Neutrino mass & sterile neutrinos

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Preambles

- Since 1998 we know that neutrinos oscillate between their flavors due to a difference between mass eigenstates and weak eigenstates
- This implies that at least 2 out of the 3 known neutrino mass eigenstates have a non-zero mass
- Oscillation experiments currently provide information on the absolute value of the mass splittings, and may reveal in the (near) future their sign
- Oscillation experiments are unable to reveal any information on the absolute mass of the neutrino eigenstates, or on the details of how this mass is generated
- Extracting the CP-violating phase is only possible by measuring

$$|P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)|$$

How is mass generated

a mass is an interaction which transforms a particle into itself or into another one

- bilinear term
- Lorentz invariant
- hermitian

⇓

for a fermion there are 2 possible types of masses:

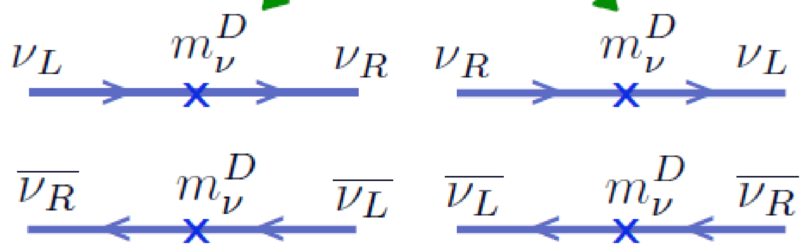
Theory introduction by T. Hambye (ULB)
Antwerp, BND school, 30/08-01/09 2016

Dirac mass

↪ an interaction of a left-handed fermion ψ_L with a right-handed fermion ψ_R which is not its anti-particle

$$\mathcal{L} \ni -m_\nu^D \left(\overline{\nu_R}\, \nu_L + \overline{\nu_L}\, \nu_R \right)$$

$\nu_L \equiv \psi_{\nu_L}$



NOT in SM, because there are no ν_R in Standard Model

Majorana mass

↪ an interaction of a left-handed fermion ψ_L with a right-handed fermion ψ_R which is its anti-particle $\psi_R = \psi_L^c$

$$\mathcal{L} \ni -\frac{1}{2} m_\nu^M \left(\overline{\nu_L^c}\, \nu_L + \overline{\nu_L}\, \nu_L^c \right)$$

$$\nu_L^c \sim \overline{\nu_L}^T \qquad \overline{\nu_L^c} \sim \nu_L^T$$

$$\mathcal{L} \ni -\frac{1}{2} m_\nu^M \left(\nu_L^T \cdot \nu_L + \overline{\nu_L} \cdot \overline{\nu_L}^T \right)$$

NOT in SM, because not gauge invariant (see later)

Neutrino mass matrix: Dirac case

$\Rightarrow$ most general Dirac mass term: $\mathcal{L} \ni -(\overline{\nu_{eR}} \ \overline{\nu_{\mu R}} \ \overline{\nu_{\tau R}}) \begin{pmatrix} m_{\nu_{ee}} & m_{\nu_{e\mu}} & m_{\nu_{e\tau}} \\ m_{\nu_{\mu e}} & m_{\nu_{\mu\mu}} & m_{\nu_{\mu\tau}} \\ m_{\nu_{\tau e}} & m_{\nu_{\tau\mu}} & m_{\nu_{\tau\tau}} \end{pmatrix} \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} + h.c.$

one can always go to a basis where mass matrix is diagonal:

$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = V_L^\nu \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix} \qquad \begin{pmatrix} \nu_{eR} \\ \nu_{\mu R} \\ \nu_{\tau R} \end{pmatrix} = V_R^\nu \begin{pmatrix} \nu_{1R} \\ \nu_{2R} \\ \nu_{3R} \end{pmatrix}$$

$$\mathcal{L} \ni -(\overline{\nu_{1R}} \ \overline{\nu_{2R}} \ \overline{\nu_{3R}}) \cdot \underline{V_R^{\nu\dagger} \cdot \begin{pmatrix} m_{\nu_{ee}} & m_{\nu_{e\mu}} & m_{\nu_{e\tau}} \\ m_{\nu_{\mu e}} & m_{\nu_{\mu\mu}} & m_{\nu_{\mu\tau}} \\ m_{\nu_{\tau e}} & m_{\nu_{\tau\mu}} & m_{\nu_{\tau\tau}} \end{pmatrix} \cdot V_L^\nu} \cdot \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix} + h.c.$$

$$\equiv M^\nu_{Diag.} = \begin{pmatrix} m_{\nu_1} & 0 & 0 \\ 0 & m_{\nu_2} & 0 \\ 0 & 0 & m_{\nu_3} \end{pmatrix}$$

$$= -m_{\nu_1} \overline{\nu_{1R}} \nu_{1L} - m_{\nu_2} \overline{\nu_{2R}} \nu_{2L} - m_{\nu_3} \overline{\nu_{3R}} \nu_{3L} + h.c.$$

$m_{\nu_{1,2,3}}$: real parameters

$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix}$ = "flavor states"

$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$ = "mass eigenstates"= physical states

Dirac case: PMNS mixing matrix

$\begin{pmatrix} \nu_{e_L} \\ \nu_{\mu_L} \\ \nu_{\tau_L} \end{pmatrix}$ = "flavor states" = states coupling in a diagonal way to e^-, μ^-, τ^- unlike mass eigenstates

$$\mathcal{L} \ni -(\overline{e_L}\ \overline{\mu_L}\ \overline{\tau_L})\, \gamma^\mu W^+_\mu \begin{pmatrix} \nu_{e_L} \\ \nu_{\mu_L} \\ \nu_{\tau_L} \end{pmatrix} + h.c. = -(\overline{e_L}\ \overline{\mu_L}\ \overline{\tau_L})\, \gamma^\mu W^+_\mu \cdot V_L^\nu \cdot \begin{pmatrix} \nu_{1_L} \\ \nu_{2_L} \\ \nu_{3_L} \end{pmatrix} + h.c.$$

$$V_L^\nu \equiv U_{PMNS}$$

Pontecorvo-Maki-Nakagawa-Sakita

same as CKM matrix but for leptons instead of quarks

for a real mass matrix and only 2 neutrinos: U_{PMNS} = a 2 by 2 rotation matrix:

$$|\nu_\mu\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$|\nu_\tau\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

Oscillation of 2 neutrinos

Suppose there are only 2 neutrinos, ν_μ and ν_τ , and a non diagonal mass matrix, $m_{\nu_{\mu\tau}} \neq 0$

Flavor states: $|\nu_\mu\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$

$|\nu_\tau\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$

Mass states: $|\nu_1\rangle = \cos\theta\,|\nu_\mu\rangle - \sin\theta\,|\nu_\tau\rangle$

$|\nu_2\rangle = \sin\theta\,|\nu_\mu\rangle + \cos\theta\,|\nu_\tau\rangle$

Consider a ν_μ state produced at $t = x = 0$ from a W^+ with energy E : how does it evolves with time????

→ one can answer to this question by rewriting the ν_μ state in terms of the mass eigenstates

$$|\nu_\mu(t=0, x=0)\rangle = |\nu_\mu\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

because we know how the mass eigenstates components evolve:

$$|\nu_{1,2}>: \text{ mass eigenstates: evolves as plane waves:} |\nu_{1,2}(t,x)\rangle = e^{-i(E_{1,2}t - p_{1,2}x)}|\nu_{1,2}\rangle$$

Each ν_1 and ν_2 component of ν_μ evolves with its own plane wave independently of the other component

$$\Rightarrow |\nu_\mu(t,x)\rangle = \cos\theta\,|\nu_1(t,x)\rangle + \sin\theta\,|\nu_2(t,x)\rangle$$

$$= \cos\theta\, e^{-i(E_1 t - p_1 x)}\,|\nu_1\rangle + \sin\theta\, e^{-i(E_2 t - p_2 x)}\,|\nu_2\rangle$$

$$= \left(\cos^2\theta\, e^{-i(E_1 t - p_1 x)} + \sin^2\theta\, e^{-i(E_2 t - p_2 x)}\right)|\nu_\mu\rangle$$

$$+\left(-\sin\theta\cos\theta\, e^{-i(E_1 t - p_1 x)} + \sin\theta\cos\theta\, e^{-i(E_2 t - p_2 x)}\right)|\nu_\tau\rangle$$

Oscillation of 2 neutrinos

⇒ Probability that a ν_μ produced at $t = x = 0$ is seen as a ν_τ at t, x :

producing a τ^- for instance by interacting with detector

$$P\Big(\nu_\mu(t=0, x=0) \to \nu_\tau(t,x)\Big) = |\langle \nu_\tau | \nu_\mu(t,x)\rangle|^2$$

$$= |\sin\theta\cos\theta\,(-e^{-i(E_1 t - p_1 x)} + e^{-i(E_2 t - p_2 x)})|^2$$

$$= \frac{1}{4}\sin^2 2\theta\,|-e^{-i(E_1 t - p_1 x)} + e^{-i(E_2 t - p_2 x)}|^2$$

$$E_1 t - p_1 x \to \frac{m_{\nu_1}^2 L}{2E} \qquad E_2 t - p_2 x \to \frac{m_{\nu_2}^2 L}{2E}$$

$$= \sin^2 2\theta \sin^2 \frac{\Delta m_\nu^2 L}{4E} \qquad \Delta m_\nu^2 \equiv m_{\nu_1}^2 - m_{\nu_2}^2$$

⇒ $P\Big(\nu_\mu(t=0, x=0) \to \nu_\mu(t,x)\Big) = 1 - P\Big(\nu_\mu(t=0, x=0) \to \nu_\tau(t,x)\Big)$

$$= 1 - \sin^2 2\theta\, \sin^2 \frac{\Delta m_\nu^2 L}{4E}$$

amplitude of oscillation ($\sin^2 2\theta$)

oscillating function ($\sin^2 \frac{\Delta m_\nu^2 L}{4E}$) with oscillation length: $L_{osc} = \frac{4E}{\Delta m^2}\cdot\pi$

⇒ oscillation depends only on squared mass difference, not on absolute mass values

What can be measured if neutrinos have Dirac mass?

⇒ most general Dirac mass term: $\mathcal{L} \ni -(\overline{\nu_{e_R}}\ \overline{\nu_{\mu_R}}\ \overline{\nu_{\tau_R}}) \begin{pmatrix} m_{\nu_{ee}} & m_{\nu_{e\mu}} & m_{\nu_{e\tau}} \\ m_{\nu_{\mu e}} & m_{\nu_{\mu\mu}} & m_{\nu_{\mu\tau}} \\ m_{\nu_{\tau e}} & m_{\nu_{\tau\mu}} & m_{\nu_{\tau\tau}} \end{pmatrix} \begin{pmatrix} \nu_{e_L} \\ \nu_{\mu_L} \\ \nu_{\tau_L} \end{pmatrix} + h.c.$

$$\begin{pmatrix} \nu_{e_L} \\ \nu_{\mu_L} \\ \nu_{\tau_L} \end{pmatrix} = V_L^\nu \begin{pmatrix} \nu_{1_L} \\ \nu_{2_L} \\ \nu_{3_L} \end{pmatrix} \qquad \begin{pmatrix} \nu_{e_R} \\ \nu_{\mu_R} \\ \nu_{\tau_R} \end{pmatrix} = V_R^\nu \begin{pmatrix} \nu_{1_R} \\ \nu_{2_R} \\ \nu_{3_R} \end{pmatrix}$$

$$\mathcal{L} \ni -(\overline{\nu_{1_R}}\ \overline{\nu_{2_R}}\ \overline{\nu_{3_R}}) \cdot \underline{V_R^{\nu\dagger} \cdot \begin{pmatrix} m_{\nu_{ee}} & m_{\nu_{e\mu}} & m_{\nu_{e\tau}} \\ m_{\nu_{\mu e}} & m_{\nu_{\mu\mu}} & m_{\nu_{\mu\tau}} \\ m_{\nu_{\tau e}} & m_{\nu_{\tau\mu}} & m_{\nu_{\tau\tau}} \end{pmatrix} \cdot V_L^\nu} \cdot \begin{pmatrix} \nu_{1_L} \\ \nu_{2_L} \\ \nu_{3_L} \end{pmatrix} + h.c.$$

$$\equiv M^\nu_{Diag.} = \begin{pmatrix} m_{\nu_1} & 0 & 0 \\ 0 & m_{\nu_2} & 0 \\ 0 & 0 & m_{\nu_3} \end{pmatrix}$$

$$= -m_{\nu_1}\overline{\nu_{1_R}}\nu_{1_L} - m_{\nu_2}\overline{\nu_{2_R}}\nu_{2_L} - m_{\nu_3}\overline{\nu_{3_R}}\nu_{3_L}$$

$m_{\nu_{1,2,3}}$: real parameters

$\begin{pmatrix} \nu_{e_L} \\ \nu_{\mu_L} \\ \nu_{\tau_L} \end{pmatrix}$ = "flavor states" = states coupling in a diagonal way to e^-, μ^-, τ^- unlike mass eigenstates

$$\mathcal{L} \ni -(\overline{e_L}\ \overline{\mu_L}\ \overline{\tau_L})\ \gamma^\mu W_\mu^+ \begin{pmatrix} \nu_{e_L} \\ \nu_{\mu_L} \\ \nu_{\tau_L} \end{pmatrix} + h.c. = -(\overline{e_L}\ \overline{\mu_L}\ \overline{\tau_L})\ \gamma^\mu W_\mu^+ \cdot V_L^\nu \cdot \begin{pmatrix} \nu_{1_L} \\ \nu_{2_L} \\ \nu_{3_L} \end{pmatrix} + h.c.$$

same as CKM matrix but for leptons instead of quarks

$V_L^\nu \equiv U_{PMNS}$

What can be measured if neutrinos have Dirac mass?

2 masses: $m_{\nu_{1,2}}$

$U_{PMNS} = 2 \times 2$ unitary matrix $\rightarrow$ one angle + 3 phases

but in fact none of these 3 phases is physical:

if we simply rephase all the mass eigenstate fields (with same phases for L and R partners):

$$\begin{pmatrix} \nu_{1_L} \\ \nu_{2_L} \end{pmatrix} = \begin{pmatrix} e^{i\phi_{\nu_1}} & 0 \\ 0 & e^{i\phi_{\nu_2}} \end{pmatrix} \begin{pmatrix} \tilde{\nu}_{1_L} \\ \tilde{\nu}_{2_L} \end{pmatrix} \qquad \begin{pmatrix} e_L \\ \mu_L \end{pmatrix} = \begin{pmatrix} e^{i\phi_e} & 0 \\ 0 & e^{i\phi_\mu} \end{pmatrix} \begin{pmatrix} \tilde{e}_L \\ \tilde{\mu}_L \end{pmatrix}$$

$$\begin{pmatrix} \nu_{1_R} \\ \nu_{2_R} \end{pmatrix} = \begin{pmatrix} e^{i\phi_{\nu_1}} & 0 \\ 0 & e^{i\phi_{\nu_2}} \end{pmatrix} \begin{pmatrix} \tilde{\nu}_{1_R} \\ \tilde{\nu}_{2_R} \end{pmatrix} \qquad \begin{pmatrix} e_R \\ \mu_R \end{pmatrix} = \begin{pmatrix} e^{i\phi_e} & 0 \\ 0 & e^{i\phi_\mu} \end{pmatrix} \begin{pmatrix} \tilde{e}_R \\ \tilde{\mu}_R \end{pmatrix}$$

⇒ $-m_{\nu_i} \overline{\nu_{i_R}} \nu_{i_L}$ mass term remains unchanged $\leftarrow m_{\nu_{1,2,3}}$ remain real

⇒ $-m_e \overline{e_R} e_L$ mass term remains unchanged $\leftarrow m_e$ remains real (and same for m_μ and m_τ)

⇒ but coupling to W term changes:

$$\mathcal{L} \ni -(\overline{\tilde{e}_L}\ \overline{\tilde{\mu}_L})\, \gamma^\mu W_\mu^+ \cdot \begin{pmatrix} e^{-i\phi_e} & 0 \\ 0 & e^{-i\phi_\mu} \end{pmatrix} \cdot V_L^\nu \cdot \begin{pmatrix} e^{i\phi_{\nu_2}} & 0 \\ 0 & e^{i\phi_{\nu_2}} \end{pmatrix} \cdot \begin{pmatrix} \tilde{\nu}_{1_L} \\ \tilde{\nu}_{2_L} \end{pmatrix} + h.c.$$

$V_L^\nu \equiv U_{PMNS}$

⇒ 4 phases to eliminate 3 phases $\rightarrow$ all 3 phases eliminated $\rightarrow U_{PMNS}$: one angle, 0 phase

$$U_{PMNS} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

What can be measured if neutrinos have Dirac mass?

3 masses: $m_{\nu_{1,2,3}}$

$U_{PMNS} = 3 \times 3$ unitary matrix $\rightarrow$ 3 angles + 6 phases

but in fact only one of these 6 phases is physical:

$$\mathcal{L} \ni -(\overline{\tilde{e}_L}\ \overline{\tilde{\mu}_L}\ \overline{\tilde{\tau}_L})\,\gamma^\mu W^+_\mu \cdot \begin{pmatrix} e^{-i\phi_e} & 0 & 0 \\ 0 & e^{-i\phi_\mu} & 0 \\ 0 & 0 & e^{-i\phi_\tau} \end{pmatrix} \cdot V_L^\nu \cdot \begin{pmatrix} e^{i\phi_{\nu_2}} & 0 & 0 \\ 0 & e^{i\phi_{\nu_2}} & 0 \\ 0 & 0 & e^{i\phi_{\nu_3}} \end{pmatrix} \cdot \begin{pmatrix} \tilde{\nu}_{1_L} \\ \tilde{\nu}_{2_L} \\ \tilde{\nu}_{3_L} \end{pmatrix} + h.c.$$

6 phases to eliminate 6 phases $\rightarrow$ 5 phases eliminated $\rightarrow U_{PMNS}$: 3 angles, 1 phase

one combination of 6 phases doesn't change U_{PMNS} : $\phi_e = \phi_\mu = \phi_\tau = \phi_{\nu_1} = \phi_{\nu_2} = \phi_{\nu_3}$

$\Rightarrow$ Summary: 3 masses, m_{ν_1}, m_{ν_2}, m_{ν_3}, 3 angles in U_{PMNS} and one CP-violating phase in U_{PMNS}

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Why no neutrino masses in the SM

→ no Dirac masses in SM because no ν_R in SM $\mathcal{L} \ni -m_\nu^D(\overline{\nu_R}\nu_L + \overline{\nu_L}\nu_R)$

→ no Majorana masses in SM because: $\mathcal{L} \ni -\frac{1}{2}m_\nu^M(\nu_L^T \cdot \nu_L + \overline{\nu_L} \cdot \overline{\nu_L}^T)$

-this breaks $SU(2)_L \times U(1)_Y$, for example since ν_L has an hypercharge this breaks hypercharge

-in principle it could be generated from $SU(2)_L \times U(1)_Y$ invariant term if this term contains the Higgs doublet, replacing it by its vacuum expectation value $H \equiv \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \rightarrow \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$

-since the ν_L is in the doublet $L \equiv \begin{pmatrix} \nu_L \\ l^- \end{pmatrix}$ this term must contain $L^T \cdot L \ni \nu_L^T \cdot \nu_L$

→ $\mathcal{L} \ni -\frac{m_\nu}{2} L^T \cdot L$? ← no because not $SU(2)_L \times U(1)_Y$ invariant

$\mathcal{L} \ni L^T \cdot L\, H$? ← no because not $SU(2)_L \times U(1)_Y$ invariant

$\mathcal{L} \ni \frac{1}{\Lambda} L^T \cdot L\, H^T H$? ← is $SU(2)_L \times U(1)_Y$ invariant but no: dimension 5

→ not there in SM but could be generated by exchange of intermediate particles

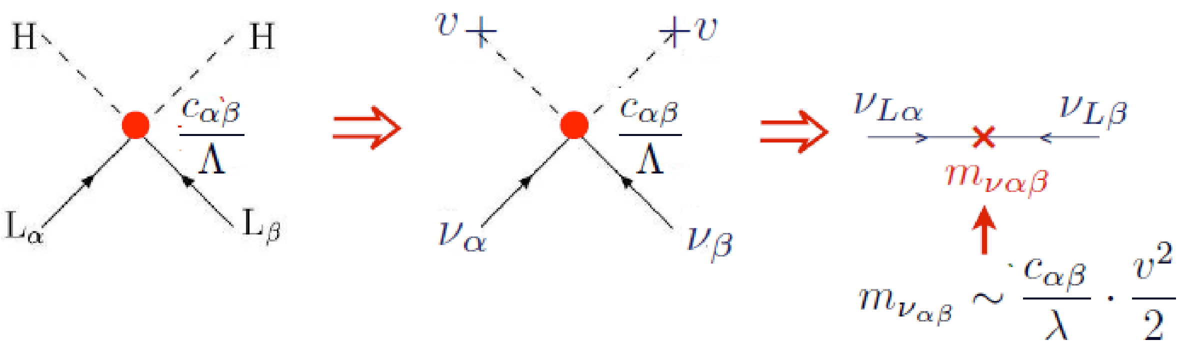
Generating Majorana neutrino masses from dimension 5 interactions

with three flavor of neutrinos the dimension-5 interaction is:

"Weinberg operator"

$$\mathcal{L} \ni \frac{c_{\alpha\beta}}{\Lambda} L_\alpha^T \cdot L_\beta H^T H \qquad \alpha, \beta = e, \mu, \tau$$

if this interaction is generated from exchange of intermediate particles between the 4 particles this generates Majorana neutrino masses:



⇒ if such intermediate particles exist there will be Majorana masses!

and this is new physics!

Let's suppose ν_R exists

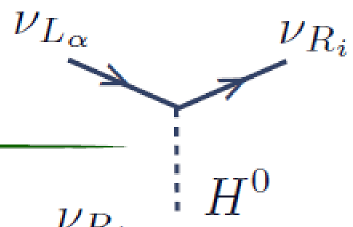
a ν_R is necessarily a singlet of the SM, otherwise it would have been seen

in this case one can have 2 new types of interactions which are $SU(2)_L \times U(1)_Y$ invariant:

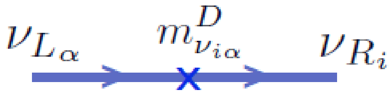
I) a Yukawa interaction:

$$\mathcal{L} \ni -Y_{\nu_{i\alpha}} \overline{\nu_{R_i}} L_\alpha H + h.c.$$

$$\ni -Y_{\nu_{i\alpha}} \overline{\nu_{R_i}} \nu_{L_\alpha} H^0 + h.c.$$



$$\ni -Y_{\nu_{i\alpha}} \frac{v}{\sqrt{2}} \overline{\nu_{R_i}} \nu_{L_\alpha} + h.c.$$



$$= m^D_{\nu_{i\alpha}}$$

in this case to have $m_\nu^D \sim 0.1\,\mathrm{eV}$ we need $Y_\nu \sim 10^{-11}$ $\qquad v = 246\,\mathrm{GeV}$

much smaller than Yukawas of all other SM fermions!

Let's suppose ν_R exists

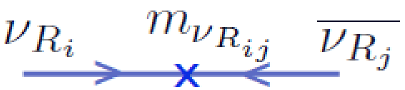
a ν_R is necessarily a singlet of the SM, otherwise it would have been seen

in this case one can have 2 new types of interactions which are $SU(2)_L \times U(1)_Y$ invariant:

2) a Majorana mass for the ν_R:

$$\mathcal{L} \ni -\frac{1}{2} m_{\nu_{R_{ij}}} \nu^T_{R_i} \cdot \nu_{R_j} + h.c.$$

not forbidden by any symmetry because ν_R is a SM singlet



to simplify the calculations we can always go to a basis where these mass matrix is diagonal and real

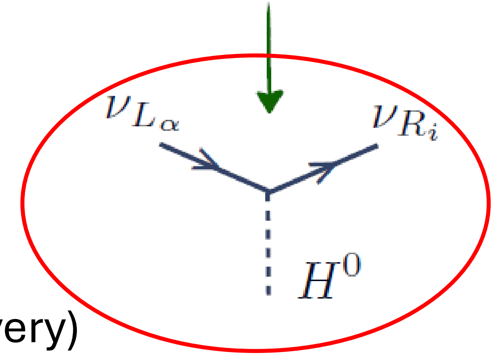
$$\mathcal{L} \ni -\frac{1}{2} m_{\nu_{R_1}} \nu^T_{R_1} \cdot \nu_{R_1} + \frac{1}{2} m_{\nu_{R_2}} \nu^T_{R_2} + \frac{1}{2} m_{\nu_{R_3}} \nu^T_{R_3} + h.c.$$

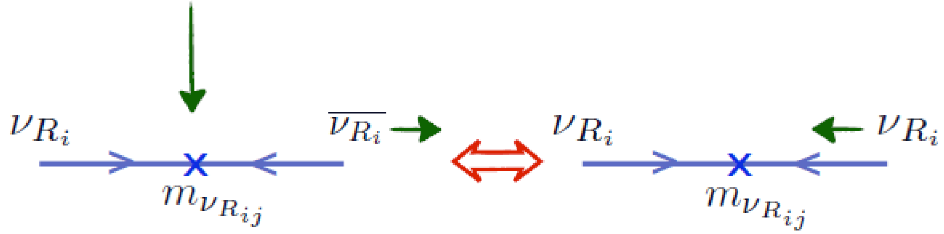
Let’s suppose ν_R exists

Summary: in full generality we have

$$\mathcal{L} \ni -Y_{\nu_{i\alpha}} \overline{\nu_{R_i}} L_\alpha H - \frac{1}{2} m_{\nu_{R_i}} \nu_{R_i}^T \cdot \nu_{R_i} + h.c.$$

The RH singlet mixes with LH neutrinos through Higgs Yukawa coupling

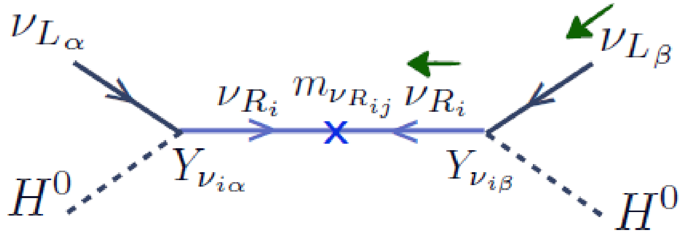


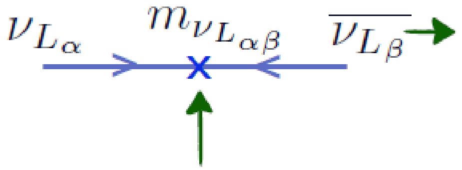


Mixing angle is typically (very) small:

$$\theta \sim \frac{m_D}{M_R}$$

These 2 interactions generate nothing but the dimension 5 interaction, and thus Majorana masses for the ν_{L_α}!

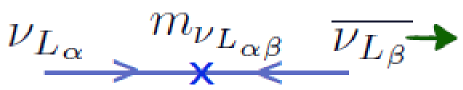




$$\Rightarrow \quad m_{\nu_{L_{\alpha\beta}}} = -\frac{Y_{\nu_{i\alpha}} Y_{\nu_{i\beta}}}{m_{\nu_{R_i}}} \cdot \frac{v^2}{2}$$

$\Rightarrow$ the presence of ν_R do not give Dirac masses but ν_L Majorana masses!

Let's suppose ν_R exists: see-saw mechanism



$$\rightarrow \quad m_{\nu L_{\alpha\beta}} = -\frac{Y_{\nu i\alpha} Y_{\nu i\beta}}{m_{\nu R_i}} \cdot \frac{v^2}{2}$$

- to get $m_{\nu_L} \sim 0.1$ eV: if $Y_\nu \sim 1 \to m_{\nu R} \sim 10^{14}$ GeV

- provides an possible explanation of the smallness of the neutrino masses: m_{ν_L} is small because m_{ν_R} which has nothing to do with the electroweak scale v, and thus could be much larger, is large

  fits very well with GUT framework: 10^{14} GeV is close to GUT scale

- the mass of the ν_R is basically $\sim m_{\nu R}$

  the much smaller Dirac mass term $m_D \sim Y_\nu \frac{v}{\sqrt{2}} \sim v \sim 246\,\mathrm{GeV}$ hardly affects it

  thus the ν_L and ν_R do not form a Dirac spinor with common mass as e.g. the electron

  the 2 physical states (mass eigenstates) are the $\sim \nu_R$ with Majorana mass $\sim m_{\nu R}$ and the $\sim \nu_L$ with Majorana mass $\sim m_{\nu_L} \sim Y_\nu^2 \frac{v^2}{2}$

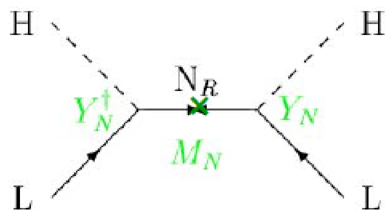
$\Rightarrow$ neutrino masses: opportunity to probe grand-unification!!

- to get $m_{\nu_L} \sim 0.1$ eV it is also possible to have e.g. $m_{\nu R} \sim TeV \to Y_\nu \sim 10^{-7}$

3 conventional seesaw ways to induce neutrino masses

ways to generate the neutrino masses from the exchange of a heavy particle between L, L, H, H to induce $LLHH$ interaction and thus small Majorana neutrino masses

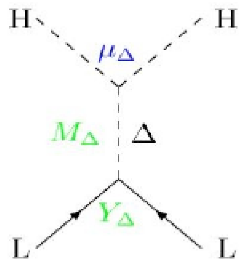
Right-handed singlet: (type-I seesaw)



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

m_ν small if M_N large (or if Y_ν small)

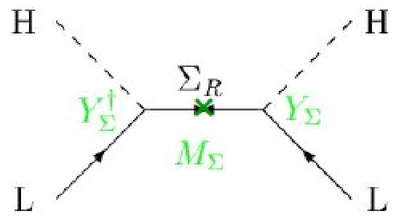
Scalar triplet: (type-II seesaw)



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

m_ν small if M_Δ large (or if Y_Δ, μ small)

Fermion triplet: (type-III seesaw)



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

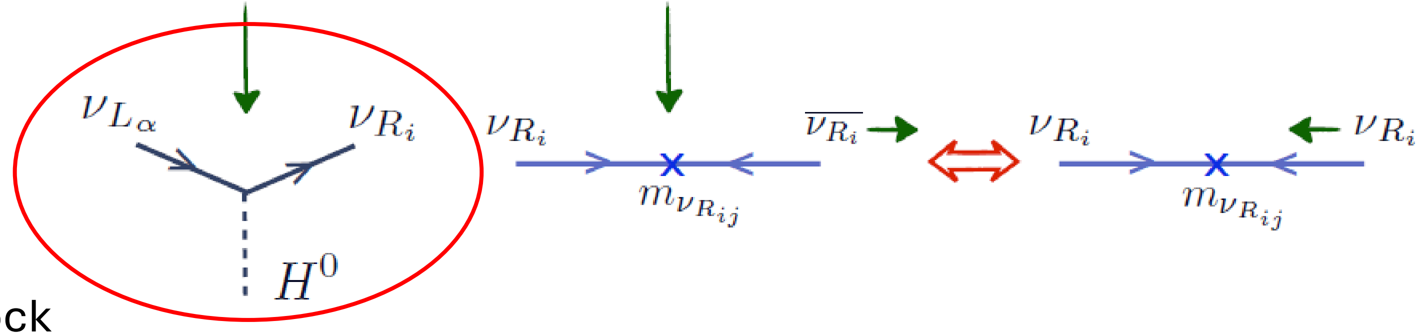
m_ν small if M_Σ large (or if Y_Σ small)

⇒ neutrino masses is really not in Standard Model: various kinds of new physics with new physical scale!

Mixing in a Type-I see-saw scenario

Summary: in full generality we have

$$\mathcal{L} \ni -Y_{\nu_{i\alpha}} \overline{\nu_{R_i}} L_\alpha H - \frac{1}{2} m_{\nu_{R_i}} \nu_{R_i}^T \cdot \nu_{R_i} + h.c.$$

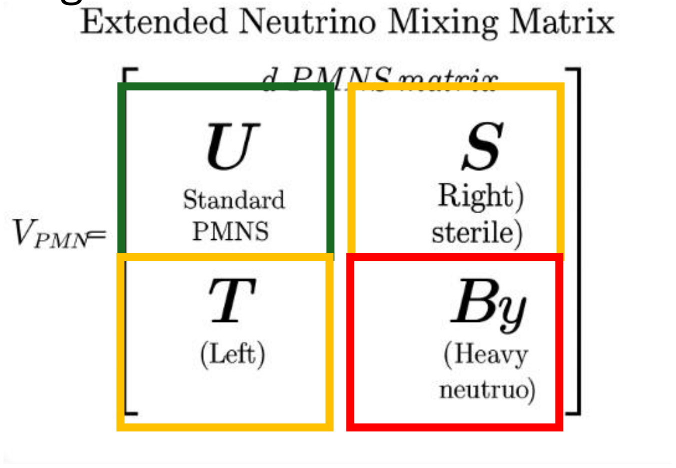


The RH singlet mixes with LH neutrino, only through Higgs Yukawa coupling!

Mixing angle is typically (very) small:

$$\theta \sim \frac{m_D}{M_R}$$

Extension of PMNS matrix with block Diagonal terms



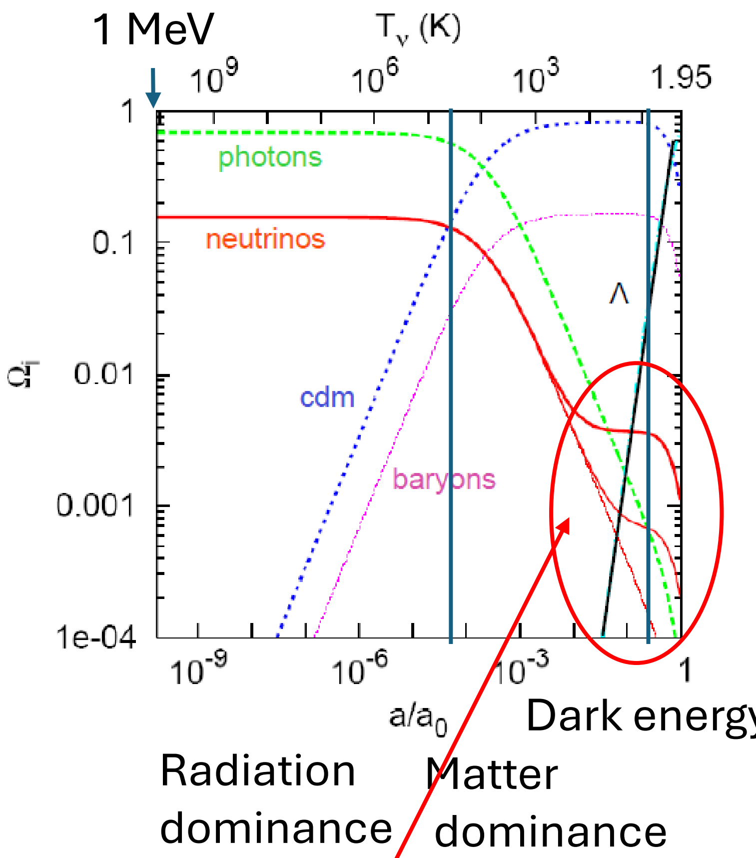
Extension of PMNS matrix with 1 right handed neutrino

$$U_{\text{extended}} \approx \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \theta_e \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \theta_\mu \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \theta_\tau \\ \theta_e^* & \theta_\mu^* & \theta_\tau^* & 1 \end{pmatrix}$$

Although it's possible, there is a Priori no reason/need to include one sterile neutrino for each SM Neutrino flavor!
Right handed neutrino's are EW singlets and do not know the concept of flavor.

Cosmology and neutrino's

- How many neutrino's in our universe?
- Big bang Cosmology in the 1st second:
  - Neutrinos, copiously produced by weak interactions, are in thermal equilibrium with other particles
  - The temperature cools down to 1MeV (10 billion K)
  - The density of neutrinos is equal to that of photons and baryons
- >1s:
  - Neutrinos decouple from the plasma and move freely in space: note that photons do so much much later (380kyr)
  - Electrons and positrons annihilate into photons, introducing extra energy into the photon bath, raising the overall photon temperature
  - Neutrino number density is frozen in comoving space, and have slightly lower energy than photons
  - Their number density only diminishes due to cosmic expansion
  - BUT: At low temperature, massive neutrinos become non-relativistic and change their impact on the universe from radiation to matter



In a late stage of the universe: massive Neutrinos become non-relativistic Their energy density scales like matter (a^{-3}), rather than radiation ((a^{-4}). Heavier neutrinos make this transition earlier that light eigenstates

Cosmology and neutrino's

- Entropy density for relativistic particles

$$s = \frac{2\pi}{45} g_* T^3$$

With Effective NDOF

$$g_*^{boson} = g$$

$$g_*^{fermion} = \frac{7}{8} g$$

Fermi-Dirac Vs. Bose-Einstein

$g = 2$ For photons (spin1 = 2 polarisations)

$g = 2$ For electrons and positrons (each spin ½, and they get factor 7/8))

- Before e+ and e- annihilate, they are in equilibrium with photons:

$$g_{before} = 2 + \frac{7}{8}(2 + 2) = 5.5$$

- After annihilation: only photons in equilibrium

$$g_{after} = 2$$

Entropy in comoving volume is conserved:

$$g_{before} T_{before}^3 = g_{after} T_{after}^3$$

Temperature of photons after e+e- annih:

$$T_{after} = T_{before} \left(\frac{5.5}{2}\right)^{1/3}$$

Neutrinos decoupled earlier:

$$T_\nu = T_{before}$$

So that Temperatures relate as:

$$\frac{T_\nu}{T_\gamma} = \left(\frac{4}{11}\right)^{1/3} \approx 0.714$$

Cosmology and neutrino's

- Number densities relate to Temperatures as:

$n = g \int \frac{d^3p}{(2\pi)^3} f(p)$, with $f(p) = \frac{1}{e^{E/T} \pm 1}$

Fermi-Dirac
Vs. Bose-Einstein

$$\boldsymbol{n = \frac{g}{2\pi^2} \int_0^\infty \frac{p^2 dp}{e^{p/T} \pm 1} \propto T^3}$$

Subsitute $\frac{p}{T} = x, dp = T dx,$ $\int_0^\infty \frac{x^2 dx}{e^x \pm 1} = number$

- So that: $\frac{n_\nu}{n_\gamma} = 3 \times \frac{3}{4} \left(\frac{T_\nu}{T_\gamma}\right)^3 \approx 0.819$

For photons $\int_0^\infty \frac{x^2 dx}{e^x - 1} = 2\zeta(3) \approx 2.404$

Temperatures today:

$T_\gamma \approx 2.725\ K$ (measured)

$T_\nu \approx 2.725 \times 0.714 = 1.95\ K$ (calculated)

- In case of 3 neutrino species $\frac{n_\nu^{tot}}{n_\gamma} = \frac{12}{11}$
- Evolution through cosmic expansion

For blackbody radiation: $\lambda_{peak} \propto \frac{1}{T}$

As space stretches, so does the photon peak wavelength

And thus: $T_\nu \propto a^{-1}$

$n_\nu \propto a^{-3}$

Number densities today:

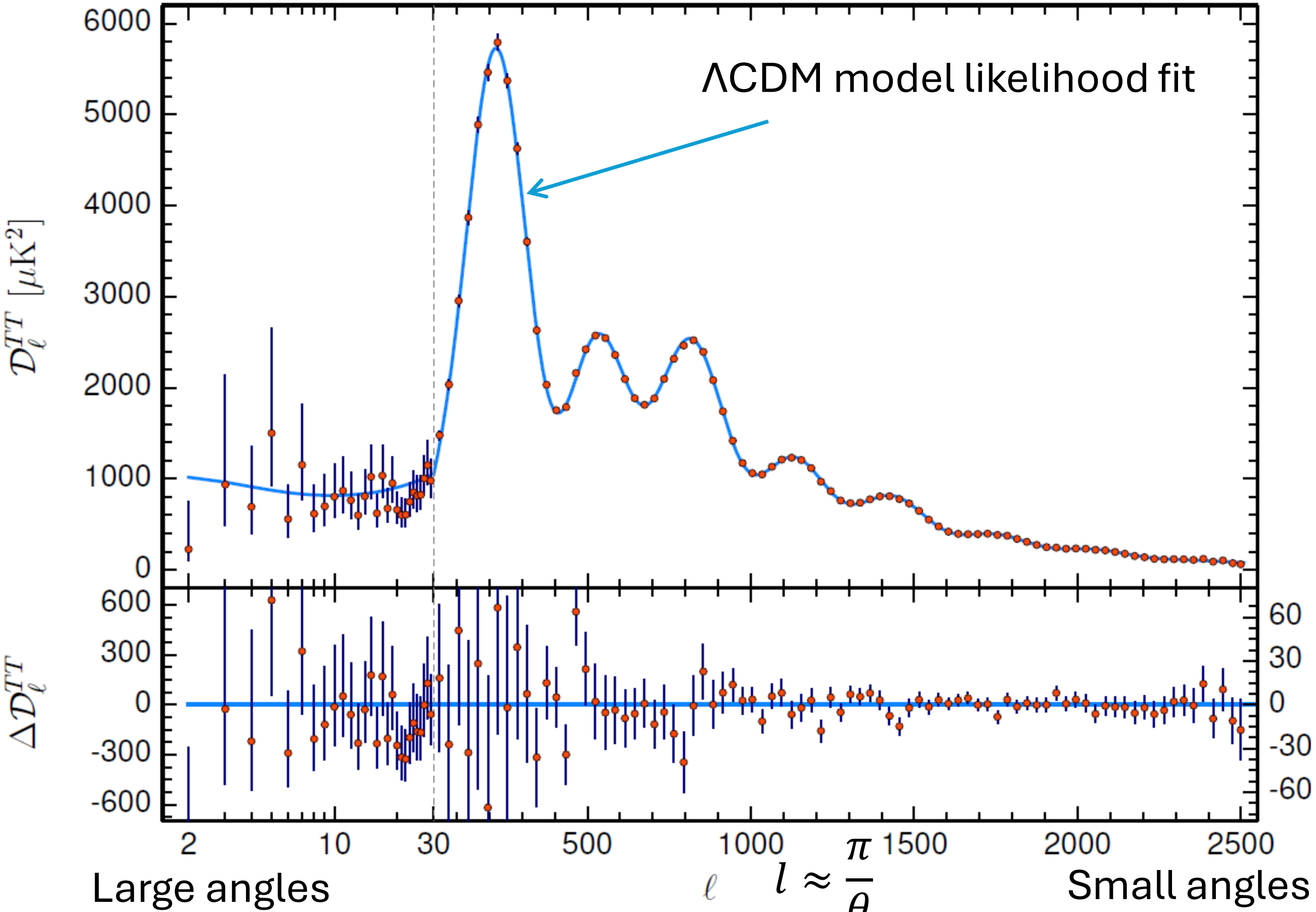
$n_\gamma = \frac{2\zeta(3)}{2\pi^2} T^3 \approx 410 cm^{-3}$

$n_\nu \approx 410 cm^{-3} \times 0.819 \approx 336 cm^{-3}$

Neutrino energy:

$E_\nu = k_B T = 8.617 \times 10^{-5} eV / K \times 1.95\ K = 1.86 \times 10^{-4} eV$

The CMB power spectrum

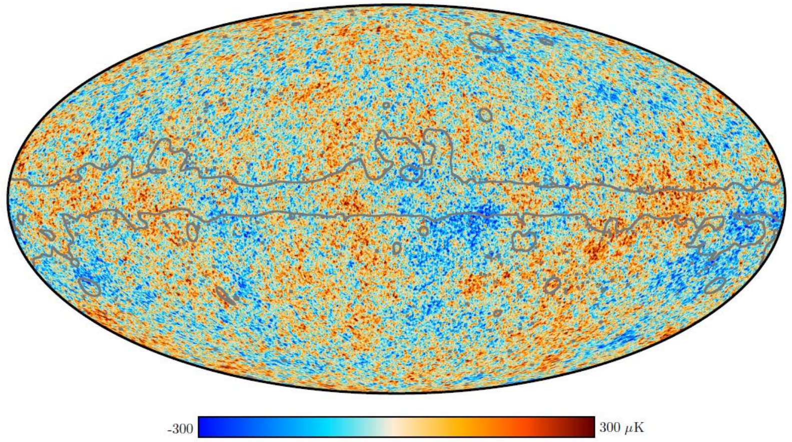


Large angles $l \approx \frac{\pi}{\theta}$ Small angles

From: Planck Collab., A&A 641, A6 (2020)

https://doi.org/10.1051/0004-6361/201833910

- Start from a cleaned sky map of $\Delta T \,/\, T$



- Temperature fluctuations in each direction, decomposed in spherical harmonic functions

$$\Theta(\vec{p}) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\vec{p})$$

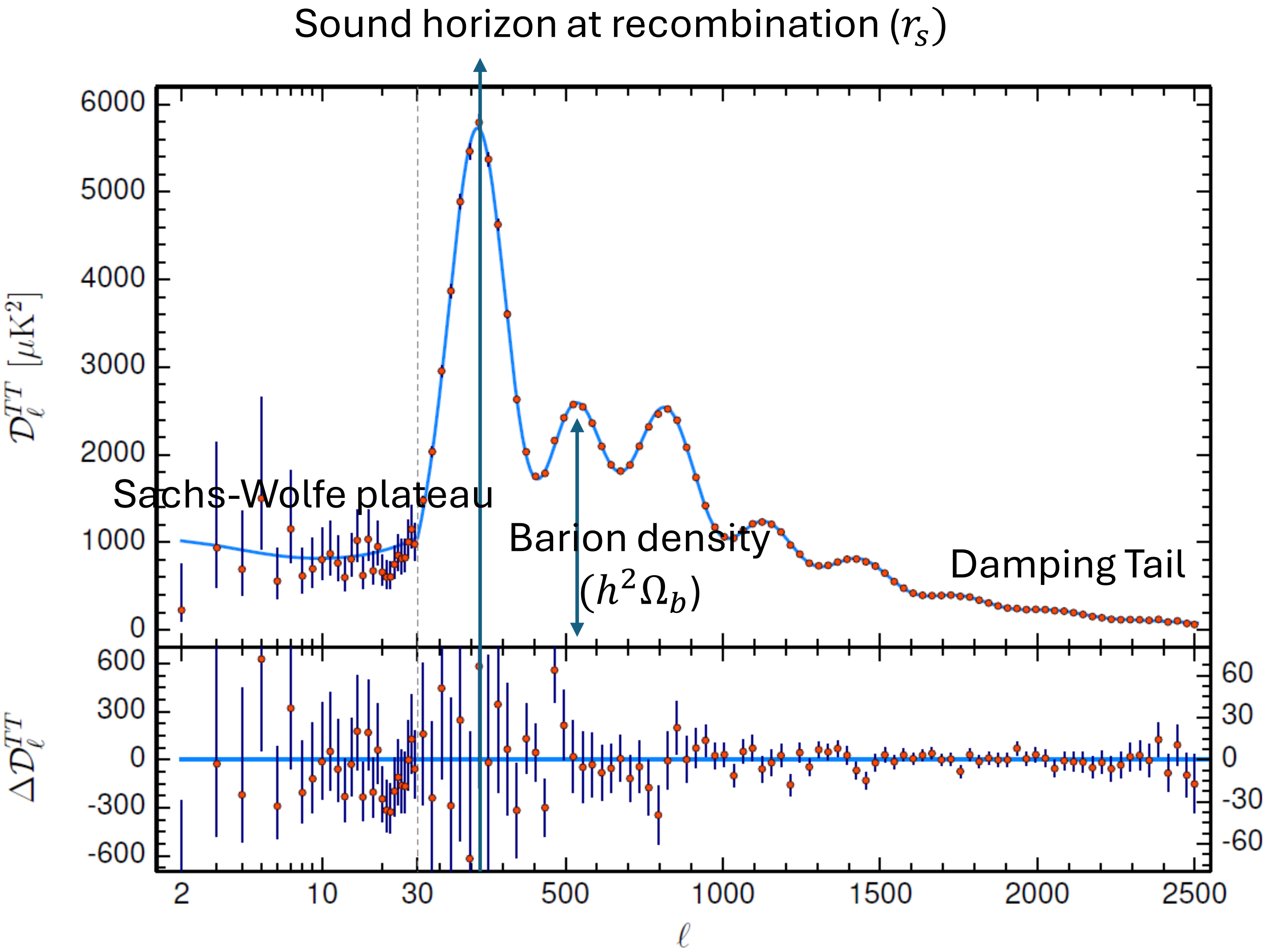
- Power spectrum, C_l,is the ensemble average of the coefficients. This depends only on l when universe is isotropic

$$C_l = \langle |a_{lm}|^2 \rangle = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

- Contribution to the variance per log interval in l

$$\mathcal{D}_l = l(l-1)C_l/\pi \; (\mu K^2)$$

What physics can be deduced from the TT spectrum?



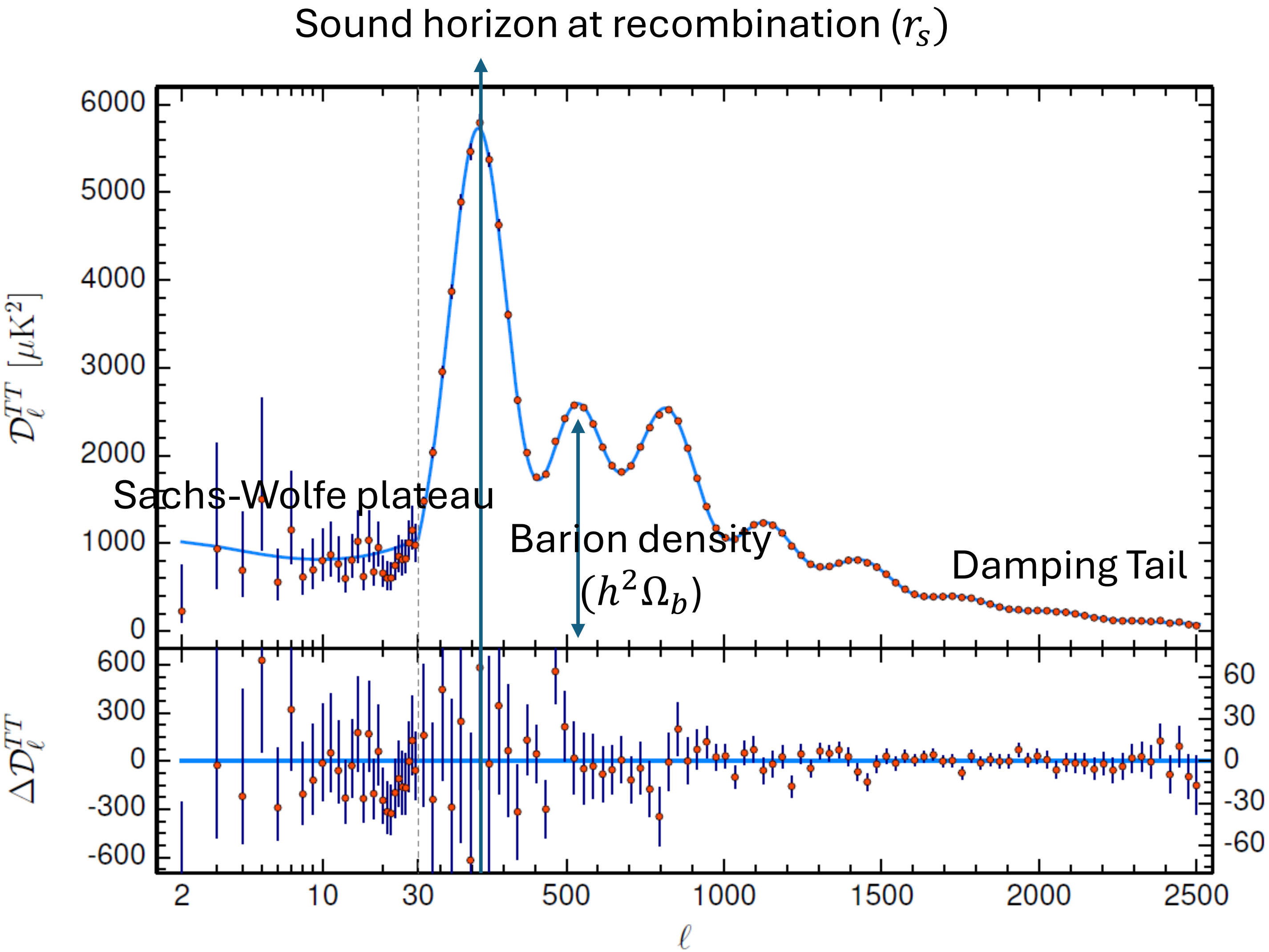
First acoustic peak, l=200:
Largest compression of photon-baryon fluid at recombination
Sensitive to:

- Baryon and DM density (height of peak)
- Geometry of the universe
- Angular scale of the sound horizon: this depends on expansion rate before recomb. And thus on nr of neutrinos (not mass because relativistic still): Expressed in N_{eff}:quantifies the total energy density in relativistic particles (except for photons). In SM: $N_{eff} \approx 3$
- Note: only neutrinos with mass

$$m \ll T_{\rm rec} \approx 0.26\,\mathrm{eV}.$$

- Heavier neutrinos contribute to total matter density, and thus hight of peak

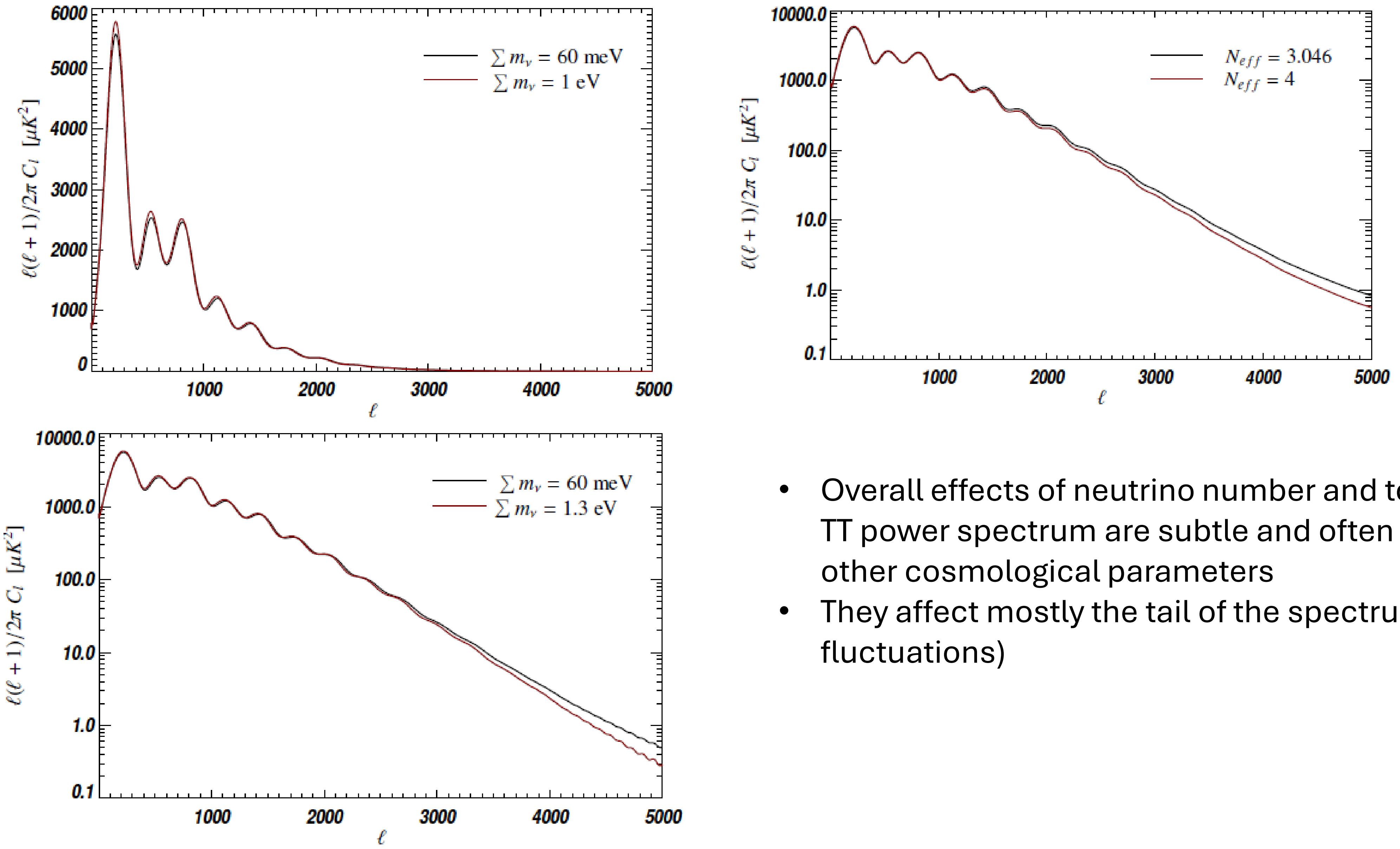
What physics can be deduced from the TT spectrum?



Damping tail, l>1500:
Measures mean free path of photons at recombination
Sensitive to:

- Baryon and electron density
- Expansion rate
- N_{eff}: faster expansion reduces the time for acoustic oscillations & photons to diffuse: start of damping tail shifts to left and becomes steeper
- $\sum m_\nu$: sum of masses of all neutrino species: affect later times when neutrinos become non-relativistic: also steeper damping tail for higher masses

Neutrino impact on CMB TT spectrum?

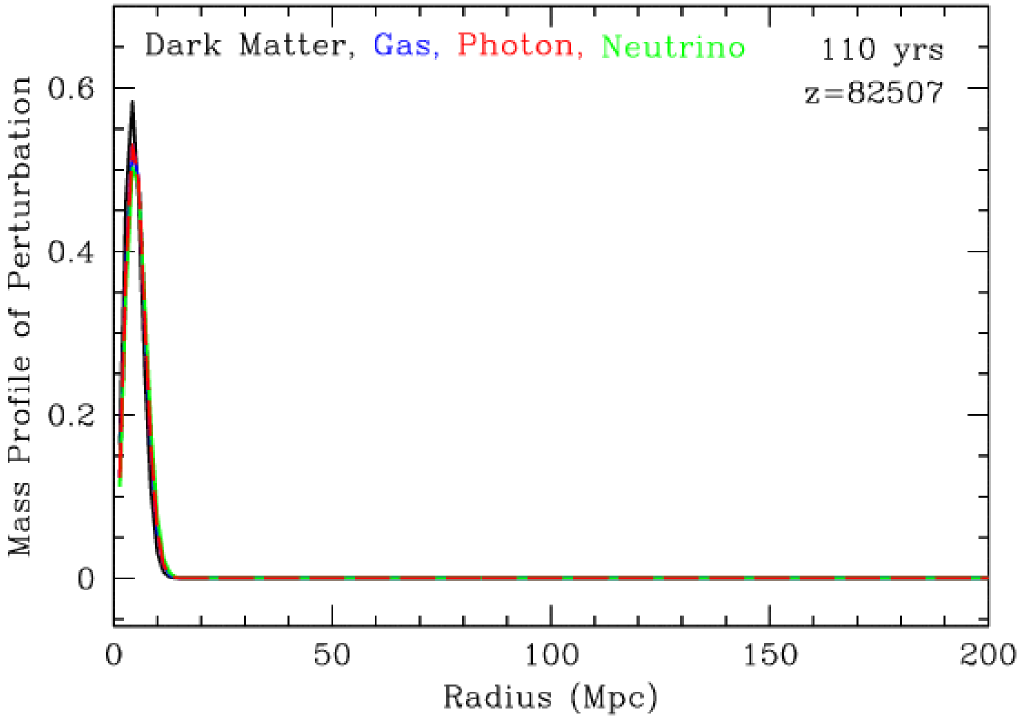


- Overall effects of neutrino number and total mass on CMB TT power spectrum are subtle and often degenerate with other cosmological parameters
- They affect mostly the tail of the spectrum (small scale fluctuations)

Baryon Acoustic Oscillations (BAO)

- A cosmological probe that was firmly established in 2005: D. J. Eisenstein *et al.* 2005 *ApJ* **633** 560
- Overdensities of curvature attract photons (and neutrinos) that push the photon-baryon plasma outward, like a sounds wave with speeds up to 0.5.c
- These sounds waves propagate until photons decouple, after which they slow down
- Maximum distance traveled: sound horizon, $r_s \approx 150\ Mpc\ (physical) \approx 100h^{-1}\mathrm{Mpc}\ (\mathrm{comoving})$
- When the universe cooled down further, these oscillations froze out in the matter distribution, observable by distribution of galaxies
- It is a probe that allows to probe the universe at much later timescales, and correspondingly much smaller redshifts, when matter effects become more important
- Key probe: spatial correlation plot of the distance between galaxies in large galaxy survey campaigns: eg. SLOAN, DESI, ...

  $\xi(r)$: Two-point correlation function of the distance between galaxies: excess probability of finding galaxies at spectif diatance wrt random distribution



Pure CDM model is disfavored:
No acoustic waves without baryons
In the early universe plasma.

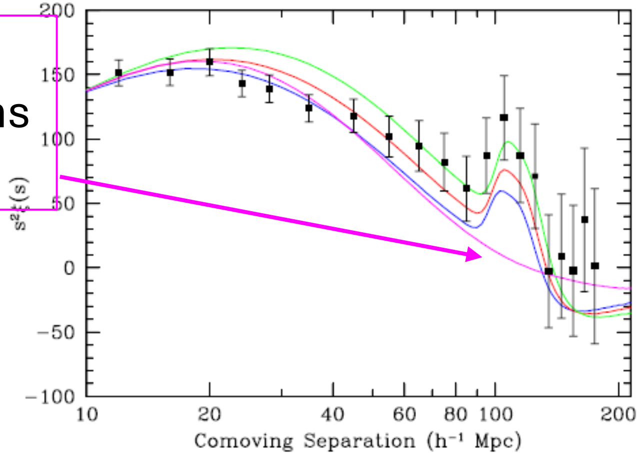
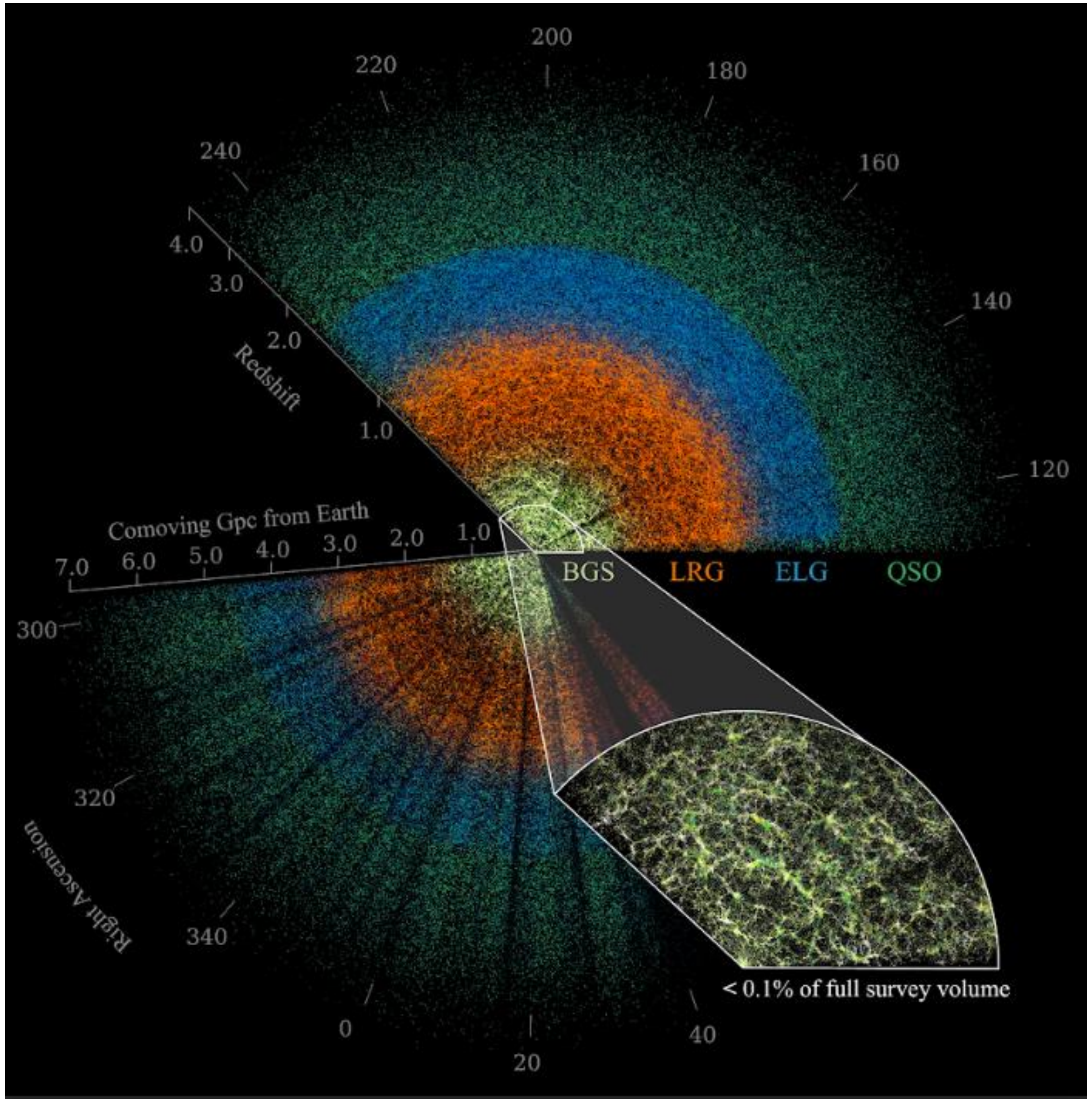


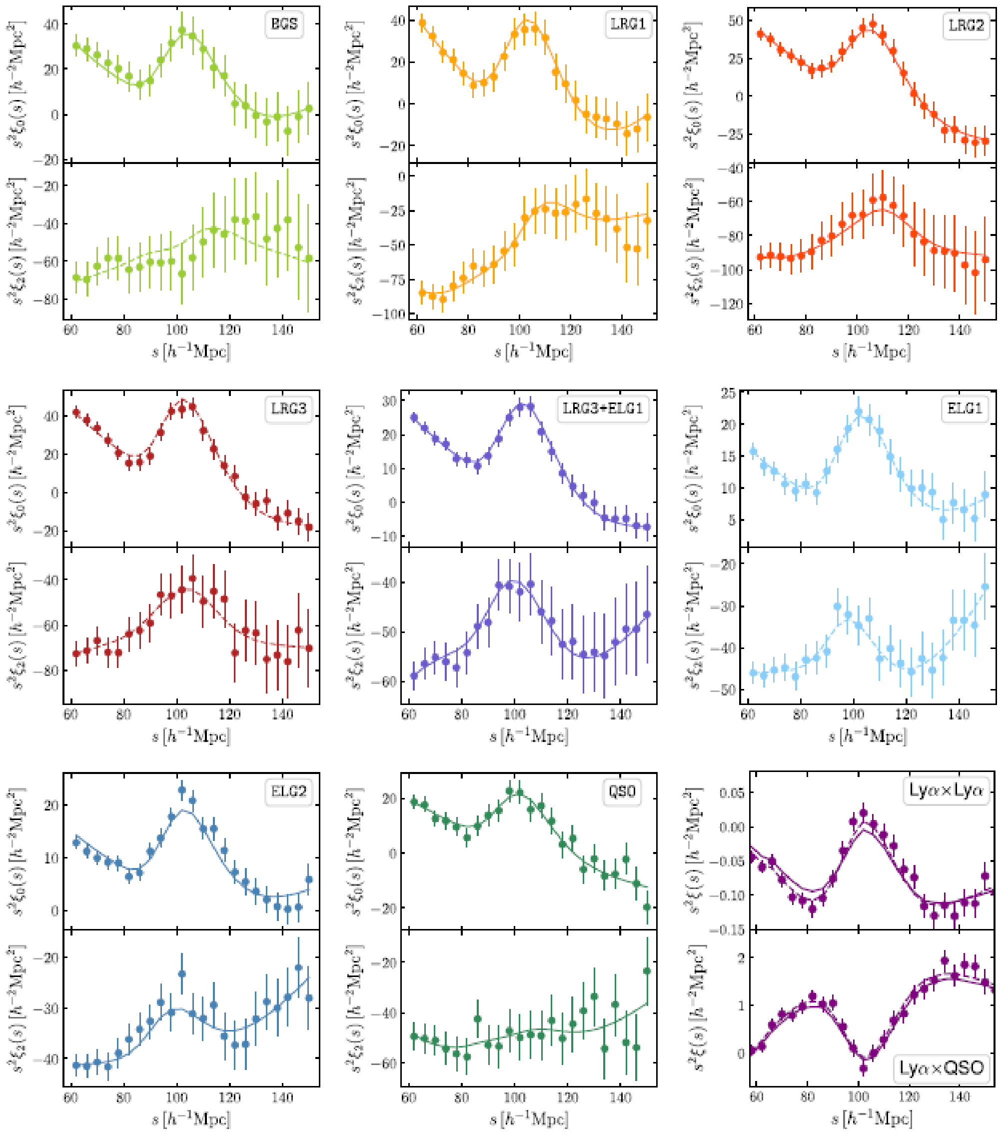
FIG. 3.— As Figure 2, but plotting the correlation function times s^2. This shows the variation of the peak at $20h^{-1}$ Mpc scales that is controlled by the redshift of equality (and hence by $\Omega_m h^2$). Varying $\Omega_m h^2$ alters the amount of large-to-small scale correlation, but boosting the large-scale correlations too much causes an inconsistency at $30h^{-1}$ Mpc. The pure CDM model (magenta) is actually close to the best-fit due to the data points on intermediate scales.

Latest results on BAO

M. A. Karim et al., Phys. Rev. D **112**, 083515 (**2025**)

14 million galaxies mapped in 3D, compared to 47.000 in the SLOAN survey





Implications of CMB and BAO on neutrinos

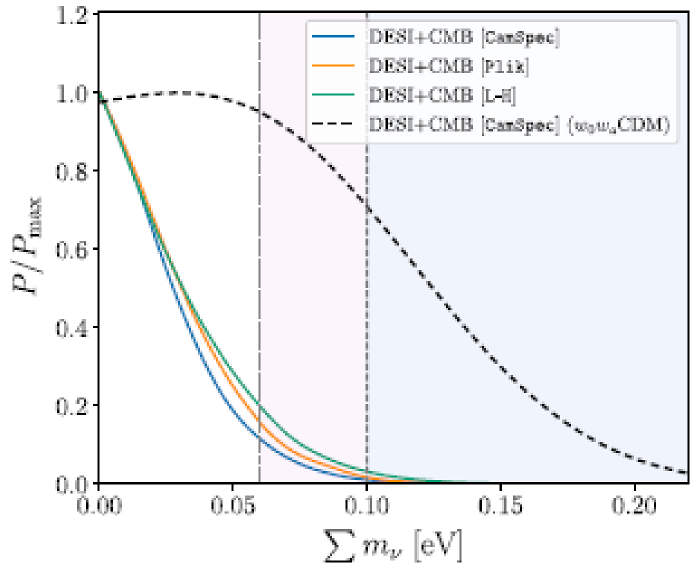


FIG. 15. One-dimensional marginalized posterior constraints on $\sum m_\nu$ from DESI DR2 BAO measurements combined with different CMB likelihoods, assuming the ΛCDM + $\sum m_\nu$ model. We show the one-dimensional posteriors for the CamSpec CMB likelihood (leading to the tightest constraint) as well as the Plik and L-H CMB likelihoods. We also show the posterior for the w_0w_aCDM + $\sum m_\nu$ model, using DESI and the CamSpec CMB. Other models and datasets are presented in Table VII. The vertical dashed lines and shaded regions indicate the minimum allowed $\sum m_\nu$ values for (from left to right) the normal and inverted mass ordering scenarios, respectively.

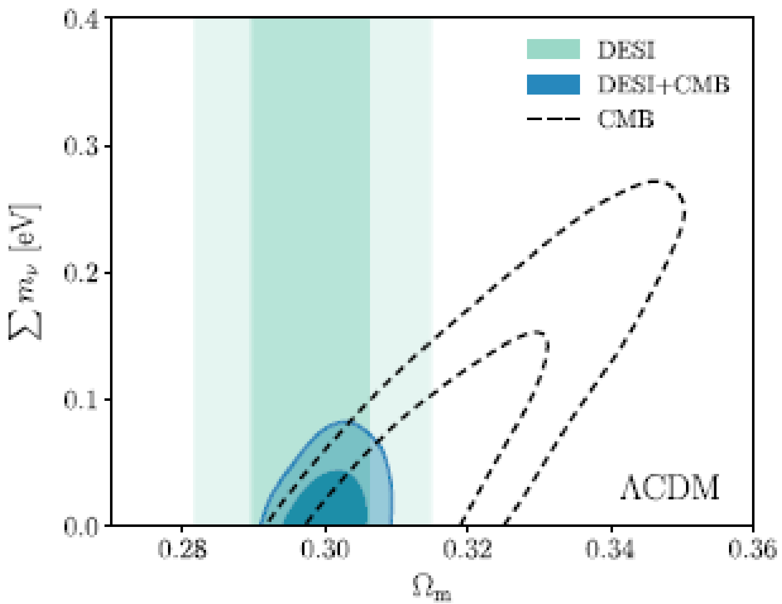


FIG. 16. 68% and 95% confidence contours for the sum of the neutrino masses and Ω_m in ΛCDM. The constraints assume a prior $\sum m_\nu > 0$ eV. The CMB constraints show a high degree of correlation between $\sum m_\nu$ and Ω_m. DESI BAO constraints are insensitive to the neutrino mass parameter but measure Ω_m, thus helping to break the geometric degeneracy and tightening the upper bound on $\sum m_\nu$. The constraint on $\sum m_\nu$ from DESI + CMB is particularly tight because of the DESI preference for lower Ω_m values.

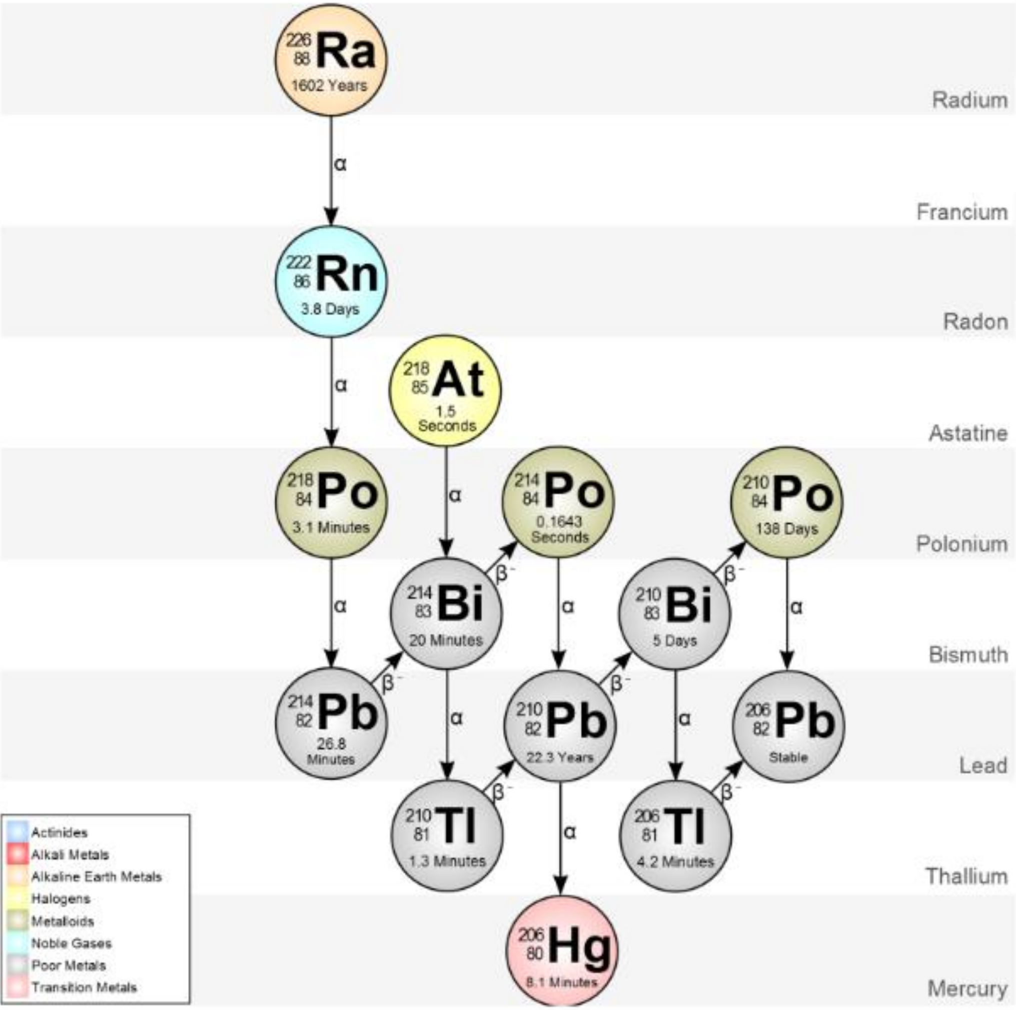
Model	Dataset	$\sum M_\nu$ (95% CL)	N_{eff} (68% CL)
ΛCDM + $\sum M_\nu$, N_{eff}	DESI BAO + CMB + SN	< 0.071 eV	3.02 ± 0.16
ΛCDM + $\sum M_\nu$, N_{eff}	DESI FS + BAO (no CMB)	< 0.32 eV	3.0 ± 0.3
w_0w_a ΛCDM + $\sum M_\nu$, N_{eff}	DESI BAO + CMB + SN	< 0.13 eV	~3.0 ± 0.2

- The upper bound $\sum M_\nu < 0.07$ eV (with CMB + SN) is **below the minimum sum allowed by the inverted hierarchy (~0.10 eV)**.
- This strongly favors the **normal hierarchy** for neutrino masses.
- It also means cosmology is approaching the sensitivity needed to **detect the neutrino mass scale**, not just constrain it.

- $N_{\text{eff}} = 3.02 \pm 0.16$ matches the Standard Model prediction (3.046).
- This rules out significant contributions from exotic particles like sterile neutrinos or dark radiation at early times.

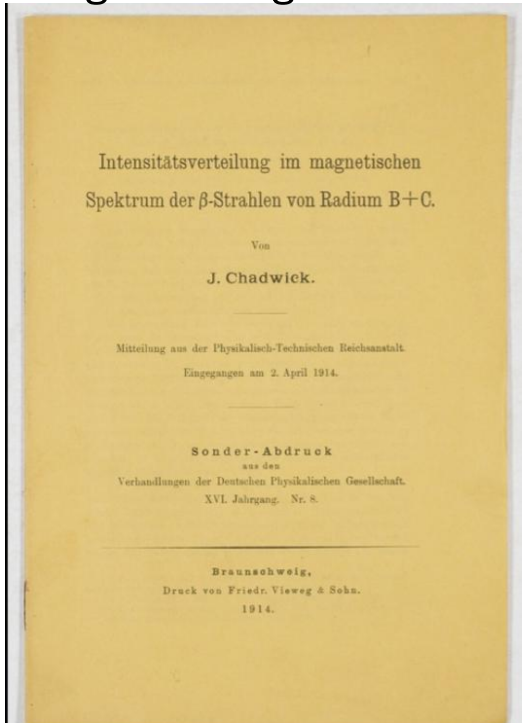
Cosmological data does not like sterile neutrinos !

Historic context



- J. Chadwick, *Verhandlungen der Deutschen Physikalischen Gesellschaft,* Vol. 16 pp.383–391
- C.D. Ellis and W.A. Wooster, Proc. Roy. Soc. A 117 (1927) 109
- Chadwick measures (roughly) the energy spectrum of β-rays from the decay of Radium B and C with a magnetic spectrometer ('tracker')
- Lise Meitner contests the conclusions by suggesting partial energy loss before detection
- Ellis and Wooster measure β -spectrum of Radium E with a calorimeter (either detecting 1MeV of energy in case of 2-body, or 390 keV in case of 3-body decay)
  - Radium B = ^{214}Pb
  - Radium C = ^{214}Bi
  - Radium E = ^{210}Bi

Chadwick 1914
Magnet+Geiger counter



Intensitätsverteilung im magnetischen Spektrum der β-Strahlen von Radium B+C.

Von

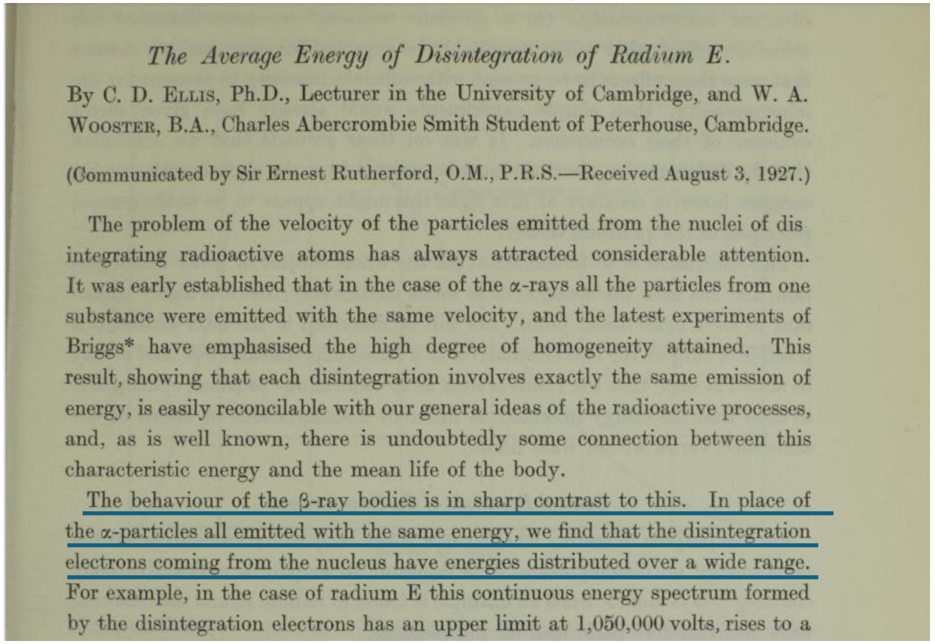
J. Chadwick.

Mitteilung aus der Physikalisch-Technischen Reichsanstalt.
Eingegangen am 2. April 1914.

Sonder-Abdruck
aus den
Verhandlungen der Deutschen Physikalischen Gesellschaft.
XVI. Jahrgang. Nr. 8.

Braunschweig,
Druck von Friedr. Vieweg & Sohn.
1914.

Ellis-Wooster 1927
Calorimeter experiment



The Average Energy of Disintegration of Radium E.

By C. D. Ellis, Ph.D., Lecturer in the University of Cambridge, and W. A. Wooster, B.A., Charles Abercrombie Smith Student of Peterhouse, Cambridge.

(Communicated by Sir Ernest Rutherford, O.M., P.R.S.—Received August 3, 1927.)

The problem of the velocity of the particles emitted from the nuclei of disintegrating radioactive atoms has always attracted considerable attention. It was early established that in the case of the α-rays all the particles from one substance were emitted with the same velocity, and the latest experiments of Briggs* have emphasised the high degree of homogeneity attained. This result, showing that each disintegration involves exactly the same emission of energy, is easily reconcilable with our general ideas of the radioactive processes, and, as is well known, there is undoubtedly some connection between this characteristic energy and the mean life of the body.

The behaviour of the β-ray bodies is in sharp contrast to this. In place of the α-particles all emitted with the same energy, we find that the disintegration electrons coming from the nucleus have energies distributed over a wide range. For example, in the case of radium E this continuous energy spectrum formed by the disintegration electrons has an upper limit at 1,050,000 volts, rises to a

Historic Context

Magnetic ‘spectrometer’

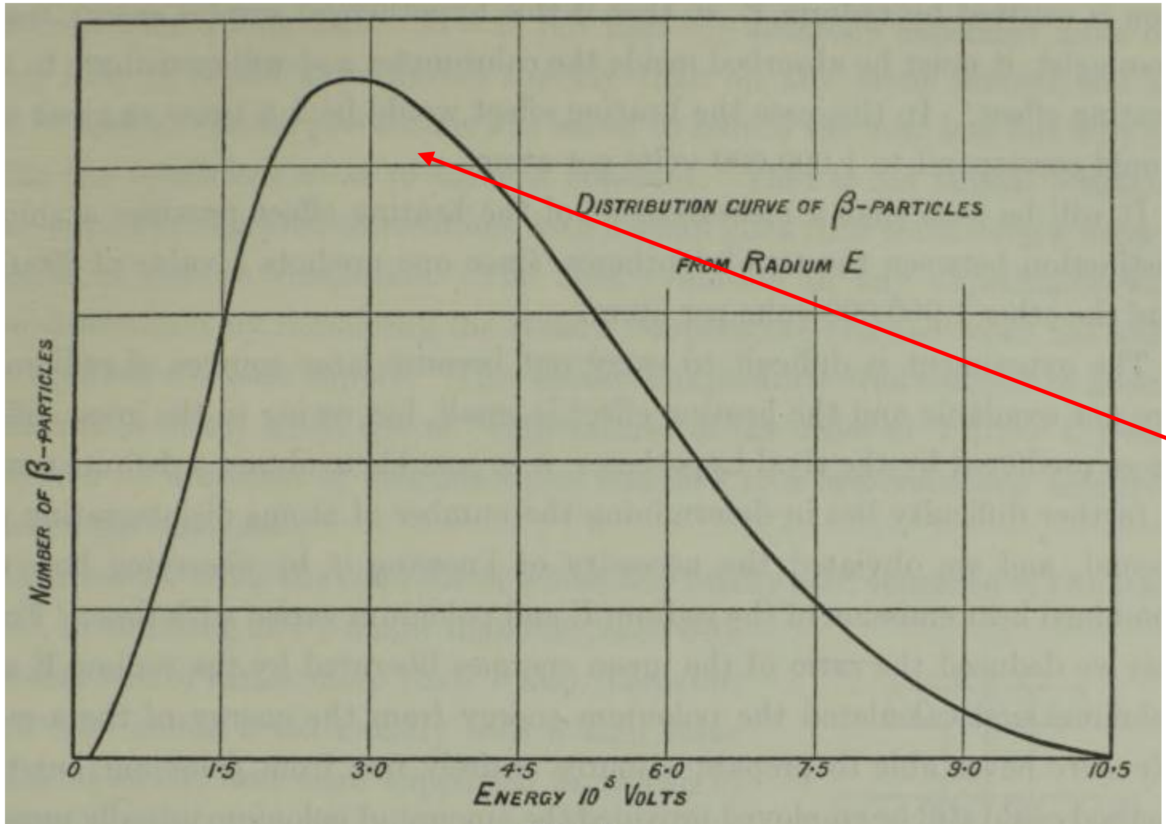


Fig. 1.

C.D. Ellis and W.A. Wooster, Proc. Roy. Soc. A 117 (1927) 109

Calorimeter

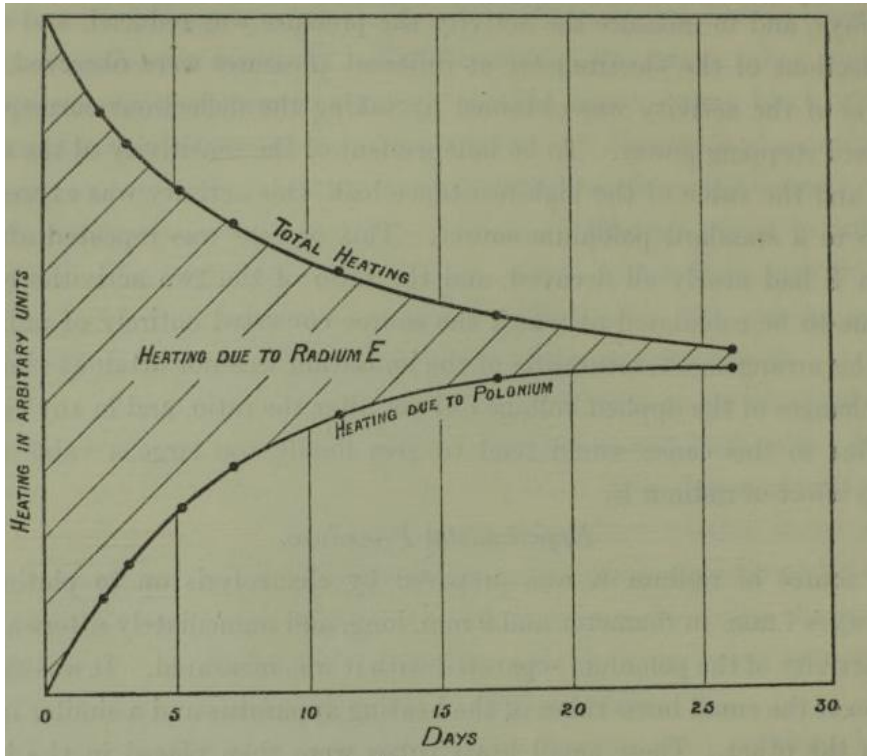


Fig. 3A.

Table I.—Heating Effect of Radium E deduced from Curves of fig. 3.

True age.	Total heating.	Portion due to Po.	Portion due to Radium E.	x.	Disintegration energy of Radium E in volts.
days.	mm.				
2·25	22·0	3·68	18·3	15·4	339000
3·20	20·8	4·91	15·9	15·5	337000
5·20	19·0	6·99	12·0	15·5	337000
7·20	17·8	8·64	9·2	15·6	335000
11·20	16·1	10·53	5·6	14·5	360000
17·20	14·2	11·83	2·4	14·7	355000
26·20	12·85	12·18	0·67	15·1	346000

→ Systematics from secondary energy loss excluded

Historic context

International Atomic Energy Agency (IAEA)
December 4, 2024 ·

94 years ago on this day, the existence of neutrinos was first postulated by Austrian physicist Wolfgang Pauli.

In an open letter sent on 4 December 1930 to a group of nuclear physicists, Pauli put forward the existence of an extremely light and very weak particle with no electric charge in the nucleus of atoms, which he called a neutron, to explain the continuous spectrum of beta decay. In 1934, Enrico Fermi took up this idea and incorporated this postulated particle into his beta decay theory, naming it neutrino, which means 'little neutral one' in Italian. However, it was not until 1956 that Pauli's prediction was finally confirmed by physicist Frederick Reines and his colleagues.

These little neutral particles have been used since the mid-20th century to probe environments in space and understand astronomical phenomena, like the conditions of the Sun's core, and to further scientific investigations in particle physics and the matter of the universe.

- Pauli 1930 in an open letter to a conference in Tubingen: postulates an "extremely light" and "electrically neutral" particle (initially called a "neutron")
- Chadwick discovers the neutron in 1932: "The Existence of a Neutron" in the journal Proceedings of the Royal Society A in May 1932
- Fermi in 1934: Took up Pauli's idea and called it the 'little neutron' or 'neutrino'. Submission to Nature got rejected! So he published in IL NUOVO CIMENTO Nuova Serie N. 1, Pag. 1–20, (1934): 'An attempt to a β rays theory'

E. Fermi, IL NUOVO CIMENTO Nuova Serie N. 1, p. 1–20 (1934)

In attempting to construct a theory of nuclear electrons and of the β rays emission, two well known difficulties are encountered. The first is that the primary β rays are emitted by the nuclei with a continuous velocity distribution. If the energy conservation principle is not abandoned, we must therefore admit that a fraction of the energy made available in the β decay escapes our present observation possibilities. According to a proposal by PAULI existence can be supposed, for instance, of a new particle, the so called ≪ neutrino ≫. with a zero electric charge and a mass of the order of magnitude of the electron mass or less. One admits, furthermore, that in every β process are simultaneously emitted an electron, observed as a β ray, and a neutrino escaping observation and carrying away part of the energy.

The endpoint spectrum

- If there were no neutrino, the energy spectrum of the electron in any beta decay process would be monochromatic.
- Can you prove this?: simple kinematic exercise

for $A \rightarrow B + C$ $$E_{B,C} = \frac{M_A^2 + M_{C,B}^2 - M_{B,C}^2}{2M_A}$$

- What E. Fermi postulated and computed in 1934:
  - Existence of a new fundamental force (Weak force)
  - Field-Theoretical description of creation of particles
  - Precise shape of the β-decay spectrum (with and without neutrino mass)
  - Relationship between half-life and Endpoint energy of the β spectrum
  - Other processes became calculable: positron emission, electron capture, inverse-beta decay, ...

Fermi's theory of β decay

Transition probability per unit time

$$\lambda = \frac{2\pi}{\hbar} |\langle f|H'|i\rangle|^2 \rho(E_f)$$

Contact interaction Hamiltonian

$$H' = G_F \bar{\psi}_p \gamma^\mu (1 - g_A \gamma^5) \psi_n \bar{\psi}_e \gamma_\mu (1 - \gamma^5) \psi_\nu$$

Density of final states for massless ν

$$\rho(E_e) \propto p_e E_e (E_0 - E_e)^2$$

$$|\langle f|H'|i\rangle|^2 \propto G_F^2 |V_{ud}|^2 (1 + 3g_A^2)$$

Dependence on the neutrino mass via phase space factor:

$$f(Q, m_\nu) = \int_{m_e}^{E_0 - m_\nu} p_e E_e p_\nu^2 \, dE_e \Rightarrow f(Q, m_\nu) = \int_{m_e}^{E_0 - m_\nu} p_e E_e \left[(E_0 - E_e)^2 - m_\nu^2 c^4\right] dE_e$$

$$\frac{p_\sigma^2}{v_\sigma} = \frac{1}{c^2}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}$$

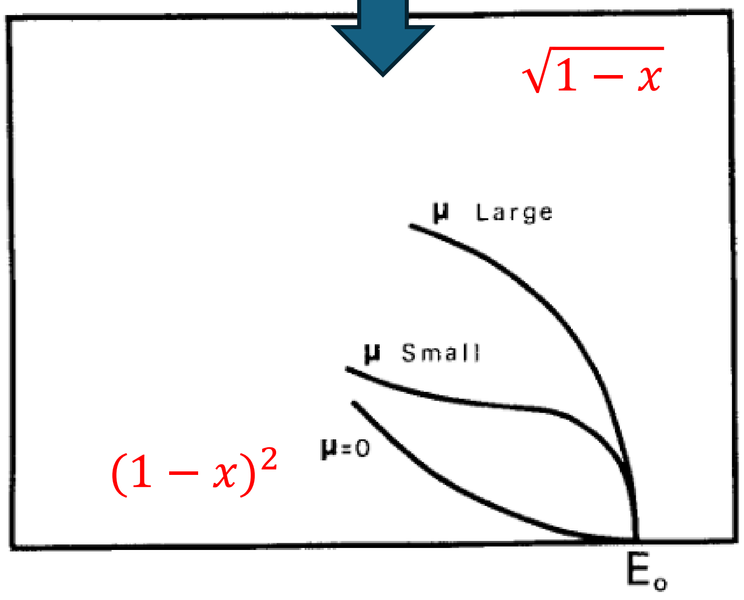


Fig. 1. The end of the distribution curve for $\mu=0$ and for large and small values of μ.

PLUS, he also proved that:

Inverse of the mean lifetime:

$$\frac{1}{\tau} = 1.75 \cdot 10^{95} g^2 \left| \int v_m^* u_n \, d\tau \right|^2 F(\eta_0)$$

with $F(\eta_0) \propto \eta_0^6$,for large values of η_0

In other words, the maximum endpoint energy of a beta decay of a nuclide with half life $T_{1/2} \propto \frac{1}{(E_0)^5}$

The way to the direct detection of the neutrino

Bruno Pontecorvo

Inverse β Process

(National Reserach Council of Canada, Division of Atomic Energy. Chalk River, 1946, Report PD-205. This version was kindly provided by Prof. W.F.Davidson).

Introduction

The Fermi theory of the β disintegration is not yet in a final stage; not only detailed problems are to be solved, but also the fundamental assumption - theneutrino hypothesis - has not yet been definitely proven. I will recall briefly the main experimental facts which have led Pauli to propose the neutrino hypothesis.

1. In a β disintegration, the atomic nucleus Z changes by one unit, while the mass number does not change.

2. The β spectrum is continuous, while the parent and the daughter states correspond to well defined energy values of the nuclei Z and Z±1.

3. The difference in energy between the initial and final states involved in a β transition is equal to the upper limit of the continuous spectrum.

We see that the fundamental facts can be reconciled only with one of the following alternative assumptions:

i. The law of the conservation of the energy does not hold in a single β process.

ii. The law of the conservation of the energy is valid, but a new hypothetical particle, undetectable in any calorimetric measurement - the neutrino - is emitted together with a β particle in a β transition, in such a way that the energy available in such transition is shared between the electron and the neutrino. This suggestion

…

Direct proof of the existence of the neutrino, consequently, must be based on experiments, the interpretation of which does not require the law of conservation of energy, i.e., on experiments in which some characteristic process produced by *free neutrinos* (a process produced by neutrinos after they have been emitted in a disintegration) is observed.

For completeness, we will mention also some inverse β processes produced by other particles than a neutrino; an inverse β process, more generally, can be defined as the transformation of a neutron into a proton, or vice versa, produced artificially by bombardment with neutrinos, electrons, or γ rays. These processes are:

a. Absorption of negative β particle (β) with emission of a neutrino

$$(\nu)\ \beta^- + Z \rightarrow \nu + (Z\text{-}1).$$

b. Absorption of a neutrino with emission of a β particle

$$\nu + Z \rightarrow \beta^- + (Z+1), \qquad \nu + Z \rightarrow \beta^+ + (Z\text{-}1).$$

On thermodynamical grounds, the crosssection σ_{inv} of an inverse β process produced by neutrino must be given by a formula of the type $\sigma = K/\tau$ (cm2), where $1/\tau$ is the probability per unit time of a β disintegration involvingenergy *E* and *K* is a constant of proportionality having the dimensions of $cm^2{\cdot}sec$. The largest possible length involved is the wave length of the impinging neutrino and the longest time involved is that length divided by *c*. We can write then, the above formula in the form

$$\sigma_{inv} \le \lambda^2 \cdot \frac{\lambda}{c} \cdot \frac{1}{\tau}$$

If Fermi's theory holds, then

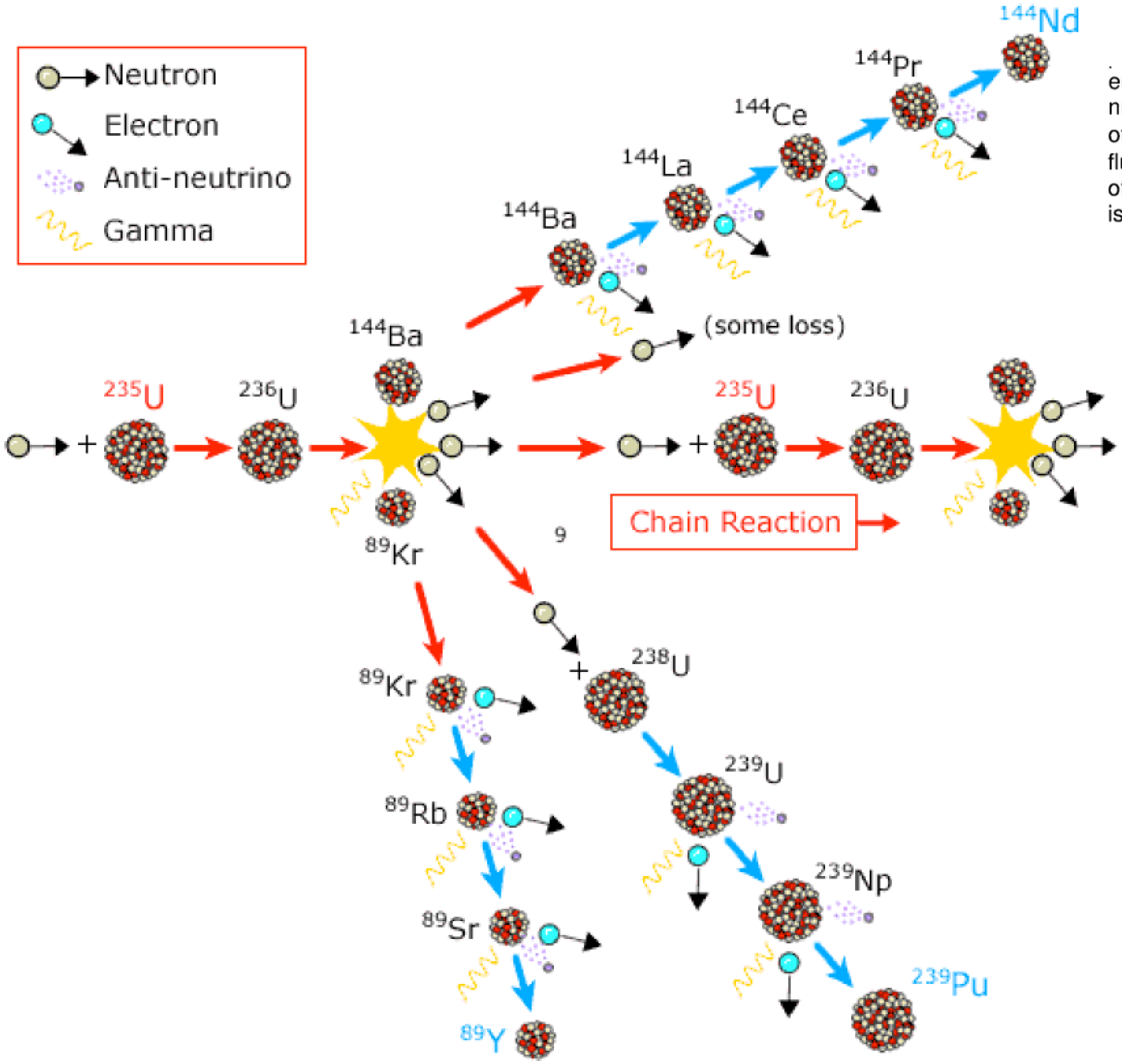
$$T_{1/2} \propto \frac{1}{(E_0)^5} \quad \Rightarrow \quad \sigma_{ibd} = \mathcal{O}(E^2)$$

$$E = 5MeV \ \Rightarrow \tau \ge 0.1s, \qquad \lambda/c = 10^{-22}s$$

$$\sigma_{ibd} = \mathcal{O}(10^{-42}cm^2) \qquad \lambda^2 = 10^{-21}cm^2$$

$$10^{-3}fb$$

The search for high fluxes of Neutrinos: From Pontecorvo's paper:



energy. Assuming, for example, that 1 m^3 of CCl_4 is used for the experiment, the number of nuclei of ^{37}Cl is about 10^{28}, and the number of disintegrations *N* per second of ^{37}Ar produced at saturation in such volume is *N*=neutrino flux$\cdot\sigma_{inv}\cdot10^{28}$ ~ neutrino flux$\cdot10^{-14}$. The effect might be detected if *N* is of the order of 1, requiring a neutrino flux of the order of $10^{14}cm^{-2}sec^{-1}$. Such a value of the neutrino flux, though extremely high, is not too far from what could be obtained with present day facilities.

- Solar flux: $\mathcal{O}(10^{10} cm^2 s^{-1})$, but low energy
- Nuclear reactors: at 10m from the core $\mathcal{O}(10^{13} cm^2 s^{-1})$
- Nuclear bombs: $\mathcal{O}(10^{14} cm^2 s^{-1})$ at 1km from a 20kTon bomb

~ 200 MeV/fission
~ 6 $\bar{\nu}_e$/fission

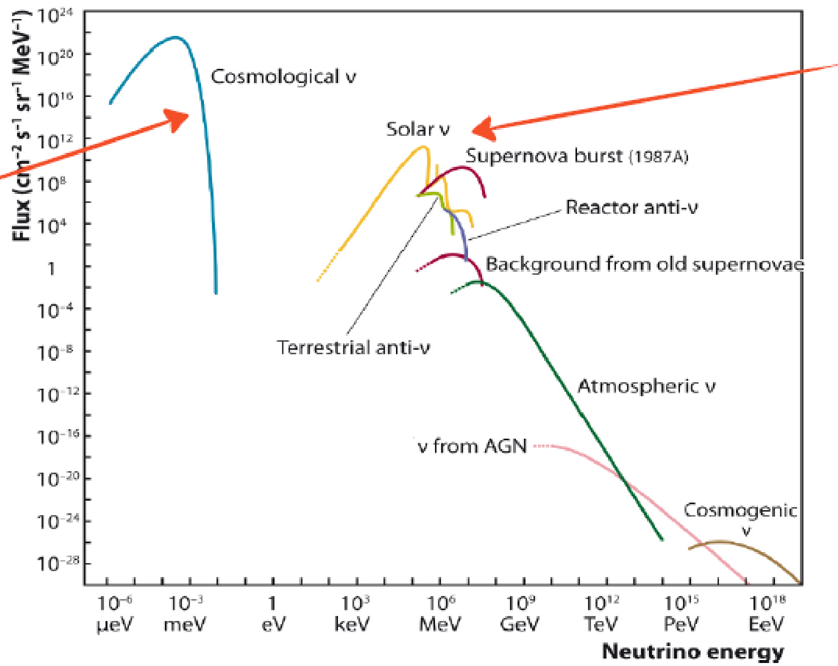
1 GW_{th} reactor
→ ~$2x10^{20}$ $\bar{\nu}_e$/sec

Size of natural fluxes

No man made neutrinos: - sun <~ detected
- atmosphere <~ detected
- supernovae <~ detected (SN1987)
- geo-neutrinos <~ detected
- astrophysical (AGN, cosmogenic, ...) <~ detected
- big-bang relic <~ undetected!

Man-made neutrinos: - reactor <~ detected
- accelerator <~ detected

330 relic ν / cm^3



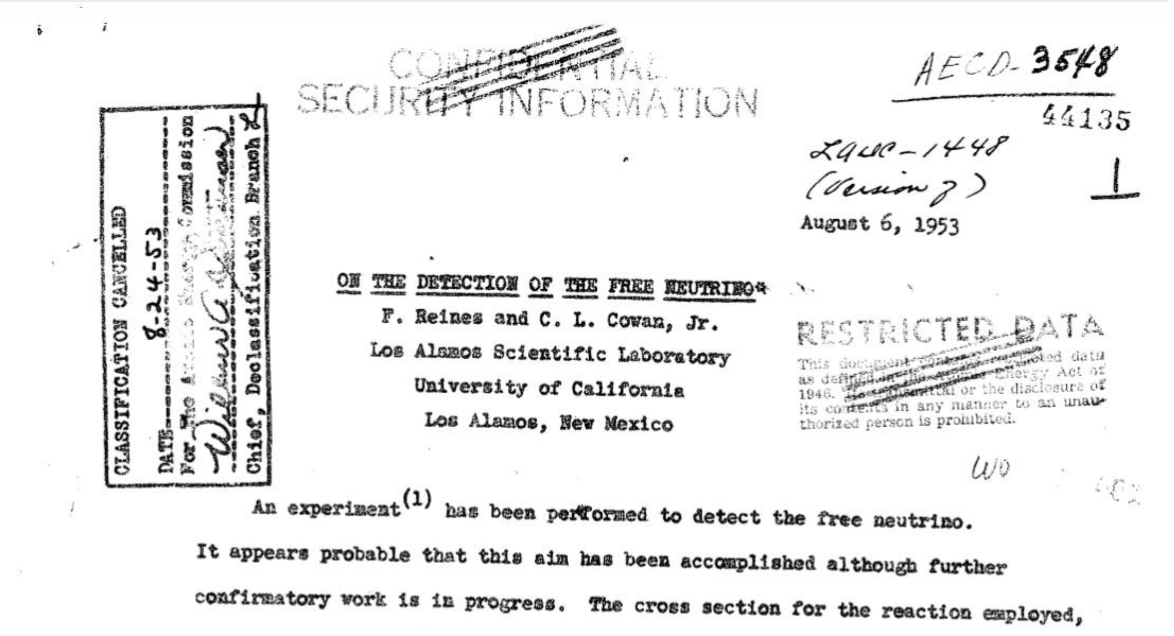
solar neutrinos: most intense detected flux: $10^{11}\ \nu/\mathrm{cm}^2/s$

1207.4952

T. HAMBYE, BND school Antwerp 2016

Project Poltergeist

- Based on proposal by Bruno Pontecorvo, two Los Alamos Nuclear weapon scientists: Frederick Reines & Clyde Cowan, placed initially a tank with 300l of liquid scintillator (new technological development) with 90 2” PMTs at close proximity to the Hanford Power plant.


CONFIDENTIAL SECURITY INFORMATION

AECD-3548

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LAMS-1448 (Version 2)

August 6, 1953

CLASSIFICATION CANCELLED
DATE 8-24-53
For The Atomic Energy Commission
Chief, Declassification Branch

ON THE DETECTION OF THE FREE NEUTRINO*

F. Reines and C. L. Cowan, Jr.

Los Alamos Scientific Laboratory

University of California

Los Alamos, New Mexico

RESTRICTED DATA

This document contains restricted data as defined in the Atomic Energy Act of 1946. Its transmittal or the disclosure of its contents in any manner to an unauthorized person is prohibited.

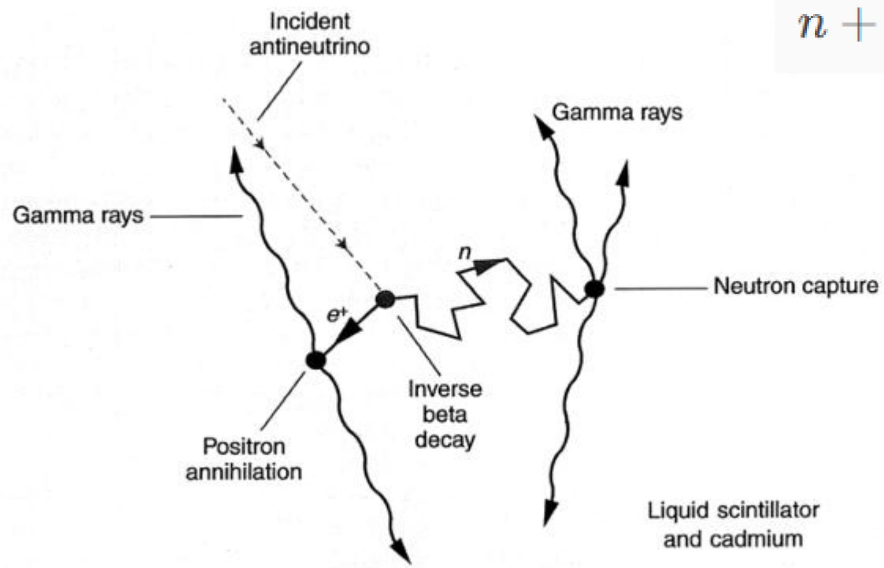
An experiment(1) has been performed to detect the free neutrino. It appears probable that this aim has been accomplished although further confirmatory work is in progress. The cross section for the reaction employed,

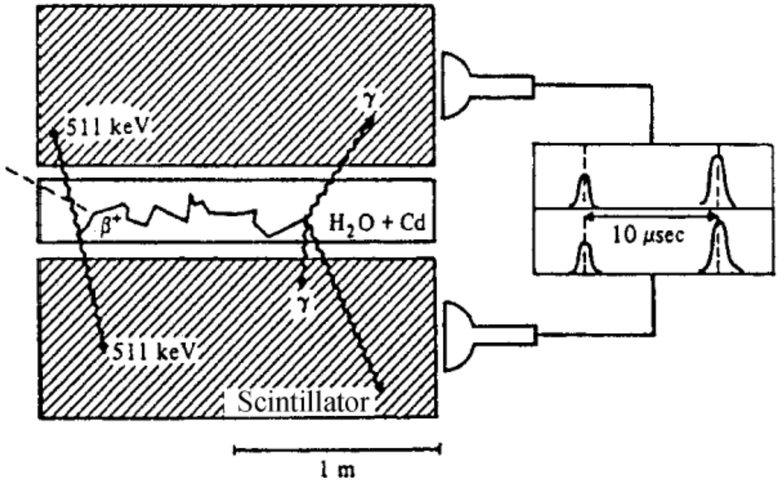
IBD Process

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

Scintillator tank loaded with moderate amounts of Cd

$$n + {}^{113}\mathrm{Cd} \rightarrow {}^{114}\mathrm{Cd}^* \rightarrow {}^{114}\mathrm{Cd} + \gamma \text{ cascade}$$





Delayed coincidence technique:

1. Detect the >1.02 MeV EM signal (2 γ’s) from the positron annihilation
2. The Neuron will be captured by Cd, 9μs later, after it has thermalized (loosing energy via elastic collisions)
3. The Excited Cd will emit a cascade of (up to 9) gamma’s with total energy of 9 MeV

Project Poltergeist

20 July 1956, Volume 124, Number 3212 **SCIENCE**

Detection of the Free Neutrino: a Confirmation

C. L. Cowan, Jr., F. Reines, F. B. Harrison, H. W. Kruse, A. D. McGuire

both triads. The detector was completely enclosed by a paraffin and lead shield and was located in an underground room of the reactor building which provides excellent shielding from both the reactor neutrons and gamma rays and from cosmic rays.

The signals from a bank of preamplifiers connected to the scintillation tanks were transmitted via coaxial lines to an electronic analyzing system in a trailer van parked outside the reactor building. Two independent sets of equipment were

— Nort

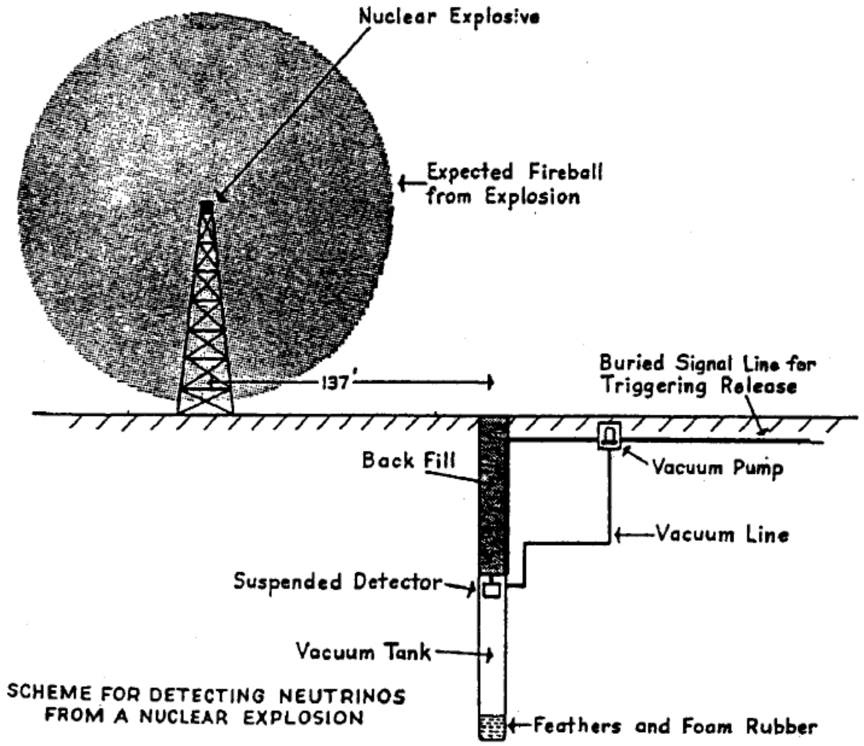


FIGURE 5.1 Scheme for detecting neutrinos from a nuclear ε
(Cowan, 1964).

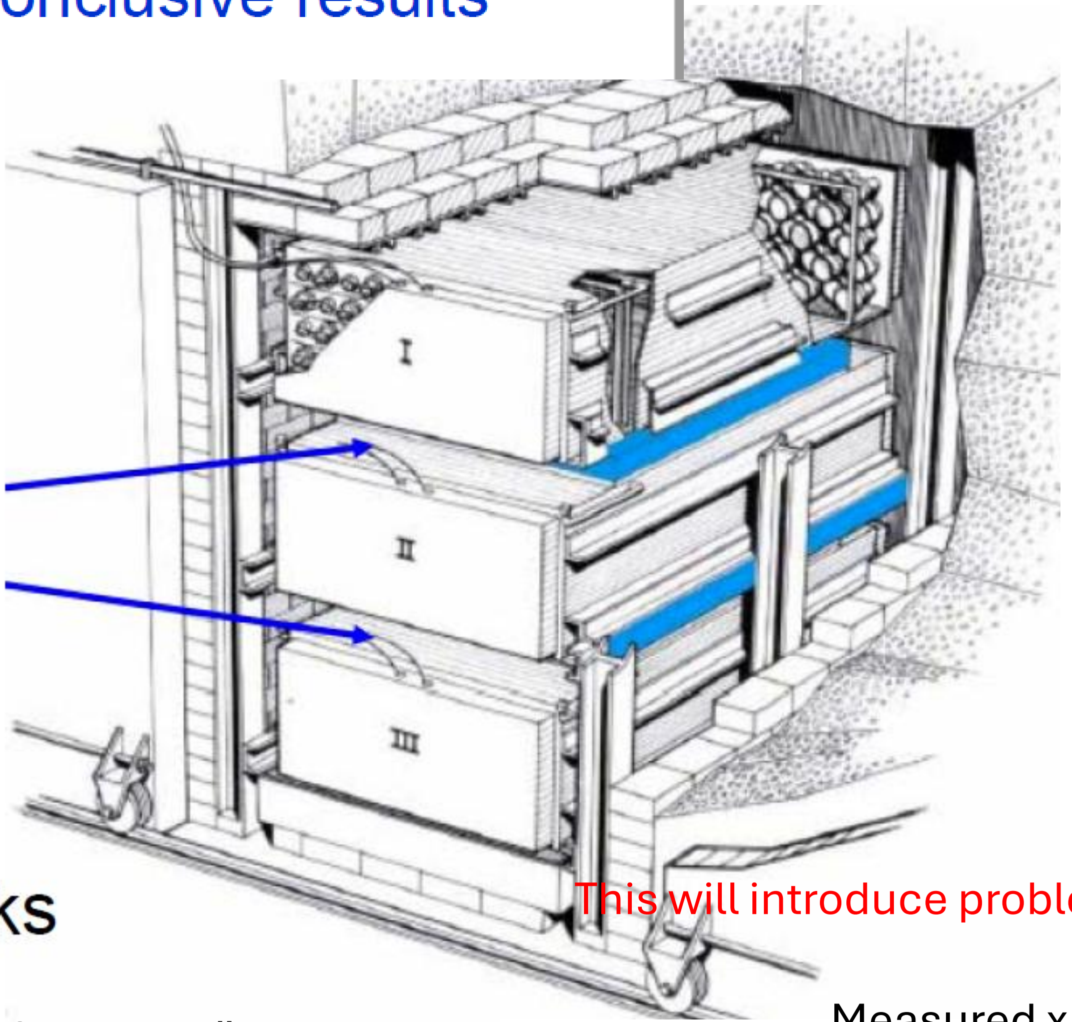
In **1956** @Savannah River Plant, S. Carolina
By Reines and Cowan

Nobel Prize in 1995

Preliminary run at Hanford site and inconclusive results

Tanks I, II, and III are filled with liquid scintillator and instrumented with 5” PMTs

Target tanks (blue) are filled with 200 liters of water + $CdCl_2$



Two signals in neighboring tanks (I, II or II, III)

Maximum rate of ~3 counts/hour

Signal/Background: ~ 3:1

This will introduce problems later on!

Measured x-section:

$$\bar{\sigma} = (11 \pm 3) \times 10^{-44}\ \mathrm{cm}^2$$

The follow up experiments leading to the reactor anomaly

PHYSICAL REVIEW VOLUME 117, NUMBER 1 JANUARY 1, 1960

Detection of the Free Antineutrino*

F. REINES,† C. L. COWAN, JR.,‡ F. B. HARRISON, A. D. MCGUIRE, AND H. W. KRUSE
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

(Received July 27, 1959)

The antineutrino absorption reaction $p(\bar{\nu},\beta^+)n$ was observed in two 200-liter water targets each placed between large liquid scintillation detectors and located near a powerful production fission reactor in an antineutrino flux of 1.2×10^{13} cm^{-2} sec^{-1}. The signal, a delayed-coincidence event consisting of the annihilation of the positron followed by the capture of the neutron in cadmium which was dissolved in the water target, was subjected to a variety of tests. These tests demonstrated that reactor-associated events occurred at the rate of 3.0 hr^{-1} for both targets taken together, consistent with expectations; the first pulse of the pair was due to a positron; the second to a neutron; the signal dependended on the presence of protons in the target; and the signal was not due to neutrons or gamma rays from the reactor.

$$\sigma=(1.2_{-0.4}^{+0.7})\times10^{-43}\ \text{cm}^2.$$

This value is in agreement with the theoretically expected value[12] of $(1.0\pm0.17)\times10^{-43}$ cm^2.

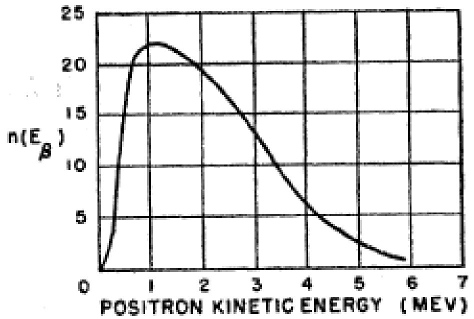


FIG. 18. Predicted kinetic-energy spectrum of positrons generated in the reaction $p(\bar{\nu},\beta^+)n$.

$$Q=(m_n-m_p)+m_e=1.8MeV$$

$$\sigma(E_\nu)=A(E_\nu-Q)[(E_\nu-Q)^2-1]^{\frac{1}{2}}, \quad (5)$$

$$N(E_\nu)=B[n(E_\beta)/\sigma(E_\beta)], \quad (6)$$

where

$$E_\beta=E_\nu-3.52.$$

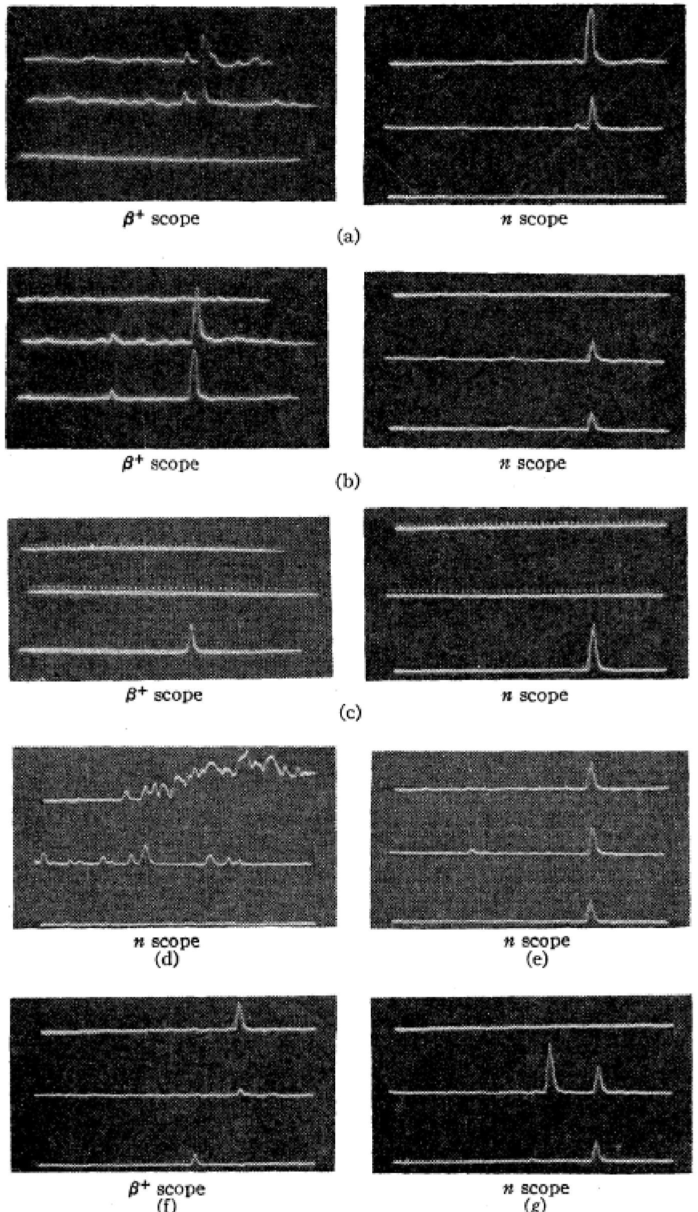
Also this will lead to future complications

signal

calibration

Electronic noise

Cosmic ray



First tensions

This placed the foundations of heavy water (D_2O) experiments, such as SNO that completed the solar neutrino puzzle!!

VOLUME 45 20 OCTOBER 1980 NUMBER 16

Evidence for Neutrino Instability

F. Reines, H. W. Sobel, and E. Pasierb
Department of Physics, University of California at Irvine, Irvine, California 92717
(Received 24 April 1980)

This Letter reports indications of neutrino instability obtained from data taken on the charged- and neutral-current branches of the reaction

$$\bar{\nu}_e + d \to \begin{cases} n + n + e^+ & (\text{ccd}) \\ n + p + \bar{\nu}_e & (\text{ncd}) \end{cases}$$

at 11.2 m from a 2000-MW reactor. These results at the (2–3)-standard-deviation level, based on the departure of the measured ratio (ccd/ncd) from the expected value, make clear the importance of further experimentation to measure the $\bar{\nu}$ spectrum versus distance.

Charged current branch (ccd)

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

- Low E threshold: 1.44 MeV
- Only Sensitive to electron neutrinos

Neutral current branch (ncd)

$$\nu_x + d \to \nu_x + p + n$$

- Equally sensitive to all neutrino flavors

$$r = (\langle \sigma_{ccd} \rangle / \langle \sigma_{ncd} \rangle)_{expt} = R^{ccd}/R^{ncd},$$

What was measured:

$$r_{expt} = 0.167 \pm 0.093,$$

deuteron experiment. It is evident that further experimentation with $\bar{\nu}_e$ at reactors, e.g., measurements of the $\bar{\nu}_e$ spectrum as a function of distance,[11] via the reaction $\bar{\nu}_e + p \to n + e^+$ and further study of the reaction $\bar{\nu}_e + d$,[12] will aid in clarifying these points and provide an independent test of these preliminary indications of neutrino instability.

It would also be useful to perform experiments at accelerators and possibly with cosmic rays[13] where the higher energies would stretch out the distance scale and allow additional tests of this phenomenon.

What was predicted by EW theory:

$$r_{theor}^{AG} = 0.44 \text{ and } r_{theor}^{DVMS} = 0.42,$$

Using two predictions of neutrino energy spectrum: this will prove a delicate issue!!

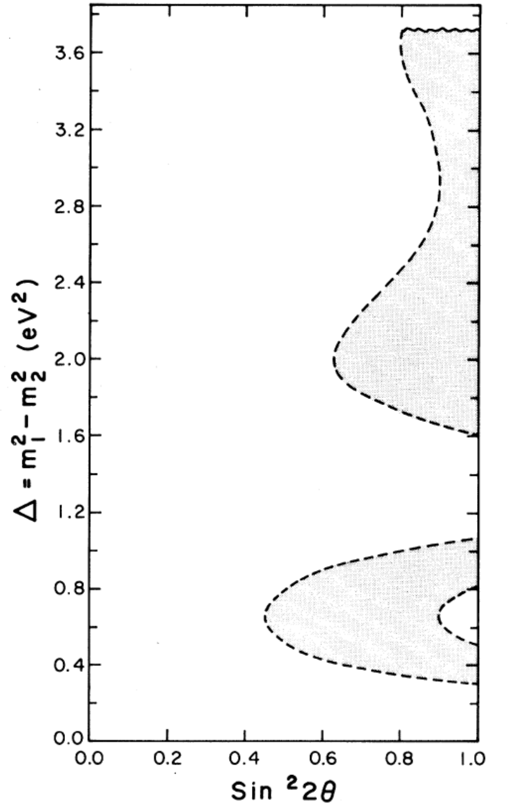


FIG. 1. Allowed regions of Δ and $\sin^2 2\theta$ for $\mathcal{R} = 0.38 \pm 0.21$.

Possible interpretation in terms of a 2 flavor mixing scenario:

could give agreement. This yields $0.5 \leq \sin^2 2\theta \leq 0.8$ ($32° > \theta > 22°$) and $0.7 \leq \Delta$ (eV^2) ≤ 1.0. We

Reactor neutrinos: the beginning

- ILL Grenoble: Very compact core and very simple fuel: 93% enriched ^{235}U
- Measurement at 8.75m, but smaller flux: $9.8 \times 10^{11} cm^2 s^{-1}$
- Measuring the neutrino energy spectrum and compare with predictions
- Measured neutrino spectrum is product of emitted neutrino spectrum from reactor, deduced from precise measurements of b-spectrum of ^{235}U, and the IBD cross-section, which is dependent on the neutron life-time

PHYSICAL REVIEW D VOLUME 24, NUMBER 5 1 SEPTEMBER 1981

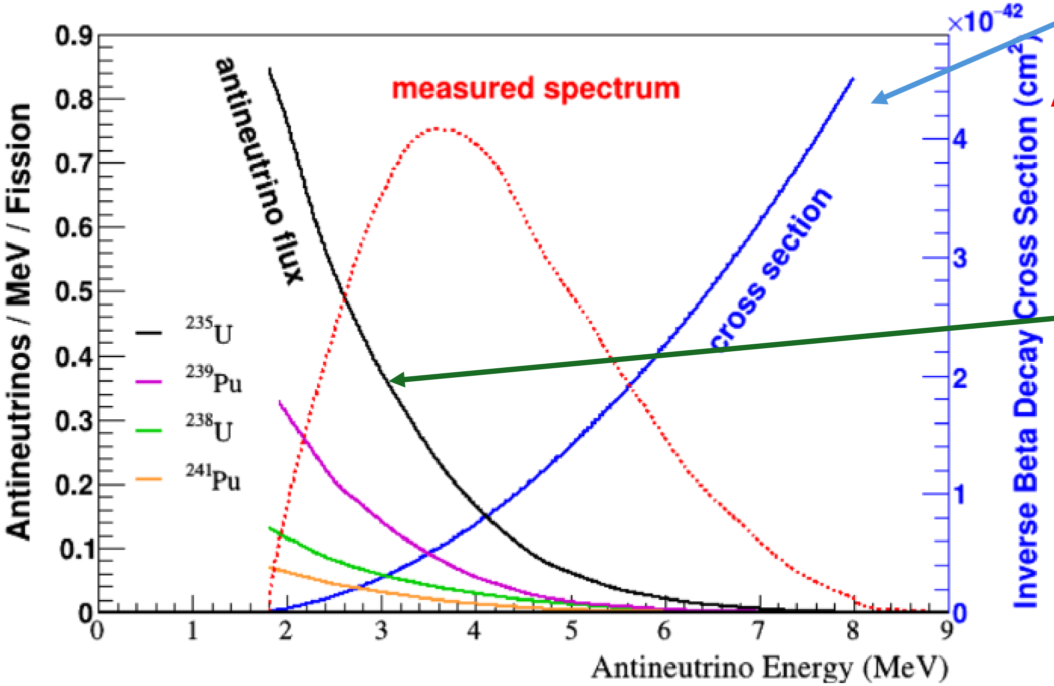
Search for neutrino oscillations at a fission reactor

H. Kwon,* F. Boehm, A. A. Hahn,* H. E. Henrikson, and J.-L. Vuilleumier*
California Institute of Technology, Pasadena, California 91125
J.-F. Cavaignac, D. H. Koang, and B. Vignon
Institut des Sciences Nucléaires de Grenoble, IN2P3, 38026 Grenoble Cedex, France
F. v. Feilitzsch* and R. L. Mössbauer
Physik-Department, Technische Universität München, 8046, Garching, Federal Republic of Germany
(Received 7 April 1981)

The energy spectrum of neutrinos from a fission reactor was studied with the aim of gaining information on neutrino oscillations. The well-shielded detector was set up at a fixed position of 8.76 m from the pointlike core of the Laue-Langevin reactor in an antineutrino flux of 9.8×10^{11} cm^{-2} s^{-1}. The target protons in the reaction $\bar{\nu}_e p \rightarrow e^+ n$ were provided by liquid-scintillator counters (total volume of 377 l) which also served as positron detectors. The product neutrons moderated in the scintillator were detected by ^{3}He wire chambers. A coincidence

$$\sigma(E_{\bar{\nu}}) \approx \kappa(E_e p_e) = (9.13 \pm 0.11) \cdot (E_{\bar{\nu}} - 1.293) \cdot \sqrt{(E_{\bar{\nu}} - 1.293)^2 - (0.511)^2} \times 10^{-44} cm^2$$

$$\kappa = \frac{2\pi^2}{m_e^5 f \tau_n} \quad \text{or} \quad \kappa = \frac{G_F^2 (\cos\theta_C)^2}{\pi \tau_n}$$



A decrease in neutron lifetime will cause an upward shift of the x-sect!

The energy spectrum of $\bar{\nu}_e$ from conventional power reactors is predominantly formed from the β-decays of the fission products of the fuel isotopes $^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu$.
The dominant contribution to all fission events and energy release comes for 95% from the three first isotopes!
Challenge: There are 1000's of decay branches in these fission chains that can produce $\bar{\nu}_e$
There are TWO approaches for obtaining the energy spectrum: The conversion method & the summation method

Conversion or summation?

K. Schreckenbach et al. ,
Phys. Lett. 998, 251 (1981).

Conversion method:

•**Basis**:

•Measured aggregate beta spectra for U-235, Pu-239, Pu-241 at ILL (or Kharkov) using a magnetic spectrometer.

•**Approach**: $$\phi_{branch}(E_\nu) \propto (E_0 - E_\nu)^2 \sqrt{(E_0 - E_\nu)^2 - m_e^2}$$

•Fit beta spectrum with virtual beta branches: each branch has specific endpoint energy and a relative contribution (weight). Note: these are hypothetical decays that parameterize the measured beta spectrum.

The most cited model is the Huber-Mueller model: uses ~40 virtual branches and applies nuclear-physics corrections

•**Strengths**:

•Direct experimental input for major isotopes.

•Historically provided the most accurate predictions for decades.

•**Weaknesses**:

•Assumes allowed beta transitions → underestimates forbidden decay corrections.

•Limited energy range (2–7.5 MeV).

•**Uncertainty**: ~2–3% statistical + model-dependent conversion errors

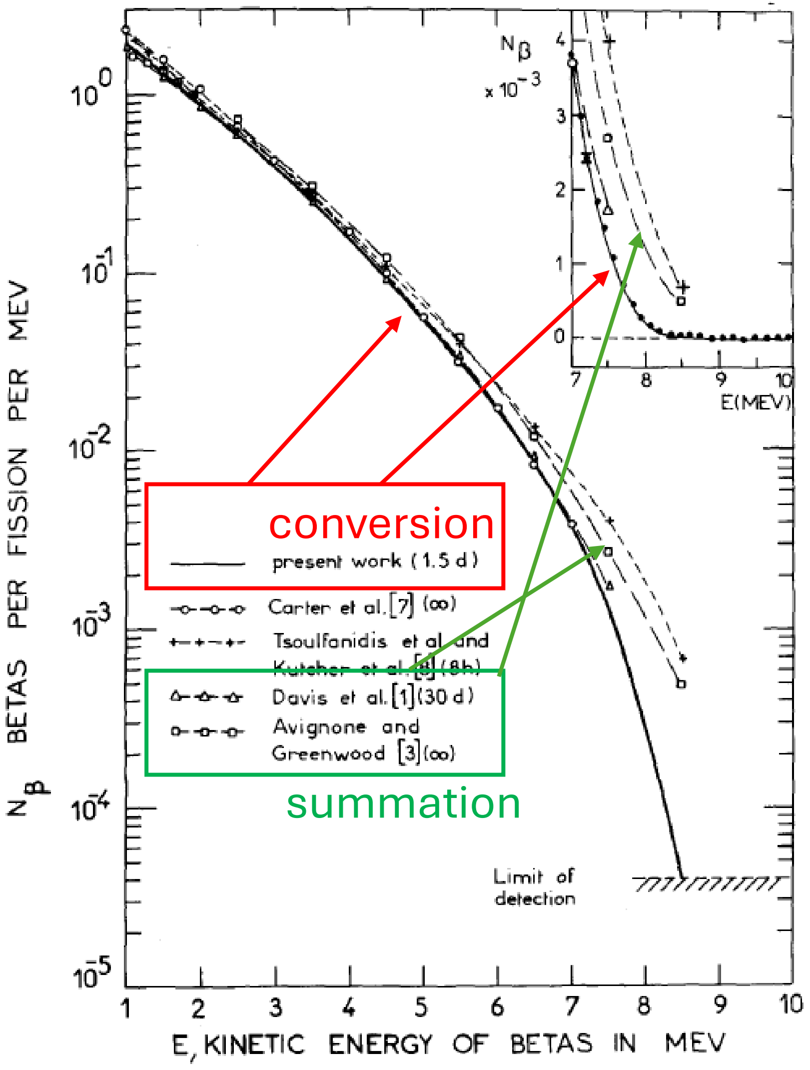
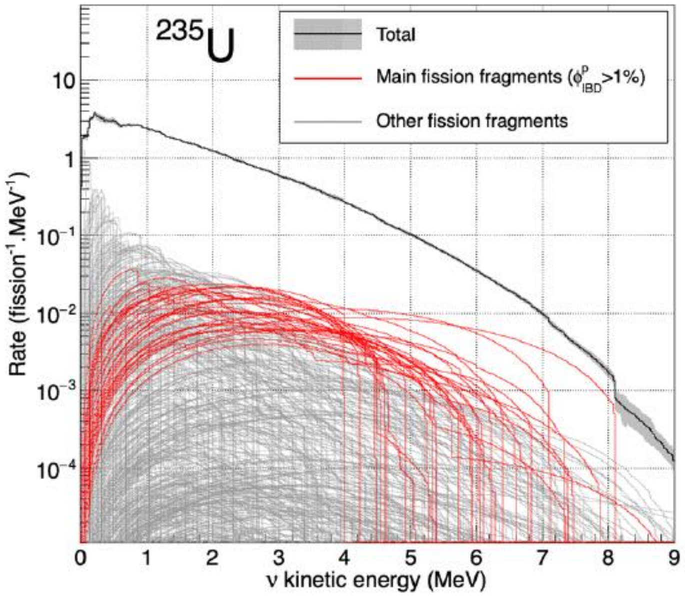


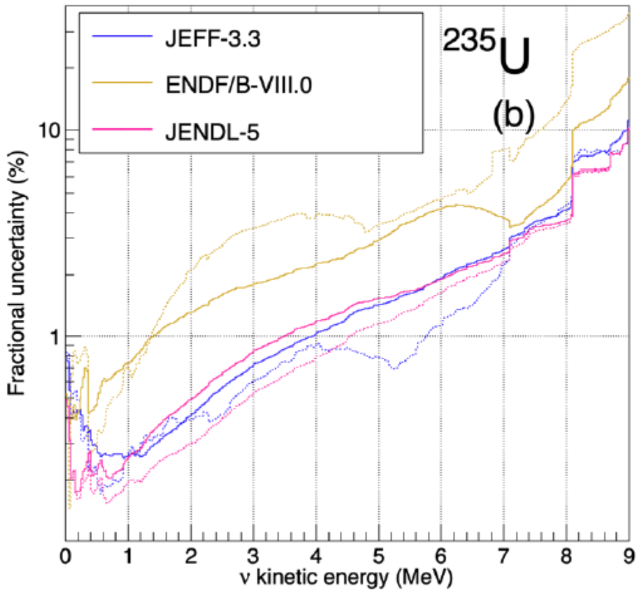
Fig. 3. Comparison of experimental and calculated beta spectra from ^{235}U fission products. The exposure time to neutrons is given in brackets. No experimental points are shown for the present work in the main figure since the statistical uncertainties are smaller than the width of the curve. The total uncertainty is 5% in the range from 2.0 to 7.5 MeV. Values as given in the publications are marked by signs, which are connected by dotted lines to guide the eye. The spectrum of ref. [7] is given in steps of 0.5 MeV. The insert illustrates in a linear scale the statistical accuracy of our experimental data at the high energy end of the spectrum.

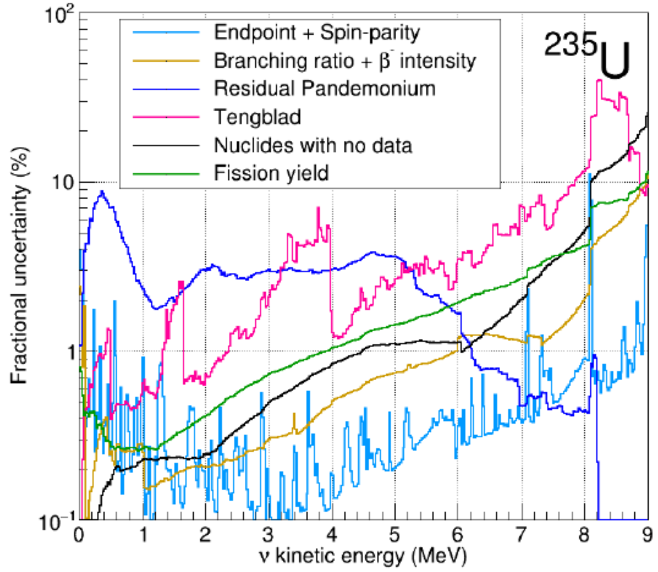
Mueller et al., Phys. Rev. C 83, 054615 (2011)
Huber, Physical Review C, Vol. 84, 024617(2011)

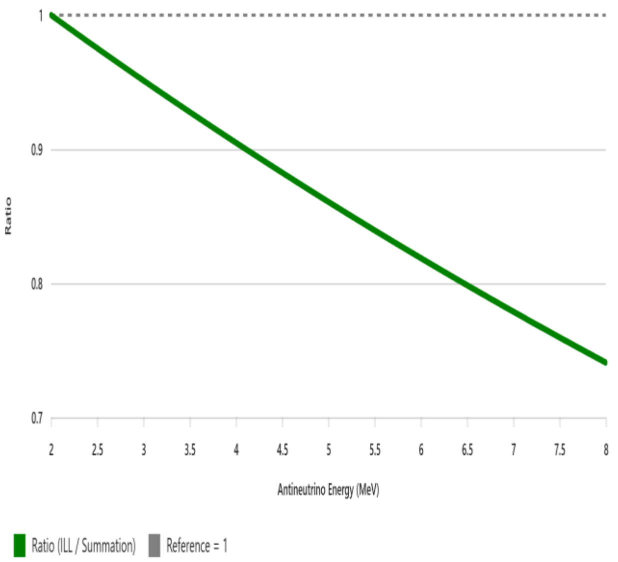
Summation method

- **Basis**: Nuclear databases (fission yields + decay schemes for thousands of isotopes).
- **Approach**:
- Sum contributions from all beta decays of fission products.
- Uses evaluated nuclear data libraries (ENDF, JEFF etc.): > 10.000 β branches
- **Strengths**:
- Covers full energy range.
- Can incorporate updated nuclear data and forbidden transitions.
- **Weaknesses**:
- Sensitive to incomplete or inaccurate nuclear databases.
- Historically had larger uncertainties (~10%), but improving.
- **Uncertainty**: Dominated by missing or poorly known beta branches.









The hunt for neutrino oscillations

- No a-priori indications of which Δm^2 and mixing parameters to look for
- Programs at reactors take full speed:
  - measuring the energy spectrum, close to the cores (to benefit from high fluxes to be measured with small detectors)
  - Compare the spectrum with predictions from the fully developed EW theory:

$$N_{meas}(E_{\bar{\nu}}) = N_{meas}^{R,on}(E_{\bar{\nu}}) - N_{meas}^{R,off}(E_{\bar{\nu}})$$

To remove reactor induced backgrounds

$$N_{pred}(E_{\bar{\nu}}) = \sigma_{IBD}(E_{\bar{\nu}})\phi(E_{\bar{\nu}}).\varepsilon^{-1}(n, E_{\bar{\nu}})$$

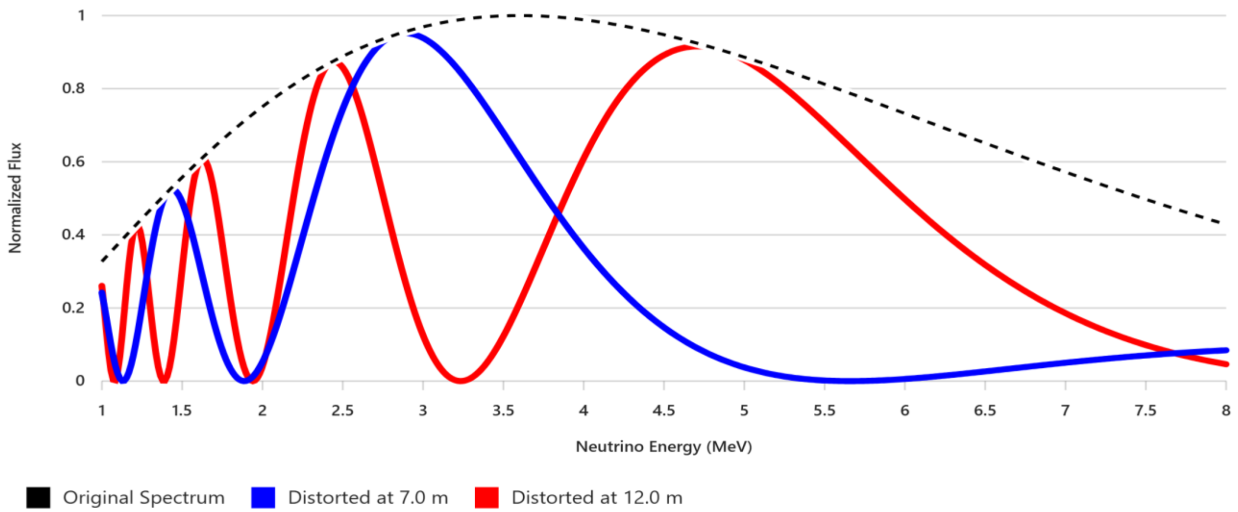
Dependent on
- n life-time
- EW corrections

Dependent on:
- reactor fuel composition and burnup
- Reactor power evolution
- Model used: conversion vs. summation
- If conversion: quality of measured b spectra

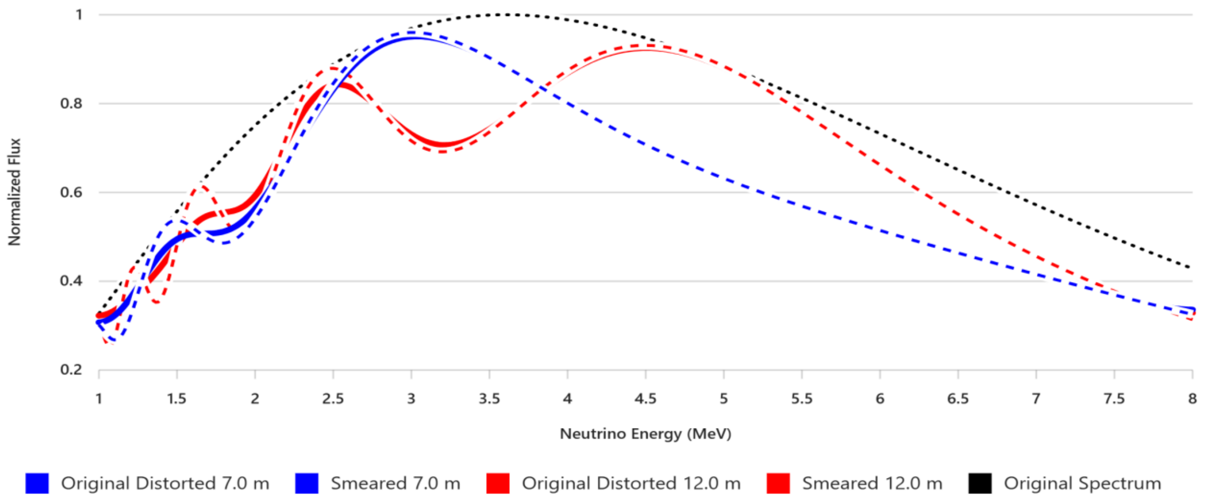
Dependent on:
- Geometrical acceptance
- Shielding and selection cuts to remove reactor independent backgrounds
- Neutron detection efficiency
- Annihilation Gamma detection efficiency

$$\frac{N_{meas}}{N_{pred}} = 1 - sin^2 2\theta \cdot sin^2\{1.27\Delta m^2(eV^2) \cdot L(m)/E_{\bar{\nu}}(MeV)\}$$

The hunt for neutrino oscillations

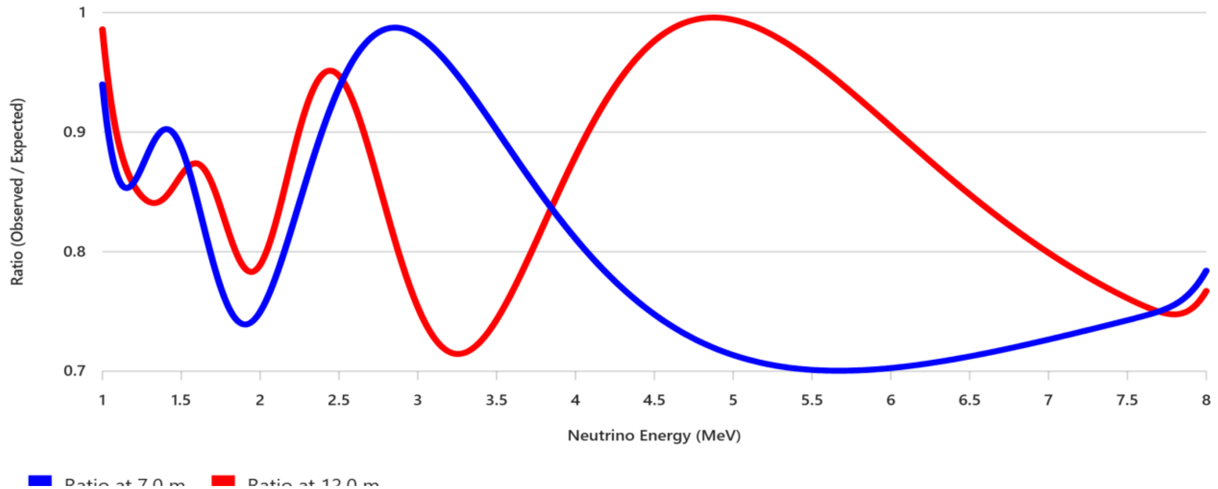


Example of energy spectrum distortion at 2 distances (7m and 12m), for maximal mixing, and $\Delta m^2 = 1eV^2$

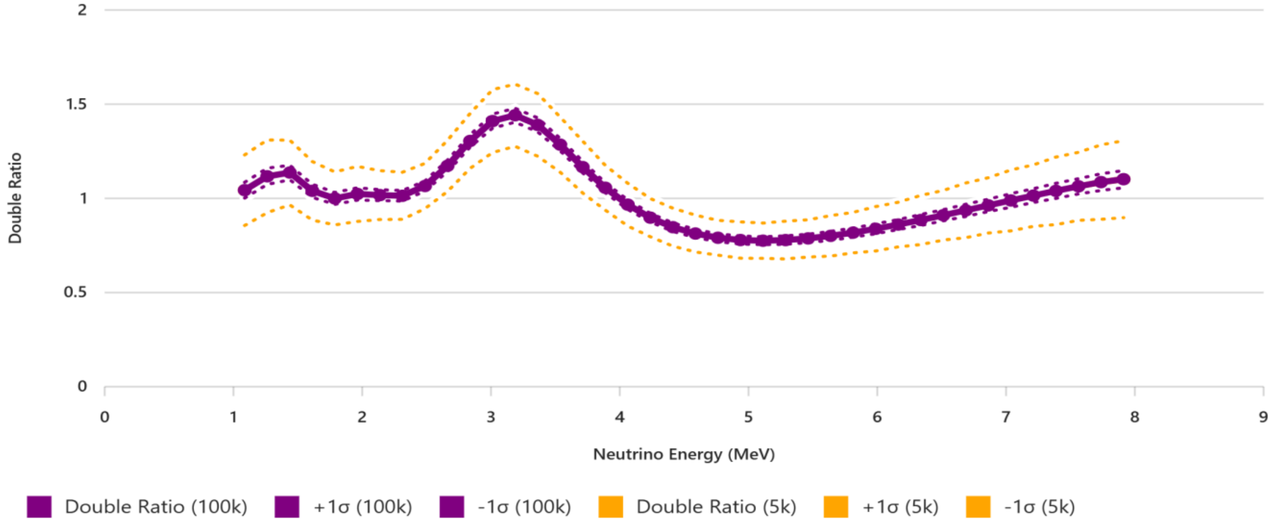


Example of energy spectrum distortion at 2 distances (7m and 12m), for mixing of $sin^2(2\theta) = 0.3$, and $\Delta m^2 = 1eV^2$, including energy resolution effects

The hunt for reactor neutrino oscillations

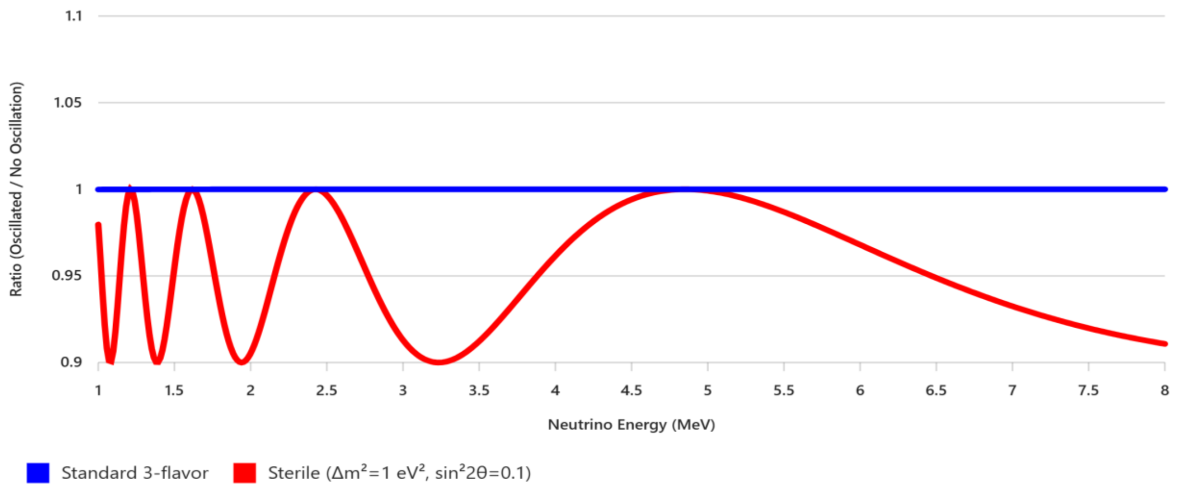


Ratio of measured/non-oscillation spectrum at 2 distances (7m and 12m), for mixing of $sin^2(2\theta) = 0.3$, and $\Delta m^2 = 1eV^2$



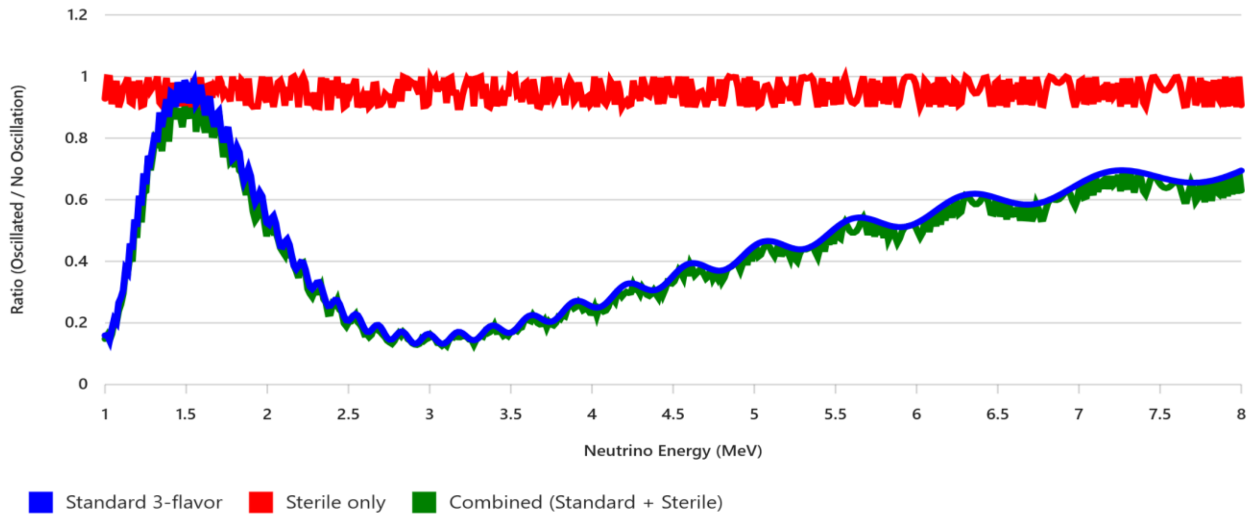
Ratio of measured spectra at 2 distances (7m and 12m), for mixing of $sin^2(2\theta) = 0.3$, and $\Delta m^2 = 1eV^2$, including statistical errors corresponding to 5000, and 100.000 detected events and with energy smearing

Scenario with current best neutrino parameters



Ratio of measured/non-oscillation spectrum at 12m distance from the core, for current best 3 neutrino mixing parameters, versus a single 'sterile' with mixing of $sin^2(2\theta) = 0.1$, and $\Delta m^2 = 1eV^2$

This implies the need for accurate measurements very close to the reactor core in order to discover 'steriles' with large values of Δm^2



Ratio of measured/non-oscillation spectrum at 50km distance from the core, for current best 3 neutrino mixing parameters, versus a single 'sterile' with mixing of $sin^2(2\theta) = 0.1$, and $\Delta m^2 = 1eV^2$

ILL energy spectrum at 8,76m: H. Kwon, et al., Phys. Rev. D**24**, 5 (1981)

4890 ±180 events

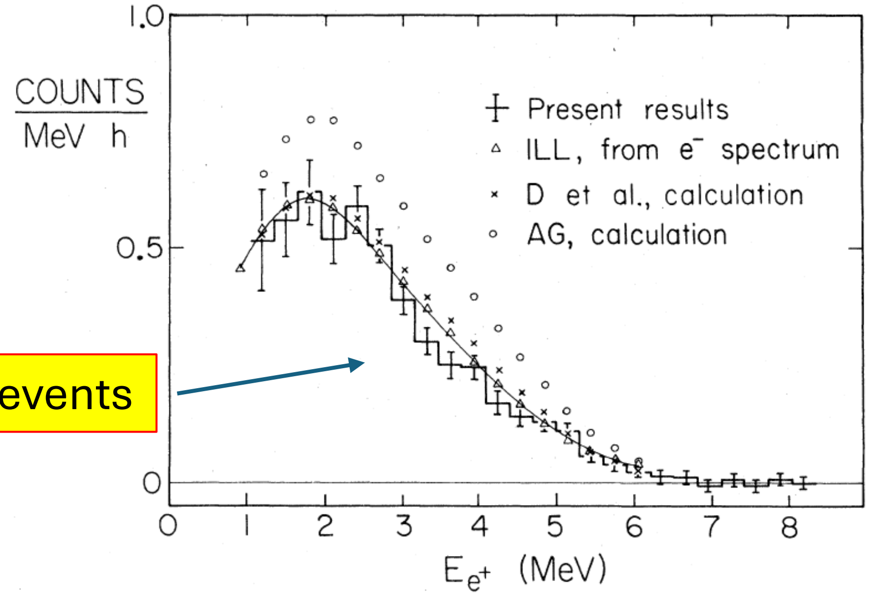
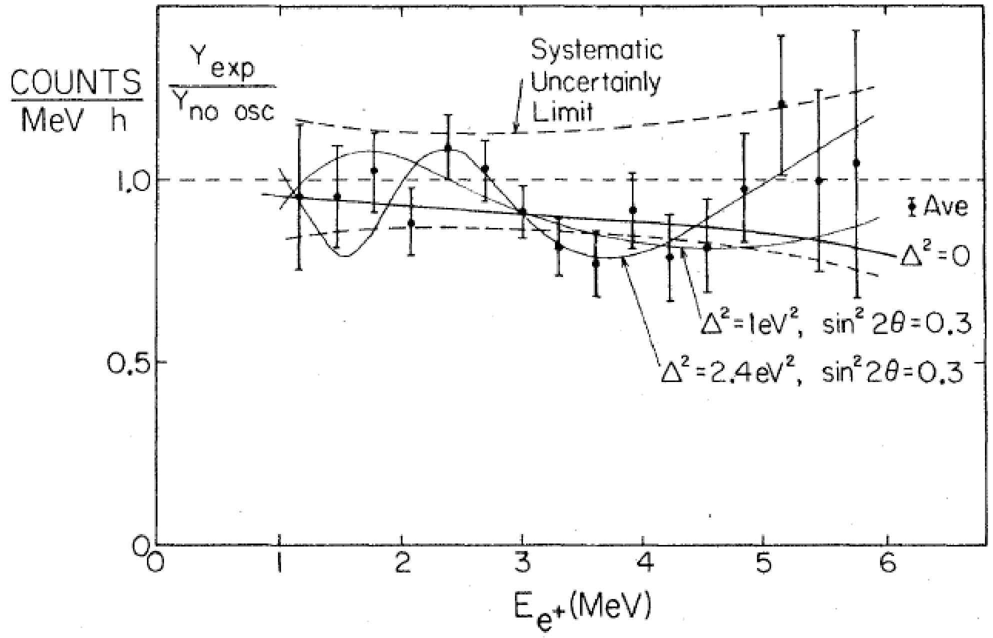


FIG. 12. Positron energy spectrum. The solid curve represents the expected positron spectrum based on the ILL electron-spectrum measurement. The calculated spectra AG (Ref. 26) and D *et al*. (Ref. 22) are also shown. No errors



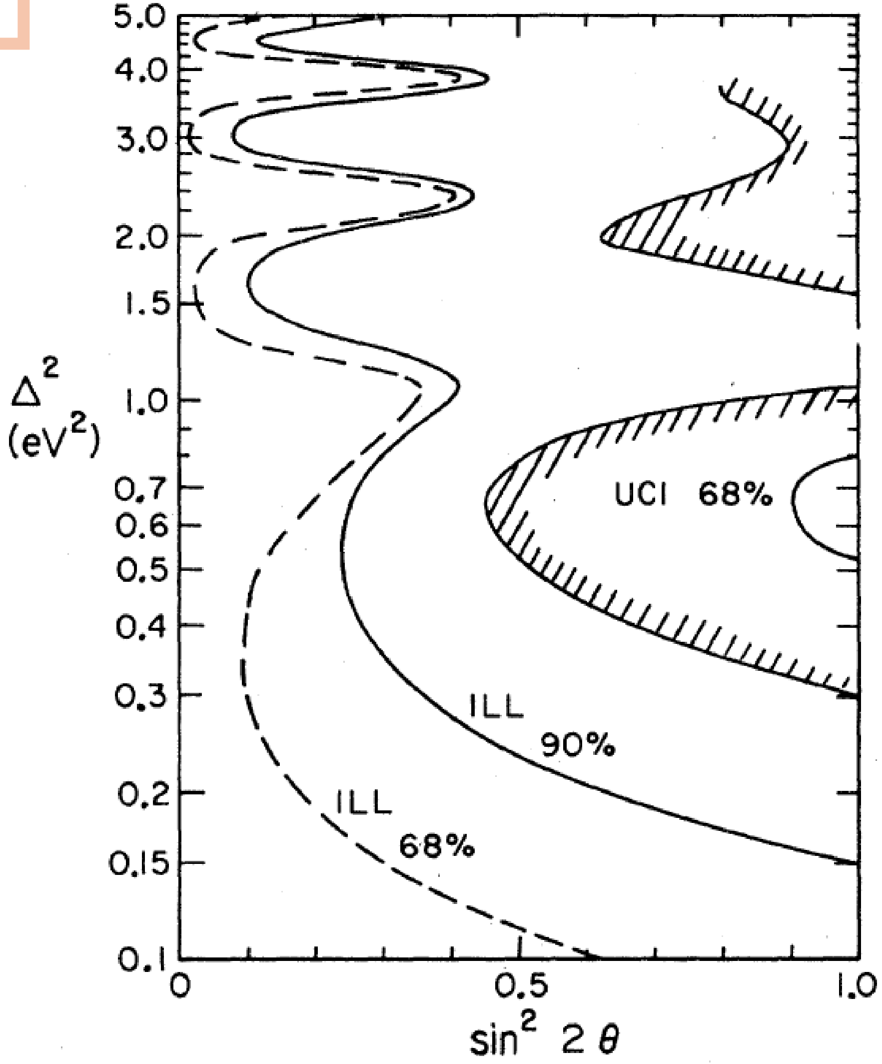
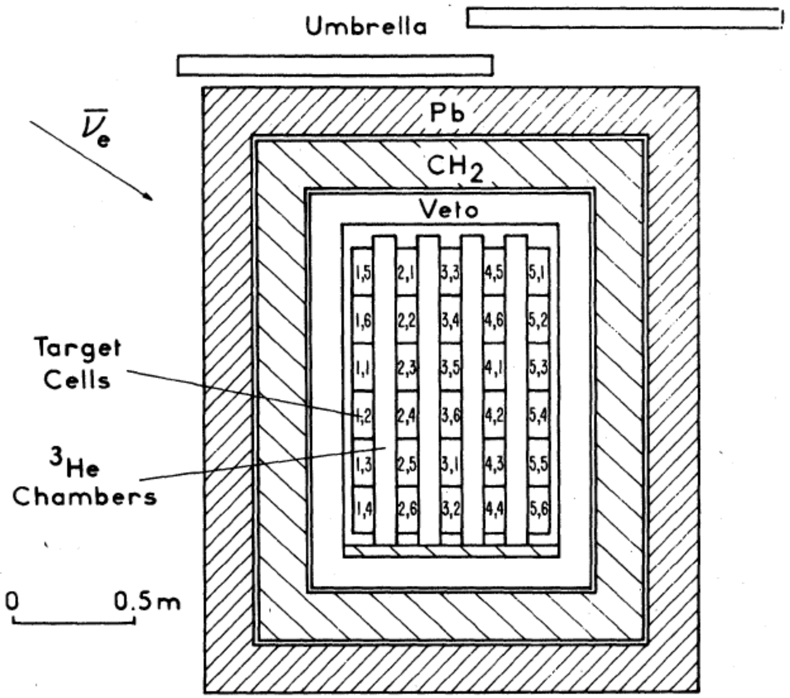


FIG. 14. The limits on the neutrino-oscillation parameters Δ^2 versus $\sin^2 2\theta$ given by the present experiment for 68% and 90% confidence level (C.L.). The regions to the right of the curve can be excluded. The allowed regions proposed in Ref. 17 are shown as a shaded area contained by the curves labeled UCI.

Modern reactor expts

J.F. Cavaignac, et al, Phys Lett. **148B**, nr4,5 (1984)

Measurements at Bugey Power plant near Lyon:
Measure anti-neutrino energy spectrum at two
Distances from the core: 13.6 & 18.3 m
Flux at 13.6 m: $2 \times 10^{13} cm^2 s^{-1}$
63.000 IBD events collected
Detector used: same as at ILL



- positron slows down by ionization in the liquid scintillator producing a prompt light pulse proportional to the energy of the positron.
- most of the annihilation γ's escape from the target cell, since their mean absorption length is 14 cm in the liquid scintillator. → Energy leakage
- neutron (of a few keV) does not make a pulse in the liquid scintillator. Instead, it is thermalized in the target cell within a few μs and diffuses into the ^3He counter with a mean diffusion time of about 150 μs
- Neutron is captured in ^3He counter via the reaction

$$n + {}^3He \rightarrow p + {}^3H + 765\ keV$$

Kinetic energy of the proton and triton

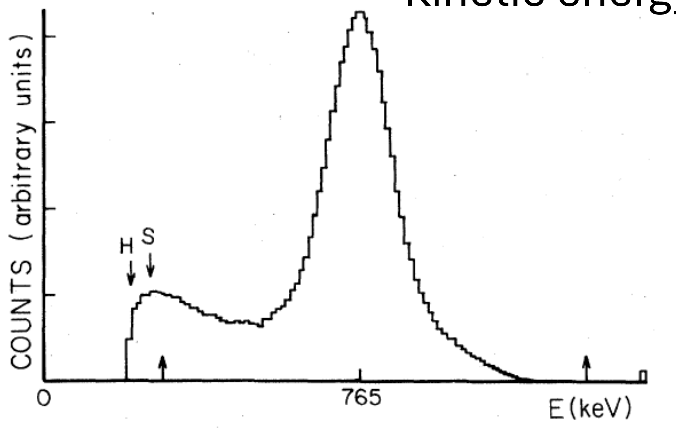


FIG. 4. The energy spectra of the ^{3}He counters. The hardware threshold is shown by the arrow (↓) with *H*. The software threshold set by a data-acquisition program is shown by the arrow (↓) with *S*. The energy window used in the analysis is shown by the arrow (↑).

Modern reactor expts.

Measured positron spectrum

$$Y(E_{e^+}, \Delta^2 d, \theta) = N_p \epsilon_n(t_w) \int \phi(E_{\bar{\nu}}, \Delta^2 d', \theta)\sigma(E_{\bar{\nu}})\epsilon_{e^+}(E_{\bar{\nu}}, E_{e^+}) \times h(d,d')\,dE_{\bar{\nu}}\,dd' , \quad (3)$$

- Nr of protons in target
- Neutron detection efficiency
- Incoming neutrino flux
- IBD cross sect., using $\tau_n = 900s$
- Positron detection eff.

- The 30 target cells are arranged in five vertical planes of six cells in each plane. Each target cell has an outside dimension of 9 cm x 20 cmx 88 cm, and is made out of 6 mm lucite. The width of the cell was chosen to be thick enough for neutron thermalization, yet sufficiently thin to prevent excessive neutron absorption by the protons.
- NE235C liquid scintillator (mineral oil based): with light output of 61.5% of that of anthracene and light transmission length >2 m.
- Energy resolution is 20% at 1MeV

•Anthracene: **100%**
•NaI(Tl): ~130% of anthracene
•Plastic scintillator: ~30–40%
•Liquid scintillator: ~50%

Backgrounds:

- Accidentals:
  - positron-like signals followed in random time by n-like signals
  - Show no exponential time-delay pattern
  - Can be reactor induced or environmental: cosmics or radioactivity in environment (concrete, detector components, shielding ,...)
- Non-accidentals:
  - Specific decay chains of contaminants or activated material with time-delay pattern

Neutron detection efficiency:
obtained with AmBe calibration source

$\epsilon_n(200\mu s) = 20.2 \pm 1.6\ \%$

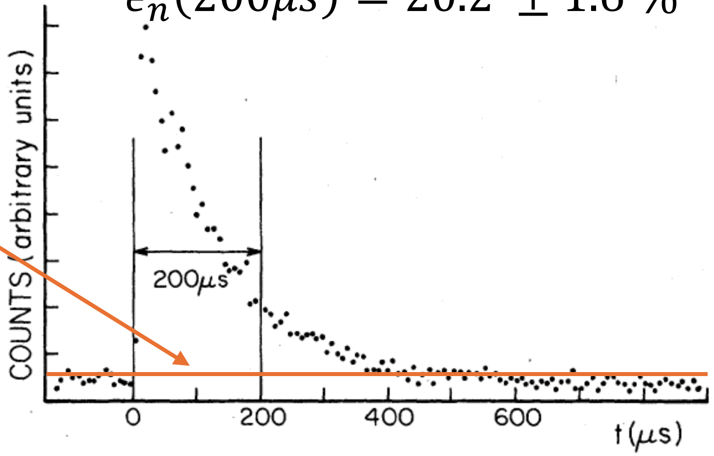


FIG. 6. Spectrum of the time distribution between a fast-neutron prompt pulse in the target cell and a delayed pulse in the ^{3}He counter. The 200-μs time window is used in the analysis.

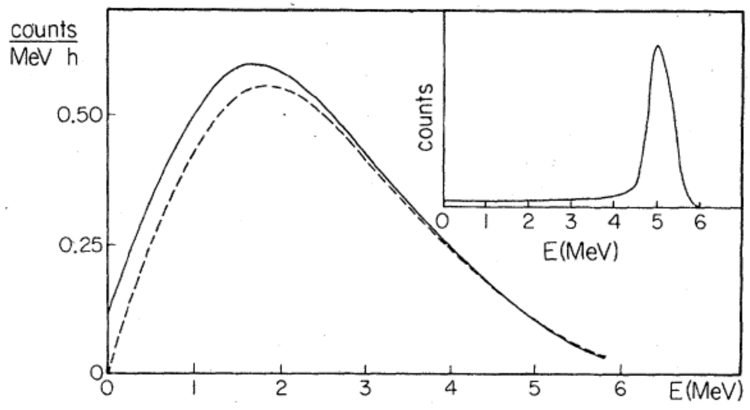


FIG. 9. Positron energy spectrum before (dashed curve) and after (solid curve) application of the positron detection response $\eta\ (E_{\bar{\nu}}, E_{e^+})$. The insert illustrates the response of the detector to monoenergetic 5-MeV positrons.

Backgrounds

Specific decay chains: several exist, but BiPo
Is very common

From ^{238}U decay chain:

$$^{214}\mathrm{Bi} \xrightarrow{\beta^-} {}^{214}\mathrm{Po} \xrightarrow{\alpha} {}^{210}\mathrm{Pb}$$

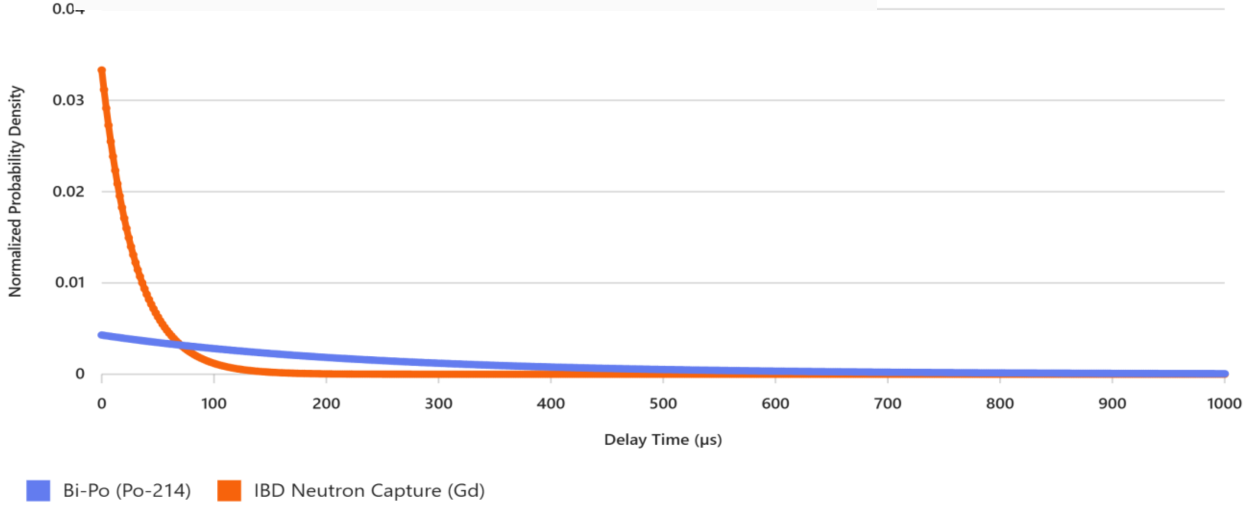
Emits e and γ: prompt signal

Half life of 164μs

From ^{232}Th decay chain:

Half life of 0.3μs

$$^{212}\mathrm{Bi} \xrightarrow{\beta^-} {}^{212}\mathrm{Po} \xrightarrow{\alpha} {}^{208}\mathrm{Pb}$$

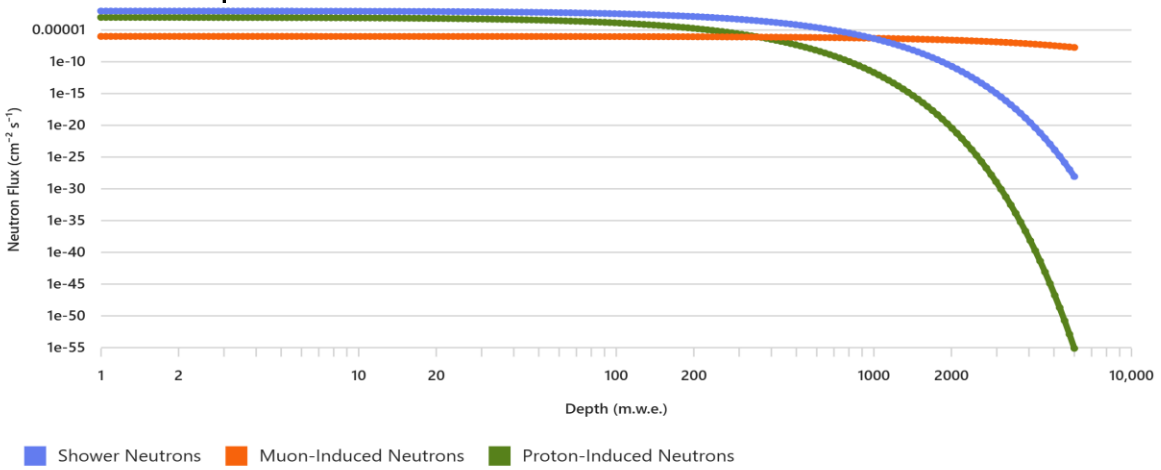


Mitigation:

- Pulse shape discrimination between alpha/gamma's/beta's
- Measurement/reconstruction of the annihilation gamma's
- Spatial/topological differences:
  - Alpha is absorbed very close to the deposit of the electron
  - Neutrons need a distance of several cm to thermalize before capture
- Radiopurity: Anything derived from natural ores (ceramics, glass, concrete) tends to have higher U/Th than synthetic polymers or purified metals.

Cosmic induced neutrons:

- primary cosmic n and proton induced spallation n's dominate at surface.
- Muon induced neutrons dominate at depth
- These change with weather conditions: air temp and pressure



Other considerations

- Avoid at all cost, reactor induced, power correlated (n, or gamma) backgrounds
- High reactor power: 2,5-4,5 GW
  - typically yields higher S/N figure, but adds risk for reactor induced bg
  - are typically commercial power stations:
    - Fuel mixture is more complex, burnup is longer and more complex: predicted neutrino spectrum harder to calculate
    - Reactor core size is extensive (not a point source): smears baseline
    - Core is often not easily approachable at short distances
- Low reactor power: 10-100 MW
  - Lower S/N due to factor 100 lower flux
  - Cores are often compact
  - Some operate with 93% enriched ^{235}U
  - Fuel mixture and power profile very well known
  - Have regular down-time for refueling or maintenance: Extensive reactor-off periods
  - Flexible access and installations close to core are often possible

Interpretation

H. Kwon, et al., Phys. Rev. D**24**, 5 (1981)

J.F. Cavaignac, et al, Phys Lett. **148B**, nr4,5 (1984)

Note the difference in S/N ratios

Bugey Power reactor:2 positions: L=13.6m and 18.3 m

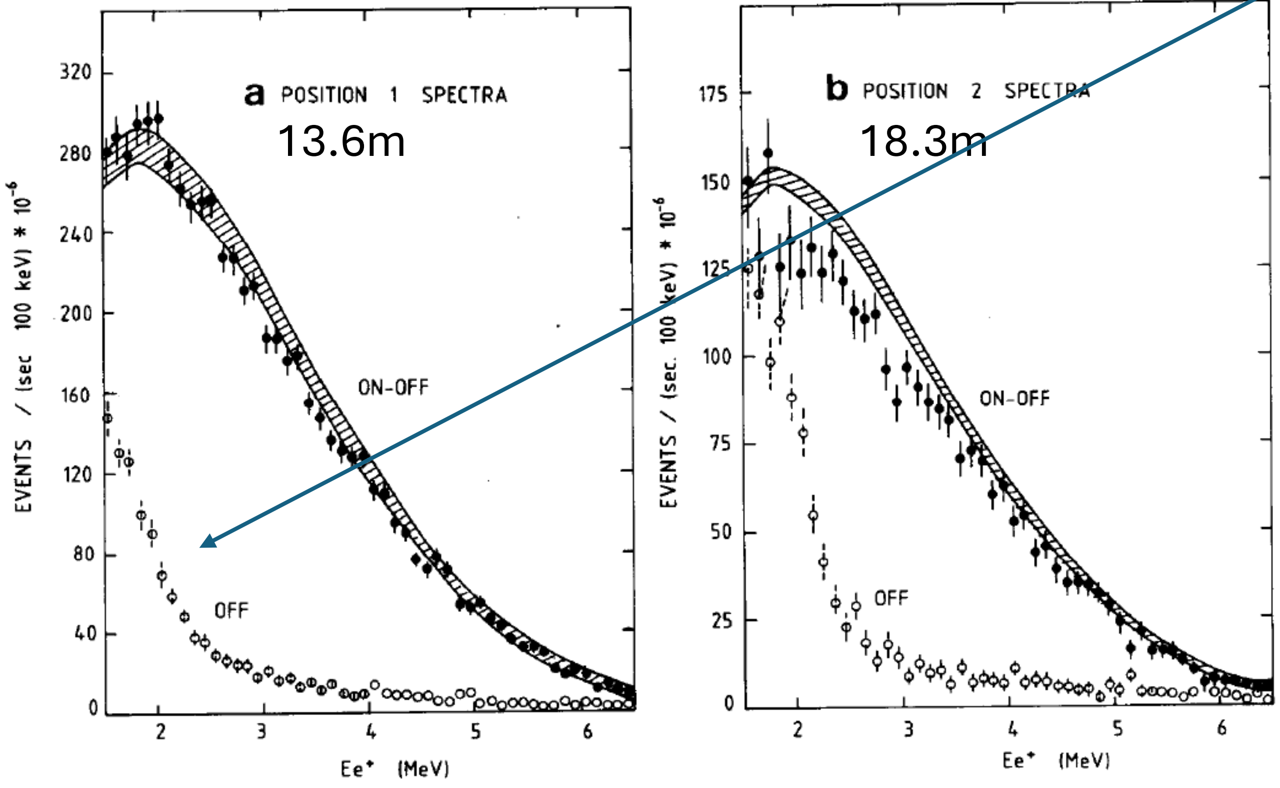


Fig. 2. (a) Positron energy spectrum measured at position 1 (reactor OFF subtracted). The data points with dashed error bars show the reactor OFF spectrum. The error bars are statistical. The expected positron energy spectrum is shown as a shaded band delimited by the point-to-point errors. (b) Ditto at position 2.

ILL research reactor: L=8.76 m

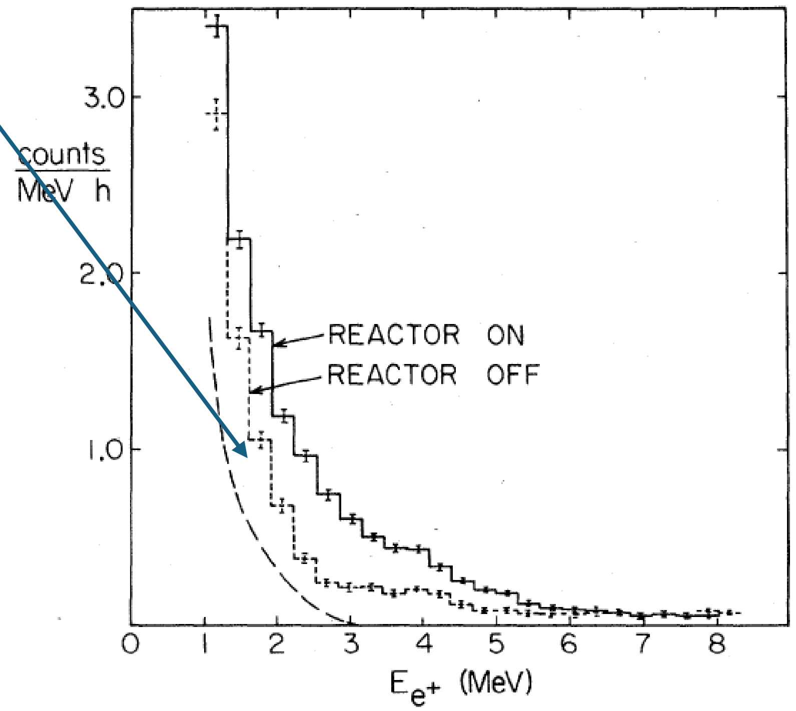
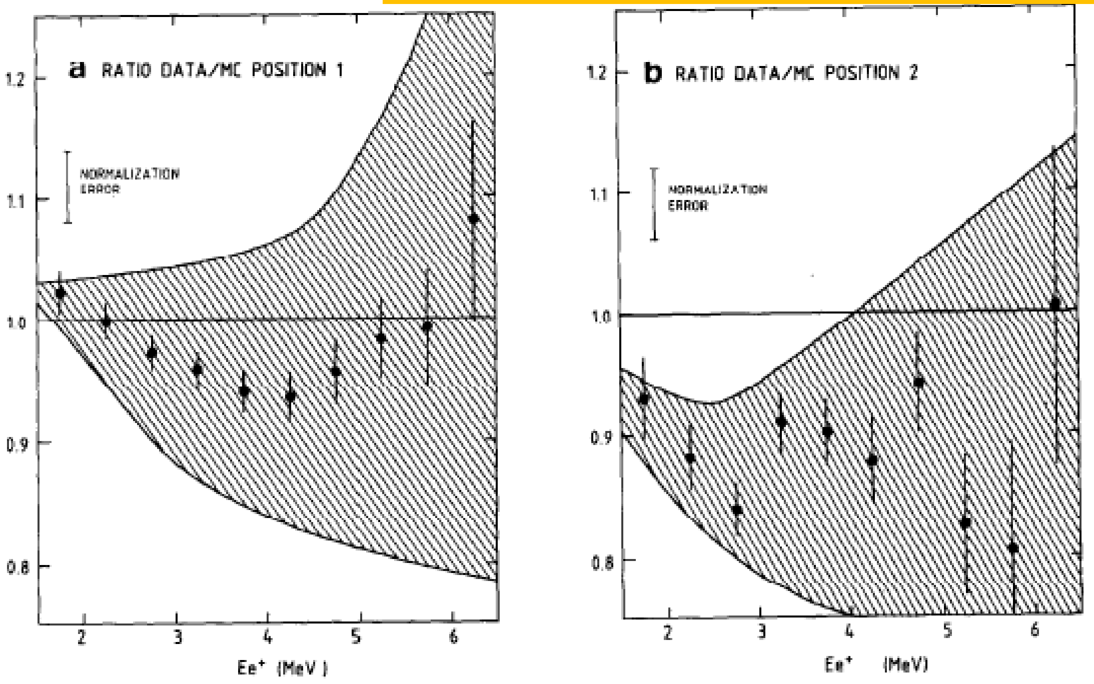
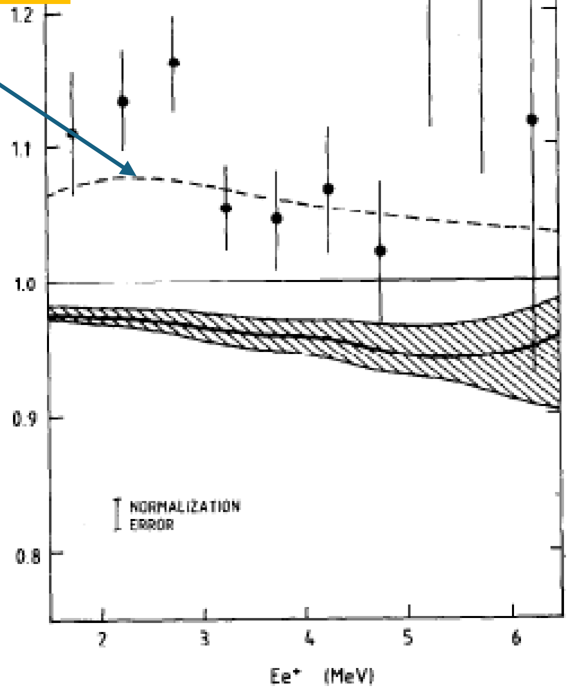


FIG. 11. Positron energy spectra for reactor on (3088.7 h live time) and reactor off (1181.8 h live time). The accidental background is shown as a dashed line.

Interpretation

mixing of $sin^2(2\theta) = 0.025$, and $\Delta m^2 = 0.2eV^2$





Note the large systematic uncertainties due to:

- Expected (no-oscillation) spectrum calculation
- Energy scale uncertainties (calibration)

Ratio of measured energy spectra at 2 baselines:

- Eliminates the need for spectrum calculation (to 1st order)
- Predicted spectra are used for acceptance, trigger and selection efficiency calculations
- Remaining systematic uncertainties are related to fuel burnup profile (related to spectrum calculations)

Chi**2 fits and exclusions

2 inputs: $R^i_{12} = Y^i_2/Y^i_2, \quad N_k = \sum_{i=1}^{10} Y^i_k,$

- Each of 10 bins, *i*, in the ratio plot of the two baselines 1 and 2
- The integrated event yield for baseline *k*, *k*=1,2

2 Constraints:

- Fitting to the expected shape with arbitrary normalization

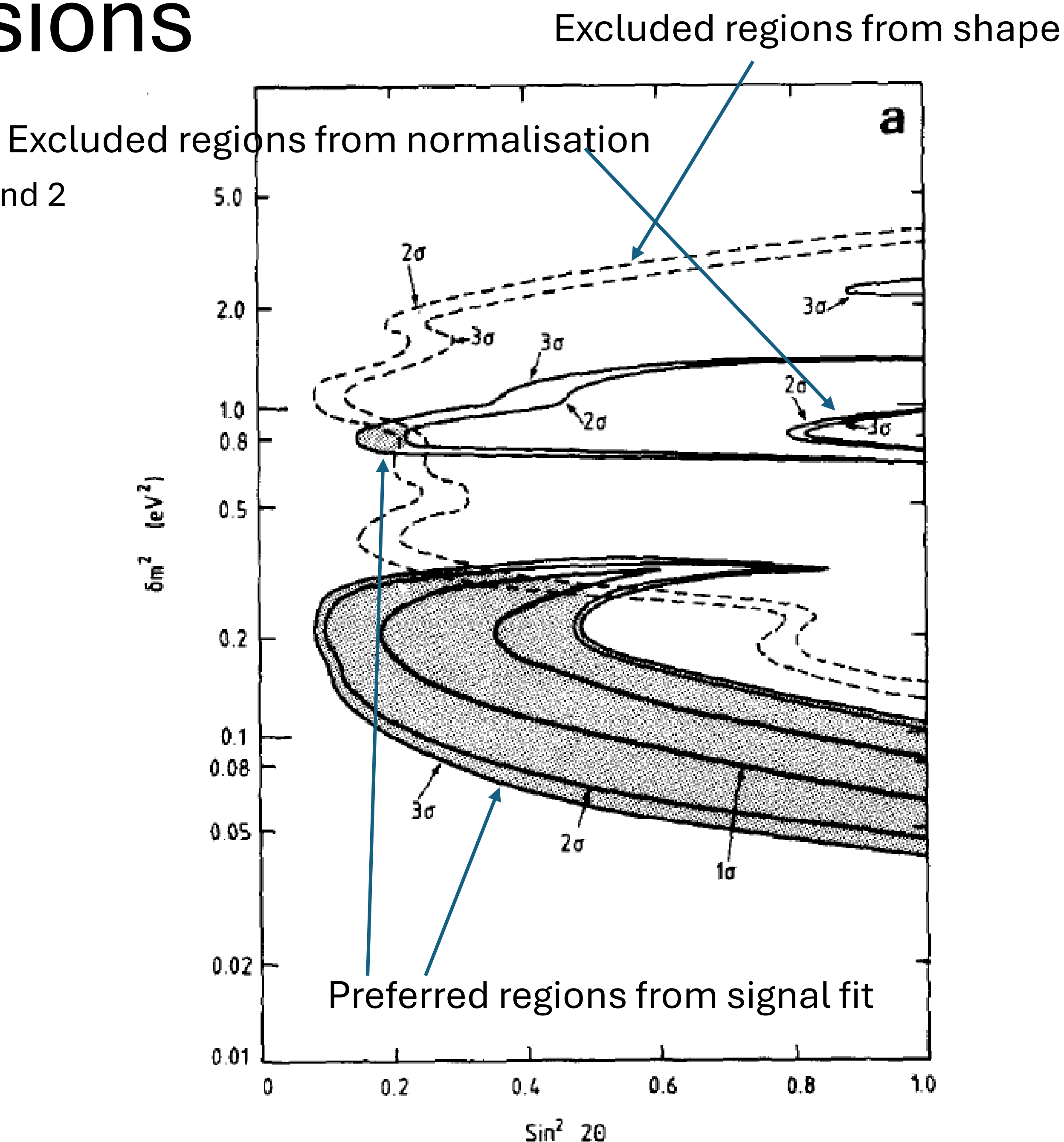
$$A = \left(\frac{N_1^{\text{expect.}}(\delta m^2,\theta)}{N_2^{\text{expect.}}(\delta m^2,\theta)}\right) \Big/ \left(\frac{N_1^{\text{meas.}}}{N_2^{\text{meas.}}}\right),$$

$$\Rightarrow \chi^2_{\text{shape}} = \sum_{i=1}^{10}\left(\frac{A R_{12}^{i\,\text{meas.}} - R_{12}^{i\,\text{expect.}}(\delta m^2,\theta)}{A\,\sigma_{12}^{i\,\text{meas.}}}\right)^2,$$

- Fitting to the normalization (counting difference)

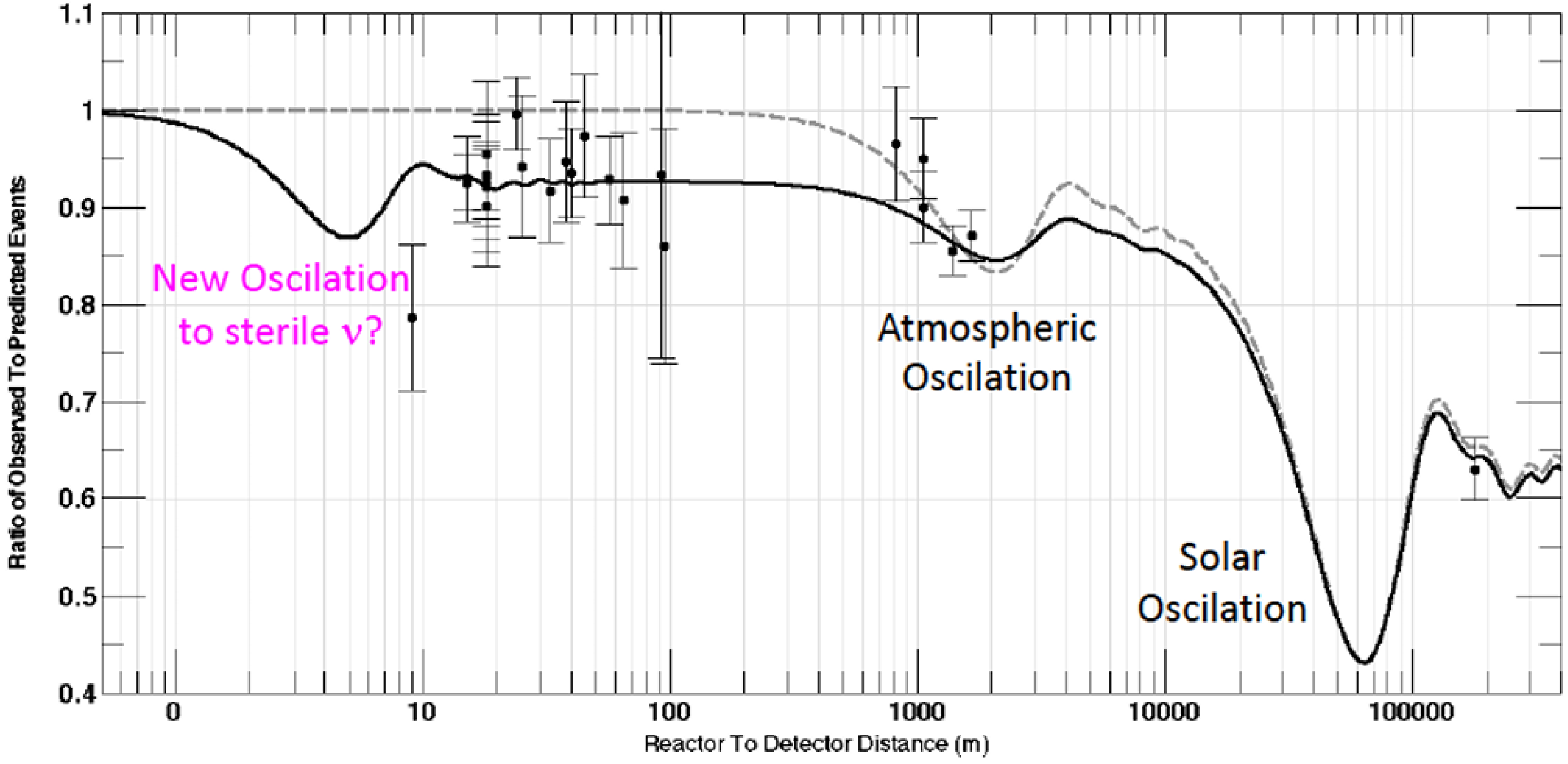
$$\chi^2_{\text{norm.}} = \left(\frac{N_1^{\text{meas.}}}{N_2^{\text{meas.}}} - \frac{N_1^{\text{expect.}}(\delta m^2,\theta)}{N_2^{\text{expect.}}(\delta m^2,\theta)}\right)^2 \Big/ \sigma_{N_{12}}^2,$$

Two preferred regions with a signal hypothesis at $\Delta m^2 \approx 0.8\ eV^2$ and $\Delta m^2 \approx 0.2\ eV^2$



Reactor Neutrino anomaly

G.Mention et al., Phys. Rev. D83,073006 (2011)



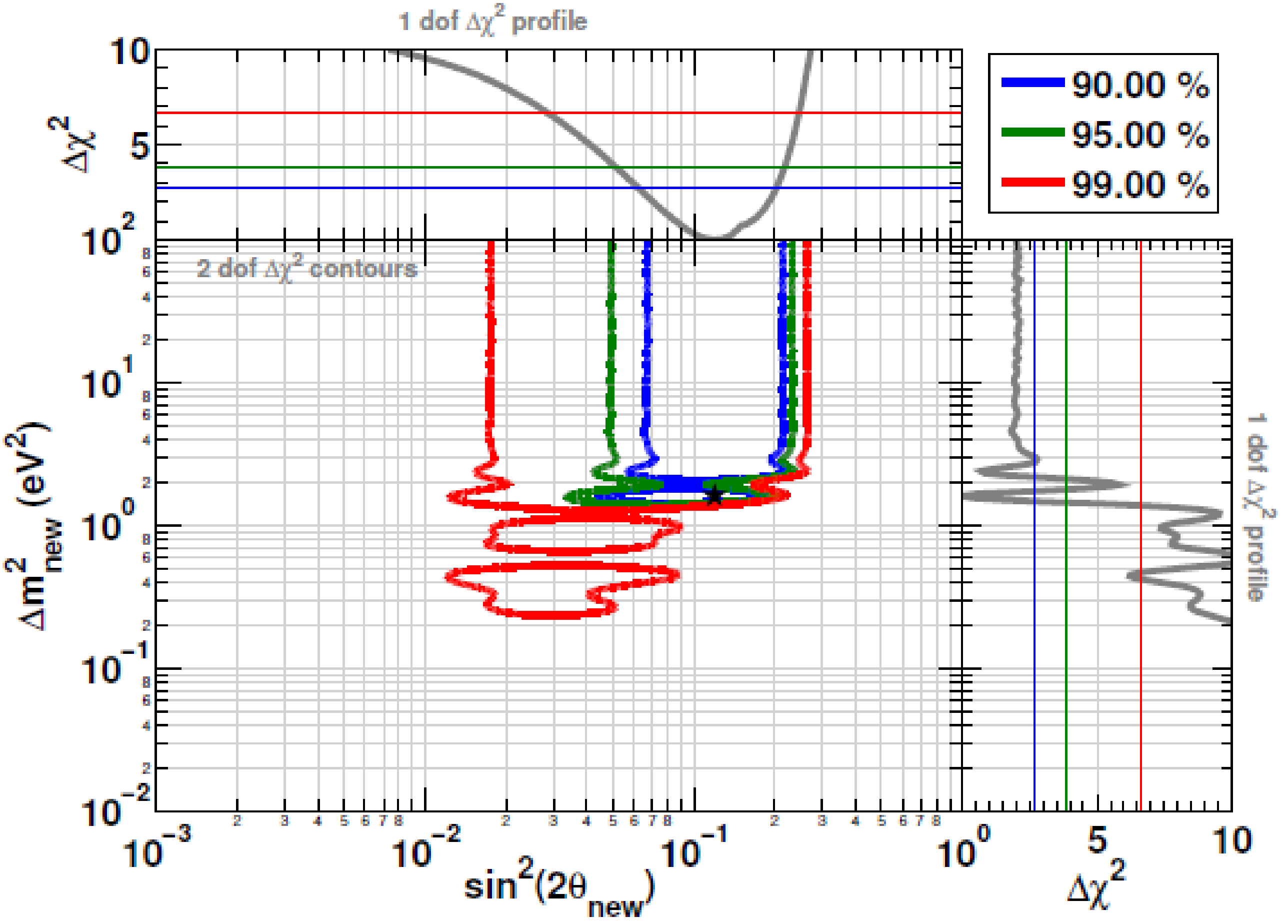
In the 2010's, 2 significant updates in the predicted anti-neutrino flux and energy spectrum:

- Update of the neutron life time:
  - 1986: 887.0 ± 2.0 s
  - 1998: 885.7 ± 0.8 s
  - 2010: 880.1 ± 1.1 s
  - 2020: 878.3 ± 0.6 s
  - Increased the IBD x-sec with 0.5%
- Updated flux calculations using improved β-conversion models (Huber & Mueller)
  - Increased the integrated flux with ~3%, depending on fuel
- Standardizing all historic measurements at short baselines led to a global deficit in measured flux of ~6%

  $\mu=0.943\pm0.023$
- Taking into account correlated uncertainties between experiments, this was a 2.2 σ effect

Reactor neutrino anomaly

G.Mention et al., Phys. Rev. D83,073006 (2011)



- Global re-fits to
  - historic reactor ν data
  - Calibration data from radiochemical experiments (Gallium anomaly)
  - Historic accelerator data (LSND, MiniBoone)
- Indicated the possibility of a 4th, 'sterile', neutrino state with $sin^2(2\theta) \approx 0.1$, and $\Delta m^2 \approx 1eV^2$
- This prompted:
  - a new global effort to measure energy spectrum and flux at very short baselines (<10m)
  - Many flagship neutrino oscillation experiments to test the sterile hypothesis

The Solar neutrino puzzle

Homestake experiment (1969~1998)

1400 m deep

615 tons of $C_2\,Cl_4$

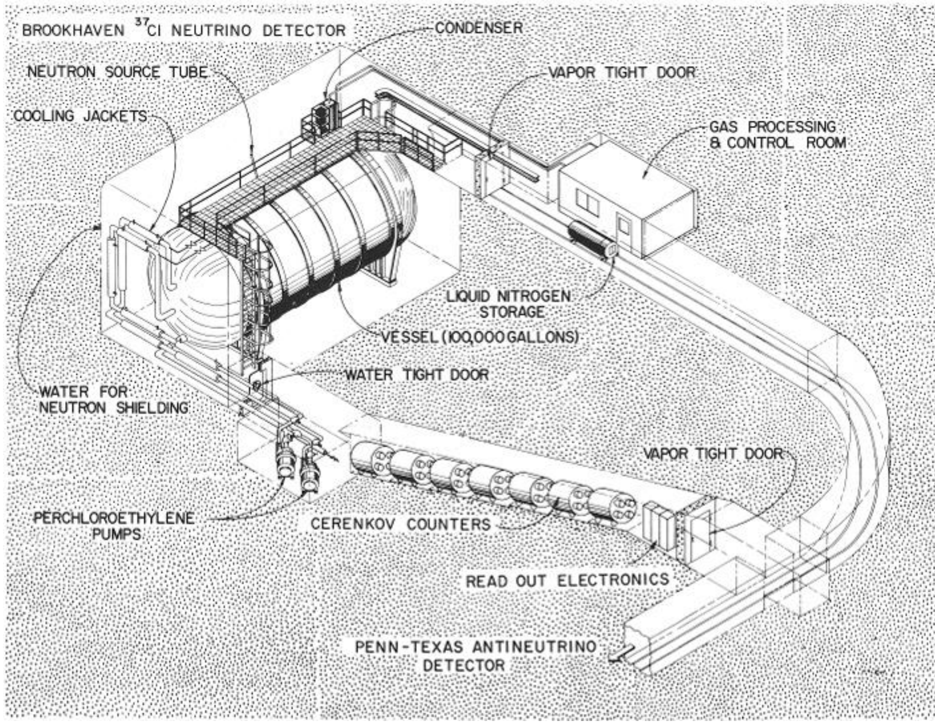
$\nu_e\,{}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar}\,e^-$

$\hookrightarrow \quad E_\nu > 0.8\,\mathrm{MeV}$

$\Downarrow$

${}^8\mathrm{B}\,,\ {}^7\mathrm{Be}$ neutrinos and Pep-chain

- 1964: J. Bahcall and R. Davis Jr. make the first quantitative prediction of the neutrino flux from the sun
- R. Davis conducts the first Clorine based radiochemical experiment and detects a flux that is 3x too small!



$\Rightarrow$ every month count of number of ${}^{37}\mathrm{Ar}$ produced flushing He to measure radioactivity resulting

$1\ \mathrm{SNU} \equiv 10^{-36}$ interactions per target atom per sec $\longleftarrow$ $\text{number of events} = \Phi_{\nu_e} \cdot \sigma_{\nu_e\,{}^{37}Cl \rightarrow {}^{37}Ar\,e^-}$

$\sim 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ $\qquad \sim 10^{-46}\,\mathrm{cm}^2$

predicted rate: 8.5 ± 1.8 SNU

measured rate: 2.56 ± 0.23 SNU

Solar neutrino production

- The main process that drives energy production by our sun

$$4p \rightarrow \alpha + 2e^{+} + 2\nu_e$$

- This processes happens through a chain of reactions

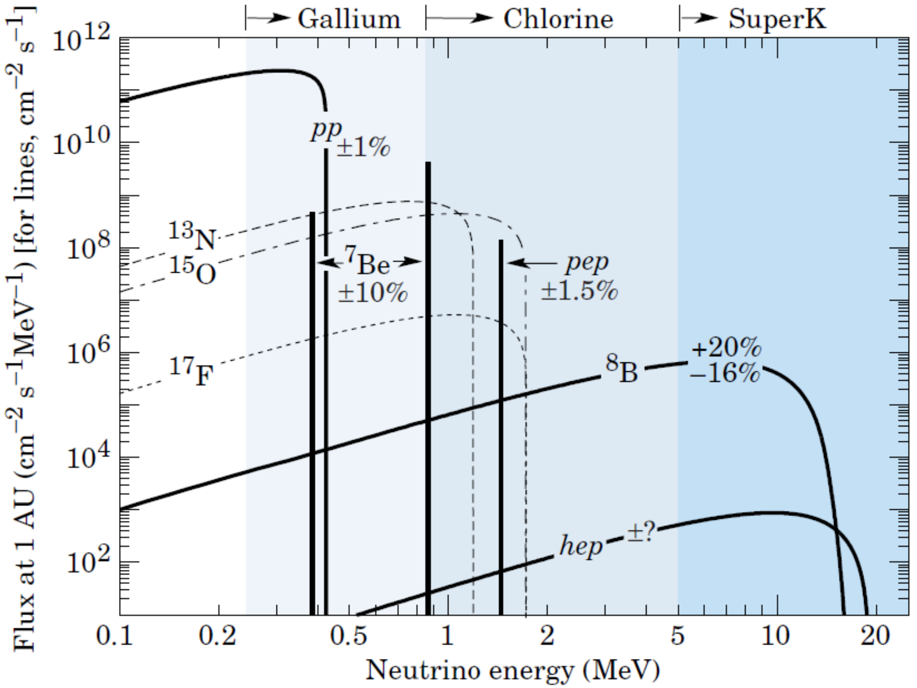


Table 1. The proton-proton chain in the sun.

Number	Reaction	Solar terminations (%)	Maximum neutrino energy (Mev)
1	$p + p \rightarrow {}^2H + e^+ + \nu$	99.75	0.420
	or		
2	$p + e^- + p \rightarrow {}^2H + \nu$	0.25	1.44 (monoenergetic)
3	${}^2H + p \rightarrow {}^3He + \gamma$		
4	${}^3He + {}^3He \rightarrow {}^4He + 2p$	86	
	or		
5	${}^3He + {}^4He \rightarrow {}^7Be + \gamma$		
6	${}^7Be + e^- \rightarrow {}^7Li + \nu$		0.861 (90%), 0.383 (10%) (both monoenergetic)
7	${}^7Li + p \rightarrow 2\,{}^4He$	14	
	or		
8	${}^7Be + p \rightarrow {}^8B + \gamma$		
9	${}^8B \rightarrow {}^8Be^* + e^+ + \nu$		14.06
10	${}^8Be^* \rightarrow 2\,{}^4He$	0.02	

P-p chain (most dominant part of the flux)

Pep chain (subdominant)

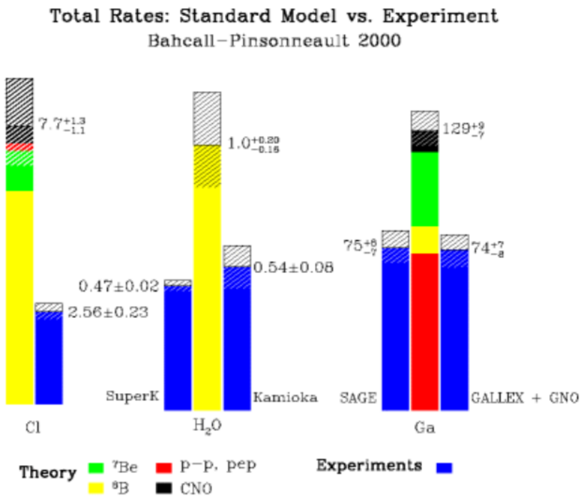
Be- chain (very small)

B- chain (very small)

Timeline of Solar Neutrino Experiments

Homestake	Kamiokande	GALLEX	SAGE	Super-Kamiokande	SNO	Borexino
1968?1994	1988?1995	1991?1997	1990?present	1996?present	1999?2006	2007?present
Radiochemical (Cl ? Ar)	Water Cherenkov	Radiochemical (Ga ? Ge)	Radiochemical (Ga ? Ge)	Water Cherenkov	Heavy Water Cherenkov	Liquid Scintillator
Threshold: ~0.8 MeV	Threshold: ~7 MeV	Threshold: ~0.233 MeV	Threshold: ~0.233 MeV	Threshold: ~5 MeV	Threshold: ~5 MeV	Threshold: ~0.2 MeV

Summary of solar neutrino deficits (2000)



Solar neutrino problem! ⇒ experimental problem?
solar model problem?
something happens on the way?

Gallium experiments are also sensitive to p-p chain neutrinos through reaction

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

Half-life: 11.4 days
X-ray emitter

With an energy threshold of 0.233 MeV
Two groups of experiments:

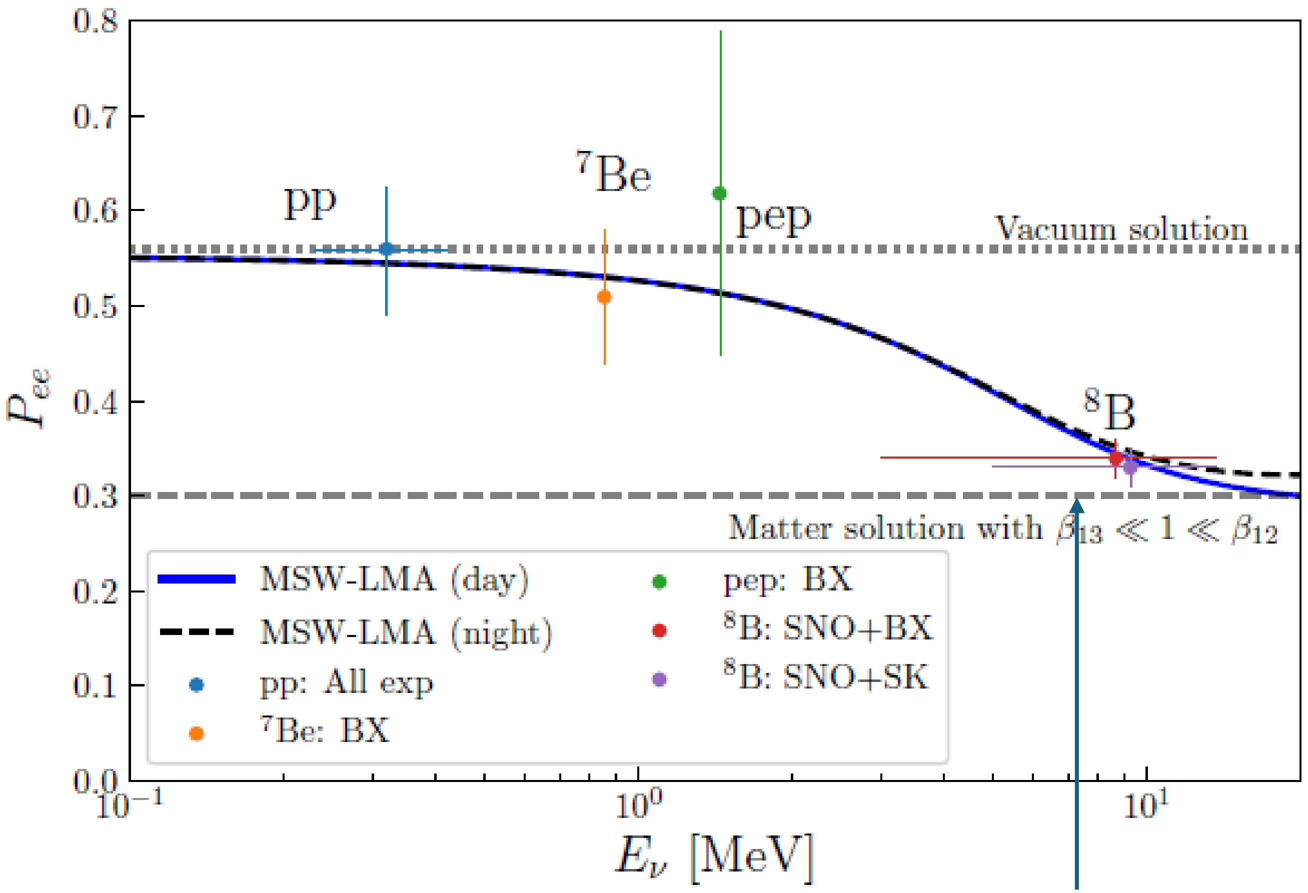
- Gran Sasso:
  - GALLEX: 30 ton $GaCl_3 - HCl$ solution
  - GNO: follow-up of GALLEX
- Baksan Neutrino Observatory, Russia:
  - SAGE: 50 ton metallic Ga (solid detector)

- GALLEX (1991–1997):
  $\Phi_{\mathrm{GALLEX}} \approx 77 \pm 6$ SNU
- GNO (1998–2003):
  $\Phi_{\mathrm{GNO}} \approx 62 \pm 6$ SNU

SSM Predicted: 129±9 SNU

$\Phi_{\mathrm{SAGE}} \approx 66.2 \pm 3.2\ (\mathrm{stat}) \pm 3.5\ (\mathrm{syst})$ SNU

Interpretation



BUT: In matter, the electron neutrinos can interact with electrons, thus changing the effective mixing. This effect becomes very effective (resonant) at $E_\nu \approx 2\ MeV$ in the sun's core. The neutrino's leaving the sun become quasi entirely mass state ϑ_2 and their flavor composition are therefore ~30% ν_e

→ Mikheyev–Smirnov–Wolfenstein (MSW)effect

- Electron neutrinos from the sun oscillate on their way to earth
- Electron neutrinos are a mixture of predominantly the first two mass eigenstates

$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

with:

$$|U_{e1}|^2 \approx \cos^2\theta_{12}\cos^2\theta_{13} \approx 0.67$$
$$|U_{e2}|^2 \approx \sin^2\theta_{12}\cos^2\theta_{13} \approx 0.30$$
$$|U_{e3}|^2 \approx \sin^2\theta_{13} \approx 0.02$$

- Their survival probability is dominated by the mixing parameters of the first two generations: $(\Delta m^2_{12}, \theta_{12})$

$\Delta m^2_{21} \approx 7.4 \times 10^{-5}\ \mathrm{eV}^2$ $\theta_{12} \approx 33.4°$

For $E \sim 1\,\mathrm{MeV}$, $L_{\mathrm{osc}} \sim 100\ \mathrm{km}$

- In vacuum, the survival probability becomes simply

$$P_{ee} \approx 1 - \frac{1}{2} sin^2(2\theta_{12}) \approx 0.5775$$

- With small negative correction due to $\theta_{13} \approx 8.6^\circ$

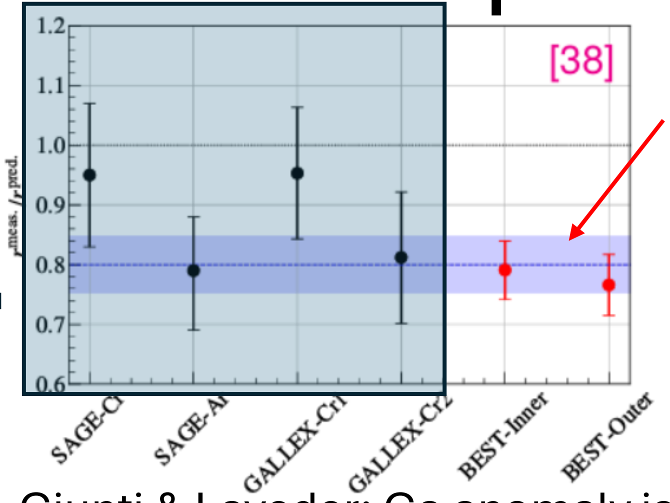
Calibration of radiochemical experiments

- Chromium and Argon can capture an orbital electron to turn into Vanadium.

$$e^- + {}^{51}\mathrm{Cr} \rightarrow {}^{51}\mathrm{V} + \nu_e$$
- **746 keV** (90% of decays)
- **426 keV** (10% of decays)

$$e^- + {}^{37}\mathrm{Ar} \rightarrow {}^{37}\mathrm{Cl} + \nu_e$$
811 keV (100%)

- They emit mono-energetic neutrinos in the same energy range as solar neutrinos
- They were used to confirm the detector efficiency which was estimated to be ~100% with an uncertainty of few %
- The activity of the sources was also known to %level accuracy
- The IBD cross section on Gallium is less well known: ~5-10% accuracy, due to nuclear corrections (excited states of ^{71}Ga $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$
- Recent evaluation of the statistical significance of the 'Gallium Anomaly':



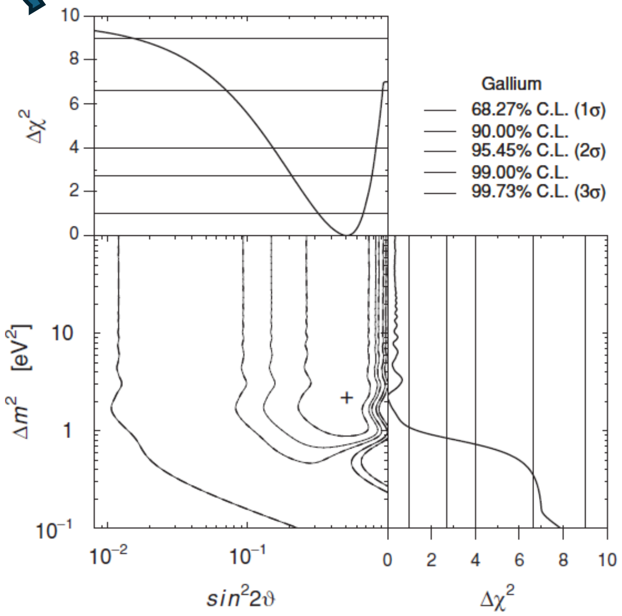
V. V. Barinov et al. [BEST], Phys.Rev.C105(2022)no.6,065502

Weighted fit: R=0.81± 003

Increase Ga –anomaly to 6σ effect

$$\Delta m^2 = 3.3^{+\infty}_{-2.3}\ \mathrm{eV}^2 \text{ and } \sin^2 2\theta = 0.42^{+0.15}_{-0.17},$$

Giunti & Laveder: Ga anomaly is a 3σ effect, taking into account x-sec uncertainties and correlations between experiments



Interpretation in terms of an extra 'sterile' neutrino:
Best fit values:

$$\sin^2 2\vartheta_{\mathrm{bf}} = 0.50, \quad \Delta m^2_{\mathrm{bf}} = 2.24\ \mathrm{eV}^2.$$

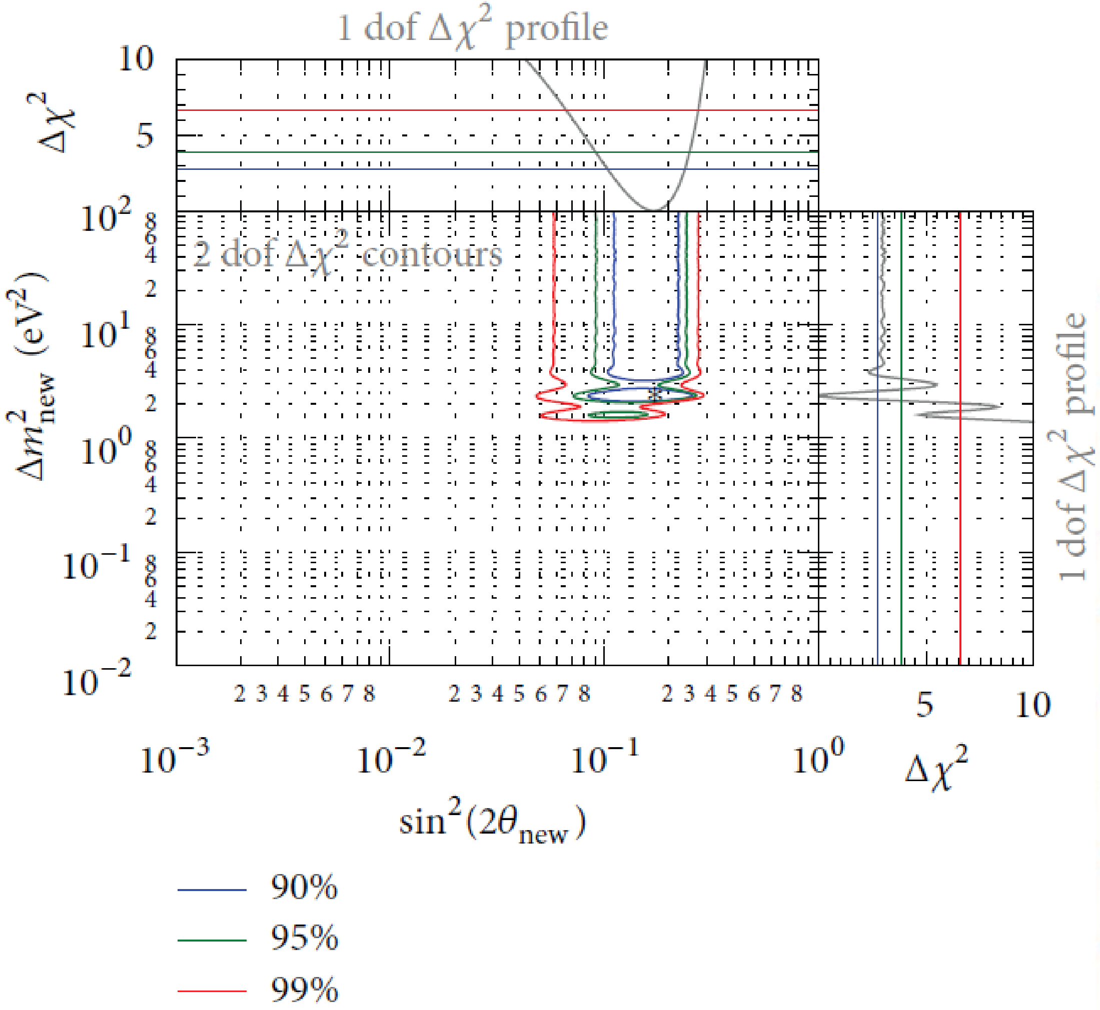
Lower limits at 99% CL:

$$\sin^2 2\vartheta > 0.07, \quad \Delta m^2 > 0.35\ \mathrm{eV}^2,$$

C. Giunti and M. Laveder, PHYSICAL REVIEW C **83**, 065504 (2011)

Modern sterile searches

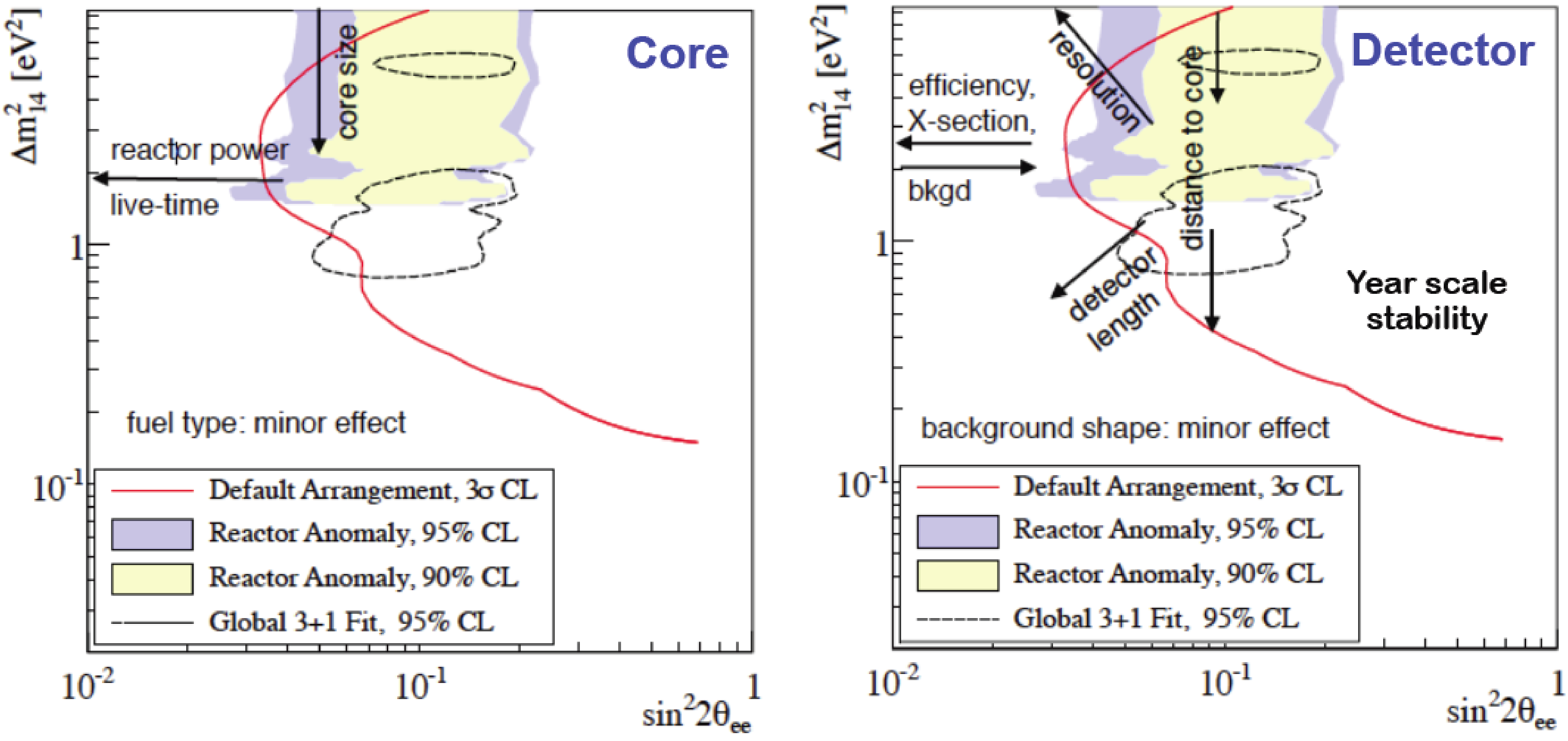
- The reactor ν anomaly, together with the Gallium anomaly hinted at the possible existence of a sterile neutrino with mixing parameters $\Delta m^2 > 1.5\ eV^2$ at 99%CL, $sin^2(2\theta) = 0.17 \pm 0.04$, and a most probable value of $\Delta m^2 = (2.3 \pm 0.1)\ eV^2$
- This prompted a large international effort to search with modern detectors for oscillations at very close proximity to reactors



Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

S-B. Kim, T. Lasserre, and Y. Wang, Advances in High Energy Physics (2013), Article ID 453816

Optimisations of sterile neutrino experiments

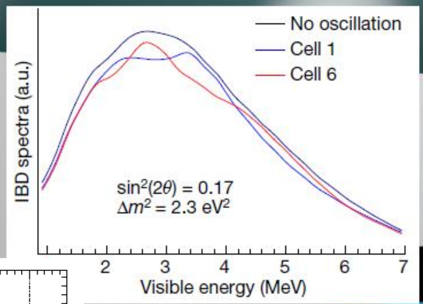


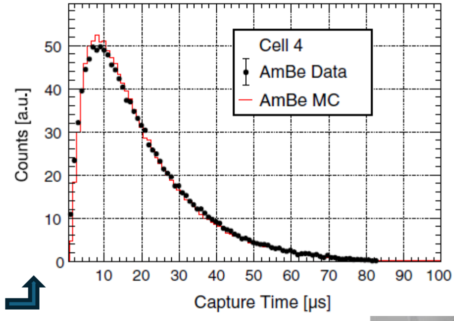
K.M. Heeger et al., arXiv:1212.2182v1

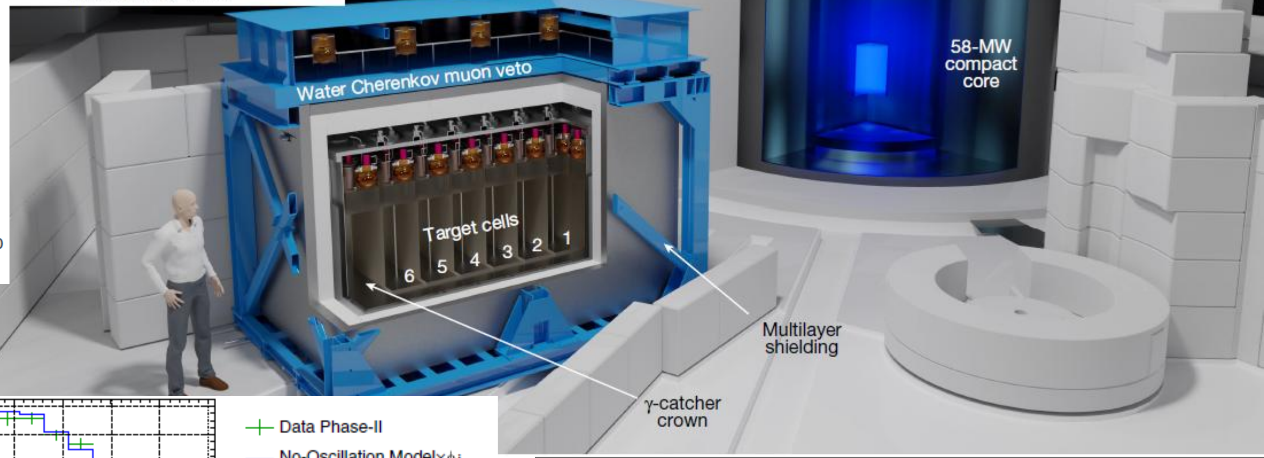
STEREO

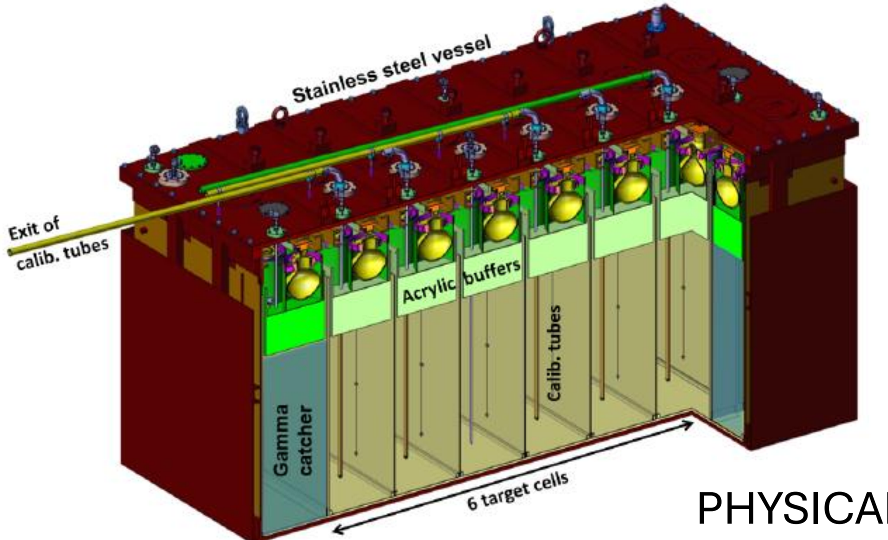
N. Allemandou et al. (2018) JINST 13, P07009

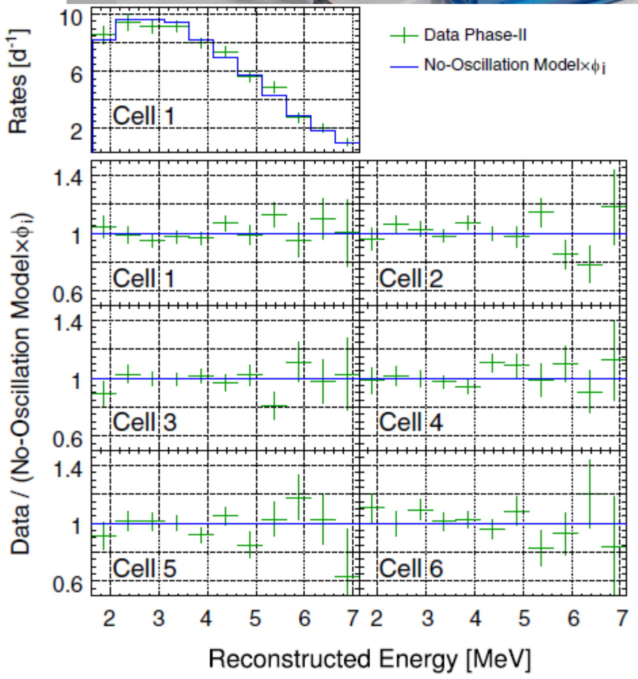
- Installed in 2016 at ILL research reactor:
  - Enriched fuel (93% ^{235}U)
  - Compact core: 40cm diam.
  - Low power: 58 MW
- Detector:
  - 6 cells of Gd doped liquid scintillator
  - Active muon veto and buffer cells
  - Distance detector center – reactor core center: 10m
  - Good Energy resolution: 8% at 3 MeV
  - IBD efficiency: ~65%, S/N= 10/1
  - 394 ν's per day, during 179 days



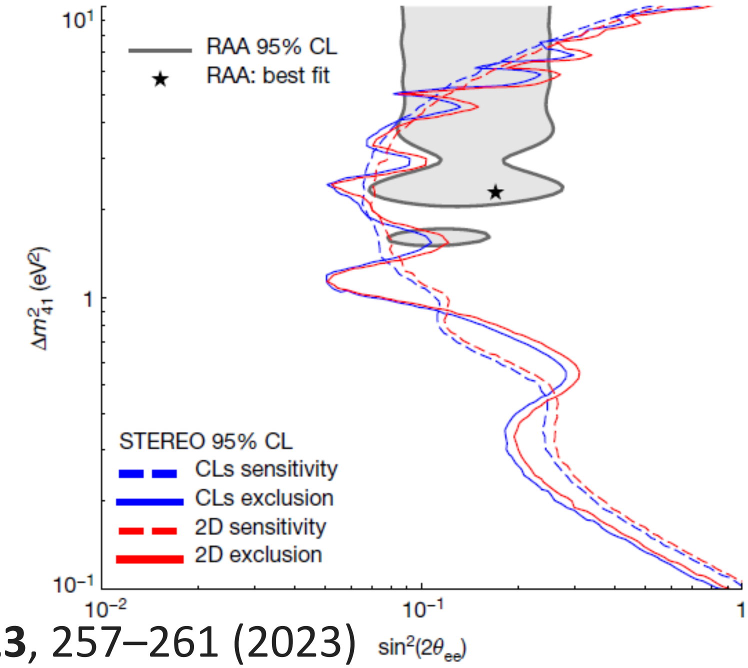








PHYSICAL REVIEW D 102, 052002 (2020)

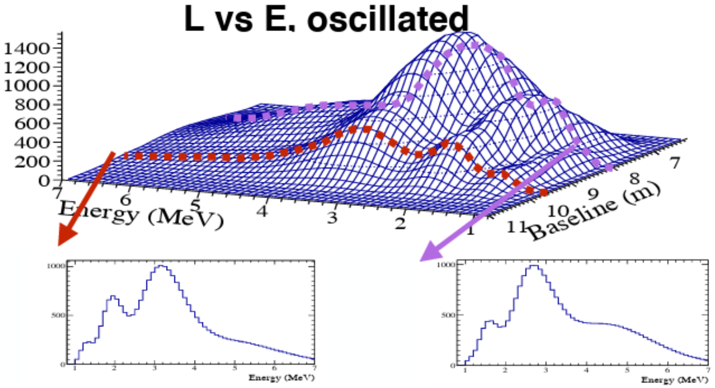


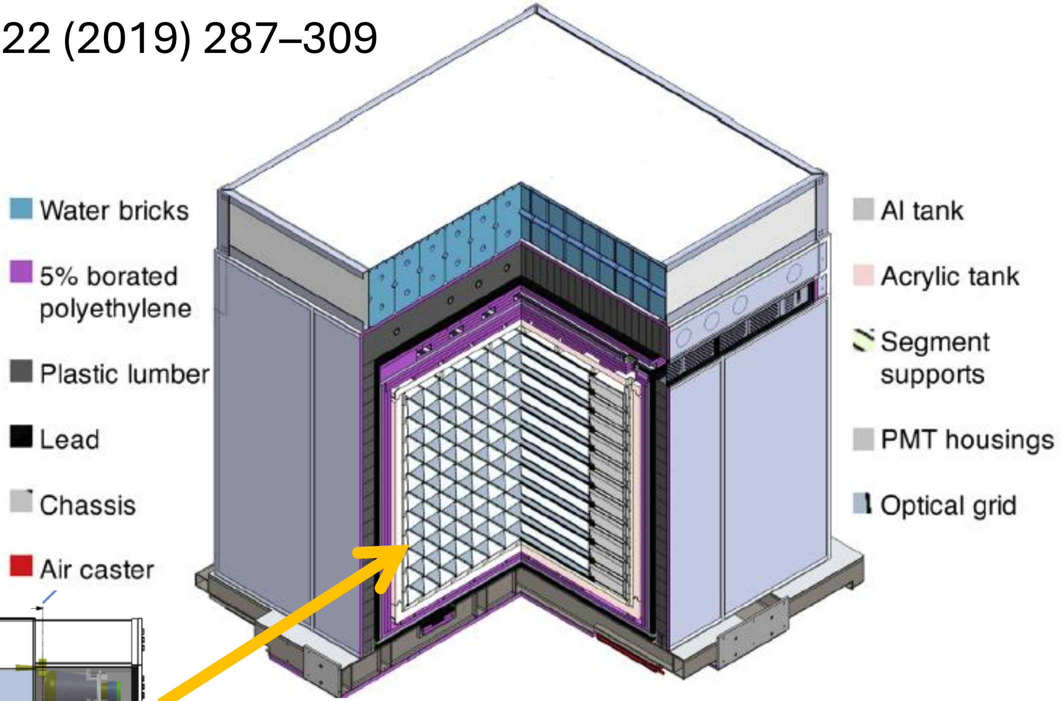
Nature **613**, 257–261 (2023)

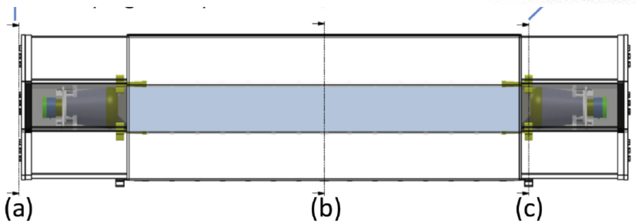
PROSPECT

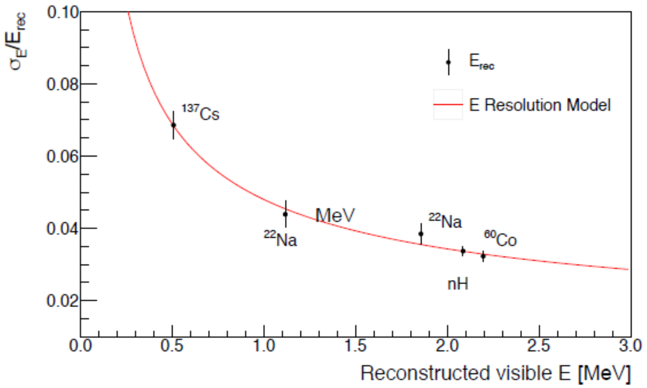
J. Ashenfelter et al., NIM A 922 (2019) 287–309

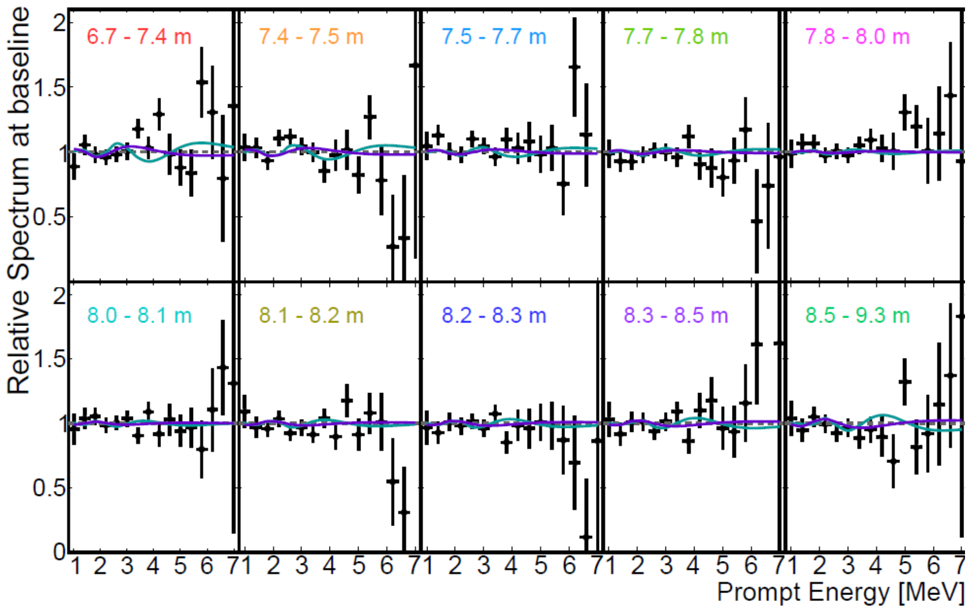
- Installed in 2016 at Oak ridge HFIR reactor:
  - Enriched fuel (93% ^{235}U)
  - Compact core: 43cm diam.
  - Moderate power: 85 MW
- Detector:
  - 11x14 array of ^{6}Li doped liquid scintillator cel
  - Cell size: 1.17m x 14.5 cm x 14.5cm
  - Moveable detector covering c-c baselines: 6.7 – 9.2m
  - Excellent Energy resolution: 4.5% at 1 MeV
  - IBD efficiency: ~42%, S/N= 2/1
  - 529 ν's per day, during 82 days



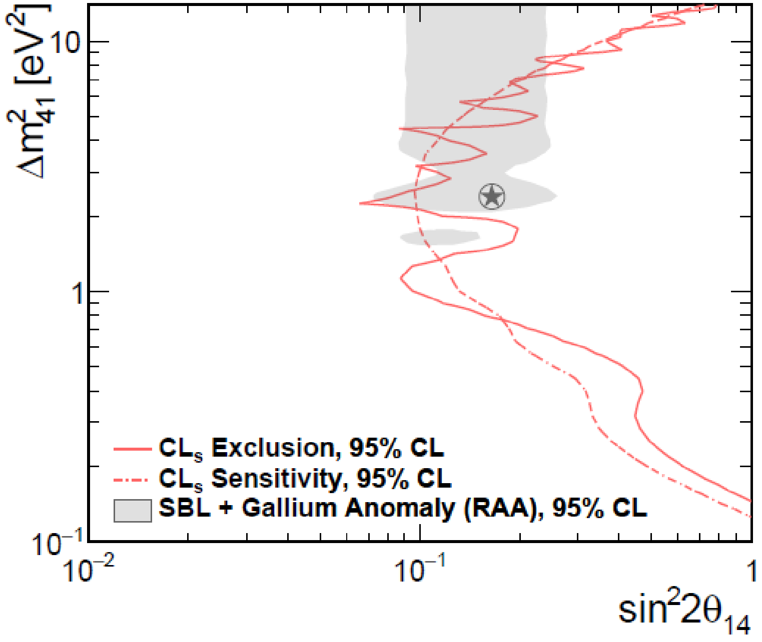








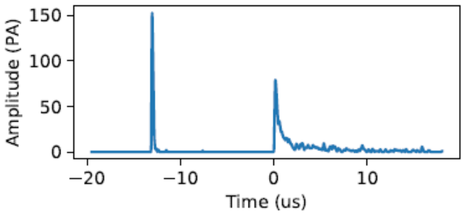
PhysRevD 103 (2021) 032001

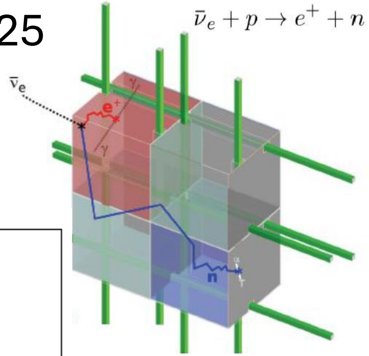


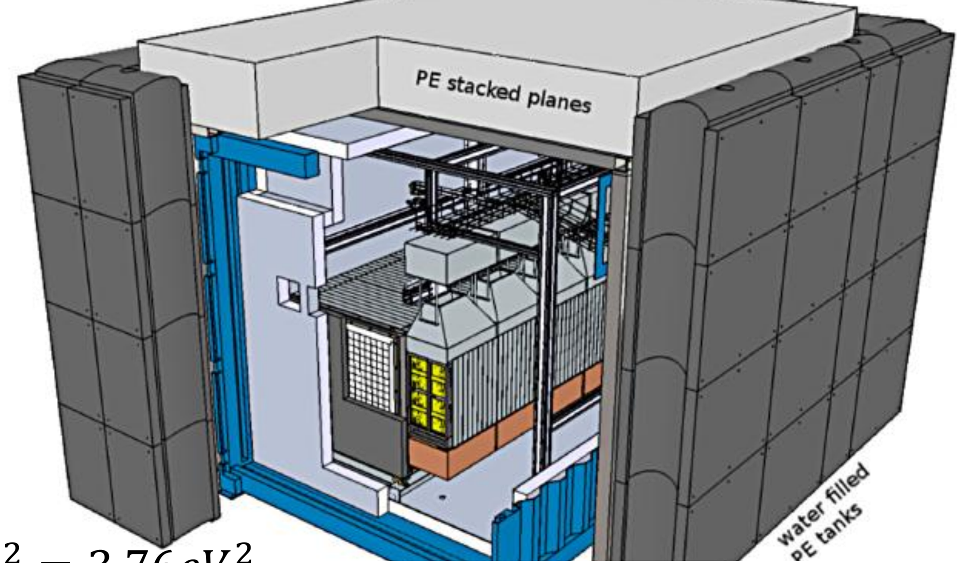
SoLi∂

Y. Abreu *et al* 2021 *JINST* **16** P02025

- Installed in 2017 at Belgian BR2:
  - Enriched fuel (93% ^{235}U)
  - Compact core: 50cm diam.
  - Moderate power: <55 MW>



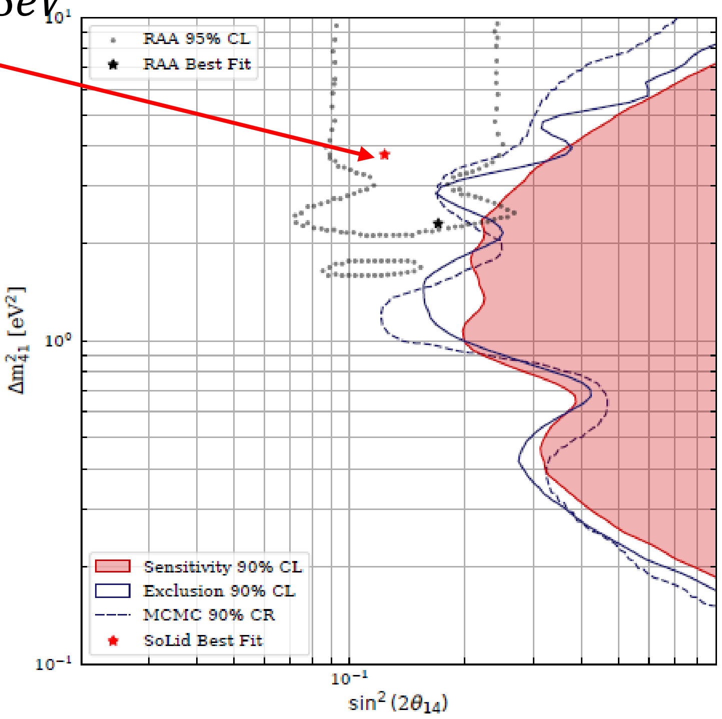


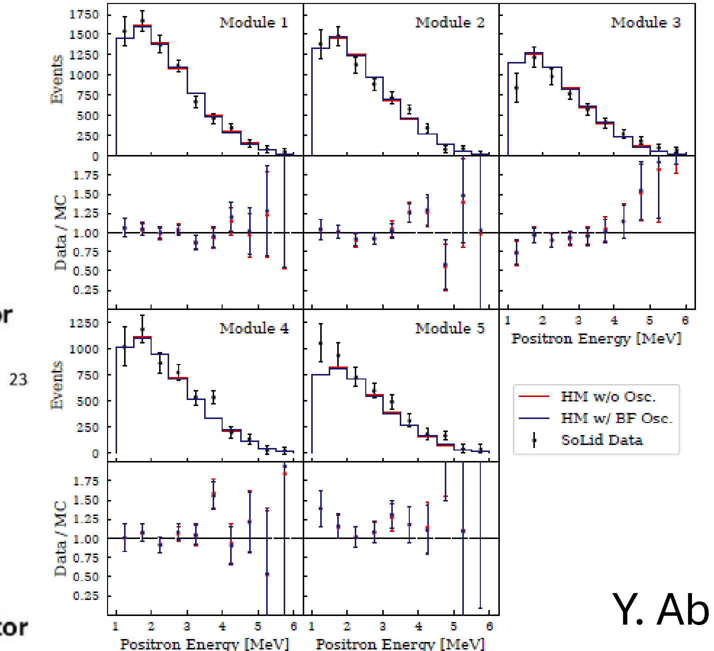


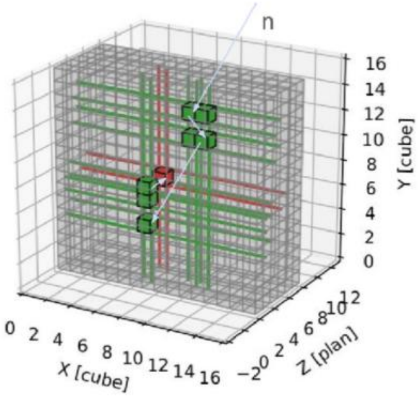
- Detector:
  - 50 planes of 16x16 plastic scintillator cubes with $^6LiF{:}ZnS(Ag)$ neutron detection scintillating sheets : 3D segmentation with 12.800 voxels!
  - Cell size: 5cm x 5cm x 5cm
  - Center of detector at 7.2m from the
  - Moderate/Poor Energy resolution: 16% at 1 MeV and no Pulse shape discrimination n/γ
  - IBD efficiency: ~40%, S/N= 0.27
  - 105 ν's per day, during 280 days

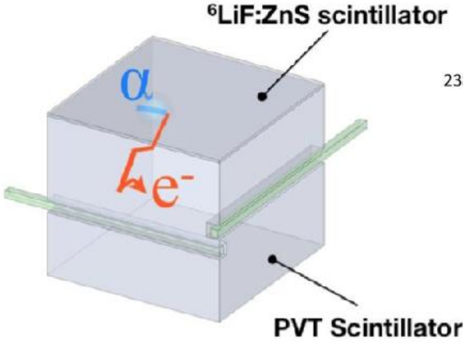
$$n + {}^6Li \to {}^3H + {}^4_2\alpha$$

$sin^2(2\theta) = 0.123$, and $\Delta m^2 = 3.76eV^2$



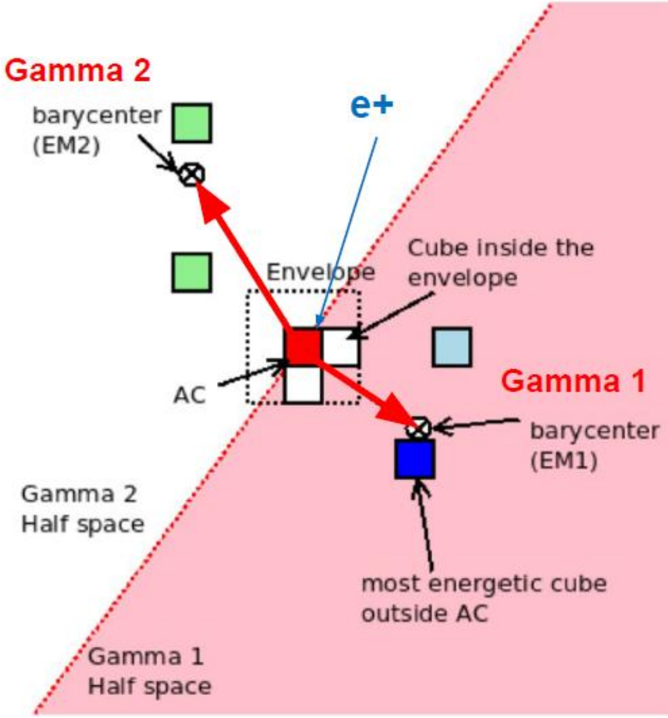


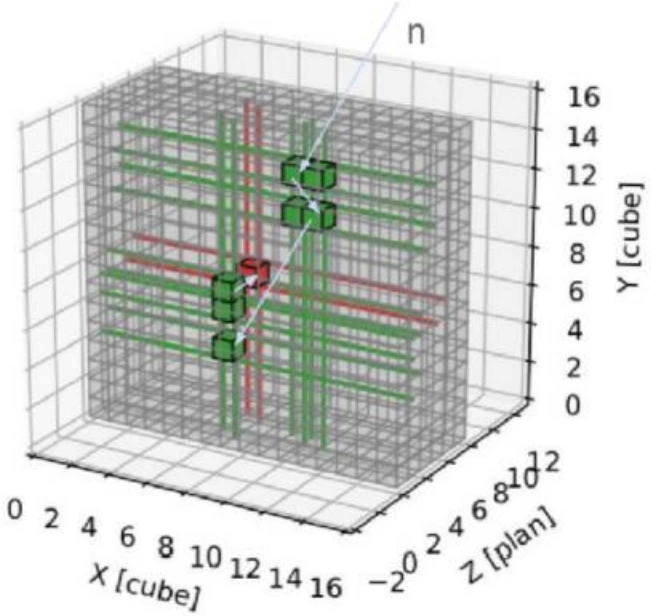


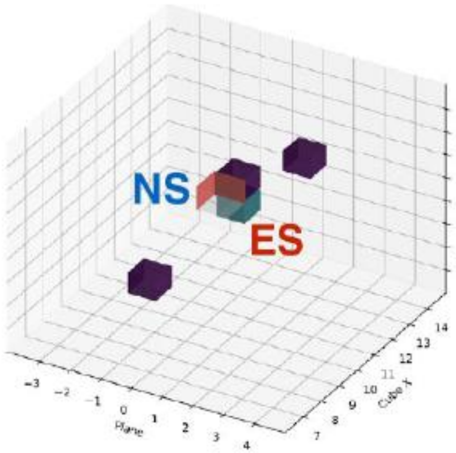


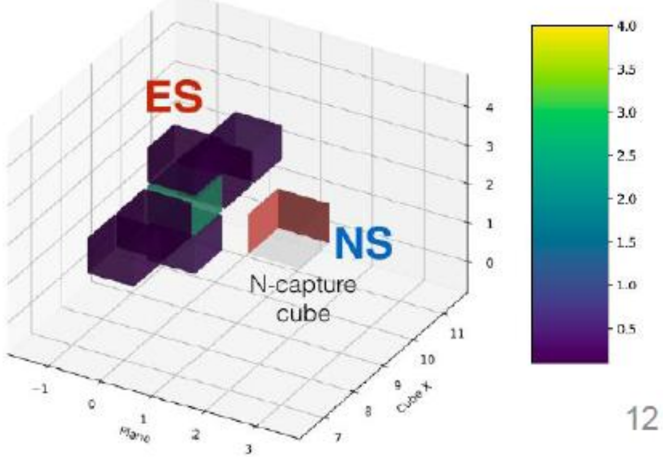
Y. Abreu et al., Phys. Rev. D **111**, 072005 (2**025)**

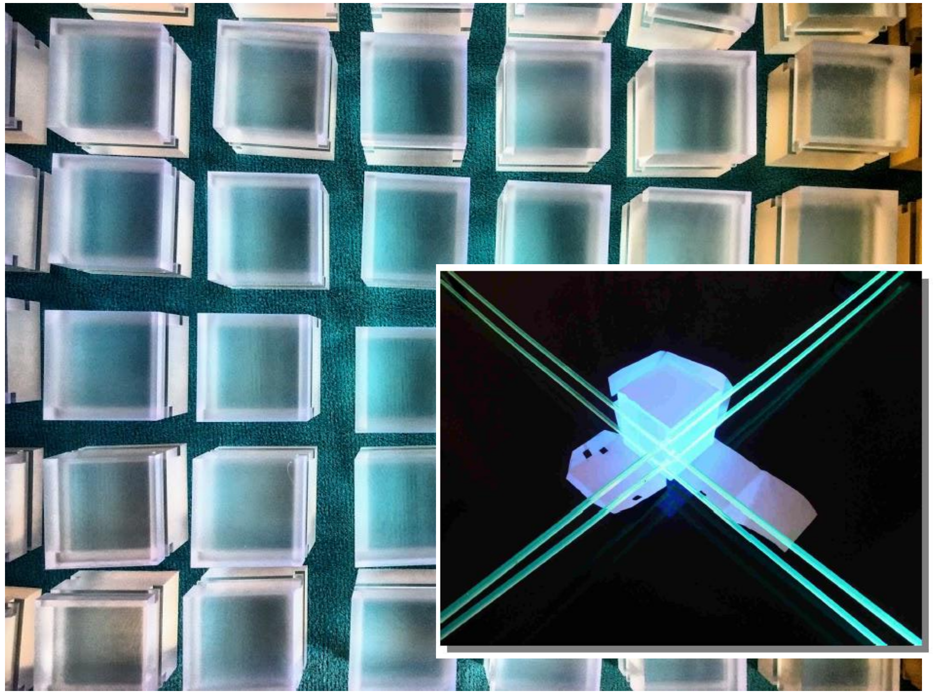
SoLi∂


Gamma 2
barycenter
(EM2)
e+
Envelope
Cube inside the
envelope
AC
Gamma 1
barycenter
(EM1)
Gamma 2
Half space
most energetic cube
outside AC
Gamma 1
Half space


n
X [cube]
Y [cube]
Z [plan]


NS
ES


ES
NS
N-capture
cube

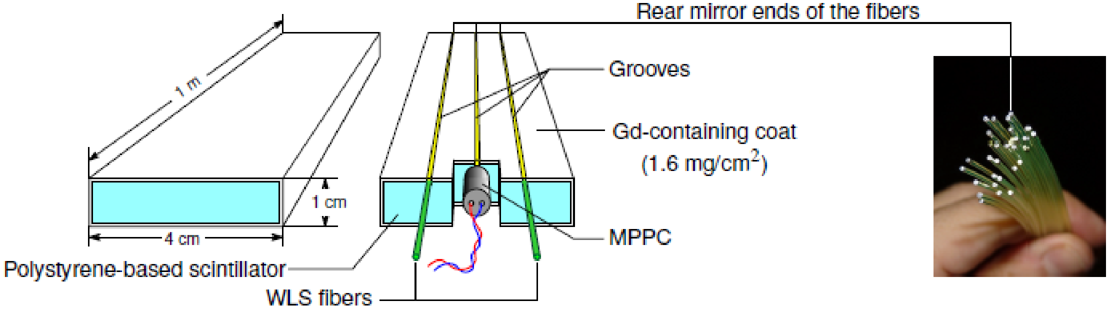


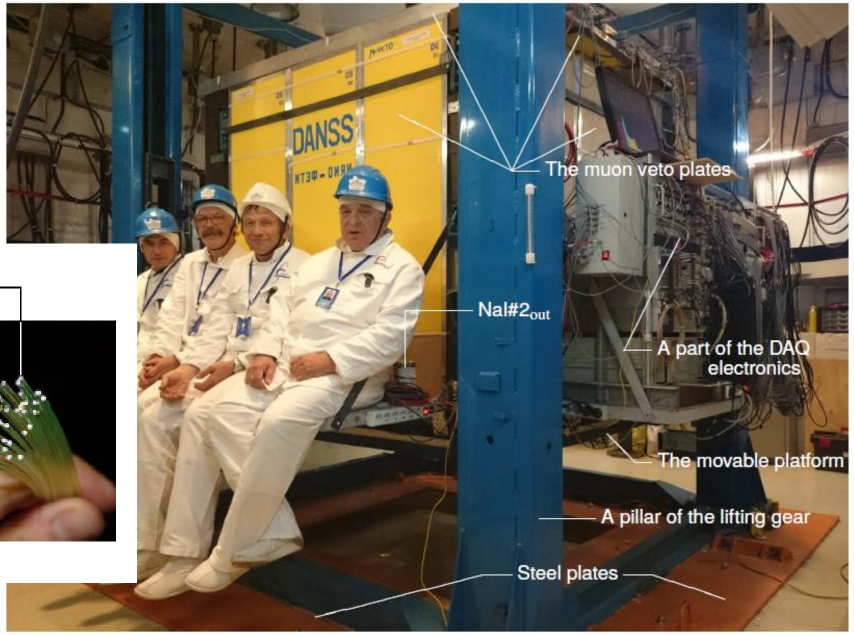

SoLi∂

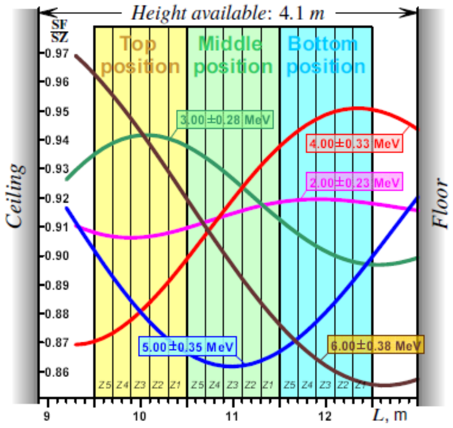
I. Alekseev *et al* 2016 *JINST* **11** P11011

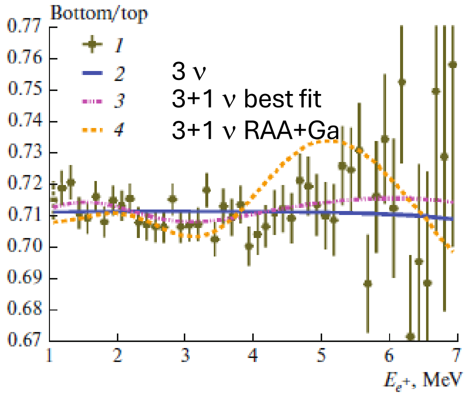
DANSS

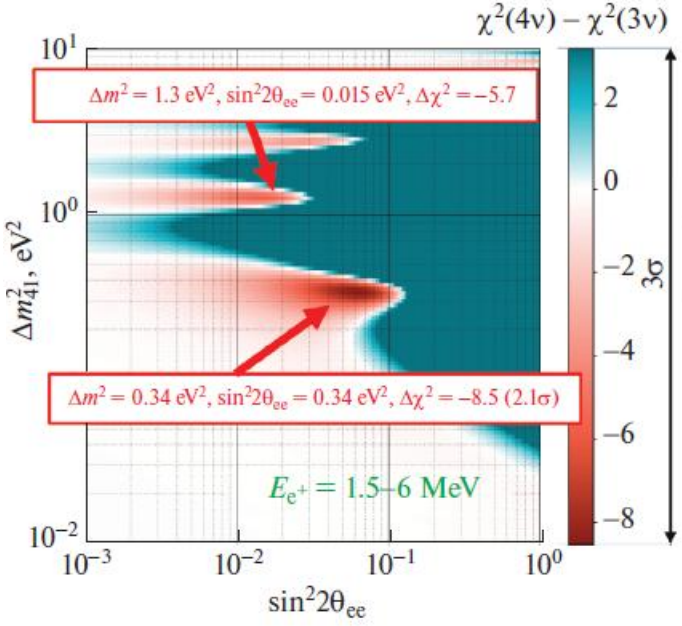
- Installed in 2016 at Kalinin Nuclear Power Plant (Moscow):
  - Low Enriched fuel (LEU)
  - Extended core: 3mx3m
  - High power: 3100 MW
- Detector:
  - 2500 Gd-doped polystyrene-based scintillator strips of 1mx1cmx4cm
  - Active and passive shielding/vetos
  - Moveable lift under core: 10.9 to 12.9 m
  - Poor Energy resolution: 32% at 1 MeV
  - IBD efficiency: ~65%, S/N= 50/1
  - 5.000 ν's per day, during 6.5 yr: 7.7 M events!

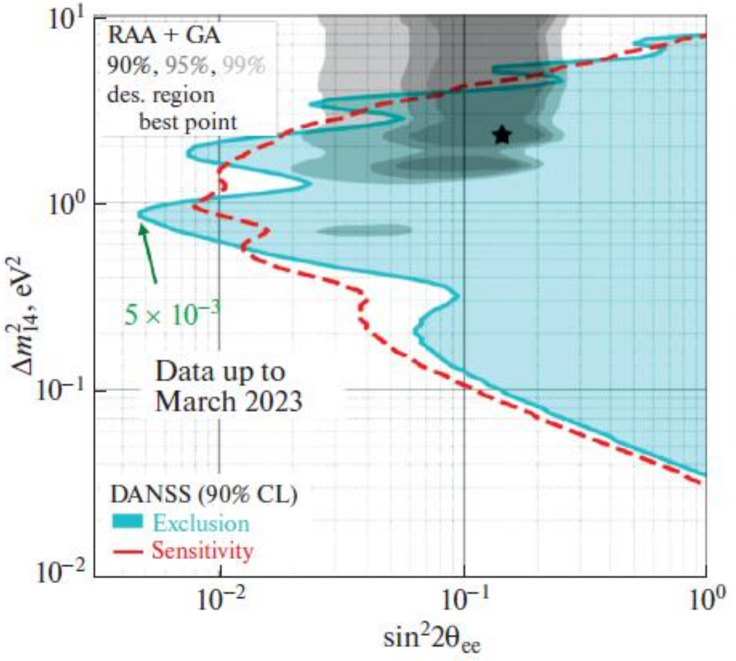












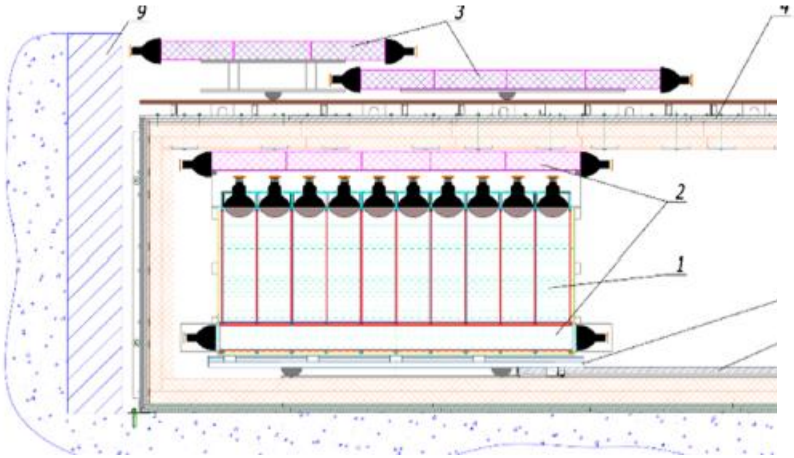
Alekseev, I.G, *Bull. Lebedev Phys. Inst.* **51**, 8–15 (2024).

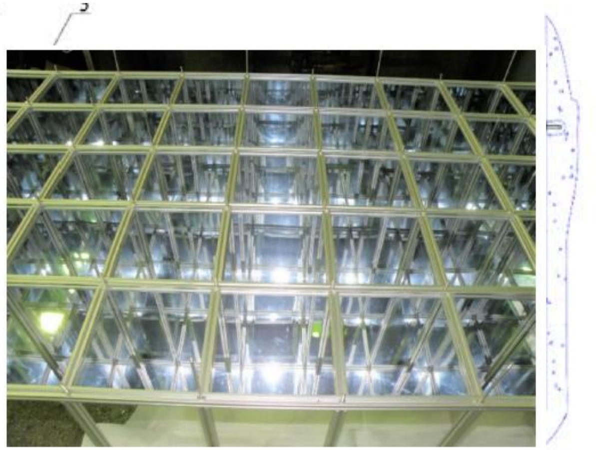
Neutrino-4

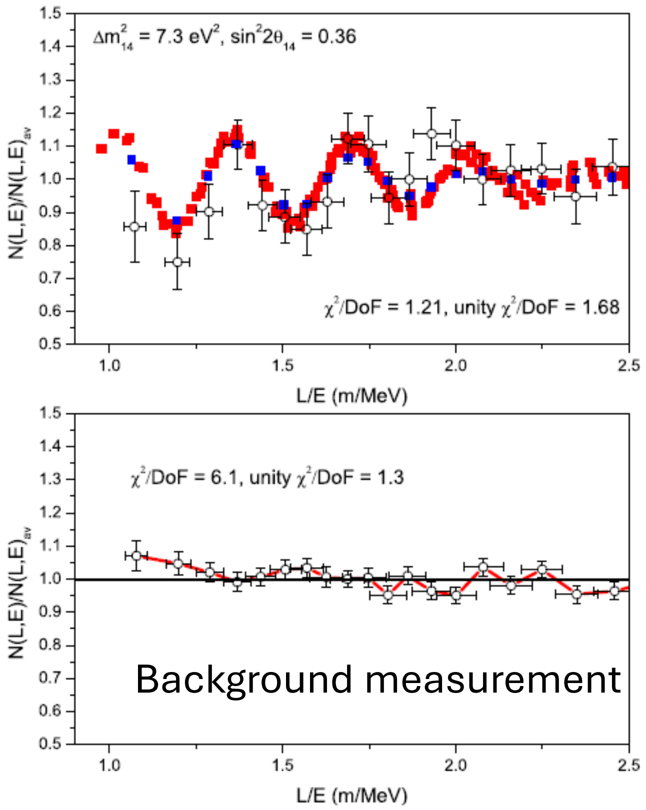
- Installed in 2016 at SM-3 reactor (Dimitrovgrad, Russia):
  - Higly Enriched fuel (93% ^{235}U)
  - small core: d=30cm
  - Moderate power: 90MW
- Detector:
  - 5x10 cells of Gd-loaded liquid scintillator
  - Active and passive shielding/vetos
  - Moveable on rail: Distance to core: 6 to 12 m
  - Moderate/Poor Energy resolution: 16% at 1 MeV
  - IBD efficiency: ~30%, S/N= 1/1
  - 300 ν's per day, 1.4 M events

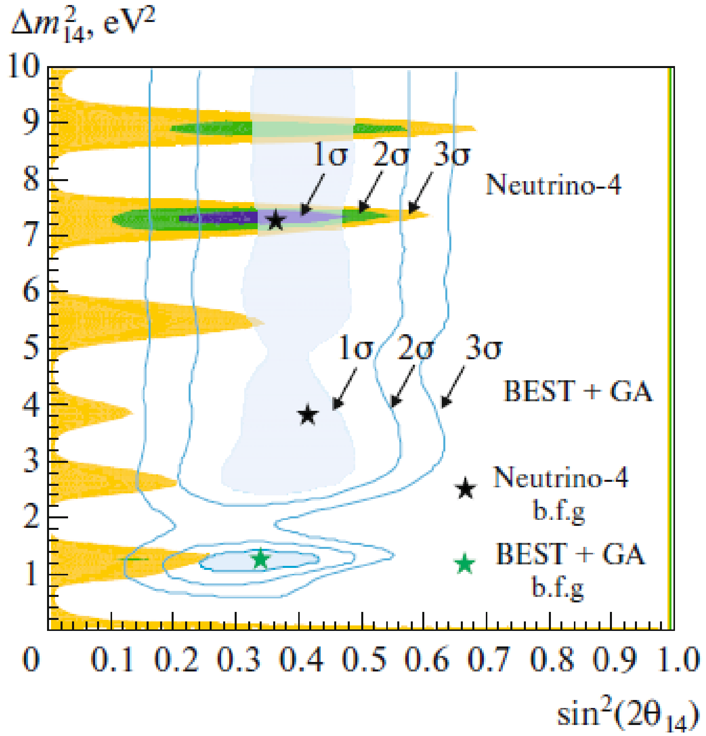
2.7 σ effect measured, corresponding to

$$\Delta m^2_{14} = 7.30 \pm 0.13_{st} \pm 1.16_{syst} = 7.30 \pm 1.17.$$
$$\sin^2 2\theta = 0.36 \pm 0.12_{stat}.$$







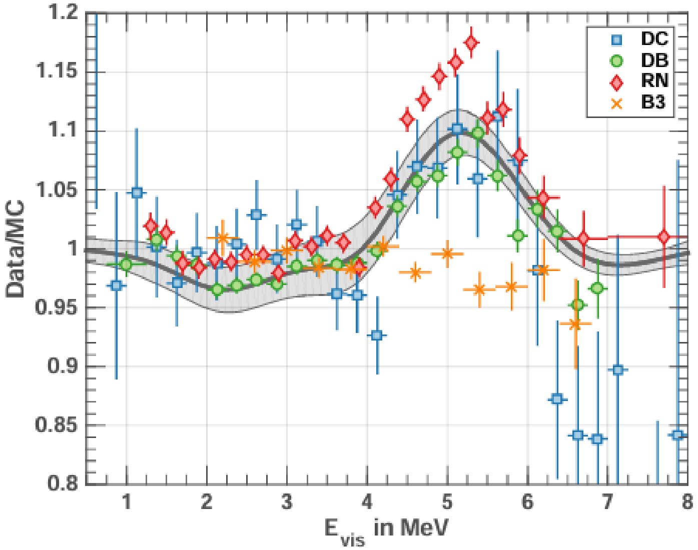


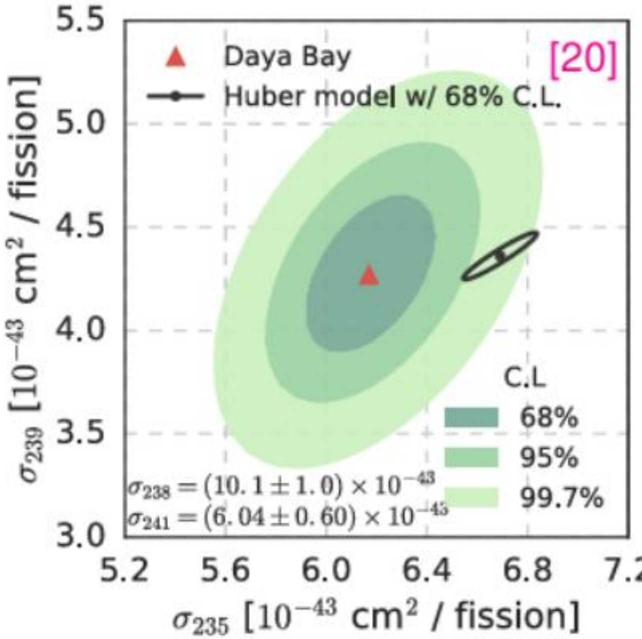
A.P. Serebrov, PHYSICAL REVIEW D 104, 032003 (2021)

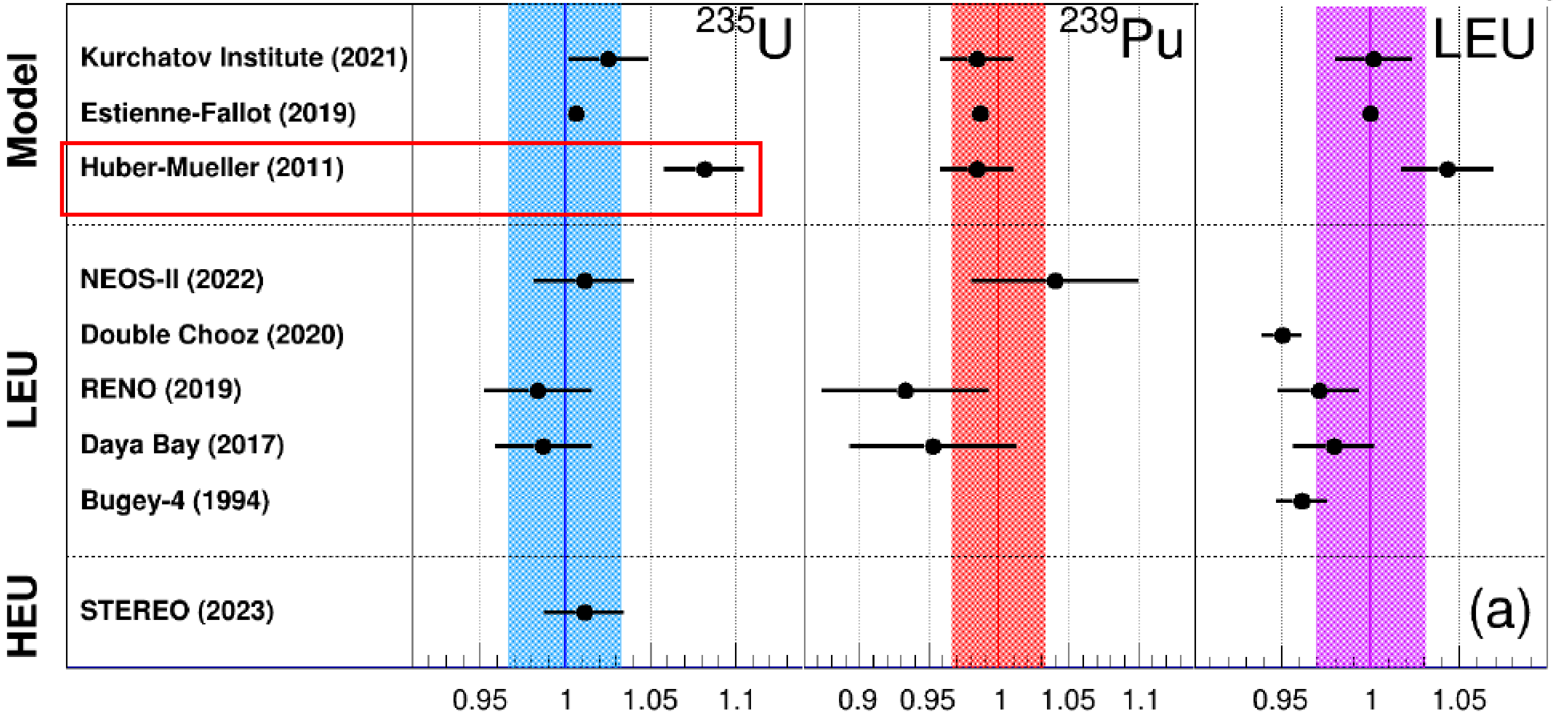
G. Mention, et al.Physics Letters B773, (2017), pp.307-312

Reactor anomaly: Bad spectrum predictions, or sterile nu's?

- θ_{13} experiments: Double Chooz, RENO & Daya Bay measured an excess in their energy spectra wrt Conversion method spectrum predictions
- Due to control of fuel burnup, the problem was traced to originate (mostly) from ^{234}U predictions
- 2 improved summation models and 1 improved conversion model agree with modern reactor data both for Highly Enriched U reactors (HEU) and Low Enriched Uranium fuels (LEU)
- One new conversion model agrees with the old HM model, fixes the 5

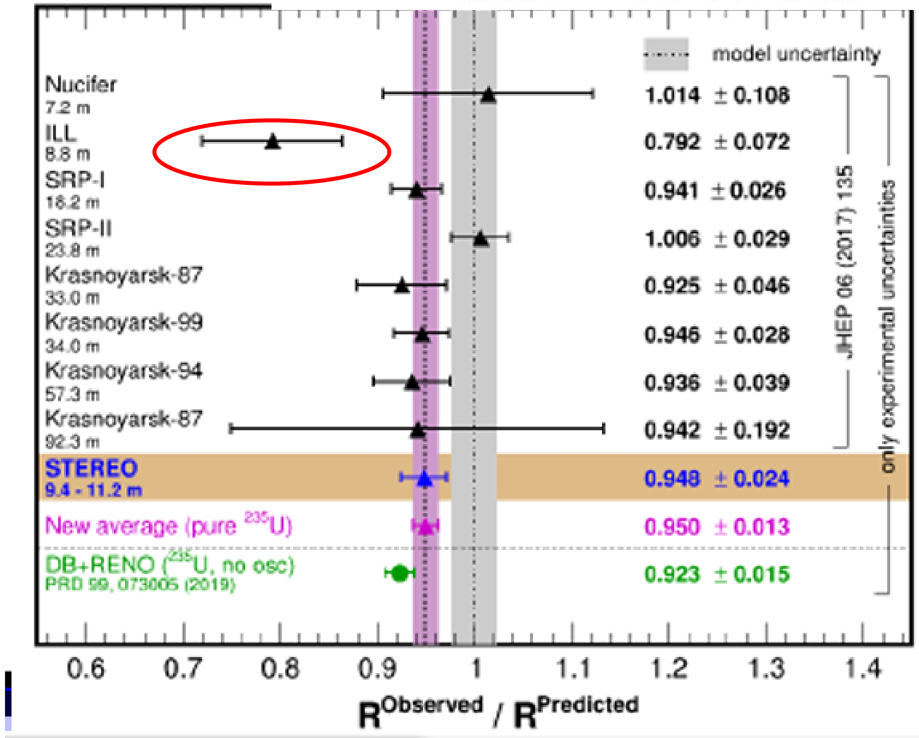






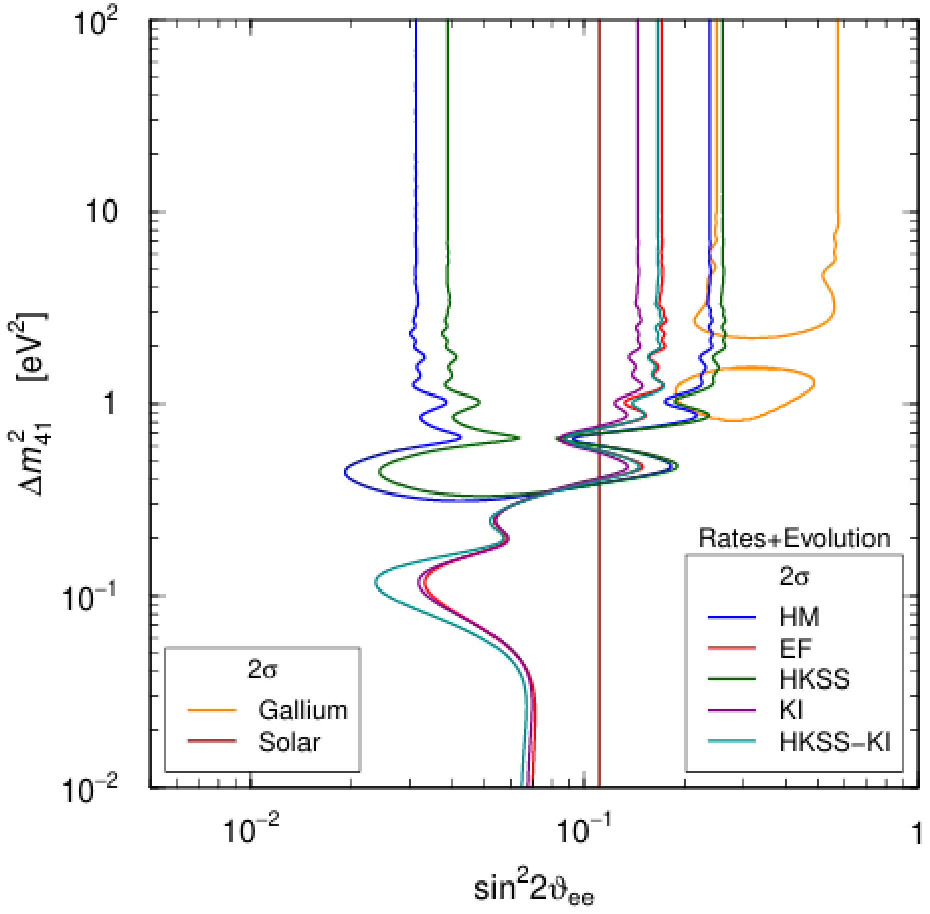
L. Périssé.et al., Phys. Rev. C **108**, 055501 (**2023**)

IBD yield ratio to BESTIOLE

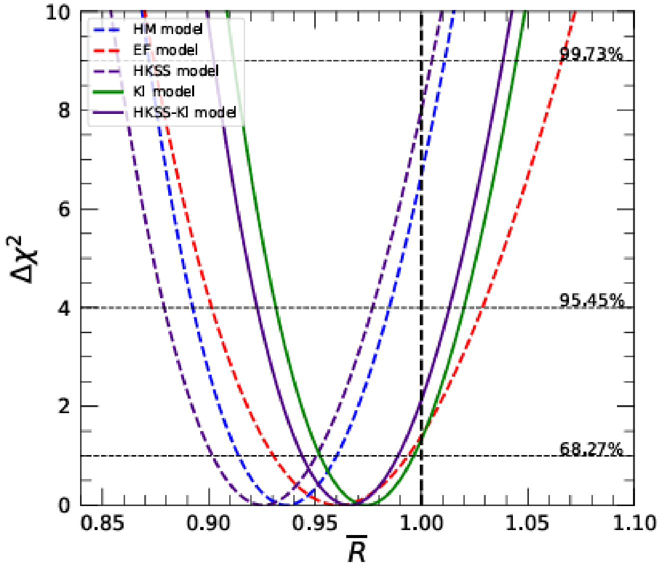


Global fits

C. Giunti *et al.*, Phys. Lett. B **829** (2022) 137054



- Current best fit or excluded parameter regions for
  - Estienne-Fallot (summation), Kopeikin (conversion) and Huber-Muller with improved ^{235}U spectra from Kopeikin They reduce the Reactor Antineutrino Anomaly (RAA) to 0.8 σ and 1.4 σ
  - The Huber-Mueller, and re-evaluated conversion method disagree with old and modern reactor data: HKSS solves part of the spectral distortions seen in the θ_{13}experiments, but increases the predicted flux further. The RAA is hereby increased to 3σ
  - The Gallium anomaly is not solved, and has even increased to a total significance of 6σ
  - The preferred fit in terms of one extra sterile neutrino using only the Gallium anomaly has moved to a higher



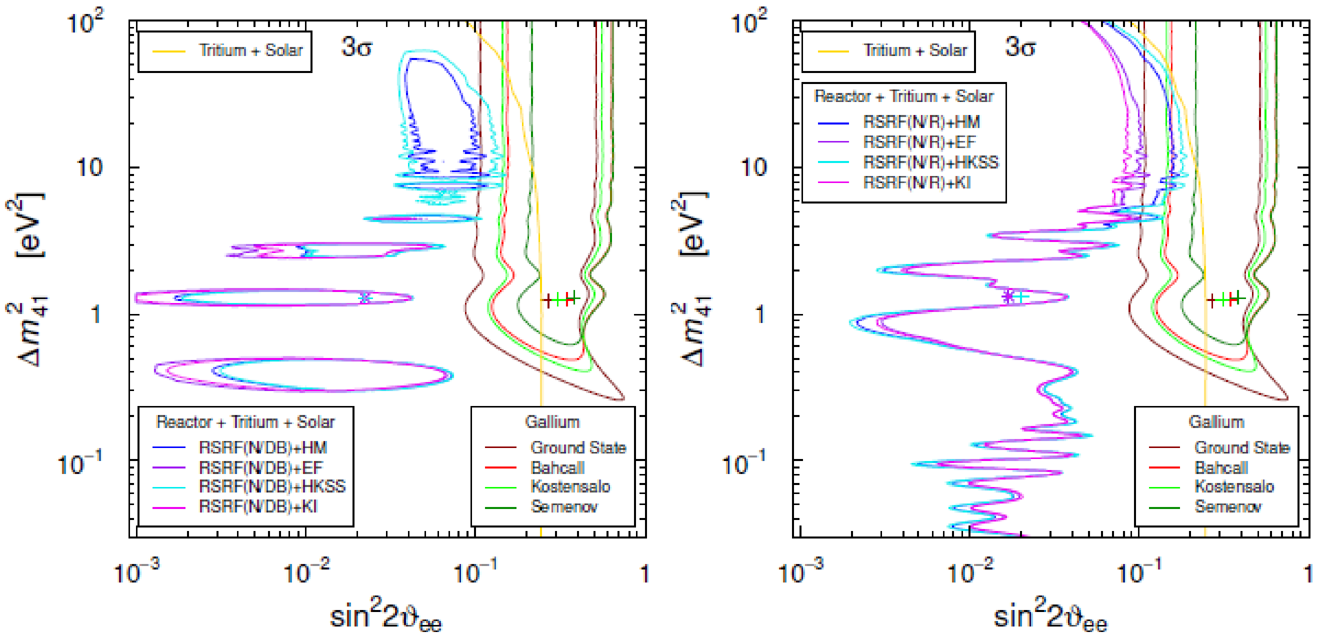
$\Delta m^2 = 3.3^{+\infty}_{-2.3}\ \mathrm{eV}^2$ and $\sin^2 2\theta = 0.42^{+0.15}_{-0.17}$,

Compared to the old gallium data

$\Delta m^2_{\mathrm{bf}} = 2.24\ \mathrm{eV}^2$. $\sin^2 2\vartheta_{\mathrm{bf}} = 0.50$,

More Global fits

- 2 types of Global fits to the Reactor short baseline, long baseline spectra, and Gallium data:
  - C. Giunti *et al.*, JHEP **10** (2022): Do **not** include Neutrino-4 data



	Global RSRF(N/DB) Fit			
	HM	HKSS	EF	KI
$\chi^2_{\min}$	393.5	395.2	391.2	391.4
GoF	43%	40%	46%	46%
$(\sin^2 2\vartheta_{ee})_{\text{b.f.}}$	0.022	0.022	0.022	0.022
$(\Delta m^2_{41})_{\text{b.f.}}/\text{eV}^2$	1.29	1.29	1.29	1.29
$\Delta\chi^2_{4\nu-3\nu}$	13.8	14.1	12.6	12.9
$n\sigma_{4\nu-3\nu}$	3.3	3.3	3.1	3.2

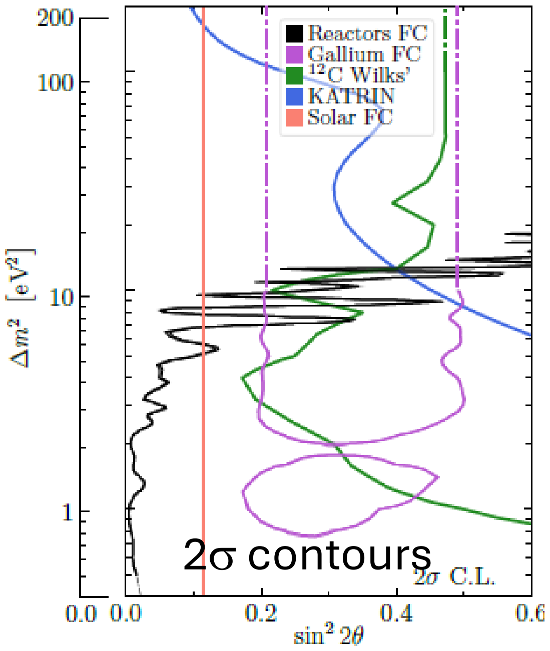
	Global RSRF(N/R) Fit			
	HM	HKSS	EF	KI
$\chi^2_{\min}$	386.5	388.3	384.0	384.2
GoF	53%	50%	56%	56%
$(\sin^2 2\vartheta_{ee})_{\text{b.f.}}$	0.017	0.019	0.017	0.017
$(\Delta m^2_{41})_{\text{b.f.}}/\text{eV}^2$	1.32	1.32	1.32	1.32
$\Delta\chi^2_{4\nu-3\nu}$	10.1	10.3	9.1	9.3
$n\sigma_{4\nu-3\nu}$	2.7	2.8	2.6	2.6

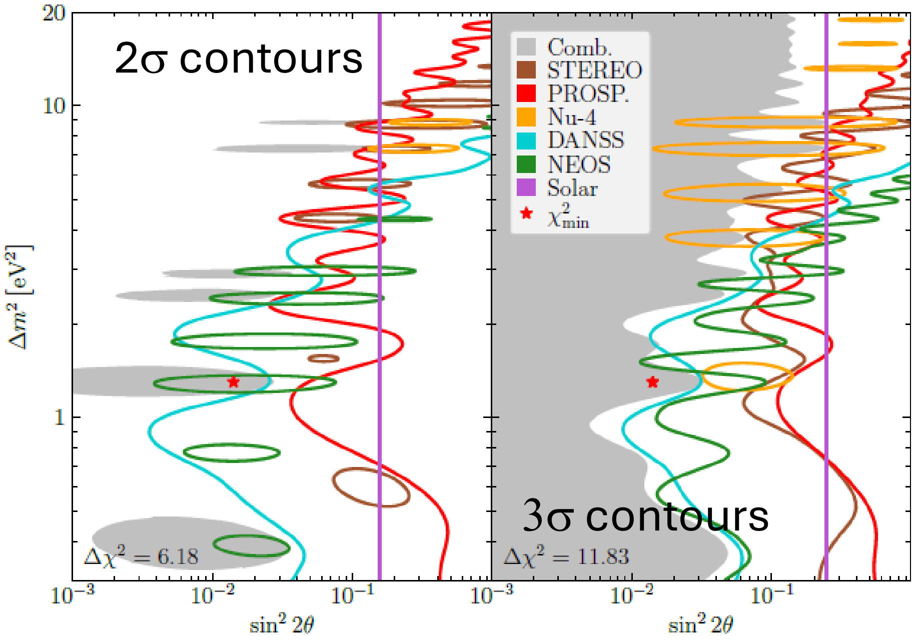
  - The Reactor data, excluding Neutrino-4, are in strong disagreement with the Ga-anomaly data (dominated by the latest BEST result), at level of 4-5σ
  - The Reactor data themselves, excluding Neutrino-4, are in quite good agreement, with each other and are now nearly independent of the flux prediction models
  - By themselves, the reactor data, even excluding Neutrino-4, favor a 4th sterile neutrino state at the level of 2.6-3.2 σ, with $sin^2(2\theta) \approx 0.02$, and $\Delta m^2 \approx 1.3eV^2$

More Global fits

- 2 types of Global fits to the Reactor short baseline, long baseline spectra, and Gallium data:
  - J.M. Berryman *et al.*, JHEP **02** (2022) 055: **<u>Do include</u>** Neutrino-4 data

	χ^2_{min}/dof	Δm^2_{min}	$\sin^2 2\theta_{min}$	$\Delta\chi^2_{3\nu}$	p_0	$\#\sigma$	$\#\sigma^{(W)}$
DANSS		1.3 eV^2	0.014	3.2			1.3
Our Fit	77.6/70	1.32 eV^2	0.011	3.6	43.8%	0.8	1.4
NEOS	57.5/59	1.73 eV^2	0.05	6.5	22%	1.2	2.1
Our Fit	59/58	2.95 eV^2	0.16	7.4	19.4%	1.3	2.2
PROSPECT	119.3/142	1.78 eV^2	0.11	4.0	57%	0.6	1.5
Our Fit	118.1/158	1.75 eV^2	0.11	4.3	63.3%	0.5	1.6
STEREO	128.4/112	8.95 eV^2	0.63	9.0	9%	1.7	2.5
Our Fit	128.6/112	8.72 eV^2	0.59	7.8	15.8%	1.4	2.3
Nu-4	14.7/17	7.26 eV^2	0.38	15.3			3.5
Our Fit	16.1/17	7.31 eV^2	0.38	12.6	1.5%	2.4	3.1
REACTORS	428/421	8.86 eV^2	0.26	7.3	27.4%	1.1	2.2
W/ Solar	432/425	1.30 eV^2	0.014	6.6	17.8%	1.3	2.1
W/ Gallium[2]	433/427	8.86 eV^2	0.32	38.8	$(0.14 \to 1.4)\times 10^{-7}$	$5.7 \to 5.3$	5.9

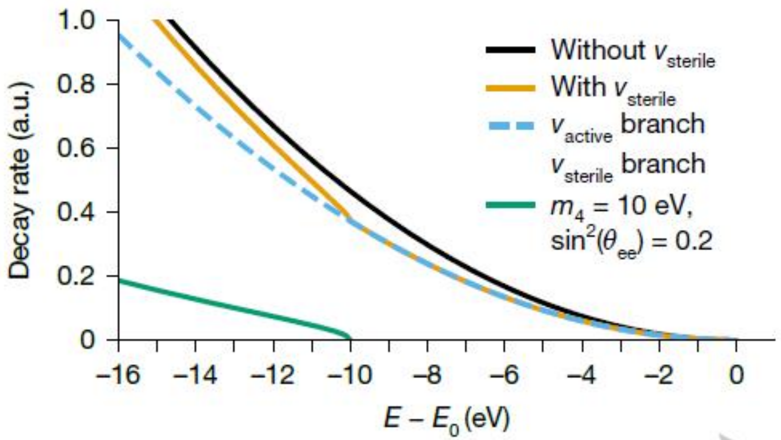


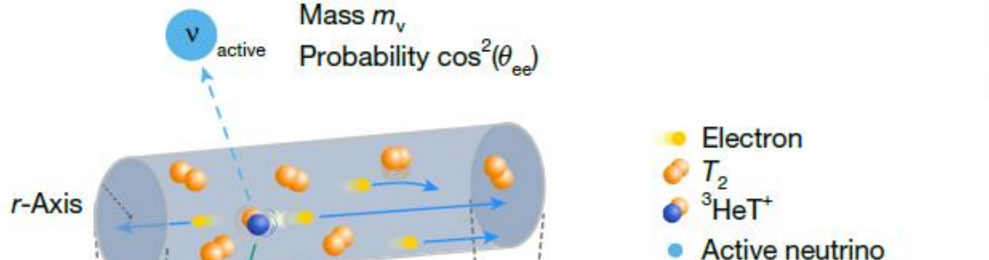
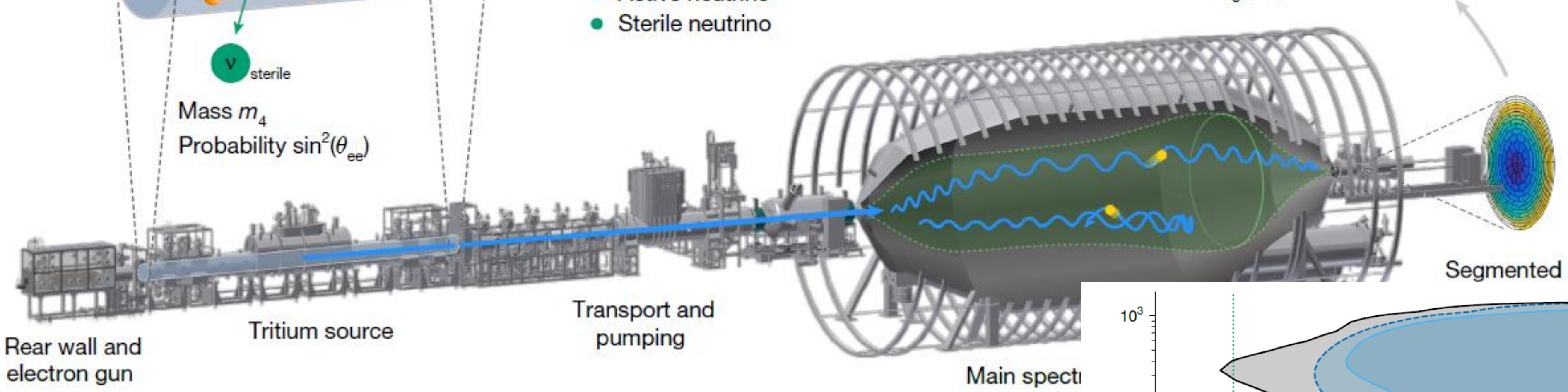


Data set	χ^2_{PG}/dof	$p^{(W)}$	$\#\sigma^{(W)}$	$p_{b.f.}$	$\#\sigma_{b.f.}$
Reactor vs Solar	0.65/1	0.42	0.8	0.39	0.9
Reactor vs Gallium	1.4/2	0.50	0.67	0.62	0.5
Solar vs Gallium	13.0/1	3.1×10^{-4}	3.6	1.6×10^{-3}	3.2
Reactor vs Solar vs Gallium	15.6/3	1.4×10^{-3}	3.2	5.1×10^{-3}	2.8

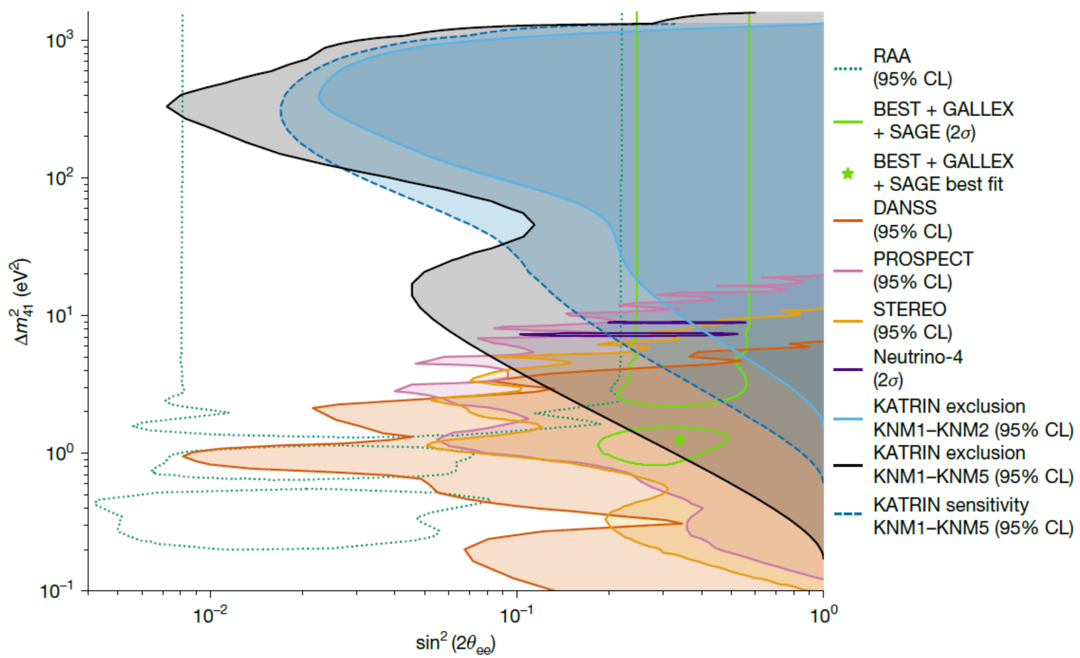
- The Reactor data, including Neutrino-4, disfavor the 3 neutrino hypothesis at the level of 1.1 σ, and have as best mixing parameters in the sterile hypothesis $sin^2(2\theta) \approx 0.26$, and $\Delta m^2 \approx 8.86\ eV^2$
- By including the Gallium data (dominated by the BEST result) the rejection of the 3 neutrino hypothesis is at the level of >5σ, with $sin^2(2\theta) \approx 0.32$, and $\Delta m^2 \approx 8.86 eV^2$
- The Gallium and reactor data are not in tension with each other, but the Solar (unitarity of solar mixing params) bound and Gallium anomaly are in severe tension

Steriles with KATRIN



- Sterile neutrino would induce a kink in the β-endpoint spectrum of Tritium decay
- This shape is independent of absolute flux/normalization
- Analysis using *36* million, endpoint β-electrons
- Results: The Neutrino-4 result is completely ruled out,
  The Gallium anomaly, is quasi completely ruled out,
  and very complementary limits at higher $\Delta m^2, up\ to\ 1000\ eV^2$



KATRIN Coll., Nature **volume 648**, pages70–75 (2025)

Meanwhile at accelerators

- Accelerators dump protons on a target (Be or Graphite)
- Protons produce chared pions and Kaons that decay into neutrinos
  - $\pi^+ \to \mu^+ + \nu_\mu$
  - $K^+ \to \mu^+ + \nu_\mu$ (and sometimes ν_e from secondary decays)
  - $\pi^- \to \mu^- + \bar{\nu}_\mu$
  - $K^- \to \mu^- + \bar{\nu}_\mu$ (and sometimes $\bar{\nu}_e$ from secondary decays)
- Charged pions and Kaons can be focused with a magnetic horn: Originally designed by S. Van der Meer for particle (antiproton) focusing

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/EF/BEAM 81-5
25 September 1981

MAGNETIC HORN FOCUSING FOR A LOW-ENERGY NEUTRINO BEAM

J.M. Flynn(*)

Trinity College, Cambridge

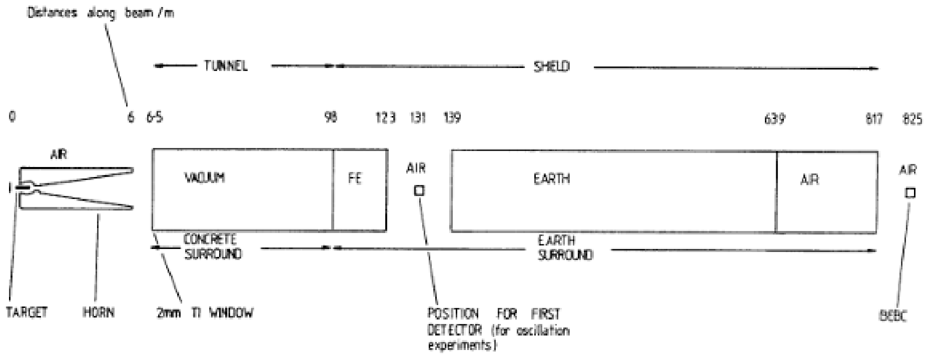


FIGURE 2: BEAMLINE LAYOUT USED FOR HORN COMPARISONS

Tunnel radius 1.75m
The designations "tunnel" and "shield" are used by the program NUBEAM

- Kaons and pions are left to decay in a vacuum decay tunnel. The muons and other chaged decay products are blocked by a wall

Meanwhile at accelerators

- Exercise: How long does the decay tunnel need to be?
- Decay length: $L = \gamma\beta c\tau$ $\qquad \gamma_{\pi,K} = \dfrac{E_{\pi,K}}{m_{\pi,K}}$

  - Charged pion ($\pi^\pm$):
    $\tau_\pi \approx 2.6 \times 10^{-8}\,\mathrm{s}$, $m_\pi \approx 140\,\mathrm{MeV}$
  - Charged kaon ($K^\pm$):
    $\tau_K \approx 1.24 \times 10^{-8}\,\mathrm{s}$, $m_K \approx 494\,\mathrm{MeV}$

  for $E_{\pi,K} = 10GeV$

  $$\gamma_\pi = \frac{E}{m} \approx \frac{10\,\mathrm{GeV}}{0.14\,\mathrm{GeV}} \approx 71$$

  $$\gamma_K \approx \frac{10}{0.494} \approx 20$$

  $$L_\pi \approx \gamma c\tau \approx 71 \times (3 \times 10^8\,\mathrm{m/s}) \times (2.6 \times 10^{-8}\,\mathrm{s}) \approx 55\,\mathrm{m}$$

  $$L_K \approx 20 \times (3 \times 10^8) \times (1.24 \times 10^{-8}) \approx 74\,\mathrm{m}$$

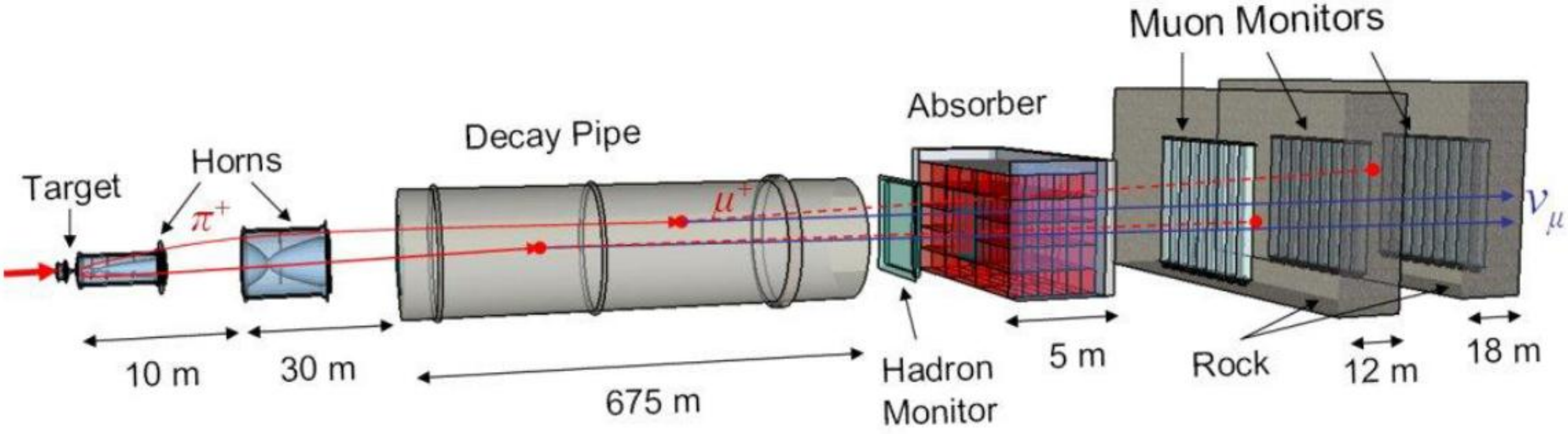
- Background of ν_e and $\bar{\nu}_e$ from muon decay and Kaon decays

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \qquad K^+ \to \pi^0 + e^+ + \nu_e$$

Yields typical contamination of order few %, and up to 5% for high energy neutrino beams. This needs to be properly modeled, because background for ν_e and $\bar{\nu}_e$ appearance experiments

Accelerator experiments
NuMI beamline (FNAL)

Similar for JPARK (Japan), CNGS (CERN)



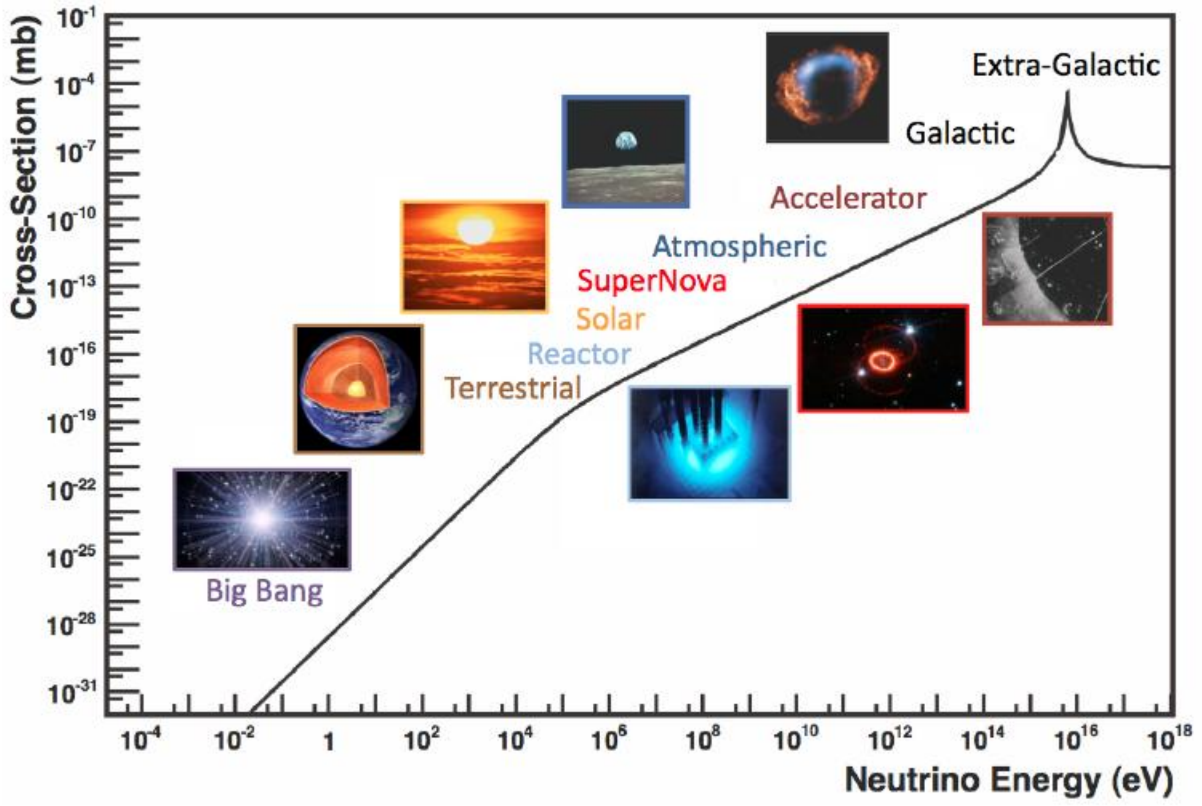
Meanwhile at accelerators

- Typical fluxes:
  - Depends strongly on the proton beam intensity: expressed in Protons-on-Target (PoT): $\Phi_\nu \propto \mathrm{POT}$
  - BUT: Higher beam energy produces more mesons, target material affects meson production, magnetic horn focusing affects flux and decay pipe length as well, ...
  - Fluxes at modern accelerator experiments: depending on the beam power

Experiment	T2K	NOvA	DUNE (future)
Beam Power	~750 kW	~700 kW	1.2 MW (up to 2.4 MW)
POT per Year	~1e21	~1e21	~1e21
Near Detector Distance	280 m	1 km	574 m
Far Detector Distance	295 km	810 km	1300 km
Flux (Near)	~1e6–1e7 /cm²/s	few × 1e6 /cm²/s	~1e7–1e8 /cm²/s
Flux (Far)	~1–10 /cm²/s	~1–5 /cm²/s	~10–100 /cm²/s
Peak Energy	~0.6 GeV	~2 GeV	~2–3 GeV
Expected Events/year	47,250	7,938	378,000

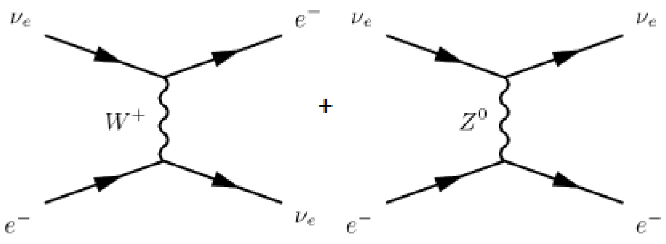
Meanwhile at accelerators

- Cross sections: See e.g. J. Formaggio, Rev. Mod. Phys. **84**, 1307 (2012)
  - Although fluxes are smaller than reactor experiments, the cross sections are bigger due to higher energy



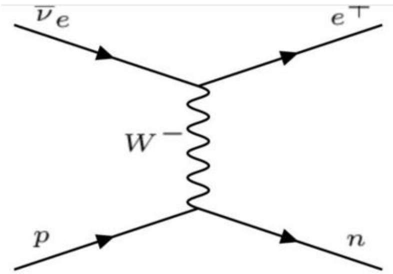
$2 < E_\nu < 10\ MeV$

$$\nu_e + e^- \rightarrow \nu_e + e^-$$



$$\sigma_{\nu e} \approx 9 \times 10^{-45} \times E_\nu(\mathrm{MeV})\ \mathrm{cm}^2$$

Versus IBD

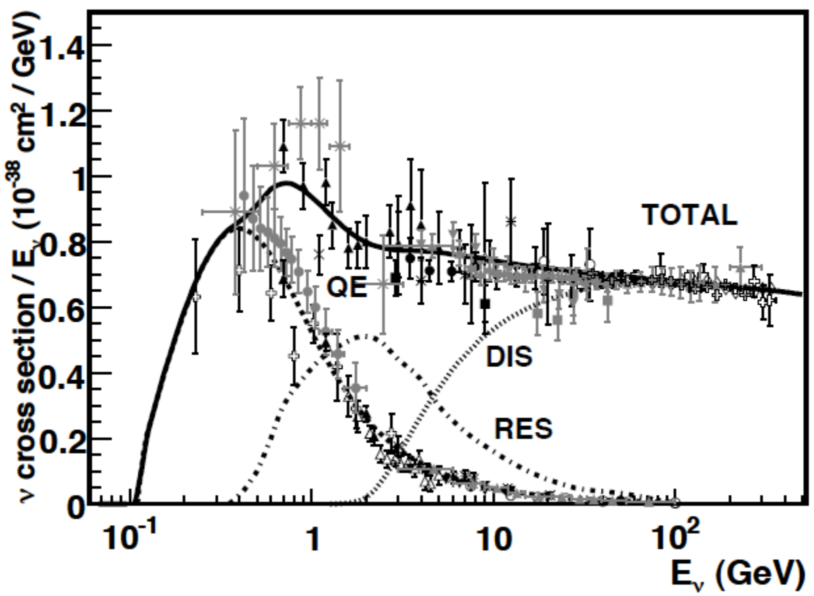


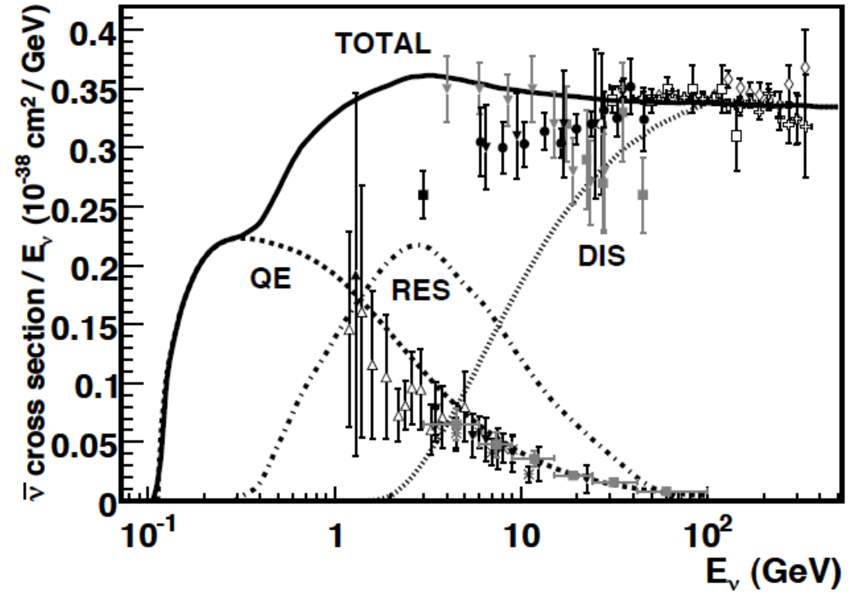
$$\sigma_{\mathrm{IBD}} \approx 9.5 \times 10^{-44} \times (E_e p)\ \mathrm{cm}^2$$

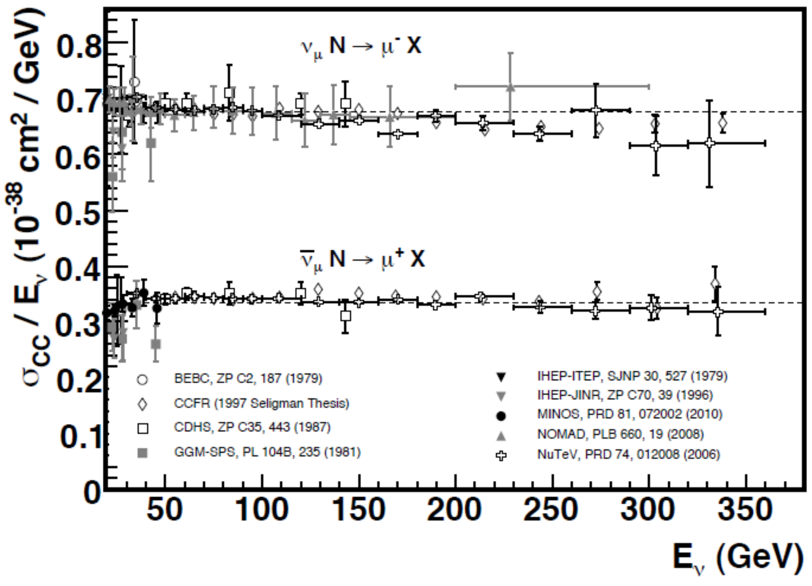
- Proton is heavier
- Electrons can not absorb much energy: limited phase space

Meanwhile at accelerators

- Cross sections: See e.g. J. Formaggio, Rev. Mod. Phys. **84**, 1307 (2012)
  - Intermediate energies: $0.1 < E_\nu < 20\ GeV$







- Remarkable, but trivial consequence of weak interactions: Due to helicity effects: LH neutrinos interact stronger with nuclei than RH antineutrinos

$$\sigma(\nu) \approx 2 \times \sigma(\bar{\nu})$$

Meanwhile at accelerators

- Cross sections: See e.g. J. Formaggio, Rev. Mod. Phys. **84**, 1307 (2012)
  - Intermediate energies: $0.1 < E_\nu < 20\ GeV$
  - Quasi-Elastic neutrino scattering

Charged-current (QECC) process

$$\nu_\ell + n \longrightarrow \ell^- + p$$

$$\bar{\nu}_\ell + p \longrightarrow \ell^+ + n$$

Neutral-current (QENC) process

$$\overset{(-)}{\nu}_l + N \rightarrow \overset{(-)}{\nu}_l + N$$

From EW theory

$$\sigma_{\rm NCQE} \approx (0.3\text{–}0.4) \times \sigma_{\rm CCQE}.$$

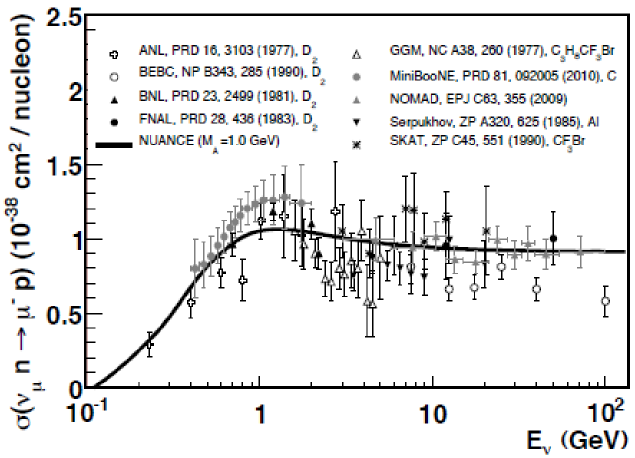


FIG. 11 Existing measurements of the ν_μ quasi-elastic scattering cross section, $\nu_\mu\, n \to \mu^-\, p$, as a function of neutrino energy on a variety of nuclear targets. The free nucleon scattering prediction assuming $M_A = 1.0$ GeV is shown for comparison (Casper, 2002).

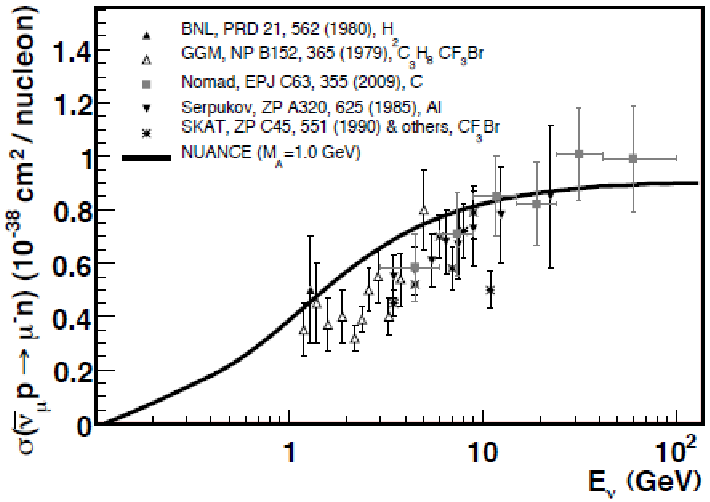


FIG. 12 Same as Figure 11 except for antineutrino QE scattering, $\overline{\nu}_\mu\, p \to \mu^+\, n$.

Cross section scales with nr of target neutrons (or protons for antineutrinos), but when normalized to total nr of nucleons it is fairly independent of the target nucleus size

Meanwhile at accelerators

- Cross sections: See e.g. J. Formaggio, Rev. Mod. Phys. **84**, 1307 (2012)
  - Intermediate energies: $0.1 < E_\nu < 20\ GeV$
  - Inelastic scattering: Resonance production

$$\nu_\mu N \to \mu^- N^*$$
$$N^* \to \pi N'$$

Predominantly pions
But heavier mesons possible

Charged-current RES process:
3 per ν flavor

$$\nu_\mu p \to \mu^- p \pi^+, \quad \overline{\nu}_\mu p \to \mu^+ p \pi^-$$
$$\nu_\mu n \to \mu^- p \pi^0, \quad \overline{\nu}_\mu p \to \mu^+ n \pi^0$$
$$\nu_\mu n \to \mu^- n \pi^+, \quad \overline{\nu}_\mu n \to \mu^+ n \pi^-$$

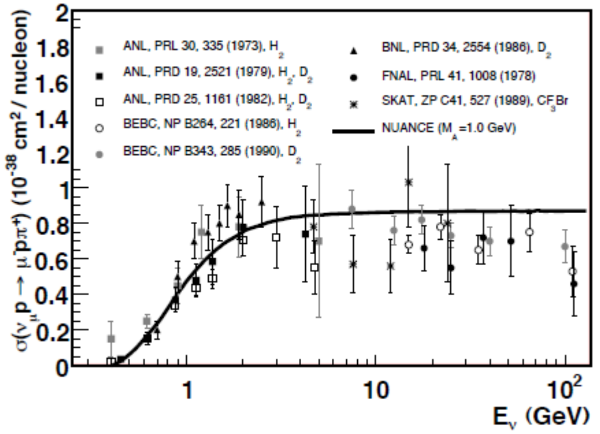


FIG. 13 Existing measurements of the cross section for the CC process, $\nu_\mu p \to \mu^- p \pi^+$, as a function of neutrino energy. Also shown is the prediction from (Casper, 2002) assuming $M_A = 1.1$ GeV.

Neutral-current RES process:
4 per ν flavor

$$\nu_\mu p \to \nu_\mu p \pi^0, \quad \overline{\nu}_\mu p \to \overline{\nu}_\mu p \pi^0$$
$$\nu_\mu p \to \nu_\mu n \pi^+, \quad \overline{\nu}_\mu n \to \overline{\nu}_\mu n \pi^0$$
$$\nu_\mu n \to \nu_\mu n \pi^0, \quad \overline{\nu}_\mu n \to \overline{\nu}_\mu n \pi^0$$
$$\nu_\mu n \to \nu_\mu p \pi^-, \quad \overline{\nu}_\mu n \to \overline{\nu}_\mu p \pi^-$$

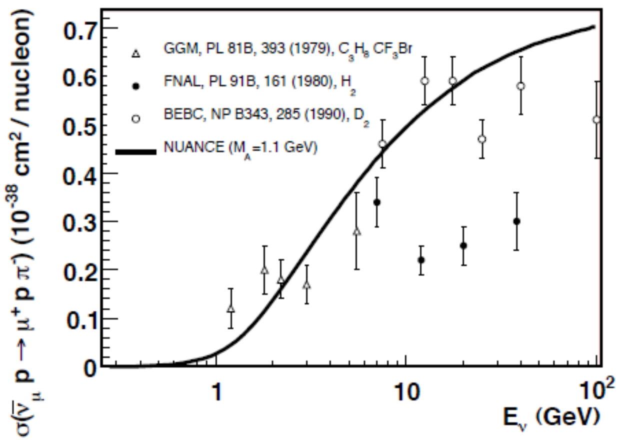


FIG. 21 Existing measurements of the cross section for the NC process, $\overline{\nu}_\mu n \to \overline{\nu}_\mu p \pi^-$, as a function of neutrino energy. Also shown is the prediction from Reference (Casper, 2002) assuming $M_A = 1.1$ GeV.

From EW theory

$$\frac{\sigma_{CC}}{\sigma_{NC}} \approx 2 \text{ to } 3$$

Cross section scales with nr of target neutrons (or protons for antineutrinos), but when normalized to total nr of nucleons it is fairly independent of the target nucleus size

Meanwhile at accelerators

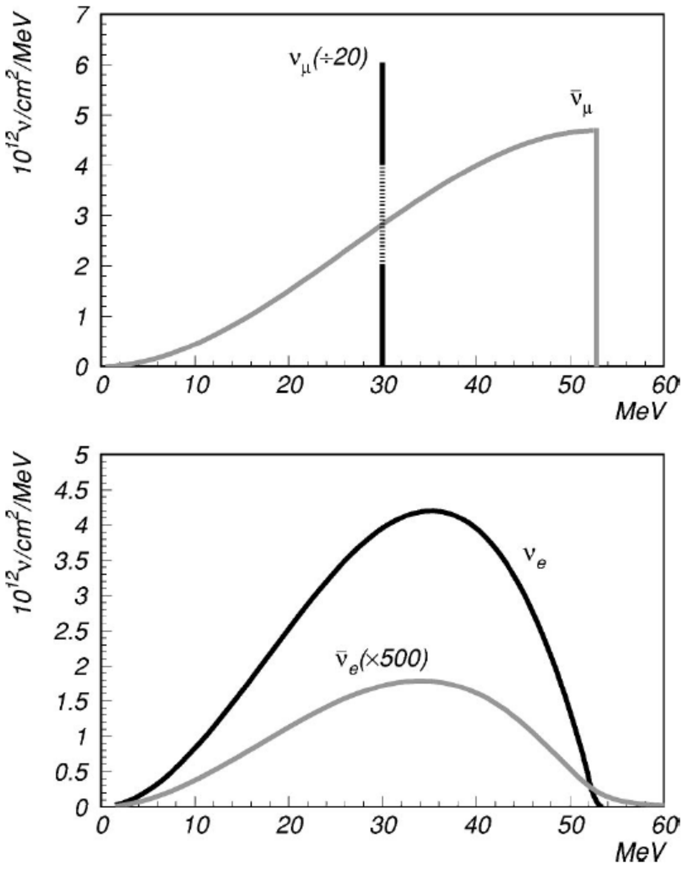
- Cross sections: See e.g. J. Formaggio, Rev. Mod. Phys. **84**, 1307 (2012)
  - Intermediate energies: $0.1 < E_{\nu} < 20\ GeV$
  - Cross section uncertainties:
    - For inclusive cross sections in the intermediate energy range, uncertainties can be **10–30% or more**, depending on the process (QE, 2p2h, pion production)
    - These uncertainties propagate into neutrino energy reconstruction, which is critical for oscillation parameter extraction.
    - Current experiments like **NOvA** and **T2K** are still statistics-dominated, so cross-section uncertainties do not strongly bias results.
    - BUT: Next stage experiments: **DUNE**, **Hyper-K**, will suffer from these uncertainties:
      - Modeling nuclear effects/corrections from first principle is very difficult
      - MC- based models exist ((e.g., GENIE, NuWro, GiBUU), but their predictions can vary a lot in certain kinematic regions
      - No complete set of reference measurements exist (MINERvA, T2K, NOvA)

Short baseline accelerator anomalies

- LSND: A. Aguilar-Arevalo *et al.* [LSND collab], Phys. Rev. D **64** (2001) 112007
  - An early (1993-1998), accelerator based, experiment with low energy neutrinos from Pion and muon decay at rest (DAR): 20-60 MeV energies:
    - around 8.9×10^{23}POT
  - Pion decay at rest produces mono-energetic muons!

    $\pi^+ \to \mu^+ + \nu_\mu$ 2-body decay $E_{\nu_\mu} \approx 29.8\,\mathrm{MeV}$

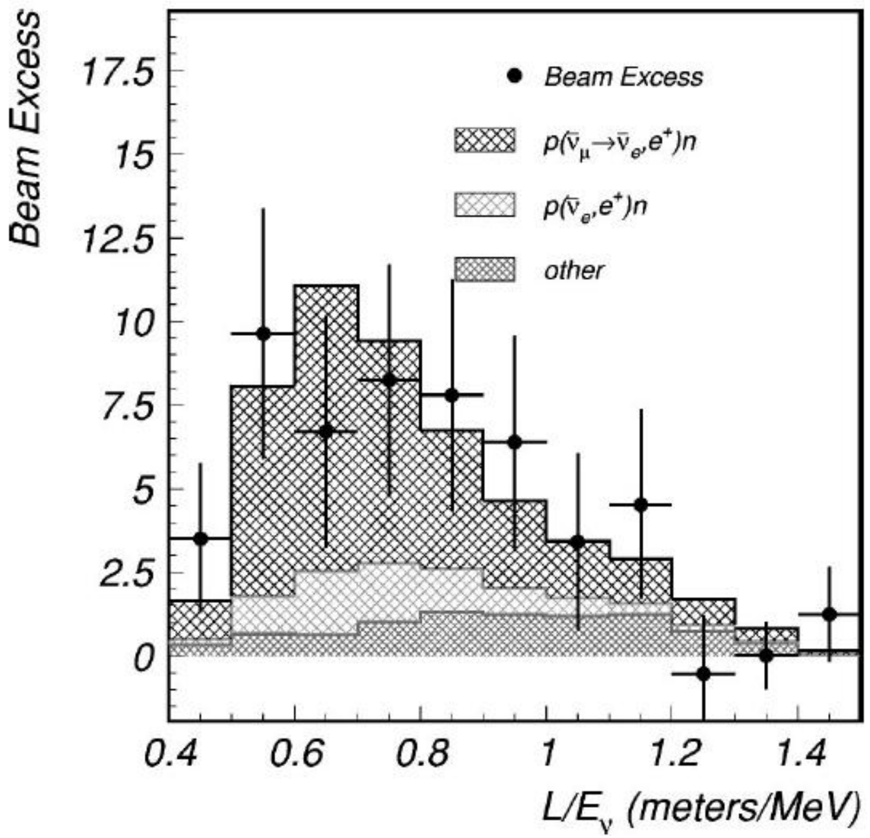
  - The LSND detector, consisting of a tank of 167 tons of liquid scintillator, instrumented with 1220 PMTs, was placed at 30m from the source
  - Detector design allowed Cherenkov detection (particle type and direction) and scintillation detection (particle id, energy)
  - LSND observed in their total run of an excess of $\bar{\nu}_e$ events (3.8σ): 87.9 $\pm$ 22.4 $\pm$ 6.0, consistent with IBD process $\bar{\nu}_e + p \to e^+ n$
  - Signature:
    - A prompt event with energy consistent with a positron.
    - A delayed 2.2 MeV gamma within ~1 ms and within ~1 m of the prompt event
  - Backgrounds: $\bar{\nu}_e$contamination in the beam: estimated to be 8.10^{-4}relative to the $\bar{\nu}_\mu$flux, and misidentified $\bar{\nu}_\mu + p \to \mu^+ n$ events: 8.2 background events estimated



Short baseline accelerator anomalies

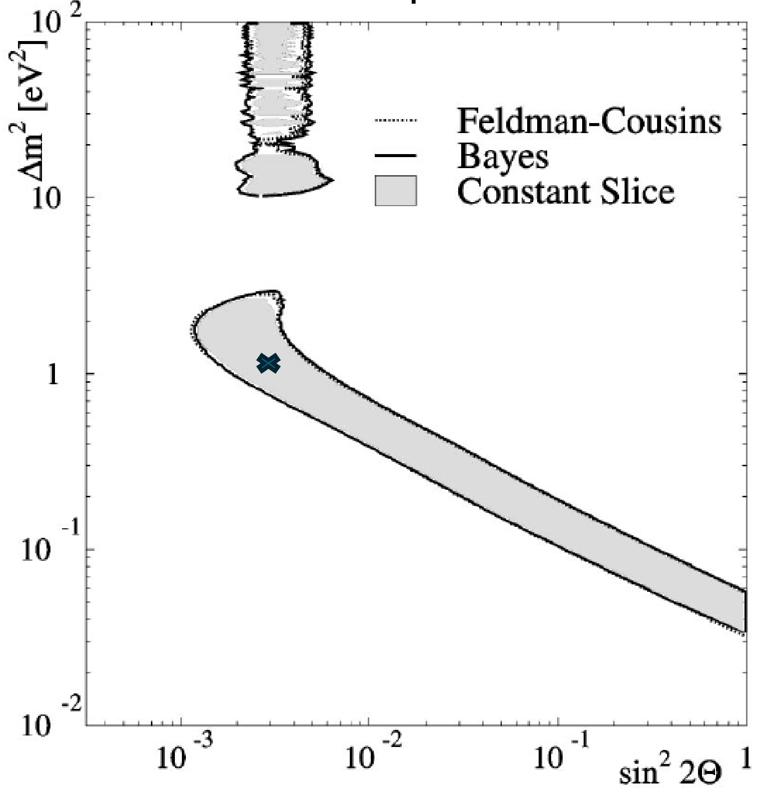
- LSND: A. Aguilar-Arevalo *et al.* [LSND collab], Phys. Rev. D **64** (2001) 112007

The excess



A 3.8σ excess deviating from backgrounds

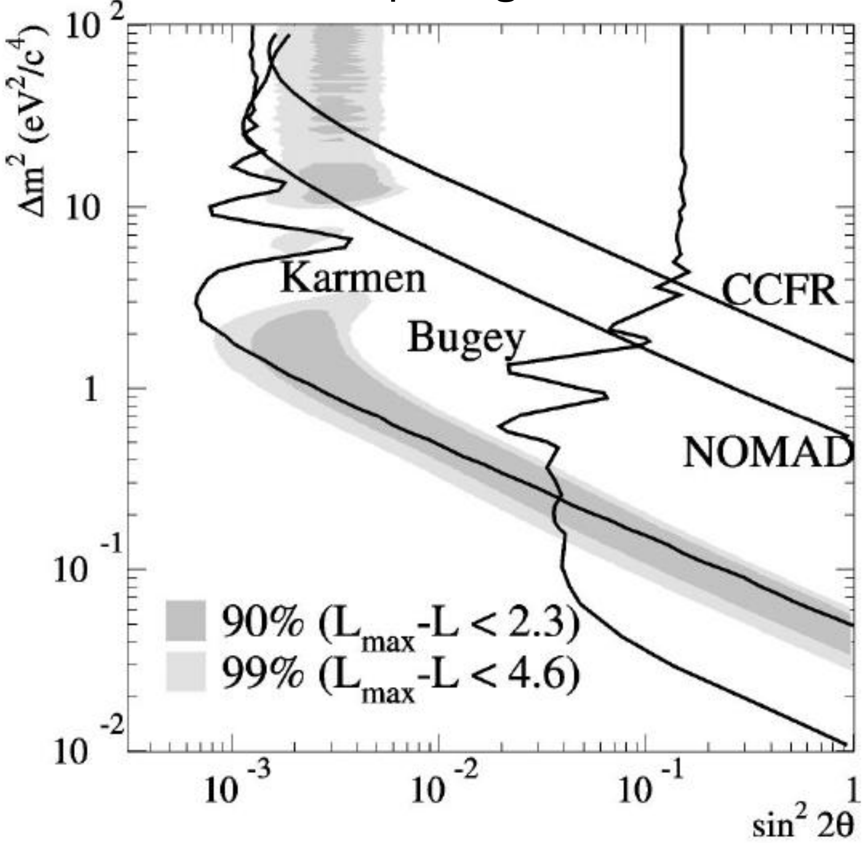
The interpretation



$$(\sin^2 2\theta, \Delta m^2)_{best\text{-}fit} = (0.003, 1.2\ \ \mathrm{eV}^2).$$

Very similar to the reactor anomalies, but with much smaller mixing parameter!

Comparing with others

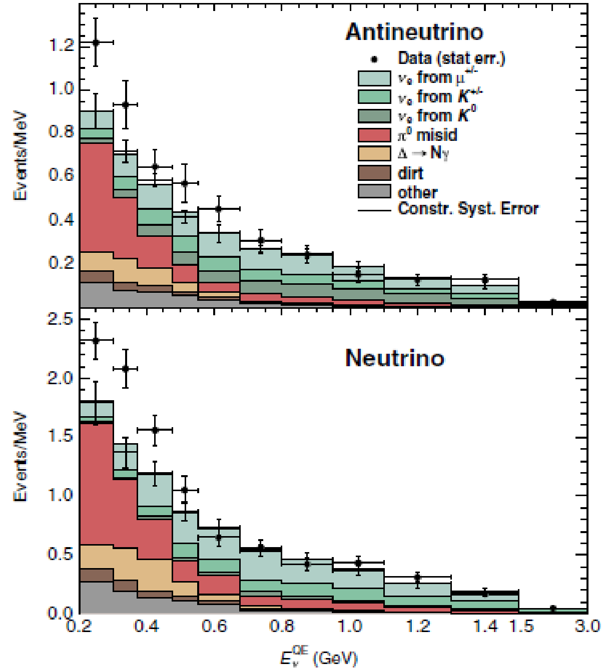


Karmen, a very similar experiment, did not confirm the excess, but could not completely exclude the LSND result

Short baseline accelerator anomalies

- MiniBooNE: A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], PRL **110** (2013) 161801
  - Experiment at the 8GeV Fermilab Booster Neutrino Beam:
    - around 11.27×10^{20} POT
  - Pion decay in flight produced more energetic muon neutrinos: ~0.5–1 GeV, with a wide energy spread
  - Distance to the source is 540m, but due to Higher energy, the L/E ratio is comparable with LSND
  - The MiniBooNE detector used 800tons of pure mineral oil, without dopant: pure Cherenkov detector
  - They observed an excess of 78.4±28.5 (2.8σ) $\bar{\nu}_e$ events in the energy range $200MeV < E_\nu < 1250\ MeV$, compatible with the LSND observation
  - BUT: They also observed an even larger excess in ν_e events of 162.0±47.8 (3.4σ), but at a different Energy range, incompatible with the $\bar{\nu}_e$ excess

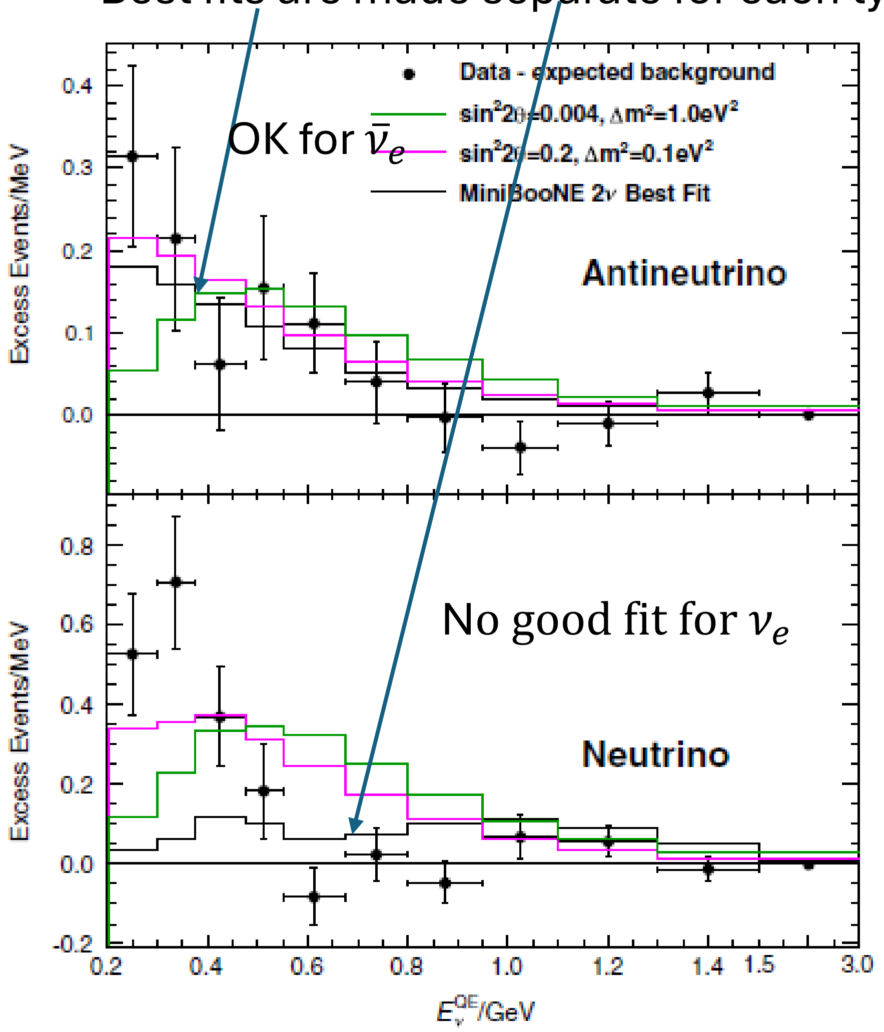
Process	Neutrino mode	Antineutrino mode
ν_μ & $\bar{\nu}_\mu$ CCQE	37.1 ± 9.7	12.9 ± 4.3
NC π^0	252.3 ± 32.9	112.3 ± 11.5
NC $\Delta \to N\gamma$	86.8 ± 12.1	34.7 ± 5.4
External events	35.3 ± 5.5	15.3 ± 2.8
Other ν_μ & $\bar{\nu}_\mu$	45.1 ± 11.5	22.3 ± 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ decay	214.0 ± 50.4	91.4 ± 27.6
ν_e & $\bar{\nu}_e$ from $K^\pm$ decay	96.7 ± 21.1	51.2 ± 11.0
ν_e & $\bar{\nu}_e$ from K_L^0 decay	27.4 ± 10.3	51.4 ± 18.0
Other ν_e & $\bar{\nu}_e$	3.0 ± 1.6	6.7 ± 6.0
Total background	797.7	398.2
0.26% $\bar{\nu}_\mu \to \bar{\nu}_e$	233.0	100.0

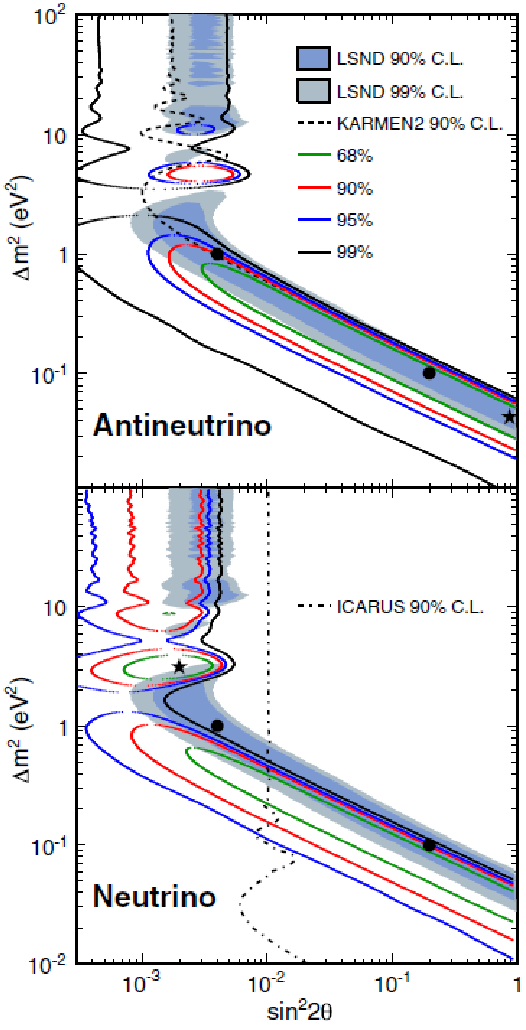


Short baseline accelerator anomalies

- MiniBooNE: A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], PRL **110** (2013) 161801

Best fits are made separate for each type of excess





Best fits to MiniBooNE data indicated with stars

$sin^2(2\theta) = 0.88$, and $\Delta m^2 = 0.043\ eV^2$
With p-value of 0.66

P-value of best fit for neutrino sampl is 0.0054

Possible systematics related to the low-E excess:
− misreconstruction of neutrino energy;
− $\pi 0$ from NC reconstructed as νe;
− single photon from NC misidentified as νe;

Short baseline accelerator anomalies

- MicroBooNE: P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **128** (2022) 241801
  - Experiment in the same beam as MiniBooNE
  - Baseline: 468.5 m (72.5 m upstream of MiniBooNE);
  - MicroBooNE is a liquid Ar TPC

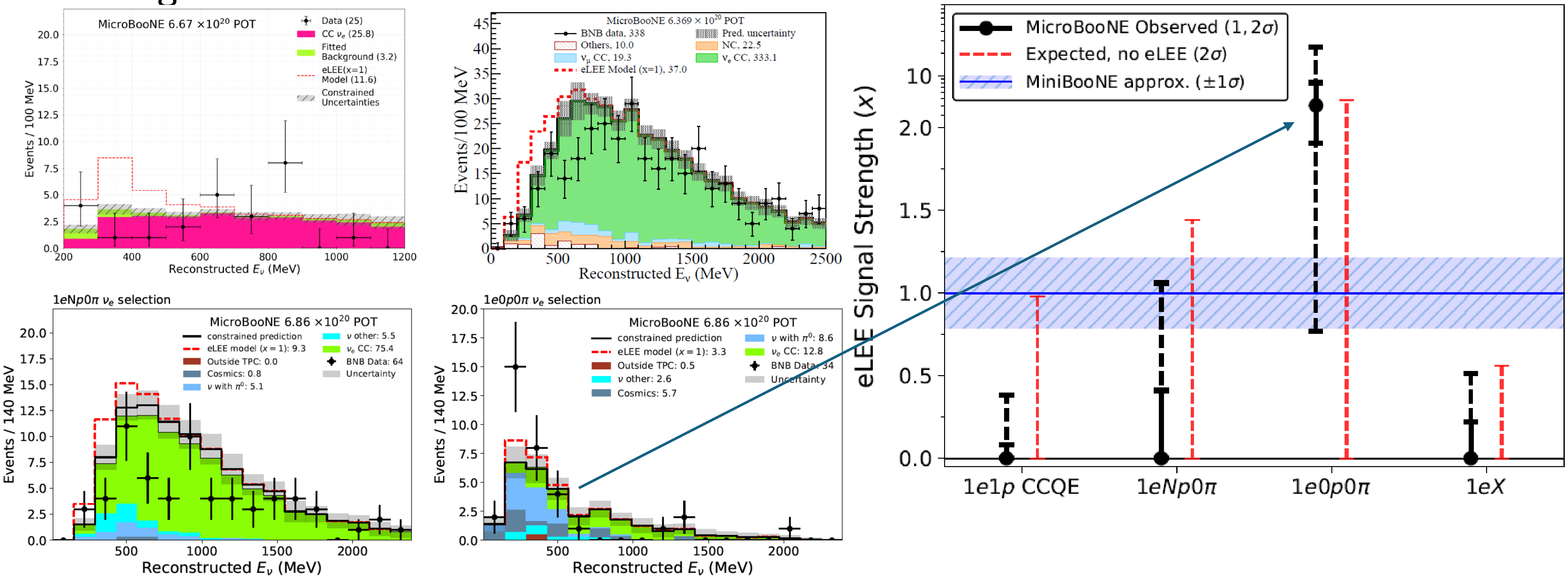
•**High-resolution imaging**:
•Tracks are reconstructed in 3D with millimeter precision.
•Allows identification of particle types by track shape and energy loss (dE/dx).
•**Calorimetry**:
•Measures deposited energy accurately → good neutrino energy reconstruction.
•**Background rejection**:
•*Fine-grained imaging helps distinguish electrons from photons (critical for oscillation searches).*

- **eLEE model**
  - A signal model constructed by **taking MiniBooNE's observed excess**, unfolding it through MiniBooNE's simulation, and applying it to the expected intrinsic ν_e spectrum in MicroBooNE.

• Predicts what MicroBooNE should see **if the MiniBooNE excess were due to real ν_e interactions** (not photons or misidentified backgrounds).

Short baseline accelerator anomalies

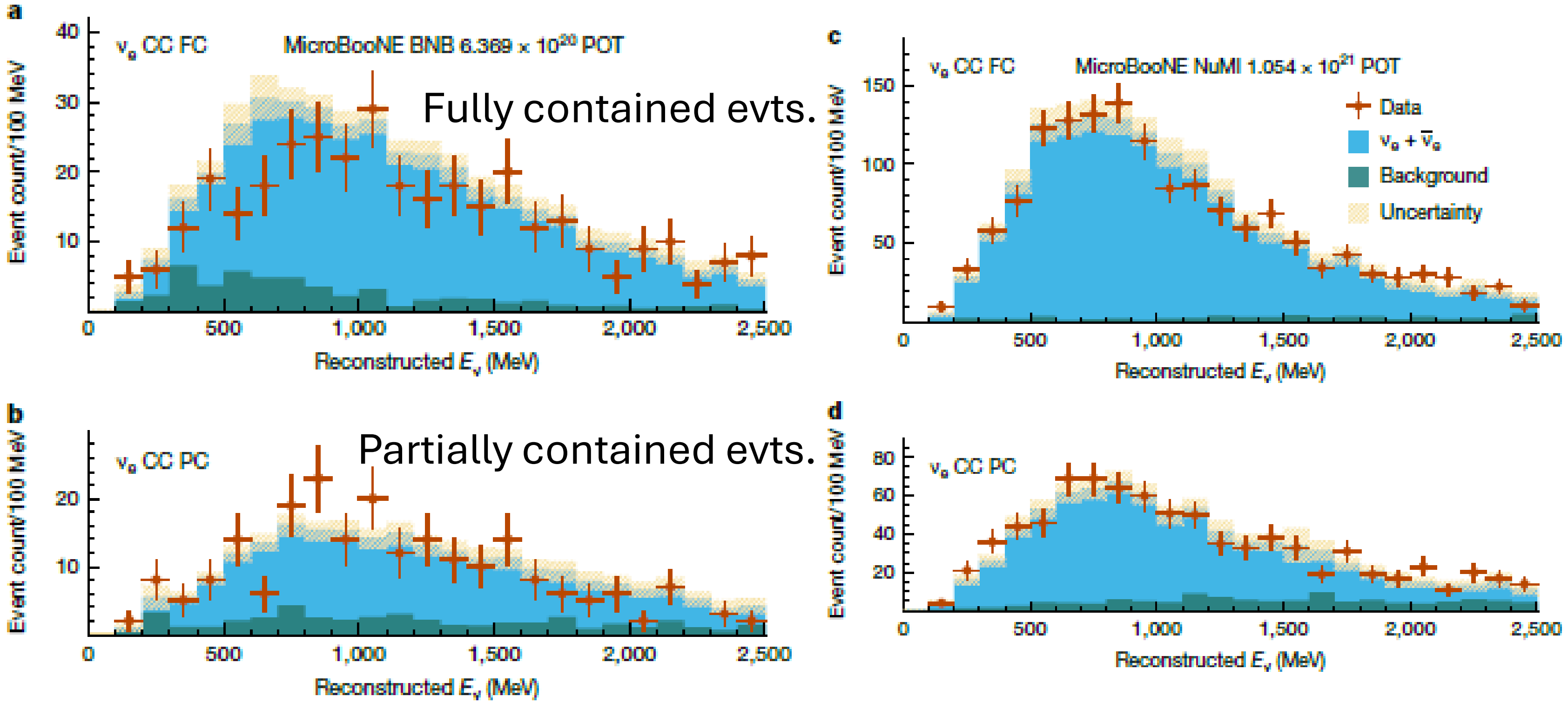
- MicroBooNE: P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **128** (2022) 241801
  - 4 different analyses with increasing level of inclusivity
  - Only one finds an excess consistent with the MiniBooNE excess, but significance is low

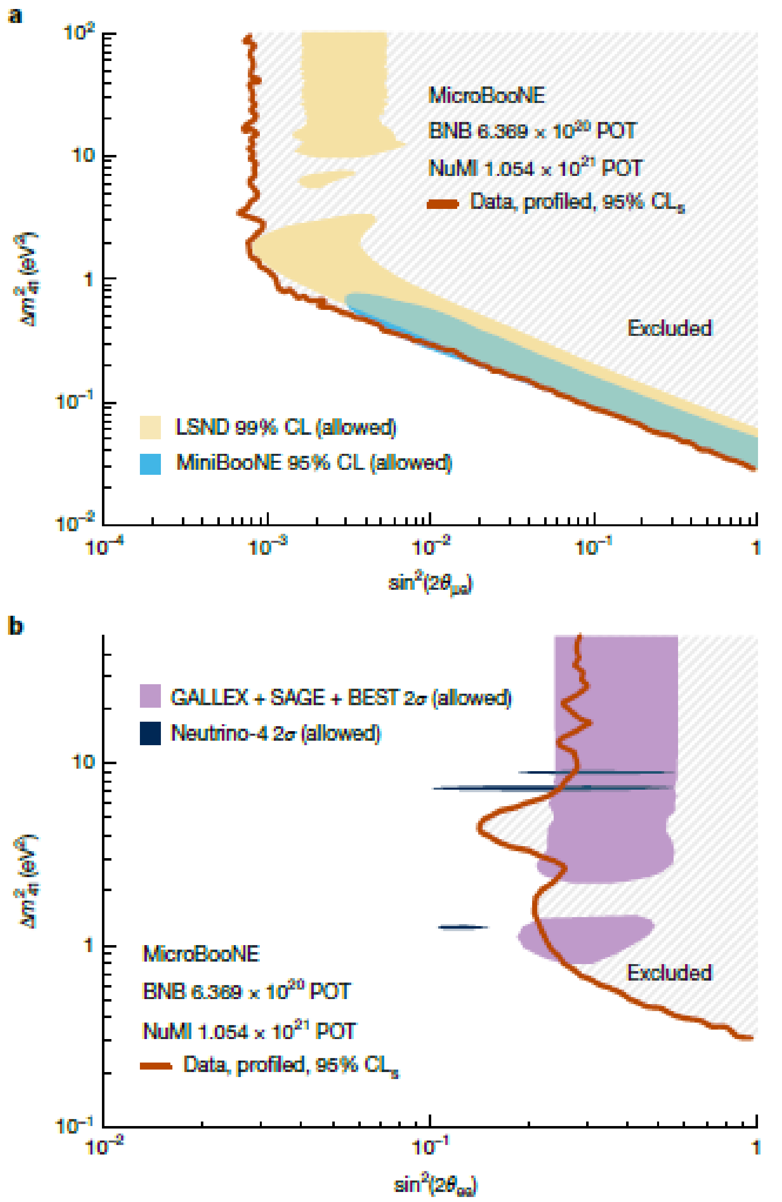


MicroBooNE

MicroBooNE Collab. *Nature* **volume 648**, pages64–69 (2025)

- New MicroBooNE result using data obtained with two different $\nu_\mu$beams (BNB beam, wich has less ν_e contamination than NuMi beam)
- Analyses are indifferent to lepton charge, and therefore also indiscriminate wrt ν_e or $\bar{\nu}_e$: In total 2x 7 final state samples





- Joint fit of the 14 data samples agree well with the no-oscillation hypothesis, with p-value of 0.92
- LSND and miniboone excess is now excluded at 95% CL, as well as majority of GA anaomaly and Neutrino-4 reactor signal

Conclusions

- Sterile neutrinos in the form of a right-handed EW singlet are the simplest way to generate neutrino masses in the standard model, preserving the Gauge symmetry of the theory
- In a type-I seesaw mechanism they explain naturally the mass scale of the light neutrinos
- Active and steriles mix exclusively through the interaction with the Higgs field
- The conventional PMNS matrix can be extended with 4 extra independent parameters
- Modern day cosmological precision data does not allow for even the lightest sterile neutrinos
- Sterile neutrino's have been found and lost and found again since the beginning of neutrino experiments
- At each stage it prompted extensive cross-checks and follow-up experiments, leading to many improvements in the fields of:
  - Reactor flux and energy spectrum calculations/predictions
  - Control and mitigation of accelerator beam backgrounds and misidentificantions of neutrino detector signatures
  - Non-dedicated experiments, placing surprisingly strong constraints
- At the moment, most of the larger significance anomalies have been excluded by modern/recent measurements
- A light sterile neutrino corresponding to a mass difference squared of O(1eV2) seems quite disfavored now, unless it mixes very weakly with other neutrinos
- Still, some explanation needs to be given and experimentally proven as to why at least 2 of the 3 known neutrino states have a non-zero mass

Questions

- What types of elementary particles oscillate, and why?
- What have we discovered/determined so far?
- What are the unknown neutrino properties?
- Why do we need to know the neutrino mass hierarchy?
- Why do we need to know the CP violating phase?
- How many neutrinos are there in the universe?
- What are the cosmological bounds on neutrino masses?
- How do you measure the mass of a particle?
- How do we measure the mass of neutrinos?
- What are majorana particles and are neutrino's majorana?
- What are the implications of this?
- What is the see-saw mechanism, and why is it important?
- What does it mean for a neutrino to be 'sterile'?
- How do you detect 'sterile' neutrino's?
- What about Heavy Nautral Leptons (HNL)?