# Progress in Neutrino Physics

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# Three-Neutrino Mixing Paradigm

$$\boxed{\nu_{\alpha L} = \sum_{k=1}^{3} U_{\alpha k} \nu_{kL}} \qquad \alpha = e, \mu, \tau$$

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \delta_{\alpha\beta} \underbrace{- 4 \sum_{k>j} \text{Re}\left[U_{\alpha k}^{*}\, U_{\beta k}\, U_{\alpha j}\, U_{\beta j}^{*}\right] \sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right)}_{\text{CP conserving}}$$

$$\underbrace{+ 2 \sum_{k>j} \text{Im}\left[U_{\alpha k}^{*}\, U_{\beta k}\, U_{\alpha j}\, U_{\beta j}^{*}\right] \sin\left(\frac{\Delta m_{kj}^2 L}{2E}\right)}_{\text{CP violating}}$$

- Squared-mass differences: $\Delta m_{kj}^2 = m_k^2 - m_j^2$
- Mixing: $U_{\alpha k}^{*}\, U_{\beta k}\, U_{\alpha j}\, U_{\beta j}^{*}$ quartic rephasing invariants
- Jarlskog invariant: $J_{\text{CP}} = \text{Im}\left[U_{\alpha k}^{*}\, U_{\beta k}\, U_{\alpha j}\, U_{\beta j}^{*}\right]$

# Standard Parameterization of Mixing Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

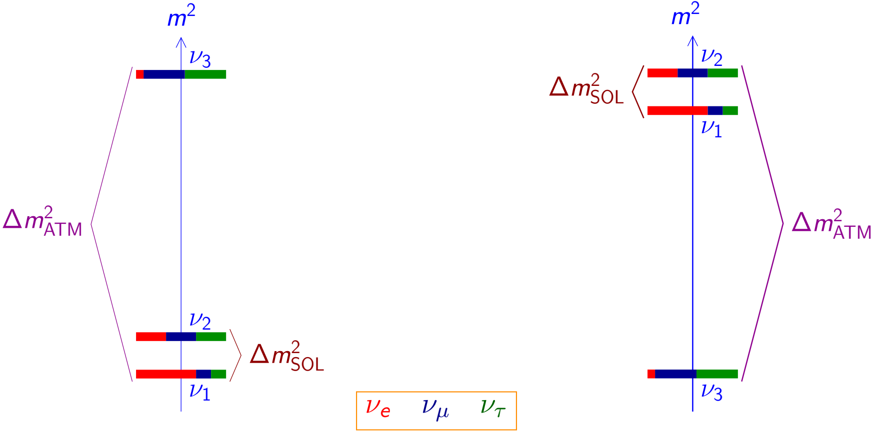
$c_{ab} \equiv \cos\vartheta_{ab}$ $s_{ab} \equiv \sin\vartheta_{ab}$ $0 \leq \vartheta_{ab} \leq \frac{\pi}{2}$ $0 \leq \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi$

OSCILLATION PARAMETERS:

- 3 Mixing Angles: $\vartheta_{12}$, $\vartheta_{23}$, $\vartheta_{13}$
- 1 CPV Dirac Phase: $\delta_{13}$
- 2 independent $\Delta m^2_{kj}$: $\Delta m^2_{21}$, $\Delta m^2_{31}$

2 CPV Majorana Phases: $\lambda_{21}$, $\lambda_{31}$ $\Longleftrightarrow$ $|\Delta L| = 2$ processes $(\beta\beta_{0\nu})$

# Mass Ordering



Normal Ordering
$\Delta m^2_{31} > \Delta m^2_{32} > 0$

Inverted Ordering
$\Delta m^2_{32} < \Delta m^2_{31} < 0$

- Absolute mass scale is not determined by neutrino oscillations.
- $\beta$ decay and cosmology $\Longrightarrow$ $\boxed{m_\nu \lesssim 1\,\mathrm{eV}}$

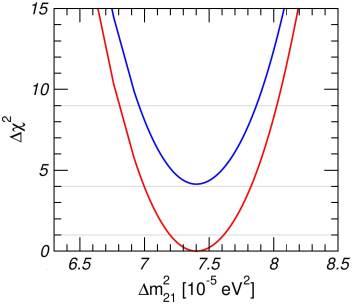
# Towards Precision Neutrino Physics

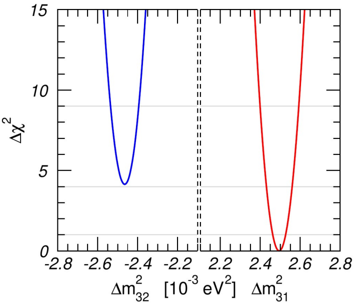
[NuFIT 3.2 (2018), www.nu-fit.org; T. Schwetz @ CERN Neutrino Platform Week, 1 Feb 2018]

[See also: Capozzi et al., Phys.Rev. D95 (2017) 096014, arXiv:1703.04471; de Salas et al., arXiv:1708.01186]

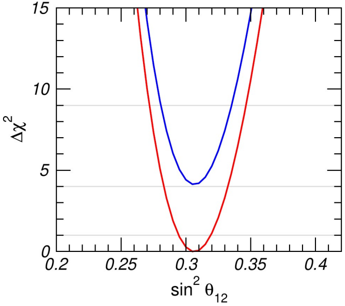
SOL: $\Delta m^2_{21} = 7.40^{+0.21}_{-0.20} \times 10^{-5}\,\text{eV}^2$ precision $\simeq 2.8\%$

ATM:
- NO : $\Delta m^2_{31} = 2.494^{+0.033}_{-0.031} \times 10^{-3}\,\text{eV}^2$ precision $\simeq 1.3\%$
- IO : $\Delta m^2_{32} = -2.465^{+0.032}_{-0.031} \times 10^{-3}\,\text{eV}^2$ precision $\simeq 1.3\%$





Normal Ordering is preferred by $\Delta\chi^2 = 4.1$



Solar

$\nu_e \to \nu_\mu, \nu_\tau$

$\left(\begin{array}{c}\text{SNO, Borexino}\\ \text{Super-Kamiokande}\\ \text{GALLEX/GNO, SAGE}\\ \text{Homestake, Kamiokande}\end{array}\right)$

VLBL Reactor

$\bar{\nu}_e$ disappearance

(KamLAND)

$\sin^2\vartheta_{12} = 0.307^{+0.013}_{-0.012}$ precision ≃ 4.2%

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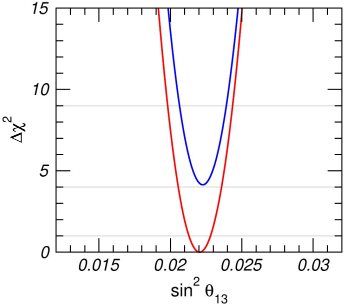


LBL Accelerator

$\nu_\mu \to \nu_e$

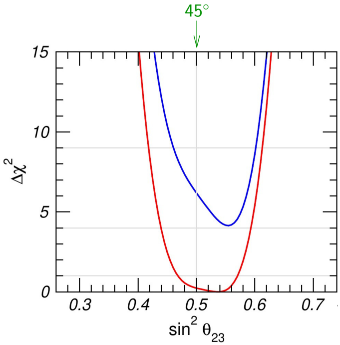
(T2K, MINOS, NO$\nu$A)

LBL Reactor

$\bar{\nu}_e$ disappearance

$\left(\begin{array}{c}\text{Daya Bay, RENO}\\ \text{Double Chooz}\end{array}\right)$

$$\sin^2\vartheta_{13} = \begin{cases} 0.02206 \pm 0.00075 \quad \text{(NO)} \\ \qquad \text{precision} \simeq 3.4\% \\ 0.02227 \pm 0.00074 \quad \text{(IO)} \\ \qquad \text{precision} \simeq 3.3\% \end{cases}$$



Atmospheric

$\nu_\mu \to \nu_\tau$

$\left(\begin{array}{c}\text{Super-Kamiokande}\\ \text{Kamiokande, IMB}\\ \text{MACRO, Soudan-2}\end{array}\right)$

LBL Accelerator

$\nu_\mu$ disappearance

$\left(\begin{array}{c}\text{K2K, MINOS}\\ \text{T2K, NO}\nu\text{A}\end{array}\right)$

LBL Accelerator

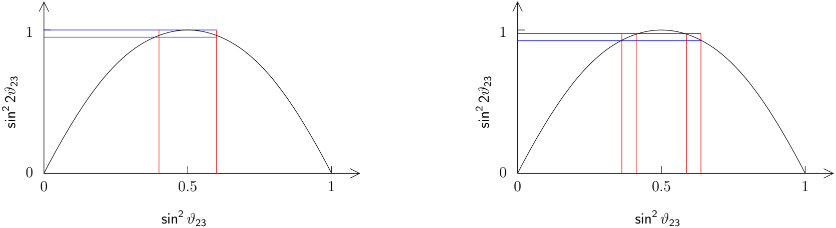
$\nu_\mu \to \nu_\tau$

(OPERA)

$$\sin^2\vartheta_{23} = \begin{cases} 0.538^{+0.033}_{-0.069} \quad \text{(NO)} \quad \text{precision} \simeq 13\% \\ \quad \text{Maximal Mixing allowed at} < 1\sigma \\ \\ 0.554^{+0.023}_{-0.033} \quad \text{(IO)} \quad \text{precision} \simeq 6\% \\ \quad \text{Second octant “favored” by } \Delta\chi^2 \simeq 2 \end{cases}$$

# Difficulty of measuring precisely $\vartheta_{23}$

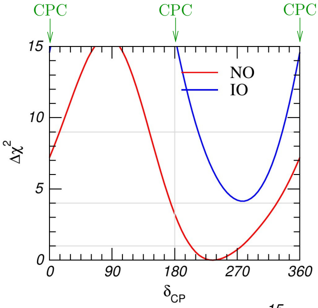
$$P^{\text{LBL}}_{\nu_\mu\to\nu_\mu} \simeq 1 - \sin^2 2\vartheta_{23}\, \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \qquad \sin^2 2\vartheta_{23} = 4 \sin^2\vartheta_{23} \left(1 - \sin^2\vartheta_{23}\right)$$



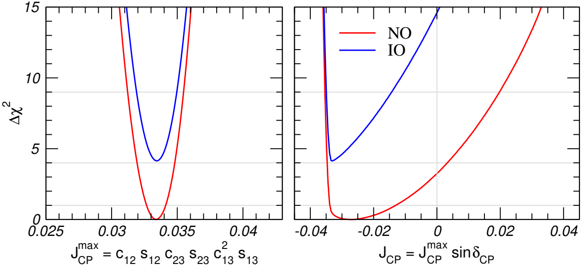
The octant degeneracy is resolved by small $\vartheta_{13}$ effects:

$$P^{\text{LBL}}_{\nu_\mu\to\nu_\mu} \simeq 1 - \left[\sin^2 2\vartheta_{23} \cos^2\vartheta_{13} + \sin^4\vartheta_{23} \sin^2 2\vartheta_{13}\right] \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$P^{\text{LBL}}_{\nu_\mu\to\nu_e} \simeq \sin^2\vartheta_{23} \sin^2 2\vartheta_{13}\, \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$



$$\frac{\delta_{13}}{\pi} = \begin{cases} 1.3^{+0.24}_{-0.17} \quad (\text{NO}) \quad \text{precision} \simeq 18\% \\ \text{CP Conservation allowed at} < 2\sigma \\ 1.54^{+0.14}_{-0.16} \quad (\text{IO}) \quad \text{precision} \simeq 10\% \\ \text{CP Violation favored at } 3\sigma \end{cases}$$



$$J_{\text{CP}}^{\text{max}} = 0.033 \pm 0.0007$$

$J_{\text{CP}}$ can be $10^3$ larger than $J_{\text{CP}}^{\text{quarks}} = (3.04^{+0.21}_{-0.20}) \times 10^{-5}$

# Towards a precise determination of the mixing matrix

well determined

totally unknown

$$U = \begin{pmatrix} \boxed{c_{12}c_{13} \quad s_{12}c_{13} \quad s_{13}}\,e^{-i\delta_{13}} & & \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \boxed{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}}$$

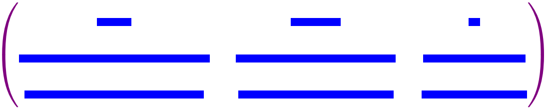
large uncertainty due to $\vartheta_{23}$ and $\delta_{13}$

medium uncertainty due to $\vartheta_{23}$

NuFIT 3.2 (2018)

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.141 \to 0.156 \\ 0.242 \to 0.494 & 0.467 \to 0.678 & 0.639 \to 0.774 \\ 0.284 \to 0.521 & 0.490 \to 0.695 & 0.615 \to 0.754 \end{pmatrix}$$

$|U|_{3\sigma} =$



only the mass composition of $\nu_e$ is well determined

# Why it is important to measure accurately the mixing parameters?

- They are fundamental parameters.
- They lead to selection in huge model space. Examples:
  - Deviation from Tribimaximal Mixing $U \simeq \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$
  - Violation of $\mu$-$\tau$ symmetry $(|U_{\mu k}| = |U_{\tau k}|)$
- They have phenomenological usefulness (e.g. to determine the initial flavor composition of astrophysical neutrinos).
- CP:
  - CP conservation would need an explanation (a new symmetry?).
  - CP violation may be linked to the CP violation in the sector of heavy neutrinos which generate the matter-antimatter asymmetry in the Universe through leptogenesis (CP-violating decay of heavy neutrinos).

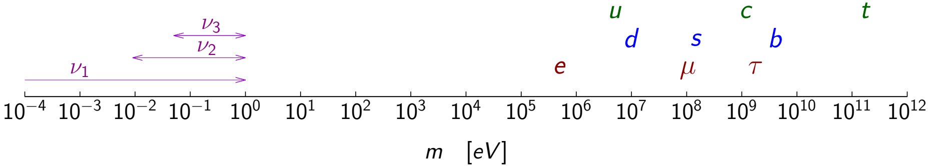
# Origin of Neutrino Masses

| | 1st Generation | 2nd Generation | 3rd Generation |
|---|---|---|---|
| **Quarks**: | $\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{matrix} u_R \\ d_R \end{matrix}$ | $\begin{pmatrix} c_L \\ s_L \end{pmatrix} \quad \begin{matrix} c_R \\ s_R \end{matrix}$ | $\begin{pmatrix} t_L \\ b_L \end{pmatrix} \quad \begin{matrix} t_R \\ b_R \end{matrix}$ |
| **Leptons**: | $\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \quad \begin{matrix} \boxed{\nu_{eR}} \\ e_R \end{matrix}$ | $\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix} \quad \begin{matrix} \boxed{\nu_{\mu R}} \\ \mu_R \end{matrix}$ | $\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix} \quad \begin{matrix} \boxed{\nu_{\tau R}} \\ \tau_R \end{matrix}$ |

- Standard Model extension: $\nu_R \Rightarrow$ Dirac mass term $\mathcal{L}_{\text{D}} \sim m_{\text{D}} \overline{\nu_L} \nu_R$
- This is Standard Model physics, because $m_{\text{D}}$ is generated by the standard Higgs mechanism:

$$y \overline{L_L} \widetilde{\Phi} \nu_R \xrightarrow[\text{Breaking}]{\text{Symmetry}} y v \overline{\nu_L} \nu_R \quad \Rightarrow \quad m_{\text{D}} = y v$$

- Bad: extremely small Yukawa couplings: $y \lesssim 10^{-11}$



# Beyond the Standard Model

- The introduction of $\nu_R$ leads us beyond the Standard Model because they can have the Majorana mass term

$$\mathcal{L}_{\text{M}} \sim m_{\text{M}} \overline{\nu_R} \nu_R^c \qquad \text{singlet under SM symmetries!}$$

- This is beyond the Standard Model because $m_{\text{M}}$ is not generated by the Higgs mechanism of the Standard Model ⇒ new physics is required.

- The Majorana mass term can be avoided by imposing lepton number conservation which should anyway be explained by some physics beyond the Standard Model.

# Seesaw Mechanism

without lepton number conservation

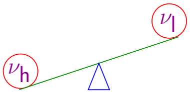
$$\mathcal{L}^{\text{D+M}} = -\frac{1}{2} \begin{pmatrix} \overline{\nu_L^c} & \overline{\nu_R} \end{pmatrix} \begin{pmatrix} 0 & m_{\text{D}} \\ m_{\text{D}} & m_{\text{M}} \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} + \text{H.c.}$$

$m_{\text{M}}$ can be arbitrarily large (not protected by SM symmetries)

$m_{\text{M}} \sim$ scale of new physics beyond Standard Model $\Rightarrow m_{\text{M}} \gg m_{\text{D}}$

diagonalization of $\begin{pmatrix} 0 & m_{\text{D}} \\ m_{\text{D}} & m_{\text{M}} \end{pmatrix} \Longrightarrow m_{\text{light}} \simeq \dfrac{m_{\text{D}}^2}{m_{\text{M}}} \qquad m_{\text{heavy}} \simeq m_{\text{M}}$

natural explanation of smallness
of light neutrino masses



seesaw mechanism

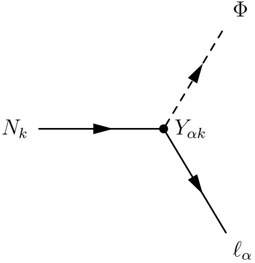
massive neutrinos are Majorana $\Rightarrow \beta\beta_{0\nu}$

$\nu_{\text{light}} \simeq -i\,(\nu_L - \nu_L^c) \qquad \nu_{\text{heavy}} \simeq \nu_R + \nu_R^c$

3-GEN $\Rightarrow$ effective low-energy 3-$\nu$ mixing

# Leptogenesis

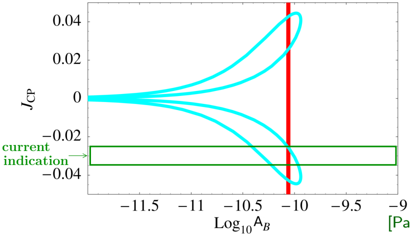
$$\mathcal{L}_I \sim \overline{L_L}\, \Phi^\dagger\, Y\, N_R$$



$$A_L \sim \frac{\sum_{k,\alpha}\left[\Gamma(N_k \to \Phi\ell_\alpha) - \Gamma(N_k \to \bar{\Phi}\bar{\ell}_\alpha)\right]}{\sum_{k,\alpha}\left[\Gamma(N_k \to \Phi\ell_\alpha) + \Gamma(N_k \to \bar{\Phi}\bar{\ell}_\alpha)\right]}$$

Seesaw $\Longrightarrow$ $Y \sim \frac{1}{v}\, \underbrace{M_R^{1/2}\, R}_{\text{inaccessible}}\, \underbrace{m_\nu^{1/2}\, U_{3\times3}}_{\text{measurable}}$ $\quad (RR^T = \mathbb{1})$

CP-violating $U_{3\times3}$ $\Longrightarrow$ plausible CP-violating $Y$



$M_{R1} = 5 \times 10^{11}$ GeV

$M_{R1} \ll M_{R2} \ll M_{R3}$

$R_{12} = 0.86$

$R_{13} = 0.5$

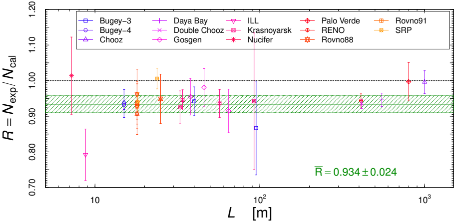
[Pascoli, Petcov, Riotto, PRD 75 (2007) 083511, arXiv:hep-ph/0609125]

- Seesaw with leptogenesis is a nice framework.
- However, it is an unproven (and maybe not falsifiable) theoretical framework.
- In general there is no constraint on the number and mass scales of the $\nu_R$'s that generate neutrino masses.
- It is possible and interesting that there is low-energy new physics (maybe connected with dark matter).
- Fermions beyond the Standard Model are neutral and can mix with neutrinos.
- They can be called right-handed neutrinos or sterile neutrinos, because they do not interact with standard weak interactions.

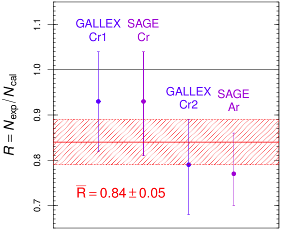
# Light Sterile Neutrinos

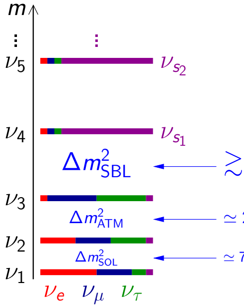
## Short-Baseline Anomalies

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



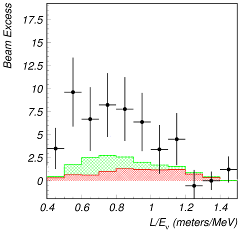
### Gallium Anomaly: $\nu_e \to \nu_x$ $(\sim 3\sigma)$





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

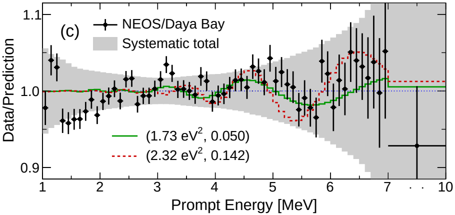
### LSND Anomaly: $\bar{\nu}_\mu \to \bar{\nu}_e$ $(\sim 4\sigma)$

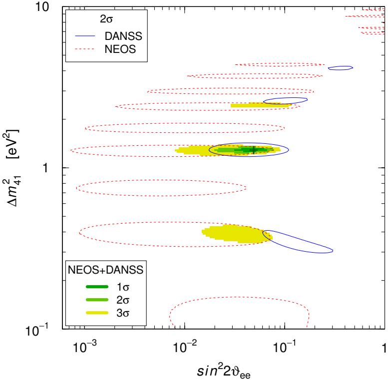


# Reactor Spectral Ratios

## NEOS

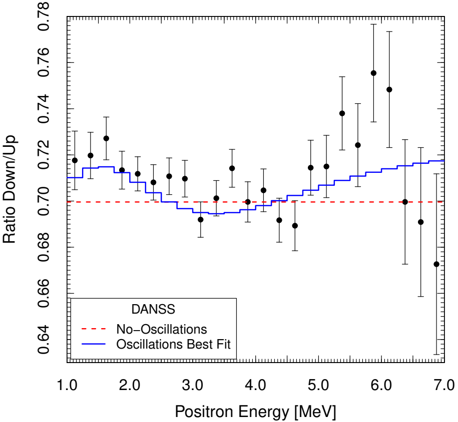
[PRL 118 (2017) 121802 (arXiv:1610.05134)]





## DANSS

[Danilov @ Brussels Solvay Workshop, 1/12/2017]



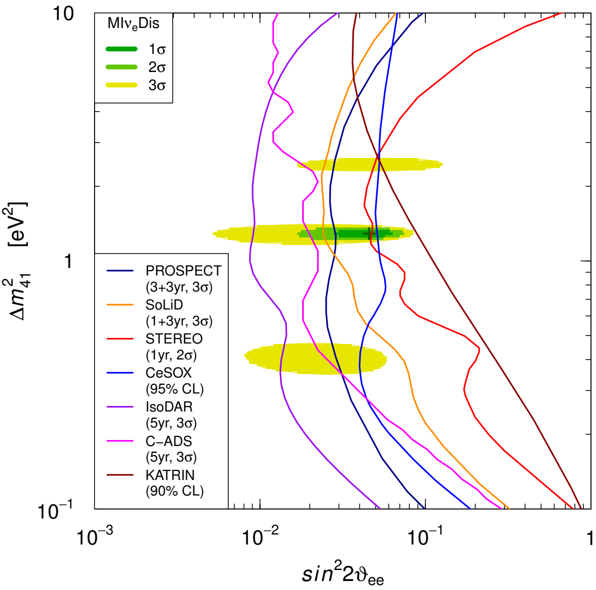
MODEL INDEPENDENT!

$\sim 3.5\sigma$

[Gariazzo, CG, Laveder, Li, arXiv:1801.06467]

# Model-Independent $\nu_e$ and $\bar{\nu}_e$ Disappearance

[Gariazzo, CG, Laveder, Li, arXiv:1801.06467]



$$\Delta m^2_{41} = 1.29 \pm 0.03$$

$$|U_{e4}|^2 = 0.012 \pm 0.003$$

# Coherent Elastic Neutrino-Nucleus Scattering

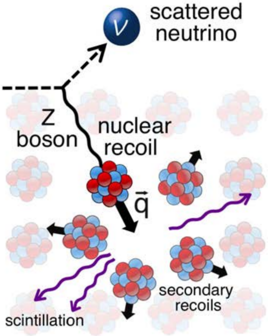
- Predicted in 1974 for $qR \lesssim 1$

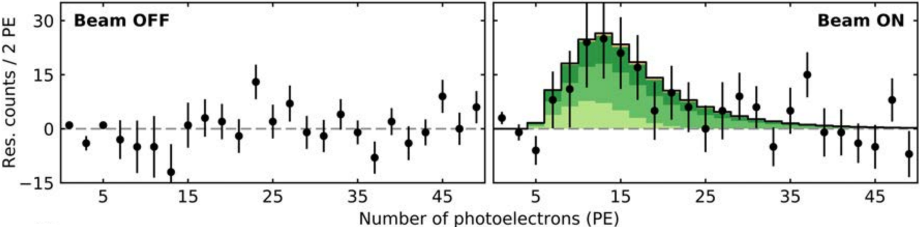
[Freedman, Phys. Rev. D9 (1974) 1389]

- $$\frac{d\sigma}{dT}(E,T) \simeq \frac{G_F^2 M}{4\pi}\left(1-\frac{MT}{2E^2}\right) N^2 F_N^2(q^2)$$

- Observed in 2017 in the COHERENT experiment at the Oak Ridge Spallation Neutron Source with CsI ($N_{Cs} = 78$, $N_I = 74$)

[Science 357 (2017) 1123, arXiv:1708.01294]





COHERENT data allowed to:

- Explore the nuclear structure: $\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E^2}\right) N^2 F_N^2(q^2)$
  [Cadeddu, CG, Li, Zhang, PRL 120 (2018) 072501, arXiv:1710.02730]

- Constrain neutrino Non Standard Interactions (NSI)
  [Coloma, Gonzalez-Garcia, Maltoni, Schwetz, PRD 96 (2017) 115007, arXiv:1708.02899; Liao, Marfatia, PLB 775 (2017) 54, arXiv:1708.04255; Kosmas, Papoulias, PRD 97 (2018) 033003, arXiv:1711.09773]

- Constrain neutrino magnetic moments and charge radii:
  $\frac{d\sigma}{dT} \simeq \frac{\pi\alpha}{m_e^2}\left(\frac{1}{T} - \frac{1}{E}\right) Z^2 F_Z^2(q^2)\, \mu_\nu^2$ [Kosmas, Papoulias, PRD 97 (2018) 033003, arXiv:1711.09773]

- Constrain active-sterile neutrino oscillations: $N(L) = P_{\nu_a \to \nu_s}(L)\, N(0)$
  [Kosmas, Papoulias, PRD 97 (2018) 033003, arXiv:1711.09773]

Several oncoming new experiments: CONNIE, CONUS, MINER, Ricochet,
TEXONO, $\nu$-cleus, $\nu$GEN

# Conclusions

- Mainstream $3\nu$-mixing research: precise measurements of masses, mixing angles and CP violating phases with neutrino oscillations, $\beta$ decay, $\beta\beta_{0\nu}$ decay.
- Neutrinos provide a Window to the New Physics beyond the Standard Model through:
  - Small (Majorana) Masses.
  - Sterile Neutrinos.
  - Non-Standard Interactions. [see Ohlsson, RPP 76 (2013) 044201, arXiv:1209.2710]
  - Electromagnetic Interactions. [see CG, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344]
  - ...
- Exciting model-independent indication of light sterile neutrinos at the eV scale from the NEOS and DANSS experiments, in agreement with the reactor and Gallium anomalies.

  It will be tested soon by several experiments.
- New tool: coherent elastic neutrino-nucleus scattering.