Sterile neutrinos: the global picture

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in collaboration with:
Joachim Kopp, Michele Maltoni,
and Thomas Schwetz

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Which steriles?

The Z invisible width measured at LEP tell us that we only have three light neutrinos ($m_\nu < M_Z/2$) coupling to the Z

Any SM singlet is generically a sterile neutrino but it may serve to many purposes

Very massive (10^{3-12} GeV) – seesaw, leptogenesis
Intermediate (few keV) – dark matter candidate
Light (~ eV) – ν oscillation anomalies

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Do we need steriles?

LSND

Los Alamos 1993-98

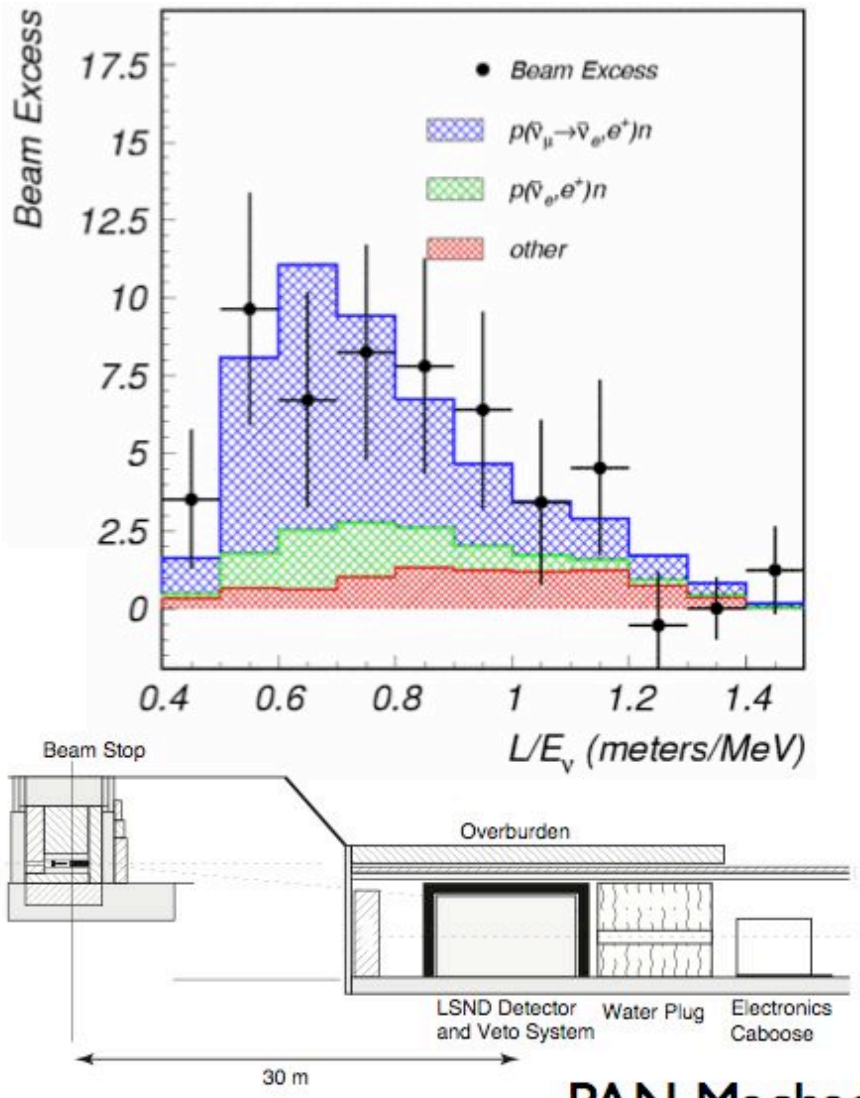
Intense proton beam

$$p + X \to \pi^+ + X'$$

$$\hookrightarrow \mu^+ \nu_\mu \text{ (DAR)}$$

$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

LSND detected more $\bar{\nu}_e$ than expected (3.8σ excess)



MiniBooNE

Fermilab 2002-...

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$$p + X \to \pi^+, \pi^-, \cdots + X'$$

e.g. $\hookrightarrow \mu^+ \nu_\mu$

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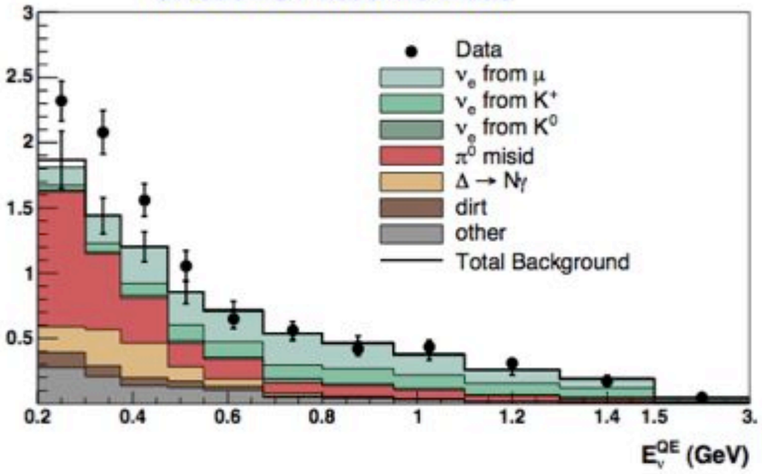
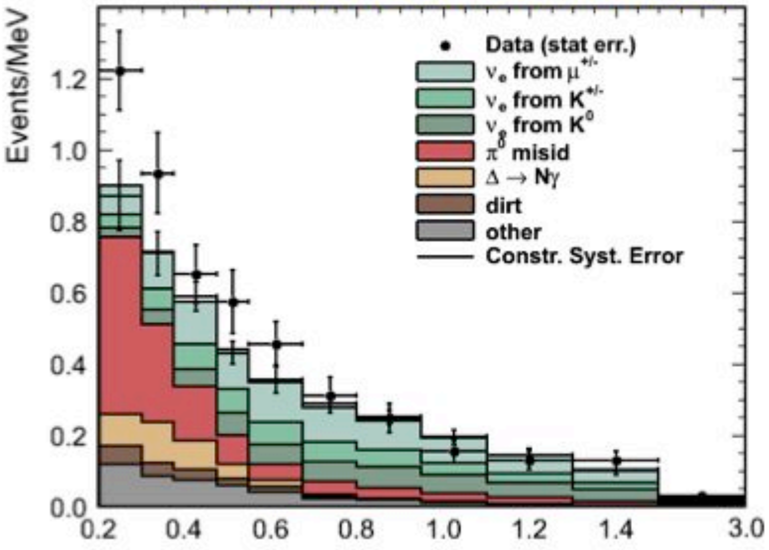
Forget about the past:
Neutrino and antineutrino modes see excesses of ν_e and $\bar{\nu}_e$
(combined is also a 3.8σ excess)


6.7e20 POT neutrino mode


11.3e20 POT anti-neutrino mode

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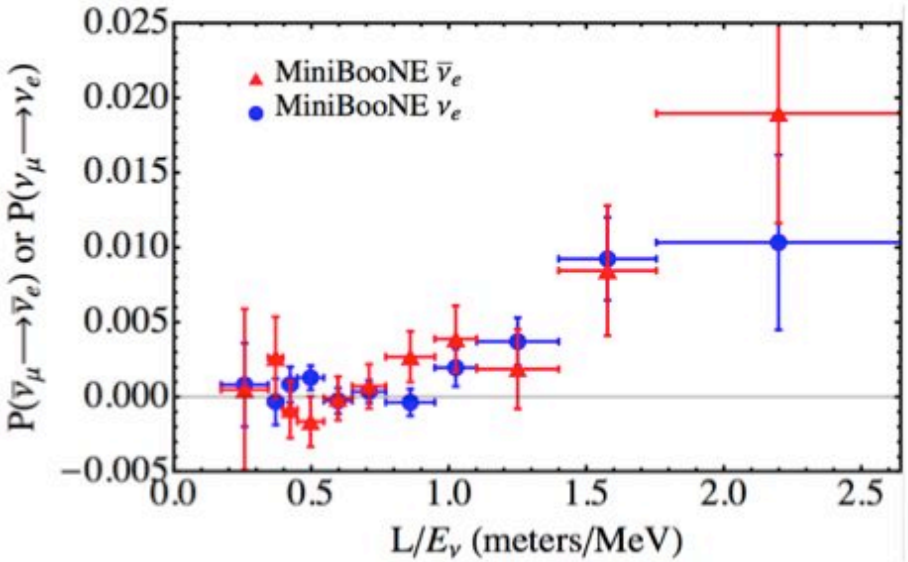
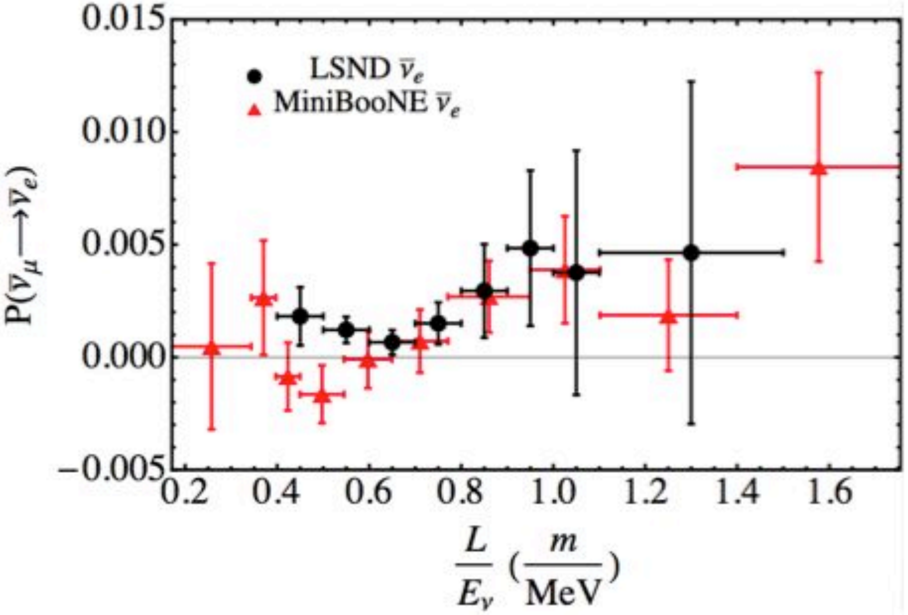
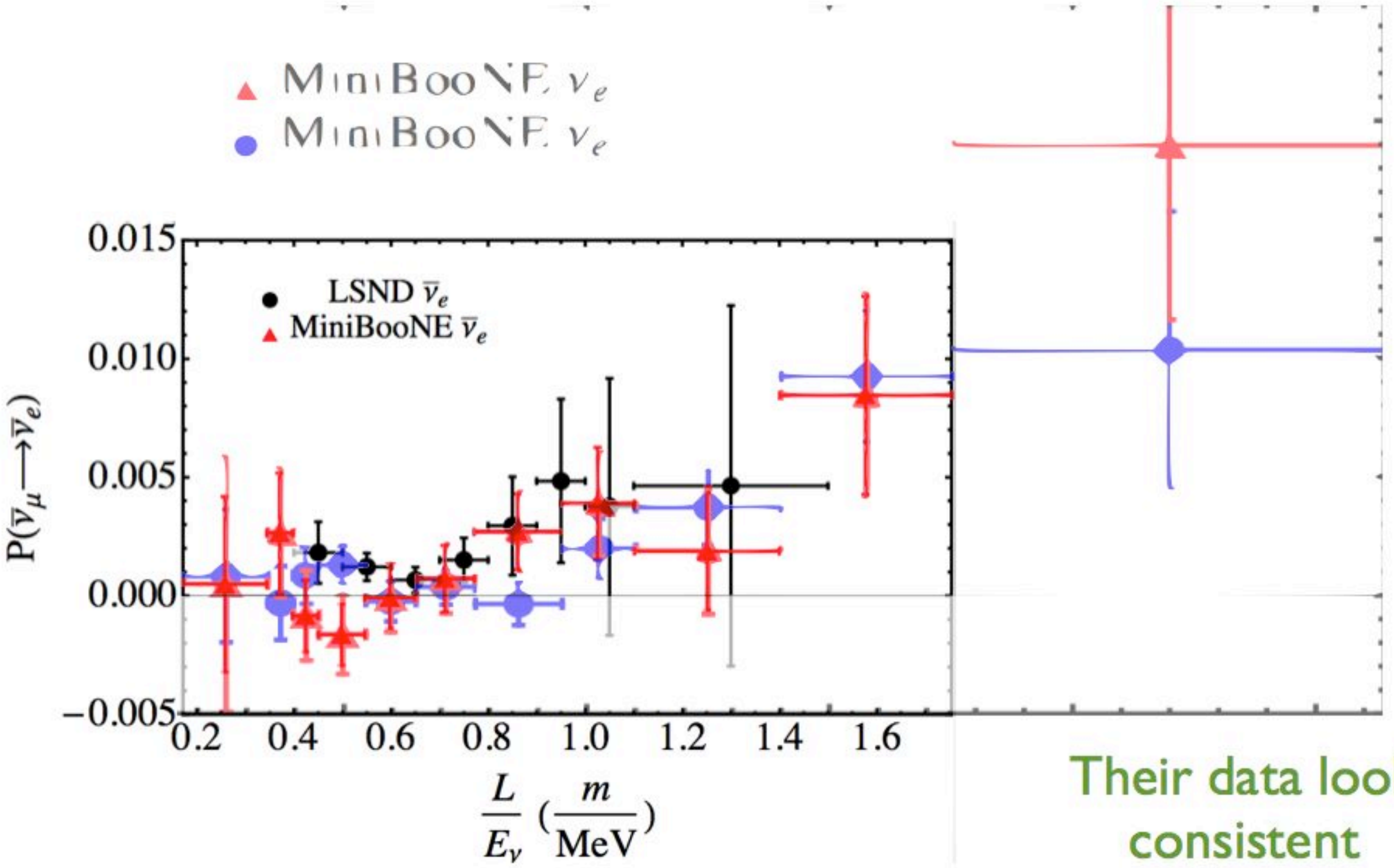




LSND + MiniBooNE



Their data look consistent

Reactor anomaly

Nuclear reactors: electron spectra from ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu are translated to $\bar{\nu}_e$ flux

Schreckenbach 82, 85

A recalculation of fluxes lead to ~ 3% increase

Müller *et al* 2011, Huber 2011

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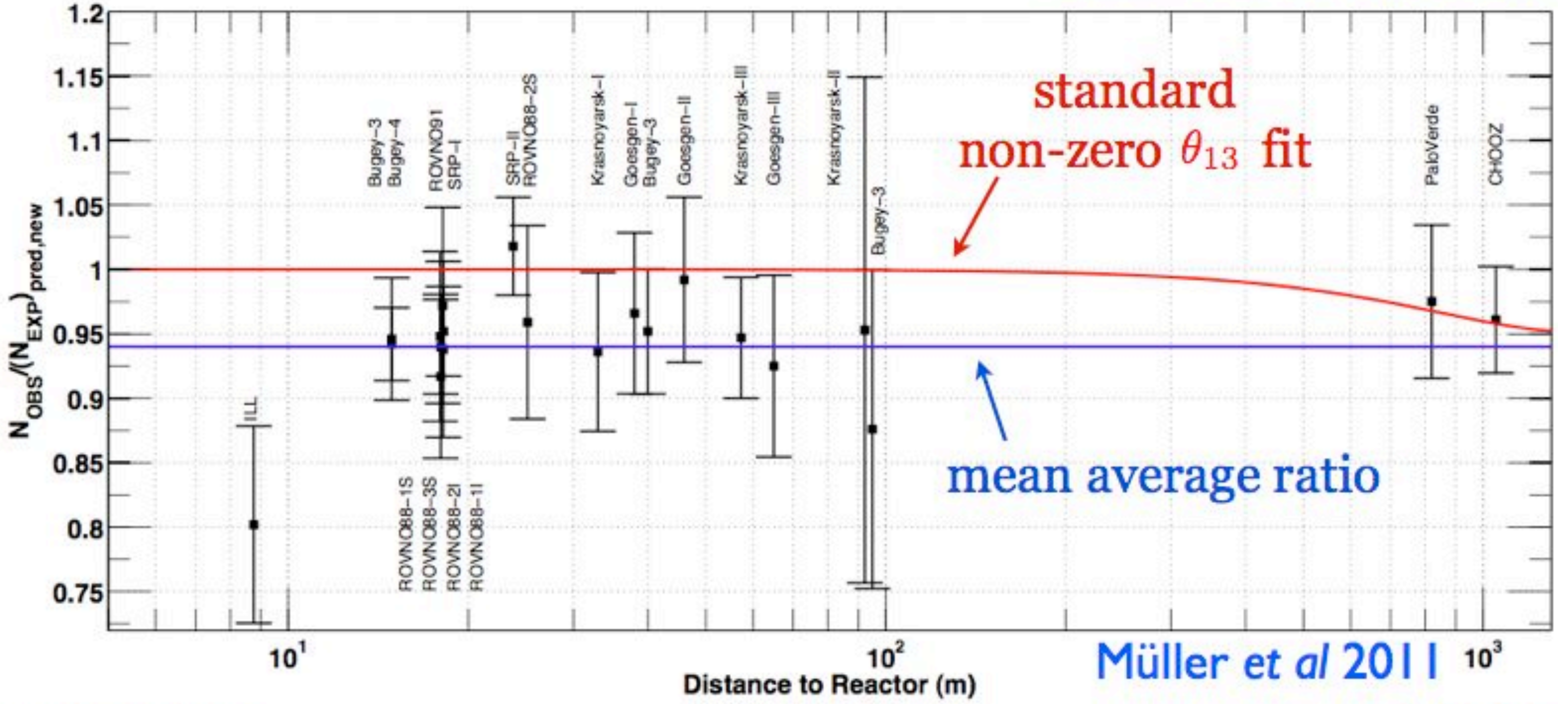

Müller *et al* 2011

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experiment	L [m]	obs/pred	unc. error [%]	tot. error [%]
Bugey4 [66]	15	0.926	1.09	1.37
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KamLAND [78]			17 bins	

We fit the data normalization *f*, taking correlations into account, and find

$$f = 0.935 \pm 0.024$$

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Comparing two hypothesis does not mean a good fit...

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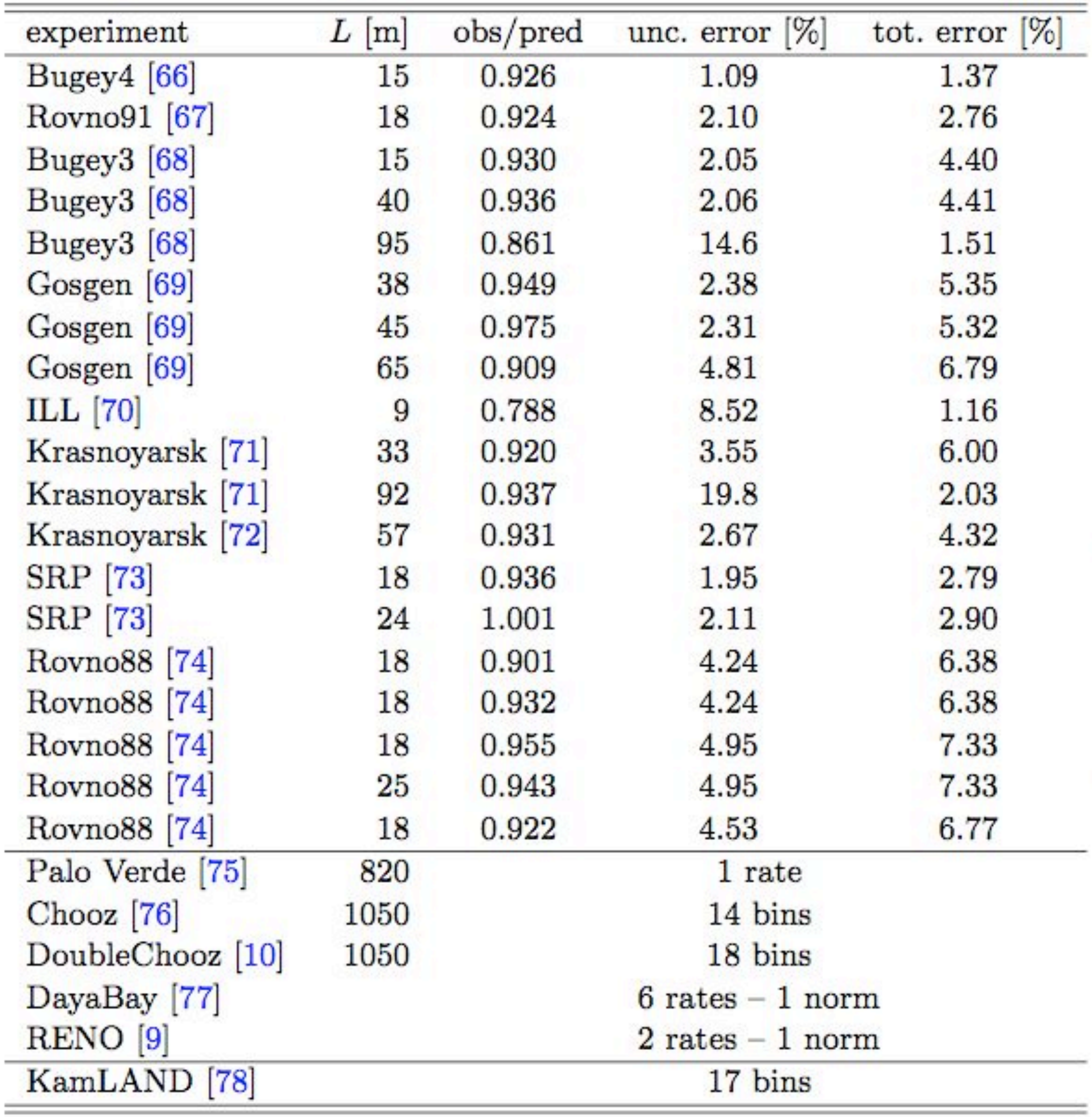

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add *adhoc* normalization error of 2% (3%)reduces the significance to 2.1σ (1.7σ)

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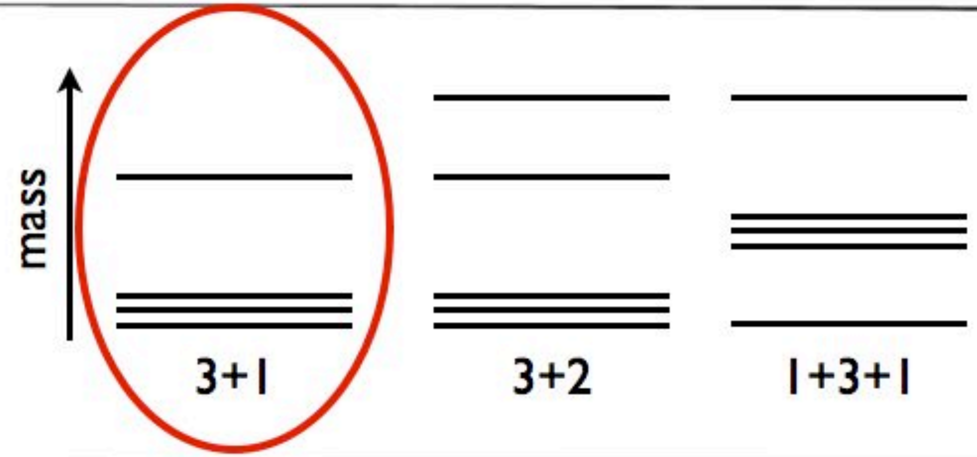
Reactor anomaly

We could explain these anomalies with additional sterile neutrinos such that $\Delta m^2 \sim O(\mathrm{eV}^2)$

We will focus on the 3+1 case



$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \end{pmatrix}$$

$$P_{ee}^{\mathrm{SBL},3+1} = 1 - \overset{\sin^2 2\theta_{14}}{\boxed{4|U_{e4}|^2(1 - |U_{e4}|^2)}} \sin^2 \frac{\Delta m_{41}^2 L}{4E}$$

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SBL reactor rates only analysis:

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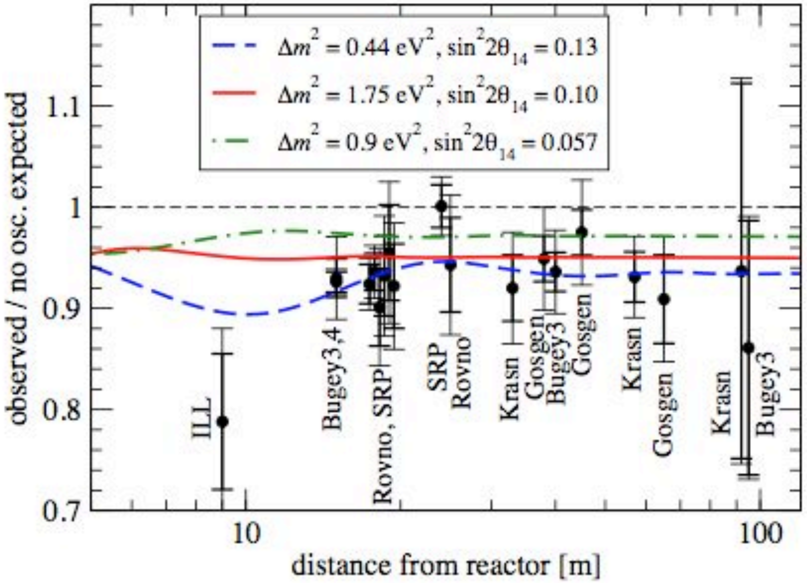

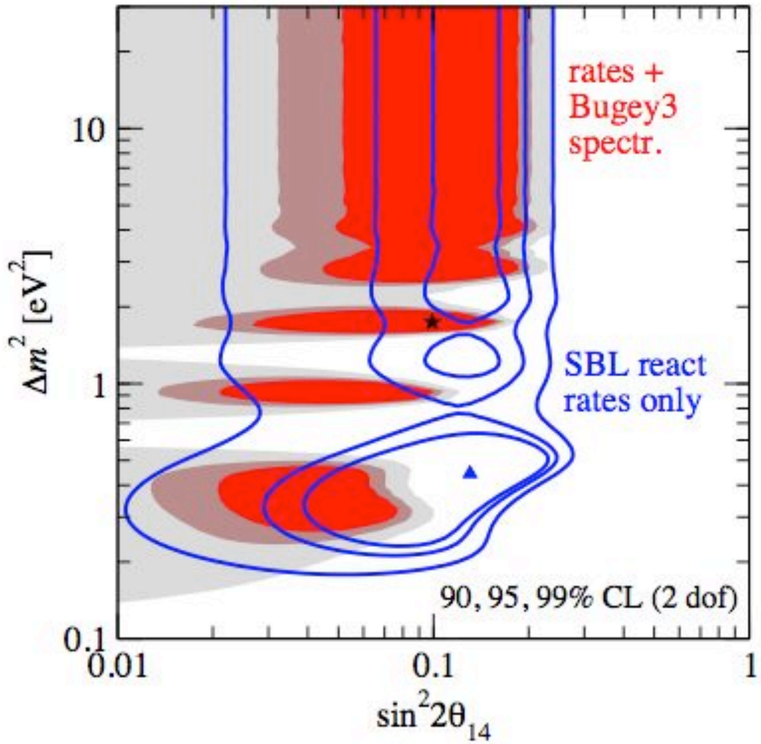

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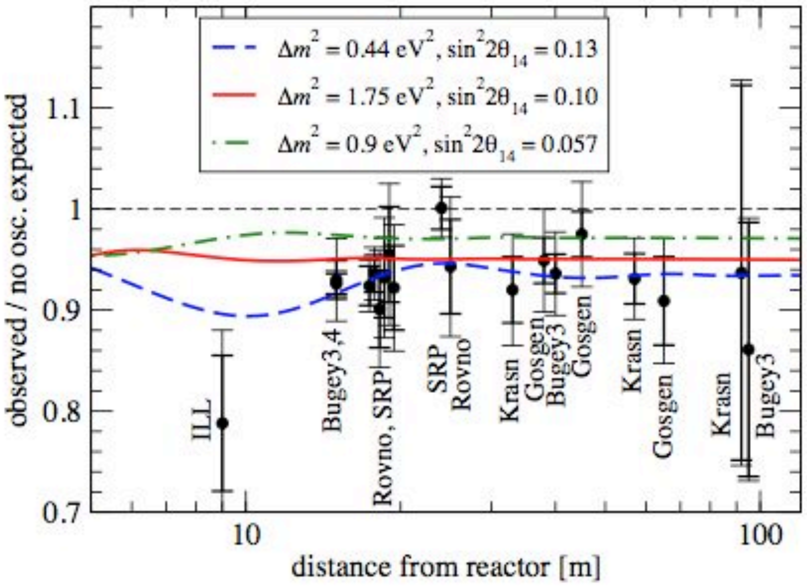

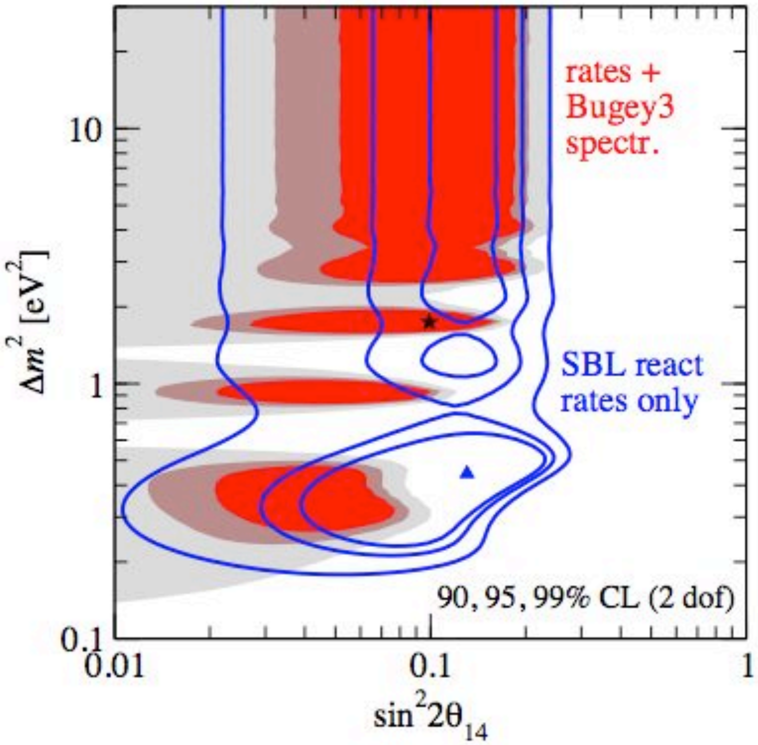

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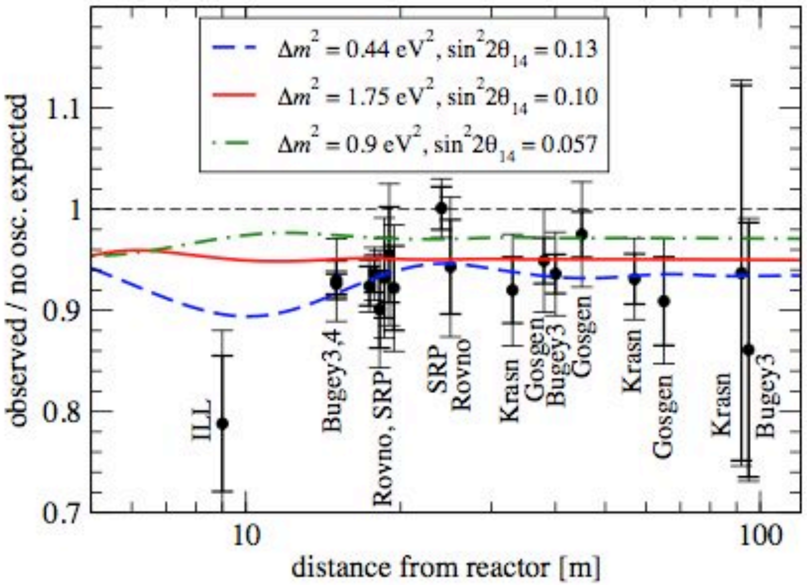

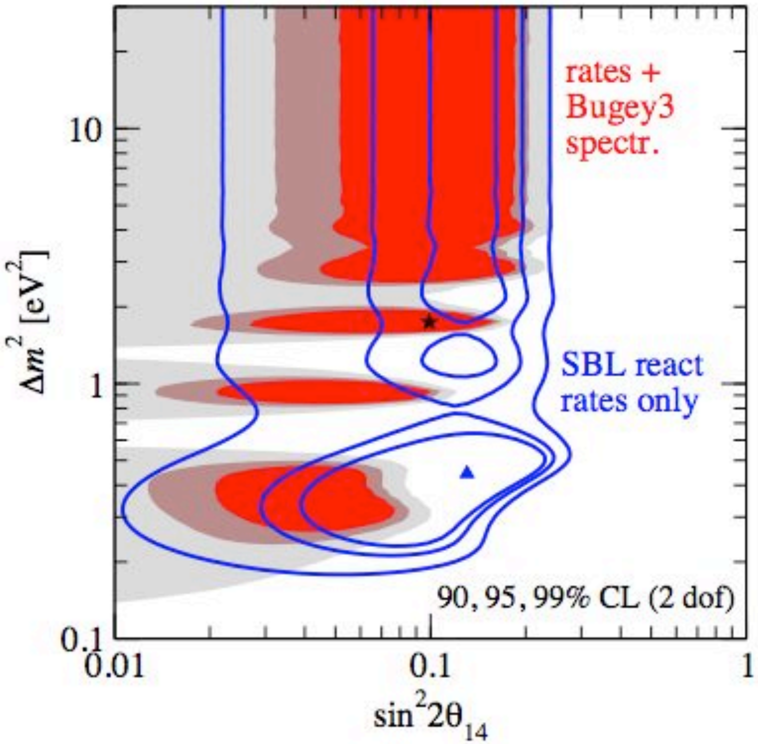

sin²2θ₁₄

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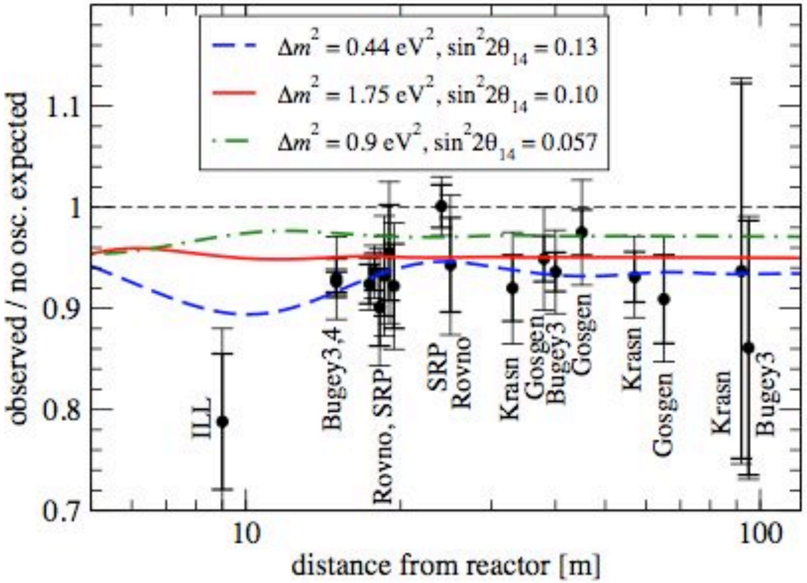
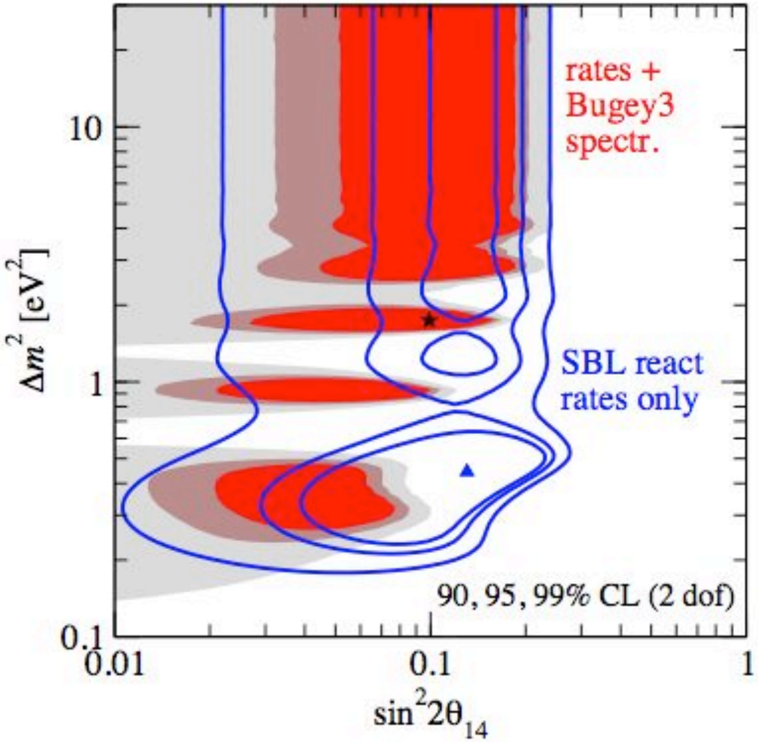




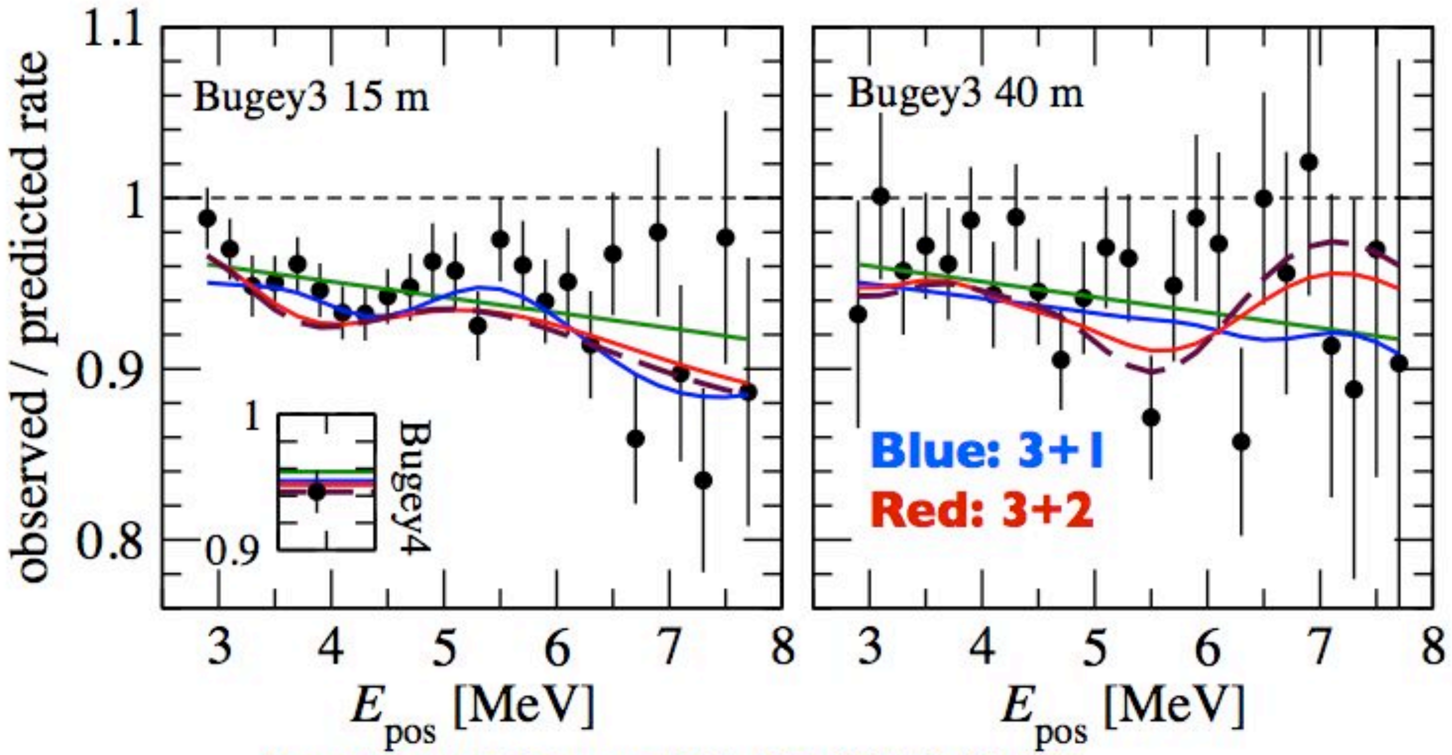
P_{ee}^{S}

SB

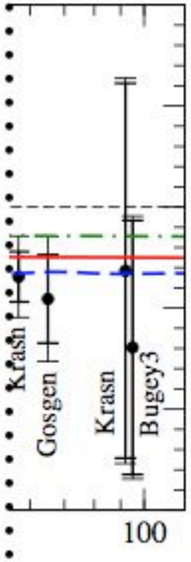
$\sin^2$

$\chi^2_{\rm mi}$

$\Delta\chi^2_{\rm n}$



Kopp Maltoni Schwetz PRL 107 (2011) 091801



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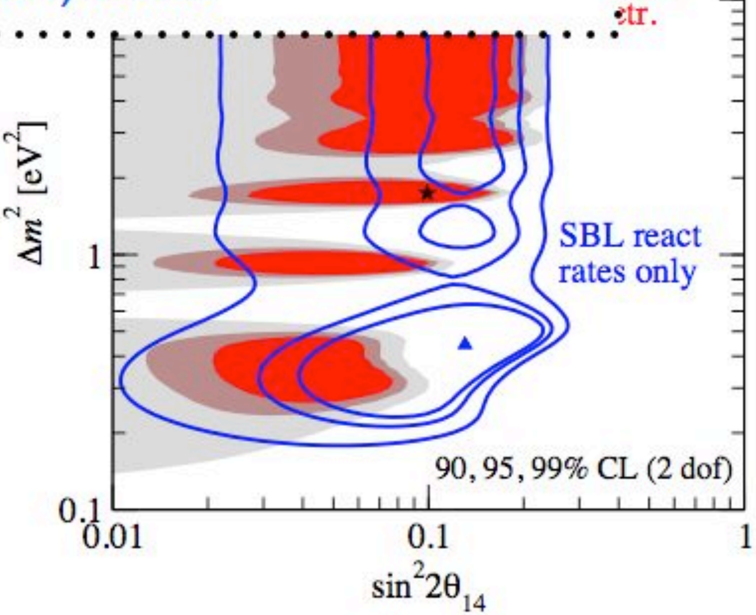
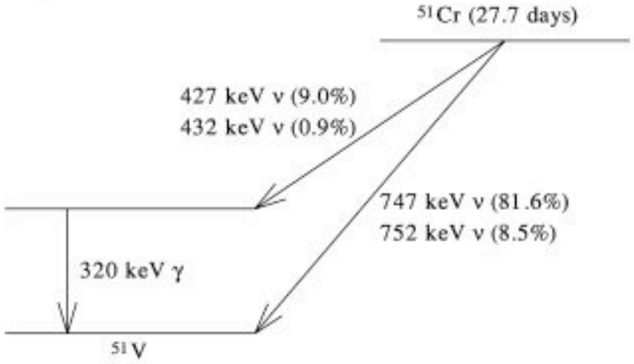


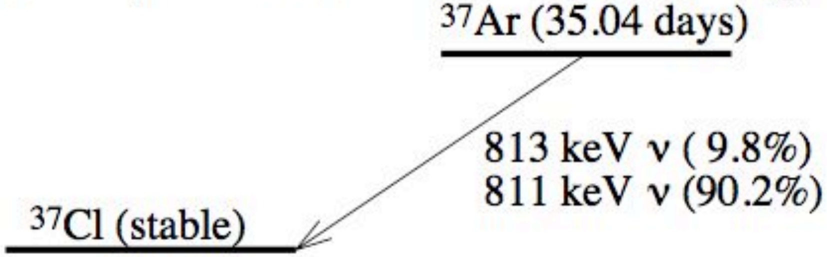
Gallium anomaly

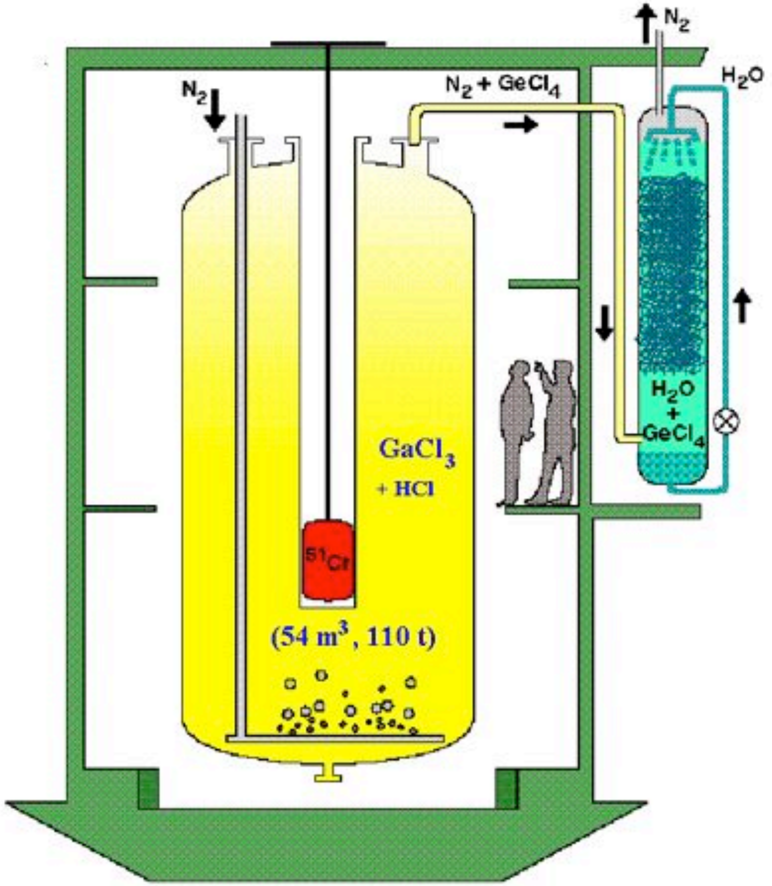
Sources:

$$e^- + {}^{51}\mathrm{Cr} \to {}^{51}\mathrm{V} + \nu_e$$



$$e^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e$$





Hampel *et al* 1998, Kaether *et al* 2010, Abdurashitov *et al* 1998, Abdurashitov *et al* 2005

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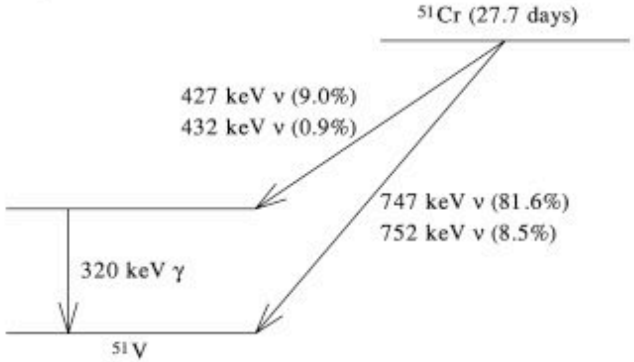
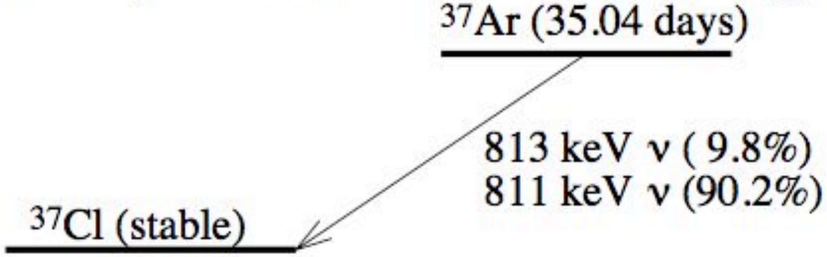
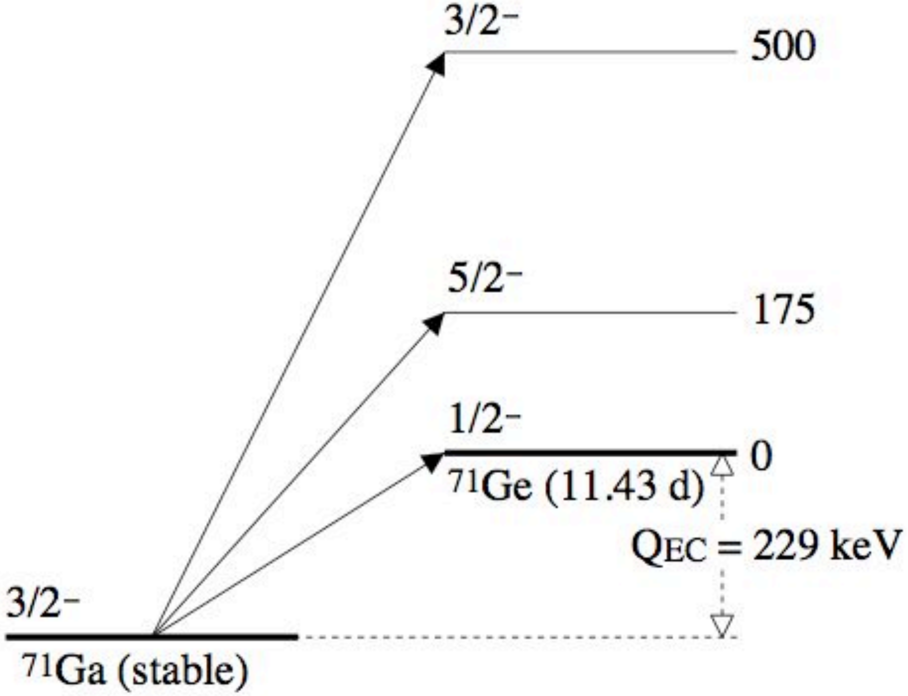


$$e^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e$$



Detection:

$$\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + \mathrm{e}^-$$



Hampel *et al* 1998, Kaether *et al* 2010, Abdurashitov *et al* 1998, Abdurashitov *et al* 2005

Gallium anomaly

Detection process can occur thru ground state or excited state

$$\sigma(X) = \sigma_{\mathrm{g.s.}}(X)\left(1 + a_X \frac{\mathrm{BGT}_{175}}{\mathrm{BGT}_{\mathrm{g.s.}}} + b_X \frac{\mathrm{BGT}_{500}}{\mathrm{BGT}_{\mathrm{g.s.}}}\right)$$

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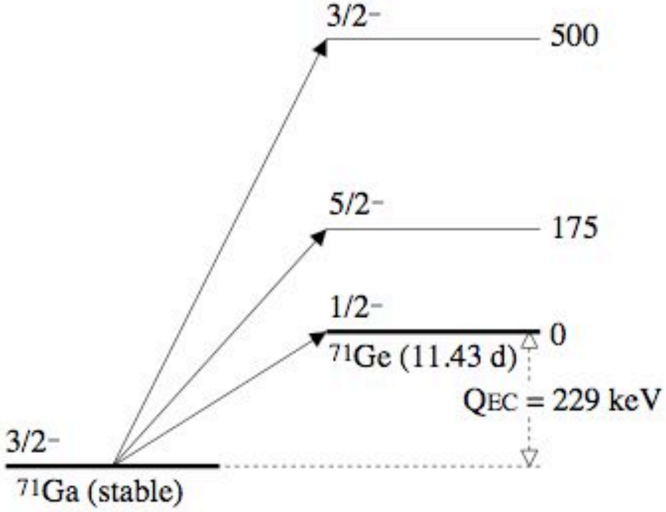

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ground state σ is well known

Gamow-Teller strength (large errors...)

See Frekers *et al* 2010

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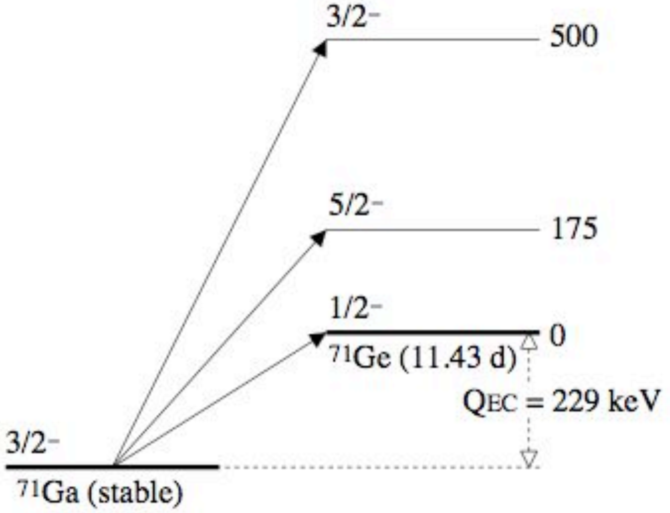

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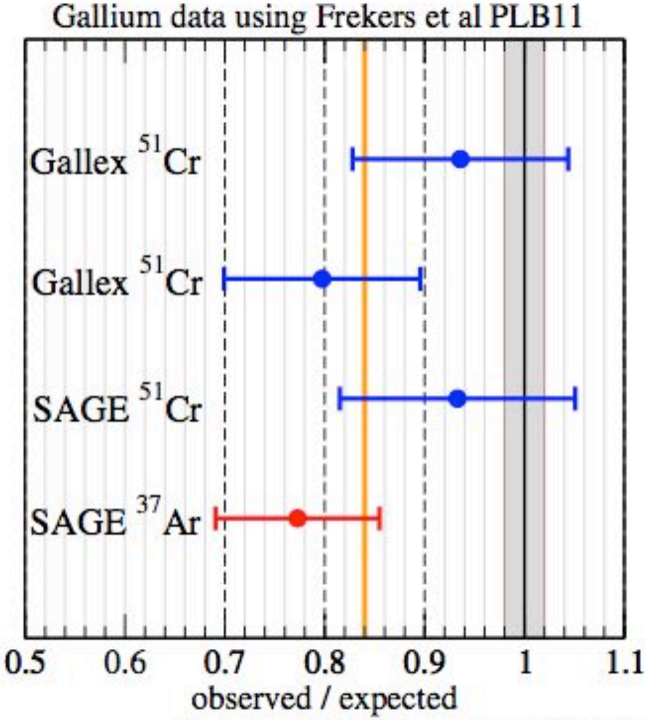

Schwetz@Neutrino 2012

$$R_1(\mathrm{Cr}) = 0.94 \pm 0.11 \quad R_3(\mathrm{Cr}) = 0.93 \pm 0.12$$

$$R_2(\mathrm{Cr}) = 0.80 \pm 0.10 \quad R_4(\mathrm{Ar}) = 0.77 \pm 0.08$$

See also Acero Giunti Laveder 2007, Giunti Laveder 2010

Gallium anomaly

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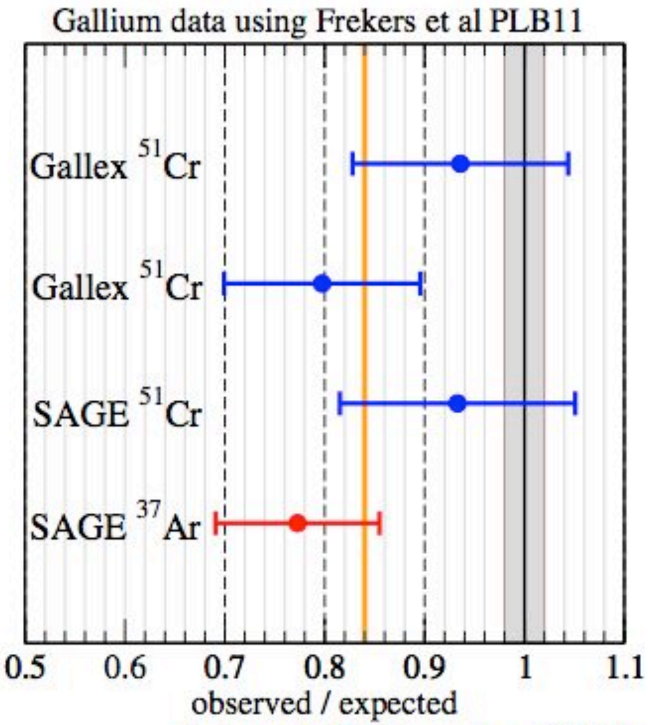

Schwetz@Neutrino 2012

$$r_{\text{min}} = 0.84^{+0.054}_{-0.051}$$

$$\chi^2_{\text{min}} = 2.26/3\,\text{dof} \qquad \Delta\chi^2_{r=1} = 8.72 \quad (2.95\sigma)$$

Compared to Giunti Laveder 2010, ratio is now higher, while significance is comparable

Gallium anomaly

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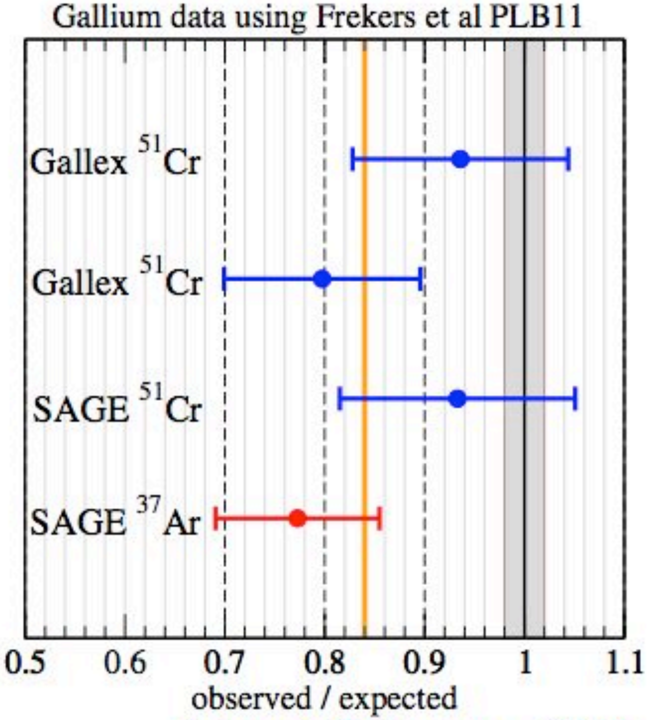

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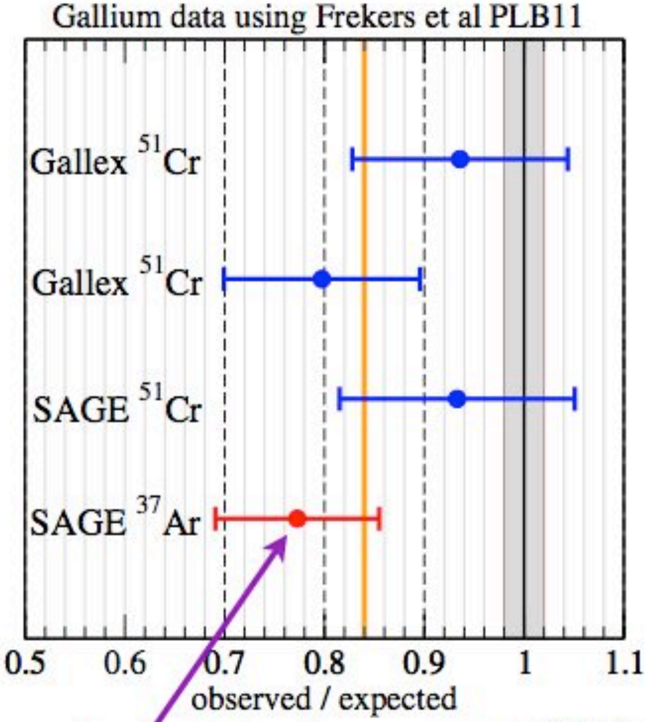

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ground state σ is well known

Gamow-Teller strength (large errors...)

See Frekers *et al* 2010

Depends on ^{37}Ar data point (1.8σ without it)

2012

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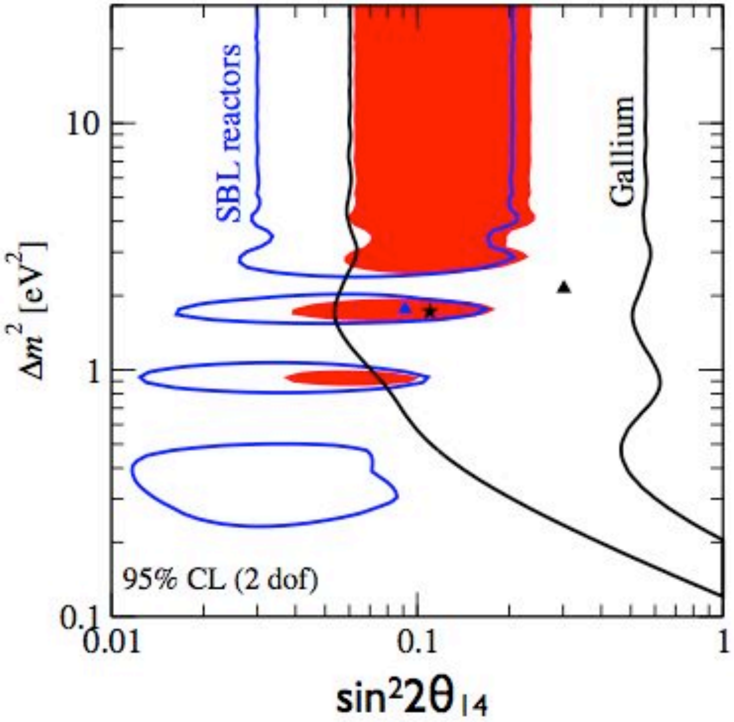
Reactor + Ga + ...

Ga + SBL reactor rates
+ Bugey-3 spectra:

Consistent!
What about other exps?

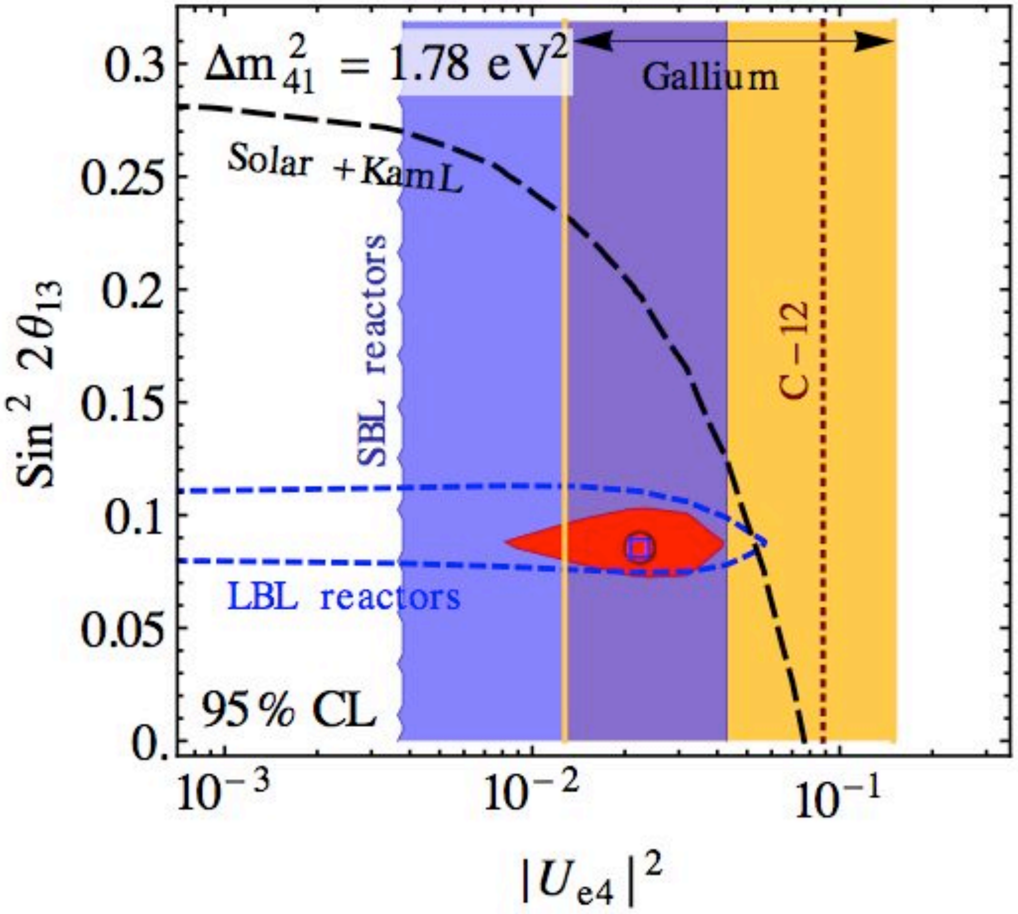


Reactor + Ga + ...

LSND and KARMEN measured $\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$

Solar neutrinos + KamLAND + Reactor MBL:
$\theta_{13} - \theta_{14}$ interplay and non-trivial bound

Reactor + Ga + ...


$\Delta m^2_{41} = 1.78$ eV^2
Gallium
Solar +KamL
SBL reactors
C−12
LBL reactors
95% CL
$\sin^2 2\theta_{13}$
0.3
0.25
0.2
0.15
0.1
0.05
0.
10^{-3}
10^{-2}
10^{-1}
$|U_{e4}|^2$

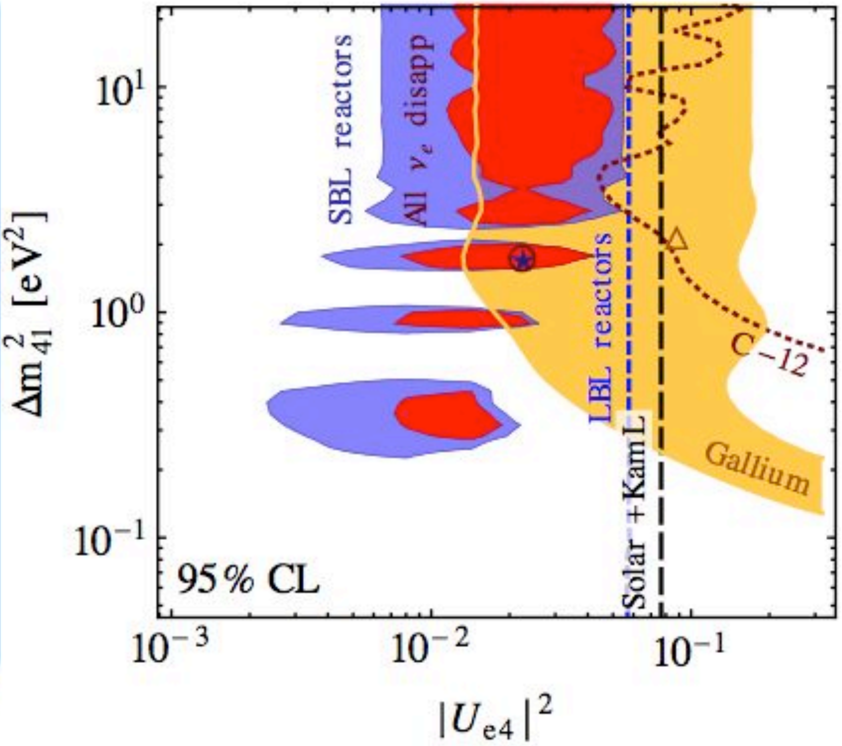
Reactor + Ga + ...

Global ν_e disappearance:

$$\sin^2\theta_{14} = 0.10 \quad \Delta m^2_{41} = 1.71\ \mathrm{eV}^2$$

$$\chi^2_{\mathrm{min}}/\mathrm{dof} = 306/329$$

$$\Delta\chi^2_{\text{no-osc}} = 12.4 \quad (99.8\%, 3.1\sigma)$$



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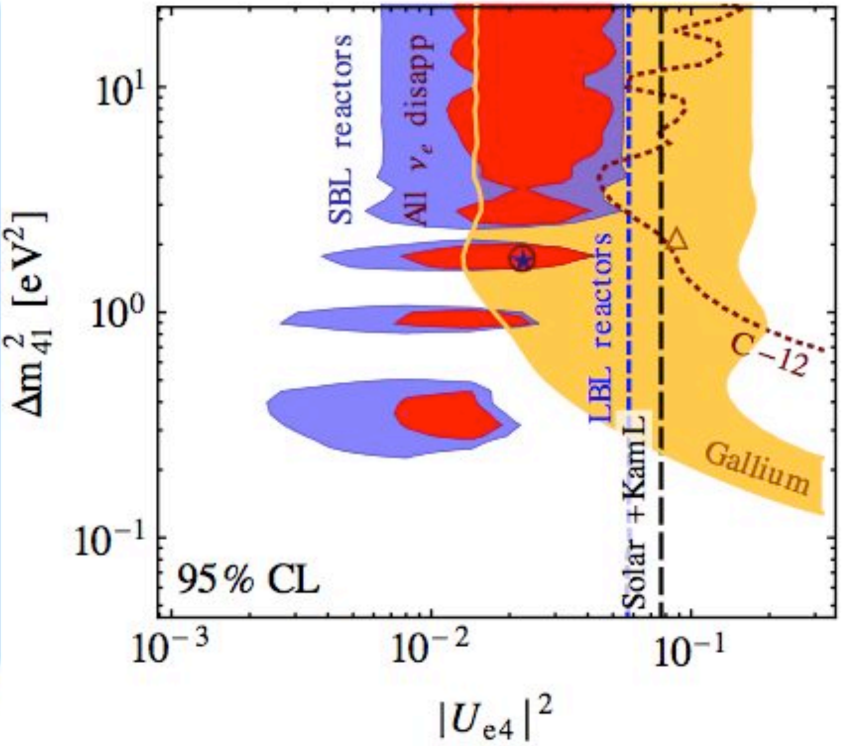
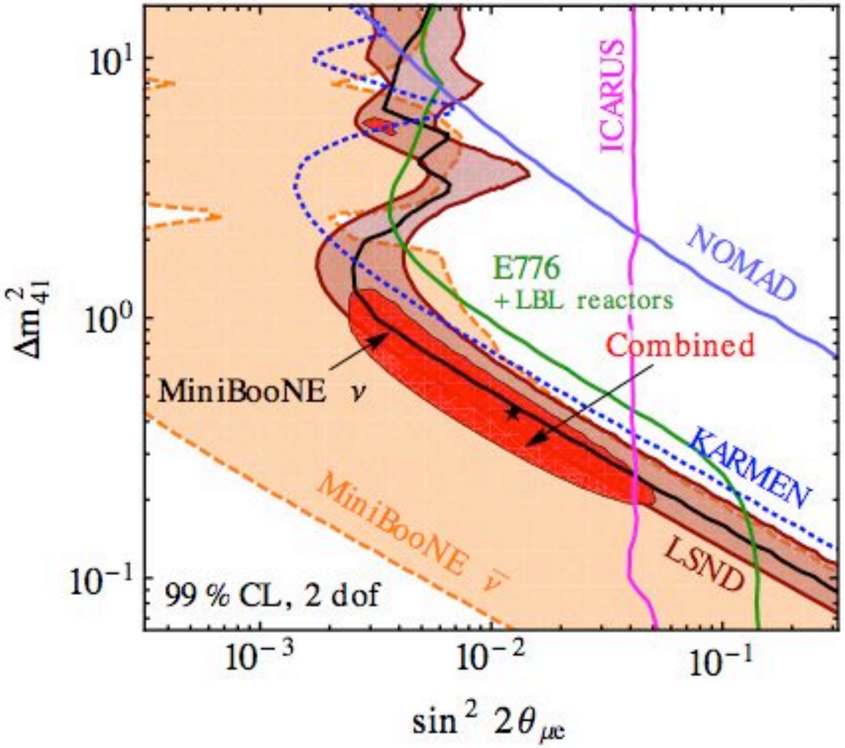


Yay! Still consistent!!

MB+LSND+app

$$P^{\mathrm{SBL},3+1}_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4\underbrace{|U_{\mu 4}U_{e4}|^2}_{\sin^2 2\theta_{\mu e}} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

LSND and MiniBooNE are consistent among themselves, as well as with the other appearance experiments



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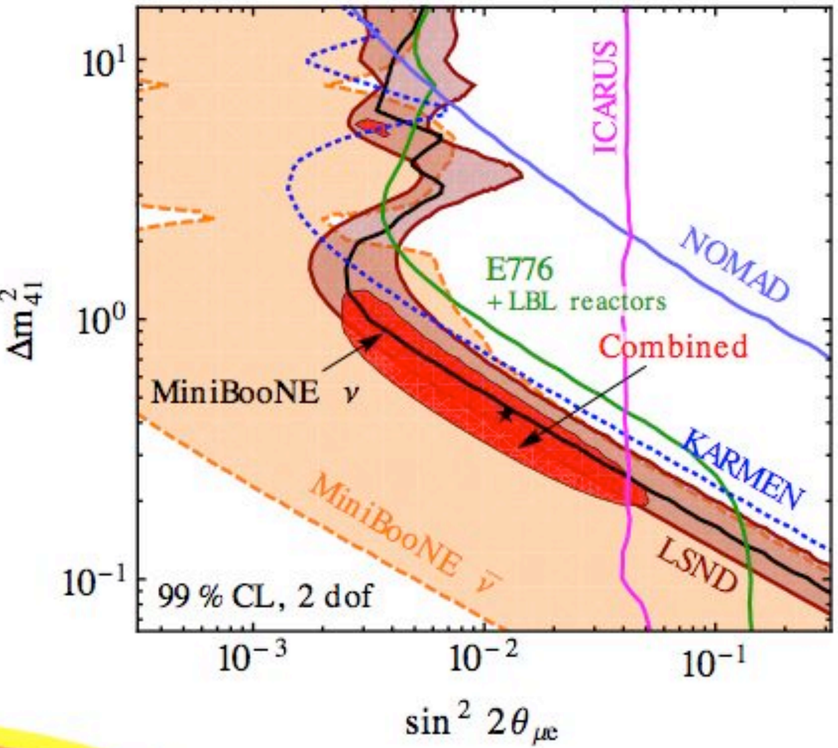
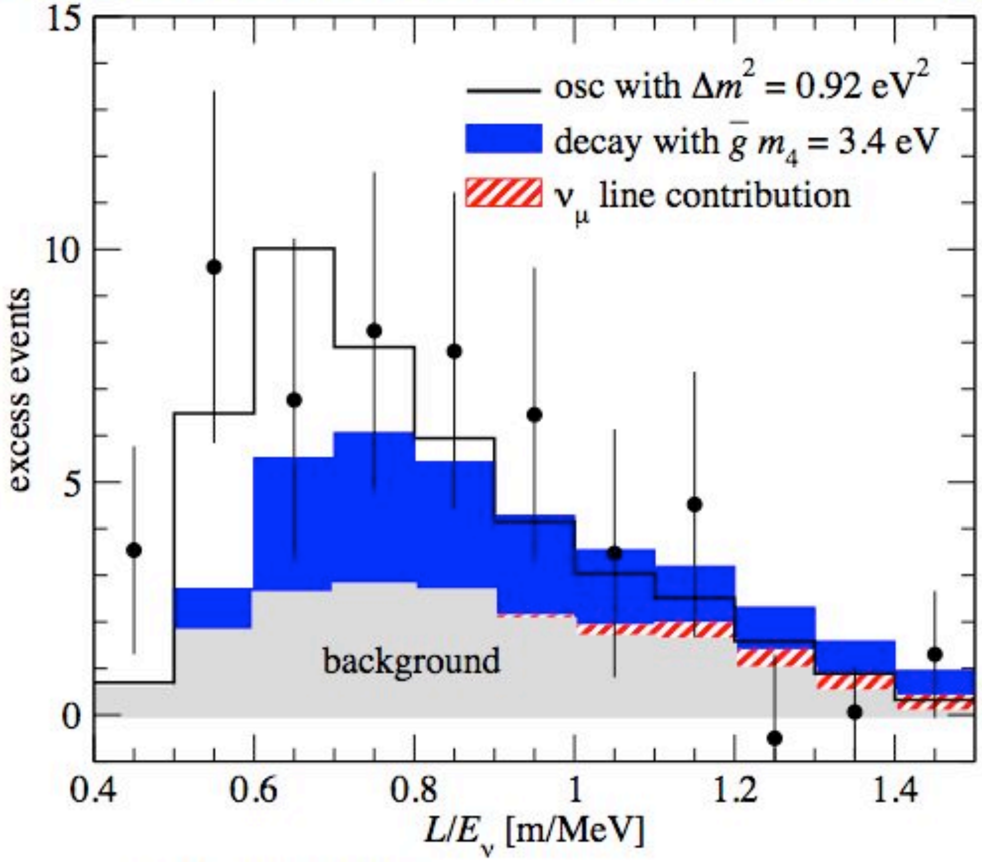


but does it look like neutrino oscillation?



LSND

Palomares-Ruiz Pascoli Schwetz
JHEP 0509 (2005) 048

experiments

10^{-3} 10^{-2} 10^{-1}

$\sin^2 2\theta_{\mu e}$

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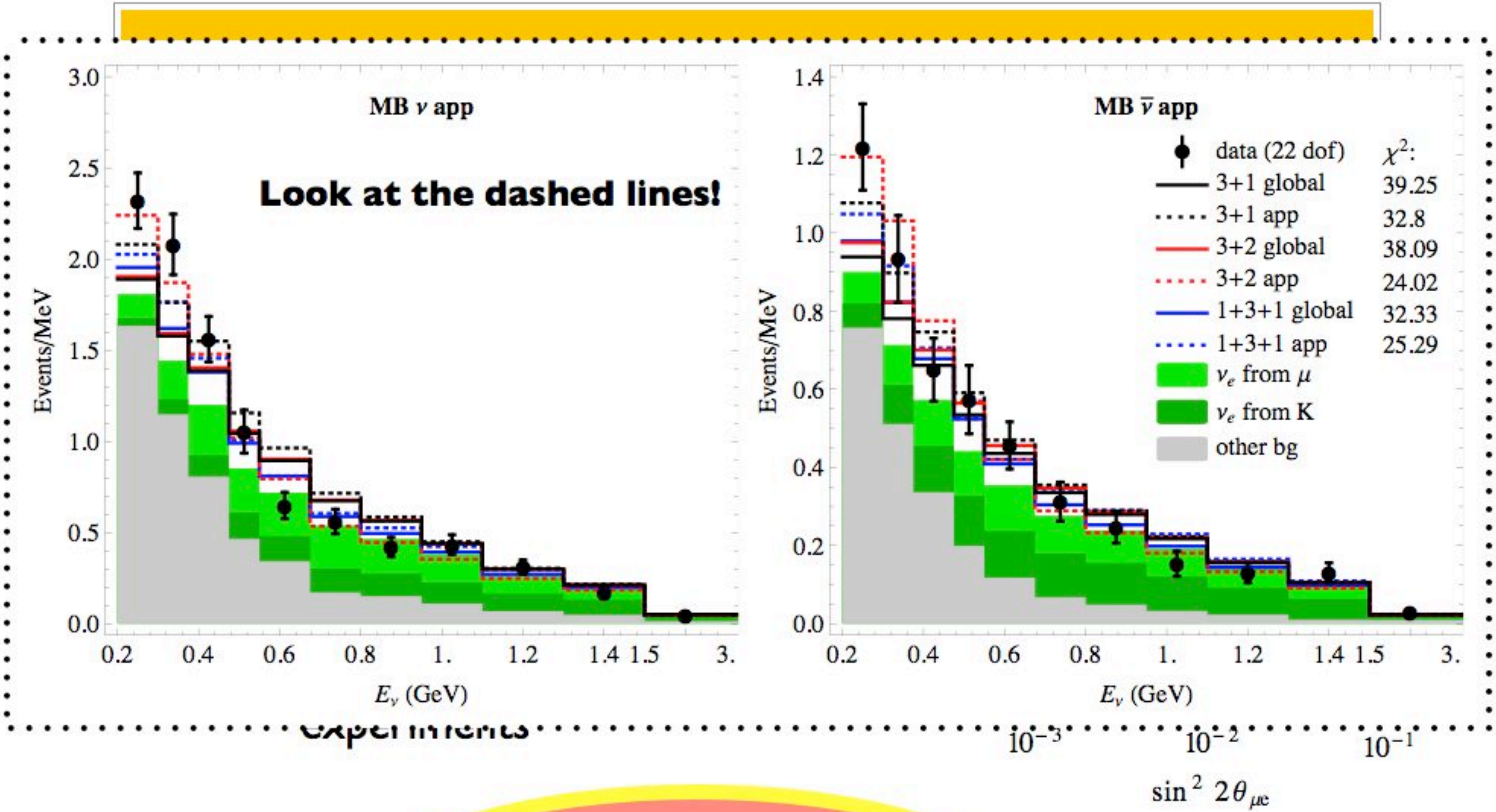


Look at the dashed lines!

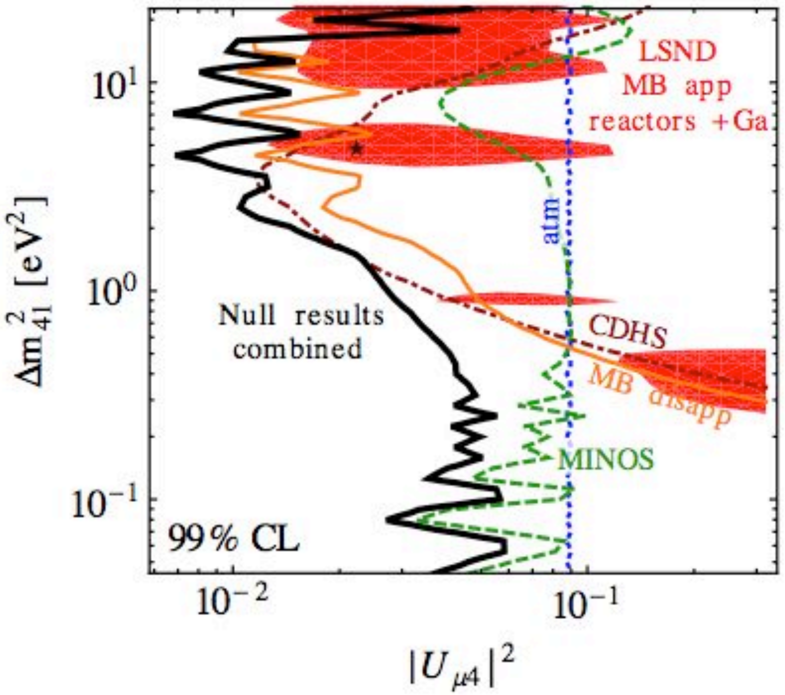
but does it look like neutrino oscillation?

ν_μ disapp bounds

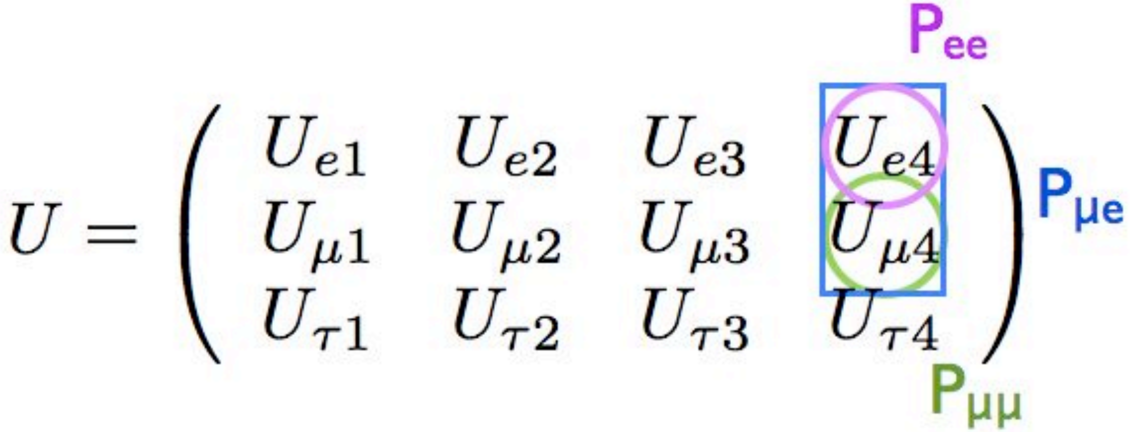
$$P_{\mu\mu}^{\mathrm{SBL},3+1} = 1 - 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)\sin^2\frac{\Delta m_{41}^2 L}{4E}$$

We combined with reactor and Ga to set a limit on U_{e4}

The ν_μ disappearance experiments are consistent with the 3 neutrino paradigm



All together now



P_{ee}

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \end{pmatrix}$$

$P_{\mu e}$

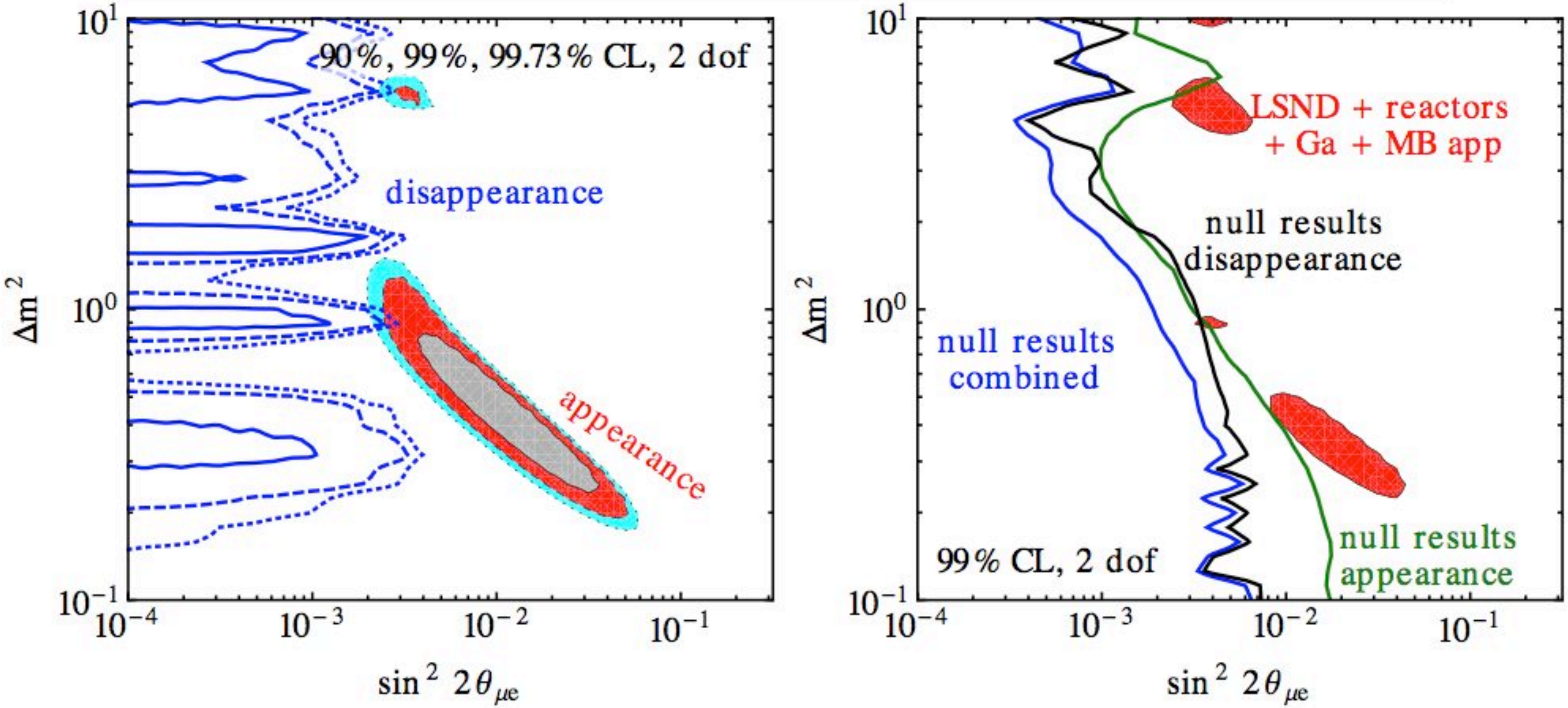
$P_{\mu\mu}$

For large Δm^2, ν_e disappearance depends on U_{e4}

For large Δm^2, ν_μ disappearance depends on $U_{\mu 4}$

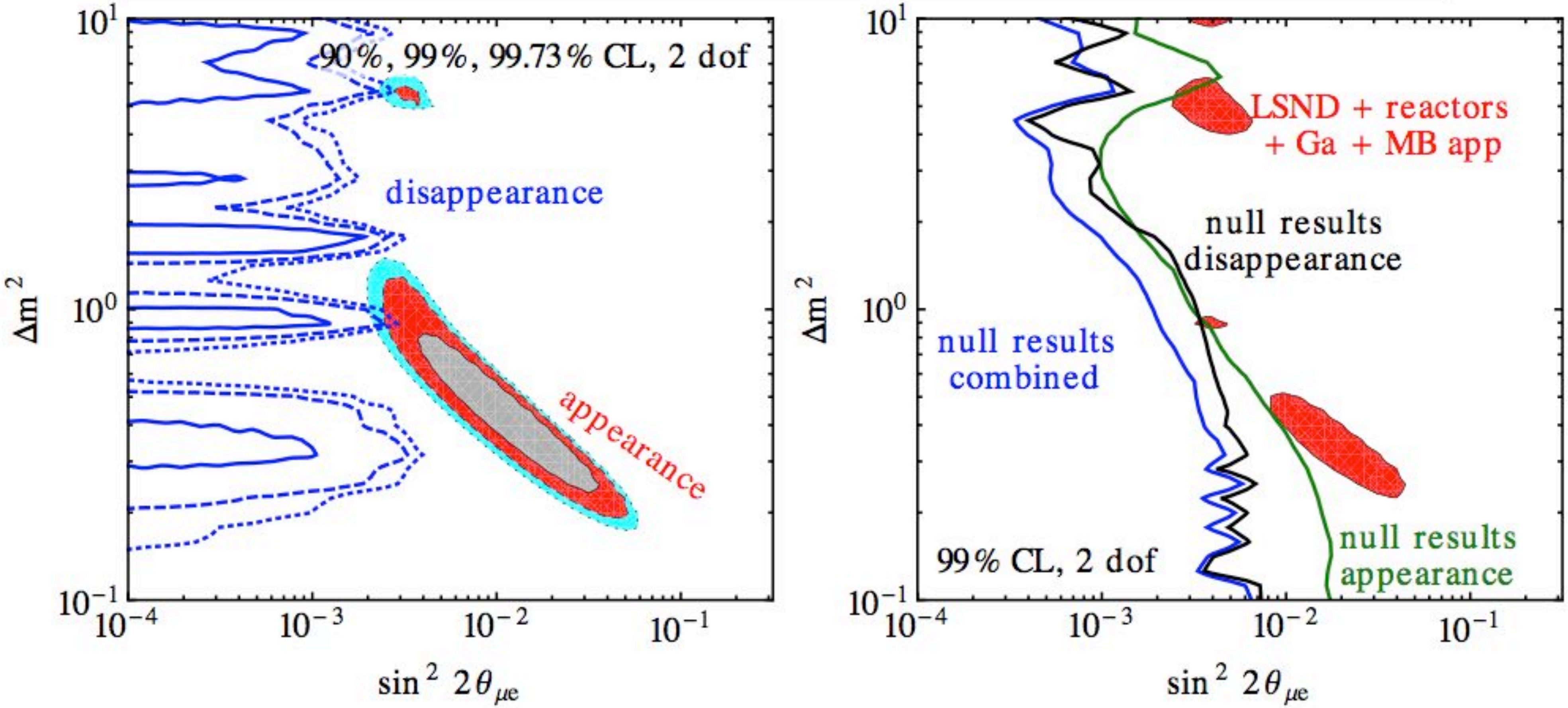
For large Δm^2, ν_e appearance depends on $U_{e4}U_{\mu 4}$

All together now



The app data is in **conflict** with the disapp data, specially ν_μ!

All together now



	$\chi^2_{\mathrm{min}}/\mathrm{dof}$	GOF	$\chi^2_{\mathrm{PG}}/\mathrm{dof}$	PG	$\chi^2_{\mathrm{app,glob}}$	$\Delta\chi^2_{\mathrm{app}}$	$\chi^2_{\mathrm{dis,glob}}$	$\Delta\chi^2_{\mathrm{dis}}$
3+1	712/(689 − 9)	19%	18,0/2	$1{,}2 \times 10^{-4}$	95,8/68	7,9	616/621	10,1

3+2 and 1+3+1

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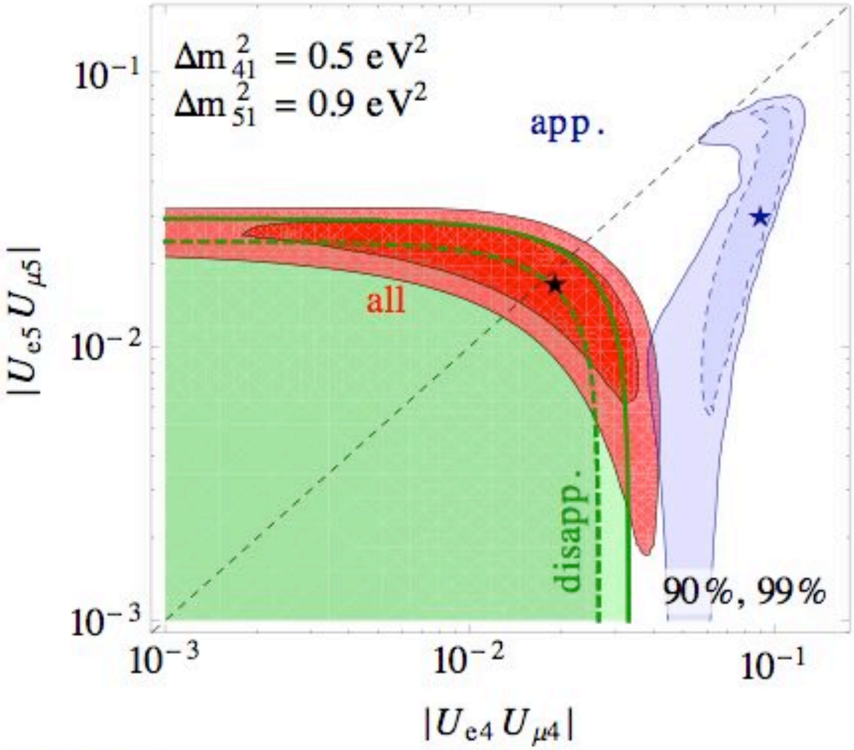
3+2	$701/(689-14)$	23%	25,8/4	$3{,}4\times10^{-5}$	92,4/68	19,7	609/621	6,1
1+3+1	$694/(689-14)$	30%	16,8/4	$2{,}1\times10^{-3}$	82,4/68	7,8	611/621	9,0

3+2: no qualitative improvement, just more free parameters

1+3+1: slightly improvement, but PG value still small

Regarding steriles, looks like this tension cannot be avoided. More neutrinos do not improve the fit, just add more free parameters



see, e.g., Karagiorgi, Shaevitz, Conrad AHEP (2013) 163897

3+2 and 1+3+1

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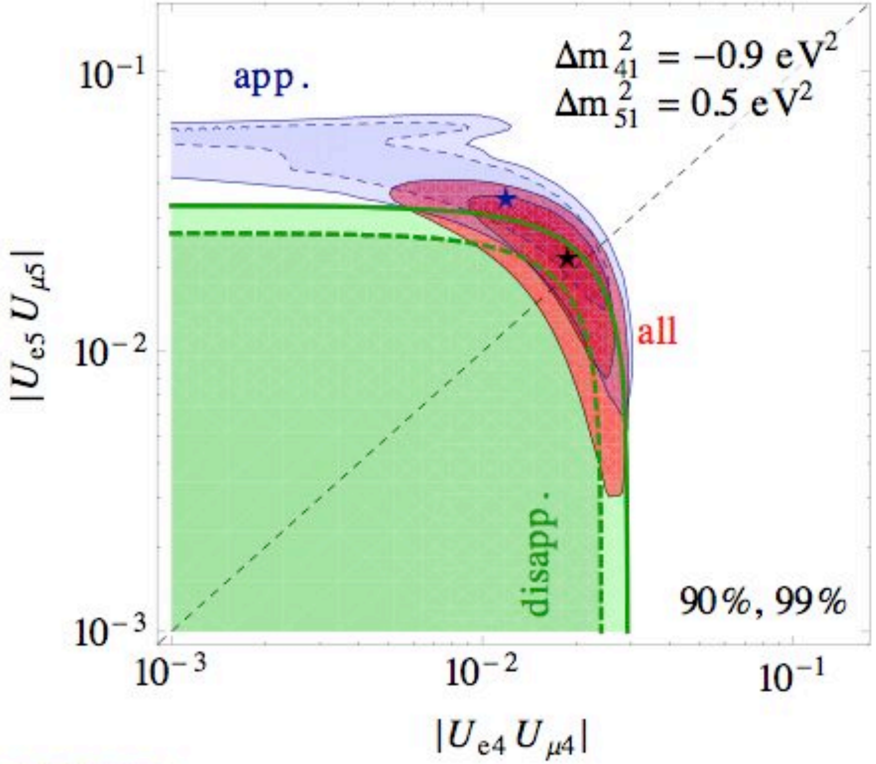
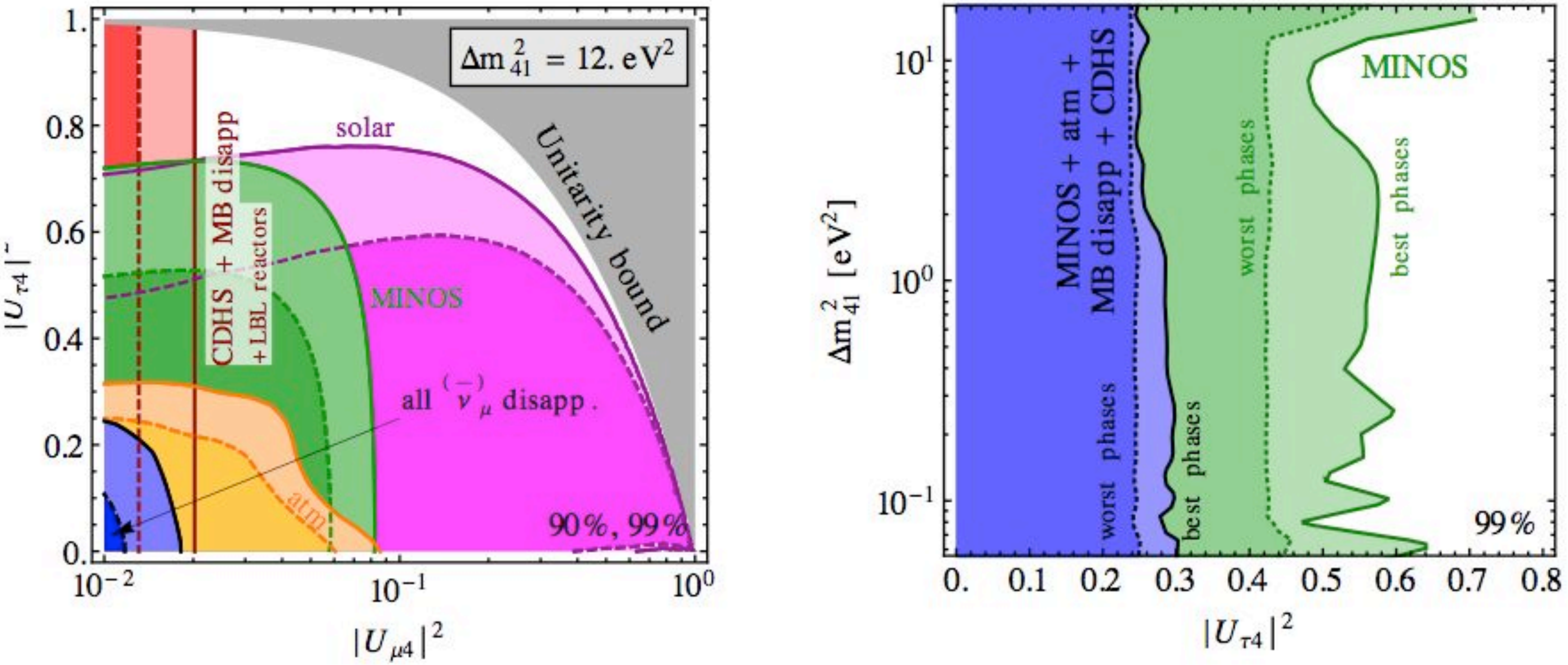


see, e.g., Karagiorgi, Shaevitz, Conrad AHEP (2013) 163897

PAN Machado

Bounds on U_{t4}

Dominated by atmospheric data



$$|U_{\tau4}|^2 \lesssim 0.2 \quad \text{at} \quad 2\sigma\,(1\ \text{dof})$$

Conclusions

[

We want wiggles!!!

]

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There is a strong tension between app and disapp data

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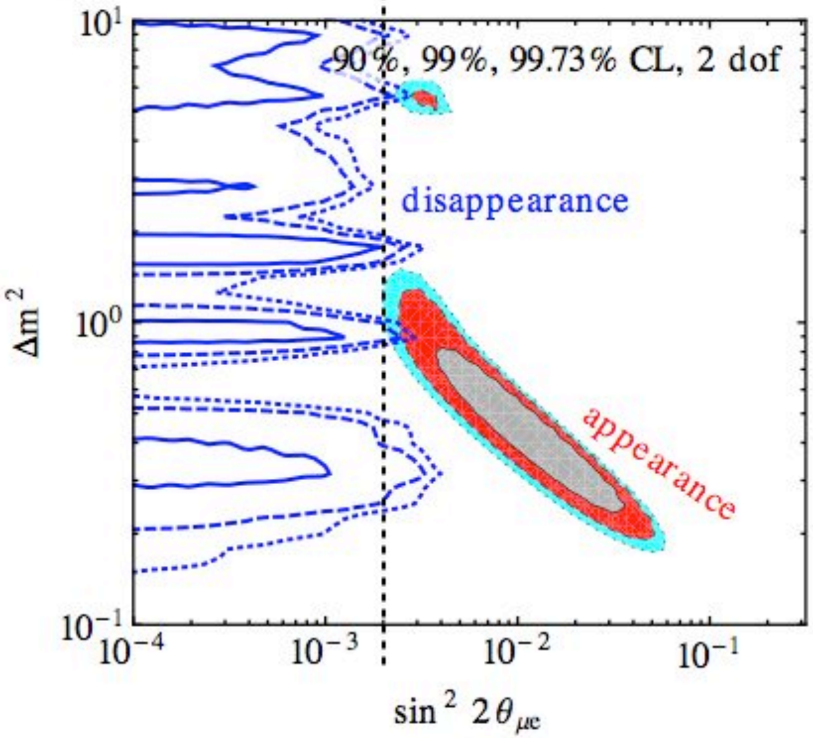
See also Maltoni Schwetz 2007, Kopp Maltoni Schwetz 2010, Giunti Laveder 2011
Giunti et al 2013
Karagiorgi Shaevitz Conrad 2012 ...

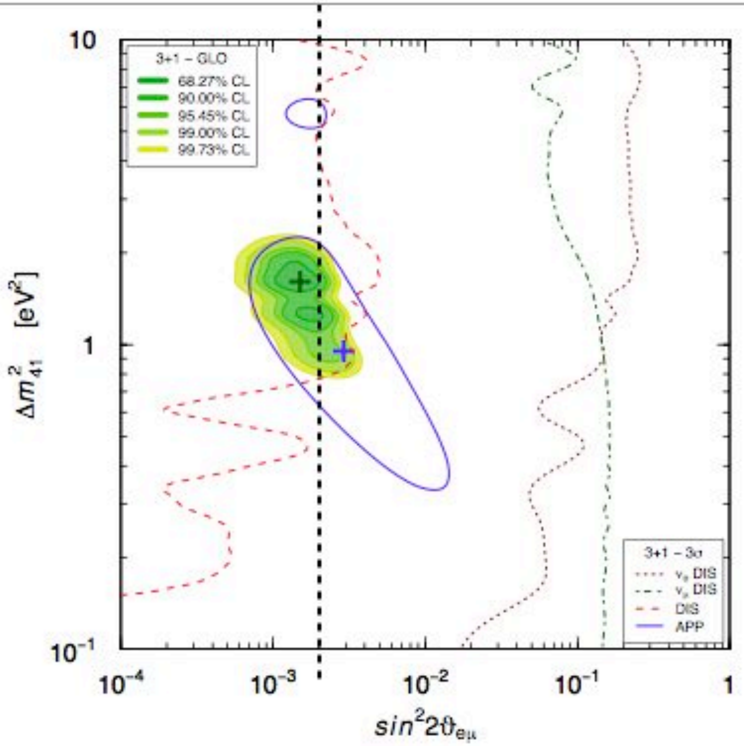
Merci!

Backup

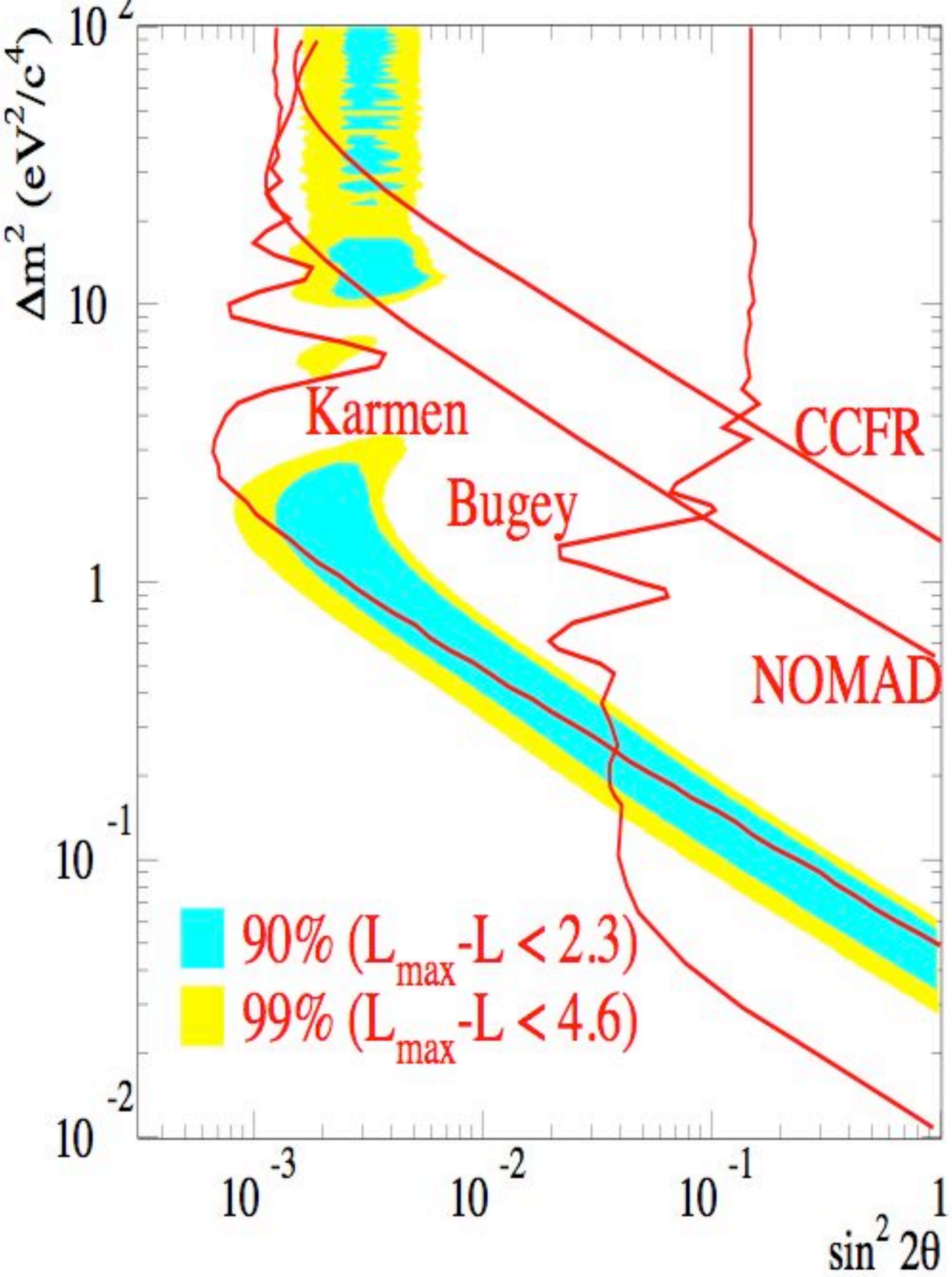
Differences between Giunti et al and our fit



Kopp et al 2013



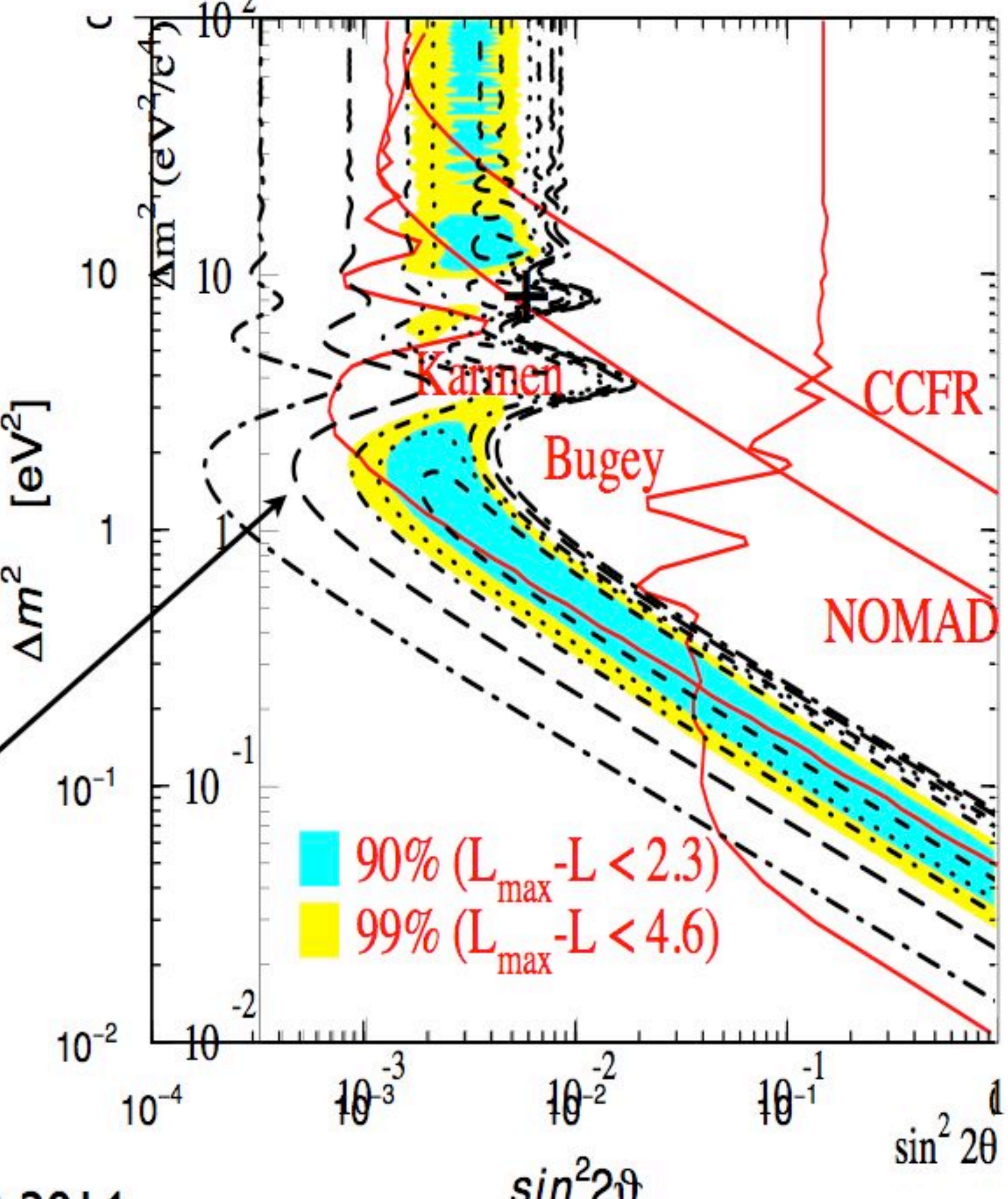
Giunti et al 2013



LSND final result
hep-ex/0104049

LSND final result:
hep-ex/0104049

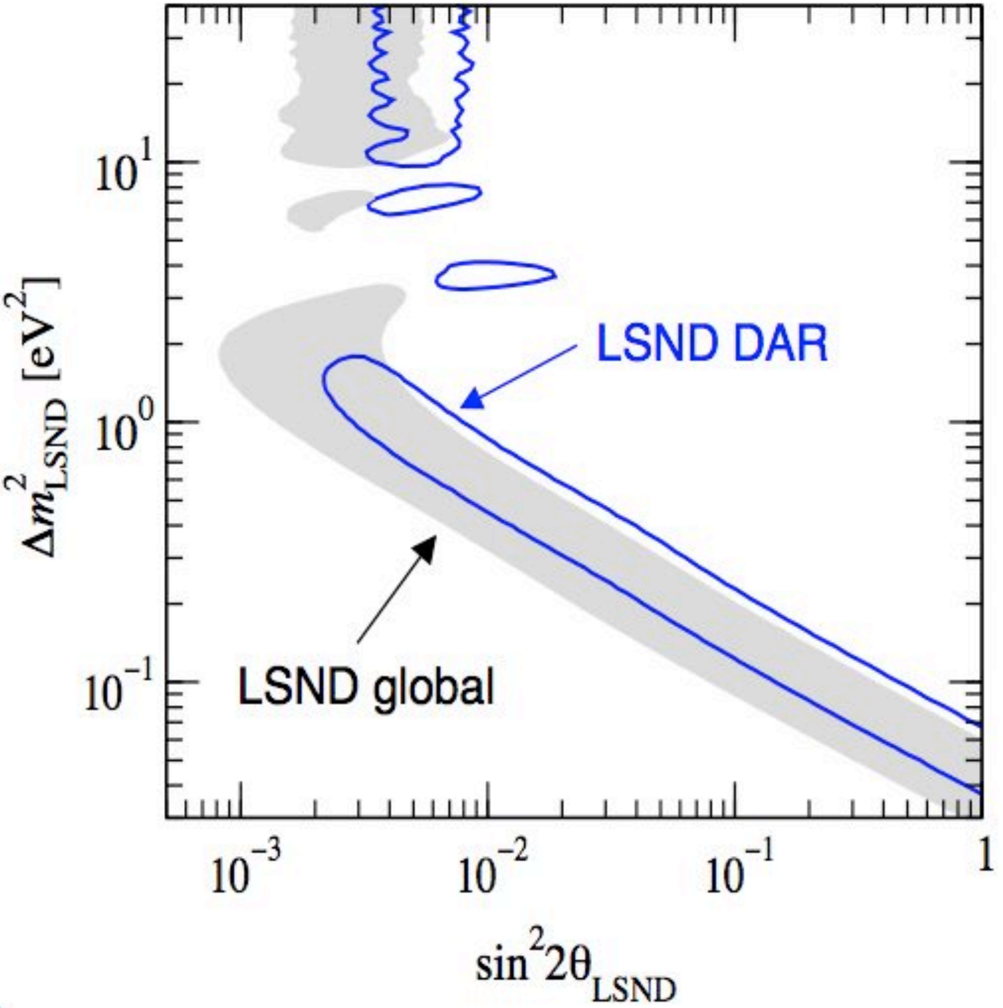
Giunti Laveder
1010.1395



99% CL

Differences between Giunti et al and our fit

99% CL



LSND official curves: see Church et al hep-ex/0203023 Maltoni et al hep-ph/0207157

Differences between Giunti et al and our fit

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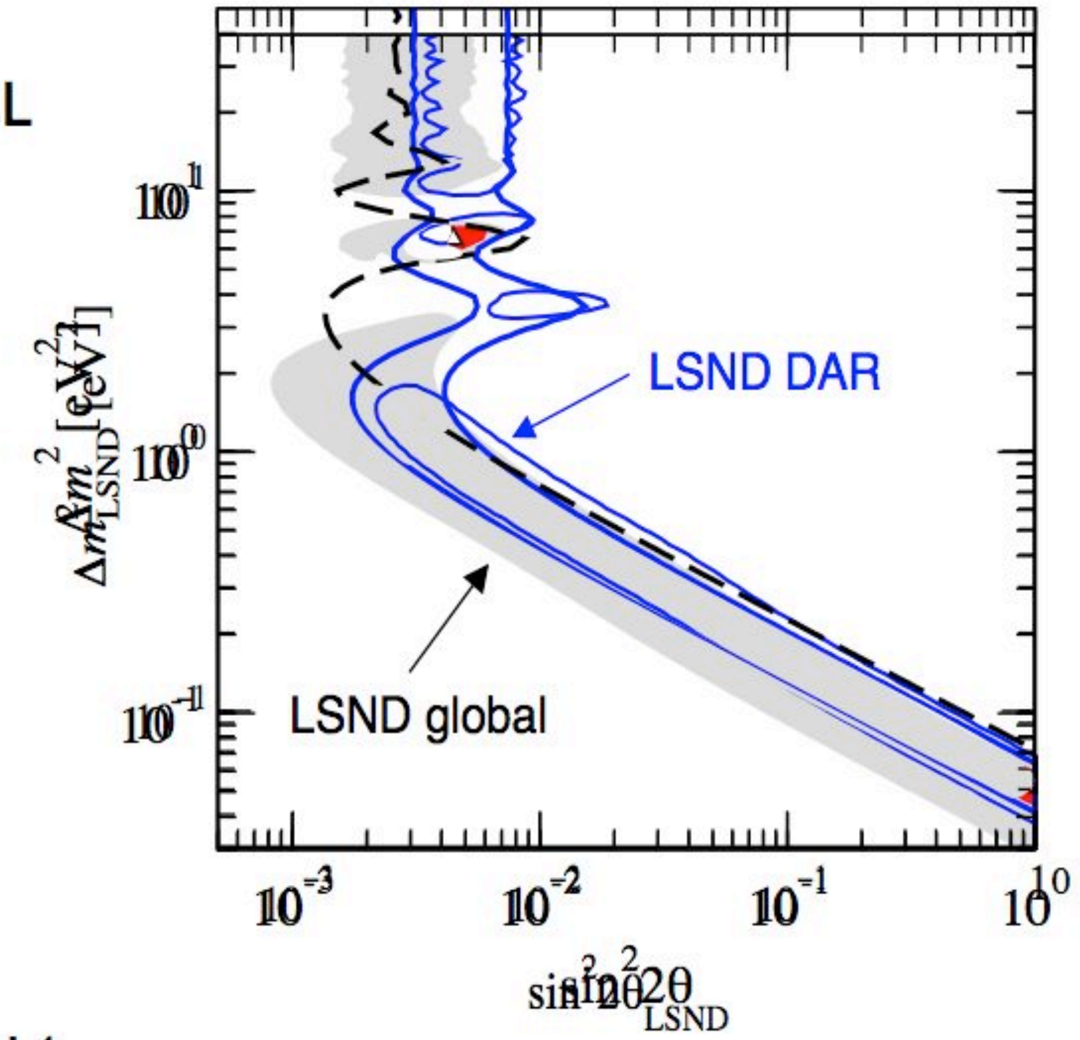
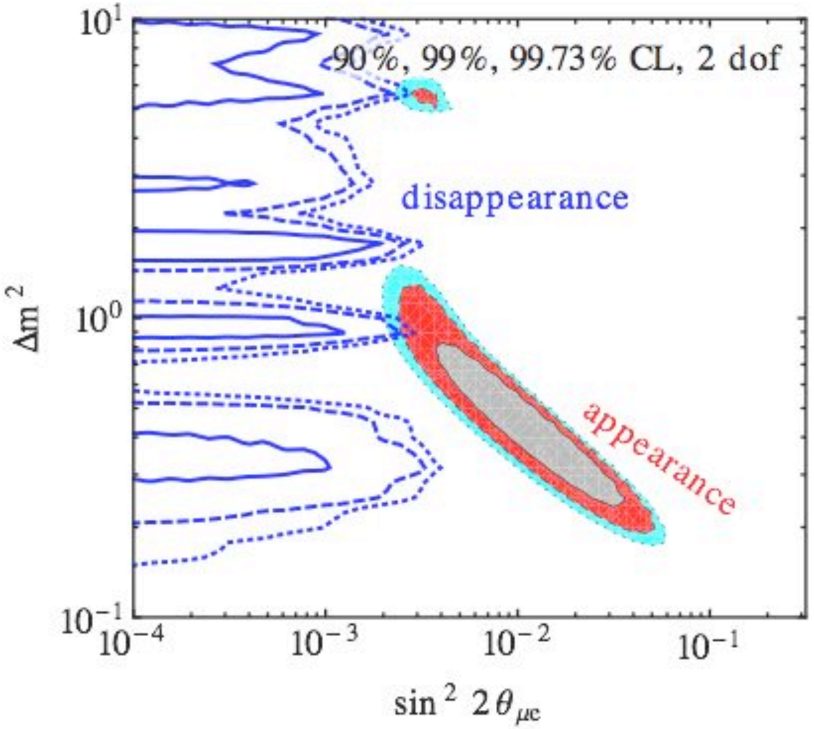
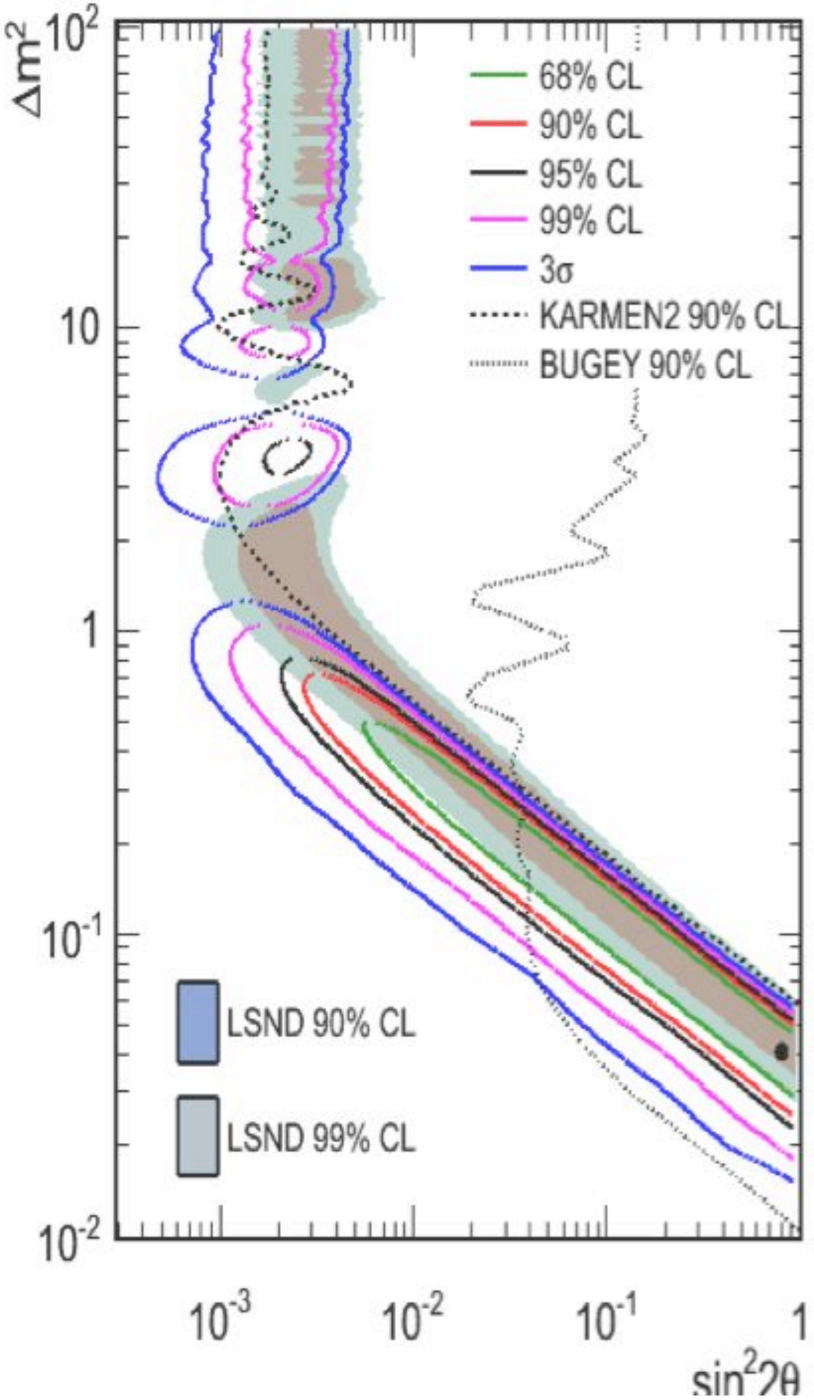
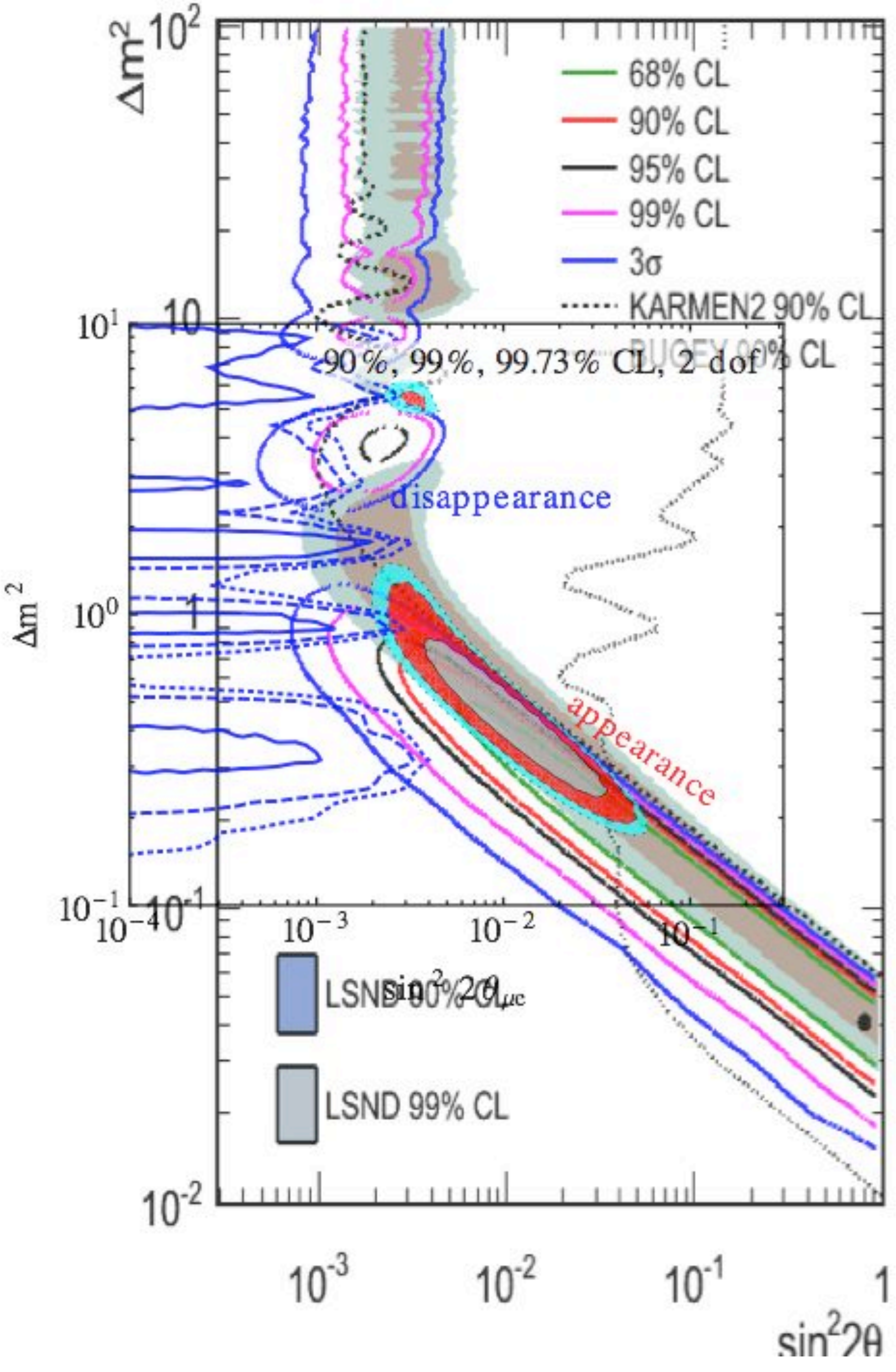


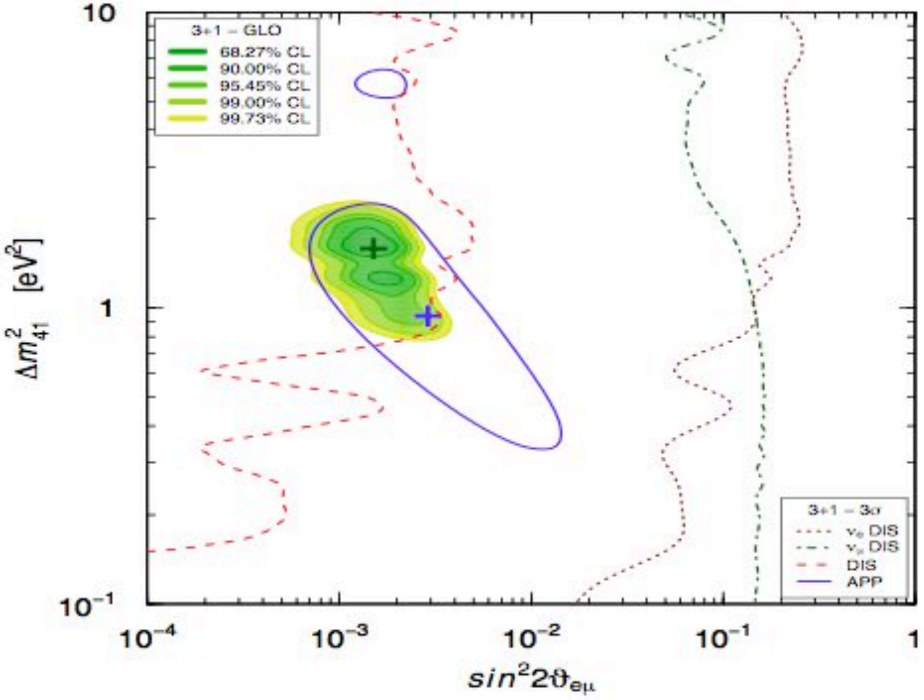
LSND official curves:
see Church et al
hep-ex/0203023
Maltoni et al
hep-ph/0207157

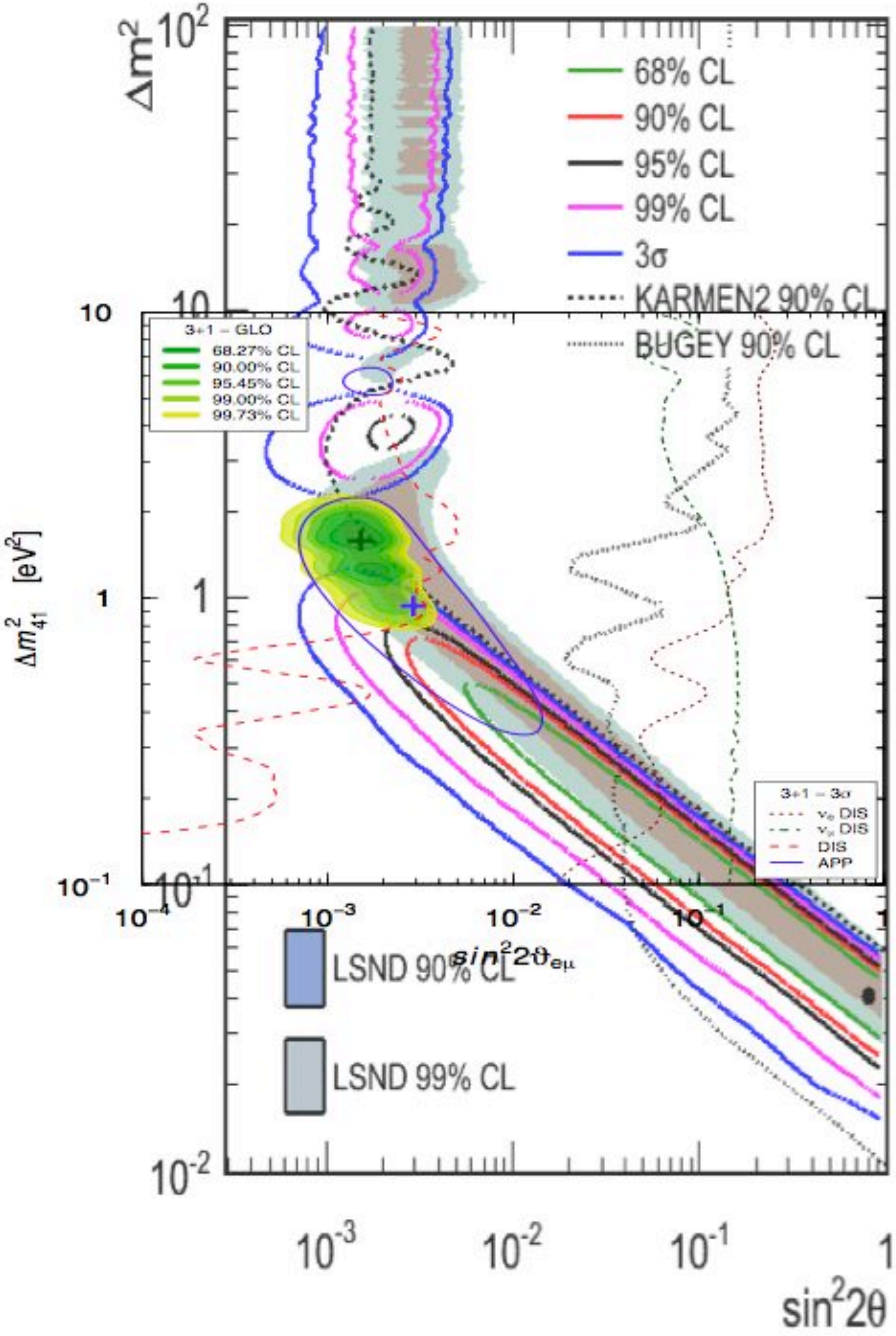
our LSND fit:
Palomares-Ruiz,
Pascoli, Schwetz
hep-ph/0505216


90%, 99%, 99.73% CL, 2 dof
disappearance
appearance
10^1
10^0
10^{-1}
Δm^2
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$\sin^2 2\theta_{\mu e}$


Δm^2
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\theta$
68% CL
90% CL
95% CL
99% CL
3σ
KARMEN2 90% CL
BUGEY 90% CL
LSND 90% CL
LSND 99% CL


68% CL
90% CL
95% CL
99% CL
3σ
KARMEN2 90% CL
BUGEY 90% CL
LSND 90% CL
LSND 99% CL
90%, 99%, 99.73% CL, 2 dof
disappearance
appearance
Δm^2
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
1
$\sin^2 2\theta$
10^1
10^0
10^{-4}
$\sin^2 2\theta_{\mu e}$


3+1 – GLO
68.27% CL
90.00% CL
95.45% CL
99.00% CL
99.73% CL
3+1 – 3σ
ν_e DIS
ν_μ DIS
DIS
APP
10
1
10^{-1}
Δm^2_{41} [eV^2]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$sin^2 2\vartheta_{e\mu}$


Δm^2
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\theta$
68% CL
90% CL
95% CL
99% CL
3σ
KARMEN2 90% CL
BUGEY 90% CL
LSND 90% CL
LSND 99% CL
3+1 – GLO
68.27% CL
90.00% CL
95.45% CL
99.00% CL
99.73% CL
Δm^2_{41} [eV^2]
10
1
10^{-1}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$sin^2 2\vartheta_{e\mu}$
3+1 – 3σ
ν_e DIS
ν_μ DIS
DIS
APP

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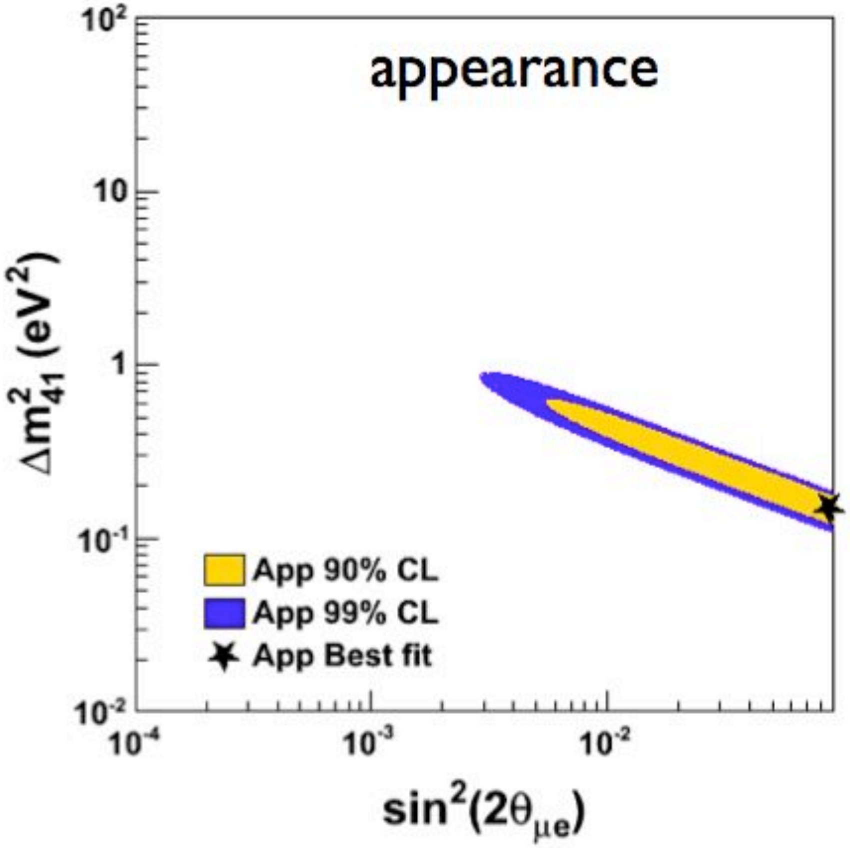

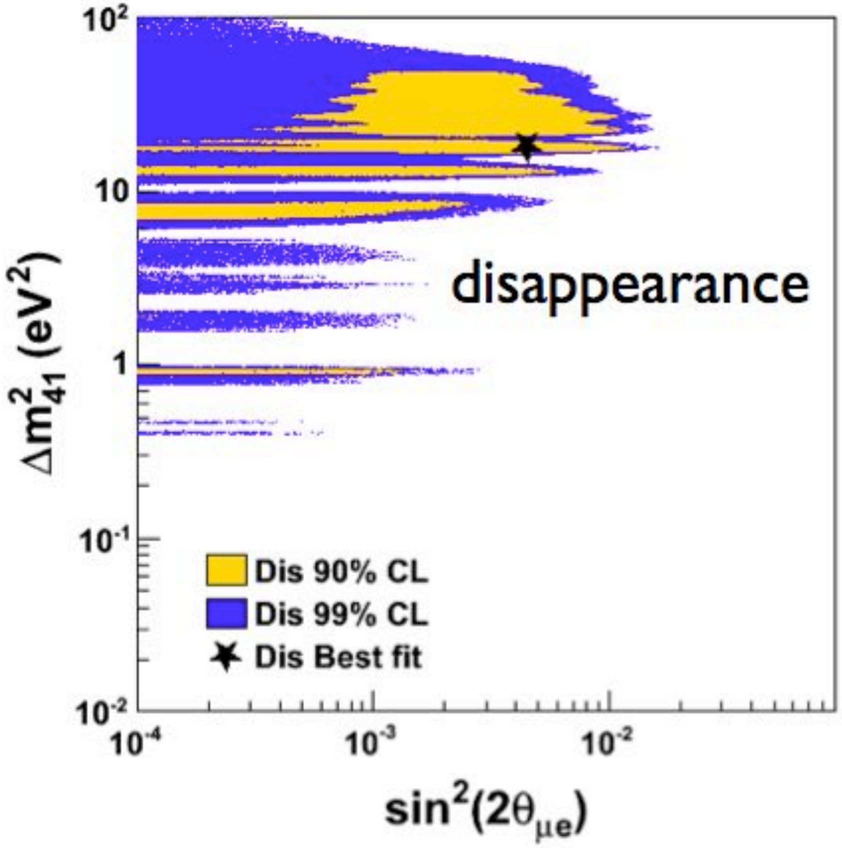

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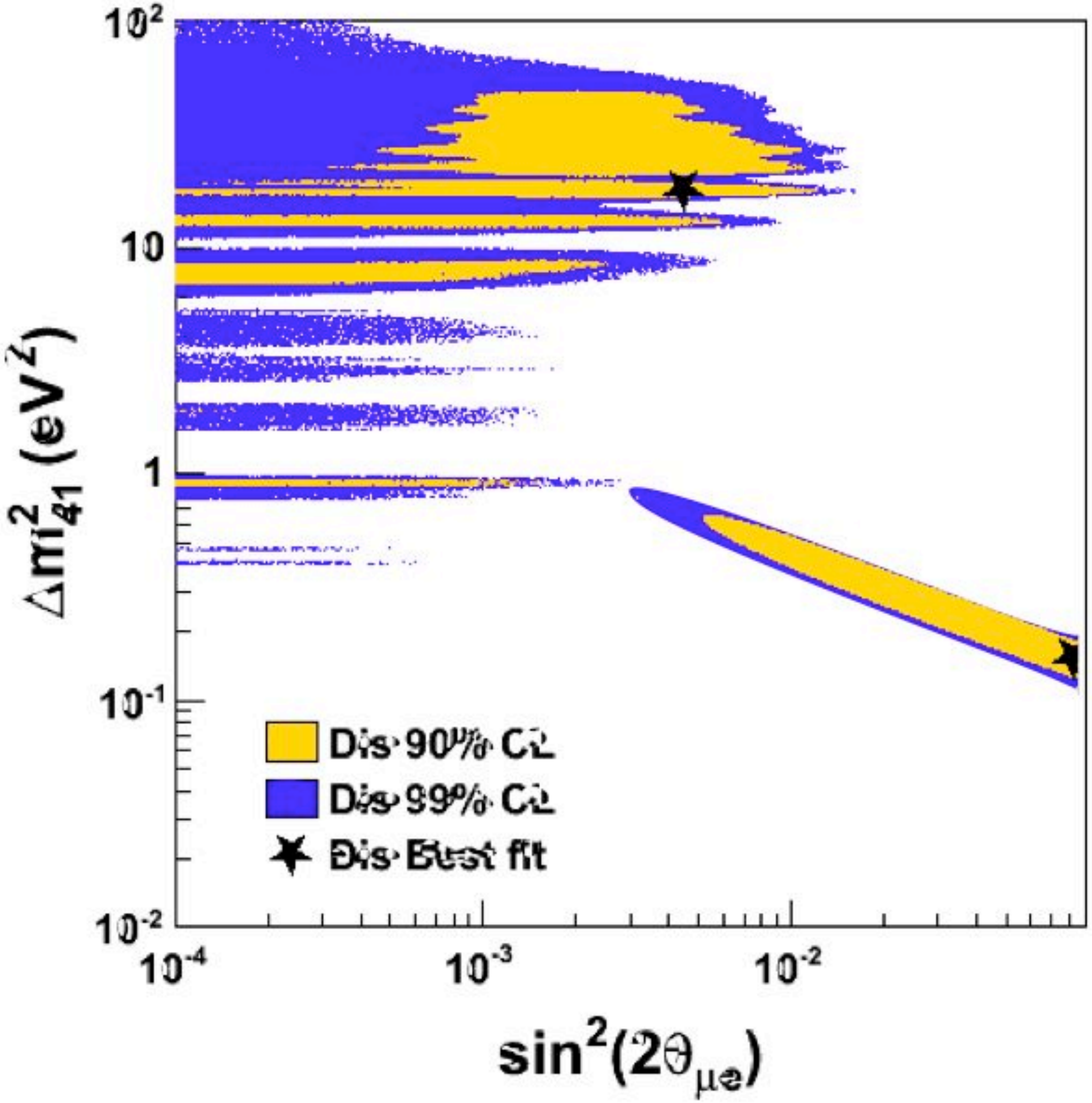

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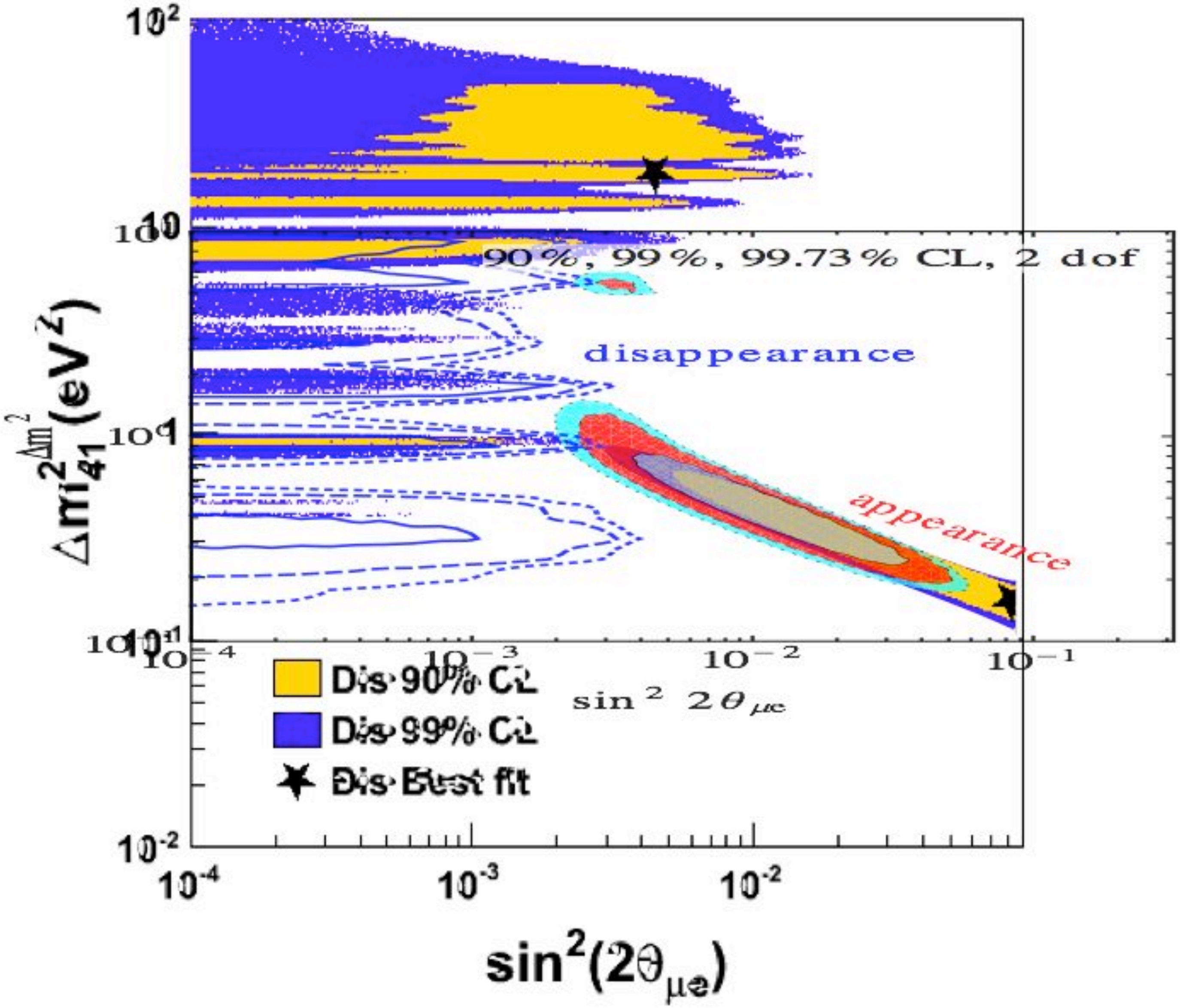
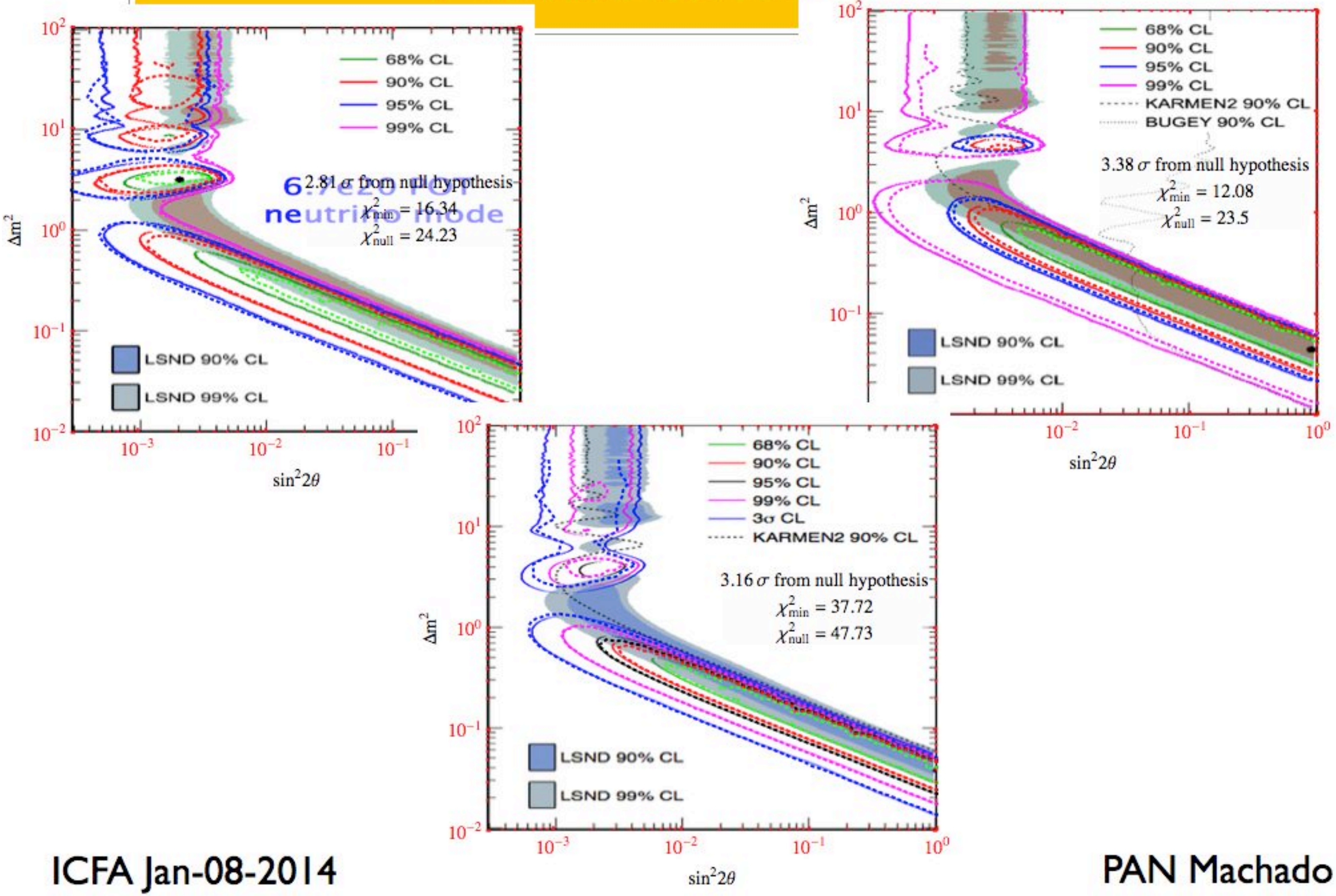
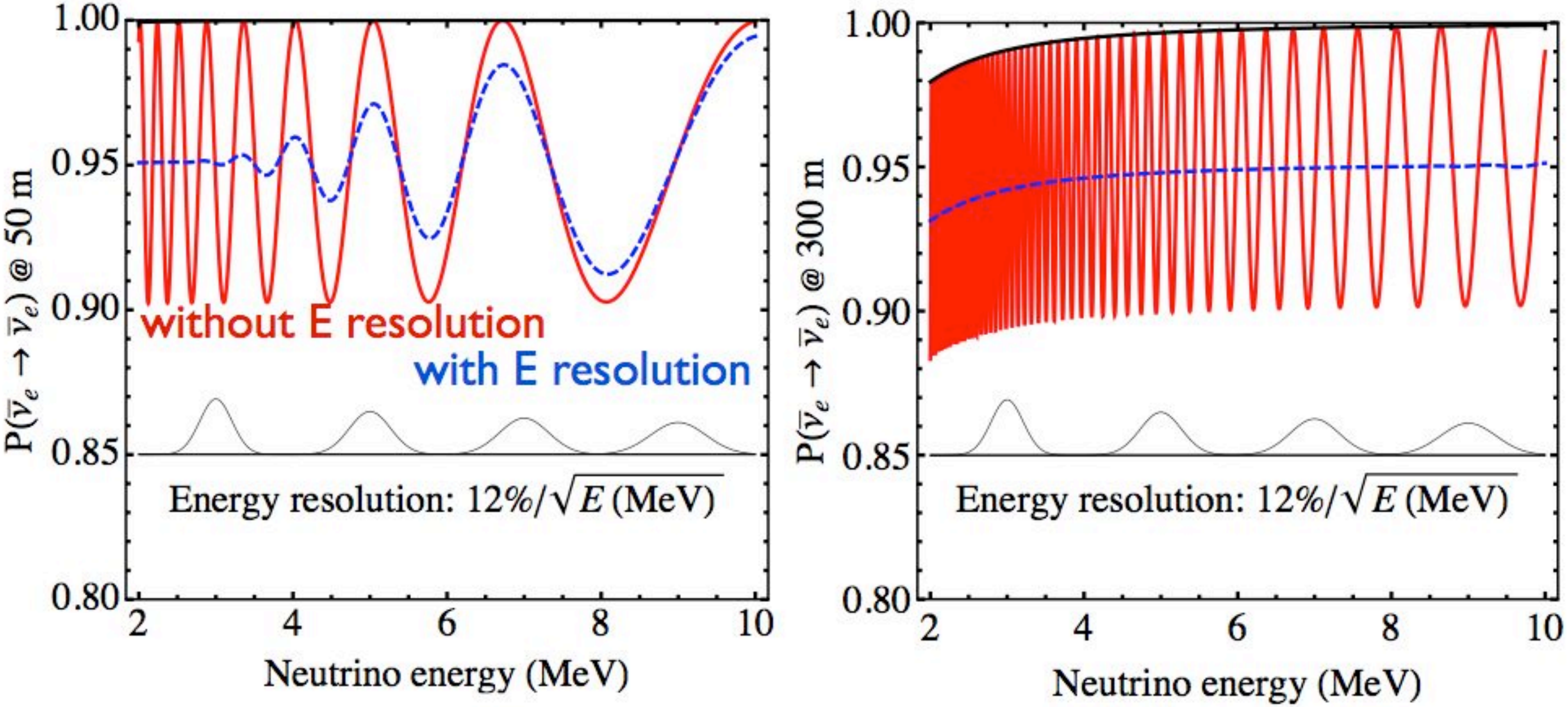


MiniBooNE


68% CL
90% CL
95% CL
99% CL
LSND 90% CL
LSND 99% CL
6.7e20 POT
neutrino mode
2.81 σ from null hypothesis
$\chi^2_{\rm min} = 16.34$
$\chi^2_{\rm null} = 24.23$
Δm^2
$\sin^2 2\theta$
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{-3}
68% CL
90% CL
95% CL
99% CL
KARMEN2 90% CL
BUGEY 90% CL
3.38 σ from null hypothesis
$\chi^2_{\rm min} = 12.08$
$\chi^2_{\rm null} = 23.5$
LSND 90% CL
LSND 99% CL
68% CL
90% CL
95% CL
99% CL
3σ CL
KARMEN2 90% CL
3.16 σ from null hypothesis
$\chi^2_{\rm min} = 37.72$
$\chi^2_{\rm null} = 47.73$
LSND 90% CL
LSND 99% CL

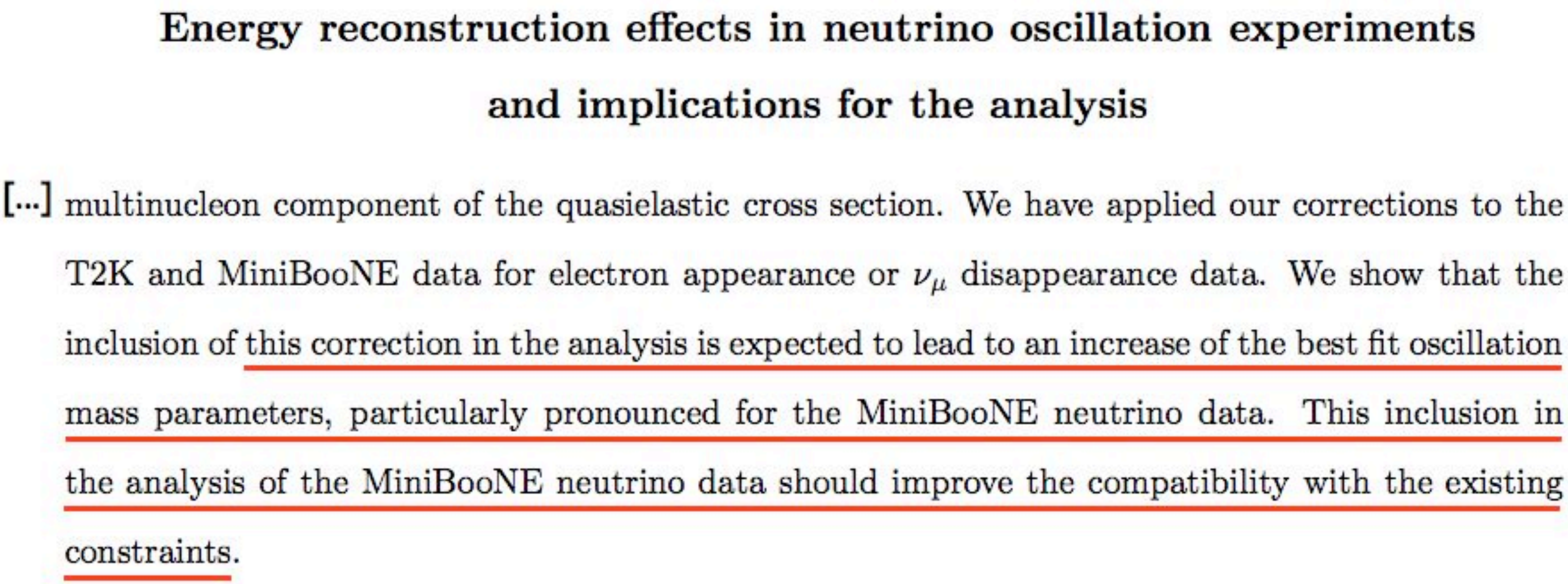
Impact of steriles on θ_{13}



$\Delta m^2_{\text{sterile}} = 1\ \text{eV}^2$ $\sin^2 2\theta_{\text{sterile}} = 0.10$

Other explanation?

Martini Ericsson Chanfray PRD 87 (2013) 013009



Energy reconstruction effects in neutrino oscillation experiments and implications for the analysis

[...] multinucleon component of the quasielastic cross section. We have applied our corrections to the T2K and MiniBooNE data for electron appearance or ν_μ disappearance data. We show that the inclusion of this correction in the analysis is expected to lead to an increase of the best fit oscillation mass parameters, particularly pronounced for the MiniBooNE neutrino data. This inclusion in the analysis of the MiniBooNE neutrino data should improve the compatibility with the existing constraints.