Sterile neutrinos: the global picture

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

JHEP 1305 (2013) 050 [arXiv:1303.3011]

Which sterile neutrinos I will talk about?

Do we want steriles?

Do we need steriles?

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

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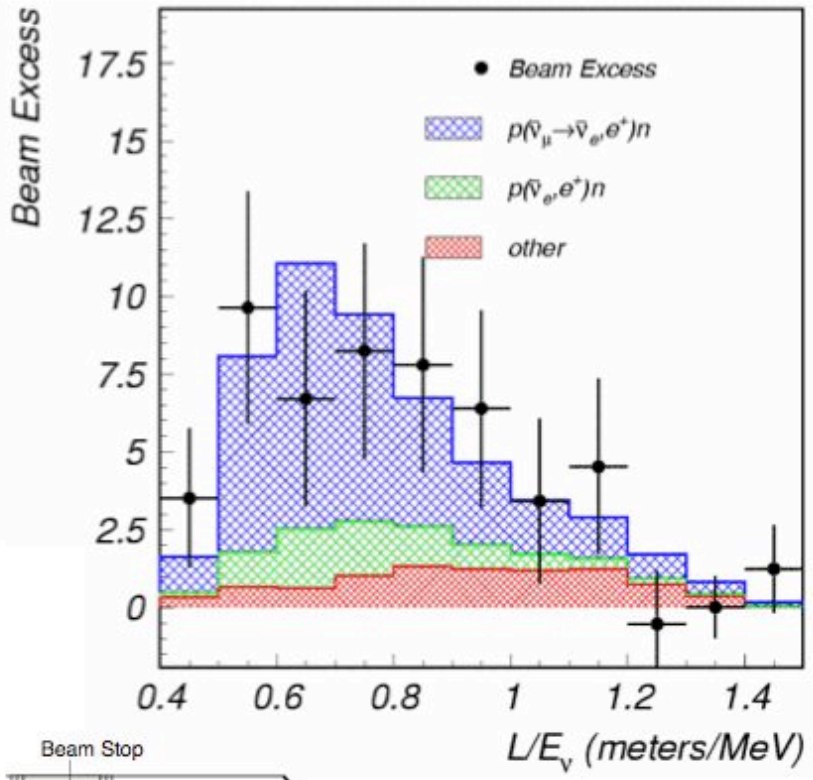
LSND

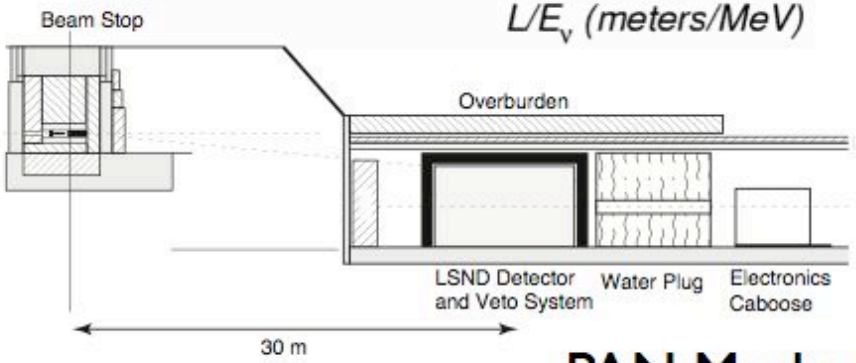
Los Alamos 1993-98

Intense proton beam

$$p + X \rightarrow \pi^+ + X'$$
$$\hookrightarrow \mu^+ \nu_\mu \text{ (DAR)}$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

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





MiniBooNE

Fermilab 2002-...

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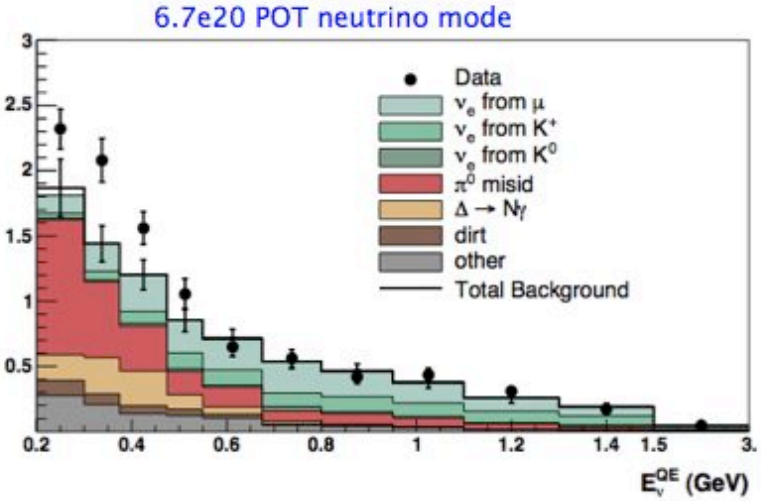
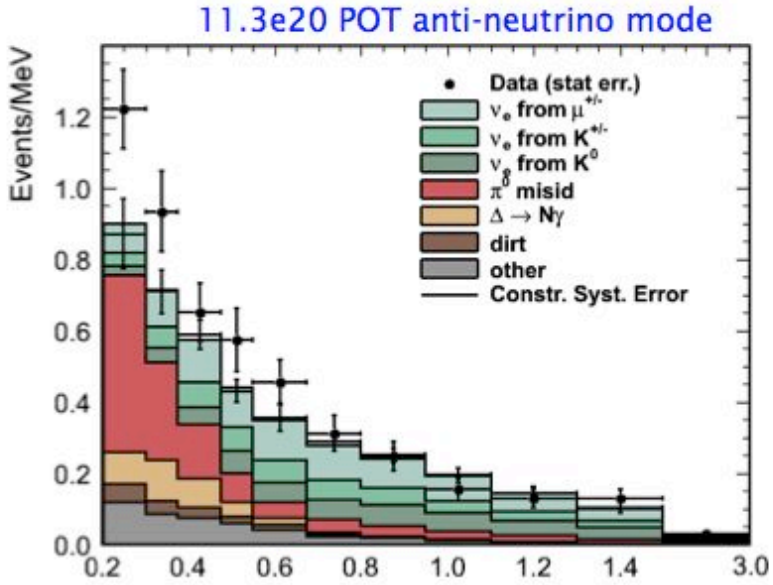
Neutrino and antineutrino modes see excesses of ν_e and $\bar{\nu}_e$
(combined is also a 3.8σ excess)





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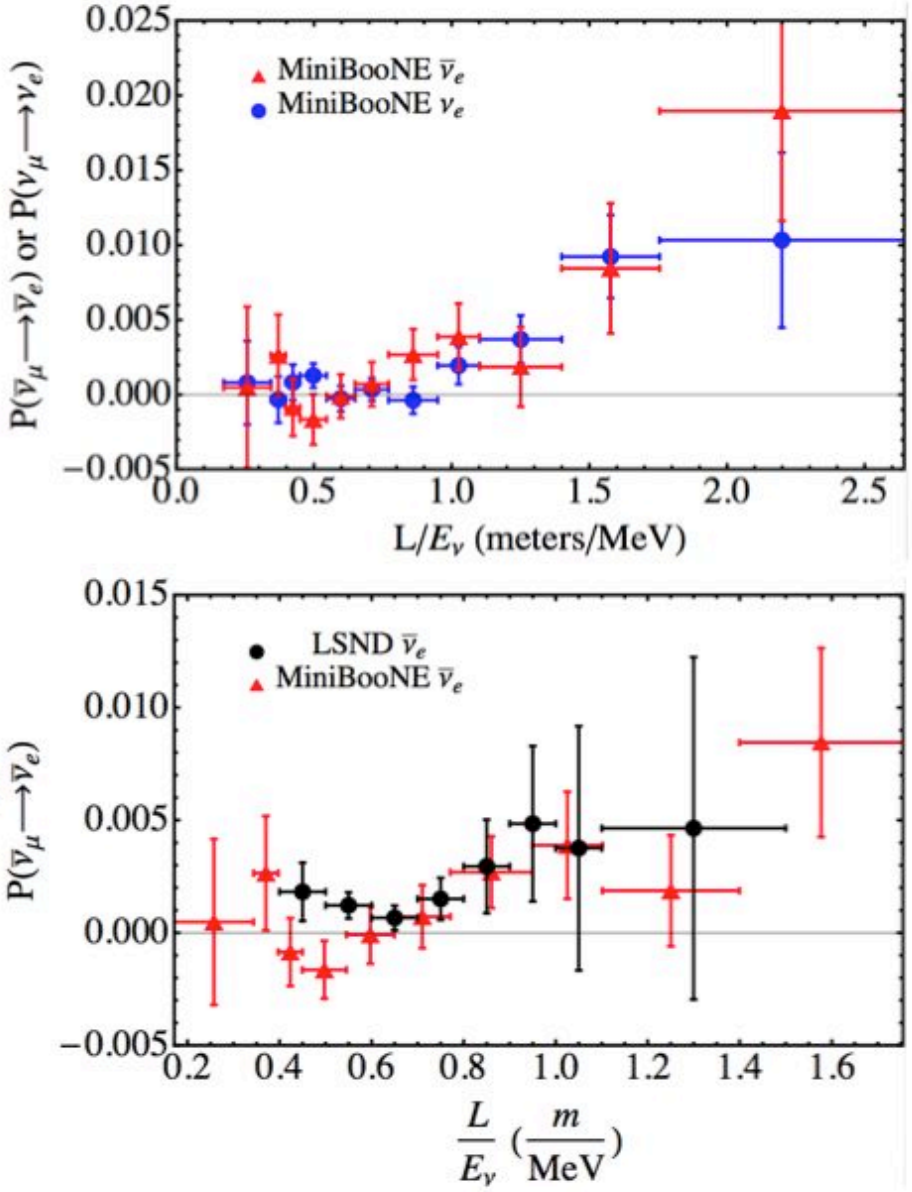

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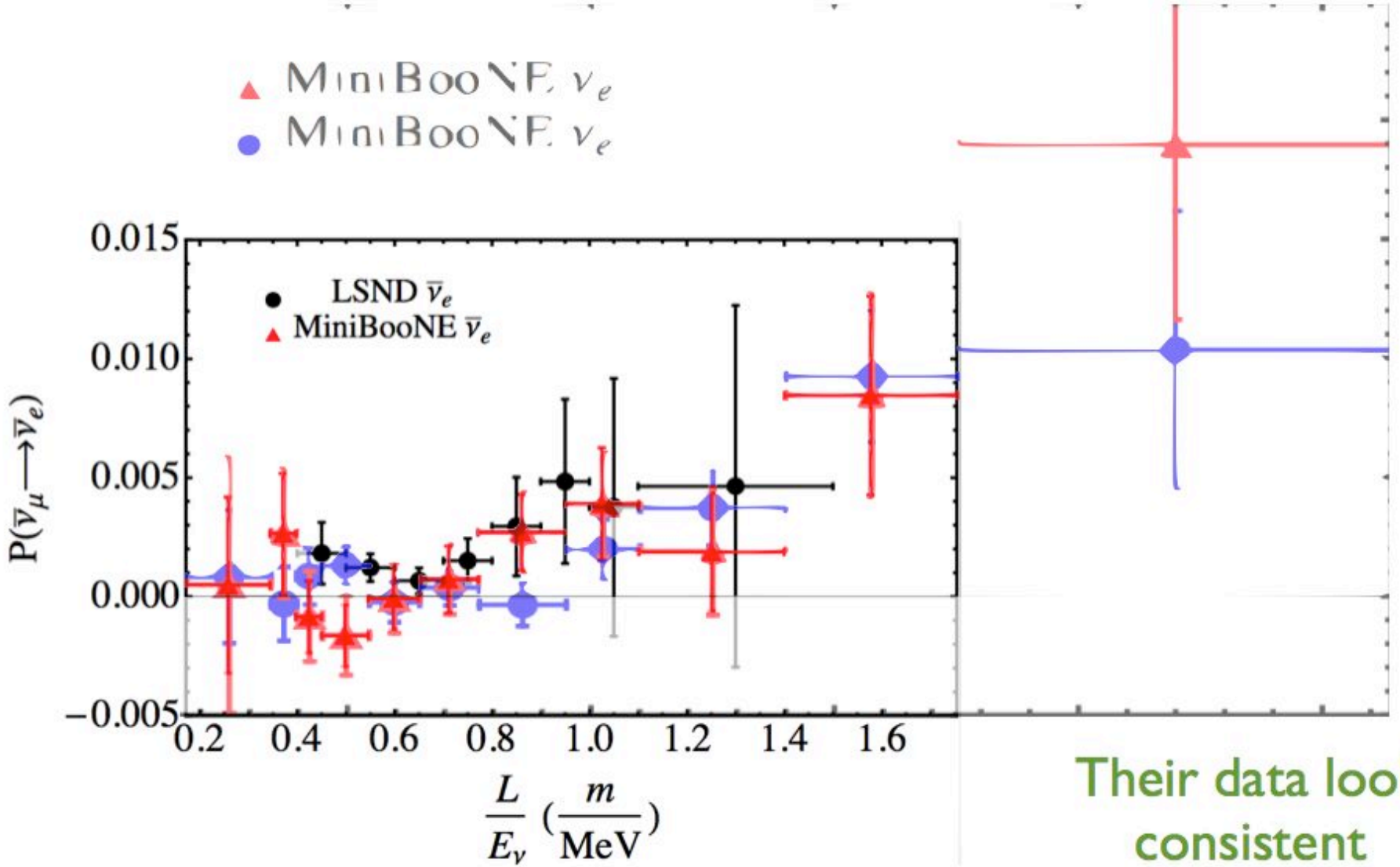
LSND + MiniBooNE



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

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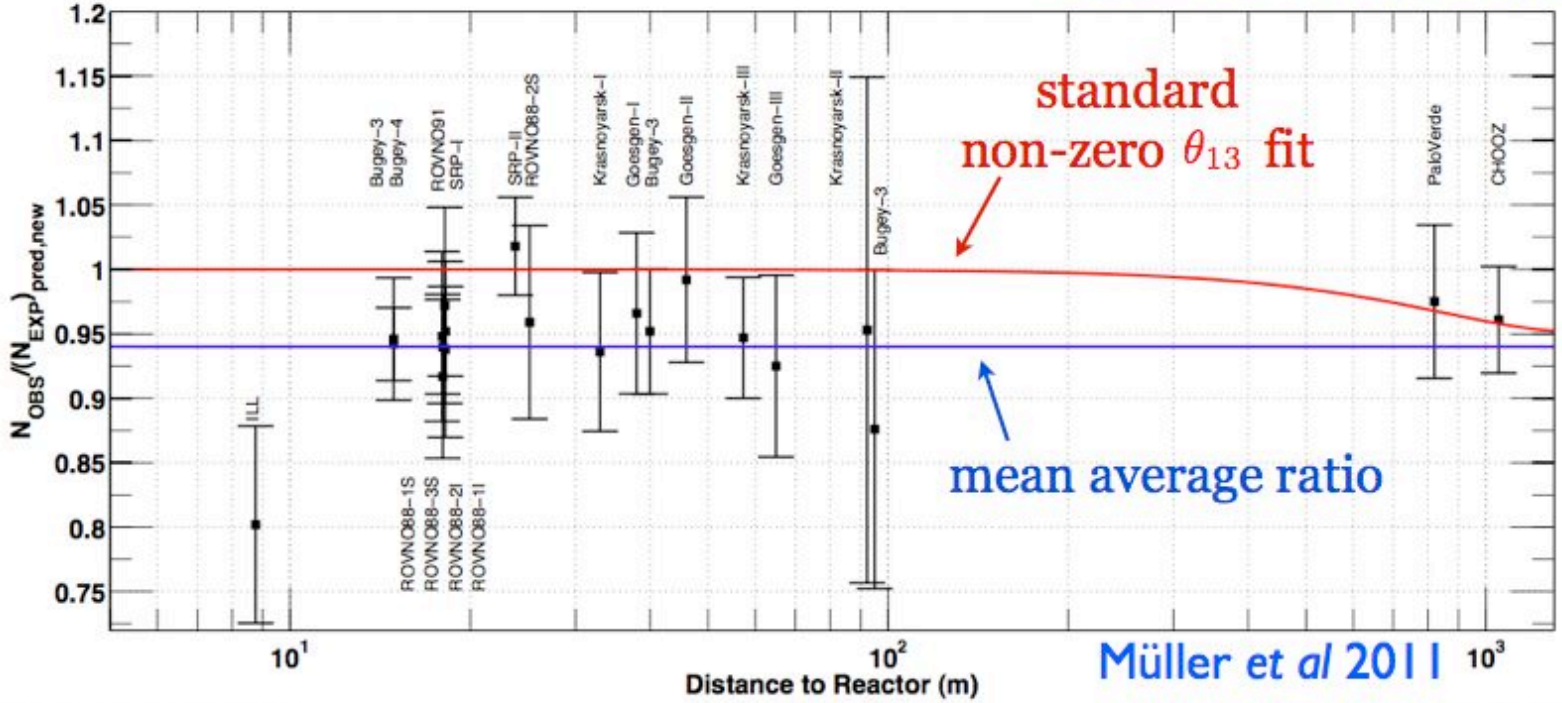

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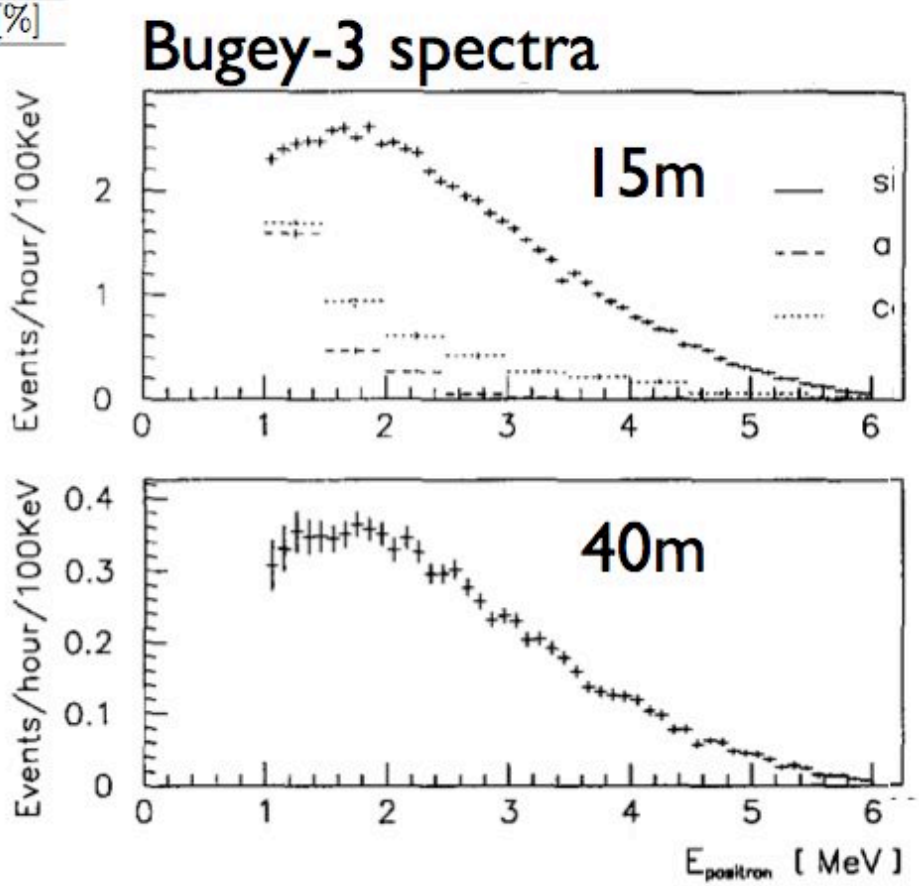

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Comparing two hypothesis does not mean a good fit...

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

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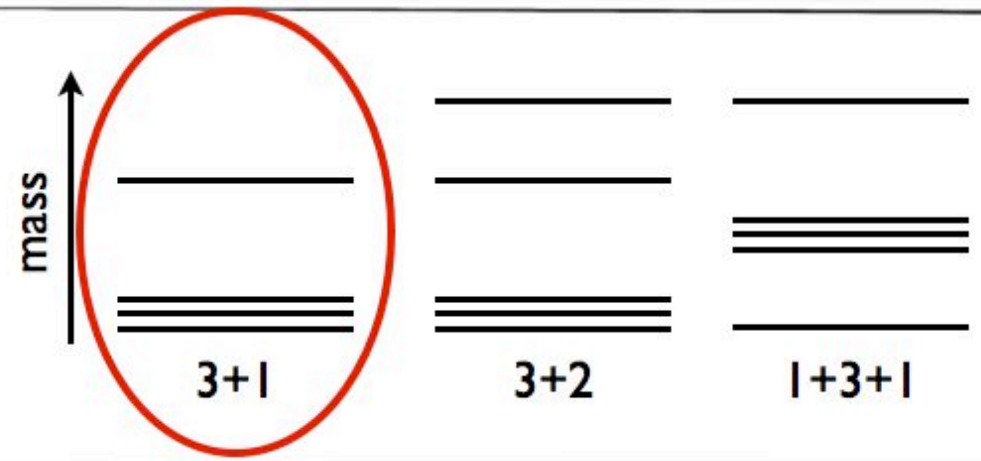
We could explain these anomalies with additional sterile neutrinos such that $\Delta m^2 \sim O(eV^2)$

We will focus on the 3+1 case



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

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

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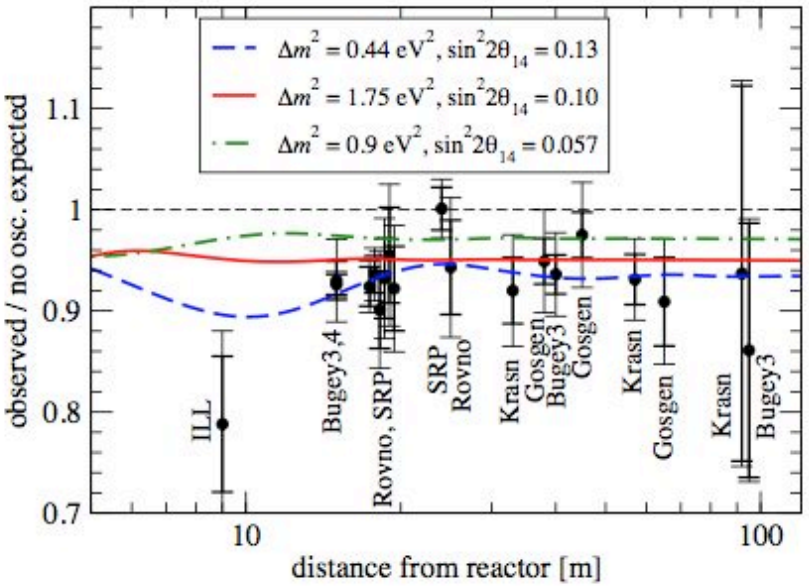

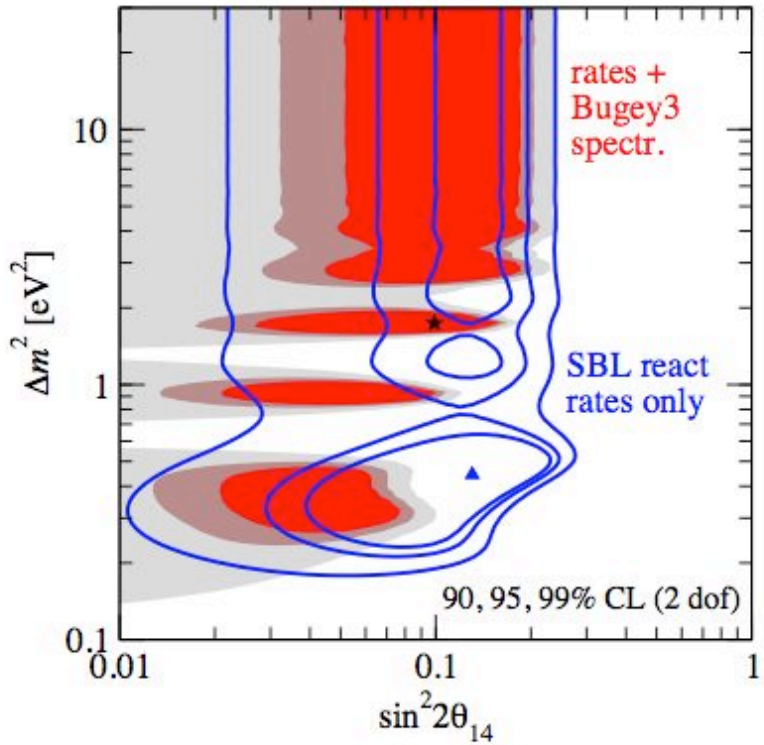

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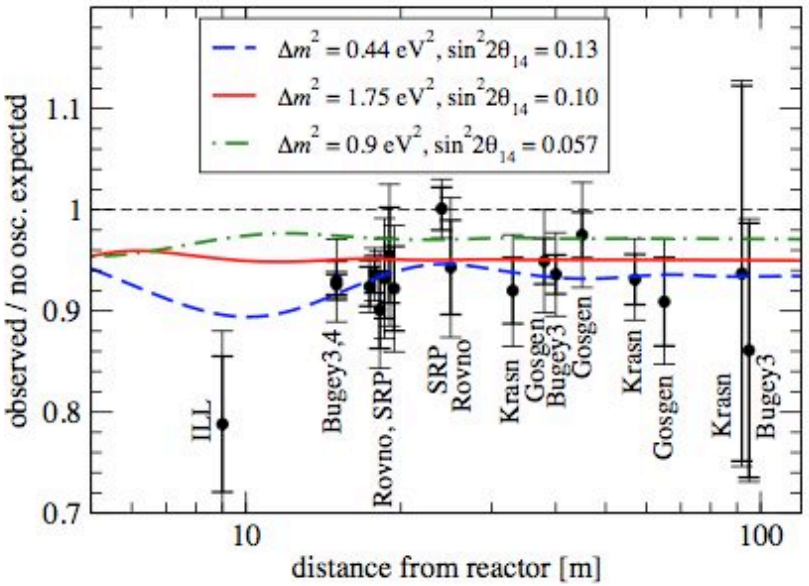

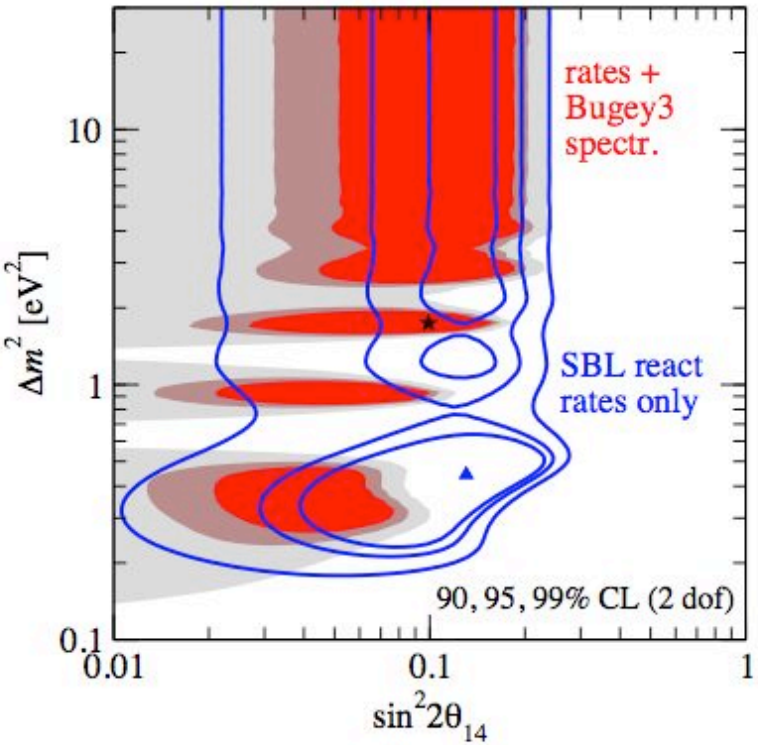

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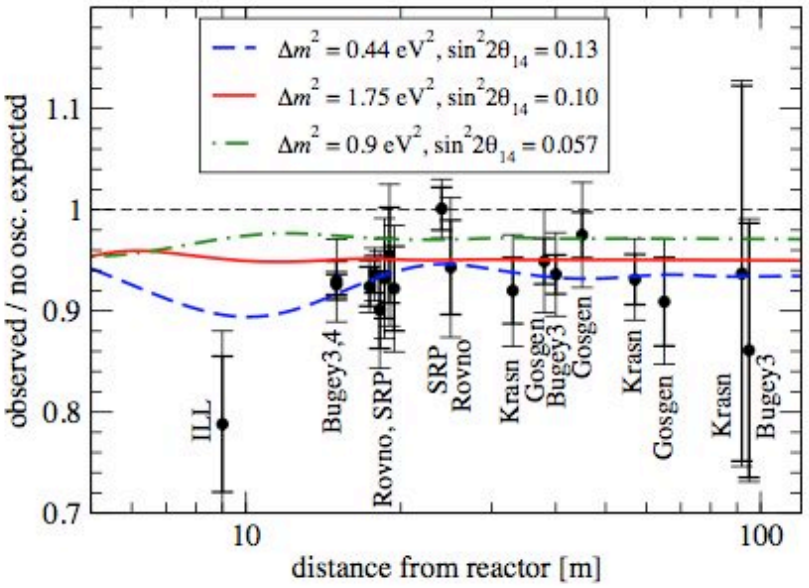

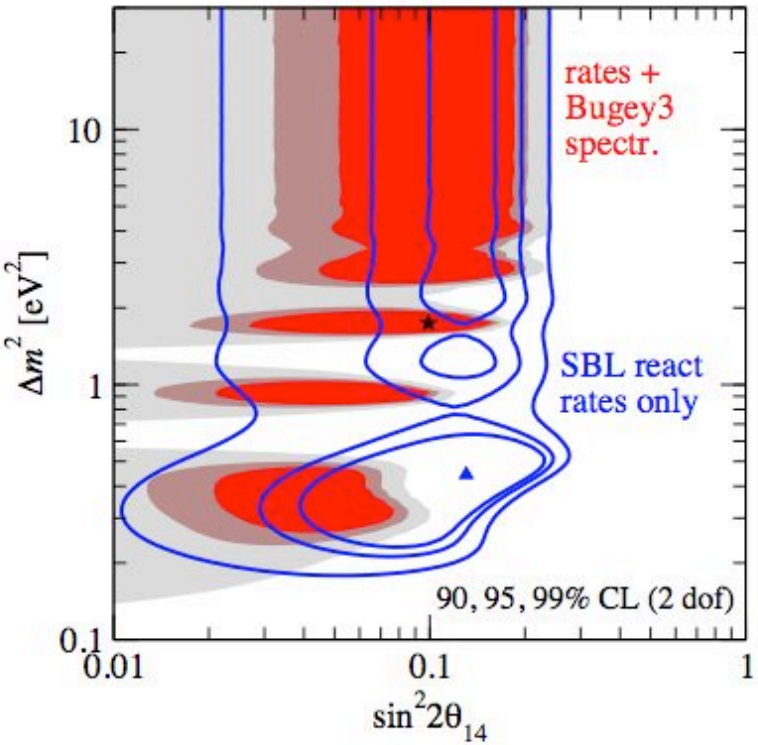

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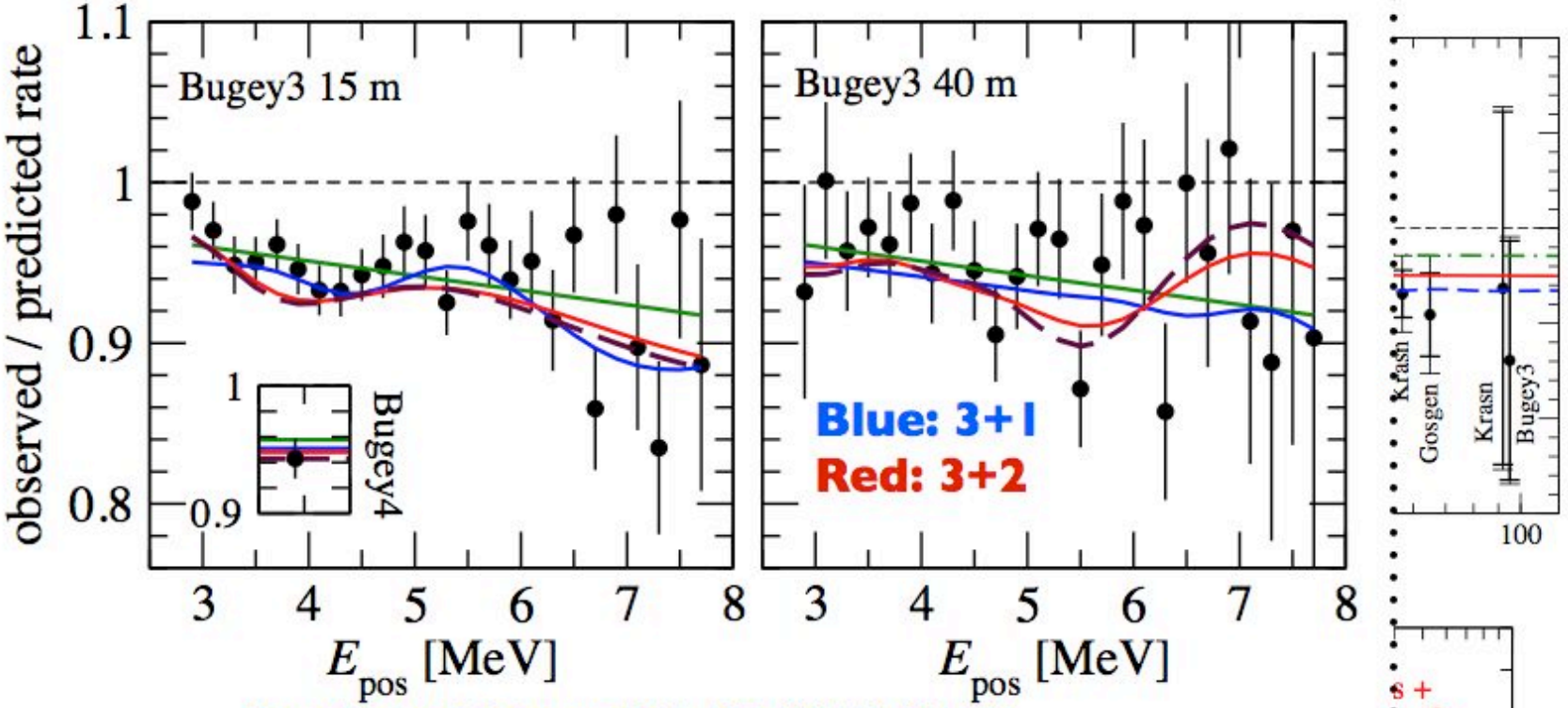
SB

$\sin^2$

χ^2_{min}

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



Kopp Maltoni Schwetz PRL 107 (2011) 091801

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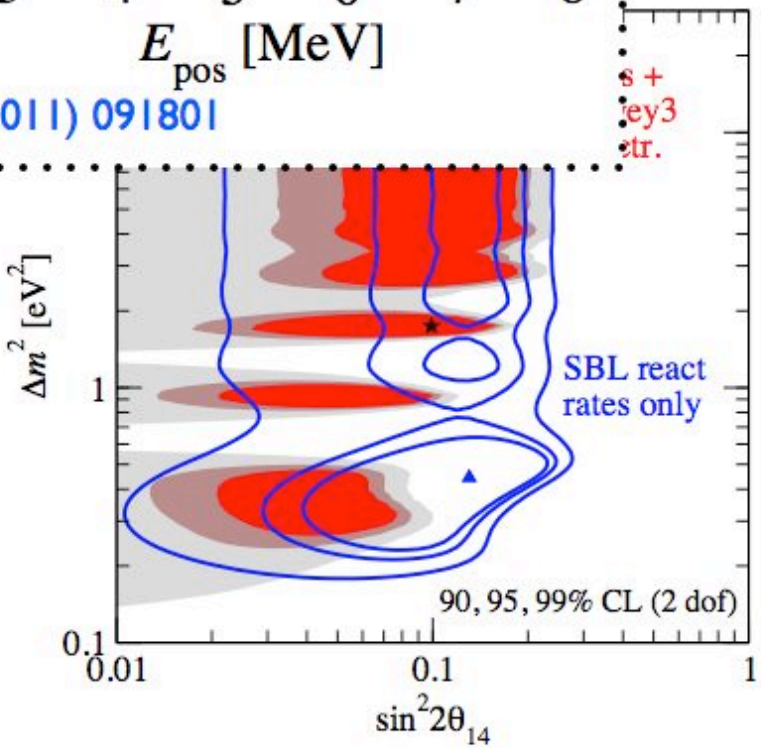

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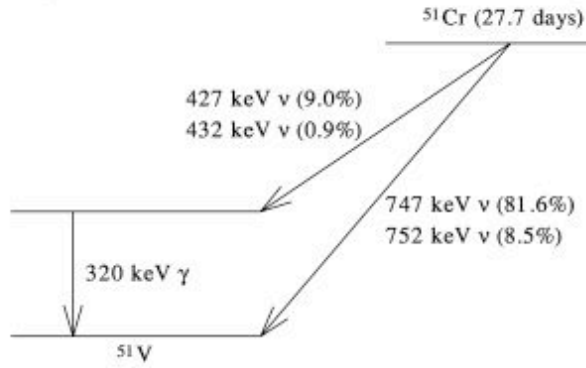
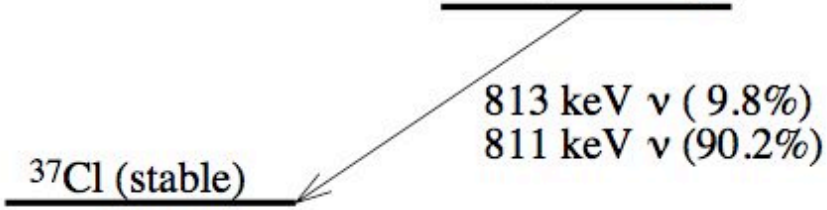
Gallium anomaly

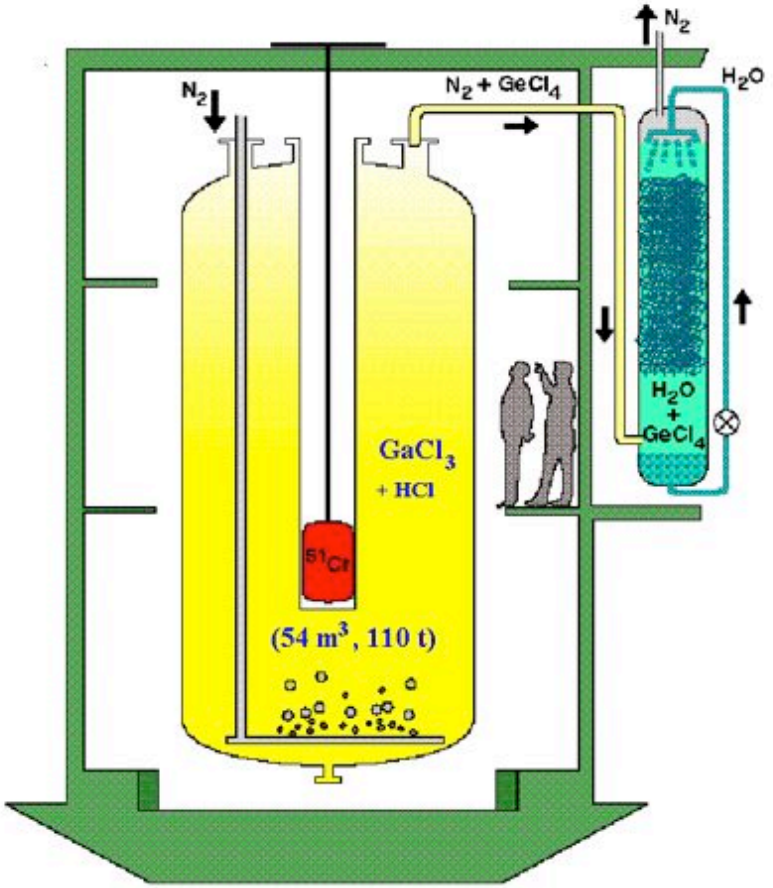
Sources:

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



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





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

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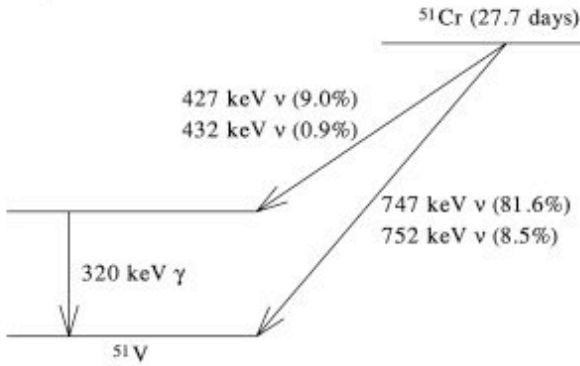

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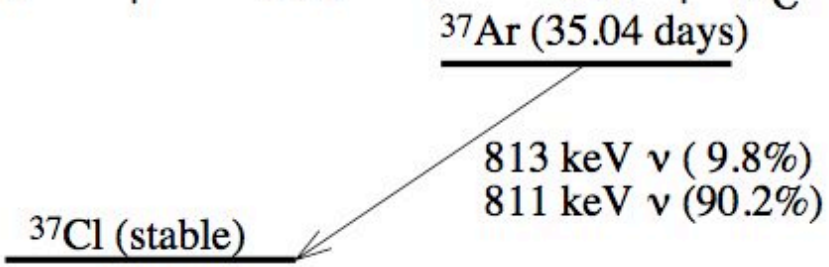
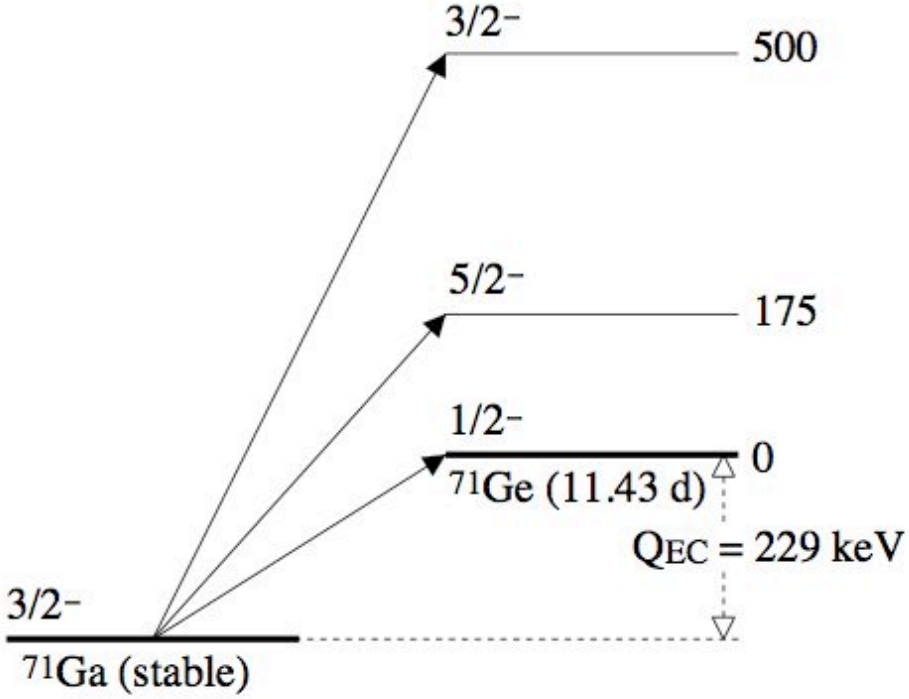


Detection:

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



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Gallium anomaly

Detection process can occur thru ground state or excited state

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

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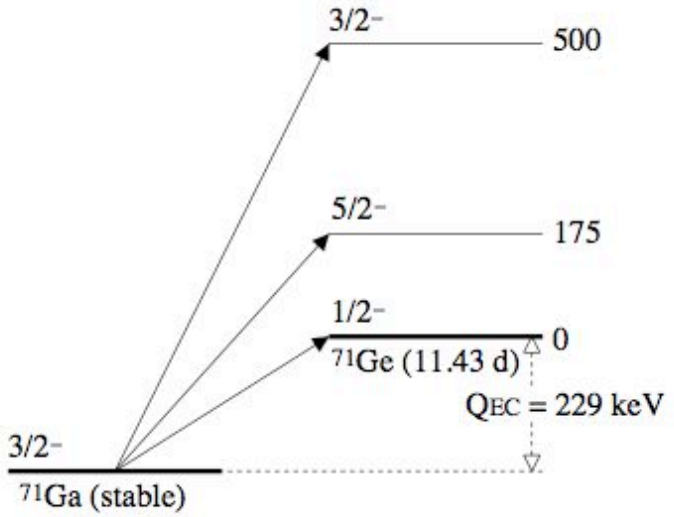

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ground state σ is well known

Gamow-Teller strength (large errors...)

See Frekers *et al* 2010

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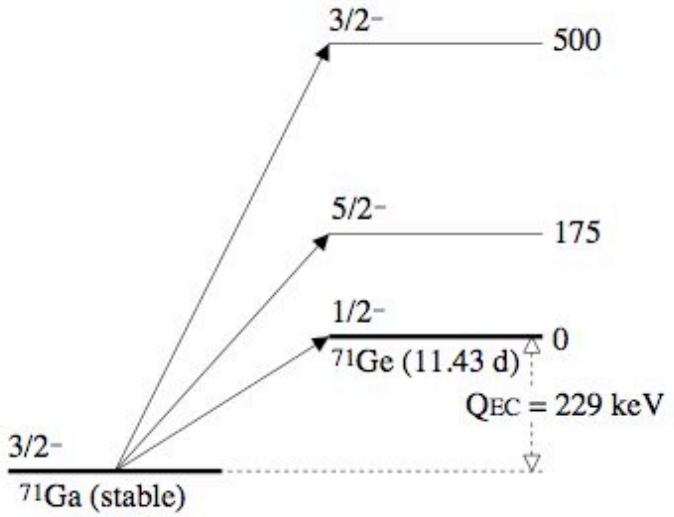

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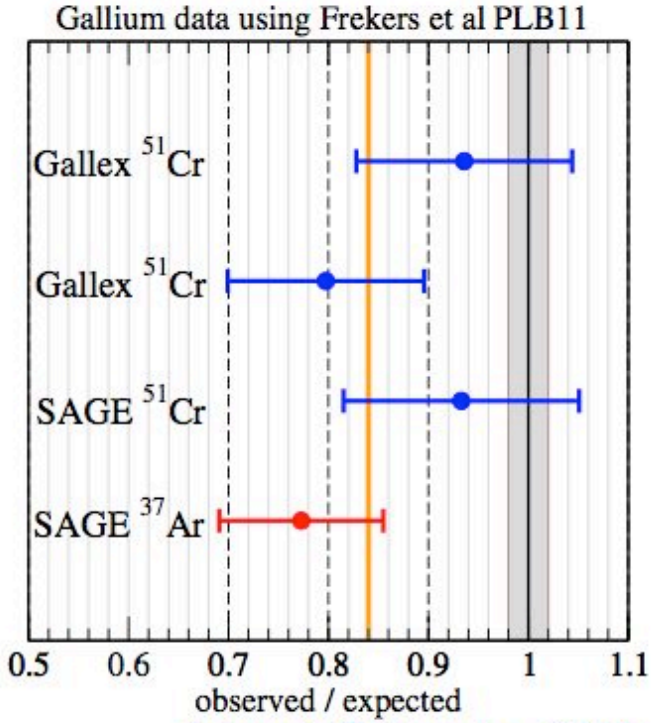

Schwetz@Neutrino 2012

$$R_1(\text{Cr}) = 0.94 \pm 0.11 \qquad R_3(\text{Cr}) = 0.93 \pm 0.12$$

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

 See also Acero Giunti Laveder 2007, Giunti Laveder 2010

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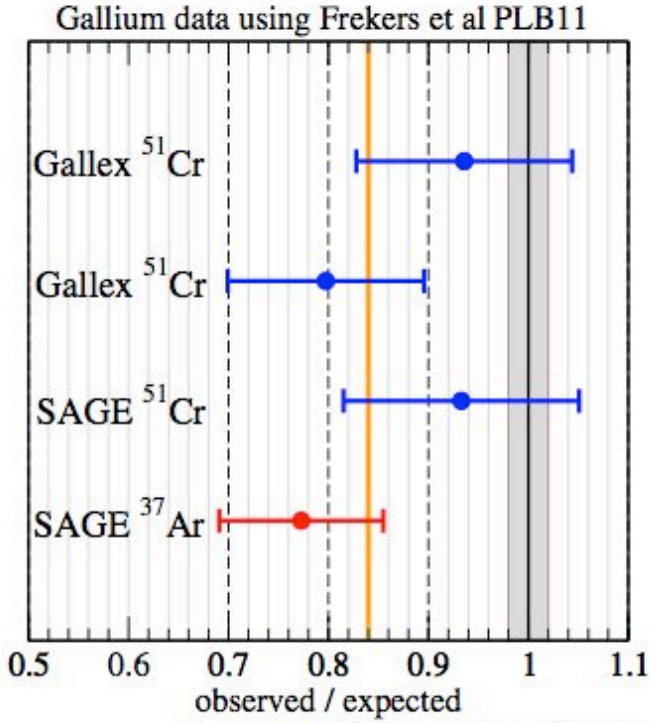

Schwetz@Neutrino 2012

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

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

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

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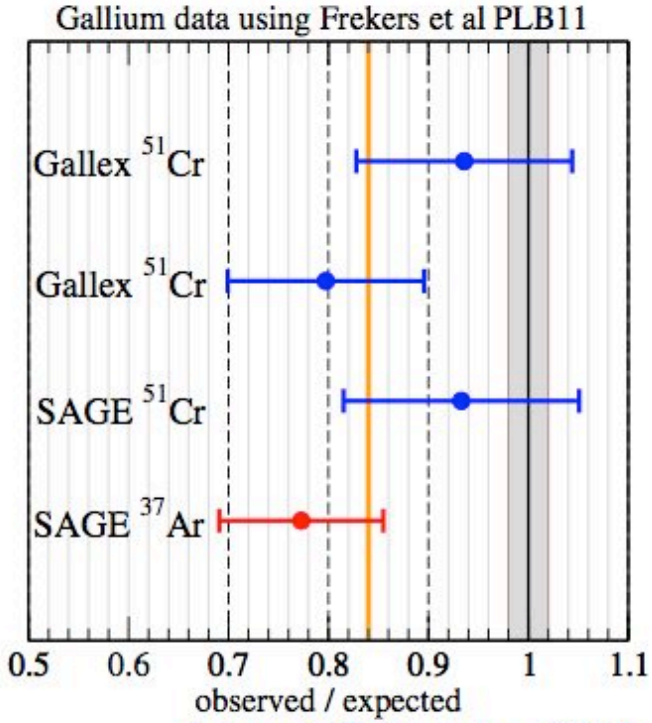

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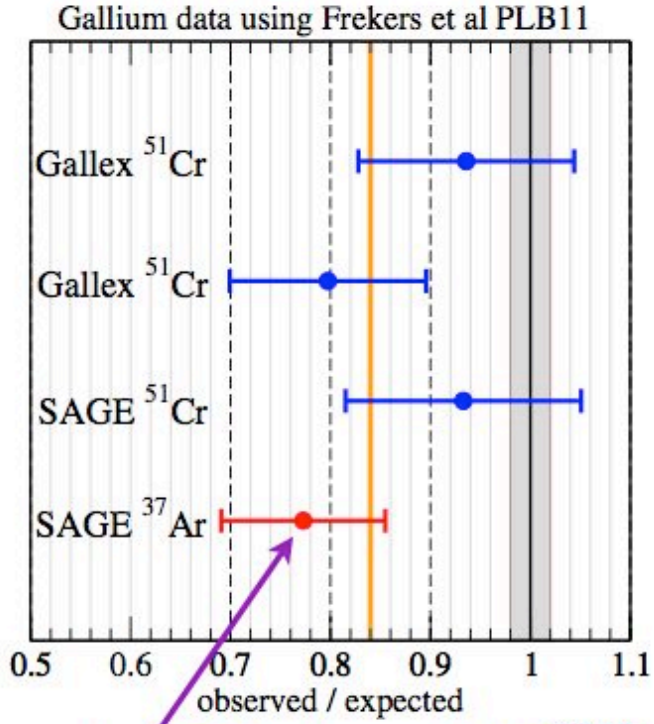

Depends on ^{37}Ar data point ○ 2012

(1.8σ without it)

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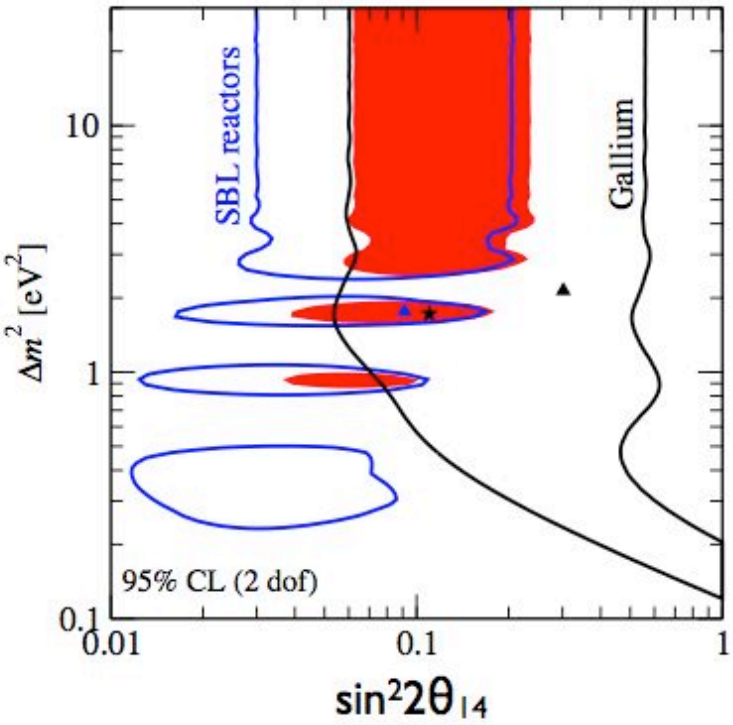
Reactor + Ga + ...

Ga + SBL reactor rates
+ Bugey-3 spectra:

Consistent!
What about other exps?

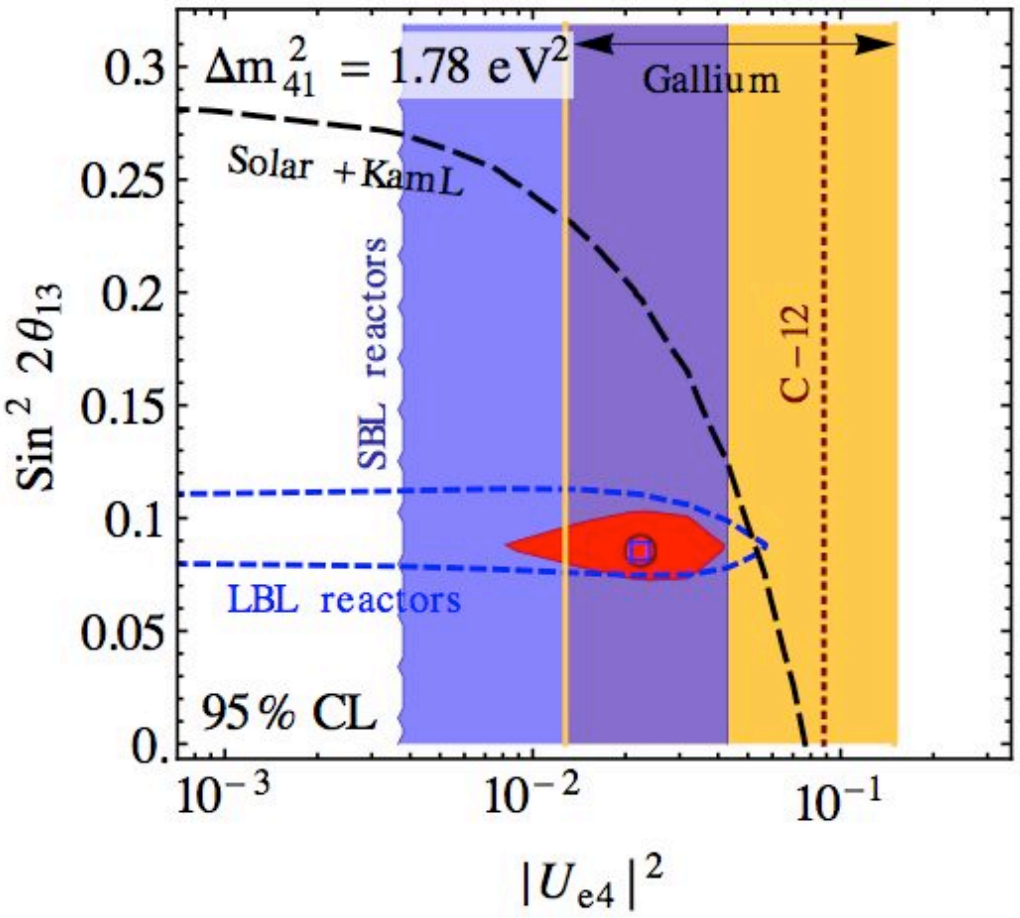


Reactor + Ga + ...

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

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
$\mathrm{Sin}^2\ 2\theta_{13}$
$|U_{e4}|^2$
0.3
0.25
0.2
0.15
0.1
0.05
0.
10^{-3}
10^{-2}
10^{-1}

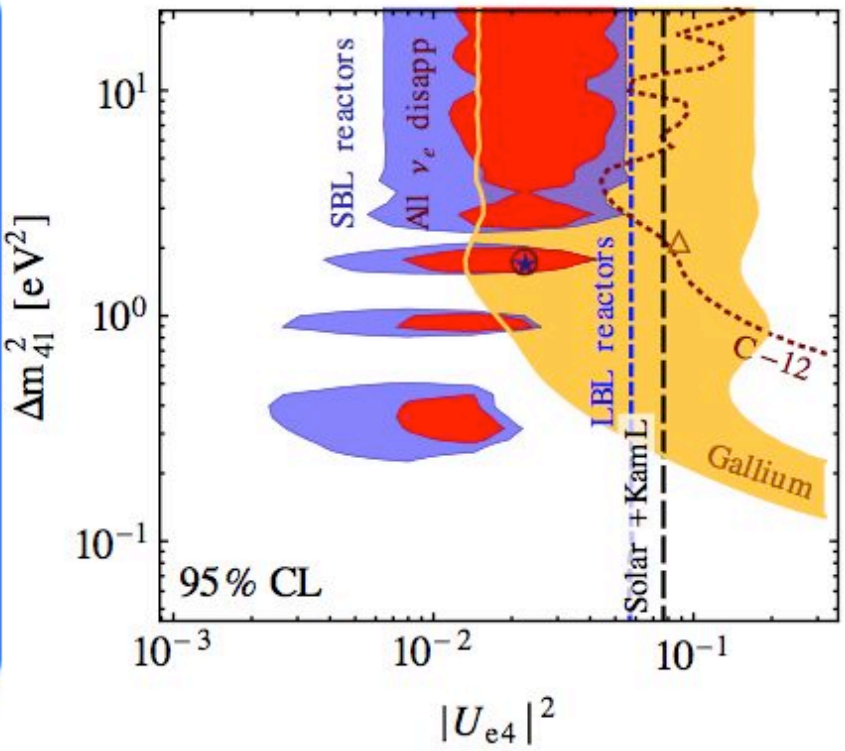
Reactor + Ga + ...

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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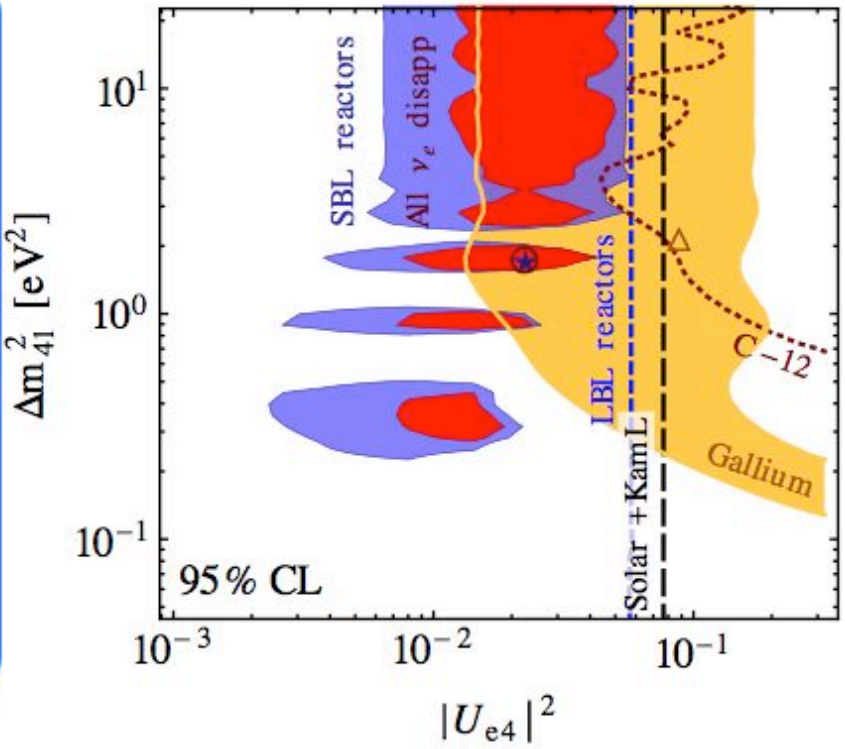
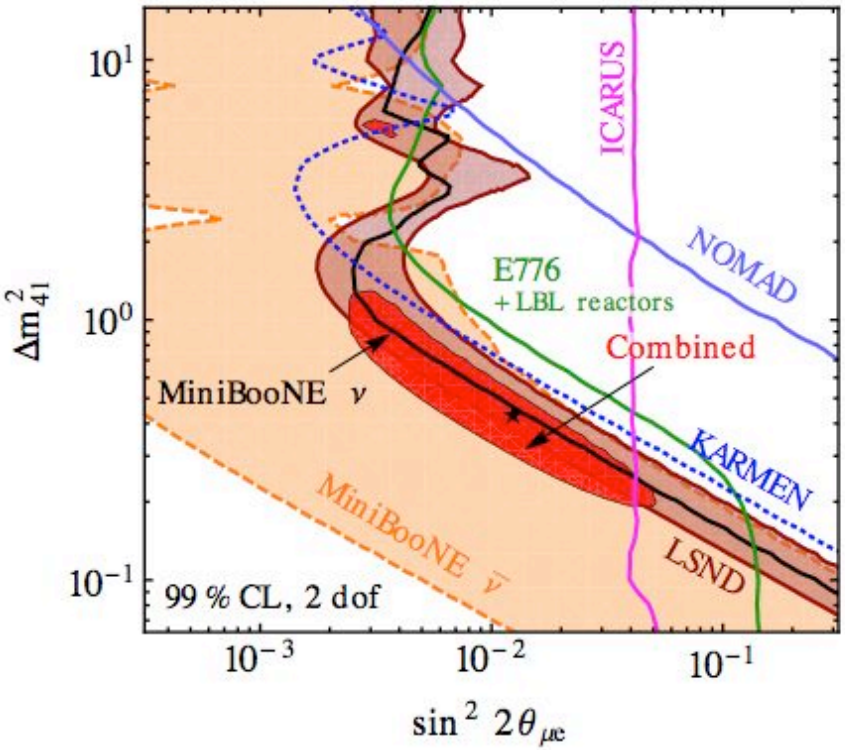


Yay! Still consistent!!

MB+LSND+app

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

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



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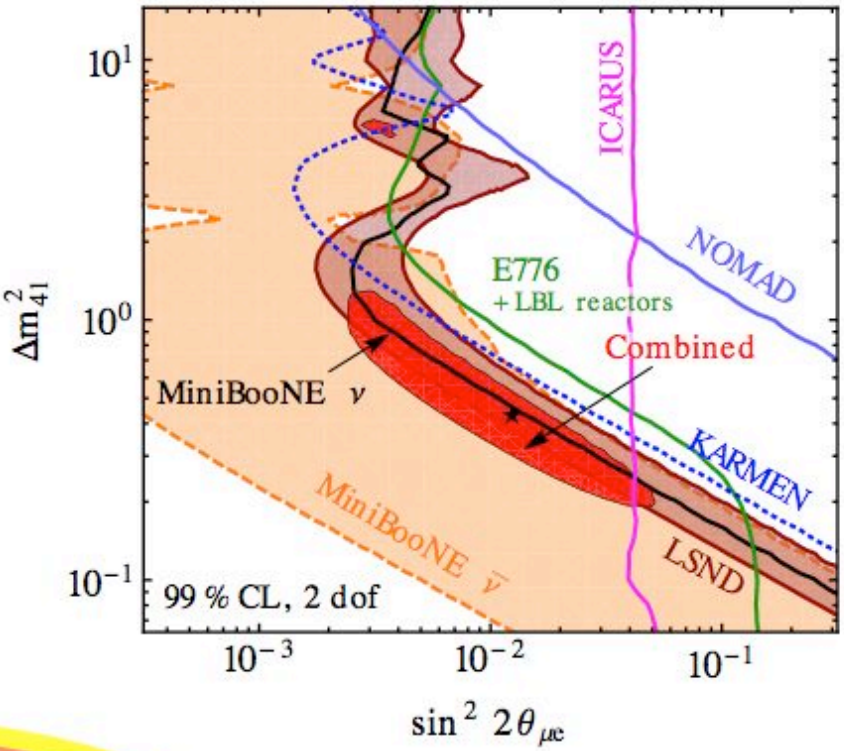
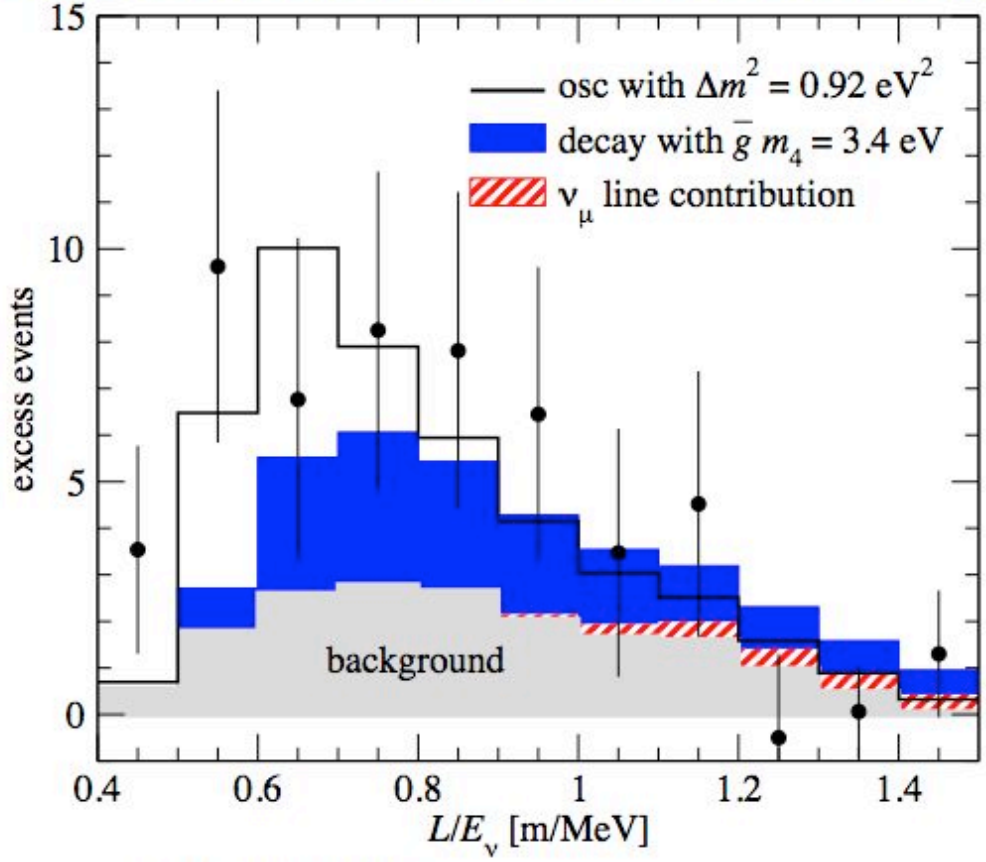
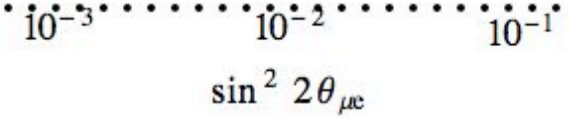


but do it look like neutrino oscillation?



LSND

Palomares-Ruiz Pascoli Schwetz
JHEP 0509 (2005) 048



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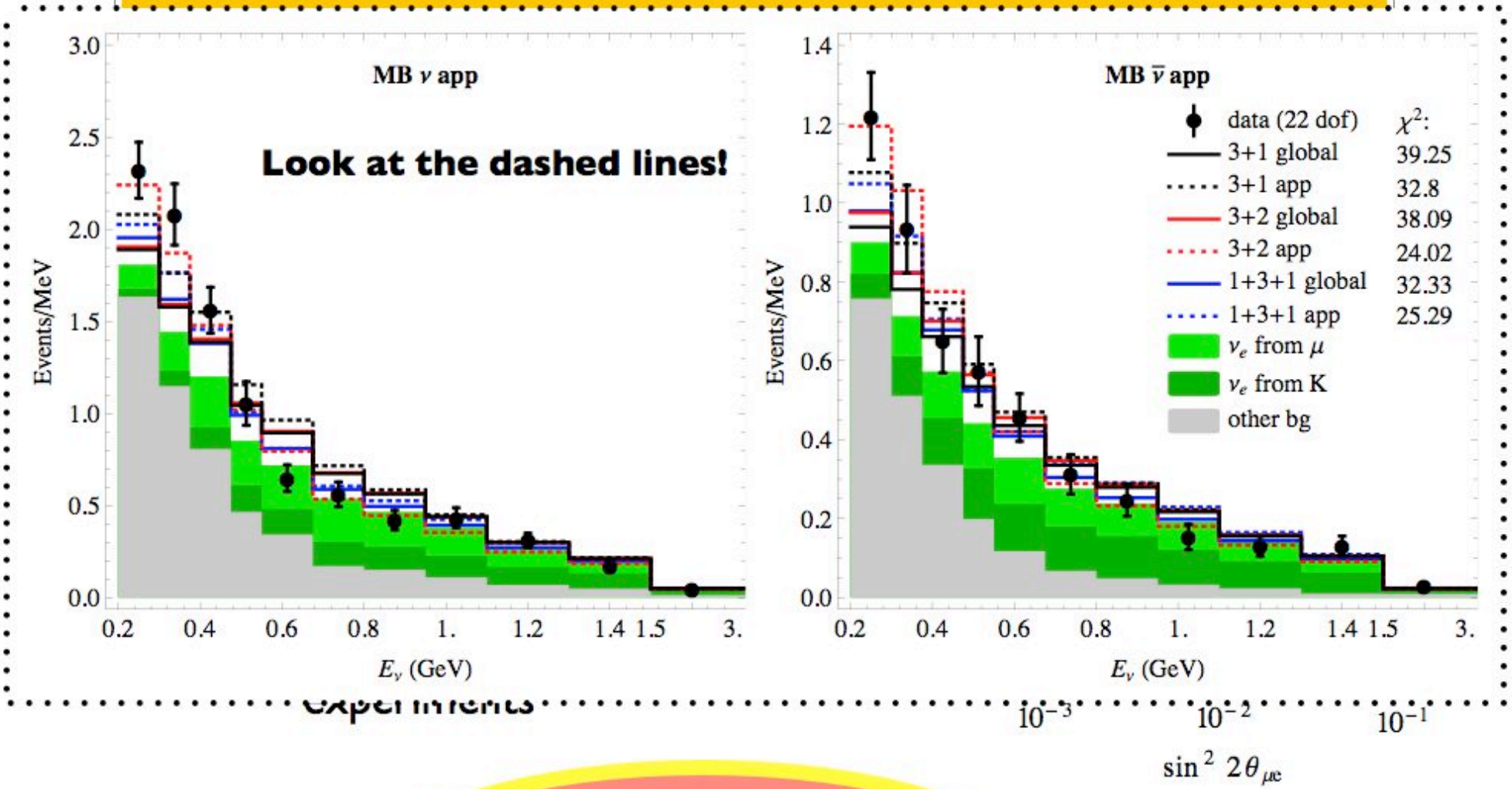

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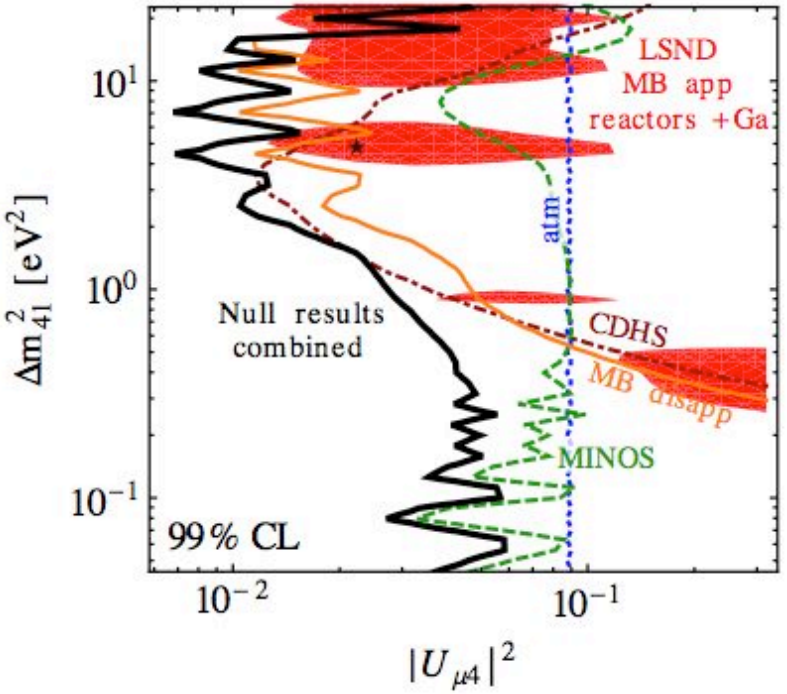
ν_μ disapp bounds

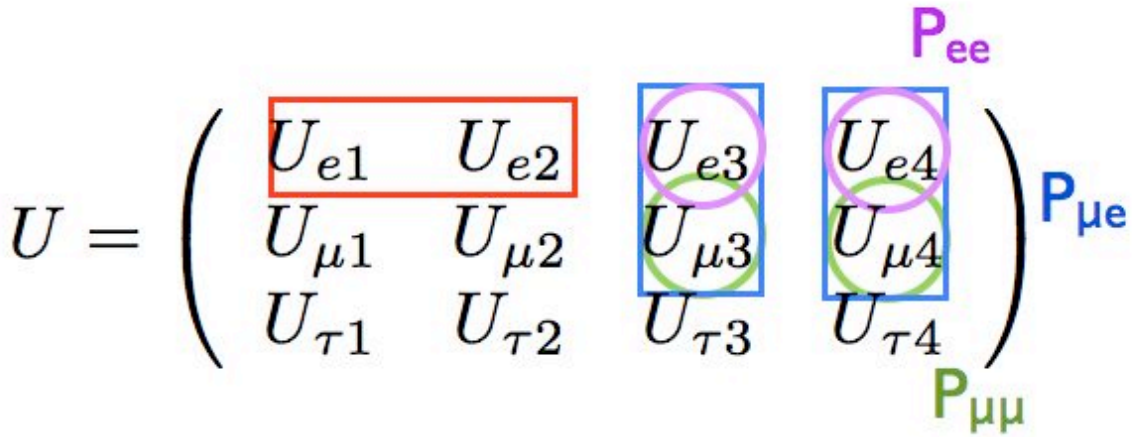
$$P^{\mathrm{SBL},3+1}_{\mu\mu} = 1 - 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)\sin^2\frac{\Delta m^2_{41}L}{4E}$$

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

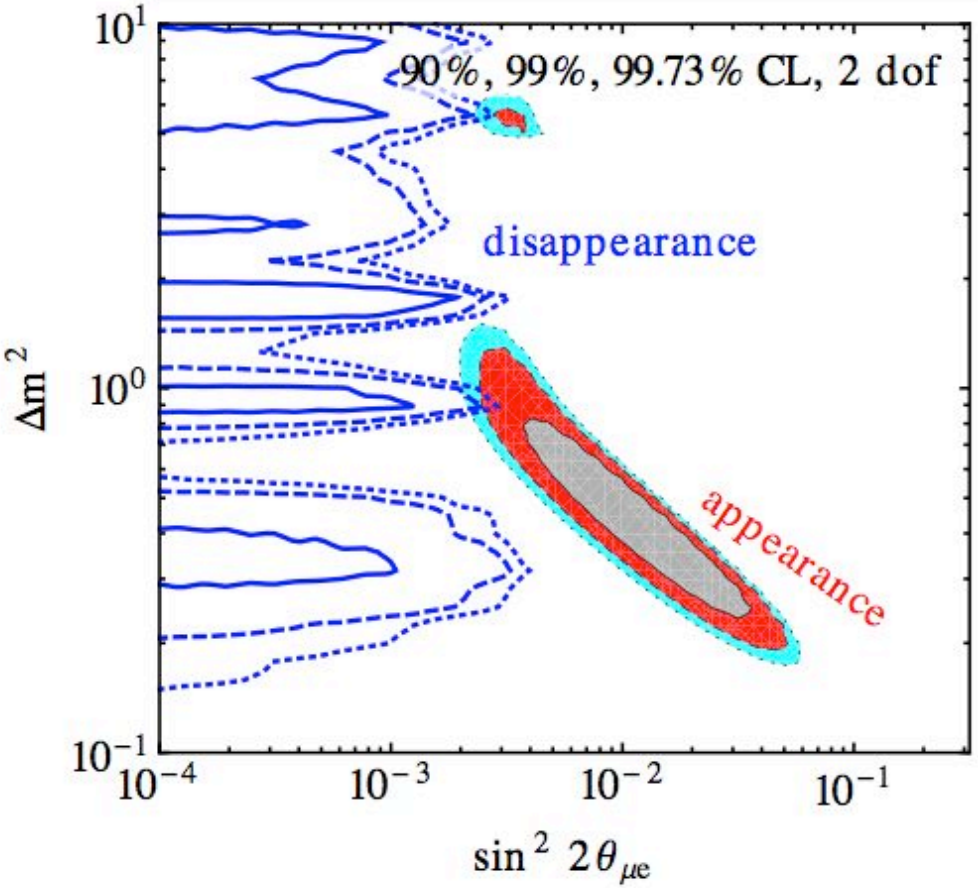


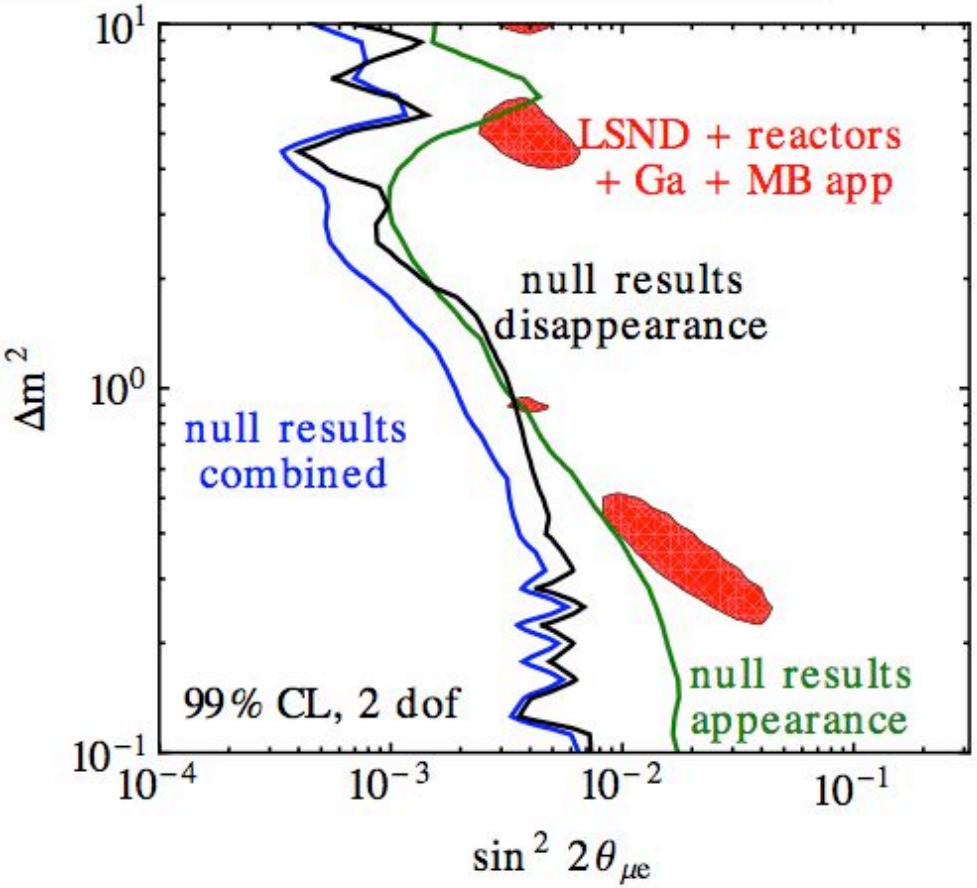
For large Δm^2, ν_e disappearance depends on U_{e4}

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

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

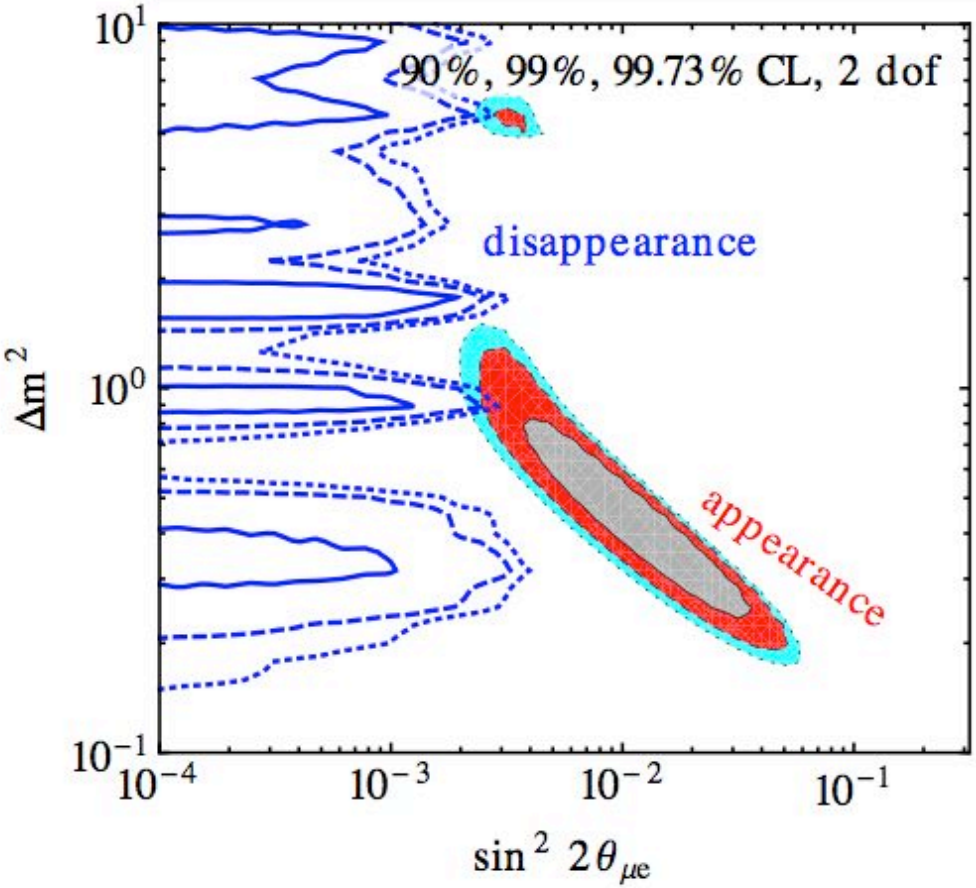
All together now

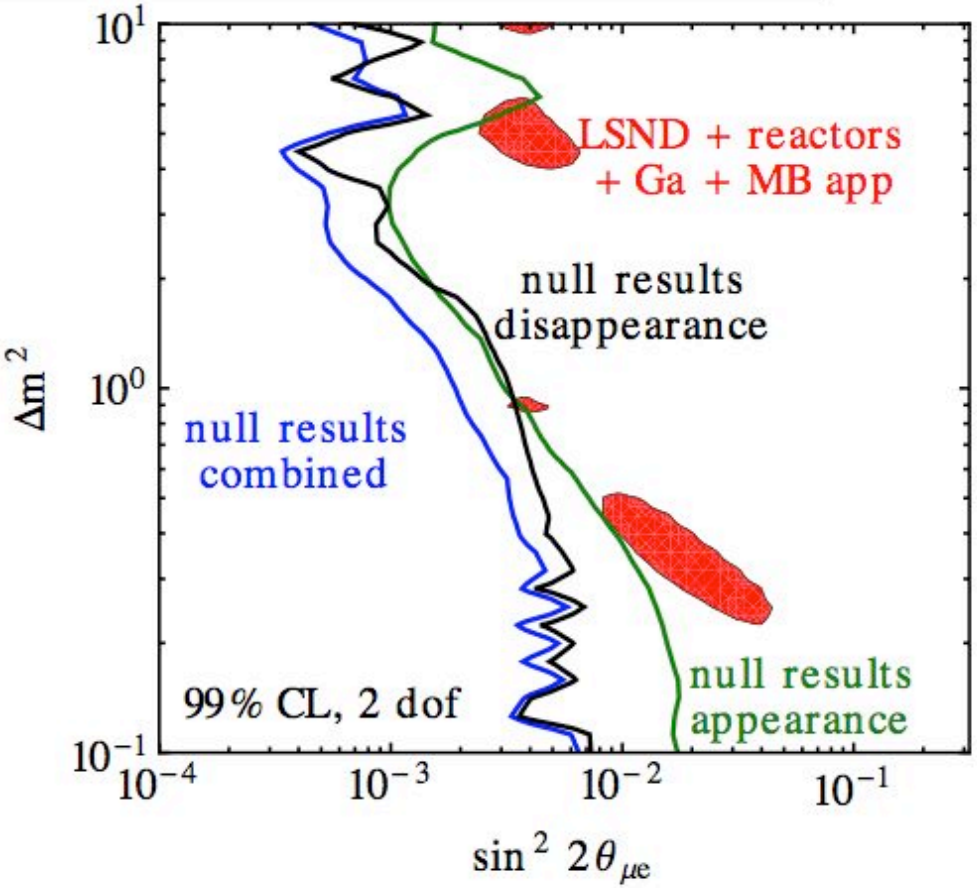




The app data is in **conflict** with the disapp data, specially ν_μ!

All together now





	$\chi^2_{\rm min}$/dof	GOF	$\chi^2_{\rm PG}$/dof	PG	$\chi^2_{\rm app,glob}$	$\Delta\chi^2_{\rm app}$	$\chi^2_{\rm dis,glob}$	$\Delta\chi^2_{\rm dis}$
3+1	$712/(689-9)$	19%	18,0/2	$1{,}2\times10^{-4}$	95,8/68	7,9	616/621	10,1

3+2 and 1+3+1

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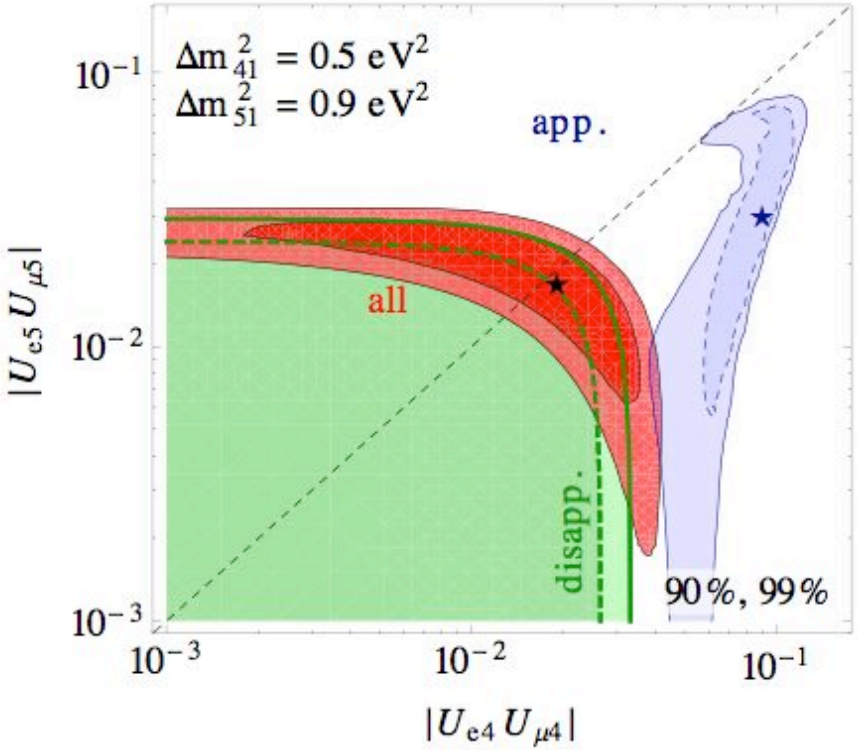
1+3+1	$694/(689-14)$	30%	16,8/4	$2{,}1\times10^{-3}$	82,4/68	7,8	611/621	9,0

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

PAN Machado

3+2 and 1+3+1

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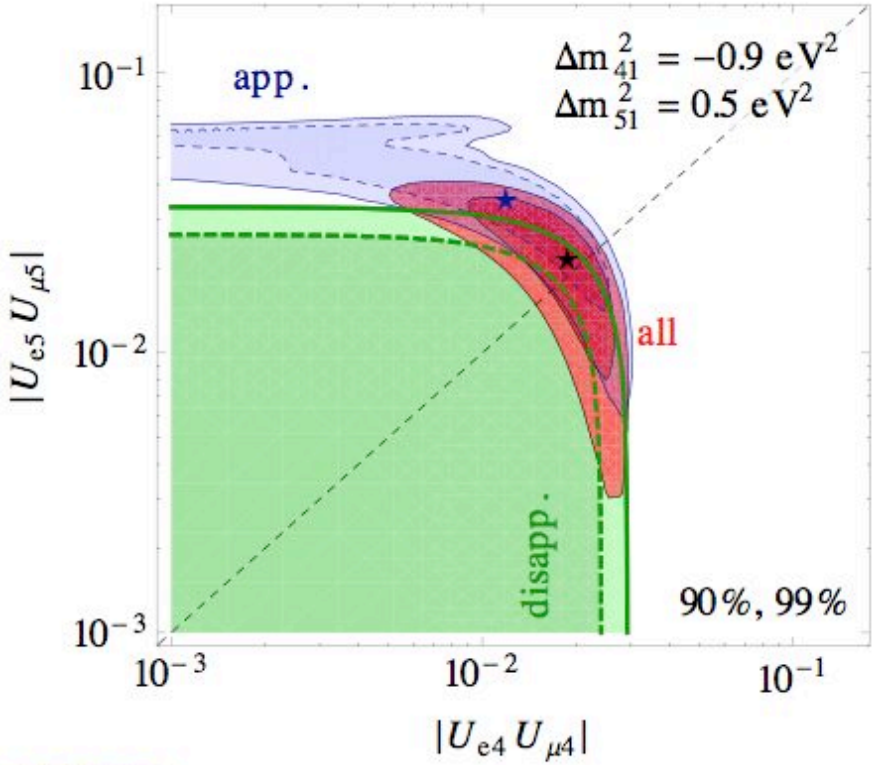

see, e.g., Karagiorgi, Shaevitz, Conrad AHEP (2013) 163897

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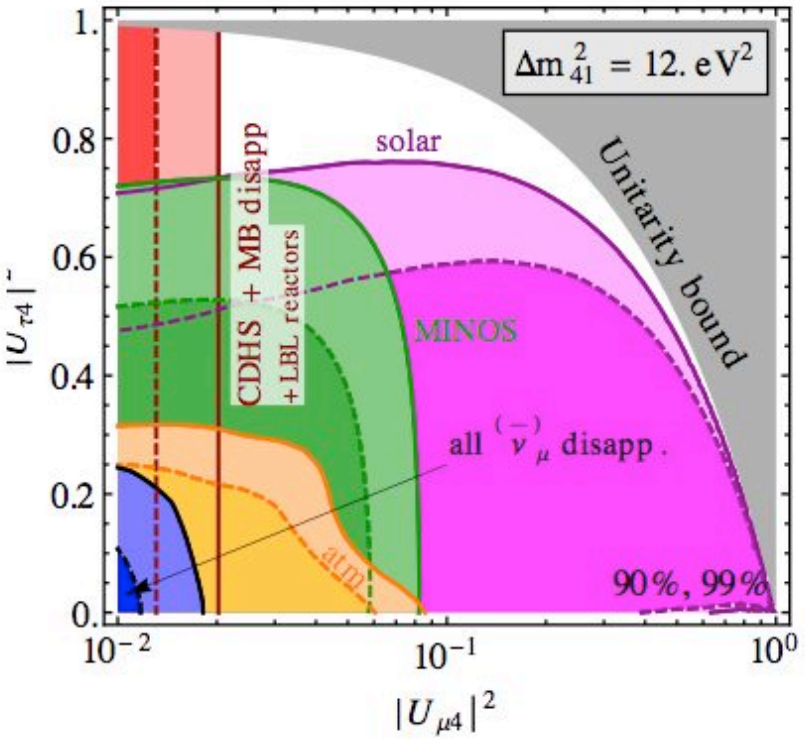
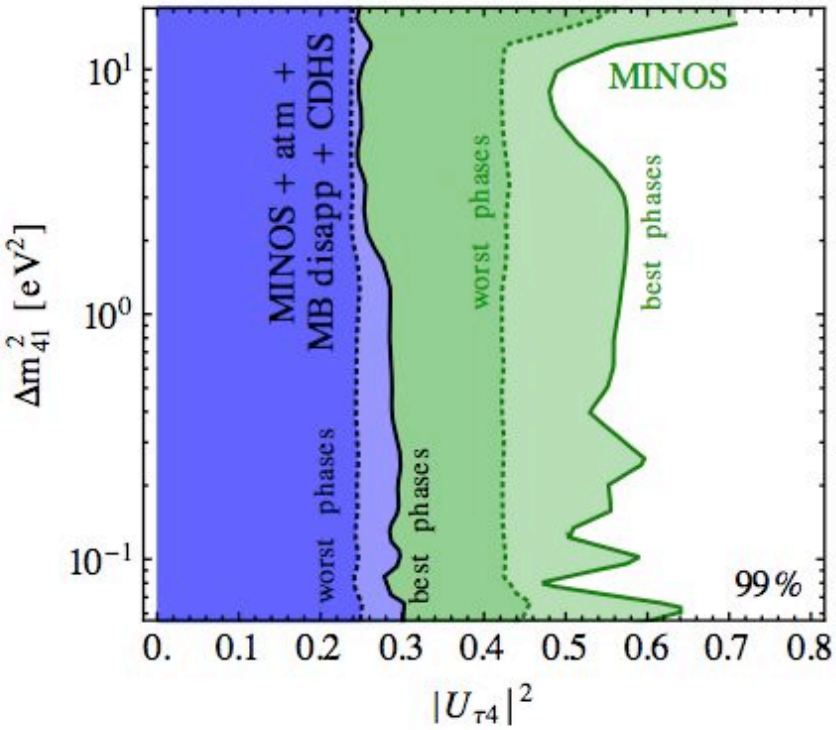
Bounds on U_{t4}

Dominated by atmospheric data





$$|U_{\tau 4}|^2 \lesssim 0.2 \quad \text{at} \quad 2\sigma\,(1\text{ dof})$$

GDRv Nov-13-2013

PAN Machado

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.

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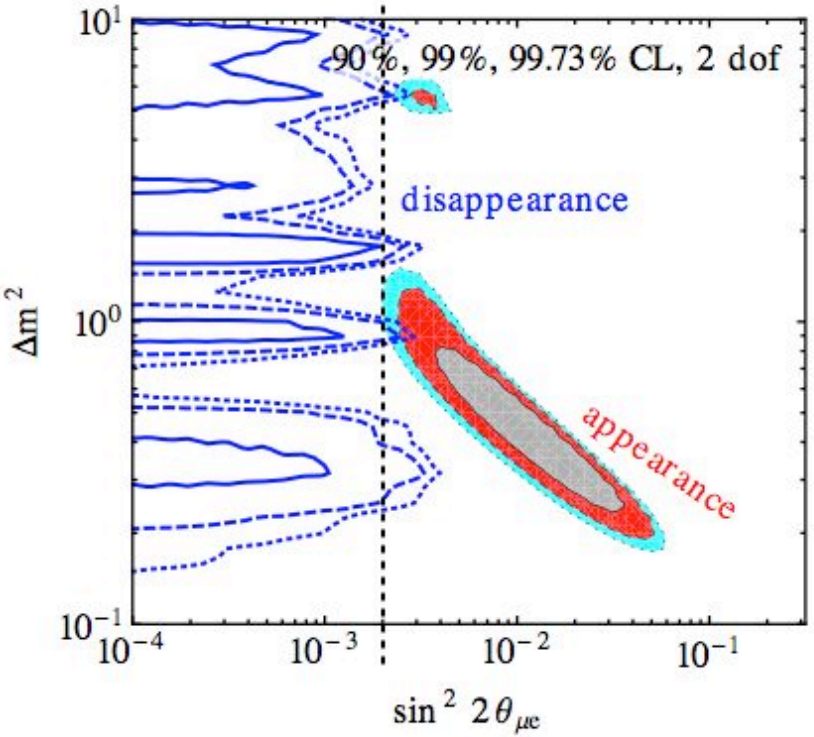
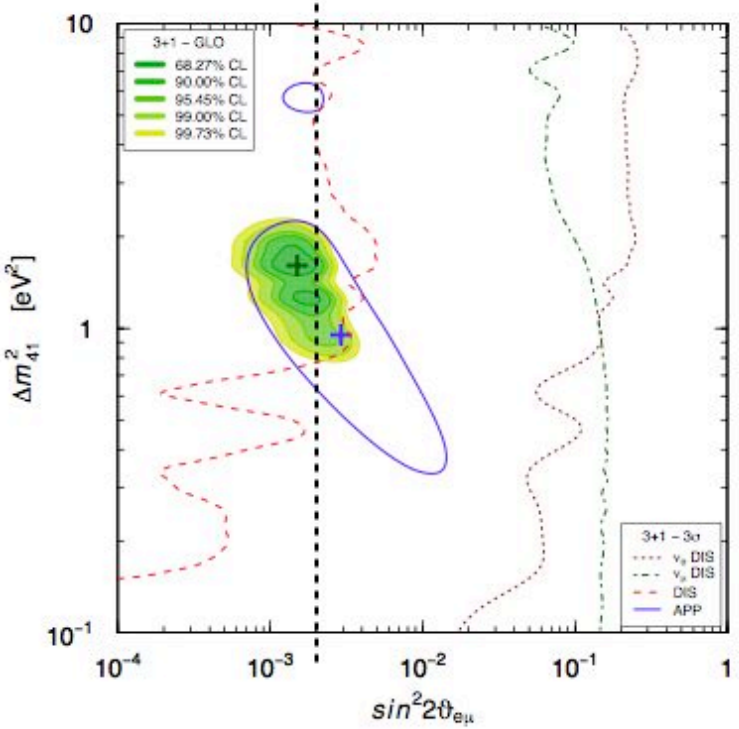
Merci!

Backup

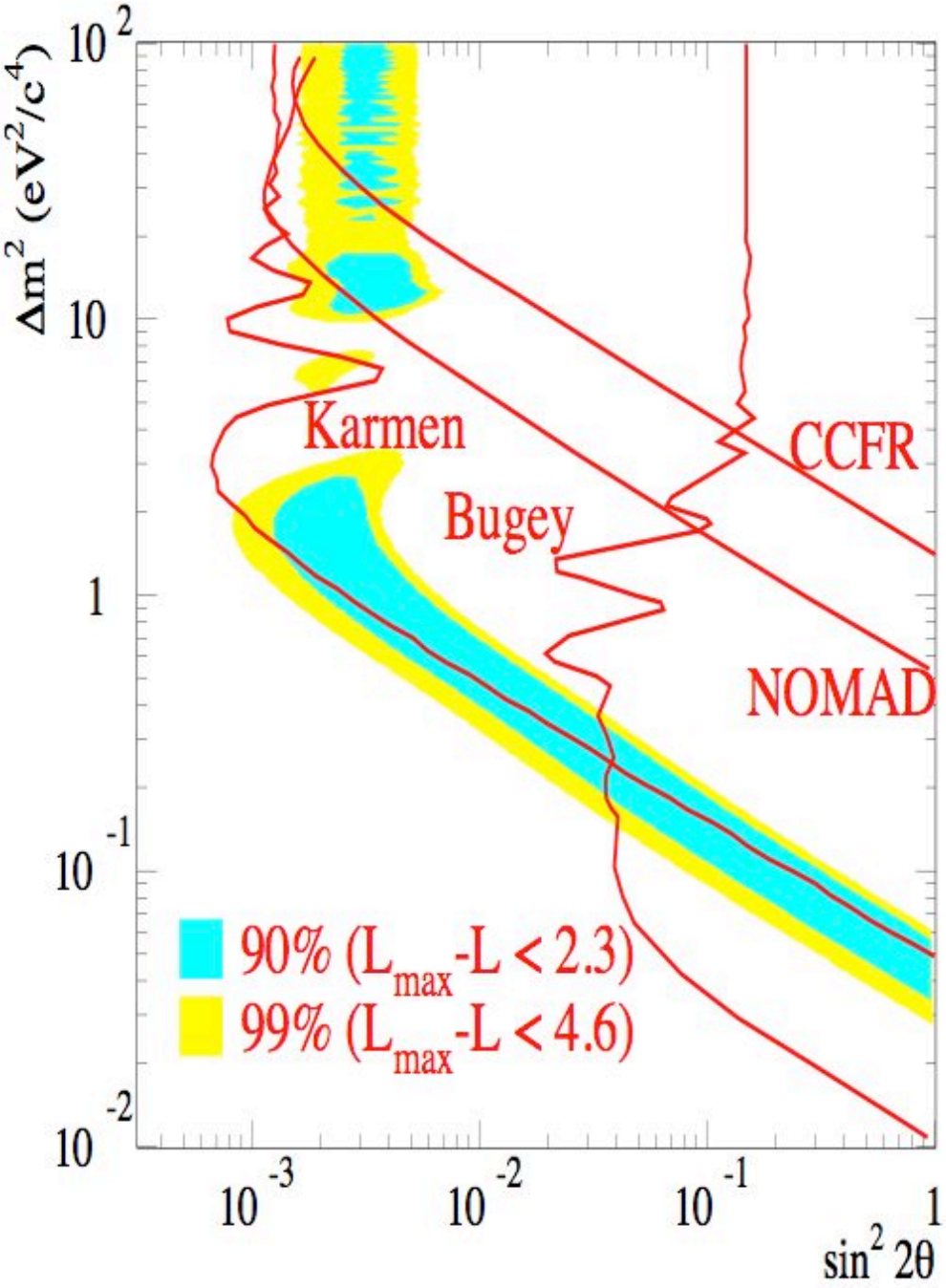
Differences between Giunti et al and our fit



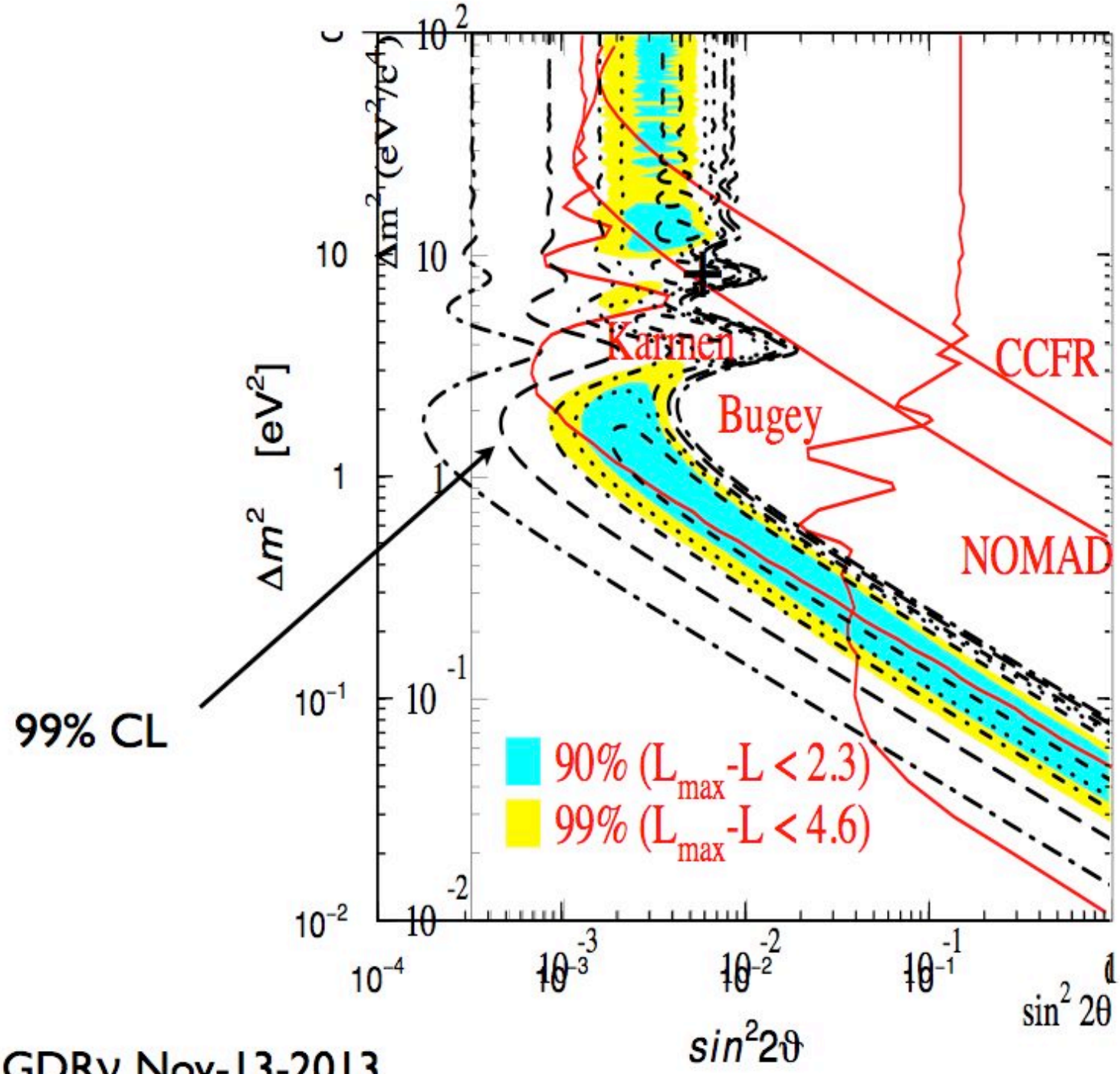
Kopp et al 2013



Giunti et al 2013



LSND final result
hep-ex/0104049



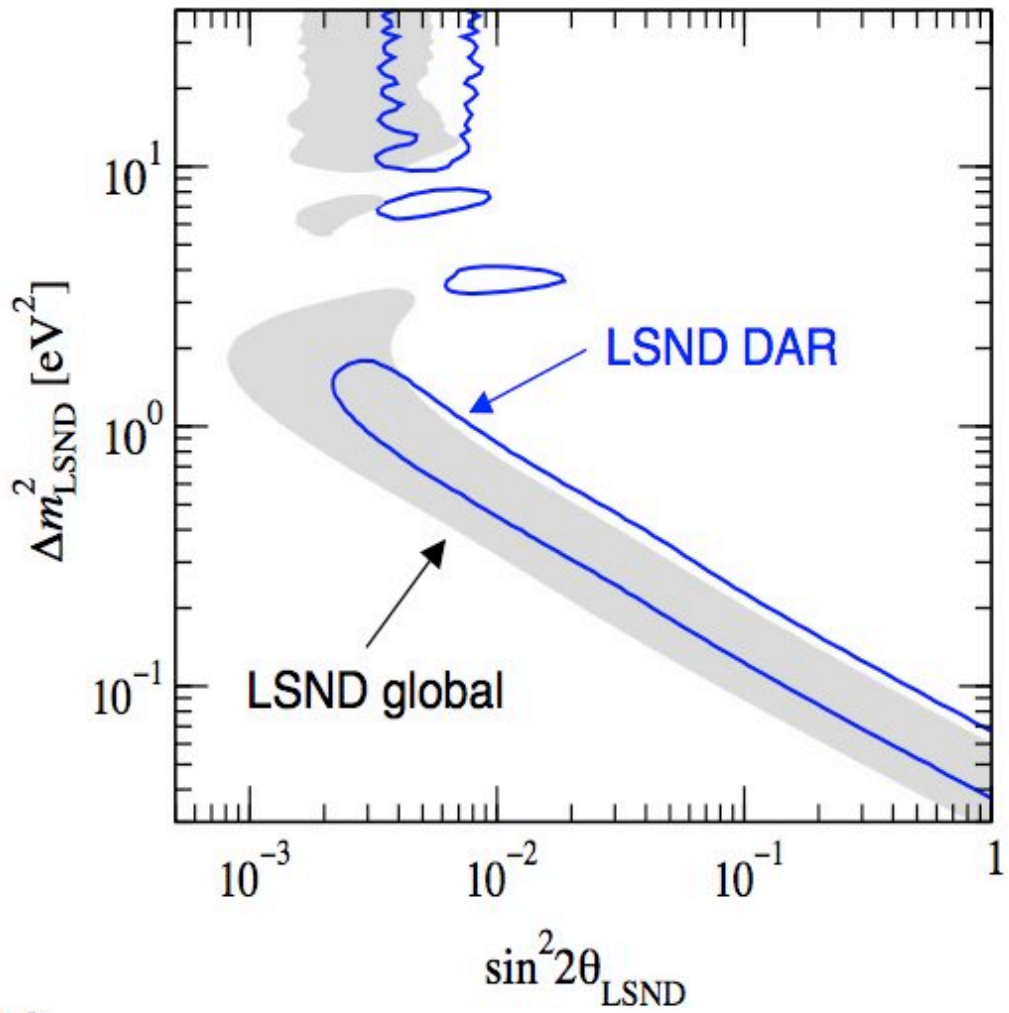
99% CL

LSND final result:
hep-ex/0104049

Giunti Laveder
1010.1395

Differences between Giunti et al and our fit

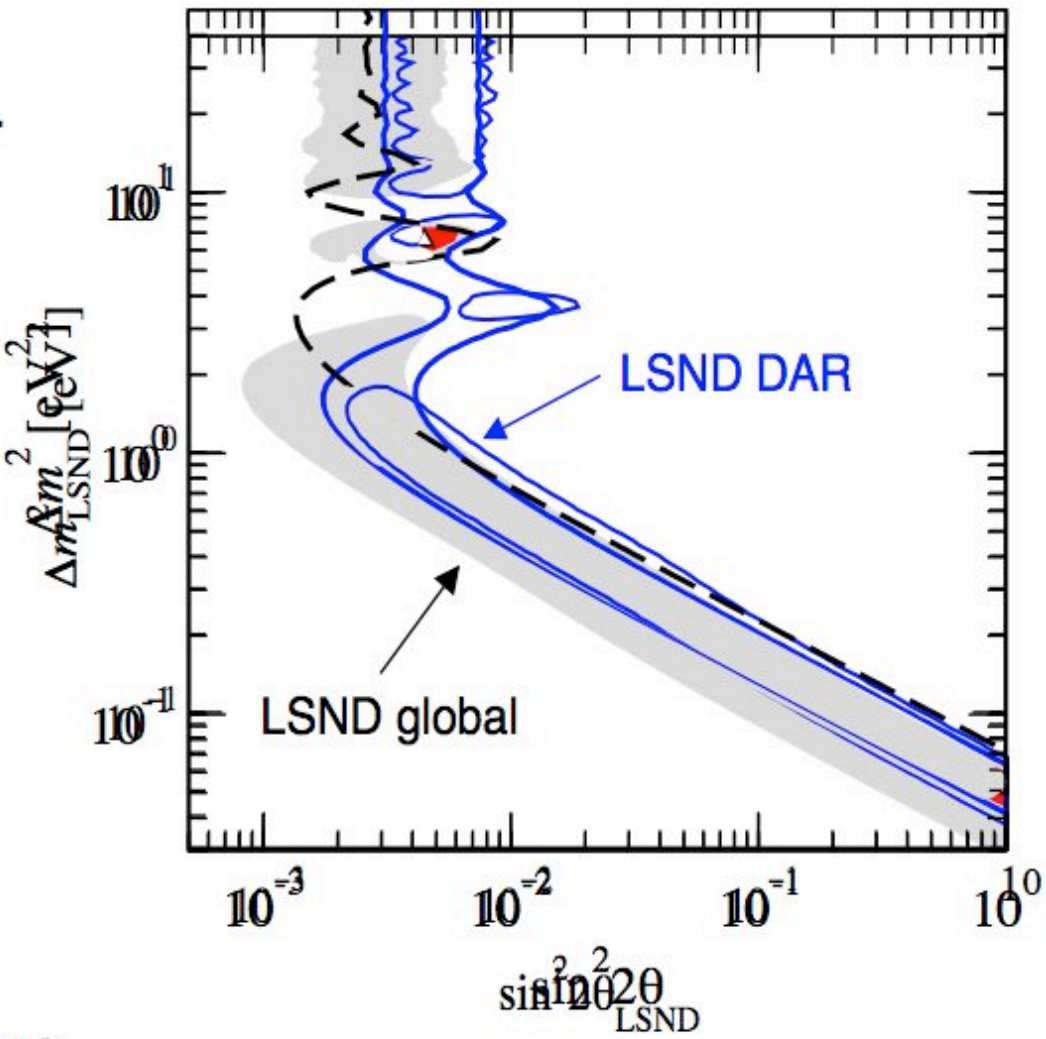
99% CL



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

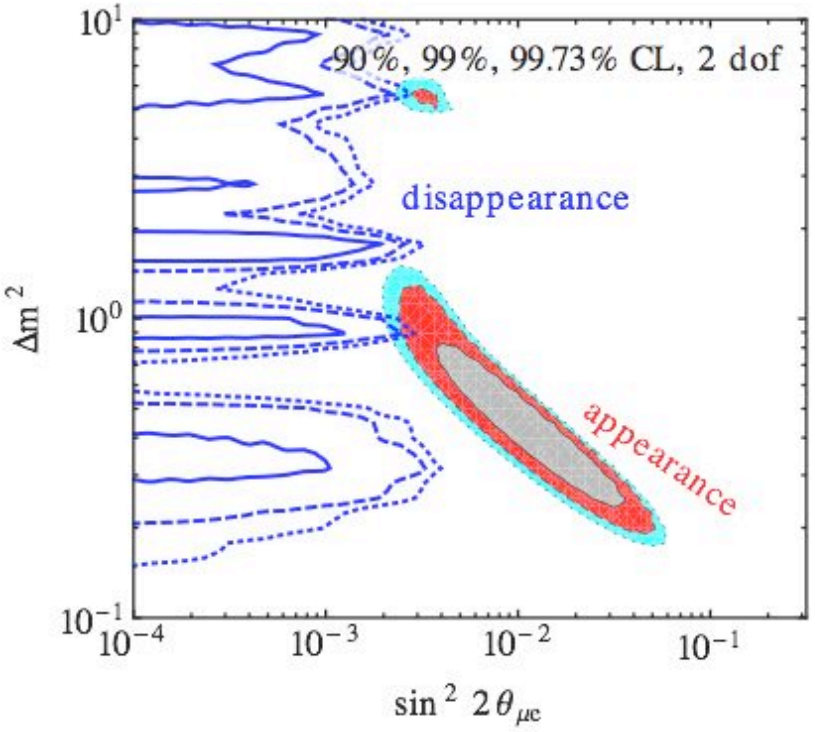
Differences between Giunti et al and our fit

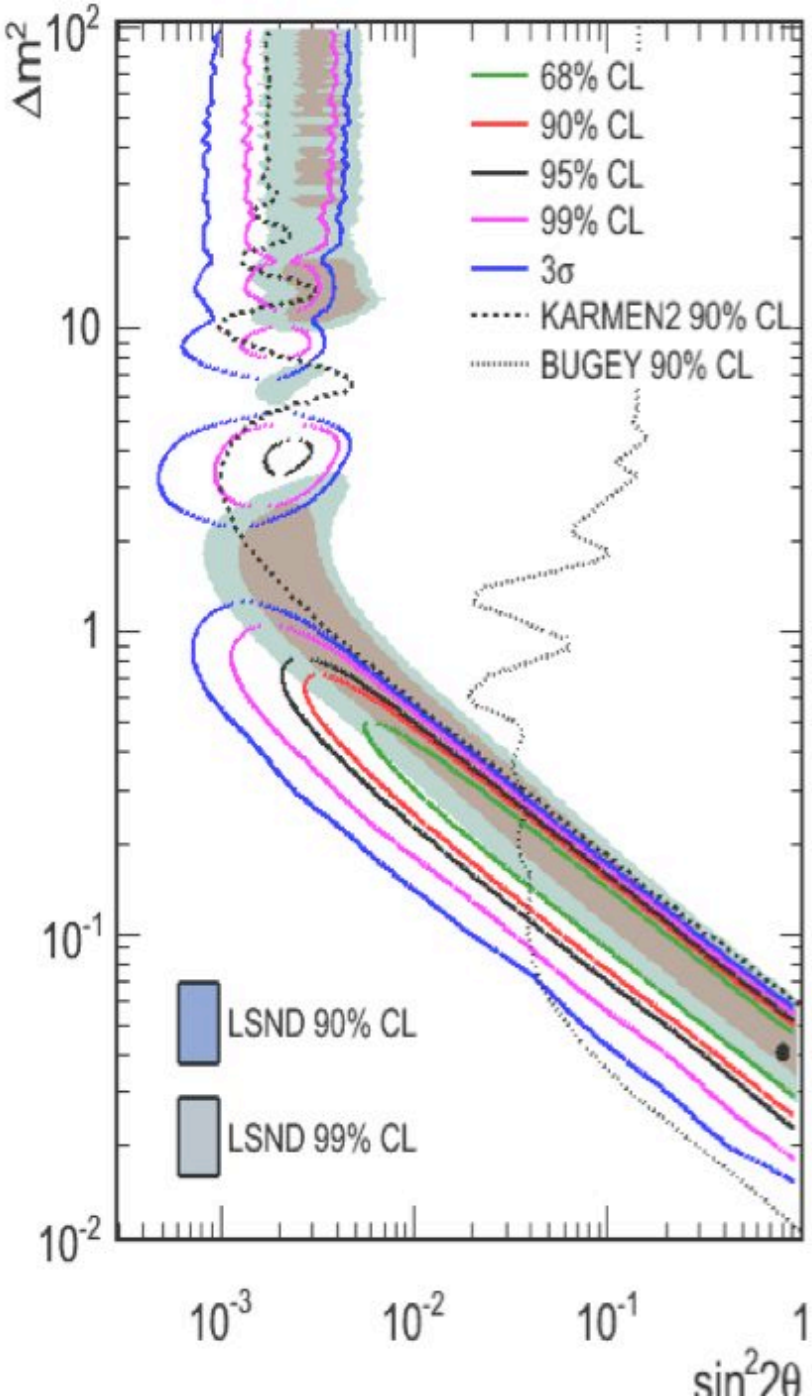
99% CL



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

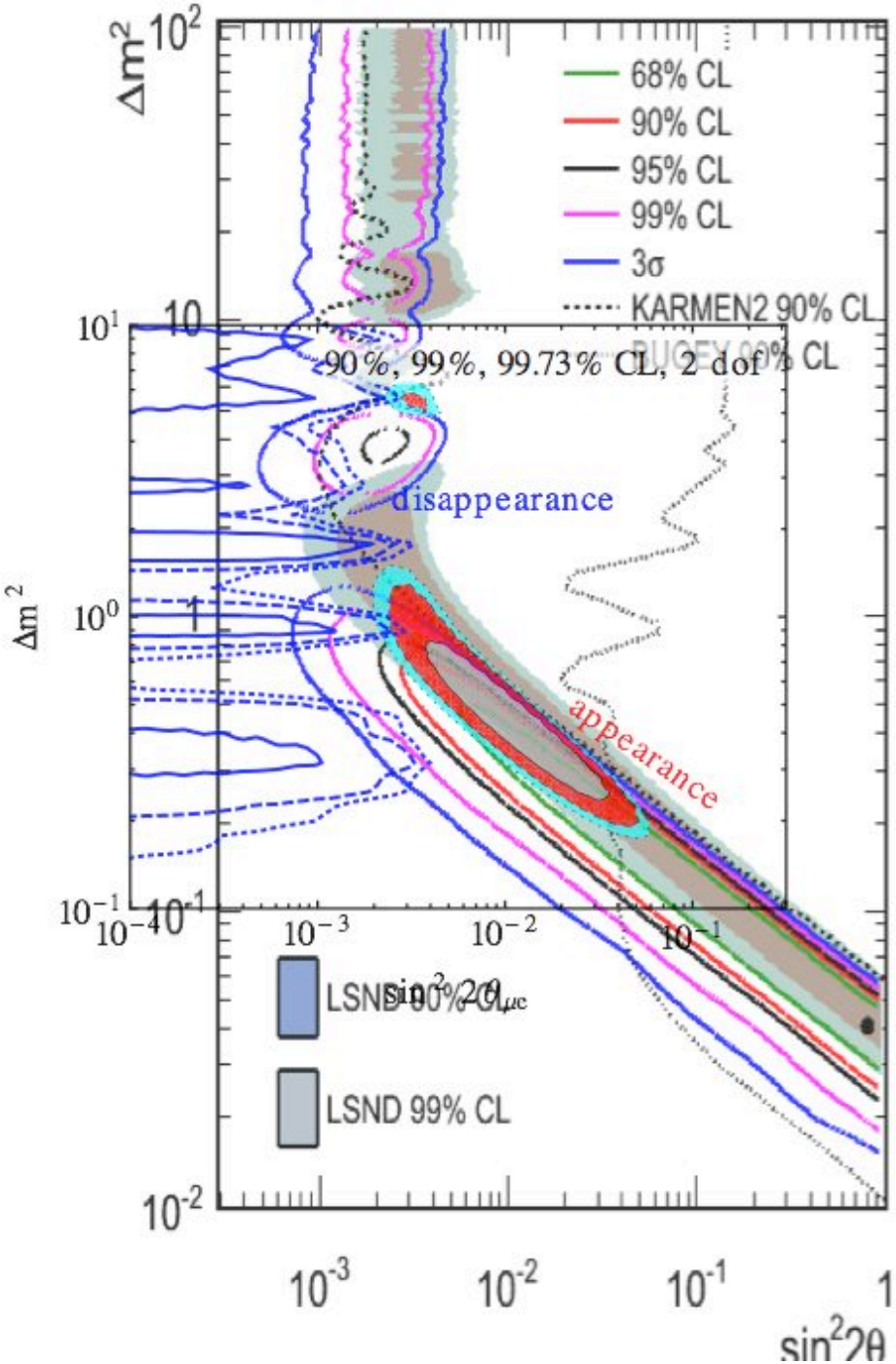
our LSND fit:
Palomares-Ruiz,
Pascoli, Schwetz
hep-ph/0505216


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



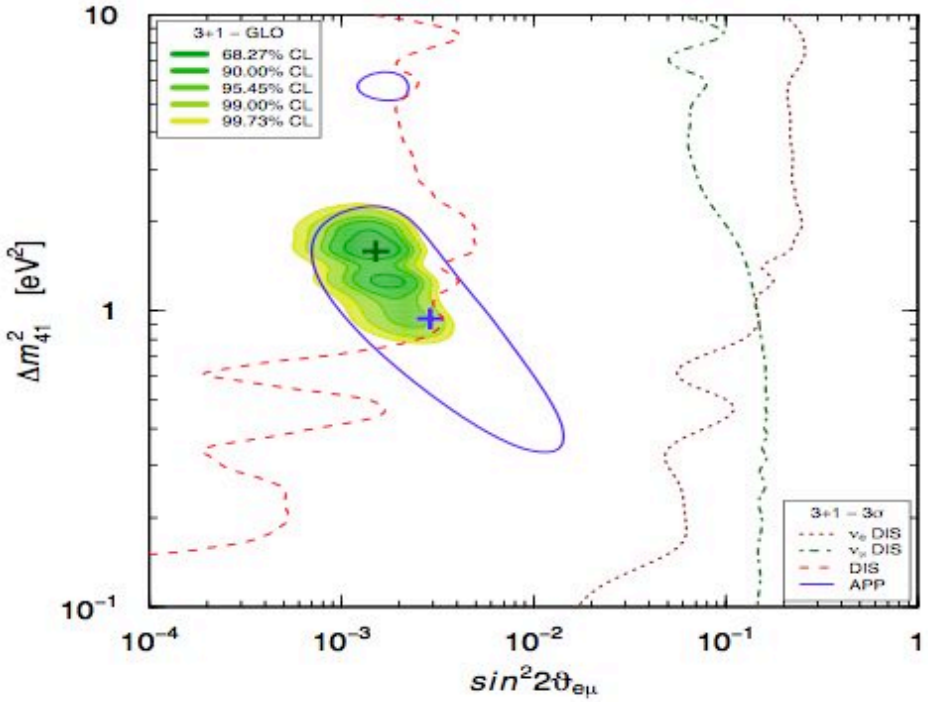
GDRv Nov-13-2013

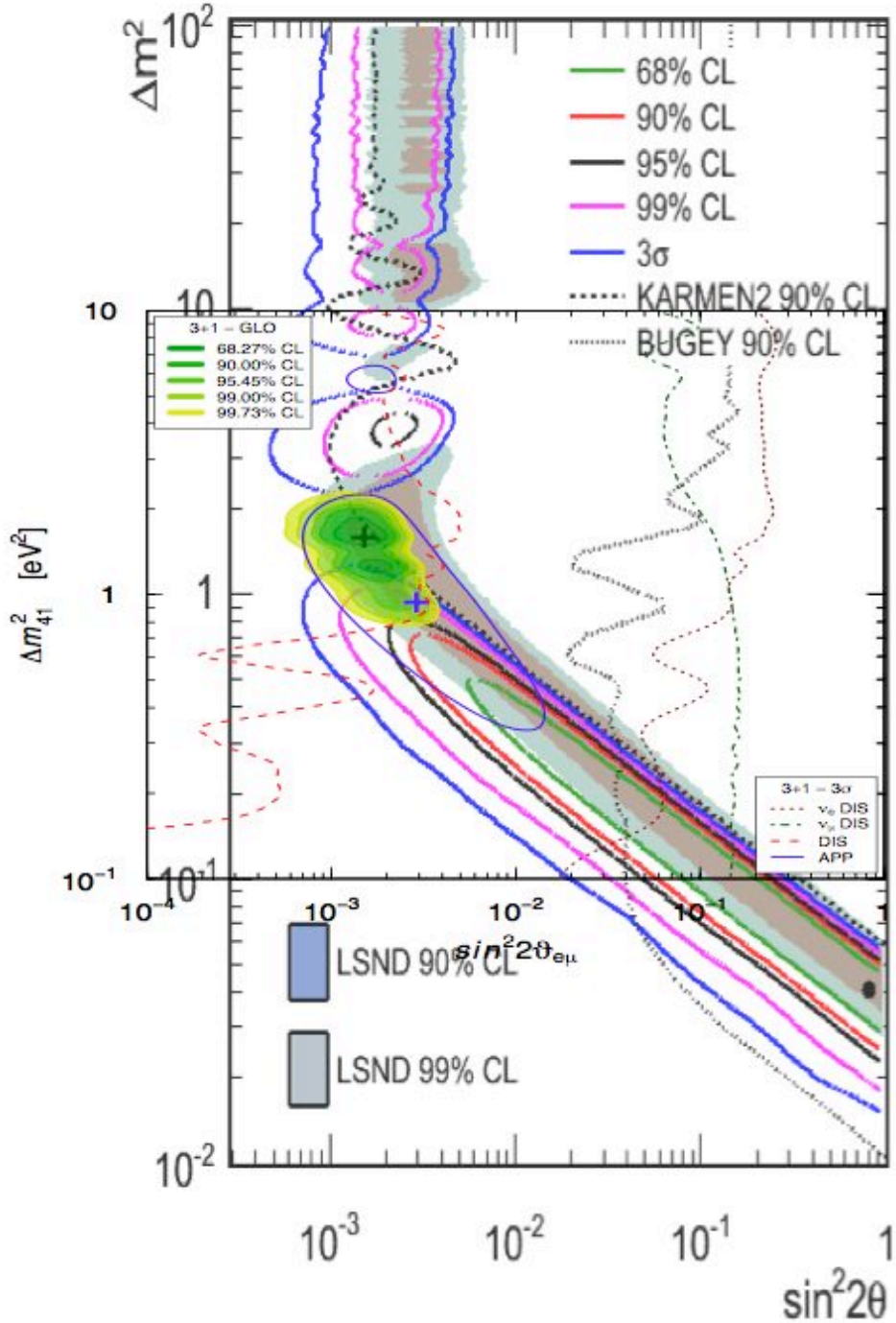
PAN Machado



GDRv Nov-13-2013

PAN Machado

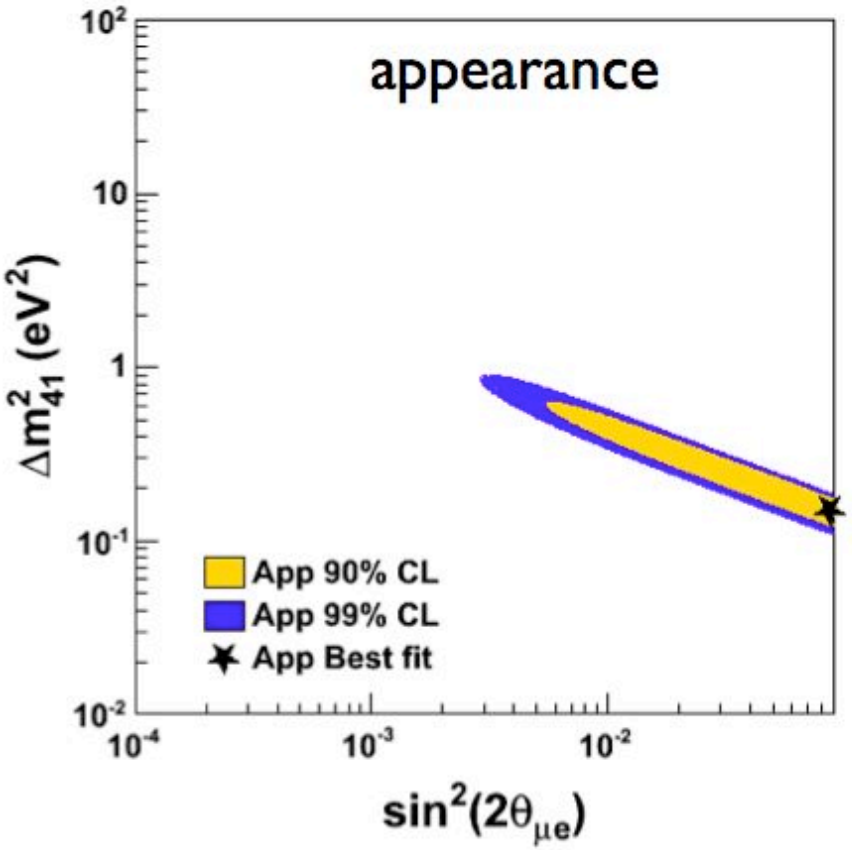

3+1 – GLO
68.27% CL
90.00% CL
95.45% CL
99.00% CL
99.73% CL
3+1 – 3σ
ν_e DIS
ν_μ DIS
DIS
APP
10
1
10^{-1}
Δm^2_{41} [eV^2]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$sin^2 2\vartheta_{e\mu}$

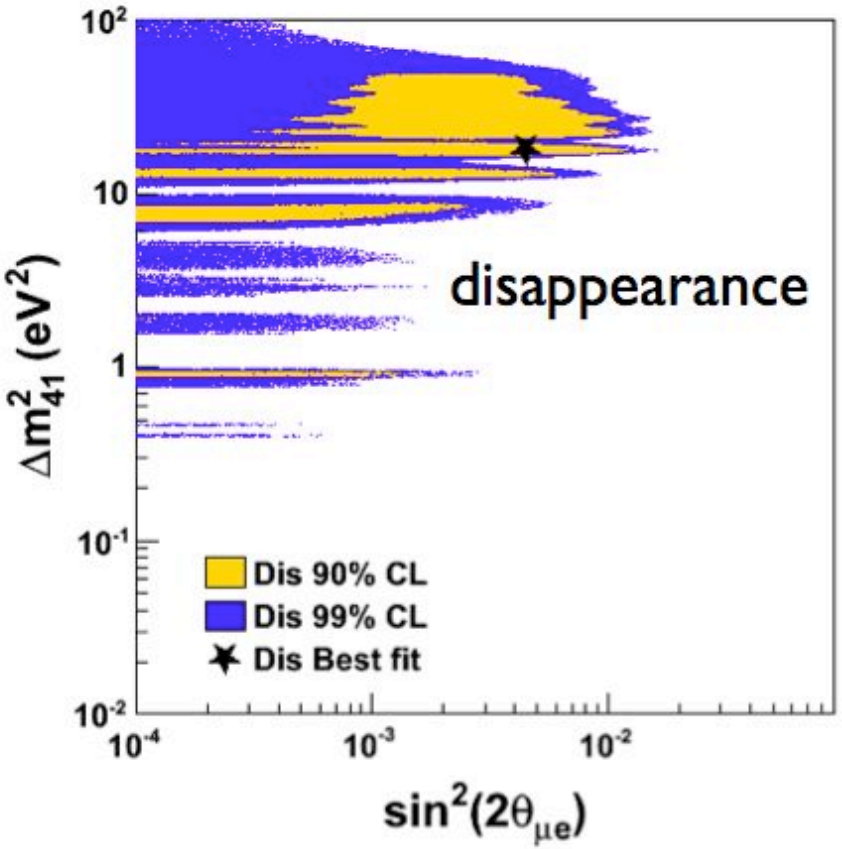


GDRv Nov-13-2013

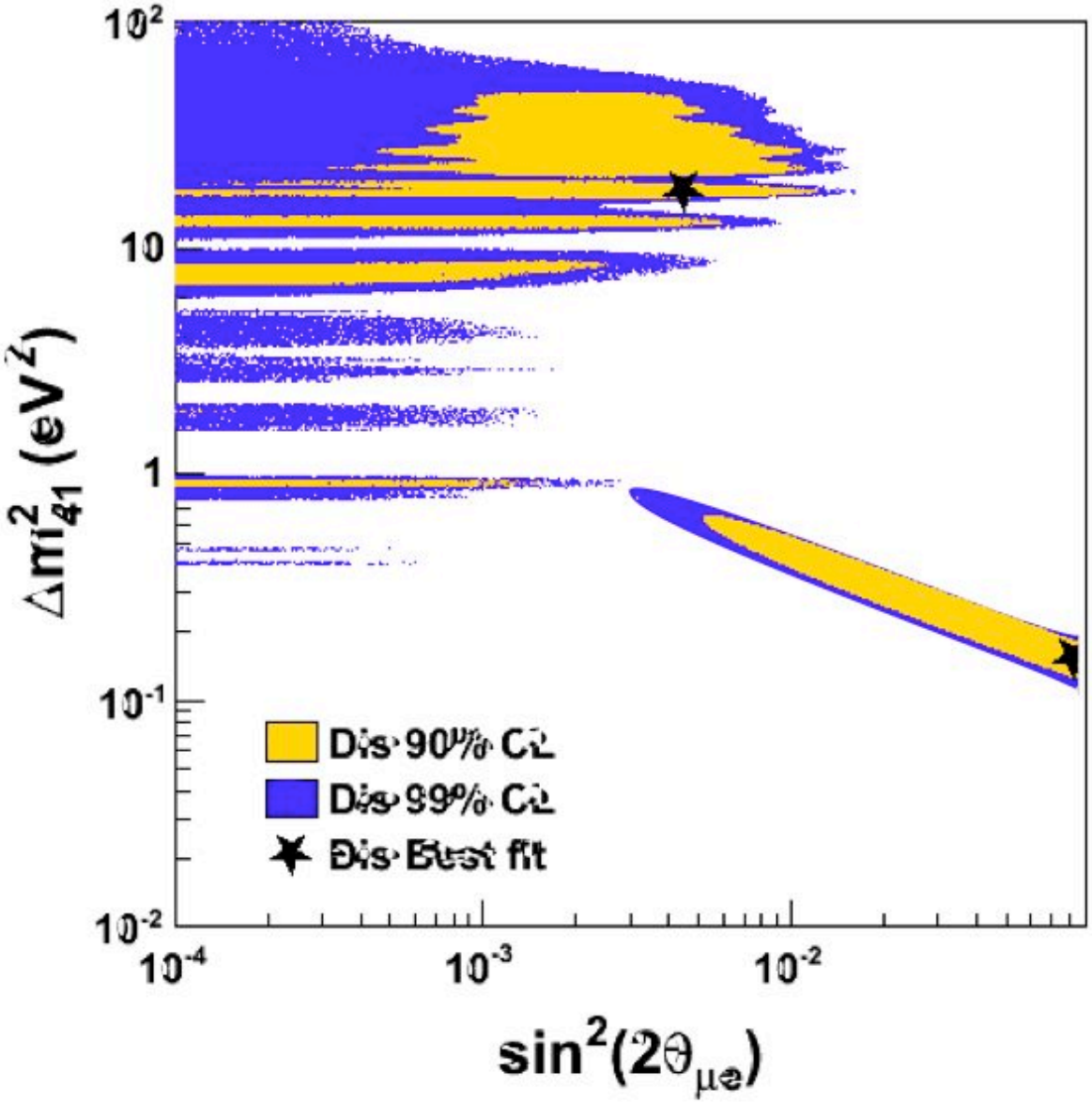
PAN Machado

Karagiorgi, Shaevitz, Conrad AHEP (2013) 163897

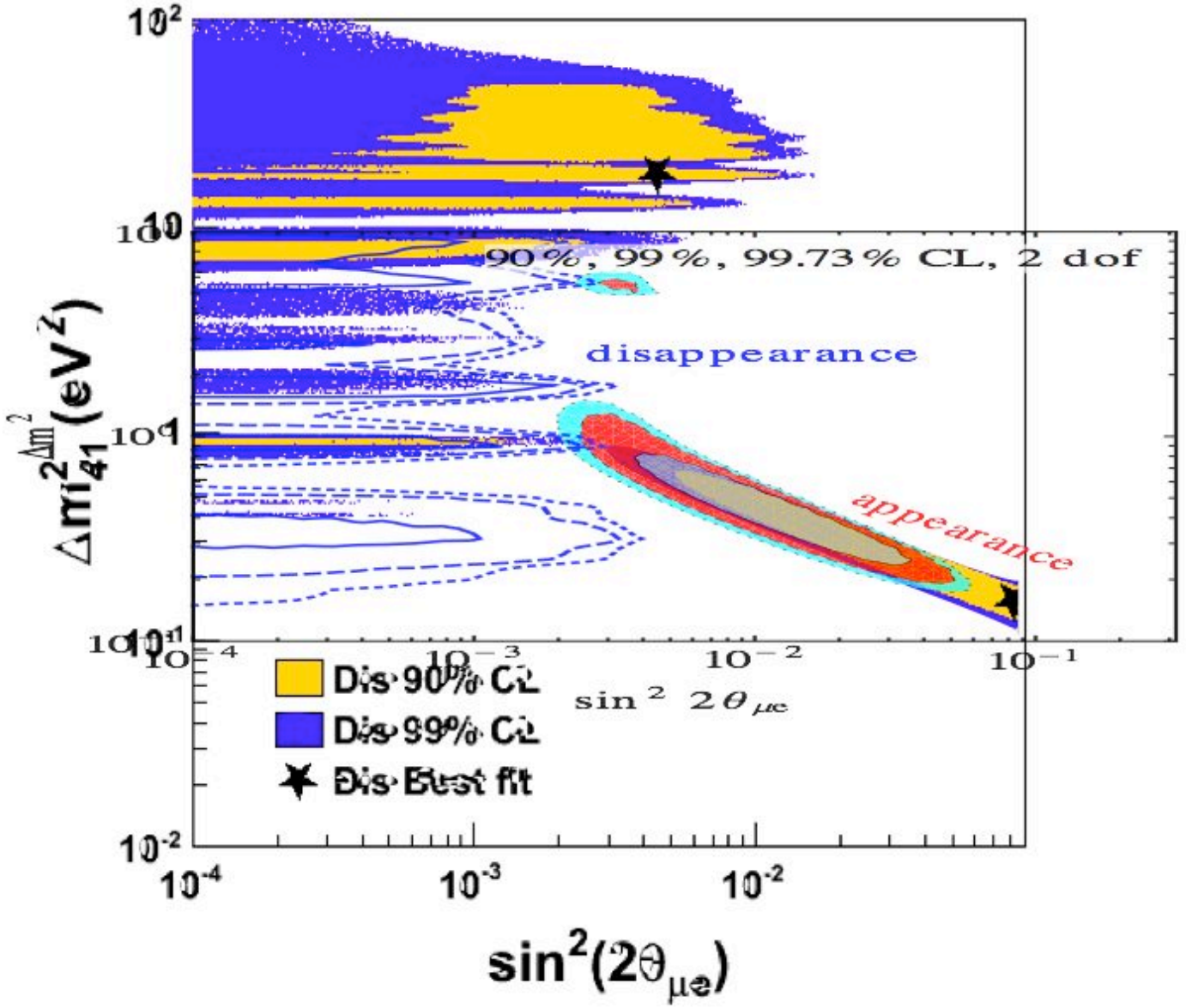




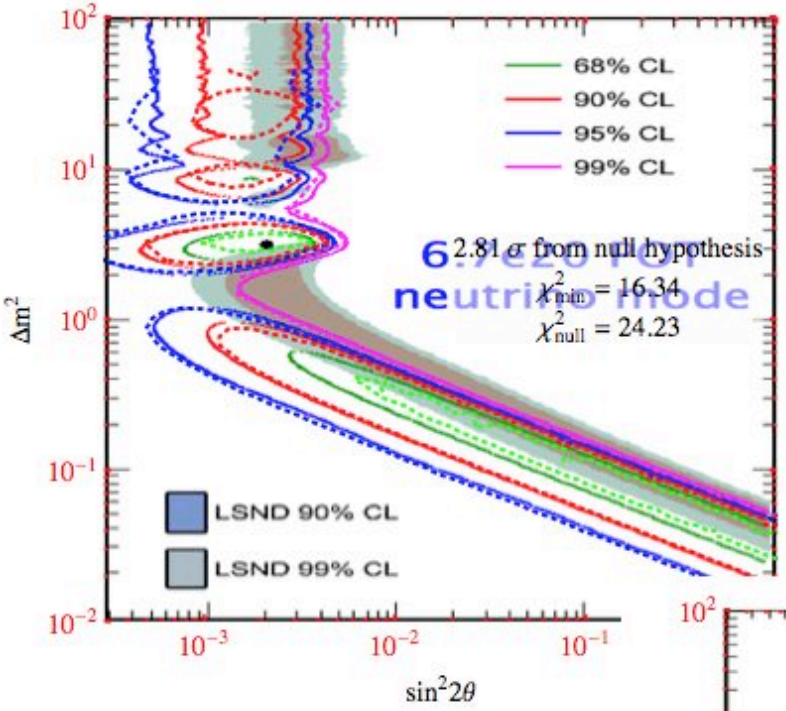
Karagiorgi, Shaevitz, Conrad AHEP (2013) 163897

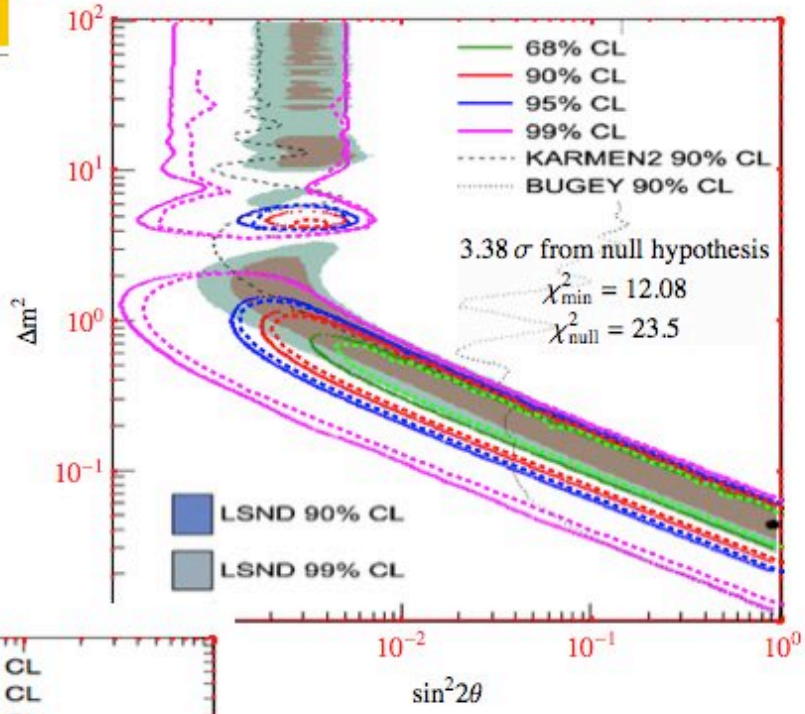


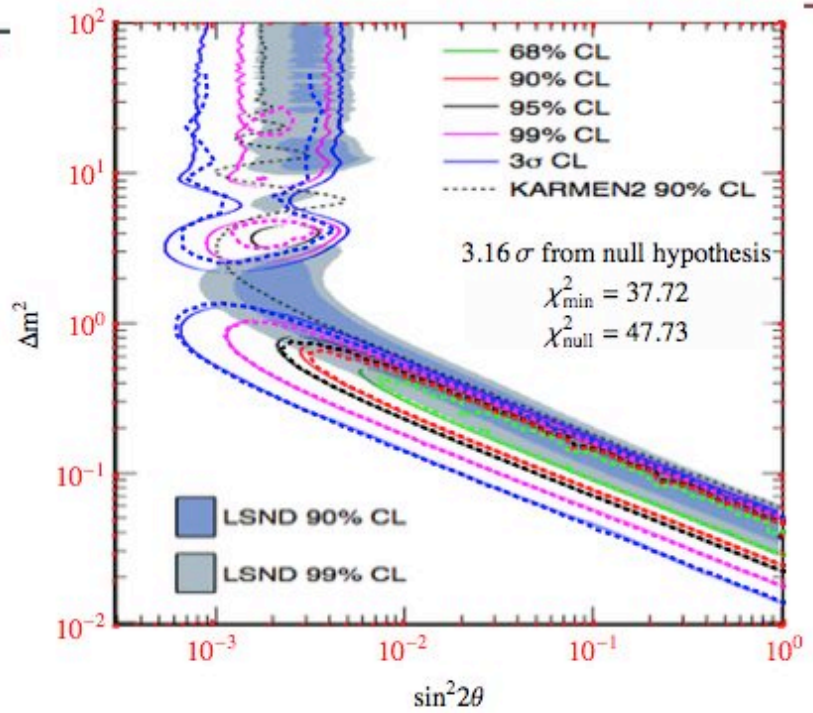
Karagiorgi, Shaevitz, Conrad AHEP (2013) 163897



MiniBooNE



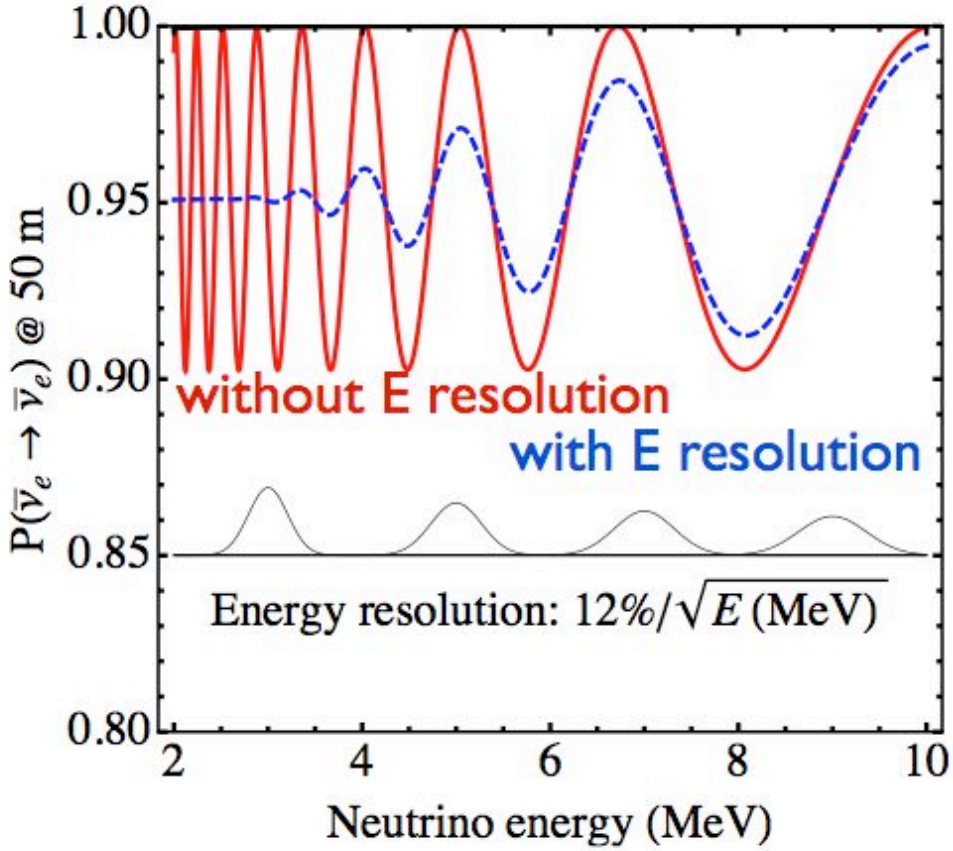


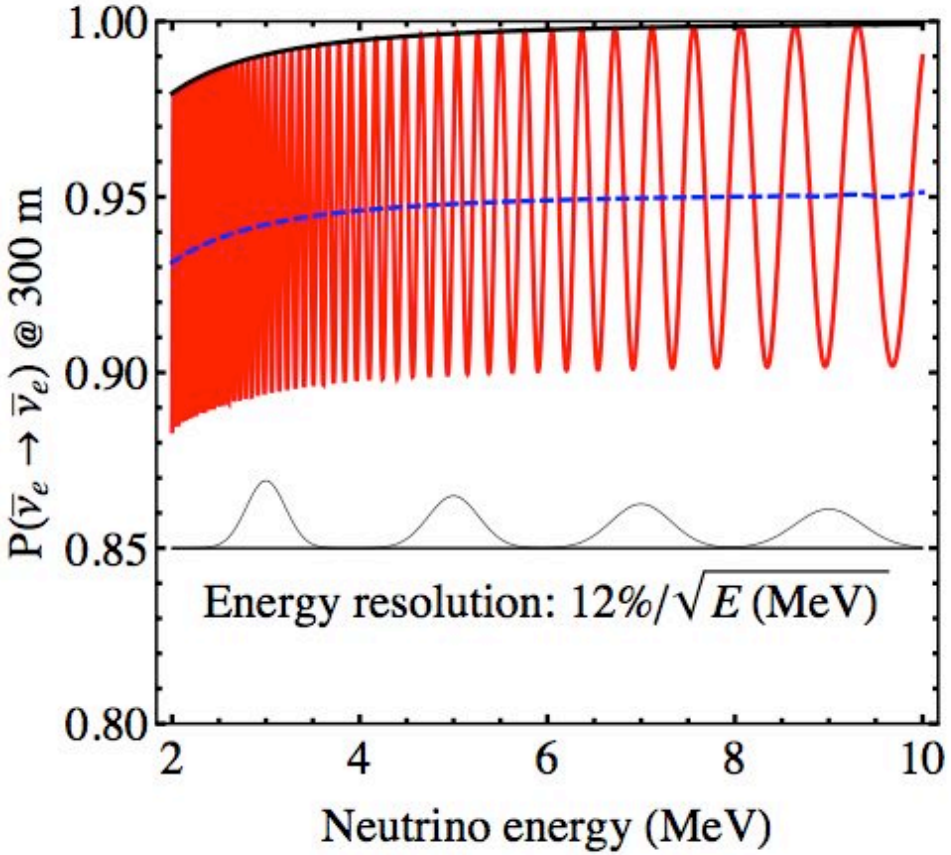


GDRv Nov-13-2013

PAN Machado

Impact of steriles on θ_{13}

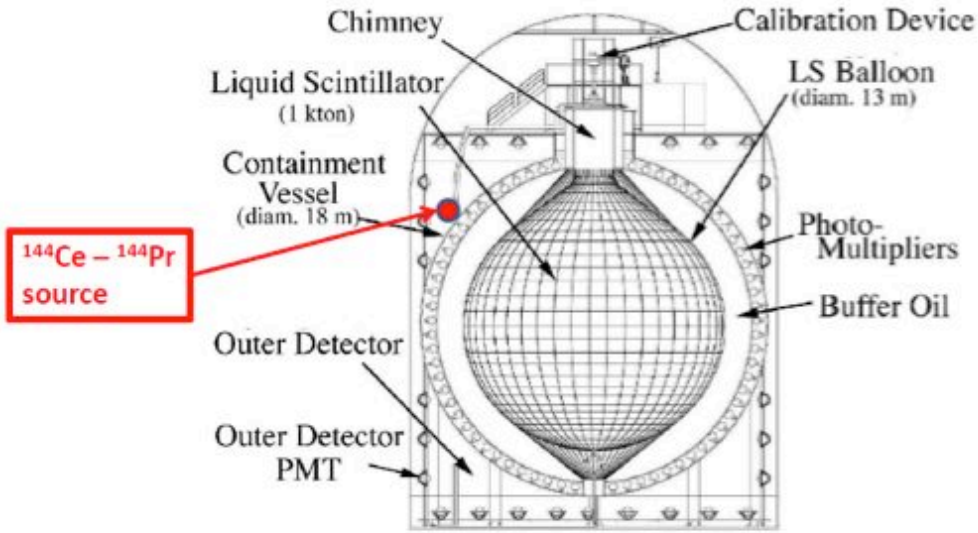


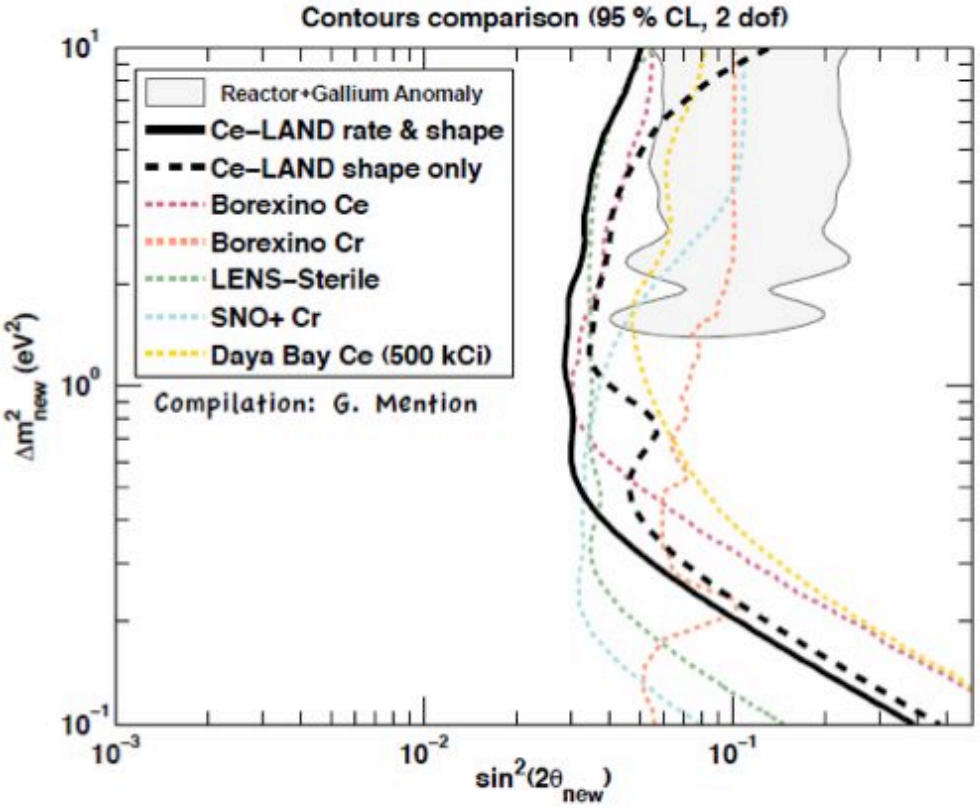


$\Delta m^2_{sterile} = 1\ eV^2$ $\sin^2 2\theta_{sterile} = 0.10$

Future

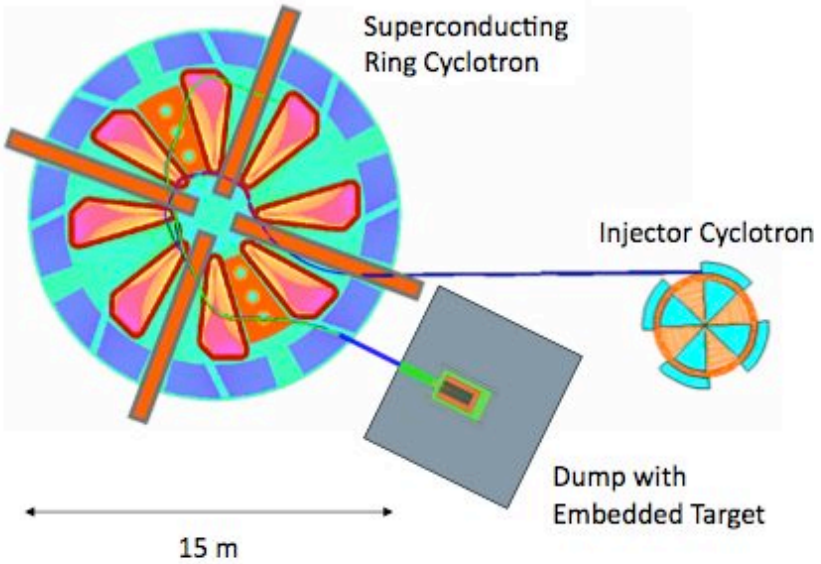
CeLAND

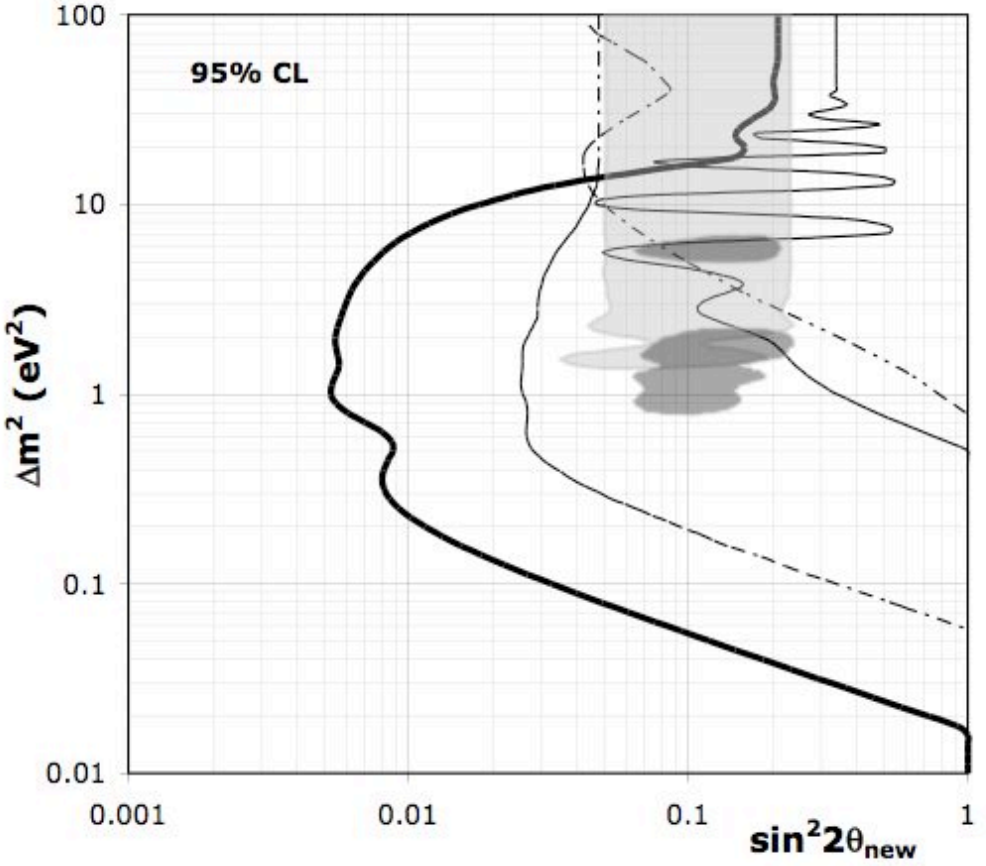




Future

DAEδALUS





Future

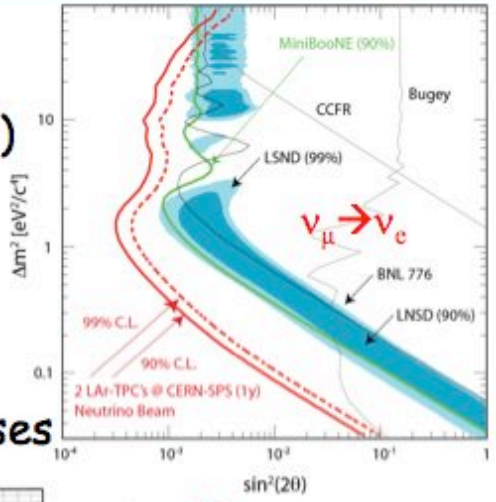
ICARUS - future

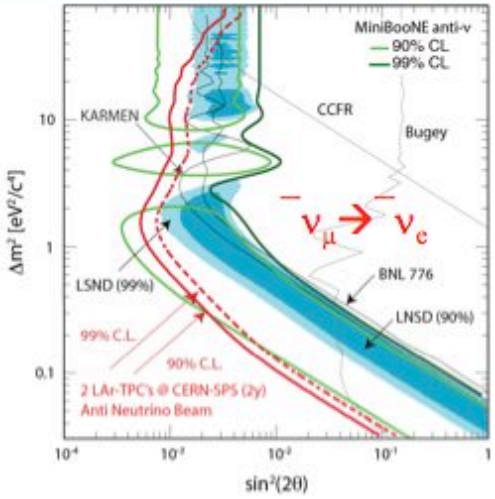
P. Sala
INFN Milano
For the ICARUS Collaboration

Nufact 2013

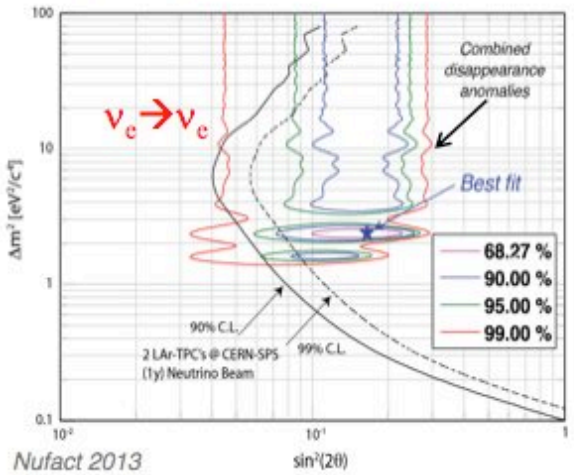
Exploring all channels: expected sensitivity

e-appearance:
1 year ν_μ beam (left)
2 year antiν_μ beam (right)
for 4.5 1019 pot/year,
3% syst. uncertainty





LSND allowed region is
fully explored in both cases



Nufact 2013

e/μ-disappearance:
1 year ν_μ beam (left)
1 year ν_μ + 2 years
anti-ν_μ beams (right)

combined "anomalies":
from reactor νs, Gallex
and Sage experiments.

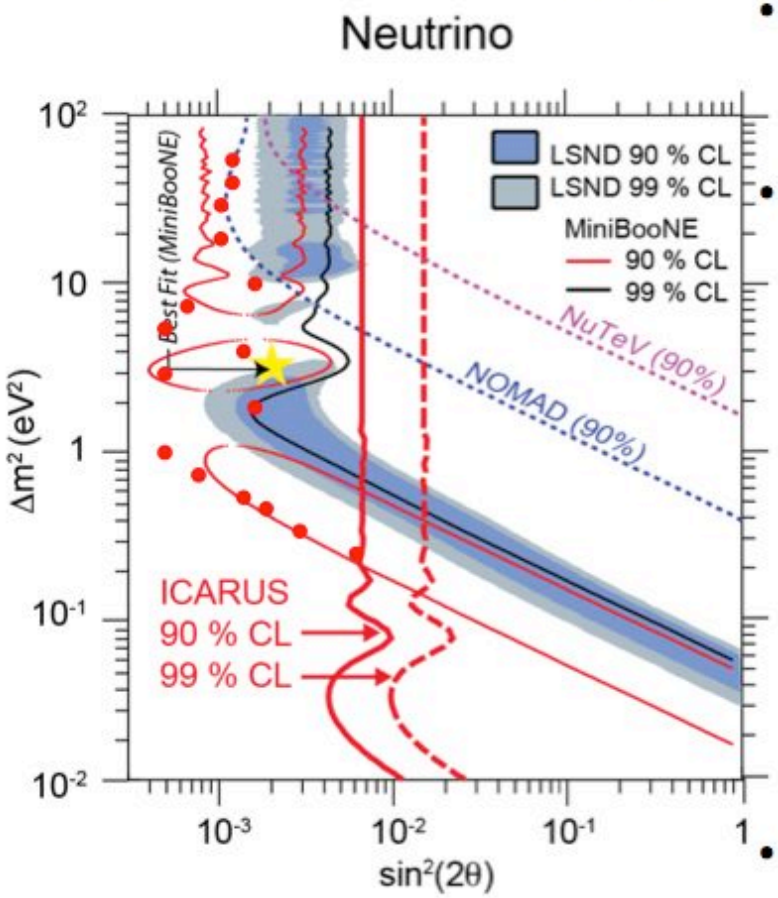
In addition:
Detector R&D (T150)
Neutrino cross sections
(huge statistcs of ν_e)
Event reconstruction
"pave the way for future LBL experiments"

Future

A Search for Sterile Neutrinos at J-PARC Materials and Life science experimental Facility

Takasumi Maruyama (KEK)
for MLF nu working group

Sensitivity (60m 1kt case)



- Red circles show 5 σ sensitivity. -> definite conclusion from the configuration.
- Assuming
  - a 1 kt detector is put at 60 m distance from Hg target.
  - 1MW x 2 years (4000 hours / year) operation
  - Detector efficiency is 50%.
  - Dominant background is $\bar{\nu}e$ from μ- , 150 events 10^{-3} compared to $\bar{\nu}\mu$ from μ+
  - Uncertainty of the BKG normalization factor is 100%, while that of signal is 10%
- Experimental setup is being designed.

Future

Microboone
MINOS+
Microboone+
...

Too many to fit here!