Physics of Neutrino Sector

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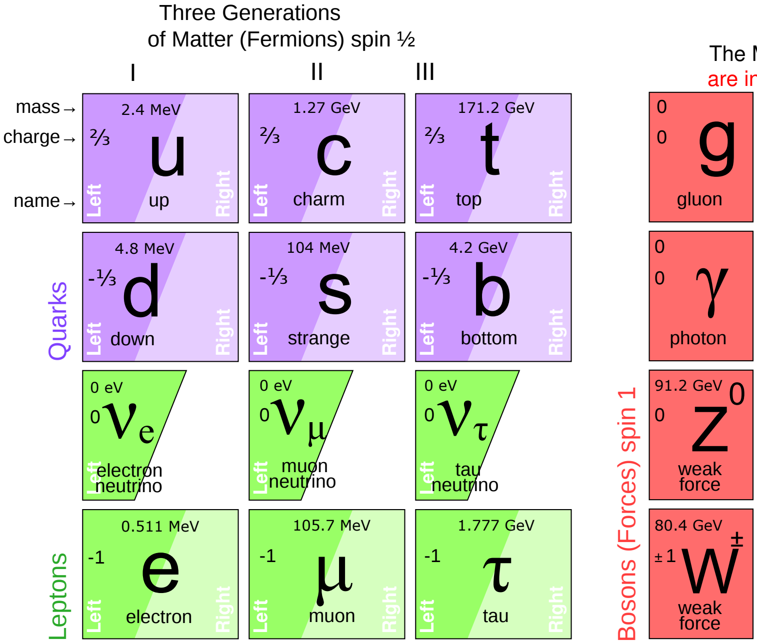
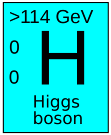


The Matter generations
are indistinguishable by
electric
weak and
strong
forces

distinguishable
by gravity
and Yukawa
forces



spin 0

$m_H \approx 125\,\text{GeV}$

Standard Model: Major Problems

Gauge fields (interactions): γ, $W^{\pm}$, Z, g

Three generations of matter: $L = \binom{\nu_L}{e_L}$, e_R; $Q = \binom{u_L}{d_L}$, d_R, u_R

- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe (PHENO) (THEORY)
  - Neutrino oscillations
  - Dark matter (Ω_{DM})
  - Baryon asymmetry (Ω_B)
  - Inflationary stage
  - Dark energy (Ω_Λ)
  - Strong CP-problem
  - Gauge hierarchy
  - Quantum gravity

Only direct evidence for New Physics

Description of neutrino oscillations (I)

- Two bases: gauge $|\nu_\alpha\rangle$, $\alpha = e,\ \mu,\ \tau$ and mass $|\nu_i\rangle$, $i = 1, 2, 3$

$$|\nu_i\rangle = U_{\alpha i}|\nu_\alpha\rangle \qquad \text{with unitary PMNS } 3\times 3 \text{ matrix} \quad U_{\alpha i}$$

- Neutrino mass matrix is then

$$M_{\alpha\beta} = \langle \nu_\alpha | M | \nu_\beta \rangle = (UM^{(m)}U^\dagger)_{\alpha\beta}\,, \quad \text{where} \quad M^{(m)}_{ij} = m_i \delta_{ij}\,.$$

- Free neutrino evolution in time and space

$$|\nu_j(t)\rangle = \mathrm{e}^{-im_j t}|\nu_j(0)\rangle \quad \to \quad |\nu_j(t,L)\rangle = \mathrm{e}^{-i\left(E_j t - p_j L\right)}|\nu_j(0)\rangle\,,$$

in ultrarelativistic case $\longrightarrow$ Hamiltonian

$$p_j = \sqrt{E^2 - m_j^2} = E - m_j^2/2E \quad \to \quad |\nu_j(L)\rangle = \mathrm{e}^{-i\frac{m_j^2}{2E}L}|\nu_j(0)\rangle\,.$$

Description of neutrino oscillations (II)

- Neutrino effective Hamiltonian

$$|\nu_j(L)\rangle = \mathrm{e}^{-i\frac{m_j^2}{2E}L}|\nu_j(0)\rangle \quad \to H_{eff} = \frac{M^2}{2E}$$

- Transition amplitude of neutrino ν_α to neutrino ν_β is

$$A(\alpha\to\beta) = \sum_j \langle\nu_\beta|\nu_j(L)\rangle\langle\nu_j(0)|\nu_\alpha\rangle = \sum_j \langle\nu_\beta|\nu_j\rangle \mathrm{e}^{-i\frac{m_j^2}{2E}L}\langle\nu_j|\nu_\alpha\rangle = \sum_j U_{\beta j}\mathrm{e}^{-i\frac{m_j^2}{2E}L}U^*_{\alpha j}$$

- Transition probability $\Delta m_{ji}^2 \equiv m_j^2 - m_i^2$

$$P(\nu_\alpha\to\nu_\beta) = |A(\alpha\to\beta)|^2$$
$$= \delta_{\alpha\beta} - 4\sum_{j>i}\mathrm{Re}[U^*_{\alpha j}U_{\beta j}U_{\alpha i}U^*_{\beta i}]\sin^2\left(\frac{\Delta m_{ji}^2}{4E}L\right)$$
$$+2\sum_{j>i}\mathrm{Im}[U^*_{\alpha j}U_{\beta j}U_{\alpha i}U^*_{\beta i}]\sin\left(\frac{\Delta m_{ji}^2}{2E}L\right),$$

Description of neutrino oscillations (III)

- Two-neutrino oscillations: transition probability

$$P(\nu_\alpha \to \nu_{\beta\neq\alpha}) = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2}{4E} L\right) ,$$

- Two-neutrino oscillations: survival probability

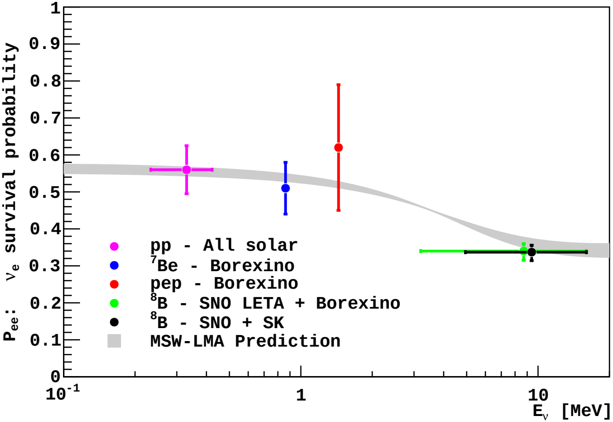
$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

- Oscillation length

$$L_{osc} = \frac{4\pi E}{\Delta m^2} = (2.5\ \text{km}) \cdot \frac{E}{\text{GeV}} \frac{\text{eV}^2}{\Delta m^2}$$

Neutrino matter effect

Mikheev–Smirnov–Wolfenstein effect



BOREXINO measurements of solar neutrino flux

Fermi charged currents

$$\mathscr{L} = -2\sqrt{2}G_F \bar{\nu}_e \gamma^\mu e \cdot \bar{e}\gamma_\mu \nu_e$$

only matter, no currents

$$\langle\langle \bar{e}_k \gamma^0_{kl} e_l \rangle\rangle = \langle\langle e^\dagger e \rangle\rangle = n_e,$$

$$\langle\langle \bar{e}_k \gamma^i_{kl} e_l \rangle\rangle = 0.$$

$$\langle\langle e_k \bar{e}_l \rangle\rangle = -\frac{1}{4}\gamma^0_{kl} \cdot n_e$$

Fermi interaction gives

$$\mathscr{L}_{eff} = -\sqrt{2}G_F n_e \bar{\nu}_e \gamma^0 \nu_e.$$

$$i\gamma^0\partial_0 \to i\gamma^0\partial_0 - \sqrt{2}G_F n_e \gamma^0,$$

effective potential

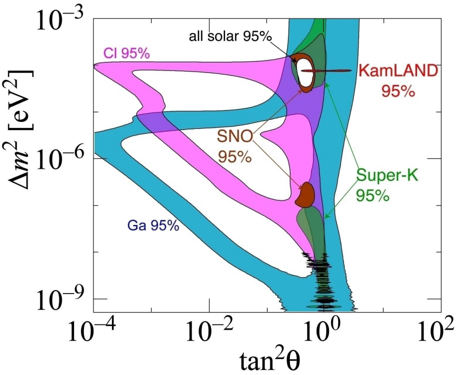
$$i\partial_0 - V, \text{ with } V = \sqrt{2}G_F n_e$$

competes with

$$H_{eff} = \Delta m^2/2E$$

Neutrino oscillations: masses and mixing angles

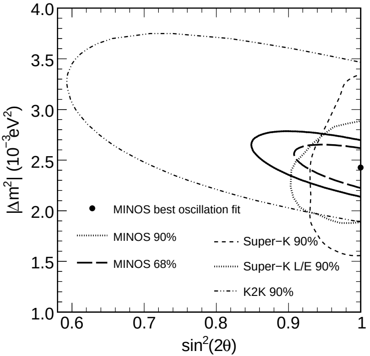
Solar 2×2 “subsector”



http://hitoshi.berkeley.edu/neutrino/

$m^2_{sol} \approx 7.4 \times 10^{-5}$ eV^2

Atmospheric 2×2 “subsector”

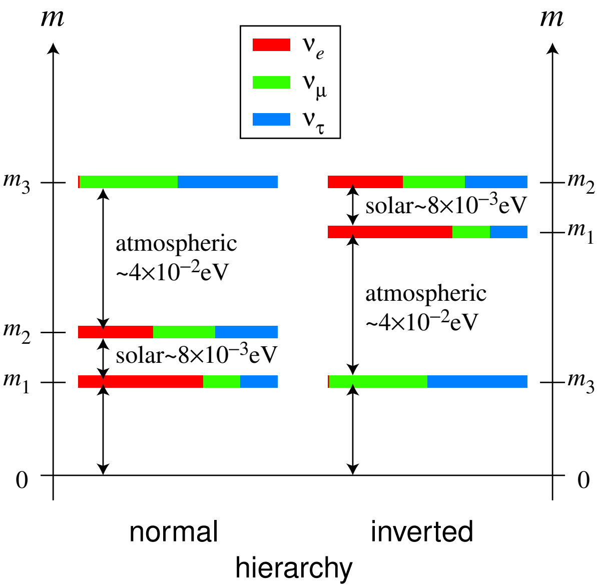


arXiv:0806.2237

$m^2_{atm} \approx 2.5 \times 10^{-3}$ eV^2

DAYA-BAY, RENO, T2K: $\sin^2 2\theta_{13} \approx 0.08$

Physics behind the neutrino oscillations is still elusive

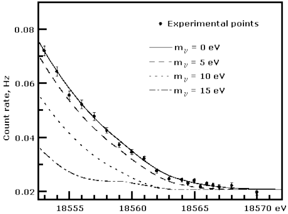


$m^2_{\rm sol} \ll m^2_{\rm atm}$

neutrino
mass
hierarchy ??

Direct searches for m_ν: cut in e-spectrum

$$\mathrm{T} \to {}^3\mathrm{He} + e + \bar{\nu}_e$$
$$(pnn) \to (ppn) + e + \bar{\nu}_e$$



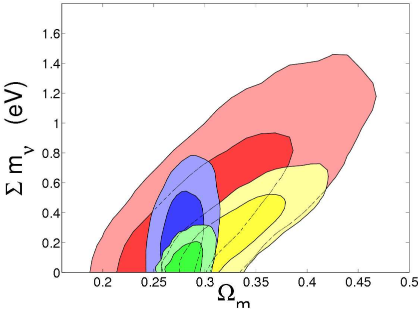
INR RAS, 1990-2000 years: $m_{\bar{\nu}_e} \lesssim 2\,\mathrm{eV}$

Mainz, 2000... : $m_{\bar{\nu}_e} \lesssim 2\,\mathrm{eV}$

present limits from KATRINE
$m_{\bar{\nu}_e} \lesssim 1\,\mathrm{eV}$

similarly: $m_{\bar{\nu}_e} \lesssim 17\,\mathrm{keV}$, $m_{\bar{\nu}_e} \lesssim 17\,\mathrm{MeV}$

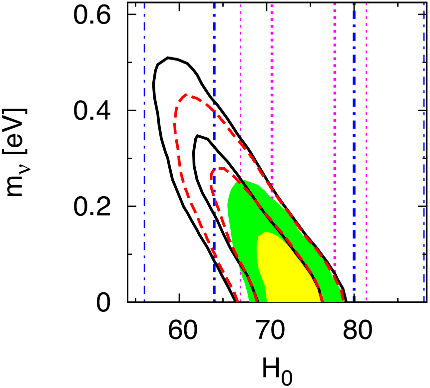
Cosmological limits: sub-eV scale... 10 years ago!!



LRG+BAO+WMAP5+SNe+BAO

$\sum m_\nu < 0.28$ eV (95% CL)

0911.5291



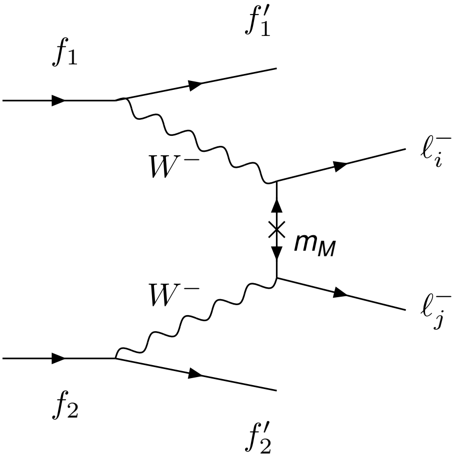
CMB+Hubble measurements

$\sum m_\nu < 0.20$ eV (95% CL)

0911.0976

Physics behind the neutrino oscillations is still elusive

nature of neutrino mass: Dirac vs Majorana?



$Z \to (Z+2) + 2e,$ $0\nu\beta\beta$

$K^+ \to \mu^+\mu^+\pi^-,$ $D \to \mu^+\mu^+K^-$

$t \to b\mu^+\mu^+W^-$

Physics behind the neutrino oscillations is still elusive

- nature of neutrino mass (Dirac vs Majorana)
- neutrino mass hierarchy
- *CP*-violation
- may be relevant for the matter-antimatter asymmetry
- neutrino anomalies do not fit to 3ν
  ask for larger mass splitting

$$m^2_{\rm sol} \ll m^2_{\rm atm} \ll m^2_{\rm anom} \simeq 1\,{\rm eV}^2$$

- LSND $\to$ MiniBooNE — appearance
- SAGE & GALLEX: gallium anomaly — disappearance
- reactor antineutrinos $\to$ DANSS, NEUTRINO-4 — disappearance

These issues must be fixed before suggesting ν as a tool

- Explore entire structures of Earth and Sun
- Investigate the SN explosion mechanism
- Monitor nuclear reactors (nuclear power plants, etc)
- ...

New Physics can interfere if its scale is low

Sterile neutrinos: NEW ingredients

One of the optional physics beyond the SM:

sterile: new fermions uncharged under the SM gauge group
neutrino: explain observed oscillations by mixing with SM (active) neutrinos

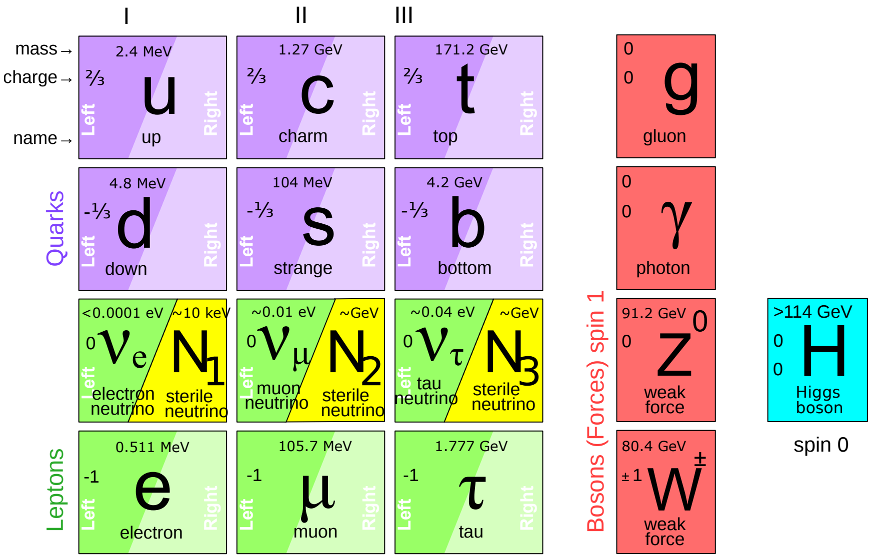
Attractive features:

- possible to achieve within renormalizable theory
- only $N = 2$ Majorana neutrinos needed
- baryon asymmetry via leptogenesis
- dark matter (with $N \geq 3$ at least)
- light(?) sterile neutrinos might be responsible for neutrino anomalies. . . ?

Disappointing feature:

Major part of parameter space is UNTESTABLE

Three Generations of Matter (Fermions) spin ½



Seesaw mechanism: $M_N \gg 1$ eV

With $m_{active} \lesssim 1$ eV we work in the seesaw (type I) regime:

$$\mathscr{L}_N = \overline{N} i \partial\!\!\!/ N - f \overline{L}_e^c \tilde{H} N - \frac{M_N}{2} \overline{N}^c N + \text{h.c.}$$

Higgs gains $\langle H \rangle = v/\sqrt{2}$ and then

$$\mathscr{V}_N = \frac{1}{2} \left(\overline{\nu}_e \, , \overline{N}^c \right) \begin{pmatrix} 0 & v \frac{f}{\sqrt{2}} \\ v \frac{f}{\sqrt{2}} & M_N \end{pmatrix} \begin{pmatrix} \nu_e \\ N \end{pmatrix} + \text{h.c.}$$

For a hierarchy $M_N \gg M^D = v \frac{f}{\sqrt{2}}$ we have

flavor state $\nu_e = U \nu_1 + \theta N$ with $U \approx 1$ and

active-sterile mixing: $$\theta = \frac{M^D}{M_N} = \frac{v f}{2 M_N} \ll 1$$

and mass eigenvalues

$$\approx M_N \quad \text{and} \quad - m_{active} = \theta^2 M_N \lll M_N$$

Seesaw mechanism: $M_N \gg 1$ eV

With $m_{active} \lesssim 1$ eV we work in the seesaw (type I) regime:

$$\mathscr{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}^c_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}^c_I N_I + \text{h.c.}$$

When Higgs gains $\langle H \rangle = v/\sqrt{2}$ we get in neutrino sector

$$\mathscr{V}_N = \frac{1}{2}\left(\overline{\nu}_1, \ldots \overline{N}^c_1 \ldots\right)\begin{pmatrix} 0 & v\,\frac{\hat{f}}{\sqrt{2}} \\ v\,\frac{\hat{f}^T}{\sqrt{2}} & \hat{M}_N \end{pmatrix}\left(\nu_1, \ldots N_1 \ldots\right)^{\mathrm{T}} + \text{h.c.}$$

Then for $M_N \gg \hat{M}^D = v\,\frac{\hat{f}}{\sqrt{2}}$ we find the eigenvalues:

$$\simeq \hat{M}_N \quad \text{and} \quad \hat{M}^\nu = -(\hat{M}^D)^T \frac{1}{\hat{M}_N}\hat{M}^D \propto f^2 \frac{v^2}{M_N} \lll M_N$$

Mixings: flavor state $\nu_\alpha = U_{\alpha i}\nu_i + \theta_{\alpha I} N_I$

active-active mixing: $U^\dagger \hat{M}^\nu U = diag\,(m_1, m_2, m_3)$

active-sterile mixing: $\theta_{\alpha I} = \frac{(M^D)^T_{\alpha I}}{M_I} \propto \hat{f}^T \frac{v}{M_N} \ll 1$

Violation of L, C and CP symmetries

$$\mathscr{L}_N = \overline{N} i \partial\!\!\!/ N - f \overline{L}_e^c \tilde{H} N - \frac{M_N}{2} \overline{N}^c N + \text{h.c.}$$

- $f = 0 \quad \longrightarrow \quad$ free fermion, no need to call 'sterile'
- $M_N = 0 \quad \longrightarrow \quad N$ and ν form pure Dirac neutrino,
  the most boring case, worth than we have with the Higgs boson
  one may refuse to call it 'new physics'
- $f \neq 0, \quad M_N \neq 0 \quad \longrightarrow \quad$ introduces new massive parameter,
  violates lepton symmetry L
  (and C- and CP-symmetry with several N's)

Active neutrino masses without new fields

Dimension-5 operator $\Delta L = 2$ appeared at energy scale Λ

$$\mathscr{L}^{(5)} = \frac{F_{\alpha\beta}}{4\Lambda} \bar{L}_\alpha \tilde{H} H^\dagger L^c_\beta + \text{h.c.}$$

L_α are SM leptonic doublets, $\alpha = 1,2,3$, $\tilde{H}_a = \varepsilon_{ab} H^*_b$, $a,b = 1,2$;
in a unitary gauge $H^T = \left(0, (v+h)/\sqrt{2}\right)$

$$\mathscr{L}^{(5)}_{\nu\nu} = \frac{v^2 F_{\alpha\beta}}{4\Lambda} \times \frac{1}{2} \bar{\nu}_\alpha \nu^c_\beta + \text{h.c.} = m_{\alpha\beta} \times \frac{1}{2} \bar{\nu}_\alpha \nu^c_\beta + \text{h.c.}$$

where

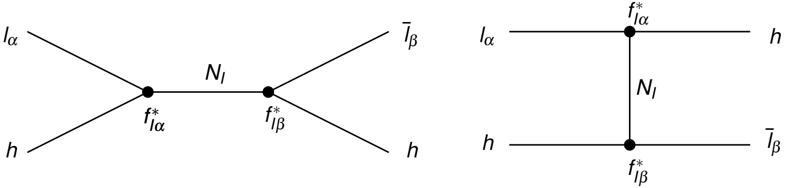
Λ is the scale of new dynamics

$F_{\alpha\beta}$ is the strength of new dynamics

only their ratio is fixed by the scale of active neutrino masses

Producing the effective dim-5 operator below M_N

integrating out the Heavy sterile neutrinos



thus we obtain

$$\propto \frac{f^2}{M_N} lhlh \quad \rightarrow \quad \frac{F(LH)(LH)}{\Lambda}$$

Sterile neutrino: a vast region of mass

Within the seesaw paradigm, as far as

$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

Any set

(mass scale M_N, Yukawa coupling f)

is viable

And with special tunning or symmetry larger (but not smaller) mixing
3 sterile neutrinos is viable

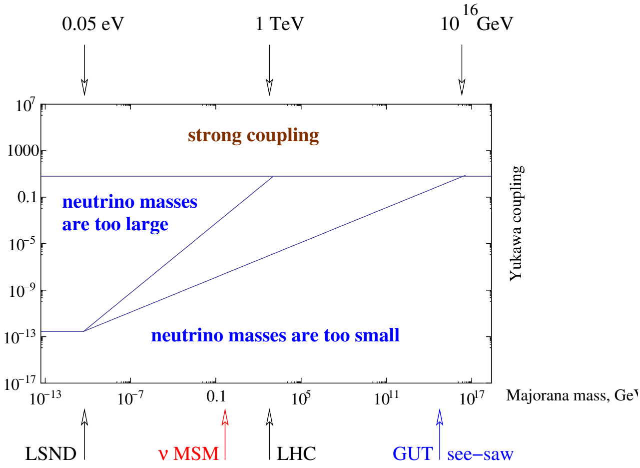
$$\hat{m}_a \sim \hat{f}^T \frac{1}{\hat{M}_N} \hat{f} v^2$$

Sterile neutrino mass scale: $\hat{M}_\nu = -v^2 \hat{f}^T \hat{M}_N^{-1} \hat{f}$

NB: With fine tuning in $\hat{M}_N$ and $\hat{f}$ we can get a hierarchy in sterile neutrino masses, and 1 keV and even 1 eV sterile neutrinos

$L_e - L_\mu - L_\tau$ or discrete symmetries
Froggatt-Nielsen mechanism

Extended seesaw



Seesaw diagram

Sterile neutrino lagrangian

Most general renormalizable with 2(3...) right-handed neutrinos N_I

$$\mathscr{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.}$$

Parameters to be determined from experiments

9(7): active neutrino sector

$2\ \Delta m_{ij}^2$: oscillation experiments

$3\ \theta_{ij}$: oscillation experiments

1 CP-phase: oscillation experiments

2(1) Majorana phases: $0\nu ee$, $0\nu\mu\mu$

1(0) m_ν: ${}^3\mathrm{H} \to {}^3\mathrm{He} + e + \bar{\nu}_e$, cosmology, ...

11: $N = 2$ sterile neutrinos (works if $m_\nu = 0$!!!)

2: Majorana masses M_{N_I}

9: New Yukawa couplings $f_{\alpha I}$ which form

- 2: Dirac masses $M^D = f\langle H\rangle$
- 3+1: mixing angles
- 2+1: CP-violating phases

4 new parameters in total

18: $N = 3$ sterile neutrinos:

3: Majorana masses M_{N_I}

15: New Yukawa couplings $f_{\alpha I}$ which form

- 3: Dirac masses $M^D = f\langle H\rangle$
- 3+3: mixing angles
- 3+3: CP-violating phases

9 new parameters in total

Profit: can suggest why neutrinos are so light, $m_\nu \sim 0.1 - 0.01\,\text{eV}$

Baryogenesis

– Need BAU $\eta_B \equiv n_B/n_\gamma \approx 6 \times 10^{-10}$ starting from BBN epoch, $T \lesssim 1$ MeV

– The same number at recombination and later

Sakharov conditions of successful baryogenesis

- B-violation $(\Delta B \neq 0)\ XY \dots \to X'Y' \dots B$
- C- & CP-violation $(\Delta C \neq 0,\ \Delta CP \neq 0)\ \bar{X}\bar{Y} \dots \to \bar{X}'\bar{Y}' \dots \bar{B}$
- processes above are out of equilibrium $X'Y' \dots B \to XY \dots$

At 100 GeV$\lesssim T \lesssim 10^{12}$ GeV nonperturbative processes (EW-sphalerons) violate B, L_α, so that only three charges are conserved out of four, e.g.

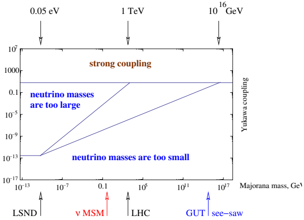
$$B - L\,, \quad L_e - L_\mu\,, \quad L_e - L_\tau$$

Leptogenesis: Baryogenesis from lepton asymmetry of the Universe ... due to sterile neutrinos

Bonus: depends on the sterile neutrino mass range

NB: With fine tuning in $\hat{M}_N$ and $\hat{f}$ we can get a hierarchy in sterile neutrino masses, and 1 keV and even 1 eV sterile neutrinos

$L_e - L_\mu - L_\tau$ or discrete symmetries
Froggatt-Nielsen mechanism
Extended seesaw



There are different regions:

$M_N \sim$ 1 eV-100 GeV

- keV-scale dark matter
- BAU via leptogenesis
- Neutrino anomalies (1 eV sterile neutrinos?)

direct searches!

$M_N \sim$ 100 GeV-5 TeV

- BAU via leptogenesis

$f \sim 10^{-6} \simeq Y_e$

but with fine tuning or new global or gauge symmetries (e.g. $SU(2)_L \times SU(2)_R$)

direct searches at colliders

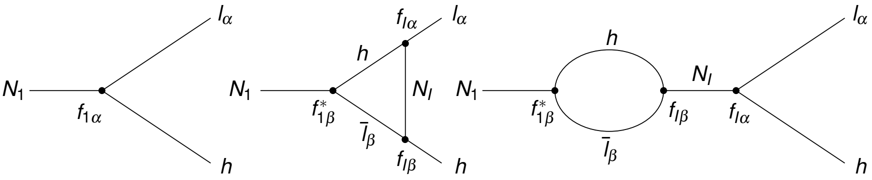
$M_N \sim 10^{12}$-10^{14} GeV

- BAU via leptogenesis

$f \simeq 0.01 - 1$

Untestable. . . ?
or already confirmed?

Lepton asymmetry δ at 1-loop level $\qquad f_{I\alpha}\bar{L}_\alpha N_I \widetilde{H}$



$$\Gamma(N_1 \to lh) = \frac{M_1}{8\pi} \cdot \sum_\alpha \left| f_{1\alpha} + \frac{1}{8\pi} \sum_{\beta, I} F\left(\frac{M_1}{M_I}\right) \cdot f^*_{1\beta} f_{I\alpha} f_{I\beta} \right|^2, \quad m_\nu \ll M_I$$

$$\delta \equiv \frac{\Gamma(N_1 \to lh) - \Gamma(N_1 \to \bar{l}h)}{\Gamma_{tot}} = -\frac{1}{8\pi} \sum_{I=2,3} \mathrm{Im}\left[F\left(\frac{M_1}{M_I}\right)\right] \cdot \frac{\mathrm{Im}\left(\sum_\alpha f_{1\alpha} f^*_{I\alpha}\right)^2}{\sum_\gamma |f_{1\gamma}|^2}\,.$$

for $M_{2,3} \gg M_1$, $f\left(\frac{M_1}{M_I}\right) = -\frac{3}{2}\frac{M_1}{M_I}$, $\delta = \frac{3\,M_1}{16\pi} \frac{1}{\sum_\gamma |y_{1\gamma}|^2} \sum_{\alpha\beta I} \mathrm{Im}\left[y_{1\alpha} y_{1\beta} \left(y^*_{I\alpha} \frac{1}{M_I} y^*_{I\beta}\right)\right]\,.$

Superheavy sterile neutrinos: $M_N \simeq 10^{12}$-10^{14} GeV

- Motivation: close to GUT scales, e.g. $SO(10)$
- Bad fact: huge finite quantum corrections $\delta m_H^2 \propto f^2 M_N^2 \gg m_H^2 (\Rightarrow M_N < 10^7\,\text{GeV})$
  SUSY solution? (New fileds...new problems: e.g. gravitino overproduction with high T_{reh} for leptogenesis)
- Good fact: If $T > M_N$ decays of thermal sterile neutrino yield the lepton asymmetry in the early Universe: M.Fukugita, T.Yanagita (1986)

$$\delta \equiv \frac{\Gamma(N_1 \to lh) - \Gamma(N_1 \to \bar{l}h)}{\Gamma_{tot}} = \frac{1}{8\pi} \sum_{l=2,3} f\left(\frac{M_{N_1}}{M_{N_l}}\right) \cdot \frac{\mathrm{Im}\left(\sum_\alpha f_{1\alpha} f_{l\alpha}^*\right)^2}{\sum_\gamma |f_{1\gamma}|^2} \,.$$

  Needs $M_{N_1} \gtrsim 10^9$ GeV or $M_{N_1} \gtrsim 10^{12}$ GeV without fine tuning in $\hat{f}$
- Exciting fact: to avoid washing out of Δ_L in $hl_\alpha \leftrightarrow h\bar{l}_\beta$ we need ...
  $M^\nu < 0.1 - 0.3\,\text{eV}$!!!
- Cooling down: No way to test further. Can get $\Delta_B \sim 10^{-10}$ even with
  $\theta_{13} = \delta_{\rm CP} = 0$!

NB: can work for nonthermal case as well

production by inflaton decay G.Lazaridies, Q.Shafi (1991) e.g. in R^2-inflation D.G., A.Panin (2010)

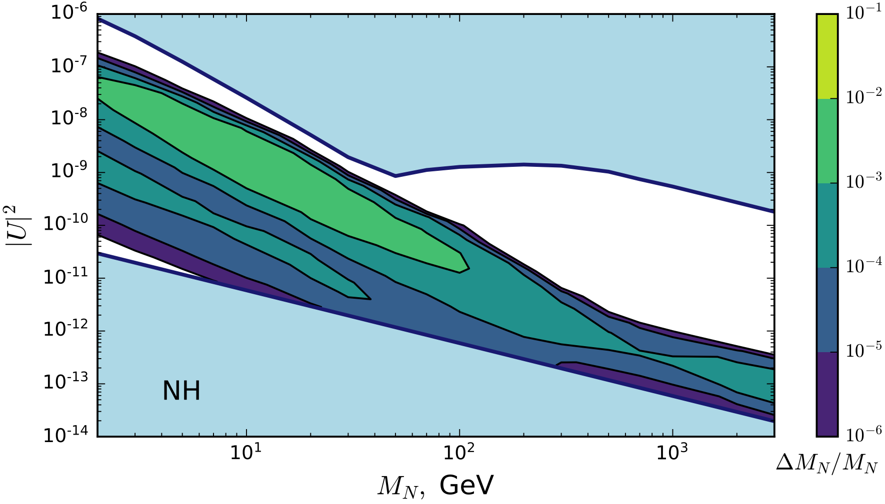
Very heavy sterile neutrinos: $M_N \simeq 100\,\text{GeV-}5\,\text{TeV}$

- Good fact: small finite quantum corrections $\delta m_H^2 \propto f^2 M_N^2 \ll m_H^2$
  No hierarchy between Λ_ν and Λ_{EW}
- Bad fact: Without extra symmetries, fine tuning or new interactions generation of lepton asymmetry and hence No BAU
- Way out: fine tunning can help: e.g. resonant enhancement of CP-violation in out-of-equilibrium sterile neutrino decays:
  leptogenesis for $M_N \gtrsim 1\,\text{TeV}$ if $\Delta M_N \sim \Gamma_N$ Pilaftsis (1997,...)
- Further cooling down:
  can be directly produced but at a tiny amount only: as small as $f \sim 10^{-6}$!
- Conclusion: Seesaw type I is generally untestable in direct searches:
  Yuakawa couplings are too small, while sterile neutrinos are quite heavy.

To make interesting either NEW fields or fine tuning (larger f)
or symmetries, e.g. $SU(2)_L \times SU(2)_R$ are required!!!

Degeneracy for Leptogenesis

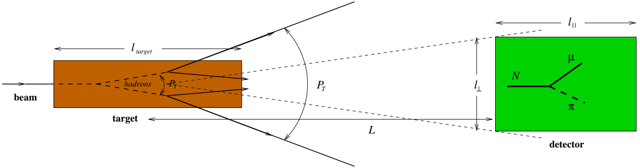
2008.13771



Heavy sterile neutrinos: direct searches

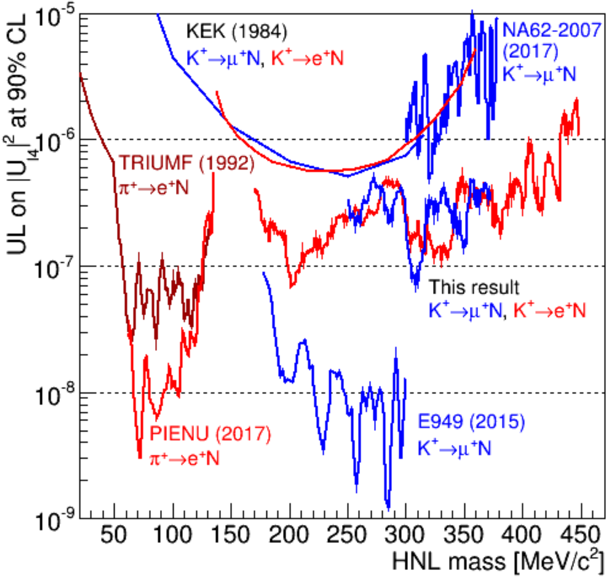
Weak decays due to mixing

Production in beam-dump experiments



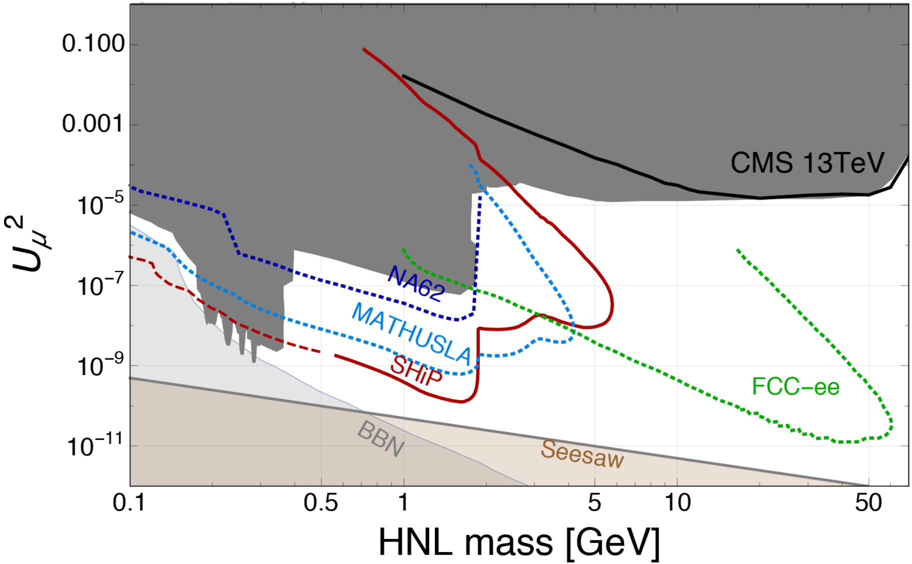
Present limits from production

1904.09124



New projects. . .

1904.09124



Sterile neutrino: well-motivated keV-mass Dark Matter

- massive fermions giving mass to active neutrino through mixing (seesaw)

$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

- unstable, $N \to \nu\nu\nu$ is always open
  but exceeding the age of the Universe if

(applicable for $M_N < M_W$)

$$\tau_{N\to 3\nu} \sim 1/\left(G_F^2 M_N^5 \theta_{\alpha N}^2\right) \quad \Longrightarrow \quad \theta^2 < 1.5\times 10^{-7}\left(\frac{50\,\text{keV}}{M_N}\right)^5$$

- with seesaw constraint $m_a \sim \theta^2 M_N$

$$\tau_{N\to 3\nu} \sim 1/\left(G_F^2 M_N^4 m_\nu\right) \sim 10^{11}\,\text{yr}\,(10\,\text{keV}/M_N)^4$$

Sterile neutrino: indirect searches

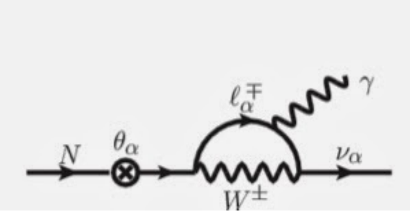
$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

- unstable, but exceeding the age of the Universe if

$$\frac{\theta^2}{3 \times 10^{-3}} < \left(\frac{10\,\text{keV}}{M_N}\right)^5$$

- DM sterile neutrinos can be searched at X-ray telescopes because of two-body radiative decay

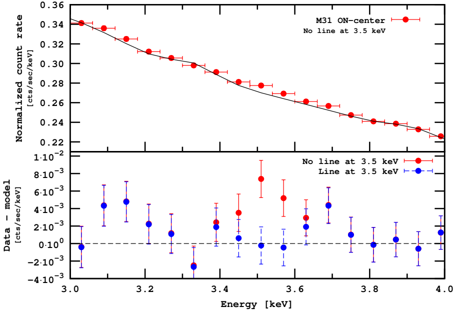
give limits in absence of the feature

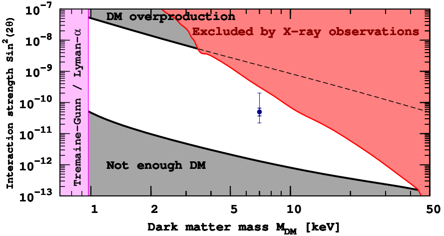


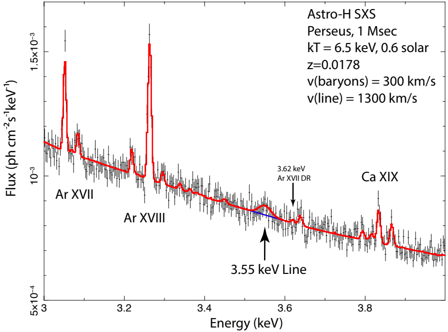
a narrow line $(\delta E_\gamma / E_\gamma \sim v \sim 10^{-3})$
at photon frequency $E_\gamma = M_N/2$

$$\frac{\theta^2}{10^{-11}} \lesssim \left(\frac{10\text{ keV}}{M_N}\right)^4$$

. . . 6 years ago: Dark Matter decay observed in X-ray?



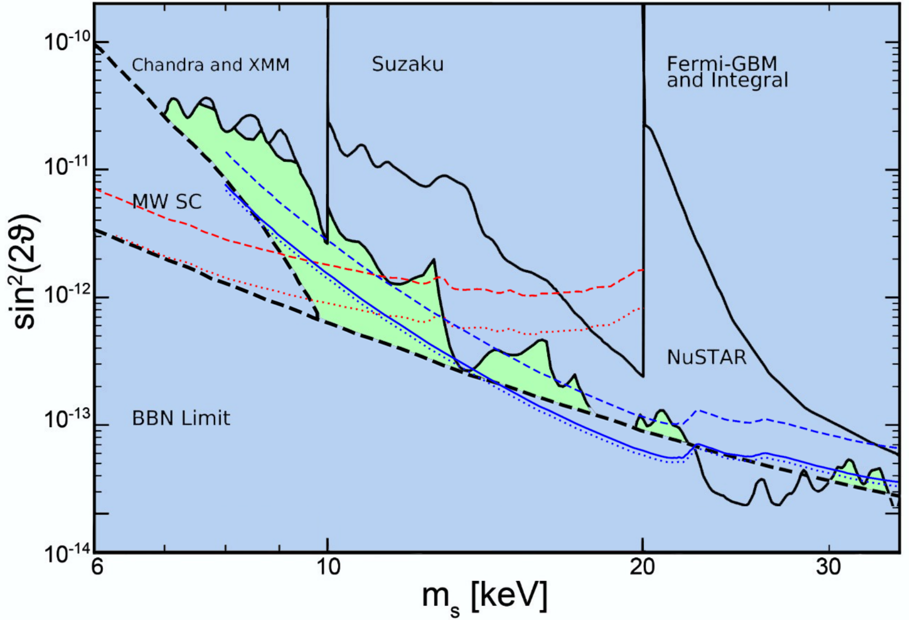




Stacking signals from many galaxies, especially Perseus cluster, then Andromeda

1402.2301, 1402.4119

Spektr-RG: eROSITA (0.2-10 keV), ART-XC (4-30 keV)



2007.07969 (V. Barinov, R. Burenin, D.G., R. Krivonos)

Disclaimer

- There are no any direct indication of the sterile neutrino scale
- In what follows we consider light, $m \sim 1$ eV sterile neutrinos
  Neutrino anomalies
- No solid theoretical motivations for this scale, $M_N \sim m_\nu$
  May be except Mirror World concept. . . ?
- $2 \leftrightarrow 2$ oscillations are enough
- Could be not exactly sterile: non-minimal models of neutrino mixing can fit to this scheme as well

Light sterile neutrinos and cosmology

- Analysis of CMB & LSS (e.g., Planck, SDSS):
  Mixing $\theta \sim 0.1$-1, mass $\sim 1\,\text{eV}$
  NONE (or, may be, one)
  – there are 2σ discrepancies in H_0, σ_8, lensing, ...
  small scale crisis, SPT vs Planck, ...
- Explanation of the combined anomalous results needs TWO or MORE
  – of course, some anomalies may be just anomalies...
- Production in the early Universe can be efficiently suppressed, e.g., by scalar field

$$\mathscr{L} = \phi \bar{N}^c N + \text{h.c.}$$

  or if the reheating scale is low, $T_{reh} \sim 10\,\text{MeV}$

Description of neutrino oscillations

- Oscillation length small $L_{osc} \leftrightarrow$ big Δm

$$L_{osc} = \frac{4\pi E}{\Delta m^2} = (2.5\text{ m}) \cdot \frac{E}{\text{MeV}} \frac{\text{eV}^2}{\Delta m^2}$$

- Oscillation probability:

$$P(\nu_\alpha \to \nu_\beta) = \left| \delta_{\alpha\beta} - \sin^2 2\theta_{\alpha\beta} \sin^2\left(\frac{L\,\Delta m^2_{41}}{4E}\right) \right|, \quad \sin^2 2\theta_{\alpha\beta} = 4\,|U_{\alpha 4}|^2 \left|\delta_{\alpha\beta} - |U_{\beta 4}|^2\right|$$

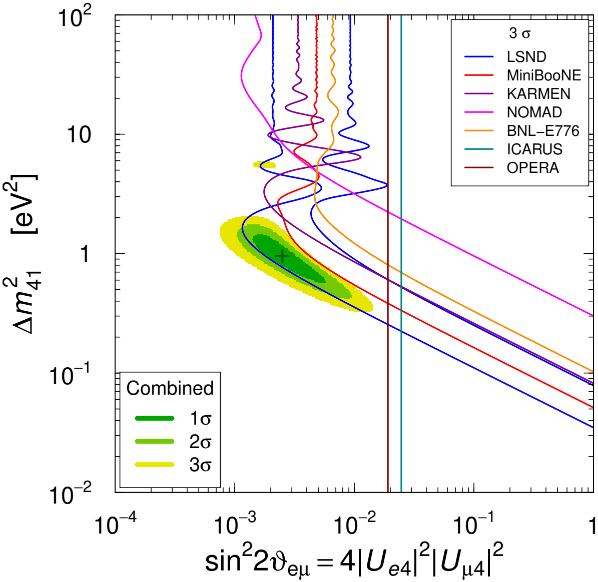
- transition probability appearance

$$P(\nu_\alpha \to \nu_{\beta\neq\alpha}) = \sin^2 2\theta_{\alpha\beta} \sin^2\left(\frac{L\,\Delta m^2_{41}}{4E}\right), \quad \sin^2 2\theta_{\alpha\beta} = 4\,|U_{\alpha 4}|^2\,|U_{\beta 4}|^2$$

- survival probability disappearance

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta_{\alpha\alpha} \cdot \sin^2\left(\frac{\Delta m^2}{4E} L\right), \quad \sin^2\theta_{\alpha\alpha} = |U_{\alpha 4}|^2$$

LSND-anomaly: appearance, $\bar{\nu}_\mu \to \bar{\nu}_e$



LSND (1993-1998): production by 798 MeV protons

$$\pi^+ \to \mu^+ \nu_\mu\,, \quad \mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

detection via inverse beta decay (IBD)

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

3.8σ effect

transition probability

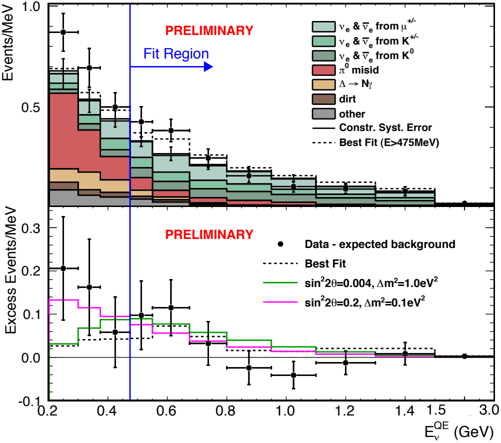
$$(2.64 \pm 0.67 \pm 0.45) \times 10^{-3}$$

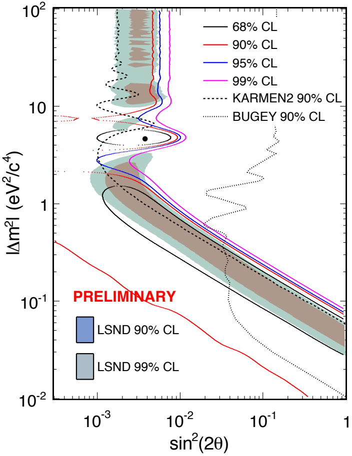
sterile neutrino mass

$$\Delta m \sim 1\,\text{eV}$$

1901.08330

MiniBooNE anomalies (2011) . . . $\bar{\nu}_\mu \to \bar{\nu}_e$, $\nu_\mu \to \nu_e$





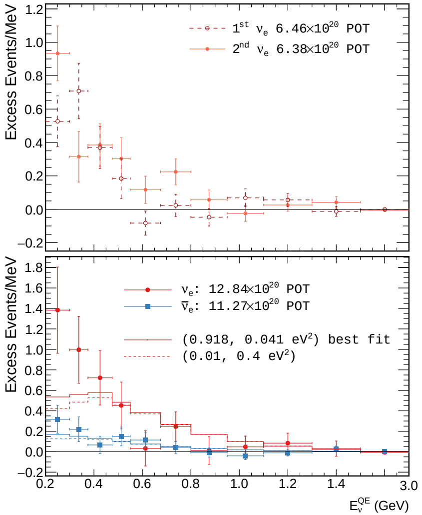
ν_e for ν_μ mode at MiniBooNE: no LSND-like effects,
However Low energy excess of ν_e

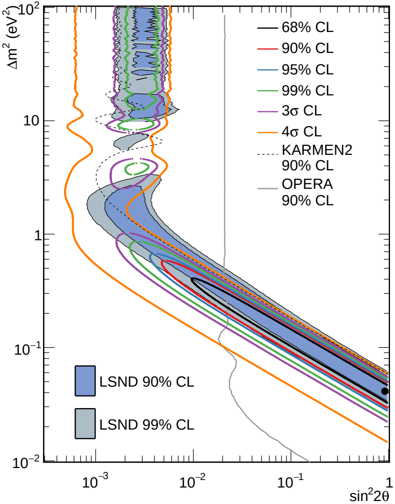
NuFuct2011, 1201.1519

LSND-like oscillations are preferable only at 90%CL

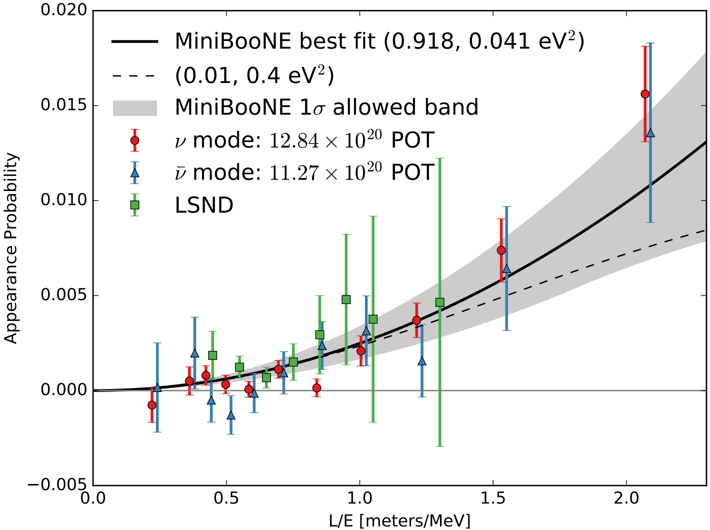
MiniBooNE anomalies (2018) . . . $\bar{\nu}_\mu \to \bar{\nu}_e$, $\nu_\mu \to \nu_e$

1805.12028



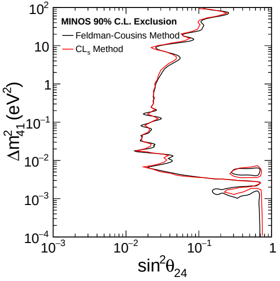


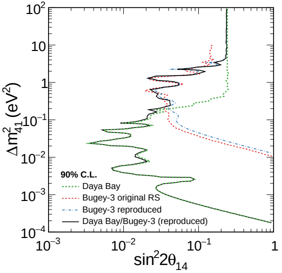
MiniBooNE anomalies (2018) ... $\bar{\nu}_\mu \to \bar{\nu}_e$, $\nu_\mu \to \nu_e$

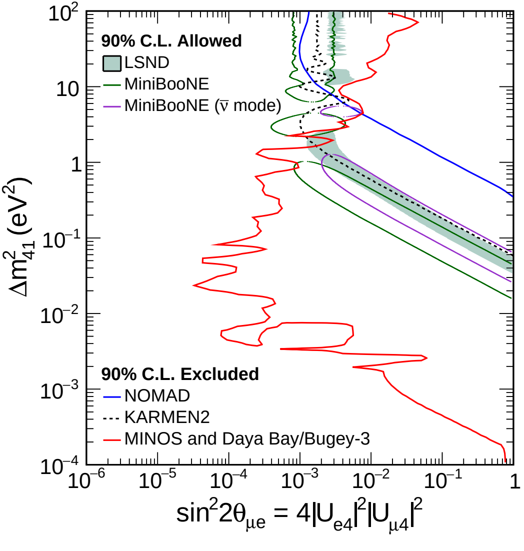


Looks like the LSND anomaly is closed . . . ?

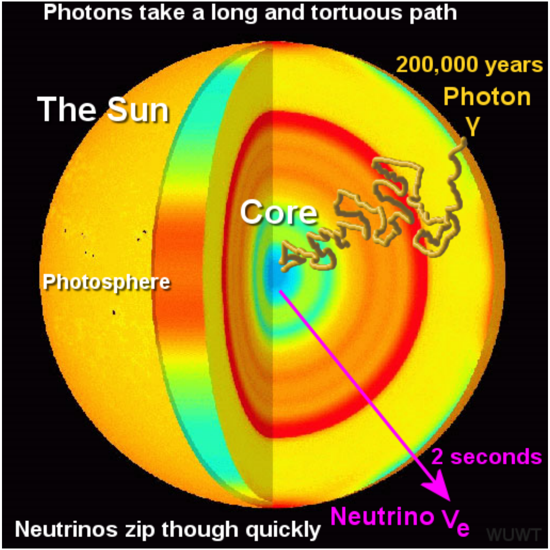
1607.01177

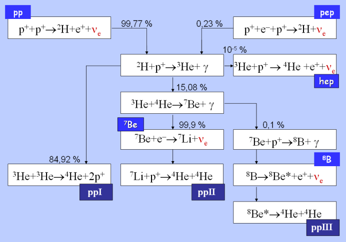


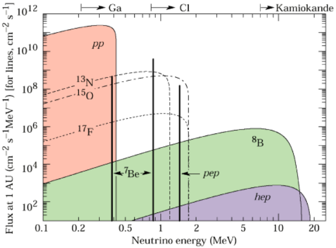




Solar neutrinos: fusion $p+p \to D+e^+ + \nu_e, \ldots$



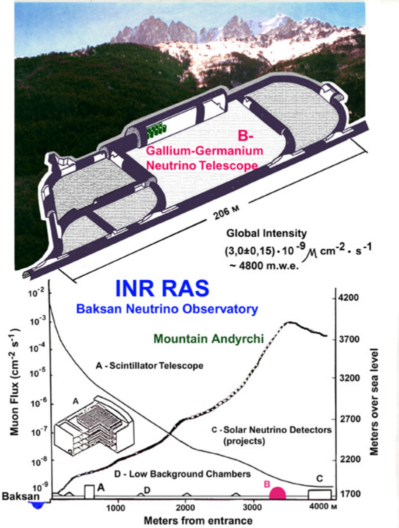




Measurement of the solar neutrino flux by SAGE

Sun: $p+p\to\ {}^2H+e^++\nu_e$

Earth: ${}^{71}\mathrm{Ga}+\nu_e\to\ {}^{71}\mathrm{Ge}+e^-$



SAGE & GALLEX anomalies in numbers

1710.06326

Sources

^{51}Cr

$E_1 = 0.75\,\text{MeV}\ (f_1 = 96\%)$
$E_2 = 0.43\,\text{MeV}\ (f_2 = 4\%)$

^{37}Ar

$E_1 = 0.811\,\text{MeV}$
$E_2 = 0.813\,\text{MeV}$

Experiments

SAGE

source $\approx$ sphere of $r = 6.3\,\text{cm}$
in the center of spherical vessel
$r_1 = 25.3\,\text{cm}$ and $r_2 = 72.6\,\text{cm}$

GALLEX

source $\approx$ sphere of $r = 0.4\,\text{m}$
in the center of spherical vessel
$r_1 = 0.45\,\text{m}$ and $r_2 = 2.5\,\text{m}$

$$R^{th} = \frac{1}{r_2 - r_1} \int_{r_1}^{r_2} dr \left[P(E_1, |\vec{r} - \delta\vec{r}|) f_1 + P(E_2, |\vec{r} - \delta\vec{r}|) f_2 \right]$$

$$R^{obs}_{\text{SAGE}} \left(^{51}\text{Cr} \right) = 0.93 \pm 0.12$$

$$R^{obs}_{\text{SAGE}} \left(^{37}\text{Ar} \right) = 0.77 \pm 0.09$$

$$R^{obs}_{\text{GALLEX}} \left(^{51}\text{Cr} \right) = 0.93 \pm 0.11$$

$$R^{obs}_{\text{GALLEX}} \left(^{51}\text{Cr} \right) = 0.80 \pm 0.11$$

The combined fit to SAGE+GALLEX

1710.06326

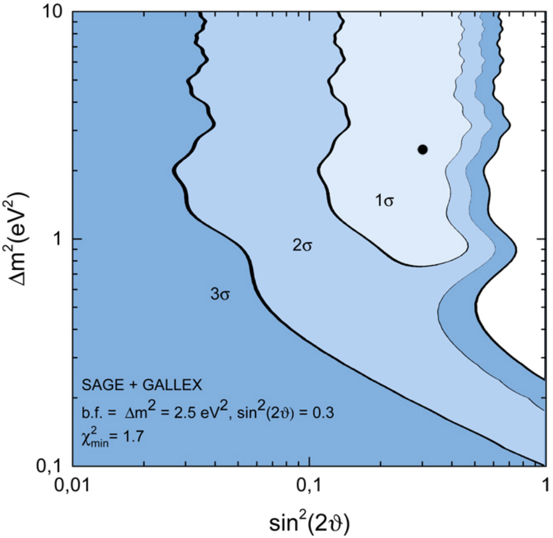
minimizing

$$\chi^2 = \sum_{i=1}^{4} \frac{\left(R_i^{obs} - R_i^{th}(\Delta m^2, \sin^2 2\theta)\right)^2}{\sigma_{R_i}^2}$$

combined best fit

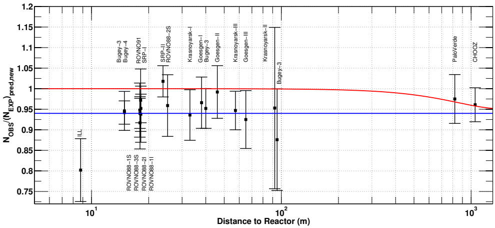
$$\Delta m^2 \approx 2.5\,\mathrm{eV}^2\,, \quad \sin^2\theta \approx 0.3$$

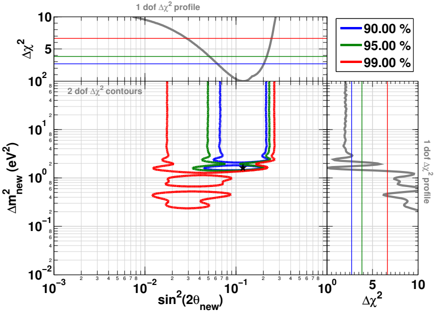
consistent with C.Giunti, M.Lavender (2011)



Reactor anomaly: $\bar{\nu}_e \to N$?

G.Mention et al. (2011)





Deficit due to 6% correction to $\bar{\nu}_e$ budget

- new nuclear rates
- new neutron life-time:

$$\tau_n : 926\,\text{s} \to 886\,\text{s}$$

However: the value of uncertainty remains the same, $\sim 3\%\ldots$

Combined fit to Reactor and Gallium data

Bunch of proposals to test the anomaly. . .

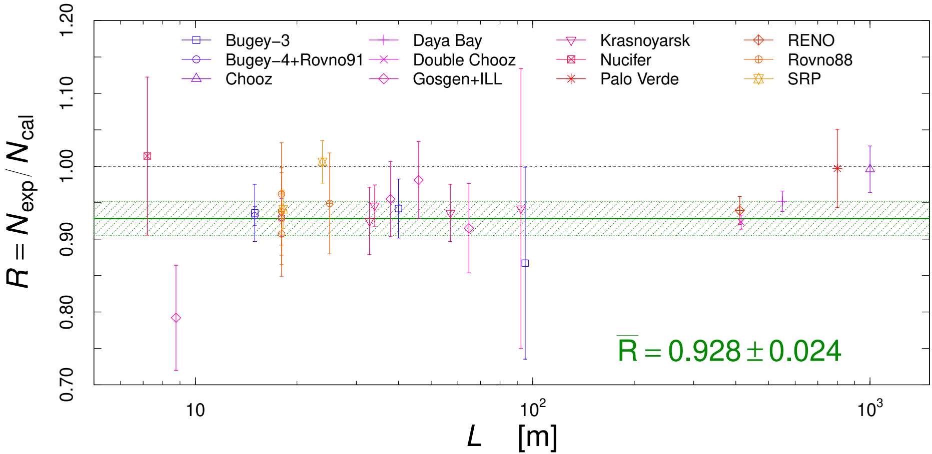
see 1204.5379

Reactor anomaly: disappearance $\bar{\nu}_e \to N$?

RENO, Daya Bay, Double Chooz

1901.08330

+ unexpected bump at $E_{\bar{\nu}} \simeq 4\,\mathrm{MeV}$



Reactor anomaly: new comers. . . new evidence?

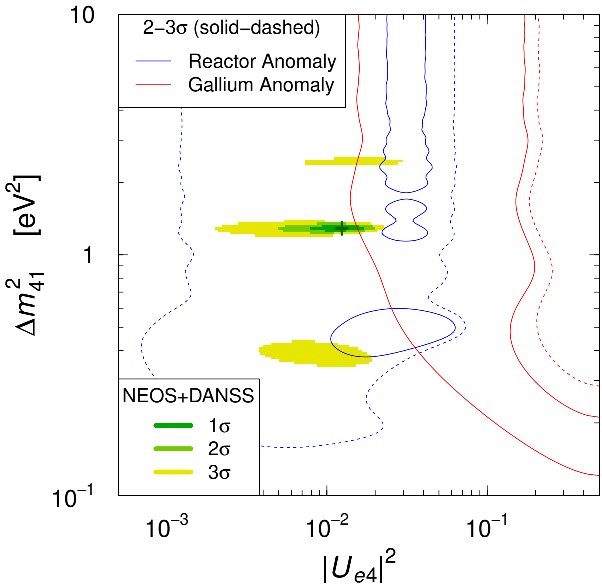
NEOS (Korea, 2017-. . .)
$\bar{\nu}_e$ from 2.8 GW_{th} reactor
detector at $L = 24$ m
events normalized to Daya Bay spectrum at 550 m
best fit

$\Delta m^2 \simeq 1.5\,\text{eV}^2, \quad \sin^2 2\theta_{ee} \simeq 0.05$

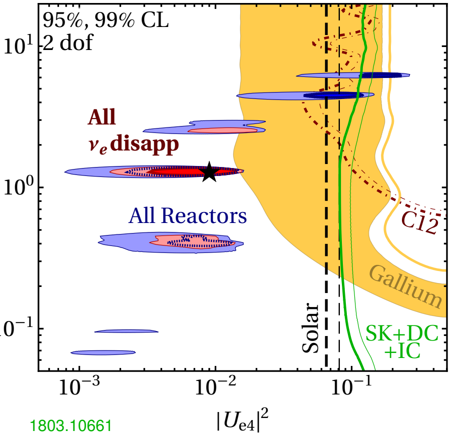
DANSS (Russia, 2017-. . .):
$\bar{\nu}_e$ from 3.1 GW_{th} reactor
movable detector at
$L = 10.7 - 12.5$ m
best fit

$\Delta m^2 \simeq 1.4\,\text{eV}^2, \quad \sin^2 2\theta_{ee} \simeq 0.05$

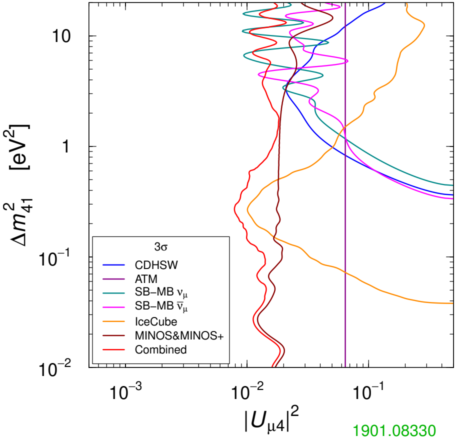
1801.06467



Disappearances of ν_e and ν_μ...

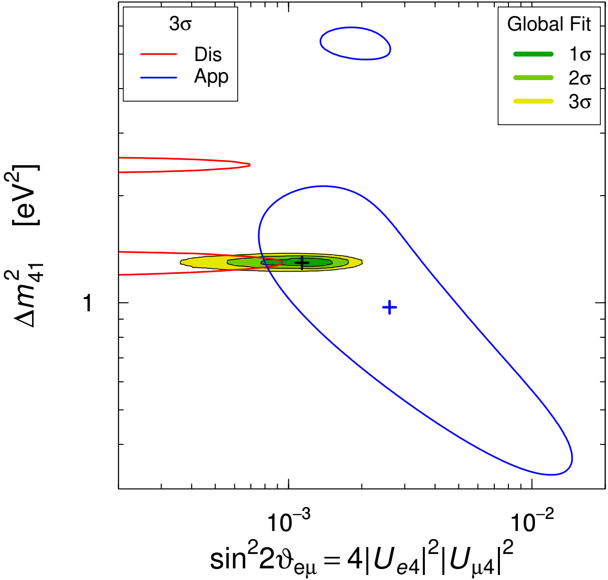


1803.10661



1901.08330

Disappearance vs Appearance: rulling out LSND ??



1901.08330

Reactor anomaly: recent results. . .

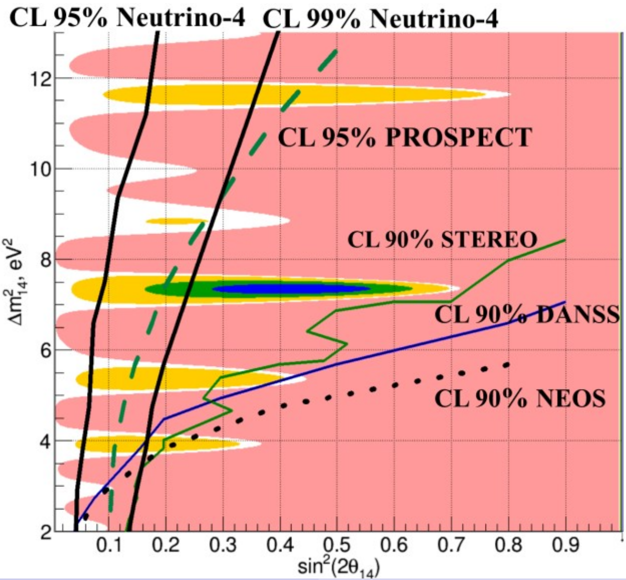
1809.10516

PROSPECT (USA, 2018-. . .)
$85\,\mathrm{MW_{th}}$ compact reactor
segmented detector covering
$L = 6-7.5\,\mathrm{m}$
measures flux ratios
STEREO (France, 2018-. . .):
$58\,\mathrm{MW_{th}}$ compact reactor
segmented detector covering
$L = 9.4-11.1\,\mathrm{m}$
measures flux ratios

NEUTRINO-4 (Russia, 2018-
$100\,\mathrm{MW_{th}}$ extracompact
reactor SM-3 (Dimitrovgrad)
segmented movable detector
$L = 6-12\,\mathrm{m}$
measures flux ratios
best fit

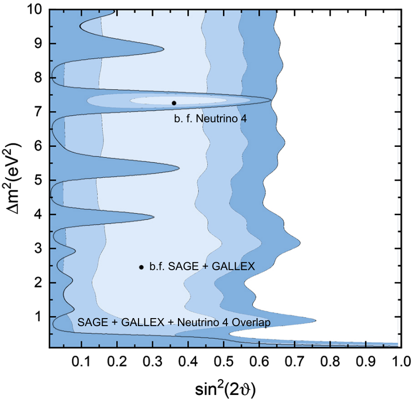
$$\Delta m^2 \simeq 7.2\,\mathrm{eV}^2$$

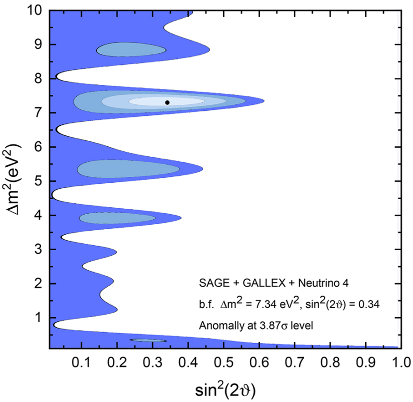
$$\sin^2 2\theta_{ee} \simeq 0.35$$



Consistencey of Gallium and NEUTRINO-4 anomalies

1809.10561





1905.07437

almost 4σ anomaly

Problems with reactor experiments

- finite size ΔL_S of antineutrino source (nuclear reactor)
  smearing oscillations after averaging over $\Delta L_S \sim L_{osc}$
- finite energy resolution ΔE_D of antineutrino detector
  smearing oscillations after averaging over $\Delta E_S \sim L_{osc}$
  DANSS: $\Delta E/E = 34\%$ at 1 MeV,
  NEUTRINO-4: $\Delta E/E = 16\%$ at 1 MeV
- poor shielding of cosmic background
  low signal-to-background ratio
  PROSPECT: S/B=1.36,
  STEREO: S/B=0.9,
  NEUTRINO-4: S/B=0.54

Monochromatic compact source is needed !!

Baksan Experiment on Sterile Transition

proposal: 1006.2103, 1204.5379, ...

artificial dichromatic source:

^{51}Cr of 3 MCi ($\Delta W/W < 0.5\%$)

neutrino flux measurment:

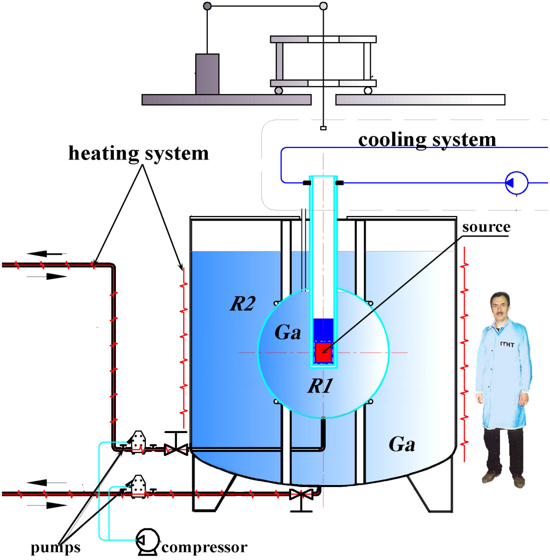
$^{71}\mathrm{Ga} + \nu_e \to {}^{71}\mathrm{Ge} + e^-$

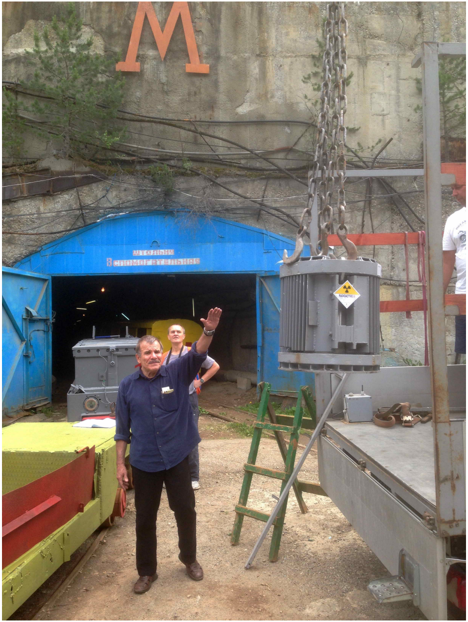
2 detector volumes:
for the flux cross check

geometry is chosen:
to search for $\simeq 1$ eV neutrino

data taking:
July–September 2019

$\tau_{^{51}\mathrm{Cr}} = 27.7$d

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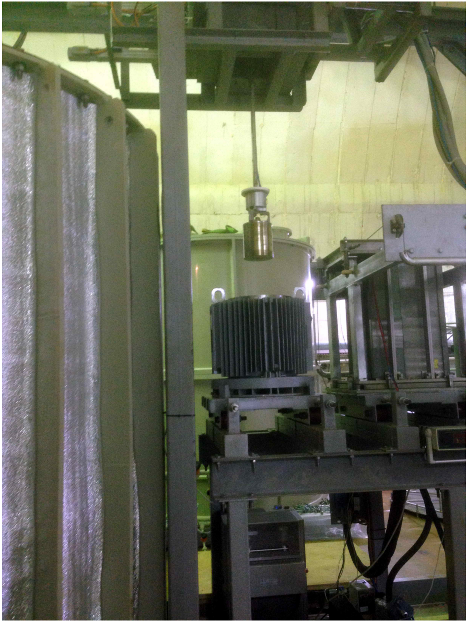
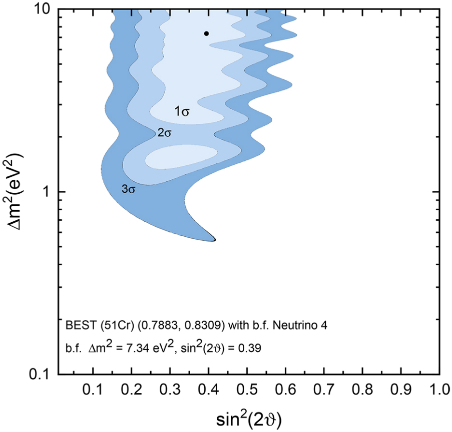
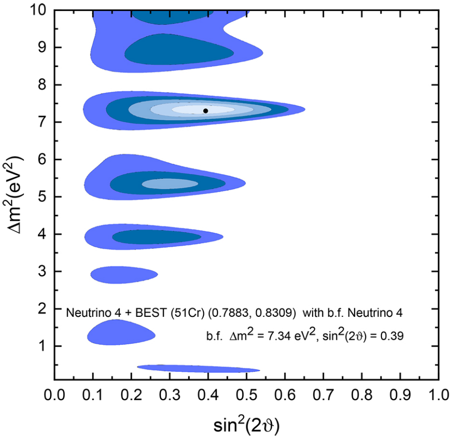


If NEUTRINO-4 confirmed





1905.07437

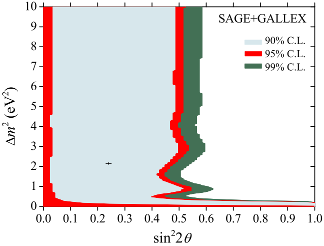
It will be 5σ discovery

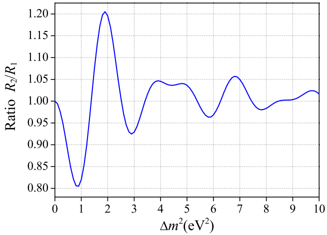
Summary on light sterile neutrinos

- Introducing sterile neutrinos is the most economic explanation of neutrino oscillations within renormalizable approach
- 1 eV- sterile neutrinos are required to explain ν anomalies
- with a little modification can be consistent with standard ΛCDM cosmology
- there are many issues in reactor neutrino anomaly...
  DANSS changed results (2019)
  $$\Delta m^2 = 1.4\,\text{eV}^2\,,\ \sin^2 2\theta = 0.05 \longrightarrow \Delta m^2 = 0.35\,\text{eV}^2\,,\ \sin^2 2\theta = 0.11$$
  which is consistent (2σ) with Gallium anomaly
- Neutrino-4 is consistent with Gallium anomaly (together $\approx 4\sigma$)
- BEST is testing all these hypotheses right now
  final results in 2021 stay tuned

Backup slides

Gallium anomaly: SAGE and GALLEX, $\nu_e \to N$?



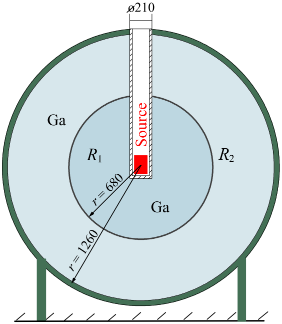


for $\sin^2 2\theta = 0.3$

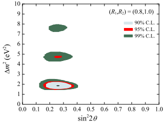
^{71}Ga$\to^{71}$Ge
due to ^{51}Cr and ^{37}Ar sources

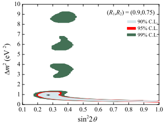
$$\frac{N^{obs}}{N^{exp}} = 0.87 \pm 0.05$$

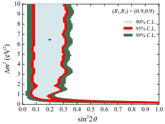
SAGE proposal of the test: 1006.2103

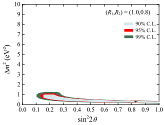


intensive ν-source ^{51}Cr



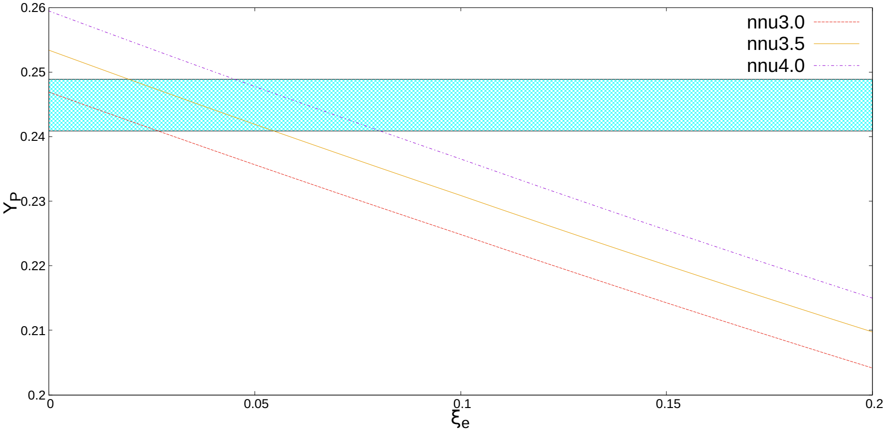




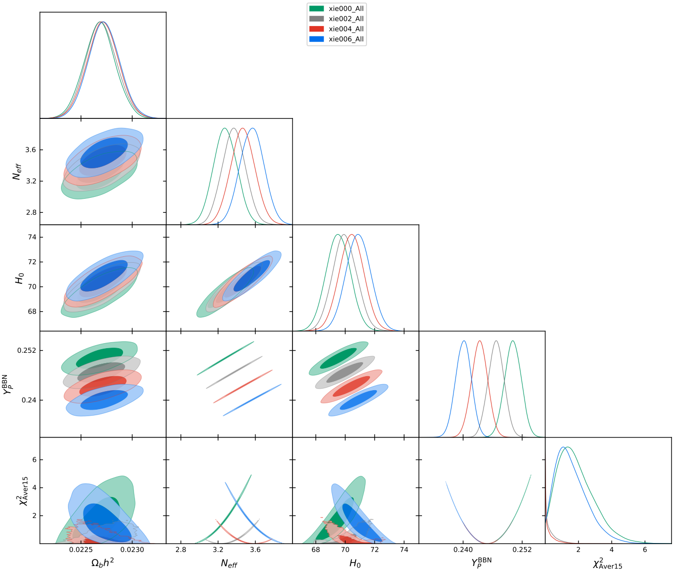


BBN: extra-radiation and lepton asymmetry

2104.04381

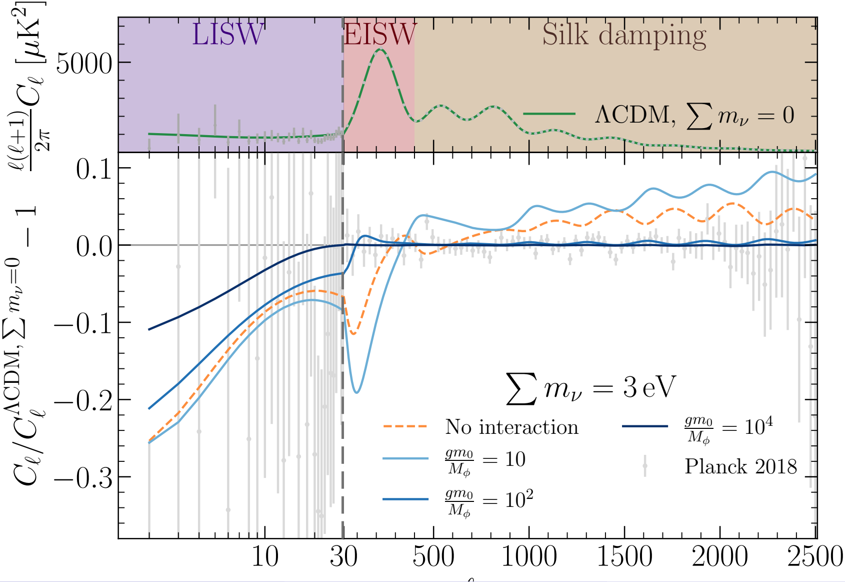


Hubble: extra-radiation and lepton asymmetry 2104.04381



CMB: 'heavy' neutrinos with long-range force

2101.05804



CMB: 'heavy' neutrinos with long-range force

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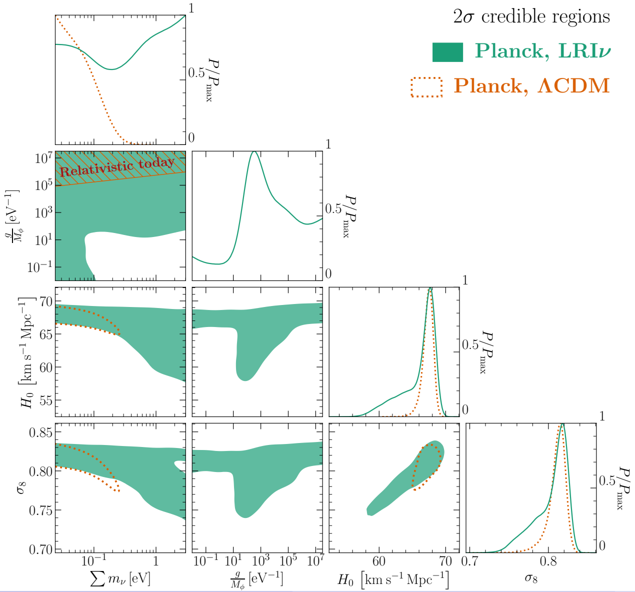

CMB: 'heavy' neutrinos with long-range force

2101.05804