# Status of Light Sterile Neutrinos


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# Standard Three Neutrino Mixing

- Flavor Neutrinos: $\nu_e, \nu_\mu, \nu_\tau$ produced in Weak Interactions
- Massive Neutrinos: $\nu_1, \nu_2, \nu_3$ propagate from Source to Detector
- Neutrino Mixing: a Flavor Neutrino is a superposition of Massive Neutrinos

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1}^* & U_{e2}^* & U_{e3}^* \\ U_{\mu1}^* & U_{\mu2}^* & U_{\mu3}^* \\ U_{\tau1}^* & U_{\tau2}^* & U_{\tau3}^* \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

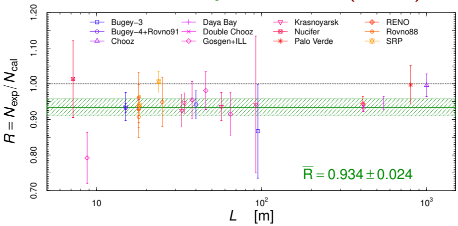
- $U$ is the $3 \times 3$ unitary Neutrino Mixing Matrix
- $P_{\nu_\alpha \to \nu_\beta}(L) = \sum_{k,j} U_{\beta k} U_{\alpha k}^* U_{\beta j}^* U_{\alpha j} \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E}\right)$ $\qquad (\alpha, \beta = e, \mu, \tau)$
- The oscillation probabilities depend on

$U$ (osc. amplitude) and $\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$ (osc. phase)

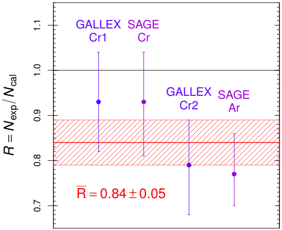
- In the standard framework of three-neutrino mixing there are two independent $\Delta m^2$'s:
  - $\Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.4 \times 10^{-5}\,\text{eV}^2$ Solar Mass Splitting
  - $\Delta m^2_{\text{ATM}} \simeq |\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\text{eV}^2$ Atmospheric Mass Splitting
- The solar and atmospheric mass splittings generate oscillations that are detectable at the distances
  - $L^{\text{osc}}_{\text{SOL}} \gtrsim \dfrac{E_\nu}{\Delta m^2_{\text{SOL}}} \approx 50\,\text{km}\,\dfrac{E_\nu}{\text{MeV}}$
  - $L^{\text{osc}}_{\text{ATM}} \gtrsim \dfrac{E_\nu}{\Delta m^2_{\text{ATM}}} \approx 1\,\text{km}\,\dfrac{E_\nu}{\text{MeV}}$
- The solar and atmospheric mass splittings cannot explain flavor neutrino transitions at shorter distances.

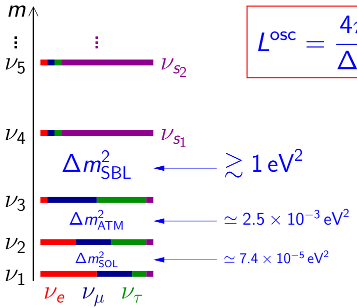
# Short-Baseline Neutrino Oscillation Anomalies

## Reactor Anomaly: $\bar{\nu}_e \to \bar{\nu}_x$ $(\sim 3\sigma)$



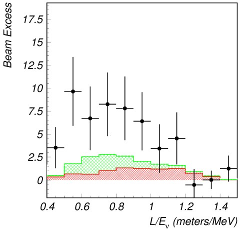

## Gallium Anomaly: $\nu_e \to \nu_x$ $(\sim 3\sigma)$




$$L^{osc} = \frac{4\pi E}{\Delta m^2}$$

## LSND Anomaly: $\bar{\nu}_\mu \to \bar{\nu}_e$ $(\sim 4\sigma)$




Minimal perturbation of $3\nu$ mixing: effective 3+1 with $|U_{e4}|, |U_{\mu 4}|, |U_{\tau 4}| \ll 1$

# Effective 3+1 SBL Oscillation Probabilities

Appearance ($\alpha \neq \beta$)

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

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

Disappearance

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

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

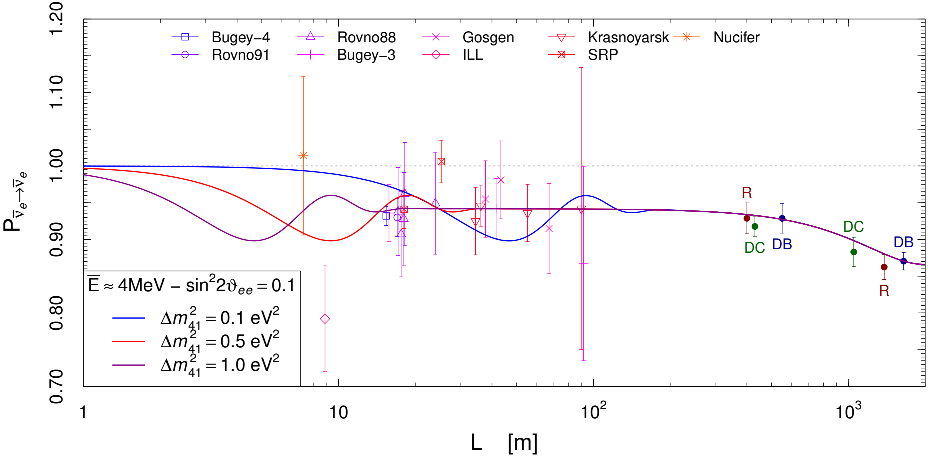
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

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

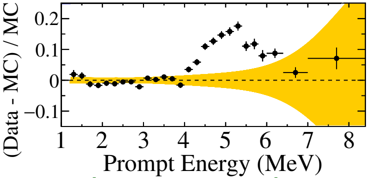
- $\Delta m^2_{\text{SBL}} = \Delta m^2_{41} \simeq \Delta m^2_{42} \simeq \Delta m^2_{43}$
- CP violation is not observable in SBL experiments!
- Observable in LBL accelerator exp. sensitive to $\Delta m^2_{\text{ATM}}$ [de Gouvea et al, arXiv:1412.1479, arXiv:1507.03986, arXiv:1605.09376; Palazzo et al, arXiv:1412.7524, arXiv:1509.03148; Kayser et al, arXiv:1508.06275, arXiv:1607.02152] and solar exp. sensitive to $\Delta m^2_{\text{SOL}}$ [Long, Li, Giunti, arXiv:1304.2207]

# Short-Baseline Reactor Neutrino Oscillations

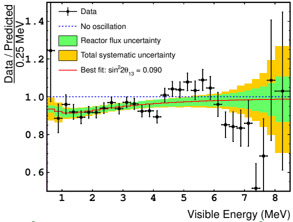



- $\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$
- SBL oscillations are averaged at the Daya Bay, RENO, and Double Chooz near detectors $\Longrightarrow$ no spectral distortion
- The reactor antineutrino anomaly is model dependent (depends on the theoretical reactor neutrino flux calculation; is it reliable?).

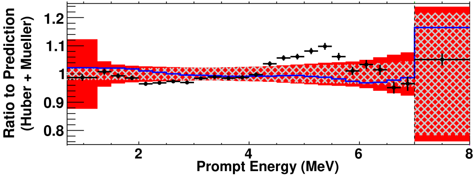
# Reactor Antineutrino 5 MeV Bump




[RENO, arXiv:1511.05849]




[Double Chooz, arXiv:1406.7763]




[Daya Bay, arXiv:1508.04233]

- Cannot be explained by neutrino oscillations (SBL oscillations are averaged in RENO, DC, DB).

- If it is due to a theoretical miscalculation of the spectrum, it can have opposite effects on the anomaly:

  [see: Berryman, Huber, arXiv:1909.09267]

  - If it is a 4-6 MeV excess it increases the anomaly: new HKSS flux calculation

    [Hayen, Kostensalo, Severijns, Suhonen, arXiv:1908.08302]

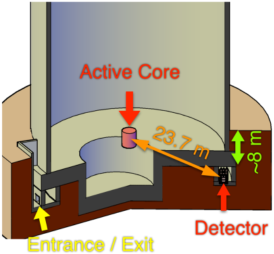
  - If it is a 1-4 MeV suppression it decreases the anomaly: new EF flux calculation

    [Estienne, Fallot, et al, arXiv:1904.09358]

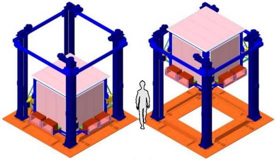
# Model Indep. Measurements of Reactor $\nu$ Osc.

## Ratios of spectra at different distances

### NEOS

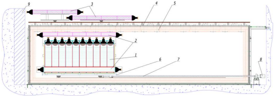



### DANSS

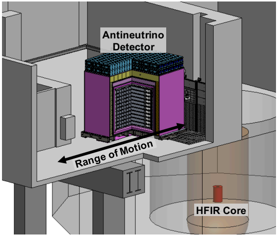


**DANSS on a lifting platform**

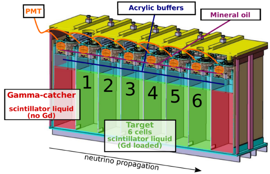
### Neutrino-4



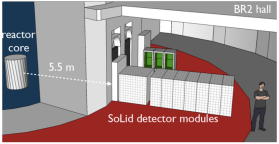
### PROSPECT




### STEREO

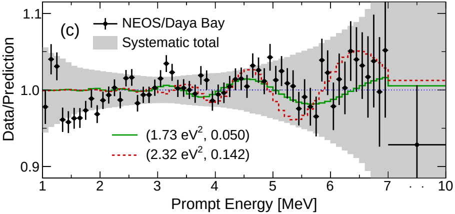



### SoLid



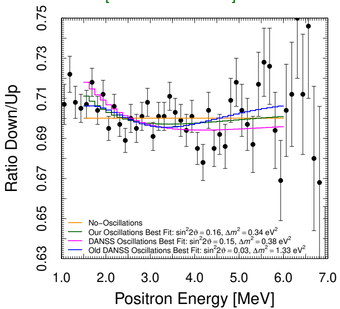
# 2018 Results

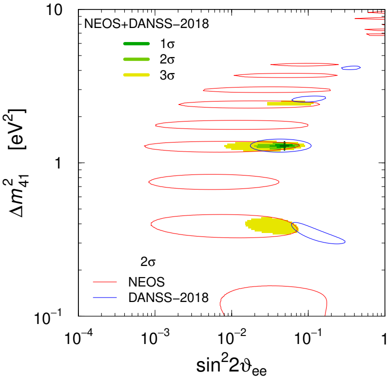
## NEOS [arXiv:1610.05134]




## DANSS-2018

[arXiv:1804.04046]




2018 model independent indication in favor of SBL oscillations

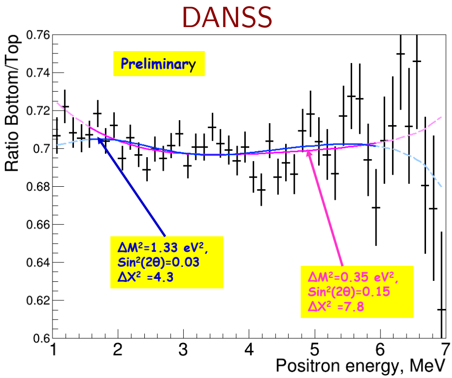
NEOS: $\sim 2.0\sigma$

DANSS-2018: $\sim 2.2\sigma$

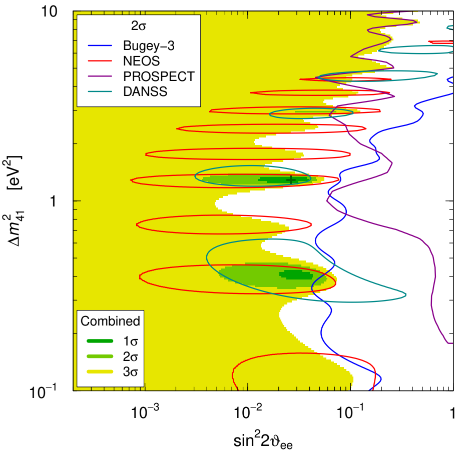
Combined: $\sim 3.5\sigma$

[Gariazzo, Giunti, Laveder, Li, arXiv:1801.06467]
[Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661]

# 2019 Results



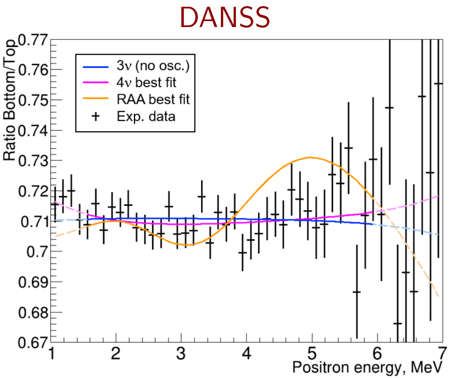

[Danilov @ EPS-HEP 2019, arXiv:1911.10140]



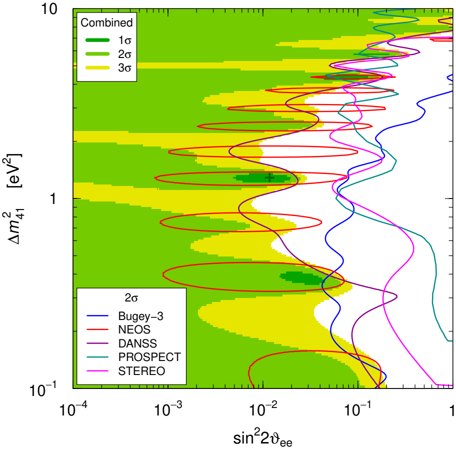

[Giunti, Y.F. Li, Y.Y. Zhang, arXiv:1912.12956]

- The agreement between NEOS and DANSS diminished.

# 2020 Results




[Shitov @ Neutrino 2020]

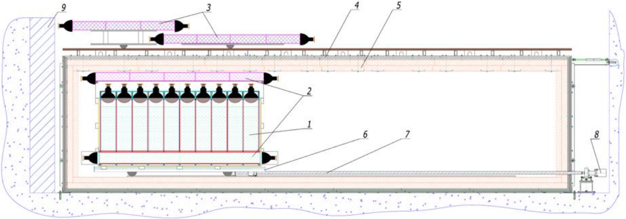



- No indication of oscillations from DANNS data.
- In practice these reactor spectral ratios give upper bound on

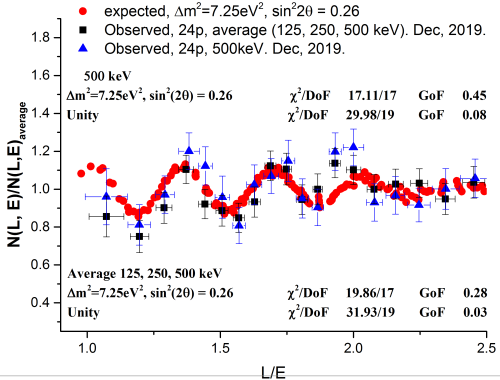
$$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$$

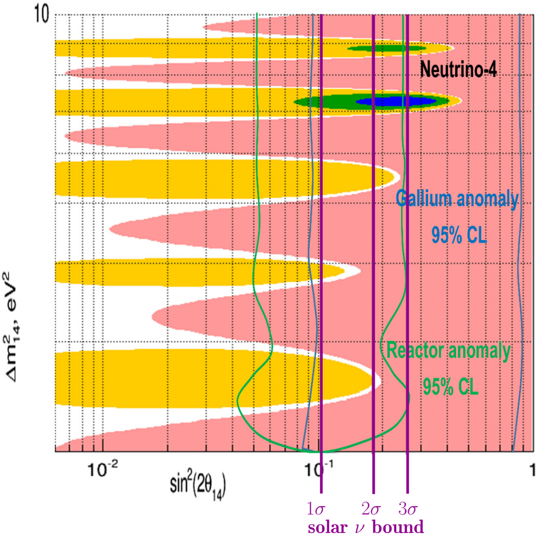
# Neutrino-4

[arXiv:1708.00421, arXiv:1809.10561, arXiv:2003.03199, arXiv:2005.05301, arXiv:2006.13639]




- SM-3 reactor at Dimitrovgrad, Russia
- Pure $^{235}$U $\bar{\nu}_e$ flux
- $L = 6 - 12\,\mathrm{m}$






- Neutrino-4 best fit:

$$\sin^2 2\vartheta_{ee} = 0.26$$

$$\Delta m^2_{41} = 7.25\,\text{eV}^2$$

- Very large mixing!

- Not a small perturbation of $3\nu$ mixing.

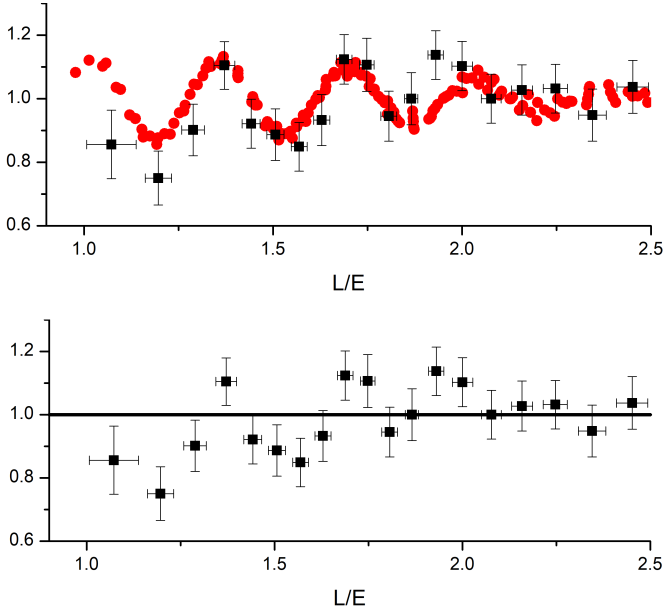
- Tension with solar neutrino bound.

[Palazzo, arXiv:1105.1705, arXiv:1201.4280]

[Giunti, Laveder, Li, Liu, Long, arXiv:1210.5715]

[Gariazzo, Giunti, Laveder, Li, arXiv:1703.00860]

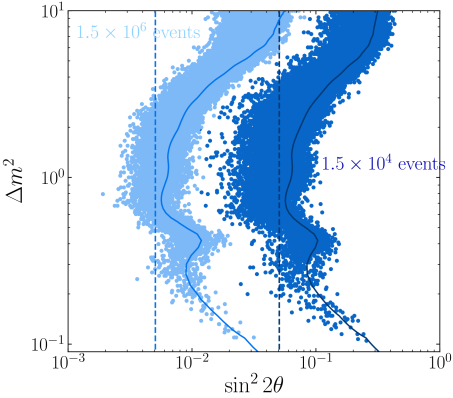
# Oscillations or Fluctuations?



# Deviations from $\chi^2$ Distribution (Wilks' Theorem)

[Agostini, Neumair, arXiv:1906.11854; Silaeva, Sinev, arXiv:2001.10752; Giunti, arXiv:2004.07577]
[PROSPECT+STEREO, arXiv:2006.13147; Coloma, Huber, Schwetz, arXiv:2008.06083]

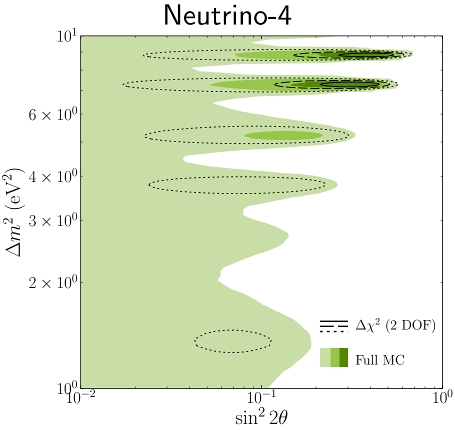
Even in the absence of real oscillations, binned data can often be fitted better by oscillations that reproduce the statistical fluctuations of the bins.




[Coloma, Huber, Schwetz, arXiv:2008.06083]

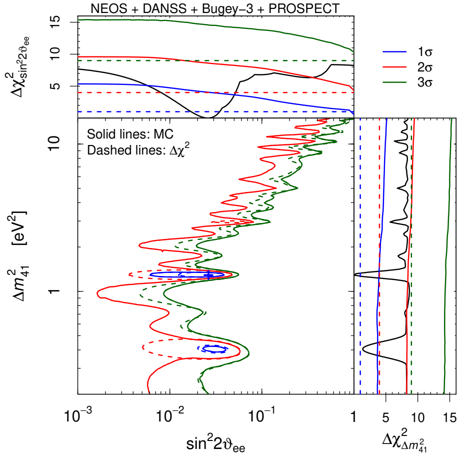
- Numerical simulations of a reactor neutrino experiment experiment: $\bar{\nu}_e$ disappearance.
- Location of the best-fit points of 20,000 pseudo-experiments simulated under the no-oscillation hypothesis.
- Vertical lines: expected analytical $\langle \sin^2 2\theta \rangle$ from a toy model.
- Solid curves: sensitivity at 95% CL assuming that Wilks' theorem holds.

# MC evaluation of test statistic distribution




$3.2\sigma\,(\Delta\chi^2) \longrightarrow 2.6\sigma\,(\text{MC})$

[Coloma, Huber, Schwetz, arXiv:2008.06083]




$2.4\sigma\,(\Delta\chi^2) \longrightarrow 1.8\sigma\,(\text{MC})$

[Giunti, arXiv:2004.07577]

- MC calculations are unfortunately difficult and require a lot of computer time.
- They must be completely redone for each combination of experiments.

- The MC evaluation of test statistic distribution decreases the statistical significance of the indications in favor of oscillations.
- Nevertheless, the indications must be checked by other experiments.
- We do not want to miss a chance to discover sterile neutrinos and physics beyond the Standard Model.
- This is valid for Neutrino-4 as well as for any other indication.
- It would be very interesting if the Neutrino-4 results are confirmed by other experiments, opening an unexpected new scenario.

# Robust kinematical probe of $\nu_e - \nu_s$ mixing

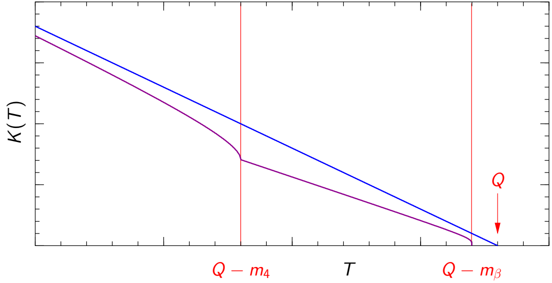
Tritium Beta-Decay: ${}^3\text{H} \to {}^3\text{He} + e^- + \bar{\nu}_e$

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

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

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

$$+ |U_{e4}|^2 \sqrt{(Q-T)^2 - m_4^2}\, \theta(Q - T - m_4)$$



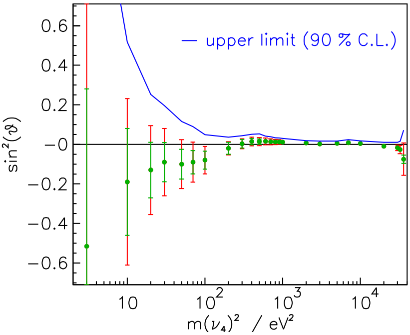

$$Q = M_{^3\text{H}} - M_{^3\text{He}} - m_e = 18.58\,\text{keV}$$

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

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

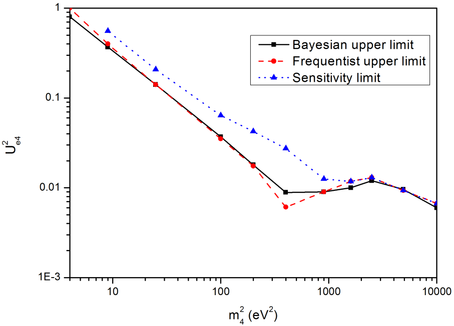
$$m_4 \gg m_{1,2,3} \quad \Longrightarrow \quad \Delta m^2_{41} \equiv m^2_4 - m^2_1 \simeq m^2_4$$

Mainz



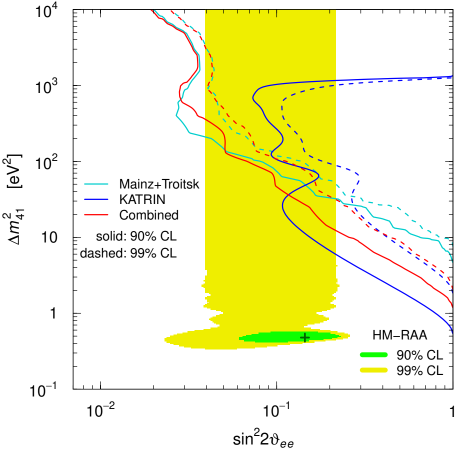

[Kraus, Singer, Valerius, Weinheimer, arXiv:1210.4194]

Troitsk



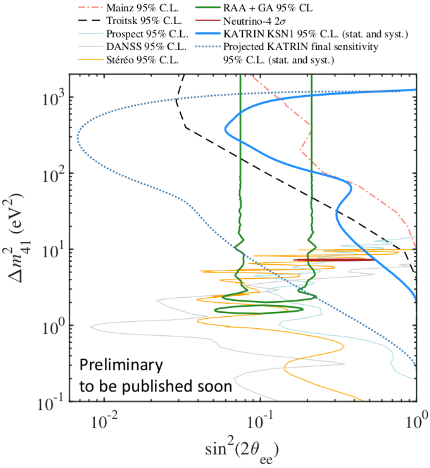

[Belesev et al, arXiv:1307.5687]

# Bound from first KATRIN data




[Giunti, Y.F. Li, Y.Y. Zhang, arXiv:1912.12956]

$$\Delta m^2_{41} \simeq m^2_4$$




[KATRIN @ Neutrino 2020]

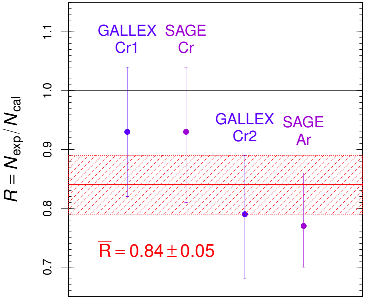
# Gallium Anomaly

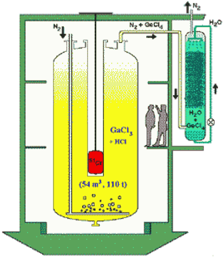
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

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




$\approx 2.9\sigma$ deficit

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

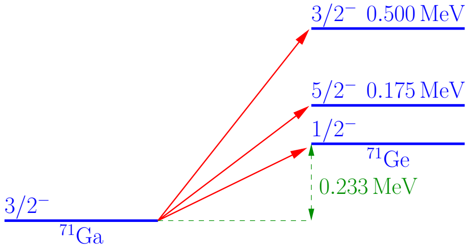
$\Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$

[SAGE, nucl-ex/0512041, arXiv:0901.2200;
Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344,
hep-ph/0610352, arXiv:0711.4222,
arXiv:1006.3244]

- Deficit could be due to an overestimate of

$$\sigma(\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-)$$

- First calculation: Bahcall, PRC 56 (1997) 3391

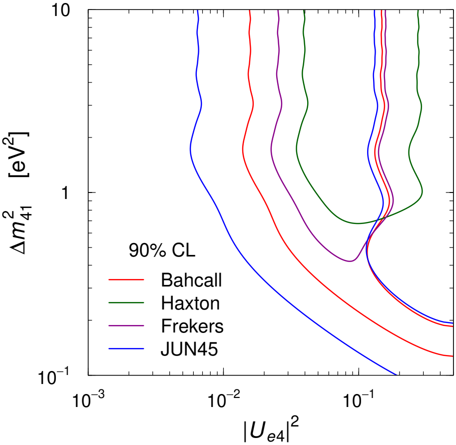



- $\sigma_{\text{G.S.}}$ from $T_{1/2}({}^{71}\text{Ge}) = 11.43 \pm 0.03\,\text{days}$ [Hampel, Remsberg, PRC 31 (1985) 666]

$$\sigma_{\text{G.S.}}({}^{51}\text{Cr}) = 55.3 \times 10^{-46}\,\text{cm}^2\,(1 \pm 0.004)_{3\sigma}$$

- $\sigma({}^{51}\text{Cr}) = \sigma_{\text{G.S.}}({}^{51}\text{Cr}) \left(1 + 0.669\,\frac{\text{BGT}_{175}}{\text{BGT}_{\text{G.S.}}} + 0.220\,\frac{\text{BGT}_{500}}{\text{BGT}_{\text{G.S.}}}\right)$

- The contribution of excited states is only $\sim 5\%$, but it is crucial for the size of the Gallium anomaly!




Cross sections in units of $10^{-45}\,\text{cm}^2$:

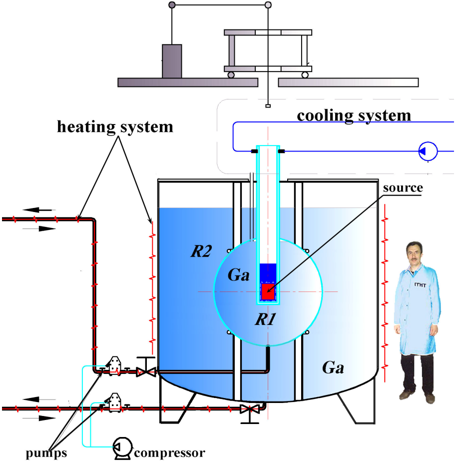
| | $\sigma(^{51}\text{Cr})$ | $\sigma(^{37}\text{Ar})$ |
|---|---|---|
| Bahcall | $5.81 \pm 0.16$ | $7.00 \pm 0.21$ |
| Haxton | $6.39 \pm 0.65$ | $7.72 \pm 0.81$ |
| Frekers | $5.92 \pm 0.11$ | $7.15 \pm 0.14$ |
| JUN45 | $5.67 \pm 0.06$ | $6.80 \pm 0.08$ |

[Kostensalo, Suhonen, Giunti, Srivastava, arXiv:1906.10980]

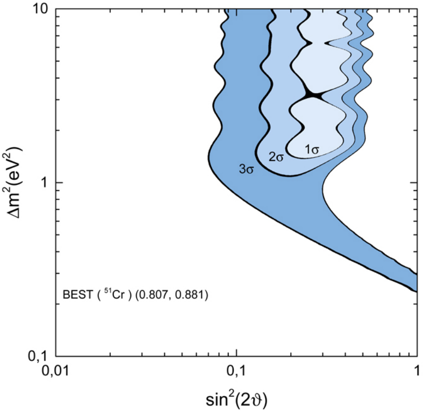
# BEST

[arXiv:1006.2103, arXiv:1602.03826, arXiv:1710.06326, arXiv:1807.02977, arXiv:1905.07437]

Direct test of the Gallium anomaly with $^{51}Cr$ source.

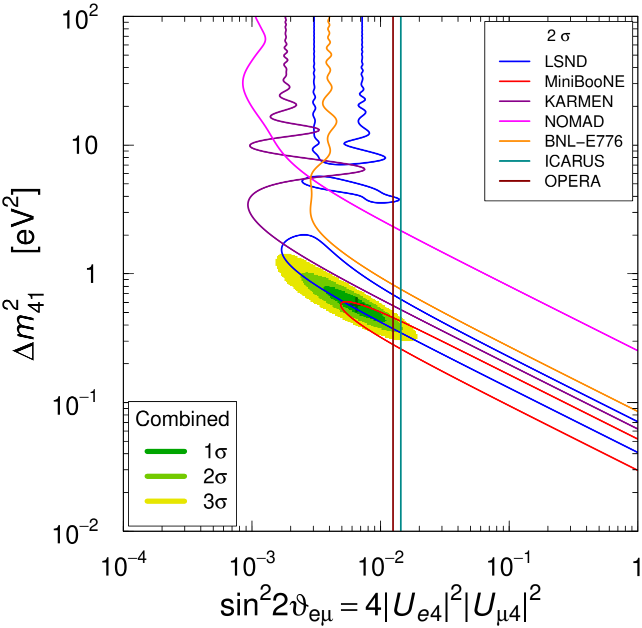



$$R_1 = 0.66\,\text{m}, \quad R_2 = 1.096\,\text{m}$$

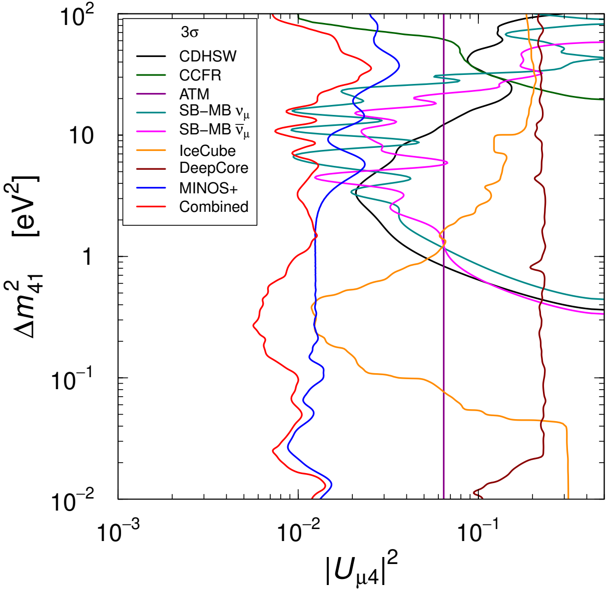



Allowed regions of oscillations parameters if the result of the BEST experiment corresponds to the best fit point for combining the SAGE + GALLEX. The numbers in parentheses indicate the most probable ratios $R$ of observed-to-expected without sterile neutrinos germanium atoms in the two vessels.

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



# $\nu_\mu$ and $\bar{\nu}_\mu$ Disappearance




[Gariazzo, Giunti, Li, Ternes, Zhang, in preparation]

# 3+1: Appearance vs Disappearance

- SBL Oscillation parameters: $\Delta m^2_{41}$ $|U_{e4}|^2$ $|U_{\mu 4}|^2$ $(|U_{\tau 4}|^2)$
- Amplitude of $\nu_e$ disappearance:

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \simeq 4|U_{e4}|^2$$

- Amplitude of $\nu_\mu$ disappearance:

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

- Amplitude of $\nu_\mu \to \nu_e$ appearance:

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

quadratically suppressed for small $|U_{e4}|^2$ and $|U_{\mu 4}|^2$

$\Downarrow$

Appearance-Disappearance Tension

[Okada, Yasuda, hep-ph/9606411; Bilenky, CG, Grimus, hep-ph/9607372]

# Global Appearance-Disappearance Tension

$\nu_e$ DIS

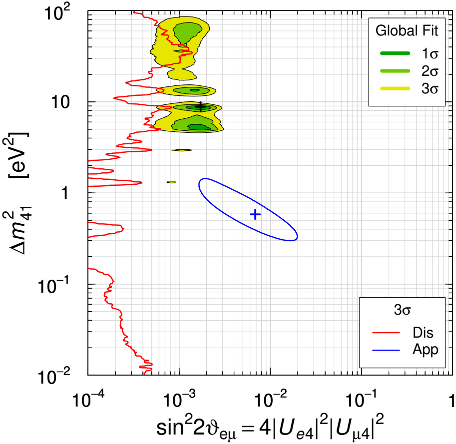
$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

$\nu_\mu$ DIS

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

$\nu_\mu \to \nu_e$ APP

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




- $\nu_\mu \to \nu_e$ is quadratically suppressed!
- Global Fit:

  $\chi^2/\text{NDF} = 843.6/794$

  $\text{GoF} = 11\%$

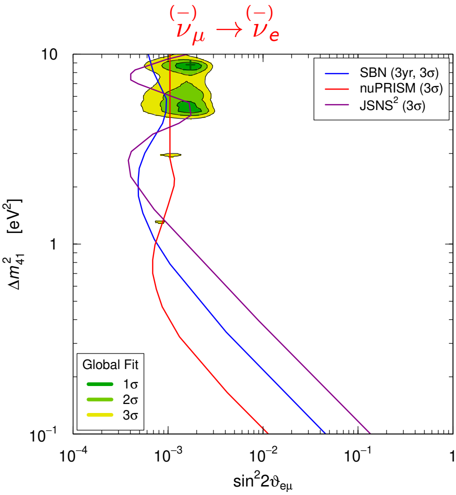
  $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 46.7/2$

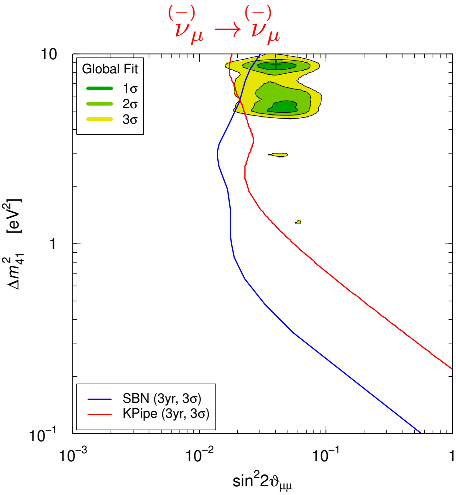
  $\text{GoF}_{\text{PG}} = 7 \times 10^{-11}$ ← ☹
- Similar tension in

  $3+2, \quad 3+3, \quad \ldots, \quad 3+N_s$

[Giunti, Zavanin, arXiv:1508.03172]

# New Dedicated Experiments



# Conclusions

- Neutrinos can be powerful messengers of new physics beyond the SM.
- The existence of light sterile neutrinos beyond the SM is indicated by the Reactor, Gallium and LSND anomalies.
- Experimental results are confusing, pointing in different directions.
- Therefore, there is no definitive conclusion yet.
- The search must be continued with enthusiasm, because a positive outcome would yield a huge reward.
- Oscillation experiments suffer of misleading oscillatory fit of statistical fluctuations of the data. Difficult MC evaluation of test statistic distribution is needed to obtain reliable confidence levels.
- Robust kinematical probe of $\nu_e - \nu_s$ mixing with $\beta$ decay (KATRIN, Project 8, ...) and electron-capture (ECHo, HOLMES, ...) experiments.