Reactor Neutrinos
Fluxes and Interactions

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CERN TH Colloquium
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Why reactors?

- 3% of the energy release in fission is in neutrinos – 100 MW for a power reactor or about $\nu\,10^{21}\,\mathrm{s}^{-1}$
- Built for weapons, energy, . . .
  – not paid from physics budget
- Flavor pure source with well understood flux and energy spectrum
- Inverse beta decay provides a well understood, flavor tagging detection reaction with a “large” cross section
- Inverse beta decay has a clean experimental signature – delayed coincidence

Beta decay

Fermi developed a first theory of beta decay (1934):

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

or in a nuclear bound state

$$(Z, A) \rightarrow (Z+1, A) + e^{-} + \nu$$

Inverse beta decay

$$\nu + p \rightarrow n + e^{+}$$

Bethe and Peierls estimate the cross section to be:

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

Neutrinos from fission

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

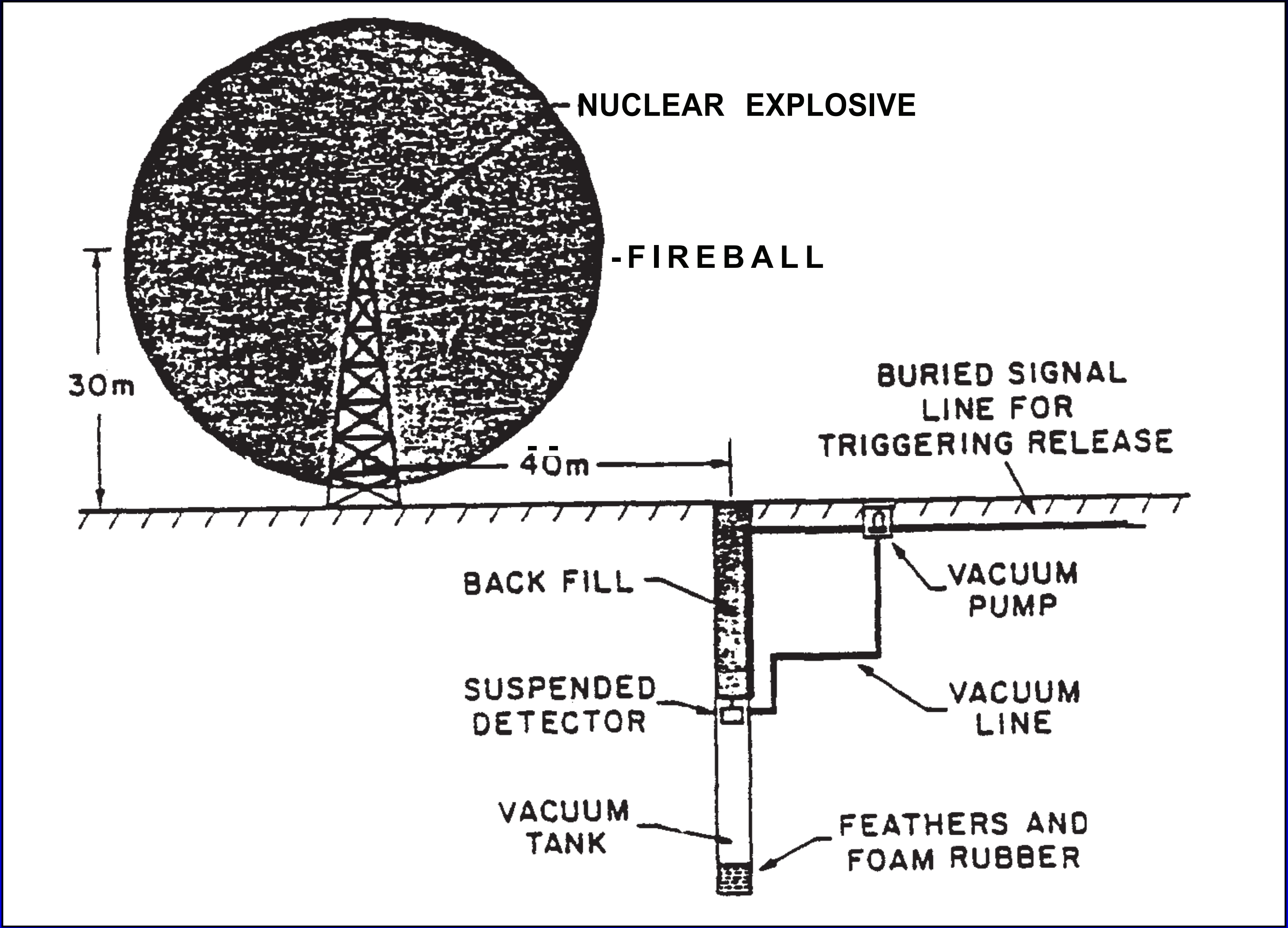
with average masses of X_1 of about A=94 and X_2 of about A=140. X_1 and X_2 have together 142 neutrons.

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

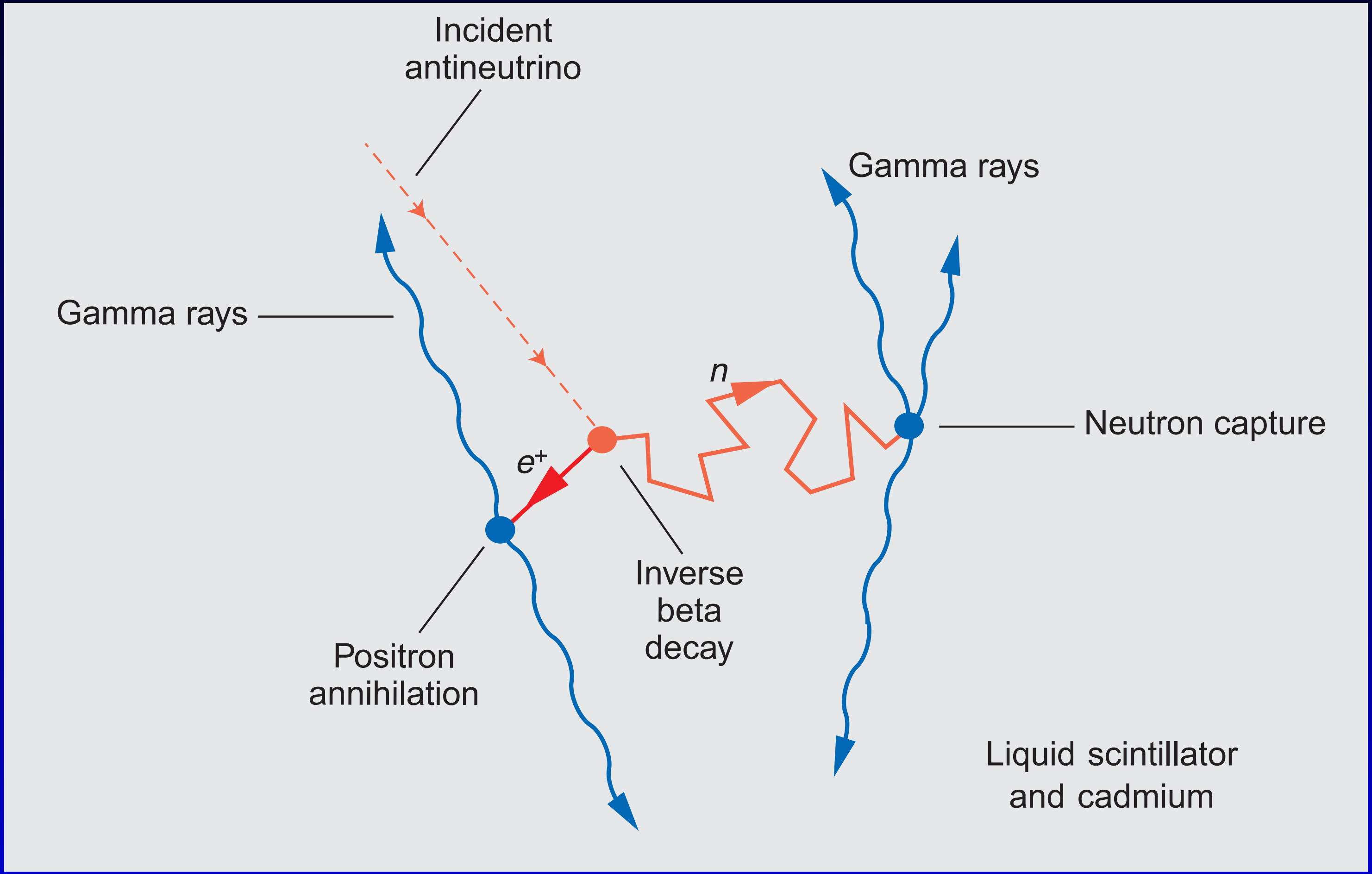


Reines’ Nobel Lecture, 1995

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.

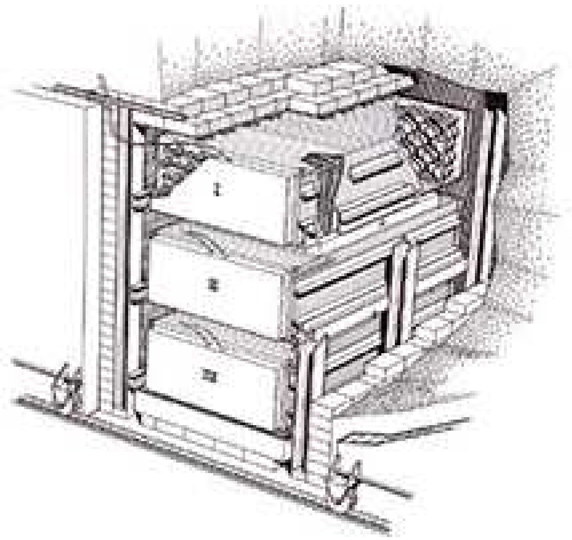
Delayed coincidence

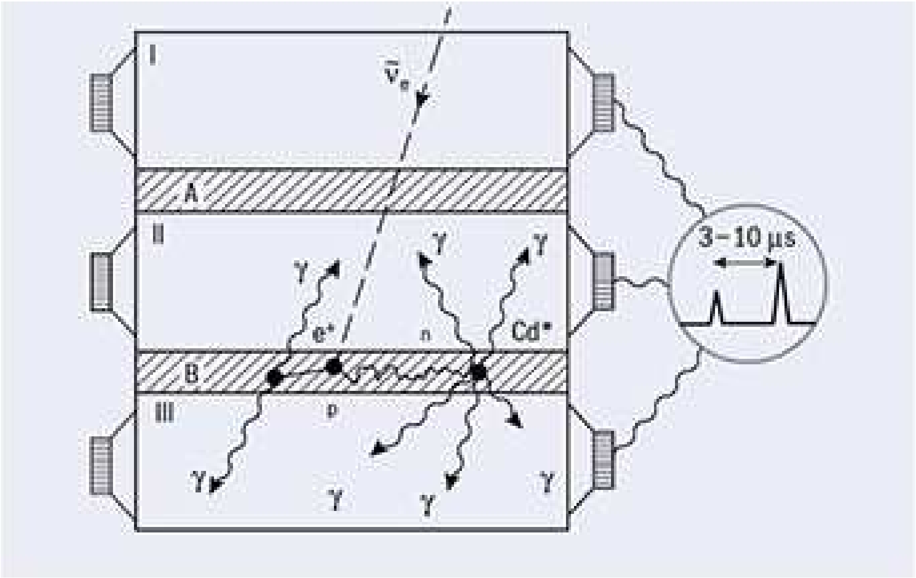


This is the basis for all reactor neutrino experiments since then.

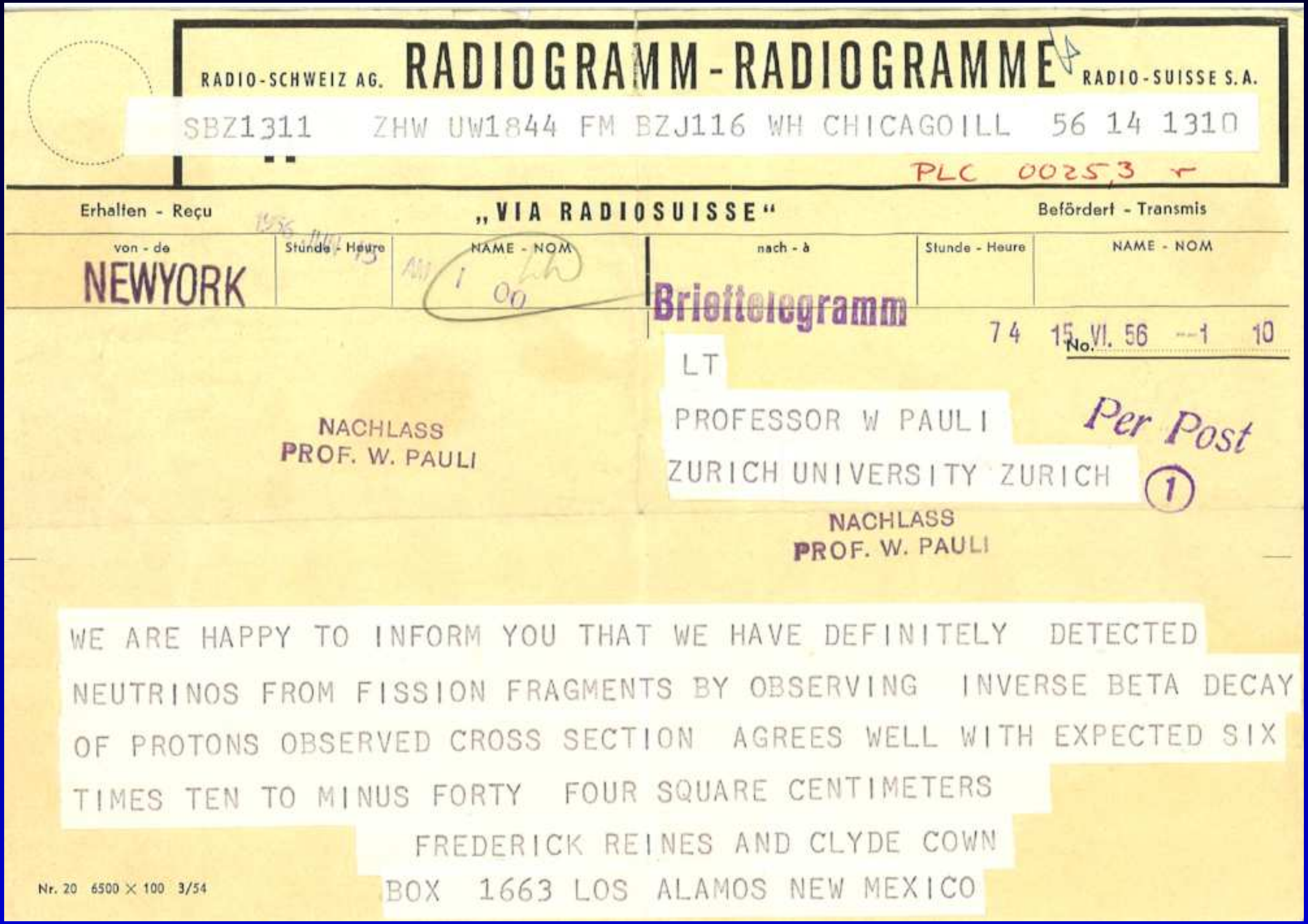
Savannah River

P-reactor became operational in Feb 1954, 500MW, heavy water cooled, plutonium production reactor.





1956



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PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

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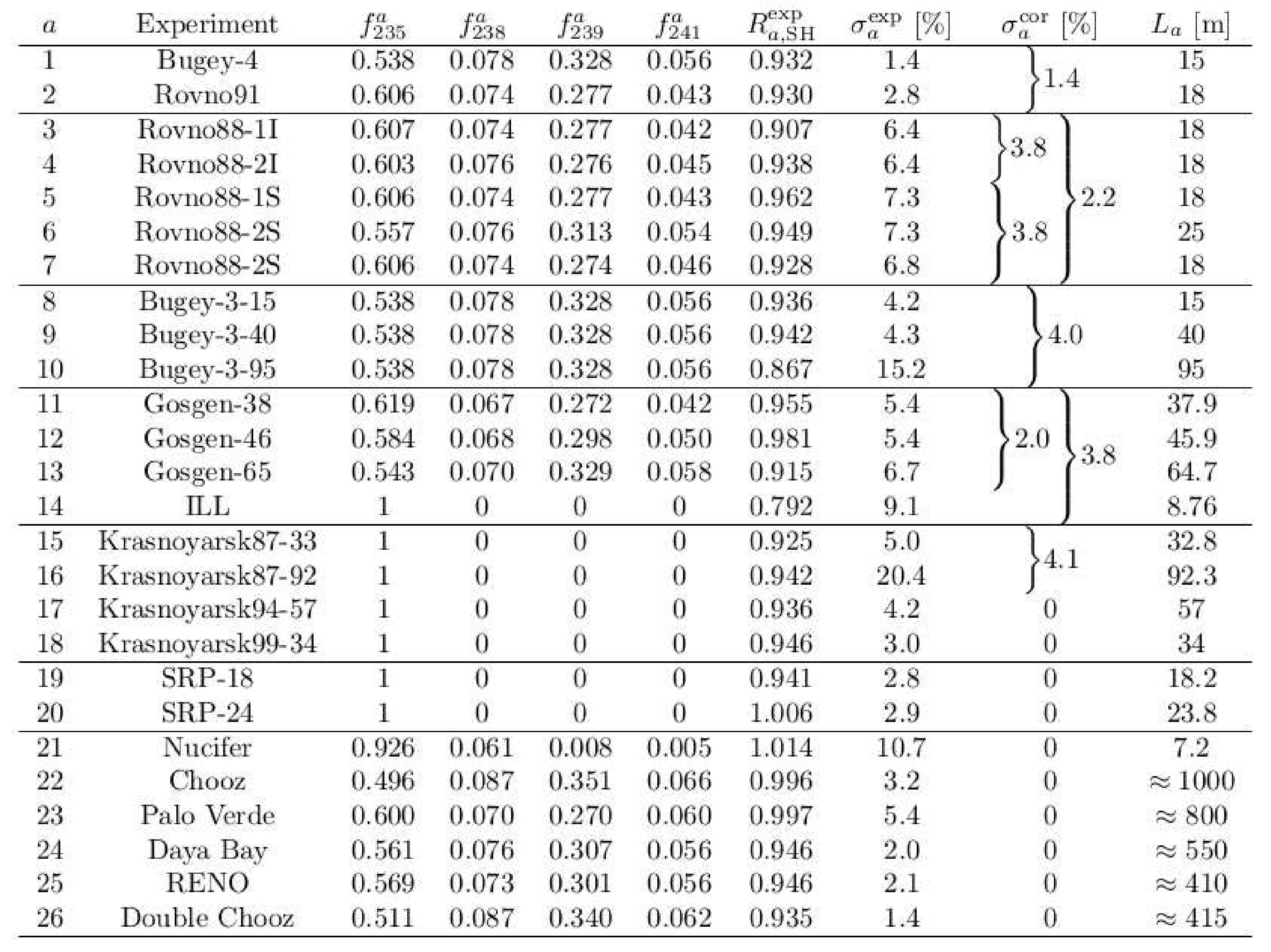
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN
BOX 1663 LOS ALAMOS NEW MEXICO

Nr. 20 6500 × 100 3/54

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

Long list of SBL experiments

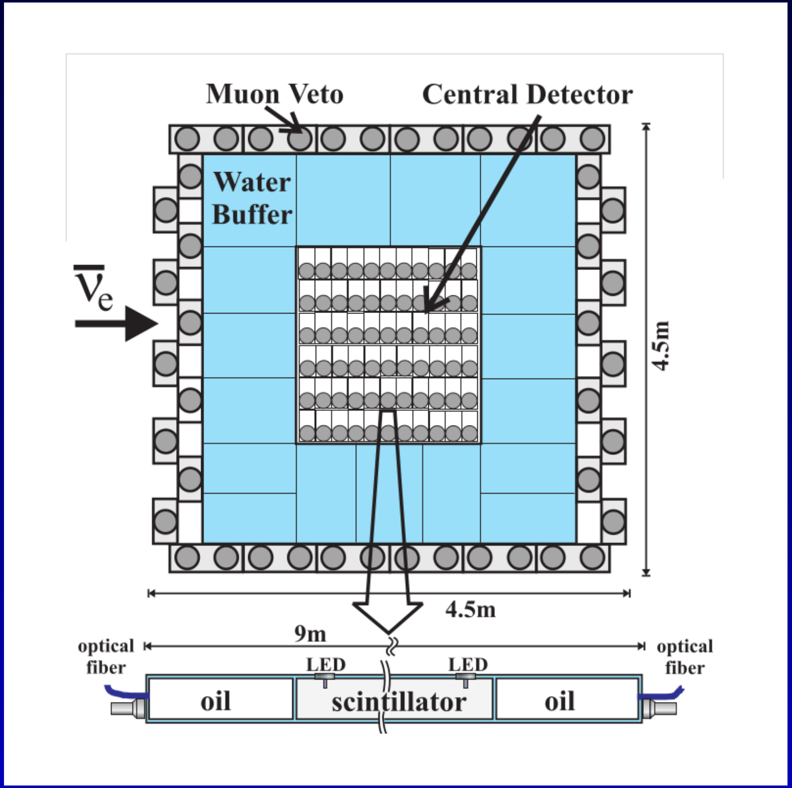


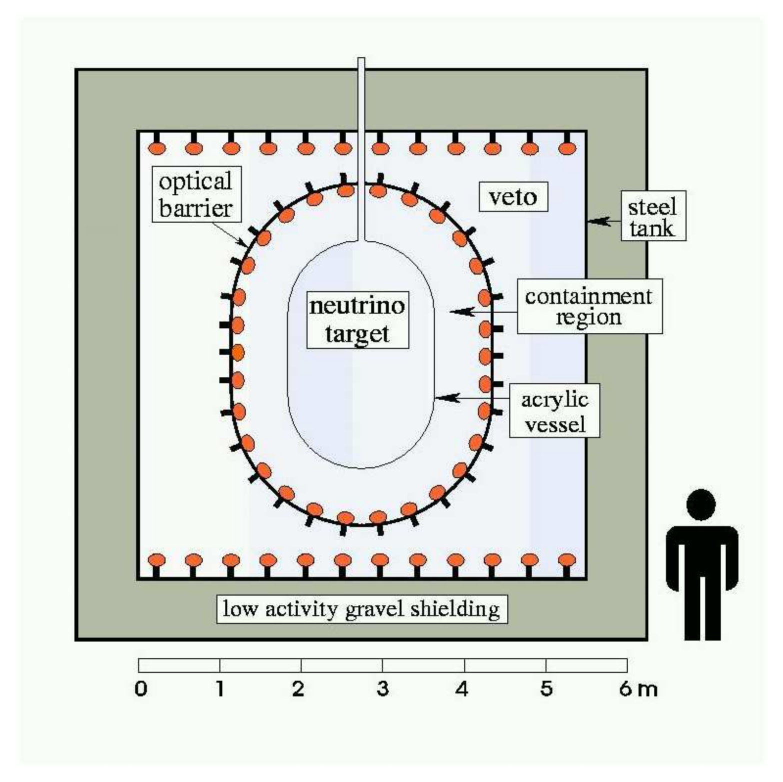
a	Experiment	f^a_{235}	f^a_{238}	f^a_{239}	f^a_{241}	$R^{\mathrm{exp}}_{a,\mathrm{SH}}$	σ^{exp}_a [%]	σ^{cor}_a [%]	L_a [m]
1	Bugey-4	0.538	0.078	0.328	0.056	0.932	1.4	1.4	15
2	Rovno91	0.606	0.074	0.277	0.043	0.930	2.8		18
3	Rovno88-1I	0.607	0.074	0.277	0.042	0.907	6.4	3.8 2.2	18
4	Rovno88-2I	0.603	0.076	0.276	0.045	0.938	6.4		18
5	Rovno88-1S	0.606	0.074	0.277	0.043	0.962	7.3	3.8	18
6	Rovno88-2S	0.557	0.076	0.313	0.054	0.949	7.3		25
7	Rovno88-2S	0.606	0.074	0.274	0.046	0.928	6.8		18
8	Bugey-3-15	0.538	0.078	0.328	0.056	0.936	4.2	4.0	15
9	Bugey-3-40	0.538	0.078	0.328	0.056	0.942	4.3		40
10	Bugey-3-95	0.538	0.078	0.328	0.056	0.867	15.2		95
11	Gosgen-38	0.619	0.067	0.272	0.042	0.955	5.4	2.0 3.8	37.9
12	Gosgen-46	0.584	0.068	0.298	0.050	0.981	5.4		45.9
13	Gosgen-65	0.543	0.070	0.329	0.058	0.915	6.7		64.7
14	ILL	1	0	0	0	0.792	9.1		8.76
15	Krasnoyarsk87-33	1	0	0	0	0.925	5.0	4.1	32.8
16	Krasnoyarsk87-92	1	0	0	0	0.942	20.4		92.3
17	Krasnoyarsk94-57	1	0	0	0	0.936	4.2	0	57
18	Krasnoyarsk99-34	1	0	0	0	0.946	3.0	0	34
19	SRP-18	1	0	0	0	0.941	2.8	0	18.2
20	SRP-24	1	0	0	0	1.006	2.9	0	23.8
21	Nucifer	0.926	0.061	0.008	0.005	1.014	10.7	0	7.2
22	Chooz	0.496	0.087	0.351	0.066	0.996	3.2	0	≈ 1000
23	Palo Verde	0.600	0.070	0.270	0.060	0.997	5.4	0	≈ 800
24	Daya Bay	0.561	0.076	0.307	0.056	0.946	2.0	0	≈ 550
25	RENO	0.569	0.073	0.301	0.056	0.946	2.1	0	≈ 410
26	Double Chooz	0.511	0.087	0.340	0.062	0.935	1.4	0	≈ 415

Giunti 2016

Palo Verde & CHOOZ

Late 1990’s inspired by KamiokaNDE



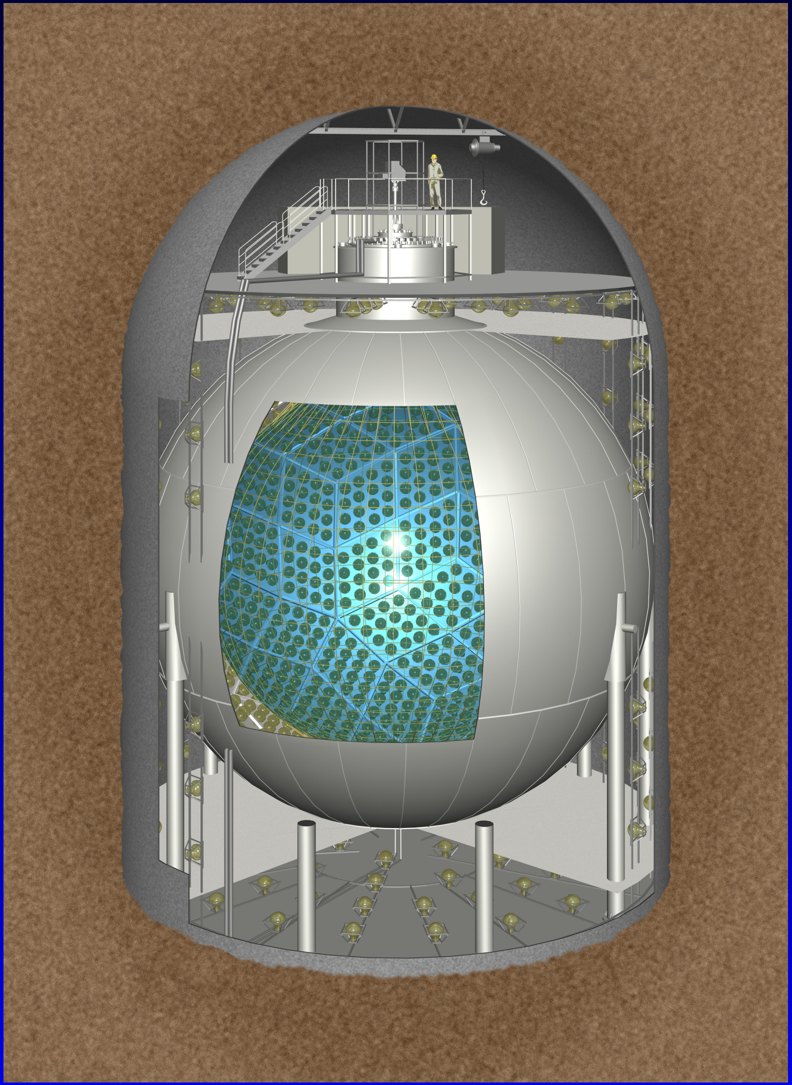


800 m from a commercial reactor

1100 m from a commercial reactor

Null result in both.

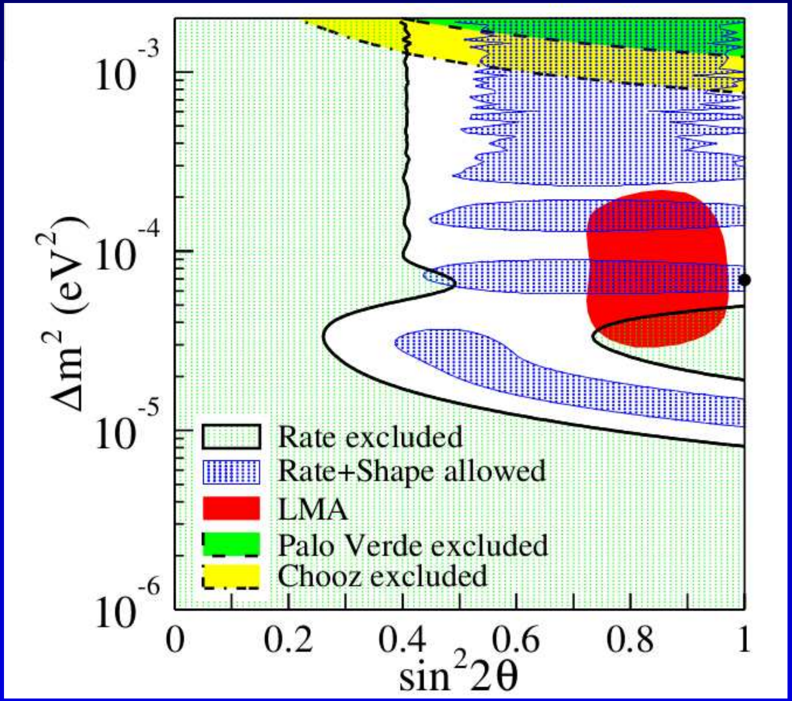
KamLAND – 2002

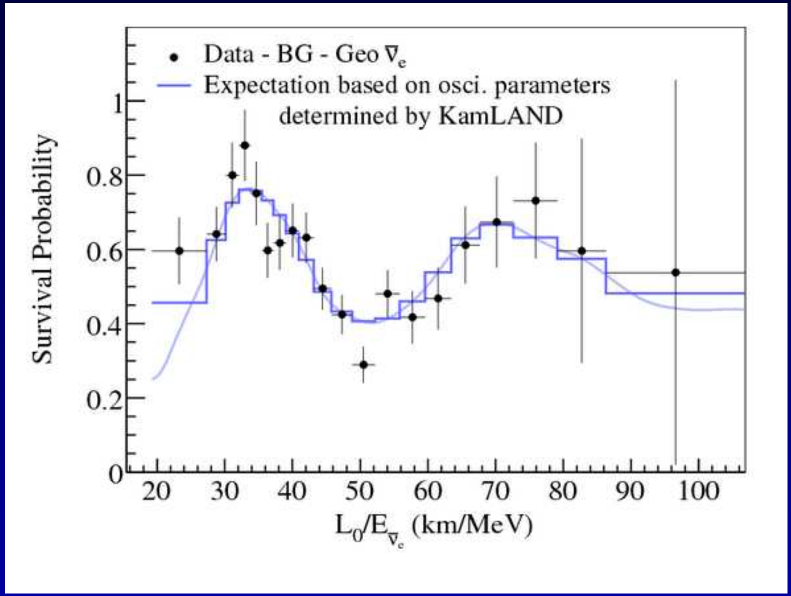


1000 t of liquid organic scintillator, undoped, deep underground.

KamLAND – results

KamLAND confirmed the oscillation interpretation of the solar neutrino results and "picked" the so-called LMA solution.

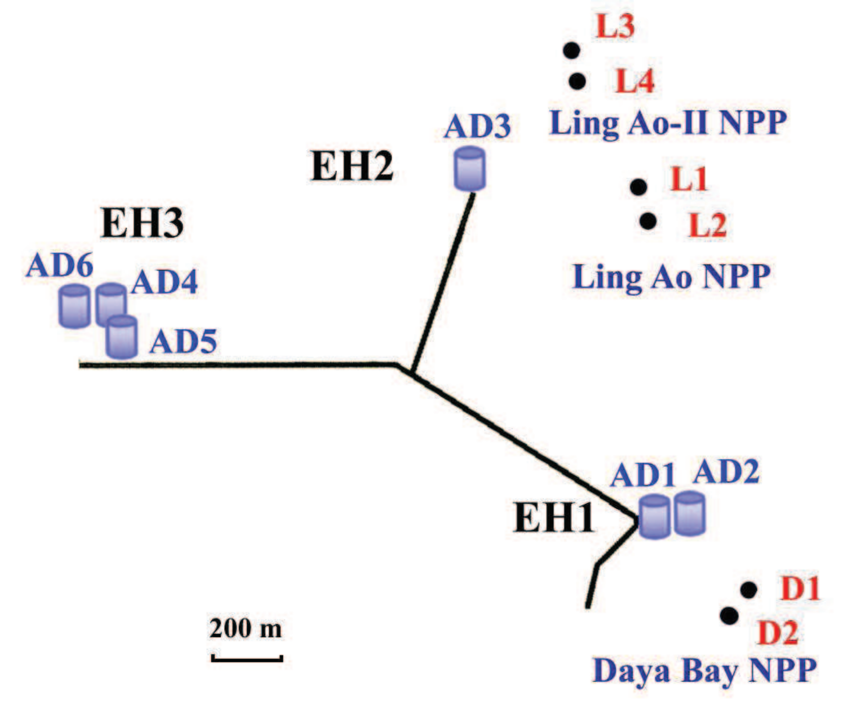




Later it was the first experiment to see an oscillatory pattern.

Daya Bay – 2011

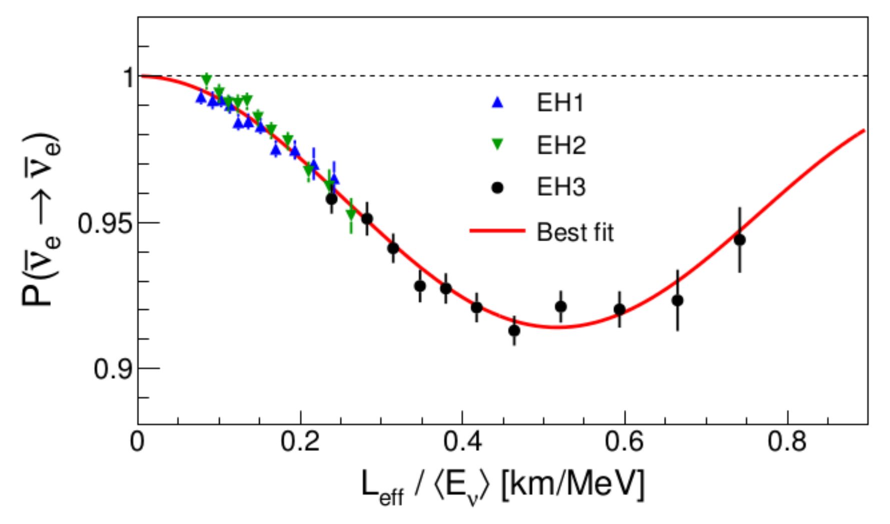
In a 1 reactor, 2 detector setup all flux related errors cancel completely in the near-to-far ratio.

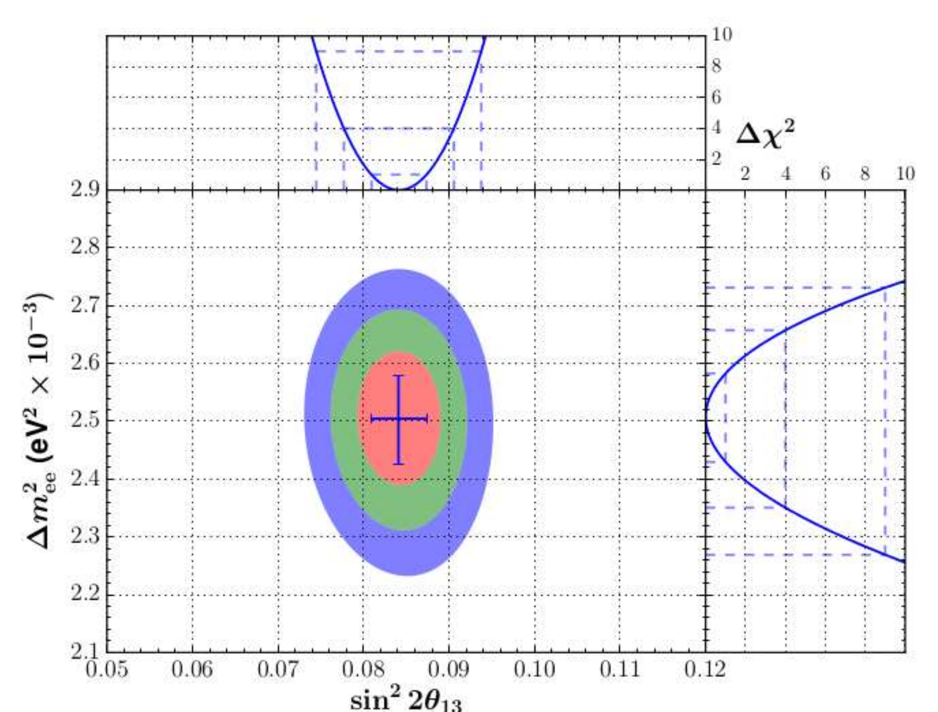


A careful choice of detector locations mitigates the complexity of the Daya Bay layout.

AD3 sees the same ratio of Ling Ao I to Ling Ao II events as do the far detectors.

Daya Bay – results





More than 2.5 million IBD events.

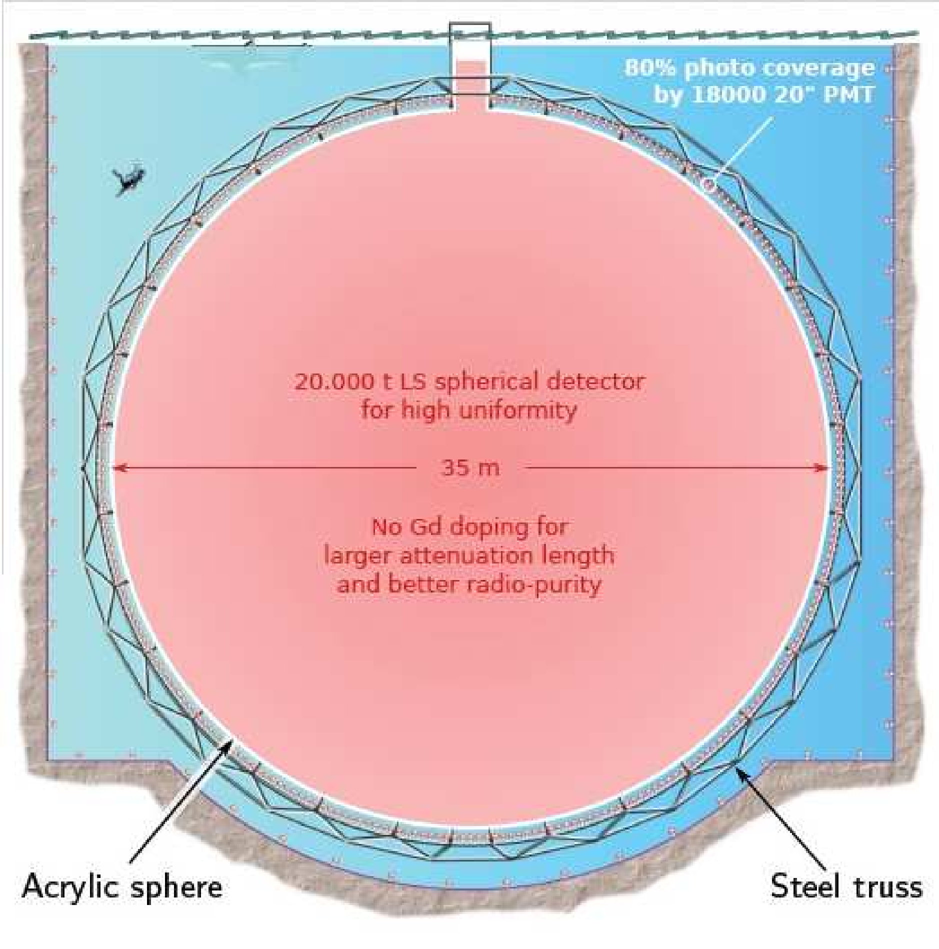
Most precise measurement of θ_{13}

Precise measurement of Δm^2_{32}

RENO and Double Chooz are very similar in concept and results between agree very well.

JUNO – under construction

JUNO – Jiangmen Underground Neutrino Observatory

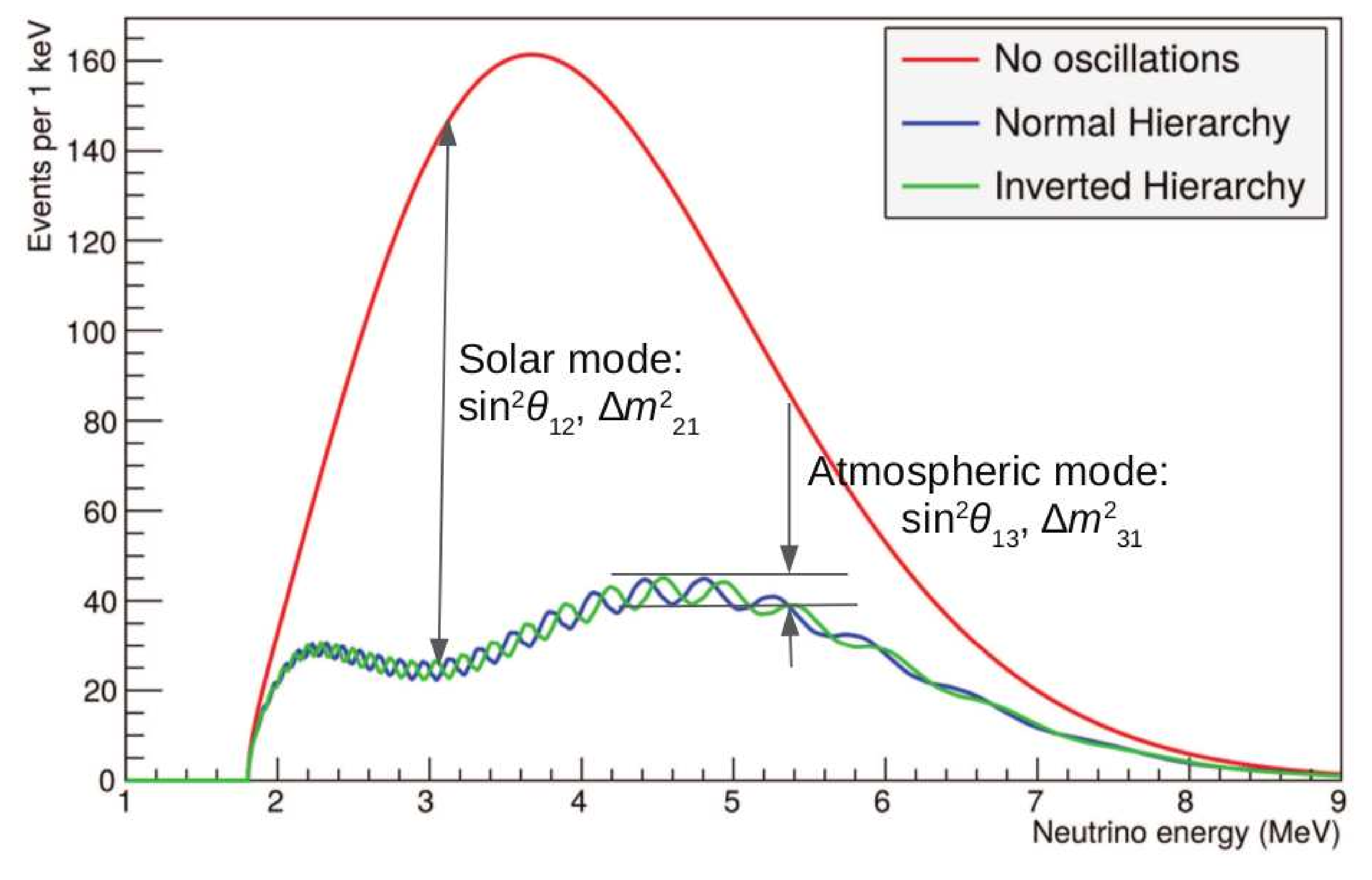


20,000 ton undoped liquid scintillator

53 km from two powerful reactor complexes, 18 GW each

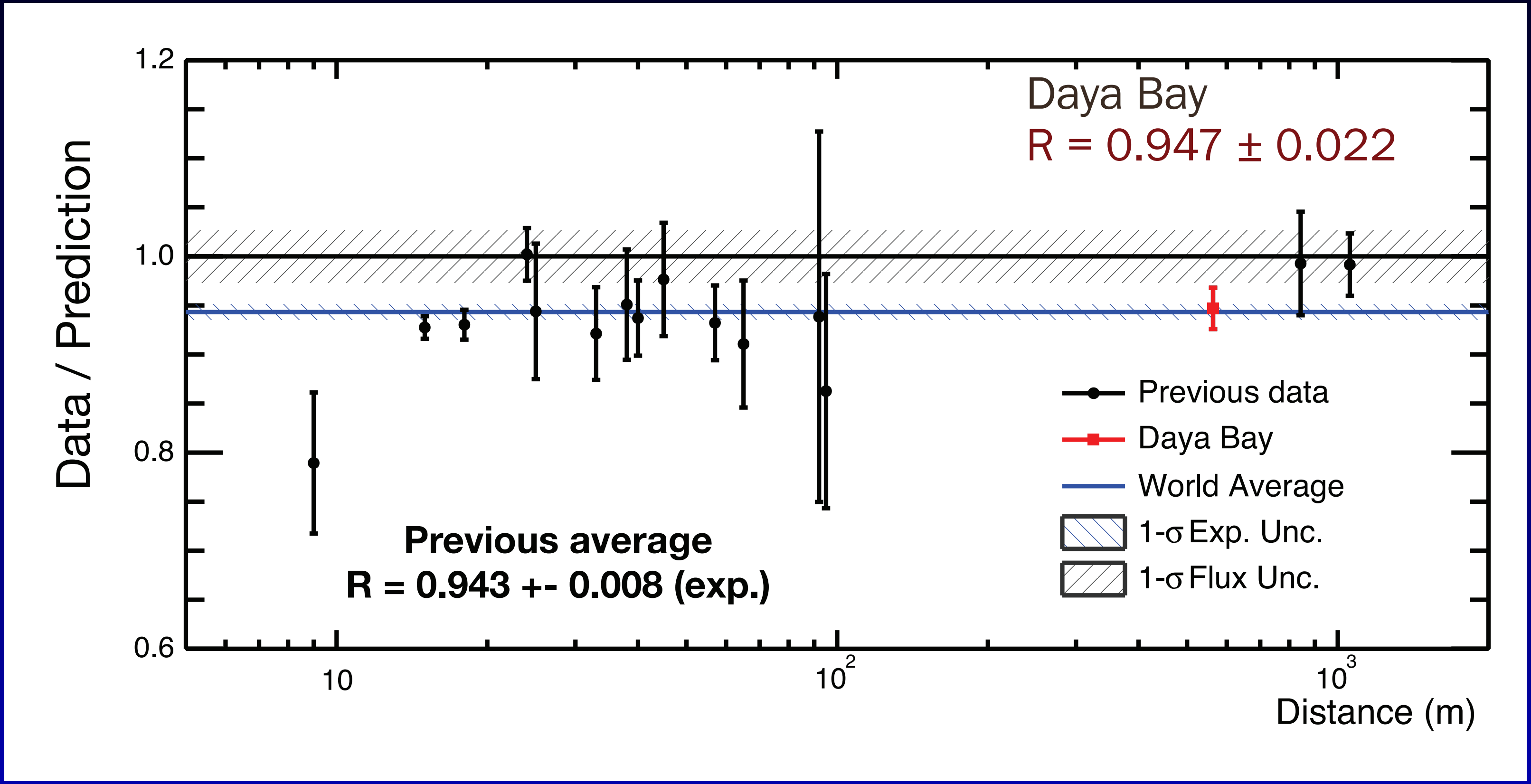
Start of data taking ∼ 2024.

JUNO – physics goals



Measurement of mass hierarchy w/o matter effects
1% level measurement of solar mixing parameters

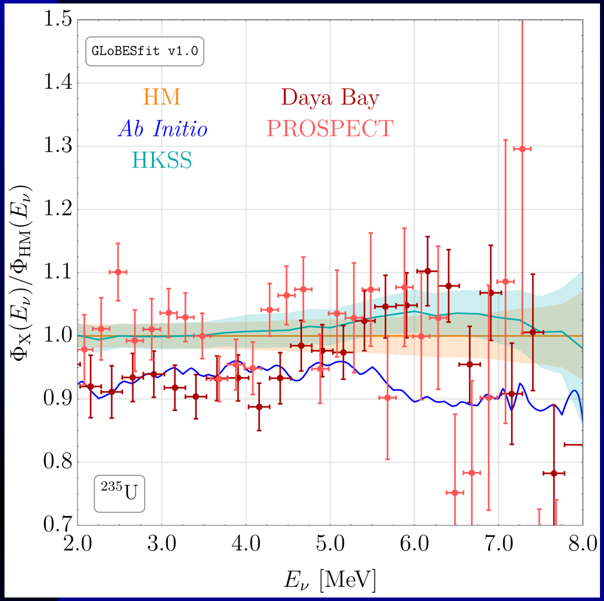
The reactor anomaly

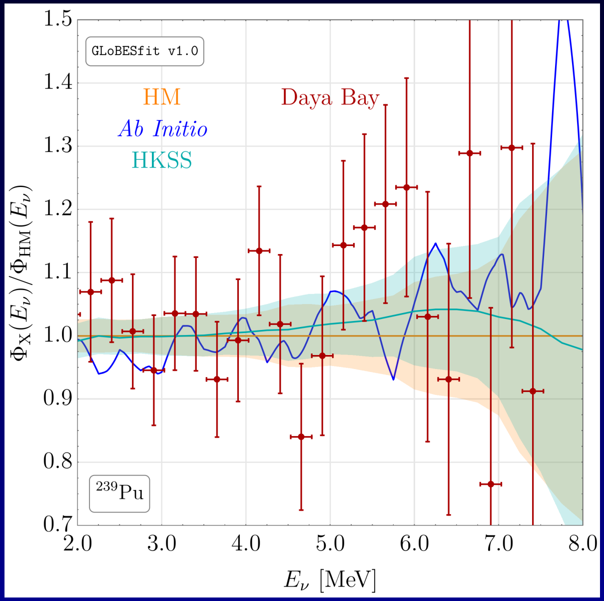


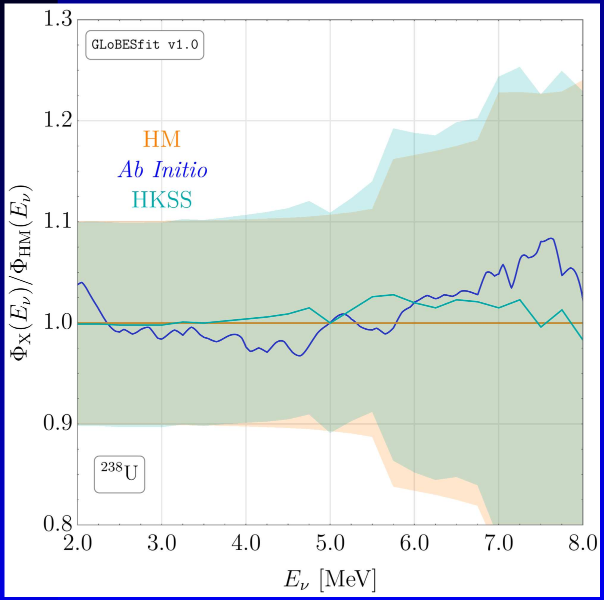
Daya Bay, 2014

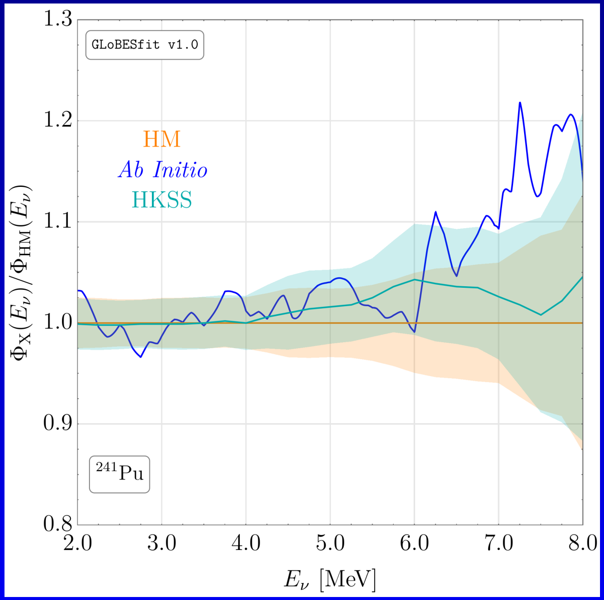
Mueller *et al.*, 2011, 2012 – where have all the neutrinos gone?

Status quo early 2021









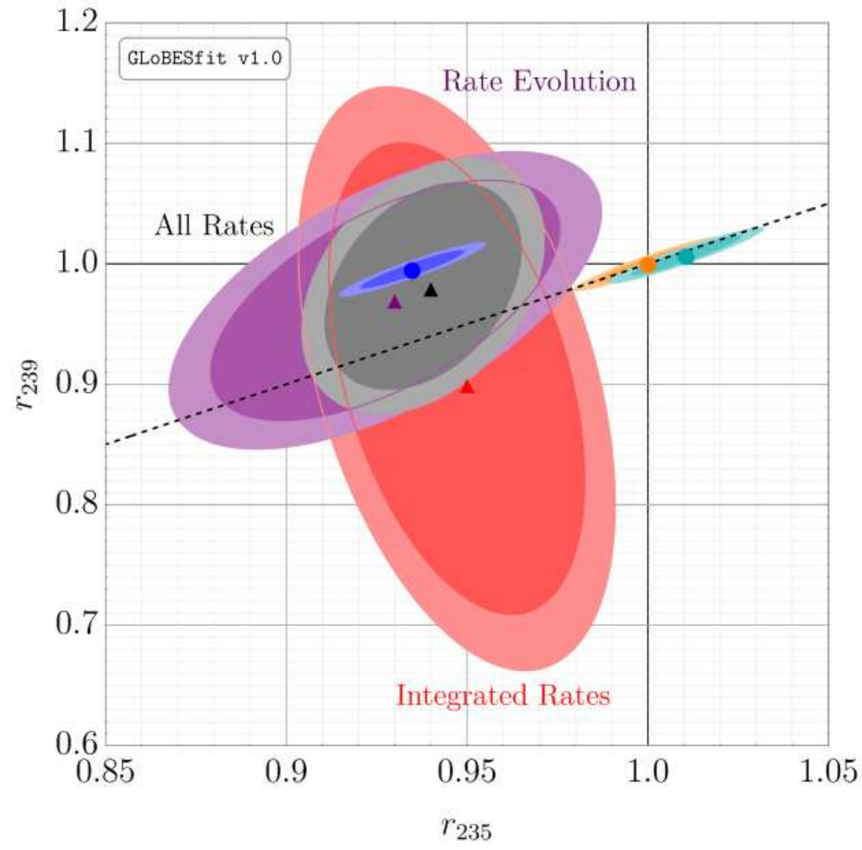
3 different flux models, data from 2 different experiments

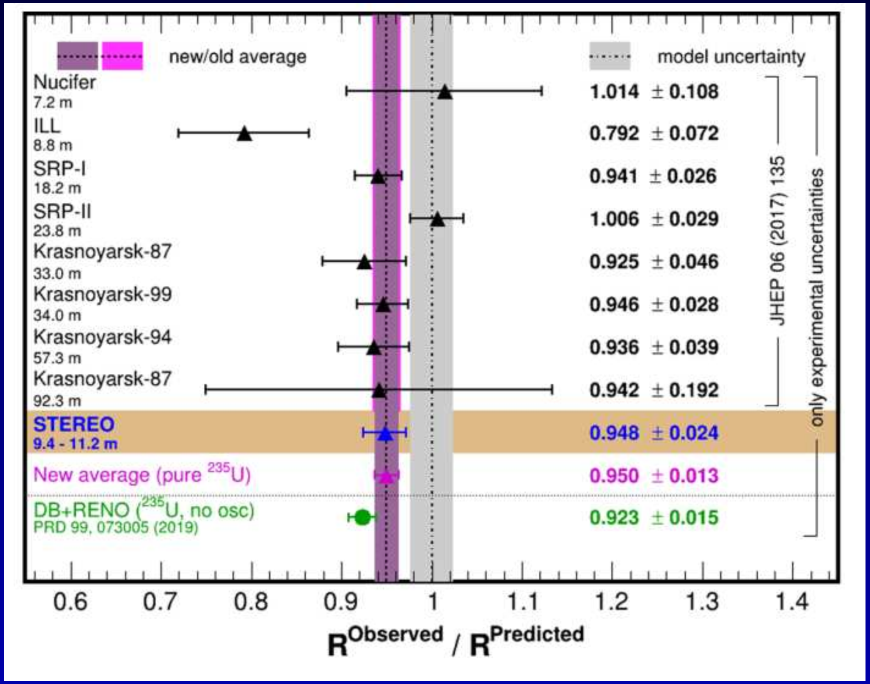
Except for U235:
+ the models agree within error bars
+ the models agree with neutrino data

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

Berryman, PH, 2020

Fuel evolution



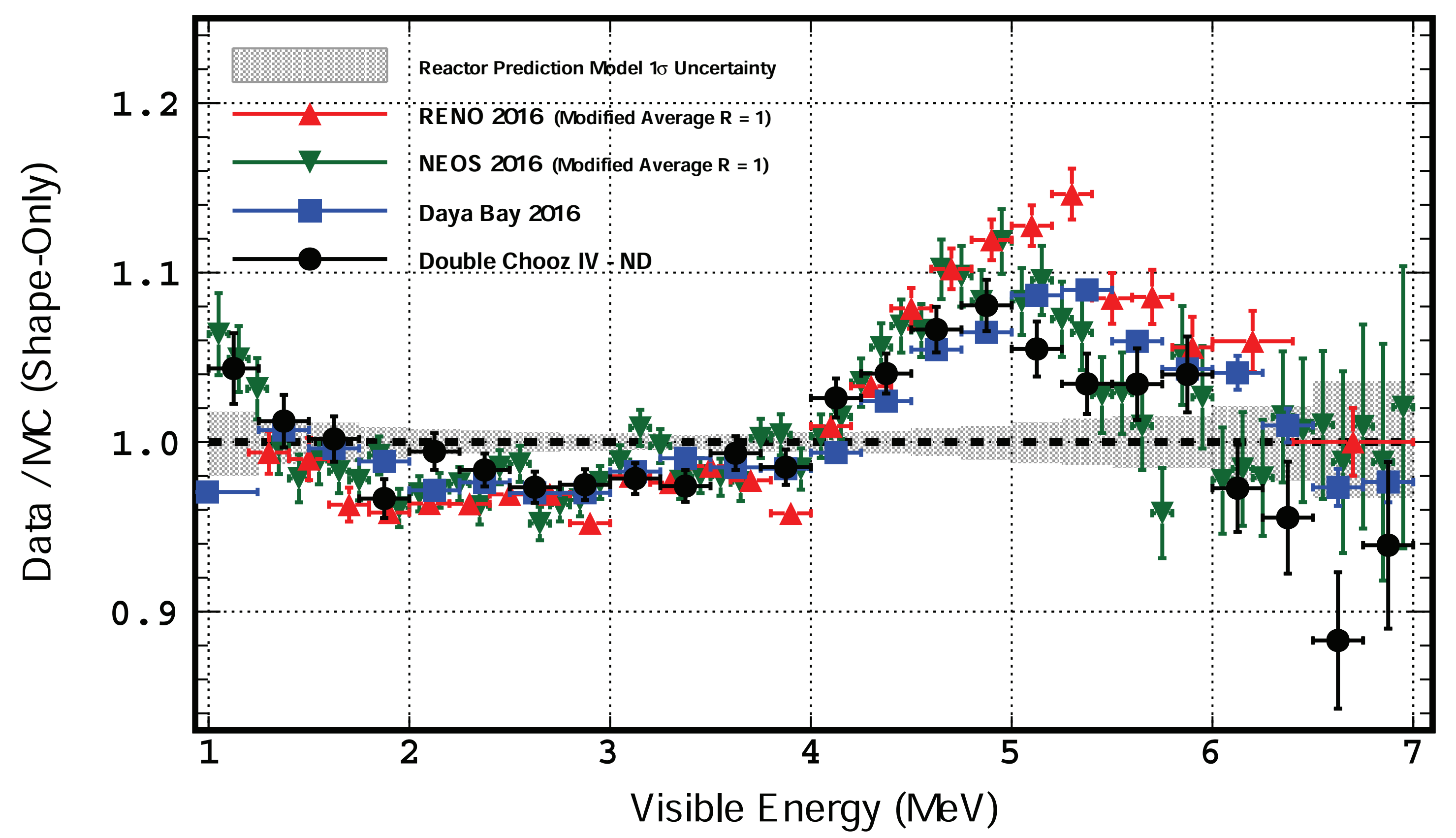


STEREO, 2020

Berryman, PH, 2020

U235 seems to “own” all of the deficit.

The 5 MeV bump

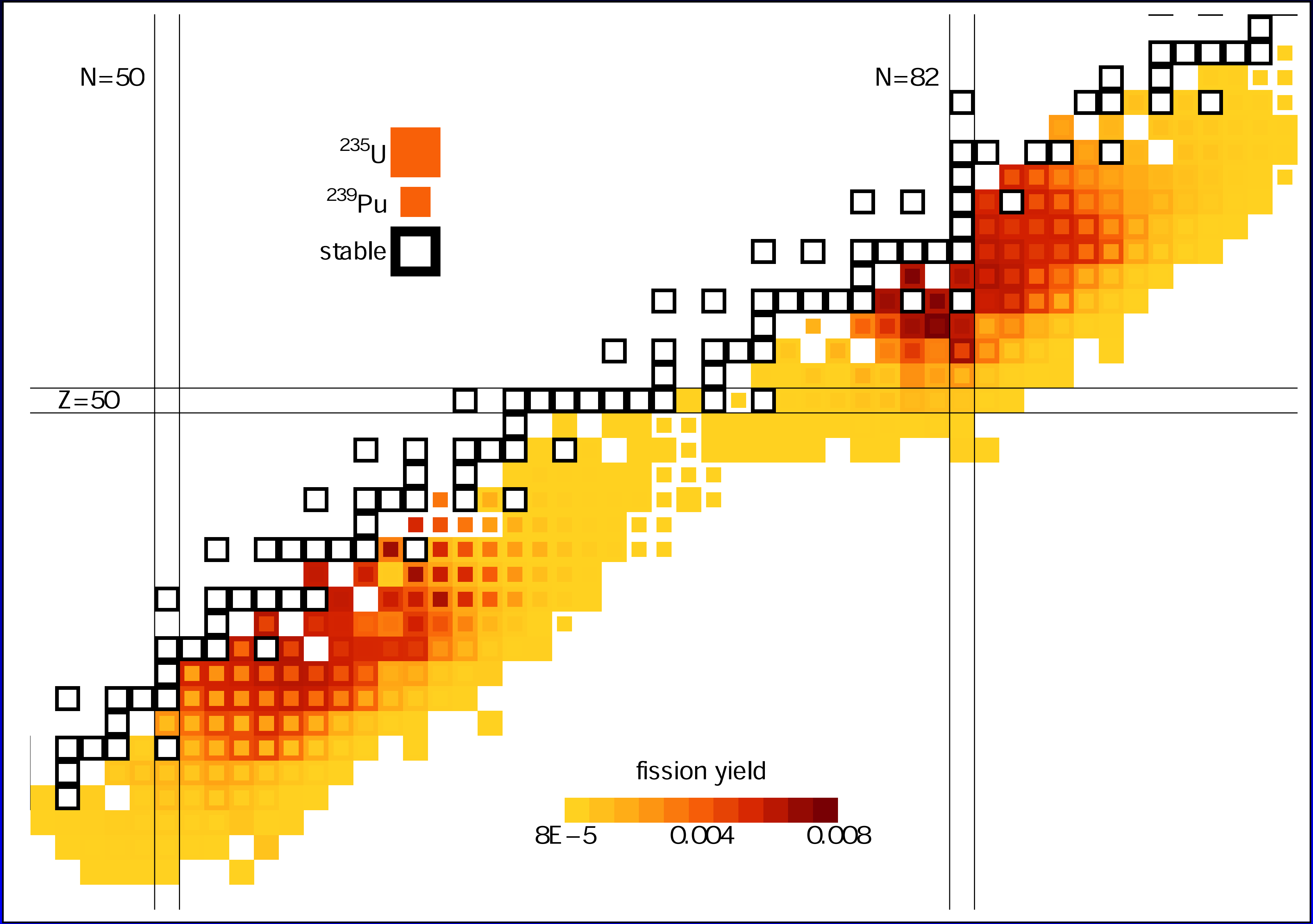


Double Chooz 2019

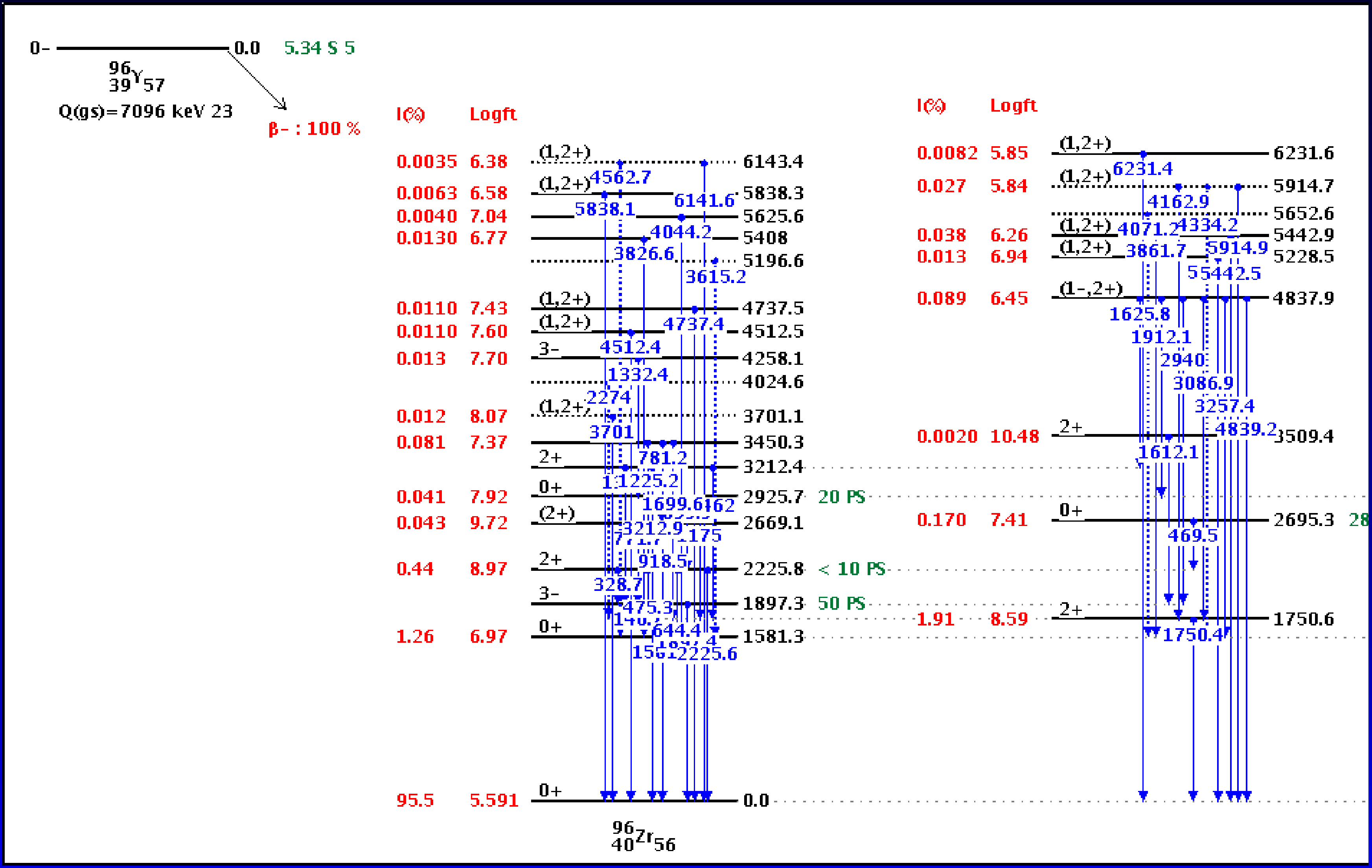
Contains only 0.5% of all neutrino events – not important for sterile neutrinos

Yet, statistically more significant than the RAA!

Why is this so complicated?



β-branches

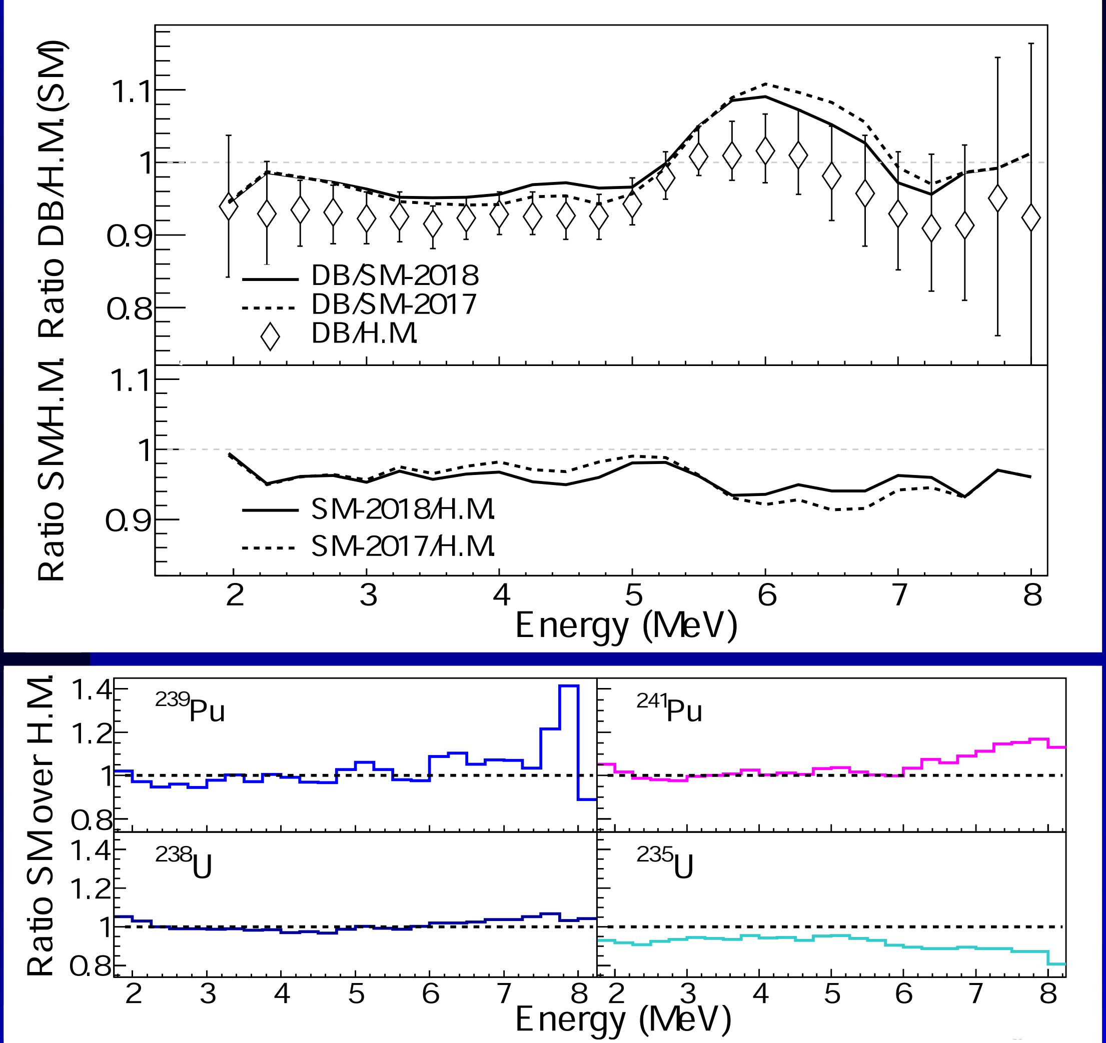


Two ways to predict

Summation calculations	Conversion calculations
Fission yields Beta yields	Cumulative beta spectra Z_{eff} from databases
Problem: databases are insufficient & difficulty of assigning an error budget	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



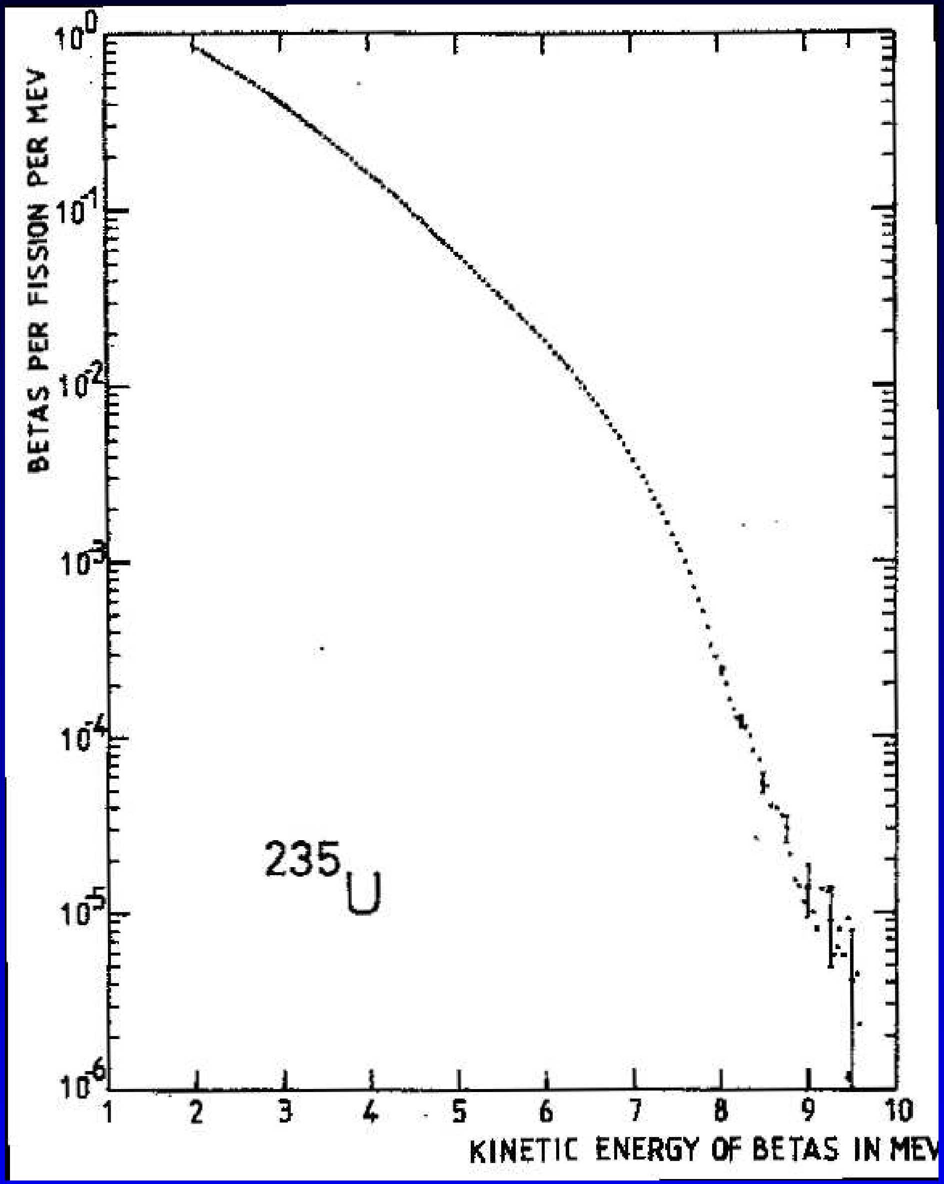
Estienne *et al.*, 2019

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.

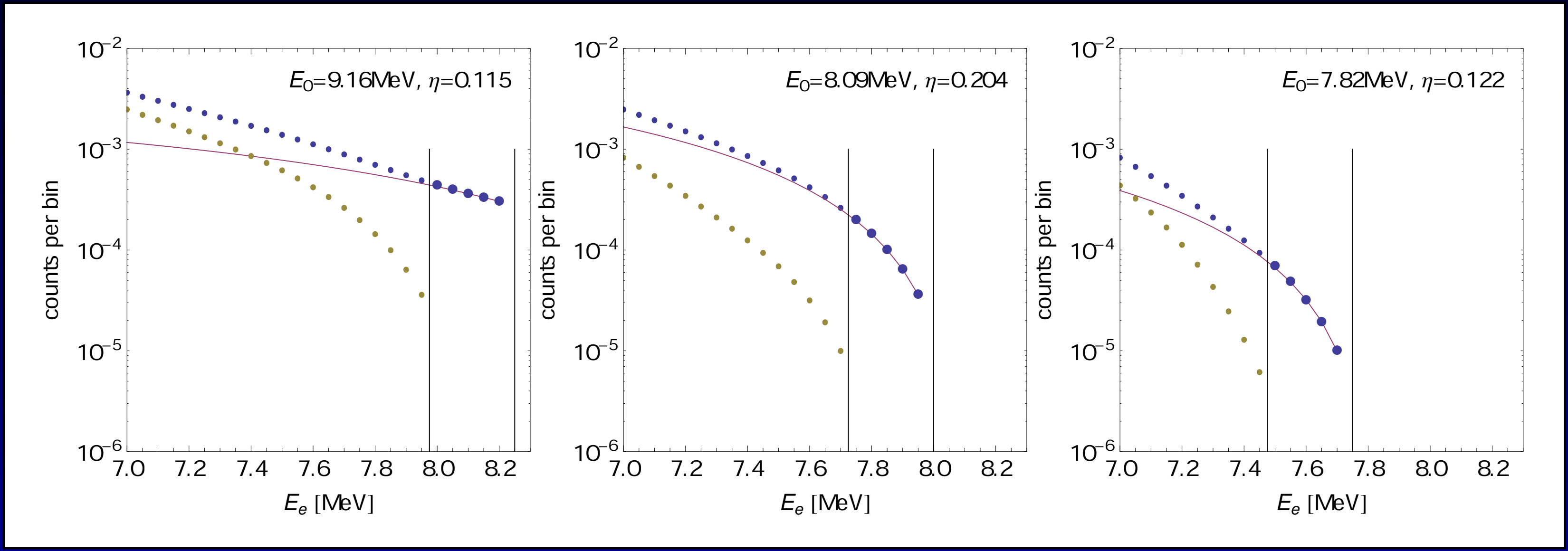
^{235}U foil inside the High Flux Reactor at ILL

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

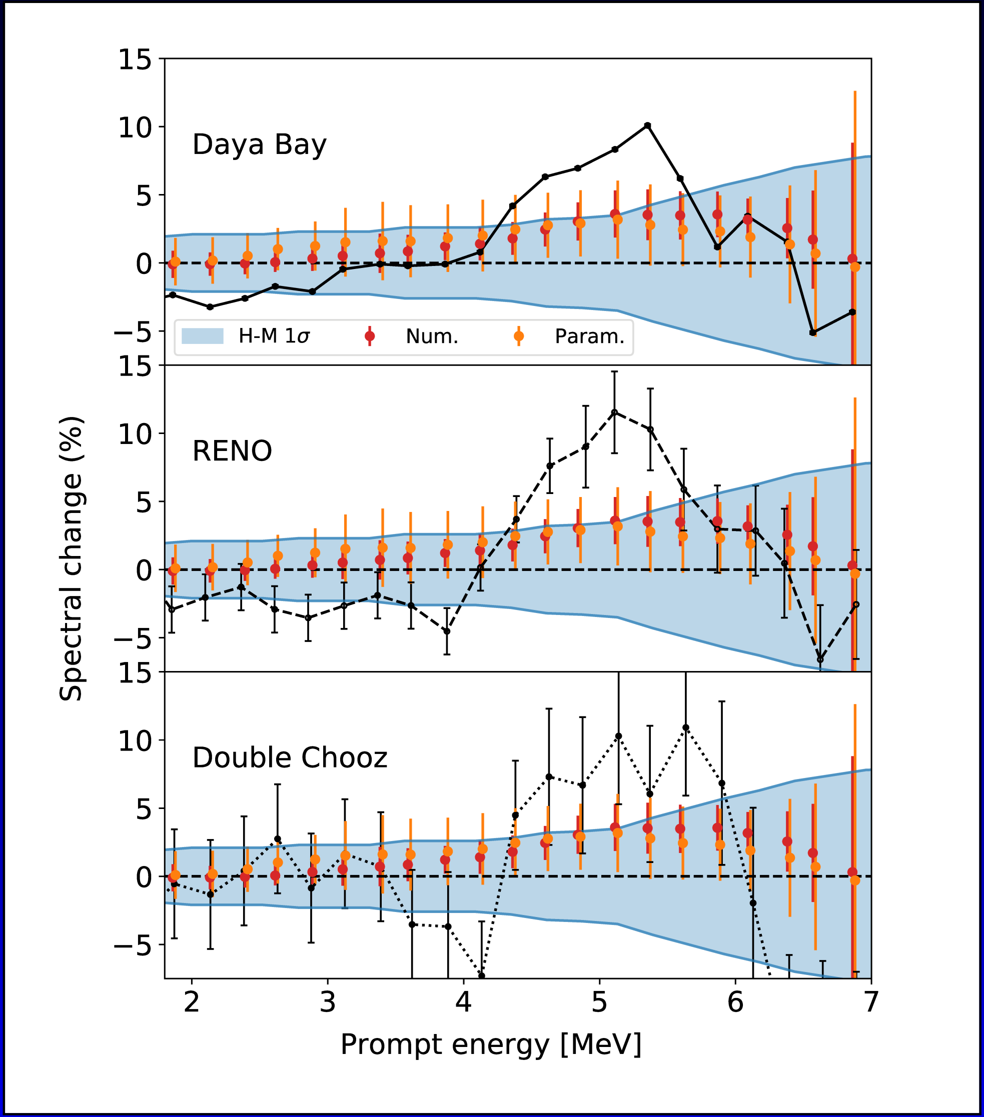
2 – delete the last s data points

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



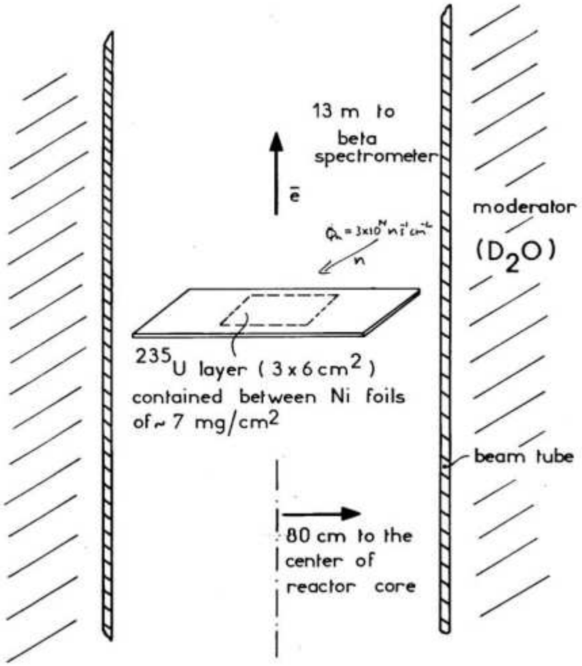
Hayen, *et al.* 2019

Forbidden decays major source of systematic.

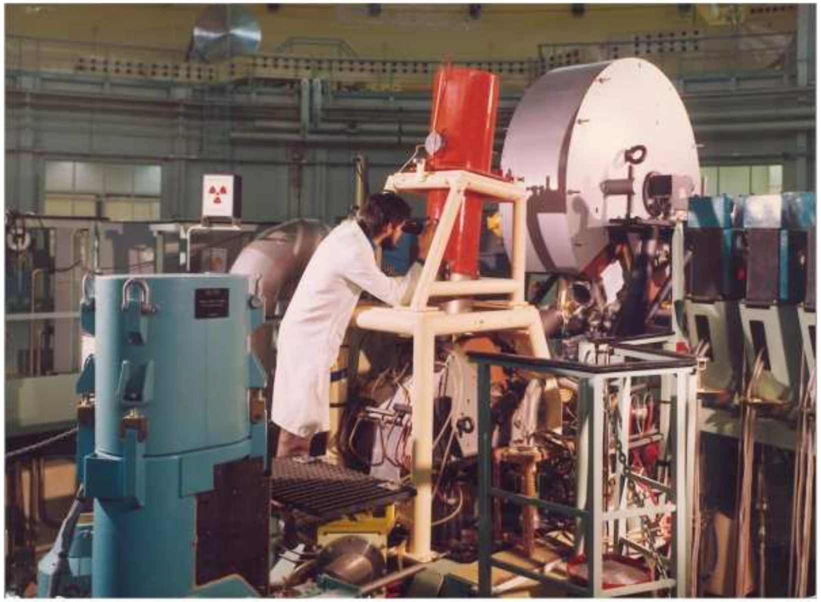
Microscopic shell model calculation of 36 forbidden isotopes, otherwise similar to HM.

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

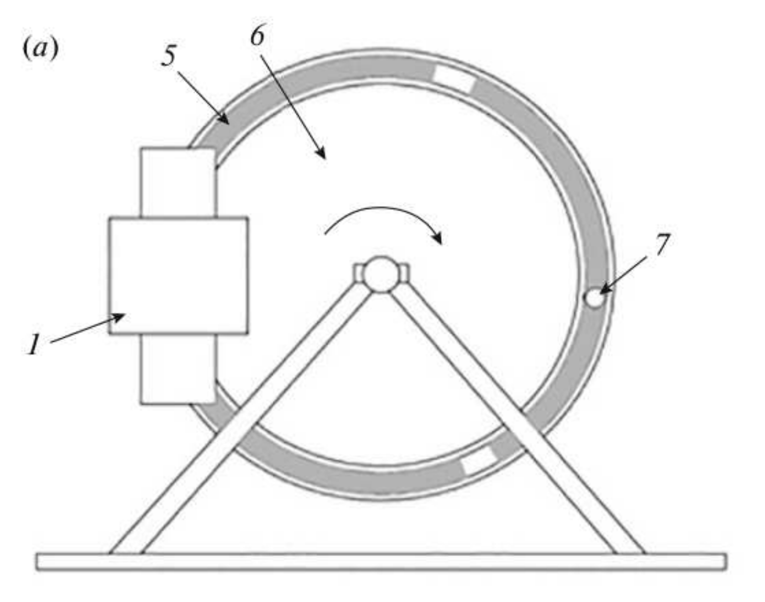
(Electron detector in focal plane: multi chamber proportional counter in transmission, rear mounted scintillator in coincidence)

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

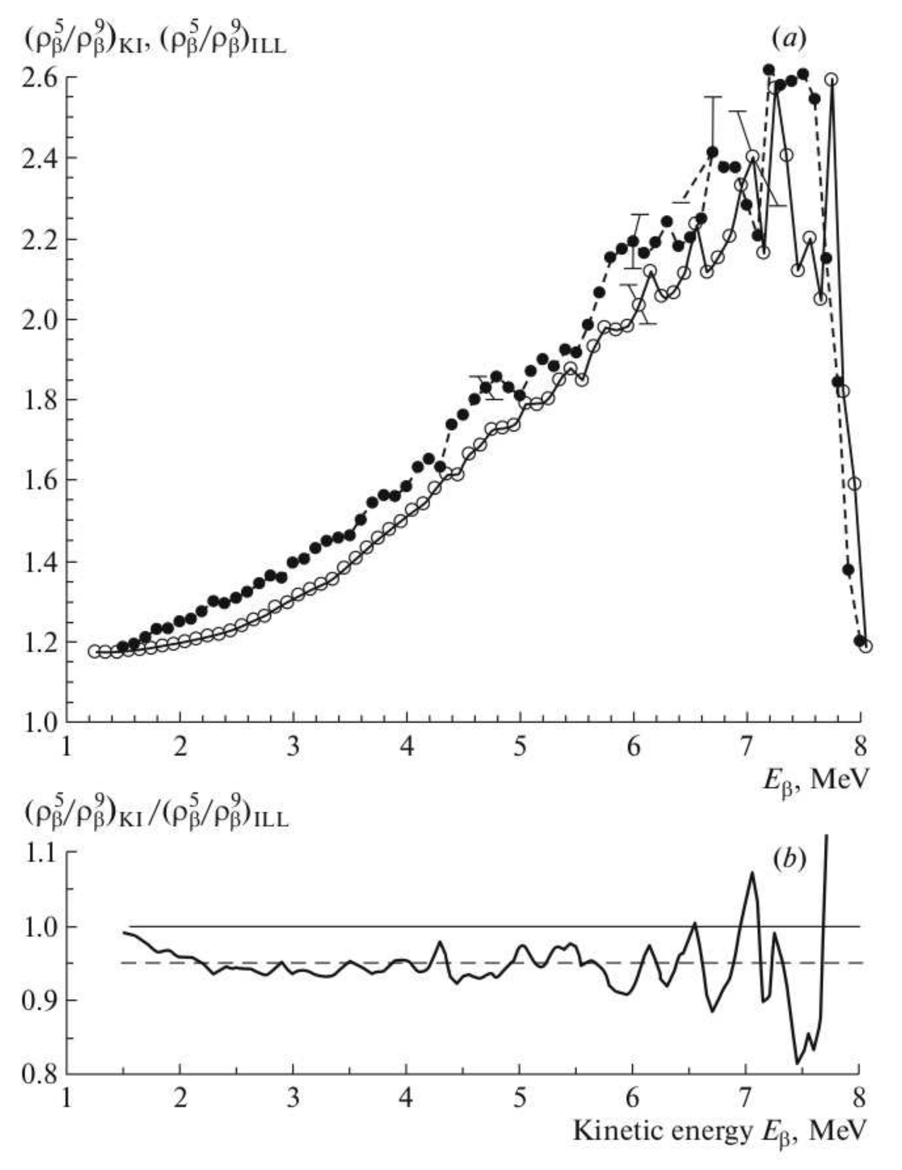


Relative measurement of U235 and Pu239 targets under identical conditions.

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.

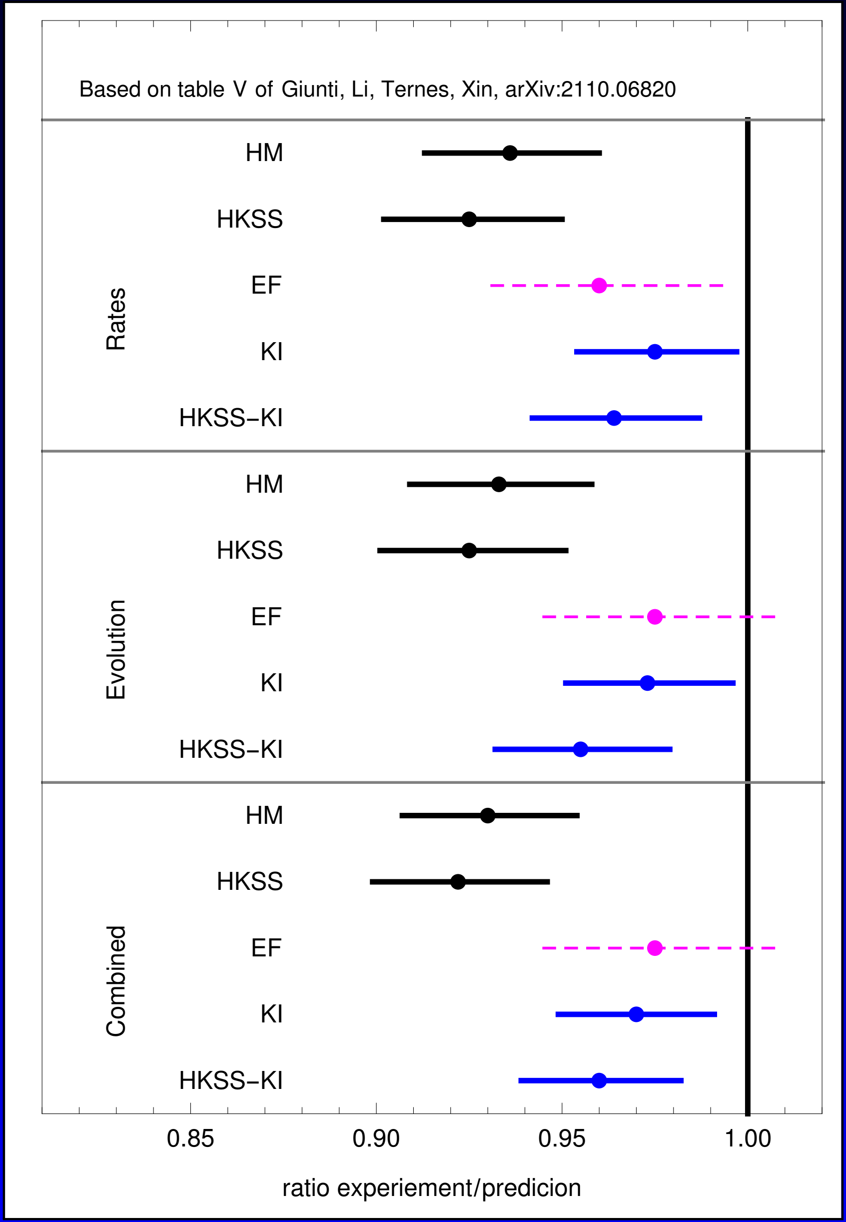
2021 beta results



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

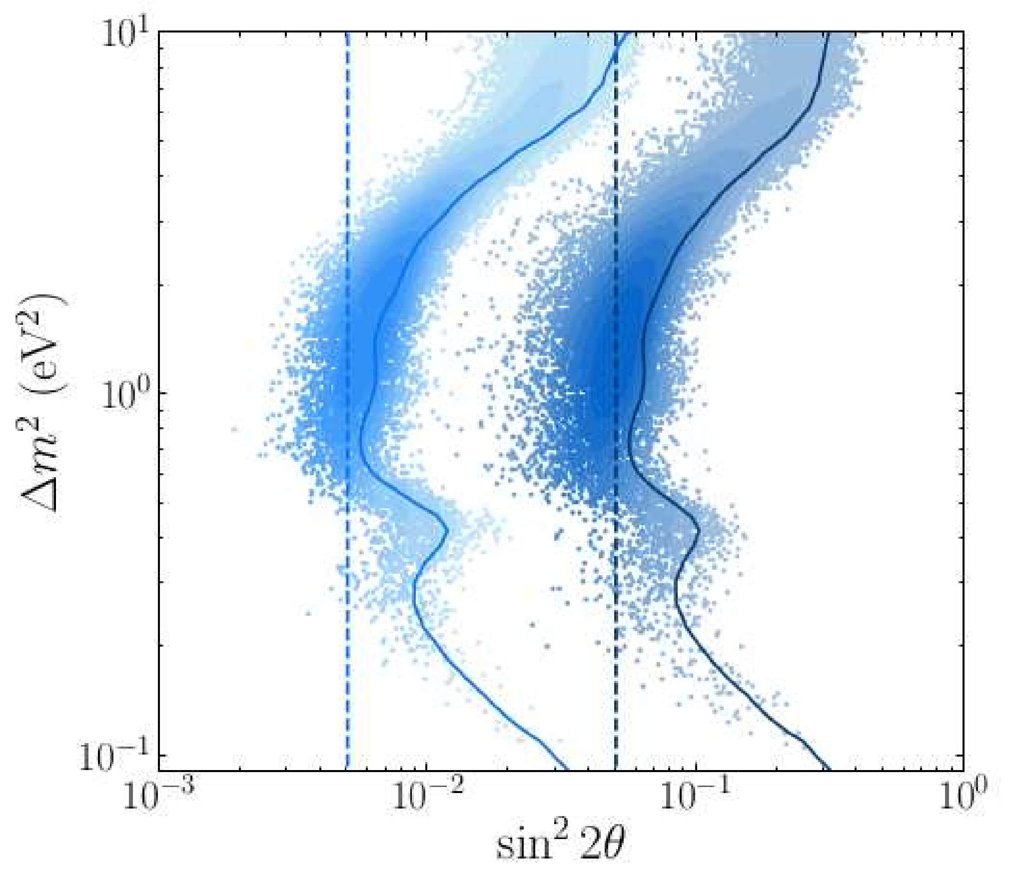


HM – conversion
HKSS – conversion
+ forbidden decays
EF – summation
unclear theory error
KI – HM + KI data
HKSS+KI – HKSS +KI

With the KI correction agreement between summation and conversion improved.

RAA significance reduced to less than 2σ

Oscillations are everywhere



Hypothetical two baseline experiment

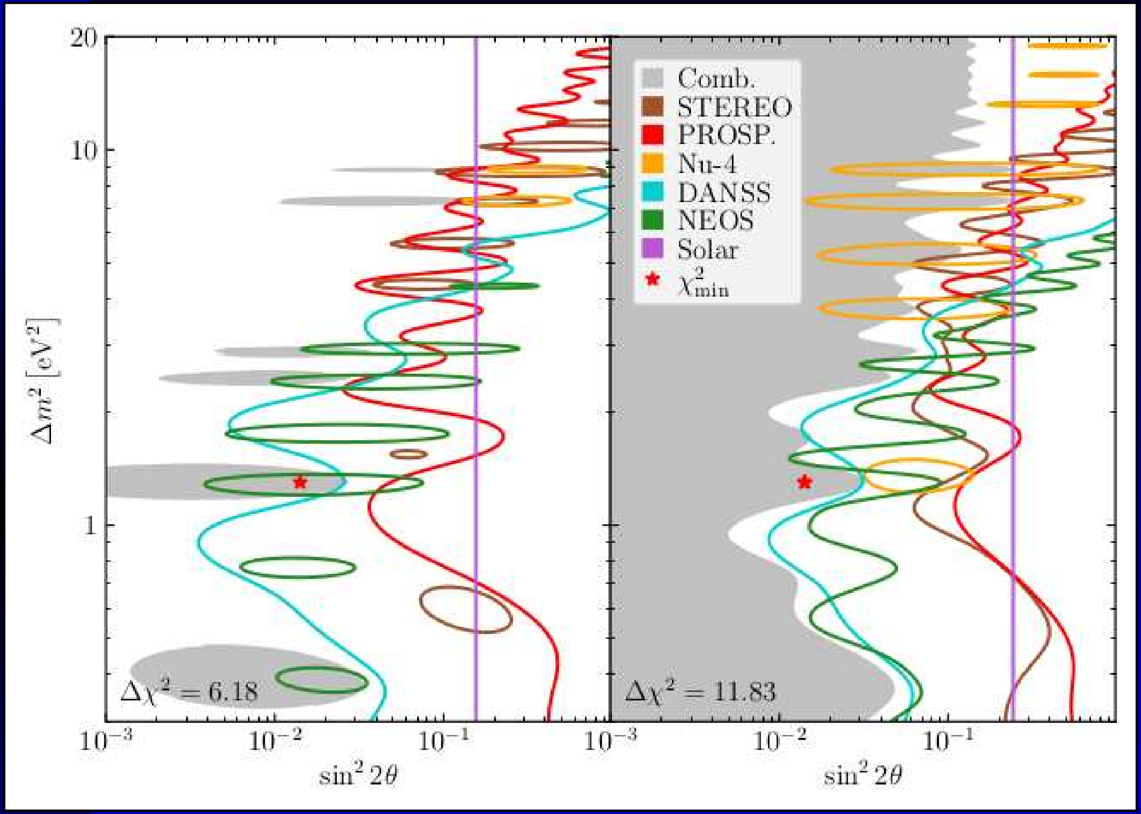
Maximum likelihood estimate is biased and not consistent.

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

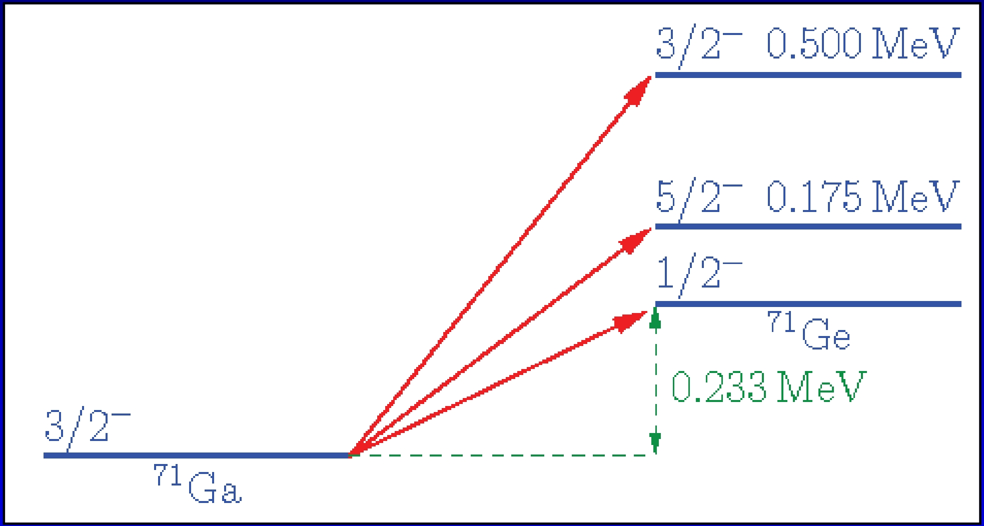
No tension with Neutrino-4

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

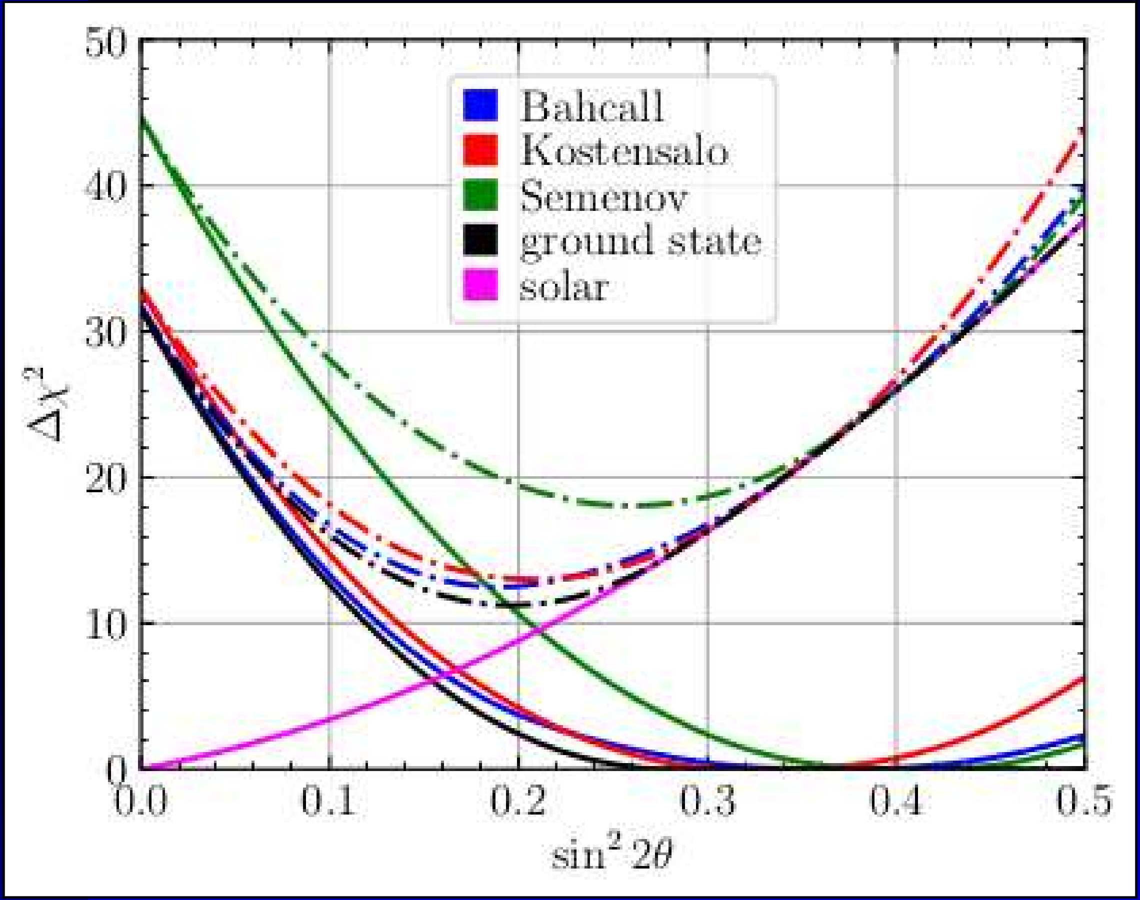
Nuclear matrix elements



ground state follows from beta decay

excited states?

Gallium and solar

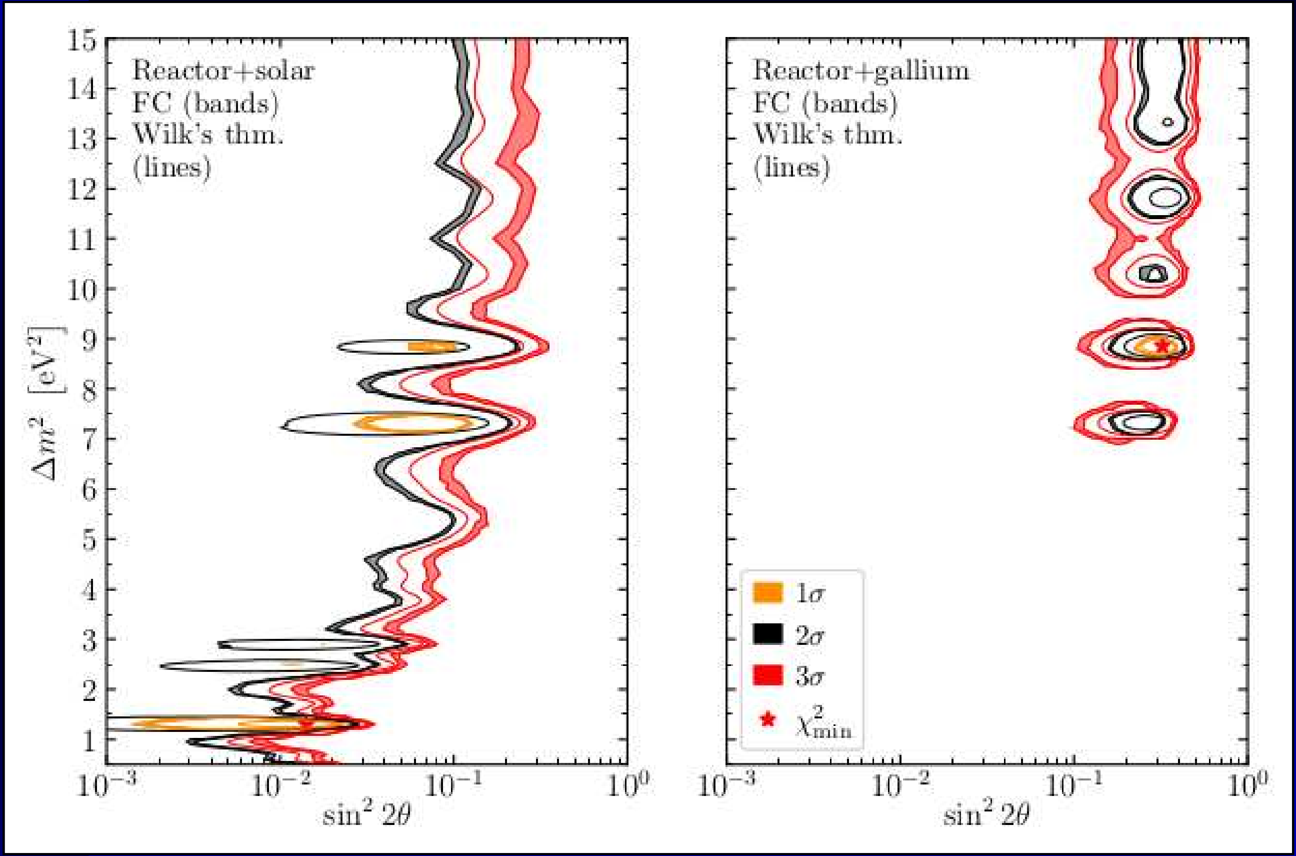


BCHSZ 2021

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.

All together now



BCHSZ 2021

Full FC analysis

Reactor+solar: 1.1σ

Reactor+gallium: 5.3-5.7σ

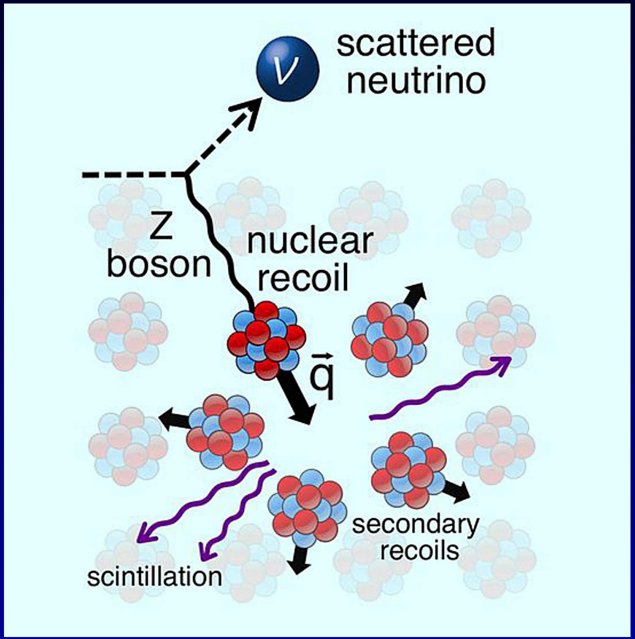
Evidence for neutrino disappearance entirely driven by gallium results,
only tension gallium vs solar at $> 3\sigma$.

CEνNS

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

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

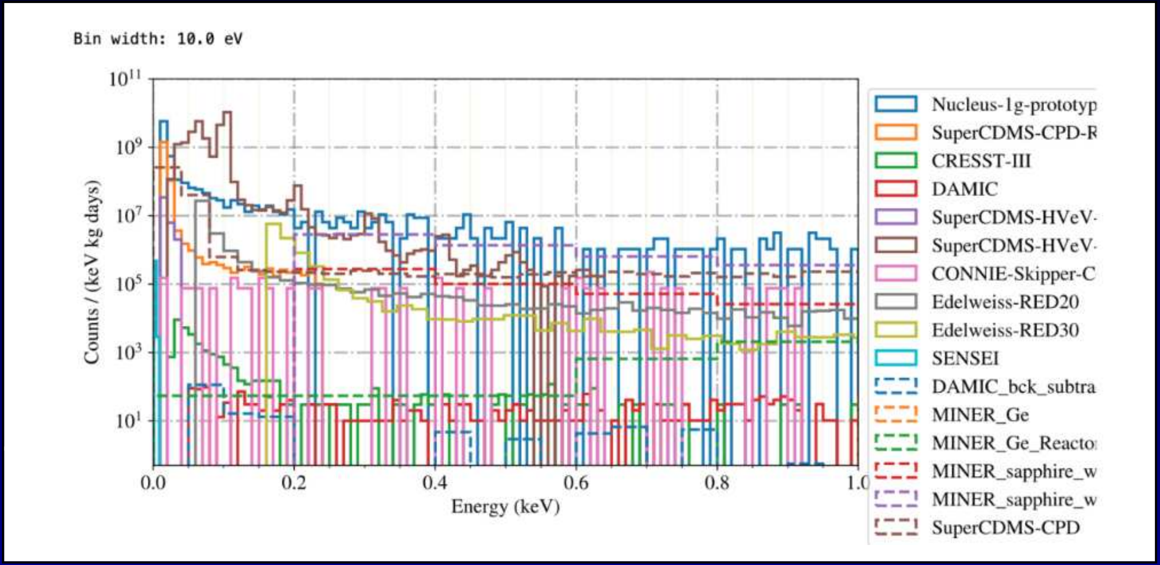
T recoil energy, N neutron number



- 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

Outlook

Reactors as neutrino source are cheap, bright and clean.

The reactor antineutrino anomaly is likely due to flawed input data and not due to new or nuclear physics.

No evidence for $\bar{\nu}_e$ disappearance from reactors, but from gallium, $> 5\sigma$!

Reactor CEvNS as proving ground for dark matter searches

Rich potential for applications (not covered here, see my previous CERN TH colloquium)