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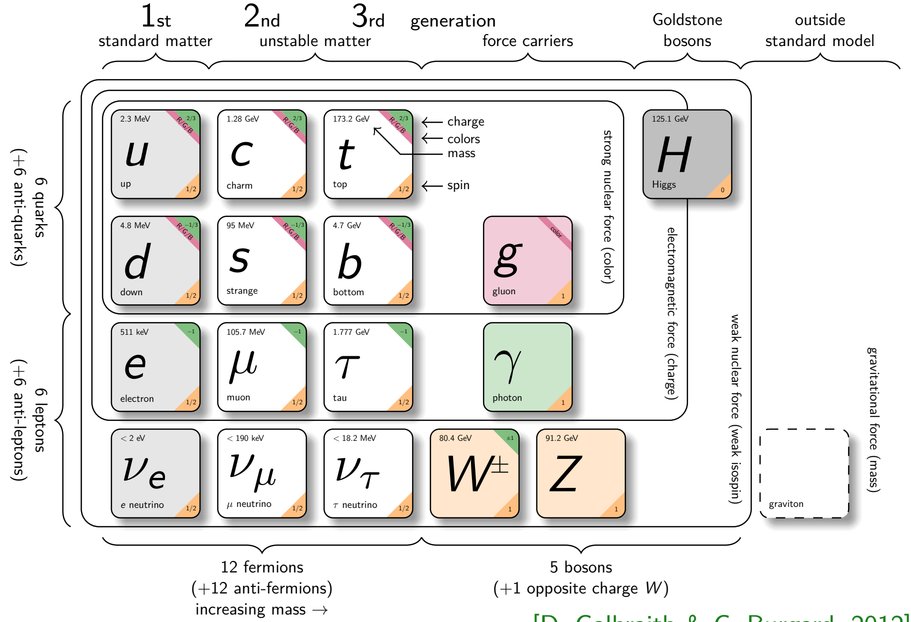
Light sterile neutrino: the 2018 status

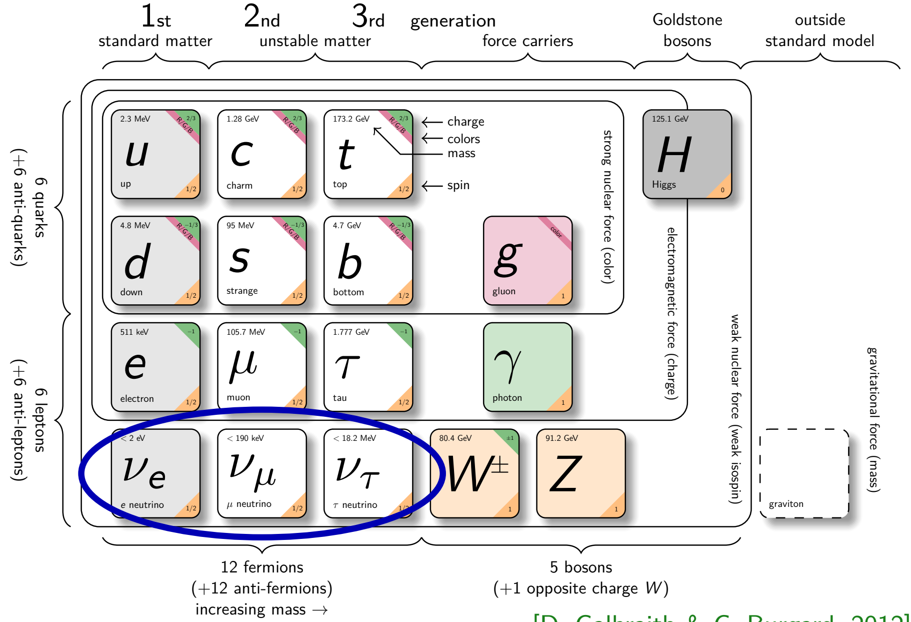
X CPAN Days, Salamanca, 29/10/2018

The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

Three Neutrino Oscillations

$$\nu_\alpha = \sum_{k=1}^{3} U_{\alpha k} \nu_k \quad (\alpha = e, \mu, \tau)$$

$U_{\alpha k}$ described by 3 mixing angles θ_{12}, θ_{13}, θ_{23} and one CP phase $\delta_{\rm CP}$

Current knowledge of the 3 active ν mixing: [de Salas et al. (2018)]

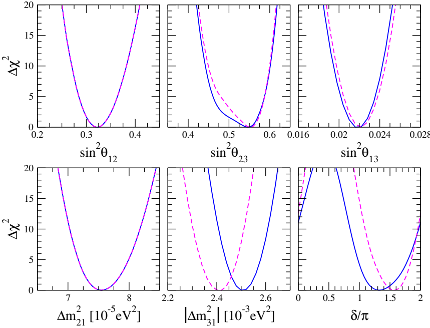
NO: Normal Ordering, $m_1 < m_2 < m_3$

IO: Inverted Ordering, $m_3 < m_1 < m_2$

$$\begin{aligned}
\Delta m^2_{21} &= (7.55^{+0.20}_{-0.16}) \cdot 10^{-5}\ \mathrm{eV}^2 \\
|\Delta m^2_{31}| &= (2.50 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO}) \\
&= (2.42^{+0.03}_{-0.04}) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})
\end{aligned}$$

$$\begin{aligned}
\sin^2(\theta_{12}) &= 0.320^{+0.020}_{-0.016} \\
\sin^2(\theta_{13}) &= 0.0216^{+0.008}_{-0.007}\ (\mathrm{NO}) \\
&= 0.0222^{+0.007}_{-0.008}\ (\mathrm{IO}) \\
\sin^2(\theta_{23}) &= 0.547^{+0.020}_{-0.030}\ (\mathrm{NO}) \\
&= 0.551^{+0.018}_{-0.030}\ (\mathrm{IO})
\end{aligned}$$

First hints for $\delta_{\rm CP} \simeq 3/2\pi$



see also: http://globalfit.astroparticles.es

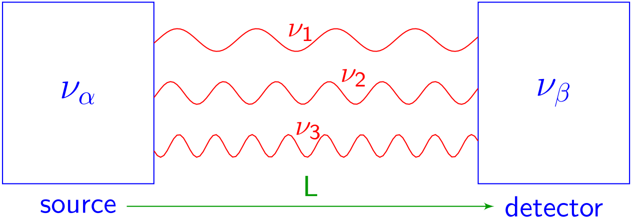
Two types of neutrinos

flavor neutrinos ν_α

$|\nu_\alpha\rangle = U_{\alpha k}|\nu_k\rangle$

massive neutrinos ν_k

$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = U_{\alpha 1}|\nu_1\rangle + U_{\alpha 2}|\nu_2\rangle + U_{\alpha 3}|\nu_3\rangle$$



$$|\nu(t>0)\rangle = |\nu_\beta\rangle = U_{\alpha 1}\, e^{-iE_1 t}|\nu_1\rangle + U_{\alpha 2}\, e^{-iE_2 t}|\nu_2\rangle + U_{\alpha 3}\, e^{-iE_3 t}|\nu_3\rangle \neq |\nu_\alpha\rangle$$

$E_k^2 = p^2 + m_k^2$ ⟵ define ⟶ $t = L$

$$P_{\nu_\alpha\to\nu_\beta}(L) = |\langle\nu_\alpha|\nu(L)\rangle|^2 = \sum_{k,j} U_{\beta k} U^*_{\alpha k} U^*_{\beta j} U_{\alpha j} \exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right)$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

A large family

In principle, previous discussion is valid for N neutrinos

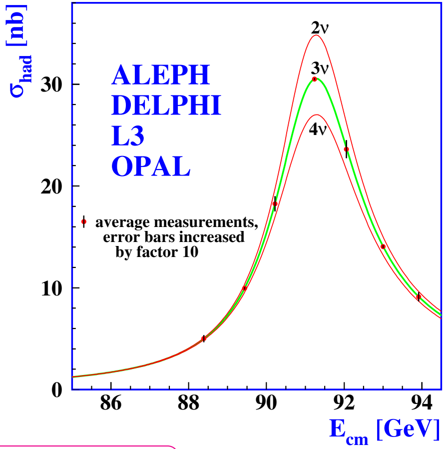
only constraint: there are exactly three flavor neutrinos in the SM

[LEP, Phys. Rept. 427 (2006) 257, arXiv:hep-ex/0509008]

$$N_\nu^{(Z)} = 2.9840 \pm 0.0082$$

through the measurement of the Z resonance

$$e^+e^- \longrightarrow Z \longrightarrow \sum_{a=e,\mu,\tau} \nu_a \bar{\nu}_a$$



neutrinos $\alpha > 3$ must be sterile

sterile neutrino = SM singlet: no couplings with other SM particles

A large family

In principle, previous discussion is valid for N neutrinos

$N \times N$ mixing matrix, N flavor neutrinos, N massive neutrinos

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \\ |\nu_{s_1}\rangle \\ \cdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \vdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} & \\ \cdots & & & & \ddots \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \\ \cdots \end{pmatrix}$$

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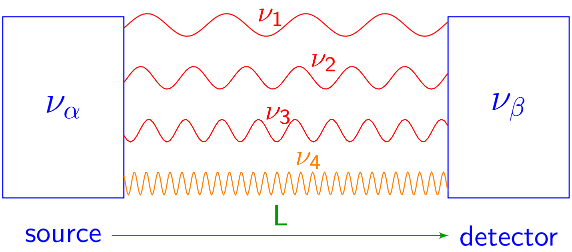
Our case will be 3 (active)+1 (sterile), a perturbation of 3 neutrinos case

$m_4 \gg m_\ell$

$\ell = 1, 2, 3$

$\Delta m^2_{41} \simeq 1\ \text{eV}^2$
$\simeq \Delta m^2_{42}$
$\simeq \Delta m^2_{43}$



6 angles

3 Dirac CP phases

3 Majorana CP phases

Short BaseLine (SBL)

$$P_{\nu_\alpha \to \nu_\beta}(L) = |\langle \nu_\alpha | \nu(L) \rangle|^2 = \sum_{k,j} U_{\beta k} U^*_{\alpha k} U^*_{\beta j} U_{\alpha j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E}\right)$$

If $m_4 \gg m_\ell$, faster oscillations

ν_4 oscillations are averaged in most neutrino oscillation experiments

Effect of 4th neutrino only visible as global normalization

Short BaseLine (SBL) oscillations: $\frac{\Delta m^2_{41} L}{E} \simeq 1$

At SBL, oscillations due to Δm^2_{21} and $|\Delta m^2_{31}|$ do not develop

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APPearance ($\alpha \neq \beta$)

source of $\overset{(-)}{\nu}_\alpha$

detect different flavor $\overset{(-)}{\nu}_\beta$

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detect different flavor $\overset{(-)}{\nu}_\beta$

DISappearance

source of $\overset{(-)}{\nu}_\alpha$

$\overset{(-)}{\nu}_s$ goes undetected

Short BaseLine (SBL)

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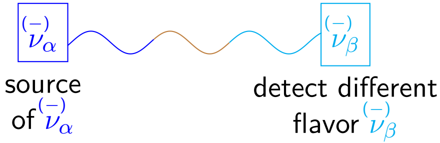
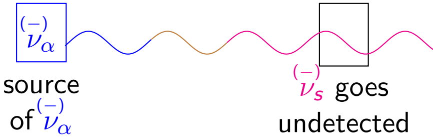


DISappearance



CP violation cannot be observed in SBL experiments!

New mixings in the 3+1 scenario

4 × 4 mixing matrix: $\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} \end{pmatrix}$

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ϑ_{14}

ϑ_{24}

ϑ_{34}

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DISappearance

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

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

$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$

reactor
gallium

$$|U_{e4}|^2 = \sin^2 \vartheta_{14}$$

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$

accelerator
atmospheric

$$|U_{\mu 4}|^2 = \cos^2 \vartheta_{14} \sin^2 \vartheta_{24}$$

New mixings in the 3+1 scenario

4 × 4 mixing matrix: $\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} \end{pmatrix}$ ϑ_{14} ϑ_{24} ϑ_{34}

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$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$ — reactor, gallium

$$|U_{e4}|^2 = \sin^2\vartheta_{14}$$

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$ — accelerator, atmospheric

$$|U_{\mu4}|^2 = \cos^2\vartheta_{14}\sin^2\vartheta_{24}$$

APPearance

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

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha4}|^2|U_{\beta4}|^2$$

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ — LSND, MiniBooNE, KARMEN, OPERA, ...

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

quadratically suppressed!

for small $|U_{e4}|^2$, $|U_{\mu4}|^2$

Gallium anomaly

[SAGE, 2006][Laveder, 2007][Giunti&Laveder, 2011]

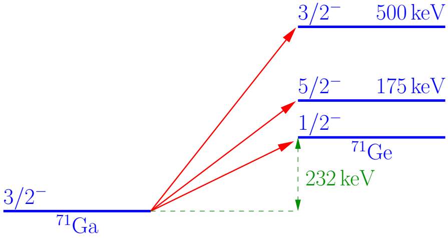
$L \simeq 1.9$ m $\quad L \simeq 0.6$ m

Gallium radioactive source experiments: GALLEX and SAGE

ν_e sources: $e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$ $\qquad e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$

$E \simeq 0.75$ MeV $\qquad E \simeq 0.81$ MeV

In the detector: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$



cross sections of
the transitions from

[Krofcheck et al., PRL 55 (1985) 1051]

[Frekers et al., PLB 706 (2011) 134]

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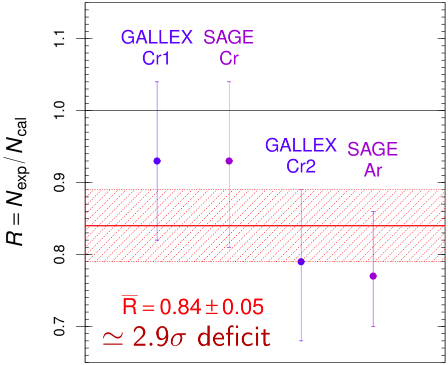
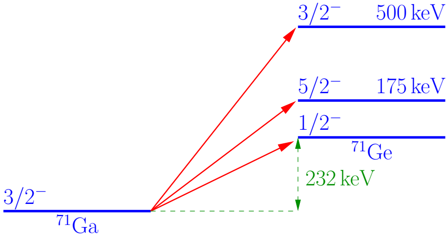
Test detection of solar ν_e





cross sections of the transitions from

[Krofcheck et al., PRL 55 (1985) 1051]

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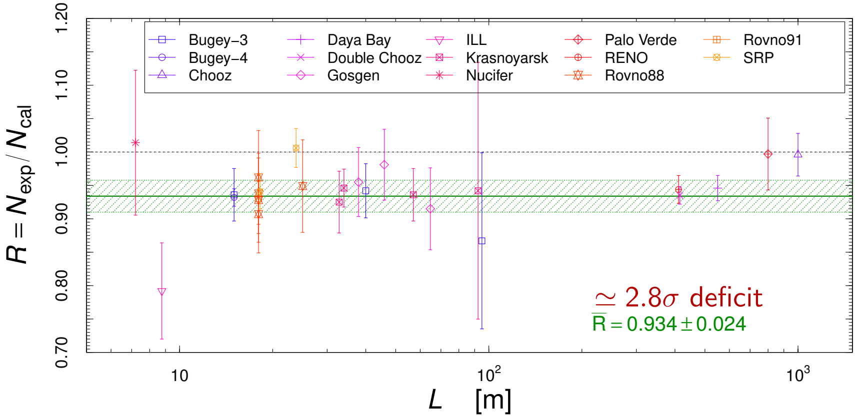
Reactor Antineutrino Anomaly (RAA)

[PRD 83 (2011) 073006]

2011: new reactor $\bar{\nu}_e$ fluxes by Huber and Mueller+ (HM)

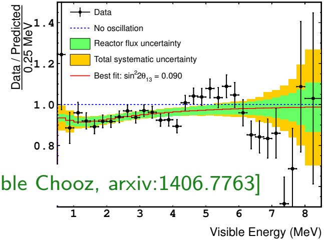
[Huber, PRC 84 (2011) 024617] [Mueller et al., PRC 83 (2011) 054615]

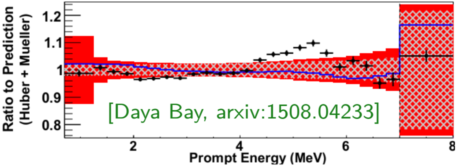
Previous reactor rates evaluated with new fluxes ⇒ deficit

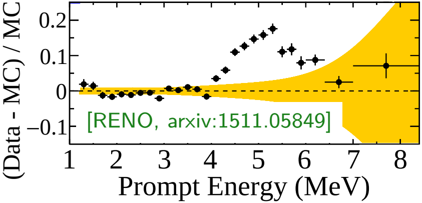


Suppression at detector due to active-sterile oscillations?

Can we trust the HM fluxes?







2014:

bump in the spectrum around 5 MeV!

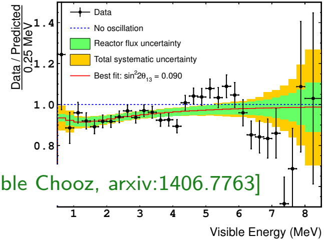
cannot be explained by SBL oscillations

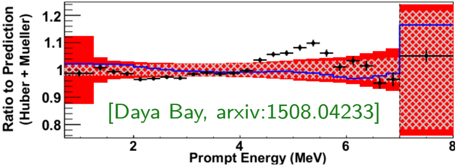
(averaged at the observed distances)

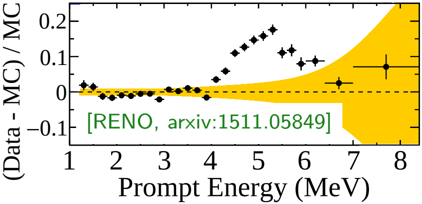
many attempts of possible explanations,

how to clarify the issue?

Can we trust the HM fluxes?







2014:

bump in the spectrum around 5 MeV!

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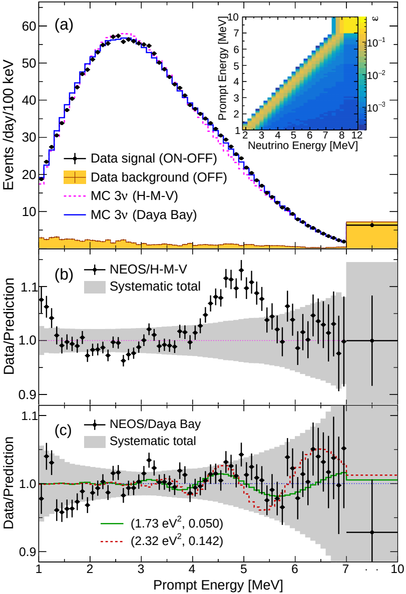
many attempts of possible explanations, how to clarify the issue?

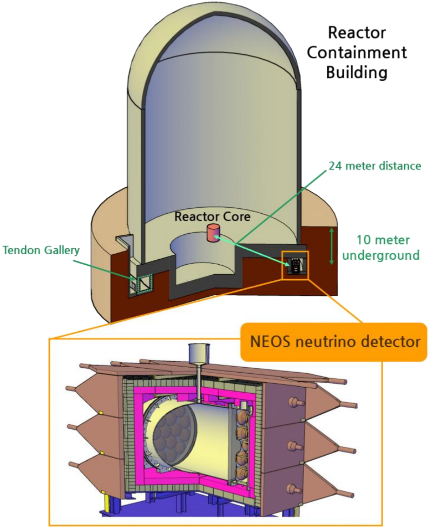
Model independent information!

(i.e. take ratio of spectra at different distances)

NEOS

Single detector experiment



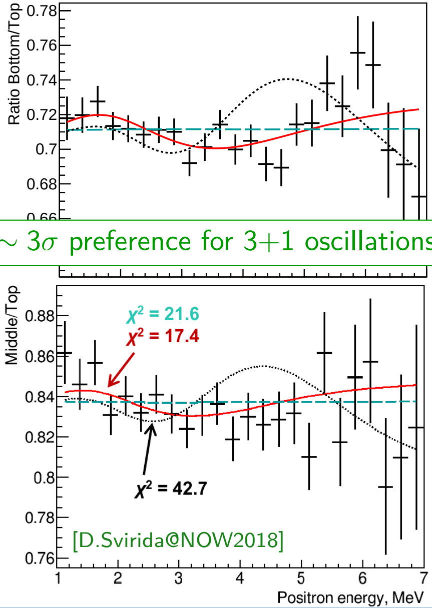


Ratio to DayaBay measurement to be model independent

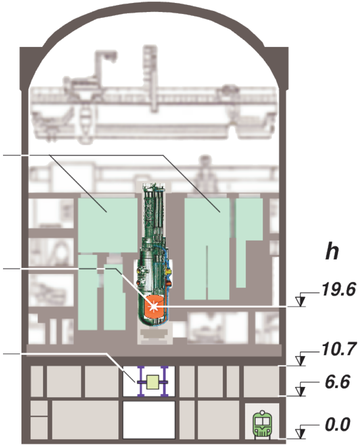
DANSS

[arxiv:1804.04046]

Single movable detector



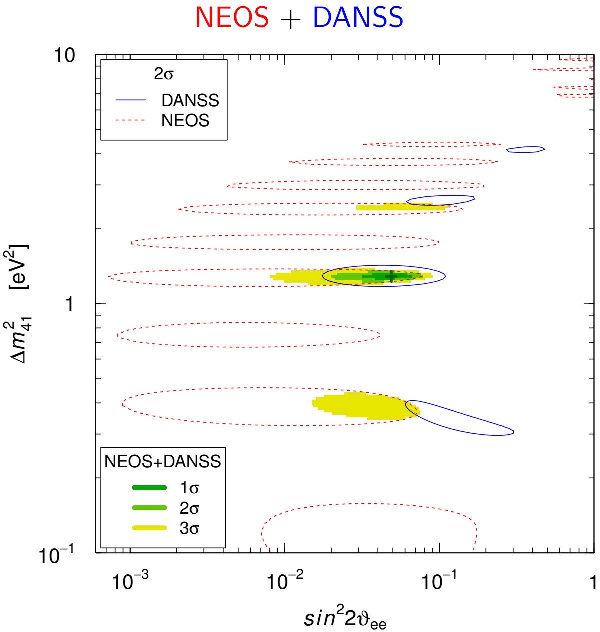
$\sim 3\sigma$ preference for 3+1 oscillations



Detector can be at $\sim$ 10.5, $\sim$ 11.5 or $\sim$ 12.5 m from reactor core

Model-independent fit of $\overset{(-)}{\nu}_e$ DIS

[SG et al., PLB 782 (2018) 13]



The NEOS and DANSS region perfectly overlap at

$\Delta m^2_{41} \simeq 1.3 \text{ eV}^2$

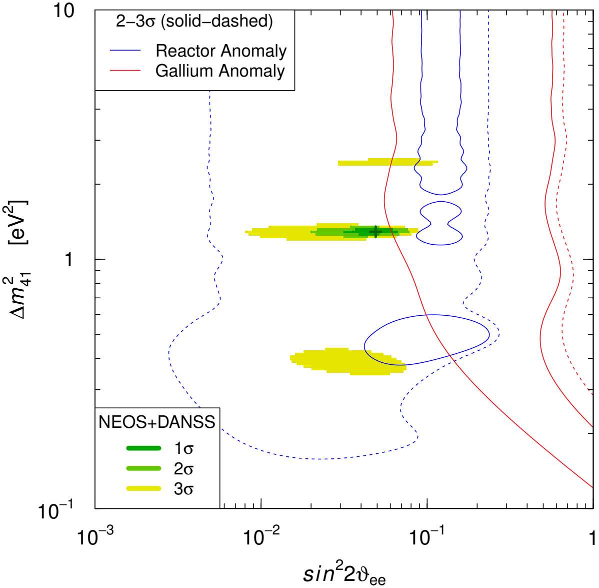
$\sin^2 2\vartheta_{ee} \simeq 0.05$

$\sin^2 \vartheta_{14} \simeq 0.01$

Model-independent fit of $\overset{(-)}{\nu}_e$ DIS

[SG et al., PLB 782 (2018) 13]

DANSS + NEOS + RAA + Gallium

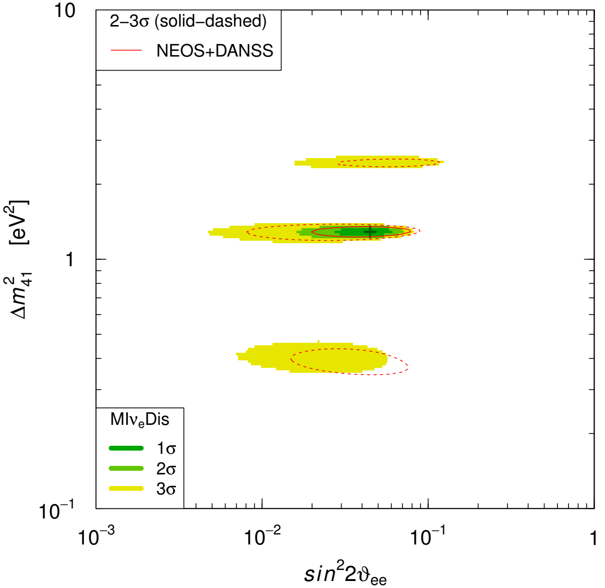


DANSS + NEOS do not agree with Gallium and RAA

Model-independent fit of $\overset{(-)}{\nu}_e$ DIS

[SG et al., PLB 782 (2018) 13]

All data:



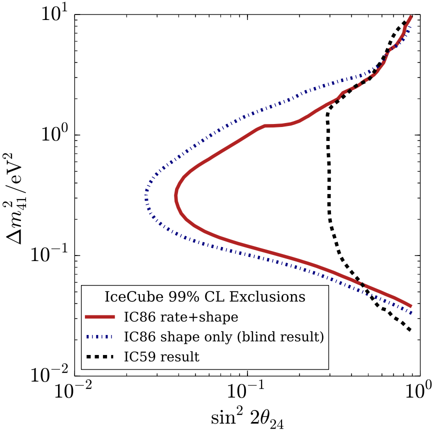
Fit dominated by
DANSS + NEOS

IceCube and DeepCore

IceCube $\mathcal{O}(10 \text{ km}) \lesssim L \lesssim \mathcal{O}(10^4 \text{ km})$

$\sim 2 \times 10^4$ High energy μ events

$320 \text{ GeV} < E < 20 \text{ TeV}$



[PRL 117 (2016) 071801]

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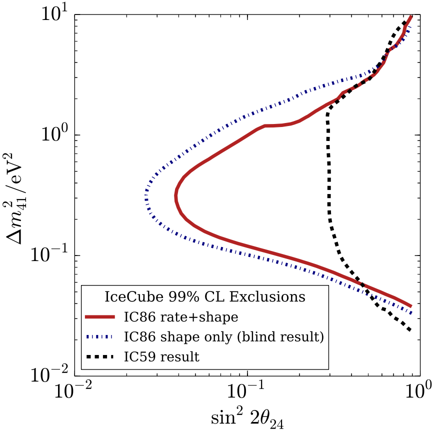

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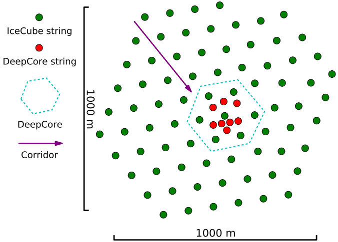
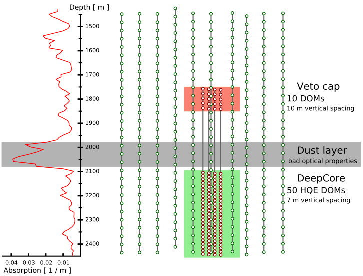




IceCube and DeepCore

IceCube

$\mathcal{O}(10\text{ km}) \lesssim L \lesssim \mathcal{O}(10^4\text{ km})$

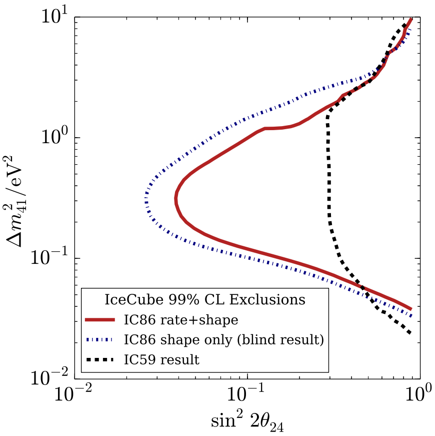
DeepCore

$\sim 2\times10^4$ High energy μ events

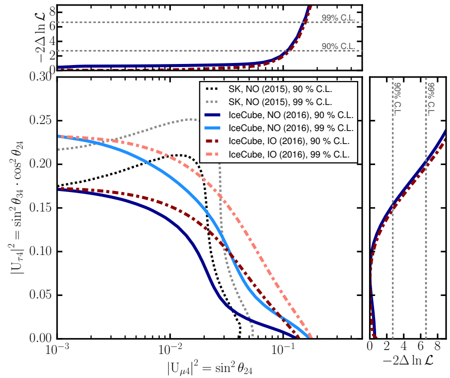
$\sim 5\times10^3$ tracklike events

$320\text{ GeV} < E < 20\text{ TeV}$

$6\text{ GeV} \lesssim E \lesssim 60\text{ GeV}$



[PRL 117 (2016) 071801]



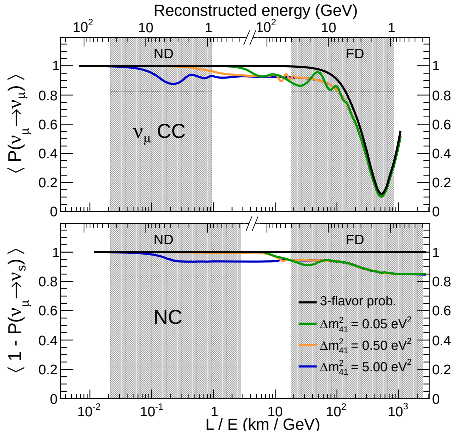
[PRD 95 (2017) 112002]

Both also constrain $|U_{\tau4}|^2$

MINOS & MINOS+

Near (ND, $\simeq$ 500 m) and far (FD, $\simeq$ 800 km) detector

1 GeV $\lesssim E \lesssim$ 40 GeV, peak at 3 GeV



[PRL 117 (2016) 151803]:

far-to-near ratio

[arxiv:1710.06488]: full two-detectors fit

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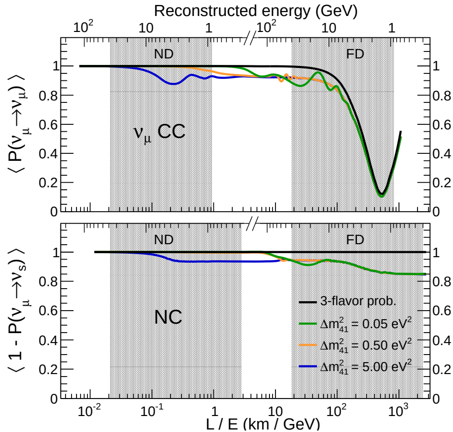

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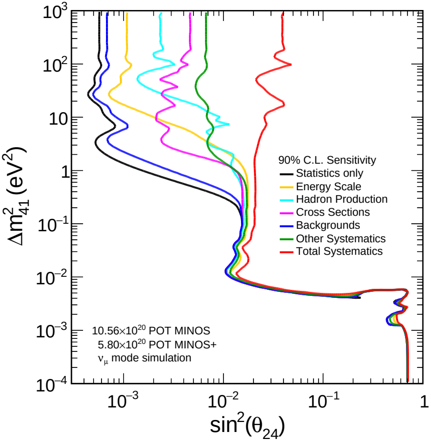
Systematics:



[arxiv:1710.06488]

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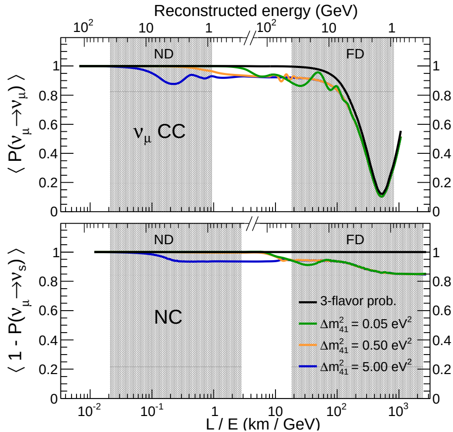
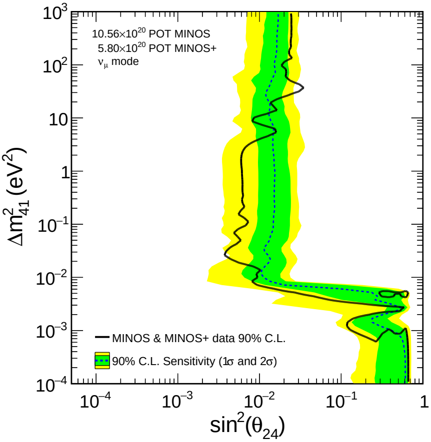


[PRL 117 (2016) 151803]: far-to-near ratio

[arxiv:1710.06488]: full two-detectors fit

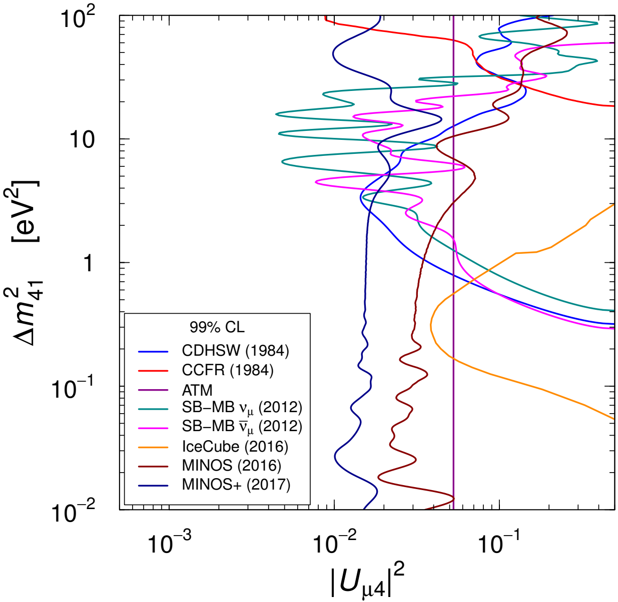
Sensitivity and exclusion limit:



[arxiv:1710.06488]

Global fit of $\overset{(-)}{\nu}_\mu$ DIS

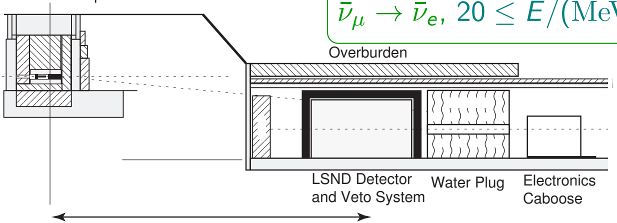
[SG+, preliminary]



MINOS(+) dominates at small Δm^2_{41}

LSND

[PRD 64 (2001) 112007]



$\bar{\nu}_\mu \to \bar{\nu}_e$, $20 \leq E/(\mathrm{MeV}) \leq 52.8$

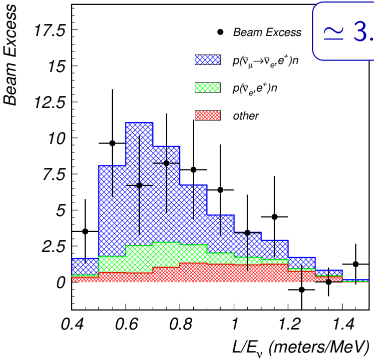
well known source of $\bar{\nu}_\mu$:

$$p + \text{target} \to \pi^+ \xrightarrow{\text{at rest}} \mu^+ + \nu_\mu$$

$$\mu^+ \xrightarrow{\text{at rest}} e^+ + \nu_e + \bar{\nu}_\mu$$

$L \simeq 30$ m

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



$\simeq 3.8\sigma$

No signal seen in KARMEN ($L \simeq 18$ m)

[PRD 65 (2002) 112001]

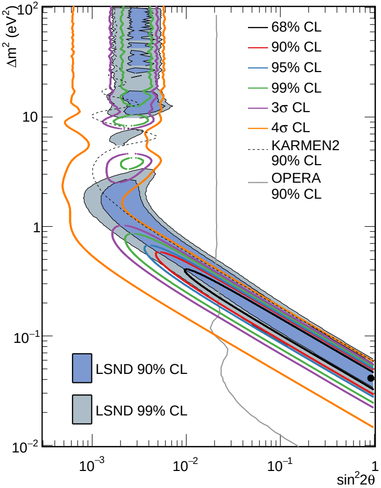
MiniBooNE

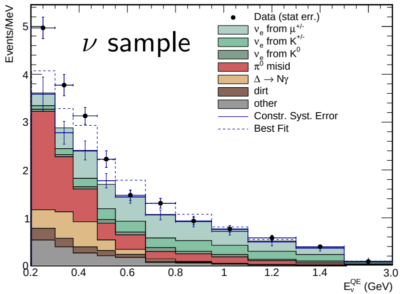
[arxiv:1805.12028]

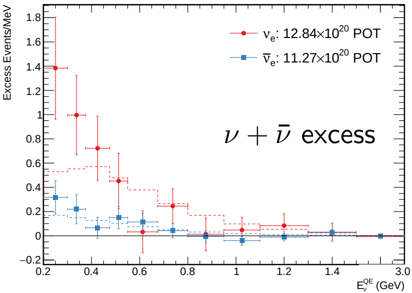
purpose: check LSND signal

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

no money, no near detector







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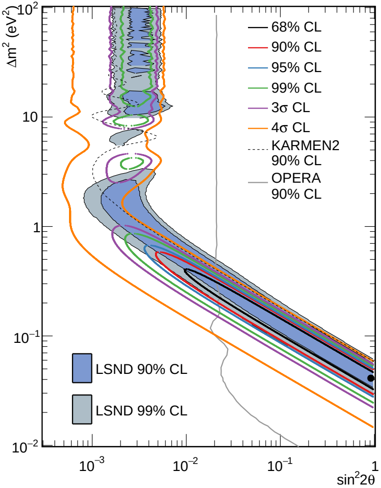
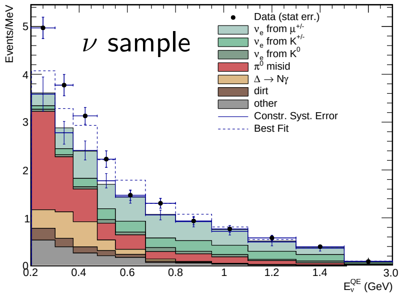
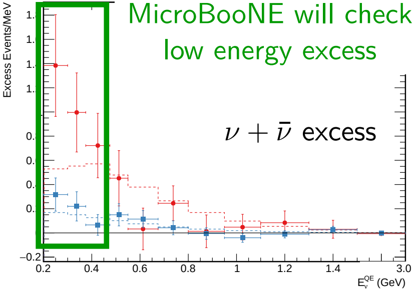
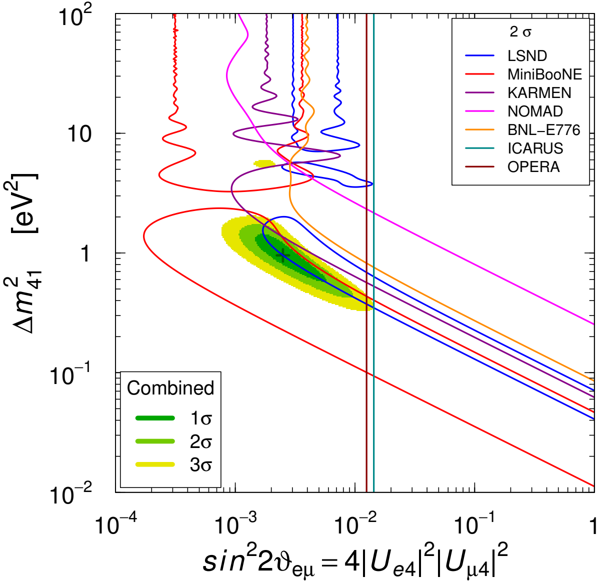






Global fit of $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ APP

[SG+, preliminary]



ICARUS and OPERA exclude MiniBooNE best fit

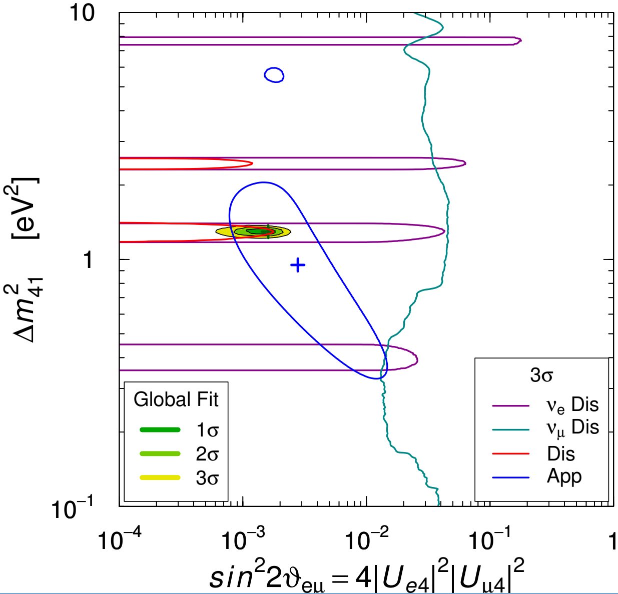
LSND and MiniBooNE only partially in agreement

KARMEN cuts part of LSND region

APPearance - DISappearance tension

[SG+, preliminary]

Without 2018 data:



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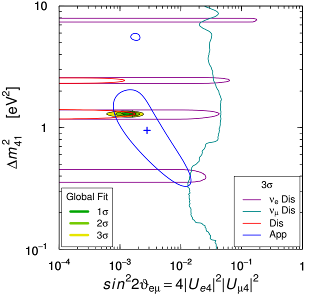
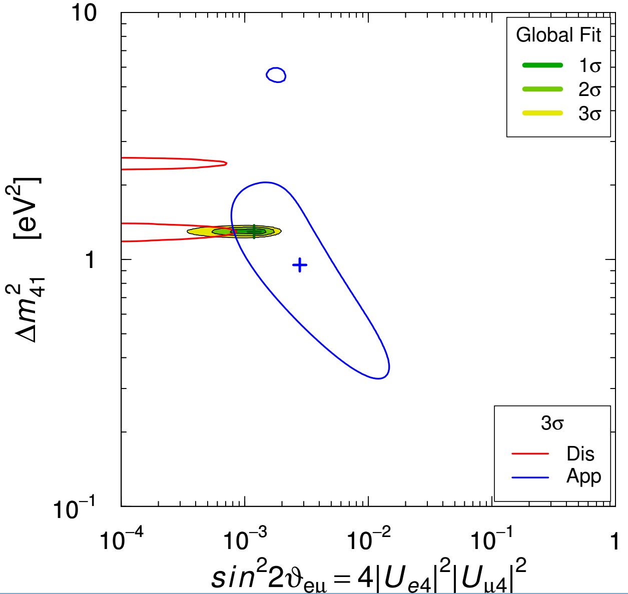


Status after Neutrino 2018:



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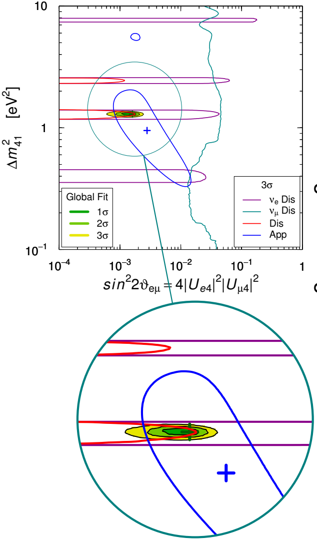

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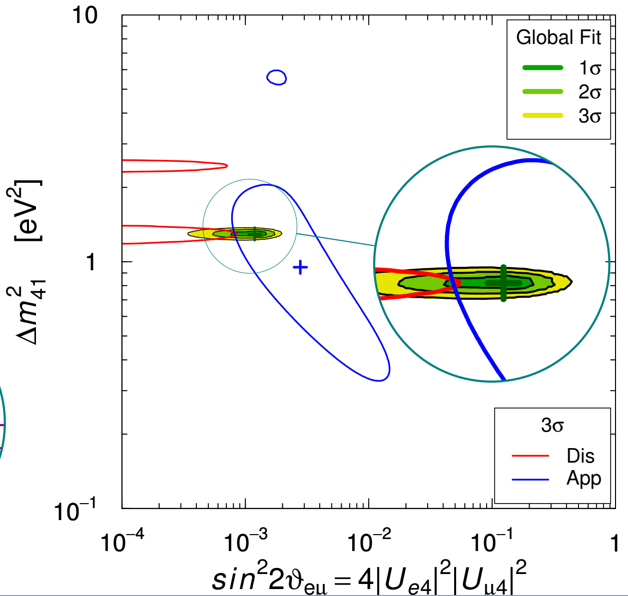

May something be wrong?

[Dentler+, JHEP 08 (2018) 010]
(2013 data from MiniBooNE)

Analysis	$\chi^2_{\rm min,global}$	$\chi^2_{\rm min,app}$	$\Delta\chi^2_{\rm app}$	$\chi^2_{\rm min,disapp}$	$\Delta\chi^2_{\rm disapp}$	$\chi^2_{\rm PG}/{\rm dof}$	PG
Global	1120.9	79.1	11.9	1012.2	17.7	29.6/2	3.71×10^{-7}
Removing anomalous data sets							
w/o LSND	1099.2	86.8	12.8	1012.2	0.1	12.9/2	1.6×10^{-3}
w/o MiniBooNE	1012.2	40.7	8.3	947.2	16.1	24.4/2	5.2×10^{-6}
w/o reactors	925.1	79.1	12.2	833.8	8.1	20.3/2	3.8×10^{-5}
w/o gallium	1116.0	79.1	13.8	1003.1	20.1	33.9/2	4.4×10^{-8}
Removing constraints							
w/o IceCube	920.8	79.1	11.9	812.4	17.5	29.4/2	4.2×10^{-7}
w/o MINOS(+)	1052.1	79.1	15.6	948.6	8.94	24.5/2	4.7×10^{-6}
w/o MB disapp	1054.9	79.1	14.7	947.2	13.9	28.7/2	6.0×10^{-7}
w/o CDHS	1104.8	79.1	11.9	997.5	16.3	28.2/2	7.5×10^{-7}
Removing classes of data							
$\overset{(-)}{\nu}_e$ dis vs app	628.6	79.1	0.8	542.9	5.8	6.6/2	3.6×10^{-2}
$\overset{(-)}{\nu}_\mu$ dis vs app	564.7	79.1	12.0	468.9	4.7	16.7/2	2.3×10^{-4}
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No improvements if MiniBooNE is not considered

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$\overset{(-)}{\nu}_\mu$ DIS also constrain $|U_{e4}|^2$, while $\overset{(-)}{\nu}_e$ DIS do not constrain $|U_{\mu4}|^2$

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Only removing LSND or all $\overset{(-)}{\nu}_\mu$ constraints the fit is almost acceptable

No reason to do so!

Conclusions

1. first model-independent hints from reactors $\overset{(-)}{\nu}_e$ DIS, some discrepancy with Gallium anomaly and RAA

2. nothing seen in $\overset{(-)}{\nu}_\mu$ DIS
strong upper bounds on $|U_{\mu4}|^2$,
but also first constraints on $|U_{\tau4}|^2$

3. strong APP-DIS tension
What are LSND and MiniBooNE observing?
Systematics or LSν or new physics?

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Thank you for the attention!

Gallium anomaly and RAA revisited

[SG et al., PLB 782 (2018) 13]

fit with free parameters:

detection efficiencies in Gallium experiments

normalization of spectra of reactor fuels

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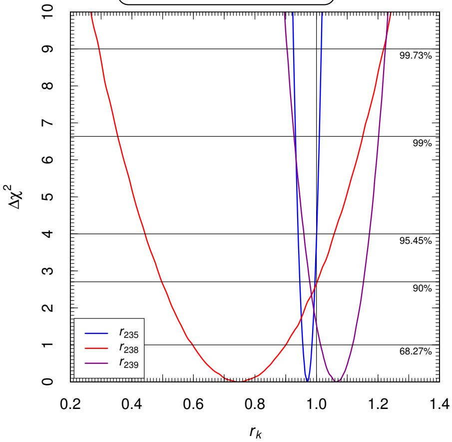
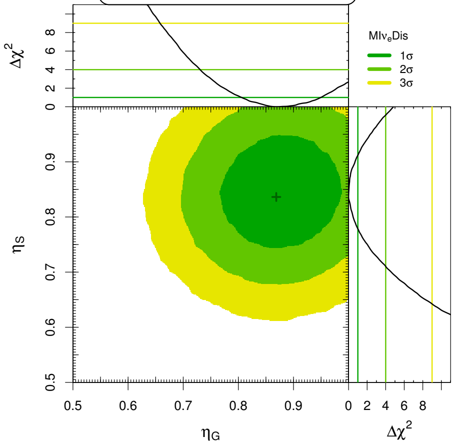
Reactor spectra:



^{235}U flux normalization smaller than 1 at $\gtrsim 2\sigma$

Gallium efficiencies:

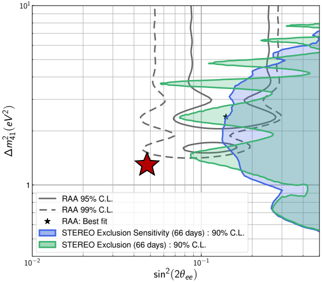


SAGE efficiency η_S smaller than 1 at $\gtrsim 2\sigma$

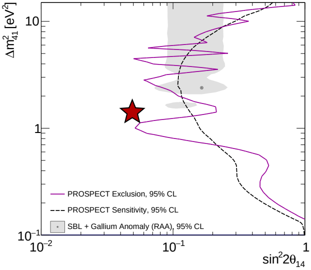
More to come...

★ = current DANSS+NEOS best fit
[SG et al., PLB 782 (2018) 13]

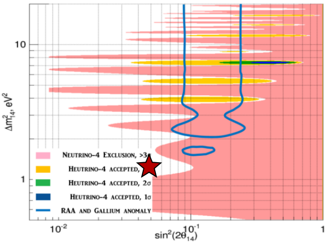
[STEREO, arxiv:1806.02096]



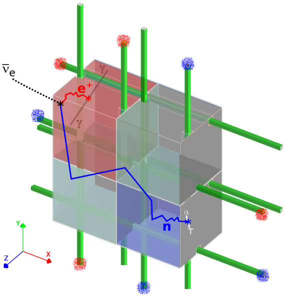
[PROSPECT, arxiv:1806.02784]



[Neutrino-4, arxiv:1809.10561]



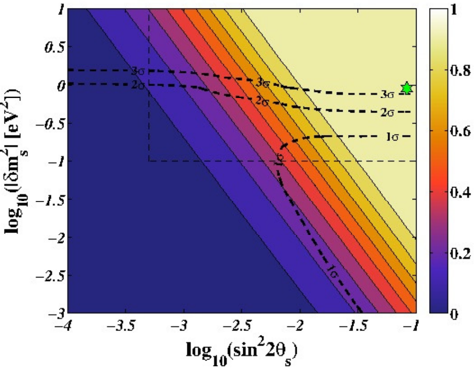
[SoLiD, arxiv:1806.02461]



LSν thermalization

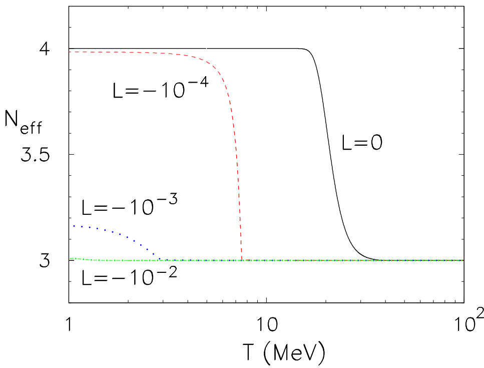
Using SBL best-fit parameters for the LSν (Δm^2_{41}, θ_s):

[Hannestad et al., JCAP 07 (2012) 025]



(colors coding $\Delta N_{\rm eff}$)

[Mirizzi et al., PRD 86 (2012) 053009]



(L: lepton asymmetry)

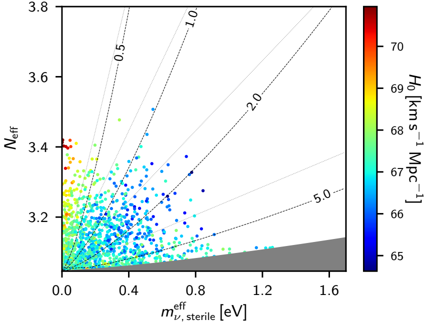
Unless $L \gtrsim \mathcal{O}(10^{-3})$, $\Delta N_{\rm eff} \simeq 1$

See also: [Saviano et al., PRD 87 (2013) 073006], [Hannestad et al., JCAP 08 (2015) 019]

[to be precise: $\Delta N_{\rm eff}$ is slightly smaller at CMB decoupling, when the LSν starts to be non-relativistic]

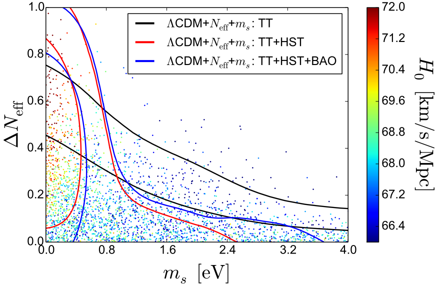
LSν constraints from cosmology

CMB+local: [Planck Collaboration, 2018]



$$\begin{cases} N_{eff} < 3.29 \\ m_s^{eff} < 0.65 \text{ eV} \end{cases}$$ (Planck18+BAO) [$m_s < 10$ eV]

[Archidiacono et al., JCAP 08 (2016) 067]



dataset	free ΔN_{eff} [$m_s < 10$ eV]	$\Delta N_{eff} = 1$
(TT)	$N_{eff} < 3.5$	$m_s < 0.66$ eV
(+H_0)	$N_{eff} < 3.9$	$m_s < 0.55$ eV
(+BAO)	$N_{eff} < 3.8$	$m_s < 0.53$ eV

BBN constraints: $N_{eff} = 2.90 \pm 0.22$ (BBN+Y_p) [Peimbert et al., 2016]

Summary: $\Delta N_{eff} = 1$ from LSν incompatible with $m_s \simeq 1$ eV!

Planck18=Planck 2018 TT,TE,EE + lowE + lensing

All the constraints are at 2σ CL