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Light sterile neutrino: oscillations and cosmology

Invisibles 19 Workshop, Valencia (ES), 10–14/06/2019

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)]

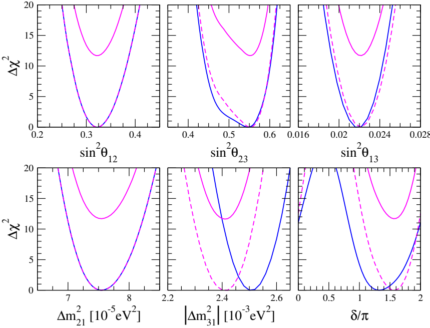
NO: Normal Ordering, $m_1 < m_2 < m_3$

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`

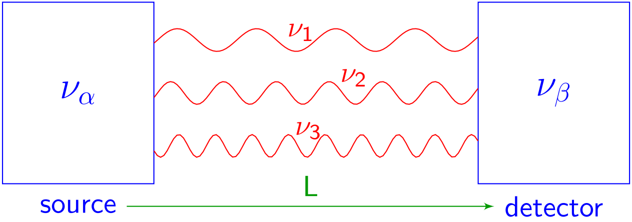
Two types of neutrinos

flavor neutrinos ν_α

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

massive neutrinos ν_k

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



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

$E_k^2 = p^2 + m_k^2 \longleftarrow$ define $\longrightarrow t = L$

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

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

A large family

In principle, previous discussion is valid for N neutrinos

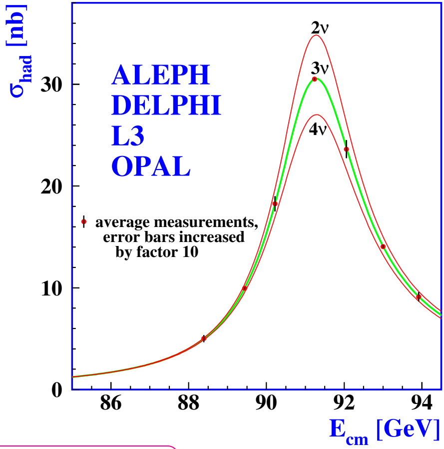
only constraint: there are exactly three flavor neutrinos in the SM

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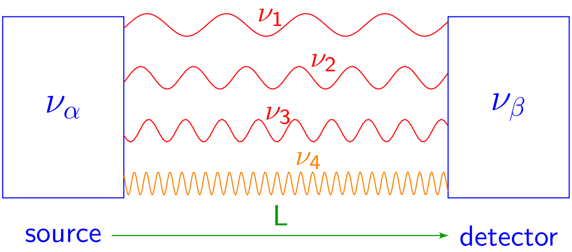
Our case will be 3 (active)+1 (sterile), a perturbation of 3 neutrinos case

$m_4 \gg m_\ell$

$\ell = 1, 2, 3$

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



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: $\dfrac{\Delta m^2_{41} L}{E} \simeq 1$

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

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DISappearance

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

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

CP violation cannot be observed in SBL experiments!

New mixings in the 3+1 scenario

4×4 mixing matrix: $\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} \end{pmatrix}$

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DISappearance

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

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

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

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

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

APPearance

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

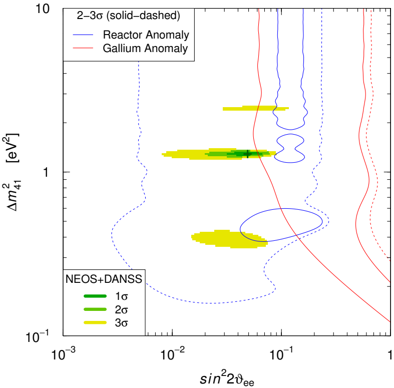
$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha4}|^2|U_{\beta4}|^2$$

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

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

quadratically suppressed!

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



2–3σ (solid–dashed)
Reactor Anomaly
Gallium Anomaly
NEOS+DANSS
1σ
2σ
3σ
10
1
10^{-1}
10^{-3}
10^{-2}
10^{-1}
1
Δm^2_{41} [eV^2]
$sin^2 2\vartheta_{ee}$

Gallium anomaly

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

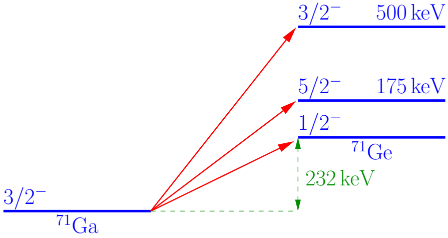
$L \simeq 1.9$ m $\quad L \simeq 0.6$ m

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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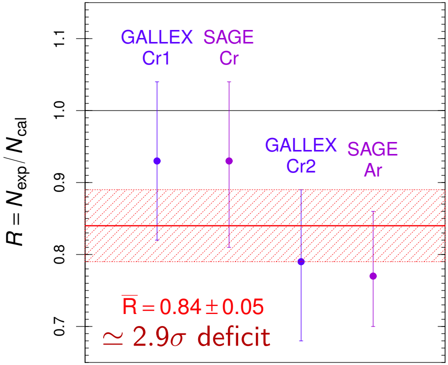
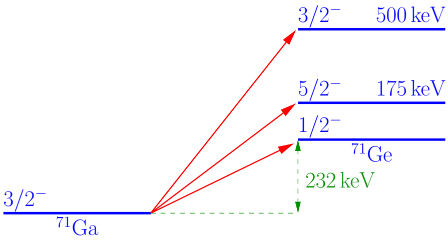
Test detection of solar ν_e





cross sections of the transitions from

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

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

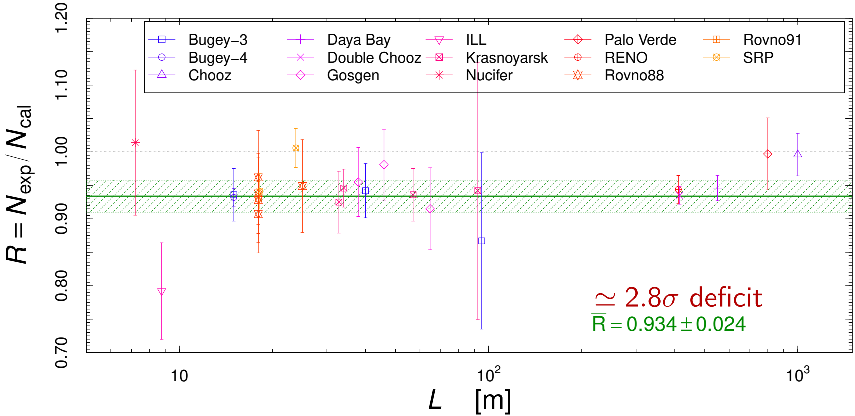
Reactor Antineutrino Anomaly (RAA)

[PRD 83 (2011) 073006]

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

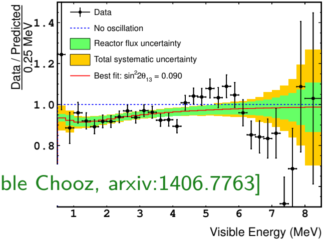
[Huber, PRC 84 (2011) 024617] [Mueller et al., PRC 83 (2011) 054615]

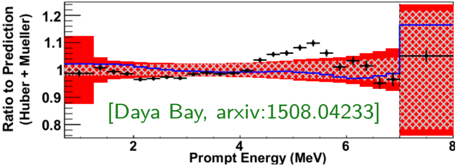
Previous reactor rates evaluated with new fluxes ⇒ deficit

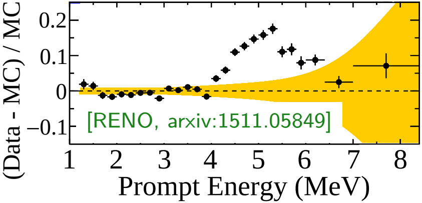


Suppression at detector due to active-sterile oscillations?

Can we trust the HM fluxes?







2014:

bump in the spectrum around 5 MeV!

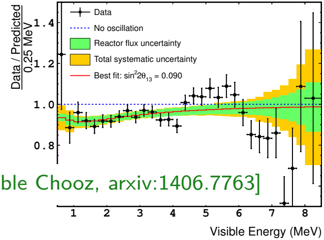
cannot be explained by SBL oscillations

(averaged at the observed distances)

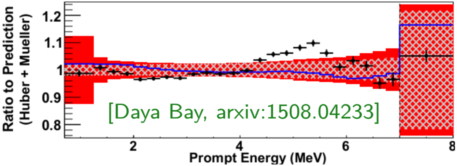
many attempts of possible explanations,

how to clarify the issue?

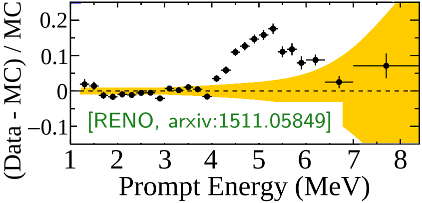
Can we trust the HM fluxes?



[Double Chooz, arxiv:1406.7763]



[Daya Bay, arxiv:1508.04233]



[RENO, arxiv:1511.05849]

2014:

bump in the spectrum around 5 MeV!

cannot be explained by SBL oscillations

(averaged at the observed distances)

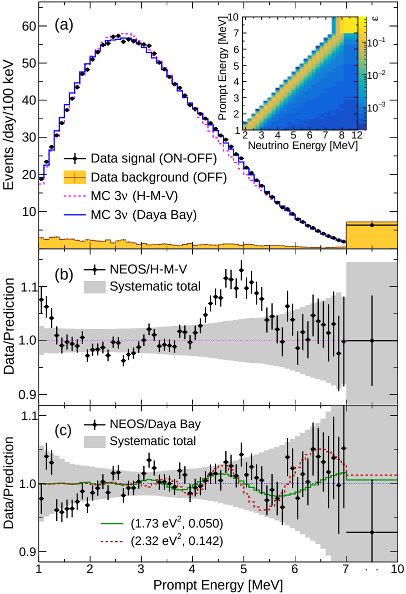
many attempts of possible explanations, how to clarify the issue?

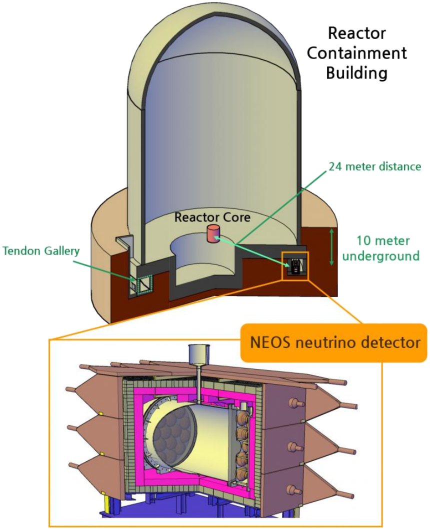
Model independent information!

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

NEOS

Single detector experiment



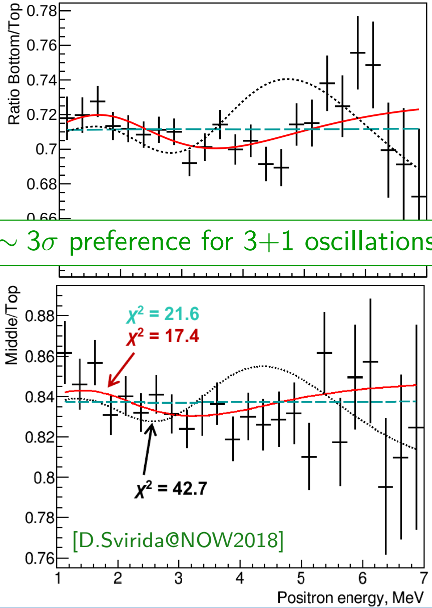


Ratio to DayaBay measurement to be model independent

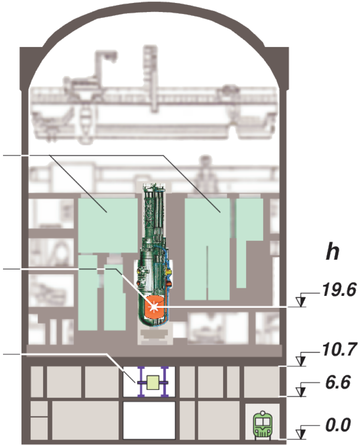
DANSS

[PLB 787 (2018) 56]

Single movable detector



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

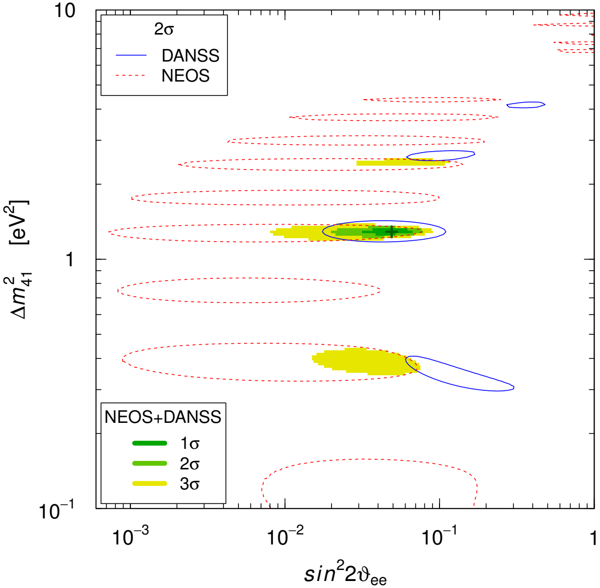


Detector can be at $\sim$ 10.5, $\sim$ 11.5 or $\sim$ 12.5 m from reactor core

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

[SG+, PLB 782 (2018) 13]

NEOS + DANSS



The NEOS and DANSS region perfectly overlap at

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

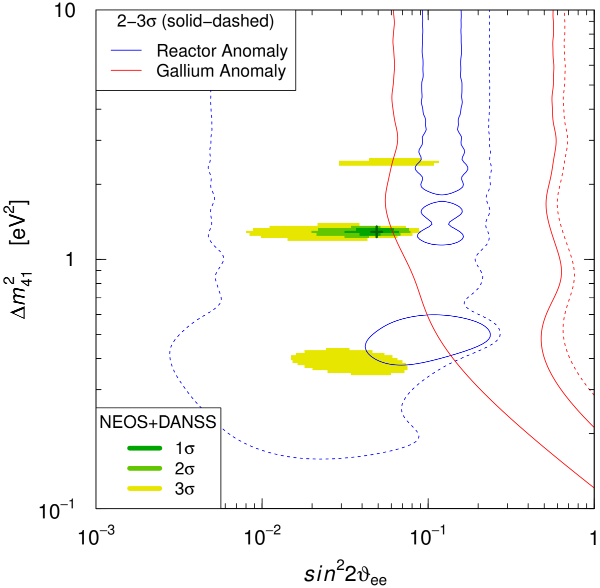
$$\sin^2 2\vartheta_{ee} \simeq 0.05$$

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

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

[SG+, PLB 782 (2018) 13]

DANSS + NEOS + RAA + Gallium

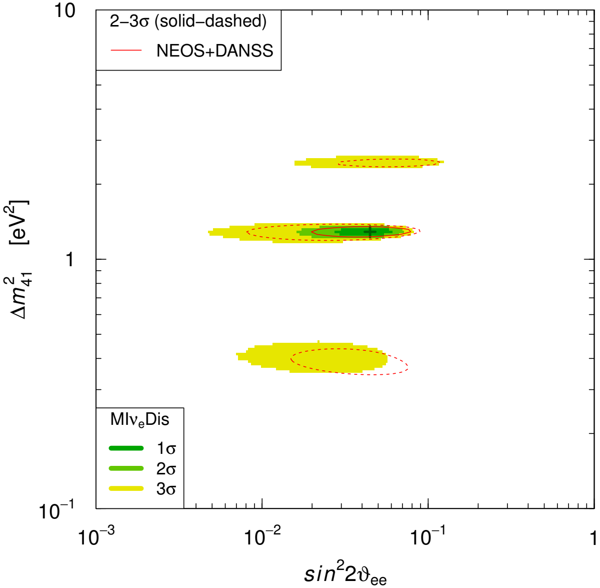


DANSS + NEOS
do not agree with
Gallium and RAA

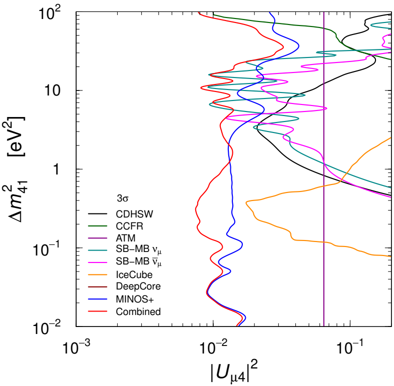
Model-independent fit of $\overset{(-)}{\nu}_e$ DIS

[SG+, PLB 782 (2018) 13]

All data:



Fit dominated by DANSS + NEOS

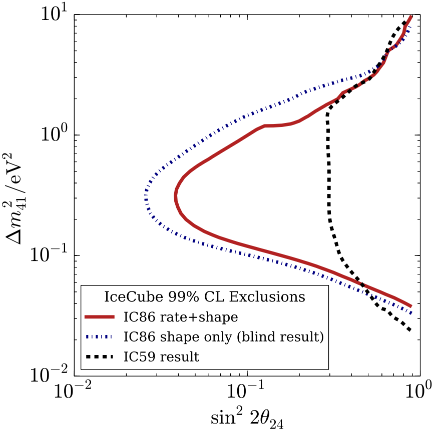

10^2
10
1
10^{-1}
10^{-2}
Δm^2_{41} [eV^2]
10^{-3}
10^{-2}
10^{-1}
$|U_{\mu 4}|^2$
3σ
CDHSW
CCFR
ATM
SB–MB ν_μ
SB–MB $\bar{\nu}_\mu$
IceCube
DeepCore
MINOS+
Combined

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]

IceCube and DeepCore

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

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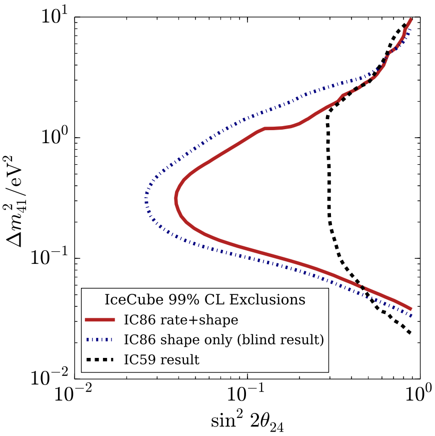
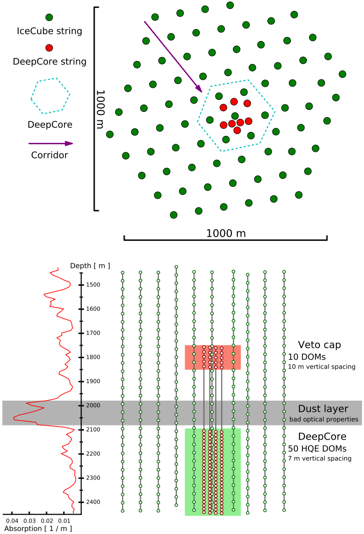
$320\ \text{GeV} < E < 20\ \text{TeV}$



[PRL 117 (2016) 071801]



IceCube and DeepCore

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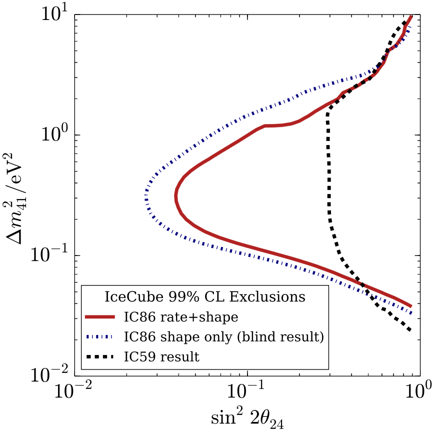
$\sim 2 \times 10^4$ High energy μ events

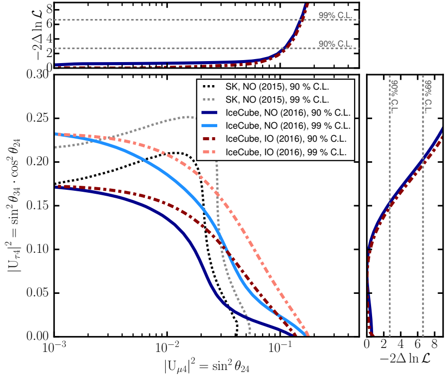
$320\text{ GeV} < E < 20\text{ TeV}$

$\sim 5 \times 10^3$ tracklike events

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



[PRL 117 (2016) 071801]



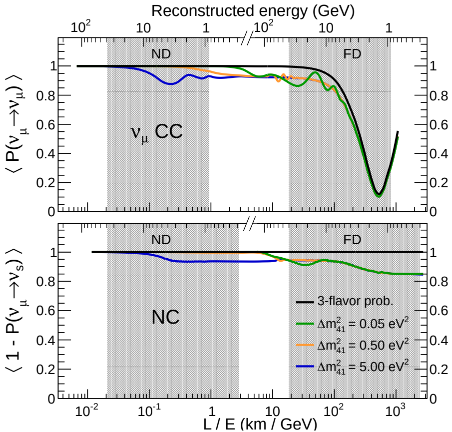
[PRD 95 (2017) 112002]

Both also constrain $|U_{\tau 4}|^2$

MINOS & MINOS+

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

$1\text{ GeV} \lesssim E \lesssim 40\text{ GeV}$, peak at 3 GeV



[PRL 117 (2016) 151803]:

far-to-near ratio

[PRL 122 (2019) 091803]:

full two-detectors fit

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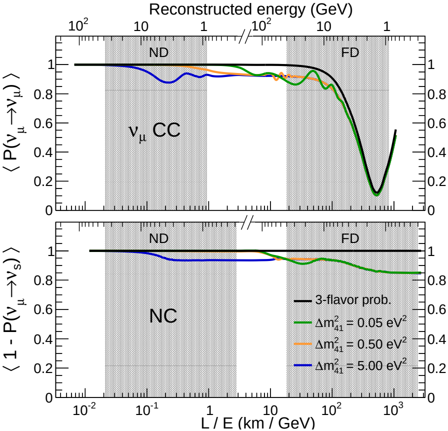
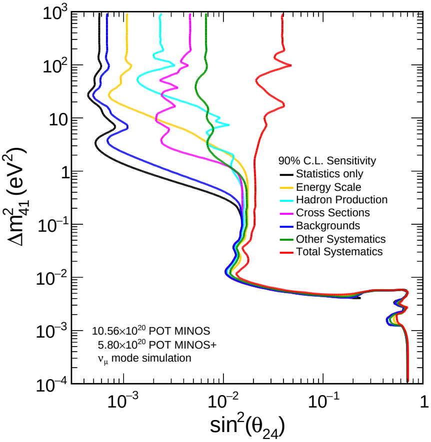


[PRL 117 (2016) 151803]: far-to-near ratio

[PRL 122 (2019) 091803]: full two-detectors fit

Systematics:



[PRL 122 (2019) 091803]

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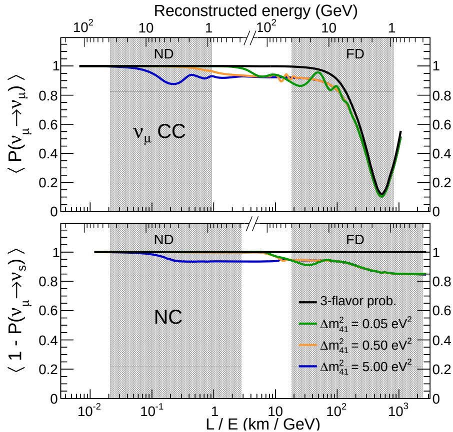
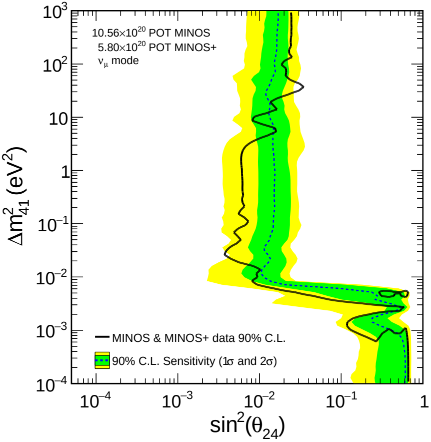


Sensitivity and exclusion limit:



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

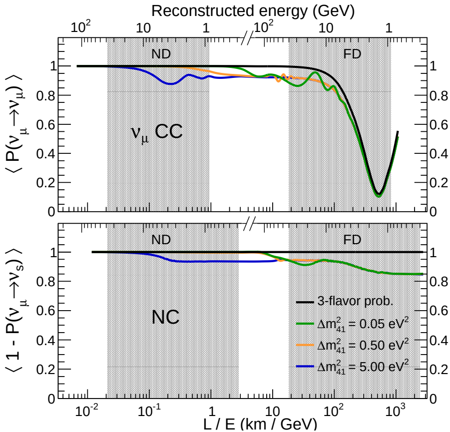
[PRL 122 (2019) 091803]: full two-detectors fit

[PRL 122 (2019) 091803]

MINOS & MINOS+

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

$1\text{ GeV} \lesssim E \lesssim 40\text{ GeV}$, peak at 3 GeV



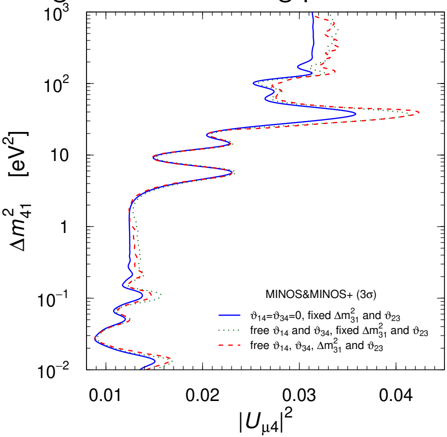
[PRL 117 (2016) 151803]:

far-to-near ratio

[PRL 122 (2019) 091803]:

full two-detectors fit

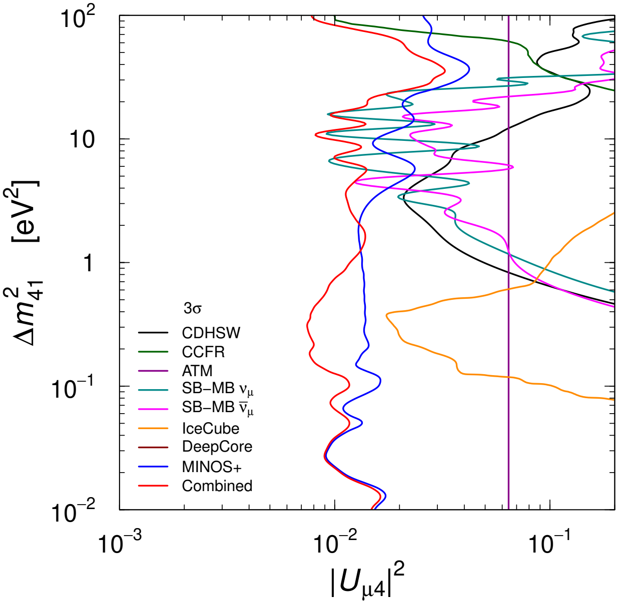
Marginalize over mixing parameters:



[SG+, in preparation]

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

[SG+, in preparation]

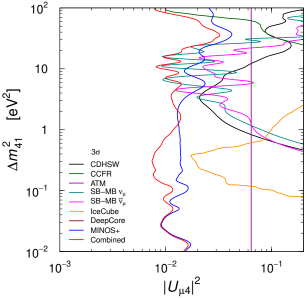


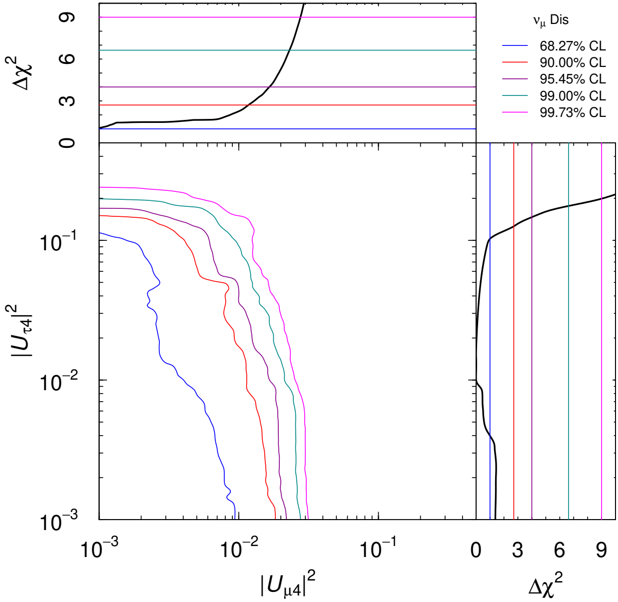
MINOS+ dominates at small Δm^2_{41}

IceCube important at $\Delta m^2_{41} \simeq 0.2$ eV^2

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

[SG+, in preparation]





1 *Neutrino Oscillations - Some theory*

2 *Electron (anti)neutrino disappearence*

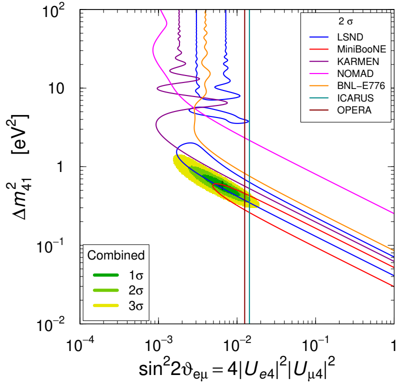
3 *Muon (anti)neutrino disappearence*

4 ***Electron (anti)neutrino appearence***

5 *Global fit*

6 *Cosmology*

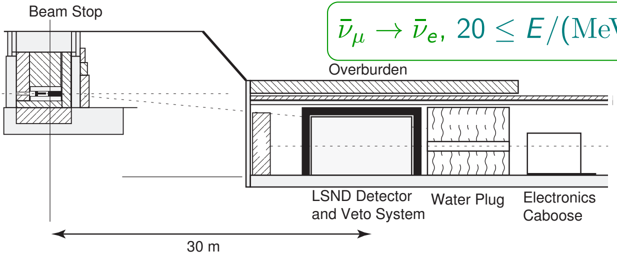
7 *Conclusions*



LSND

[PRD 64 (2001) 112007]

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



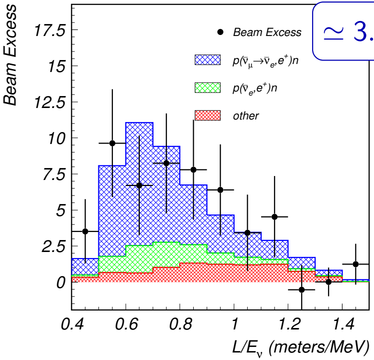
well known source of $\bar{\nu}_\mu$:

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

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

$L \simeq 30$ m

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



$\simeq 3.8\sigma$

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

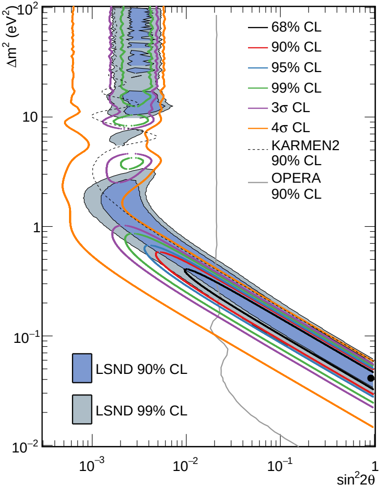
[PRD 65 (2002) 112001]

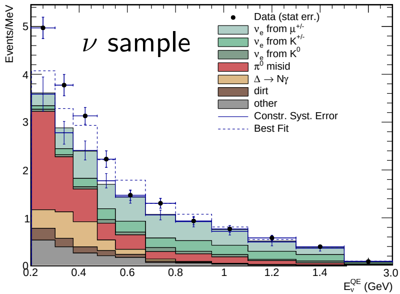
[PRL 121 (2018) 221801]

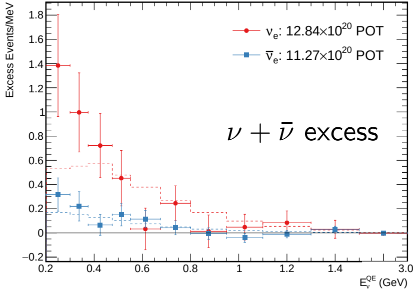
purpose: check LSND signal

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

no money, no near detector







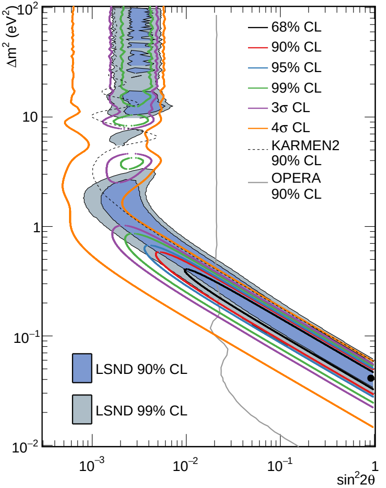
MiniBooNE

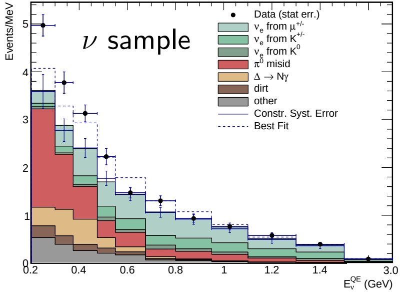
[PRL 121 (2018) 221801]

purpose: check LSND signal

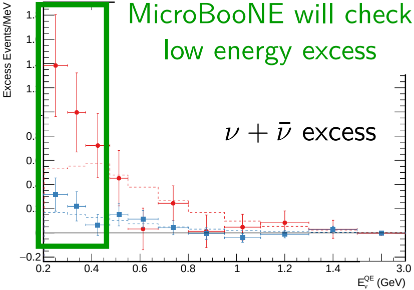
$L \simeq 541$ m, 200 MeV $\leq E \lesssim 3$ GeV

no money, no near detector

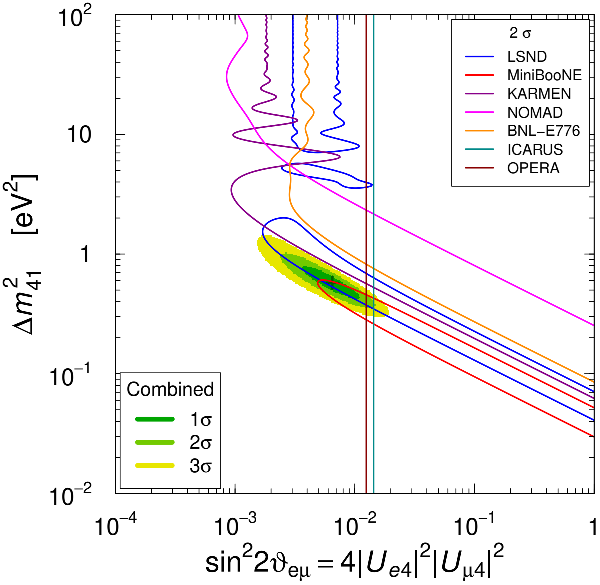




MicroBooNE will check low energy excess



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



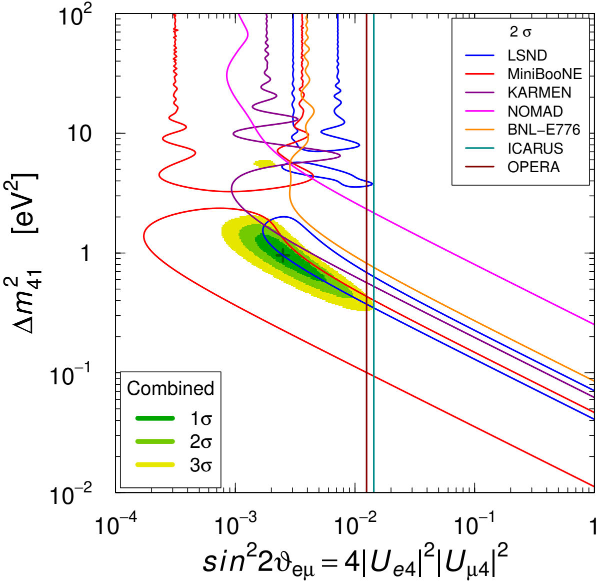
with full MiniBooNE data

ICARUS and OPERA exclude MiniBooNE best fit

LSND and MiniBooNE only partially in agreement

KARMEN cuts part of LSND region

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

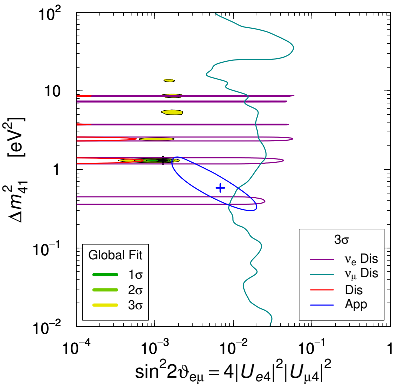


without MiniBooNE low energy bins

ICARUS and OPERA exclude MiniBooNE best fit

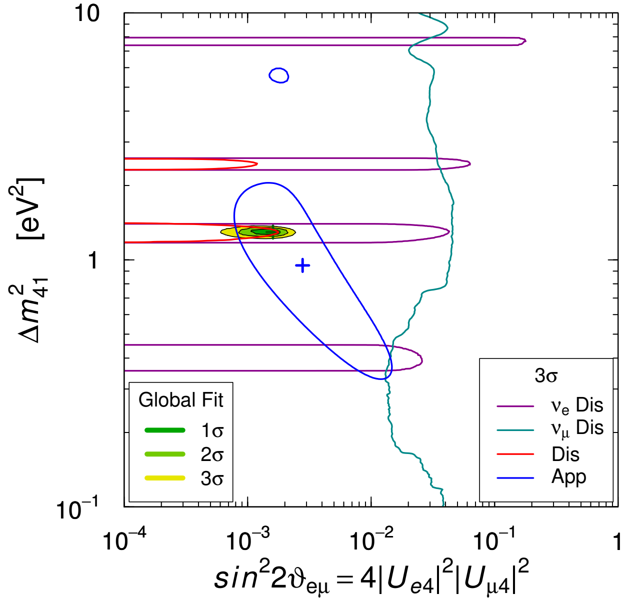
LSND and MiniBooNE only partially in agreement

KARMEN cuts part of LSND region


10^2
10
1
10^{-1}
10^{-2}
Δm^2_{41} [eV^2]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2$
Global Fit
1σ
2σ
3σ
3σ
ν_e Dis
ν_μ Dis
Dis
App

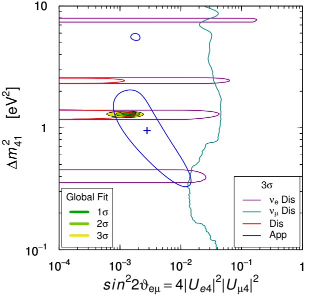
APPearance - DISappearance tension

Without 2018 data and MiniBooNE low-E bins:

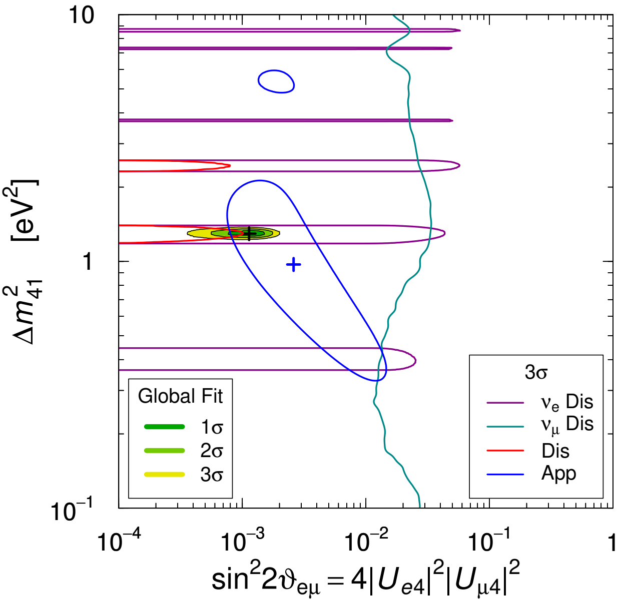


APPearance - DISappearance tension

Without 2018 data and MiniBooNE low-*E* bins:

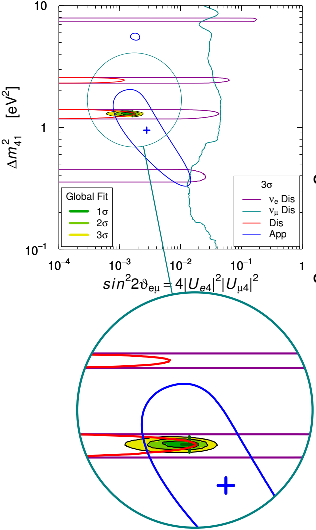


Same just after Neutrino 2018:

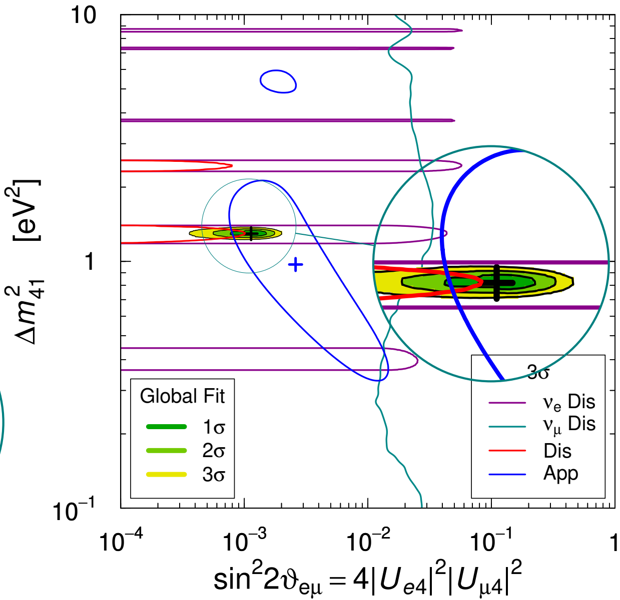


APPearance - DISappearance tension

Without 2018 data and MiniBooNE low-E bins:



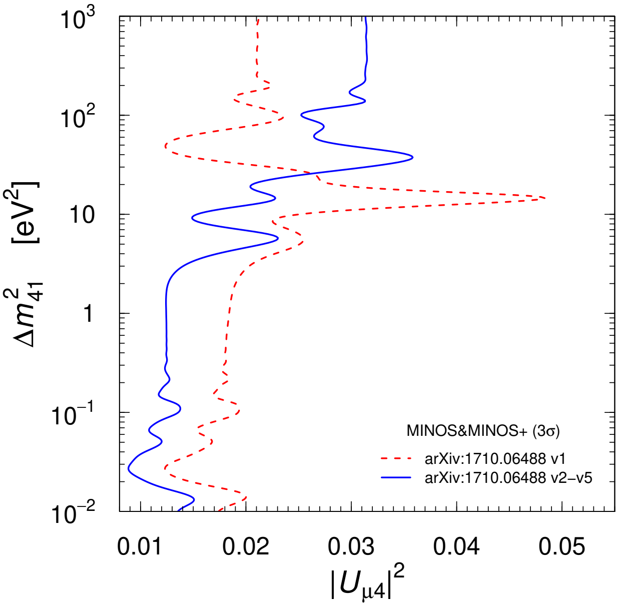
Same just after Neutrino 2018:



APP – DIS tension in 2019

[SG+, in preparation]

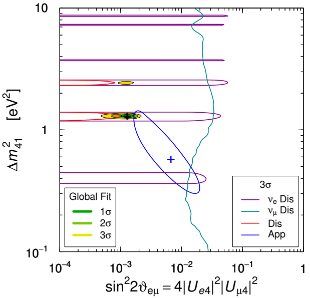
MINOS+ update:



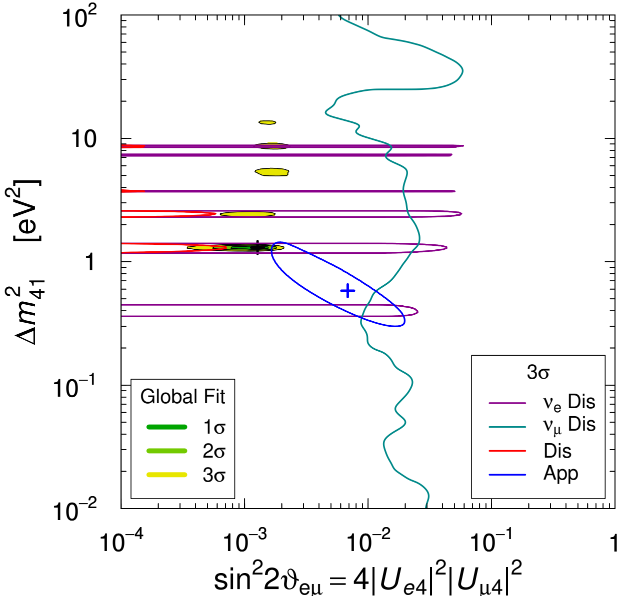
APP – DIS tension in 2019

[SG+, in preparation]

Status just after Neutrino 2018:



Status in 2019

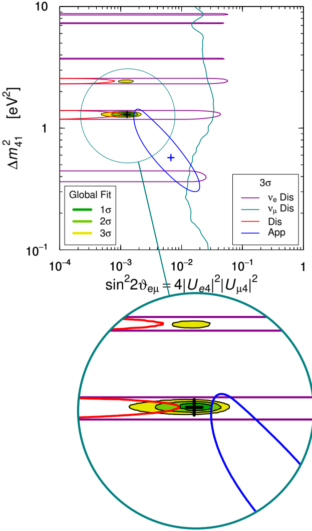


MINOS+ update,
new data
including MiniBooNE
(all bins)

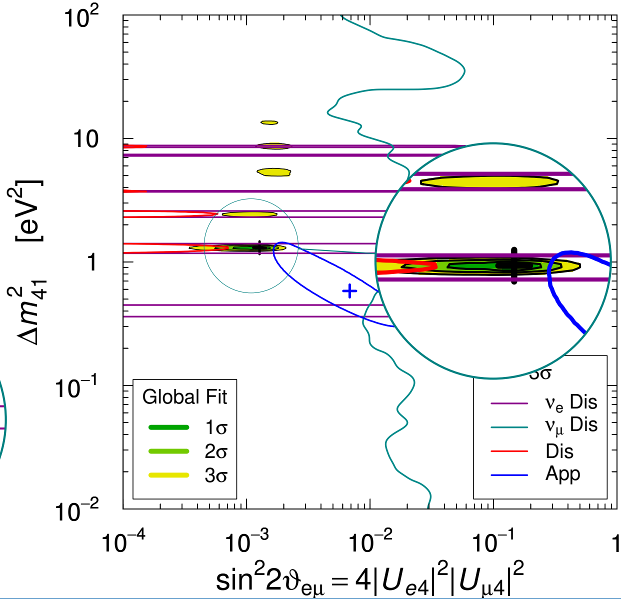
APP – DIS tension in 2019

[SG+, in preparation]

Status just after Neutrino 2018:

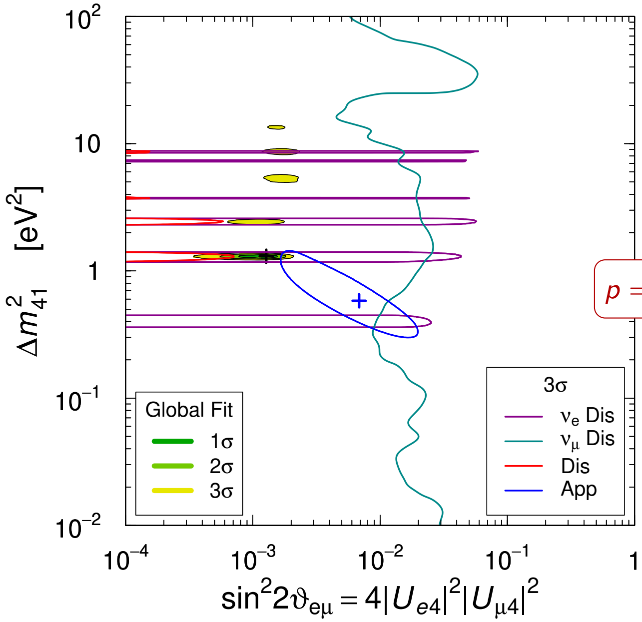


Status in 2019



APP – DIS tension in 2019

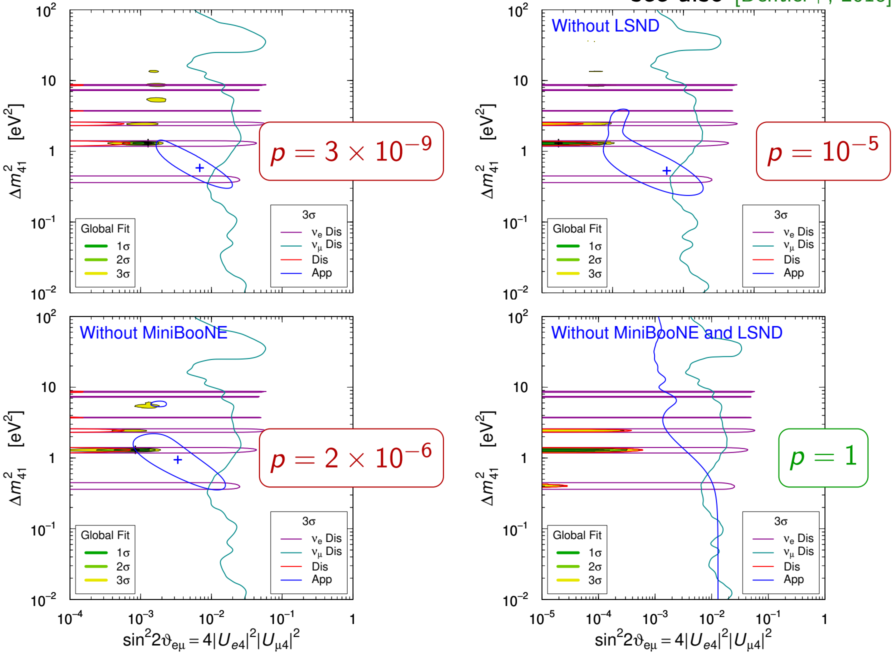
[SG+, in preparation]

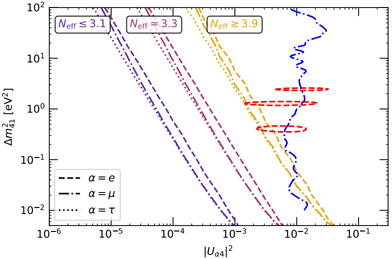


$p = 3 \times 10^{-9}$

APP – DIS tension in 2019

[SG+, in preparation]
see also [Dentler+, 2018]




$N_{eff} \leq 3.1$
$N_{eff} \simeq 3.3$
$N_{eff} \geq 3.9$
Δm^2_{41} [eV^2]
$|U_{\alpha 4}|^2$
$\alpha = e$
$\alpha = \mu$
$\alpha = \tau$

ν oscillations in the early universe

[SG+, arxiv:1905.11290]

comoving coordinates: $a = 1/T \quad x \equiv m_e\, a \quad y \equiv p\, a \quad z \equiv T_\gamma\, a \quad w \equiv T_\nu\, a$

density matrix: $$\varrho(x,y) = \begin{pmatrix} \varrho_{ee} \equiv f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} & \varrho_{es} \\ \varrho_{\mu e} & \varrho_{\mu\mu} \equiv f_{\nu_\mu} & \varrho_{\mu\tau} & \varrho_{\mu s} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} \equiv f_{\nu_\tau} & \varrho_{\tau s} \\ \varrho_{se} & \varrho_{s\mu} & \varrho_{s\tau} & \varrho_{ss} \equiv f_{\nu_s} \end{pmatrix}$$

$$\frac{\mathrm{d}\varrho(y,x)}{\mathrm{d}x} = \sqrt{\frac{3m_{\mathrm{Pl}}^2}{8\pi\rho_{\mathrm{T}}}} \left\{ -i\frac{x^2}{m_e^3}\left[\frac{\mathbb{M}_{\mathrm{F}}}{2y} - \frac{8\sqrt{2}G_{\mathrm{F}}\, y m_e^6}{3x^6}\left(\frac{\mathbb{E}_\ell}{m_W^2} + \frac{\mathbb{E}_\nu}{m_Z^2}\right), \varrho\right] + \frac{m_e^3 G_{\mathrm{F}}^2}{(2\pi)^3 x^4 y^2}\mathcal{I}(\varrho) \right\}$$

m_{Pl} Planck mass – ρ_T total energy density – $m_{W,Z}$ mass of the W, Z bosons – G_{F} Fermi constant – $[.,.]$ commutator

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$$\frac{\mathrm{d}\varrho(y,x)}{\mathrm{d}x} = \sqrt{\frac{3 m_{\rm Pl}^2}{8\pi\rho_{\rm T}}} \left\{ -i\frac{x^2}{m_e^3}\left[\frac{\mathbb{M}_{\rm F}}{2y} - \frac{8\sqrt{2}G_{\rm F}\, y m_e^6}{3x^6}\left(\frac{\mathbb{E}_\ell}{m_W^2} + \frac{\mathbb{E}_\nu}{m_Z^2}\right), \varrho\right] + \frac{m_e^3 G_{\rm F}^2}{(2\pi)^3 x^4 y^2}\mathcal{I}(\varrho)\right\}$$

$m_{\rm Pl}$ Planck mass – ρ_T total energy density – $m_{W,Z}$ mass of the W, Z bosons – $G_{\rm F}$ Fermi constant – $[.,.]$ commutator

$$\mathbb{M}_{\rm F} = U \mathbb{M} U^\dagger$$

$$\mathbb{M} = \mathrm{diag}(m_1^2, \ldots, m_N^2)$$

$$U = R^{34} R^{24} R^{14} R^{23} R^{13} R^{12}$$

e.g. $$R^{14} = \begin{pmatrix} \cos\theta_{14} & 0 & 0 & \sin\theta_{14} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin\theta_{14} & 0 & 0 & \cos\theta_{14} \end{pmatrix}$$

$$|U|^2 = \begin{pmatrix} \ldots & \ldots & \ldots & \sin^2\theta_{14} \\ \ldots & \ldots & \ldots & \cos^2\theta_{14}\sin^2\theta_{24} \\ \ldots & \ldots & \ldots & \cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34} \\ \ldots & \ldots & \ldots & \cos^2\theta_{14}\cos^2\theta_{24}\cos^2\theta_{34} \end{pmatrix}$$

ν oscillations in the early universe

[SG+, arxiv:1905.11290]

comoving coordinates: $a = 1/T \quad x \equiv m_e\, a \quad y \equiv p\, a \quad z \equiv T_\gamma\, a \quad w \equiv T_\nu\, a$

density matrix: $$\varrho(x,y) = \begin{pmatrix} \varrho_{ee} \equiv f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} & \varrho_{es} \\ \varrho_{\mu e} & \varrho_{\mu\mu} \equiv f_{\nu_\mu} & \varrho_{\mu\tau} & \varrho_{\mu s} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} \equiv f_{\nu_\tau} & \varrho_{\tau s} \\ \varrho_{se} & \varrho_{s\mu} & \varrho_{s\tau} & \varrho_{ss} \equiv f_{\nu_s} \end{pmatrix}$$

$$\frac{\mathrm{d}\varrho(y,x)}{\mathrm{d}x} = \sqrt{\frac{3m_{\mathrm{Pl}}^2}{8\pi\rho_{\mathrm{T}}}} \left\{ -i\frac{x^2}{m_e^3} \left[\frac{\mathbb{M}_{\mathrm{F}}}{2y} - \frac{8\sqrt{2}G_{\mathrm{F}}\, y m_e^6}{3x^6} \left(\frac{\mathbb{E}_\ell}{m_W^2} + \frac{\mathbb{E}_\nu}{m_Z^2} \right), \varrho \right] + \frac{m_e^3 G_{\mathrm{F}}^2}{(2\pi)^3 x^4 y^2} \mathcal{I}(\varrho) \right\}$$

m_{Pl} Planck mass – ρ_T total energy density – $m_{W,Z}$ mass of the W, Z bosons – G_{F} Fermi constant – $[.,.]$ commutator

$$\mathbb{M}_{\mathrm{F}} = U \mathbb{M} U^\dagger$$

$\mathbb{E}_\ell = \mathrm{diag}(\rho_e, \rho_\mu, 0, 0)$ $\qquad \mathbb{E}_\nu = S_a \left(\int dy y^3 \varrho \right) S_a$ $\quad$ with $S_a = \mathrm{diag}(1,1,1,0)$

lepton densities $\qquad$ neutrino densities $\qquad$ (only for active neutrinos)

take into account matter effects in oscillations

ν oscillations in the early universe

[SG+, arxiv:1905.11290]

comoving coordinates: $a = 1/T \quad x \equiv m_e\, a \quad y \equiv p\, a \quad z \equiv T_\gamma\, a \quad w \equiv T_\nu\, a$

density matrix: $\varrho(x,y) = \begin{pmatrix} \varrho_{ee} \equiv f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} & \varrho_{es} \\ \varrho_{\mu e} & \varrho_{\mu\mu} \equiv f_{\nu_\mu} & \varrho_{\mu\tau} & \varrho_{\mu s} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} \equiv f_{\nu_\tau} & \varrho_{\tau s} \\ \varrho_{se} & \varrho_{s\mu} & \varrho_{s\tau} & \varrho_{ss} \equiv f_{\nu_s} \end{pmatrix}$

$$\frac{\mathrm{d}\varrho(y,x)}{\mathrm{d}x} = \sqrt{\frac{3m_{\mathrm{Pl}}^2}{8\pi\rho_{\mathrm{T}}}} \left\{ -i\frac{x^2}{m_e^3}\left[\frac{\mathbb{M}_{\mathrm{F}}}{2y} - \frac{8\sqrt{2}G_{\mathrm{F}}\, y m_e^6}{3x^6}\left(\frac{\mathbb{E}_\ell}{m_W^2} + \frac{\mathbb{E}_\nu}{m_Z^2}\right), \varrho\right] + \frac{m_e^3 G_{\mathrm{F}}^2}{(2\pi)^3 x^4 y^2}\mathcal{I}(\varrho)\right\}$$

m_{Pl} Planck mass – ρ_T total energy density – $m_{W,Z}$ mass of the W, Z bosons – G_{F} Fermi constant – $[.,.]$ commutator

$$\mathbb{M}_{\mathrm{F}} = U\mathbb{M}U^\dagger \qquad \mathbb{E}_\ell = \mathrm{diag}(\rho_e, \rho_\mu, 0, 0) \qquad \mathbb{E}_\nu = S_a\left(\int dy y^3 \varrho\right) S_a$$

$\mathcal{I}(\varrho)$ collision integrals

take into account neutrino-electron scattering and pair annihilation

2D integrals over the momentum, take most of the computation time

ν oscillations in the early universe

[SG+, arxiv:1905.11290]

comoving coordinates: $a = 1/T \quad x \equiv m_e\, a \quad y \equiv p\, a \quad z \equiv T_\gamma\, a \quad w \equiv T_\nu\, a$

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$\mathcal{I}(\varrho)$ collision integrals

from continuity equation
$\dot{\rho} = -3H(\rho + P)$

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$r = x/z$, $r_\ell = m_\ell/m_e\, r$ $\quad$ $J(r)$, $Y(r)$ from non-relativistic transition of $e^\pm$, $\mu^\pm$
$G_1(r)$ and $G_2(r)$ from electromagnetic corrections

ν oscillations in the early universe

[SG+, arxiv:1905.11290]

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FORTran-Evolved PrimordIAl Neutrino Oscillations (FortEPiaNO)

https://bitbucket.org/ahep_cosmo/fortepiano

from continuity equation $\dot\rho = -3H(\rho + P)$

will be public soon

$$\frac{\mathrm{d}z}{\mathrm{d}x} = \frac{\sum_{\ell=e,\mu}\left[r \;\ldots \right] \ldots) - \frac{1}{2\pi^2 z^3}\int_0^\infty dy\, y^3 \sum_{\alpha=e}^{s}\frac{\mathrm{d}\varrho_{\alpha\alpha}}{\mathrm{d}x}}{\sum_{\ell=e,\mu}\left[r_\ell^2 J(r_\ell) + Y(r_\ell)\right] + G_2(r) + \frac{2\pi^2}{15}}$$

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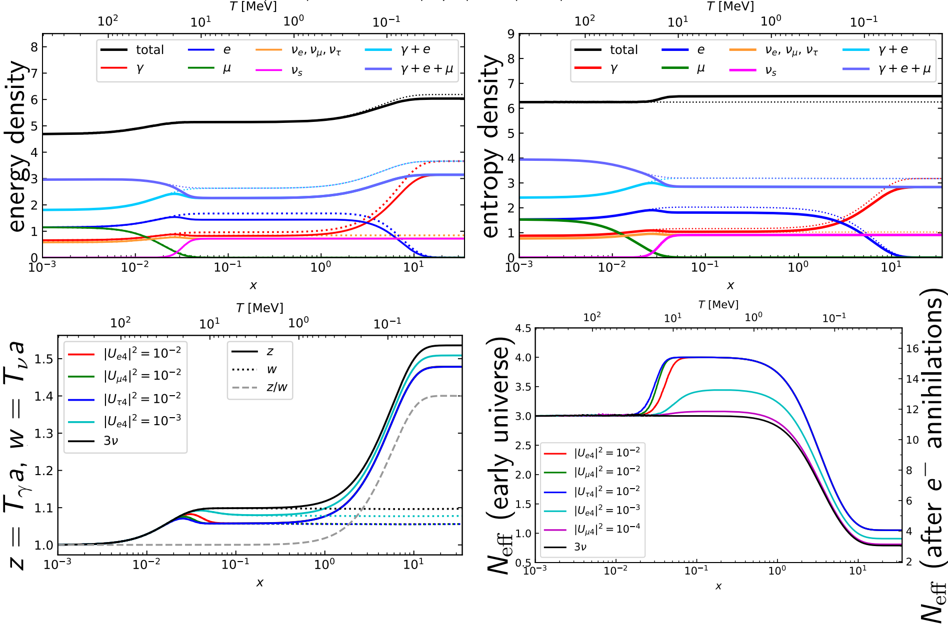
Energy, entropy, temperatures, $N_{\rm eff}$

[SG+, arxiv:1905.11290]

dashed: 3ν, solid: $|U_{e4}|^2 = 10^{-2}$, $|U_{\mu4}|^2 = |U_{\tau4}|^2 = 0$. $\Delta m^2_{41} = 1.29$ eV^2 always



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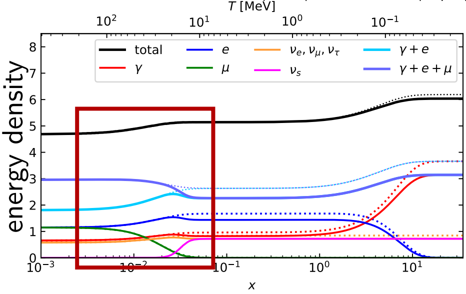

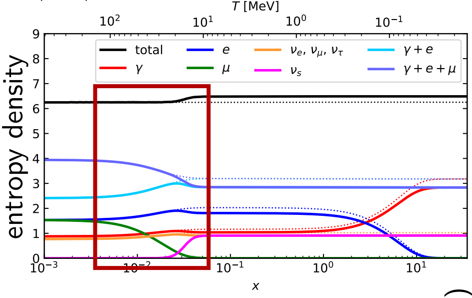

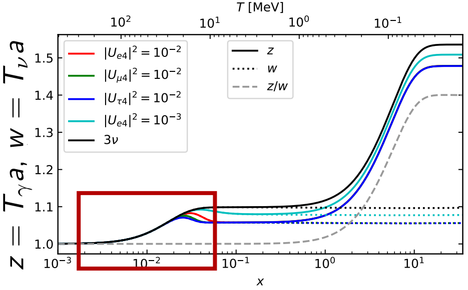

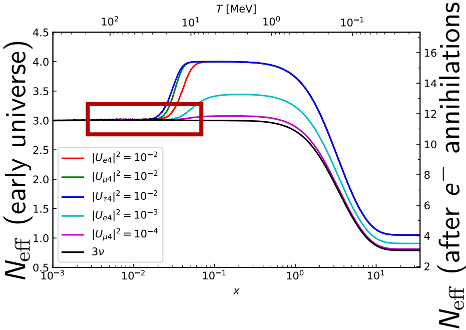

muons annihilate

Energy, entropy, temperatures, $N_{\rm eff}$

[SG+, arxiv:1905.11290]

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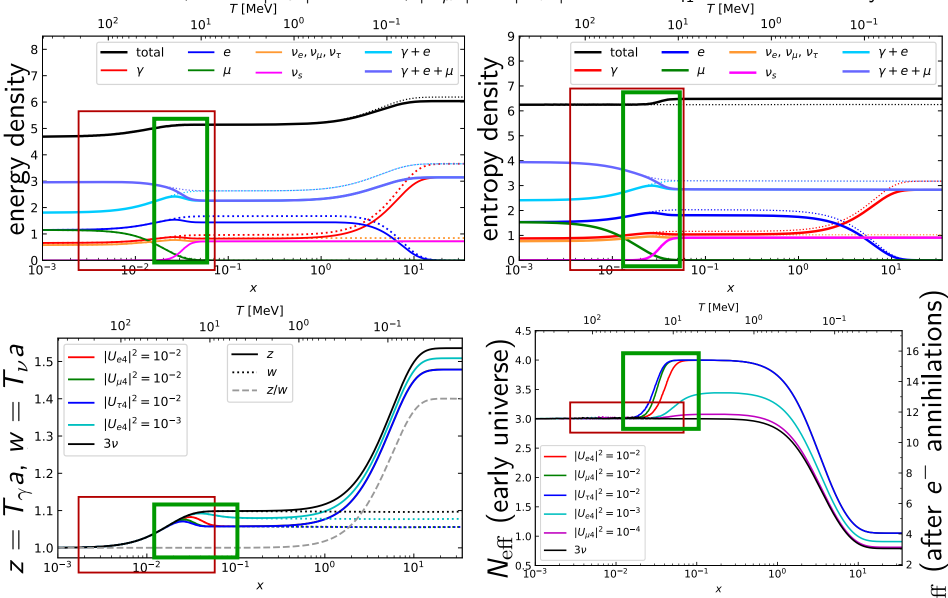

muons annihilate $\qquad$ ν_s thermalizes

Energy, entropy, temperatures, $N_{\rm eff}$

[SG+, arxiv:1905.11290]

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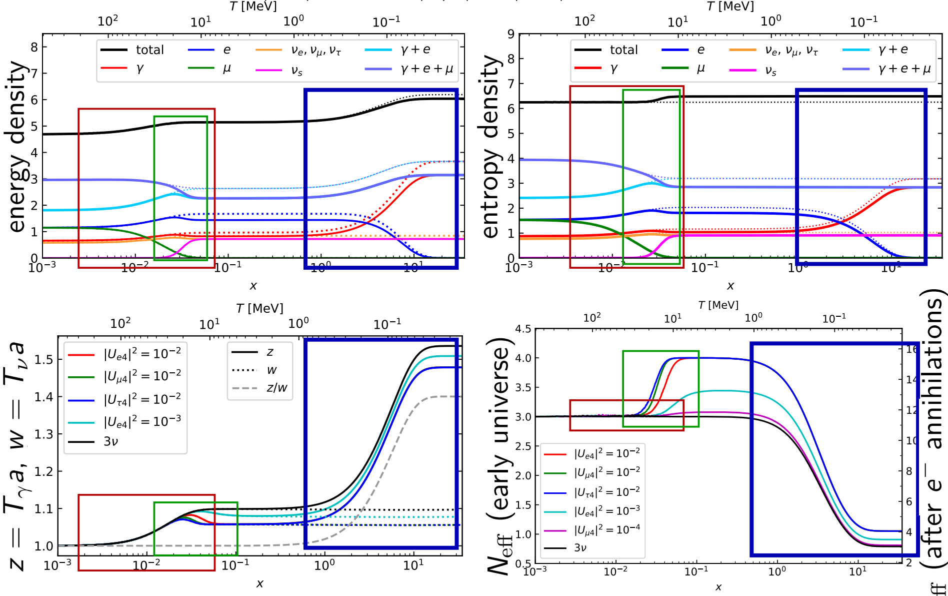
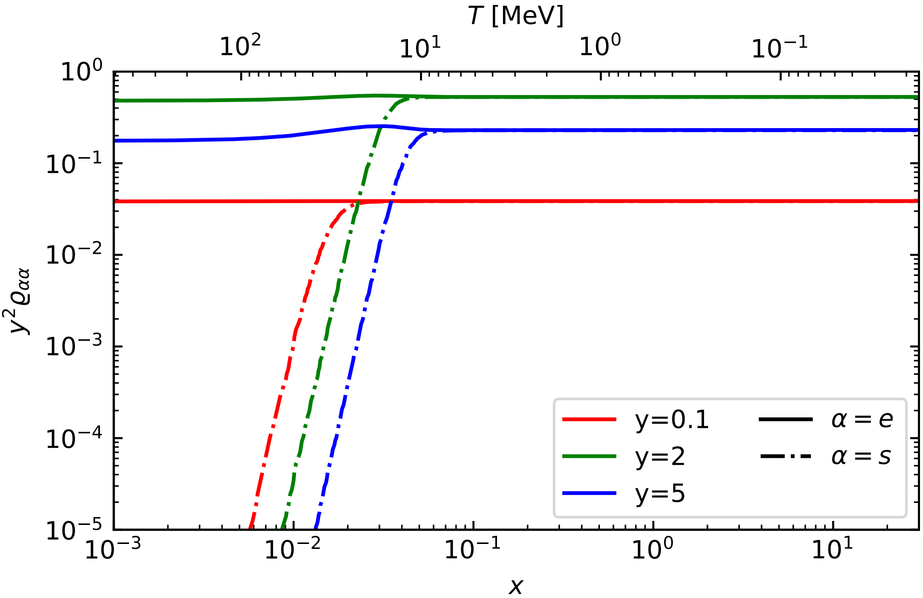


muons annihilate ν_s thermalizes electrons annihilate

Momentum distributions

[SG+, arxiv:1905.11290]

$\Delta m_{41}^2 = 1.29$ eV^2, $|U_{e4}|^2 = 10^{-2}$, $|U_{\mu 4}|^2 = |U_{\tau 4}|^2 = 0$, $N_{\rm eff} \simeq 4.05$



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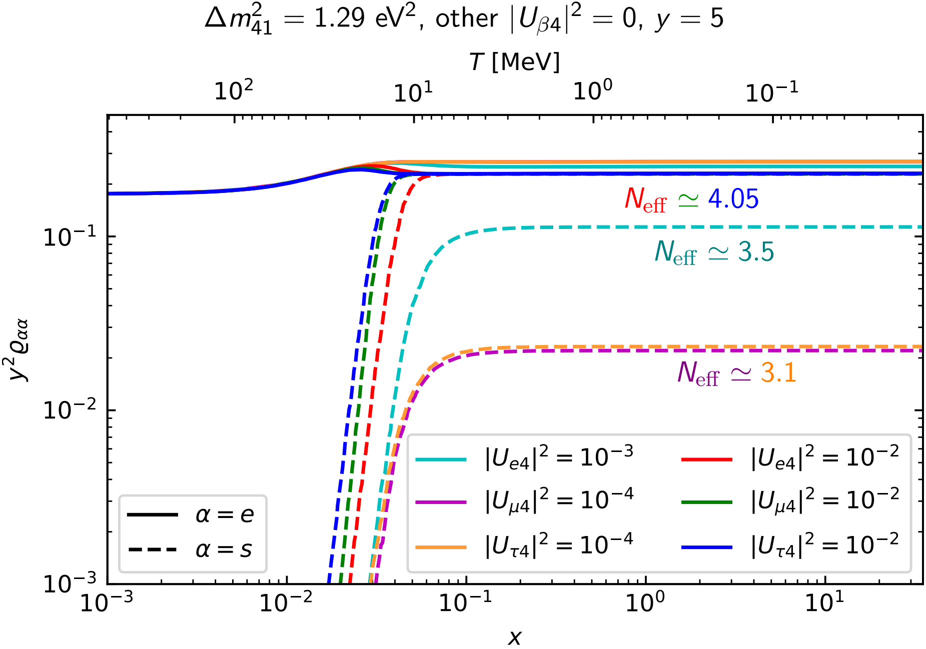

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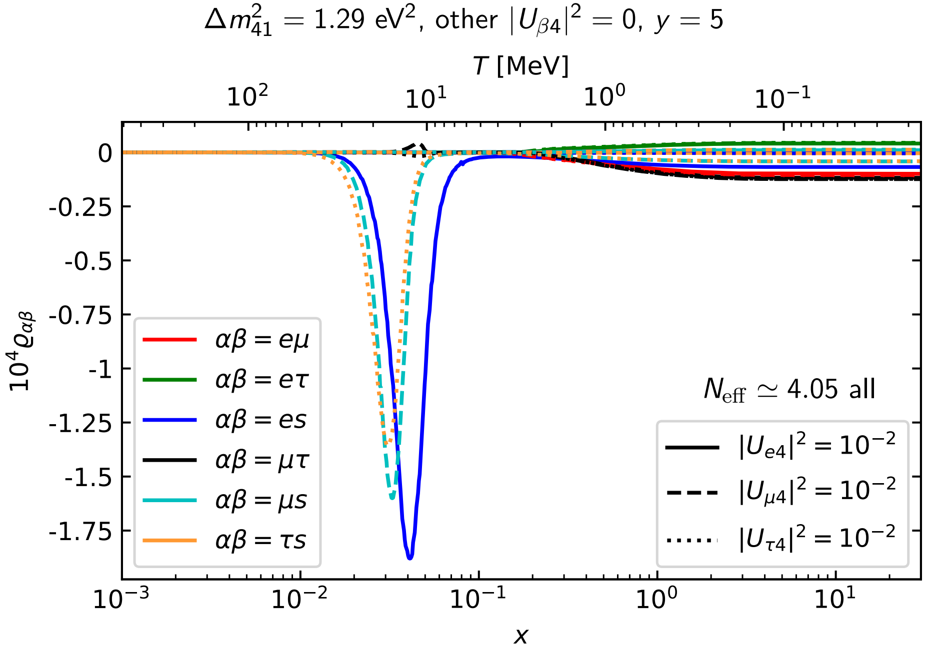
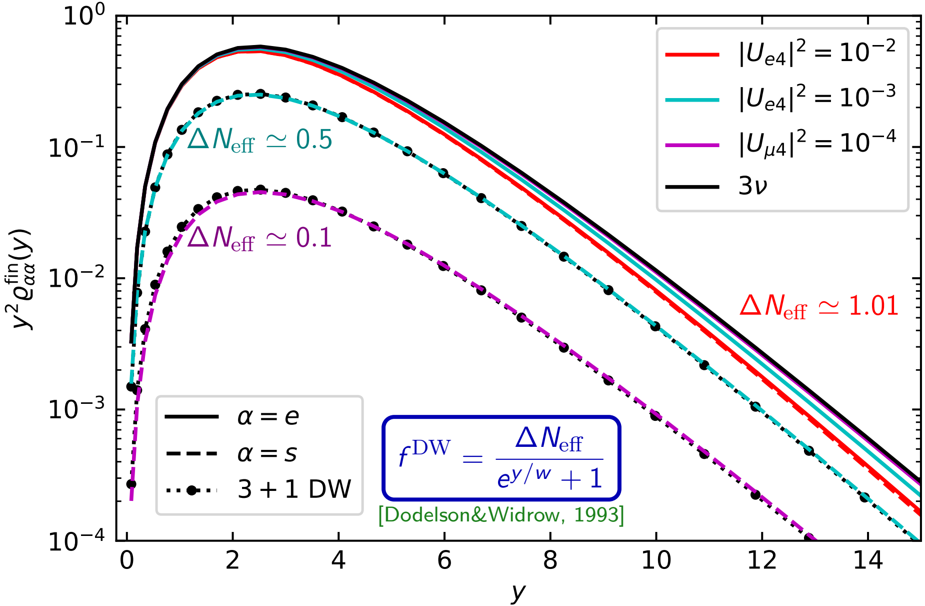


Momentum distributions

[SG+, arxiv:1905.11290]

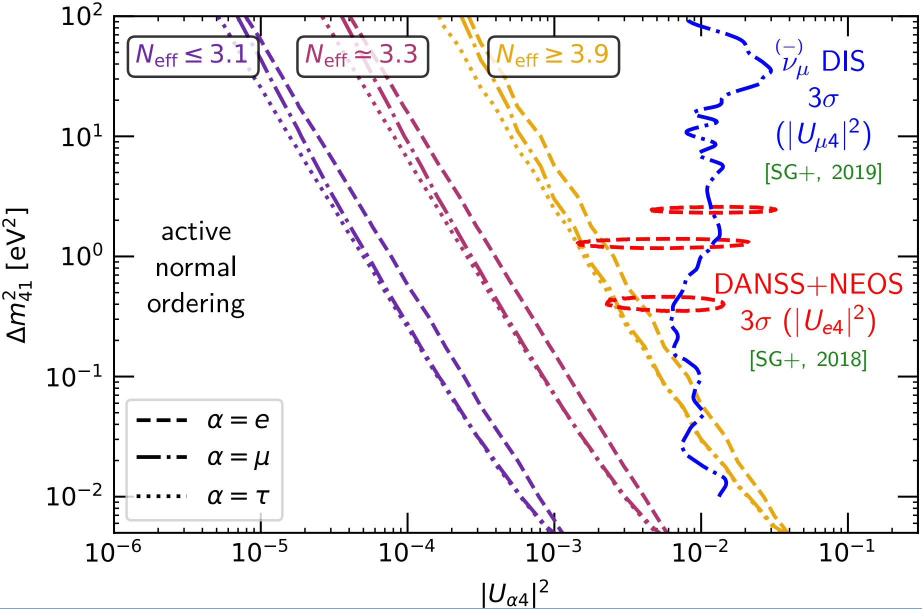
$\Delta m^2_{41} = 1.29$ eV^2, other $|U_{\beta 4}|^2 = 0$, $\Delta N_{\rm eff} = N_{\rm eff} - N_{\rm eff}^{\rm active}$



$N_{\rm eff}$ and the new mixing parameters

[SG+, arxiv:1905.11290]

Only vary one angle and fix two to zero: do they have the same effect?



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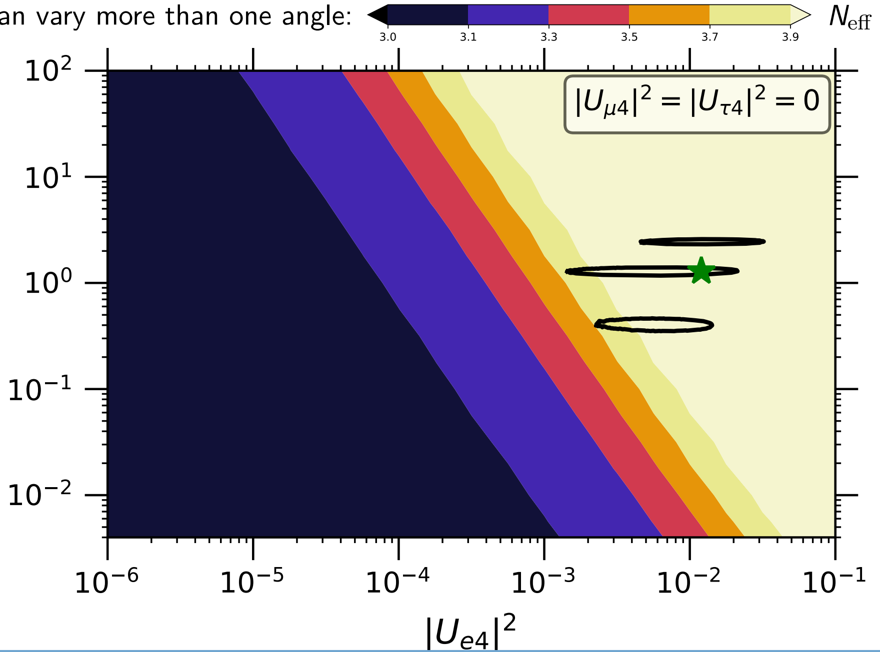
[SG+, arxiv:1905.11290]

We can vary more than one angle:



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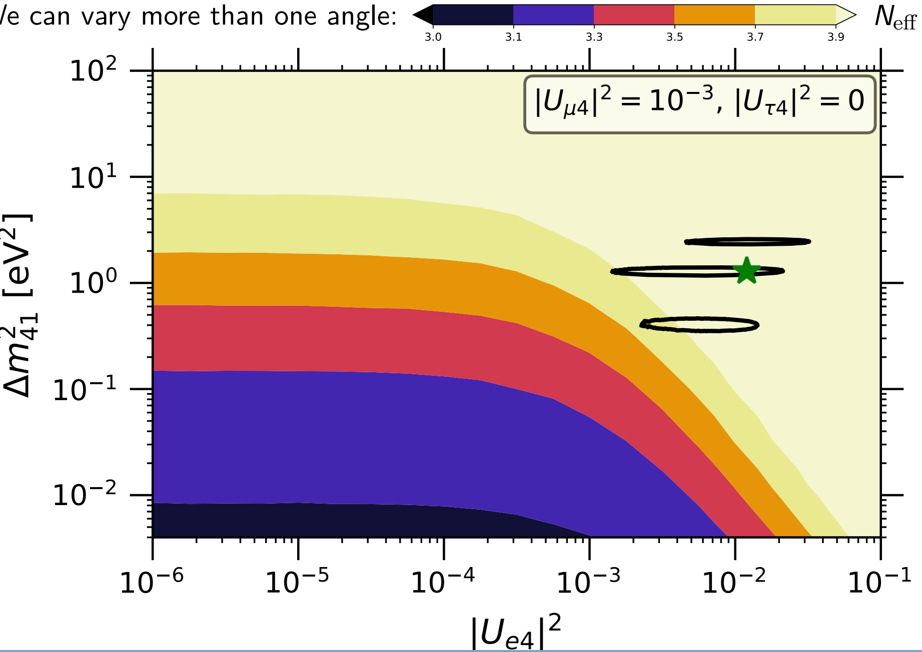

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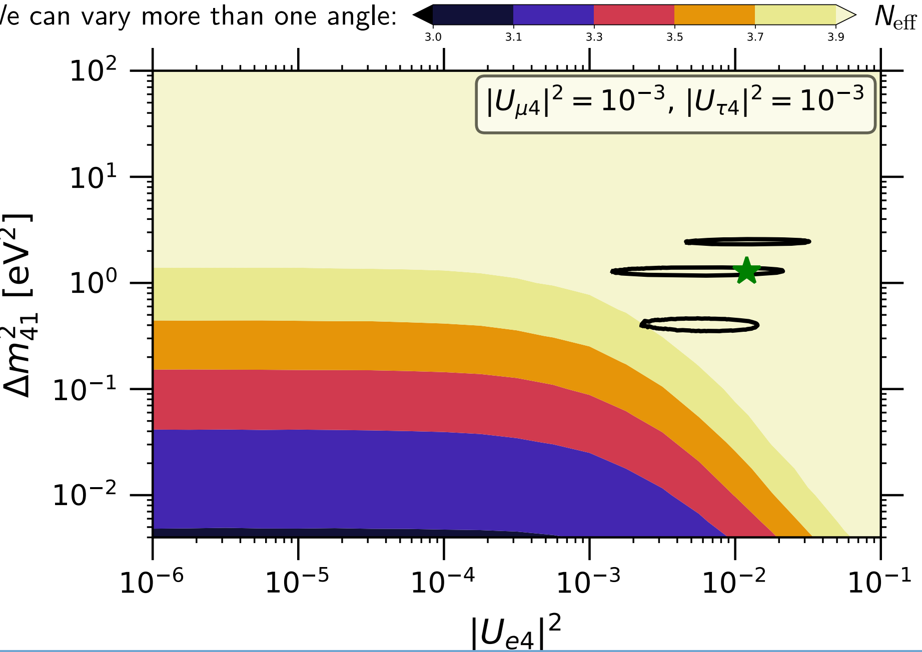
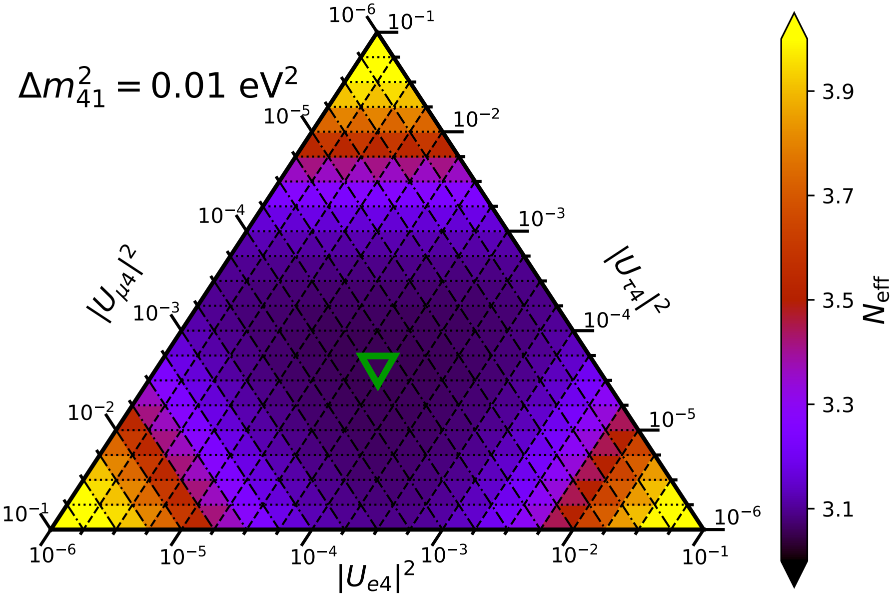


$N_{\rm eff}$ and the new mixing parameters

Sort of ternary plot (sum of $|U_{\alpha 4}|^2$ does not add up to 1!):



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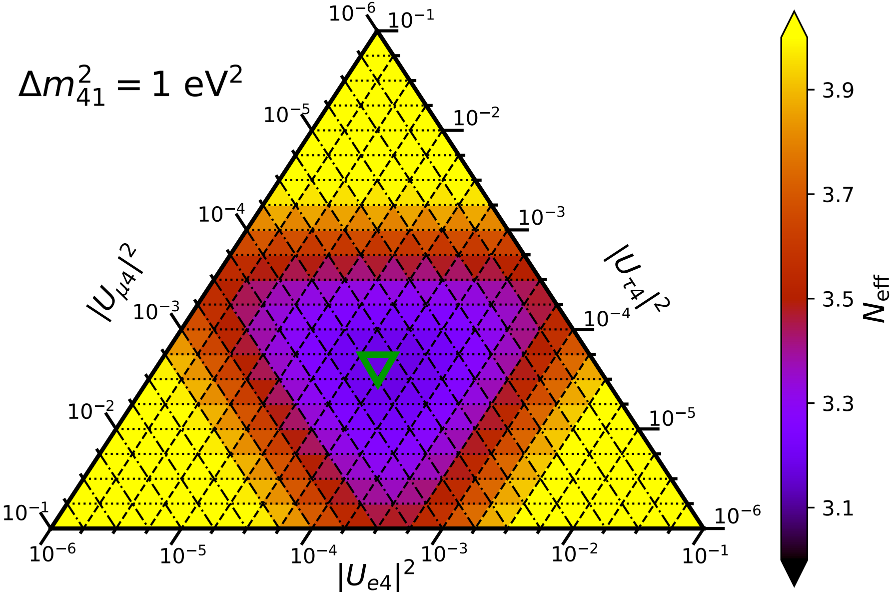

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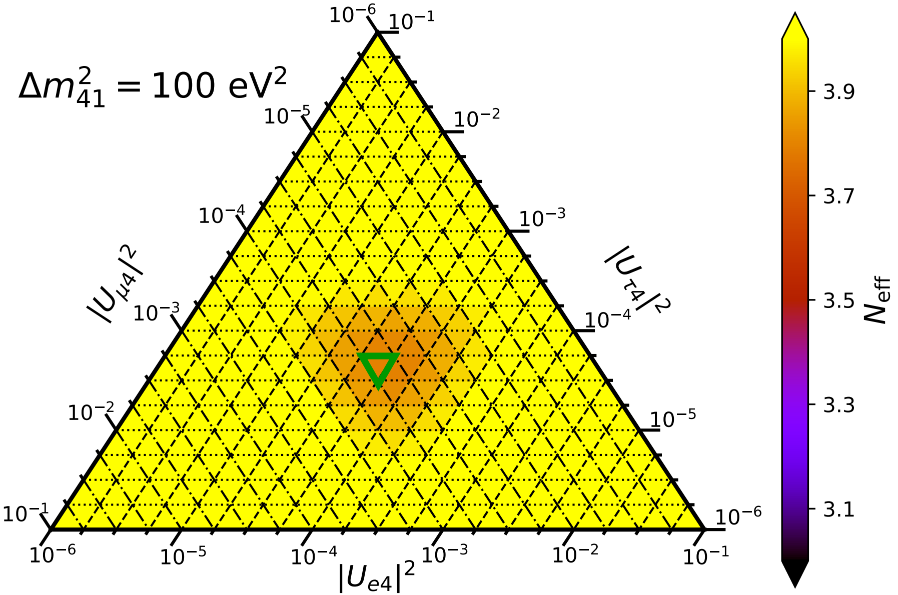
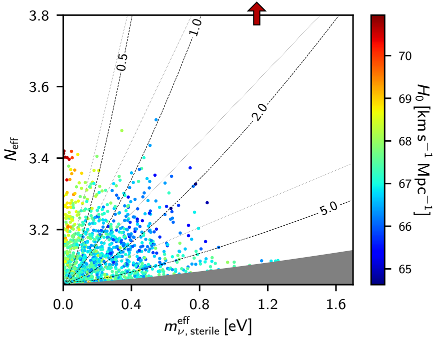


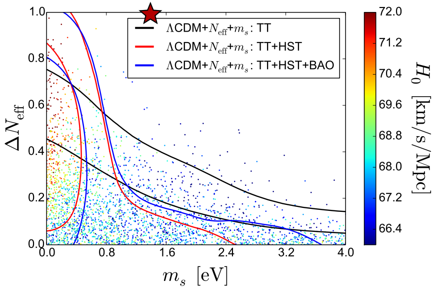
LSν constraints from cosmology

CMB+local: [Planck Collaboration, 2018]



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

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



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

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

Summary: $\Delta N_{\rm eff} = 1$ from LSν incompatible with CMB and BBN!

Planck18=Planck 2018 TT,TE,EE + lowE + lensing All the constraints are at 2σ CL

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 $|U_{\mu 4}|^2$,
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3. strong APP-DIS tension
   What are LSND and MiniBooNE observing?
   Systematics or LSν or new physics?

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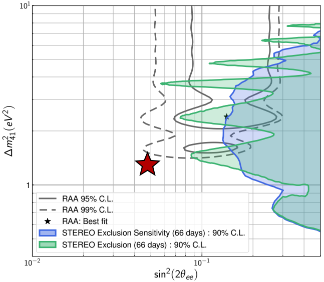
Thank you for the attention!

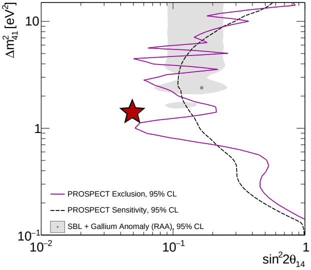
More to come...

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

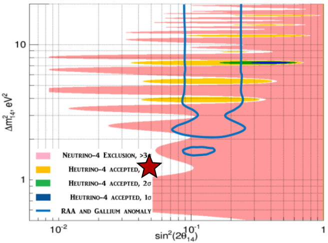
[STEREO, PRL 121 (2018) 161801]



[PROSPECT, PRL 121 (2018) 251802]



[Neutrino-4, PZETF 109 (2019) 209-218]



[SoLiD, JINST 13 (2018) P09005]