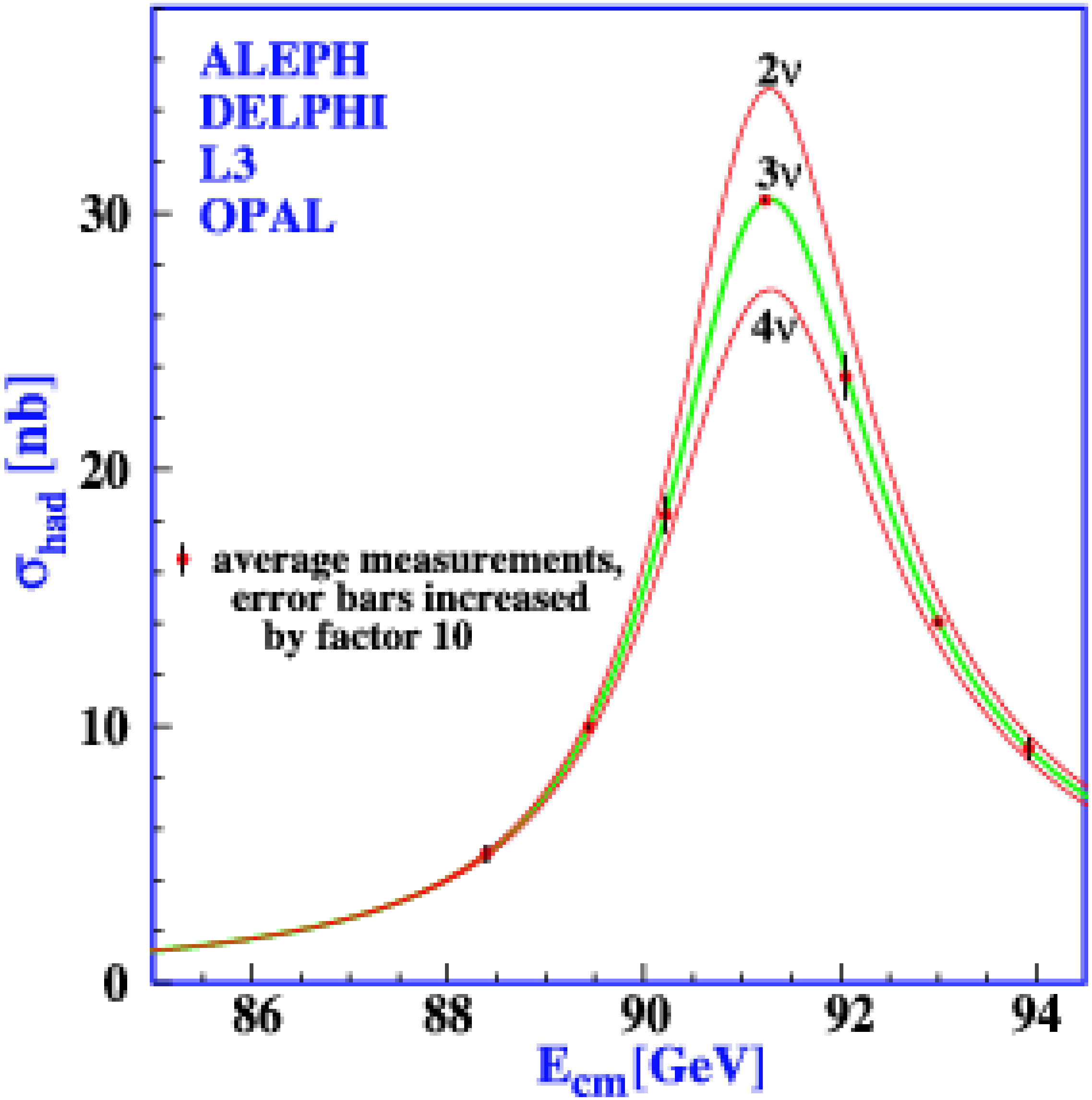
~~Lecture 3~~ Lecture 1

24th Indian-Summer School
Understanding Neutrinos
Petr Vogel, Caltech

~~Friday, Sept.7, 2012~~ Monday, Sept.3, 2012

Light Sterile Neutrinos; to be or not to be?

*We know for sure that there are only 3 `active' neutrinos. If indeed (at least) one light `sterile' neutrino exists, <u>all bets are off.</u> That would be physics **<u>far beyond</u>** the Standard Model*



The most precise measurements of the number of active neutrino types N_ν come from studies of Z production in e^+e^- collisions. From LEP $\mathbf{N_\nu = 2.984 \pm 0.008}$.

If additional neutral particles with mass < $M_Z/2$ exist, they must be ***sterile*** *with respect to weak interactions. (Coupling to W is related to the coupling to Z in Standard Model.) They might couple, however, to various so far unobserved but predicted particles.*

Such sterile neutrinos might be observable only if they mix with the active standard neutrinos.

Possible existence of light sterile neutrinos:

a) Most models of neutrino mass involve sterile neutrinos.
b) Their mass can be large, M_{GUT}, for the see-saw type I.
Such heavy ν_R do not mix with the light ν noticeably,
but are needed in order to explain the smallness of m_ν.

- *The situation is similar for the ν_R masses of ~TeV scale.*

- *However, a variety of indications point to the existence of sterile neutrinos at the ~ eV scale that mix noticeably with the light neutrinos. If they really exist, their existence would require some additional physics reasons for their small mass. Nevertheless, it is worthwhile to consider the experimental indications.*

How did hints of existence of sterile neutrinos arose?

Oscillation length $L_{osc}(m) = 2.48xE_\nu(MeV)/\Delta m^2 (eV^2)$ (this is the full osc. length, the first minimum is at $L_{osc}/2$)

Since $\Delta m^2_{21} = 7.6x10^{-5}$ eV^2 and $\Delta m^2_{31} \sim \Delta m^2_{32} = 2.4x10^{-3}$ eV^2.

*Therefore for reactors **$L_{osc}^{atm}/2 \sim 2$ km**, and **$L_{osc}^{sol}/2 \sim 65$ km** ($E_\nu \sim 4$ MeV) ,*
*for the π and μ decay at rest **$L_{osc}^{atm}/2 \sim 20$ km**, **$L_{osc}^{sol}/2 \sim 650$ km** ($E_\nu \sim 40$ MeV),*
*and for accelerators **$L_{osc}^{atm}/2 \sim 520$ km**, **$L_{osc}^{sol}/2 \sim 16,000$ km** ($E_\nu \sim 1$ GeV)*

Observing noticeable neutrino flavor change at distances substantially less than $L_{osc}/2$ is incompatible with the standard oscillation paradigm.

Here is a list of hints for the existence of sterile neutrinos with ~ eV mass scale. These results (~3 σ) are not directly ruled out by other experiments.

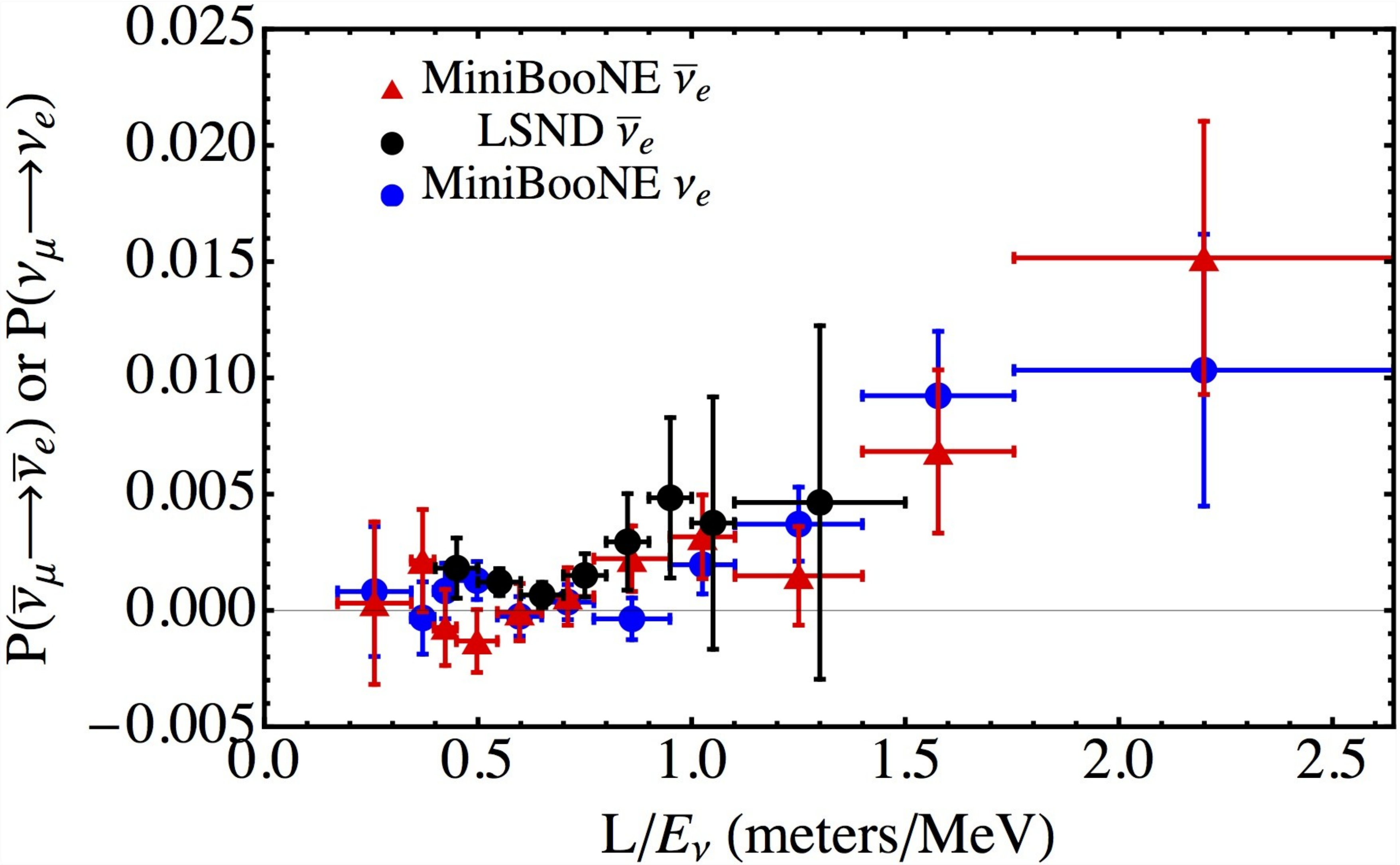
- LSND
- MiniBooNE ν
- MiniBooNE $\bar{\nu}$
- Reactor Anomaly
- Radioactive Neutrino Source Anomaly

LSND and MiniBoone involve indications for the ***appearance*** *of ν_e or $\bar{\nu}_e$ in the beams that was initially ν_μ or $\bar{\nu}_\mu$ at L/E_ν ~ 1 m/MeV that is incompatible with standard oscillation paradigm.*

Reactor experiments involve indications of the ***disappearance*** *of ν_e again at L/E_ν ~ 1 m/MeV .*

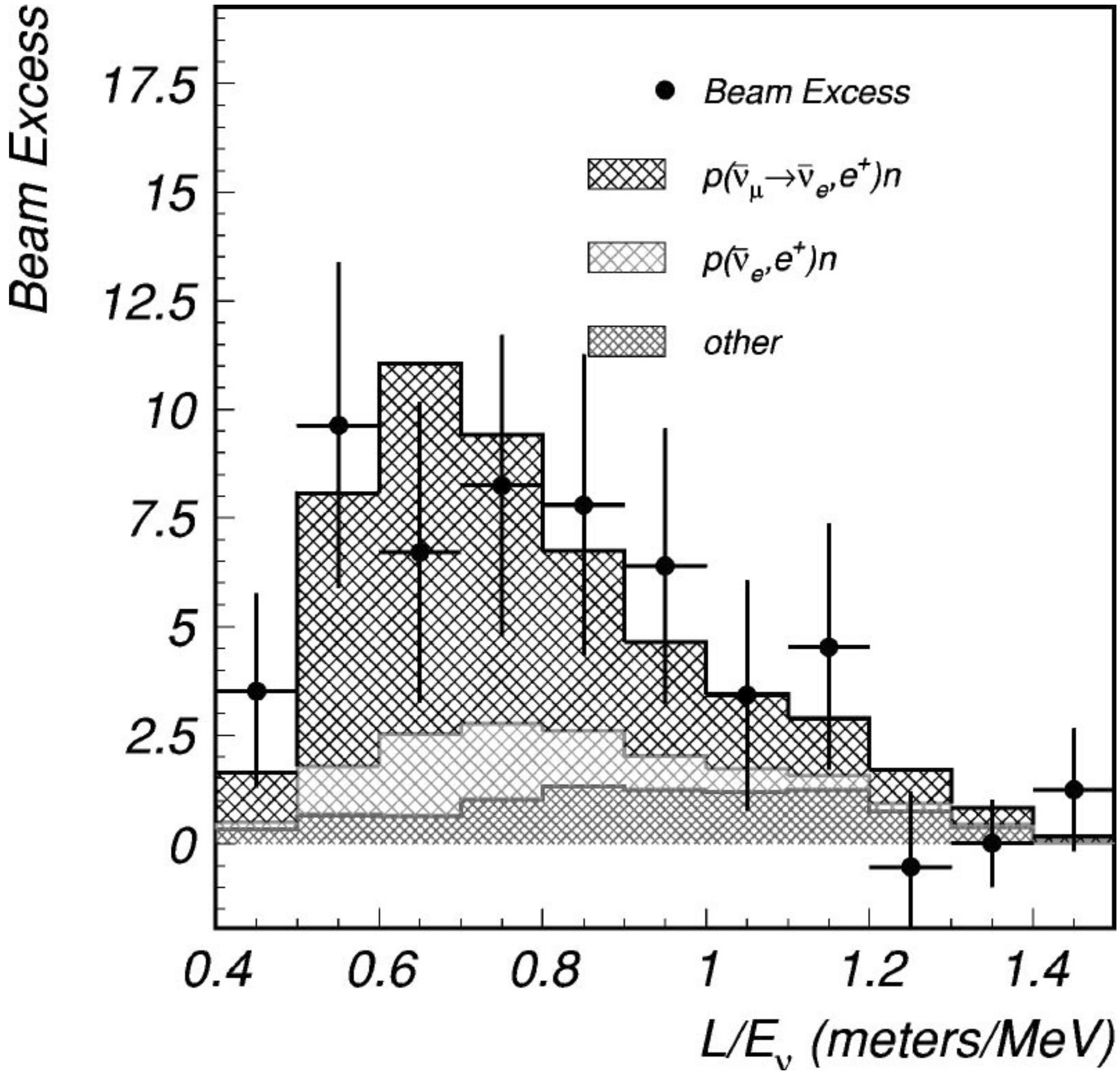
Calibration of the gallium solar neutrino detectors with radioactive sources involve indications of the ***disappearance*** *of ν_e again at L/E_ν ~ 1 m/MeV .*

In addition analysis of the CMB and Large Structures also indicates that additional relativistic fermions existed at the corresponding epochs.



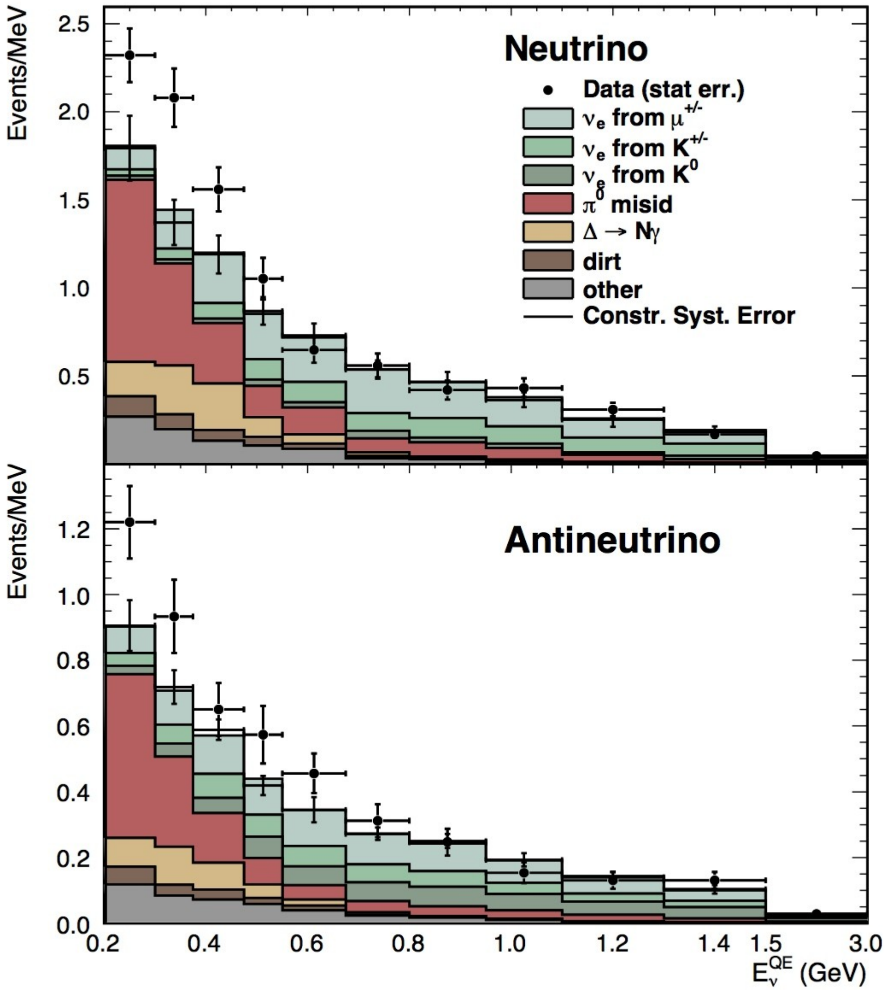
*Probability of the ν_μ -> ν_e flavor change as a function of L/E_ν. Note, however that if $L/E_\nu \sim 0.6$ m/MeV would be the minimum of oscillations, the next minimum should be at 1.2 and another one at 1.8. Clearly, this probability shows a consistency of these experiments but **does not follow** the standard formula.*

remember that the oscillation hypothesis means that $P \sim \sin^2(\Delta m^2 L/E)$. Thus $P = 0$ when $\Delta m^2 L/E = n\pi$

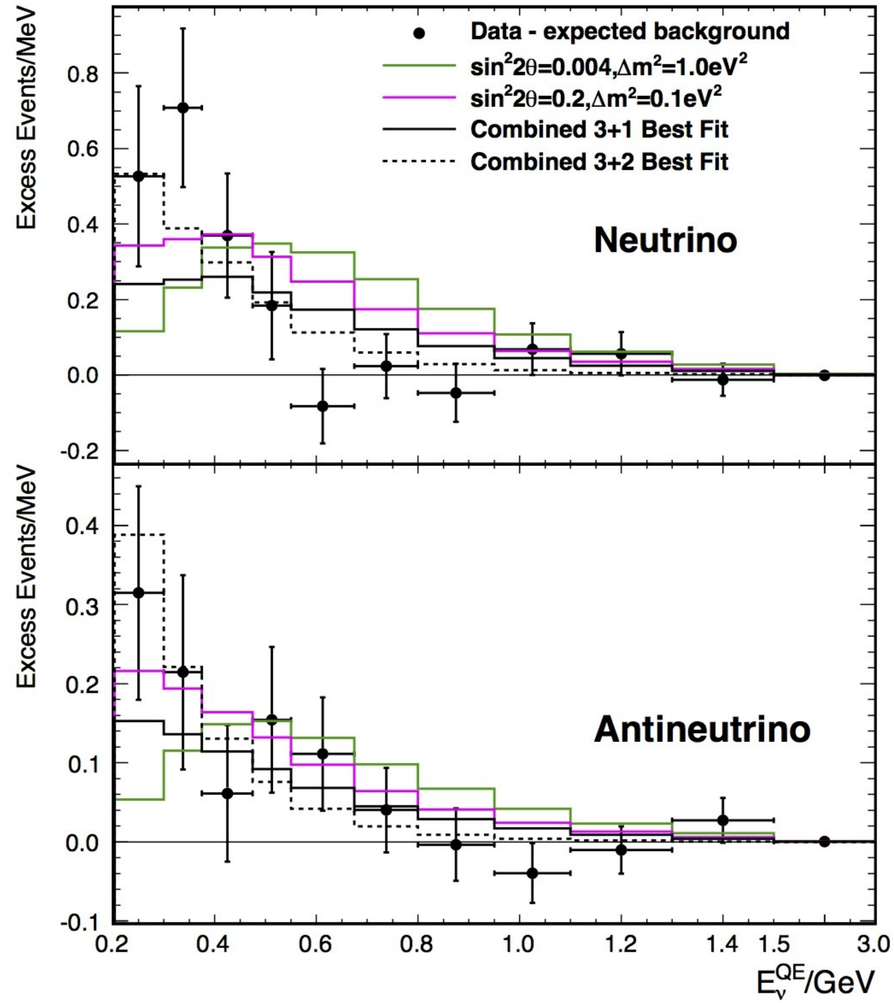


Candidate appearance events at LSND; 49.1±9.4 for 20 ≤ E_ν ≤ 60 MeV

*From Aguilar et al., PRD **64**. 112007 (2001)*

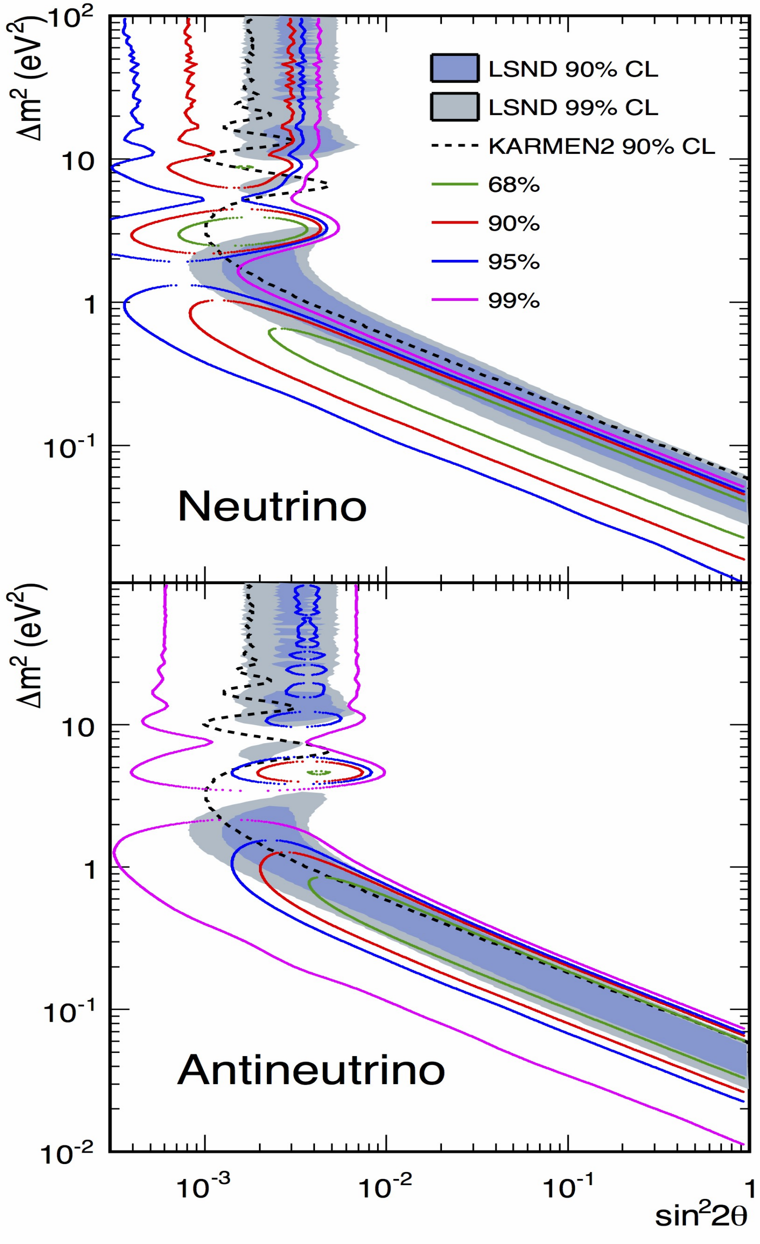


MiniBoone electron-like events vs. background for the charged current quasi-elastic events as a function of the deduced ν_μ energy for both neutrinos and antineutrinos.



Excess events and various oscillation fits. Combined excess 240.3±34.5±52.6 events.

from Aguilar-Arevalo et al. arXiv:1207.4809

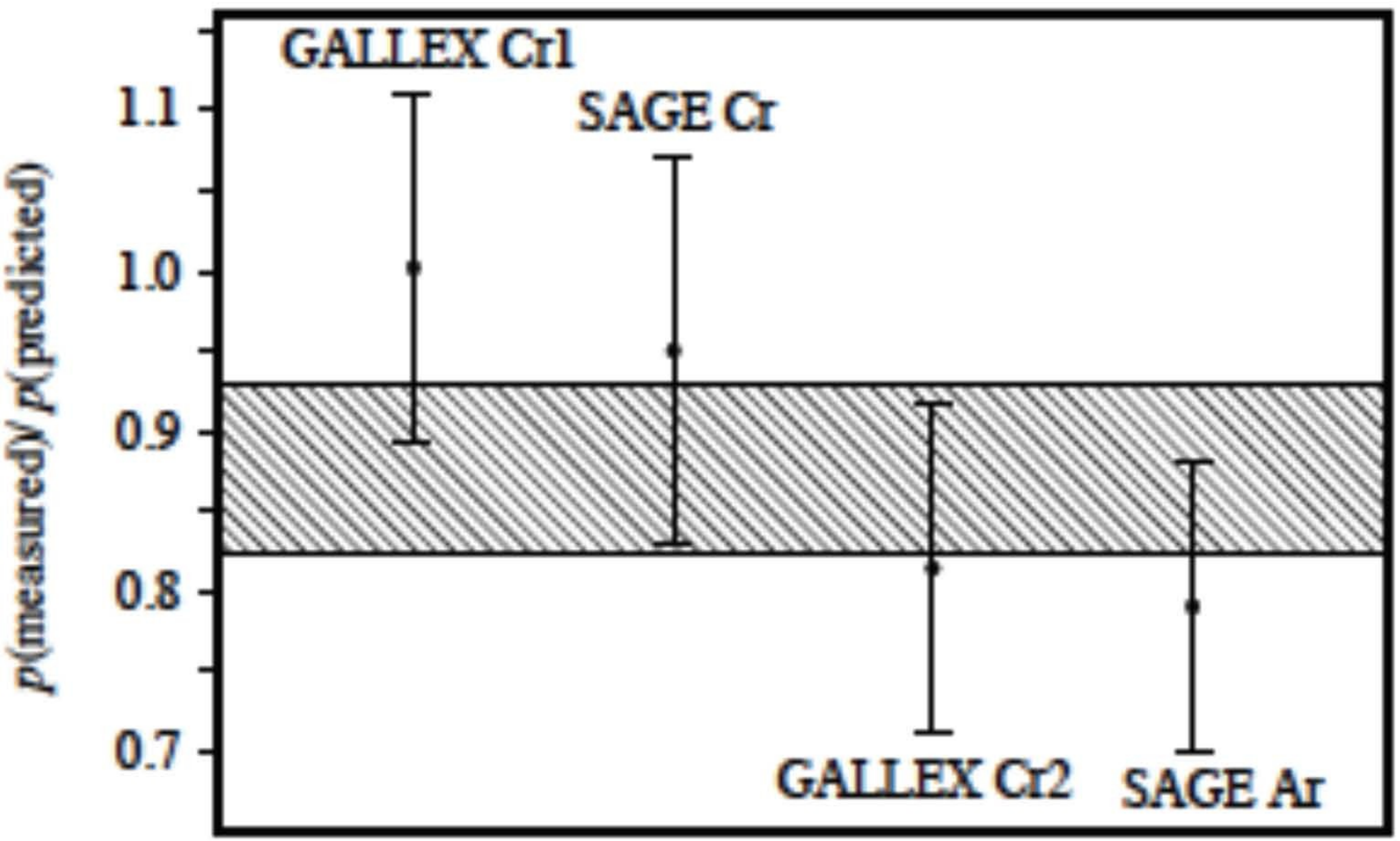


Allowed regions in the two-neutrino oscillation space for the 3+1 model. The lines are for MiniBoone, the shaded are for LSND. The excluded region by Karmen is to the right of the dashed lines.

The solar neutrino detectors GALLEX and SAGE based on the ν_e capture on ^{71}Ga leading to ^{71}Ge were tested with strong man-made radioactive sources of ^{51}Cr and ^{37}Ar which were placed inside the detectors. ^{51}Cr and ^{37}Ar produce monoenergetic ν_e by electron capture (Q = 751 and 814 keV).

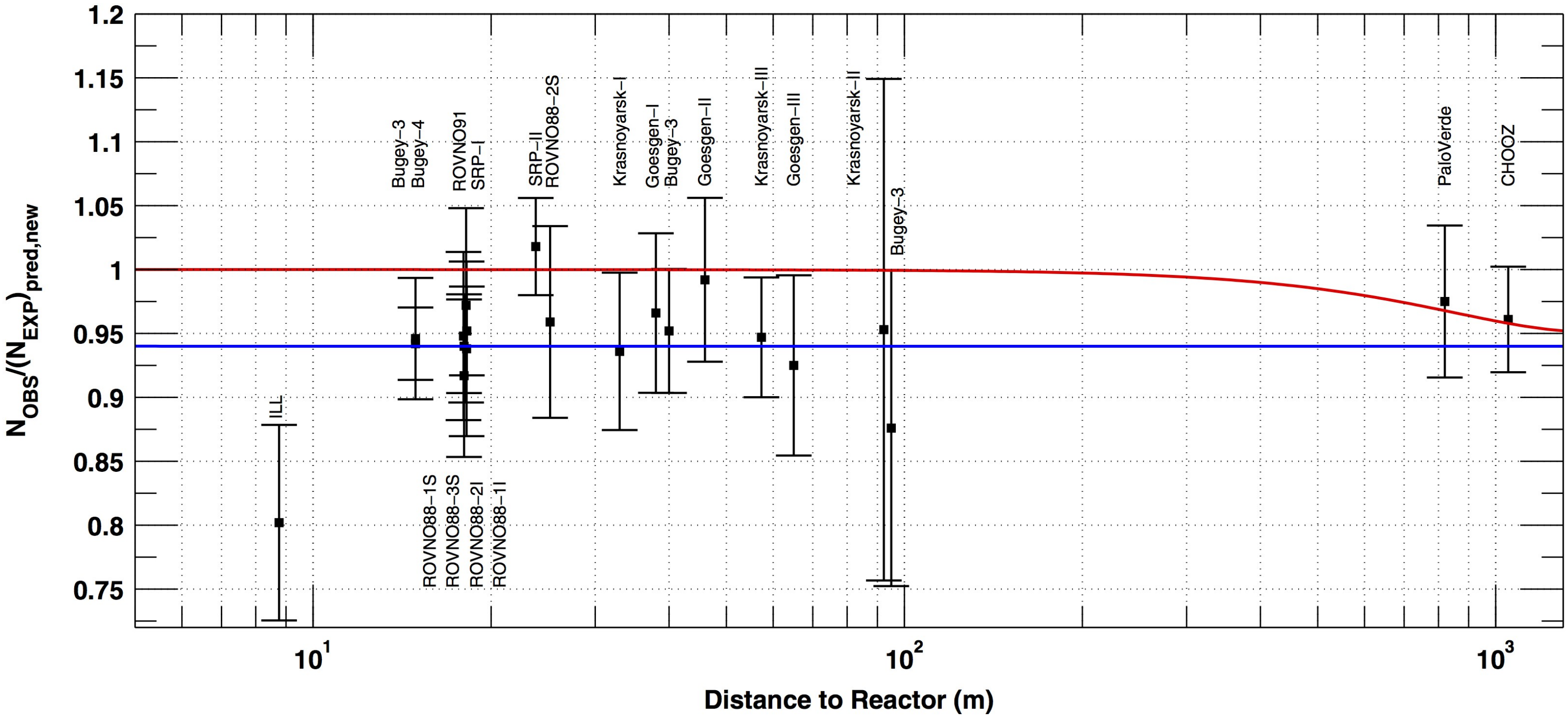
There were four calibration runs. The corresponding measured/expected ratios are shown below. When averaged they give ***<R> = 0.86±0.05***

*When one tries to explain these ratios as resulting from oscillations, the best fit values are $\Delta m^2 = 2.24\ eV^2$ and $\sin^2 2\theta = 0.50$ (Giunti & Lavender, Phys. Rev C**83**,065504(2011)).*

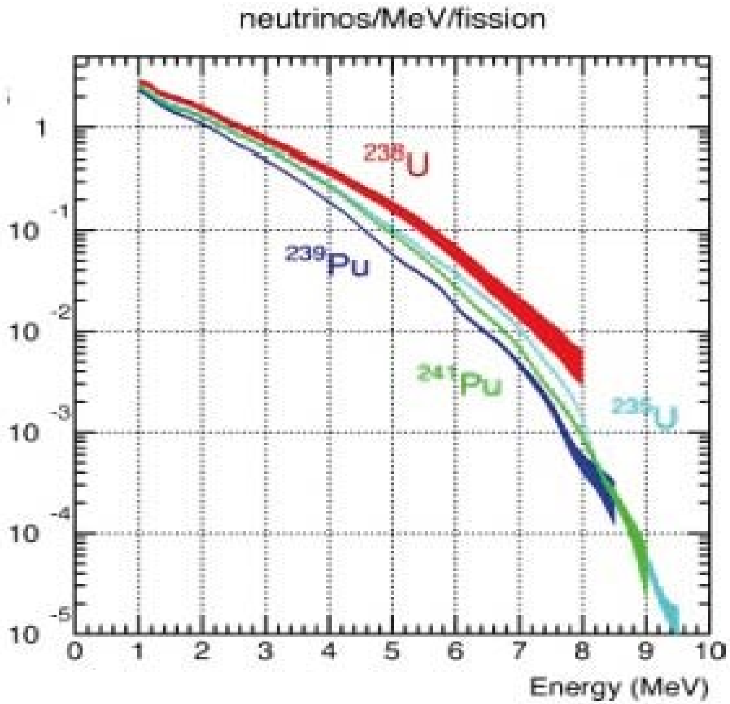


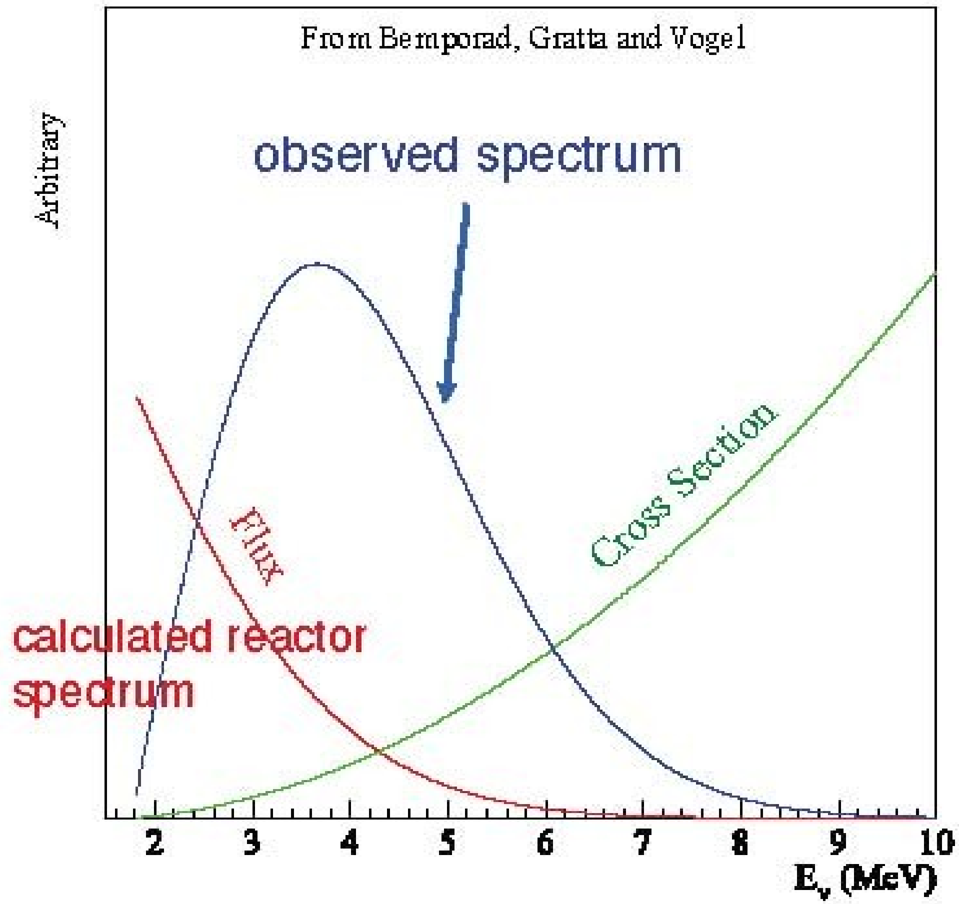
*Last year (Mueller et al., Phys. Rev. C**83**,054615(2011)) published a new evaluation of the expected flux of $\bar{\nu}_e$ by nuclear reactors. That flux was ~ 3% stronger than what was the standard until that time. When measurements in many (~20) independent experiments at 10-100 m plus two more At ~ 1 km are compared to that prediction one finds that the corresponding average is only* ***0.943±0.023*** *, thus starting at ~20 m ~ 6% of the $\bar{\nu}_e$ have `disappeared'. The experiment at 9 m, at ILL in 1981 is anomalous and not understood.*

*The figure from Mention et al., Phys. Rev. D**83**, 073006(2011) illustrates the `anomaly', The red line is for three neutrinos only, but with $\sin^2 2\theta_{13} = 0.06$, the blue line is for additional sterile neutrino with $\Delta m^2_{new} >> 1\ eV^2$ and $\sin^2 2\theta_{new} = 0.12$.*



Reactor Antineutrinos





$\bar{\nu}_e$ from n-rich fission products

~ 200 MeV per fission

~ 6 $\bar{\nu}_e$ per fission

~ 2 x 10^{20} $\bar{\nu}_e$/GW_{th}-sec

mean energy of $\bar{\nu}_e$: 3.6 MeV

only disappearance expts possible

cross-section accurate to +/-0.2%

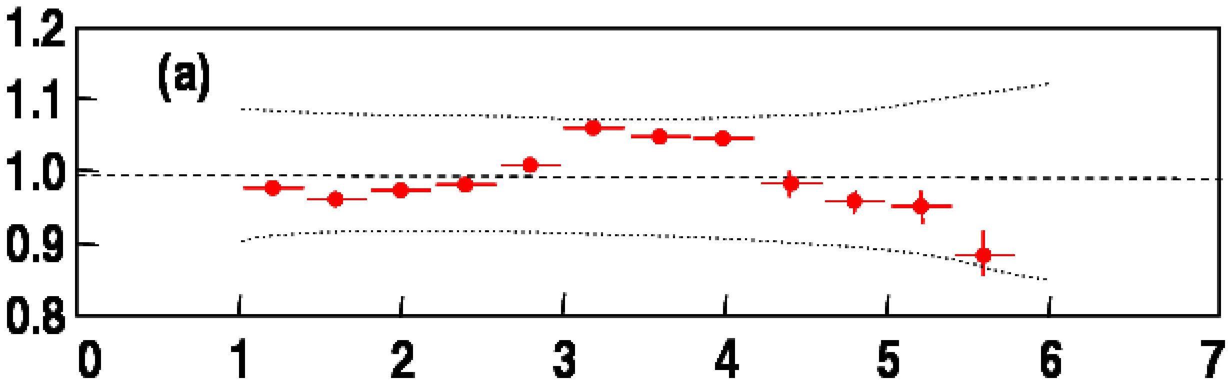
detection reaction $\bar{\nu}_e + p \rightarrow e^+ + n$

Brief history of the reactor neutrino spectrum determination:

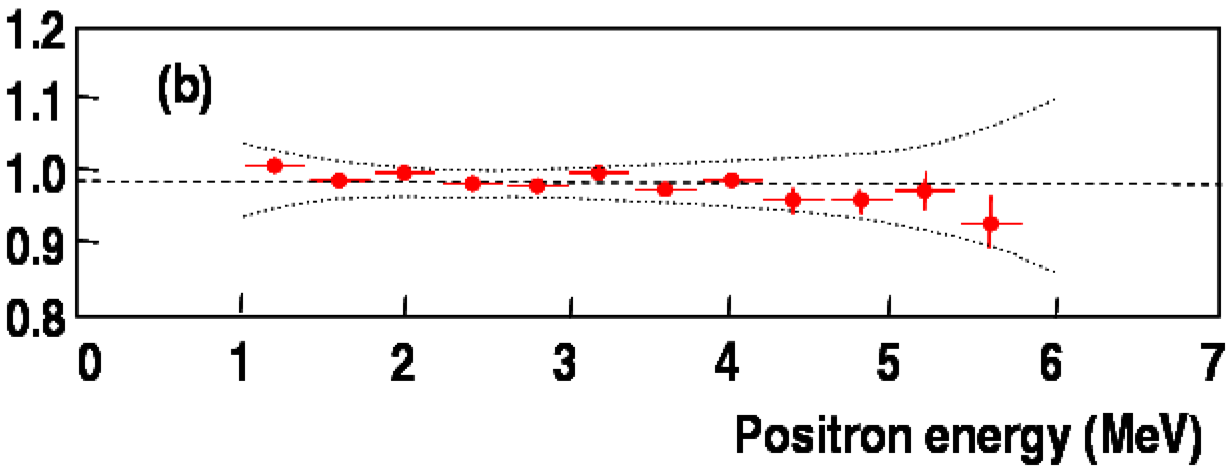
1. *First `modern' evaluations were done in late 1970 and early 1980 (Davis et al. 1979, Vogel et al. 1981, Klapdor & Metzinger 1982)*
2. *During the 1980-1990 a series of measurements of the **electron** spectra associated with the fission of ^{235}U, ^{239}Pu and ^{241}Pu were performed at ILL Grenoble by Schreckenbach et al. These were **converted** into the electron antineutrino spectra by the authors.*
3. *This is basically what was used until now, even though some effort was made to measure the β decay of various short lived fission fragments (Tengblad et al, 1989, Rudstam et al. 1990) and new calculations were performed (see e.g. Kopeikin et al, hep-ph/0308186).*

- *New evaluation (Mueller et al. 2011) uses a combination of the ab initio approach with updated experimental data and the input from the converted electron spectra (see 2) above). **This results in the upward shift by ~3% of the reactor flux (keeping the shape almost unchanged).***

Measured ν_e spectrum shape and normalization agreed with calculated predictions to ~10% and with converted electron spectra even better



Calculation only
Klapdor and Metzinger, 1982



Beta calibrated
Schreckenbach, 1985
Hahn, 1989

Results of Bugey experiment (1996)

Conclusions:

1)All evaluations of the reactor neutrino flux depend on two basic assumptions:

1a) That the electron spectra measured at ILL by Schreckenbach et al. are correct (there is little doubt of that, even though the results were not independently confirmed).

1b) That the spectrum shape of the individual β decays is well understood.

2)For the allowed β decays (ΔI = 0,1, $\Delta\pi$ = no) the assumption 1b) is reasonably well fulfilled, even though the slope parameters A_{WM} and A_C have considerable uncertainty.

- *However, many transitions involve forbidden β decays since*

2)$\Delta\pi$=*yes is often the case, there is an additional uncertainty involved.*

3)It is at present difficult to estimate how large it is, but simple

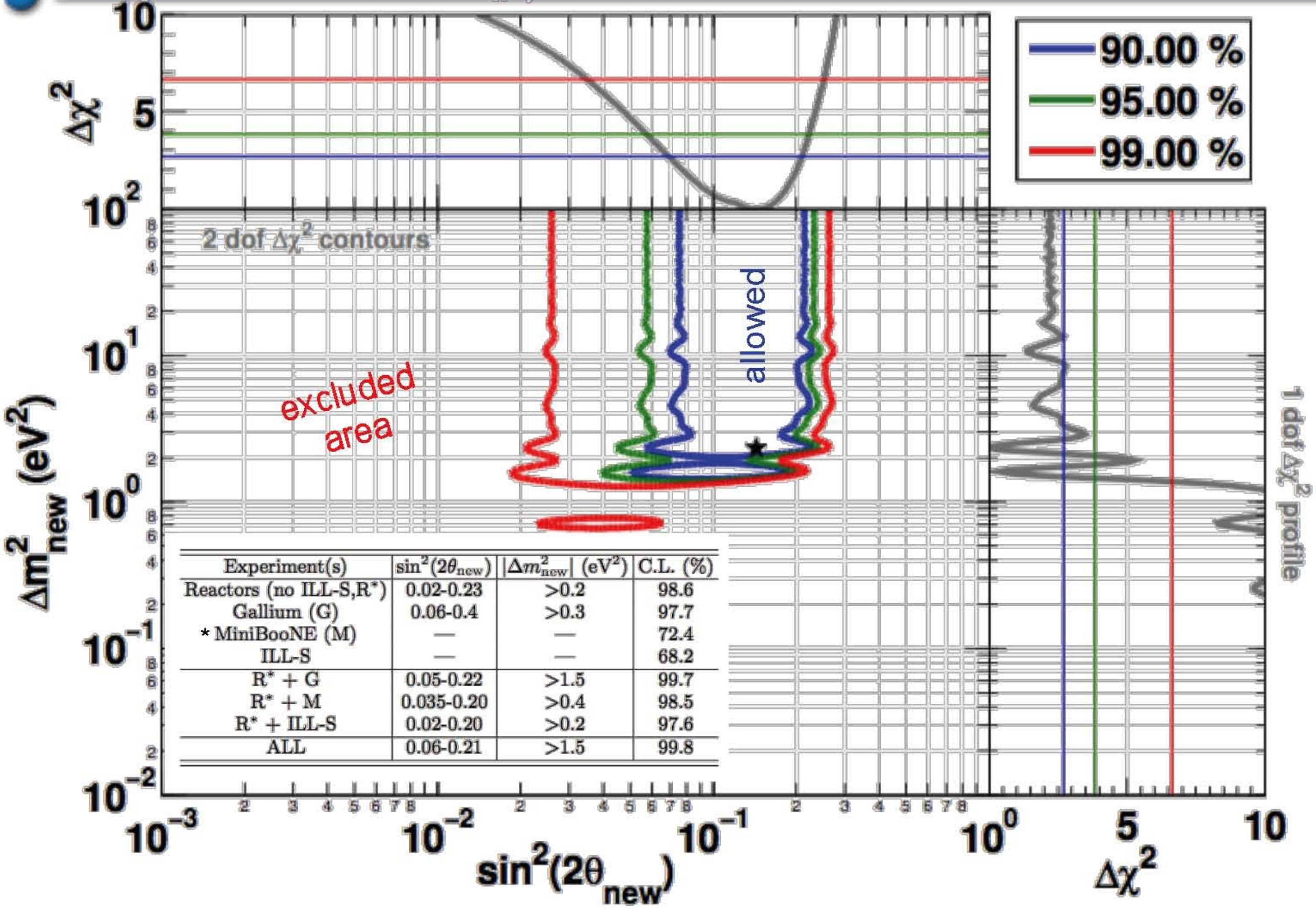
4)examples suggest that it could be comparable to the stated

5)uncertainty 2-3%.

Analysis based on $P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{new})\sin^2(\Delta m^2_{new} L/E_\nu)$

Best fit $\Delta m^2_{new} = 2.35 \pm 0.1\ eV^2$, $\sin^2(2\theta_{new}) = 0.165 \pm 0.04$

Combination: reactor rates + shape + Gallium + (MB)



Experiment(s)	$\sin^2(2\theta_{new})$	$\lvert\Delta m^2_{new}\rvert$ (eV^2)	C.L. (%)
Reactors (no ILL-S,R*)	0.02-0.23	>0.2	98.6
Gallium (G)	0.06-0.4	>0.3	97.7
* MiniBooNE (M)	—	—	72.4
ILL-S	—	—	68.2
R* + G	0.05-0.22	>1.5	99.7
R* + M	0.035-0.20	>0.4	98.5
R* + ILL-S	0.02-0.20	>0.2	97.6
ALL	0.06-0.21	>1.5	99.8

The no-oscillation hypothesis is disfavored at 99.8% CL

From Mention et al.

Very brief outline to see why the study of the early universe can provide some information about sterile neutrinos.

In the radiation dominated epoch the energy density, temperature and time are related through

$\rho = 3t^{-2}/(32\,\pi\, G_N)$, $kT = \{45/32\,\pi^3\, G_N\, g_s^*\}^{1/4}\, t^{-1/2}$,

Where g_s^* *counts the relativistic particles in thermal equilibrium, i.e. photons, electrons and tw0-components neutrinos;*

$g_s^* = 1(\text{photons}) + 7/4(\text{electrons}) + N_{eff}\, 7/8$ *(neutrinos, nominally* $N_{eff} = 3$*)*

Thus the contribution of N_{eff} *neutrinos to the energy density is*

$\rho_\nu = 7\,\pi^2 / 120\, N_{eff}\, (kT)^4/(hc)^3$

From `White paper on light sterile neutrinos', arXiv: 1204.5379.

η *is the baryon/photon ratio and* Y_p *is the primordial* ^{4}*He mass fraction*

Table II. Current constraints on N_{eff} from BBN, with 68% (95%) uncertainties. Different results for the same nominal data set are due to different measurements of Y_p.

Model	Data	N_{eff}	Ref.
$\eta+N_{eff}$	$\eta_{CMB}+Y_\mathrm{p}+$D/H	$3.8^{(+0.8)}_{(-0.7)}$	[331]
	$\eta_{CMB}+Y_\mathrm{p}+$D/H	$< (4.05)$	[332]
	$Y_\mathrm{p}+$D/H	3.85 ± 0.26	[333]
	$Y_\mathrm{p}+$D/H	3.82 ± 0.35	[333]
	$Y_\mathrm{p}+$D/H	3.13 ± 0.21	[333]

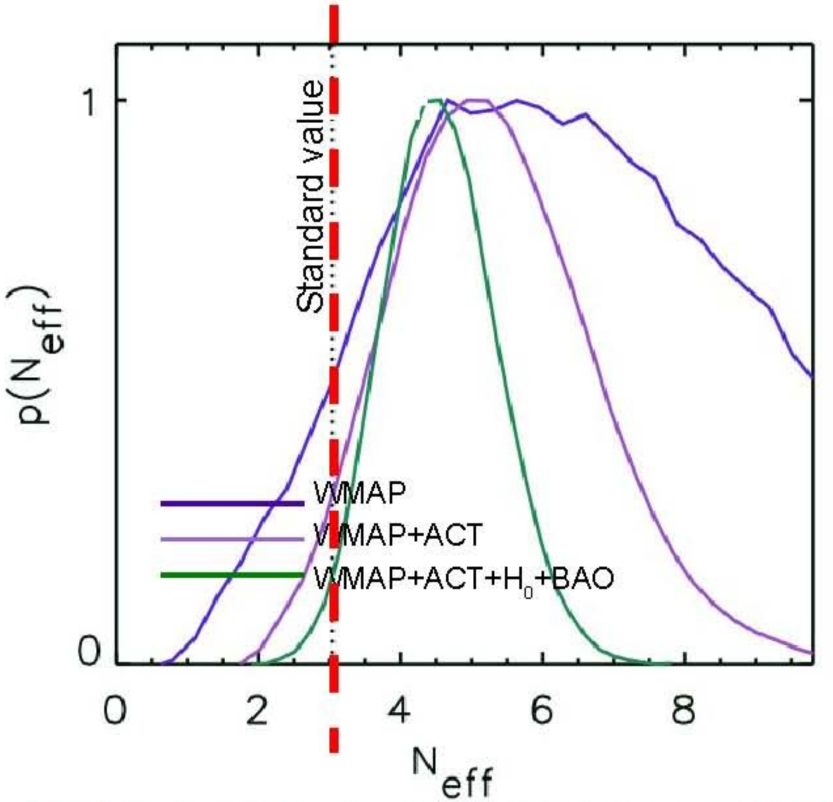
Another table from `White paper on light sterile neutrinos', arXiv: 1204.5379.

Table III. A selection of recent constraints on N_{eff}, with 68% (95%) uncertainties. W-5 and W-7 stand for WMAP 5-year and 7-year data respectively, H_0 refers to the constraint $H_0 = 74.2 \pm 3.6$ km s^{-1} from [347], LRG the halo power spectrum determined from the luminous red galaxy sample of the SDSS data release 7 [348], while CMB denotes a combination of small-scale CMB experiments such as ACBAR, BICEP and QUaD.

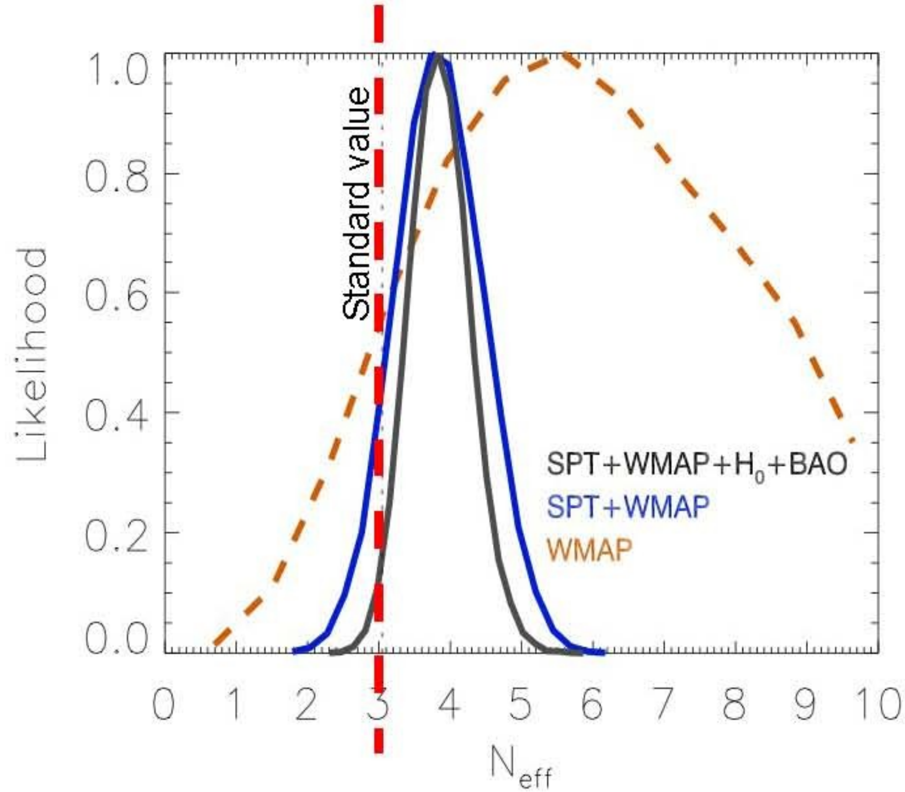
Model	Data	N_{eff}	Ref.
N_{eff}	W-5+BAO+SN+H_0	$4.13^{+0.87(+1.76)}_{-0.85(-1.63)}$	[346]
	W-5+LRG+H_0	$4.16^{+0.76(+1.60)}_{-0.77(-1.43)}$	[346]
	W-5+CMB+BAO+XLF+f_{gas}+H_0	$3.4^{+0.6}_{-0.5}$	[349]
	W-5+LRG+maxBCG+H_0	$3.77^{+0.67(+1.37)}_{-0.67(-1.24)}$	[346]
	W-7+BAO+H_0	$4.34^{+0.86}_{-0.88}$	[338]
	W-7+LRG+H_0	$4.25^{+0.76}_{-0.80}$	[338]
	W-7+ACT	5.3 ± 1.3	[343]
	W-7+ACT+BAO+H_0	4.56 ± 0.75	[343]
	W-7+SPT	3.85 ± 0.62	[344]
	W-7+SPT+BAO+H_0	3.85 ± 0.42	[344]
	W-7+ACT+SPT+LRG+H_0	$4.08^{(+0.71)}_{(-0.68)}$	[350]
	W-7+ACT+SPT+BAO+H_0	3.89 ± 0.41	[351]

Evidence for $N_{eff} > 3$ from CMB+LSS...

- Recent CMB+LSS data appear to prefer $N_{eff} > 3$!



Dunkley et al. [Atacama Cosmology Telescope] 2010



Keisler et al. [South Pole Telescope] 2011

However, reconciling this with m_ν ~ 1-2 eV is problematic, due to the cosmological mass limit.

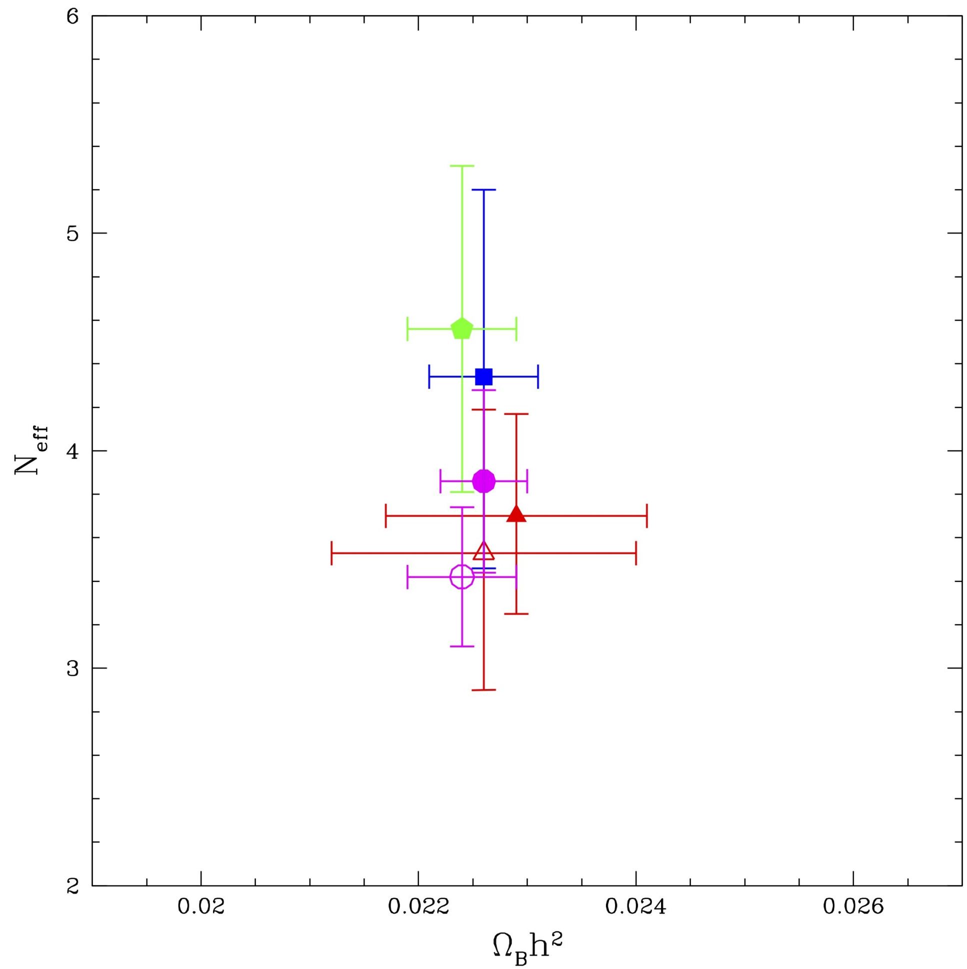


Figure 7: Comparing the BBN predictions of N_{eff} and $\Omega_B h^2$ with those from various CMB determinations: BBN D + ^{4}He (red filled triangle), BBN D + WMAP7 [36] $\Omega_B h^2$ (red open triangle), WMAP7 [36] (blue filled square), ACT [37] (green filled pentagon), SPT [38] (purple filled circle), SPT + Clusters [39] (purple open circle).

from G. Steigman, 1208.0032

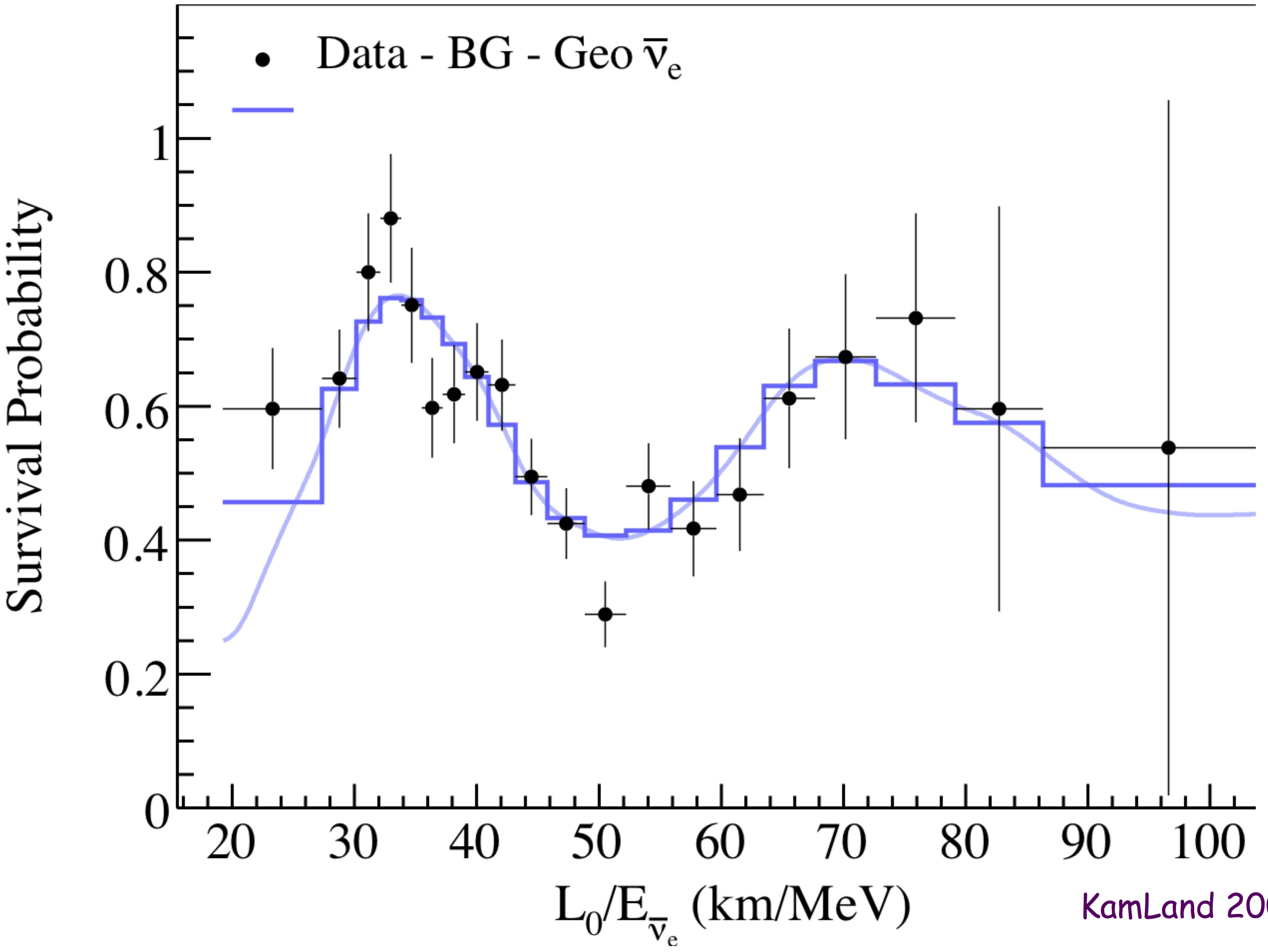
How could one test whether all of that is just a statistical fluke or a big new discovery?

a)Repeat all or some of the experiments. That is obvious but not easy to do. This was the idea of MiniBoone, check LSND with similar E_ν/L but very different systematics. The result is, however, not more convincing than LSND itself.

b)Recalculate the reactor spectrum. Again, not clear that one can control the uncertainty sufficiently.

c)Look for oscillatory behavior with oscillation length corresponding to $\Delta m^2 \sim 1\ eV^2$ and amplitude ~ 0.1. That would be truly convincing but not easy.

This textbook type figure shows clearly the oscillatory pattern

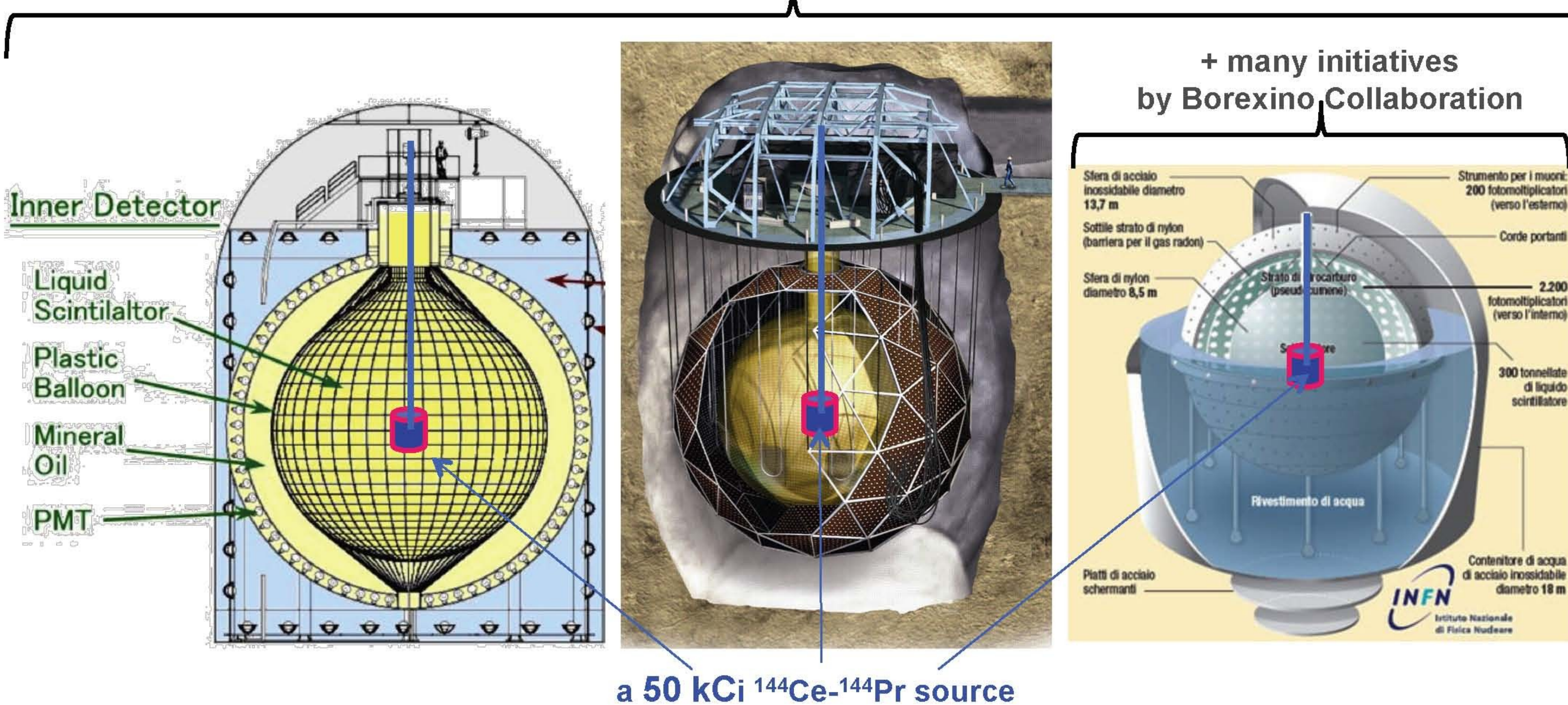


KamLand 2008

Proposals to verify the L/E_{ν} variation using strong β decay source and a large liquid scintillator detector.

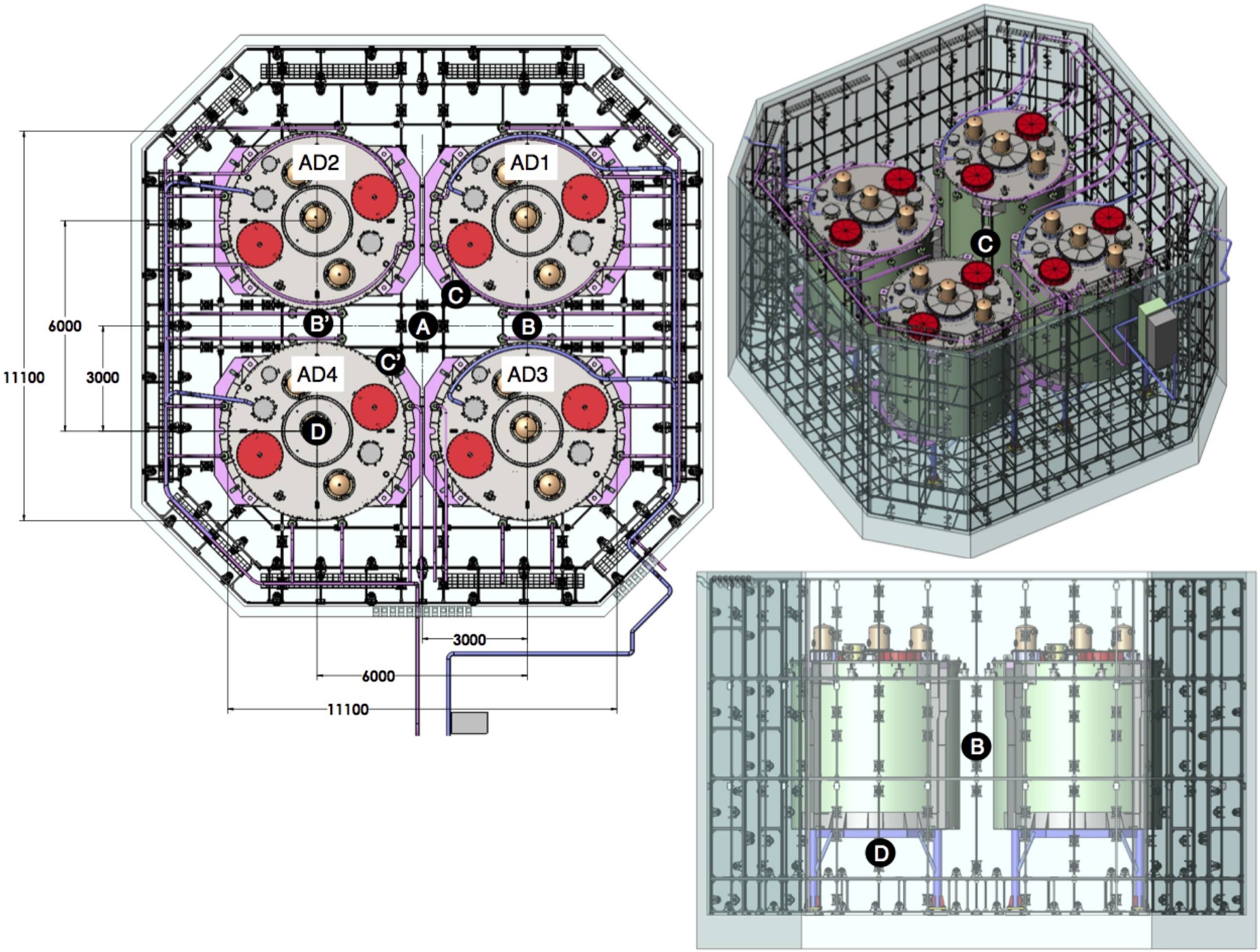
^{144}Ce-^{144}Pr Proposal: 3+1 Potential Detector

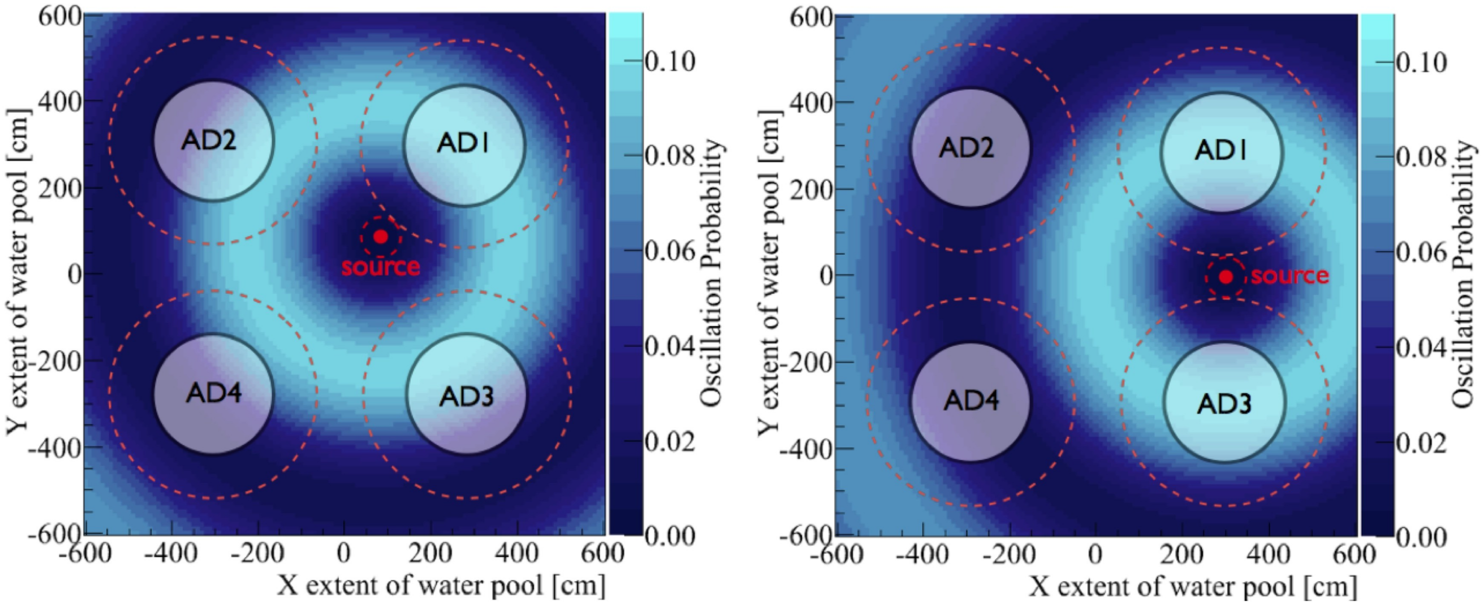
A proposal: M. Cribier, M Fechner, T. Lasserre, D. Lhuillier , et al. (arXiv:1107.2335)

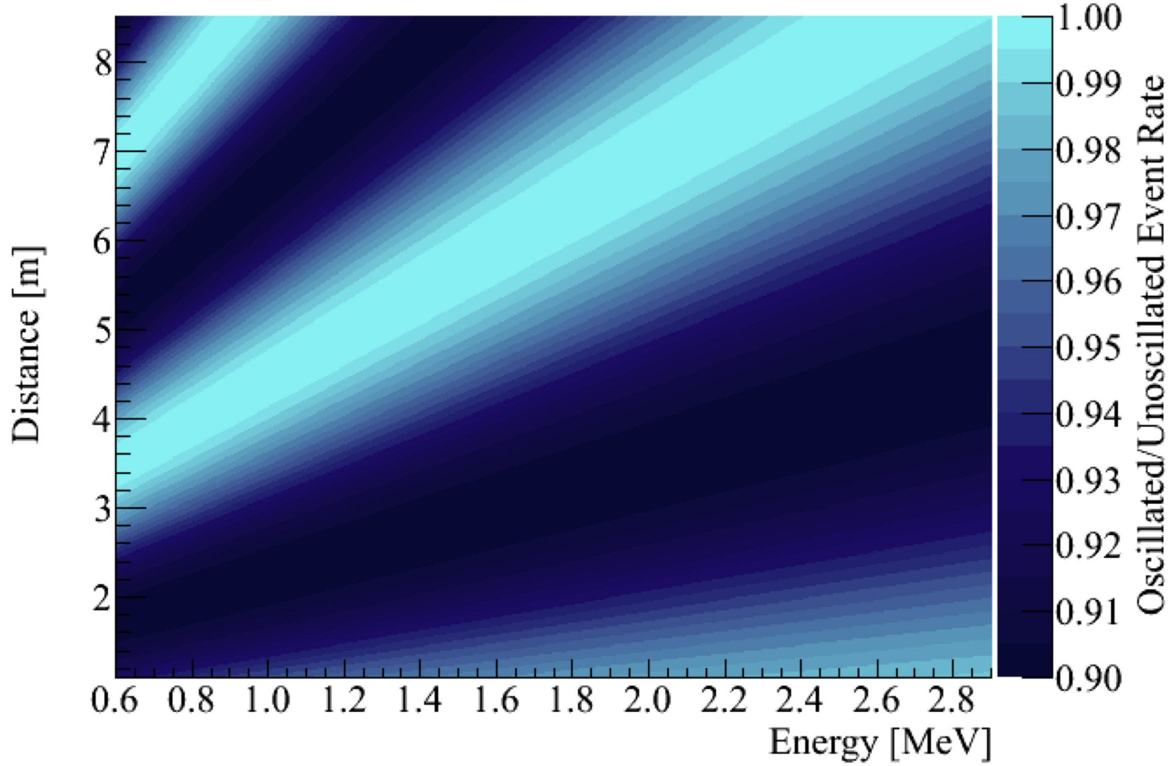


^{144}Ce is a prominent fission fragment with $T_{1/2}$= 284 d. Its daughter ^{144}Pr decays promptly with Q = 3 MeV

Alternative proposal (Dwyer et al., arXiv: 1109.6036). Place a stronger ^{144}Ce source into the far detector at Daya-Bay. Various positions in the water between the four detectors are indicated.

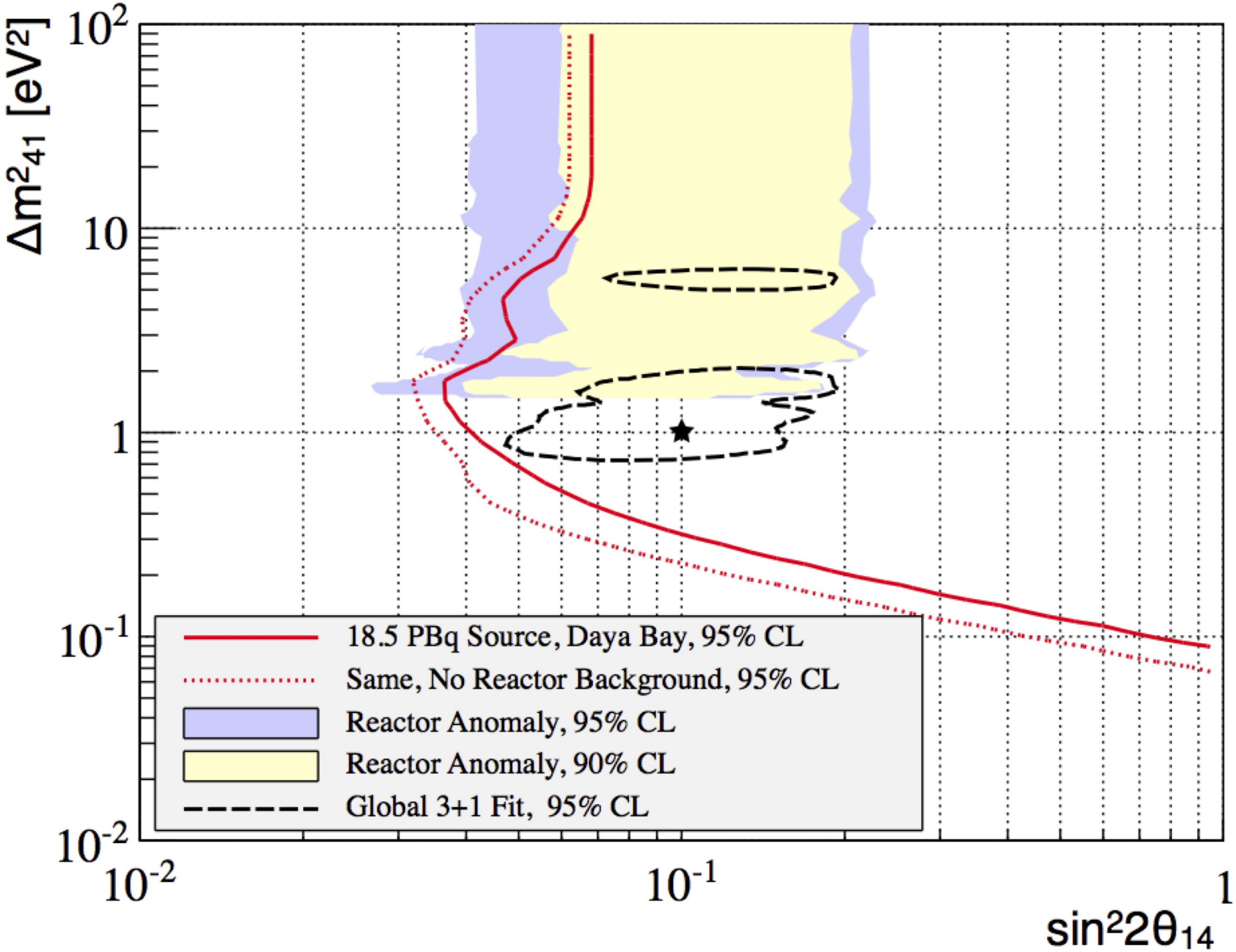






Signature of oscillations for $\Delta m^2_{41} = 1\ eV^2$ and $\sin^2 2\theta_{41} = 0.1$. Upper panels for two positions in the detector complex. Lower figure as a function of energy and distance.

Sensitivity to the oscillation parameters for the 500 kCi ^{144}Ce source at the far hall at Daya-Bay. This is for position B and one year of measurement. The `reactor anomaly' region would be covered.



Conclusions: Something has to be done !!!

1)While neither of these hints is very convincing, the fact that several of them seem to point in the same direction need to be taken seriously (but is not taken very seriously by the wider particle physics community).
2)Certainly each of these hints must be examined independently. If one or several of them turns out to have simpler explanation, it would weaken, but not completely resolve the problem.
3) There are many attempts to describe all of it as resulting from oscillations with 1 or 2 sterile neutrinos (3+1 and 3+2 models). Such attempts typically come to the conclusion that no consistent description of all of these phenomena is possible. I would not worry about it much. Since the statistical significance of each of them is not strong, it is possible (perhaps likely) that one or more is indeed a statistical fluke. But we do not know which.
4) Fresh ideas are urgently needed.

spares

What the possible existence of such sterile neutrino has to do with the $0\nu\beta\beta$ decay?

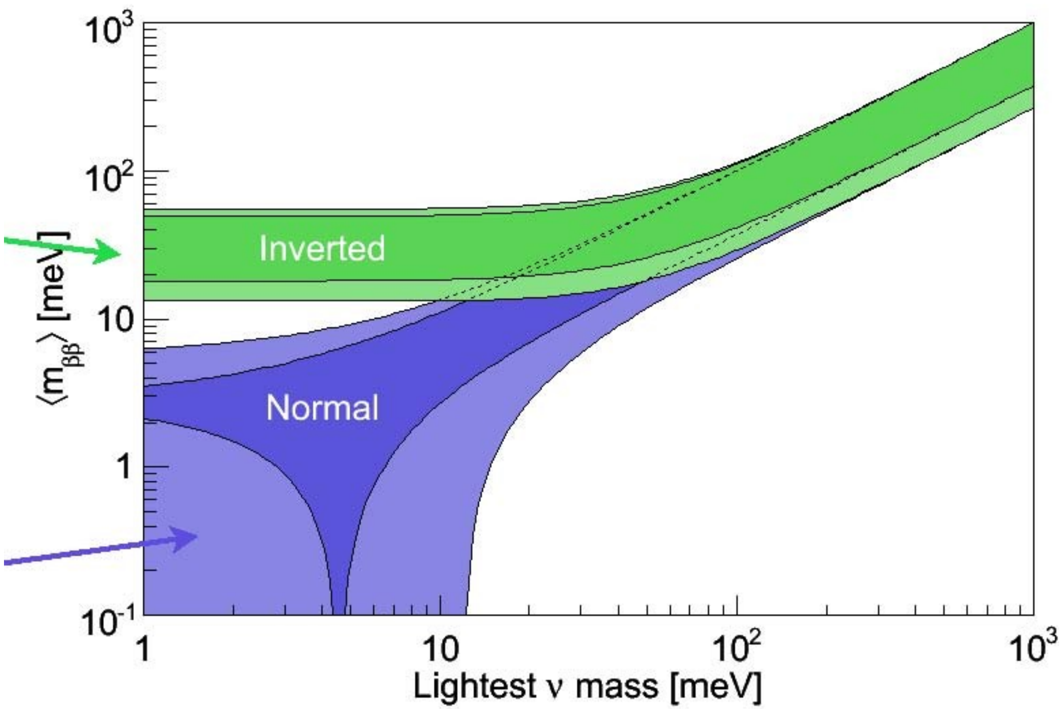
Remember that $\langle m_{\beta\beta} \rangle = |\Sigma\, U_{ei}^2\, m_i|$

If we add the 4th neutrino to this sum,

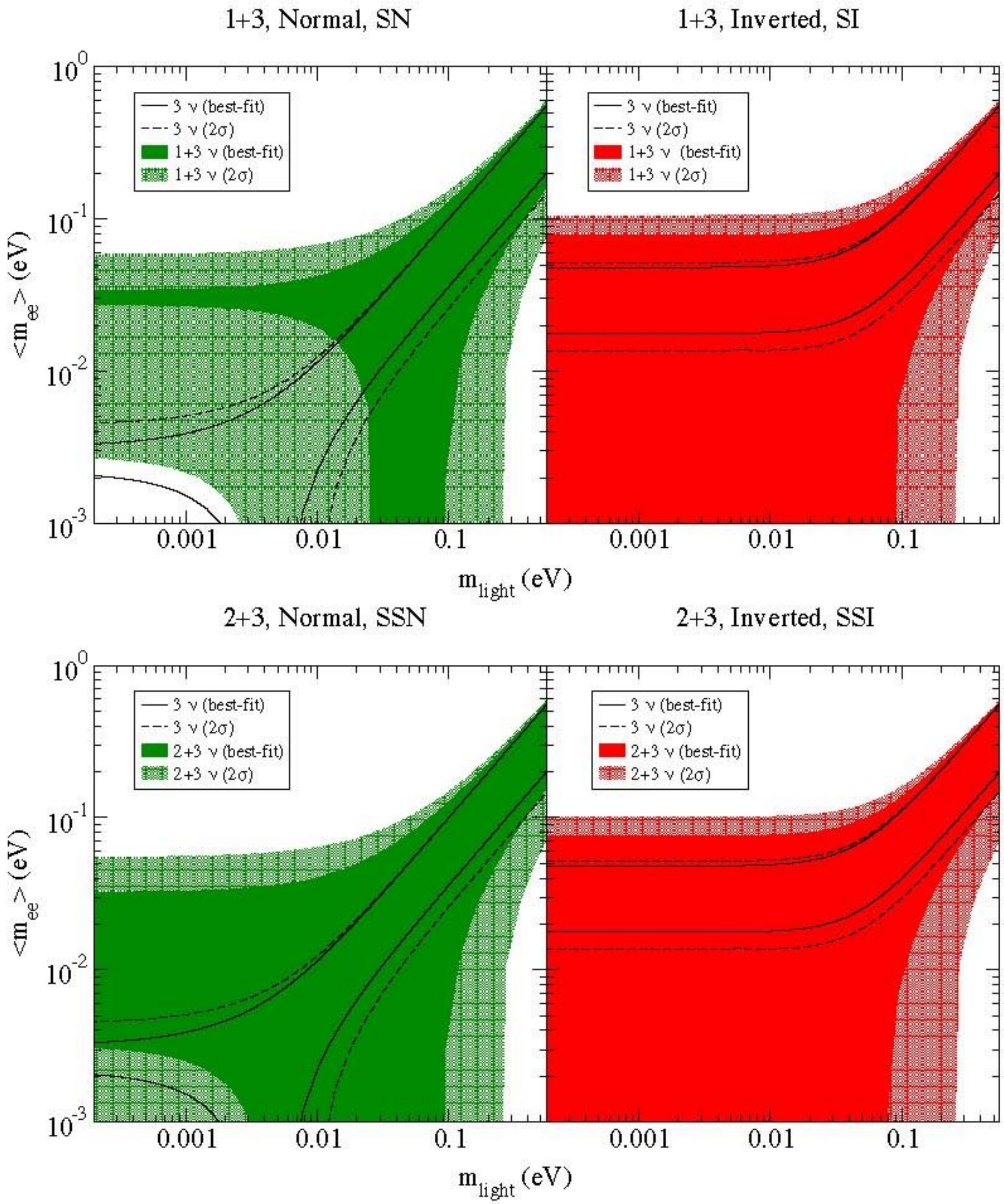
it will contribute ~0.14 eV using the

previous best fit $\sin^2(2\theta_{new})$ and $m_{new} = (\Delta m^2_{new})^{1/2}$

That would dominate the $\langle m_{\beta\beta} \rangle$ for all but highly degenerate scenario of neutrino masses



This widely used picture would be totally useless



1+3, Normal, SN
1+3, Inverted, SI
2+3, Normal, SSN
2+3, Inverted, SSI
3 ν (best-fit)
3 ν (2σ)
1+3 ν (best-fit)
1+3 ν (2σ)
2+3 ν (best-fit)
2+3 ν (2σ)
<m_ee> (eV)
m_light (eV)
10^0
10^-1
10^-2
10^-3
0.001
0.01
0.1

A bit of theory:

The most general renormalizable Lagrangian that includes additional neutrinos N_i is:

$$\mathcal{L}_\nu \supset \mathcal{L}_{\rm old} - \frac{M_{Rij}}{2} N_i N_j - y^{\alpha i} L_\alpha N_i H + h.c.,$$

where M_R are the mass parameters of the righthanded (sterile) neutrinos and y are the neutrino Yukawa coupling constants. In general M_R and y are not restricted, their values could be chosen such that some experimental fact is explained.

The `standard' choice is $y \sim 1$, $M = (10^{10} – 10^{15})$ GeV (see-saw I), but other possibilities are not excluded.