Neutrino anomalies, light sterile neutrinos and Baksan Experiment on Sterile Transitions (BEST)

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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

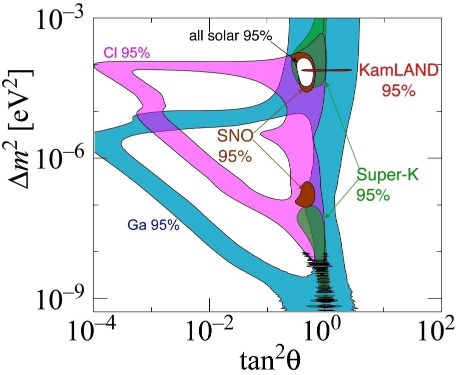
(PHENO)	(THEORY)
Neutrino oscillations	Dark energy (Ω_Λ)
Dark matter (Ω_{DM})	Strong CP-problem
Baryon asymmetry (Ω_B)	Gauge hierarchy
Inflationary stage	Quantum gravity

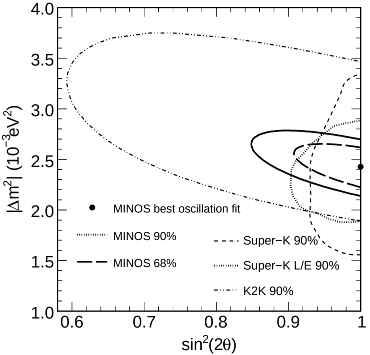
Only direct evidence for New Physics ???

Neutrino oscillations: masses and mixing angles

Solar 2×2 "subsector"

Atmospheric 2×2 "subsector"





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

arXiv:0806.2237

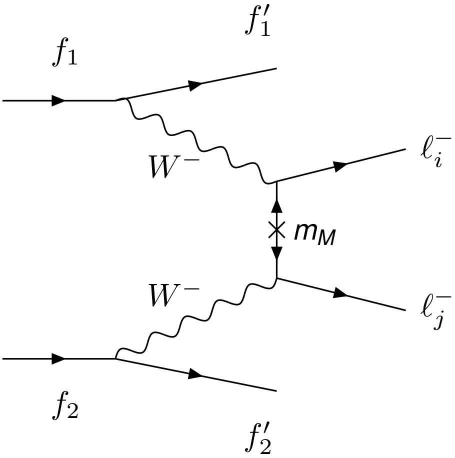
$m^2_{sol} \approx 7.4 \times 10^{-5}$ eV^2

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

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

Physics behind the neutrino oscillations is still elusive

nature of neutrino mass: Dirac vs Majorana?

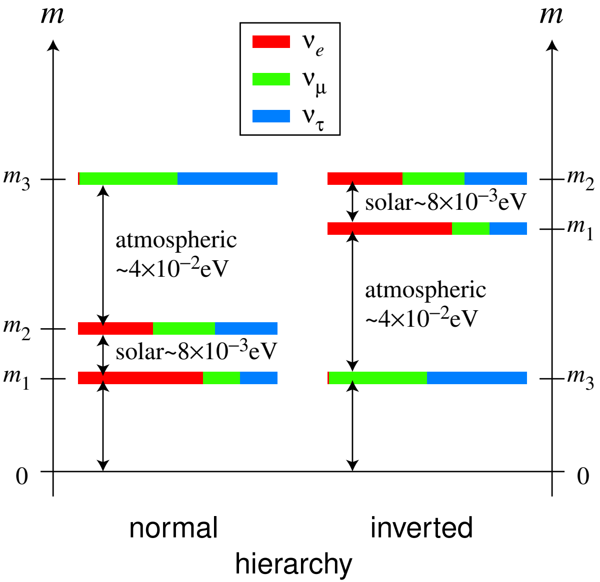


$0\nu\beta\beta$

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

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

Physics behind the neutrino oscillations is still elusive



$m_{sol}^2 \ll m_{atm}^2$

neutrino
mass
hierarchy ??

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

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

- 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

One more light neutral fermion. . .

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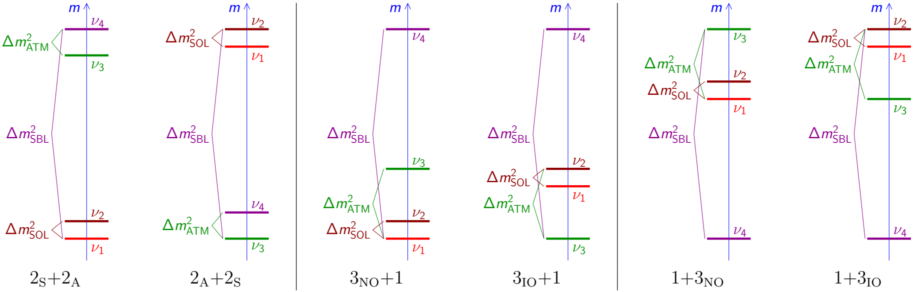


2 'heavy' neutrinos

- TOO bad for standard cosmology
- CONTRADICTS precise measurements of solar and atmospheric neutrino fluxes
- Too heavy for $0\nu\beta\beta$ if Majorana

1 'heavy' neutrino

- bad for standard cosmology
- some tension between appearence and disappearence

3 'heavy' neutrinos

- VERY bad for standard cosmology
- Too heavy for $0\nu\beta\beta$ if Majorana

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

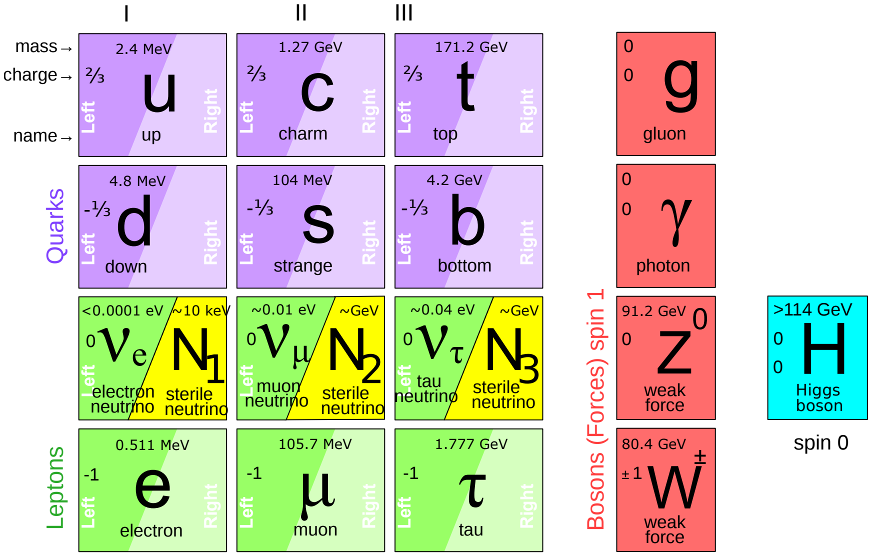
Attractive features:

- 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

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

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, ...
- 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:

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

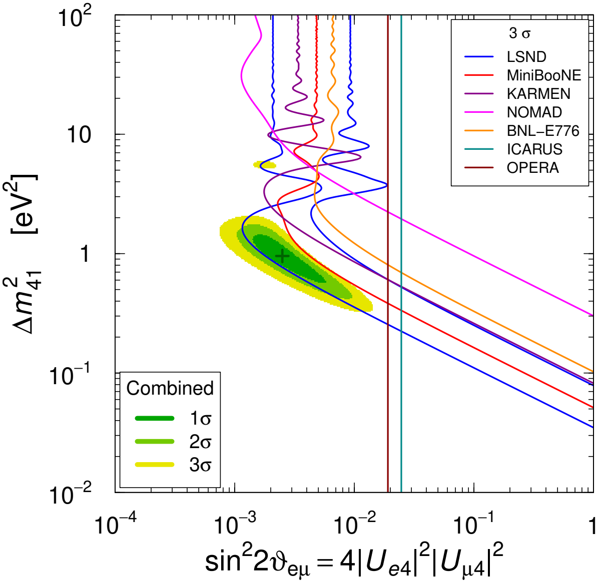
- transition probability — appearance

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

- 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

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

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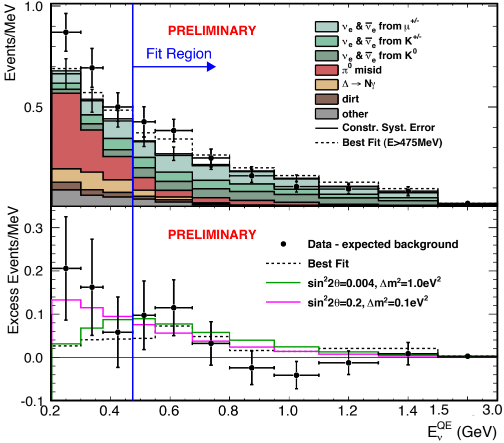
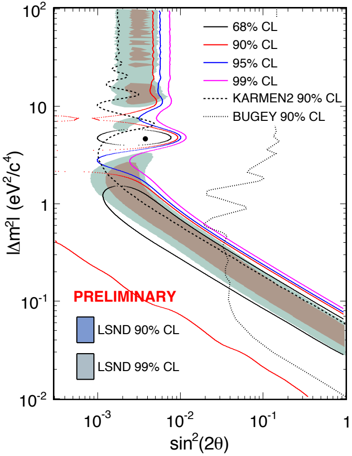
MiniBooNE anomalies (2011) ... $\bar{\nu}_\mu \to \bar{\nu}_e$, $\nu_\mu \to \nu_e$





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) . . . $\bar{\nu}_\mu \to \bar{\nu}_e$, $\nu_\mu \to \nu_e$

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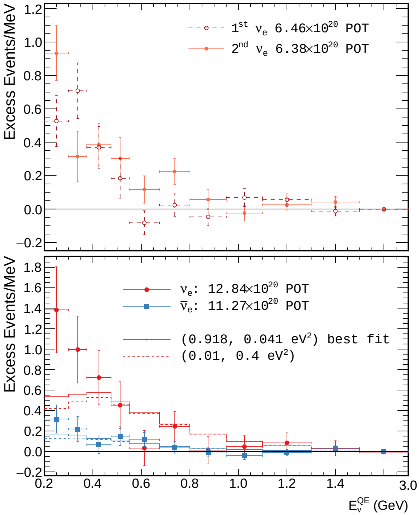
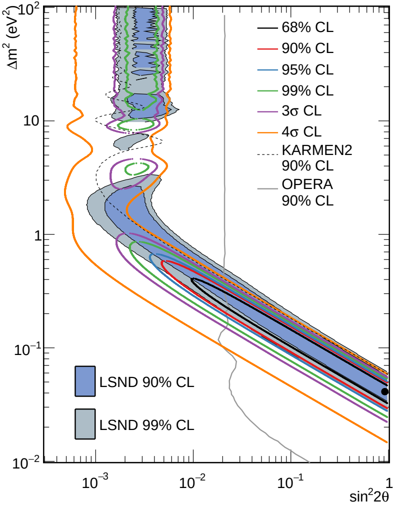
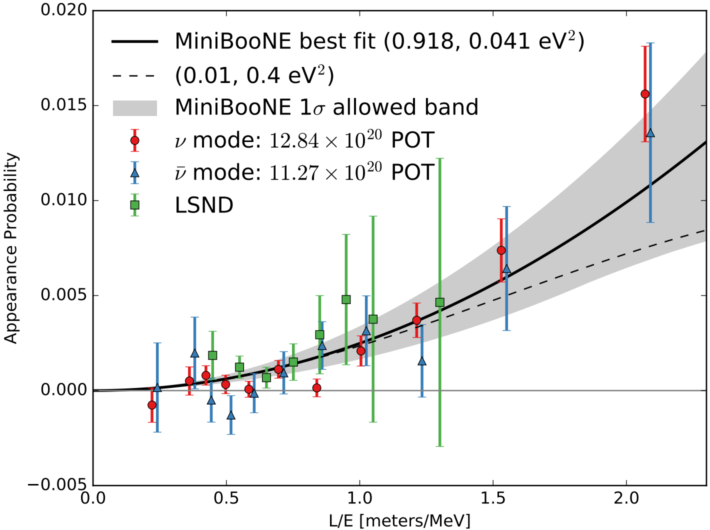
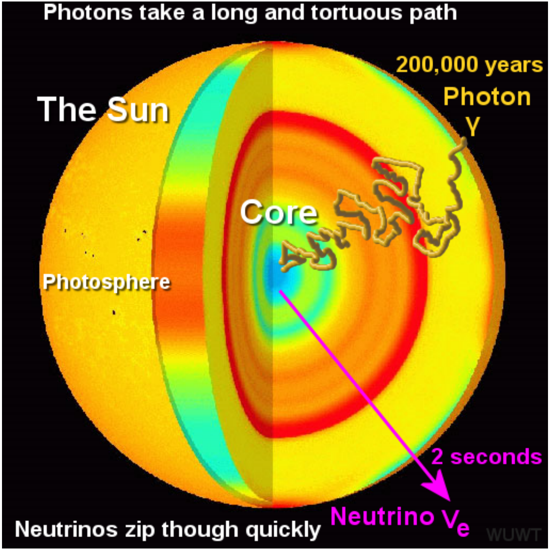


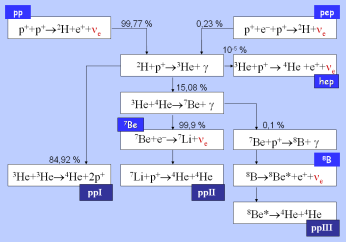


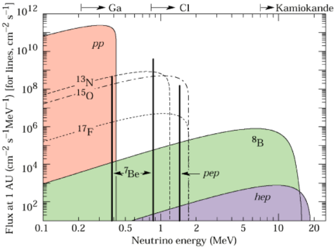
MiniBooNE anomalies (2018) . . . $\bar{\nu}_\mu \to \bar{\nu}_e$, $\nu_\mu \to \nu_e$



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



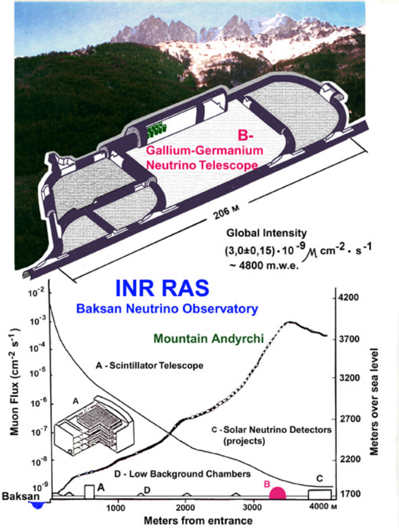




Measurement of the solar neutrino flux by SAGE

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

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



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

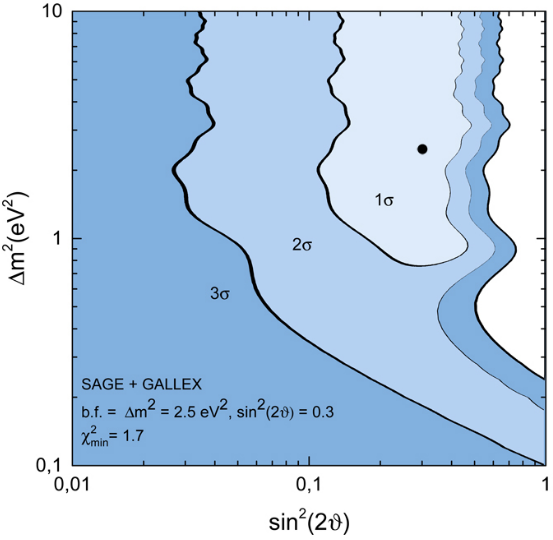
minimizing

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

combined best fit

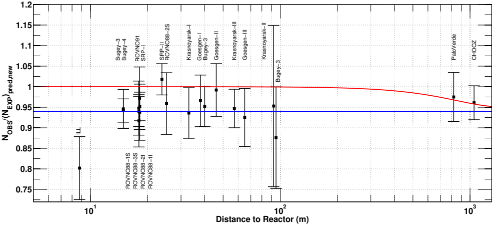
$$\Delta m^2 \approx 2.5\,\mathrm{eV}^2\,, \quad \sin^2\theta \approx 0.3$$

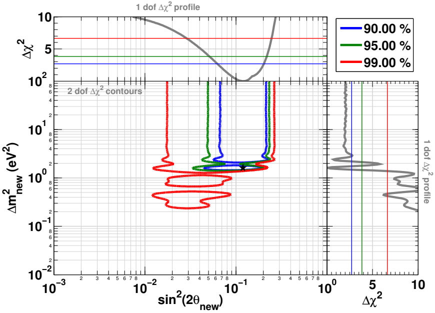
consistent with C.Giunti, M.Lavender (2011)



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

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, $\sim 3\%\ldots$

Combined fit to Reactor and Gallium data

Bunch of proposals to test the anomaly...

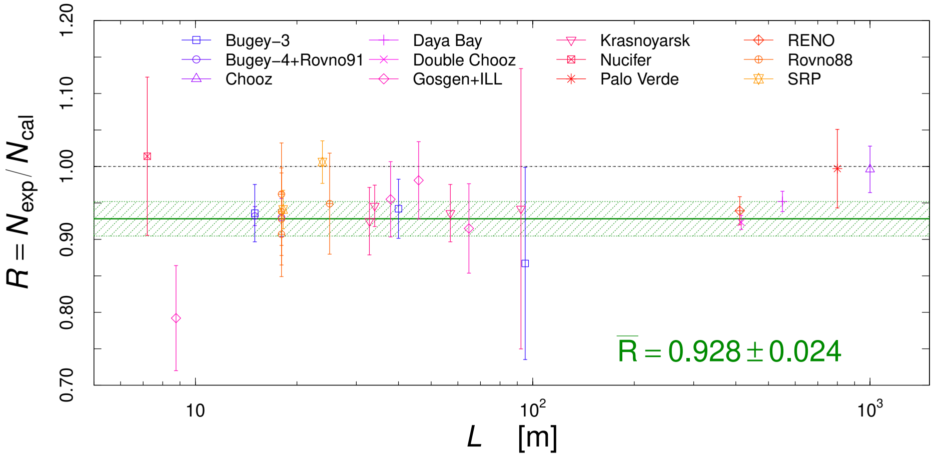
see 1204.5379

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

RENO, Daya Bay, Double Chooz

1901.08330

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



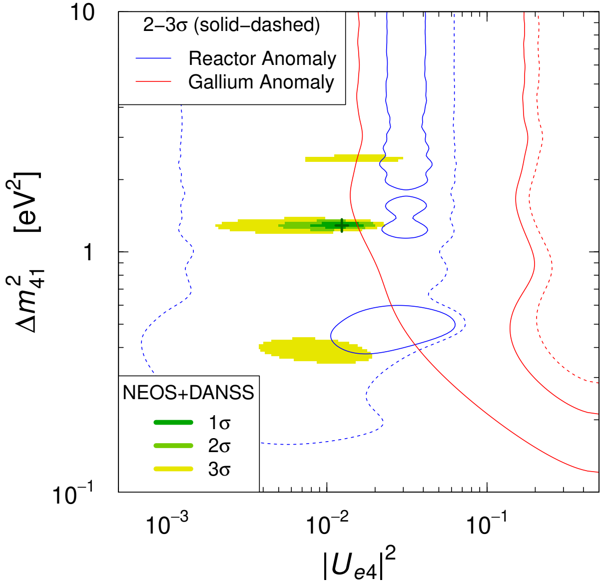
Reactor anomaly: new comers. . . new evidence?

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

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

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

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



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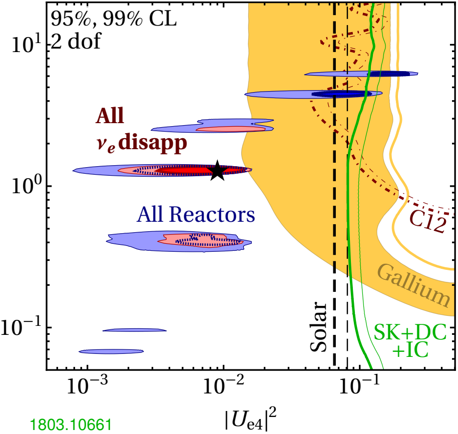
Disappearances of ν_e and ν_μ...



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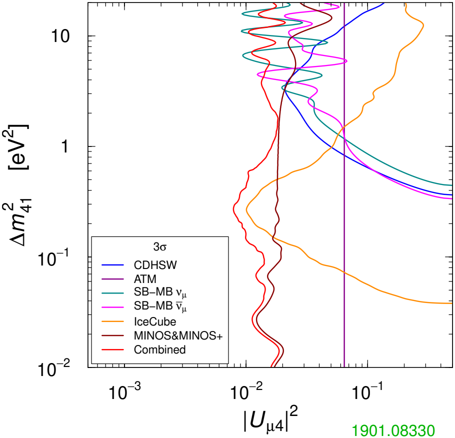

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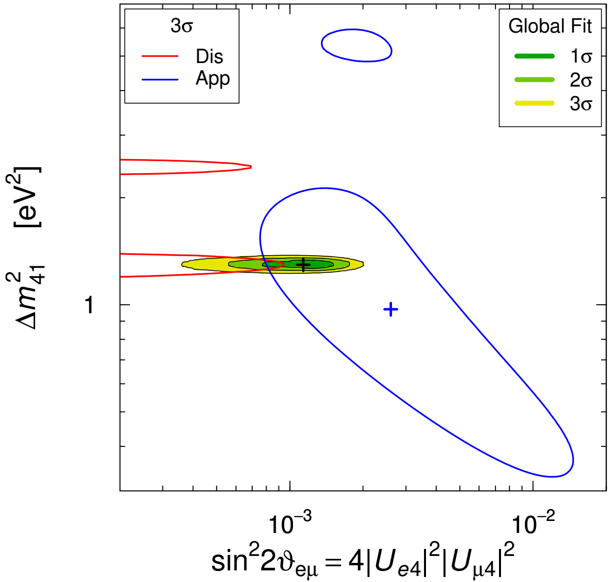
Disappearance vs Appearance: rulling out LSND ??



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Reactor anomaly: last year results. . .

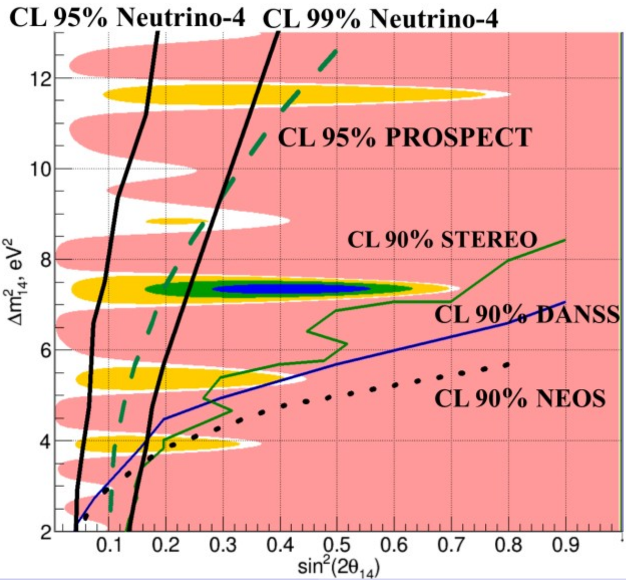
1809.10516

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

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

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

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



Consistencey of Gallium and NEUTRINO-4 anomalies

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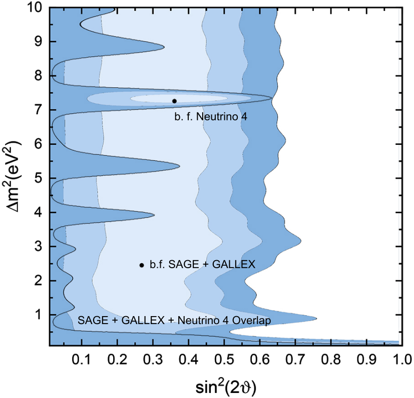

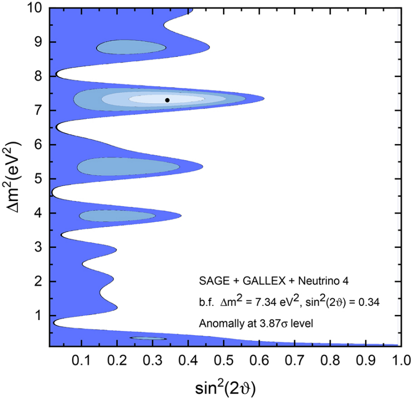

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almost 4σ anomaly

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:

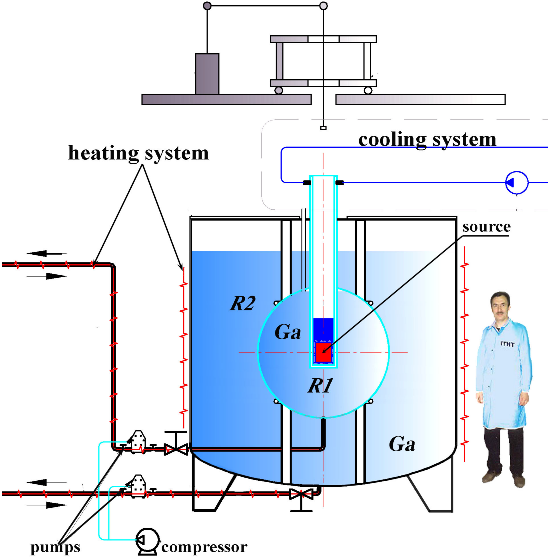
$^{71}\mathrm{Ga} + \nu_e \to {}^{71}\mathrm{Ge} + e^-$

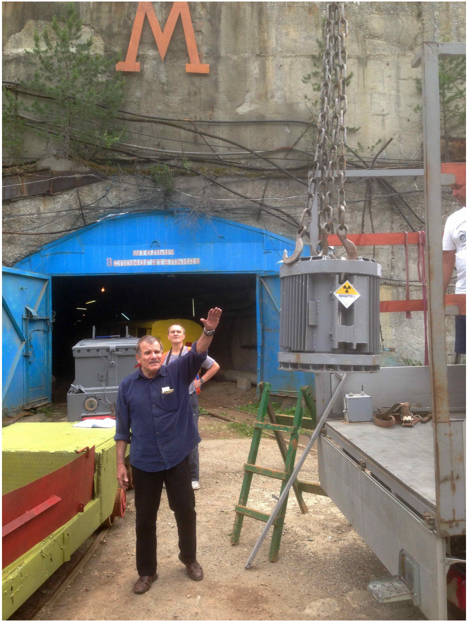
2 detector volumes:
for the flux cross check

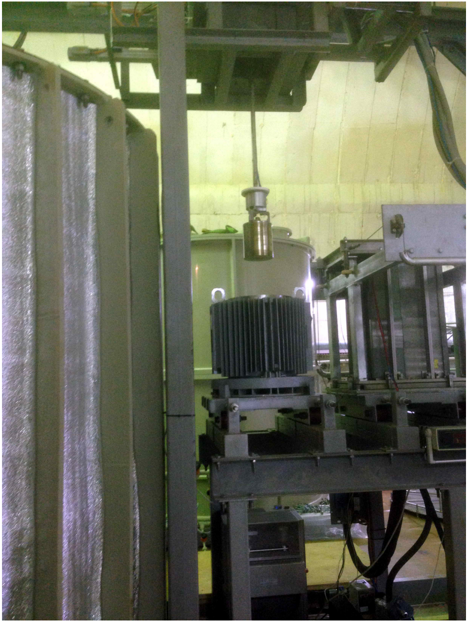
geometry is chosen:
to search for $\simeq 1$ eV neutrino

data taking:
July–September 2019

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




М
штольня
вспомогательная



BEST layout

1602.03826

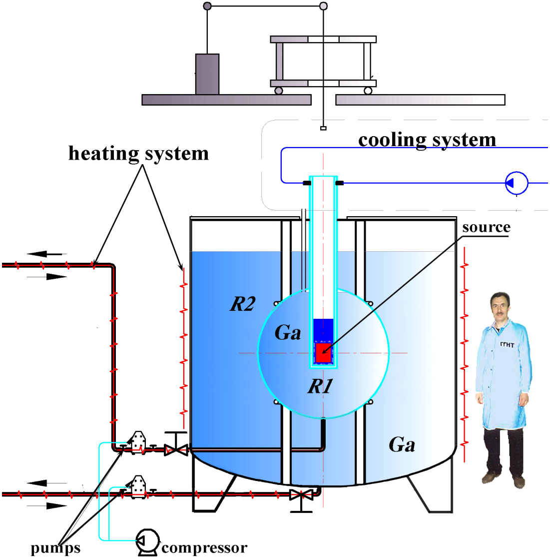
Geometry:

^{51}Cr source is
$\approx$ sphere of $r = 10.5\,\mathrm{cm}$

2 detector volumes:
sphere of
$R_1 = 0.66\,\mathrm{m}$,
inside a cylindrical vessel of
$R_2 = 1.096\,\mathrm{m}$ and $h = 2\,R_1$

use each volume separately
$R^{th} \propto \int_V dr\,\left[P(E_1, |\vec{r} - \delta\vec{r}|) f_1 + \ldots\right]$

Take the uncertainty as
$\sigma = 0.05\,R$



BEST constraints in case of null results

Let would-be measured value R_m be Gaussian with c.v. R_c and $\sigma = 0.05\,R_c$

$$D_{R_c,\sigma_{\text{BEST}}}(R_m) = \frac{1}{\sqrt{2\pi}\sigma_{\text{BEST}}} \times \exp\left(-\frac{(R_m - R_c)^2}{2\sigma^2_{\text{BEST}}}\right).$$

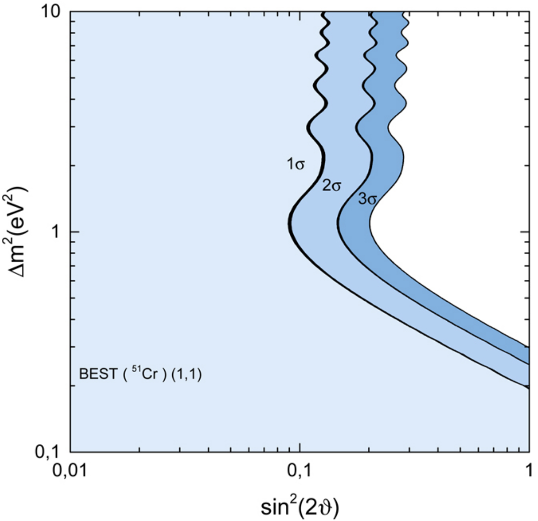
and the model parameters are distributed by maximization of

$$\mathscr{L}_{\sigma_{\text{BEST}}}(\Delta m^2, \sin^2 2\theta; R_m) \propto \exp\left(-\frac{\left(R_m - R^{th}(\Delta m^2, \sin^2 2\theta)\right)^2}{2\sigma^2_{\text{BEST}}}\right)$$

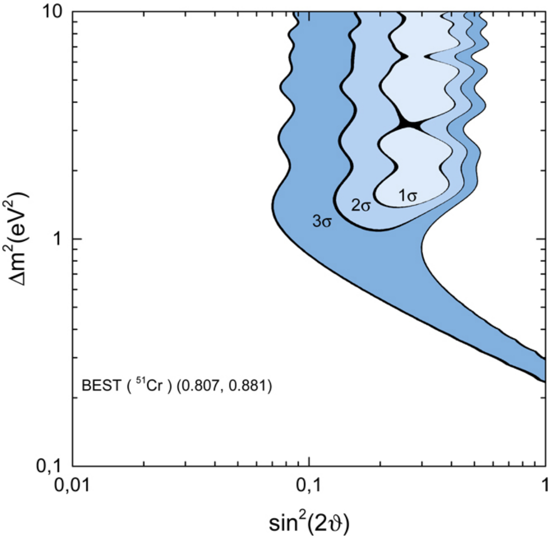
marginalizing over R_m

$$\int dR_m \mathscr{L}_{\sigma_{\text{BEST}}}(\Delta m^2, \sin^2 2\theta; R_m) D_{R_c,\sigma_{\text{BEST}}}(R_m) = \mathscr{L}_{\sqrt{2}\sigma_{\text{BEST}}}(\Delta m^2, \sin^2 2\theta; R_c).$$

the same distribution but with $\sigma \to \sqrt{2}\sigma$

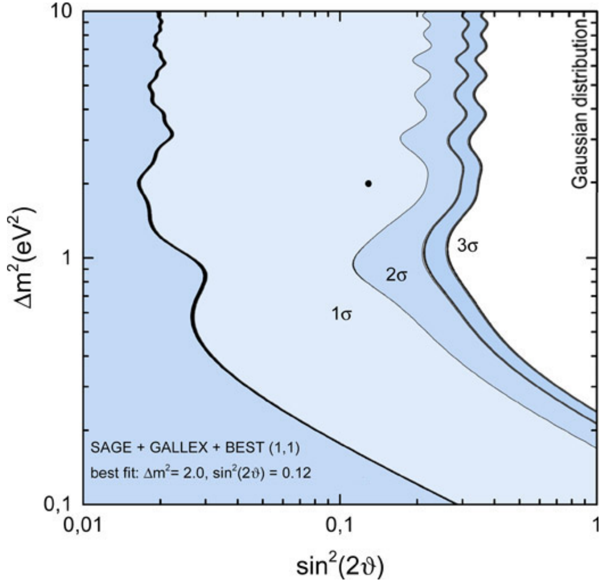


BEST confirming the anomaly



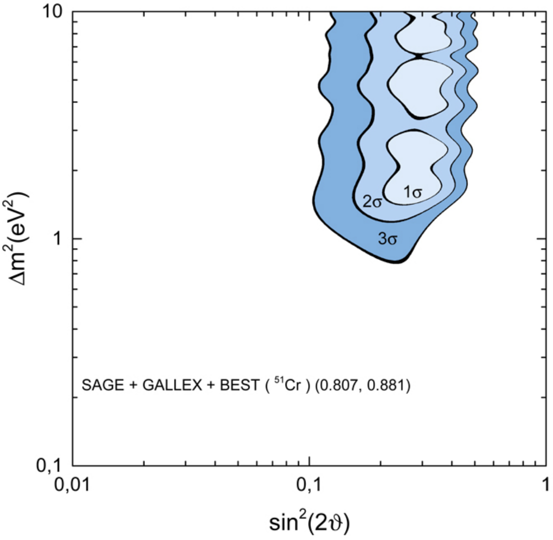
null BEST combined with previous anomalies

6 experiments together

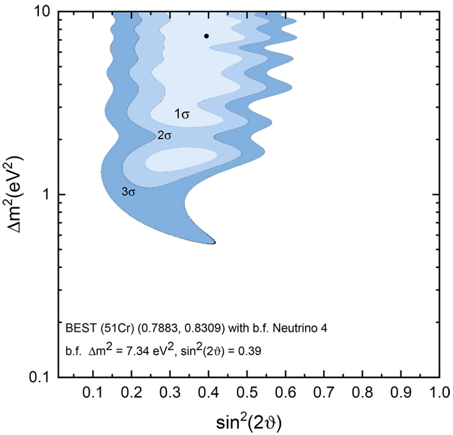


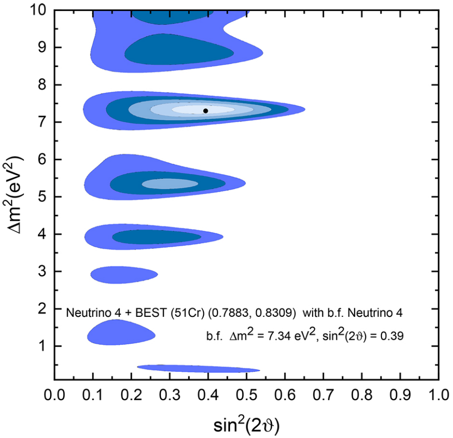
SAGE+GALLEX+BEST confirmed anomaly

6 experiments together



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
  new results at 2019/2020 stay tuned

Backup slides

two stages with sources: Cr+Cr vs Cr+Zn