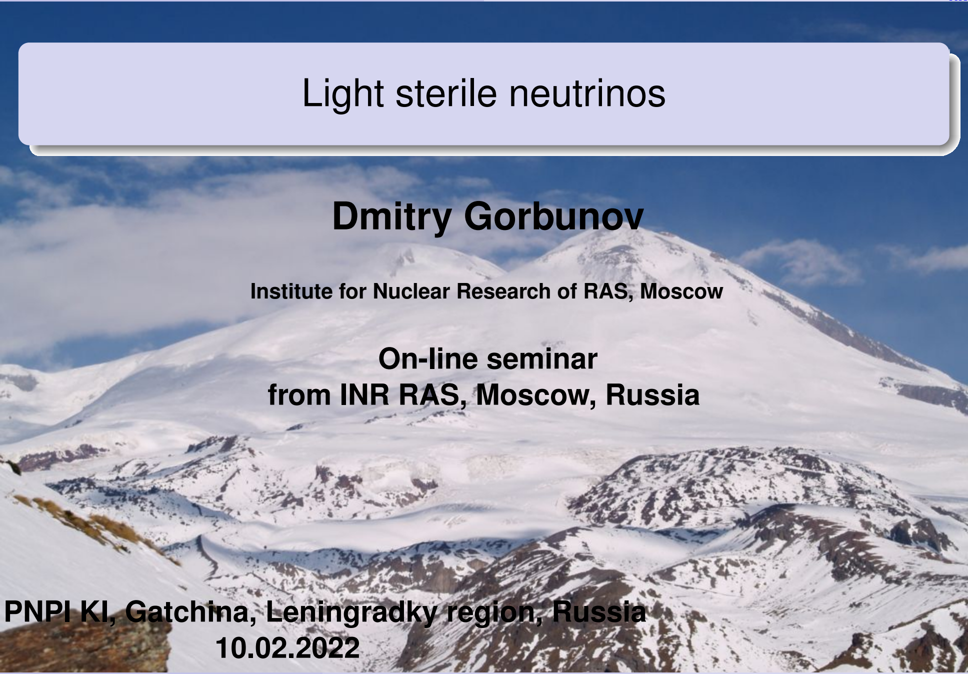

Light sterile neutrinos

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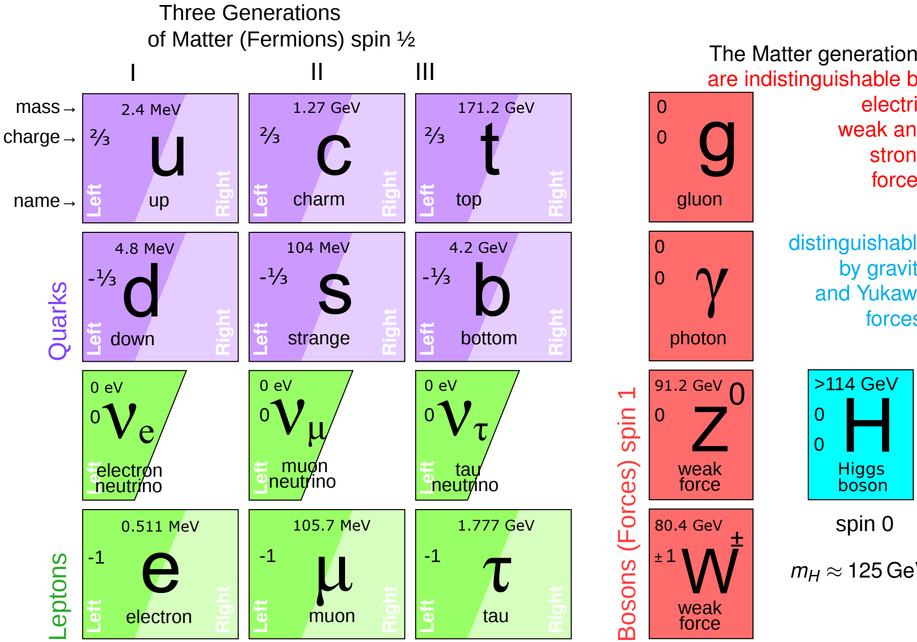
On-line seminar
from INR RAS, Moscow, Russia

PNPI KI, Gatchina, Leningradky region, Russia
10.02.2022



Three Generations
of Matter (Fermions) spin ½

	I	II	III
mass → charge → name →			
Quarks	2.4 MeV ⅔ u up Left Right	1.27 GeV ⅔ c charm Left Right	171.2 GeV ⅔ t top Left Right
Quarks	4.8 MeV -⅓ d down Left Right	104 MeV -⅓ s strange Left Right	4.2 GeV -⅓ b bottom Left Right
Leptons	0 eV 0 ν_e electron neutrino Left	0 eV 0 ν_μ muon neutrino Left	0 eV 0 ν_τ tau neutrino Left
Leptons	0.511 MeV -1 e electron Left Right	105.7 MeV -1 μ muon Left Right	1.777 GeV -1 τ tau Left Right

Bosons (Forces) spin 1

0 0 g gluon	
0 0 γ photon	
91.2 GeV 0 Z^0 weak force	>114 GeV 0 0 H Higgs boson
80.4 GeV ±1 $W^\pm$ weak force	spin 0

The Matter generations
are indistinguishable by
electric
weak and
strong
forces

distinguishable
by gravity
and Yukawa
forces

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

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

$$|\nu_j(t)\rangle = \mathrm{e}^{-im_jt}|\nu_j(0)\rangle \quad \to \quad |\nu_j(t,L)\rangle = \mathrm{e}^{-i\left(E_jt-p_jL\right)}|\nu_j(0)\rangle\ ,$$

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

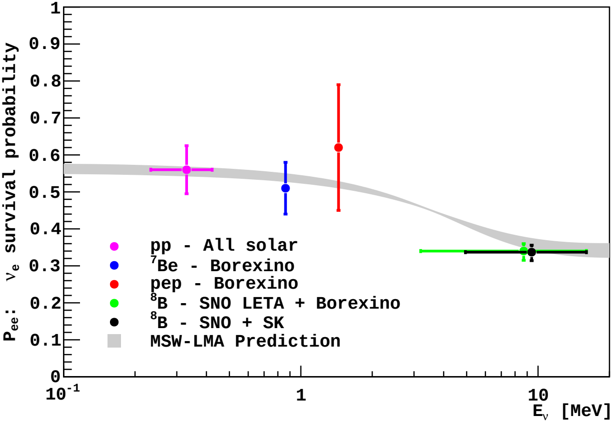
$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2}{4E}L\right)$$

- 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

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

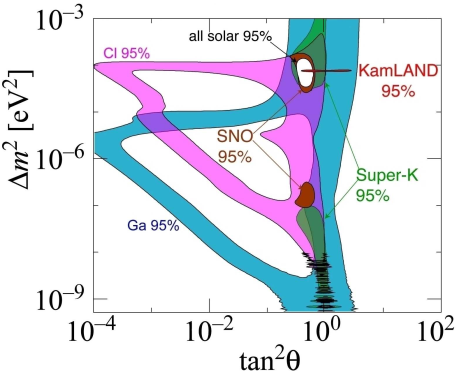
competes with

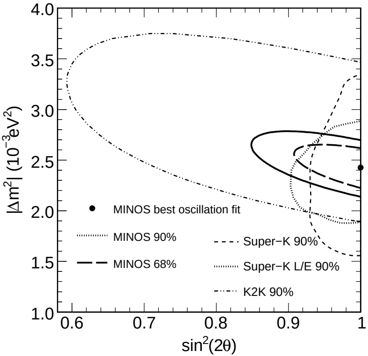
$$H_{eff} = \Delta m^2/2E$$

Neutrino oscillations: masses and mixing angles

Solar 2 × 2 “subsector”

Atmospheric 2 × 2 “subsector”





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

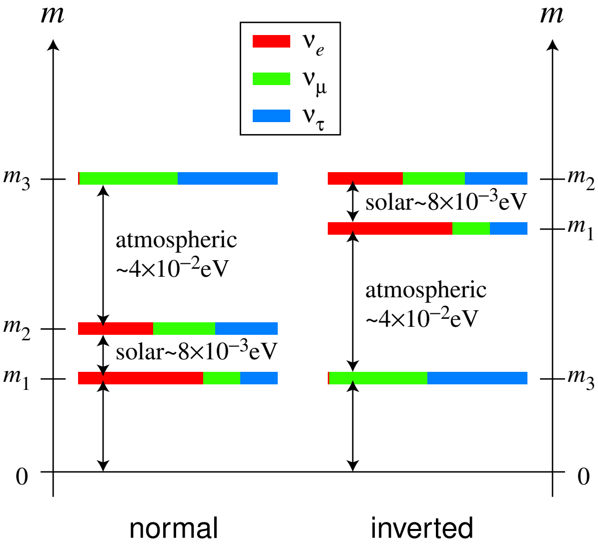
arXiv:0806.2237

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

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

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

Physics behind the neutrino oscillations is still elusive



hierarchy

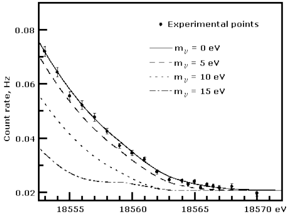
$m^2_{\text{sol}} \ll m^2_{\text{atm}}$

neutrino
mass
hierarchy ??

Direct searches for m_ν: cut in e-spectrum

$$\mathrm{T} \to {}^3\mathrm{He} + e + \bar{\nu}_e$$

$$(pnn) \to (ppn) + e + \bar{\nu}_e$$



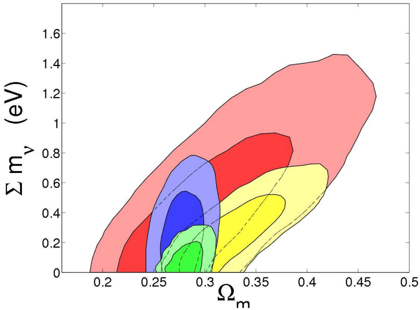
INR RAS, 1990-2000 years: $m_{\bar{\nu}_e} \lesssim 2\,\mathrm{eV}$

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

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

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

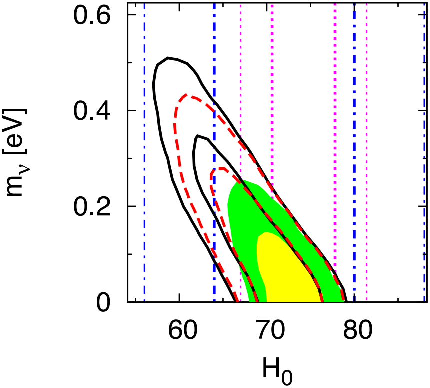
Cosmological limits: sub-eV scale... 12 years ago!!



LRG+BAO+WMAP5+SNe+BAO

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

0911.5291



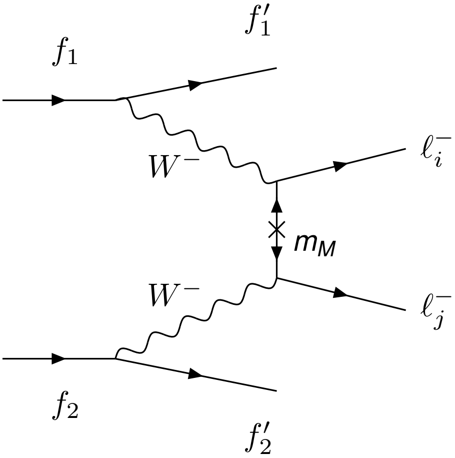
CMB+Hubble measurements

$\sum m_\nu < 0.20$ 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 → MiniBooNE appearance
  - SAGE & GALLEX: gallium anomaly disappearance
  - reactor antineutrinos → 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

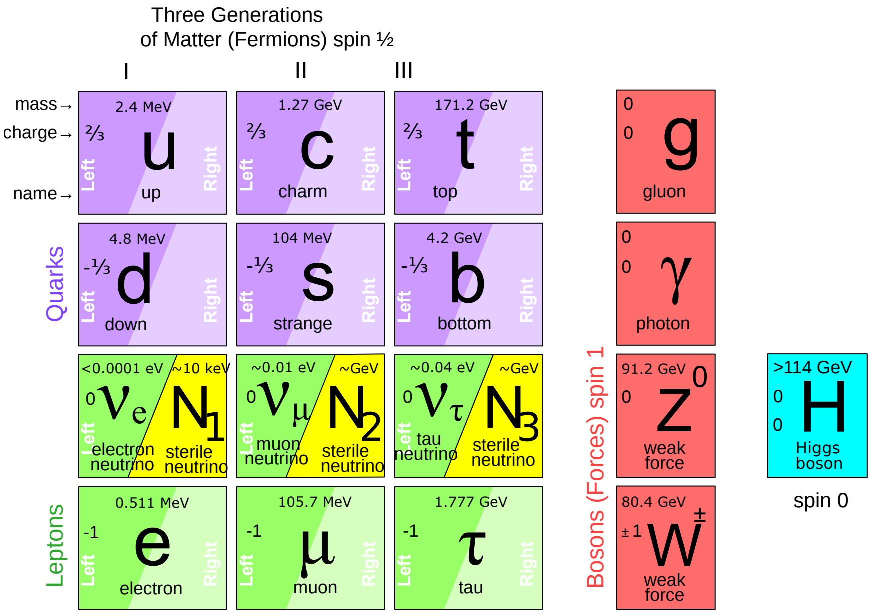
neutrino: explain observed oscillations by mixing with SM (active) neutrinos

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

	I	II	III
mass → charge → name →	2.4 MeV ⅔ u up Left Right	1.27 GeV ⅔ c charm Left Right	171.2 GeV ⅔ t top Left Right
Quarks	4.8 MeV -⅓ d down Left Right	104 MeV -⅓ s strange Left Right	4.2 GeV -⅓ b bottom Left Right
	<0.0001 eV 0 ν_e electron neutrino Left ~10 keV N_1 sterile neutrino	~0.01 eV 0 ν_μ muon neutrino Left ~GeV N_2 sterile neutrino	~0.04 eV 0 ν_τ tau neutrino Left ~GeV N_3 sterile neutrino
Leptons	0.511 MeV -1 e electron Left Right	105.7 MeV -1 μ muon Left Right	1.777 GeV -1 τ tau Left Right

Bosons (Forces) spin 1

0 0 g gluon	
0 0 γ photon	
91.2 GeV 0 Z^0 weak force	>114 GeV 0 0 H Higgs boson
80.4 GeV ±1 $W^\pm$ weak force	spin 0

Seesaw mechanism: $M_N \gg 1\,\mathrm{eV}$

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

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

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

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

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: $$\theta = \frac{M^D}{M_N} = \frac{v\,f}{2M_N} \ll 1$$

and mass eigenvalues

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

Violation of *L*, *C* and *CP* symmetries

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

- $f = 0 \quad \longrightarrow$ free fermion, no need to call 'sterile'
- $M_N = 0 \quad \longrightarrow$ 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'
- $f \neq 0, \quad M_N \neq 0 \quad \longrightarrow$ introduces new massive parameter,
  violates lepton symmetry *L*
  (and *C*- and *CP*-symmetry with several *N*'s)

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

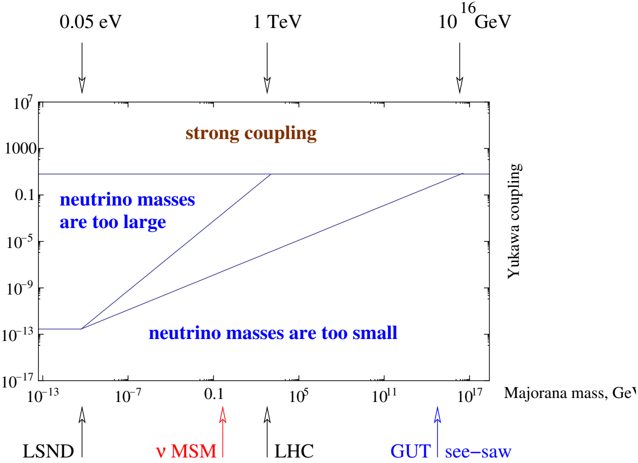
$$\hat{m}_a \sim \hat{f}^T \frac{1}{\hat{M}_N} \hat{f} v^2$$

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

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 $\sim 1\,\mathrm{eV}$
  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, $T_{reh} \sim 10\,\mathrm{MeV}$

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:

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

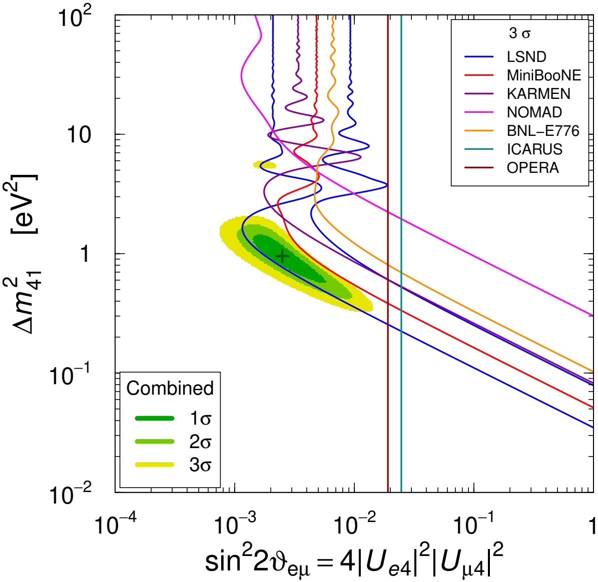
- transition probability appearance

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

- survival probability disappearance

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta_{\alpha\alpha} \cdot \sin^2\left(\frac{\Delta m^2_{41}}{4E} L\right), \quad \sin^2\theta_{\alpha\alpha} = |U_{\alpha 4}|^2$$

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



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

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

detection via inverse beta decay (IBD)

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

3.8σ effect transition probability

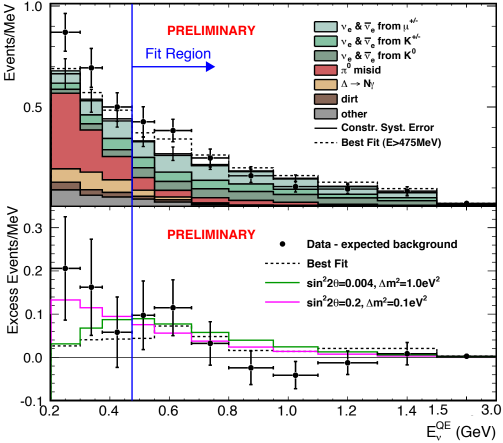
$$(2.64 \pm 0.67 \pm 0.45) \times 10^{-3}$$

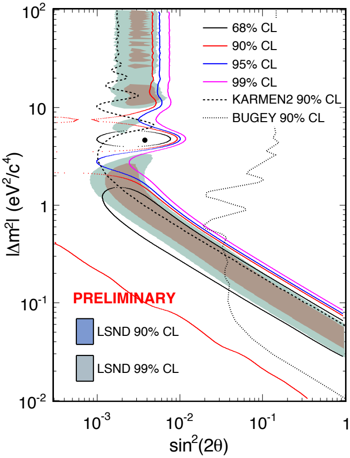
sterile neutrino mass

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

1901.08330

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





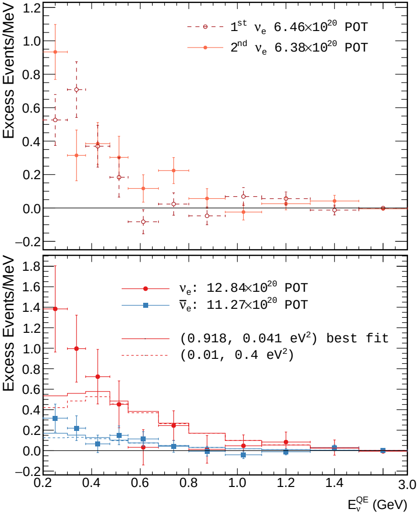
ν_e for ν_μ mode at MiniBooNE: no LSND-like effects,
However Low energy excess of ν_e

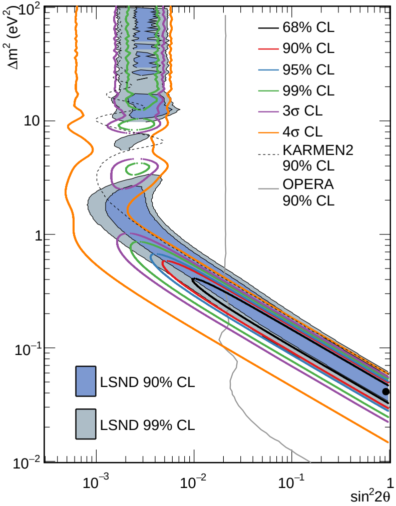
NuFuct2011, 1201.1519

LSND-like oscillations are preferable
only at 90%CL

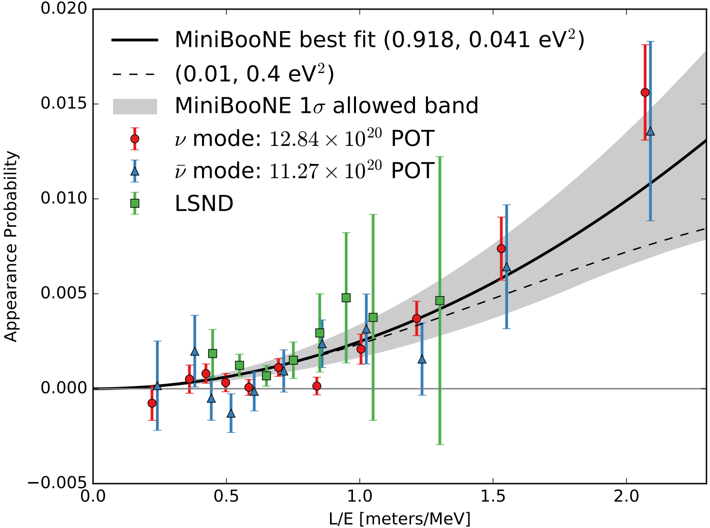
MiniBooNE anomalies (2018) . . . $\bar{\nu}_\mu \to \bar{\nu}_e$, $\nu_\mu \to \nu_e$

1805.12028



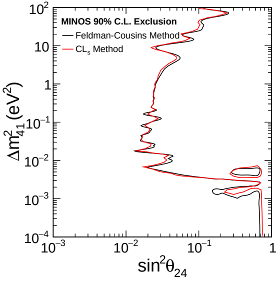


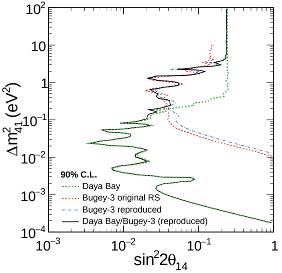
MiniBooNE anomalies (2018) . . . $\bar{\nu}_\mu \to \bar{\nu}_e$, $\nu_\mu \to \nu_e$

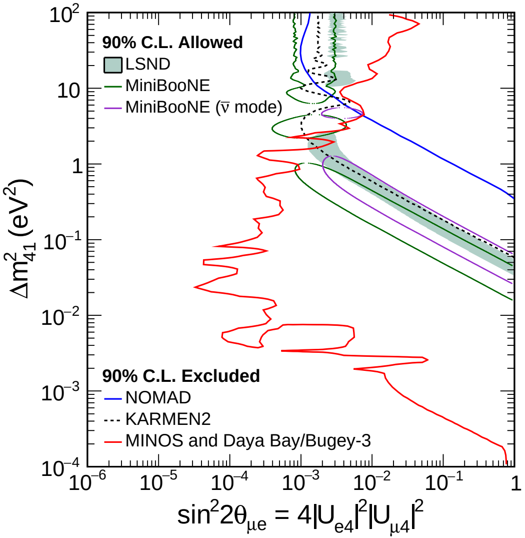


Looks like the LSND anomaly is closed . . . ?

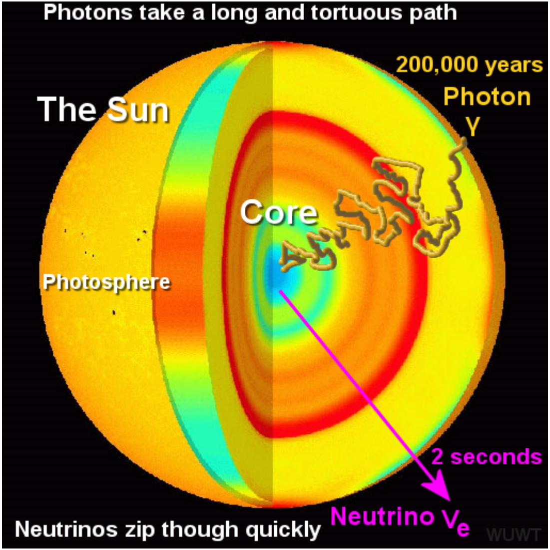
1607.01177

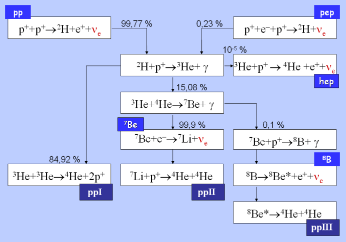


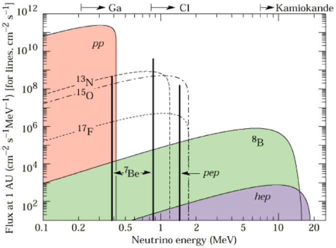




Solar neutrinos: fusion $p+p\to\ D+e^{+}+\nu_e, \ldots$



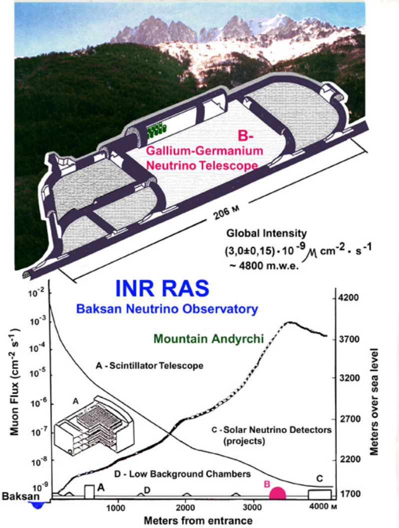




Measurement of the solar neutrino flux by SAGE

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

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

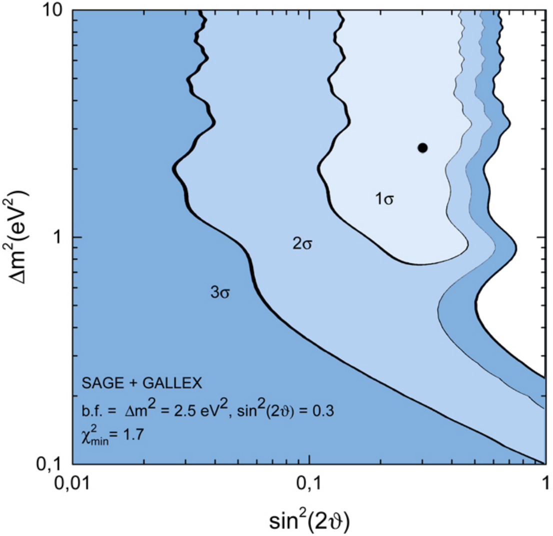
minimizing

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

combined best fit

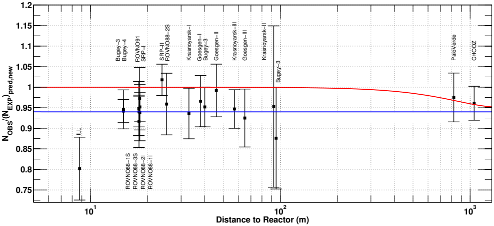
$$\Delta m^2 \approx 2.5\,\mathrm{eV}^2\,, \quad \sin^2\theta \approx 0.3$$

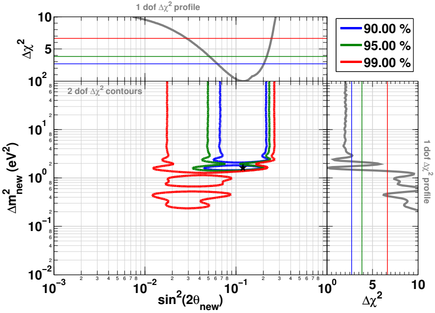
consistent with C.Giunti, M.Lavender (2011)



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:

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

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

Combined fit to Reactor and Gallium data

Bunch of proposals to test the anomaly…

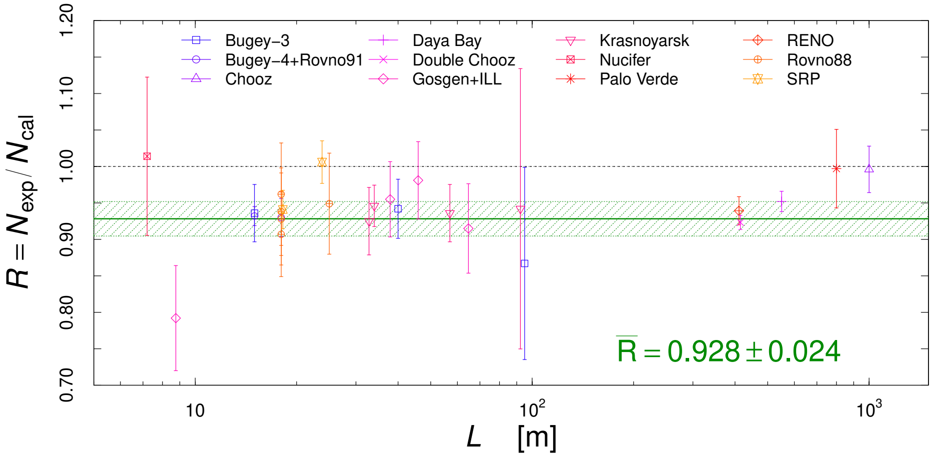
see 1204.5379

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

RENO, Daya Bay, Double Chooz

1901.08330

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



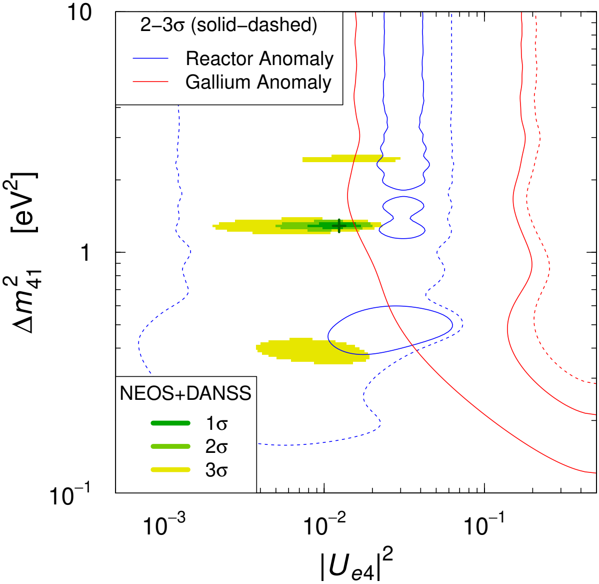
Reactor anomaly: new comers. . . new evidence?

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

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

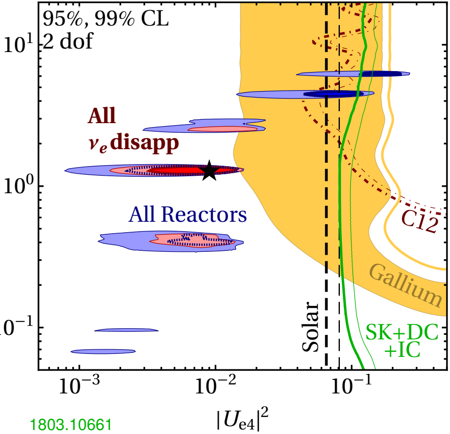
DANSS (Russia, 2017-. . .):
$\bar{\nu}_e$ from 3.1 $\mathrm{GW_{th}}$ reactor
movable detector at
$L = 10.7 - 12.5$ m
best fit

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

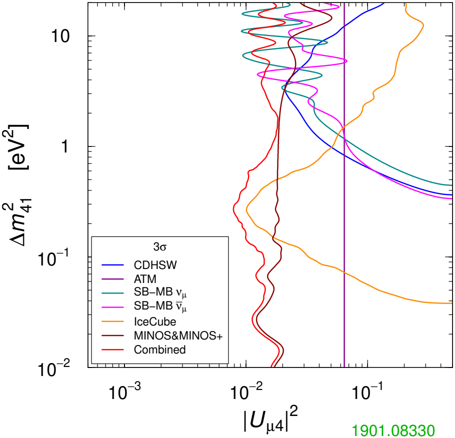


1801.06467

Disappearances of ν_e and ν_μ…

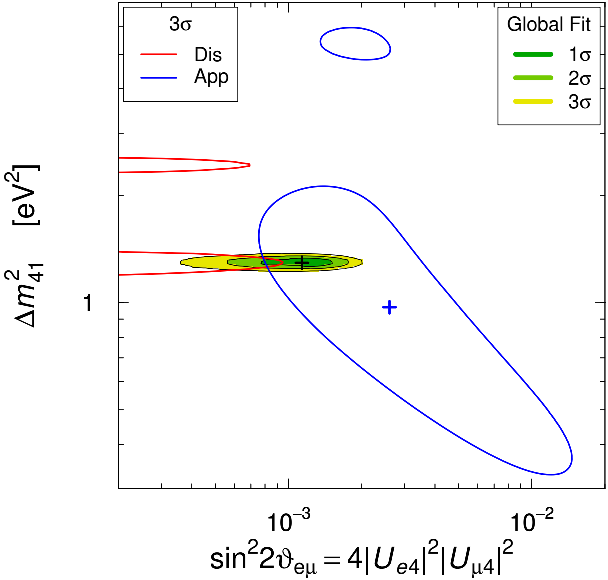


1803.10661



1901.08330

Disappearance vs Appearance: rulling out LSND ??



1901.08330

Reactor anomaly: recent results...

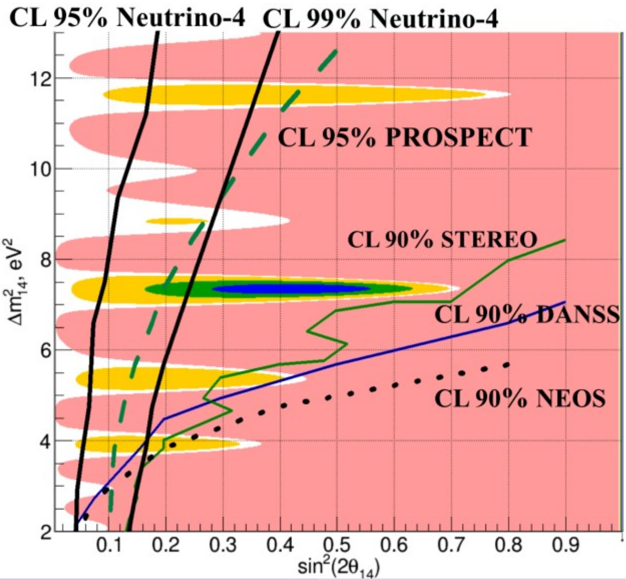
1809.10516

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

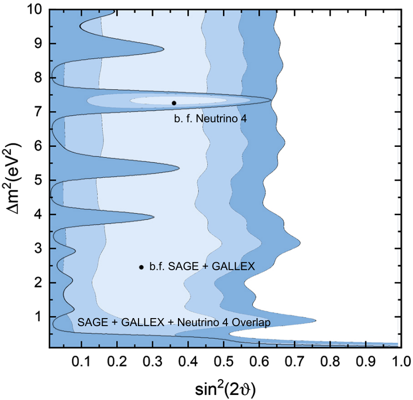
$$\Delta m^2 \simeq 7.2\,\mathrm{eV}^2$$

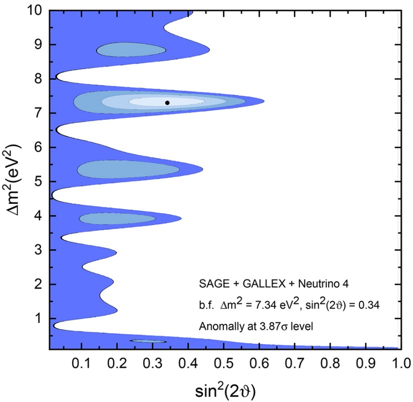
$$\sin^2 2\theta_{ee} \simeq 0.35$$



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 ($\Delta W/W < 0.5\%$)

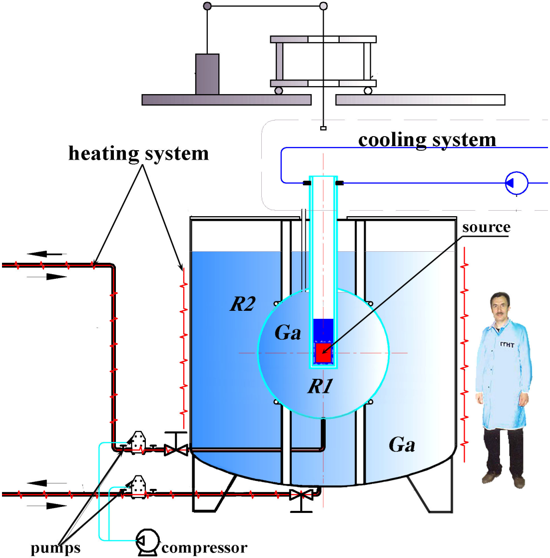
neutrino flux measurment:
$^{71}\mathrm{Ga} + \nu_e \to {}^{71}\mathrm{Ge} + e^-$

2 detector volumes:
for the flux cross check

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

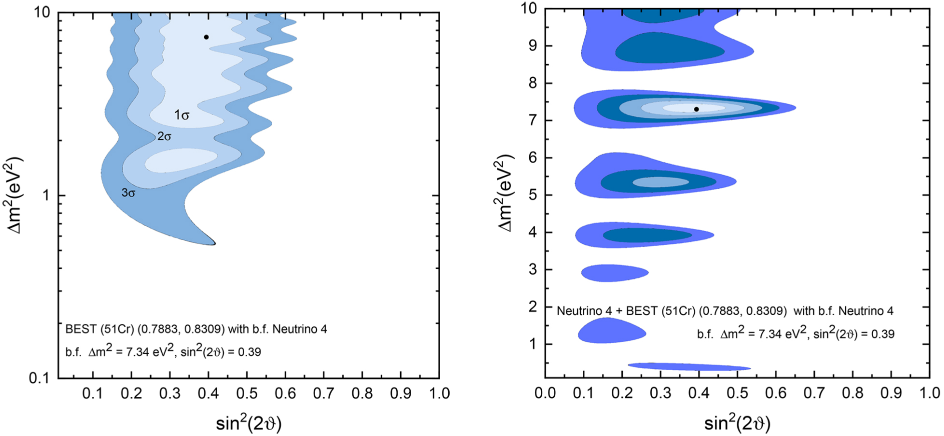
data taking:
July–September 2019

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




М
ШТОЛЬНЯ
ВСПОМОГАТЕЛЬНАЯ
RADIOACTIVE

If NEUTRINO-4 confirmed



1905.07437

It will be 5σ discovery

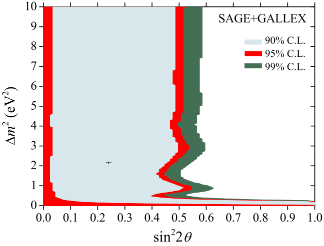
Summary on light sterile neutrinos

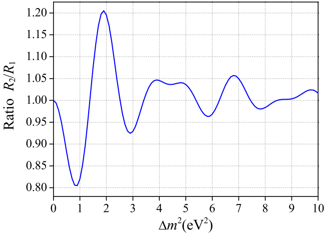
- Introducing sterile neutrinos is the most economic explanation of neutrino oscillations within renormalizable approach
- 1 eV- sterile neutrinos are required to explain ν anomalies
- with a little modification can be consistent with standard ΛCDM cosmology
- there are many issues in reactor neutrino 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

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



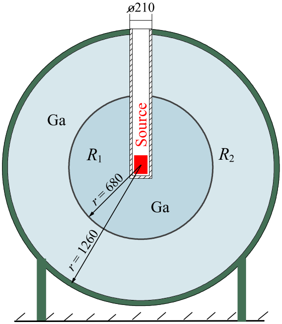


for $\sin^2 2\theta = 0.3$

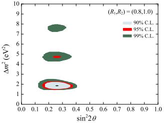
^{71}Ga$\to$^{71}Ge
due to ^{51}Cr and ^{37}Ar sources

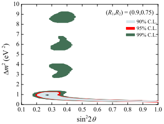
$$\frac{N^{obs}}{N^{exp}} = 0.87 \pm 0.05$$

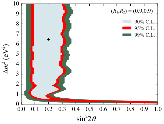
SAGE proposal of the test: 1006.2103

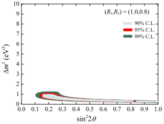


intensive ν-source ^{51}Cr



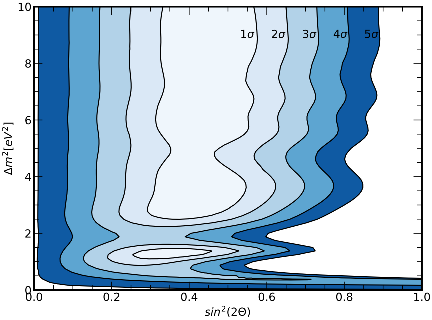


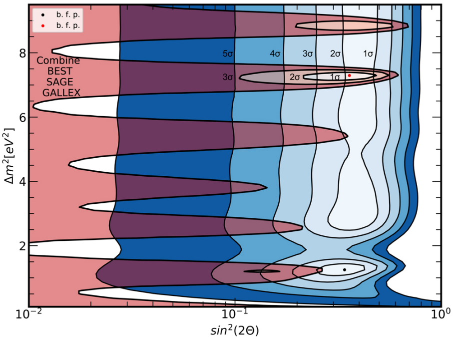




BEST: $R_1 = 0.791 \pm 0.050$, $R_2 = 0.766 \pm 0.050$

2109.11482



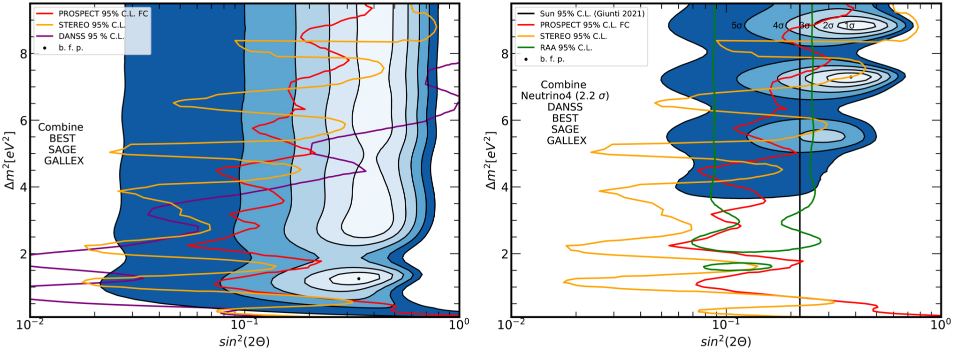


2109.14654

5-σ evidence for ν_s
confirmation of Gallium anomaly
consistent with NEUTRINO-4

BEST combined with others

2109.14654



5.7-σ combined evidence for ν_s

BEST b.f.p. is excluded by reactor neutrino experiments

Combined 2-σ region is consistent with all reactor experiments

Combined 2-σ region is excluded

from solar neutrinos
and from cosmology

Light sterile neutrinos in cosmology

Impact on processes

- Big Bang Nucleosynthesis: increase of expansion rate

$$H^2 = \frac{8\pi}{3} G\rho\,, \quad \rho = \frac{\pi^2}{30}\left(2\times T_\gamma^4 + 2\times(3+\Delta N_\nu)\times T_\nu^4\right)$$

  with $\Delta N_\nu > 0$ higher H neutrons freeze out earlier giving more Helium

- expansion rate at Equality, $\rho_{rad} = \rho_{mat}$, and at CMB epoch
  change of CMB anisotropy $-0.34 < \Delta N_\nu < 0.33$ (95% CL)

- become non-relativistic, but have high velocity
  free streaming leads to washing out of low-scale perturbations
  change galaxy spectrum limits on ΔN_ν & neutrino masses

Sterile neutrino production in cosmology

$$P(\nu_\alpha \to \nu_s) = \sin^2 2\theta_\alpha \cdot \sin^2\left(\frac{t}{2t_\alpha^{vac}}\right),$$

$$t_\alpha^{vac} = \frac{2E_\nu}{\Delta m^2}, \quad \Delta m^2 = m_s^2 - m_1^2 \simeq m_s^2.$$

$$H = U \cdot \mathrm{diag}\left(\frac{m_1^2}{2E_\nu}, \frac{m_2^2}{2E_\nu}\right) \cdot U^\dagger + V_{int},$$

$$U = \begin{pmatrix} \cos\theta_\alpha & \sin\theta_\alpha \\ -\sin\theta_\alpha & \cos\theta_\alpha \end{pmatrix}, \quad V_{int} = \begin{pmatrix} V_{\alpha\alpha} & 0 \\ 0 & 0 \end{pmatrix}.$$

$$V_{\tau\tau} = -\frac{14\pi}{45\alpha}\sin^2\theta_W \cos^2\theta_W \cdot G_F^2 T^4 \cdot E_\nu \approx -25 \cdot G_F^2 T^4 \cdot E_\nu,$$

Sterile neutrino production in cosmology

$$P\left(\nu_\alpha \to \nu_s\right) = \sin^2 2\theta_\alpha^{\text{pl}} \cdot \sin^2\left(\frac{t}{2t_\alpha^{\text{pl}}}\right),$$

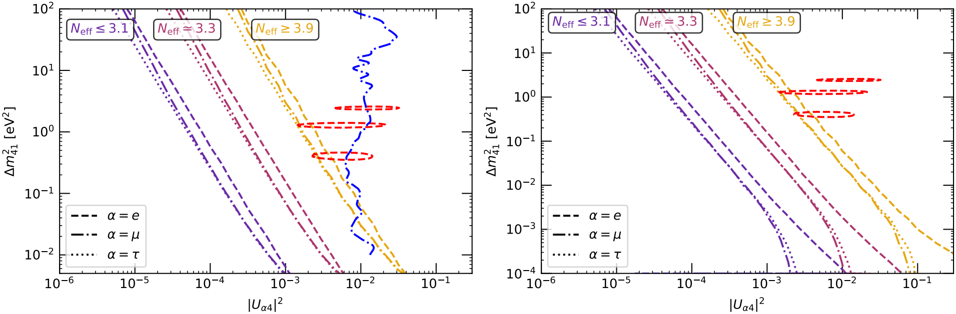
$$t_\alpha^{\text{pl}} = \frac{t_\alpha^{vac}}{\sqrt{\sin^2 2\theta_\alpha + (\cos 2\theta_\alpha - V_{\alpha\alpha}\cdot t_\alpha^{vac})^2}}, \quad \sin 2\theta_\alpha^{\text{pl}} = \frac{t_\alpha^{\text{pl}}}{t_\alpha^{vac}}\cdot \sin 2\theta_\alpha,$$

$$\frac{\partial}{\partial t} f_s - H\mathbf{p}\,\frac{\partial}{\partial \mathbf{p}} f_s = \frac{1}{4}\,\Gamma_\alpha \sin^2 2\theta_\alpha^{\text{pl}}\, f_\alpha(t,\mathbf{p})\,.$$

$$\Omega_{\nu_s} \simeq 0{,}2\cdot\left(\frac{\sin 2\theta_\alpha}{10^{-4}}\right)^2\cdot\left(\frac{m_s}{1\text{ keV}}\right)^2.$$

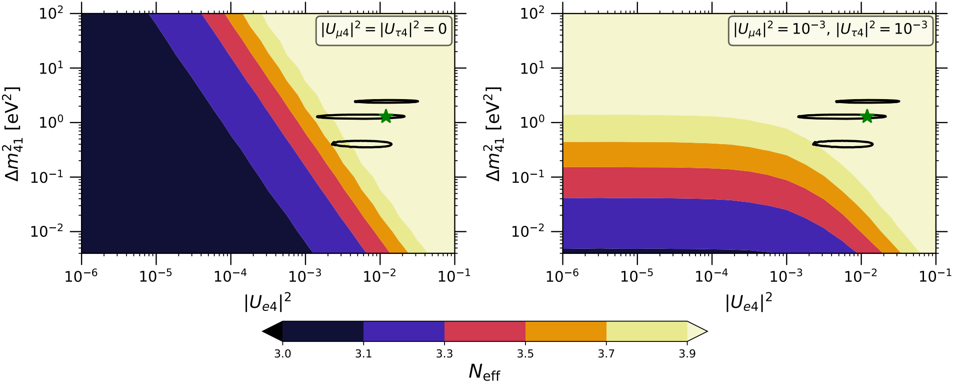
Limits from cosmology

1905.11290



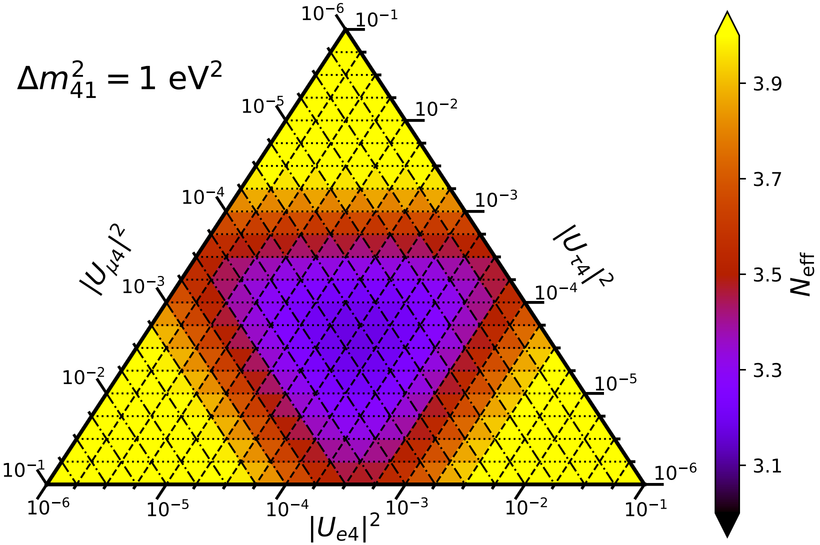
Limits from cosmology

1905.11290



Limits from cosmology

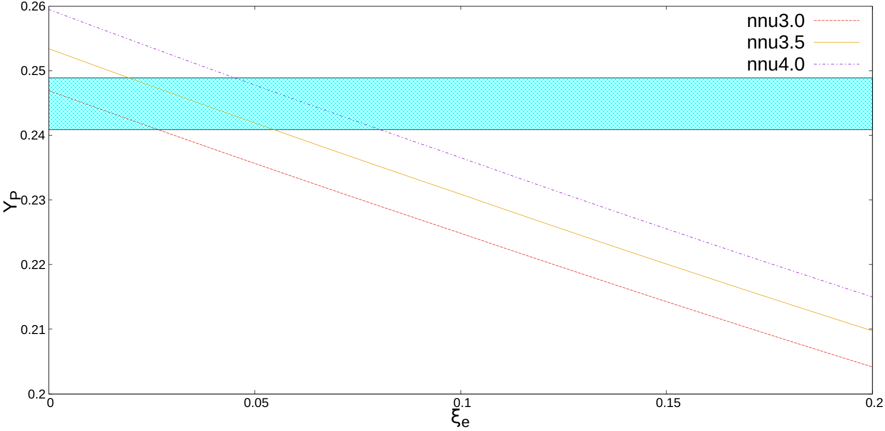
1905.11290



Backup slides

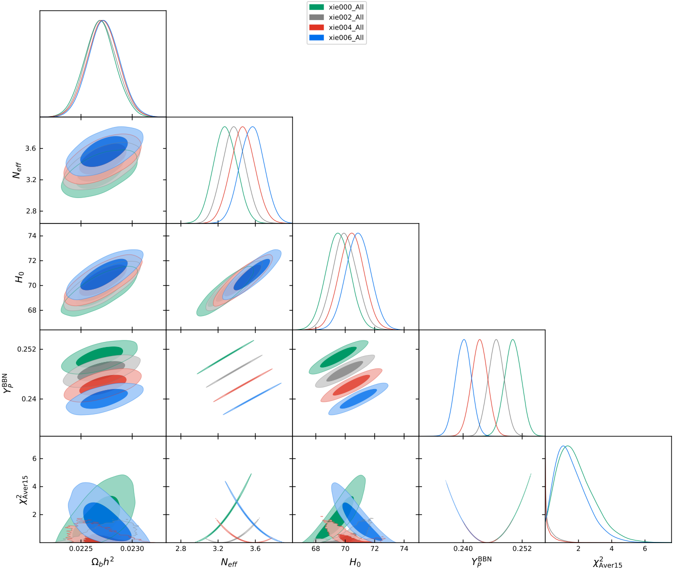
BBN: extra-radiation and lepton asymmetry

2104.04381



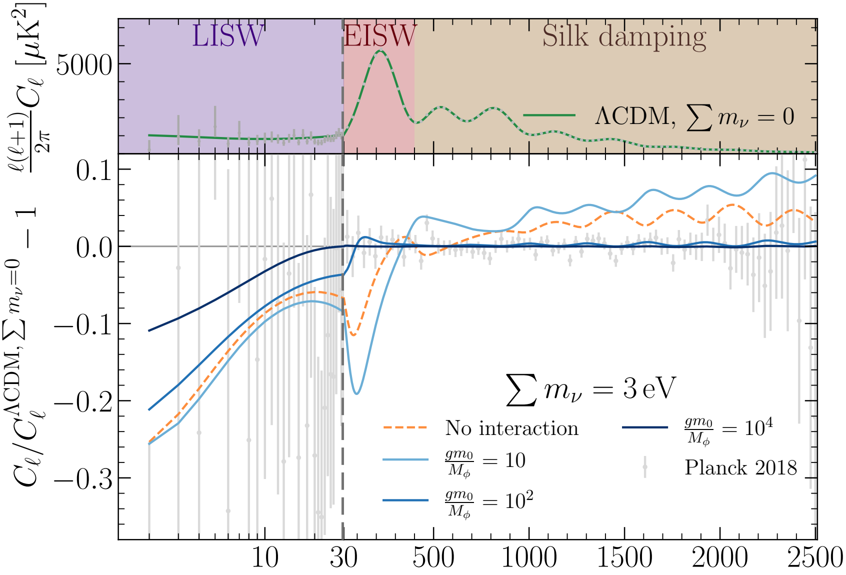
Hubble: extra-radiation and lepton asymmetry

2104.04381



CMB: 'heavy' neutrinos with long-range force

2101.05804



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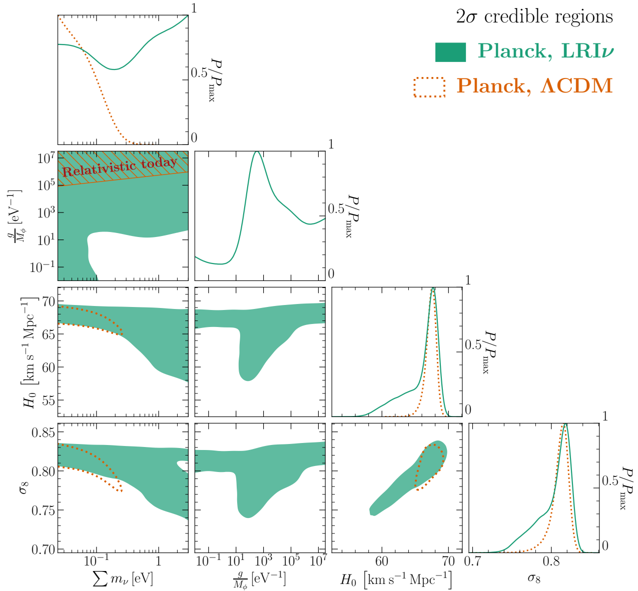
2101.05804



CMB: 'heavy' neutrinos with long-range force

2101.05804