Reactor Neutrinos

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International Neutrino Summer School 2021 – Zoomland
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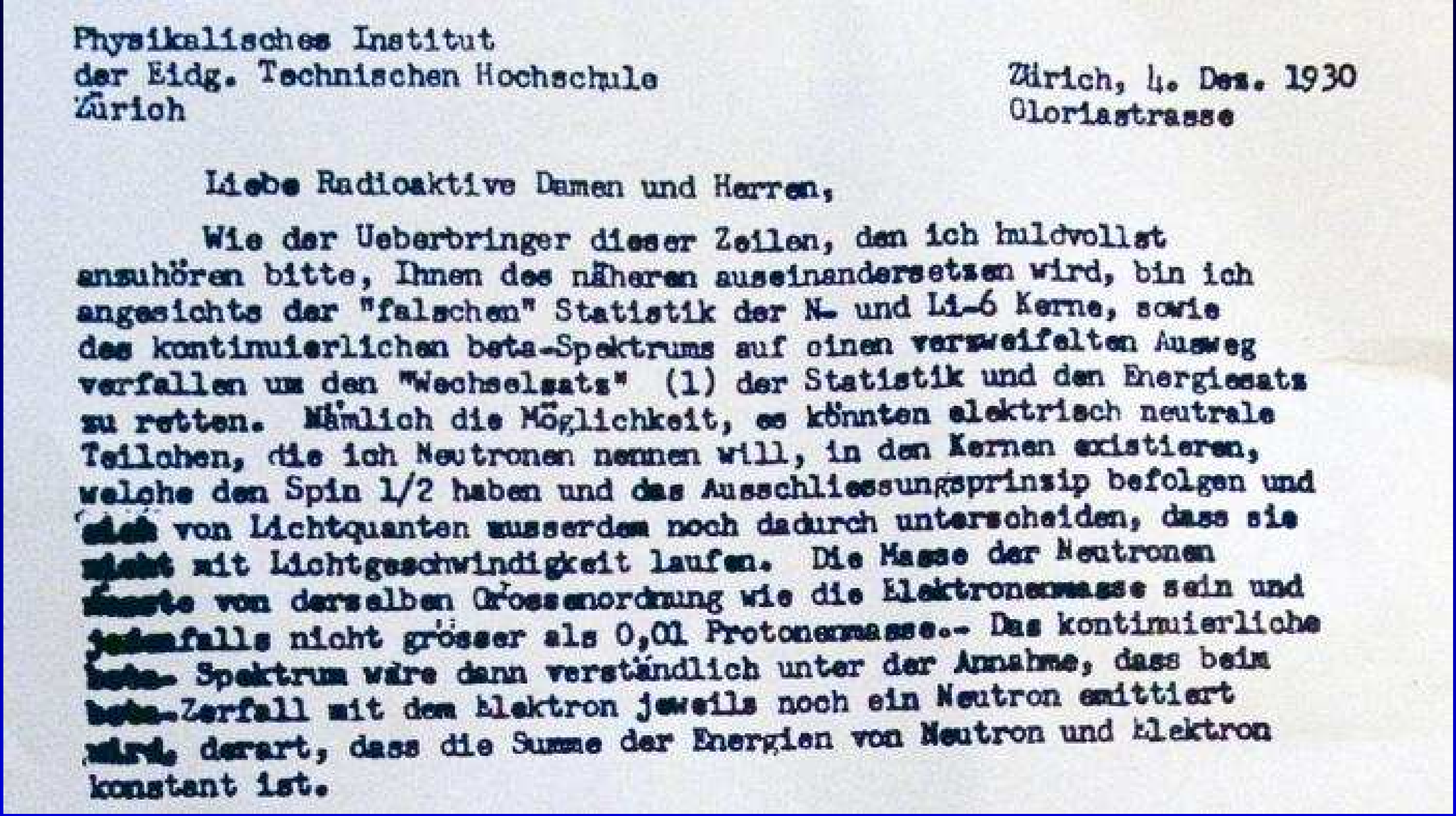
Enter – the neutrino

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 kontimuierlichen 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 Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontimuierliche 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):

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

or in a nuclear bound state

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

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

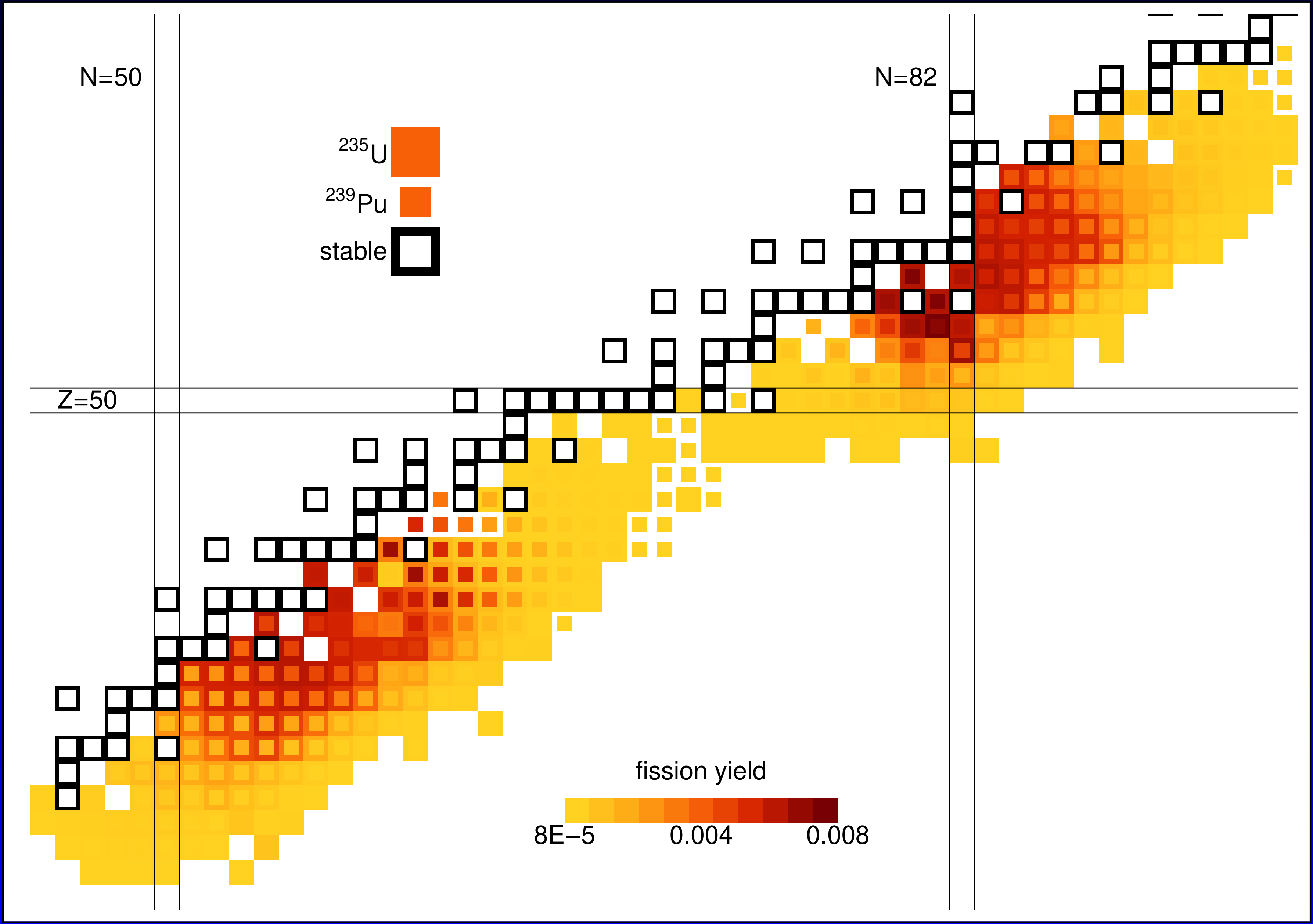
Using a cross section of around $10^{-42}\mathrm{cm}^2\ldots$

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?

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

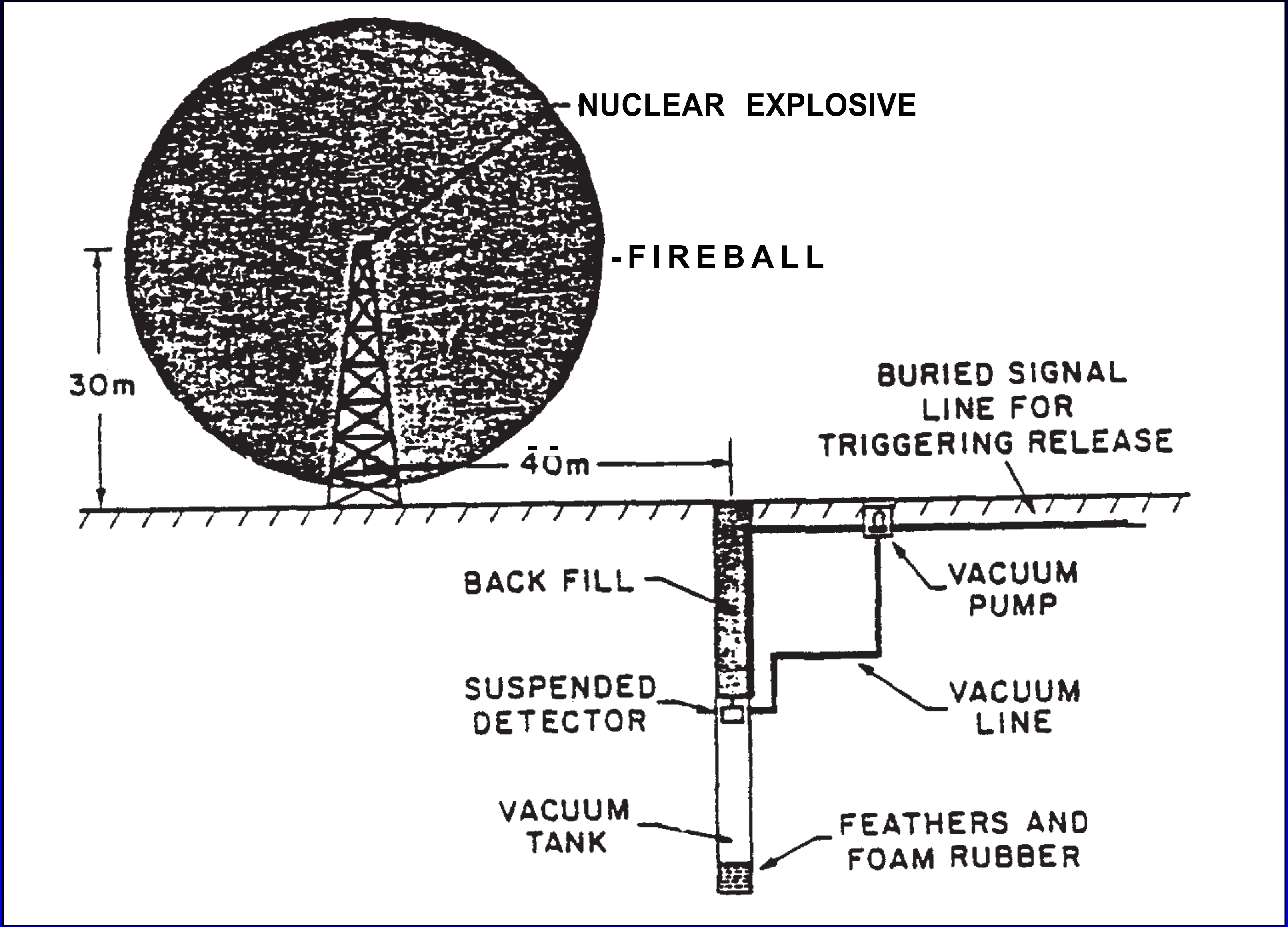
with average masses of X_1 of about A=94 and X_2 of about A=140. X_1 and X_2 have together 142 neutrons.

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

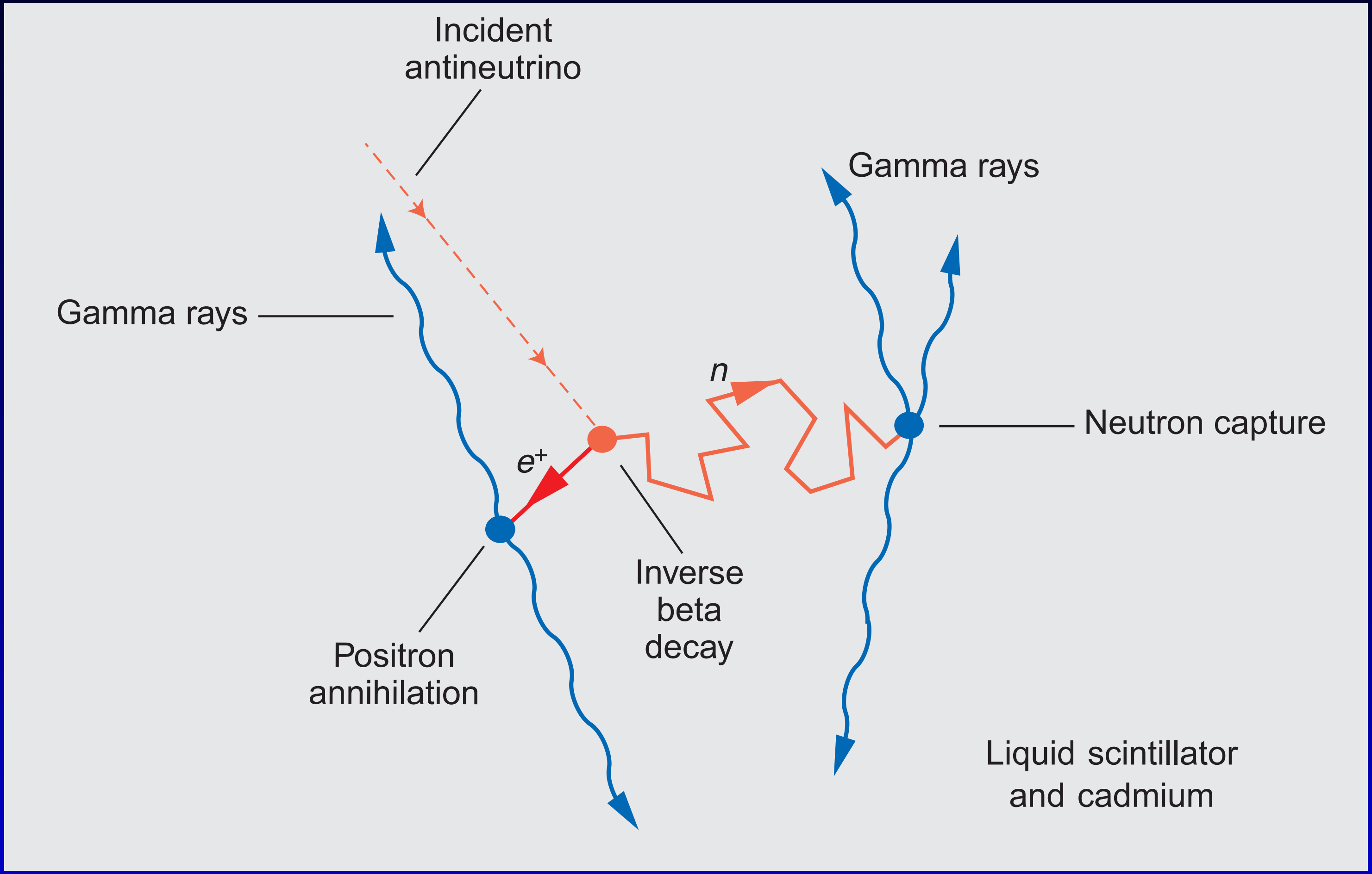
In the fall of 1952 Reines & Cowan revisited the idea of using a reactor:

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.

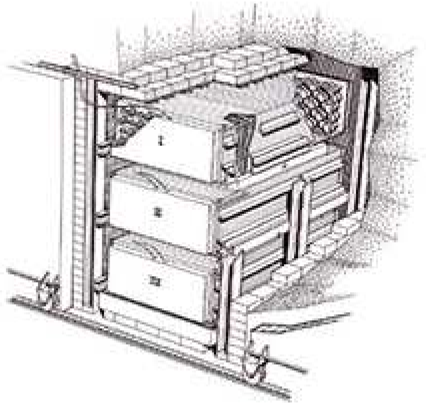
Delayed coincidence

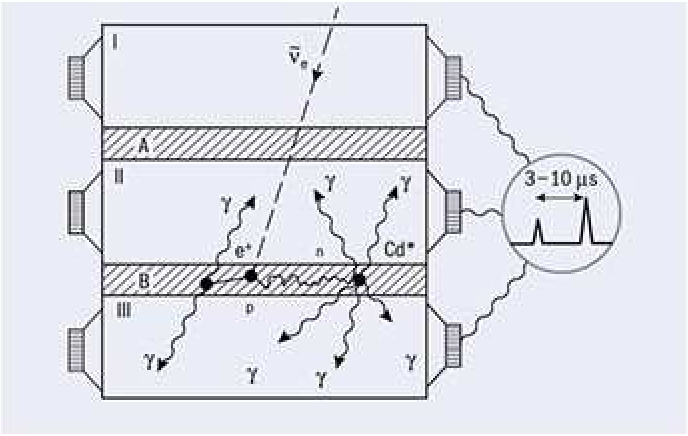


This is the basis for all reactor neutrino experiments since then.

Savannah River

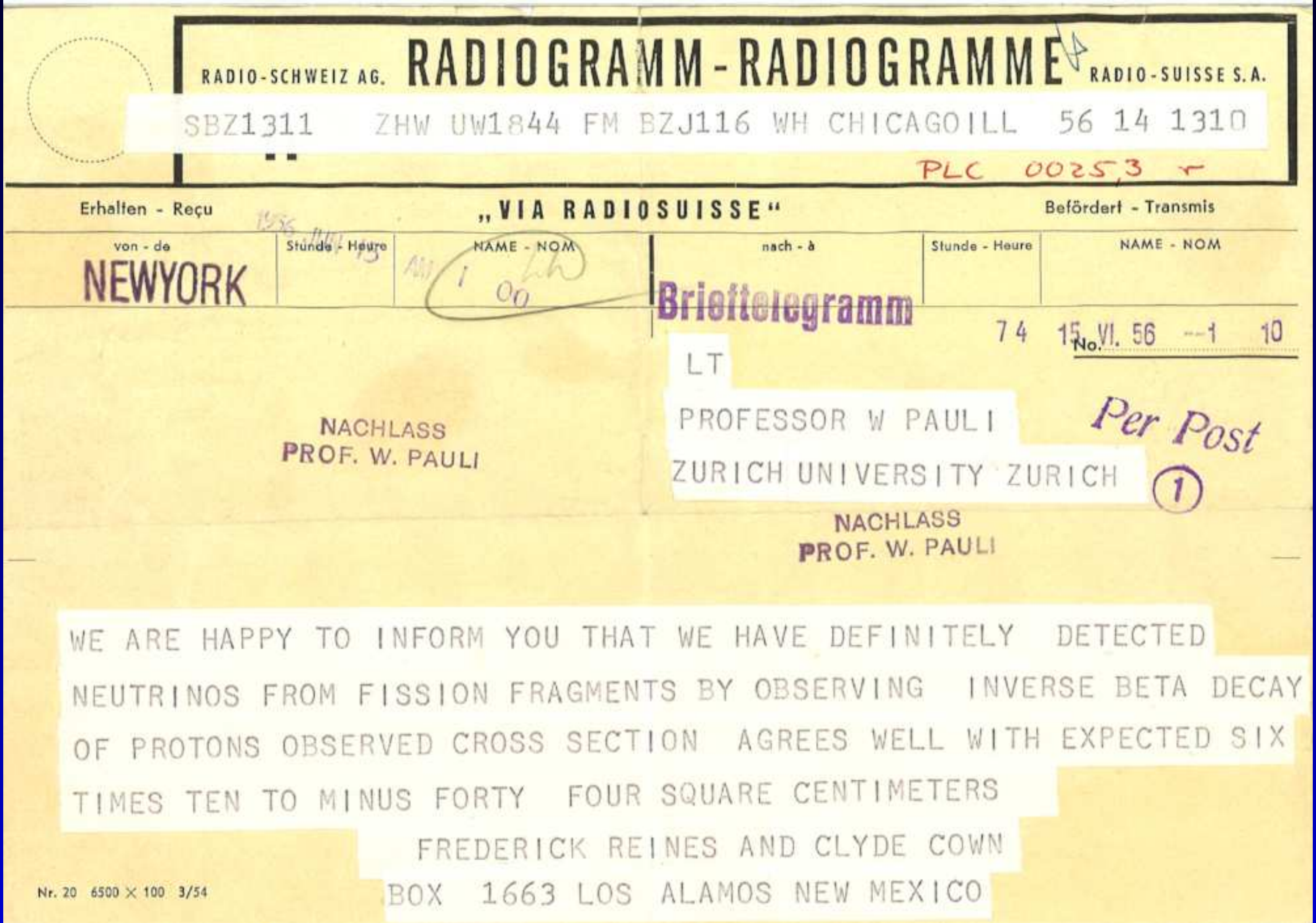
P-reactor became operational in Feb 1954, initially rated for less than 500MW, heavy water cooled, plutonium production reactor.





Note, positron energy is NOT observed.

1956



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ZURICH UNIVERSITY ZURICH

Per Post ①

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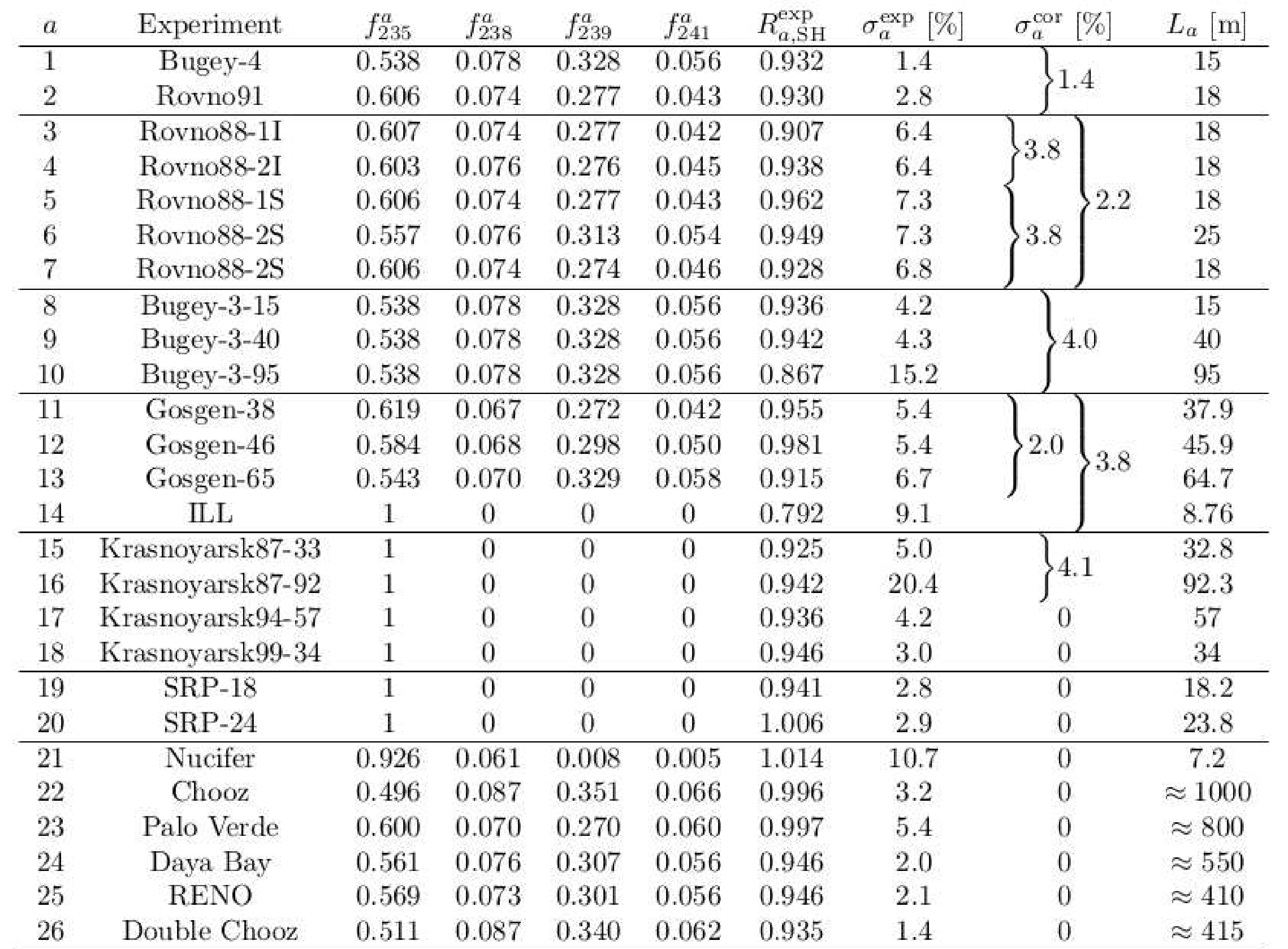
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

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		$\approx$ 1000
23	Palo Verde	0.600	0.070	0.270	0.060	0.997	5.4	0		$\approx$ 800
24	Daya Bay	0.561	0.076	0.307	0.056	0.946	2.0	0		$\approx$ 550
25	RENO	0.569	0.073	0.301	0.056	0.946	2.1	0		$\approx$ 410
26	Double Chooz	0.511	0.087	0.340	0.062	0.935	1.4	0		$\approx$ 415

Giunti 2016

SBL reactors summary

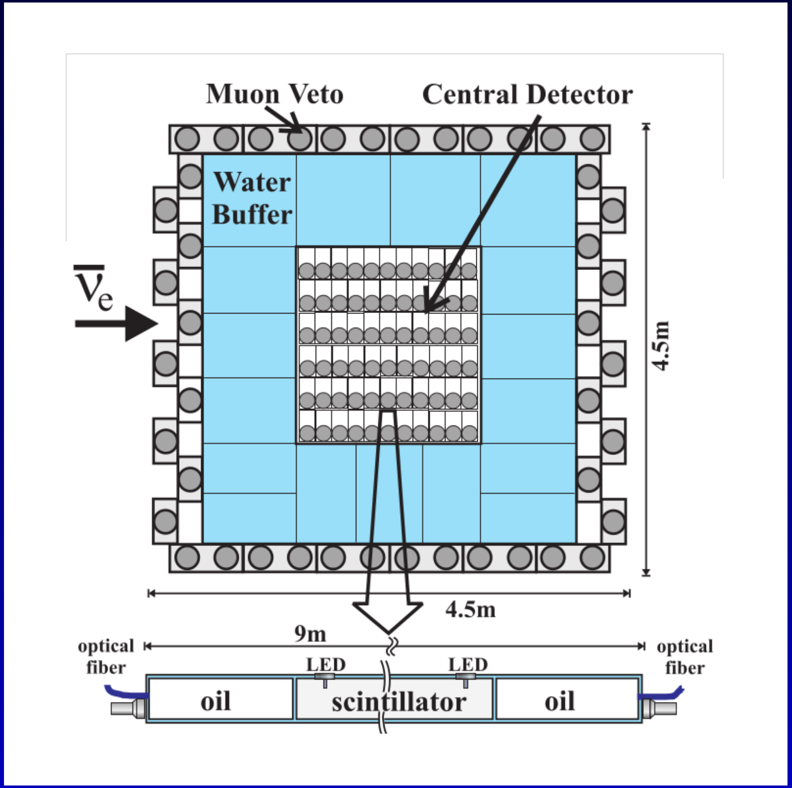
Technological achievements:

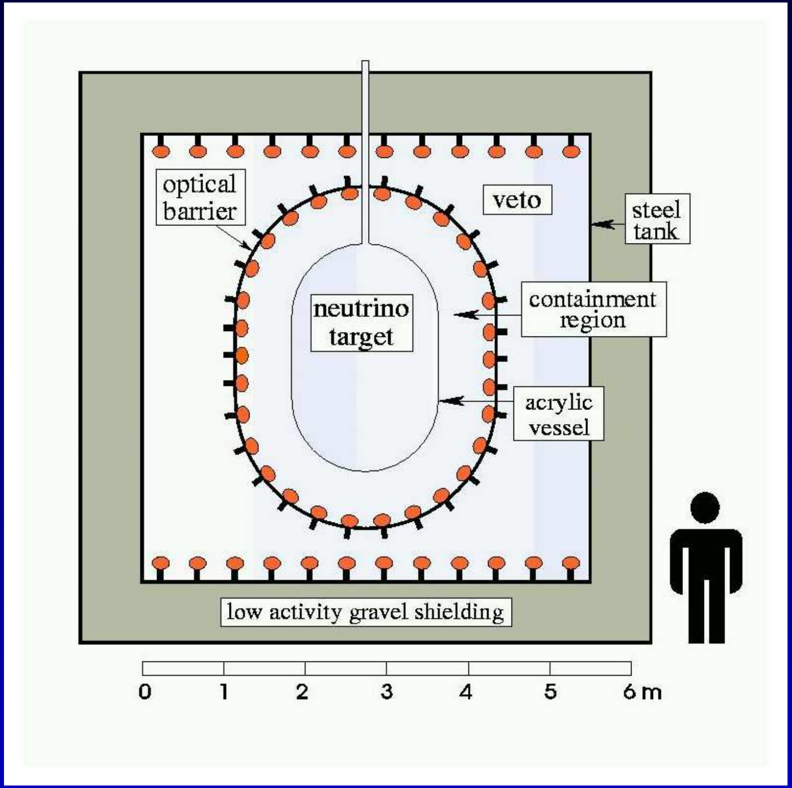
large liquid scintillator detectors
target and detector are one, *cf.* original Reines/Cowan detector
single volume and segmented detectors
many different neutron tagging concepts
Gd-doped scintillators

Science results as of 2011: In the baseline range from 7 – 93 m all results are consistent with NO oscillation.

Palo Verde & CHOOZ

Late 1990’s inspired by KamiokaNDE



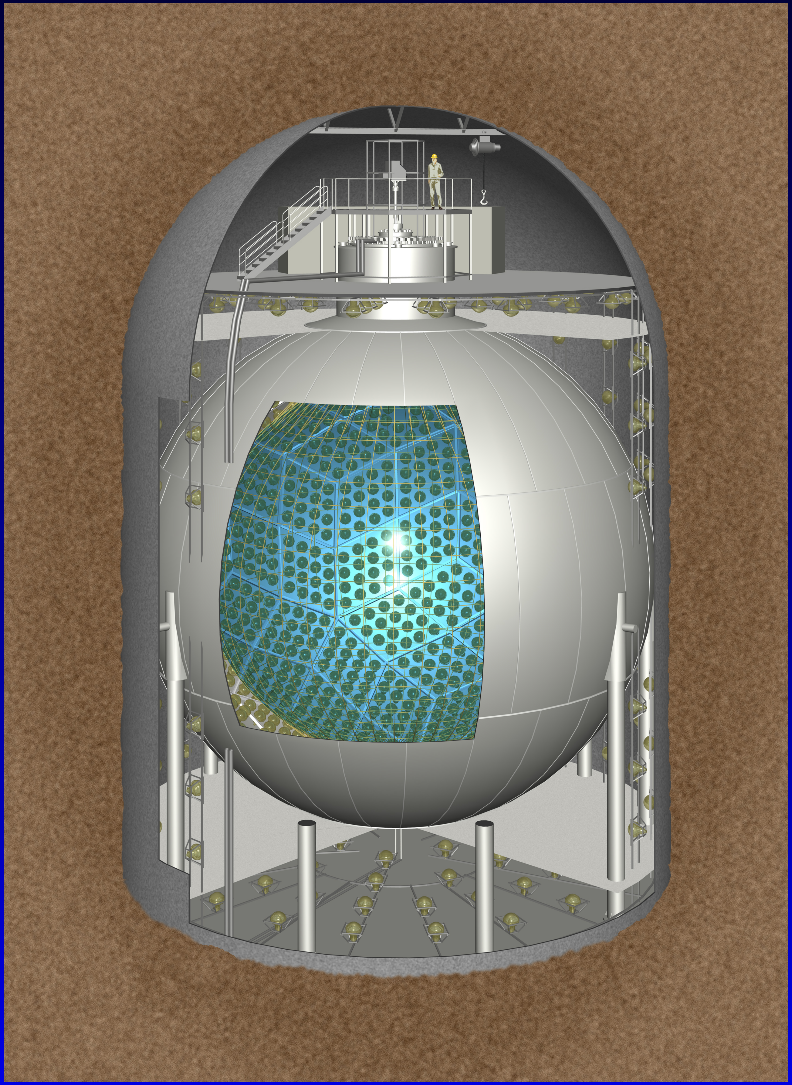


800 m from a commercial reactor

1100 m from a commercial reactor

Null result in both.

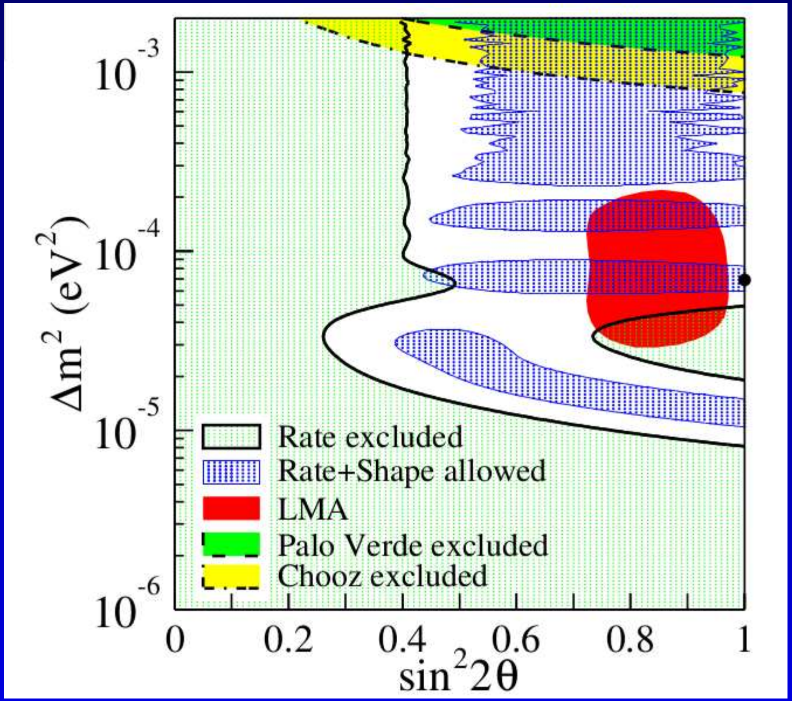
KamLAND – 2002

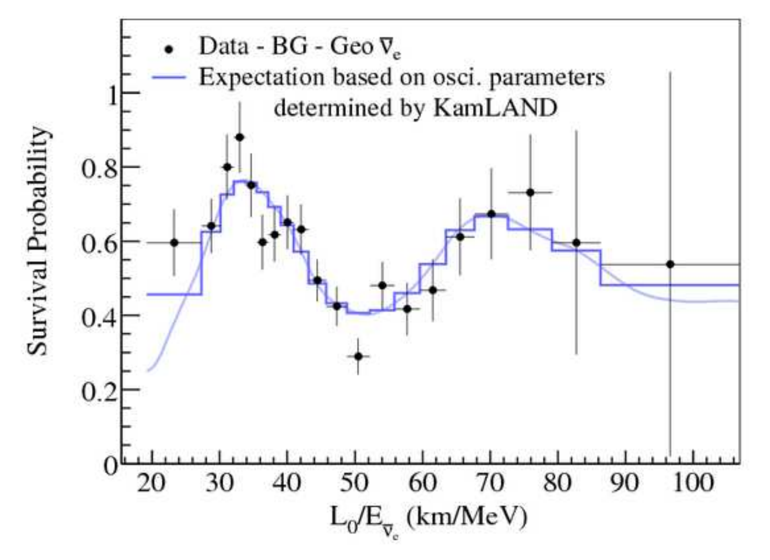


1000 t of liquid organic scintillator, undoped, deep underground.

KamLAND – results

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

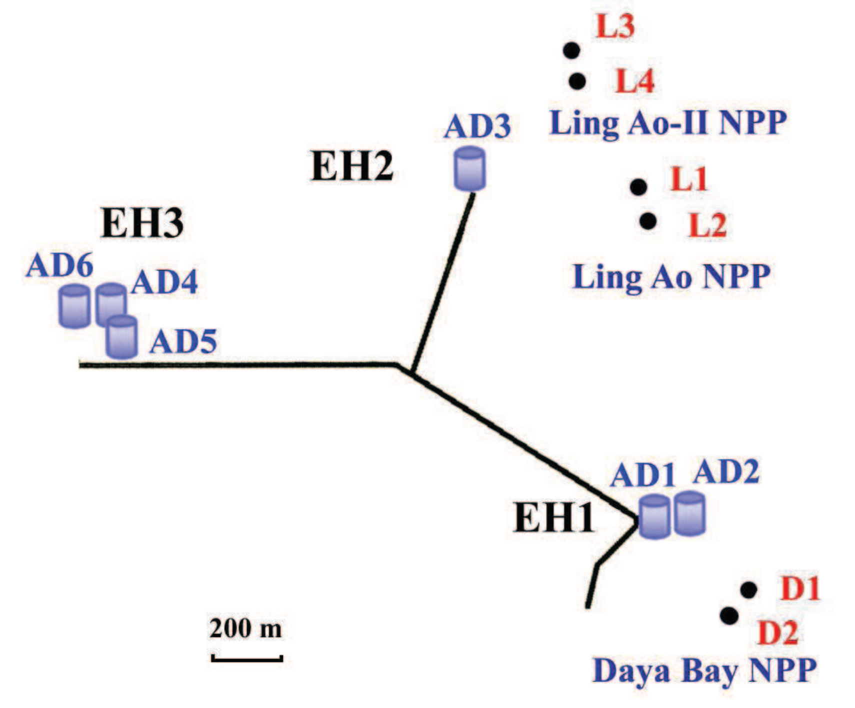




Later it was the first experiment to see an oscillatory pattern.

Daya Bay – 2011

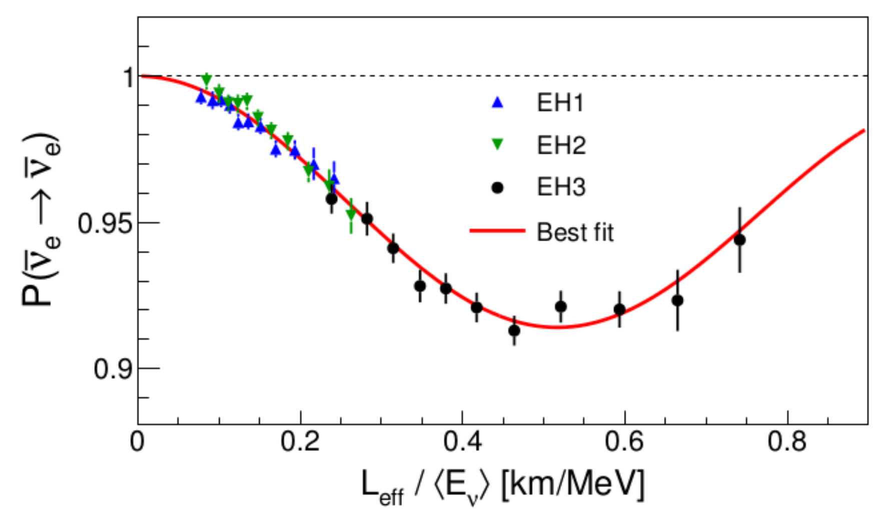
In a 1 reactor, 2 detector setup all flux related errors cancel completely in the near-to-far ratio.

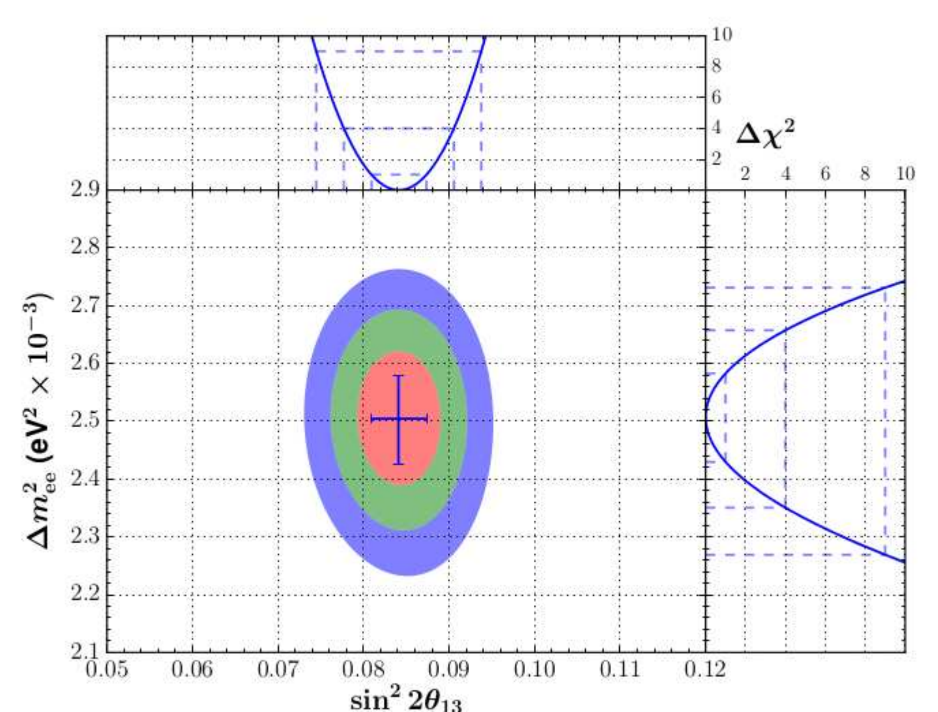


A careful choice of detector locations mitigates the complexity of the Daya Bay layout.

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.

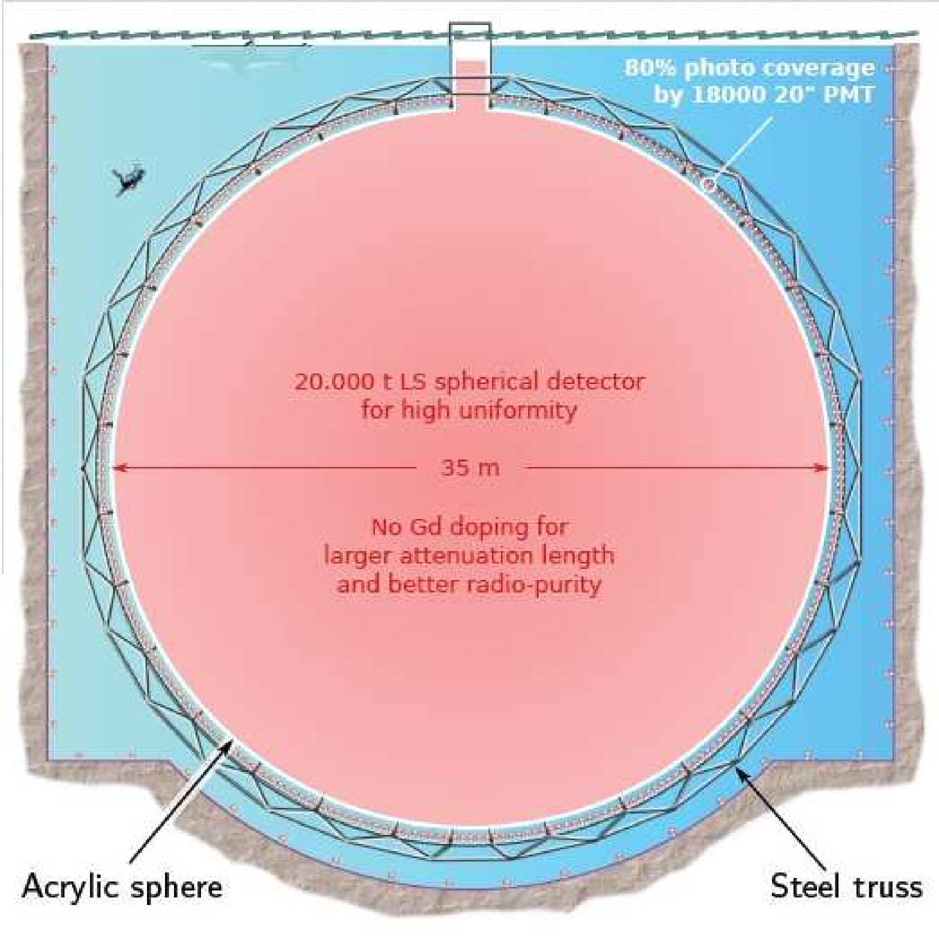
Most precise measurement of θ_{13}

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

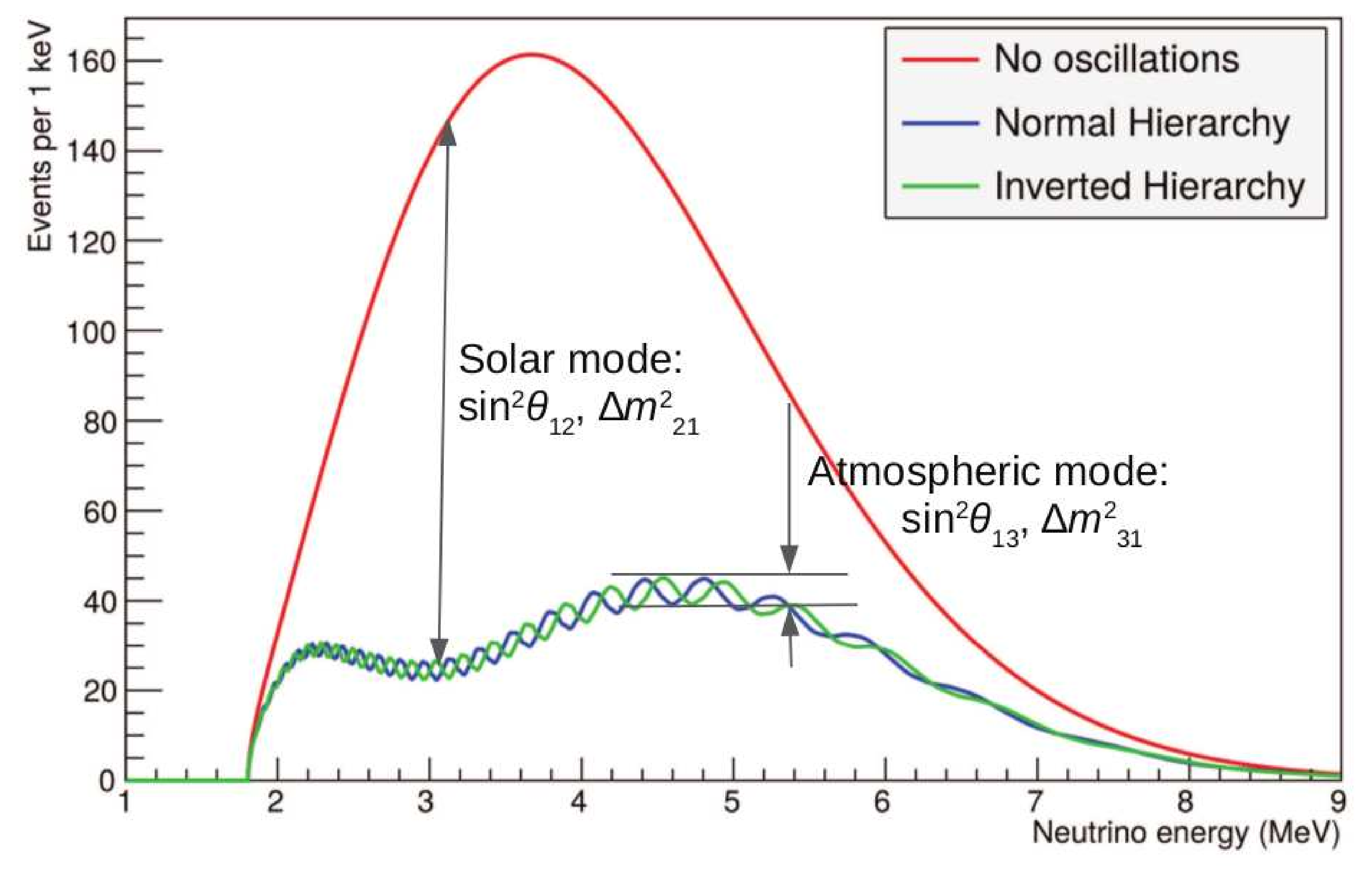


20,000 ton undoped liquid scintillator

53 km from two powerful reactor complexes, 18 GW each

Start of data taking ∼ 2024.

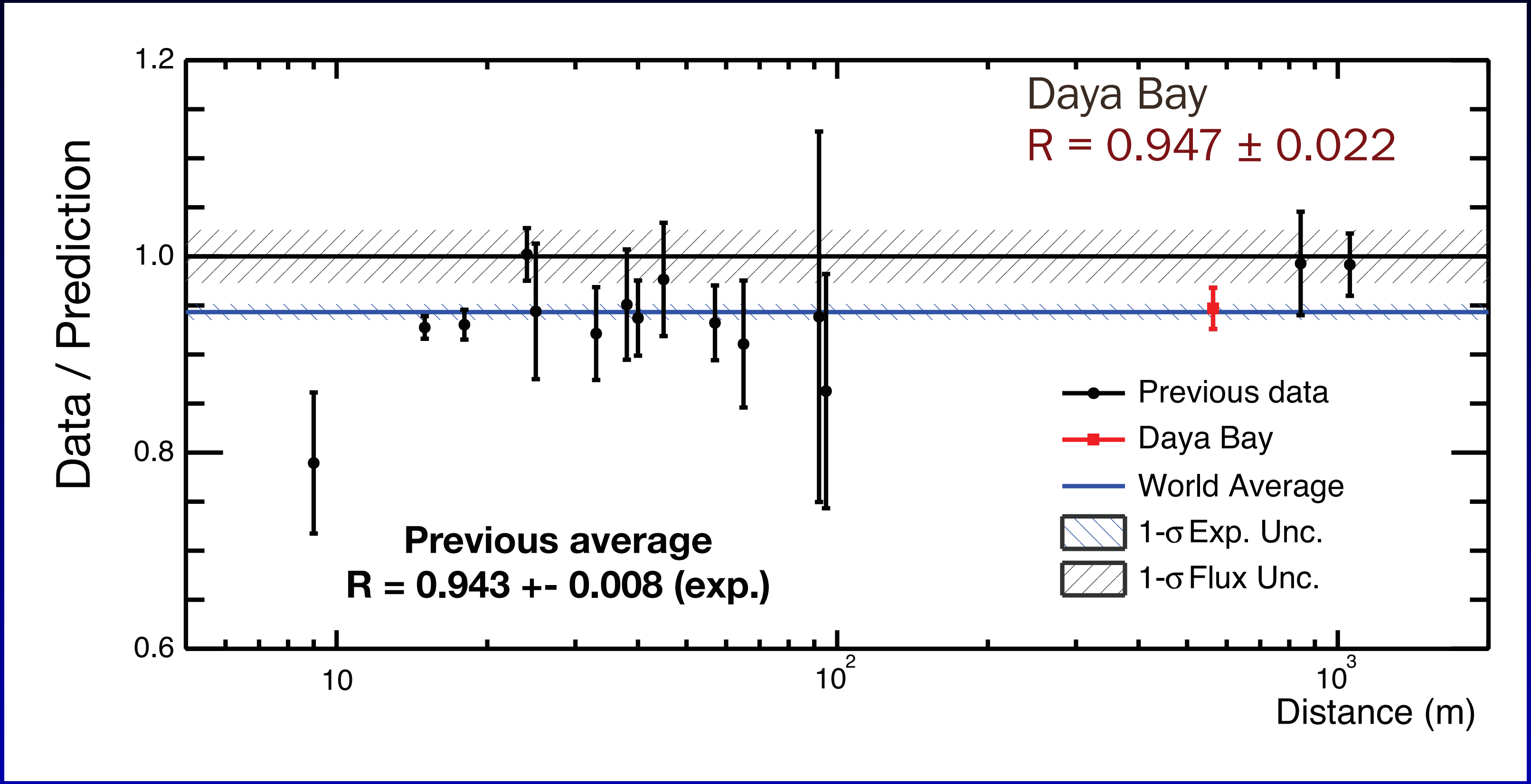
JUNO – physics goals



Measurement of mass hierarchy w/o matter effects

1% level measurement of solar mixing parameters

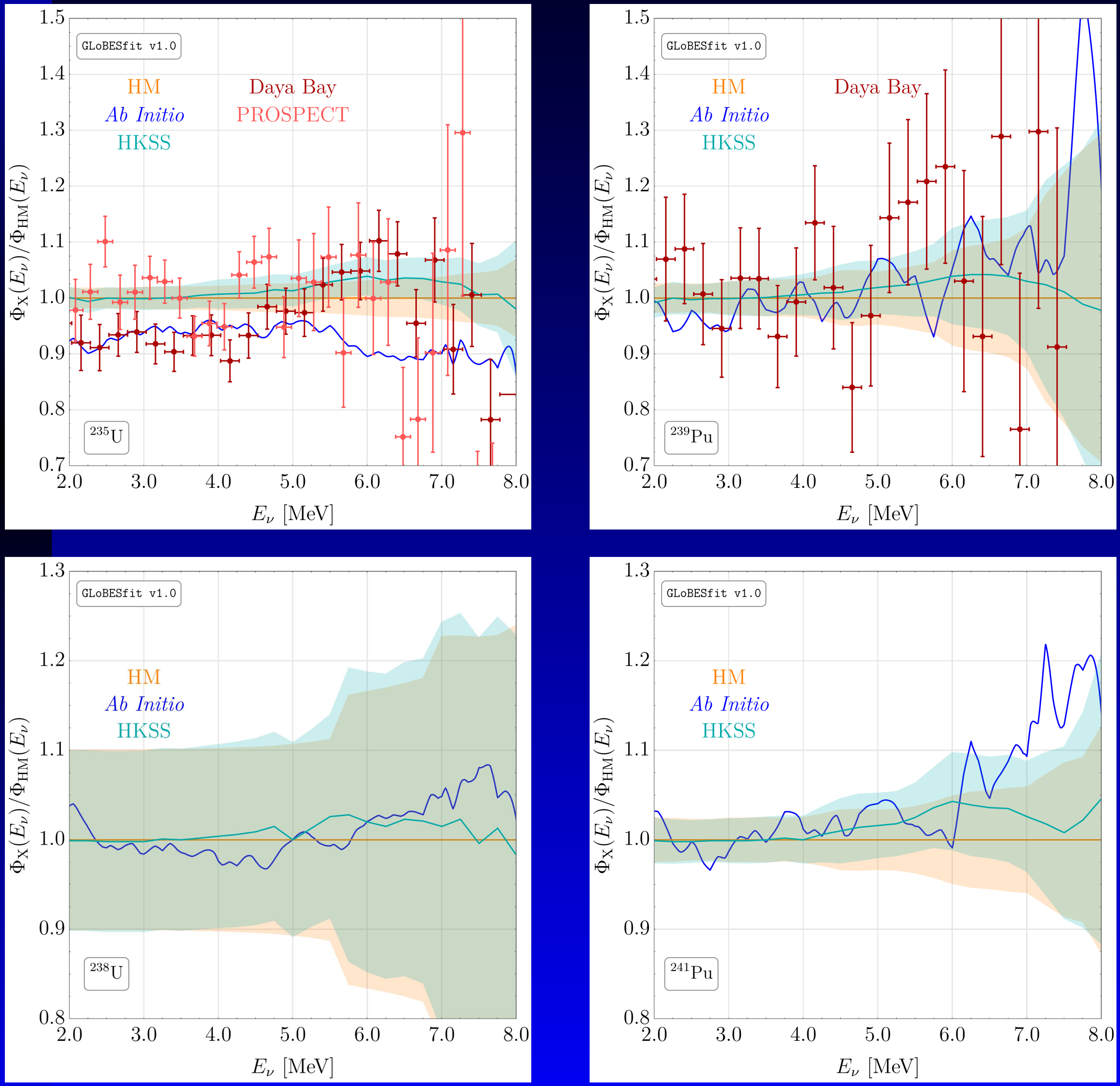
The reactor anomaly



Daya Bay, 2014

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

Where we are



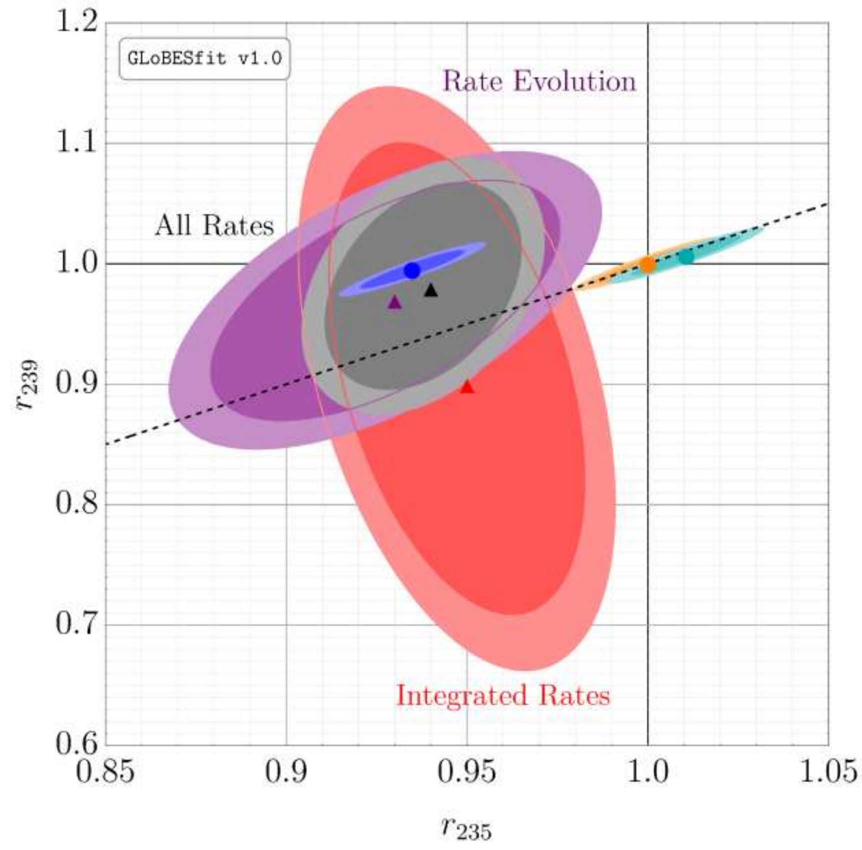
3 different flux models, data from 2 different experiments

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

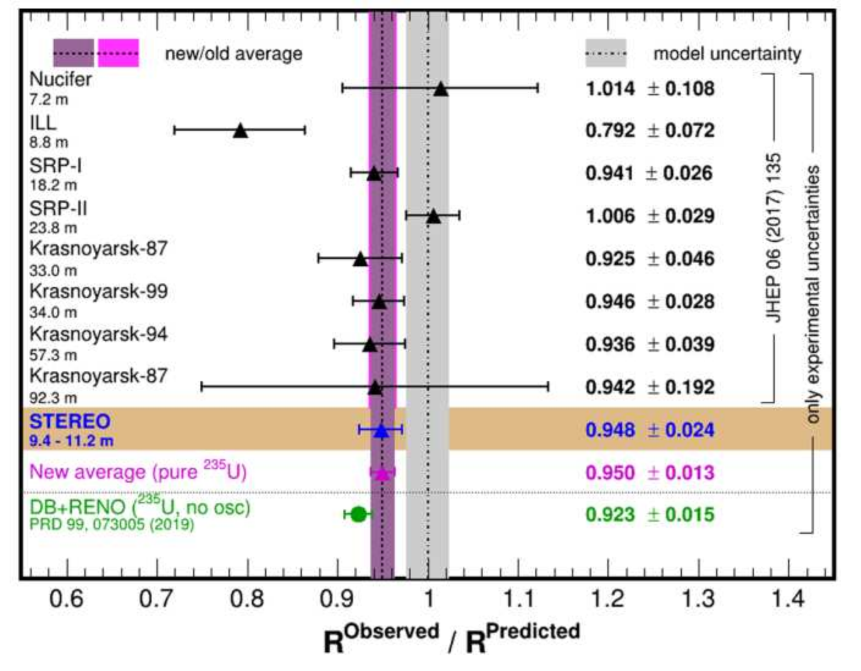
U235 has smallest error bars, not surprising that discrepancies show up first.

Berryman, PH, 2020

Fuel evolution



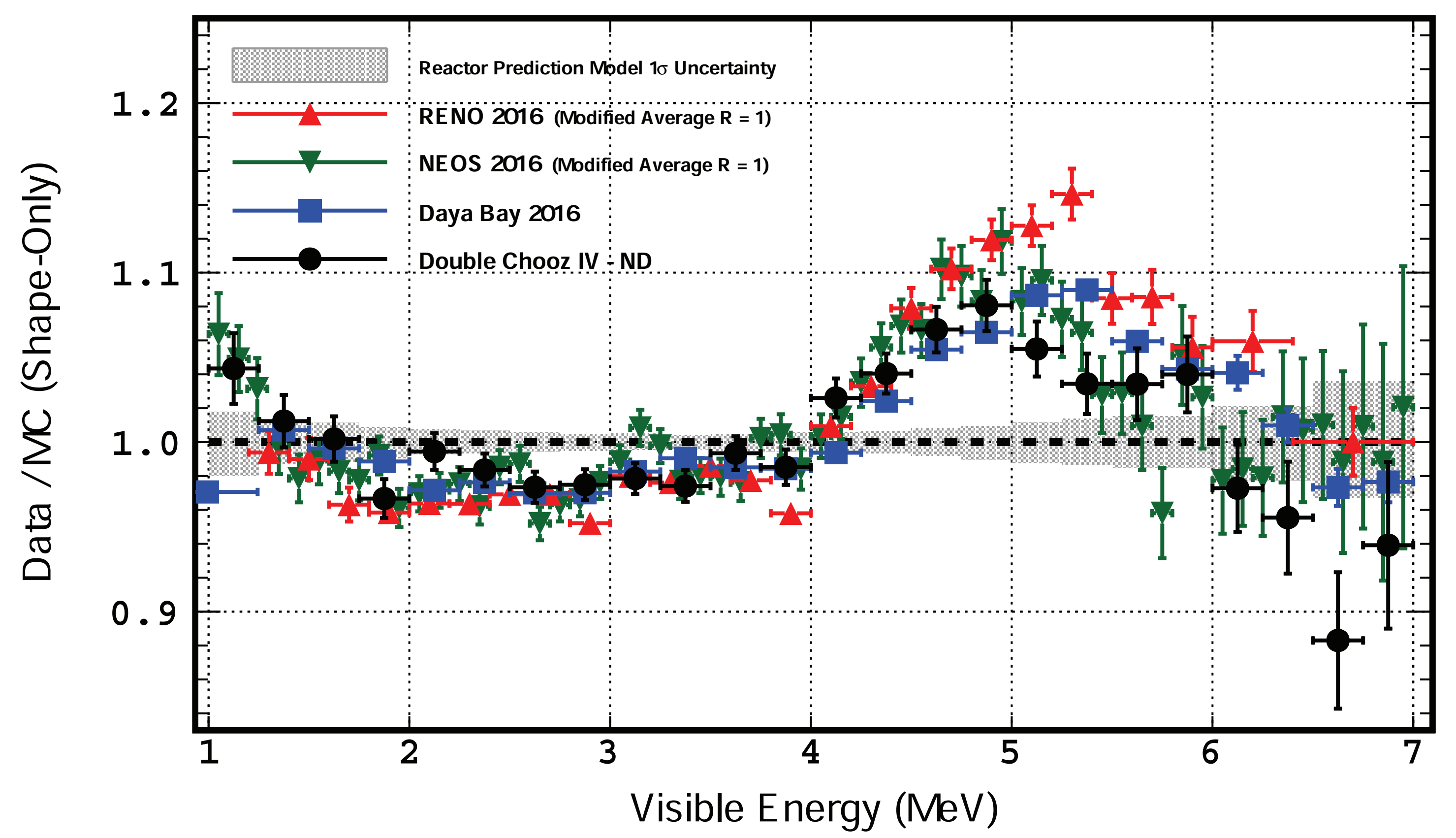
Berryman, PH, 2020



STEREO, 2020

U235 seems to “own” all of the deficit.

The 5 MeV bump

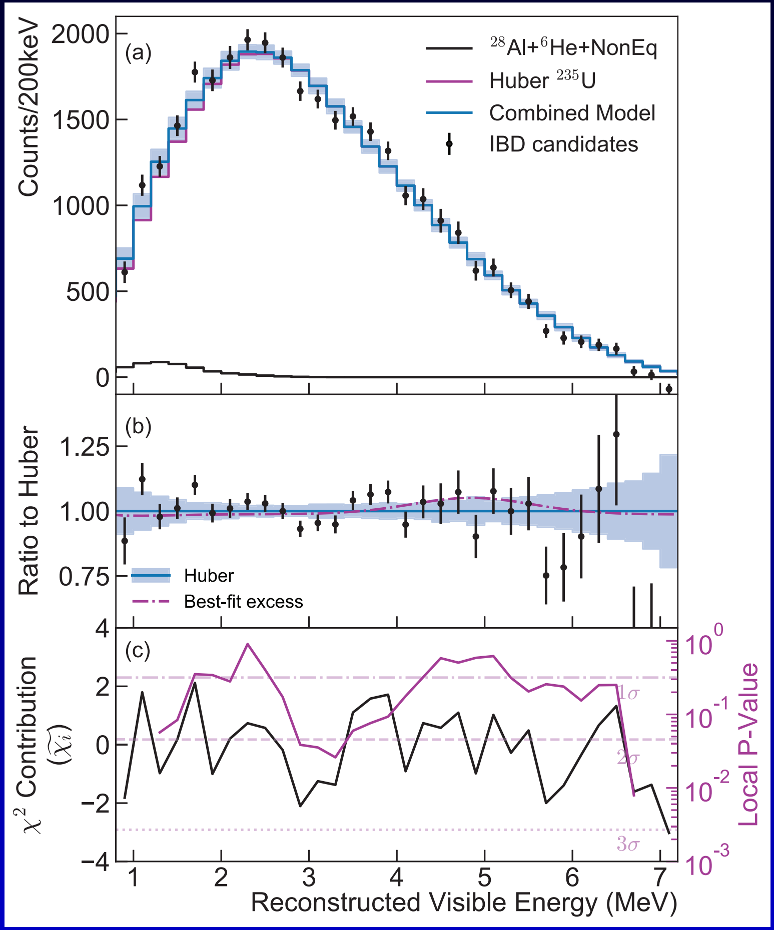


Double Chooz 2019

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

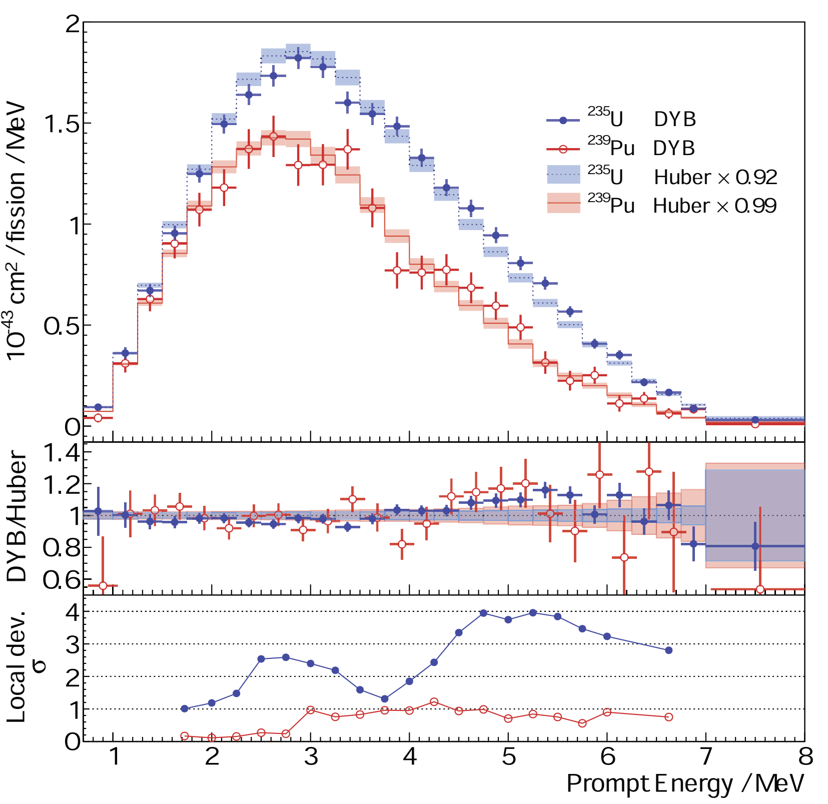
Yet, statistically more significant than the RAA!

Latest data vs bump



PROSPECT 2018

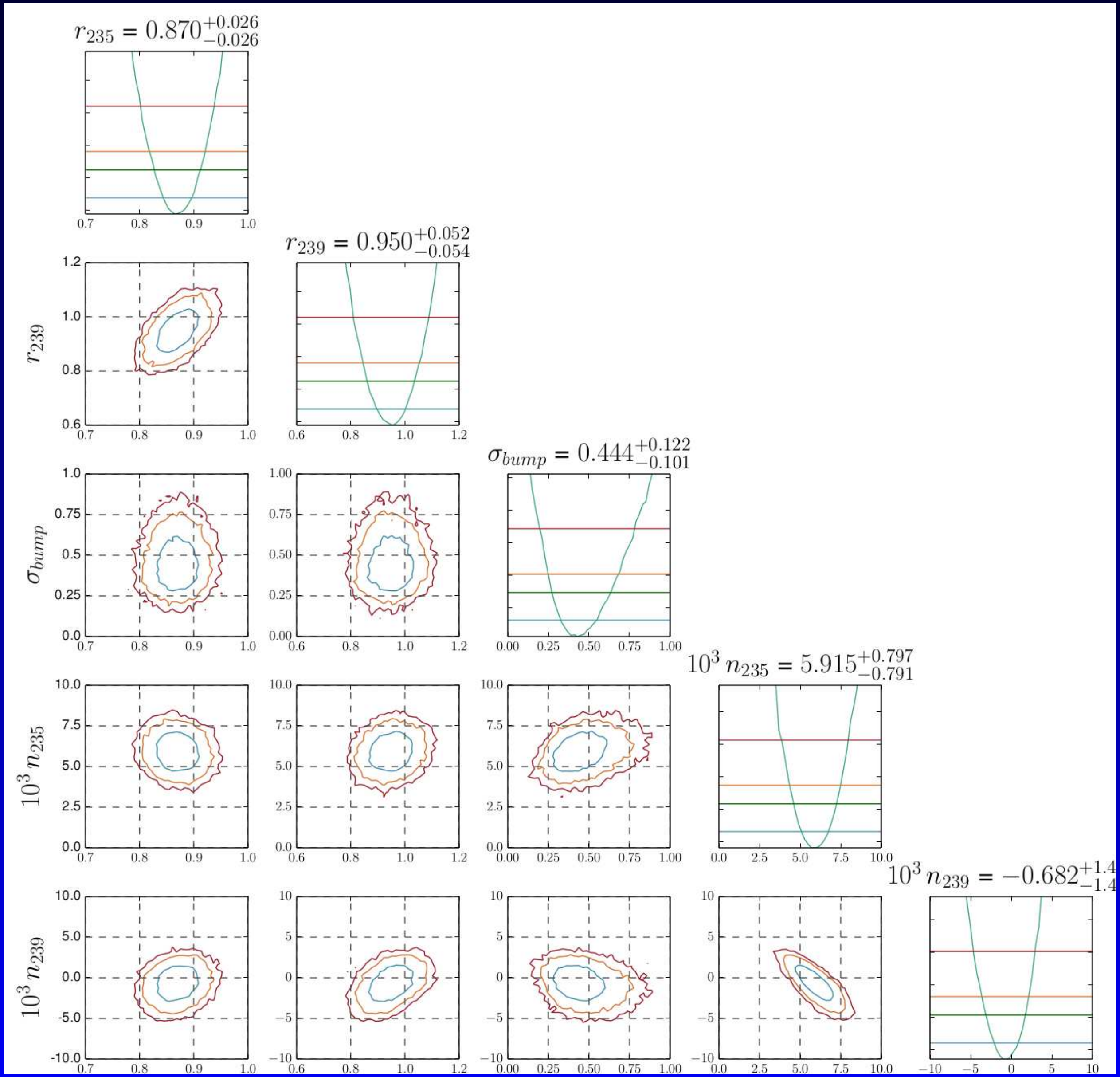
Disfavors ^{235}U as sole culprit at 2.1 σ



Daya Bay 2019, 2021

Requires a bump in ^{235}U at 4 σ

Bumpology

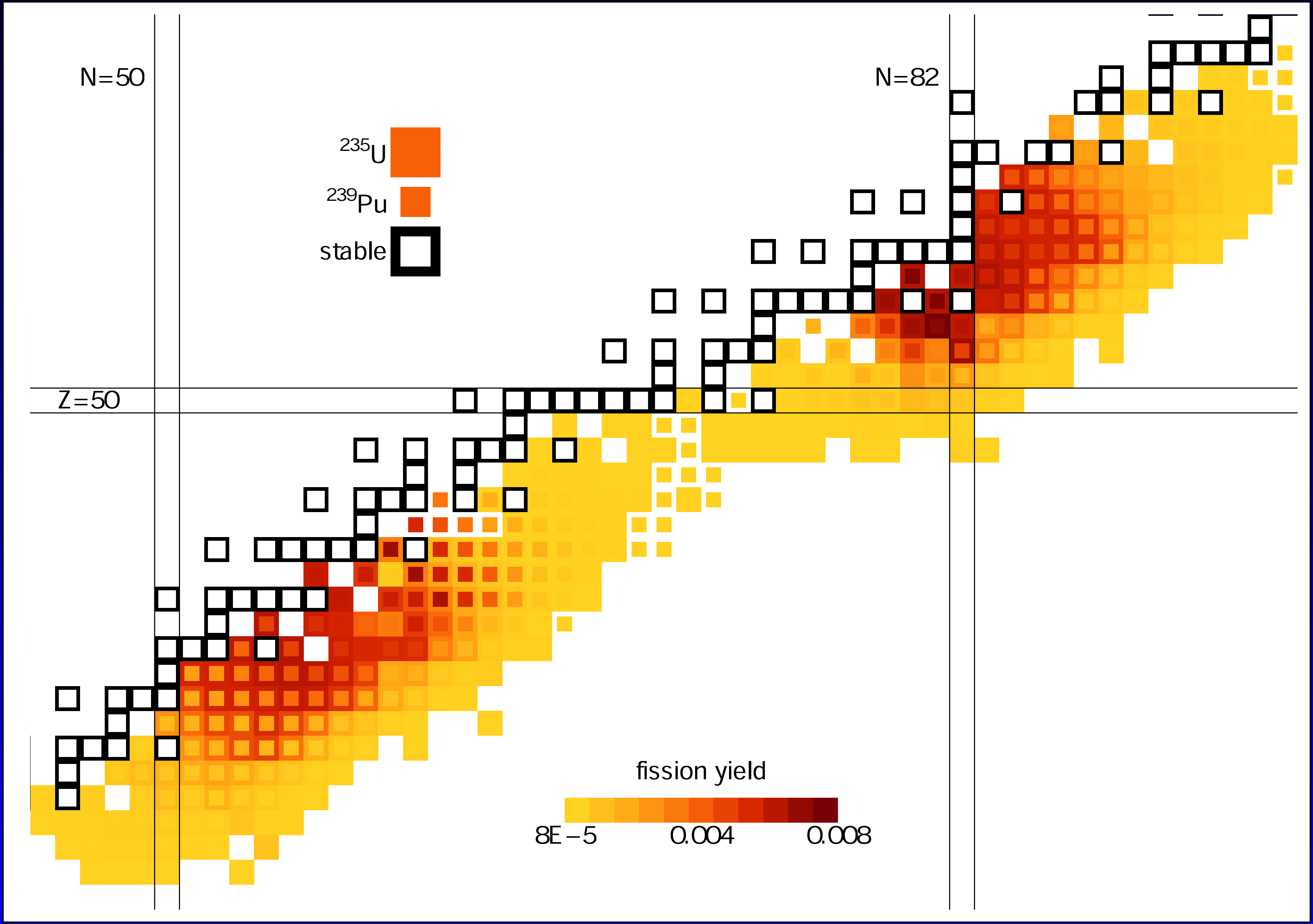


Daya Bay, RENO and PROSPECT as of 2019

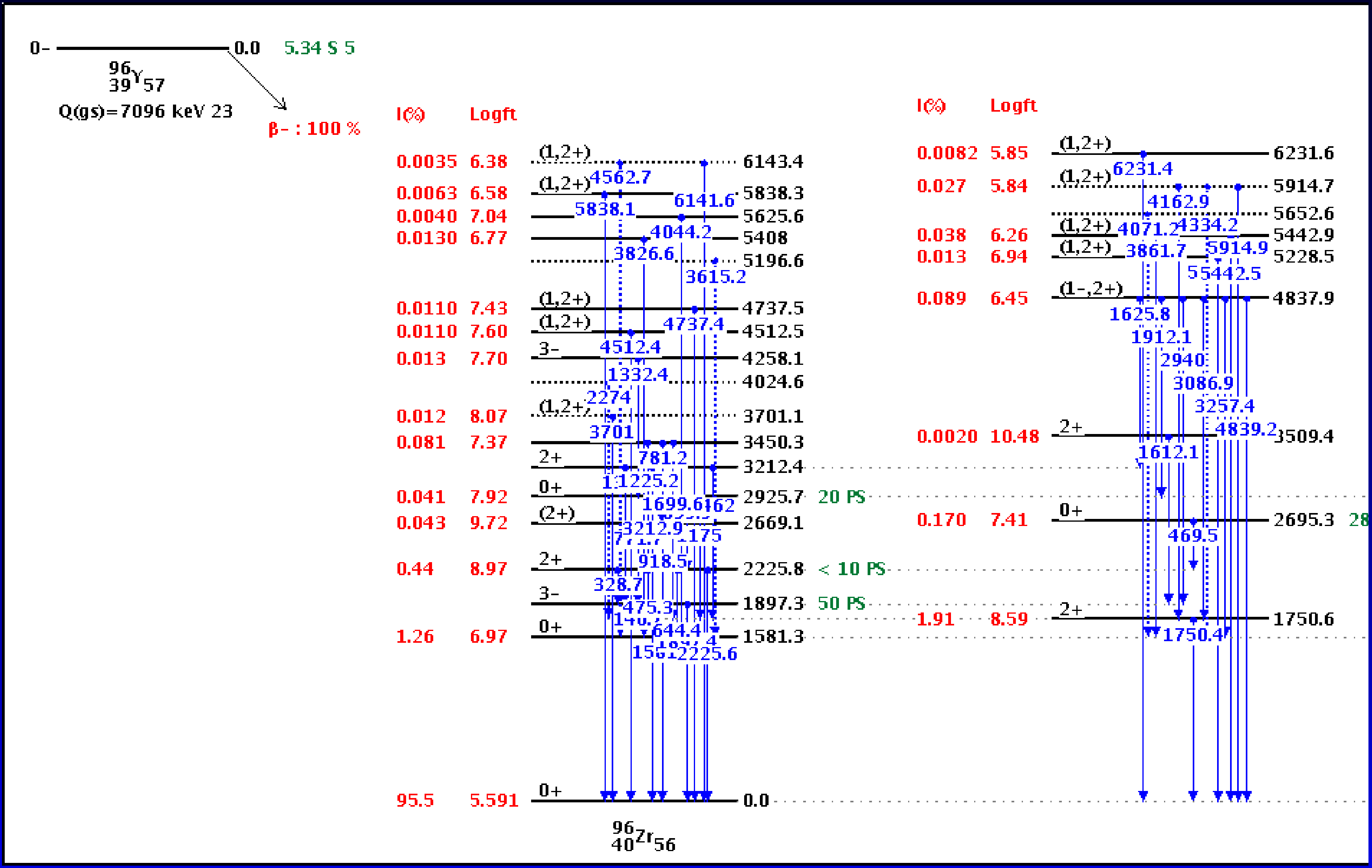
Only $n_{235} \neq 0$ with any significance

Berryman, PH, 2020

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

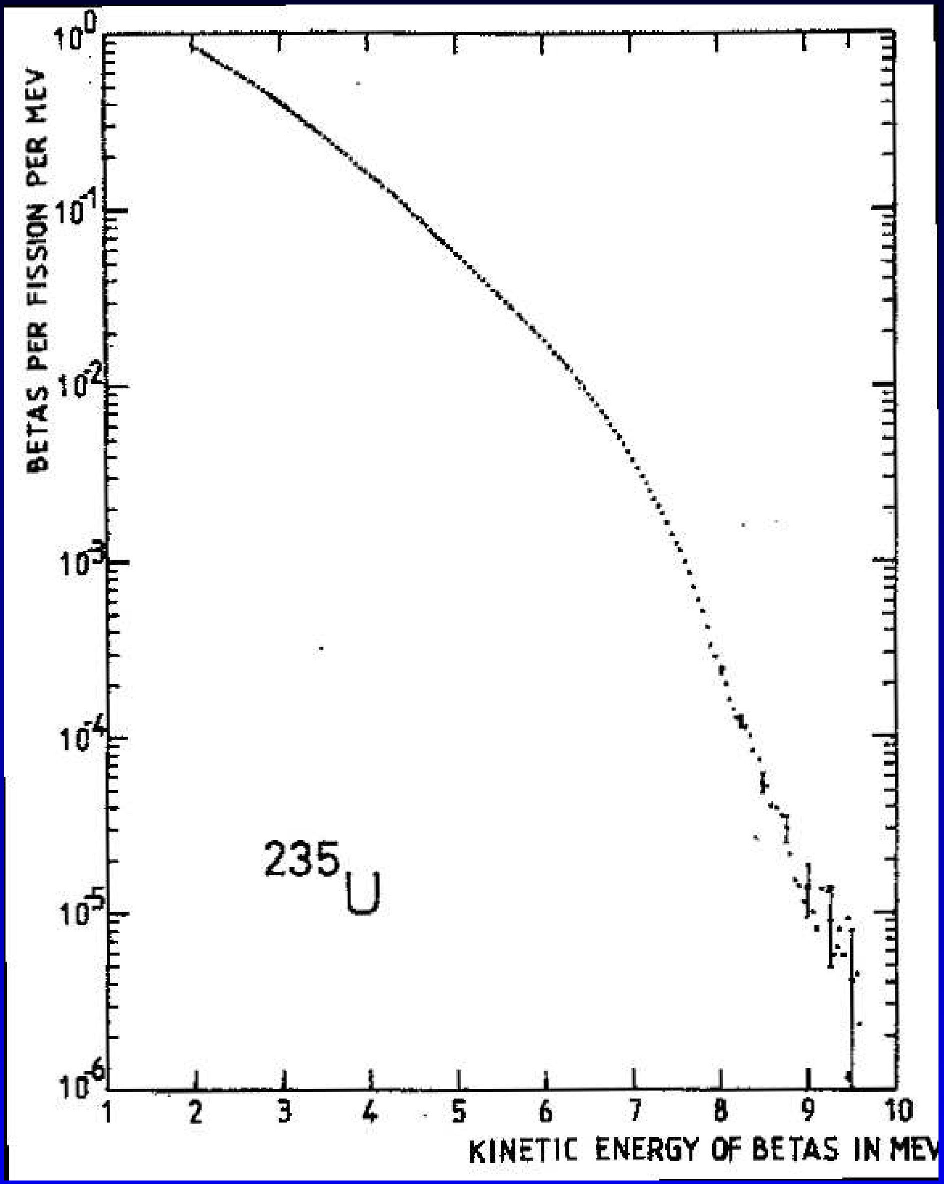
Conversion calculations

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

Conversion method



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

For ^{238}U recent measurement by Haag *et al.*, 2013

Extraction of ν-spectrum

We can measure the total β-spectrum

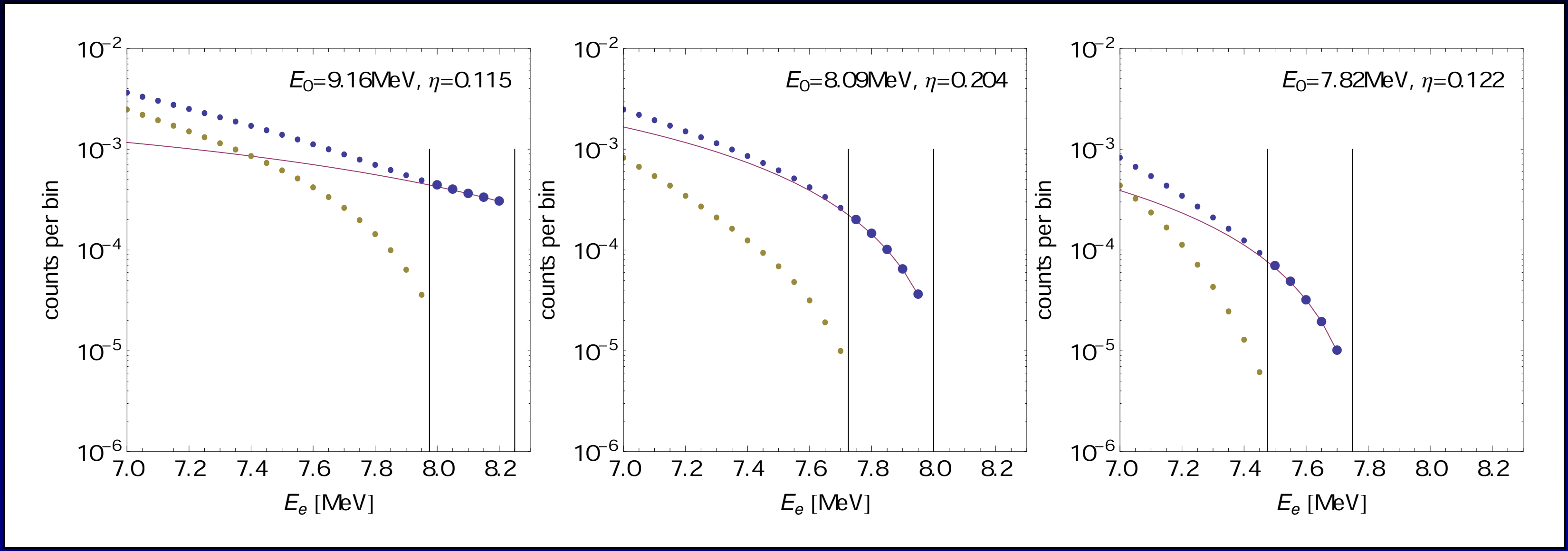
$$\mathcal{N}_\beta(E_e) = \int dE_0 N_\beta(E_e, E_0; \bar{Z})\, \eta(E_0)\,. \qquad (1)$$

with $\bar{Z}$ effective nuclear charge and try to “fit” the underlying distribution of endpoints, $\eta(E_0)$.

This is a so called Fredholm integral equation of the first kind – mathematically ill-posed, *i.e.* solutions tend to oscillate, needs regulator (typically energy average), however that will introduce a bias.

This approach is know as “virtual branches”

Virtual branches



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

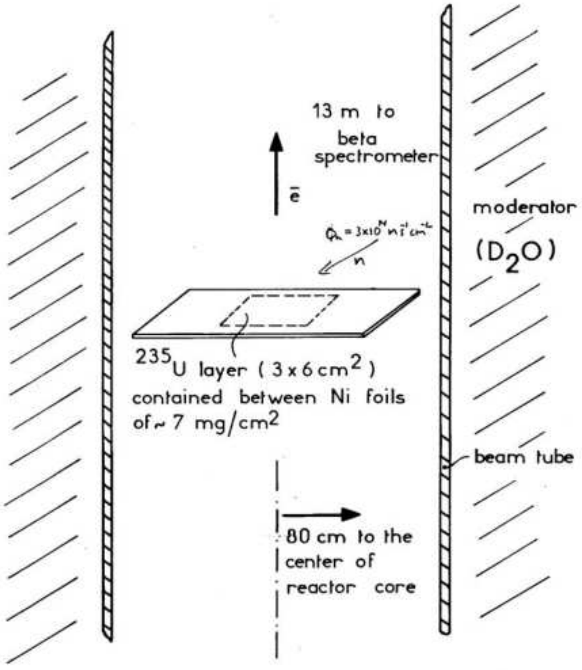
2 – delete the last s data points

3 – subtract the fitted spectrum from the data

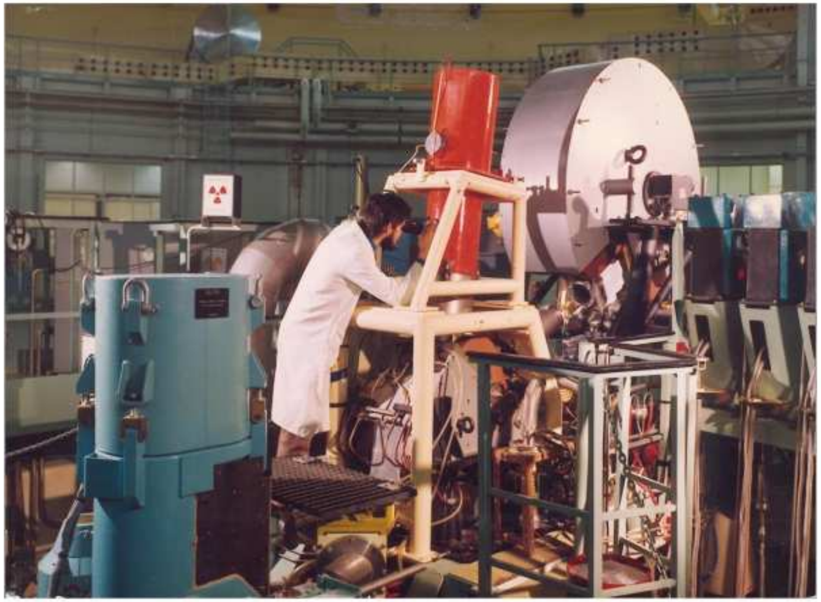
4 – goto 1

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

Kill BILL?



SCHEMATIC VIEW OF THE TARGET SITE



Magnetic BILL spectrometer at ILL, 1972-1991

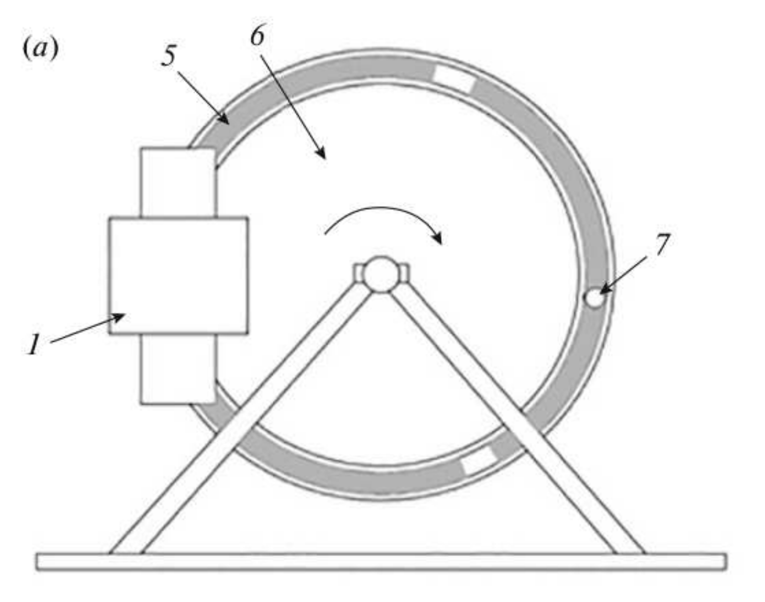
(Electron detector in focal plane: multi chamber proportional counter in transmission, rear mounted scintillator in coincidence)

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

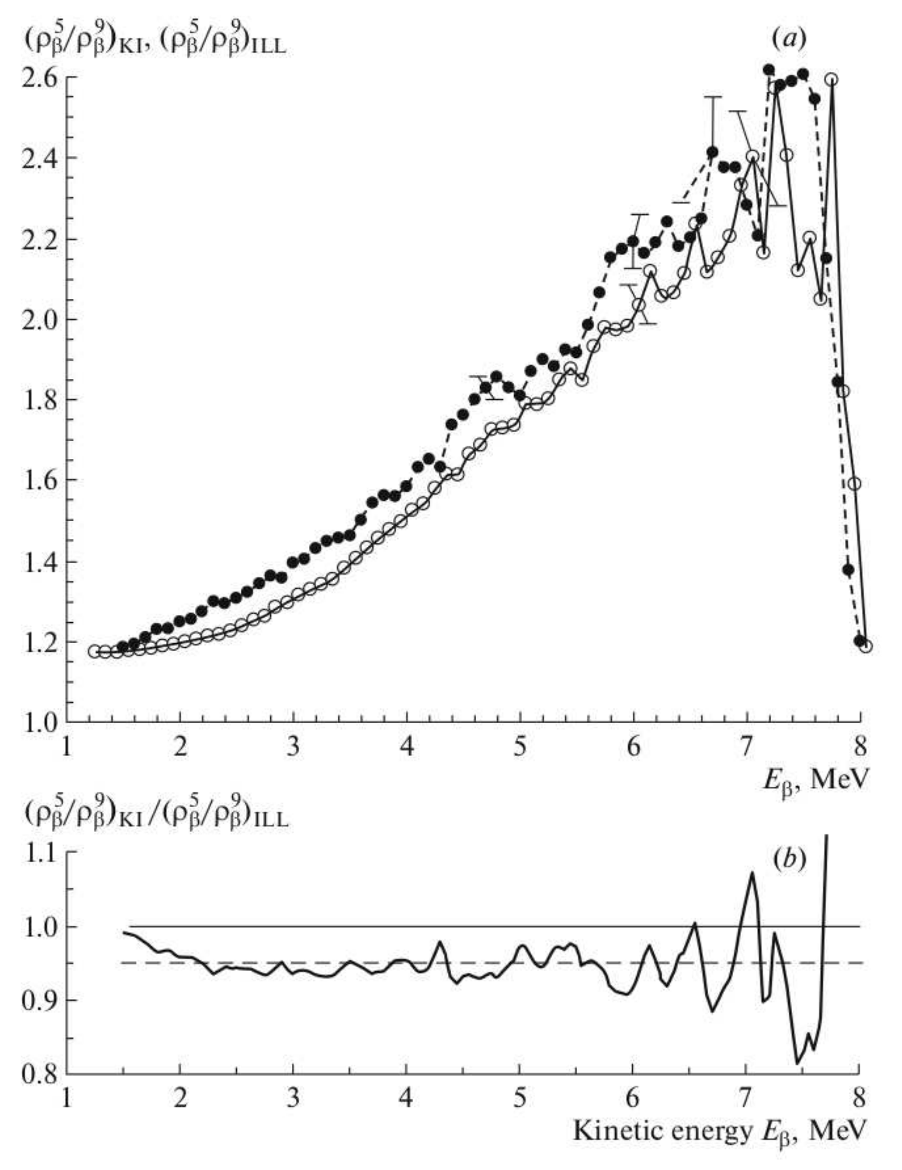


Relative measurement of U235 and Pu239 targets under identical conditions.

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)

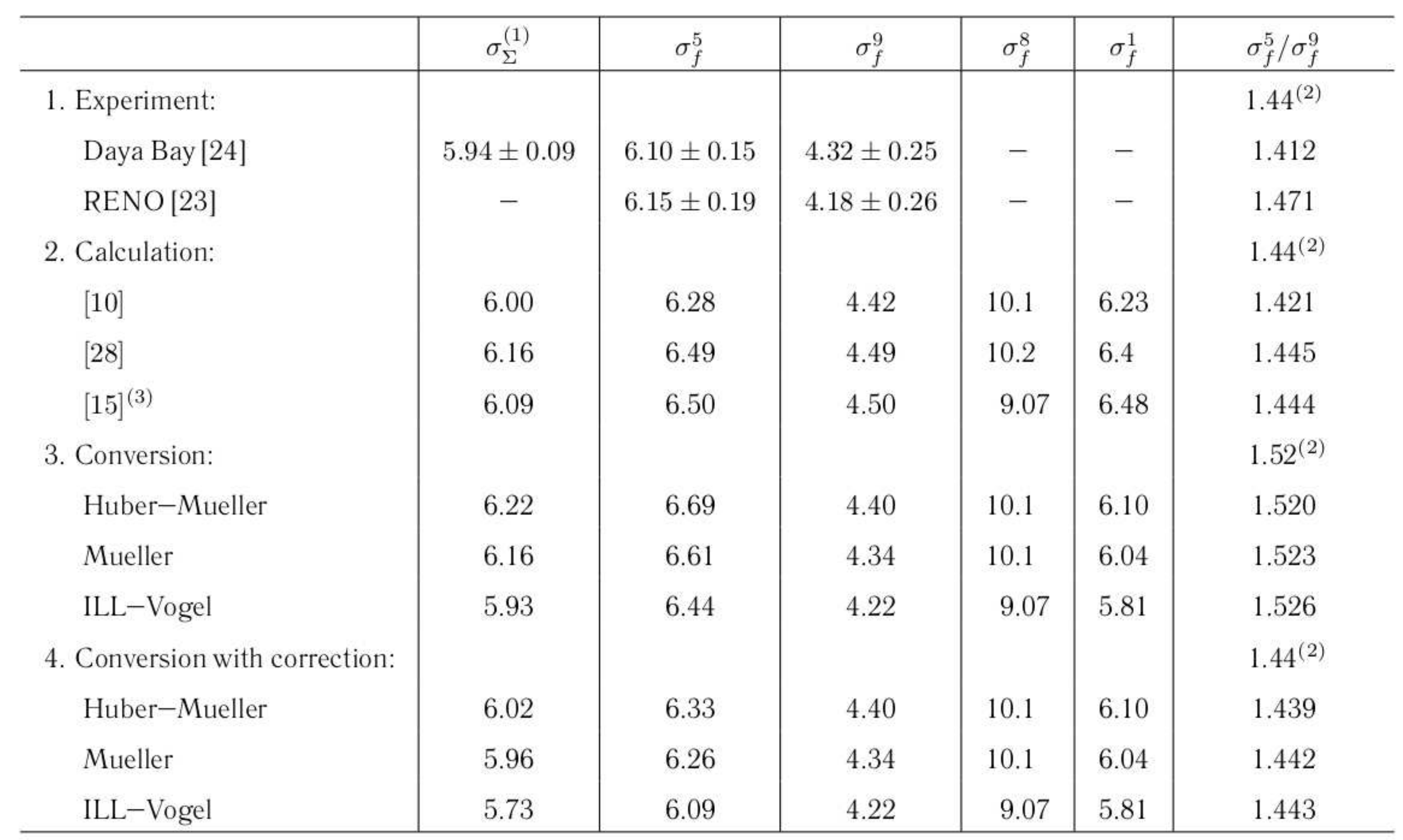
2021 beta results



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

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

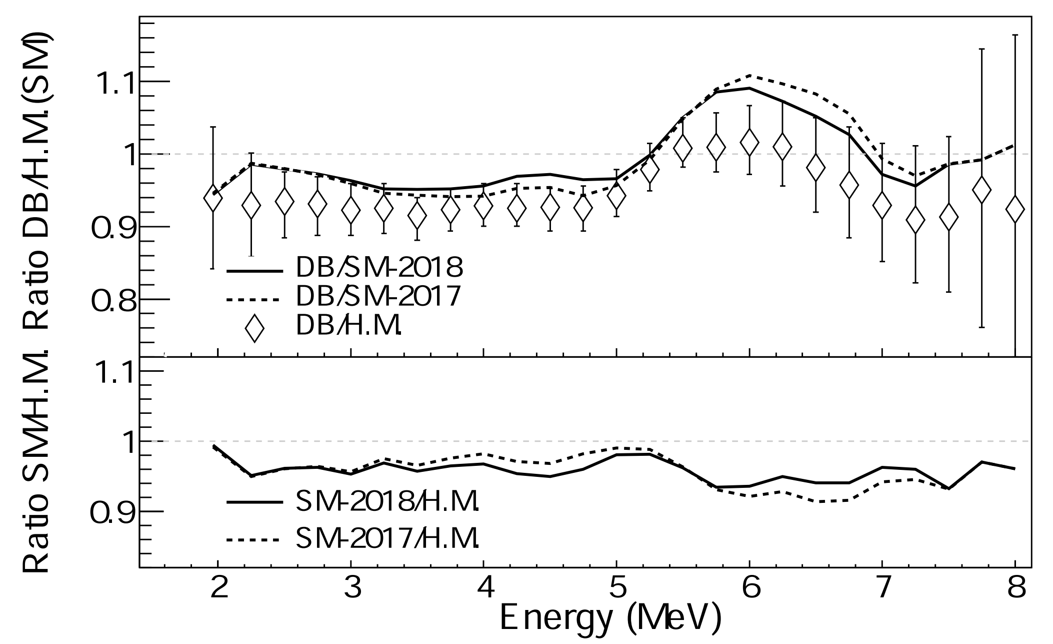
2021 beta impact

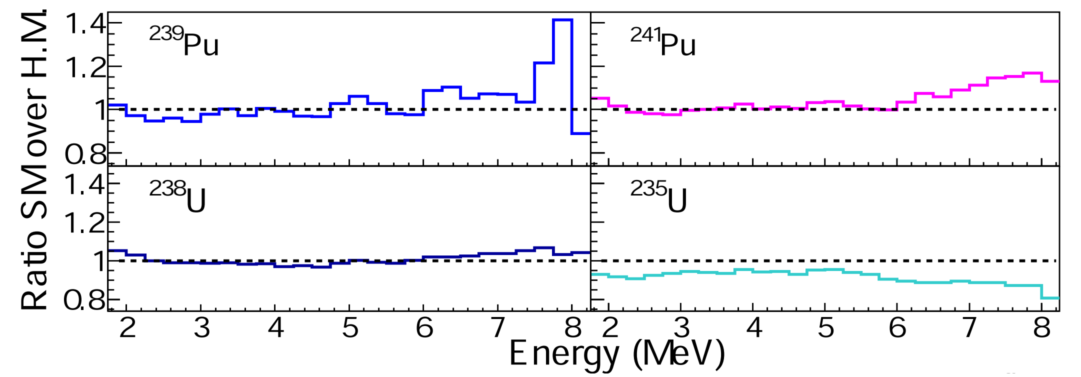


	$\sigma_\Sigma^{(1)}$	σ_f^5	σ_f^9	σ_f^8	σ_f^1	σ_f^5/σ_f^9
1. Experiment:						$1.44^{(2)}$
Daya Bay [24]	5.94 ± 0.09	6.10 ± 0.15	4.32 ± 0.25	–	–	1.412
RENO [23]	–	6.15 ± 0.19	4.18 ± 0.26	–	–	1.471
2. Calculation:						$1.44^{(2)}$
[10]	6.00	6.28	4.42	10.1	6.23	1.421
[28]	6.16	6.49	4.49	10.2	6.4	1.445
[15]$^{(3)}$	6.09	6.50	4.50	9.07	6.48	1.444
3. Conversion:						$1.52^{(2)}$
Huber–Mueller	6.22	6.69	4.40	10.1	6.10	1.520
Mueller	6.16	6.61	4.34	10.1	6.04	1.523
ILL–Vogel	5.93	6.44	4.22	9.07	5.81	1.526
4. Conversion with correction:						$1.44^{(2)}$
Huber–Mueller	6.02	6.33	4.40	10.1	6.10	1.439
Mueller	5.96	6.26	4.34	10.1	6.04	1.442
ILL–Vogel	5.73	6.09	4.22	9.07	5.81	1.443

Now the predicted and measured U235/Pu235 IBD ratio agree well. IF confirmed, no RAA!

Summation method





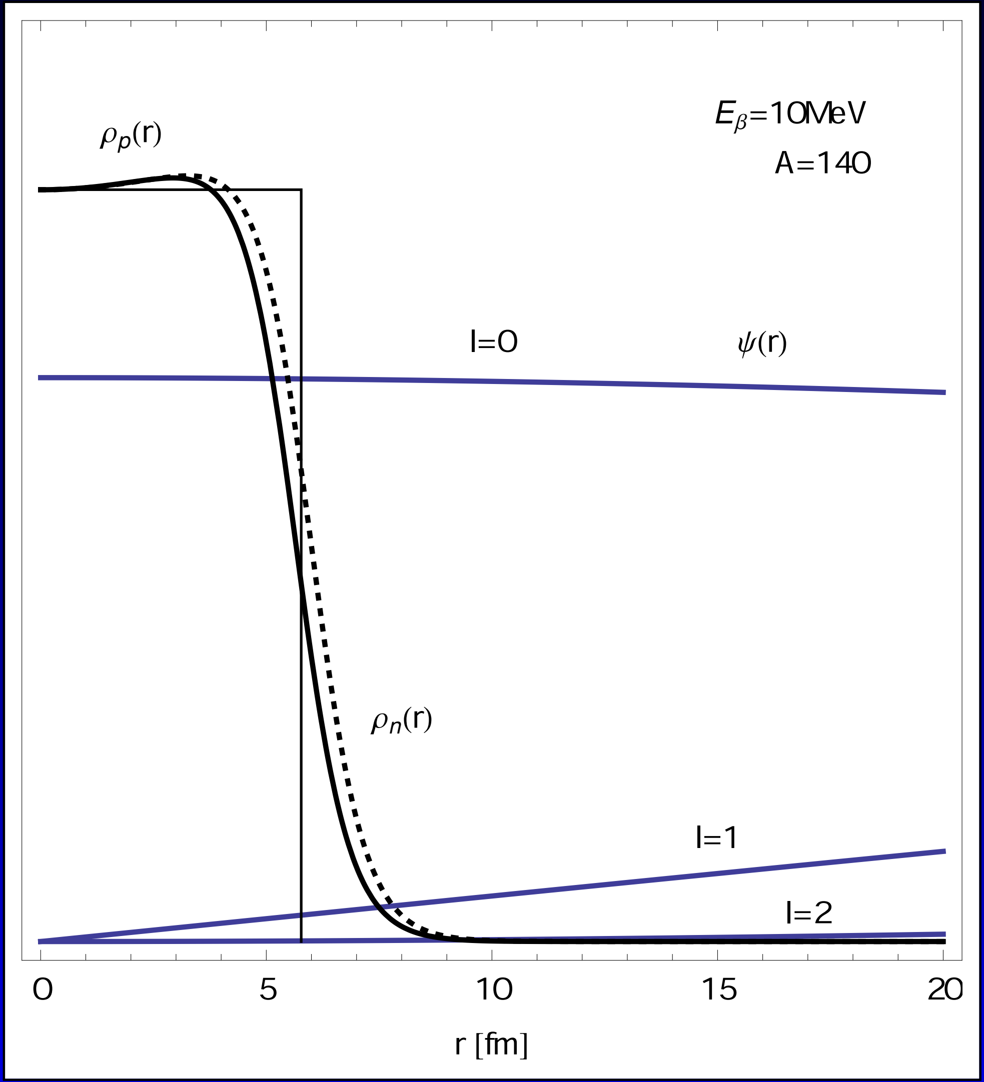
Estienne *et al.*, 2019

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.

Forbidden decays



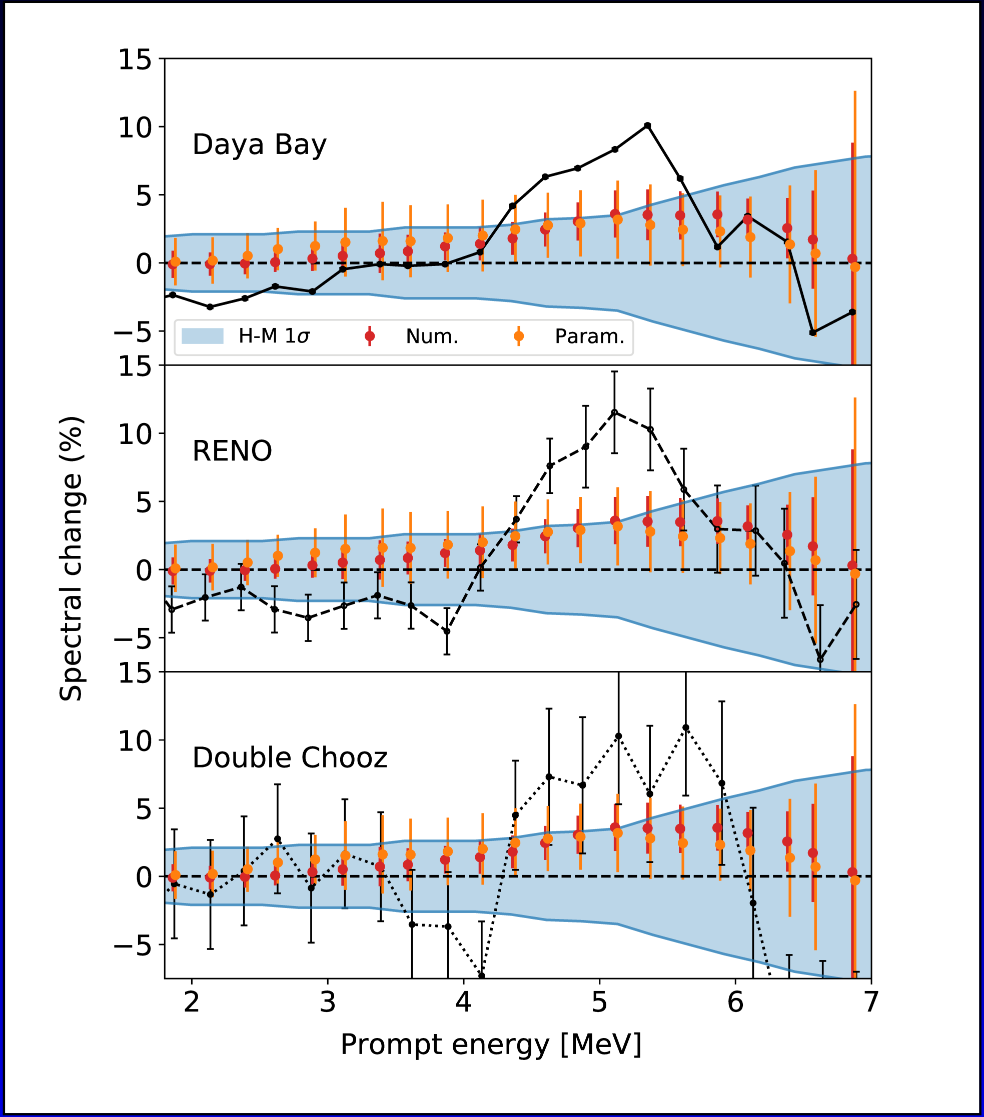
e,$\bar{\nu}$ final state can form a singlet or triplet spin state J=0 or J=1

Allowed:
s-wave emission ($l = 0$)

Forbidden:
p-wave emission ($l = 1$) or $l > 1$

Significant nuclear structure dependence in forbidden decays→ **sizable uncertainties?**

Forbidden decays – shell model



Hayen, *et al.* 2019

Microscopic shell model calculation of 36 forbidden isotopes.

Parameterization of the resulting shape factors for all other branches.

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

END of PART I