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(Light) Sterile neutrinos, from A to Z

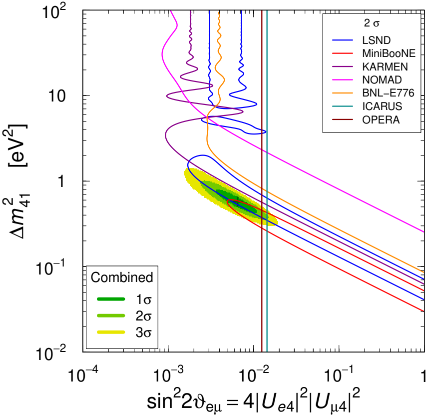
Seminar at Universidad Adolfo Ibañez, Stgo / online, 11/06/2021

A Appearance probes

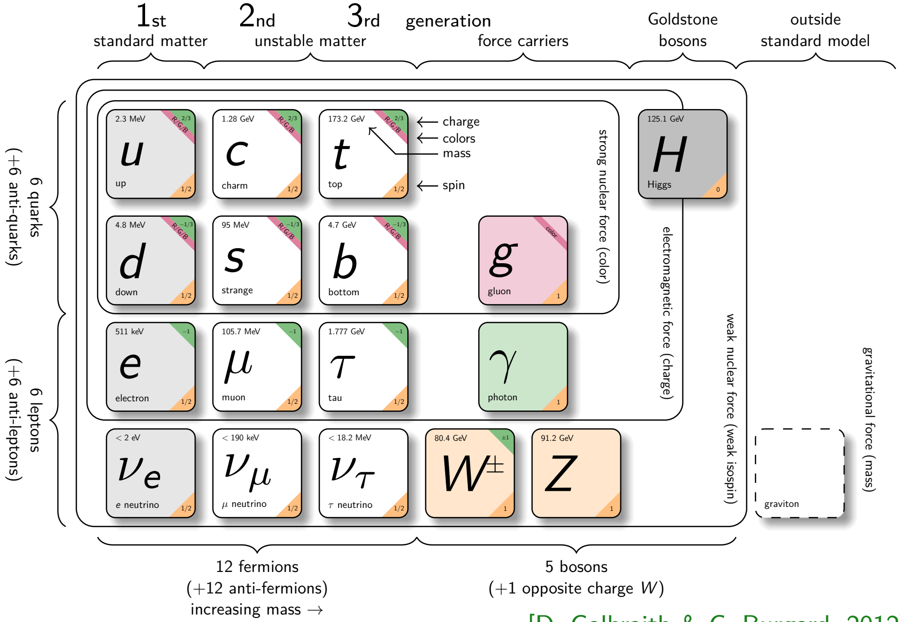
Appearance: the first anomaly

Based on:

- JPG 43 (2016) 033001
- LSND
- MiniBooNE
- in preparation

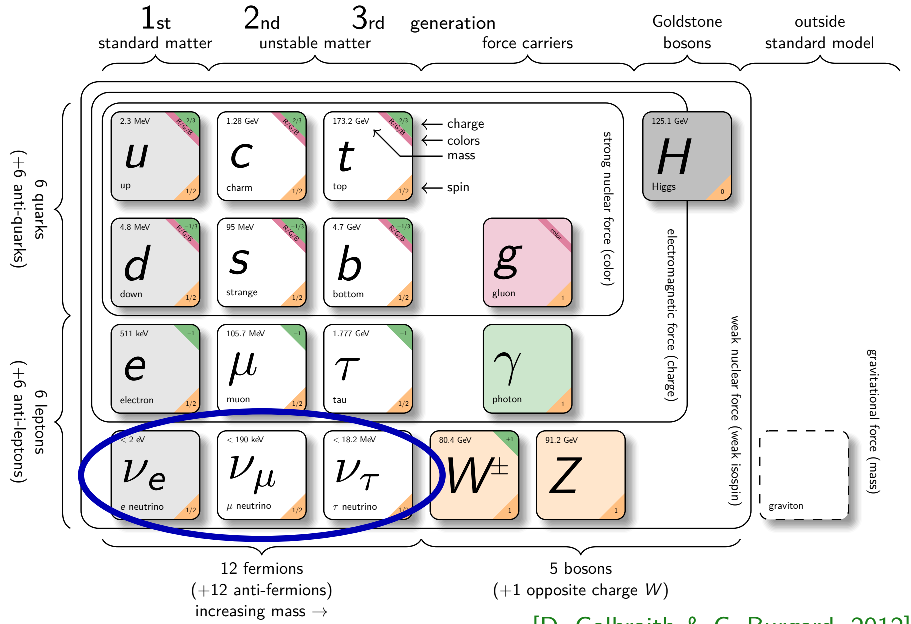


The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

The Standard Model of Particle Physics

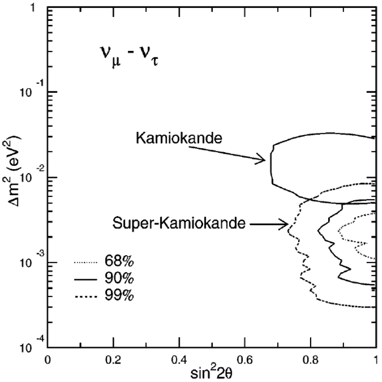


[D. Galbraith & C. Burgard, 2012]

Neutrino oscillations

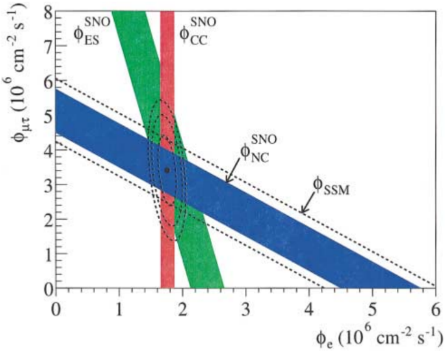
Major discoveries:

[SuperKamiokande, 1998]



first discovery of $\nu_\mu \to \nu_\tau$ oscillations from atmospheric ν

[SNO, 2001-2002]



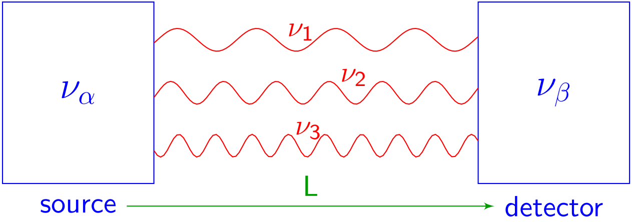
first discovery of $\nu_e \to \nu_\mu, \nu_\tau$ oscillations from solar ν

Nobel prize in 2015

Two neutrino bases

flavor neutrinos ν_α $\quad |\nu_\alpha\rangle = \sum_k U_{\alpha k}|\nu_k\rangle \quad$ 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 $\longrightarrow t = L$

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

$$\Delta m^2_{ij} = m_i^2 - m_j^2$$

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 δ

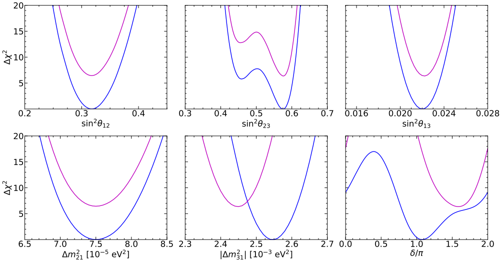
Current knowledge of the 3 active ν mixing: [JHEP 02 (2021)]

NO/NH: Normal Ordering/Hierarchy, $m_1 < m_2 < m_3$ IO/IH: Inverted O/H, $m_3 < m_1 < m_2$

$$\Delta m^2_{21} = (7.50^{+0.22}_{-0.20}) \cdot 10^{-5}\ \mathrm{eV}^2$$
$$|\Delta m^2_{31}| = (2.55^{+0.02}_{-0.03}) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO})$$
$$= (2.45^{+0.02}_{-0.03}) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})$$

$$10\sin^2(\theta_{12}) = 3.18 \pm 0.16$$
$$10^2\sin^2(\theta_{13}) = 2.200^{+0.069}_{-0.062}\ (\mathrm{NO})$$
$$= 2.225^{+0.064}_{-0.070}\ (\mathrm{IO})$$
$$10\sin^2(\theta_{23}) = 5.74 \pm 0.14\ (\mathrm{NO})$$
$$= 5.78^{+0.10}_{-0.17}\ (\mathrm{IO})$$

$$\delta/\pi = 1.08^{+0.13}_{-0.12}\ (\mathrm{NO})$$
$$= 1.58^{+0.15}_{-0.16}\ (\mathrm{IO})$$



mass ordering still unknown

δ still unknown

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

Short Baseline (SBL) anomalies

[SG+, JPG 43 (2016) 033001]

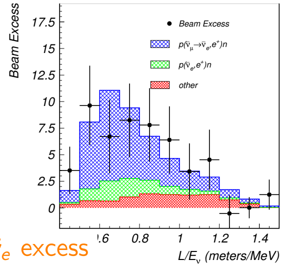
Do three-neutrino oscillations explain all experimental results?

Short Baseline (SBL) anomalies

[SG+, JPG 43 (2016) 033001]

Do three-neutrino oscillations explain all experimental results?

LSND



[Aguilar+, 2001]

3.8σ

$\bar{\nu}_\mu \to \bar{\nu}_e$ excess

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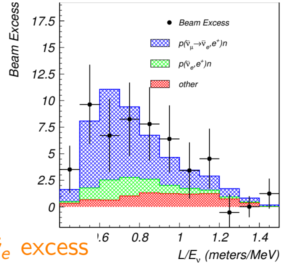

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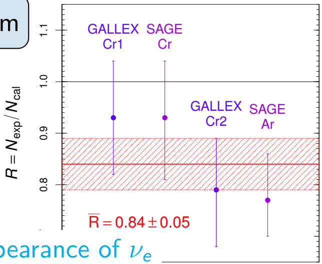
Gallium



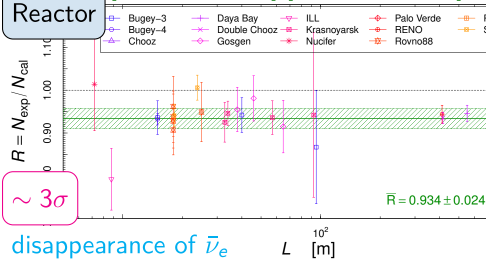
[Giunti, Laveder, 2011]

2.7σ

disappearance of ν_e

Reactor

[Mention+, 2011] [Azabajan+, 2012]



$\sim 3\sigma$

disappearance of $\bar{\nu}_e$

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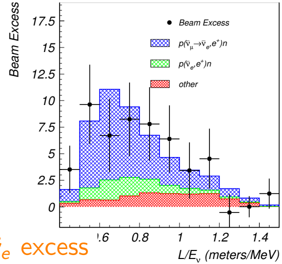
LSND



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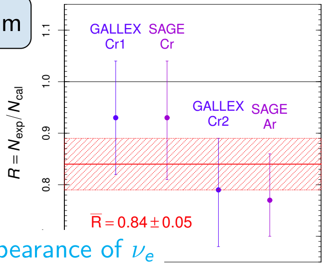

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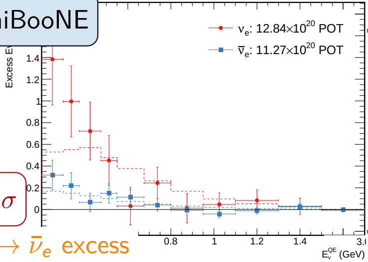
MiniBooNE



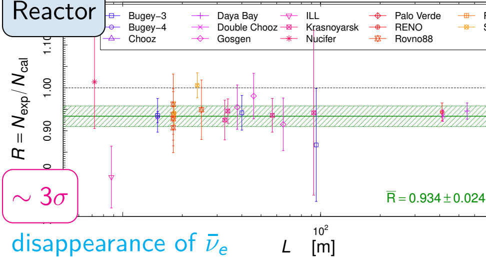
[Aguilar+, 2008-2018]

$\sim 5\sigma$

$\bar{\nu}_\mu \to \bar{\nu}_e$ excess

Reactor

[Mention+, 2011] [Azabajan+, 2012]



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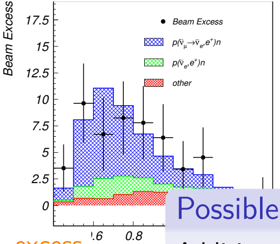
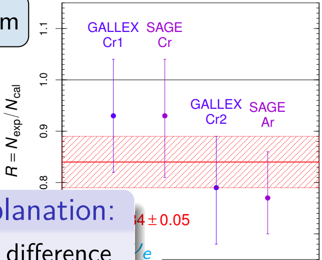


guilar+, 2001]

3.8σ

$\bar{\nu}_\mu \to \bar{\nu}_e$ excess

Gallium



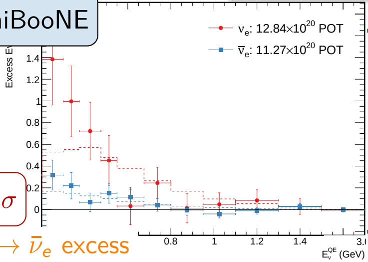
[Giunti, Laveder, 2011]

34 ± 0.05

Possible common explanation:

Additional squared mass difference $\Delta m^2_{SBL} \simeq 1\ \mathrm{eV}^2$

MiniBooNE



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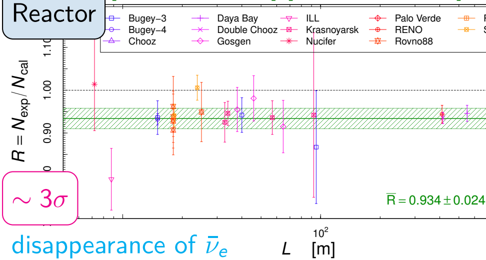


$\sim 3\sigma$

disappearance of $\bar{\nu}_e$

A large family

In principle, previous discussion is valid for N neutrinos

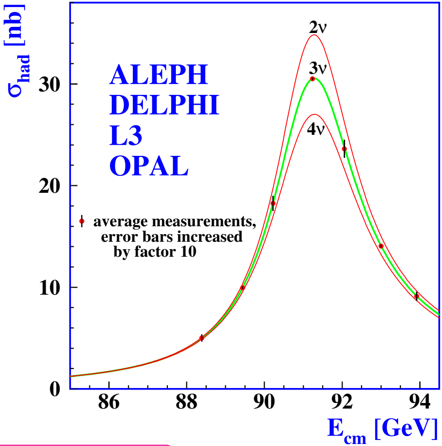
only constraint: there are exactly three flavor neutrinos in the SM

[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

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \\ |\nu_{s_1}\rangle \\ \cdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \vdots \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & \\ U_{s_11} & U_{s_12} & U_{s_13} & U_{s_14} & \\ \cdots & & & & \ddots \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \\ \cdots \end{pmatrix}$$

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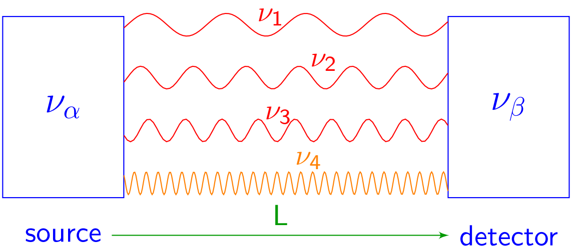
Our case will be 3 (active)+1 (sterile), a perturbation of 3 neutrinos case

$m_4 \gg m_\ell$
$\ell = 1, 2, 3$

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



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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DISappearance

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

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

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

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

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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

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

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ϑ_{14}

ϑ_{24}

ϑ_{34}

DISappearance

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

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha4}|^2(1 - |U_{\alpha4}|^2)$$

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

reactor

gallium

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

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

accelerator

atmospheric

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

New mixings in the 3+1 scenario

4 × 4 mixing matrix: $\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s_11} & U_{s_12} & U_{s_13} & U_{s_14} \end{pmatrix}$ ϑ_{14} ϑ_{24} ϑ_{34}

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$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha4}|^2(1 - |U_{\alpha4}|^2)$$

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

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

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

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

APPearance

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

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

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

LSND
MiniBooNE
KARMEN
OPERA
...

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

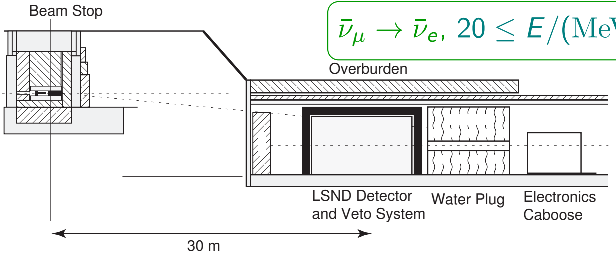
quadratically suppressed!

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

LSND

[PRD 64 (2001) 112007]

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



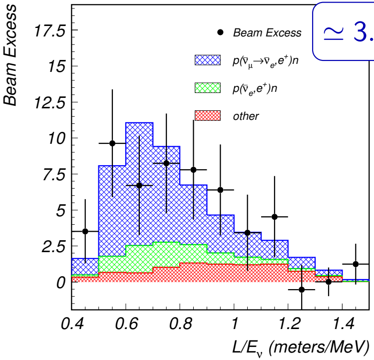
well known source of $\bar{\nu}_\mu$:

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

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

$L \simeq 30$ 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]

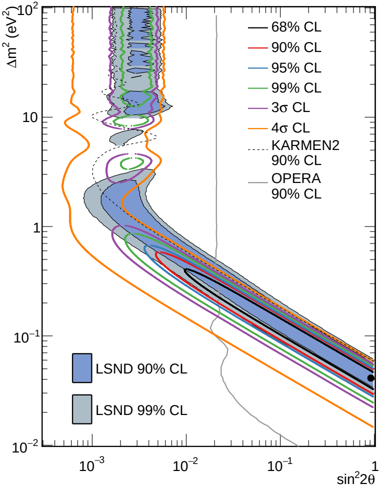
MiniBooNE

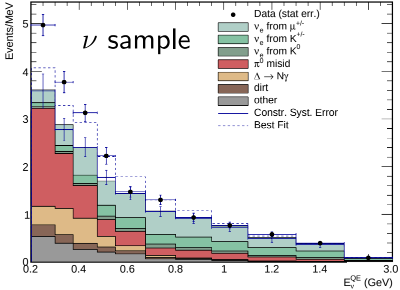
[PRL 121 (2018) 221801]

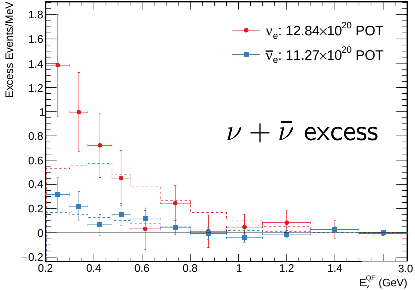
purpose: check LSND signal

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

no money, no near detector







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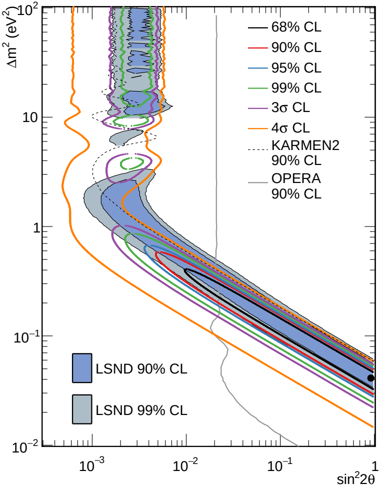
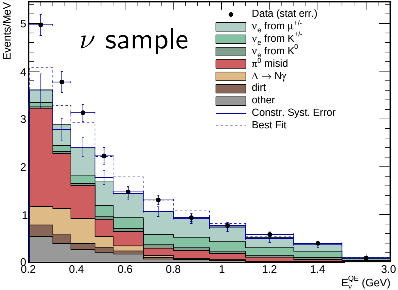
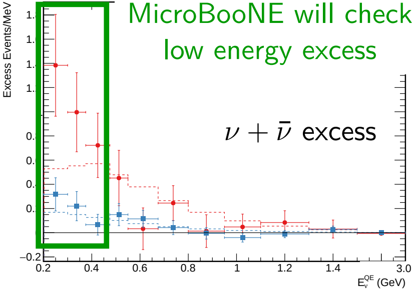


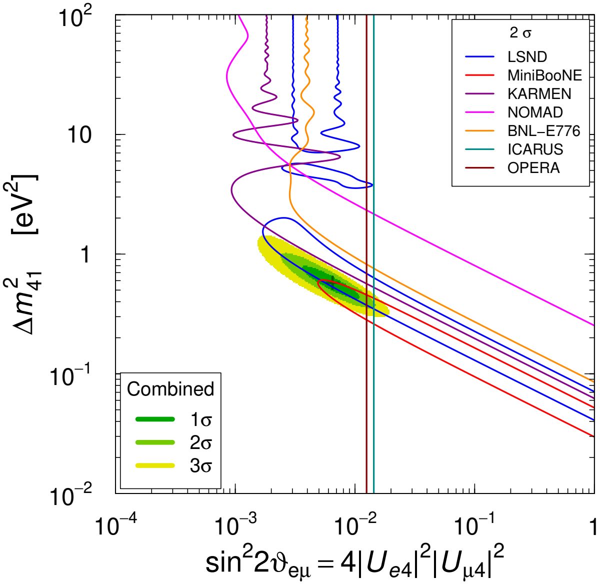


MicroBooNE will check low energy excess



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

[SG+, in preparation]



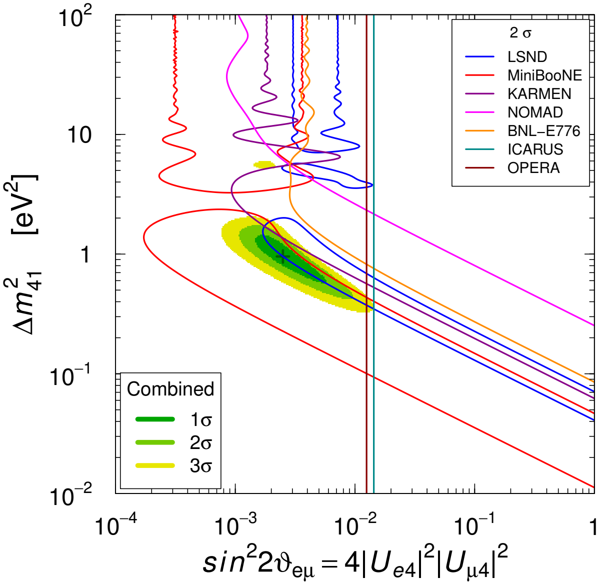
with full MiniBooNE data

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

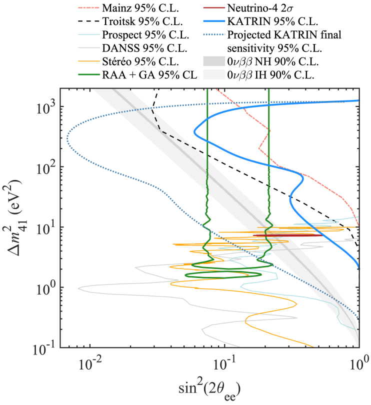
KARMEN cuts part of LSND region

B Beta/double beta constraints

i.e. non-oscillation probes, first part

Based on:

- KATRIN
- Giunti+ JHEP 2015



β decay

$$\beta \text{ decay: } \mathcal{N}(A,Z) \longrightarrow \mathcal{N}(A,Z+1) + e^- + \bar{\nu}_e$$

$$Q_\beta = M_i - M_f - m_e$$

total available energy

$$E_\nu = Q_\beta - T = Q_\beta - (E_e - m_e)$$

neutrino energy

notice that max electron energy is:

$$T_{\max} = Q_\beta - m_{\bar{\nu}_e}$$

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Kurie function: (degenerate ν masses)

$$K(T) = \left[(Q_\beta - T)\sqrt{(Q_\beta - T)^2 - m^2_{\bar{\nu}_e}}\right]^{1/2}$$

Useful to describe the e^- spectrum near the endpoint

notice: flavor neutrinos have no definite mass!

$$m^2_{\bar{\nu}_e} = \sum |U_{ei}|^2 m_i^2$$

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Useful to describe the e^- spectrum near the endpoint

notice: flavor neutrinos have no definite mass!

$m^2_{\bar{\nu}_e} = \sum |U_{ei}|^2 m_i^2$

Full expression:

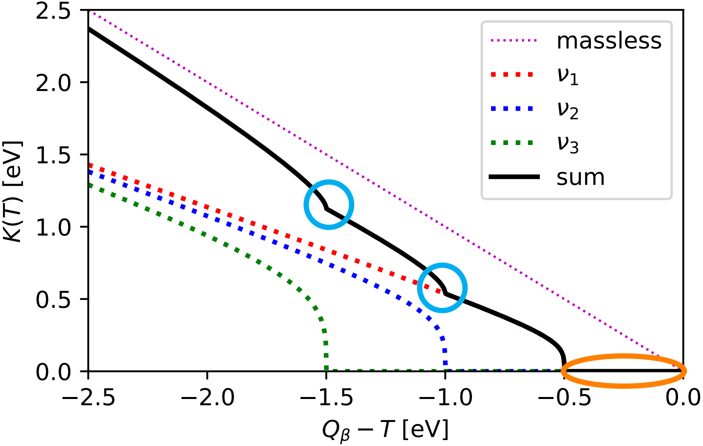
$$K(T) = \left[(Q_\beta - T)\sum_{i=1}^{N_\nu} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2}\right]^{1/2}$$

N_ν neutrinos with different masses m_i

mixing angles enter ($|U_{ei}|^2$)

β decay

$$K(T) = \left[(Q_\beta - T) \sum_{i=1}^{N_\nu} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2} \right]^{1/2}$$



Fake case:
3 neutrinos

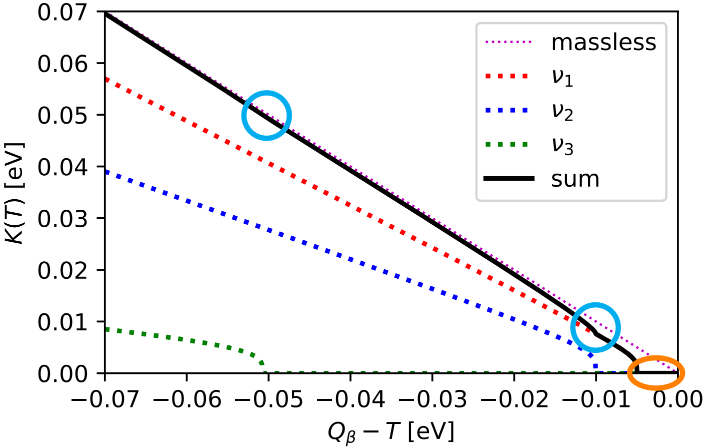
masses:
$m_i = i \cdot 0.5$ eV,

mixings:
$|U_{ei}|^2 = 1/3$

endpoint shifted + one kink for each mass eigenstate

β decay

$$K(T) = \left[(Q_\beta - T) \sum_{i=1}^{N_\nu} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2} \right]^{1/2}$$



Realistic case:
3 neutrinos,
normal
ordering

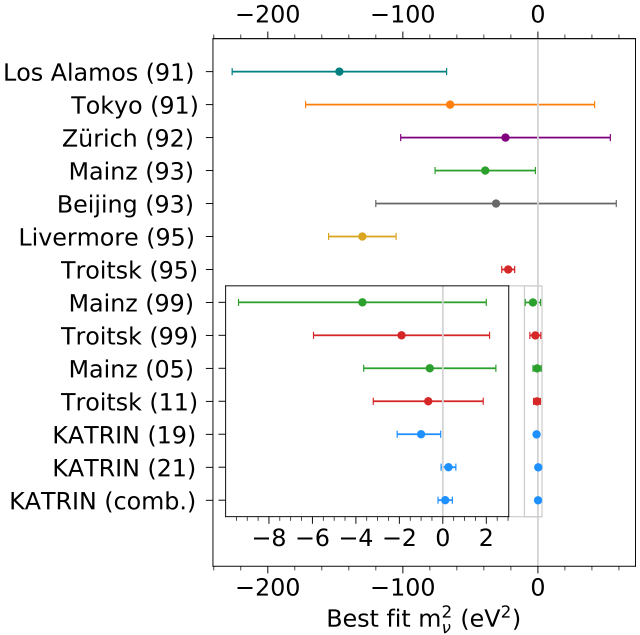
masses: $m_i =$ $[5, 10, 51]$ meV,

mixings: $|U_{ei}|^2 =$ $[0.67, 0.31, 0.02]$

Much harder to see the endpoint shift and kinks!

KATRIN results

[KATRIN, 2105.08533]

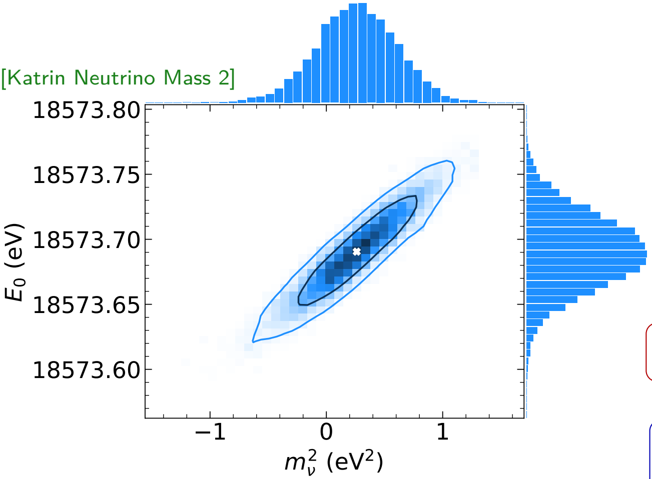


KATRIN results

[KATRIN, 2105.08533]

strongest bound on $m_\nu (\equiv m_{\bar{\nu}_e})$ are from KATRIN

[Katrin Neutrino Mass 2]



KNM1+KNM2:
$m_\nu^2 = (0.1 \pm 0.3)$ eV^2

Upper limit 90%:
$m_\nu < 0.8$ eV

Bayesian 90%:
$m_\nu < 0.7$ eV

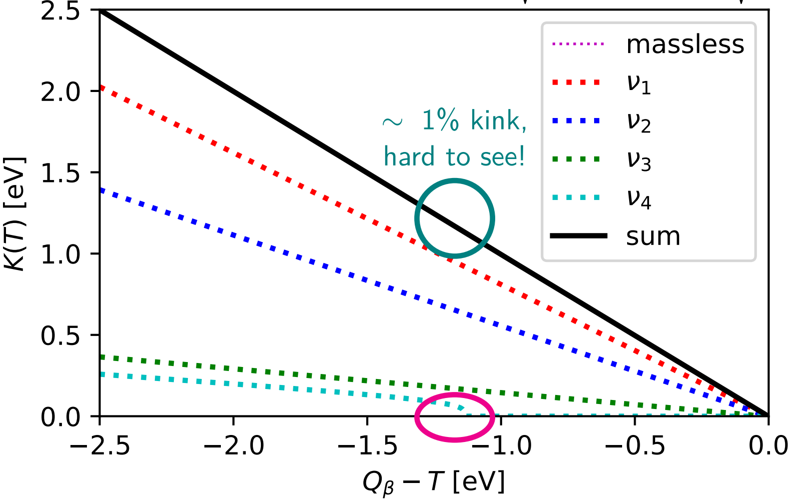
statistics dominated!

expected final sensitivity (90%):
$m_\nu \lesssim 0.2$ eV

Sterile neutrino in β decay

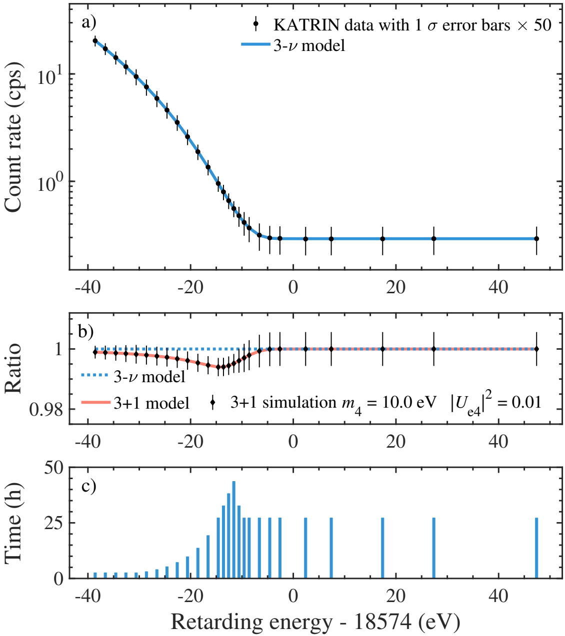
$$K(T) = \left[(Q_\beta - T) \sum_{i=1}^{N_\nu} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2} \right]^{1/2}$$

$|U_{e4}|^2 \sim 0.01$ $\quad$ $m_4 = \sqrt{m_1^2 + \Delta m_{41}^2} \sim \sqrt{\Delta m_{41}^2}$



Sterile neutrino in β decay

[KATRIN, PRL 126 (2021)]



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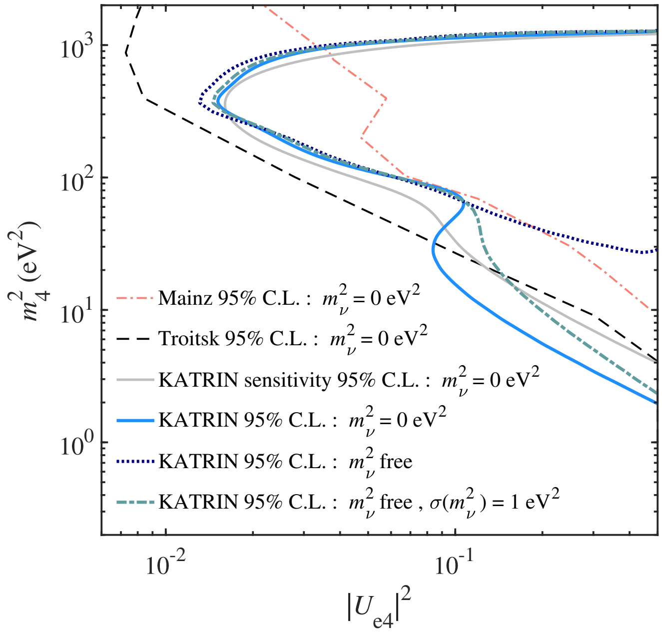

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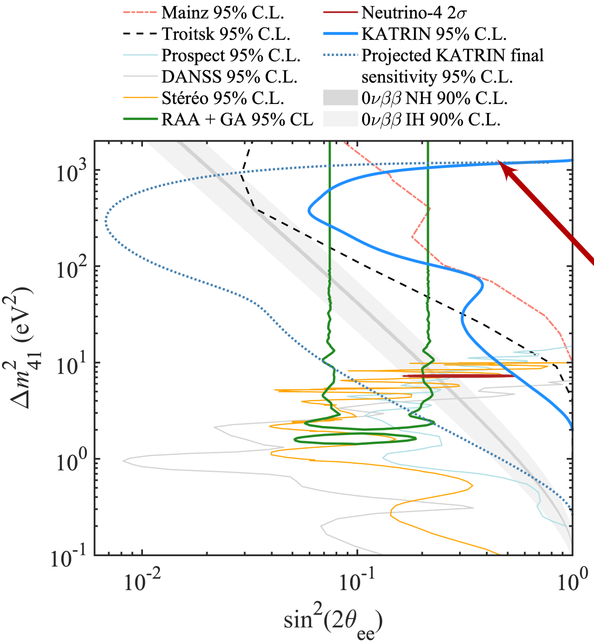


final sensitivity will test several oscillation results!

search for keV states needs to measure the spectrum much further from the endpoint...

Neutrino masses from neutrinoless double β decay

(if neutrino is Majorana)

[Schechter&Valle, 1982]

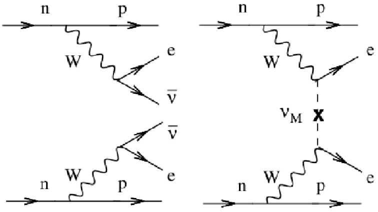
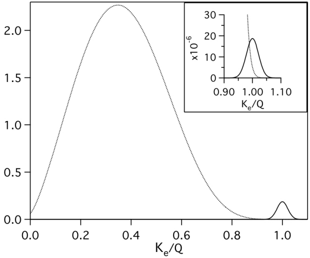
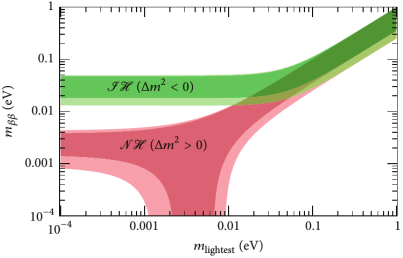


figure from [NEXT] webpage





[Dell'Oro et al., 2016]

Measure $T^{0\nu}_{1/2}$

m_e electron mass,
$G_{0\nu}$ phase space,
$\mathcal{M}'^{\nu}$ matrix element

convert into $m_{\beta\beta} = \dfrac{m_e}{\mathcal{M}'^{\nu}\sqrt{G_{0\nu}\, T^{0\nu}_{1/2}}}$

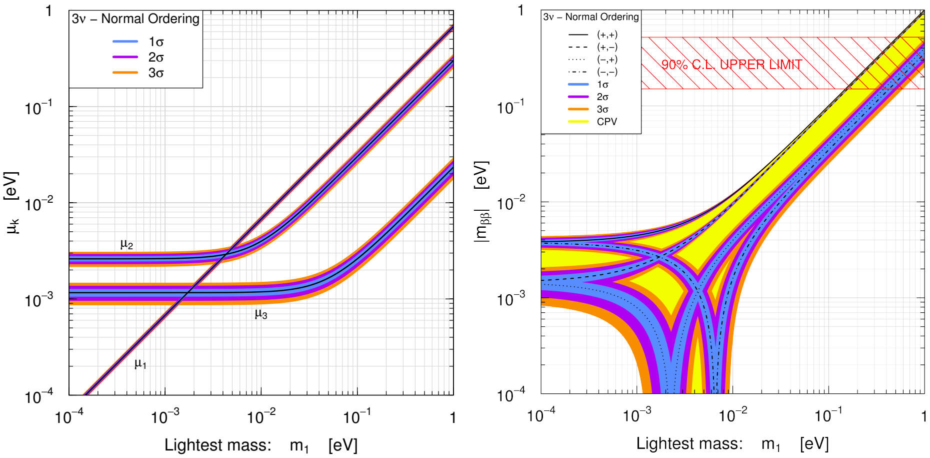
α_k Majorana phases

and then use $m_{\beta\beta} = \left| \sum_k e^{i\alpha_k} U^2_{ek}\, m_k \right|$

Mass eigenstates and $0\nu\beta\beta$

[Giunti&Zavanin, JHEP 07 (2015) 171]

effective Majorana mass: $m_{\beta\beta} = \left|\sum_k e^{i\alpha_k}\,\mu_k\right|$, with $\mu_k \equiv U_{ek}^2\, m_k$



3 neutrinos, normal ordering (NO): $m_1 < m_2 < m_3$, $|U_{e1}| > |U_{e2}| > |U_{e3}|$

Mass eigenstates and $0\nu\beta\beta$

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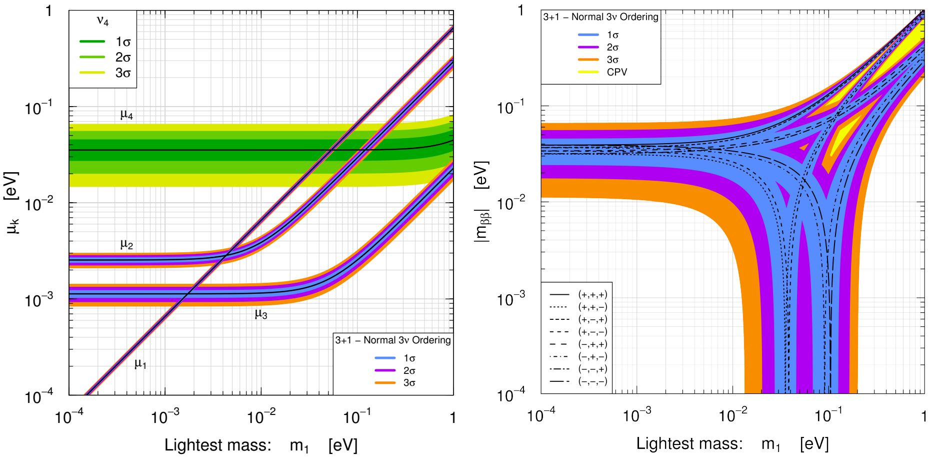

3+1 neutrinos, NO: $m_1 < m_2 < m_3 < m_4$, $|U_{e1}| > |U_{e2}| > |U_{e3}| \gtrsim |U_{e4}|$

Mass eigenstates and $0\nu\beta\beta$

[Giunti&Zavanin, JHEP 07 (2015) 171]

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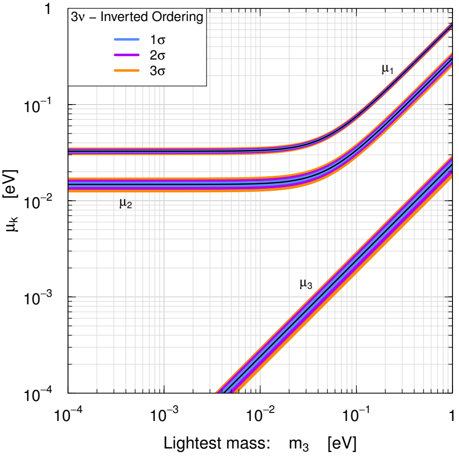
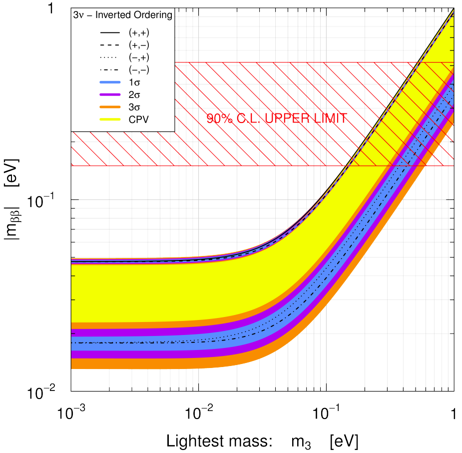
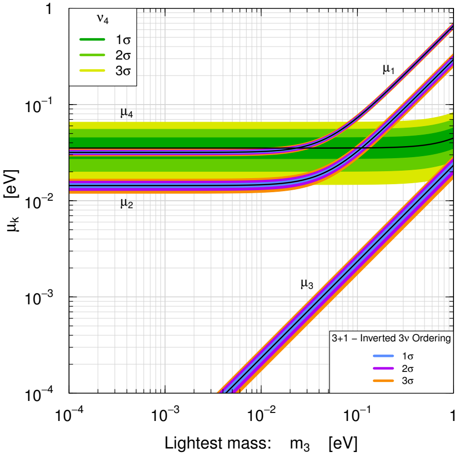


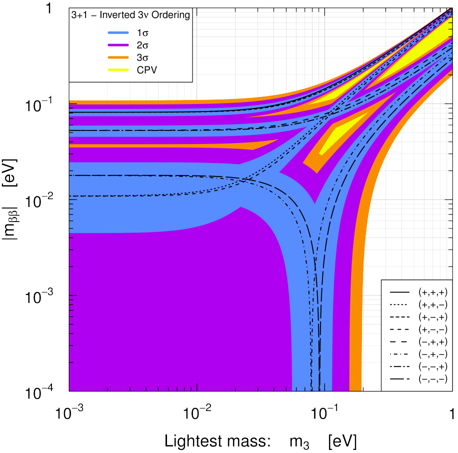


3 neutrinos, inverted ordering (IO): $m_3 < m_1 \lesssim m_2$, $|U_{e1}| > |U_{e2}| > |U_{e3}|$

Mass eigenstates and $0\nu\beta\beta$

effective Majorana mass: $m_{\beta\beta} = \left|\sum_k e^{i\alpha_k}\,\mu_k\right|$, with $\mu_k \equiv U_{ek}^2\, m_k$



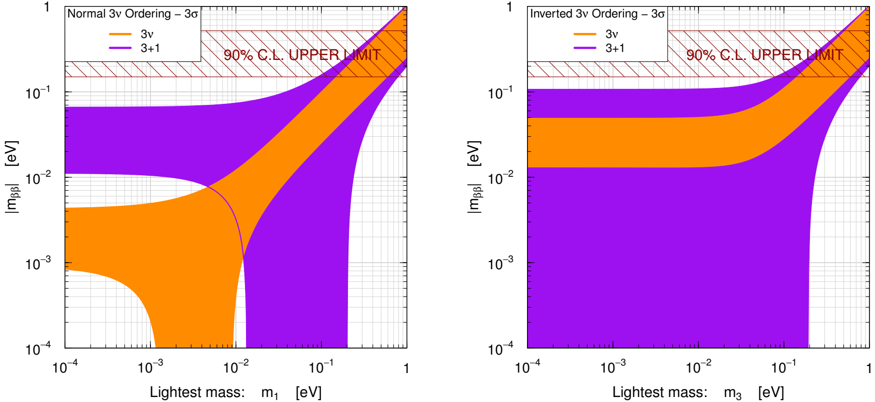


3+1 neutrinos, IO: $m_3 < m_1 \lesssim m_2 < m_4$, $|U_{e1}| > |U_{e2}| > |U_{e3}| \gtrsim |U_{e4}|$

Light sterile neutrino and $0\nu\beta\beta$

[Giunti&Zavanin, JHEP 07 (2015) 171]
[Giunti @ MEDEX 2017]

NO for active neutrinos | **IO** for active neutrinos



one more neutrino completely changes the picture!

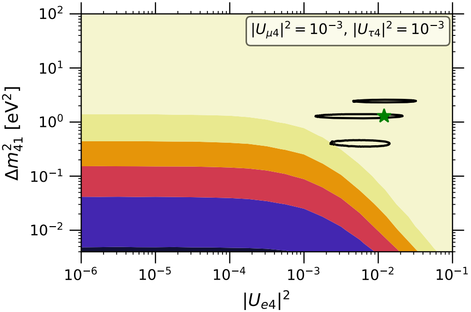
with 3+1 νs, incoming experiments could see $m_{\beta\beta}$ even if $m_{\text{lightest}} = 0$

C Cosmology

i.e. non-oscillation probes, second part

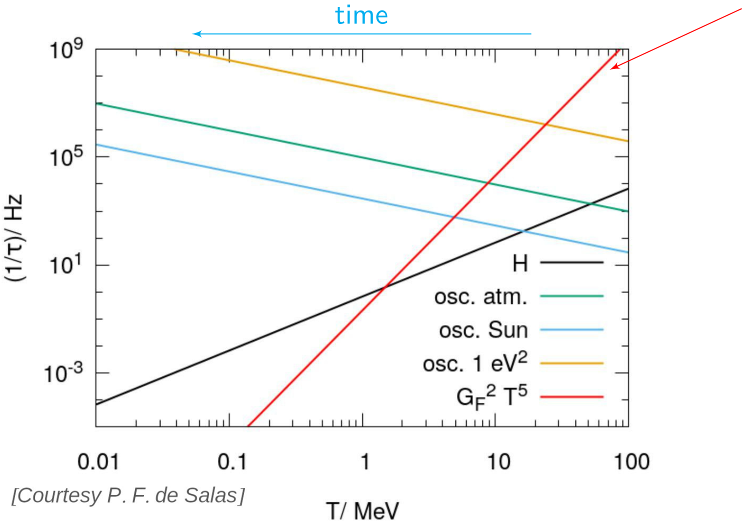
Based on:

- JCAP 04 (2021) 073
- JCAP 07 (2019) 014
- arxiv:2003.02289



Neutrinos in the early Universe

before BBN: neutrinos coupled to plasma ($\nu_\alpha \bar{\nu}_\alpha \leftrightarrow e^+ e^-$, $\nu e \leftrightarrow \nu e$)



[Courtesy P. F. de Salas]

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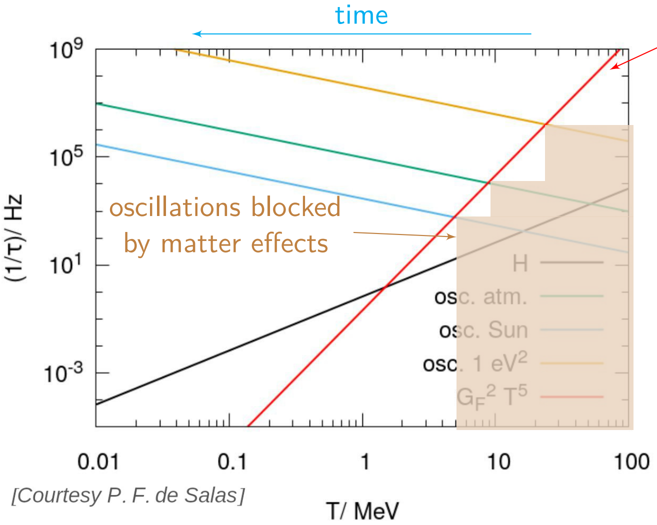

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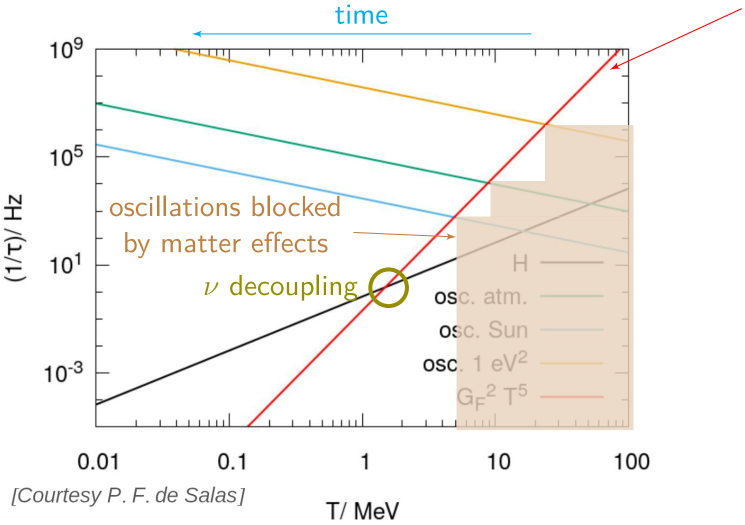

[Courtesy P. F. de Salas]

ν decouple mostly before $e^+e^- \to \gamma\gamma$ annihilation!

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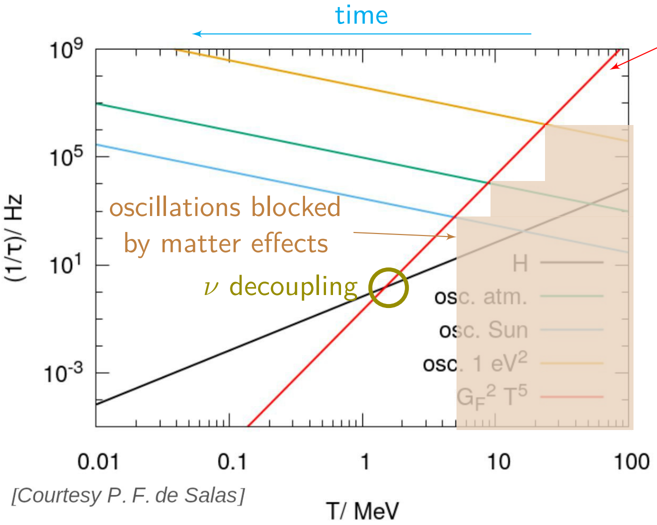

[Courtesy P. F. de Salas]

$T_\nu \simeq (4/11)^{1/3}\,T_\gamma$
after $e^+e^- \to \gamma\gamma$

f_ν: frozen Fermi-Dirac distribution

Today:

$T_{\nu,0} = 1.945$ K $\simeq 1.676 \times 10^{-4}$ eV

$\langle E_\nu \rangle \simeq 3.1\,T_{\nu,0} \simeq 5 \times 10^{-4}$ eV

$n_0 = n_{\nu,0} = n_{\bar{\nu},0} \simeq 56$ cm^{-3} per family

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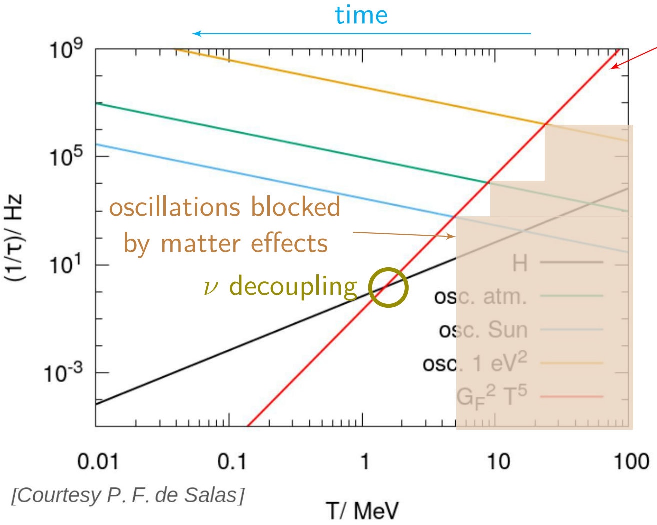

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ν decouple mostly before $e^+e^- \to \gamma\gamma$ annihilation!

actually, the decoupling T is momentum dependent! → distortions to equilibrium f_ν!

ν oscillations in the early universe

[Bennett, SG+, JCAP 2021]

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

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

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

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

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

e.g. $$R^{13} = \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta_{13} & 0 & \cos\theta_{13} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

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

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

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

[Bennett, SG+, JCAP 2021]

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

take into account neutrino-electron scattering and pair annihilation, plus neutrino–neutrino interactions

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

ν oscillations in the early universe

[Bennett, SG+, JCAP 2021]

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

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

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

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

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

from continuity equation

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

$$\frac{\mathrm{d}z}{\mathrm{d}x} = \frac{\sum_{\ell=e,\mu}\left[\frac{r_\ell^2}{r}J(r_\ell)\right] + G_1(r) - \frac{1}{2\pi^2 z^3}\int_0^\infty dy\, y^3 \sum_{\alpha=e}^{s}\frac{\mathrm{d}\varrho_{\alpha\alpha}}{\mathrm{d}x}}{\sum_{\ell=e,\mu}\left[r_\ell^2 J(r_\ell)+Y(r_\ell)\right] + G_2(r) + \frac{2\pi^2}{15}}$$

$r = x/z$, $r_\ell = m_\ell/m_e\, r$ $\quad$ $J(r)$, $Y(r)$ 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

[Bennett, SG+, JCAP 2021]

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neutrino temperature w: same equation as z, but electrons always relativistic

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initial conditions: $\varrho_{\alpha\alpha}$ = Fermi-Dirac at $x_{\mathrm{in}} \simeq 0.001$, with $w = z \simeq 1$

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FORTran-Evolved PrimordIAl Neutrino Oscillations (FortEPiaNO)

https://bitbucket.org/ahep_cosmo/fortepiano_public

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

$$\frac{\mathrm{d}z}{\mathrm{d}x} = \frac{\displaystyle\sum_{\ell=e,\mu}\left[\frac{r_\ell^2}{r}J(r_\ell)\right] + G_1(r) - \frac{1}{2\pi^2 z^3}\int_0^\infty dy\, y^3 \sum_{\alpha=e}^{s}\frac{\mathrm{d}\varrho_{\alpha\alpha}}{\mathrm{d}x}}{\displaystyle\sum_{\ell=e,\mu}\left[r_\ell^2 J(r_\ell) + Y(r_\ell)\right] + G_2(r) + \frac{2\pi^2}{15}}$$

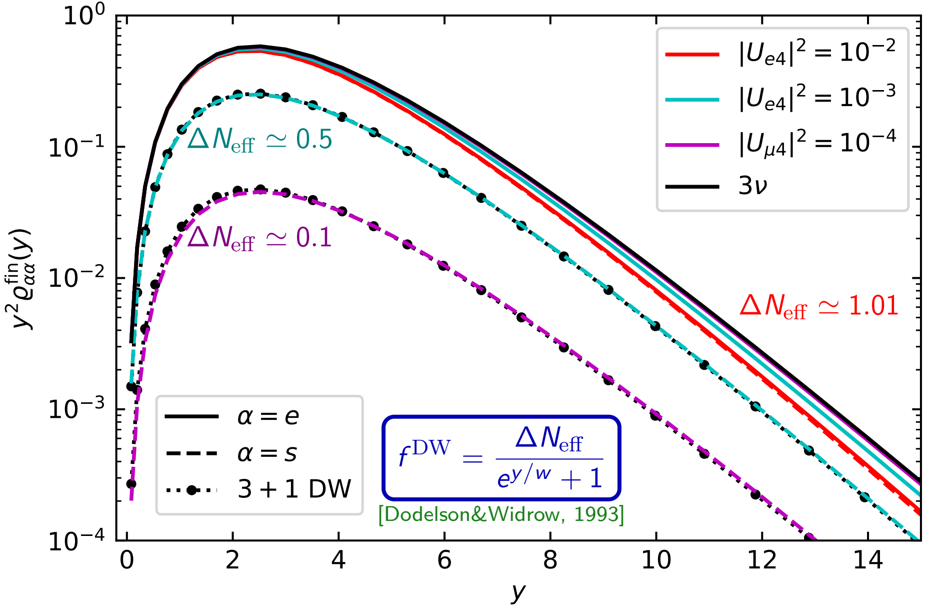
neutrino temperature w: same equation as z, but electrons always relativistic

initial conditions: $\varrho_{\alpha\alpha}$ = Fermi-Dirac at $x_{\mathrm{in}} \simeq 0.001$, with $w = z \simeq 1$

Momentum distributions

[SG+, JCAP 07 (2019) 014]

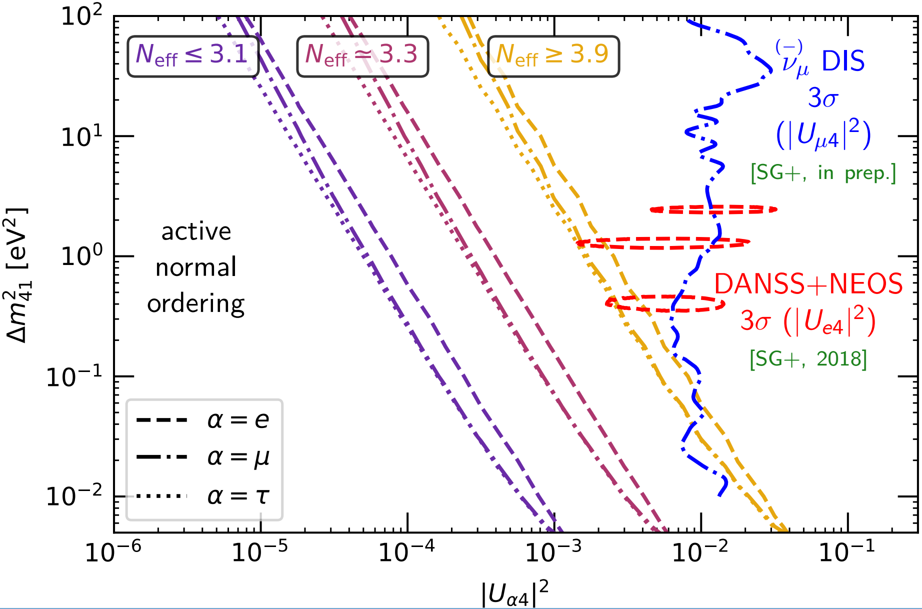
$\Delta m^2_{41} = 1.29$ eV^2, other $|U_{\beta 4}|^2 = 0$, $\Delta N_{\rm eff} = N_{\rm eff} - N_{\rm eff}^{\rm active}$



N_{eff} and the new mixing parameters

[SG+, JCAP 07 (2019) 014]

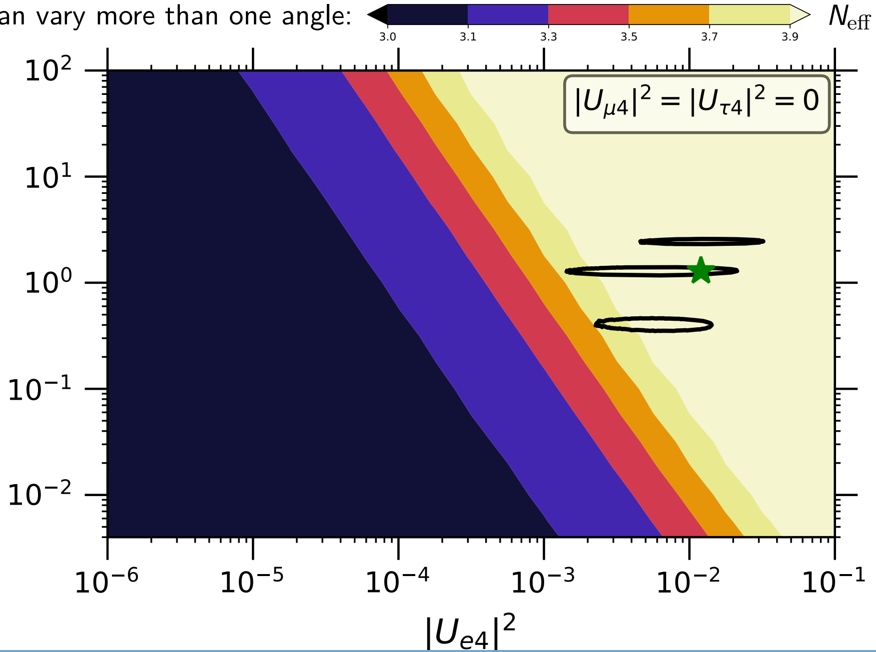
Only vary one angle and fix two to zero: do they have the same effect?



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

[SG+, JCAP 07 (2019) 014]

We can vary more than one angle:



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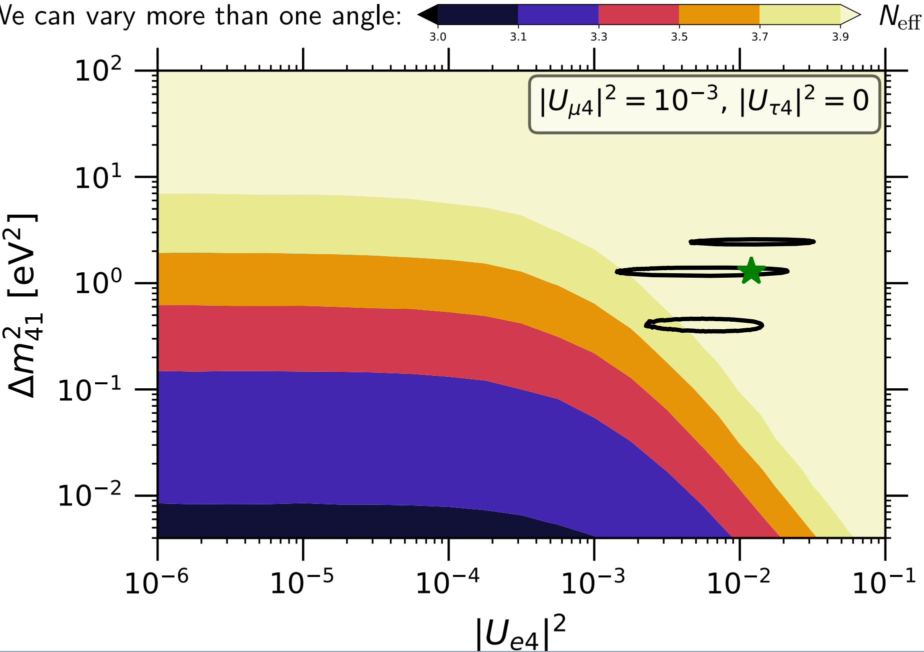

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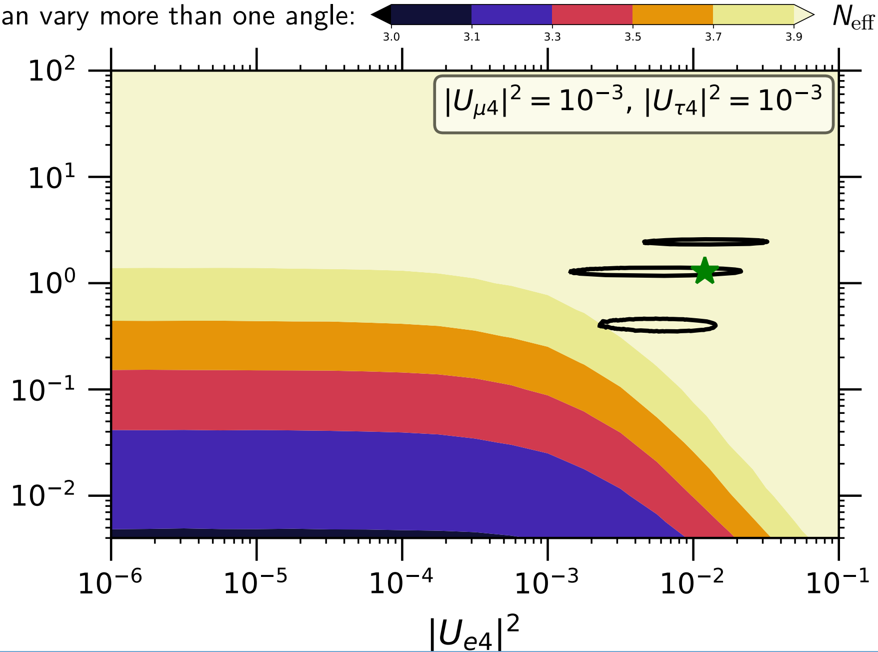
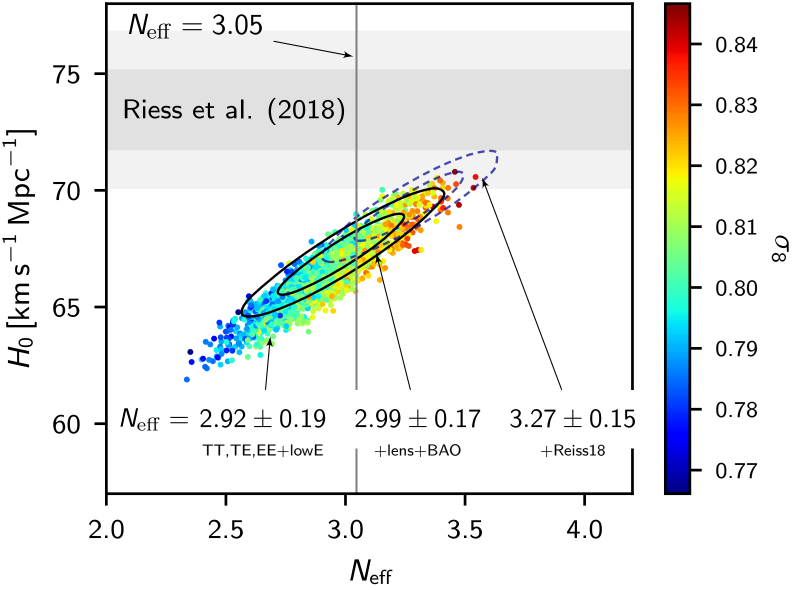


$N_{\rm eff}$ and CMB

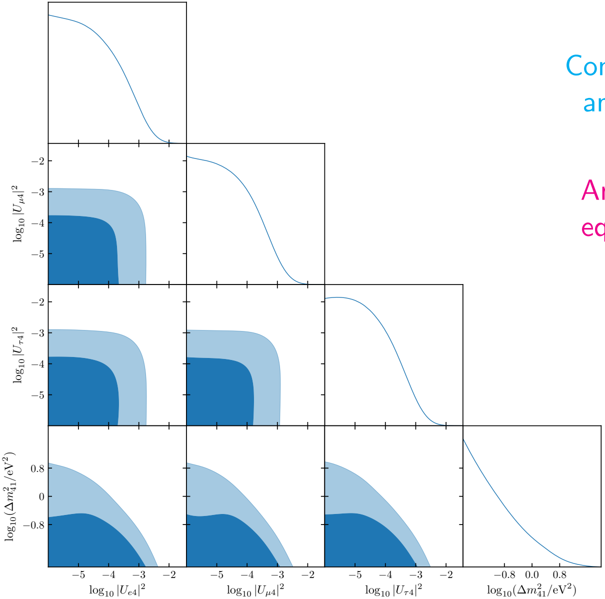
[Planck Collaboration, 2018]



Cosmological constraints on $|U_{\alpha 4}|^2$

[arxiv:2003.02289]

Use multi-angle results from `FortEPiaNO` to derive constraints on $|U_{\alpha 4}|^2$:



Constraints come from $N_{\rm eff}$ and late-time density Ω_s

Angles $|U_{\alpha 4}|^2$ are almost equivalent for cosmology

Prevent ν_s thermalization?

oscillation parameters suggest $\Delta N_{\rm eff} \simeq 1$ [SG+, 2019]

is there a way to suppress ν_s contribution to $N_{\rm eff}$?

suppress oscillations/reduce $\Delta N_{\rm eff}$

large lepton asymmetry [Foot+1995, Mirizzi+2012, many more]

new neutrino interactions [Bento+2001, Dasgupta+2014, Hannestad+2014, Saviano+2014, Dentler+2019, de Gouvea+2019, Moulai+2019, Fischer+2019, Diaz+2019, Liao+2019, Archidiacono+2020, many more]

very low reheating temperature [Gelmini+2004, Smirnov+2006, deSalas+2015, in preparation]

compensate effects of $\Delta N_{\rm eff} \simeq 1$

time varying dark energy components [Giusarma+2012]

larger expansion rate at the time of ν_s production [Rehagen+2014]

freedom in the Primordial Power Spectrum (PPS) of scalar perturbations from inflation compensate damping due to $\Delta N_{\rm eff}$ [SG+2015]

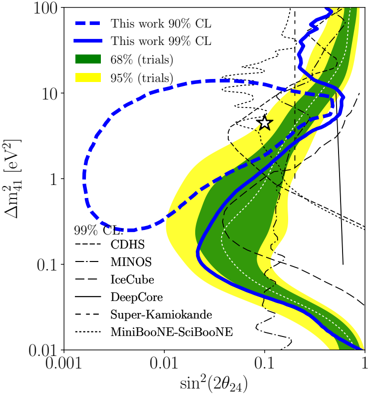
These are just some ideas (incomplete list!)

D Disappearance (Muon channel)

strong constraints, and a recent first hint

Based on:

- IceCube 2016
- DeepCore
- Minos/Minos+
- in preparation
- IceCube 2020



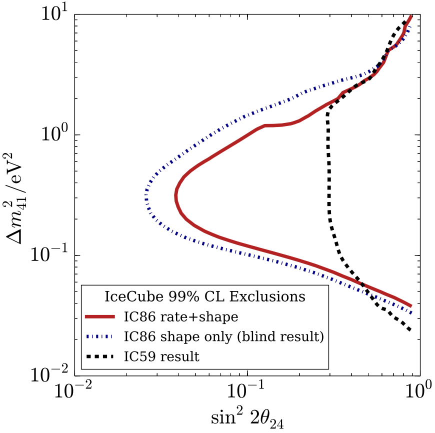
IceCube and DeepCore

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 GeV $<$ E $<$ 20 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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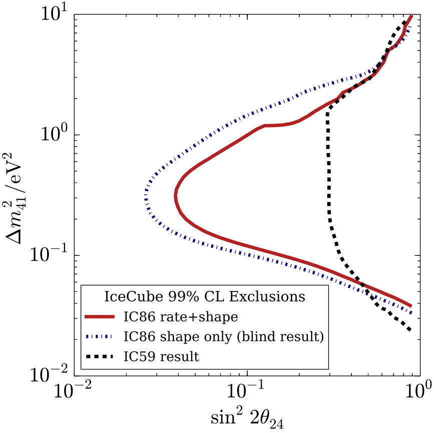
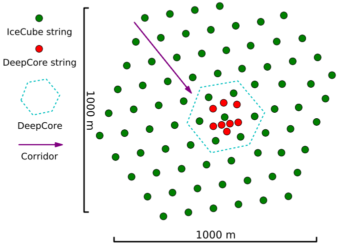
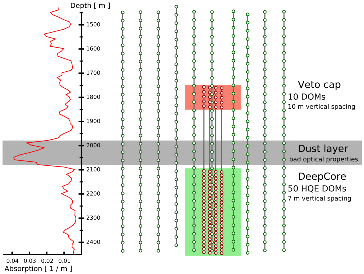


[PRL 117 (2016) 071801]





IceCube and DeepCore

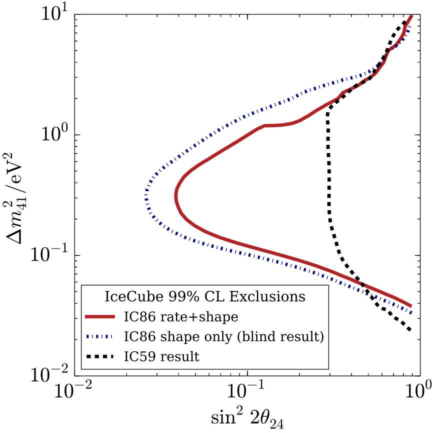
IceCube $\mathcal{O}(10\text{ km}) \lesssim L \lesssim \mathcal{O}(10^4\text{ km})$ DeepCore

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

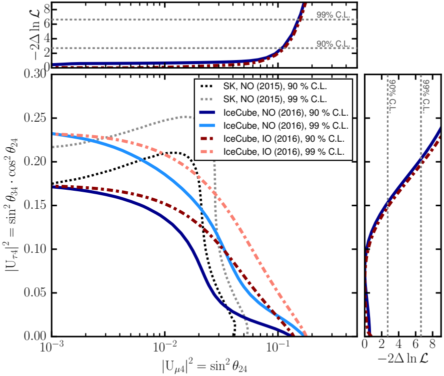
320 GeV $< E <$ 20 TeV

$\sim 5\times10^3$ tracklike events

6 GeV $\lesssim E \lesssim$ 60 GeV



[PRL 117 (2016) 071801]



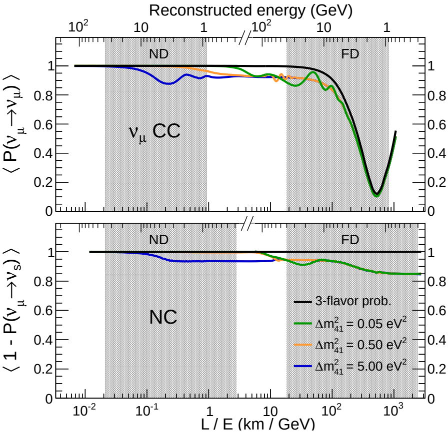
[PRD 95 (2017) 112002]

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

MINOS & MINOS+

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

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



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

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

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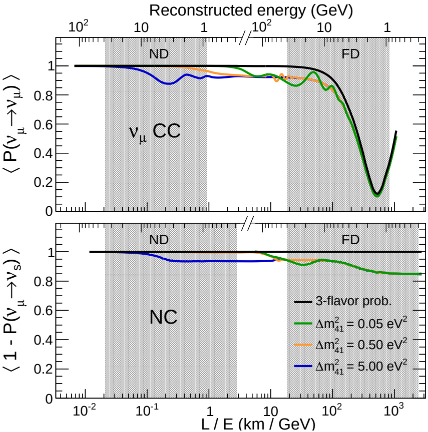

[PRL 117 (2016) 151803]:

far-to-near ratio

[PRL 122 (2019) 091803]:

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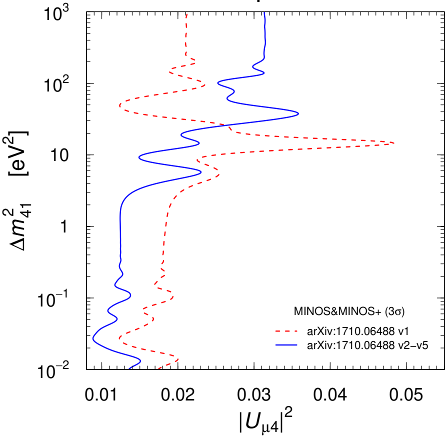
MINOS+ update:



[SG+, in preparation]

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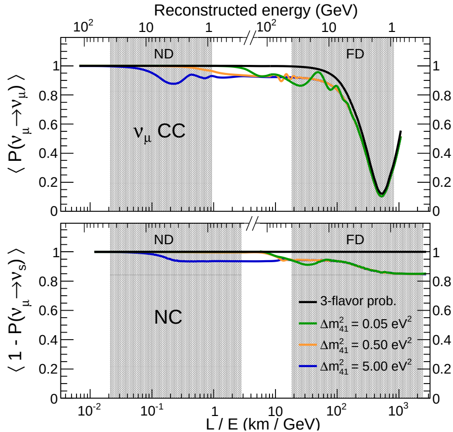


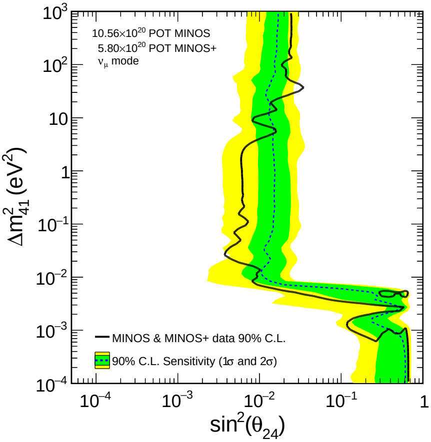
[PRL 117 (2016) 151803]:

far-to-near ratio

[PRL 122 (2019) 091803]:

full two-detectors fit

Sensitivity and exclusion limit:



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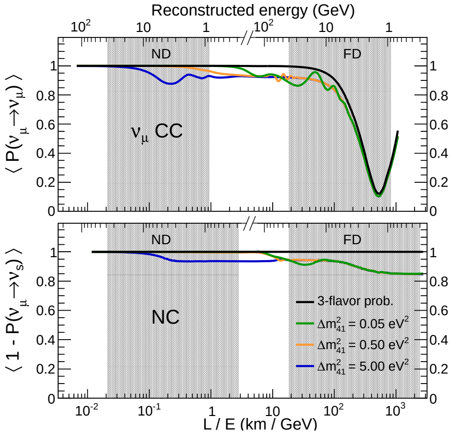

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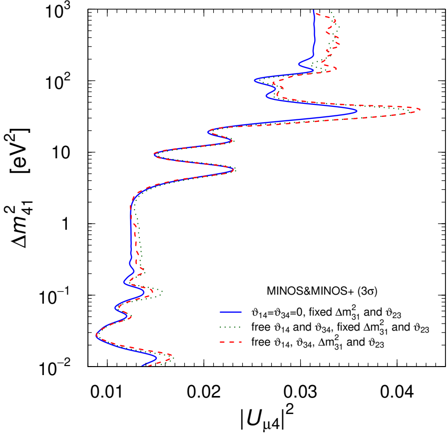
Marginalize over mixing parameters:



[SG+, in preparation]

MINOS & MINOS+

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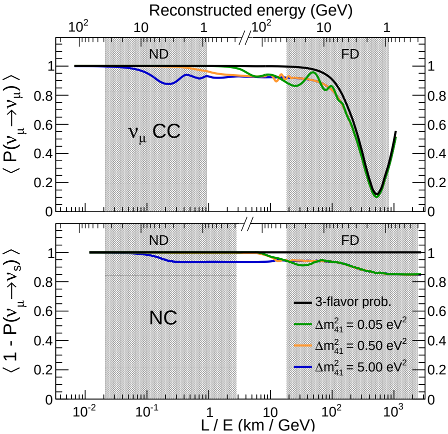

[PRL 117 (2016) 151803]:

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full two-detectors fit

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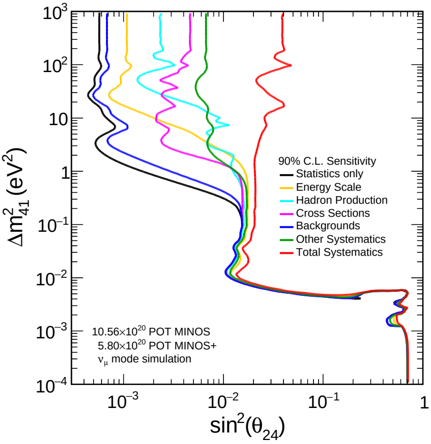
Systematics:



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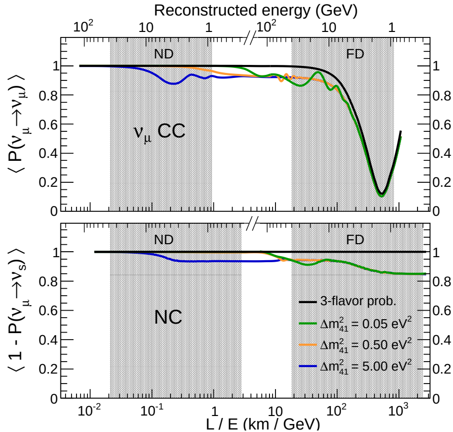

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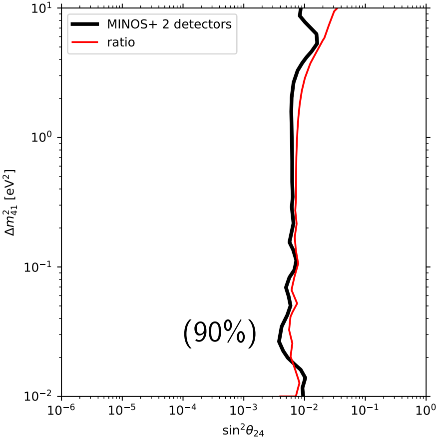
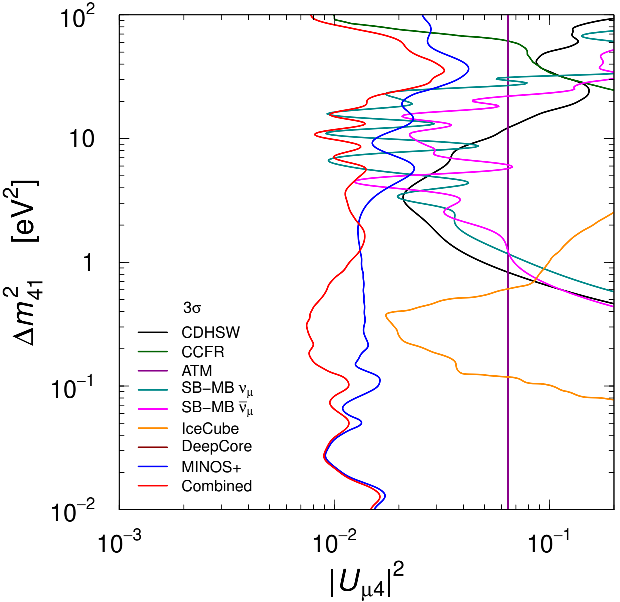
$1\ \text{GeV} \lesssim E \lesssim 40\ \text{GeV}$, peak at 3 GeV

Two detectors vs ratio fit:



[SG+, in preparation]

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



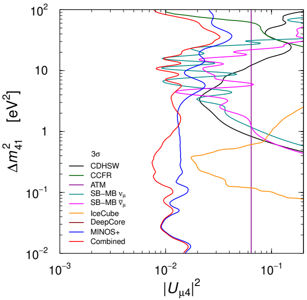
MINOS+
dominates
at small Δm^2_{41}

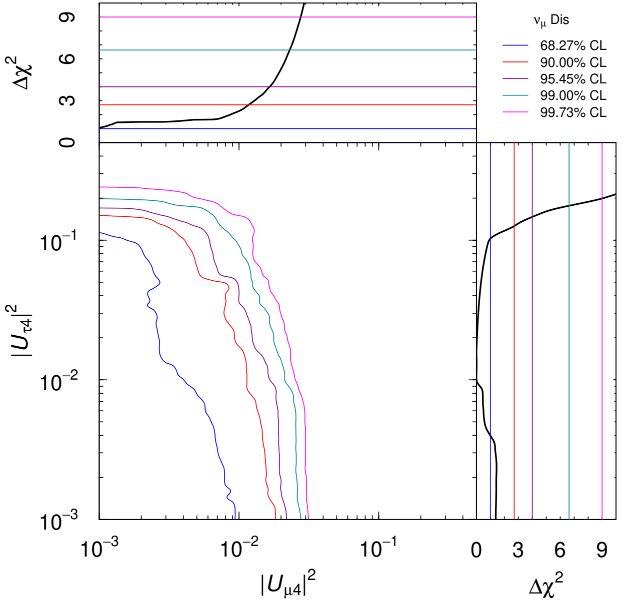
IceCube (1 yr)
important at
$\Delta m^2_{41} \simeq 0.2$ eV^2

see later for
IceCube 8 yr!

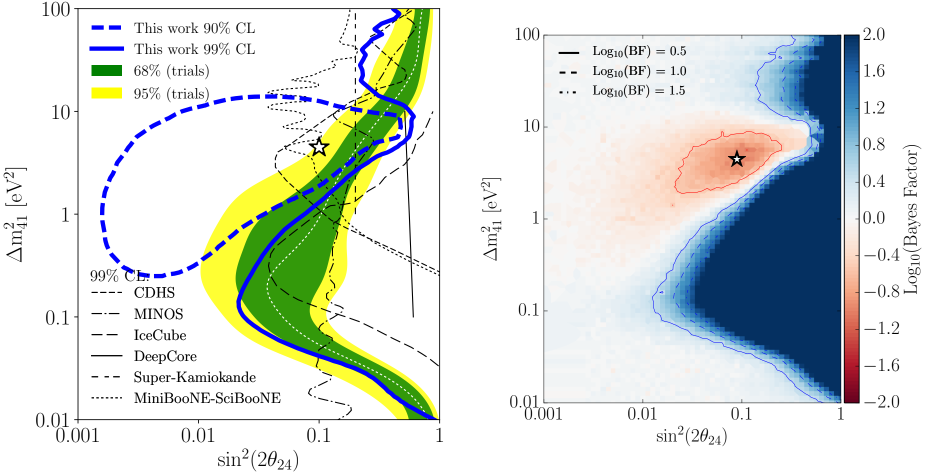
Global fit of $\overset{(-)}{\nu}_\mu$ DIS

[SG+, in preparation]





IceCube 8 yr update



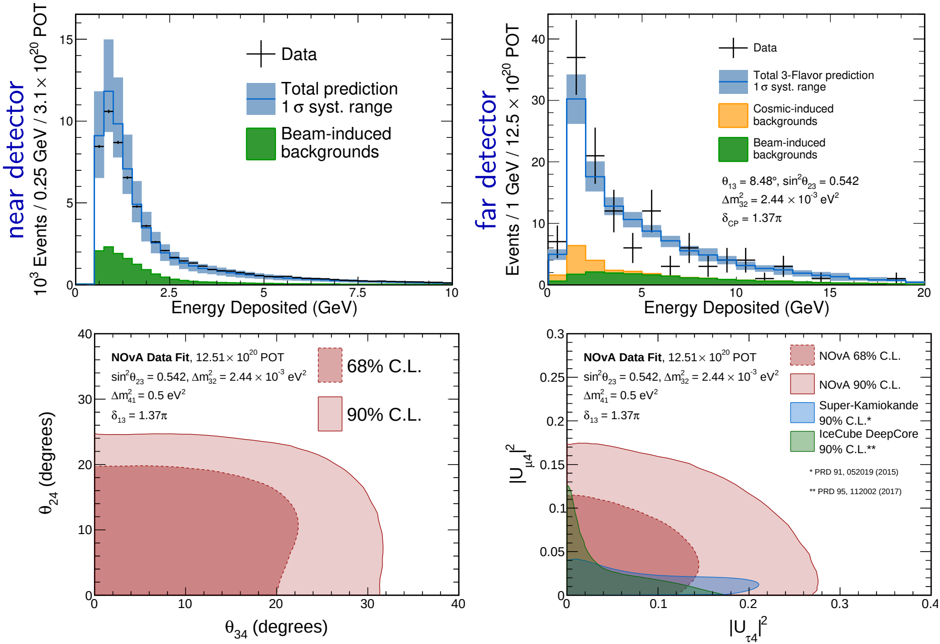
first indication in favor of sterile from ν_μ DIS!

although rather weak: $\log_{10} BF \simeq 1$ (weak preference)

or compatible with no oscillations at p-value of 8%

First LBL constraints from NOvA

[NOvA, 2106.04673]

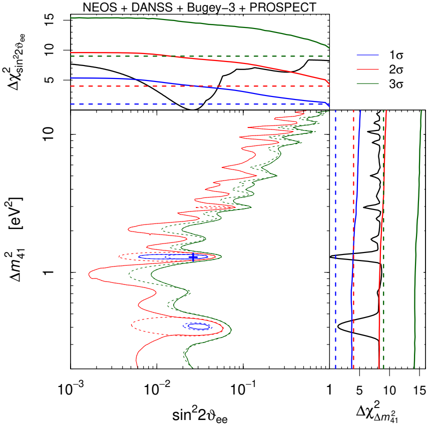


E disappearance (Electron channel)

reactor and Gallium experiments

Based on:

- JPG 43 (2016) 033001
- Neutrino4
- Giunti+ 2020/2021
- Kostensalo+ 2019
- RENO
- DayaBay
- PLB 782 (2018)



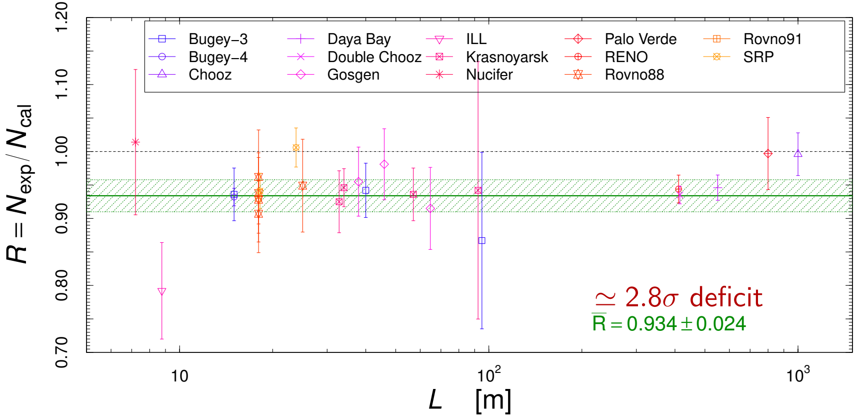
Reactor Antineutrino Anomaly (RAA)

[PRD 83 (2011) 073006]

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

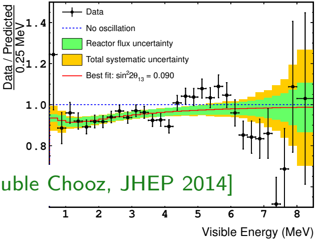
[Huber, PRC 84 (2011) 024617] [Mueller et al., PRC 83 (2011) 054615]

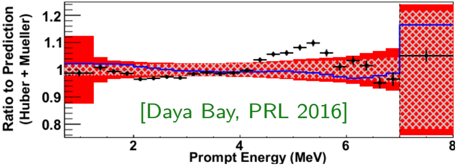
Previous reactor rates evaluated with new fluxes ⇒ deficit

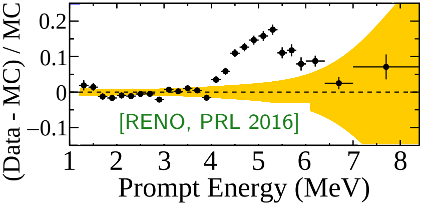


Suppression at detector due to active-sterile oscillations?

Can we trust the HM fluxes?







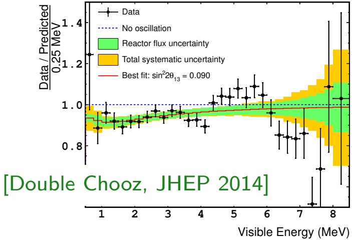
known since 2014:
bump in the spectrum around 5 MeV!

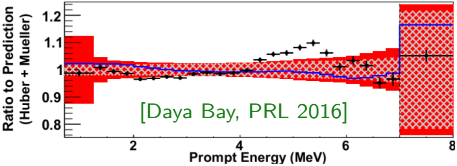
cannot be explained by SBL oscillations

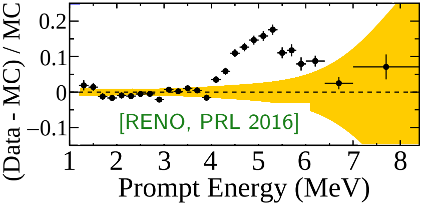
(averaged at the observed distances)

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

Can we trust the HM fluxes?







known since 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!

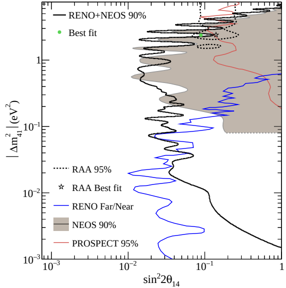
(i.e. take ratio of spectra at different distances)

$$\Phi_1 = \Phi_0(E) f(L_1, E) \quad \Phi_2 = \Phi_0(E) f(L_2, E)$$

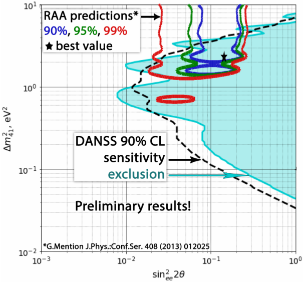
$$\Phi_1/\Phi_2 = f(L_1, E)/f(L_2, E)$$

ν_s at reactors in 2020

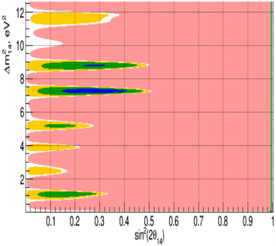
[RENO+NEOS, 2020]



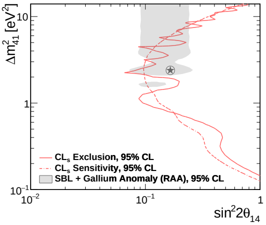
[DANSS, 2020]



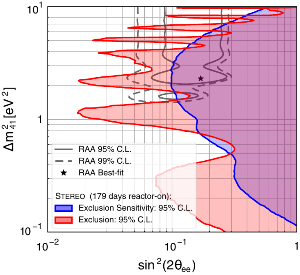
[Neutrino-4, PZETF 2020]



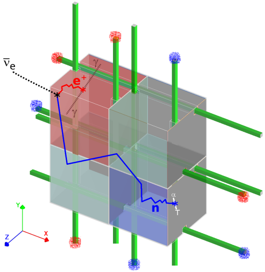
[PROSPECT, PRD 2020]



[STEREO, PRD 2020]



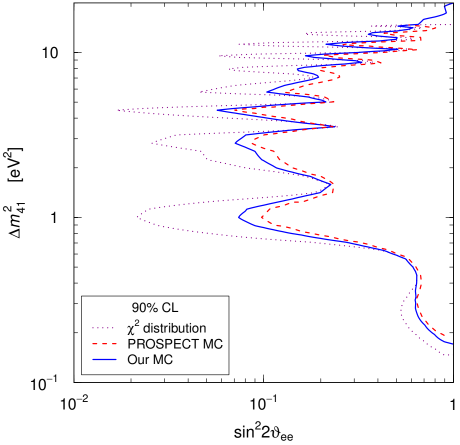
[SoLiD, JINST 2018]



Significance of the preference?

[Giunti, PRD 101 (2020)]

standard χ^2 distribution may be not appropriate to study the significance due to undercoverage at angles below the experiment sensitivity



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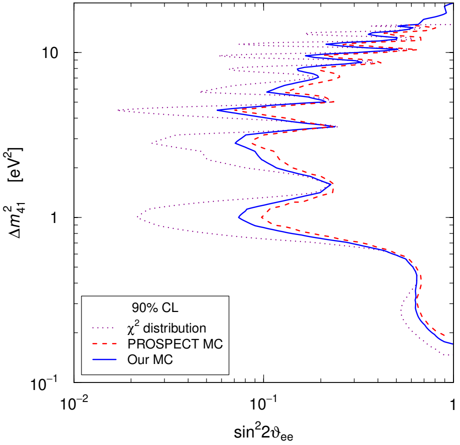
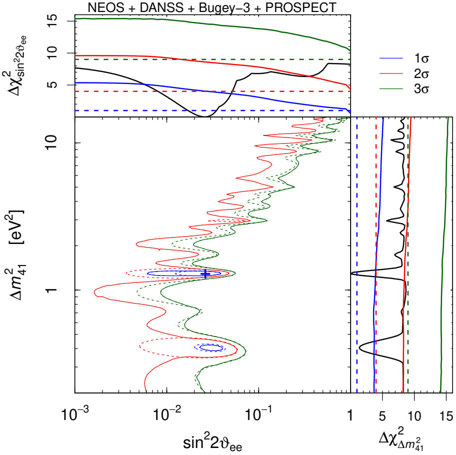


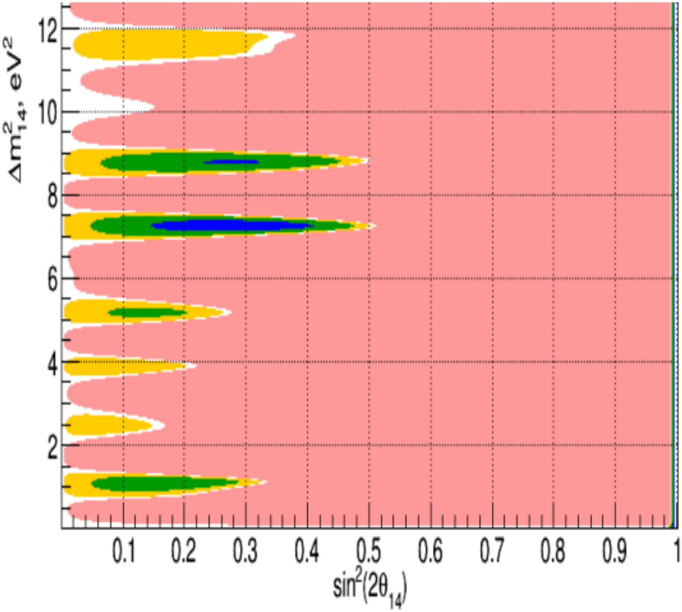


solid: MC, dashed: χ^2

True significance smaller than usually quoted (e.g. $2.4 \to 1.8\sigma$)

Neutrino-4

[Neutrino-4 2020]

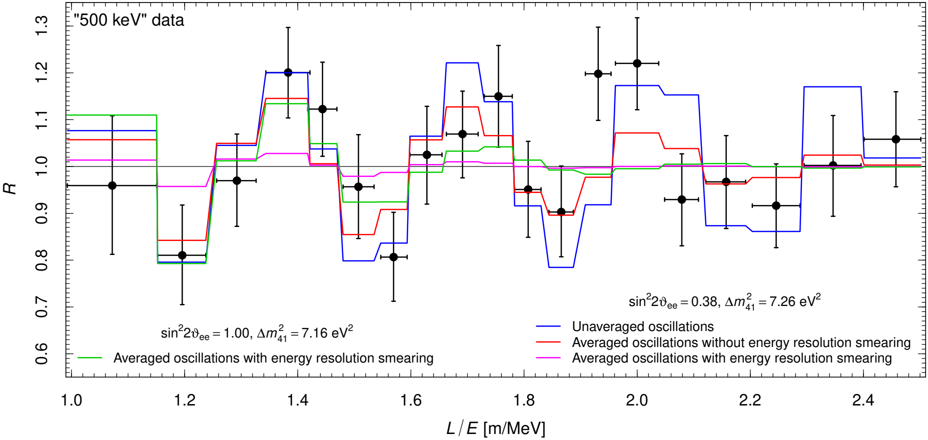


claimed $> 3\sigma$ preference for 3+1 over 3ν case

best fit incompatible with other reactor experiments

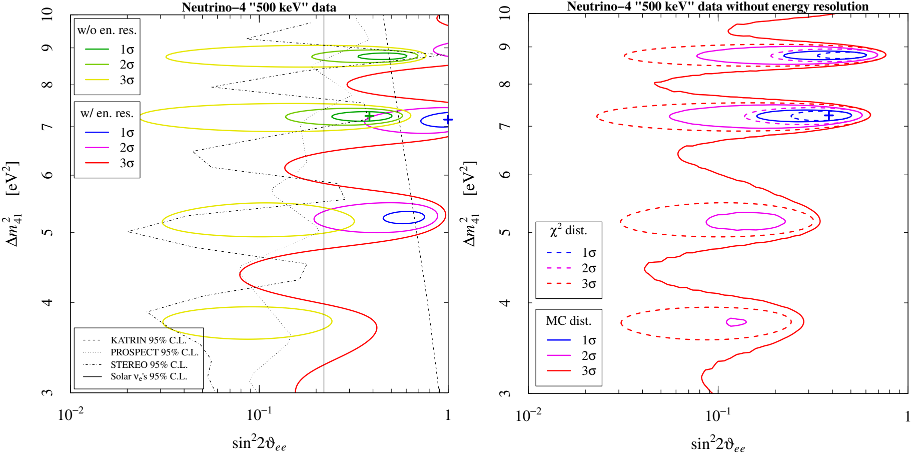
Neutrino-4

[Giunti+, PLB 2021]



energy resolution smearing not properly taken into account?

Neutrino-4



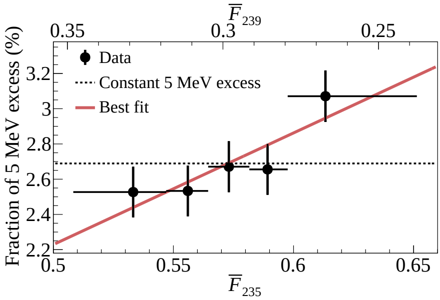
proper energy resolution treatment
moves best-fit $\rightarrow \sin^2 2\vartheta \simeq 1$

need to take into account
violation of Wilk's theorem
↓
relaxed constraints

Fuel evolution

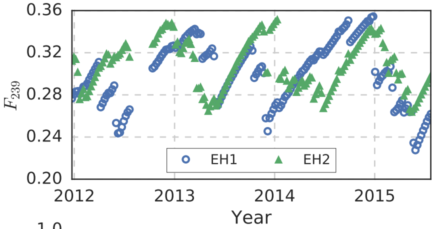
Reactor fluxes produced
by decay fissions of
^{235}U ^{238}U ^{239}Pu ^{241}Pu

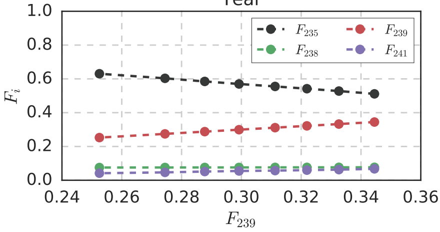
Can we use time evolution to identify source of 5 MeV bump?



[RENO, PRL 122 (2019)]

Fuel fractions in reactors change with time

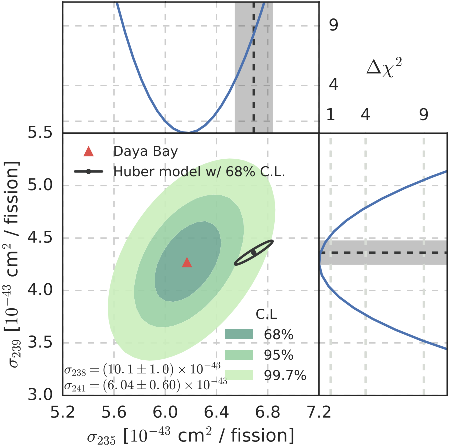




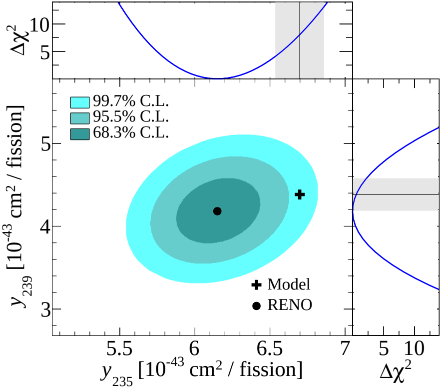
[Daya Bay, PRL 118 (2017)]

Fuel evolution

Fit bump amplitude as a function of flux normalizations → Normalization of ^{235}U flux smaller than prediction!



[Daya Bay, PRL 118 (2017) 251801]



[RENO, PRL 122 (2019)]

Again, we need model-independent information!

take ratios at different distances to avoid normalization dependency

Gallium anomaly

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

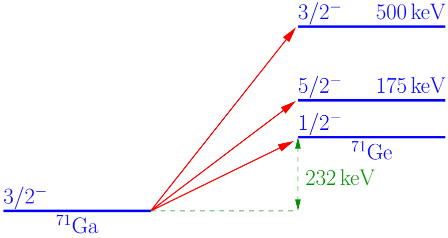
$L \simeq 1.9$ m $\quad L \simeq 0.6$ m

Gallium radioactive source experiments: GALLEX and SAGE

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

$E \simeq 0.75$ MeV $\quad E \simeq 0.81$ 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]

Gallium anomaly

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

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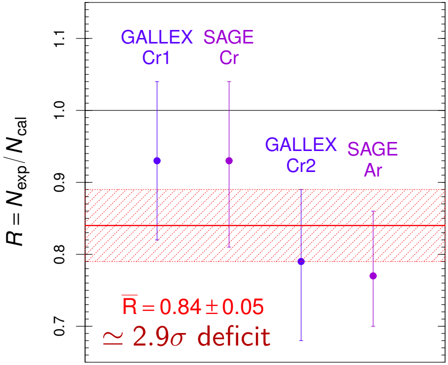
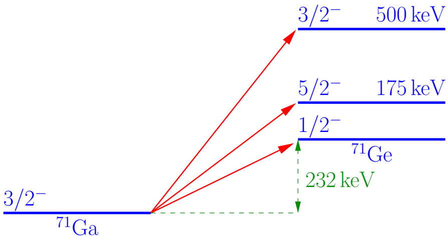
In the detector: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

Test detection of solar ν_e





cross sections of the transitions from

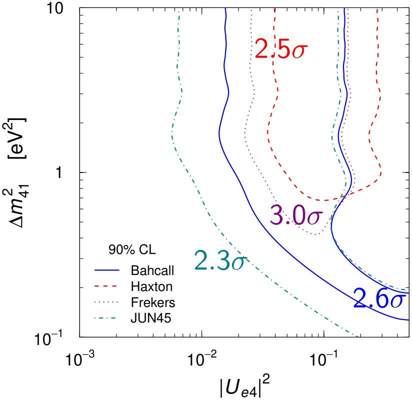
[Krofcheck et al., PRL 55 (1985) 1051]

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

Gallium anomaly revisited

[Kostensalo+, PLB 795 (2019) 542-547]

New cross section calculations:
(interacting nuclear shell model)



original Gallium anomaly: $\sim 2.9\sigma$

[SAGE, 2006]

[Laveder, 2007]

[Giunti&Laveder, 2011]

Gallium anomaly revisited

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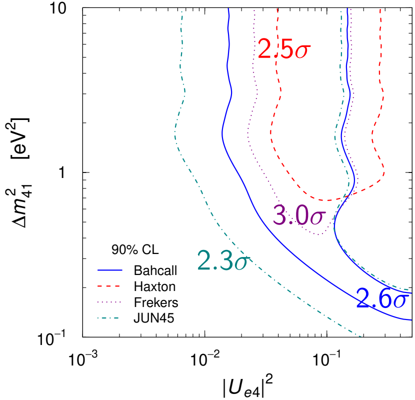


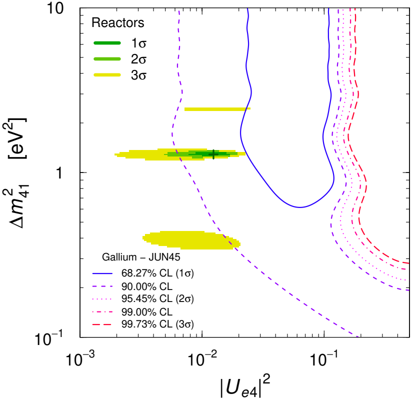
original Gallium anomaly: $\sim 2.9\sigma$

[SAGE, 2006]

[Laveder, 2007]

[Giunti&Laveder, 2011]

Compare with DANSS+NEOS:

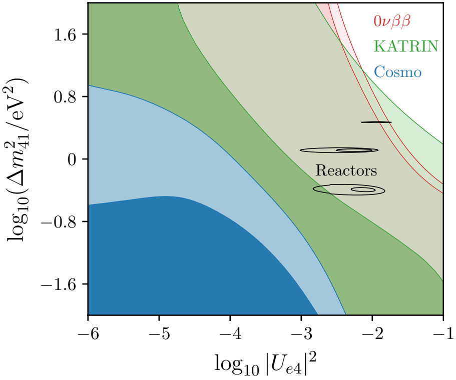


Better compatibility with reactors

F Fit

Based on:

- in preparation
- Dentler+ 2018
- arxiv:2003.02289



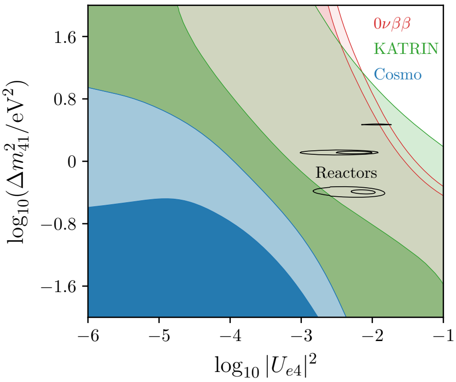
G

Fit = Global Fit

like “Bond, James Bond”

Based on:

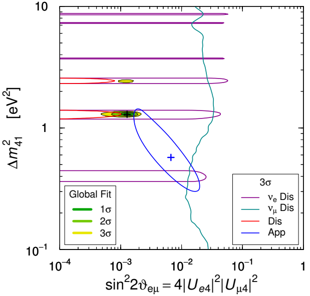
- in preparation
- Dentler+ 2018
- arxiv:2003.02289



APP – DIS tension in 2019

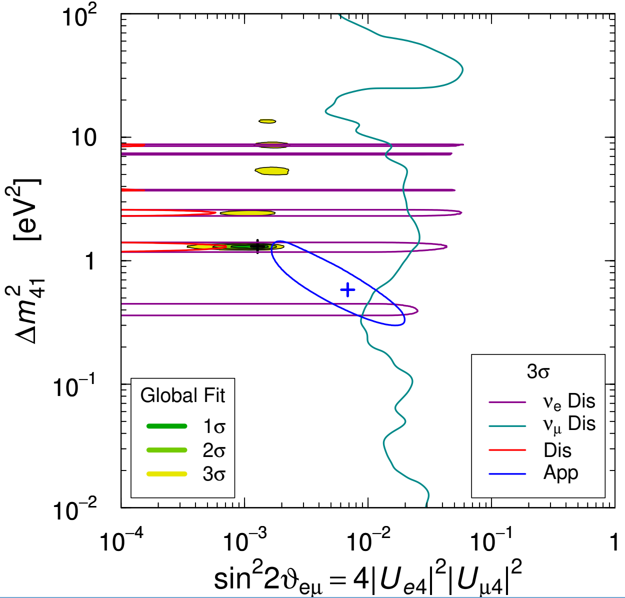
[SG+, in preparation]

Status just after Neutrino 2018:



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

Status in early 2019



APP – DIS tension in 2019

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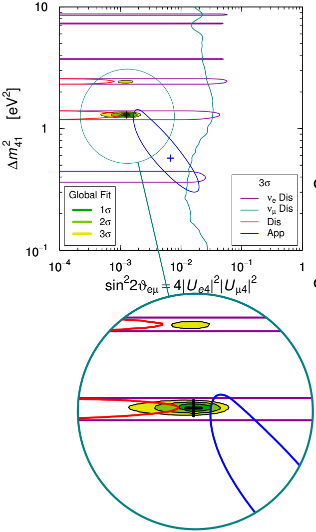
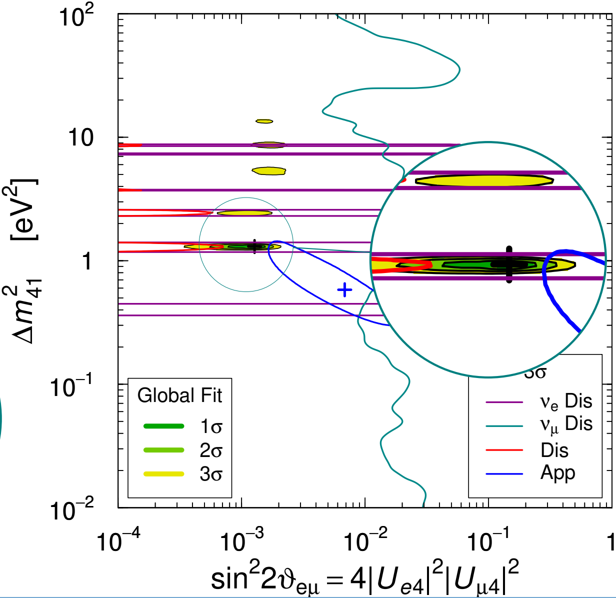


Status in early 2019



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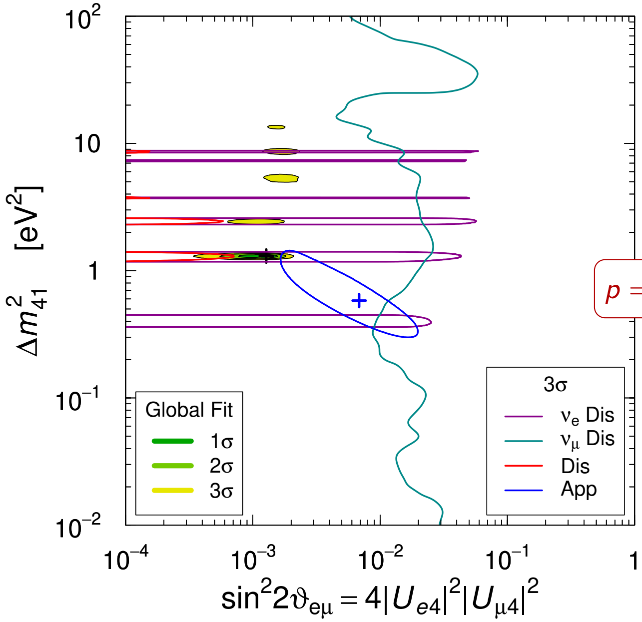
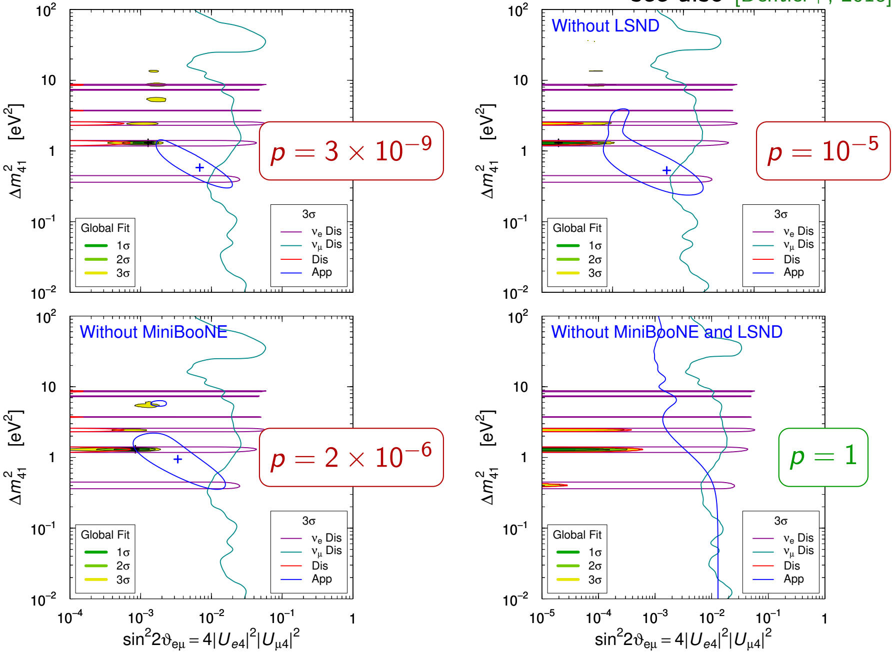


$p = 3 \times 10^{-9}$

APP – DIS tension in 2019

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



May something be wrong?

[Dentler+, JHEP 08 (2018) 010]
(2013 data from MiniBooNE, MINOS+ v1!)

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}
$\overset{(-)}{\nu}_\mu$ dis + solar vs app	884.4	79.1	13.9	781.7	9.7	23.6/2	7.4×10^{-6}

May something be wrong?

[Dentler+, JHEP 08 (2018) 010]
(2013 data from MiniBooNE, MINOS+ v1!)

Analysis	$\chi^2_{\rm min,global}$	$\chi^2_{\rm min,app}$	$\Delta\chi^2_{\rm app}$	$\chi^2_{\rm min,disapp}$	$\Delta\chi^2_{\rm disapp}$	$\chi^2_{\rm PG}$/dof	PG
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$\overset{(-)}{\nu}_\mu$ dis + solar vs app	884.4	79.1	13.9	781.7	9.7	23.6/2	7.4×10^{-6}

No improvements if MiniBooNE is not considered

May something be wrong?

[Dentler+, JHEP 08 (2018) 010]
(2013 data from MiniBooNE, MINOS+ v1!)

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
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$\overset{(-)}{\nu}_\mu$ dis + solar vs app	884.4	79.1	13.9	781.7	9.7	23.6/2	7.4×10^{-6}

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

May something be wrong?

[Dentler+, JHEP 08 (2018) 010]
(2013 data from MiniBooNE, MINOS+ v1!)

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
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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}
$\overset{(-)}{\nu}_\mu$ dis + solar vs app	884.4	79.1	13.9	781.7	9.7	23.6/2	7.4×10^{-6}

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

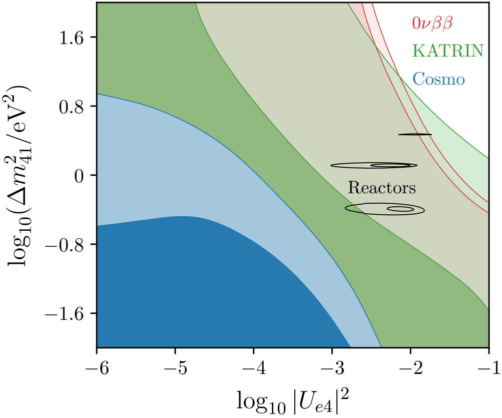
No reason to do so!

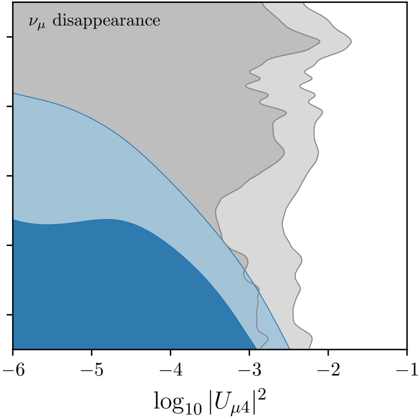
Comparing constraints

[arxiv:2003.02289]

Cosmological constraints are stronger than most other probes

But much more model dependent (as all the cosmological constraints)!





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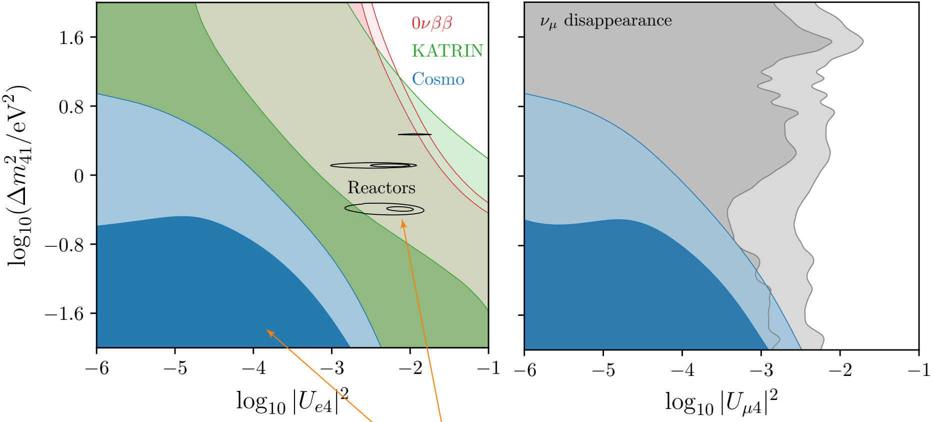


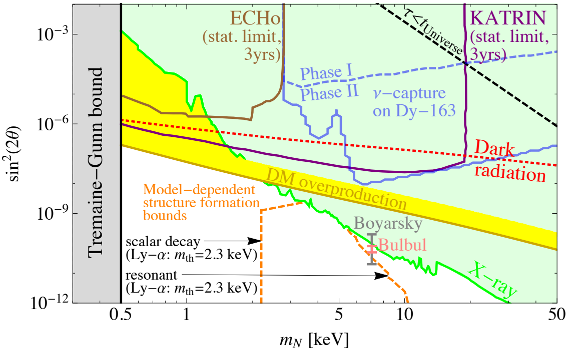
Warning: tension between reactor experiments and CMB bounds!

H Heavier sterile neutrinos

beyond eV: other types of sterile neutrinos

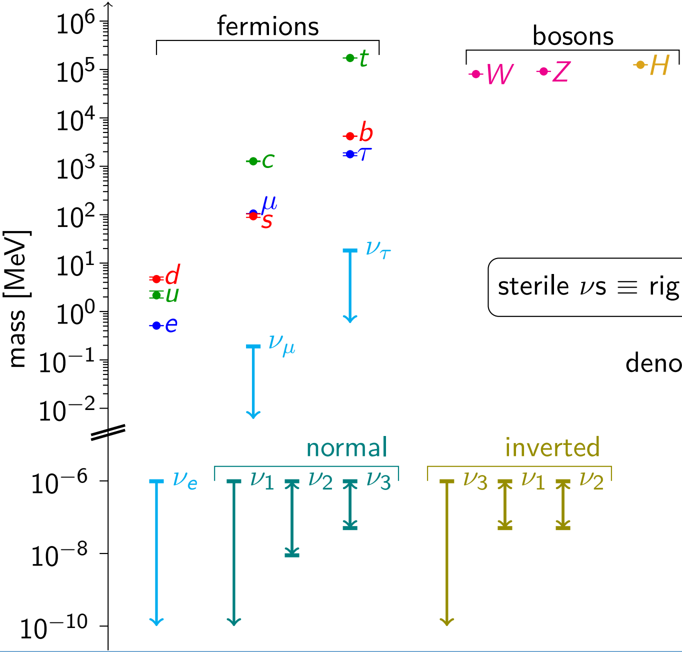
Based on:

- JCAP 01 (2017) 025



Masses in the Standard Model

[masses from PDG 2020]



sterile νs $\equiv$ right-handed fermions?

denote with N

Masses in the Standard Model

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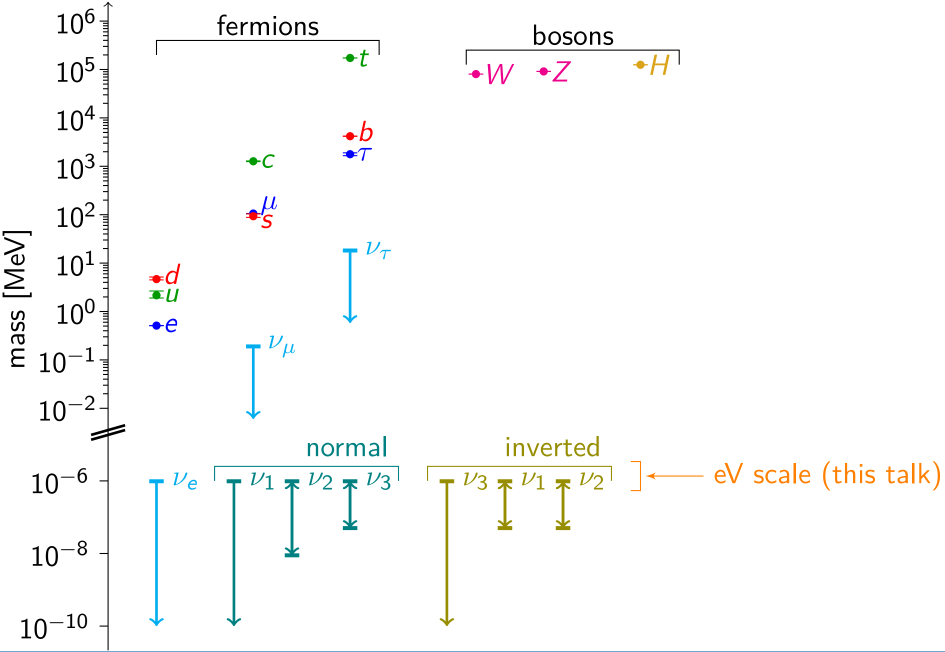

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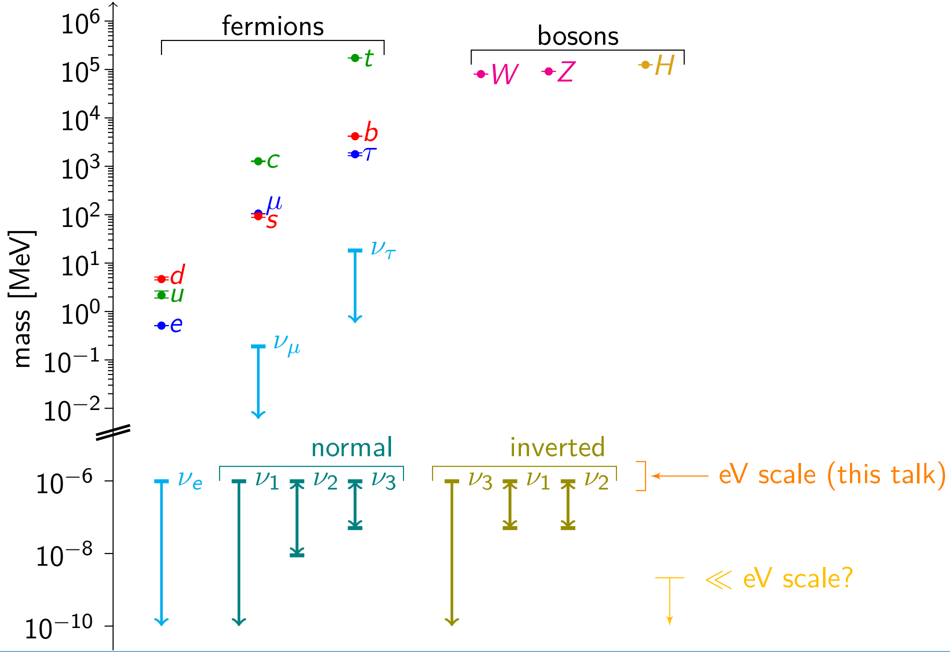

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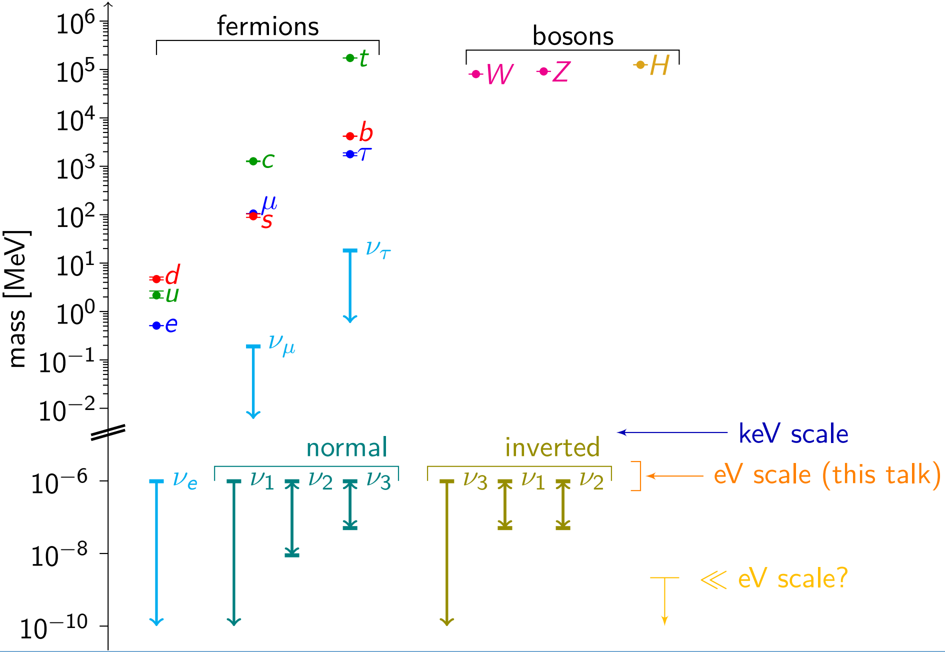

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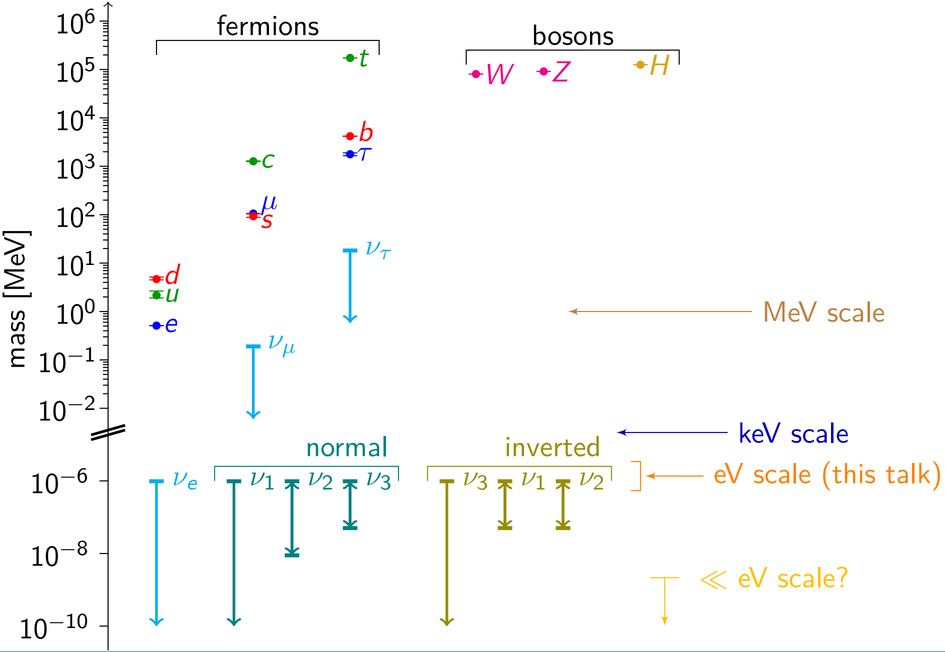

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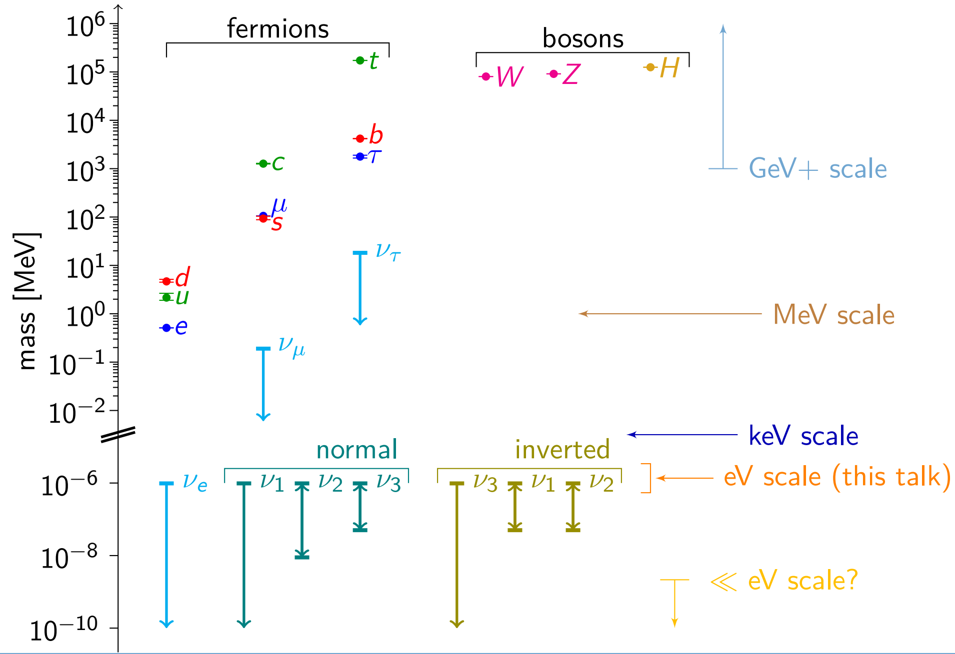

Heavier neutrino states at oscillation/mass experiments

Oscillation probability:

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

oscillation length decreases with increasing Δm^2_{kj}!

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Concerning the mixing matrix (3+1 scenario):

$$U = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & c_{34} & s_{34} \\ 0 & 0 & -s_{34} & c_{34} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{24} & 0 & s_{24} \\ 0 & 0 & 1 & 0 \\ 0 & -s_{24} & 0 & c_{24} \end{pmatrix} \begin{pmatrix} c_{14} & 0 & 0 & s_{14} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s_{14} & 0 & 0 & c_{14} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{23} & s_{23} & 0 \\ 0 & -s_{23} & c_{23} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} & 0 \\ 0 & 1 & 0 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 & 0 \\ -s_{12} & c_{12} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\Rightarrow |U|^2 = \begin{pmatrix} c^2_{14}c^2_{13}c^2_{12} & c^2_{14}c^2_{13}s^2_{12} & c^2_{14}s^2_{13} & s^2_{14} \\ \cdots & \cdots & \cdots & c^2_{14}s^2_{24} \\ \cdots & \cdots & \cdots & c^2_{14}c^2_{24}s^2_{34} \\ \cdots & \cdots & \cdots & c^2_{14}c^2_{24}c^2_{34} \end{pmatrix}, \; s_{i4} \simeq 0, \; c_{i4} \simeq 1$$

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Effect of neutrino masses in β and $0\nu\beta\beta$ decays:

$$K(T) = \left[(Q_\beta - T) \sum_{i=1}^{N_\nu} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2} \right]^{1/2} \quad \text{and} \quad m_{\beta\beta} = \left| \sum_k e^{i\alpha_k} \mu_k \right|, \text{ with } \mu_k \equiv {U_{ek}}^2 m_k$$

Production in the early Universe

[keV ν white paper, JCAP 01 (2017) 025]

N production in the early Universe?

Thermal

cannot be only through neutrino oscillations if they are copiously produced in the early Universe

↓

given mean number of active neutrinos n_0, $\rho_N = m_N n_0 > \rho_C$

↓

OK if early decoupling

↓

dilution of energy density ρ_N to acceptable values during expansion

→ OK also if N is not produced in the early Universe

↓

produced through oscillations, but never reaches equilibrium thanks to small mixing angle

Non thermal

decay of heavier particles

includin e.g. decoupling of inflatons or generic scalar fields

keV sterile neutrino effects

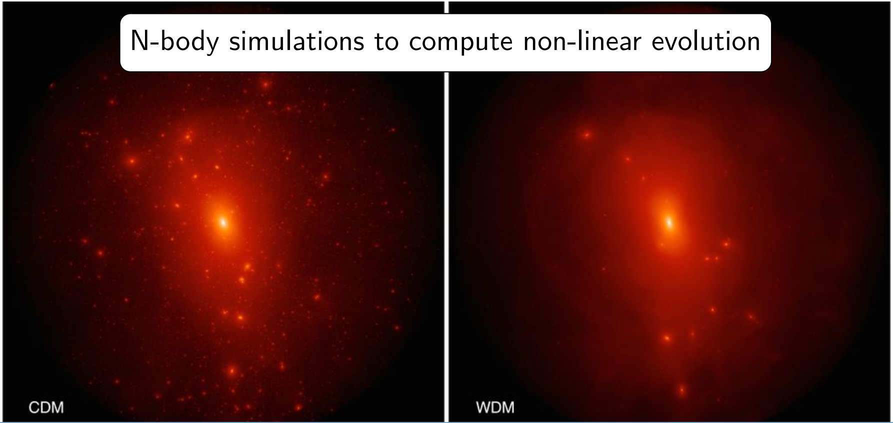
[keV ν white paper, JCAP 01 (2017) 025]

$m_{\rm sn} \simeq \mathcal{O}(\mathrm{keV})$ ⟶ non-relativistic at CMB decoupling

indistinguishable from Cold Dark Matter at the CMB level

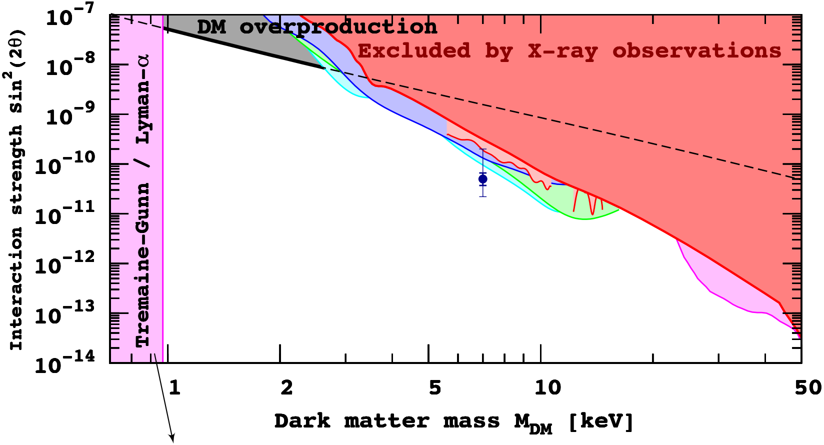
but its free-streaming affects small scales! → Warm Dark Matter (WDM)

N-body simulations to compute non-linear evolution



KeV N constraints - I

[keV ν white paper, JCAP 01 (2017) 025]

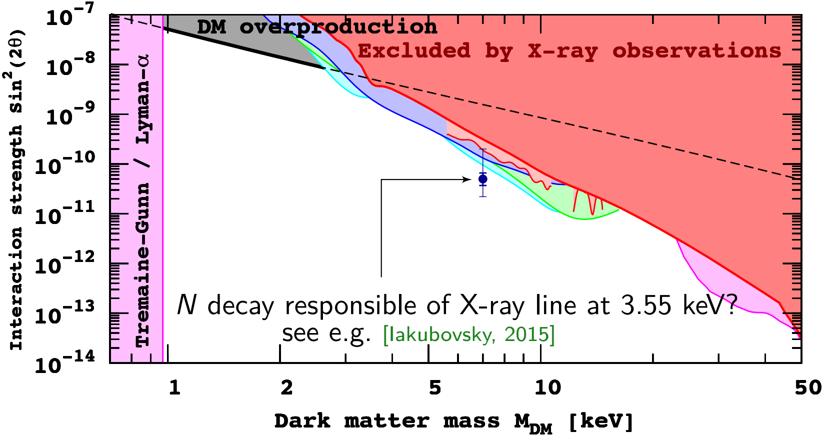


[Tremaine-Gunn 1979]

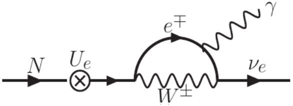
phase space distribution in galaxy cannot exceed degenerate Fermi gas

KeV N constraints - I

[keV ν white paper, JCAP 01 (2017) 025]



radiative decay $N \to \nu + \gamma$

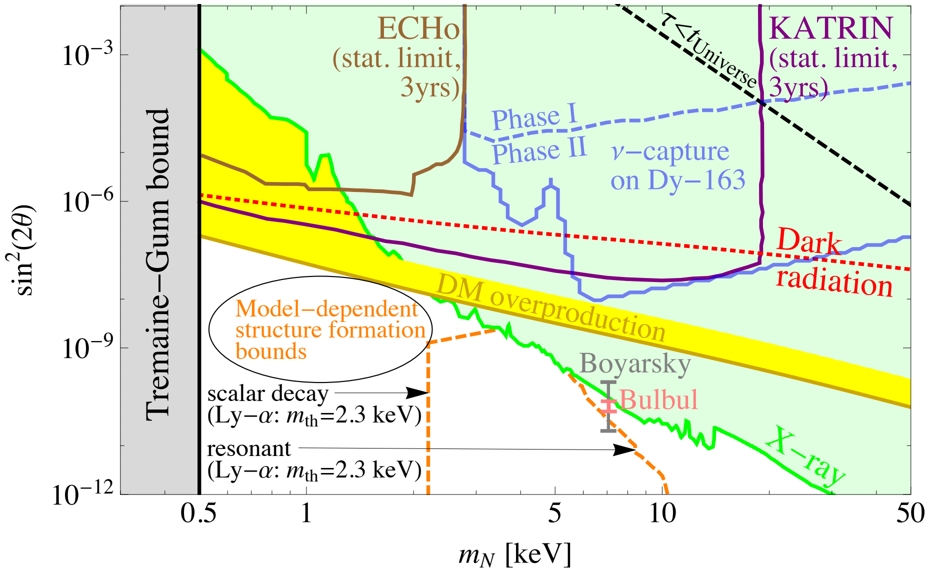


with $E_\gamma = E_\nu = m_{\rm sn}/2 \longrightarrow$ X-rays

$$\Gamma_{N\to\gamma\nu} \simeq 1.38 \times 10^{-22} \sin^2 2\theta \left(\frac{m_{\rm sn}}{\rm keV}\right)^5 s^{-1}$$

KeV N constraints - II

[keV ν white paper, JCAP 01 (2017) 025]



Astrophysics bounds stronger than those at terrestrial experiments!

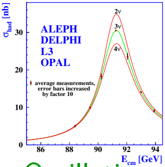
Z

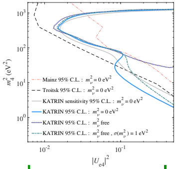
Conclusions

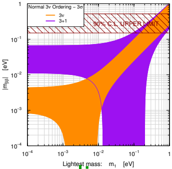
The situation is NOT favorable
for the light sterile neutrino...

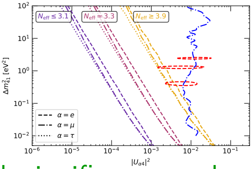
What do we learn on sterile neutrinos?

N Non-oscillation probes: no signal, possibly strong constraints

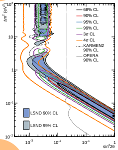


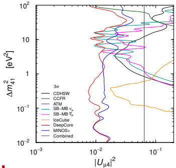


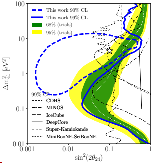


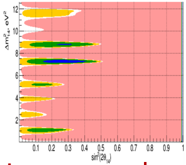


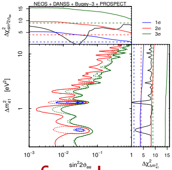
O Oscillation probes: several anomalies, weak significance each



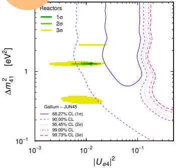


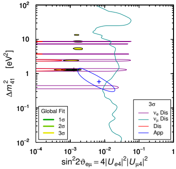


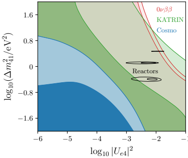


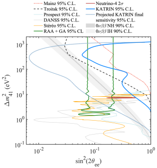


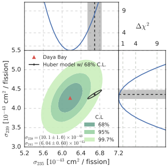
T Tensions! even strong, between experiments or classes of probes











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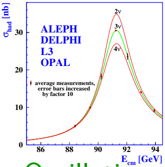

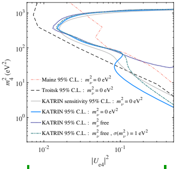

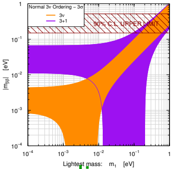

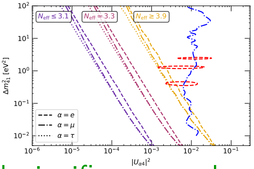

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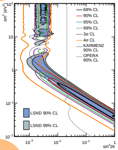

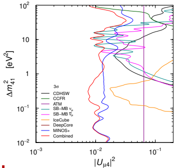

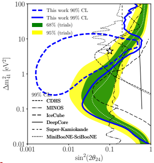

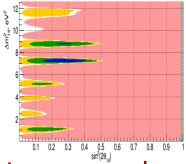

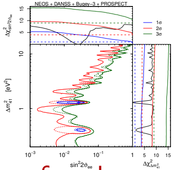

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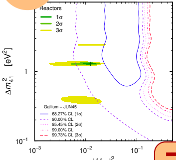

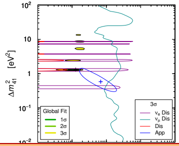

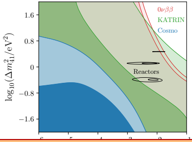

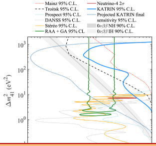

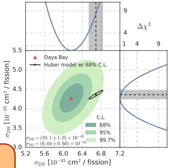

Thanks for your attention!