Neutrino Fits, Tensions and Puzzles

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MPA Summer School 2023

Abtei Frauenwörth, Fraueninsel, Chiemsee

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All theorists are liars

Neutrino physics has a rich history of anomalies:

It took 40 years for Ray Davis and John Bahcall to be taken seriously with the solar neutrino anomaly.

The atmospheric neutrino anomaly did not last quite that long, but still was labeled an anomaly till Super-K came around in 1998.

Much of the anomalous nature stemmed from theoretical prejudice: neutrinos are massless, neutrino mixing angles are small, astrophysics isn't an exact science, chemistry is really scary asf.

Of course, I happen to be a theorist . . .

Why sterile?

We have measured in neutrino oscillation:

- $\Delta m^2_{21} \sim 8 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\theta_{12} \sim 1/2$
- $\Delta m^2_{31} \sim 2 \cdot 10^{-3}\,\mathrm{eV}^2$ and $\theta_{23} \sim \pi/4$
- $\theta_{13} \sim 0.16$

This implies a lower bound on the mass of the heaviest neutrino

$\sqrt{2 \cdot 10^{-3}\,\mathrm{eV}^2} \sim 0.04\,\mathrm{eV}$ This IS BSM physics!

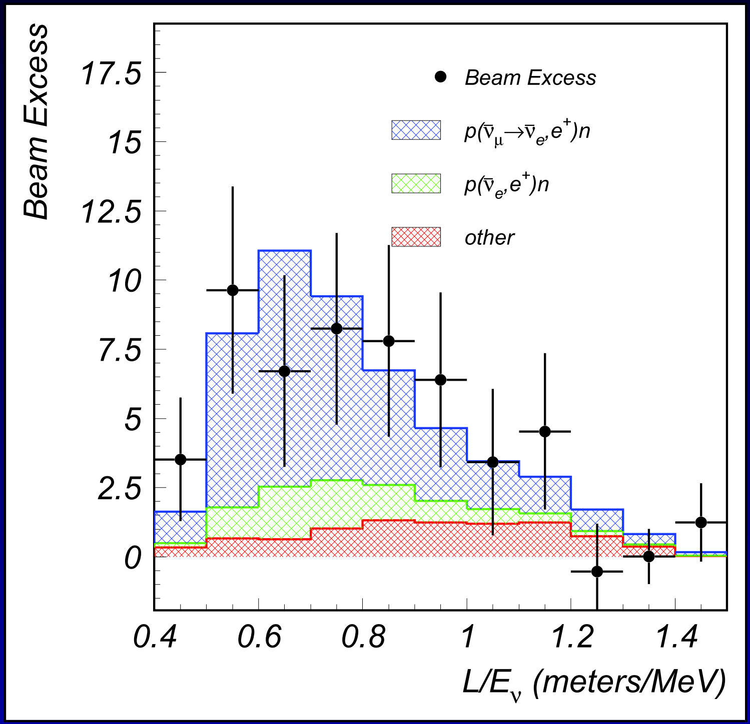
Any $\Delta m^2 \gg \Delta m^2_{21}, \Delta m^2_{31}$ requires a 4^{th} neutrino, BUT only three neutrinos with $m_\nu \leq m_Z$ couple to the Z $\Rightarrow$ “sterile” neutrino.

Evidence in favor

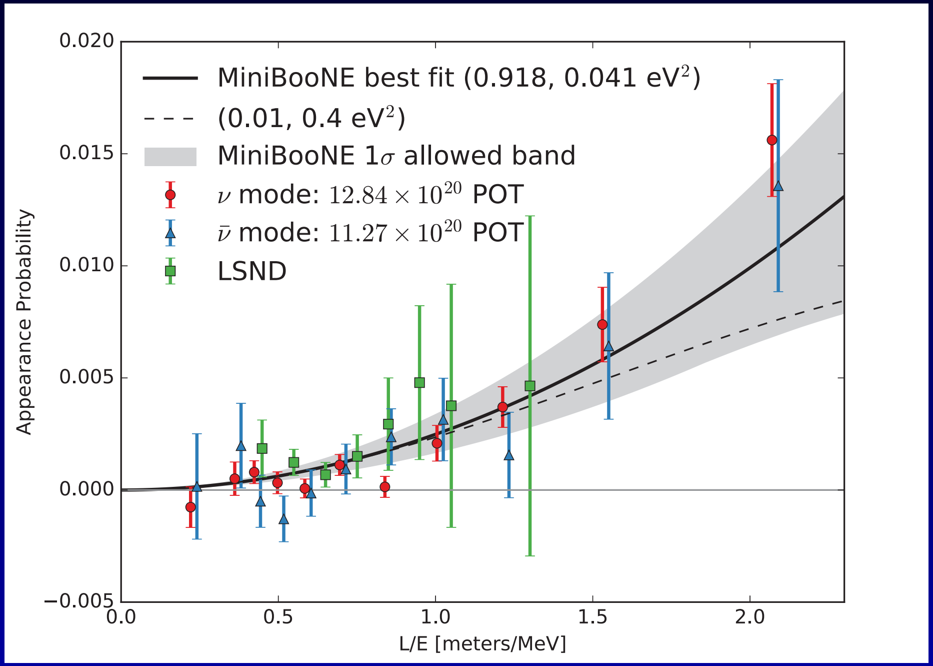
Or at least at odds with a simple 3-flavor framework

- LSND $\bar{\nu}_\mu \to \bar{\nu}_e$
- MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$
- Reactors $\nu_e \to \nu_e$
- Gallium $\nu_e \to \nu_e$

LSND and MiniBooNE



LSND 1995



MiniBooNE 2018

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq 0.003$$

Statistically significant: $4 - 6\sigma$

Fermilab SBN

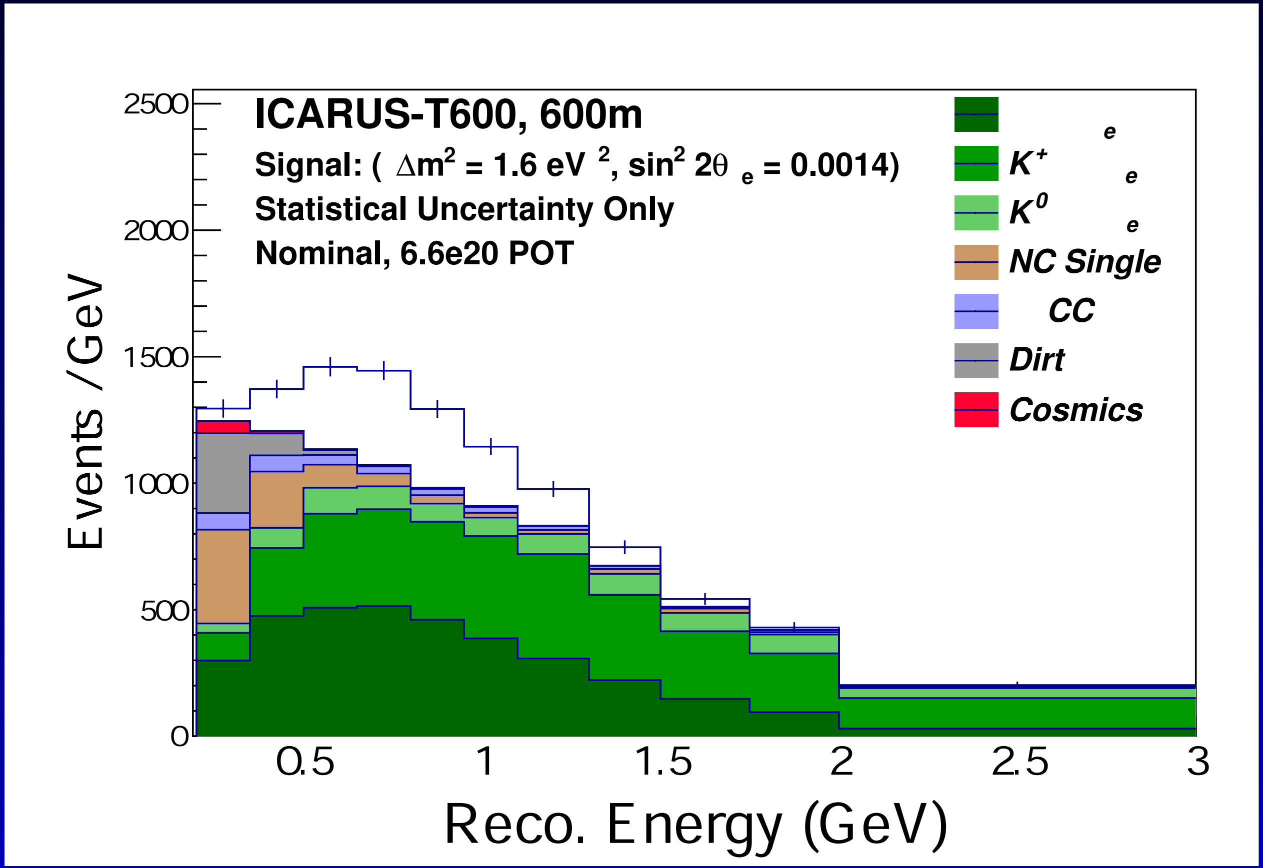
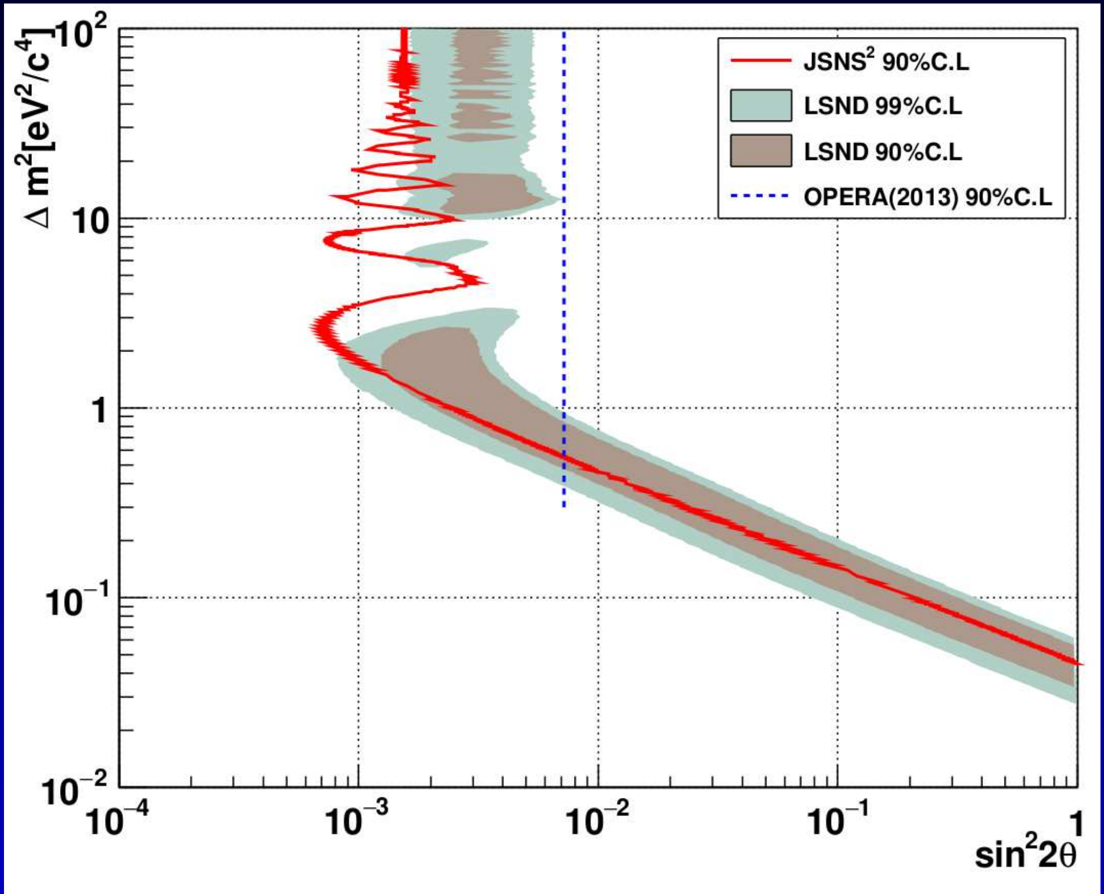


Figure courtesy D. Schmitz and C. Adams

Signal to noise not so different from LSND. . . will a near detector of completely different design help?

JSNS2



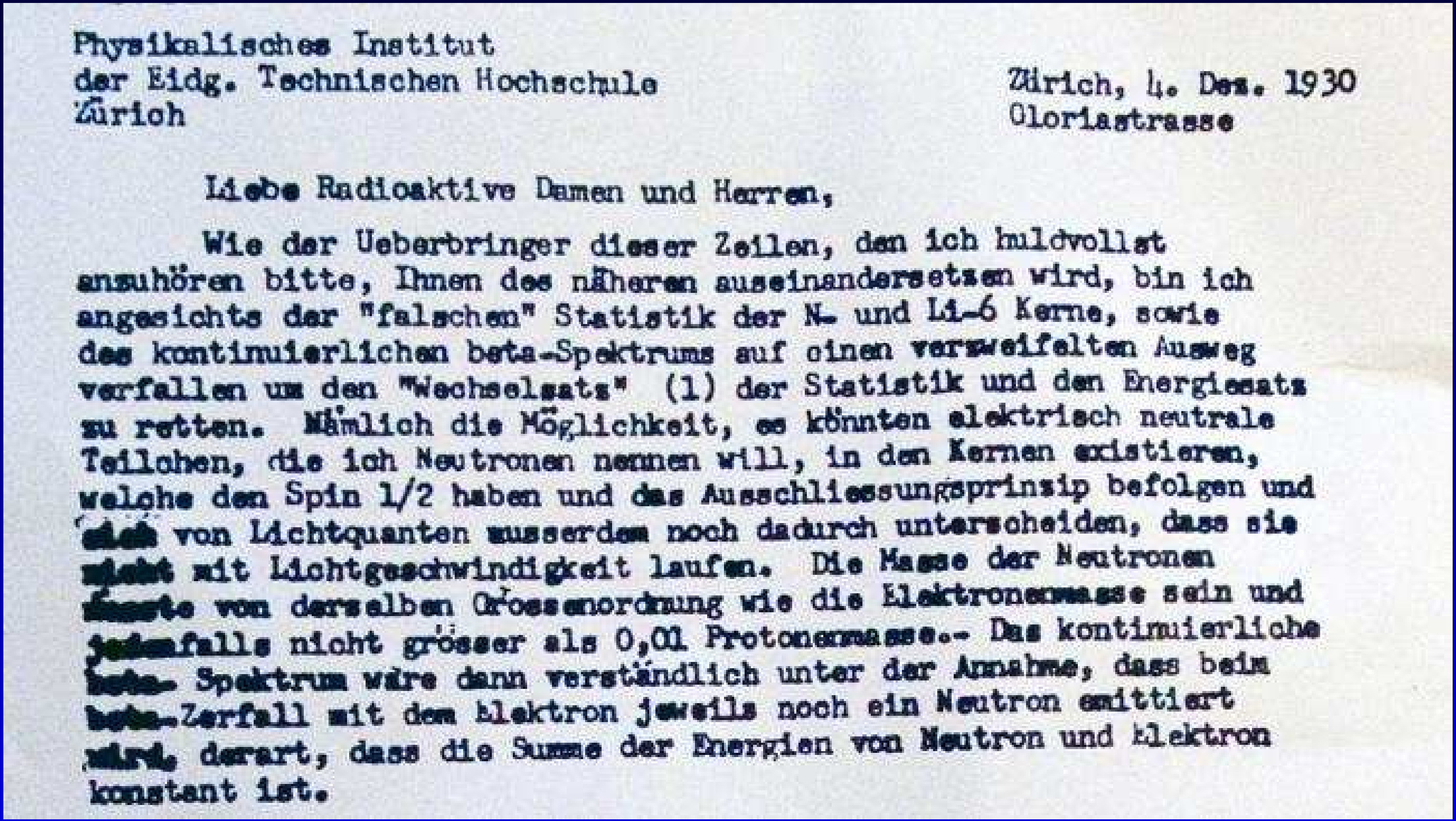
Pion decay at rest at JSNS, Gd-doped scintillator.

JSNS2, 2017

Direct test of the LSND result $\rightarrow$ should have been done 20 years ago!

Pauli’s idea

The neutrino was first proposed by Wolfgang Pauli



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen dürfte von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

He postulates a neutral, very light, spin 1/2 particle inside the nucleus.

Beta decay 101

Fermi would take this idea and develop a first theory of beta decay (1934):

$$n \to p + e^- + \nu$$

or in a nuclear bound state

$$(Z, A) \to (Z+1, A) + e^- + \nu$$

Fermi's Golden Rule (invented for this problem) reads as, with **O** being the operator for weak interactions

$$\frac{dP}{dt} \propto \underbrace{|\langle\psi_f|\mathbf{O}|\psi_i\rangle|^2}_{\text{matrix element } \mathcal{H}_{fi}} \quad \underbrace{\rho(E)}_{\text{phase space density}} \quad dE$$

Beta decay 101 – cont'd

$$d\Gamma = \int \frac{\mathbf{p}_e}{(2\pi)^3}\frac{\mathbf{p}_\nu}{(2\pi)^3}|\mathcal{H}_{fi}|^2 2\pi\delta(E_0 - E_e - E_\nu)$$

assuming $|\mathcal{H}_{fi}|^2$ is independent of momentum transfer this becomes for $m_\nu = 0$ and $M_N \to \infty$

$$d\Gamma = |\mathcal{H}_{fi}|^2 p_e E_e (E_0 - E_e)^2 dE_e$$

The electron wave function is not a plane wave, but an unbound solution of the hydrogen atom, yielding a correction term

$$|\psi_e(r=0)|^2 =: F(Z, E_e)$$

so called Fermi function

Beta decay 101 – cont'd

Cleaning up our notation (and make it compatible with modern literature)

$$|\mathcal{H}_{fi}|^2 = F(Z, E_e)\frac{G_F^2|V_{ud}|^2}{2\pi^3}|\mathcal{M}_{fi}|^2$$

Fermi used the solution to the relativistic, point-like, infinitely heavy hydrogen atom to compute $F(Z, E_e)$. $|\mathcal{M}_{fi}|^2$ incorporates all the nuclear bound state physics and the assumption that it is independent of momentum transfer implies that we approximate the nucleus as a point. Transitions for which this approximation is valid are called "allowed".

Beta decay 101 – cont'd

Now the lifetime is given by

$$\frac{1}{\tau} = \Gamma = \frac{G_F^2 |V_{ud}|^2}{2\pi^3} |\mathcal{M}_{fi}|^2 \underbrace{\int_{m_e}^{E_0} dE_e\, F(Z, E_e) p_e E_e (E_0 - E_e)^2}_{=:f(Z,E_0)}$$

or

$$ft := \log 2 f\tau = \frac{2\pi^3 \log 2}{G_F^2 |V_{ud}|^2} |\mathcal{M}_{fi}|^{-2}$$

The ft-value of more often $\log ft$-value is a measure of the nuclear matrix element.

Inverse beta decay

Now that we can describe

$$n \rightarrow p + e^- + \nu$$

what about the inverse beta decay

$$\nu + p \rightarrow n + e^+ \,?$$

Bethe and Peirls in 1934 estimate the cross section to be (neutron decay was not yet discovered!)

$$\sigma \simeq \frac{\hbar^3}{m^3 c^4 \tau} (E_\nu / mc^2)^2 \simeq E_\nu^2 \, 10^{-43} \, \mathrm{cm}^2$$

and conclude: “there is no practically possible way of observing the neutrino.”

Avogadro's number

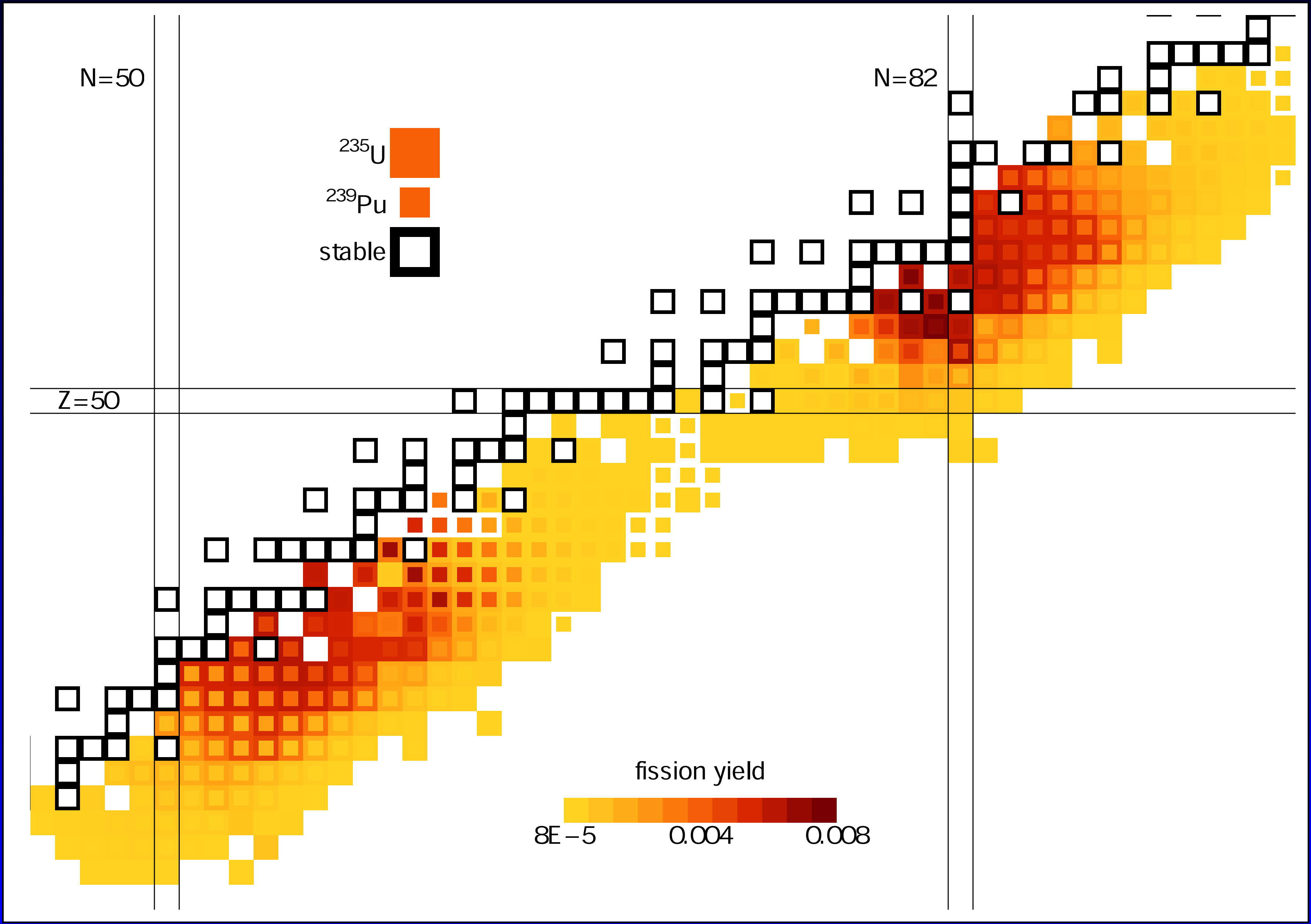
Using a cross section of around $10^{-42}\mathrm{cm}^2\ldots$

We can get a factor 10^{24} from Avogadro's number but that still leaves us with 10^{18} neutrinos to see anything.

Where do we get 10^{18} neutrinos?

$\rightarrow$ digression on nuclear fission

Neutrinos from fission



How many?

$$^{235}U + n \rightarrow X_1 + X_2 + 2n$$

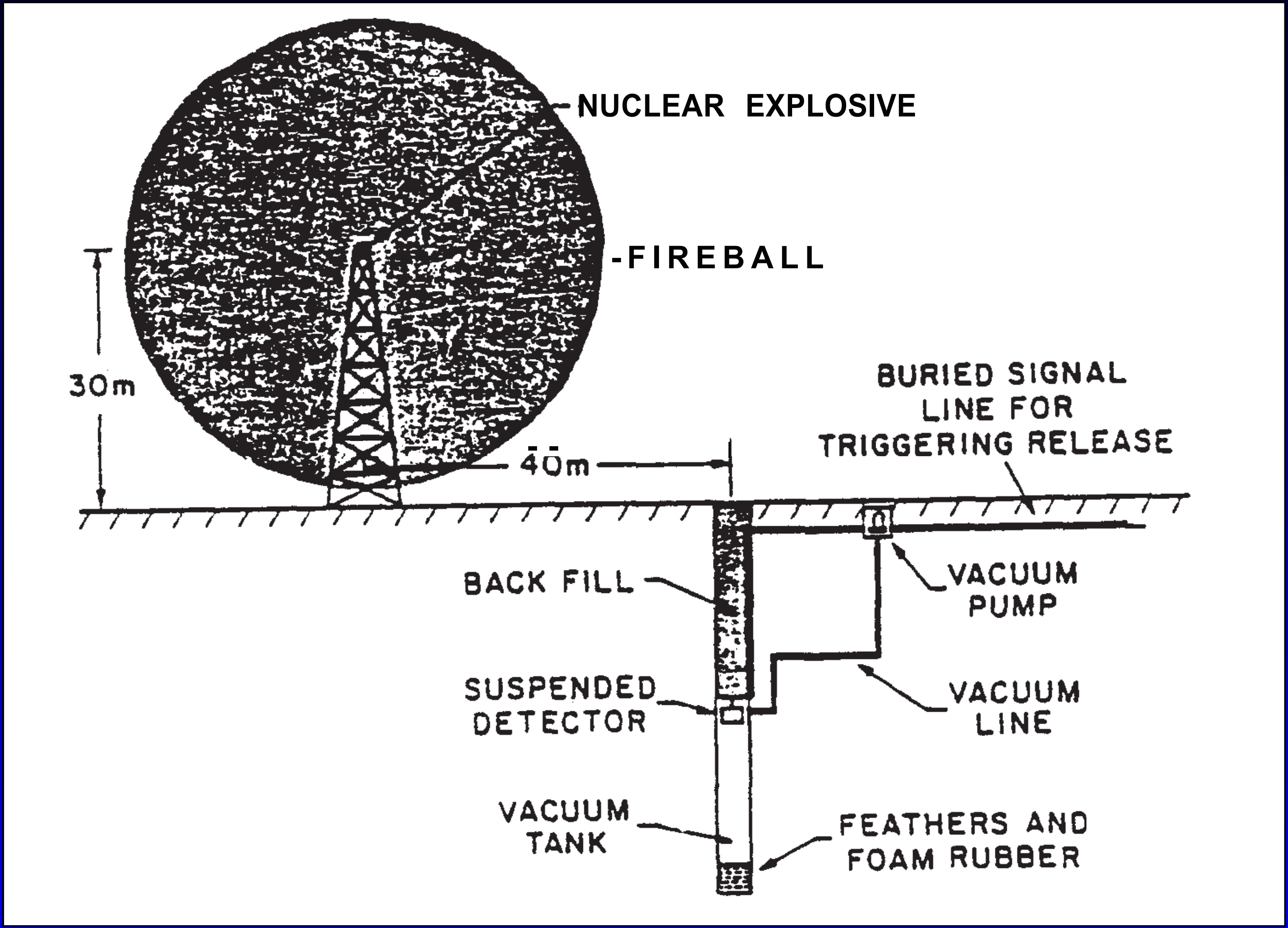
with average masses of X_1 of about A=94 and X_2 of about A=140. X_1 and X_2 have together 142 neutrons.

The stable nuclei with A=94 and A=140 are $^{94}_{40}Zr$ and $^{140}_{58}Ce$, which together have only 136 neutrons.

Thus 6 β-decays will occur, yielding 6 $\bar{\nu}_e$.

Fissioning 1kg of 235U gives 10^{24} neutrinos, or at distance of 50 m about $10^{16}\,\mathrm{cm}^{-2}$.

Ca. 1951



Reines' Nobel Lecture, 1995

Reines & Cowan's day job was to instrument nuclear weapons tests.

Bethe and Fermi thought this was a good idea and thus, not surprisingly their A-bomb proposal was approved.

What really happened

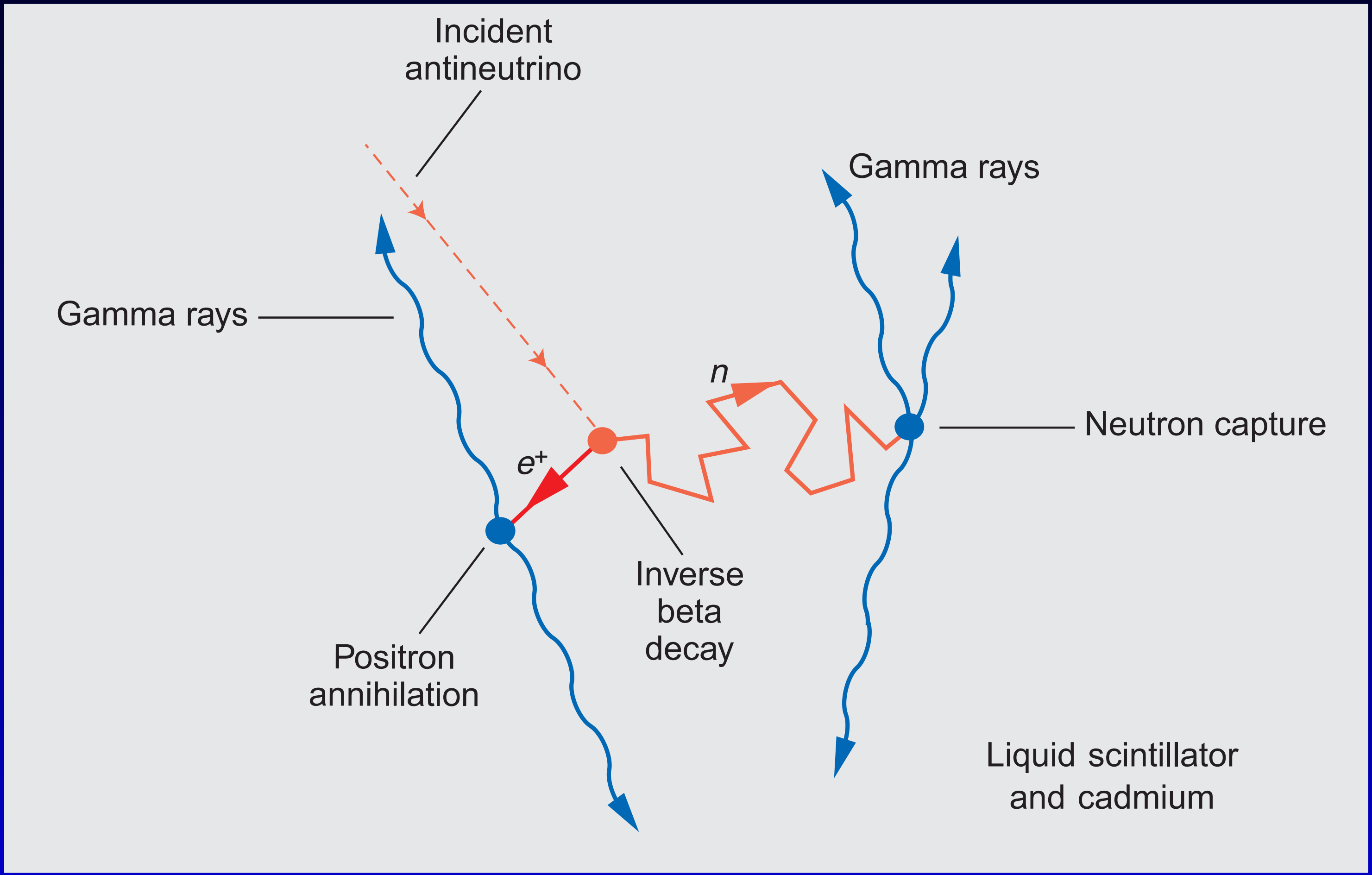
In the fall of 1952 Reines & Cowan revisited the idea of using a reactor:

number of fissions per second = thermal reactor power / energy per fission

$$\frac{300\,\mathrm{MW}}{200\,\mathrm{MeV}} \simeq 10^{19}\,\mathrm{s}^{-1}$$

so 10^5 seconds yields the same fluence, 10^{24} as a $20\,\mathrm{kt}$ explosion.

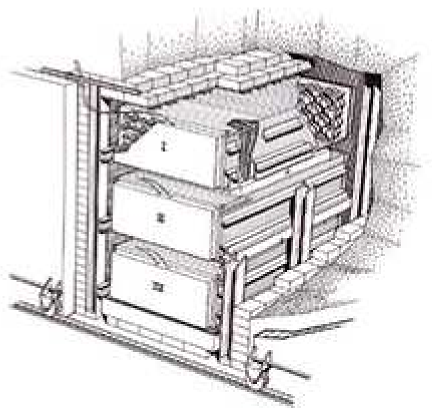
Delayed coincidence

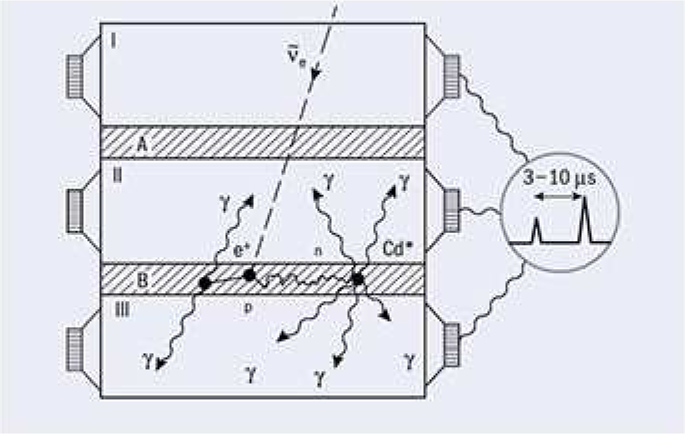


This is the basis for all reactor neutrino experiments since then.

Savannah River

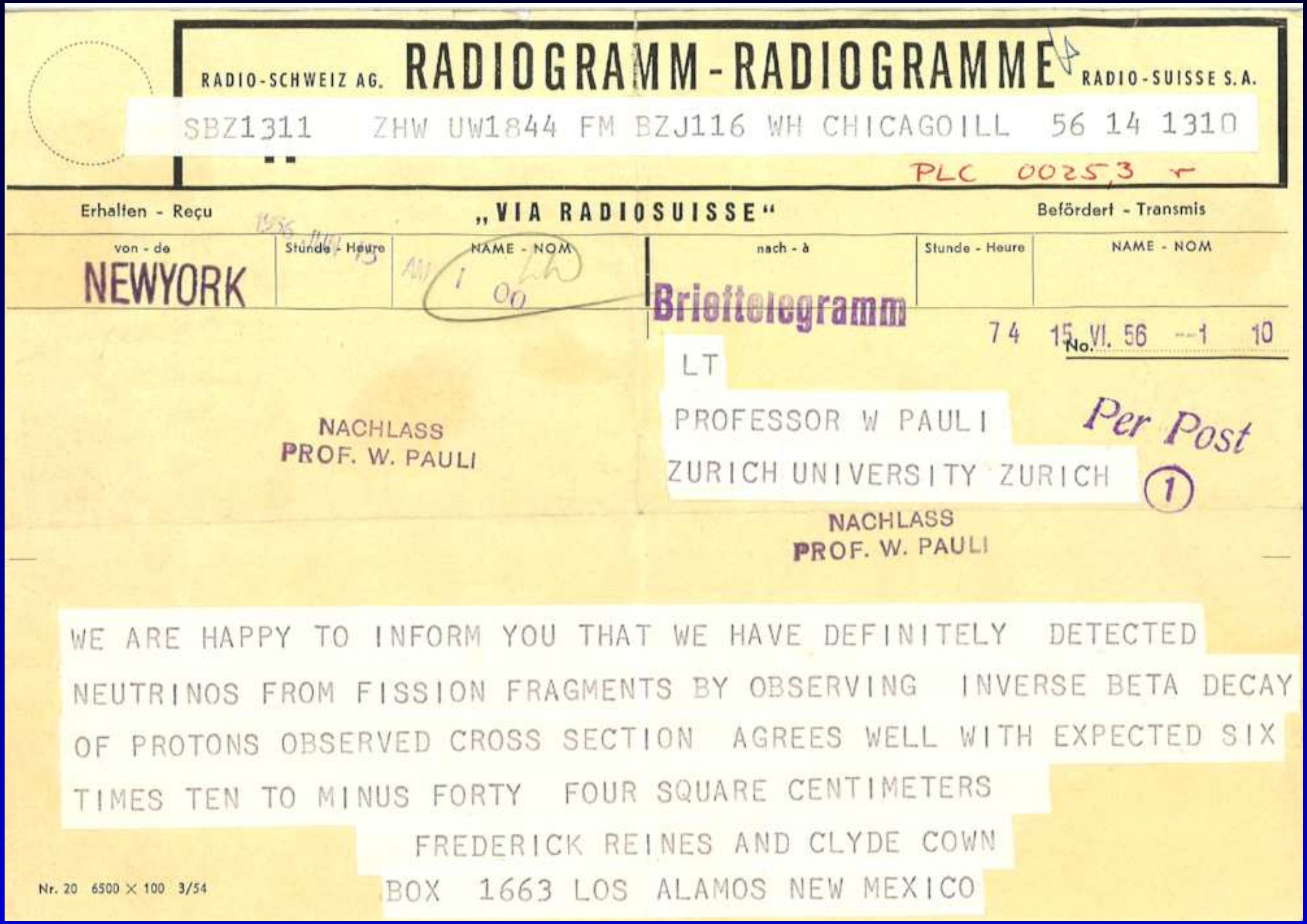
P-reactor became operational in Feb 1954, initially rated for less than 500MW, heavy water cooled, plutonium production reactor.





Note, positron energy is NOT observed.

1956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PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

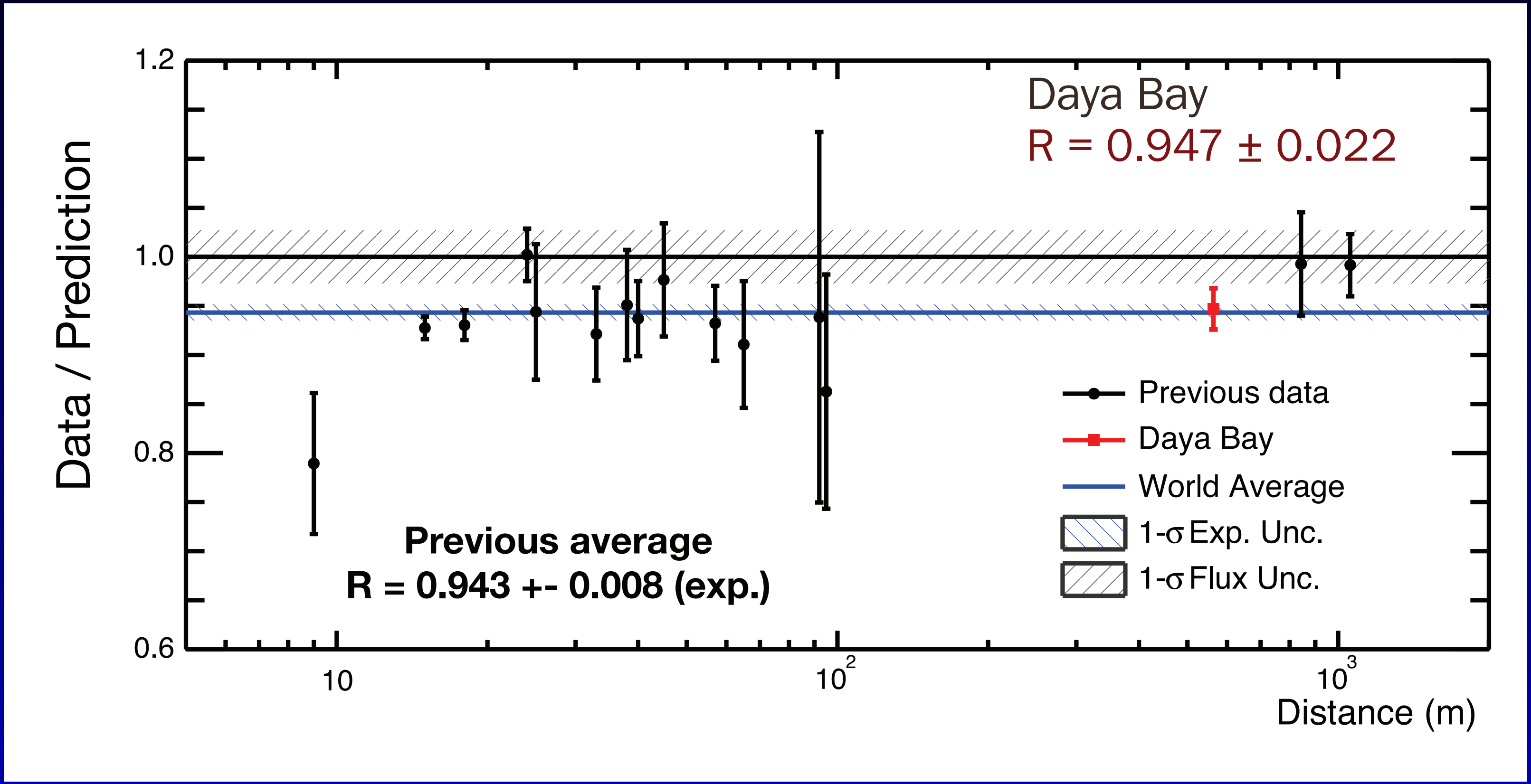
FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

Nr. 20 6500 × 100 3/54

They report a cross section (!) of $6 \times 10^{-44}\,\mathrm{cm}^{-2}$.

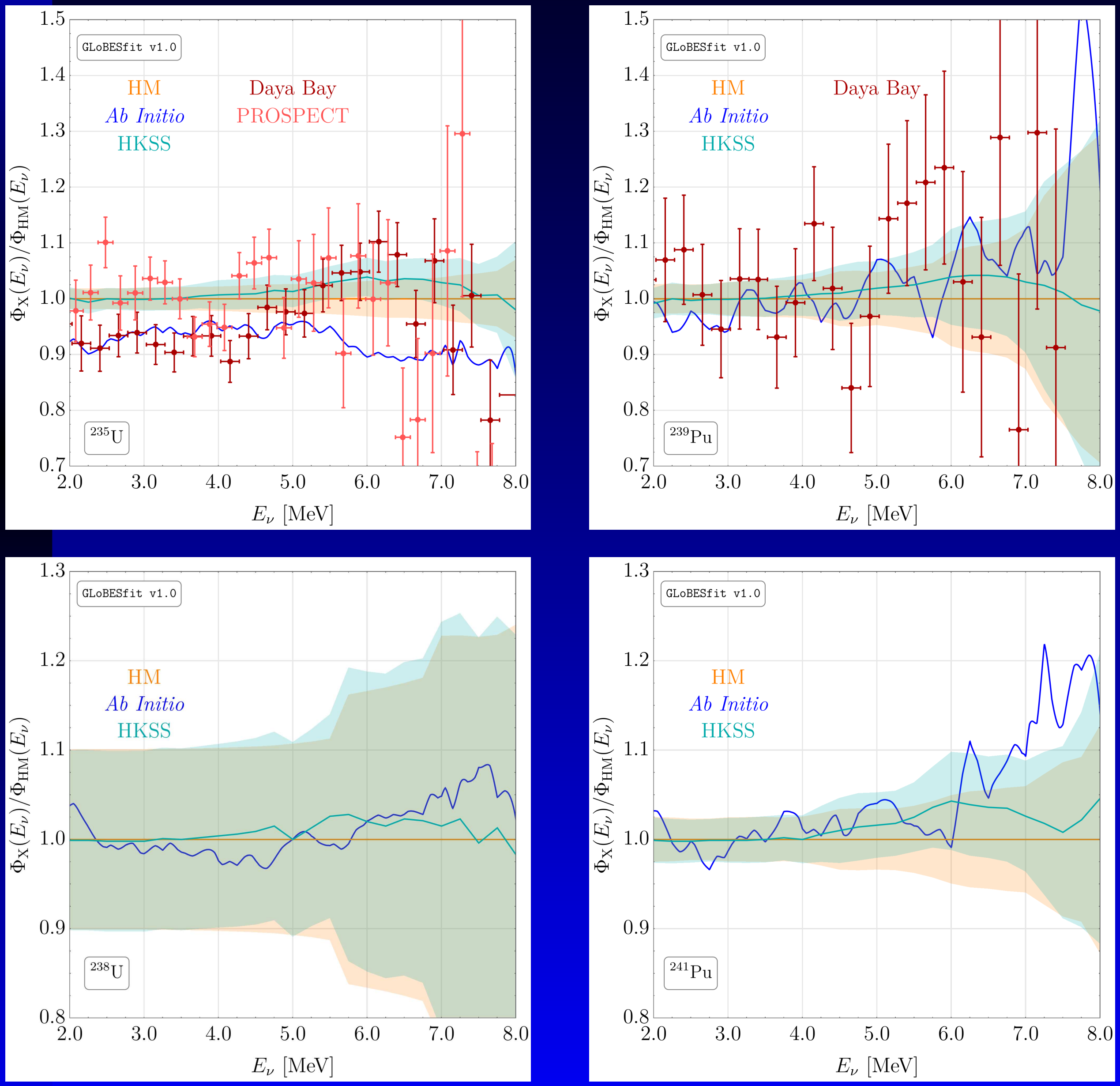
The reactor anomaly



Daya Bay, 2014

Mueller *et al.*, 2011, 2012 – where have all the neutrinos gone?

Status quo early 2021



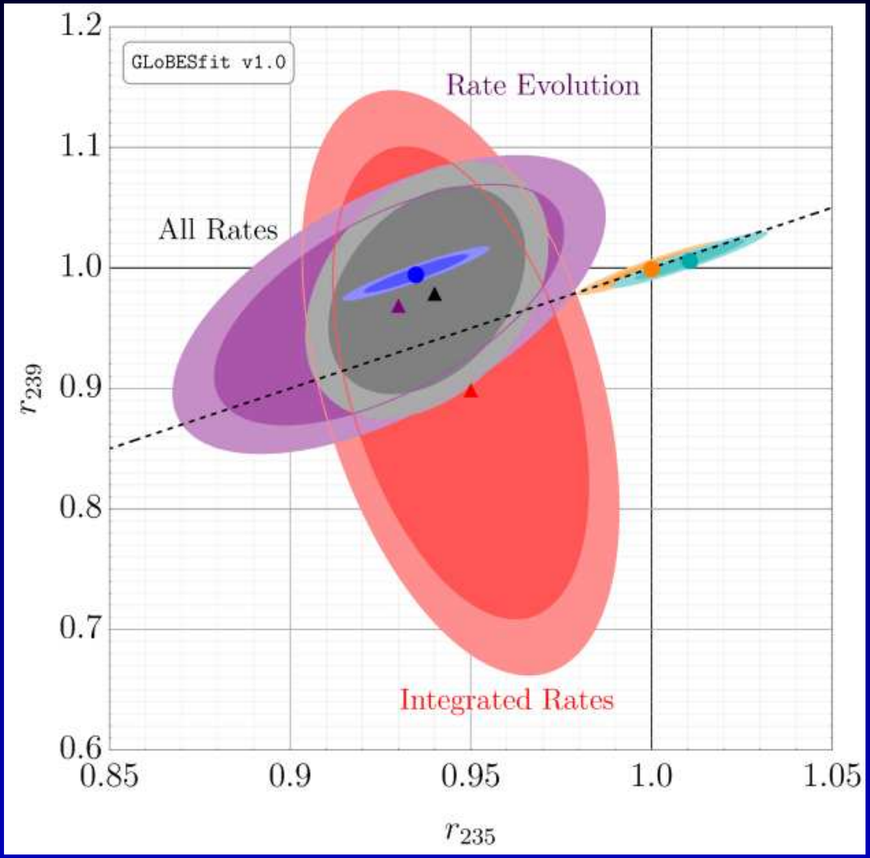
3 different flux models, data from 2 different experiments

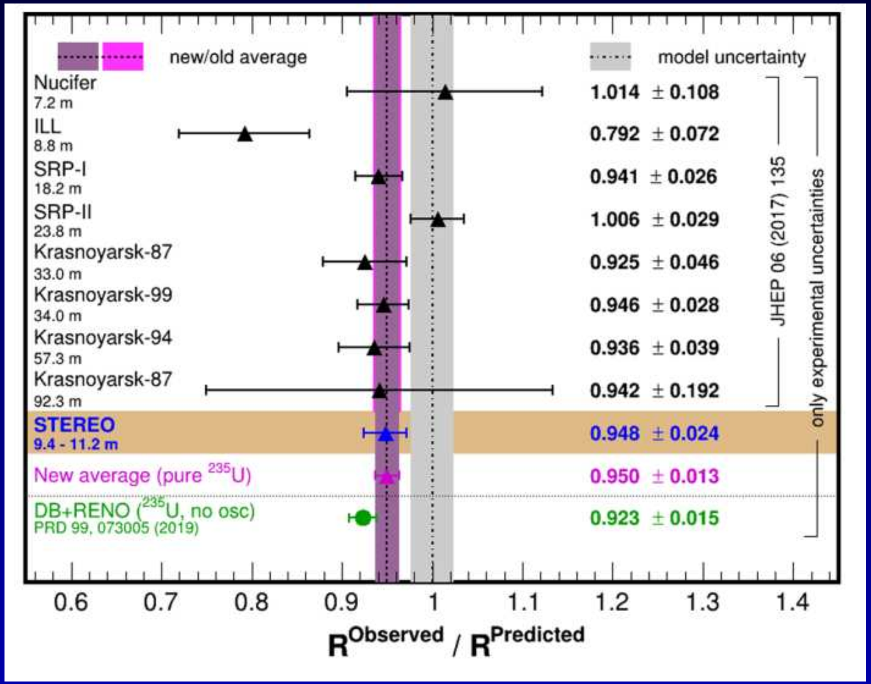
Except for U235:
+ the models agree within error bars
+ the models agree with neutrino data

U235 has smallest error bars, not surprising that discrepancies show up first.

Berryman, PH, 2020

Fuel evolution



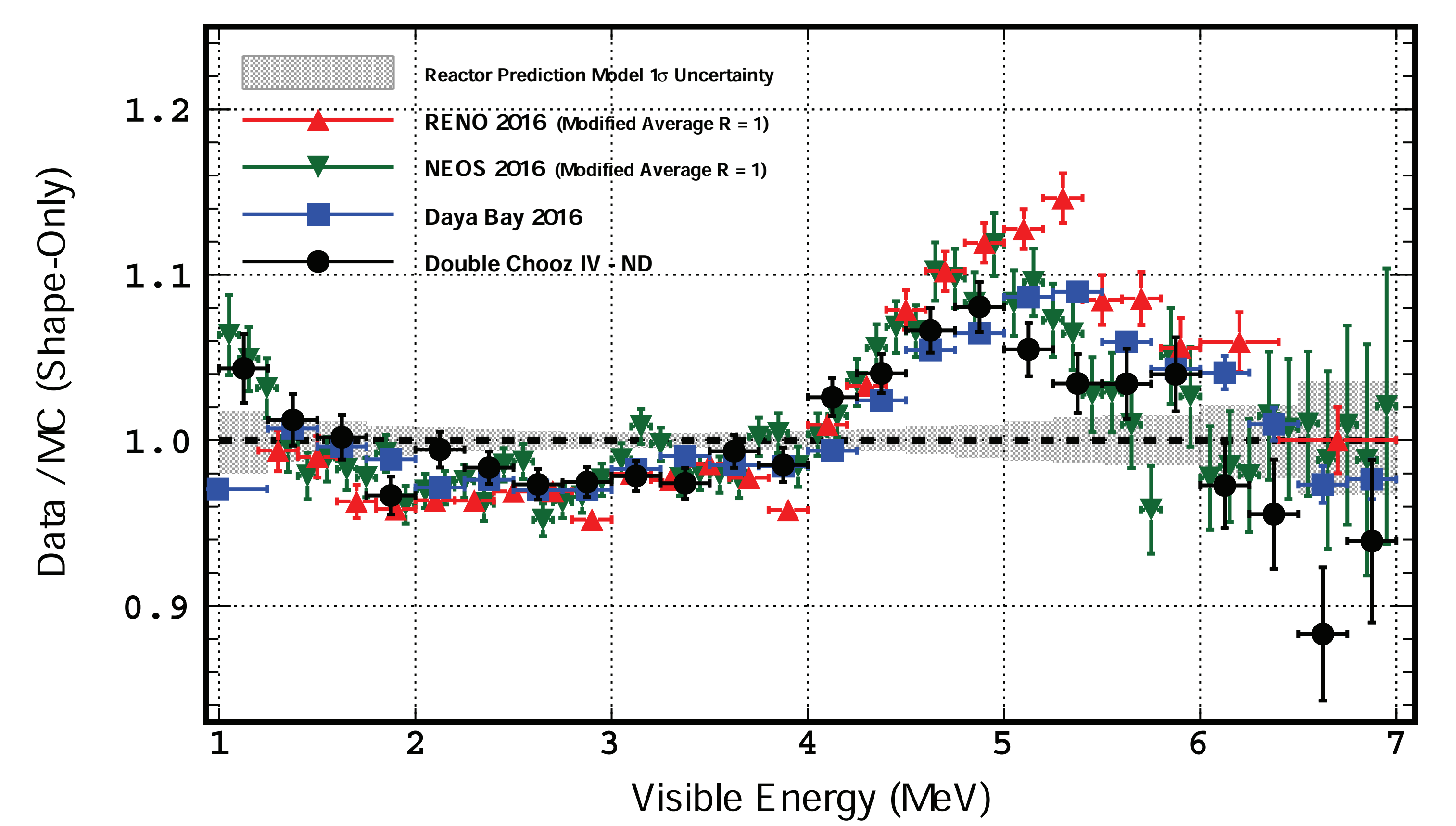


STEREO, 2020

Berryman, PH, 2020

U235 seems to "own" all of the deficit.

The 5 MeV bump

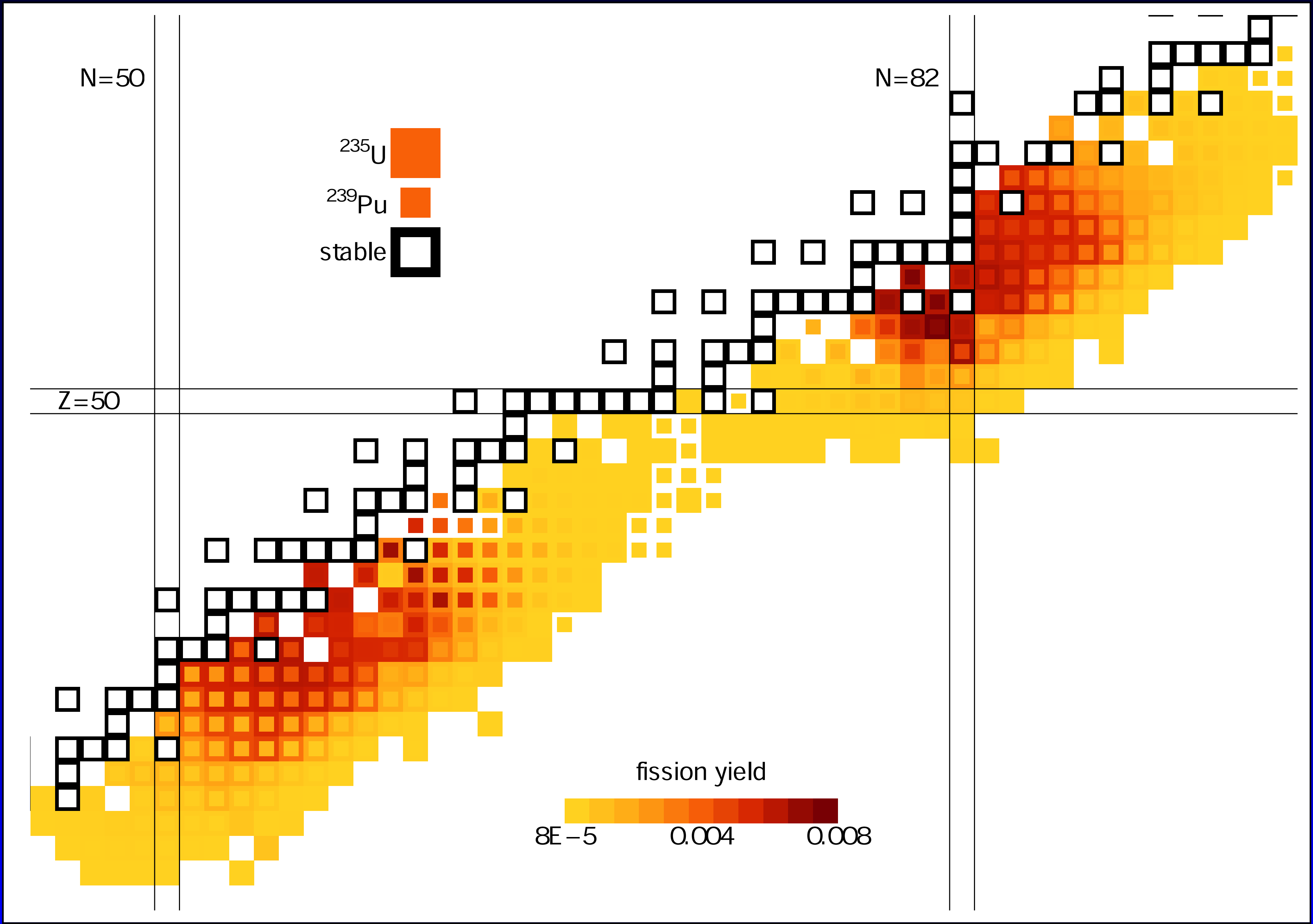


Double Chooz 2019

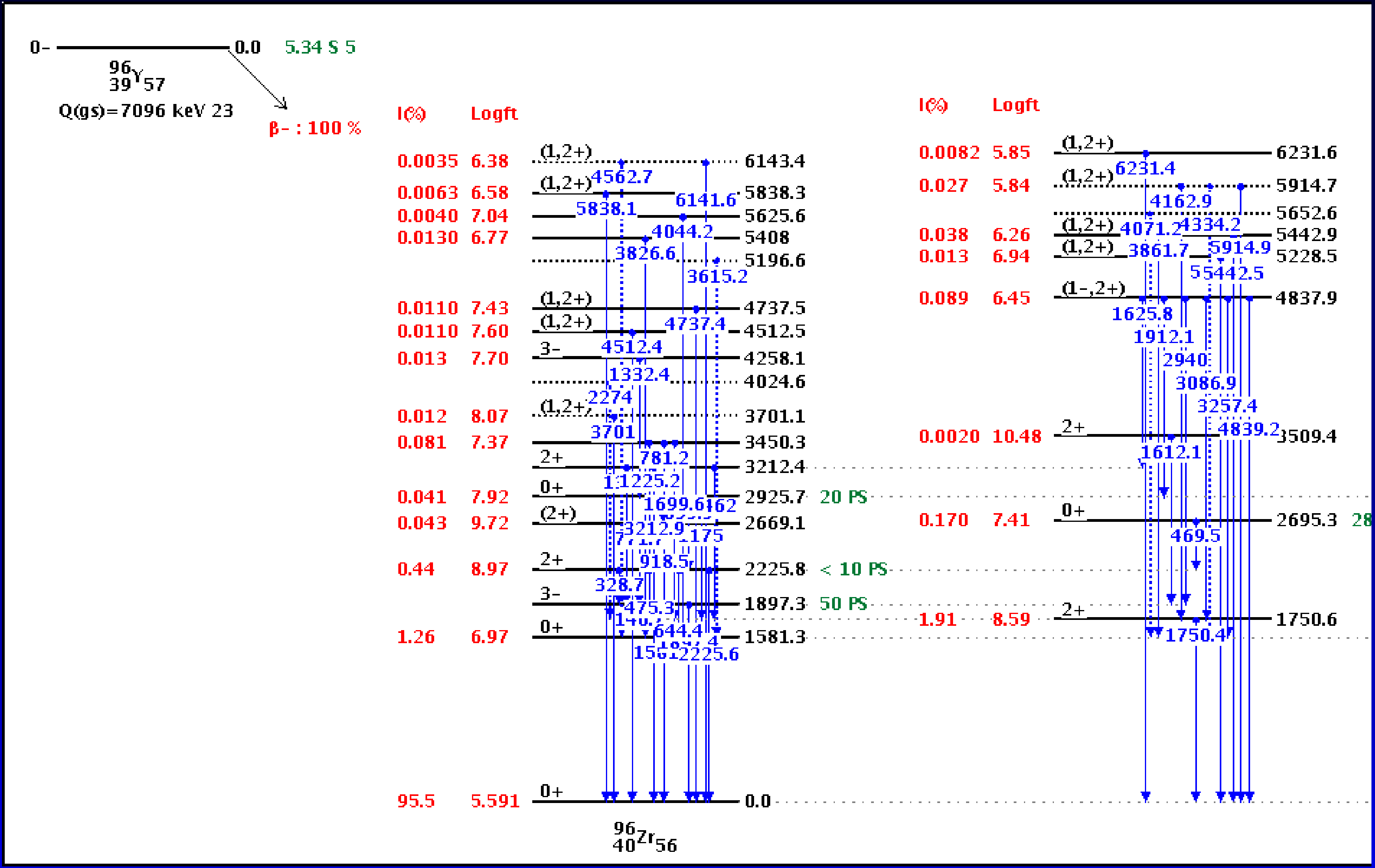
Contains only 0.5% of all neutrino events – not important for sterile neutrinos

Yet, statistically more significant than the RAA!

Why is this so complicated?



β-branches



Two ways to predict

Summation calculations

Fission yields
Beta yields

Problem: databases are insufficient & difficulty of assigning an error budget

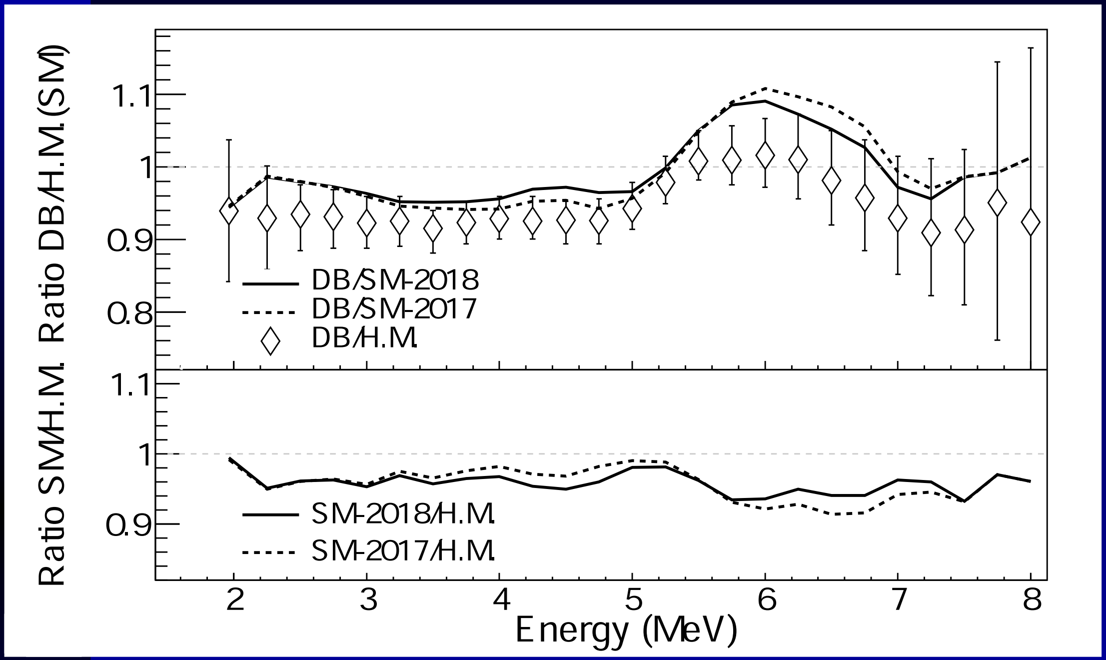
Conversion calculations

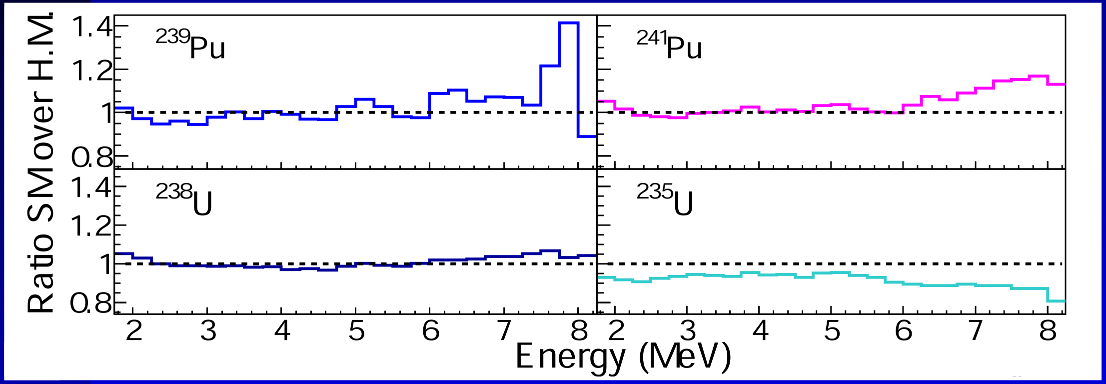
Cumulative beta spectra
Z_{eff} from databases

Problem: single set of cumulative beta spectra & forbidden corrections have to rely on databases

In both approaches, one has to deal with:
- Forbidden decays
- Weak magnetism corrections
- Non-equilibrium corrections
- Structural materials in the reactor

Summation method – EF





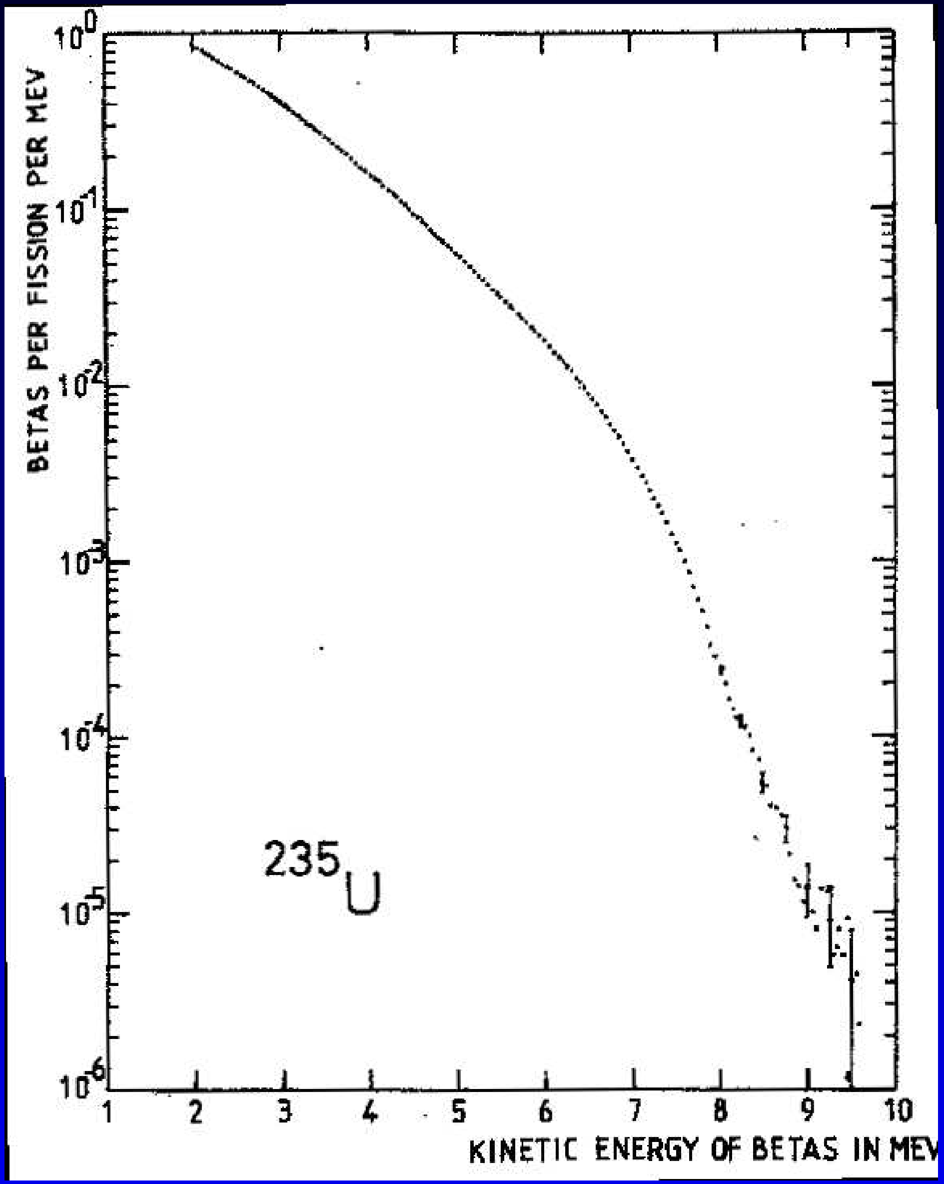
Estienne *et al.*, 2019

Take fission yields from database.

Take beta decay information from database.

For the most crucial isotopes use β-feeding functions from total absorption γ spectroscopy.

Conversion method – HM



Schreckenbach, *et al.* 1985.

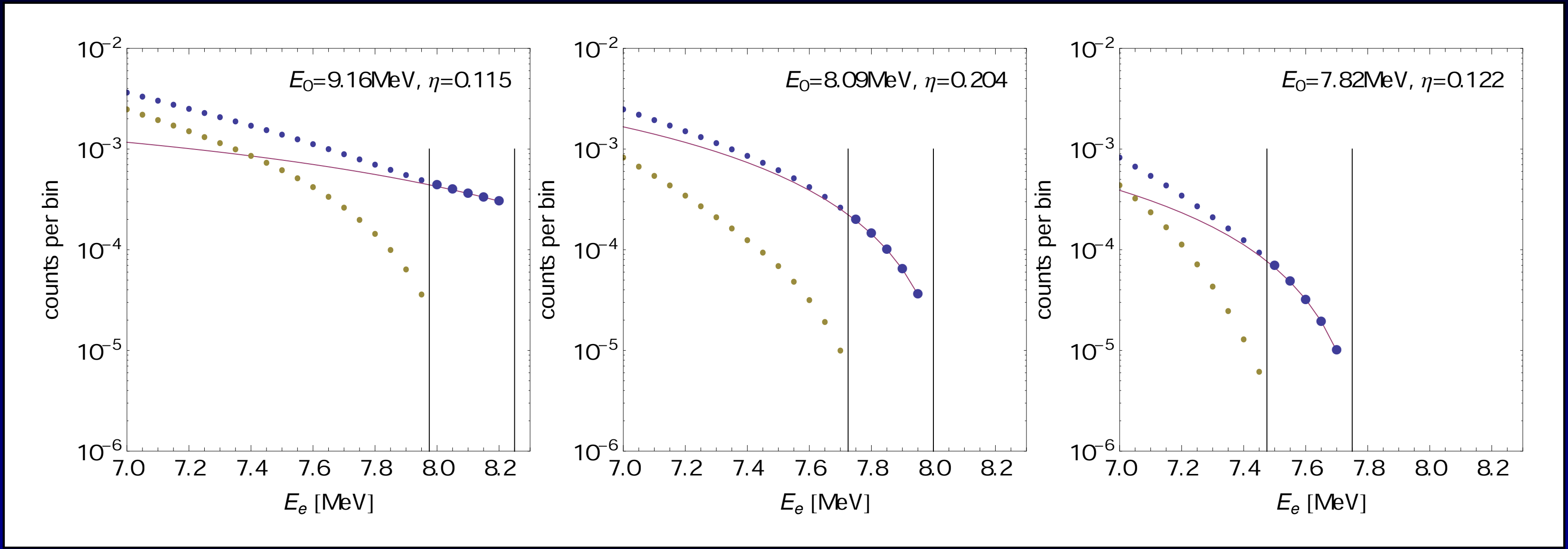
^{235}U foil inside the High Flux Reactor at ILL

Electron spectroscopy with a magnetic spectrometer

Same method used for ^{239}Pu and ^{241}Pu

Mueller *et al.*, 2011; PH, 2011

Virtual branches



1 – fit an allowed β-spectrum with free normalization η and endpoint energy E_0 the last s data points

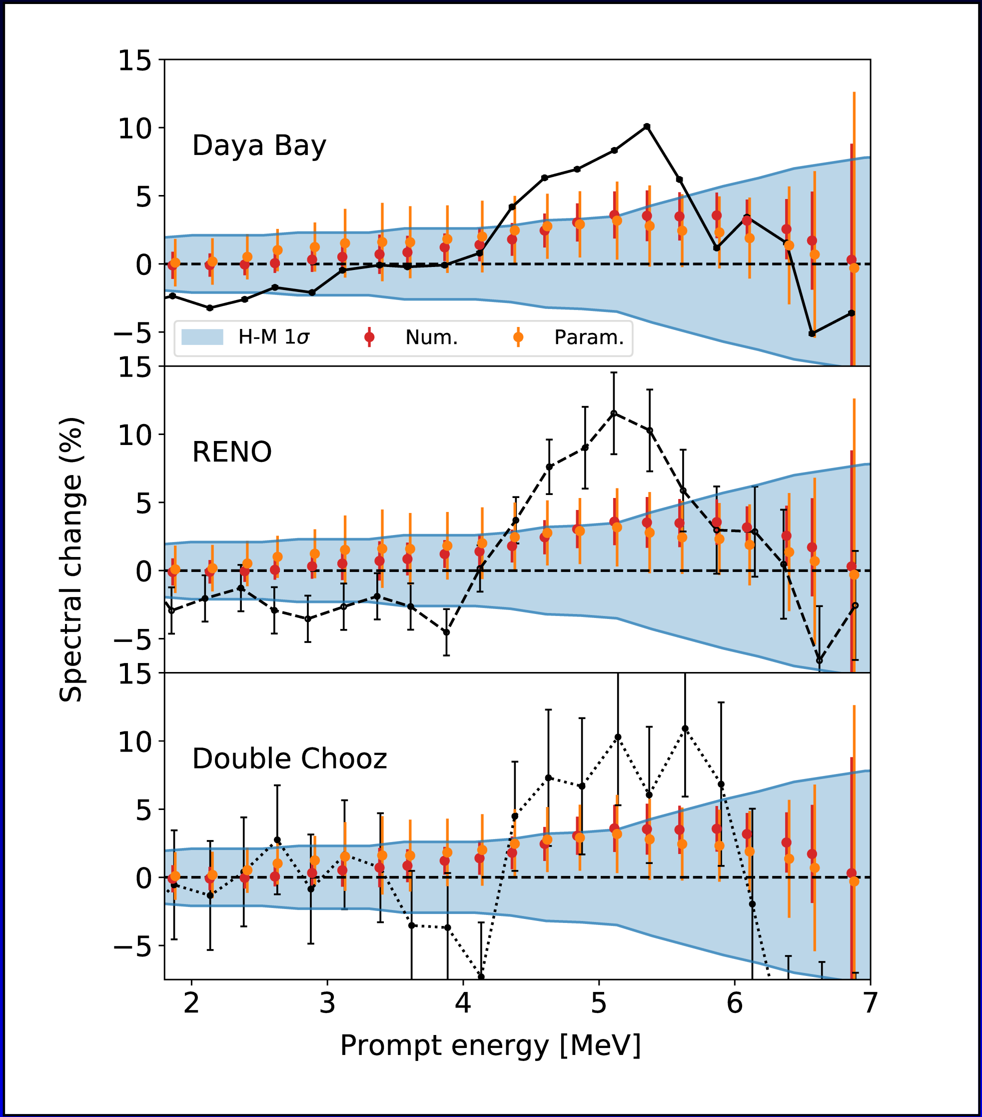
2 – delete the last s data points

3 – subtract the fitted spectrum from the data

4 – goto 1

Invert each virtual branch using energy conservation into a neutrino spectrum and add them all.

Shell model – HKSS



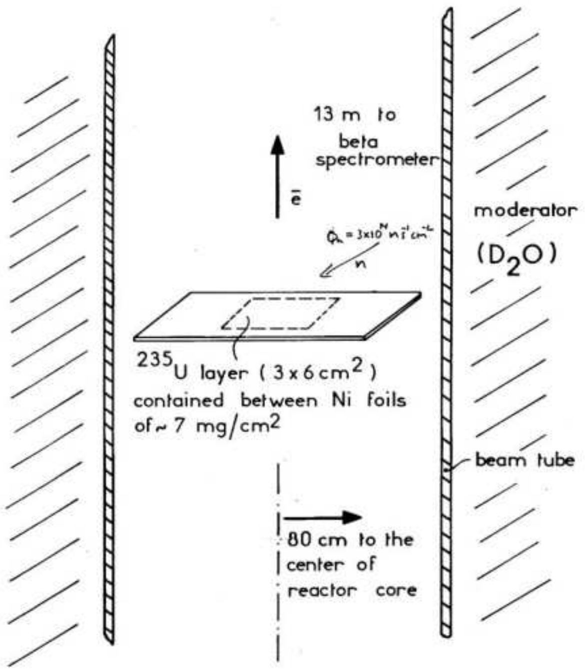
Hayen, *et al.* 2019

Forbidden decays major source of systematic.

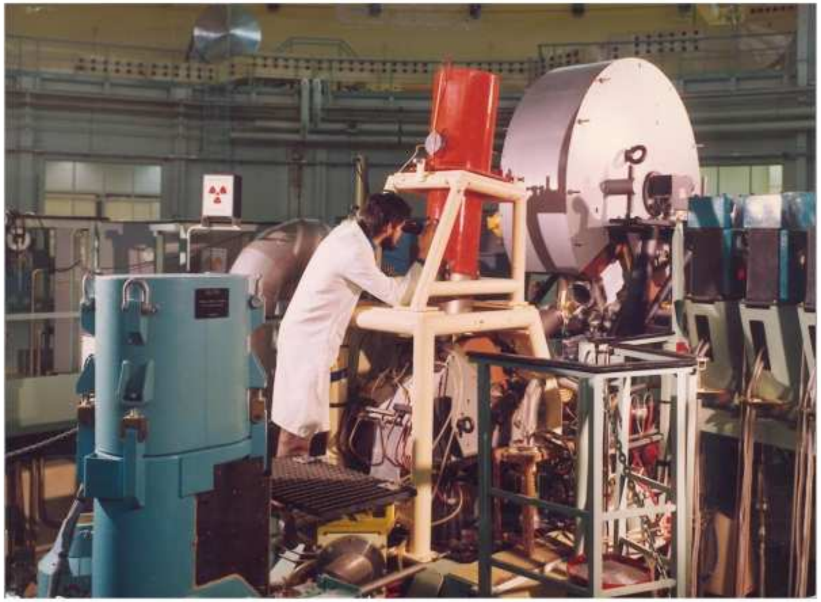
Microscopic shell model calculation of 36 forbidden isotopes, otherwise similar to HM.

Increases the IBD rate anomaly by 40%, but the uncertainty increases by only 13% relative to HM

Kill BILL?



SCHEMATIC VIEW OF THE TARGET SITE



Magnetic BILL spectrometer at ILL, 1972-1991

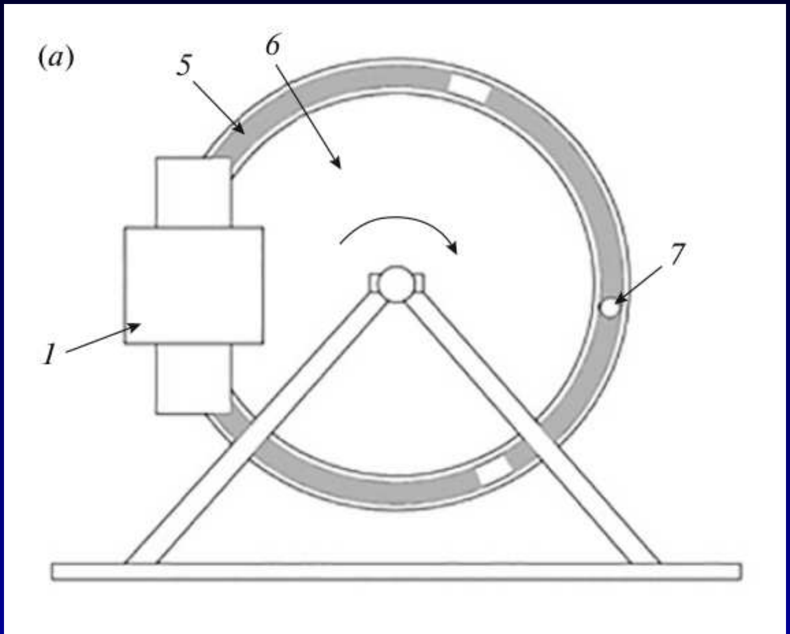
(Electron detector in focal plane: multi chamber proportional counter in transmission, rear mounted scintillator in coincidence)

Neutron flux calibration standards different for U235 and Pu239: 207Pb and 197Au respectively.

Combined with potential differences in neutron spectrum – room for a 5% shift of U235 normalization?

A. Letourneau, A. Onillon, AAP 2018

2021 beta measurement

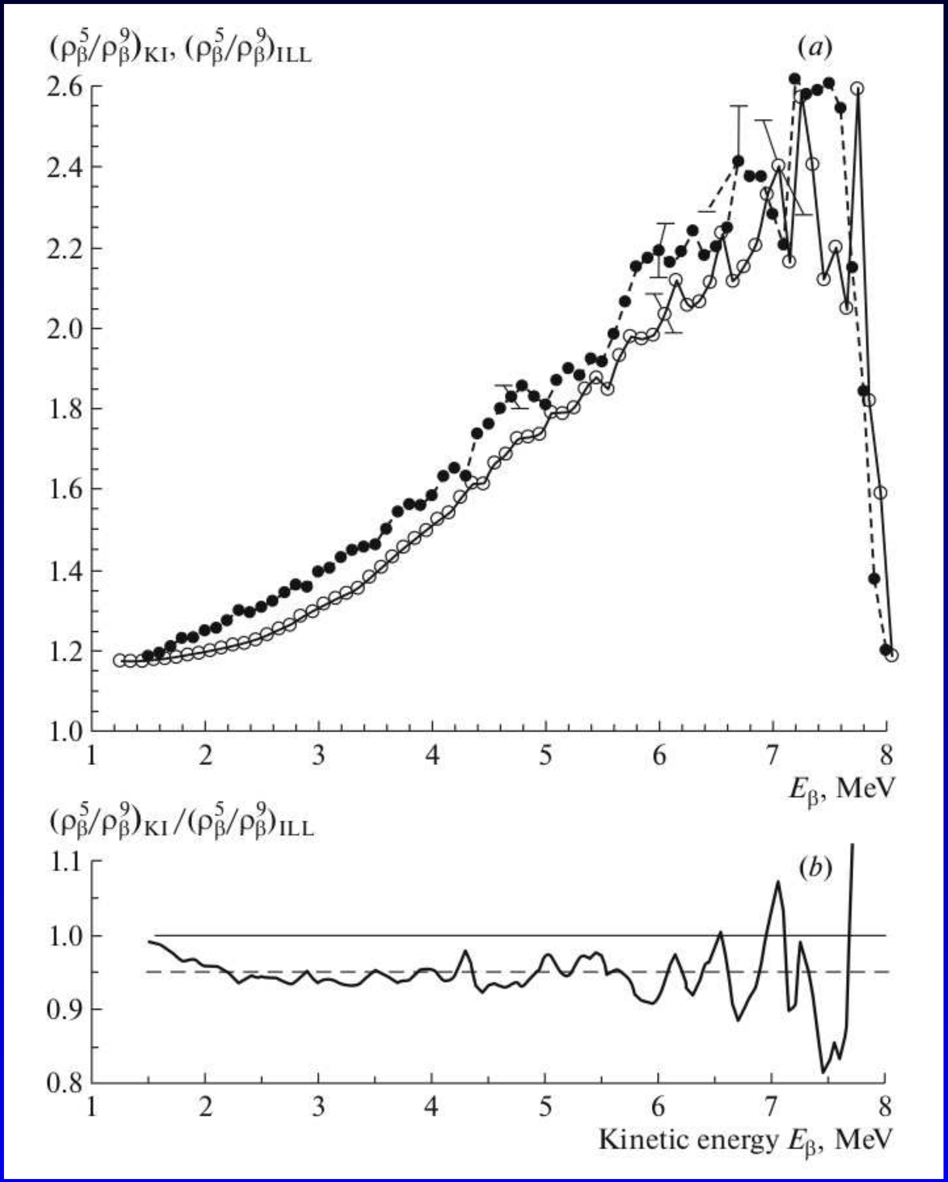


Relative measurement of U235 and Pu239 targets under identical conditions.

Beta detection with stilbene.

This slide and the following are based on V. Kopeikin, M. Skorokhvatov, O. Titov (2021) and V. Kopeikin , Yu. Panin, A. Sabelnikov (2020) and we will refer to this as the Kurchatov Institute (KI) data.

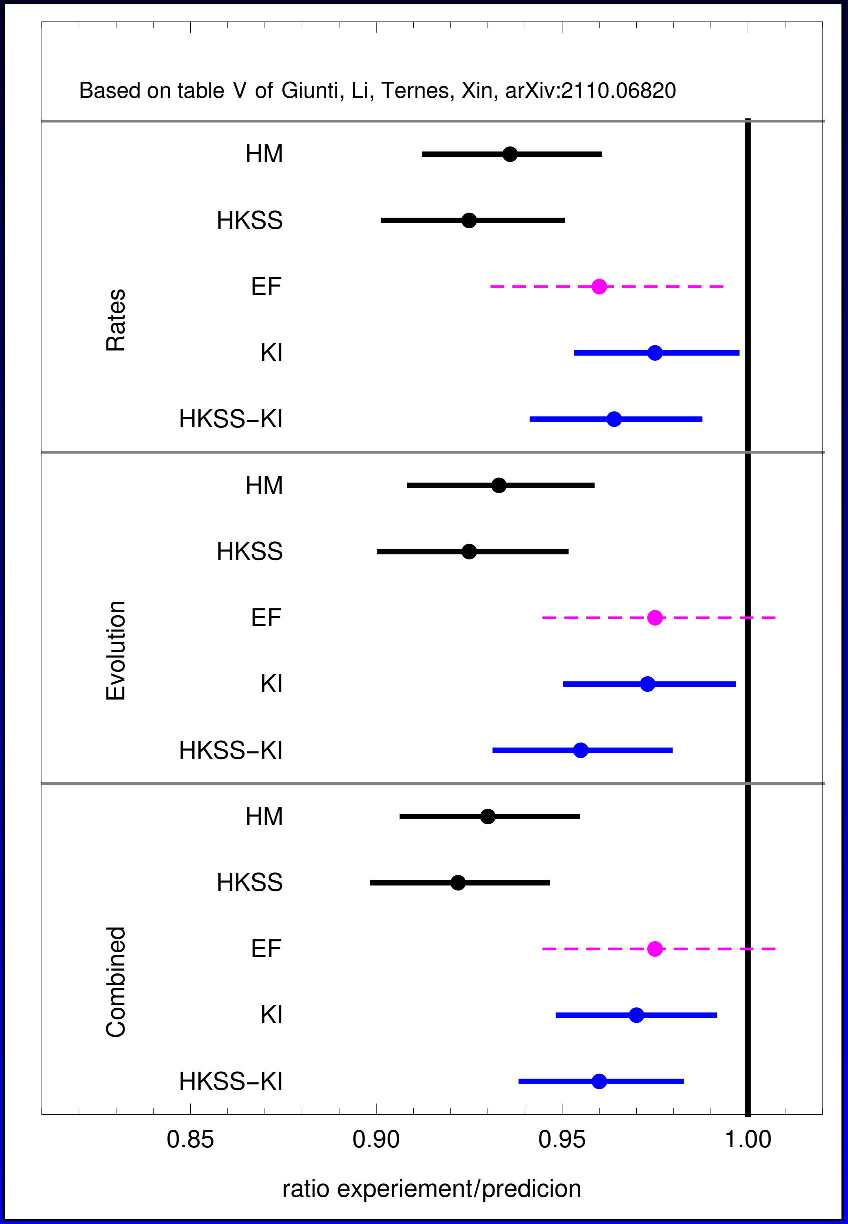
2021 beta results



At relevant energies the new measurement is about 5% below the previous one

Systematics is difficult in these measurements, but no obvious issues.

2021 beta impact

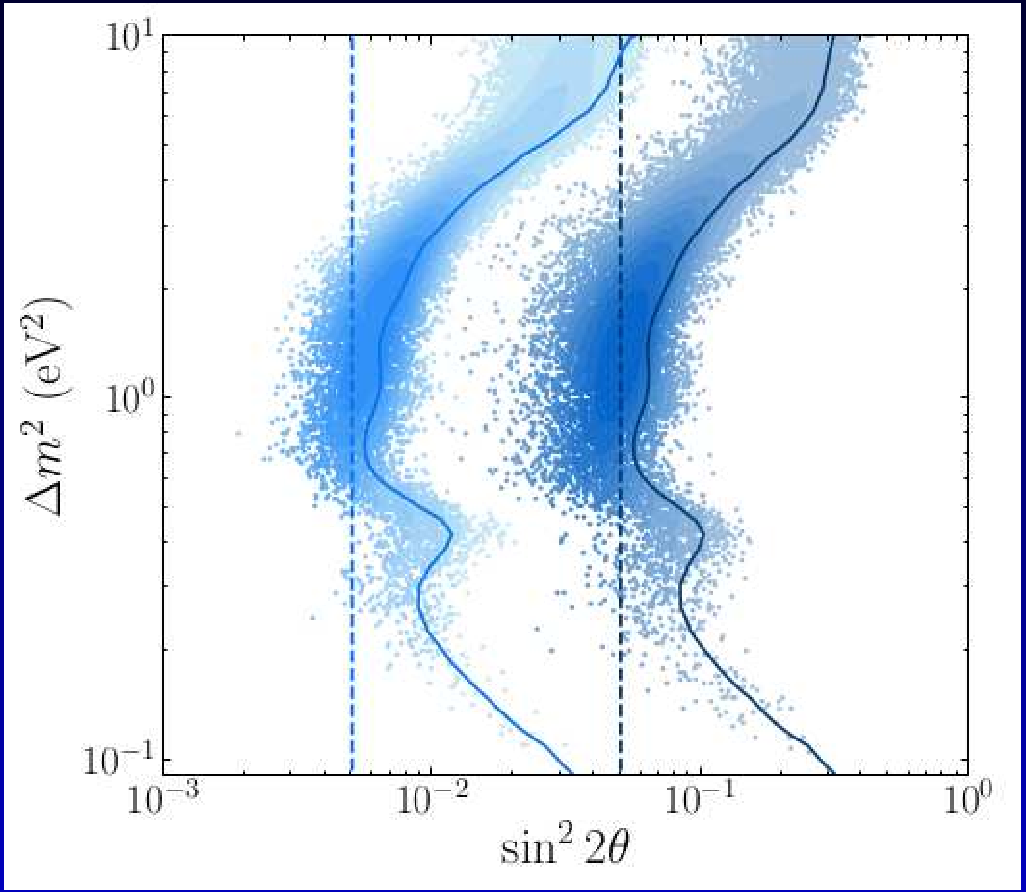


HM – conversion
HKSS – conversion
+ forbidden decays
EF – summation
unclear theory error
KI – HM + KI data
HKSS+KI – HKSS +KI

With the KI correction agreement between summation and conversion improved.

RAA significance reduced to less than 2σ

Oscillations are everywhere



Hypothetical two baseline experiment

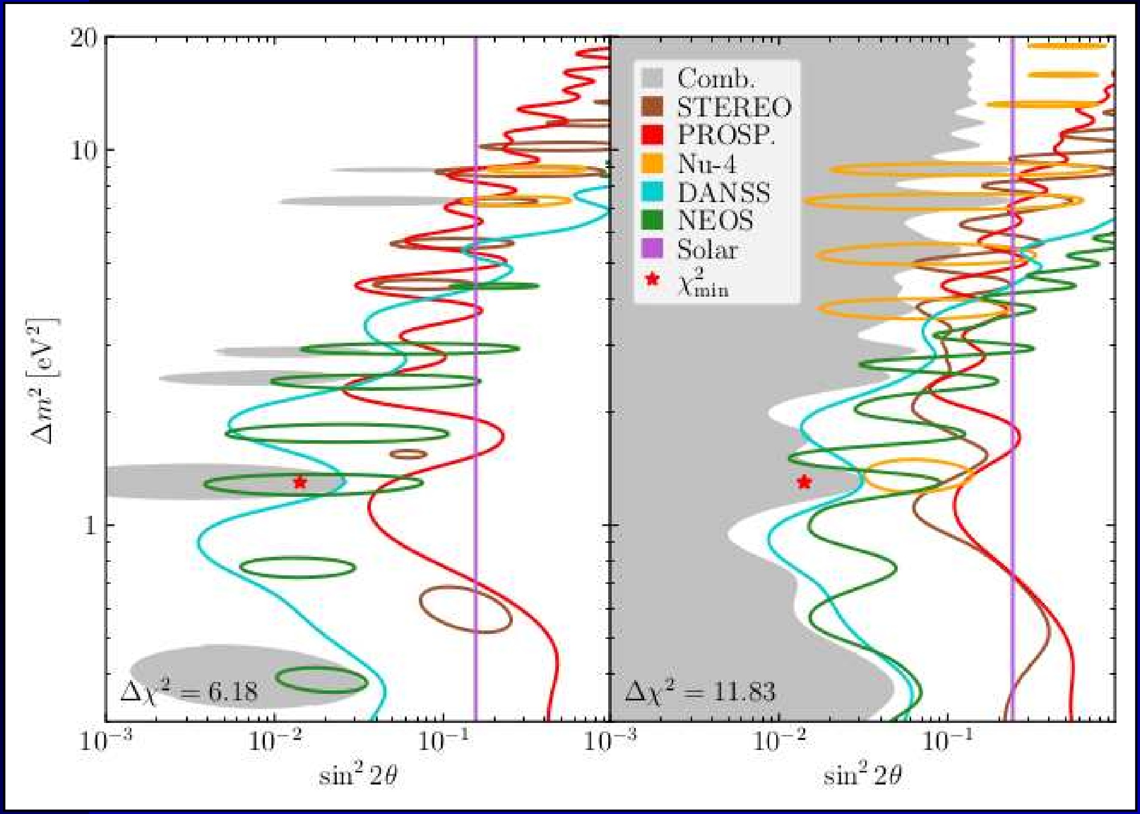
Maximum likelihood estimate is biased and not consistent.

Wilks' theorem does not apply

Coloma, PH, Schwetz, 2020

Agostini, Neumair, 2019; Silaeva, Sinev, 2020; Giunti, 2020
PROSPECT+STEREO, 2020

Global reactor data



Berryman, Coloma, PH, Schwetz, Zhou 2021

$\Delta\chi^2 = 7.3$ for no-oscillation hypothesis, flux model-independent

Solar data provides a strong constraint at large $\sin^2 2\theta$

Feldman-Cousins p-value 24.7% (1.1σ)
$\Rightarrow$ no evidence for oscillation

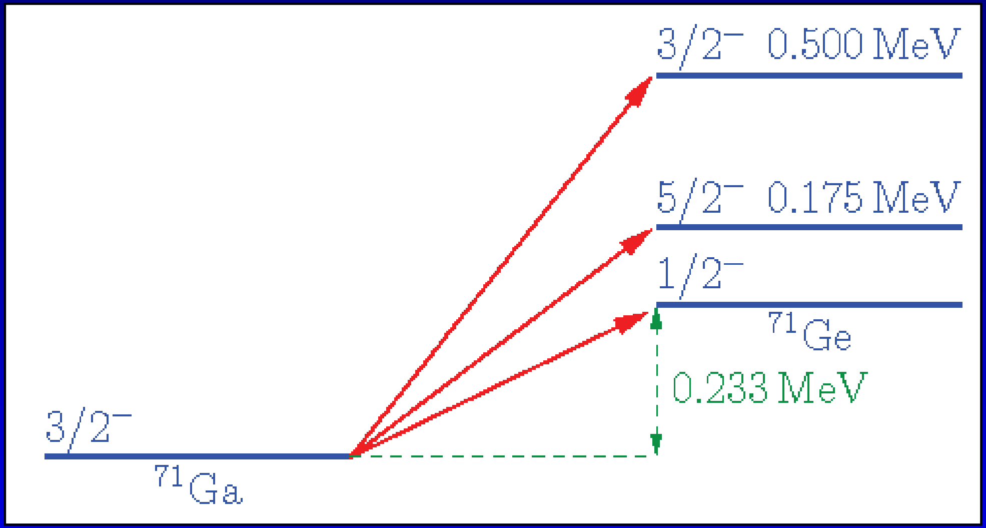
No tension with Neutrino-4

Gallium anomaly

Radioactive source experiments

GALLEX	GALLEX	SAGE	SAGE	BEST (inner)	BEST (outer)
0.953 ± 0.11	0.812 ± 0.10	0.95 ± 0.12	0.791 ± 0.084	0.791 ± 0.044	0.766 ± 0.045

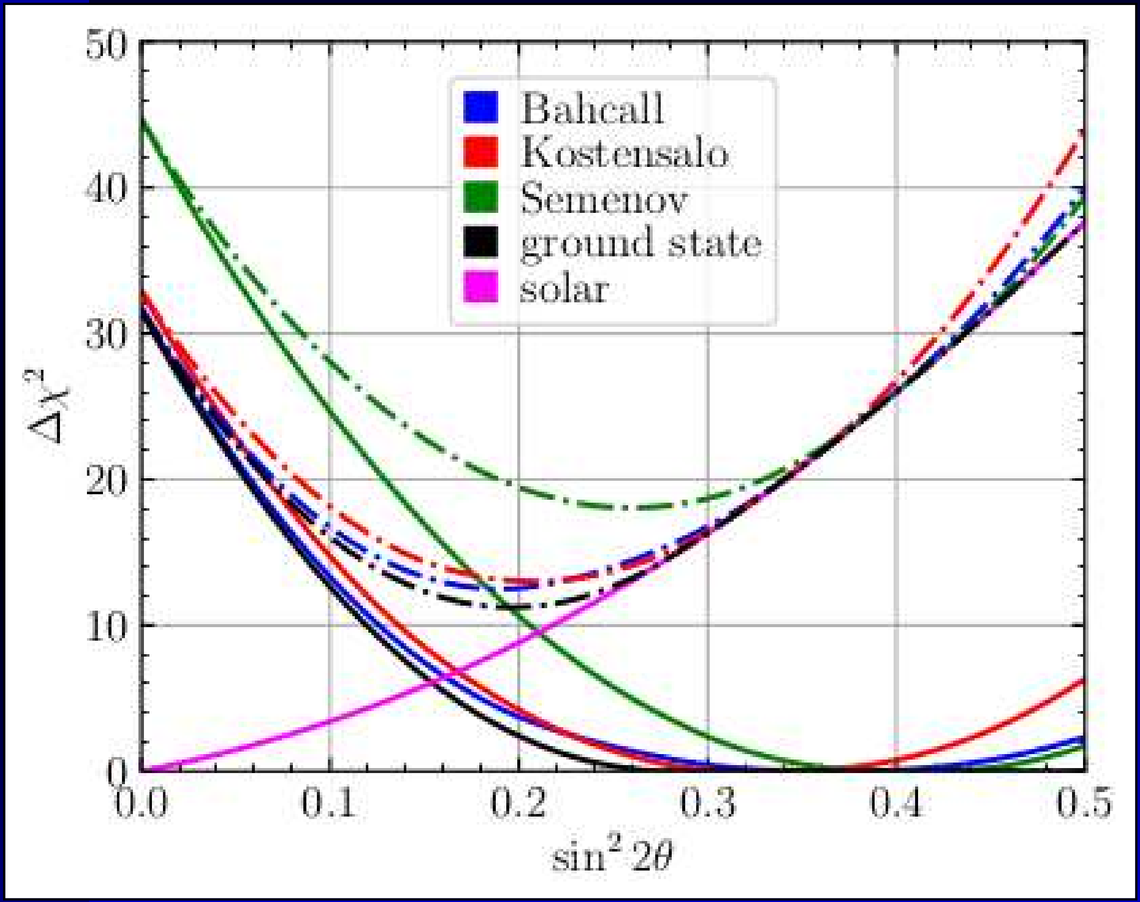
Nuclear matrix elements



ground state follows from beta decay

excited states?

Gallium and solar



BCHSZ 2021

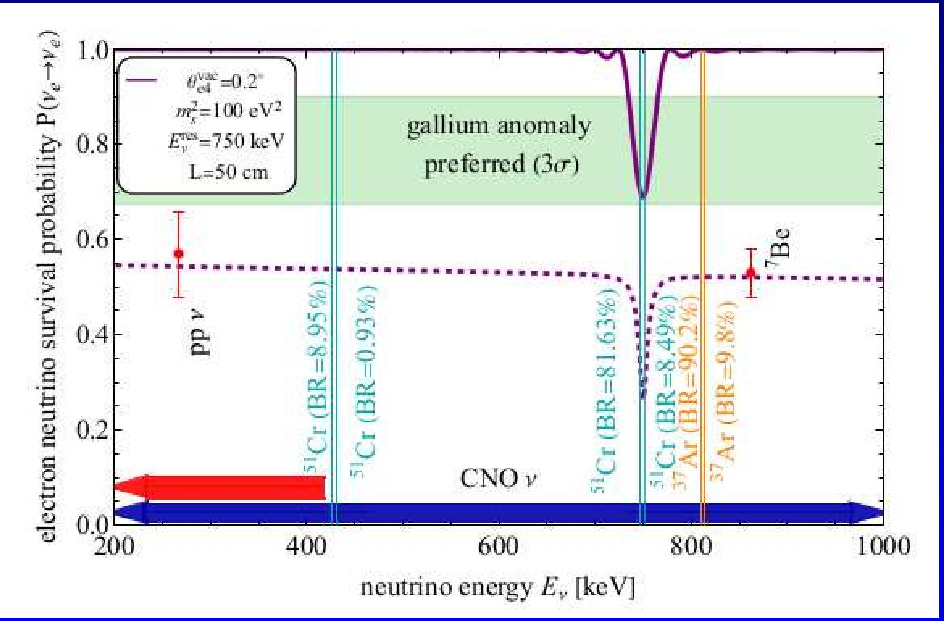
Any model for the matrix element yields than 5σ for the gallium anomaly, even the ground state contribution by itself.

BUT, there is a more than 3σ tension with solar data.

Explanations?

Experimental reasons (all disfavored)

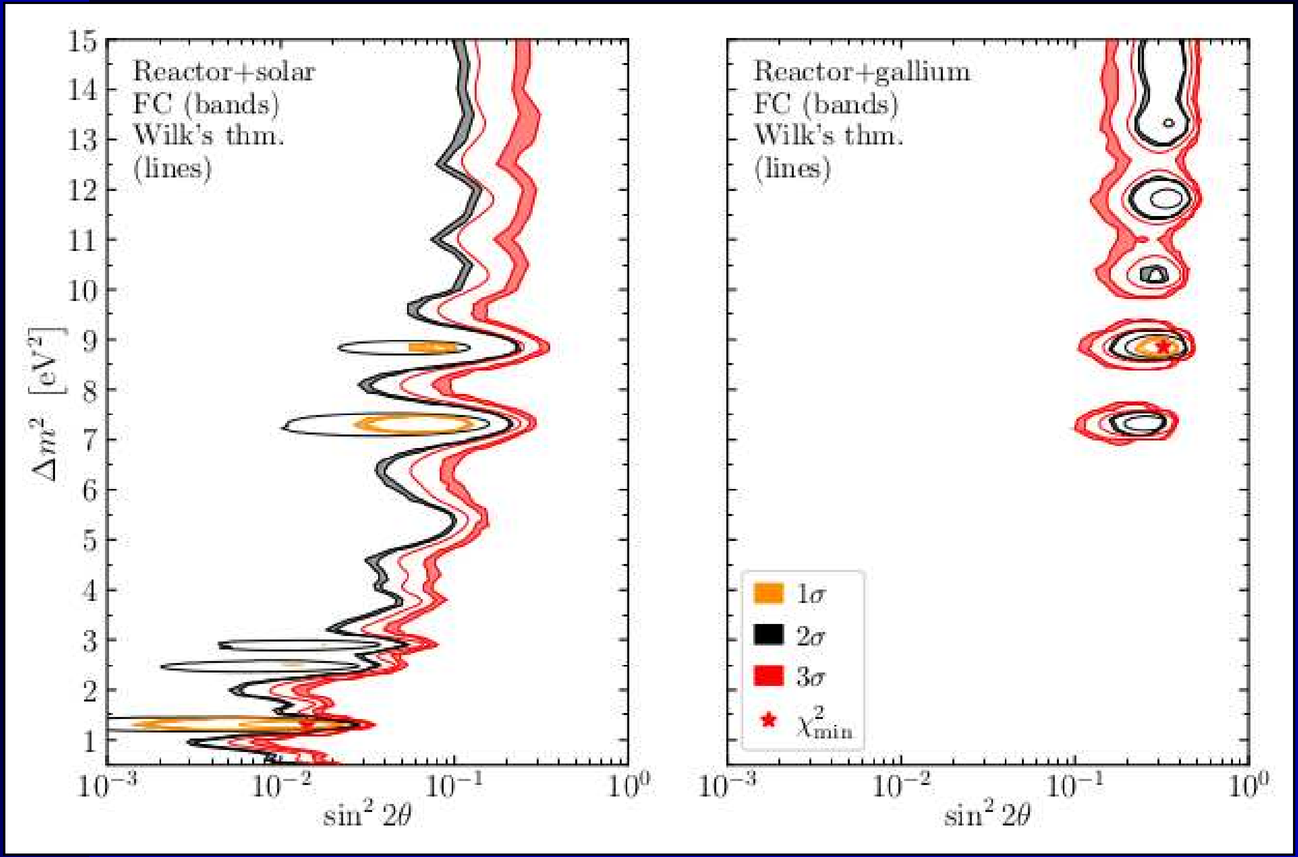
longer ^{71}Ge halflife	smaller matrix element, smaller cross section
	see also Giunti 2023
new excited state in ^{71}Ga	would change the matrix element
larger BR($^{51}\text{Cr} \to {}^{51}\text{V}^*$)	changes relation between decay heat and source strength
^{71}Ge extraction efficiency	some ^{71}Ge does not get extracted



Engineer a MSW resonance at the ^{51}Cr neutrino energy.

Brdar, Gehrlein, Kopp, 2023

All together now



Full FC analysis

Reactor+solar: 1.1σ

Reactor+gallium: 5.3-5.7σ

BCHSZ 2021

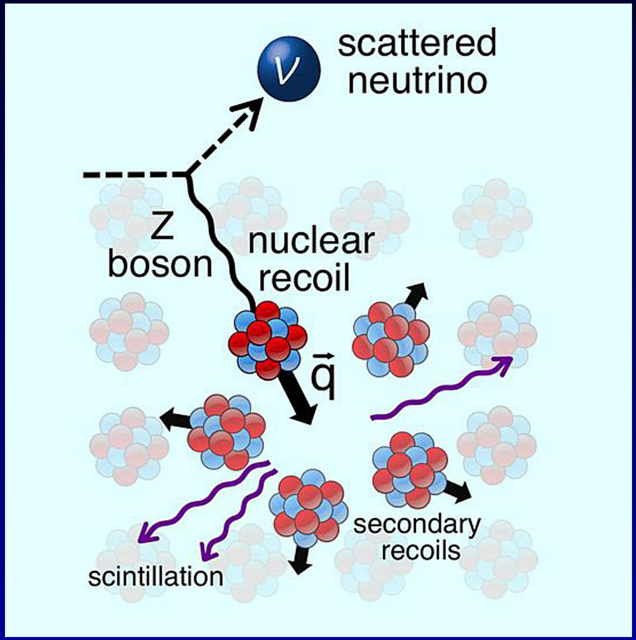
Evidence for neutrino disappearance entirely driven by gallium results,
only tension gallium vs solar at $> 3\sigma$.

CEvNS

Coherent elastic neutrino nucleus scattering (CEvNS) is threshold-less.

$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} N^2 M_N \left(1 - \frac{M_N T}{2E_\nu^2}\right)$$

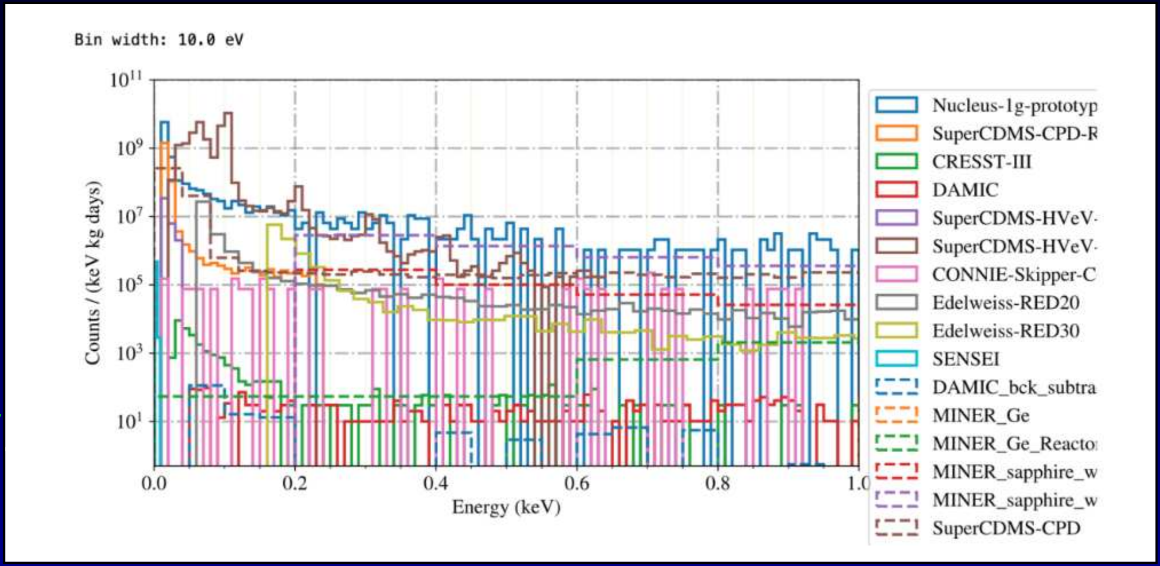
T recoil energy, N neutron number



- Measured for the 1st time in 2017 by COHERENT.
- Perfect proxy for dark matter detection
- Requires nuclear recoil (!) threshold of less than 1 keV

Hic sunt leones

Shown is the data of a number of different dark matter/CEvNS experiments below 1 keV as reported at the EXCESS workshop 2021 https://indico.cern.ch/event/1013203/



Observed accross a wide range of technologies and shielding configurations – origin unknown!

Reactor CEvNS is a critical testbed for dark matter detection.

Optical detection of crystal defects as technological alternative? Goel, Cogswell, PH 2021

Disappearance and appearance

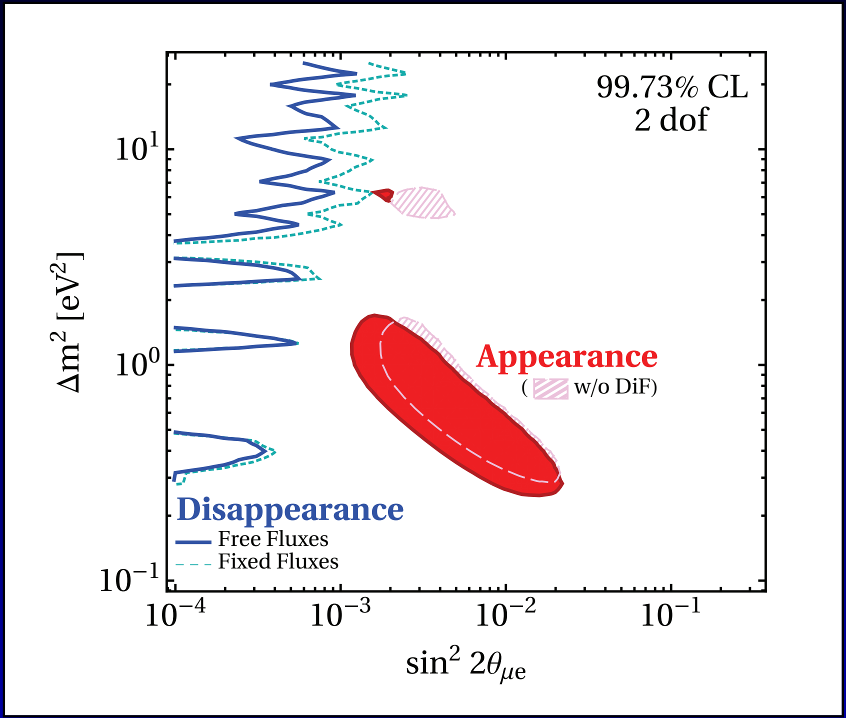
$\nu_\mu \to \nu_e$ requires that the sterile neutrino mixes with both ν_e and ν_μ

$\Rightarrow$ there must be effects in *both* $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_\mu$

Up to factors of 2, the energy averaged probabilities obey

$$P_{\mu e} \lesssim (1 - P_{\mu\mu})(1 - P_{ee})$$

Disappearance data



Dentler, *et al.*, 2018

$$\sin^2 2\theta_{e\mu} = 4|U_{e4}U_{\mu 4}|^2$$

with $1 - P_{ee} \propto |U_{e4}|^2$
and $1 - P_{\mu\mu} \propto |U_{\mu 4}|^2$

There is (and has been for decades) a strong tension between global appearance data and disappearance data.

Finding a sterile neutrino

All pieces of evidence have in common that they are less than 5 σ effects and they may be all due to the extraordinary difficulty of performing neutrino experiments, if not:

- N sterile neutrinos are the simplest explanation for each data set
- Tension with null results in disappearance remains
- It is difficult for only a sterile neutrino to fit all data
- At this point only the gallium seems to be robust