An overview of light sterile neutrinos (at the eV scale)

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合肥

Experimental evidence of ν oscillations

Solar
$\nu_e \to \nu_\mu, \nu_\tau$

VLBL Reactor
$\bar{\nu}_e$ disappearance

SNO, BOREXino
Super-Kamiokande
GALLEX/GNO, SAGE
Homestake, Kamiokande

(KamLAND)

$$\to \begin{cases} \Delta m^2_{\mathrm{S}} = \Delta m^2_{21} \simeq 7.6 \times 10^{-5}\,\mathrm{eV}^2 \\ \sin^2\vartheta_{\mathrm{S}} = \sin^2\vartheta_{12} \simeq 0.30 \end{cases}$$

Atmospheric
$\nu_\mu \to \nu_\tau$

LBL Accelerator
ν_μ disappearance

LBL Accelerator
$\nu_\mu \to \nu_\tau$

Super-Kamiokande
Kamiokande, IMB
MACRO, Soudan-2

K2K, MINOS
T2K, NOνA

(Opera)

$$\to \begin{cases} \Delta m^2_{\mathrm{A}} = |\Delta m^2_{31}| \simeq 2.4 \times 10^{-3}\,\mathrm{eV}^2 \\ \sin^2\vartheta_{\mathrm{A}} = \sin^2\vartheta_{23} \simeq 0.50 \end{cases}$$

LBL Accelerator
$\nu_\mu \to \nu_e$

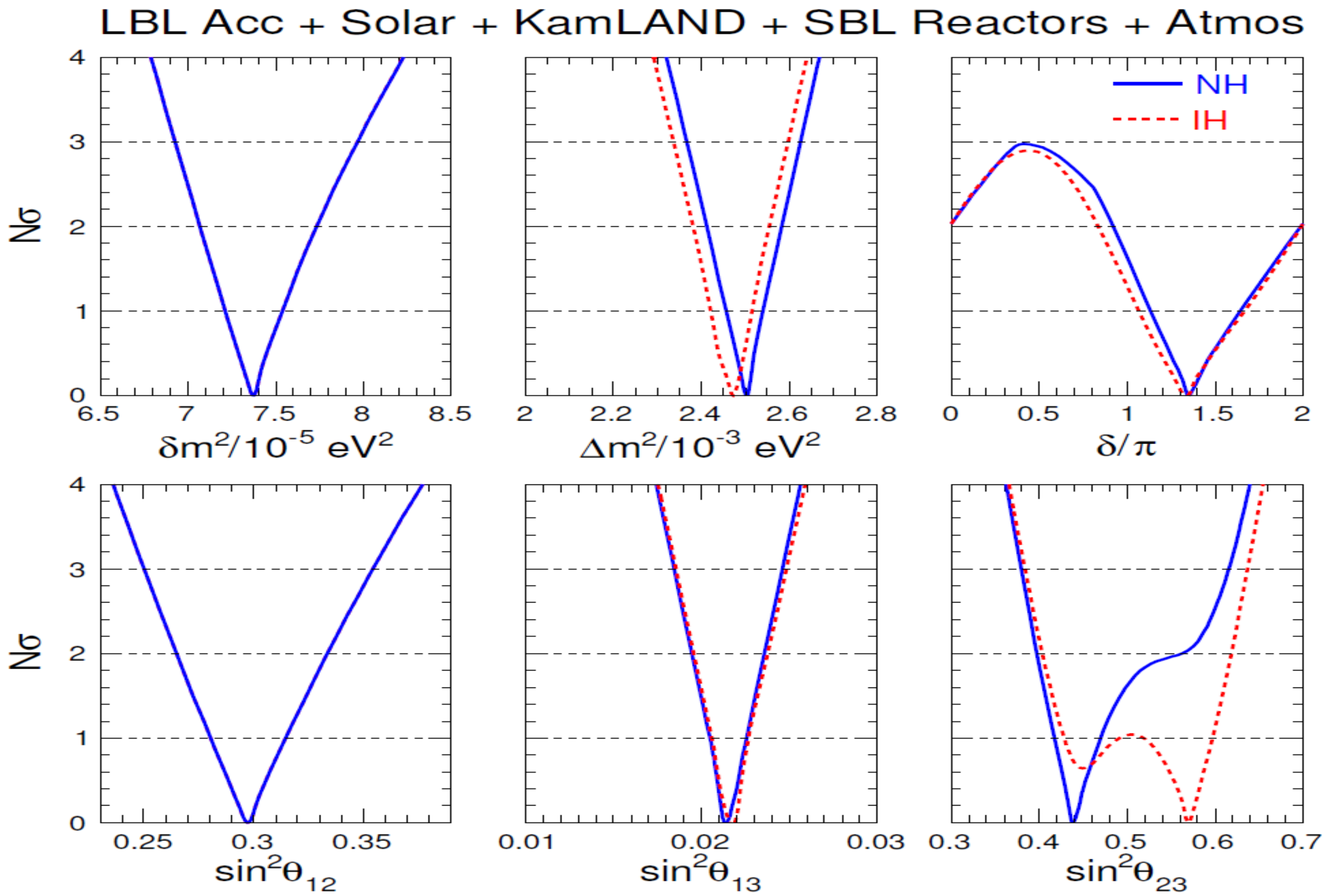
LBL Reactor
$\bar{\nu}_e$ disappearance

(T2K, MINOS, NOνA)

Daya Bay, RENO
Double Chooz

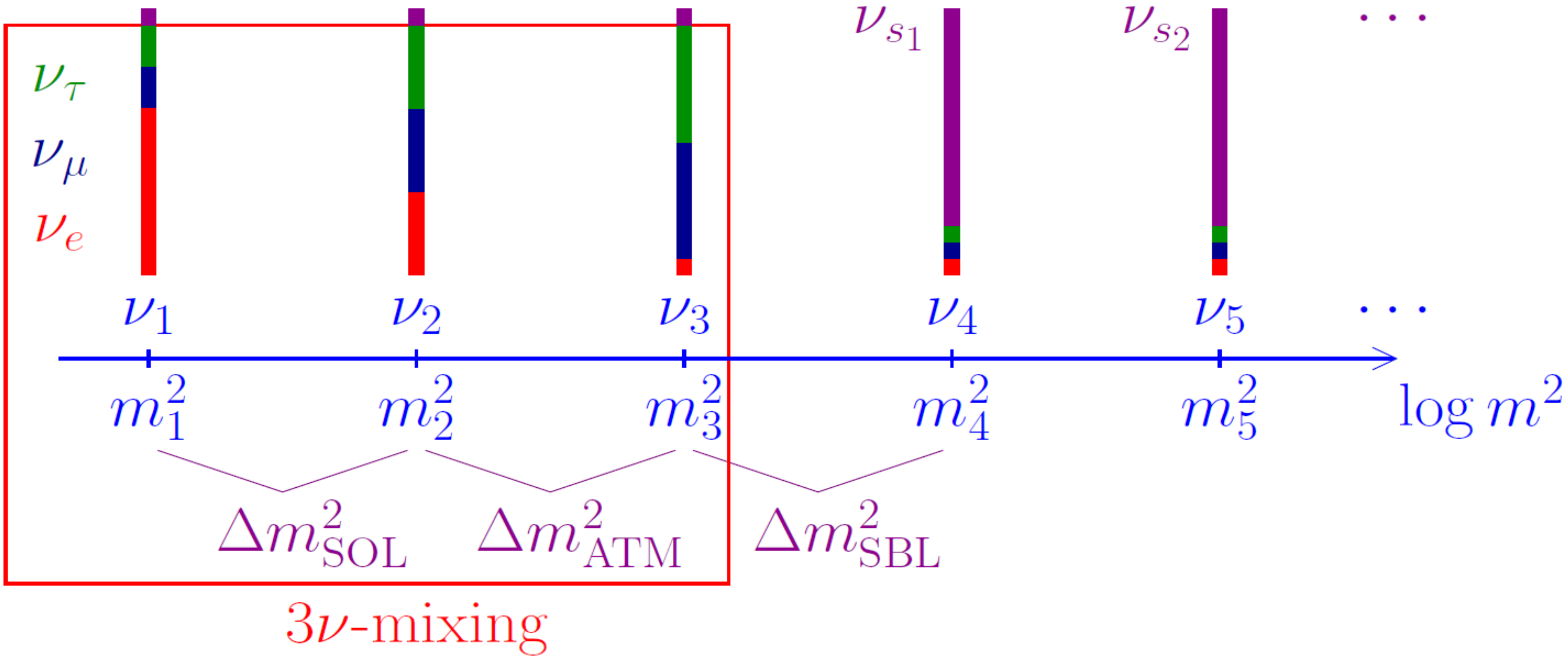
$$\to \begin{cases} \Delta m^2_{\mathrm{A}} = |\Delta m^2_{31}| \\ \sin^2\vartheta_{13} \simeq 0.023 \end{cases}$$

Status of 3-ν oscillations



[Capozzi, Lisi, Marrone, Montanino, Palazzo, arXiv:1601.07777]

Beyond 3-ν oscillations: Sterile neutrinos



eV-scale sterile neutrinos: mass eigenstates of mostly sterile neutrinos

Explanation of short baseline oscillations

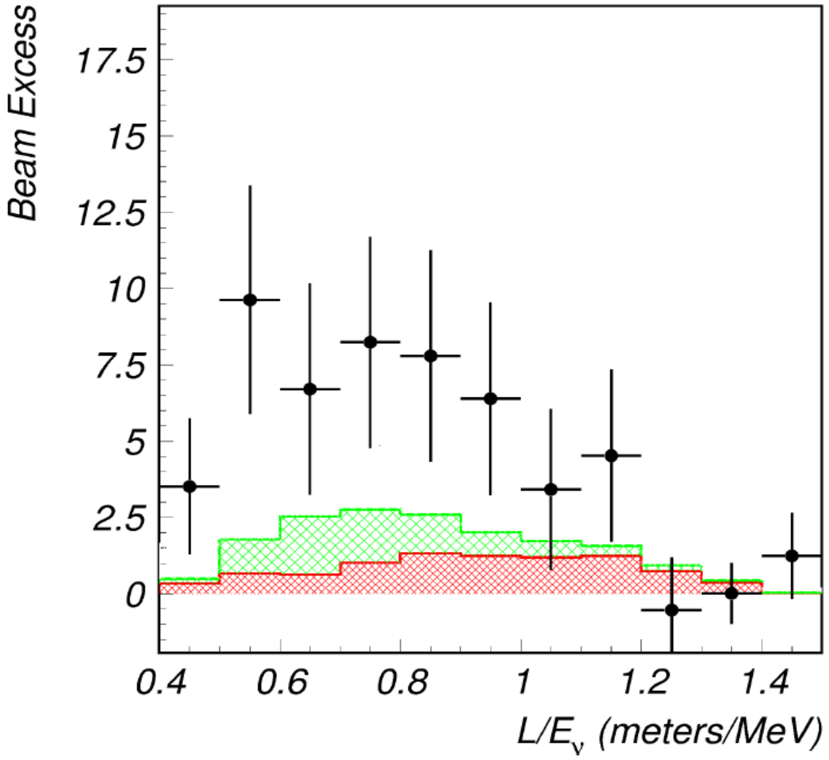
Topical review: ***Gariazzo, Giunti, Laveder, YFL, Zavanin, JPG 43 (2016) 033001***

Indications of SBL oscillations beyond 3-νs

LSND: Liquid Scintillator Neutrino Detector

[PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

$\bar{\nu}_\mu \to \bar{\nu}_e \qquad 20\,\text{MeV} \leq E \leq 60\,\text{MeV}$



- Well-known source of $\bar{\nu}_\mu$

μ^+ at rest $\to e^+ + \nu_e + \bar{\nu}_\mu$

$L \simeq 30\,\text{m}$

$\bar{\nu}_e + p \to n + e^+$

Well-known detection process of $\bar{\nu}_e$

- But signal not seen by KARMEN at $L \simeq 18\,\text{m}$ with the same method

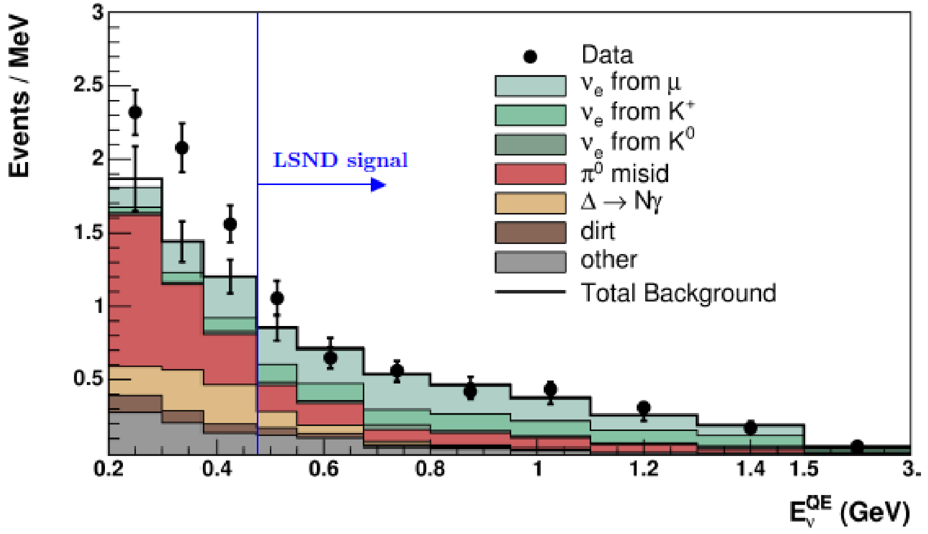
[PRD 65 (2002) 112001]

$\approx 3.8\sigma$ excess $\qquad \Delta m^2_{\text{SBL}} \gtrsim 0.2\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$

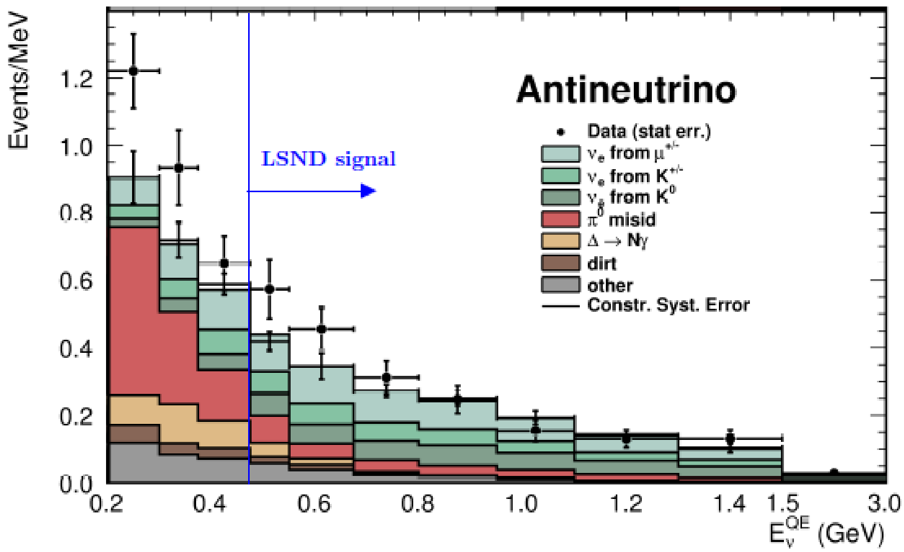
MiniBooNE

$L \simeq 541\,\mathrm{m}$ $200\,\mathrm{MeV} \leq E \lesssim 3\,\mathrm{GeV}$

$\nu_\mu \to \nu_e$ [PRL 102 (2009) 101802]



$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]



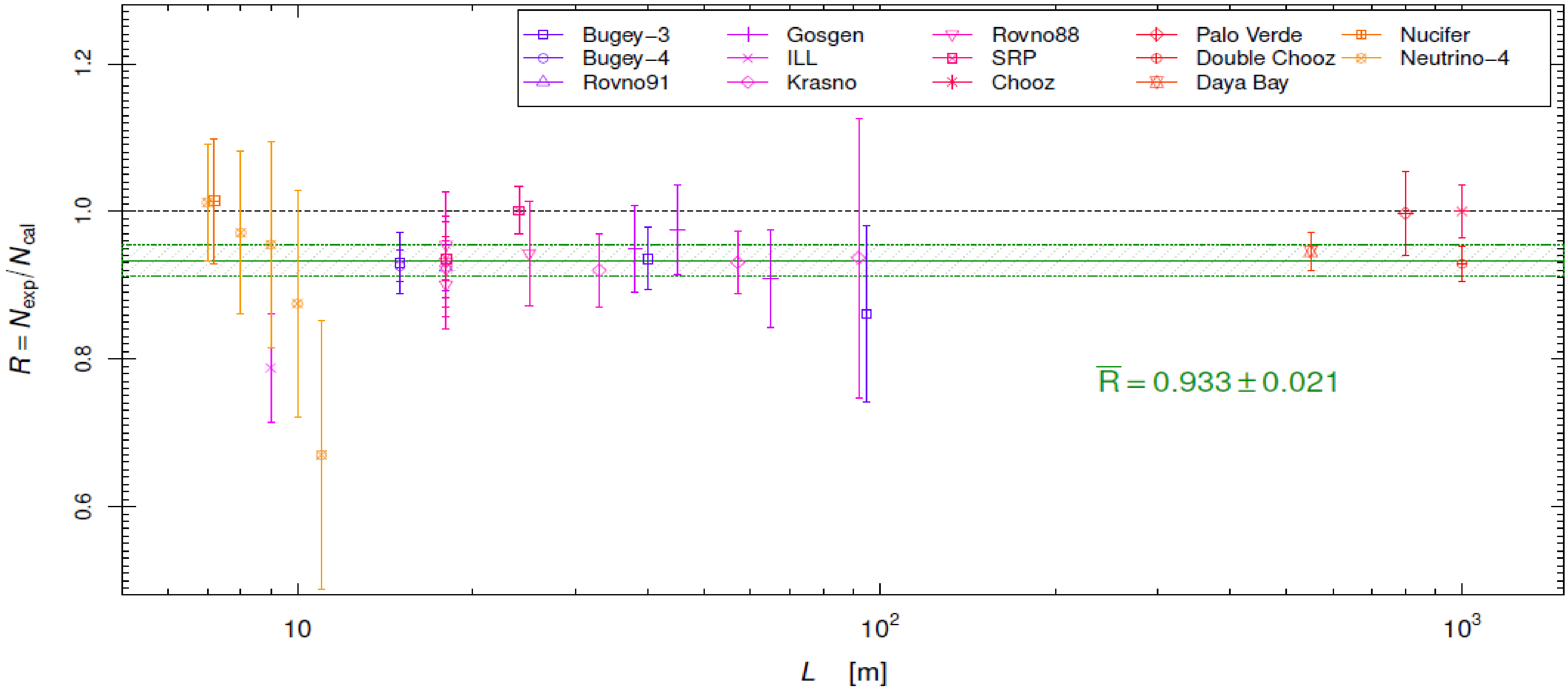
Purpose: **check LSND signal with different L&E, but the same L/E**

~3σ excess: **Agreement with LSND? V.S. Low energy anomaly?**

Reactor antineutrino anomaly

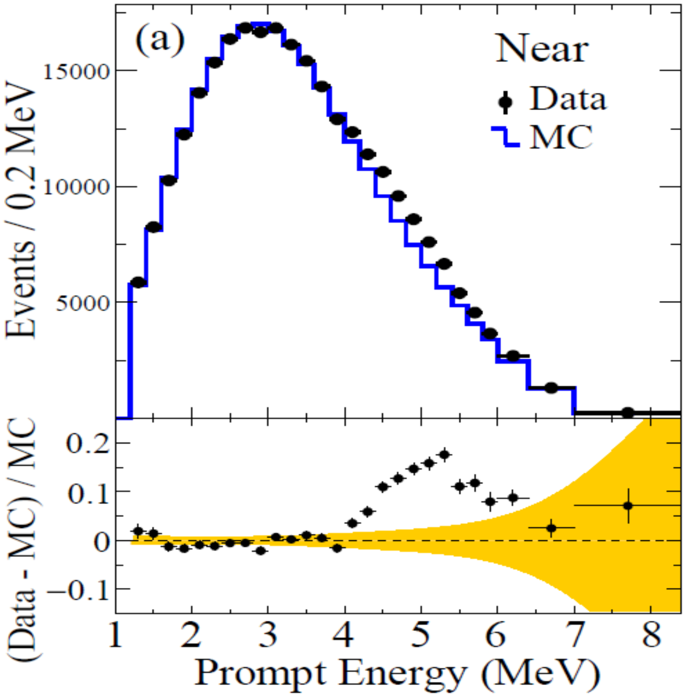
[Mention et al, PRD 83 (2011) 073006; updated in White Paper, arXiv:1204.5379]

New reactor $\bar{\nu}_e$ fluxes [Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]

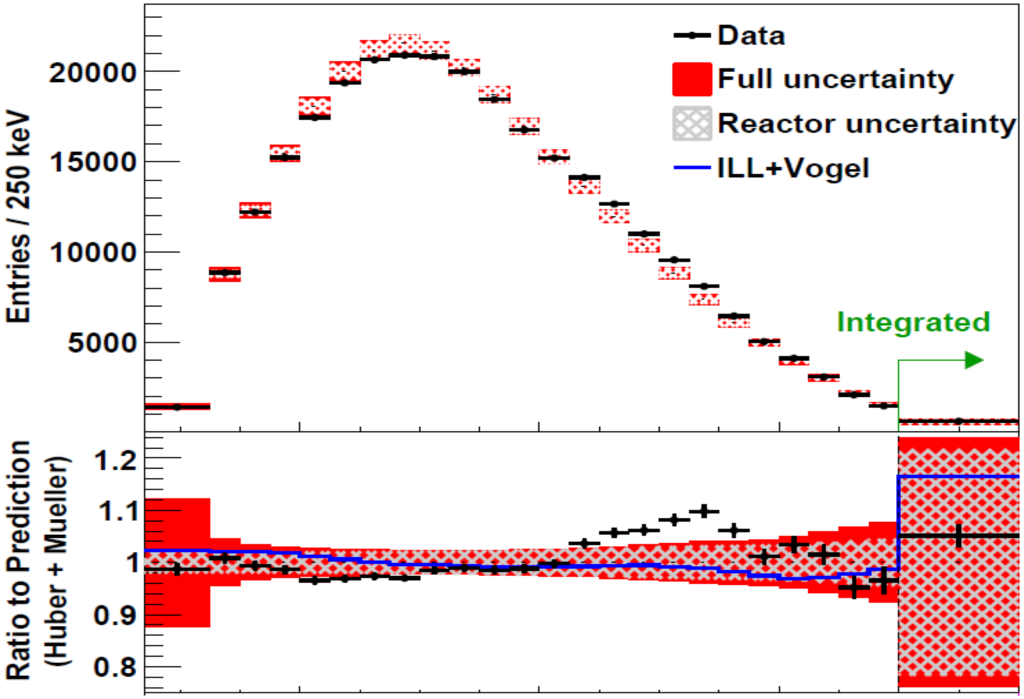


$\approx 3.2\sigma$ deficit $\Delta m^2_{SBL} \gtrsim 0.5\,eV^2 \gg \Delta m^2_{ATM} \gg \Delta m^2_{SOL}$

New feature in reactors: 5 MeV “bump”



[RENO, arXiv:1511.05849]



[Daya Bay, arXiv:1508.04233]

- Local problem with $\sim 3\%$ effect on total flux.
- It is an excess!
- It occurs both for the new high Muller-Huber fluxes and the old low Schreckenbach-Vogel fluxes.
- Real problem: apparent incompatibility of the bump with the β spectra from ^{235}U and ^{239}Pu measured by Schreckenbach et al. at ILL in 1982-1985.

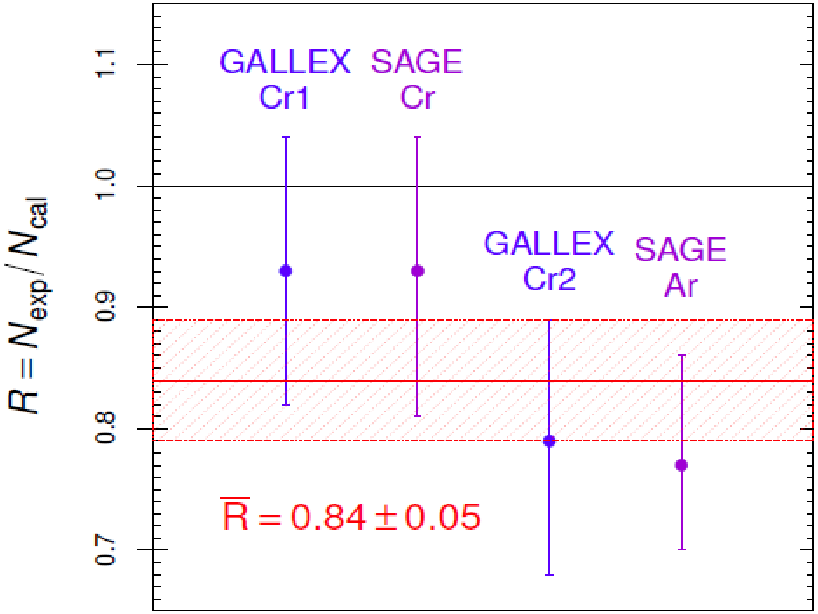
Gallium anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

ν_e Sources: $e^- + {}^{51}\mathrm{Cr} \to {}^{51}\mathrm{V} + \nu_e$ $\quad$ $e^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e$

$E \simeq 0.75\,\mathrm{MeV}$ $\quad$ $E \simeq 0.81\,\mathrm{MeV}$

Test of Solar ν_e Detection: $\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$



$\langle L \rangle_{\mathrm{GALLEX}} = 1.9\,\mathrm{m}$

$\langle L \rangle_{\mathrm{SAGE}} = 0.6\,\mathrm{m}$

$\approx 2.9\sigma$ deficit

$$\Delta m^2_{\mathrm{SBL}} \gtrsim 1\,\mathrm{eV}^2 \gg \Delta m^2_{\mathrm{ATM}} \gg \Delta m^2_{\mathrm{SOL}}$$

[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807]

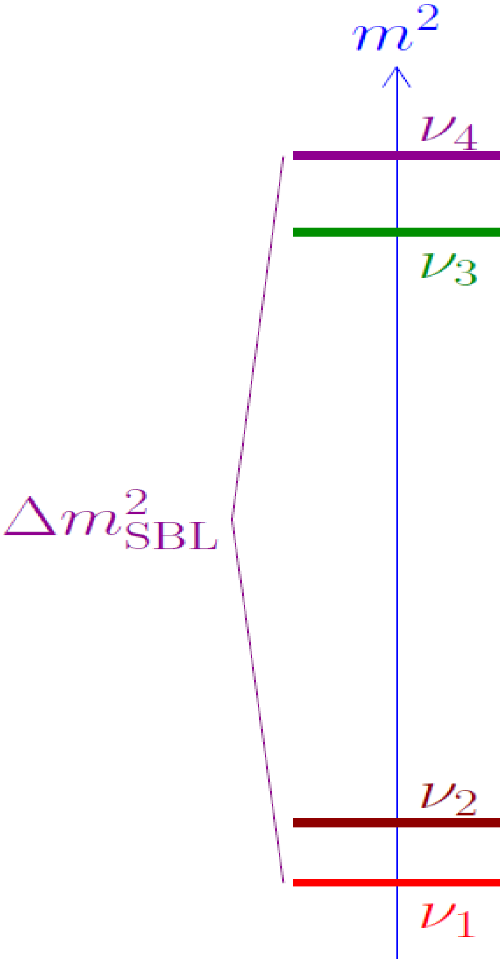
[Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344; MPLA 22 (2007) 2499; PRD 78 (2008) 073009; PRC 83 (2011) 065504]

- ${}^3\mathrm{He} + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + {}^3\mathrm{H}$ cross section measurement [Frekers et al., PLB 706 (2011) 134]
- $E_{\mathrm{th}}(\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-) = 233.5 \pm 1.2\,\mathrm{keV}$ [Frekers et al., PLB 722 (2013) 233]

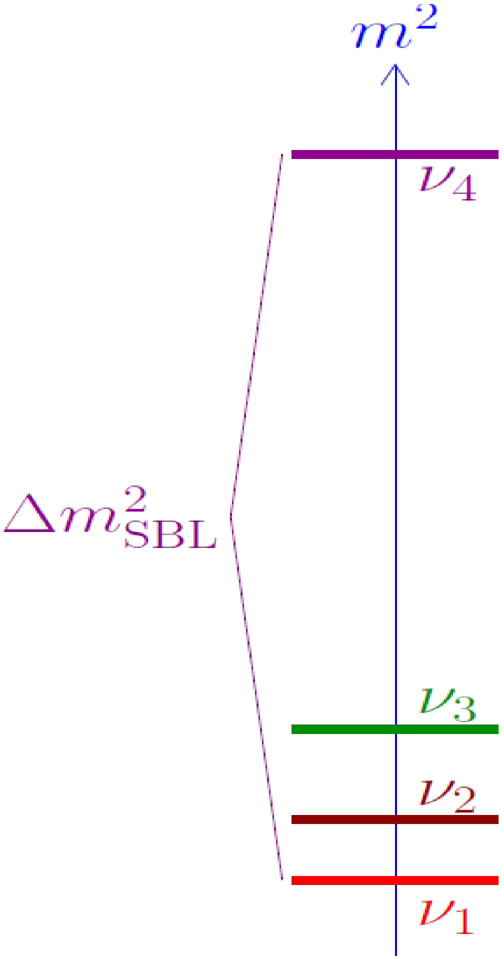
Global status of light sterile neutrinos

Consider all positive and negative results

Four-Neutrino Schemes: 2+2 and 3+1

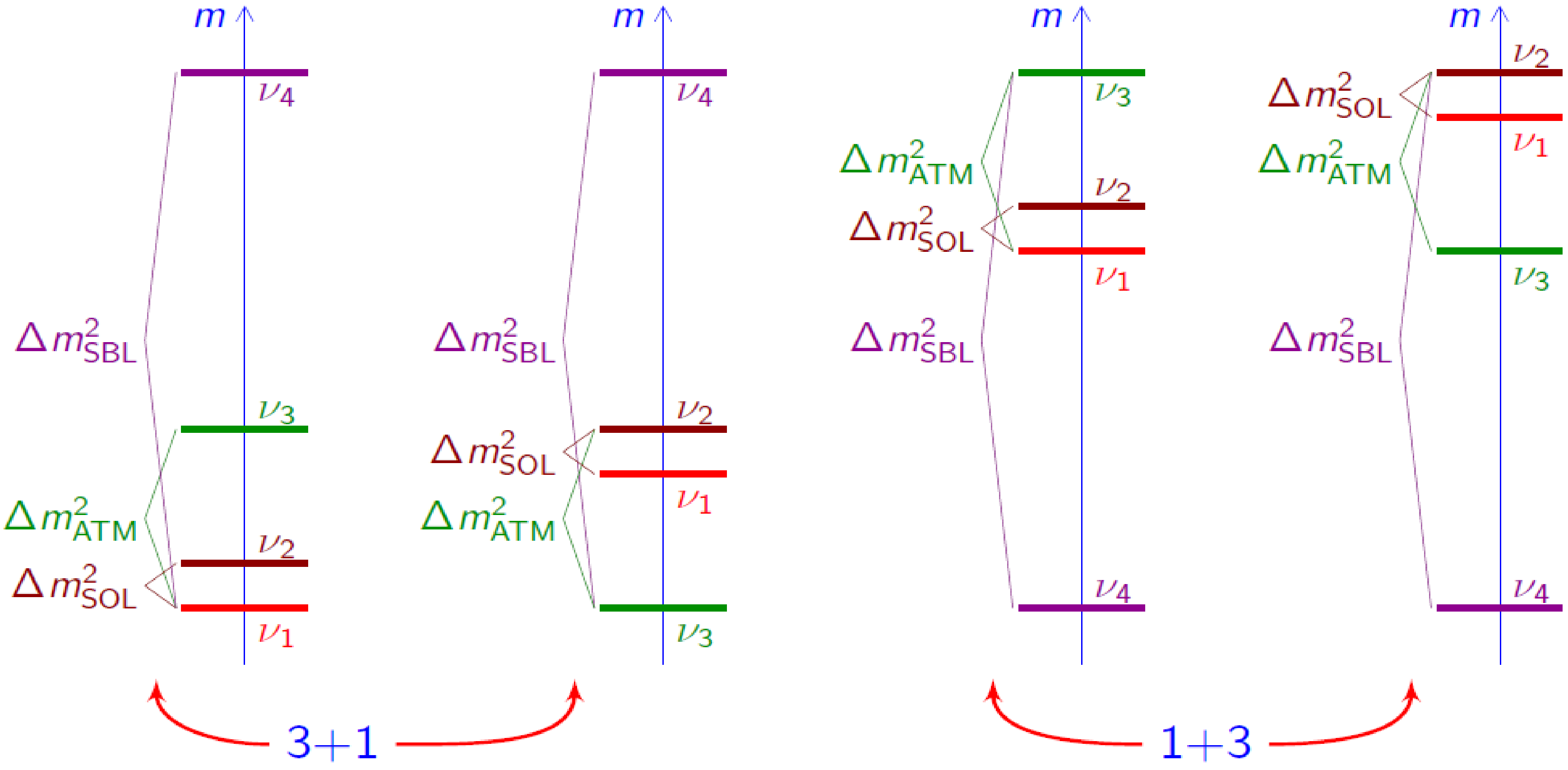


"2+2"



"3+1"

3+1 and 1+3 schemes



- Perturbation of 3-ν Mixing: $|U_{e4}|^2, |U_{\mu4}|^2, |U_{\tau4}|^2 \ll 1 \quad |U_{s4}|^2 \simeq 1$
- 1+3 schemes are disfavored by cosmology (ΛCDM):

$$\sum_{k=1}^{3} m_k < 0.21\,\text{eV} \text{ (95\%, Planck TT + lowP + BAO)}$$

[arXiv:1502.01589]

Effective SBL oscillations in 3+1 schemes

Appearance $(\alpha \neq \beta)$

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

Disappearance

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

$$U = \left(\begin{array}{ccc|c|} \cline{4-4} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \\ \cline{4-4} \end{array}\right)$$

SBL

- CP violation is not observable in SBL experiments!
- Observable in LBL accelerator exp. sensitive to Δm^2_{ATM} [de Gouvea et al, PRD 91 (2015) 053005, PRD 92 (2015) 073012, arXiv:1605.09376; Palazzo et al, PRD 91 (2015) 073017, PLB 757 (2016) 142; Gandhi et al, JHEP 1511 (2015) 039] and solar exp. sensitive to Δm^2_{SOL} [Long, Li, CG, PRD 87, 113004 (2013) 113004]

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases

Appearance-Disappearance Tension

ν_e DIS

$$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$$

ν_μ DIS

$$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu4}|^2$$

$\nu_\mu \to \nu_e$ APP

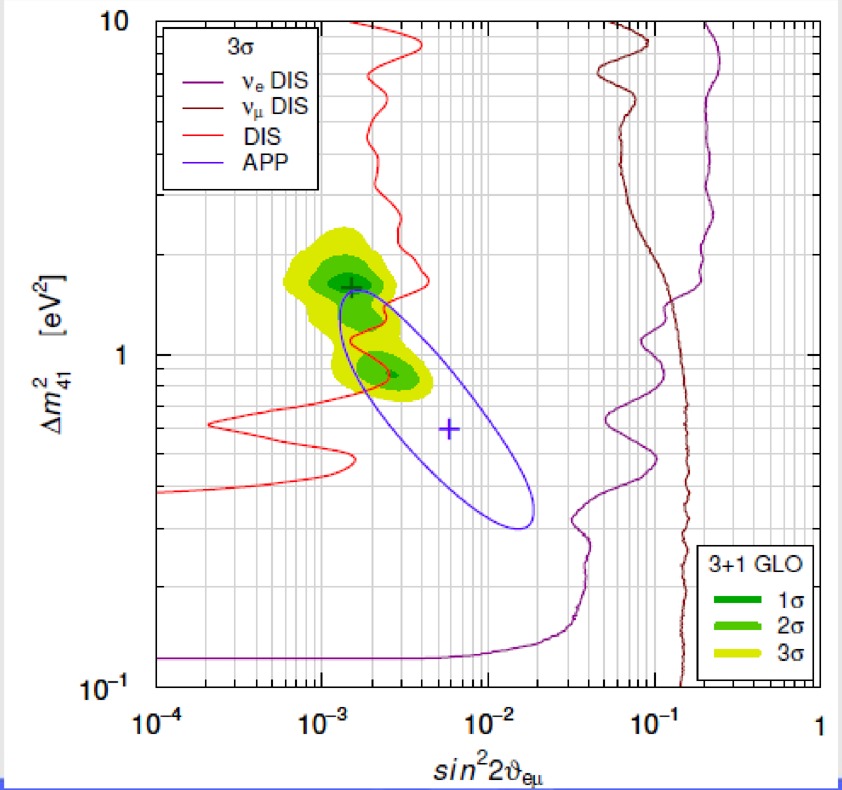
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$$

[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, CG, Grimus, EPJC 1 (1998) 247]

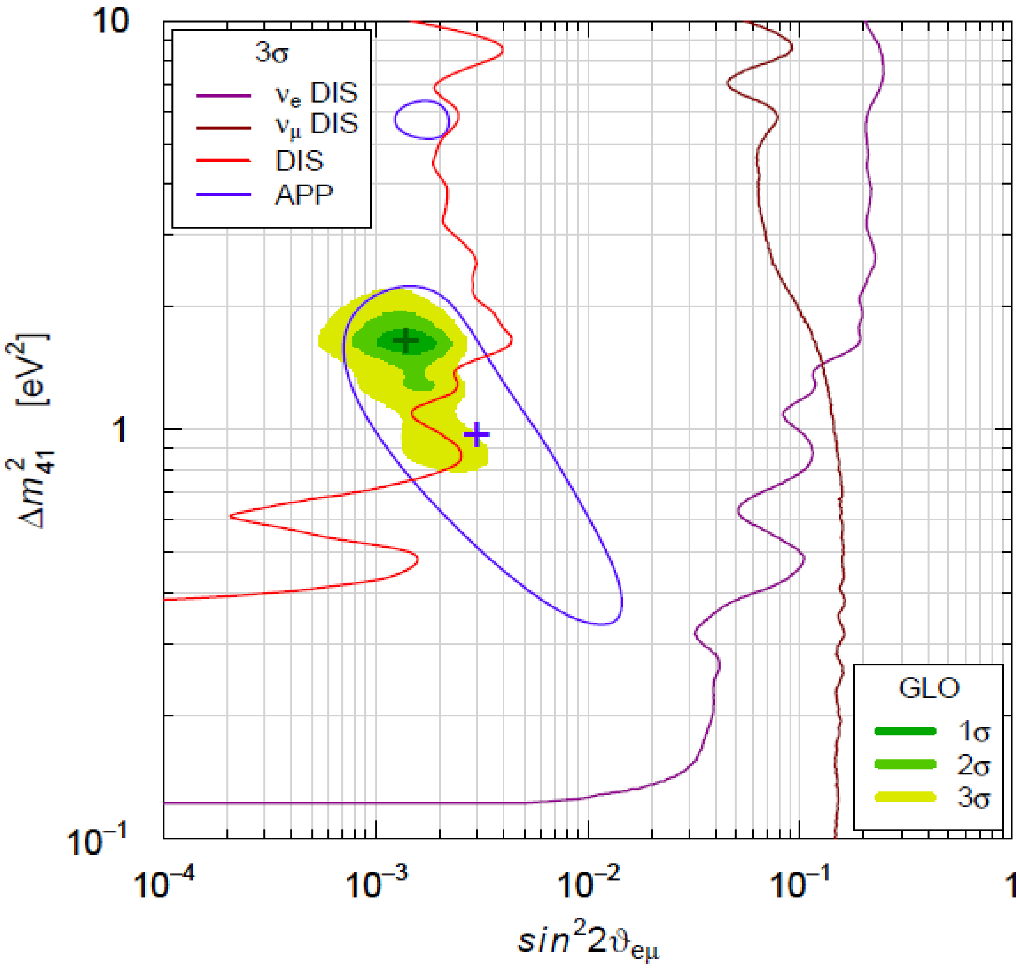
Disappearance channels (ee, μμ) give indirect constraints on the appearance channel.

νμ→ νe: the appearance channel is quadratically suppressed.

Similar constraints in the 3+2, 3+3, 3+Ns framework.



Pragmatic approach



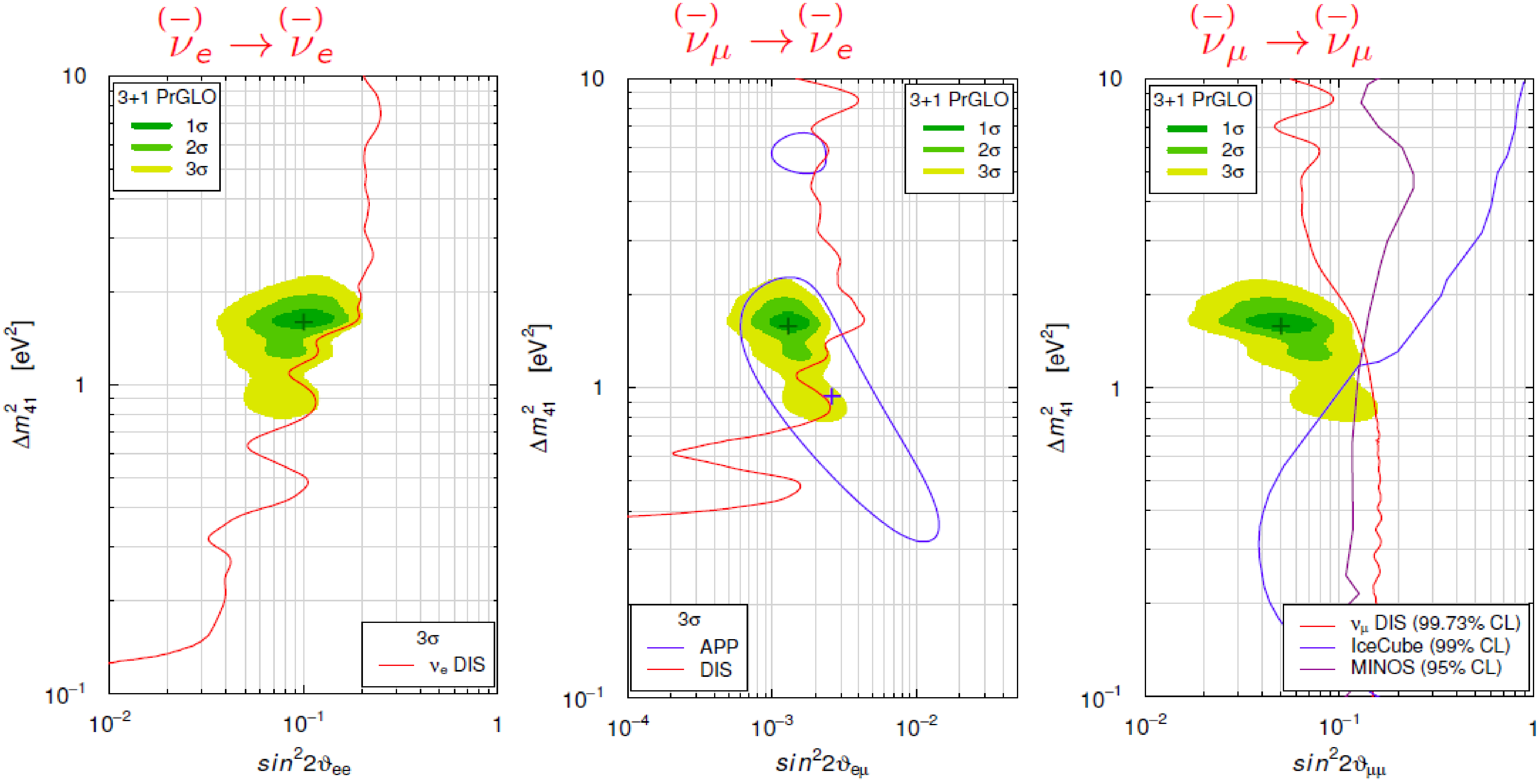
MiniBooNE $E > 475$ MeV

GoF $= 26\%$ PGoF $= 7\%$

- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND ($\nu_s$), MiniBooNE (?), OPERA ($\cancel{\nu_s}$), ICARUS ($\cancel{\nu_s}$), KARMEN ($\cancel{\nu_s}$), NOMAD ($\cancel{\nu_s}$), BNL-E776 ($\cancel{\nu_s}$)
- DIS ν_e & $\bar{\nu}_e$: Reactors (ν_s), Gallium (ν_s), ν_eC ($\cancel{\nu_s}$), Solar ($\cancel{\nu_s}$)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW ($\cancel{\nu_s}$), MINOS ($\cancel{\nu_s}$), Atmospheric ($\cancel{\nu_s}$), MiniBooNE/SciBooNE ($\cancel{\nu_s}$)

No Osc. nominally disfavored
at $\approx 6.3\sigma$
$\Delta\chi^2/\text{NDF} = 47.7/3$

Global status of the 3+1 fit



GoF = 24% PGoF = 7%

No Osc. disfavored at $\approx 6.2\sigma$

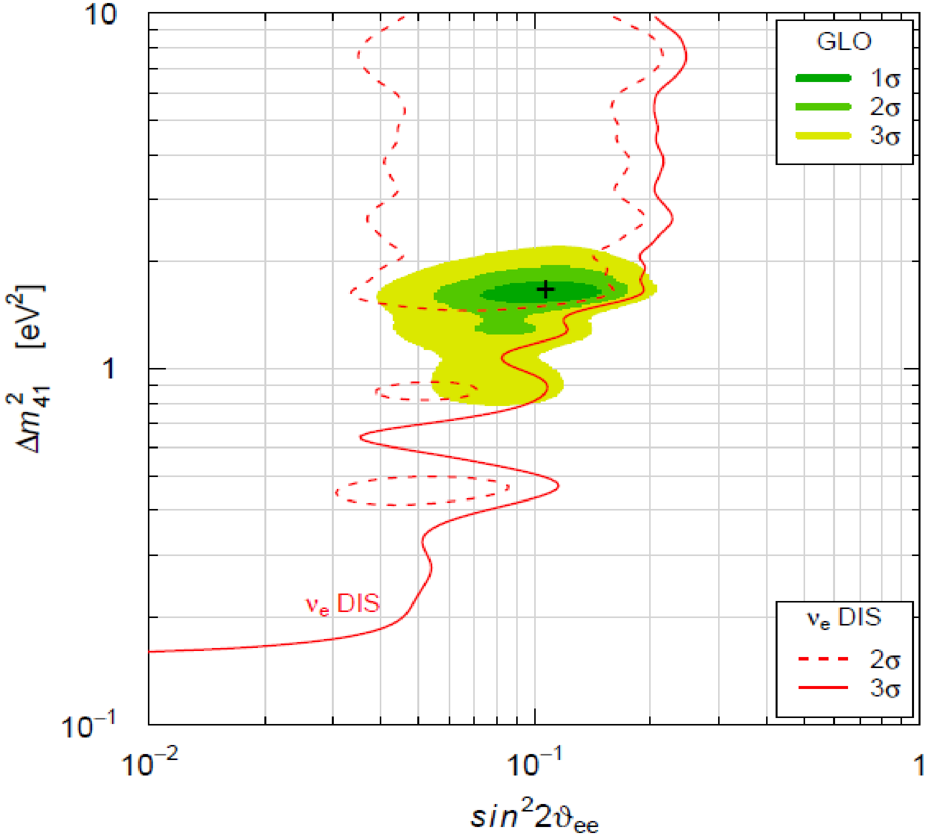
$\Delta\chi^2/\mathrm{NDF} = 46.6/3$

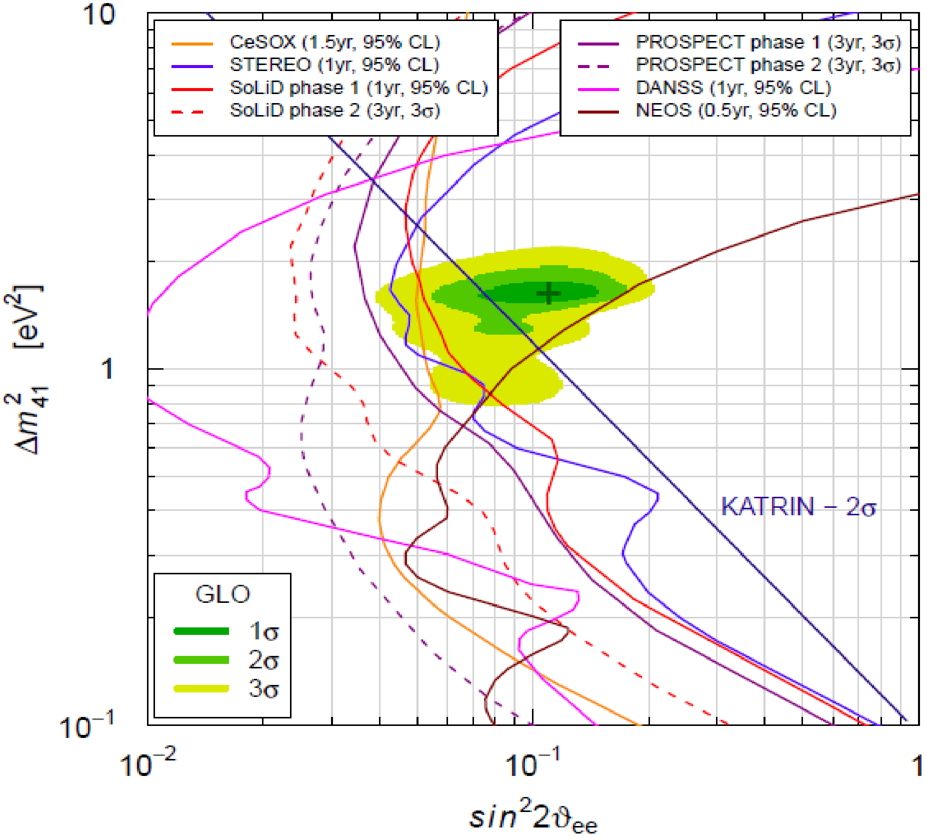
Not yet included:

- IceCube, arXiv:1605.01990
- MINOS Preliminary, arXiv:1605.04544

Future prospective

Near future: νe disappearance

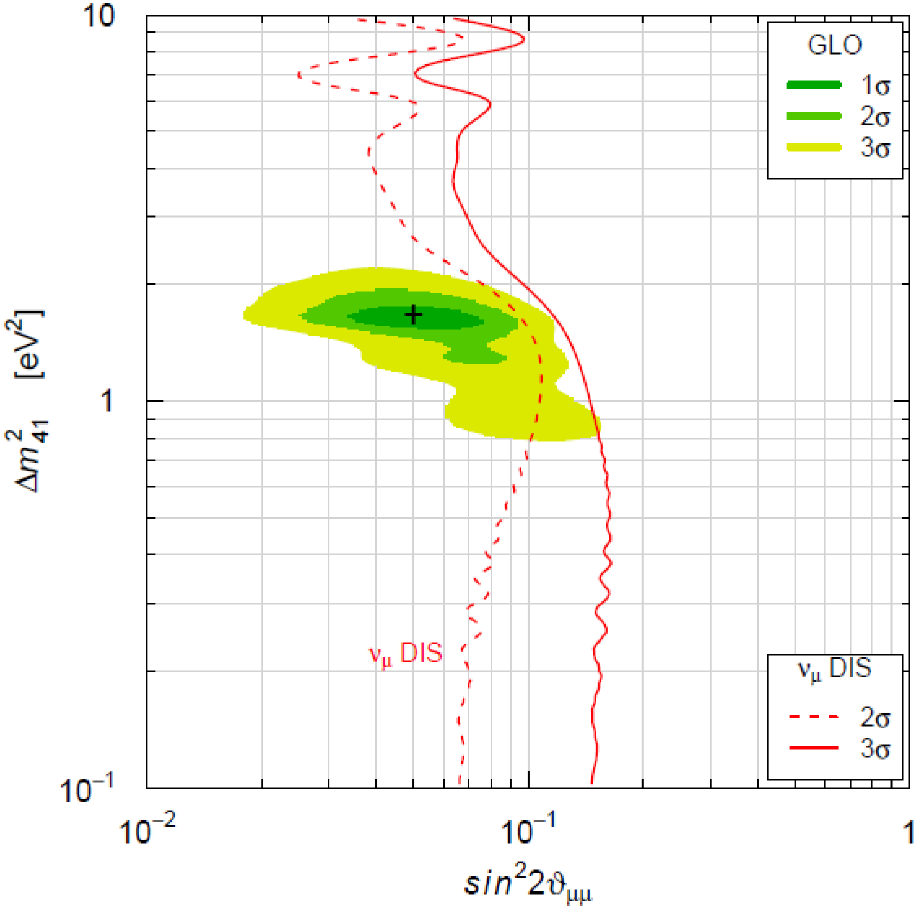




CeSOX (BOREXINO, Italy)
^{144}Ce — 100 kCi [Vivier@TAUP2015]
rate: 1% normalization uncertainty
8.5 m from detector center
KATRIN (Germany)
Tritium β decay [Mertens@TAUP2015]

STEREO (France) $L \simeq$ 8-12m [Sanchez@EPSHEP2015]
SoLid (Belgium) $L \simeq$ 5-8m [Yermia@TAUP2015]
PROSPECT (USA) $L \simeq$ 7-12m [Heeger@TAUP2015]
DANSS (Russia) $L \simeq$ 10-12m [arXiv:1412.0817]
NEOS (Korea) $L \simeq$ 25m [Oh@WIN2015]

Near future: νμ disappearance

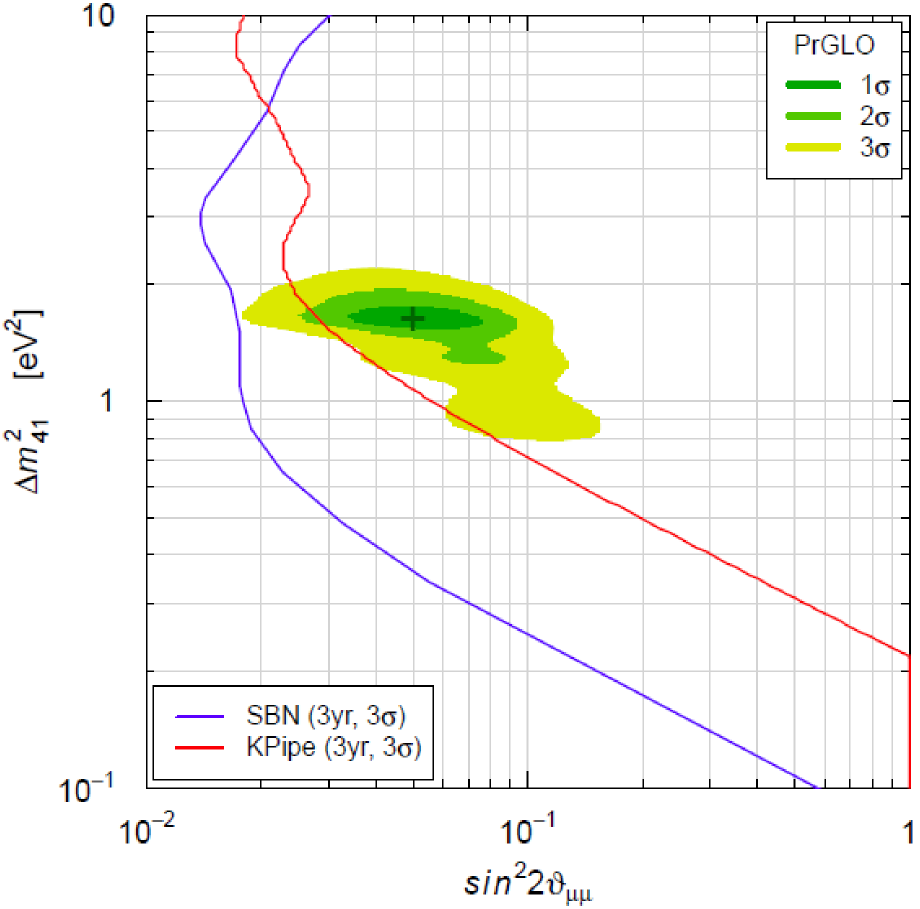


SBN (USA) [arXiv:1503.01520]

LAr1-ND $L \simeq 100$m

MicroBooNE $L \simeq 470$m

ICARUS T600 $L \simeq 600$m

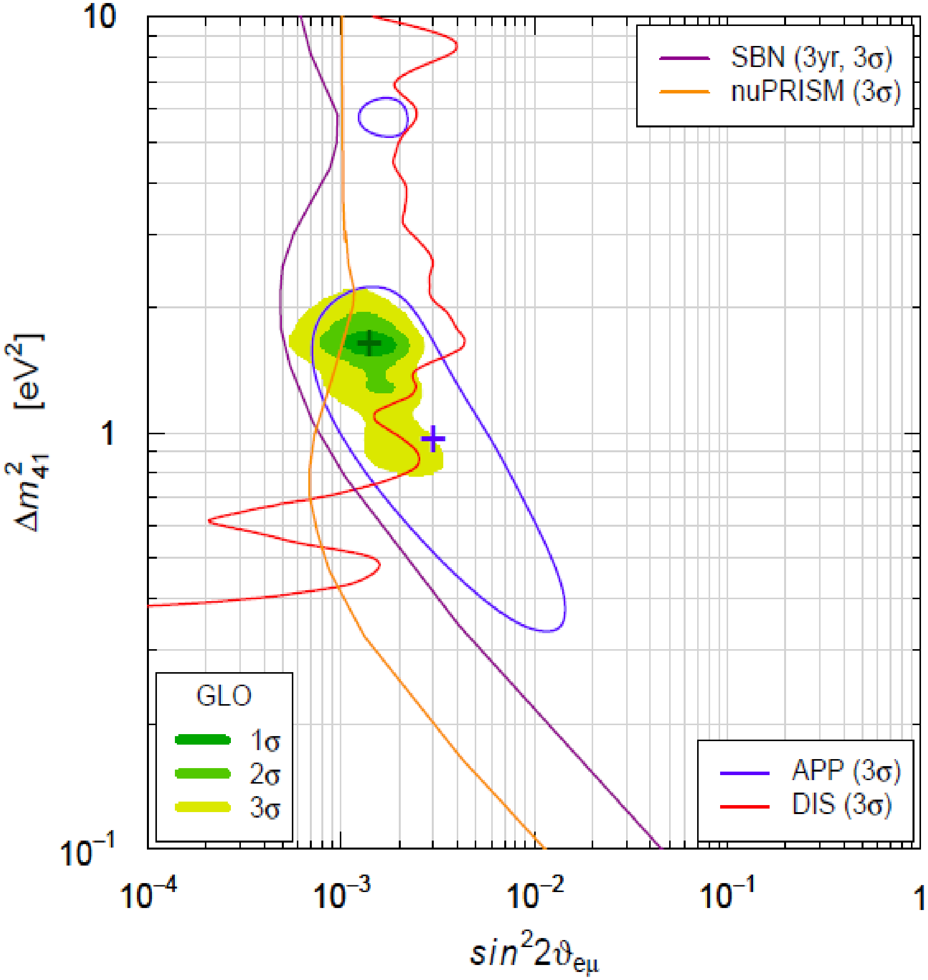


KPipe (Japan) [arXiv:1510.06994]

$L \simeq 30$-150m

120 m long detector!

Near future: νμ→νe appearance



SBN (FNAL, USA)

[arXiv:1503.01520]

3 Liquid Argon TPCs

LAr1-ND $L \simeq 100\,\mathrm{m}$

MicroBooNE $L \simeq 470\,\mathrm{m}$

ICARUS T600 $L \simeq 600\,\mathrm{m}$

nuPRISM (J-PARC, Japan)

[Wilking@NNN2015]

$L \simeq 1\,\mathrm{km}$

50 m tall water Cherenkov detector

1° – 4° off-axis

can be improved with T2K ND

Conclusions (1)

(1) Short baseline electron neutrino disappearance:

a) Experimental data agree on reactor and Gallium anomalies

b) Problem: total rates and spectra may have unknown systematic uncertainties

c) Many promising projects using reactors and radioactive sources

(2) LSND short baseline appearance signal

d) Not seen by other appearance experiments

e) MiniBooNE has been inconclusive

f) Fermi-lab short baseline program aimed at a conclusive solution:

a near detector (LAr1-ND), an intermediate detector (MicroBooNE) and a far detector (ICARUS-T600):

all Liquid Argon Time Projection Chambers

Conclusions (2)

Pragmatic 3+1 Fit:

has moderate APP-DIS tension.

3+2 is not needed:

same APP-DIS tension and no experimental evidence of CP violation.

Effects in beta decays and neutrinoless double beta decays

Cosmology:

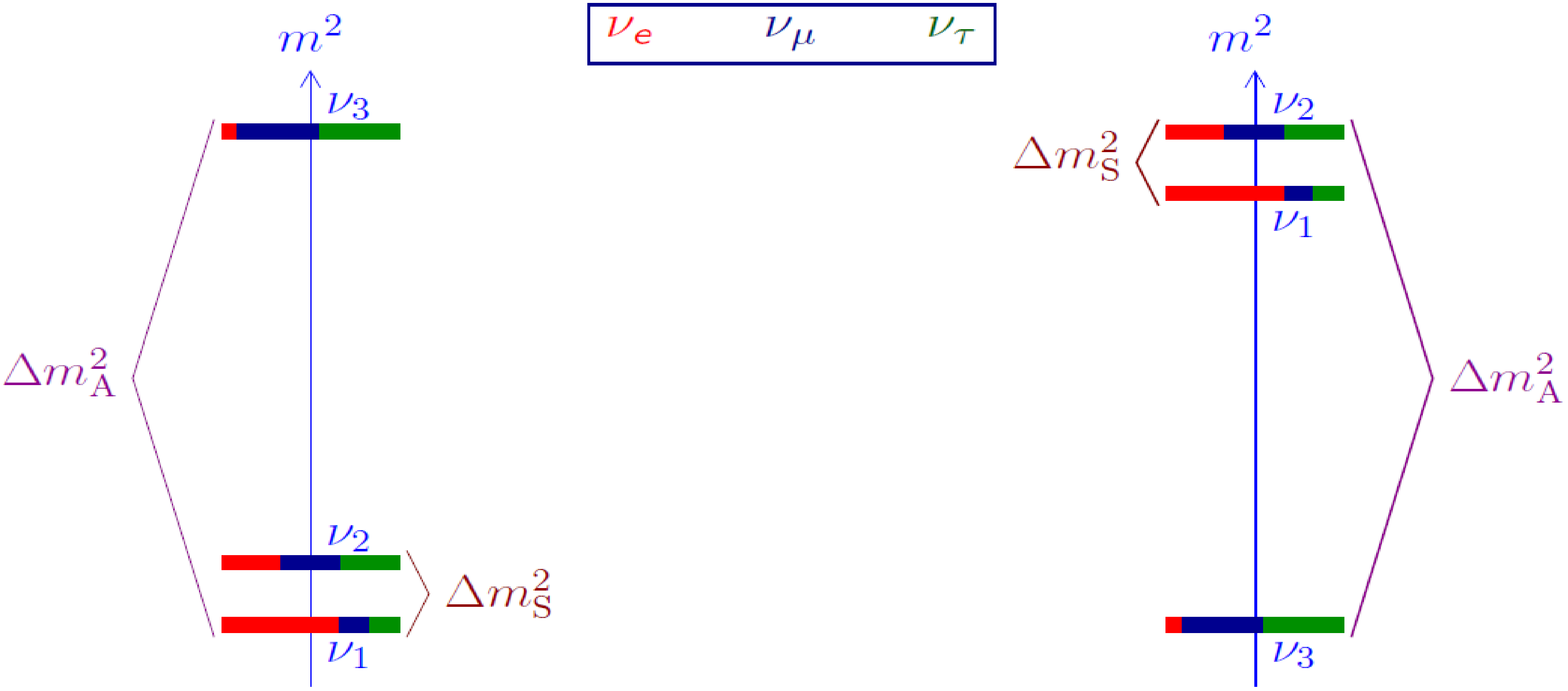
Tension between $N_{eff} = 4$ and $m_s \approx 1$ eV.

Cosmological and oscillation data may be reconciled by a non-standard cosmological mechanism.

Thank you

Backup

Unknown mass ordering



Normal Ordering

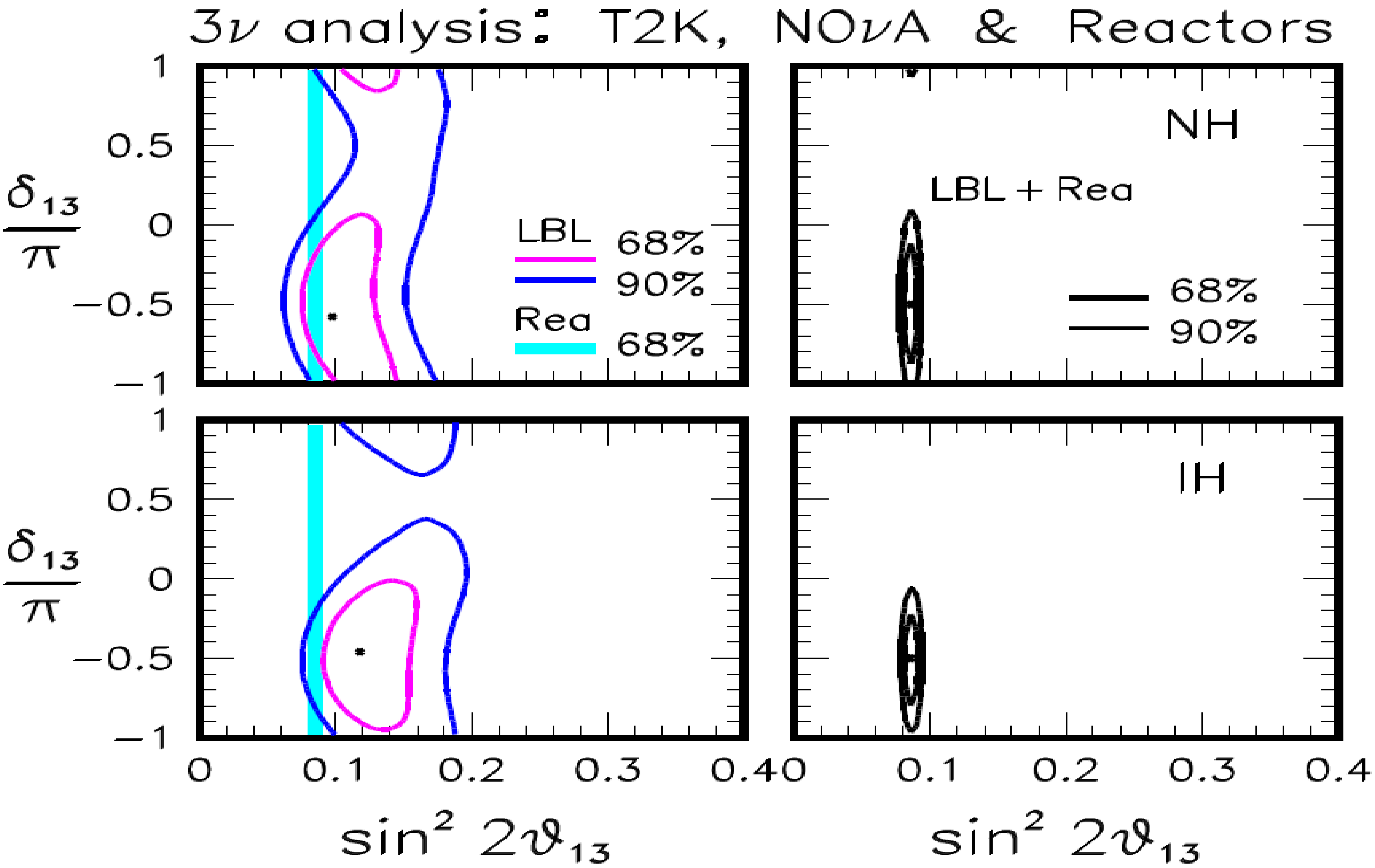
Inverted Ordering

$\Delta m^2_{31} > \Delta m^2_{32} > 0$

$\Delta m^2_{32} < \Delta m^2_{31} < 0$

absolute scale is not determined by neutrino oscillation data

Maximal CP violation ?



[Palazzo, arXiv:1509.03148]

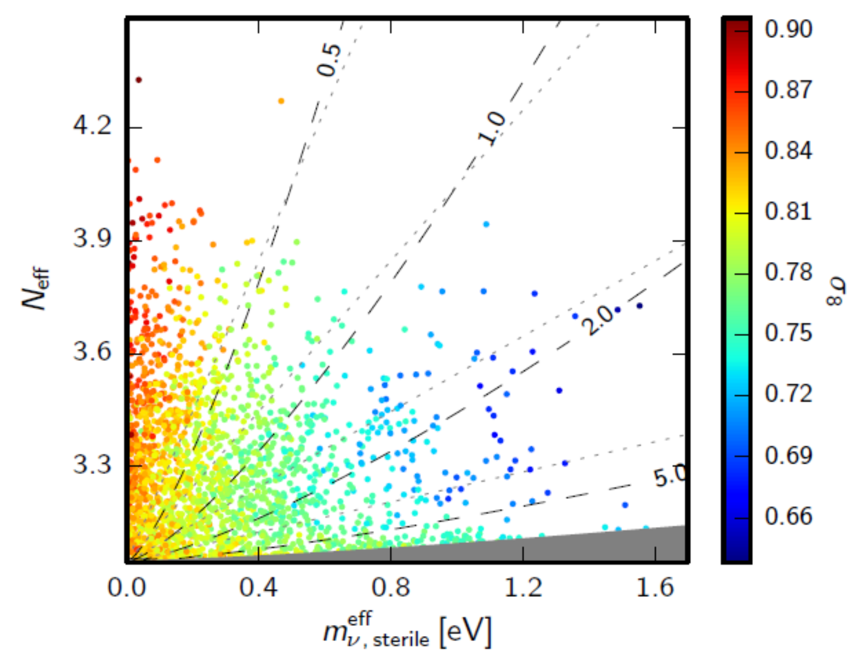
Cosmological effects

Effects of two parameters:

neutrino mass and effective degrees of freedom

$$\left.\begin{aligned} N_{\rm eff} &< 3.7 \\ m_s^{\rm eff} &< 0.52~{\rm eV} \end{aligned}\right\} \quad 95\%,~{\rm Planck~TT{+}lowP{+}lensing{+}BAO}$$

Planck (2015)



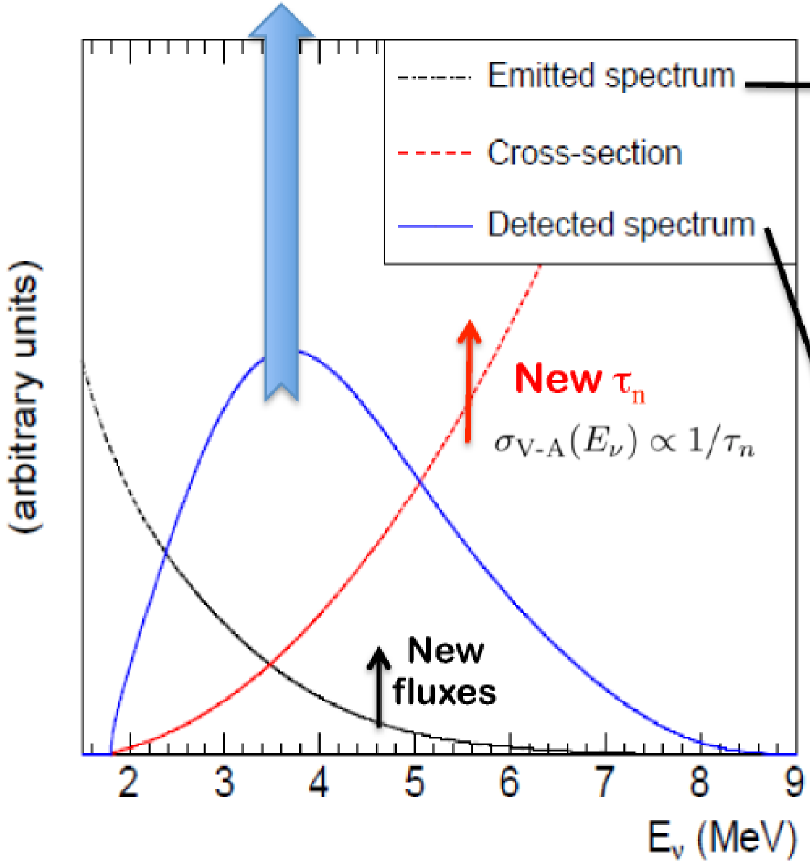
Proposed mechanisms to avoid the tension:

Large lepton asymmetry: ***Hannestad et. al. (2012,2013), Mirizzi, et. al. (2012), Saviano et al. (2013), etc.***

Self-interactions in the sterile sector: ***Hannestad et. al. (2014), Dasgupta, Kopp (2014), Ko, Tang (2014), etc.***

New Reactor $\bar{\nu}_e$ Fluxes

Increased prediction of detected flux by 6.5%



i) Neutrino Emission:

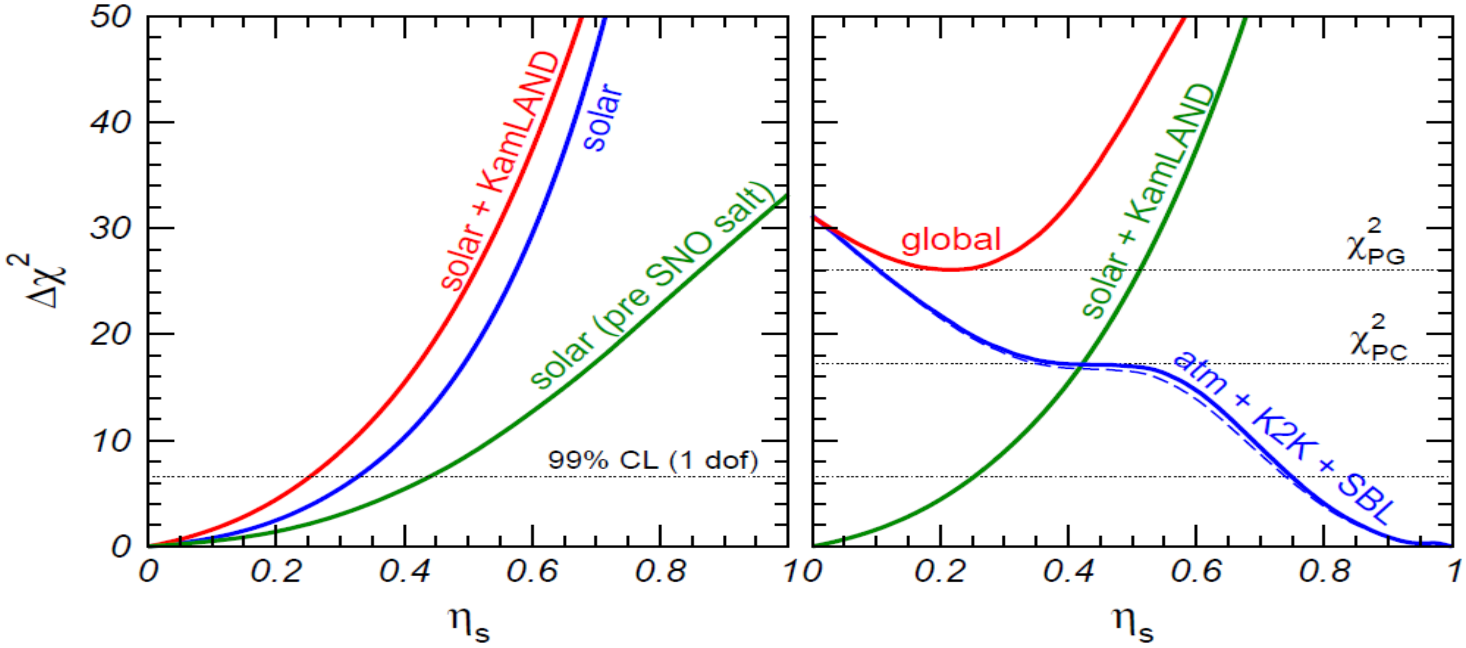
- **Improved reactor neutrino spectra → <u>+3.5%</u>**
- **Accounting for long-lived isotopes in reactors → <u>+1%</u>**

ii) Neutrino Detection:

- **Reevaluation of σ_{IBD} → <u>+1.5%</u> (evolution of the neutron life time)**
- **Reanalysis of all SBL experiments**

[T. Lasserre, TAUP 2013]

2+2 schemes are disfavored



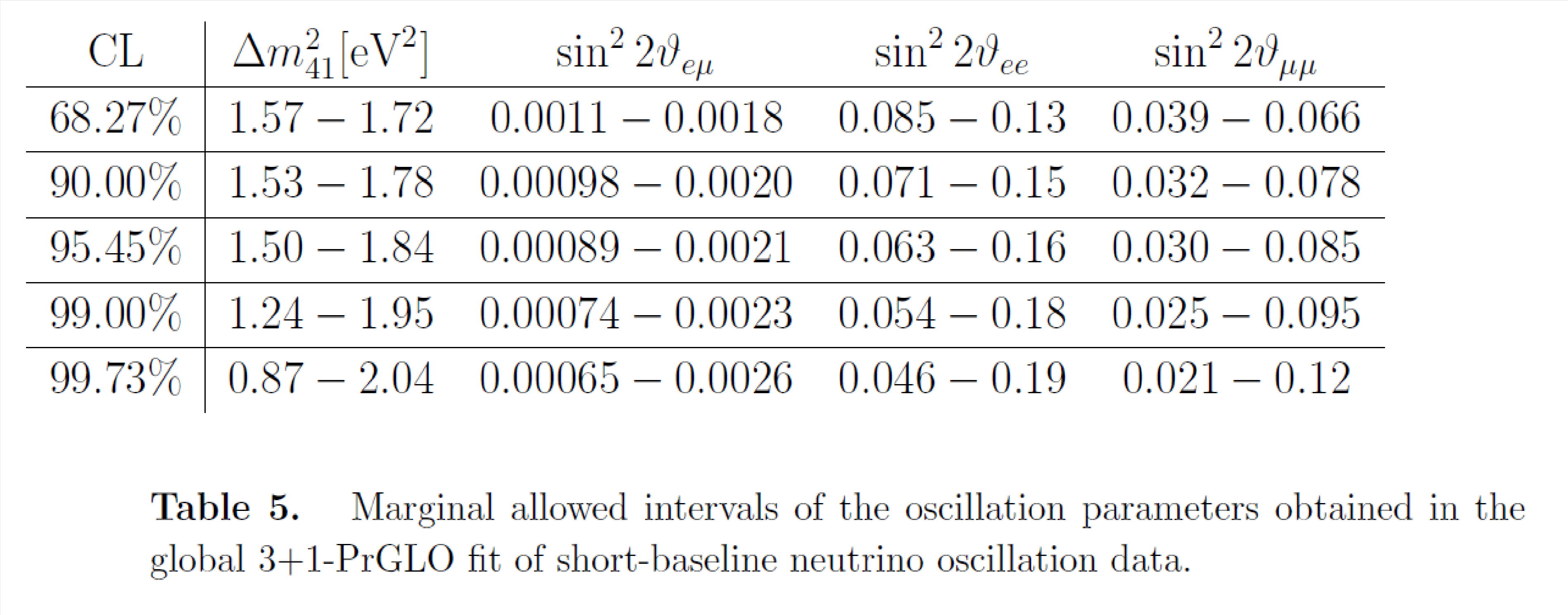
matter effects + SNO NC

matter effects

$$\eta_s = |U_{s1}|^2 + |U_{s2}|^2$$
$$1 - \eta_s = |U_{s3}|^2 + |U_{s4}|^2$$

$$99\% \text{ CL: } \begin{cases} \eta_s < 0.25 & \text{(solar + KamLAND)} \\ \eta_s > 0.75 & \text{(atmospheric + K2K)} \end{cases}$$

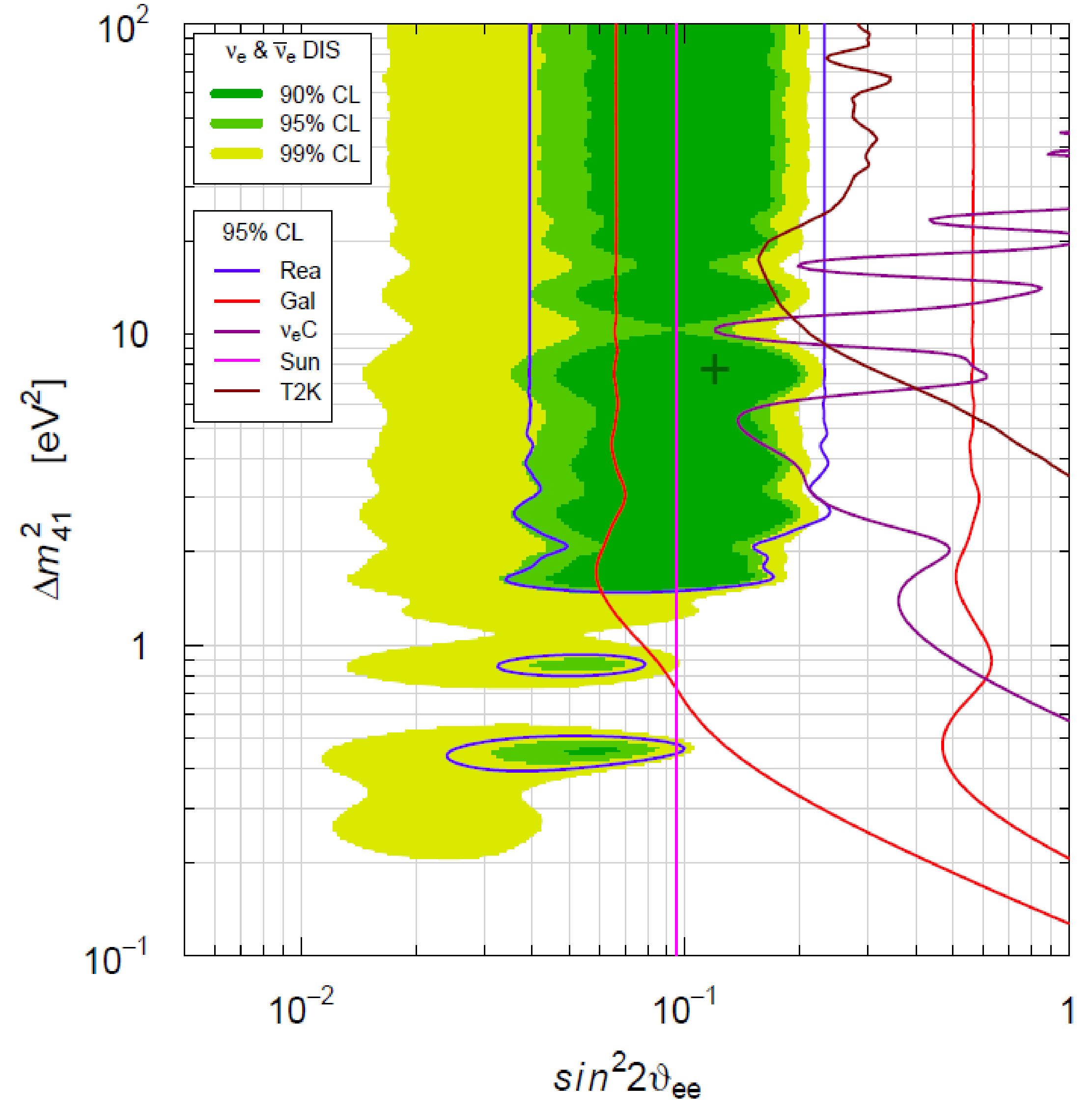
[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122, arXiv:hep-ph/0405172]



CL	$\Delta m^2_{41}\,[\mathrm{eV}^2]$	$\sin^2 2\vartheta_{e\mu}$	$\sin^2 2\vartheta_{ee}$	$\sin^2 2\vartheta_{\mu\mu}$
68.27%	$1.57 - 1.72$	$0.0011 - 0.0018$	$0.085 - 0.13$	$0.039 - 0.066$
90.00%	$1.53 - 1.78$	$0.00098 - 0.0020$	$0.071 - 0.15$	$0.032 - 0.078$
95.45%	$1.50 - 1.84$	$0.00089 - 0.0021$	$0.063 - 0.16$	$0.030 - 0.085$
99.00%	$1.24 - 1.95$	$0.00074 - 0.0023$	$0.054 - 0.18$	$0.025 - 0.095$
99.73%	$0.87 - 2.04$	$0.00065 - 0.0026$	$0.046 - 0.19$	$0.021 - 0.12$

Table 5. Marginal allowed intervals of the oscillation parameters obtained in the global 3+1-PrGLO fit of short-baseline neutrino oscillation data.

Global νe and νe-bar Disappearance



Limits:

(1) Solar constraints on ϑ_{14} :

Fit of solar and KamLAND data with Daya Bay and RENO constraints on ϑ_{13} and free $|U_{\mu4}|$ and $|U_{\tau4}|$

(2) νe+C process

(3) T2K near detector

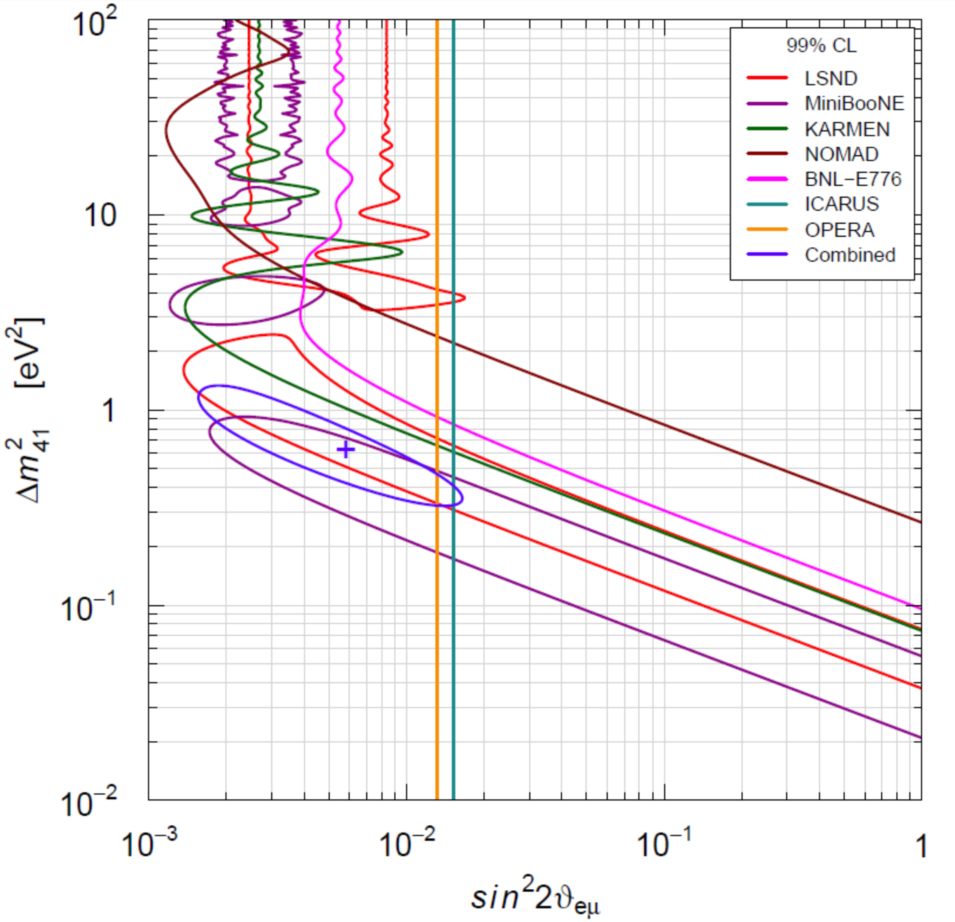
No Osc. excluded at 2.9σ
$(\Delta\chi^2/NDF = 11.2/2)$

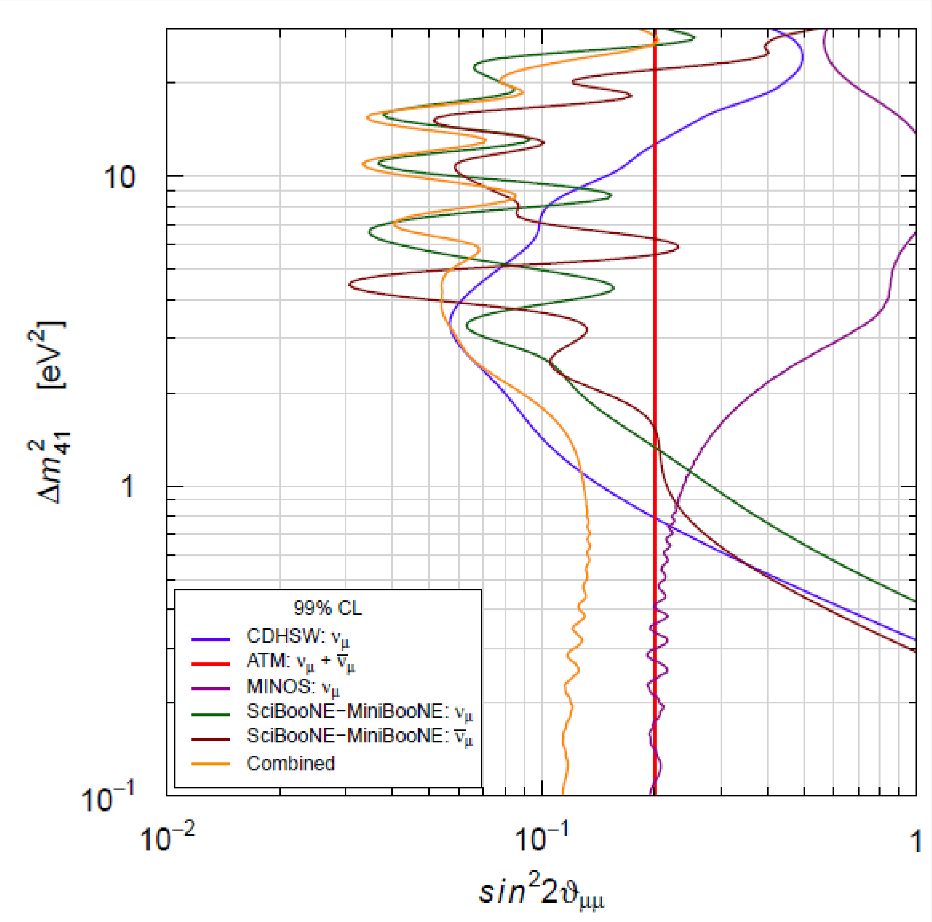
KARMEN + LSND $\nu_e + {}^{12}C \to {}^{12}N_{g.s.} + e^-$
[Conrad, Shaevitz, PRD 85 (2012) 013017]
[Giunti, Laveder, PLB 706 (2011) 200]

solar ν_e + KamLAND $\bar{\nu}_e$ + ϑ_{13}
[Giunti, Li, PRD 80 (2009) 113007]
[Palazzo, PRD 83 (2011) 113013; PRD 85 (2012) 077301]
[Giunti, Laveder, Li, Liu, Long, PRD 86 (2012) 113014]

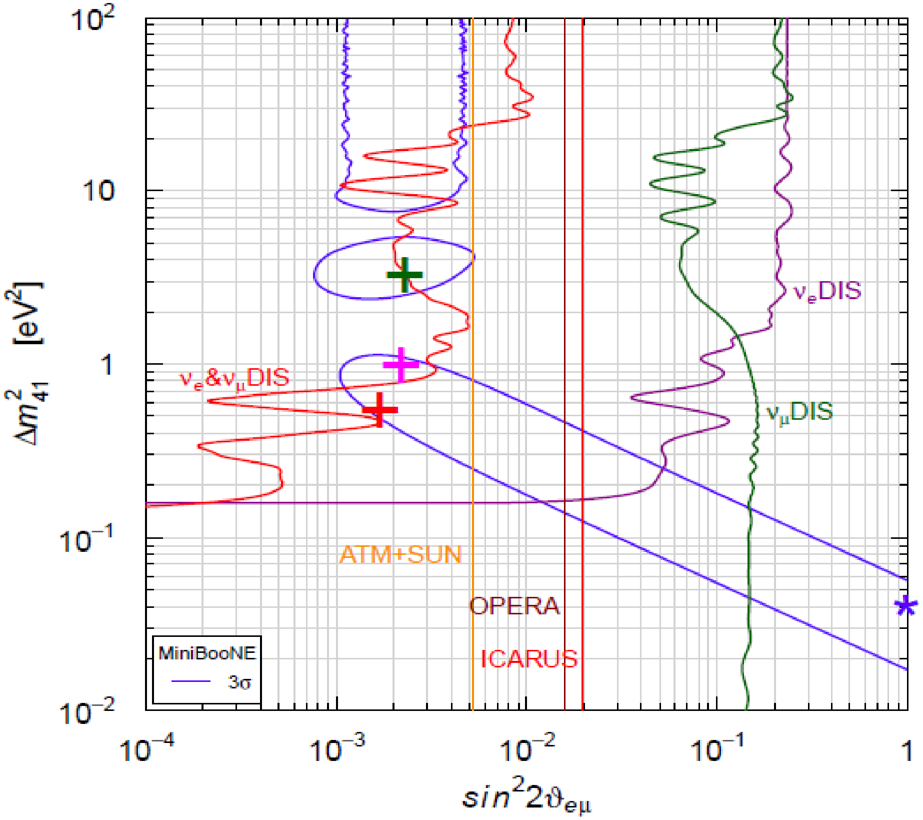
T2K Near Detector ν_e disappearance
[T2K, PRD 91 (2015) 051102]

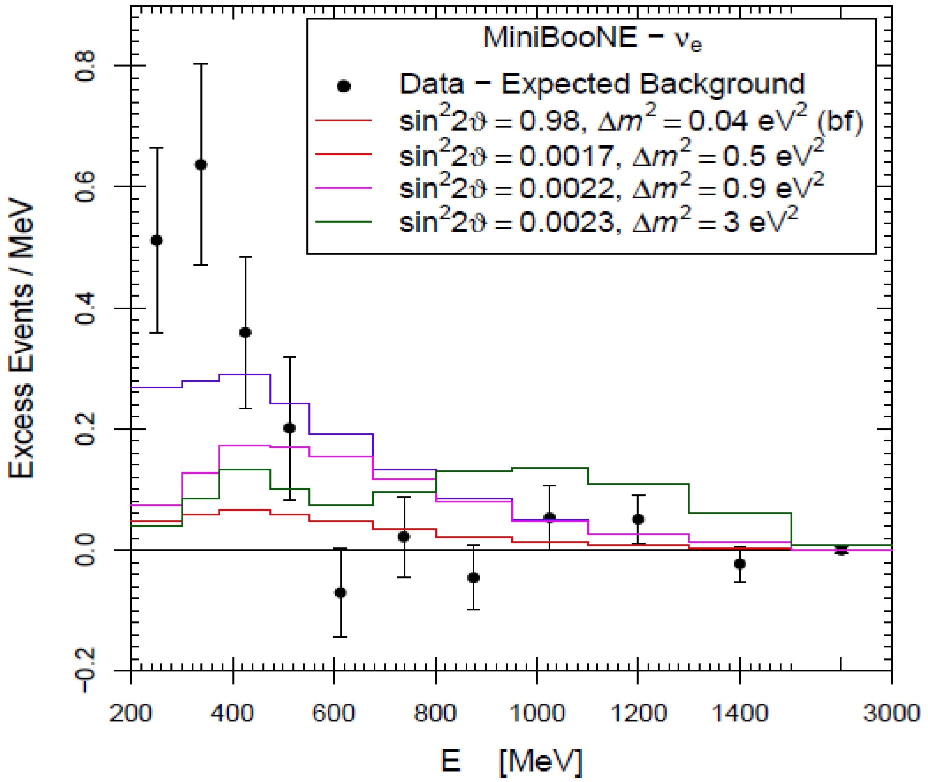
νμ→νe appearance & νμ disappearance





MiniBooNE Low-Energy Excess?



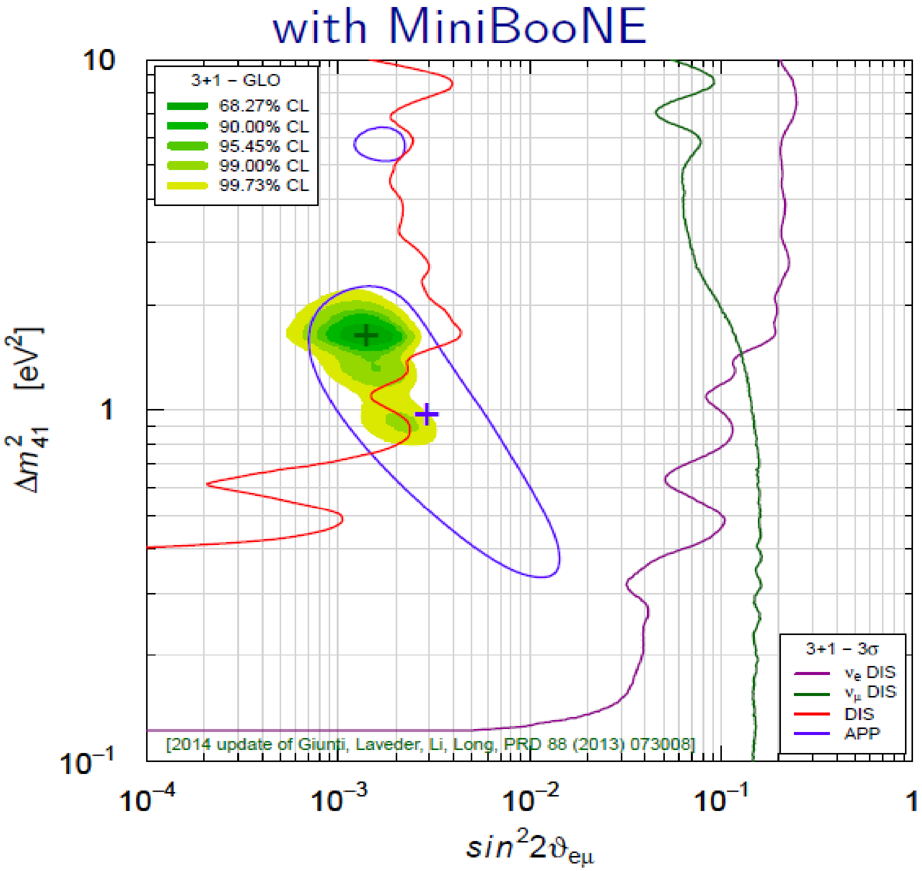


- No fit of low-energy excess for realistic $\sin^2 2\vartheta_{e\mu} \lesssim 3 \times 10^{-3}$
- MB low-energy excess is the main cause of bad APP-DIS PGoF $= 0.1\%$
- Pragmatic Approach: discard the Low-Energy Excess because it is very likely not due to oscillations

[Giunti, Laveder, Li, Long, PRD 88 (2013) 073008]

MiniBooNE Impact in Pragmatic 3+1 Fit?

with MiniBooNE

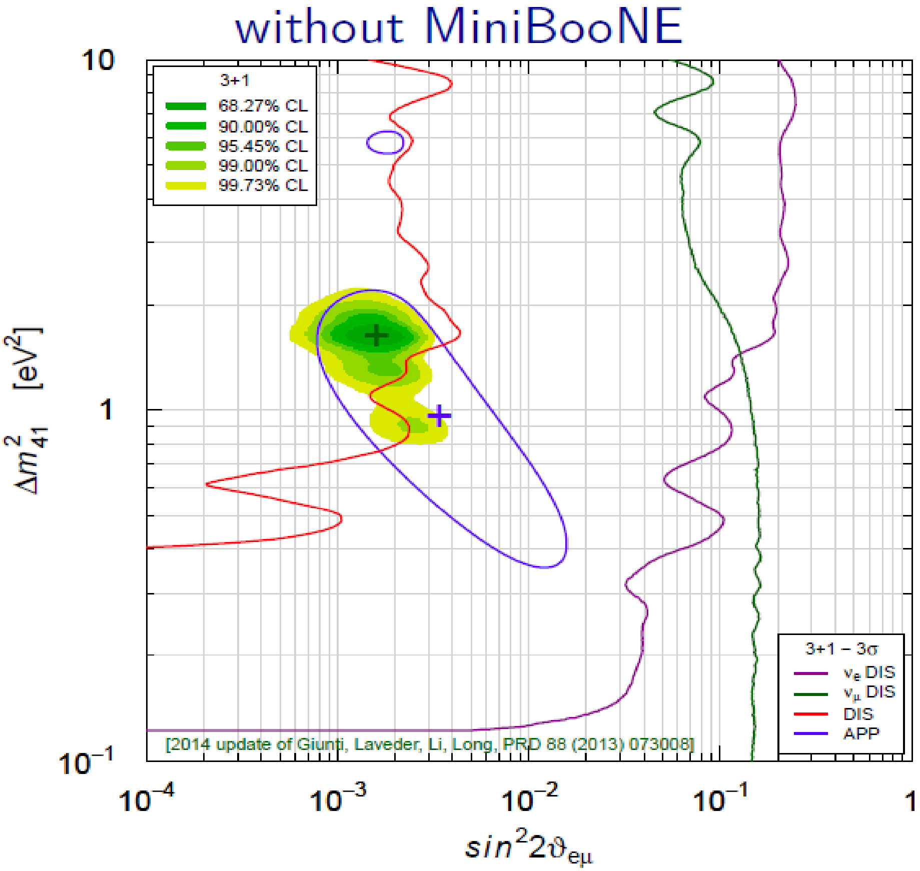


$\text{GoF} = 26\%$ $\text{PGoF} = 7\%$

No Osc. nominally disfavored

at $\approx 6.3\sigma$ $(\Delta\chi^2/\text{NDF} = 47.7/3)$

without MiniBooNE



$\text{GoF} = 16\%$ $\text{PGoF} = 5\%$

No Osc. nominally disfavored

at $\approx 6.4\sigma$ $(\Delta\chi^2/\text{NDF} = 48.1/3)$

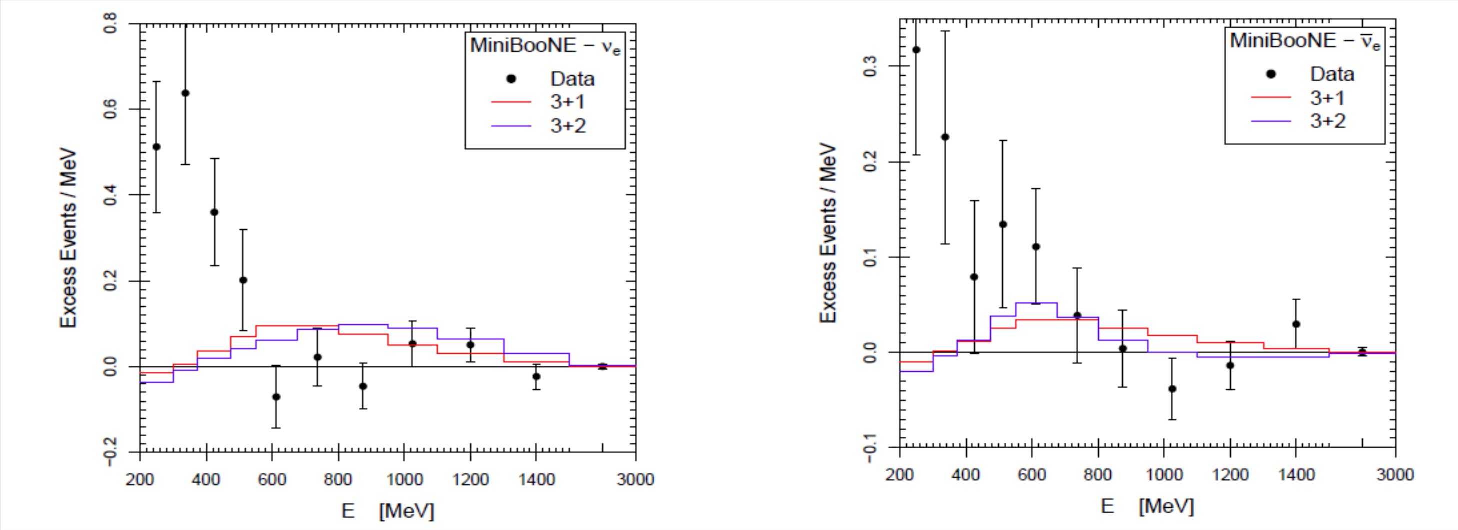
Without LSND: No Osc. nominally disfavored at $\approx 2.6\sigma$ $(\Delta\chi^2/\text{NDF} = 11.4/3)$

Status of 3+2 fit

Can we include two sterile neutrinos to improve the fit?

(1) It contains more mixing and mass parameters

(2) It allows CP violation between neutrino and antineutrino channels



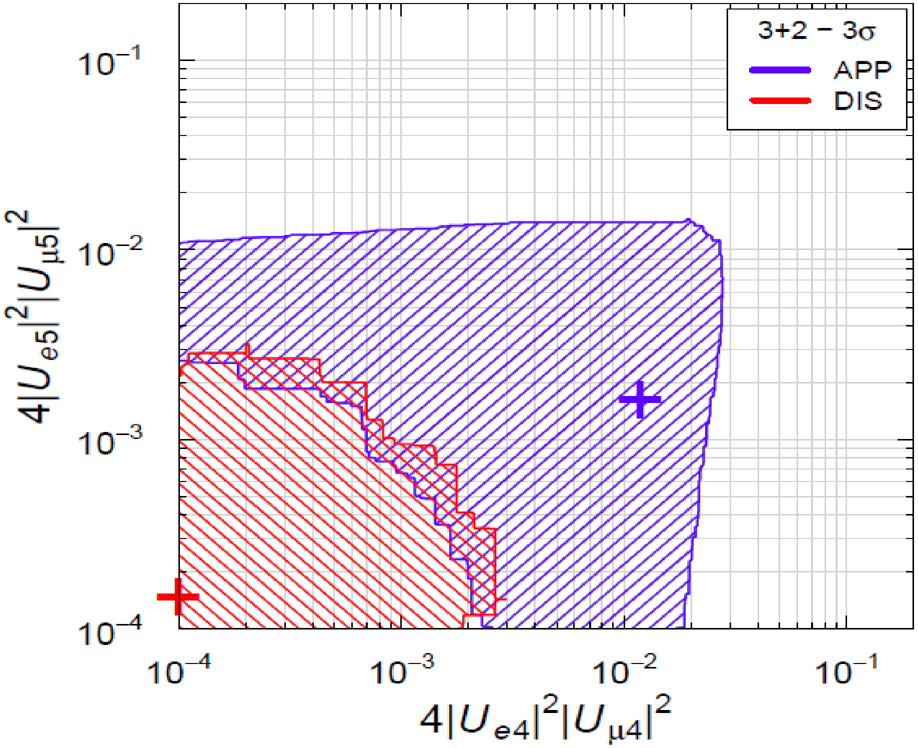
- 3+2 can fit slightly better the small $\bar{\nu}_e$ excess at about 600 MeV
- 3+2 fit of low-energy excess as bad as 3+1
- Claims that 3+2 can fit low-energy excess do not take into account constraints from other data

APP-DIS tension

Global Fits	Our Fit		KMMS	
	3+1	3+2	3+1	3+2
GoF	5%	7%	19%	23%
PGoF	0.1%	0.04%	0.01%	0.003%

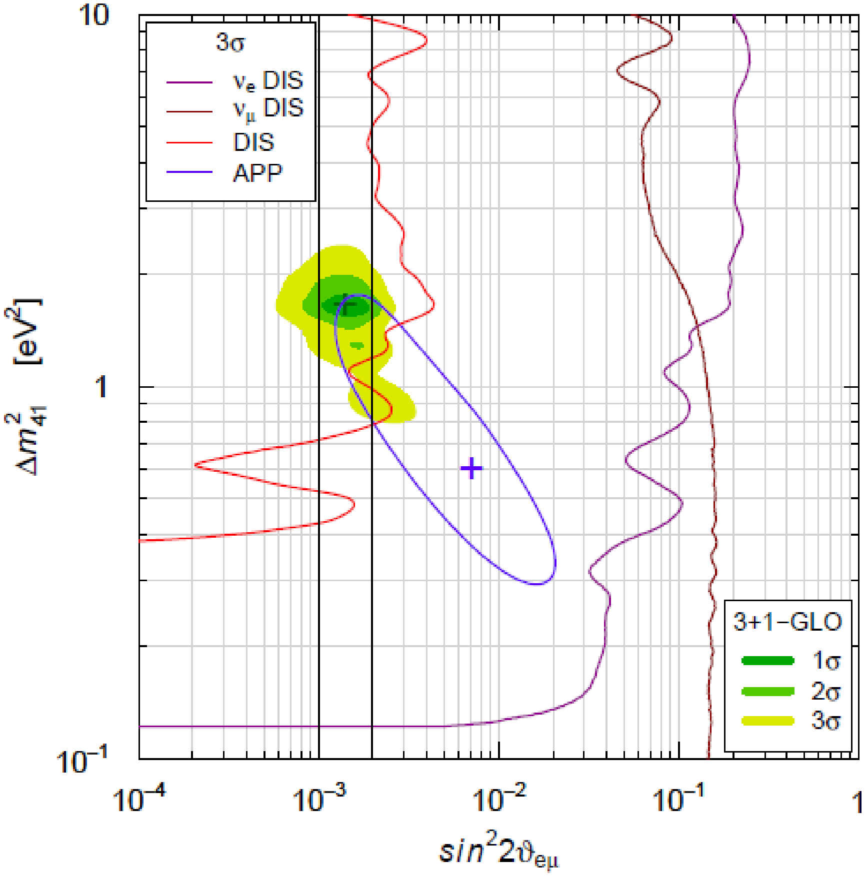
- Our Fit: Gariazzo, Giunti, Laveder, Li, Zavanin, JPG 43 (2016) 033001
- KMMS: Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050

APP-DIS 3+2 Tension:



Global 3+1 Fit

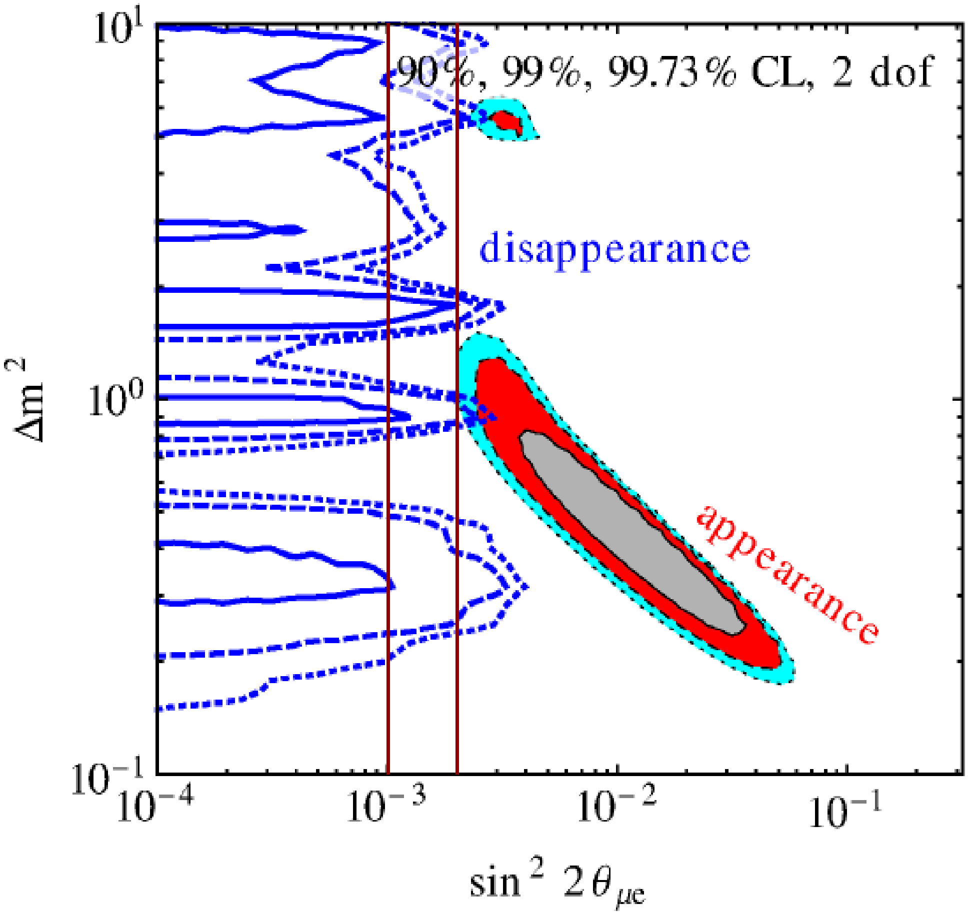
Our Fit



GoF = 5% PGoF = 0.1%

[Gariazzo, Giunti, Laveder, Li, Zavanin, JPG 43 (2016) 033001]

Kopp, Machado, Maltoni, Schwetz



GoF = 19% PGoF = 0.01%

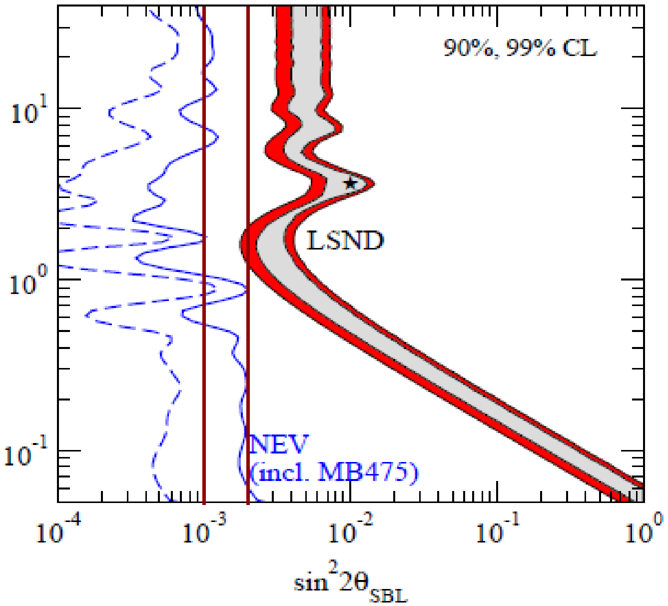
[Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

Different LSND Treatments

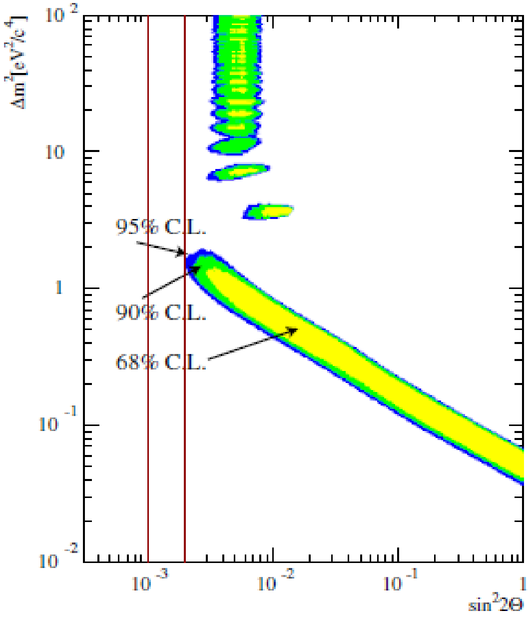
only LSND data from $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ decay at rest

[Kopp, Machado, Maltoni, Schwetz]

[Maltoni, Schwetz, PRD 76 (2007) 093005]

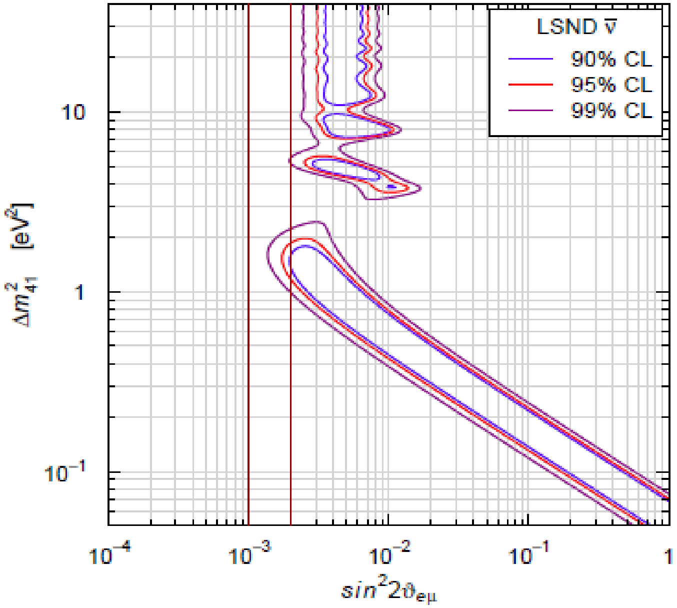


[Church, Eitel, Mills, Steidl, PRD 66 (2002) 013001]

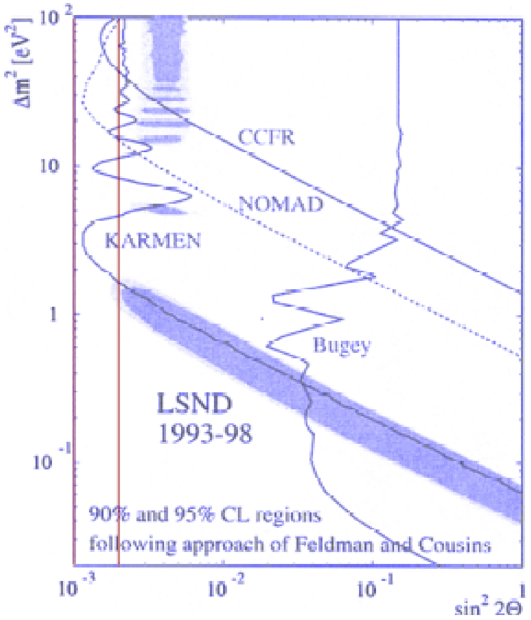


[Our Fit]

[improvement of Giunti, Laveder, PRD 82 (2010) 093016]



[Church (LSND), NPA 663 (2000) 799]



Goodness of Fit

- Assumption or approximation: Gaussian uncertainties and linear model
- $\chi^2_{\rm min}$ has χ^2 distribution with Number of Degrees of Freedom

$$\mathrm{NDF} = N_{\rm D} - N_{\rm P}$$

$N_{\rm D}$ = Number of Data $\qquad N_{\rm P}$ = Number of Fitted Parameters

- $\langle \chi^2_{\rm min} \rangle = \mathrm{NDF} \qquad \mathrm{Var}(\chi^2_{\rm min}) = 2\mathrm{NDF}$
- $\mathrm{GoF} = \int_{\chi^2_{\rm min}}^{\infty} p_{\chi^2}(z, \mathrm{NDF})\, dz \qquad p_{\chi^2}(z, n) = \dfrac{z^{n/2-1} e^{-z/2}}{2^{n/2}\Gamma(n/2)}$

Parameter Goodness of Fit

Maltoni, Schwetz, PRD 68 (2003) 033020, arXiv:hep-ph/0304176

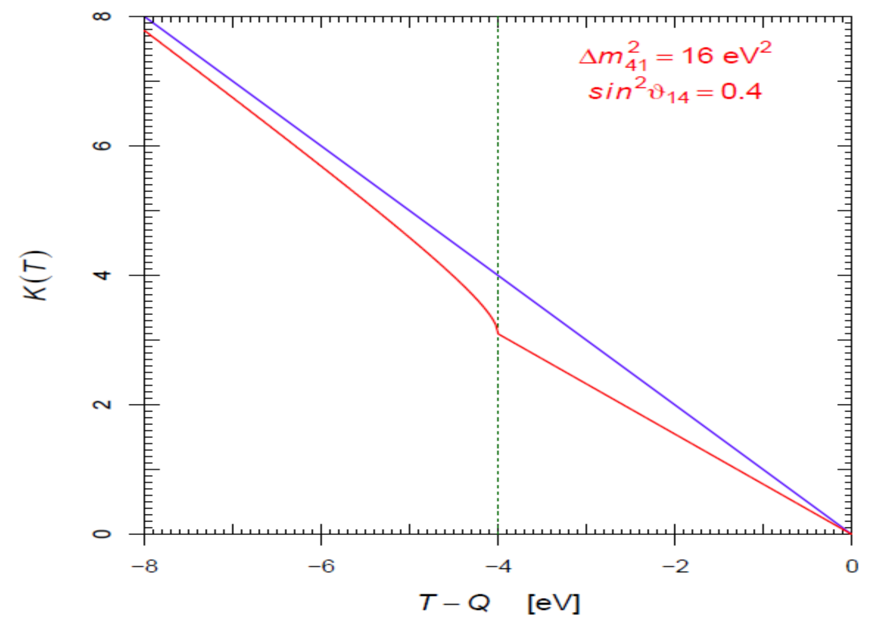
- Measure compatibility of two (or more) sets of data points A and B under fitting model
- $\chi^2_{\rm PGoF} = (\chi^2_{\rm min})_{\rm A+B} - [(\chi^2_{\rm min})_{\rm A} + (\chi^2_{\rm min})_{\rm B}]$
- $\chi^2_{\rm PGoF}$ has χ^2 distribution with Number of Degrees of Freedom

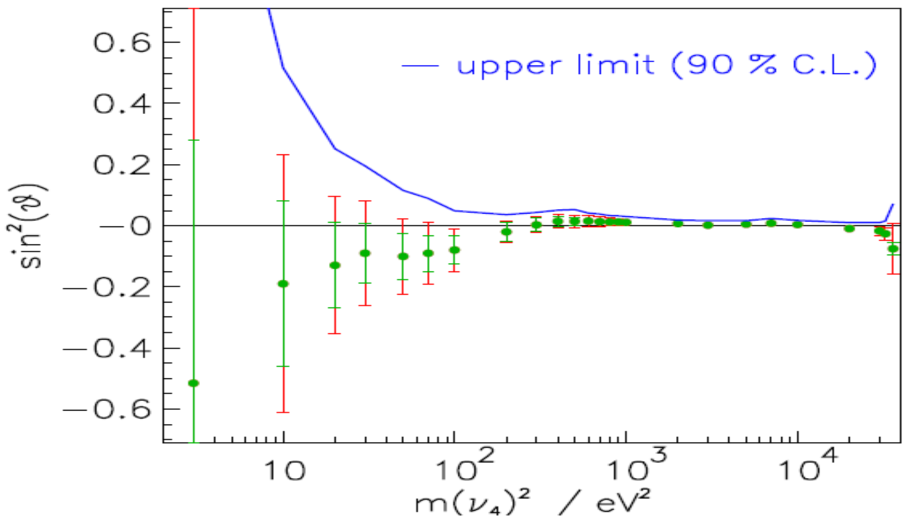
$$\mathrm{NDF}_{\rm PGoF} = N_{\rm P}^{\rm A} + N_{\rm P}^{\rm B} - N_{\rm P}^{\rm A+B}$$

- $\mathrm{PGoF} = \int_{\chi^2_{\rm PGoF}}^{\infty} p_{\chi^2}(z, \mathrm{NDF}_{\rm PGoF})\, dz$

Implications in non-oscillation probes

Beta decay: Mainz and Troitsk Limits



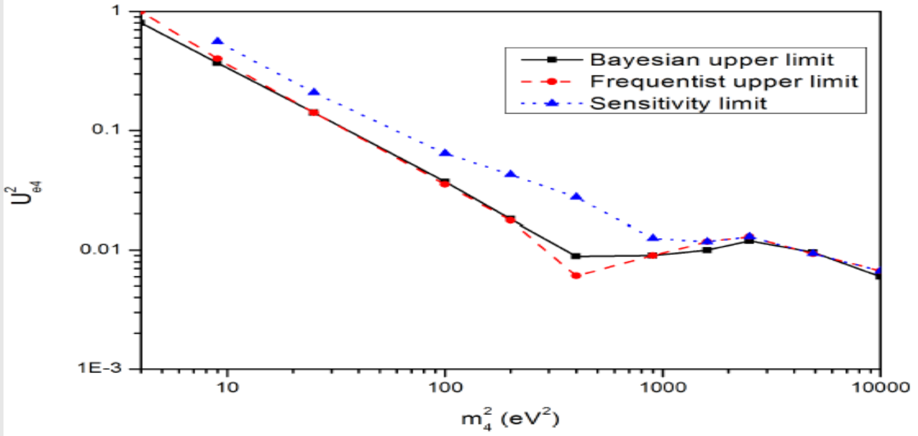


[Kraus, Singer, Valerius, Weinheimer, EPJC 73 (2013) 2323]

Search for spectra distortion can put limits on the heavy neutrino component.

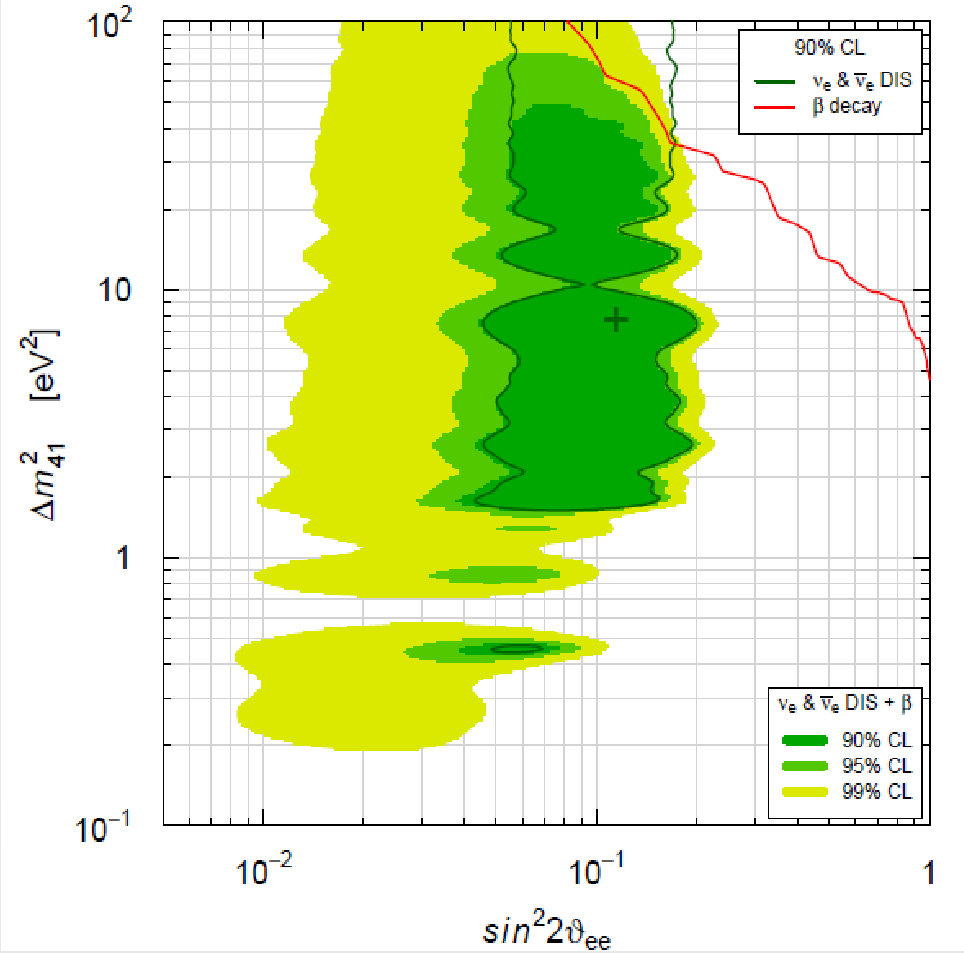
Current limits from Mainz and Troitsk are rather poor.

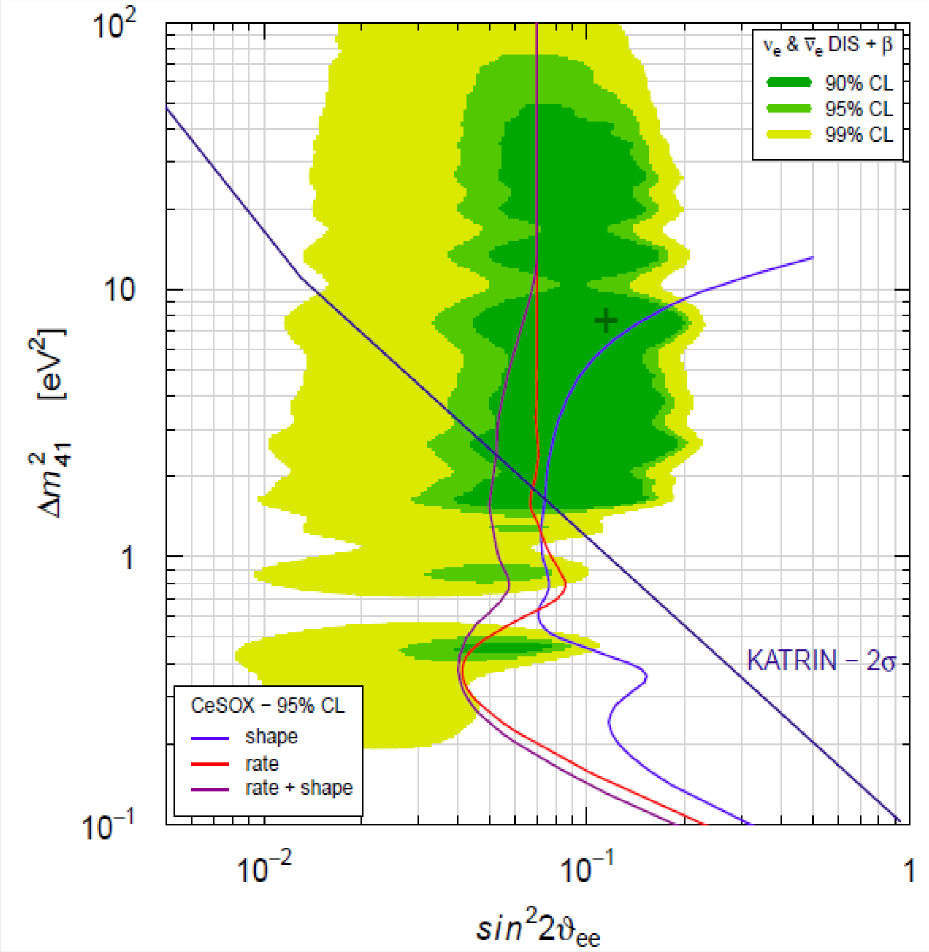
Future KATRIN is very competitive.



[Belesev et al, JPG 41 (2014) 015001]

Beta decay (2)



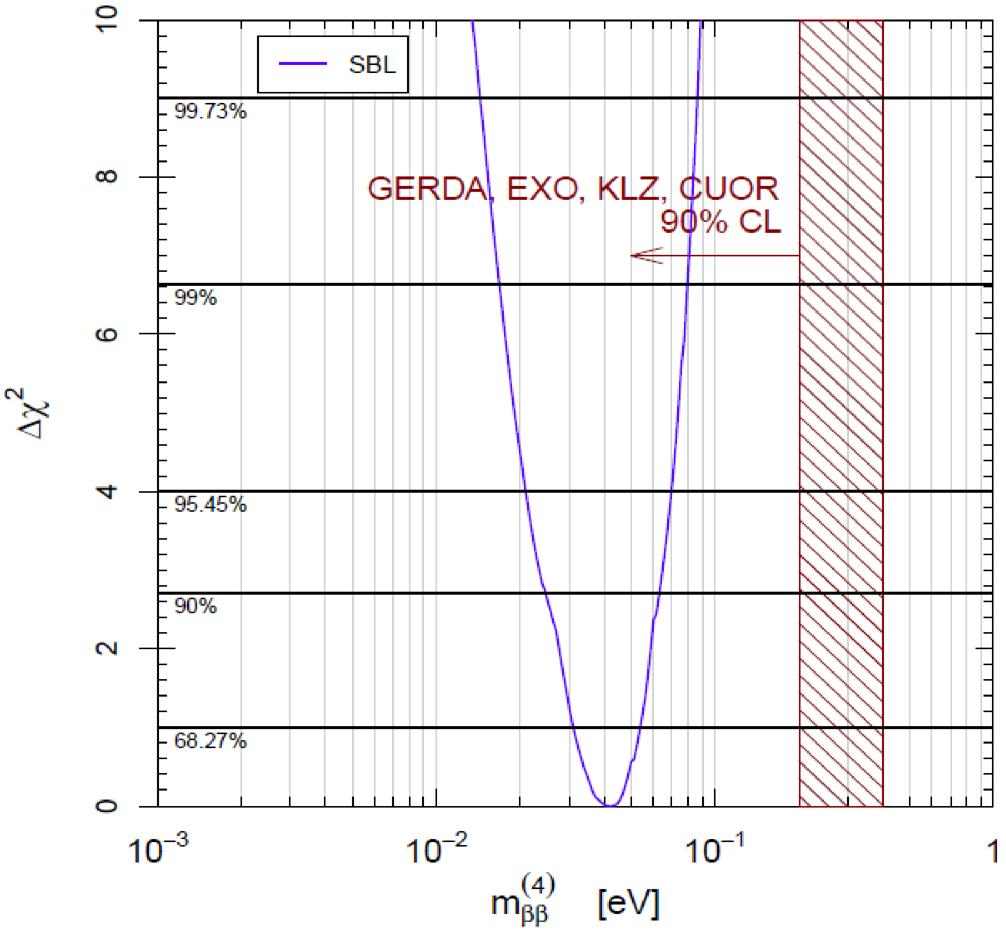


Mainz and Troitsk → lower limit:

$$7\,\text{cm} \lesssim \frac{L^{\text{osc}}_{41}}{E\,[\text{MeV}]} \lesssim 2\,\text{m} \qquad (2\sigma)$$

Double beta decay

$$m_{\beta\beta} = |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{i\alpha_{21}}\, m_2 + |U_{e3}|^2\, e^{i\alpha_{31}}\, m_3 + |U_{e4}|^2\, e^{i\alpha_{41}}\, m_4$$



Pragmatic 3+1 Fit

$$m_{\beta\beta}^{(k)} = |U_{ek}|^2 m_k$$

$$m_1 \ll m_4$$

$$\Downarrow$$

$$m_{\beta\beta}^{(4)} \simeq |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

surprise:

possible cancellation

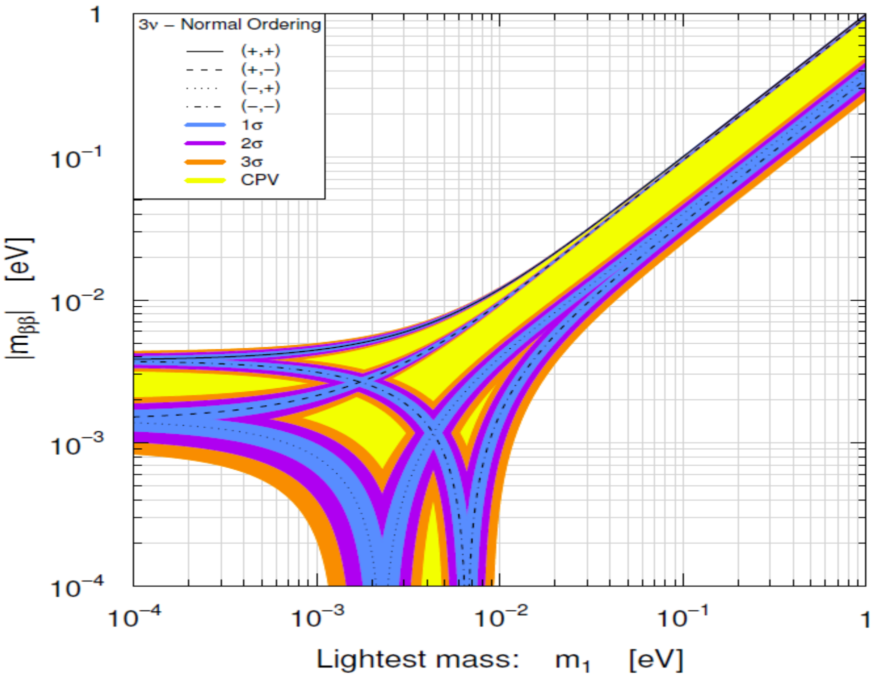
with $m_{\beta\beta}^{(3\nu)}$

[Barry et al, JHEP 07 (2011) 091]

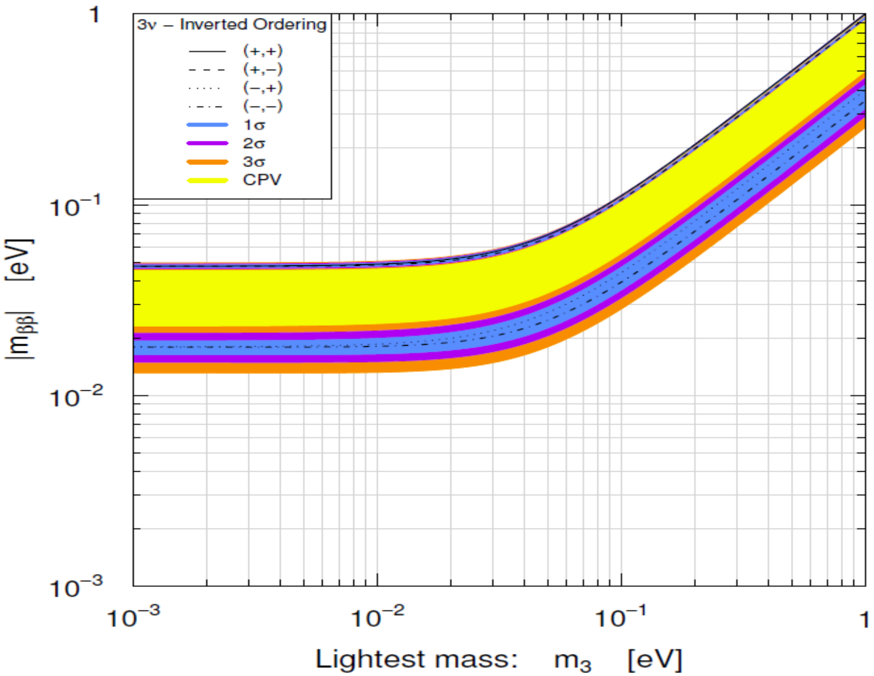
[Li, Liu, PLB 706 (2012) 406]

[Rodejohann, JPG 39 (2012) 124008]

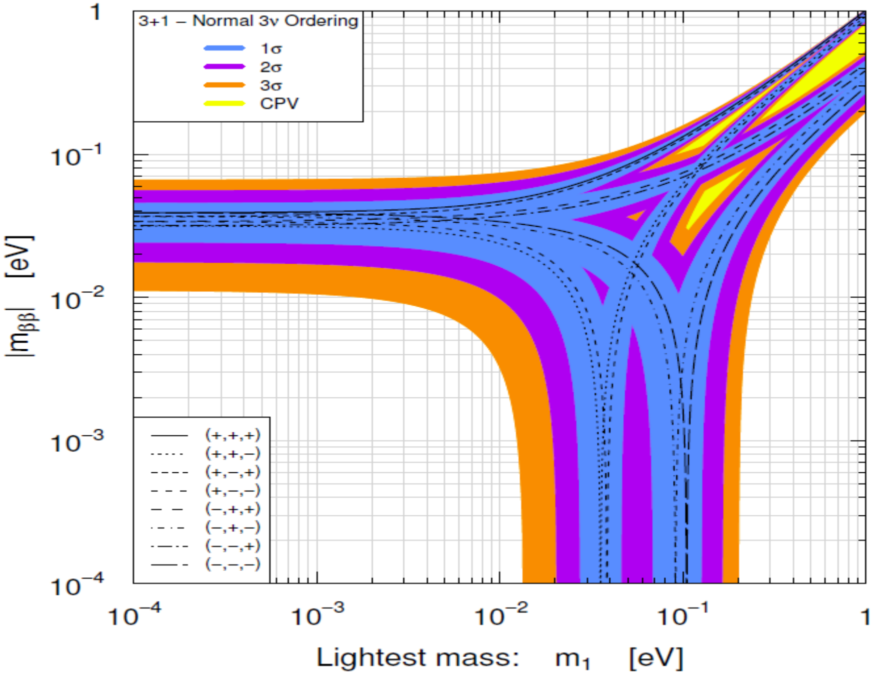
[Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]



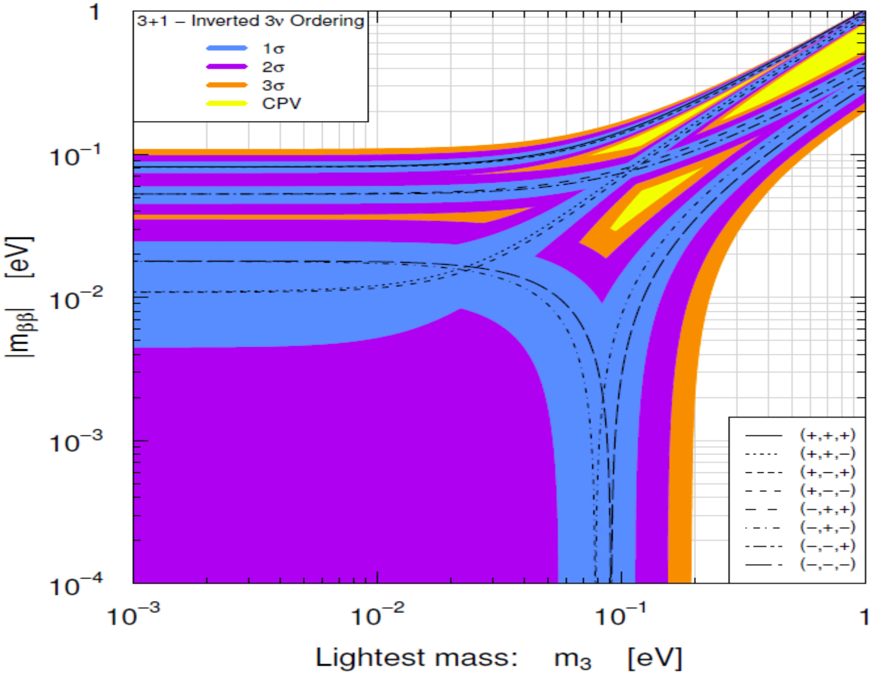
3ν – Normal Ordering
(+,+)
(+,−)
(−,+)
(−,−)
1σ
2σ
3σ
CPV
$|m_{\beta\beta}|$ [eV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
Lightest mass: m_1 [eV]



3ν – Inverted Ordering
(+,+)
(+,−)
(−,+)
(−,−)
1σ
2σ
3σ
CPV
$|m_{\beta\beta}|$ [eV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-3}
10^{-2}
10^{-1}
1
Lightest mass: m_3 [eV]



3+1 – Normal 3ν Ordering
1σ
2σ
3σ
CPV
(+,+,+)
(+,+,−)
(+,−,+)
(+,−,−)
(−,+,+)
(−,+,−)
(−,−,+)
(−,−,−)
$|m_{\beta\beta}|$ [eV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
Lightest mass: m_1 [eV]



3+1 – Inverted 3ν Ordering
1σ
2σ
3σ
CPV
(+,+,+)
(+,+,−)
(+,−,+)
(+,−,−)
(−,+,+)
(−,+,−)
(−,−,+)
(−,−,−)
$|m_{\beta\beta}|$ [eV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
Lightest mass: m_3 [eV]