Oscillations Beyond Three-Neutrino Mixing

Carlo Giunti

INFN, Torino, Italy

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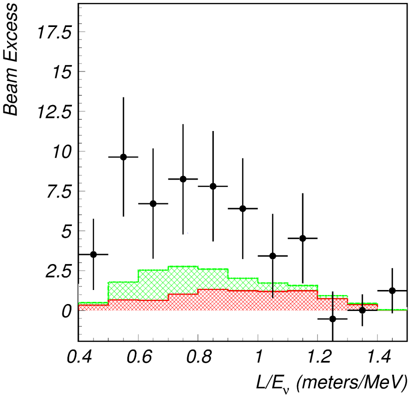
LSND

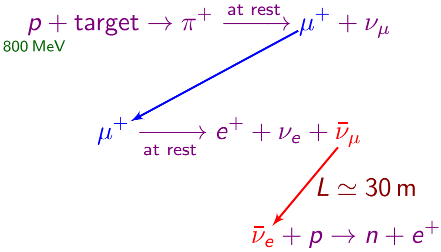
[PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

$\bar{\nu}_\mu \to \bar{\nu}_e \qquad 20\,\text{MeV} \leq E \leq 52.8\,\text{MeV}$



$\Delta m^2_{\text{SBL}} \gtrsim 0.1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$

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



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

800 MeV

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

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

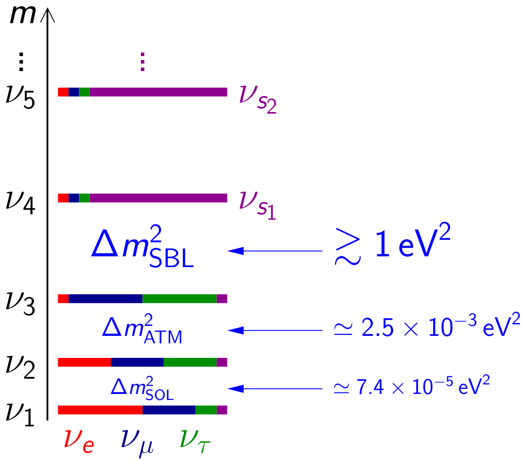
$\bar{\nu}_e + p \to n + e^+$

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

- $\approx 3.8\sigma$ excess
- But signal not seen by KARMEN at $L \simeq 18\,\text{m}$ with the same method

[PRD 65 (2002) 112001]

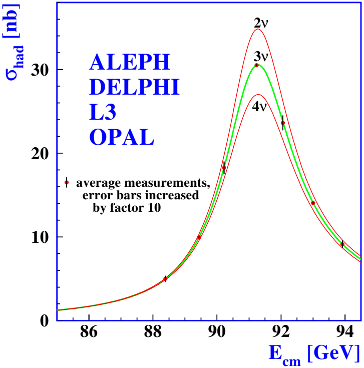
Beyond Three-Neutrino Mixing: Sterile Neutrinos



$\Delta m^2_{\text{SBL}} \longleftarrow \gtrsim 1\,\text{eV}^2$

$\Delta m^2_{\text{ATM}} \longleftarrow \simeq 2.5 \times 10^{-3}\,\text{eV}^2$

$\Delta m^2_{\text{SOL}} \longleftarrow \simeq 7.4 \times 10^{-5}\,\text{eV}^2$



$$\boxed{N^{\text{LEP}}_{\nu_{\text{active}}} = 2.9840 \pm 0.0082}$$

Terminology: a eV-scale sterile neutrino

means: a eV-scale massive neutrino which is mainly sterile

Effective 3+1 SBL Oscillation Probabilities

Appearance $(\alpha \neq \beta)$

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

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

Disappearance

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

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

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

SBL

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

- CP violation is not observable in SBL experiments!
- Observable in LBL accelerator exp. sensitive to Δm^2_{ATM} [de Gouvea et al, PRD 91 (2015) 053005, PRD 92 (2015) 073012, arXiv:1605.09376; Palazzo et al, PRD 91 (2015) 073017, PLB 757 (2016) 142; Kayser et al, JHEP 1511 (2015) 039, JHEP 1611 (2016) 122] and solar exp. sensitive to Δm^2_{SOL} [Long, Li, CG, PRD 87, 113004 (2013) 113004]

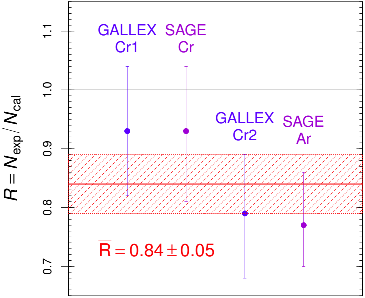
Gallium Anomaly

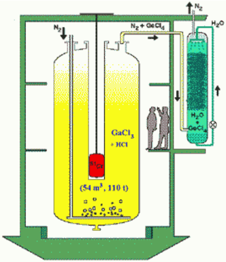
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

$E \simeq 0.75\,\text{MeV}$ $\qquad$ $E \simeq 0.81\,\text{MeV}$

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





≈ 2.9σ deficit

$\langle L \rangle_{\text{GALLEX}} = 1.9\,\text{m}$ $\qquad$ $\langle L \rangle_{\text{SAGE}} = 0.6\,\text{m}$

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

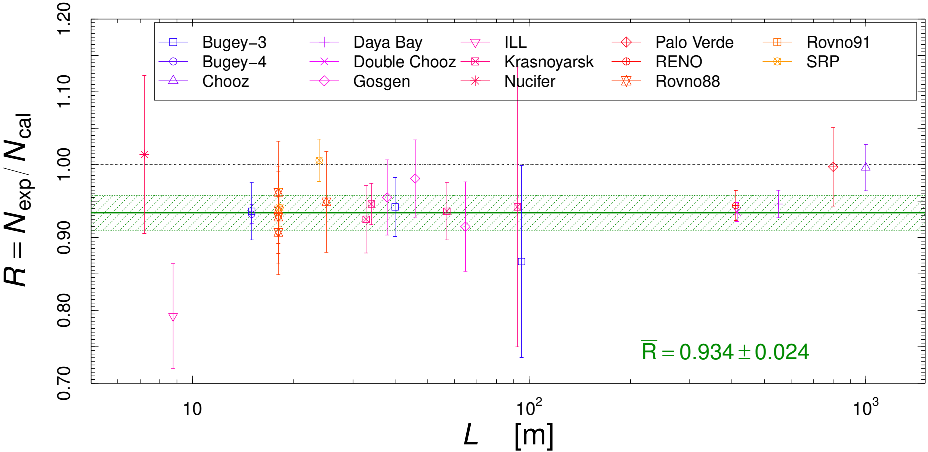
[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807;
Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344,
MPLA 22 (2007) 2499, PRD 78 (2008) 073009,
PRC 83 (2011) 065504]

- ${}^3\text{He} + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + {}^3\text{H}$ cross section measurement [Frekers et al., PLB 706 (2011) 134]

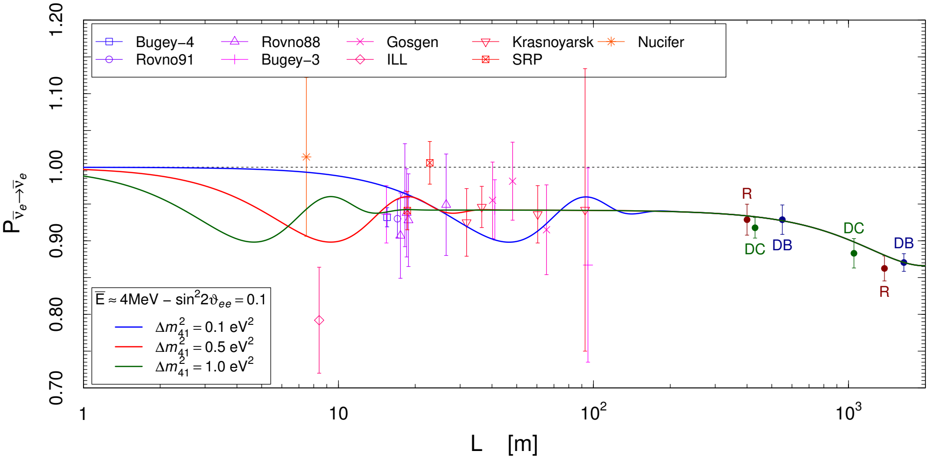
Reactor Electron Antineutrino Anomaly

[Mention et al, PRD 83 (2011) 073006]

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



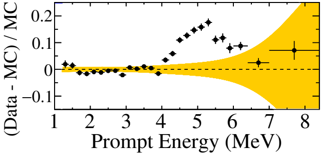
$\approx 2.8\sigma$ deficit



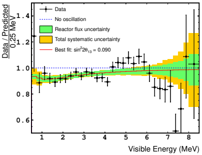
$$\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$$

- SBL oscillations are averaged at the Daya Bay, RENO, and Double Chooz near detectors $\Longrightarrow$ no spectral distortion

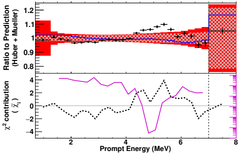
Reactor Antineutrino 5 MeV Bump



[RENO, arXiv:1511.05849]



[Double Chooz, arXiv:1406.7763]



[Daya Bay, arXiv:1508.04233]

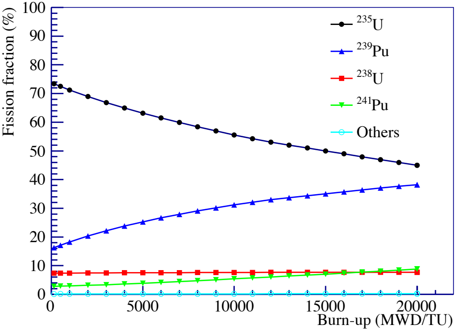
- Cannot be explained by neutrino oscillations (SBL oscillations are averaged in Double Chooz, Daya Bay, RENO).
- It is likely due to theoretical miscalculation of the spectrum.
- $\sim 3\%$ effect on total flux, but if it is an excess it increases the anomaly!
- No post-bump complete calculation of the neutrino fluxes.
- Saclay-Huber flux calculation uncertainty is about 2.5%.
- Increasing the flux uncertainty is a game that one can play, but there are only guesses, e.g. about 5%. [Hayes and Vogel, 2016]
- Increasing the flux uncertainty decreases the statistical significance of the anomaly, but more anomaly is allowed in combined fits with other data!
- At the moment it is better to consider the calculated flux and uncertainties in order to predict the signal that must be tested in new experiments.

Daya Bay Reactor Fuel Evolution

[Daya Bay, PRL 118 (2017) 251801 (arXiv:1704.01082)]

- Reactor $\bar{\nu}_e$ flux produced by the β decays of the fission products of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu.
- Effective fission fractions:

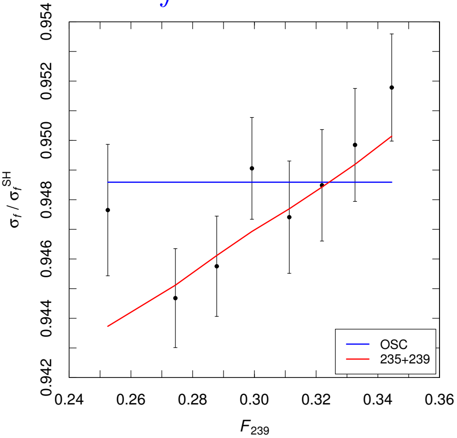
$$F_{235}, \; F_{238}, \; F_{239}, \; F_{241}.$$

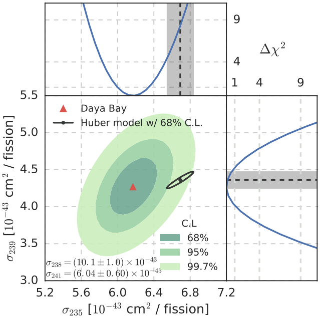


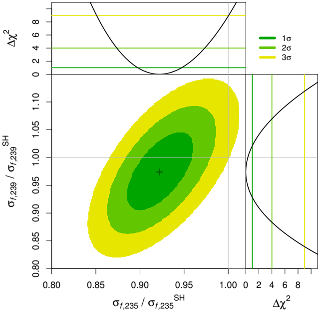
- Cross section per fission:

$$\sigma_f = \sum_{k=235,238,239,241} F_k \, \sigma_{f,k}$$

$$\sigma_{f,k} = \int dE_\nu \, \phi_k(E_\nu) \, \sigma(E_\nu)$$







- Best fit: mainly suppression of $\sigma_{f,235}$
- Equal fluxes suppression:

$$\Delta\chi^2/\text{NDF} = 7.9/1$$

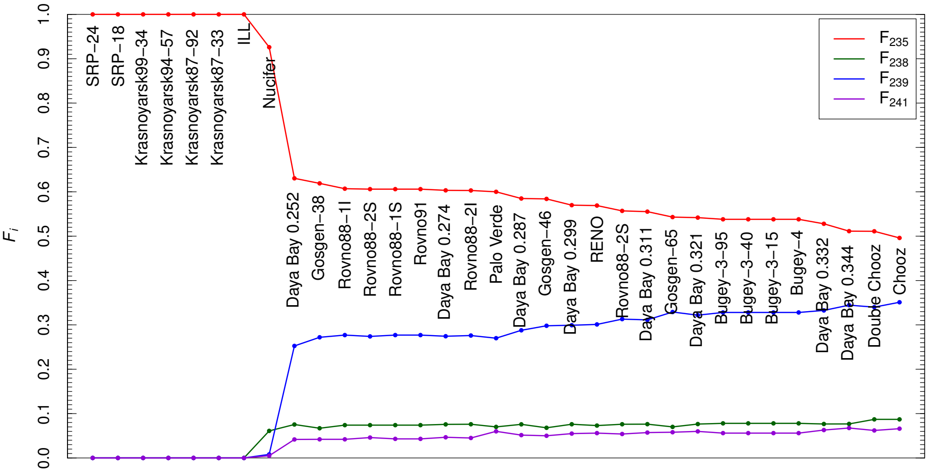
  disfavored at 2.8σ
- Equal fluxes suppression corresponds to SBL oscillations, but theoretical flux uncertainties must be taken into account
- With theoretical flux uncertainties:

Daya Bay	^{235}U	OSC
χ^2_{min}	3.8	9.5
NDF	7	7
GoF	80%	22%

- MC: OSC disfavored at 2.6σ

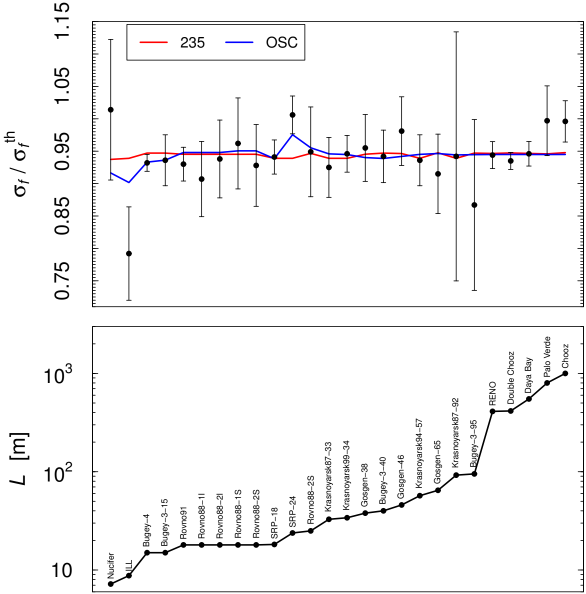
[CG, X.P. Ji, M. Laveder, Y.F. Li, B.R. Littlejohn, arXiv:1708.01133]

Fuel Fractions of All Reactor Experiments



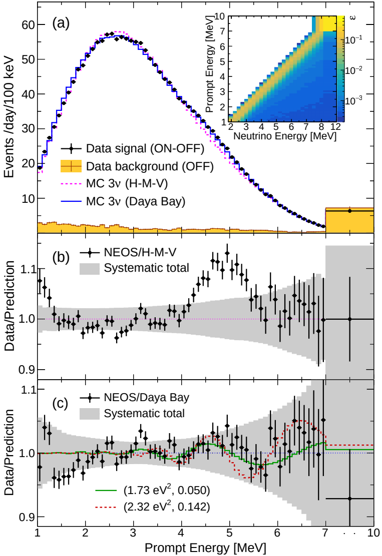
All Reactors	^{235}U	OSC
χ^2_{min}	25.3	23.0
NDF	32	31
GoF	79%	85%

MC: ^{235}U disfavored at 1.7σ

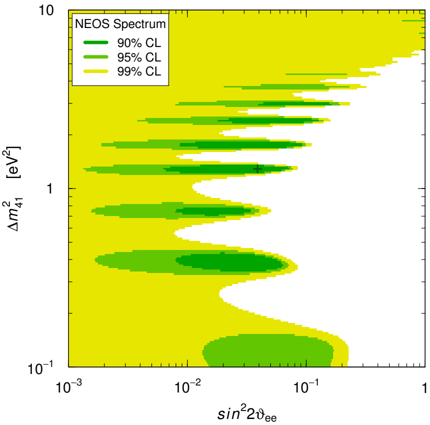


NEOS

[PRL 118 (2017) 121802 (arXiv:1610.05134)]



- Hanbit Nuclear Power Complex in Yeong-gwang, Korea.
- Thermal power of 2.8 GW.
- Detector: a ton of Gd-loaded liquid scintillator in a gallery approximately 24 m from the reactor core.
- The measured antineutrino event rate is 1976 per day with a signal to background ratio of about 22.



Best Fits:

$\Delta m^2_{41} = 1.7\,\text{eV}^2 \quad \sin^2 2\theta_{14} = 0.05$

$\Delta m^2_{41} = 1.3\,\text{eV}^2 \quad \sin^2 2\theta_{14} = 0.04$

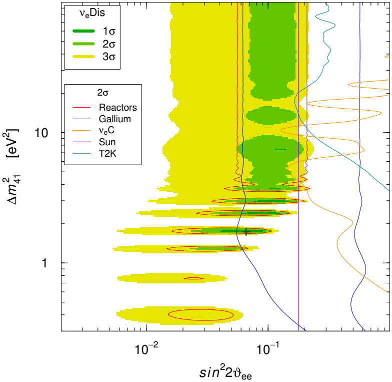
$\chi^2_{\text{no osc.}} - \chi^2_{\text{min}} = 6.5$

χ^2 distribution: $\approx 2.1\sigma$ anomaly

NEOS Monte Carlo: $\approx 1.2\sigma$ anomaly

Global ν_e and $\bar{\nu}_e$ Disappearance

[Gariazzo, CG, Laveder, Li, JHEP 1706 (2017) 135 (arXiv:1703.00860)]



- KARMEN+LSND ν_e–^{12}C

  [Conrad, Shaevitz, PRD 85 (2012) 013017]
  [CG, Laveder, PLB 706 (2011) 20]

- Solar ν_e + KamLAND $\bar{\nu}_e$

  [Li et al, PRD 80 (2009) 113007, PRD 86 (2012) 113014]
  [Palazzo, PRD 83 (2011) 113013, PRD 85 (2012) 077301]

- T2K Near Detector ν_e disappearance

  [T2K, PRD 91 (2015) 051102]

- $\Delta\chi^2_{\text{NO}}/\text{NDF}_{\text{NO}} = 14.1/2 \Rightarrow \approx 3.3\sigma$ anom.

- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$

  $\sin^2 2\vartheta_{ee} = 0.066 \quad \Leftrightarrow \quad |U_{e4}|^2 = 0.017$

- $\chi^2_{\text{min}}/\text{NDF} = 163.0/174 \Rightarrow \text{GoF} = 71\%$

$$L^{\text{OSC}}_{41} = \frac{4\pi E}{\Delta m^2_{41}}$$

In agreement with Dentler, Hernandez-Cabezudo, Kopp, Maltoni, Schwetz, arXiv:1709.04294

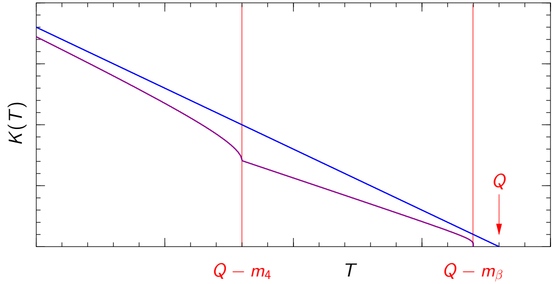
Tritium Beta-Decay: $^{3}\text{H} \to {}^{3}\text{He} + e^{-} + \bar{\nu}_{e}$

$$Q = M_{^3\text{H}} - M_{^3\text{He}} - m_e = 18.58\,\text{keV}$$

$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E)\, p\, E\, K^2(T)$$

$$\frac{K^2(T)}{Q-T} = \sum_k |U_{ek}|^2 \sqrt{(Q-T)^2 - m_k^2}\,\theta(Q-T-m_k)$$

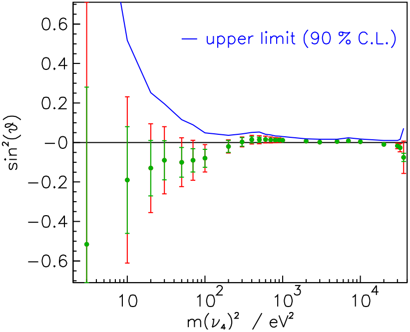
$$m_4 \gg m_{1,2,3} \Rightarrow \simeq \left(1 - |U_{e4}|^2\right)\sqrt{(Q-T)^2 - m_\beta^2}\,\theta(Q-T-m_\beta) + |U_{e4}|^2\sqrt{(Q-T)^2 - m_4^2}\,\theta(Q-T-m_4)$$



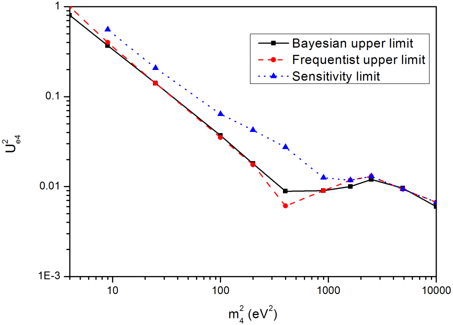
$$m_\beta^2 = \sum_{k=1}^{3} |U_{ek}|^2 m_k^2$$

Mainz and Troitsk Limit on $\Delta m^2_{41} \simeq m^2_4$

$$m_4 \gg m_{1,2,3} \quad \Longrightarrow \quad \Delta m^2_{41} \equiv m^2_4 - m^2_1 \simeq m^2_4$$



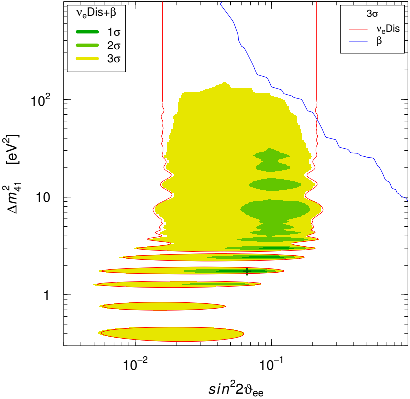
[Kraus, Singer, Valerius, Weinheimer, EPJC 73 (2013) 2323]



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

Global ν_e and $\bar{\nu}_e$ Disappearance + β Decay

[Gariazzo, CG, Laveder, Li, JHEP 1706 (2017) 135 (arXiv:1703.00860)]

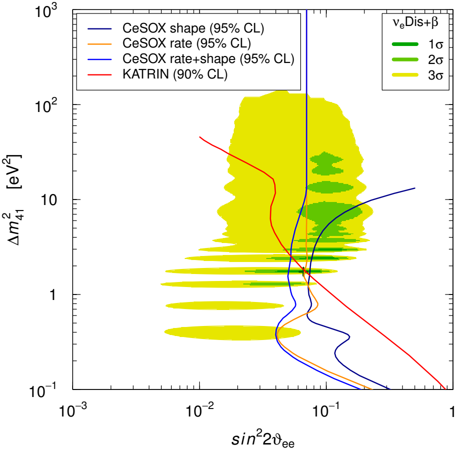


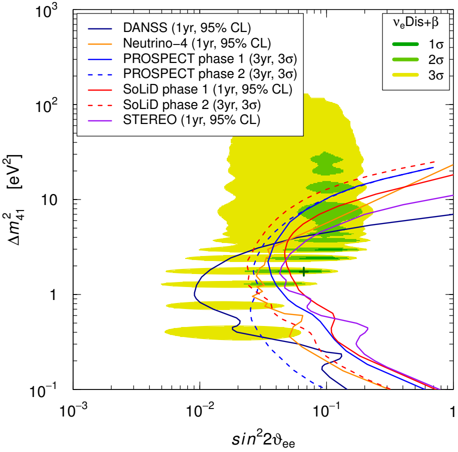
- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$
  $\sin^2 2\vartheta_{ee} = 0.066 \quad \Leftrightarrow \quad |U_{e4}|^2 = 0.017$

- $2\,\text{cm} \lesssim \dfrac{L^{\text{osc}}_{41}}{E\,[\text{MeV}]} \lesssim 7\,\text{m}$ at 3σ

- $0.0050 \lesssim \sin^2 2\vartheta_{ee} \lesssim 0.23$ at 3σ

The Race for ν_e and $\bar{\nu}_e$ Disappearance



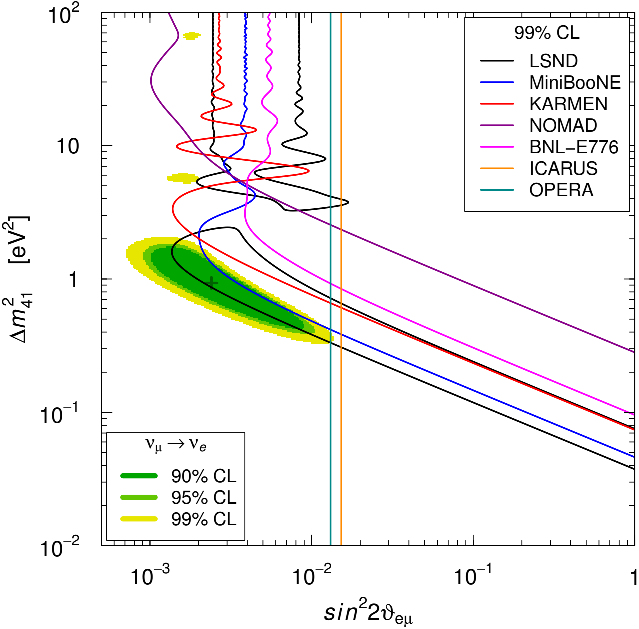


CeSOX (Gran Sasso, Italy) $^{144}\mathrm{Ce} \to \bar{\nu}_e$
BOREXINO: $L \simeq$ 5-12m [Vivier@TAUP2015]

KATRIN (Karlsruhe, Germany) $^{3}\mathrm{H} \to \bar{\nu}_e$
[Drexlin@NOW2016]

DANSS (Kalinin, Russia) $L \simeq$ 10-12m [arXiv:1606.02896]
Neutrino-4 (RIAR, Russia) $L \simeq$ 6-11m [JETP 121 (2015) 578]
PROSPECT (ORNL, USA) $L \simeq$ 7-12m [arXiv:1512.02202]
SoLid (SCK-CEN, Belgium) $L \simeq$ 5-8m [arXiv:1510.07835]
STEREO (ILL, France) $L \simeq$ 8-12m [arXiv:1602.00568]

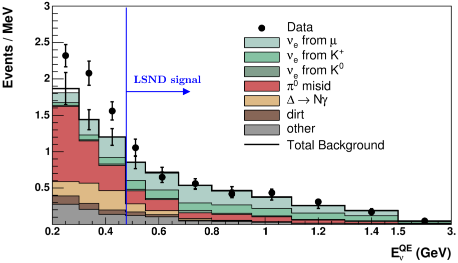
$\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ Appearance



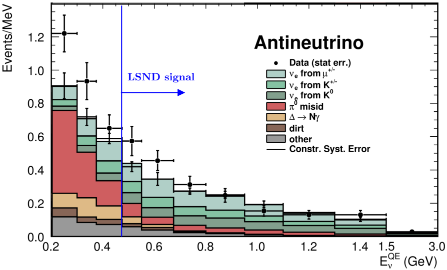
MiniBooNE

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

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

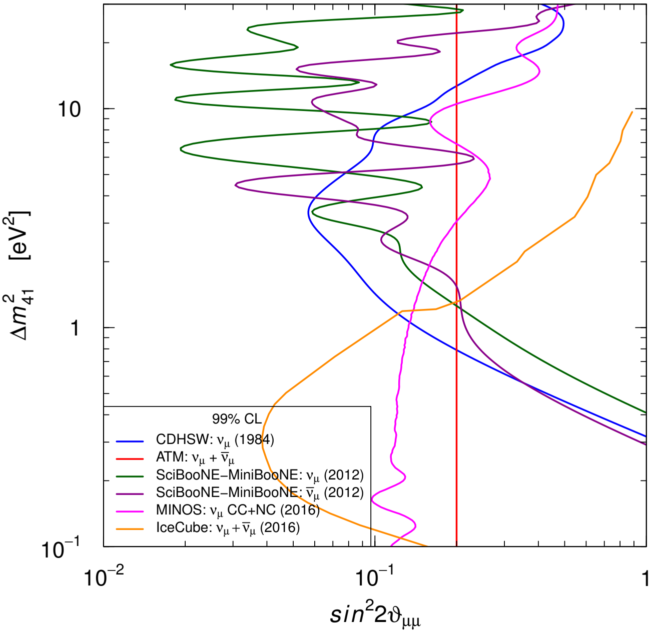


$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]



- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- No money, no Near Detector.
- LSND signal: $E > 475\,\mathrm{MeV}$.
- Agreement with LSND signal?
- Low-energy anomaly $\Rightarrow$ MicroBooNE
- Pragmatic Approach: $E > 475\,\mathrm{MeV}$.

ν_μ and $\bar{\nu}_\mu$ Disappearance



3+1 Appearance-Disappearance Tension

ν_e DIS

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

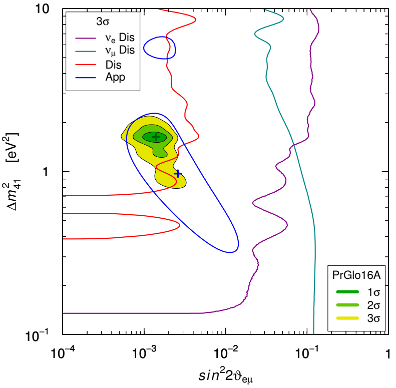
ν_μ DIS

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

$\nu_\mu \to \nu_e$ APP

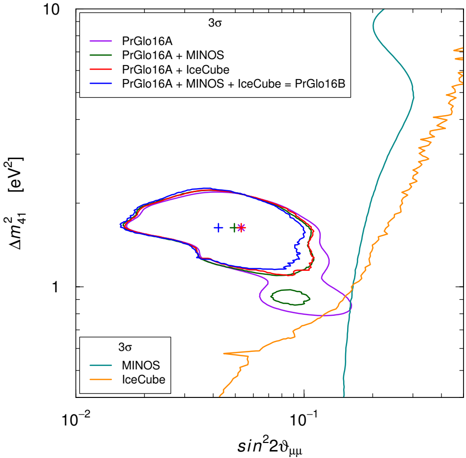
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$$

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



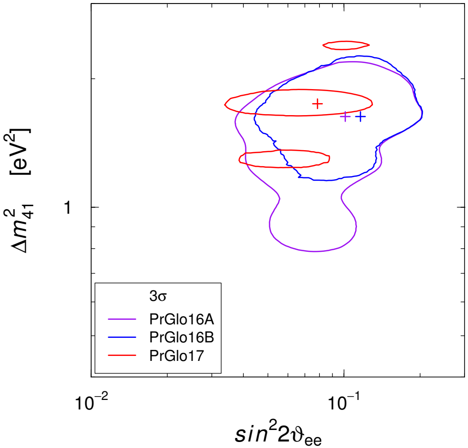
- $\nu_\mu \to \nu_e$ is quadratically suppressed!
- PrGlo16A = 2016 data except MINOS and IceCube
  [Gariazzo, CG, Laveder, Li, JHEP 1706 (2017) 135]
- $\Delta\chi^2_{\text{NO}}/\text{NDF}_{\text{NO}} = 48.3/3 \Rightarrow \approx 6.4\sigma$ anom.
- Best Fit: $\Delta m^2_{41} = 1.6\,\text{eV}^2$
  $|U_{e4}|^2 = 0.026 \quad |U_{m4}|^2 = 0.013$
- $\chi^2_{\text{min}}/\text{NDF} = 262.0/244 \Rightarrow \text{GoF} = 20\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 3.8/2 \Rightarrow \text{GoF}_{\text{PG}} = 15\%$
- Similar tension in 3+2, 3+3, . . . , $3+N_s$
  [CG, Zavanin, MPLA 31 (2015) 1650003]

Effects of MINOS and IceCube



- IceCube effect in agreement with
  Collin, Arguelles, Conrad, Shaevitz, PRL 117 (2016) 221801
- Best Fit: $\Delta m^2_{41} = 1.6\,\text{eV}^2$ $|U_{e4}|^2 = 0.030$ $|U_{\mu 4}|^2 = 0.011$
- $\chi^2_{\text{min}}/\text{NDF} = 530.3/519 \Rightarrow \text{GoF} = 36\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 4.7/2 \Rightarrow \text{GoF}_{\text{PG}} = 9.7\%$ ← More tension!

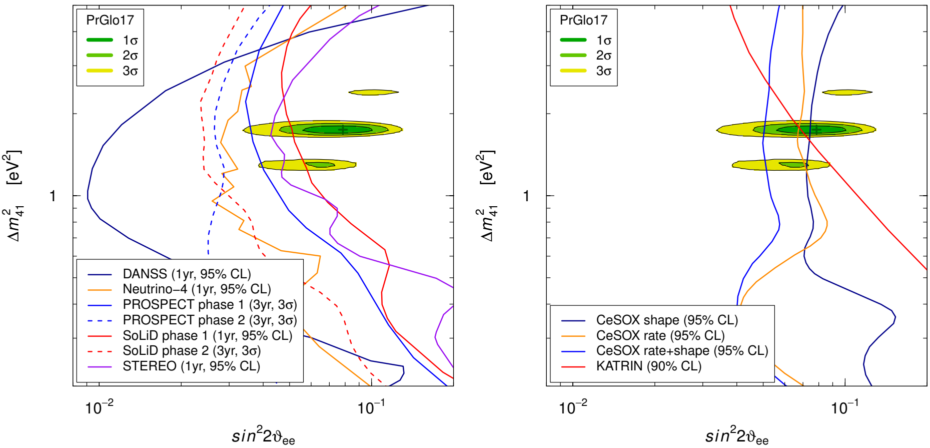
Effects of NEOS

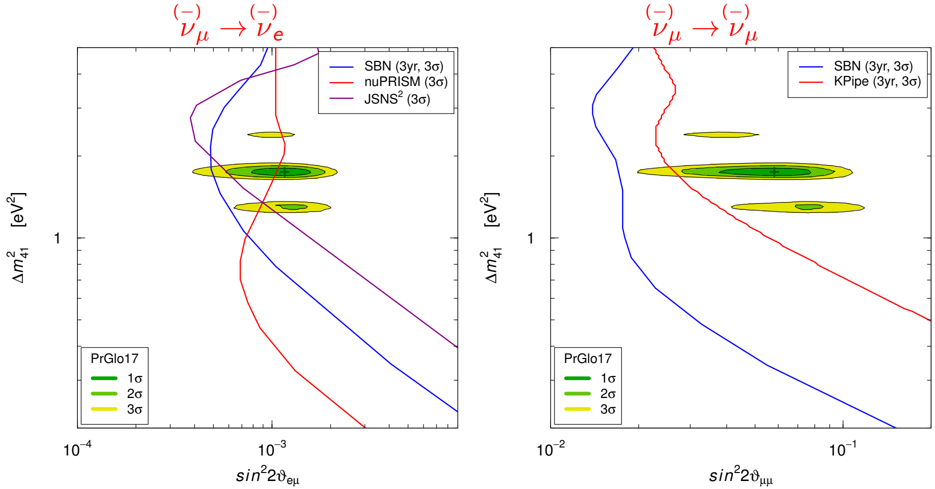


- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2 \quad |U_{e4}|^2 = 0.020 \quad |U_{\mu 4}|^2 = 0.015$
- $\chi^2_{\text{min}}/\text{NDF} = 595.1/579 \Rightarrow \text{GoF} = 31\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 7.2/2 \Rightarrow \text{GoF}_{\text{PG}} = 2.7\%$ ← More tension!

The Race for the Light Sterile

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



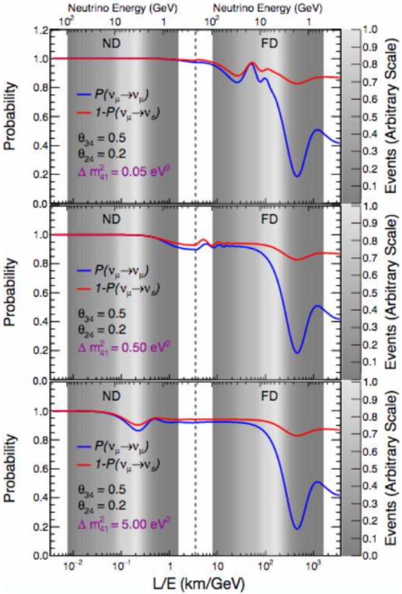


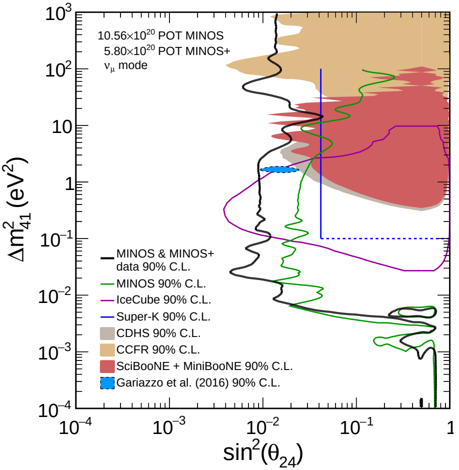
$\overset{(-)}{\nu}_{\mu} \to \overset{(-)}{\nu}_{e}$

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

New Bound from MINOS & MINOS+

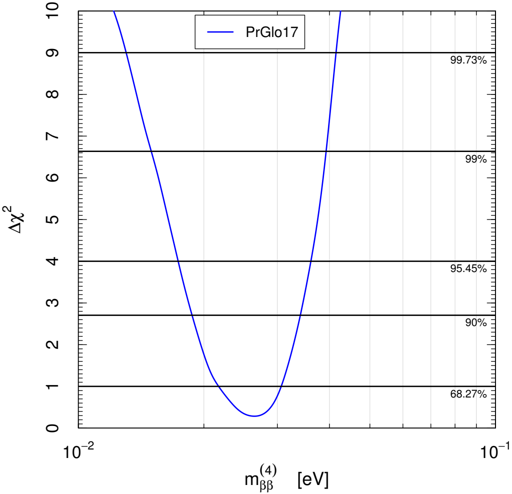
[arXiv:1710.06488, today!]





Neutrinoless Double-Beta Decay

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



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

$$m_1 \ll m_4$$

$$\Downarrow$$

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

warning:

possible cancellation

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

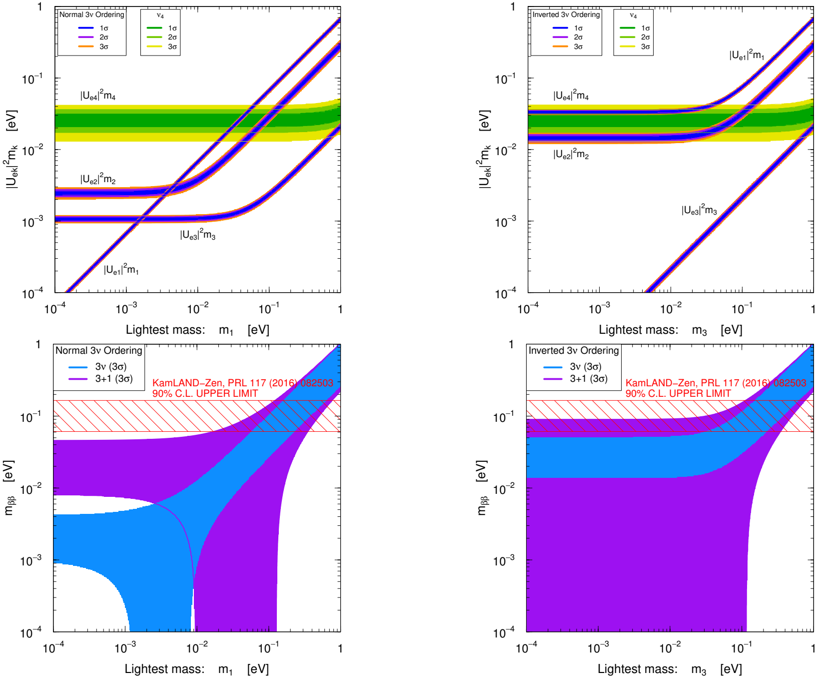
[Barry, Rodejohann, Zhang, JHEP 07 (2011) 091]

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

[Rodejohann, JPG 39 (2012) 124008]

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

[CG, Zavanin, JHEP 07 (2015) 171]


Normal 3ν Ordering
1σ
2σ
3σ
ν_4
1σ
2σ
3σ
$|U_{e4}|^2 m_4$
$|U_{e2}|^2 m_2$
$|U_{e3}|^2 m_3$
$|U_{e1}|^2 m_1$
$|U_{ek}|^2 m_k$ [eV]
Lightest mass: m_1 [eV]
Inverted 3ν Ordering
1σ
2σ
3σ
ν_4
1σ
2σ
3σ
$|U_{e1}|^2 m_1$
$|U_{e4}|^2 m_4$
$|U_{e2}|^2 m_2$
$|U_{e3}|^2 m_3$
$|U_{ek}|^2 m_k$ [eV]
Lightest mass: m_3 [eV]
Normal 3ν Ordering
3ν (3σ)
3+1 (3σ)
KamLAND−Zen, PRL 117 (2016) 082503
90% C.L. UPPER LIMIT
$m_{\beta\beta}$ [eV]
Lightest mass: m_1 [eV]
Inverted 3ν Ordering
3ν (3σ)
3+1 (3σ)
KamLAND−Zen, PRL 117 (2016) 082503
90% C.L. UPPER LIMIT
$m_{\beta\beta}$ [eV]
Lightest mass: m_3 [eV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}

Conclusions

- Exciting indications of sterile neutrinos (new physics!) at the eV scale:
  - LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal (caveat: single experimental signal).
  - Gallium ν_e disappearance (caveat: overestimated detector efficiency?).
  - Reactor $\bar{\nu}_e$ disappearance (caveat: flux calculation dependence).
- Vigorous experimental program to check conclusively in a few years:
  - ν_e and $\bar{\nu}_e$ disappearance with reactors and radioactive sources.
  - $\nu_\mu \to \nu_e$ transitions with accelerator neutrinos.
  - ν_μ disappearance with accelerator neutrinos.
- Independent tests through effect of m_4 in β-decay and $\beta\beta_{0\nu}$-decay.
- Cosmology: strong tension with $\Delta N_{\text{eff}} = 1$ and $m_4 \approx 1\,\text{eV}$. It may be solved by a non-standard cosmological mechanism.
- Possibilities for the next years:
  - Reactor and source experiments ν_e and $\bar{\nu}_e$ observe SBL oscillations: big excitement and explosion of the field.
  - Otherwise: still marginal interest to check the LSND appearance signal.
  - In any case the possibility of the existence of sterile neutrinos related to New Physics beyond the Standard Model will continue to be studied (e.g keV sterile neutrinos).