

Neutrinos, reactors & anomalies

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Why reactors?

- 3% of the energy release in fission is in neutrinos
 - 100 MW for a power reactor or about $\nu 10^{21} \text{ s}^{-1}$
- 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):



or in a nuclear bound state



Inverse beta decay



Bethe and Peierls estimate the cross section to be:

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

Neutrinos from fission



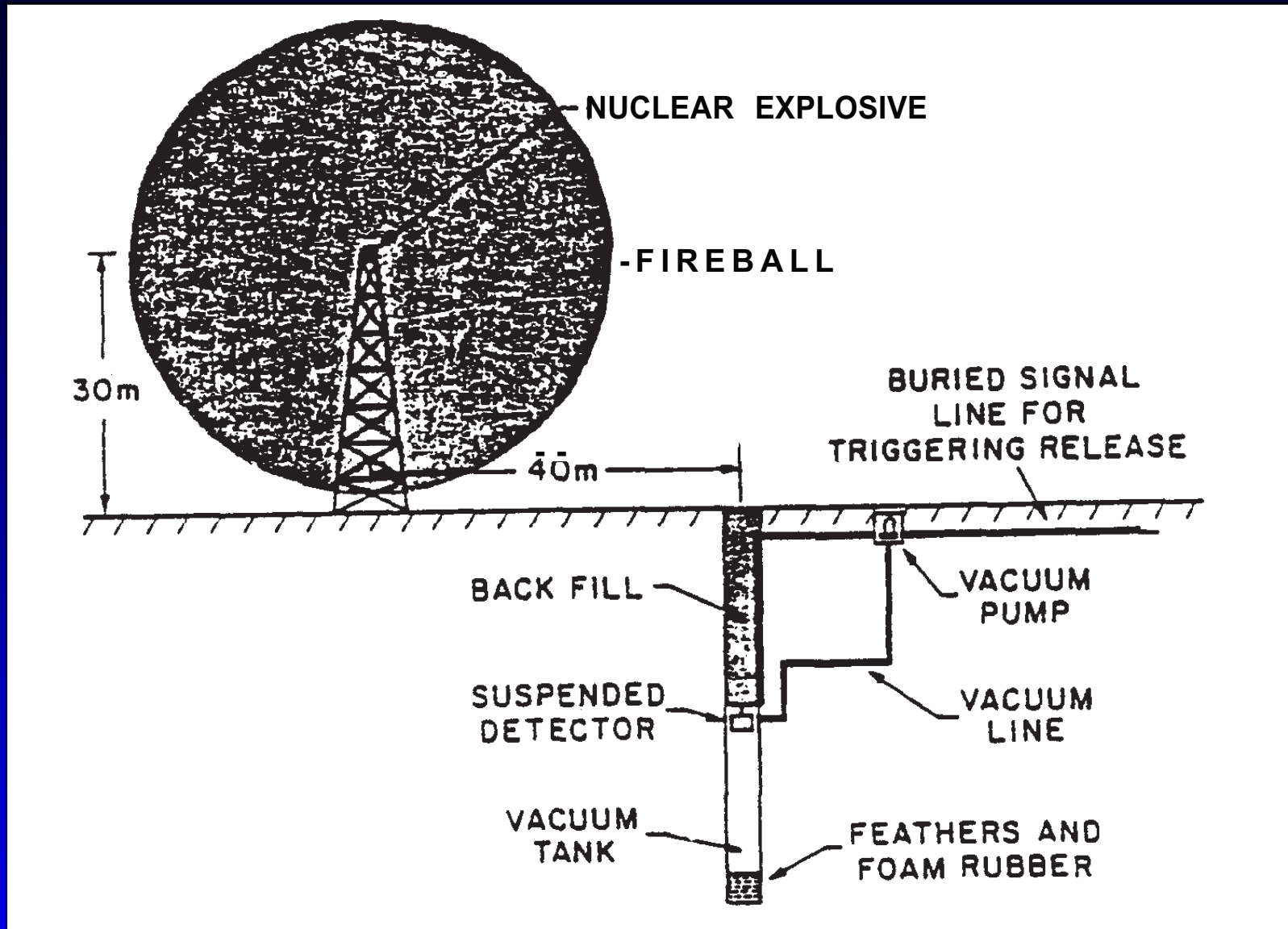
with average masses of X_1 of about $A=94$ and X_2 of about $A=140$. X_1 and X_2 have together 142 neutrons.

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

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

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

Ca. 1951



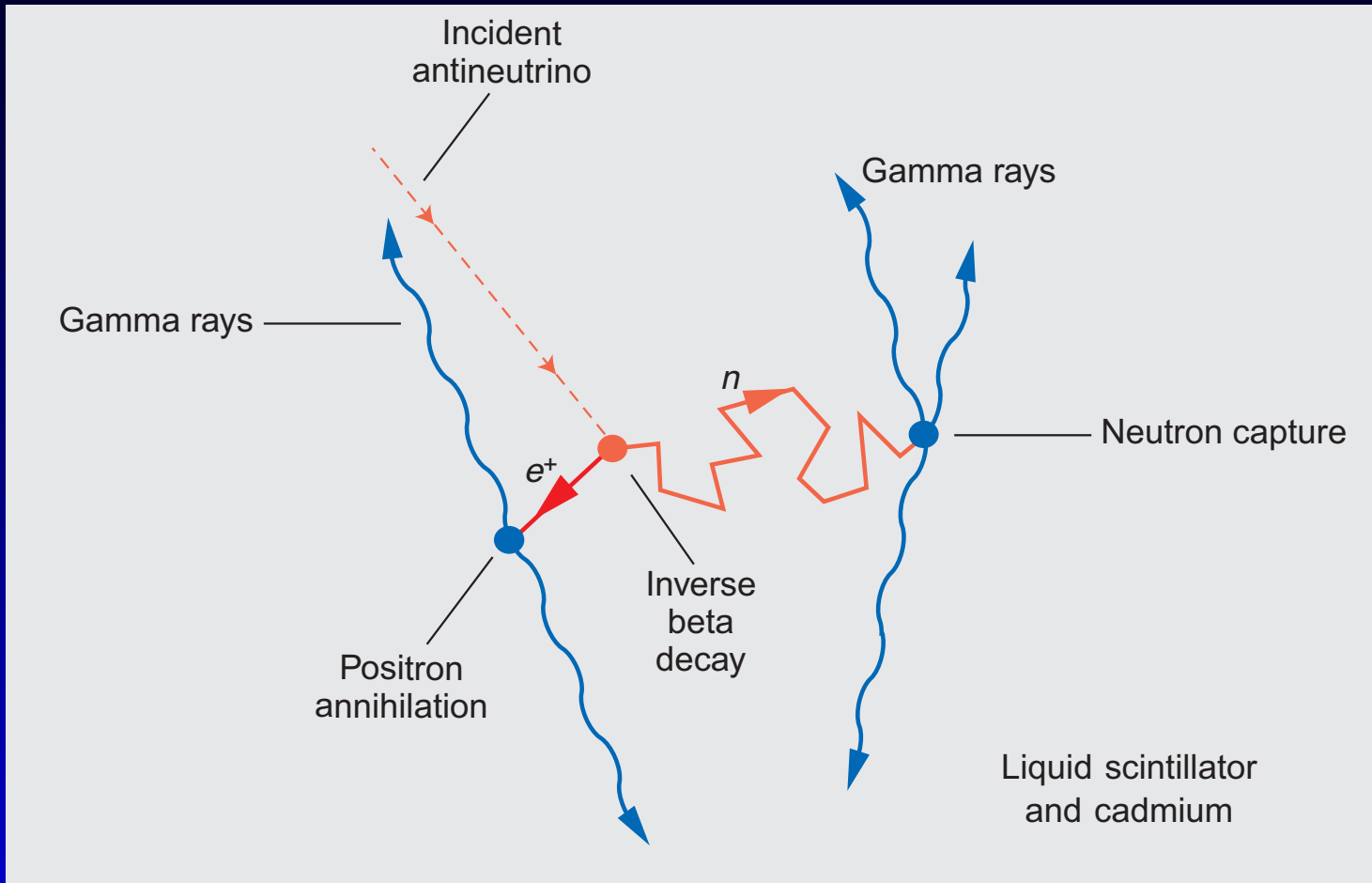
Reines' Nobel Lecture, 1995



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.

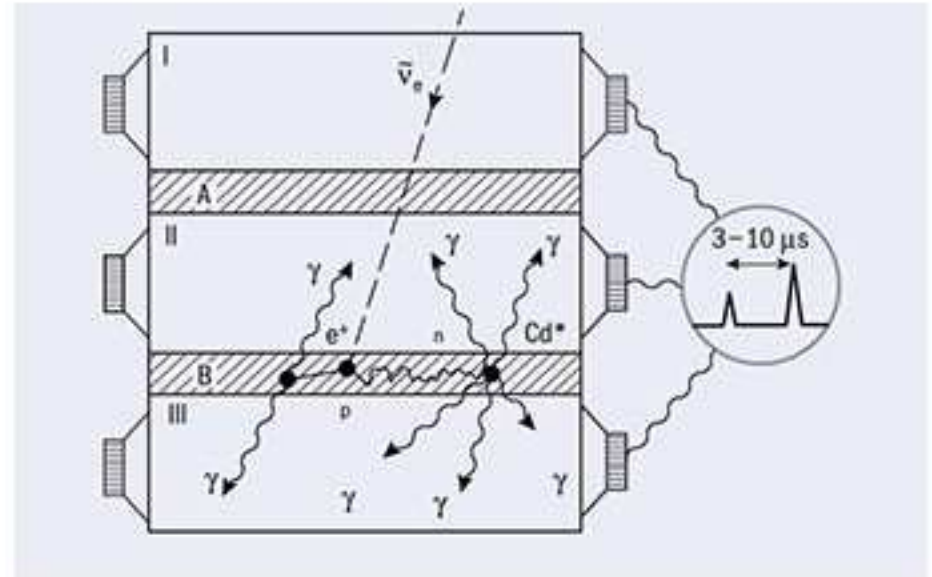
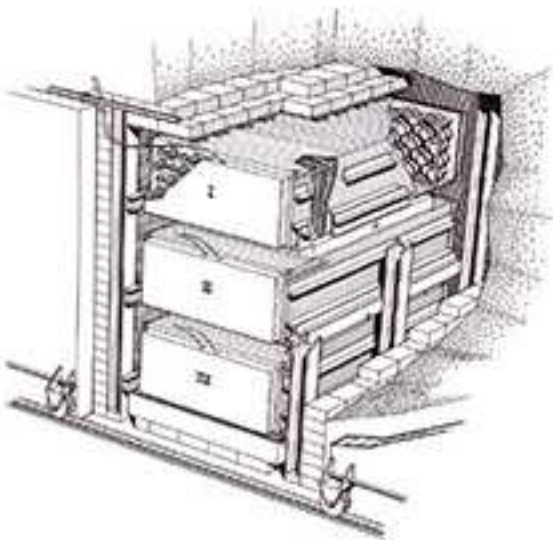
Delayed coincidence



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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NACHLASS PROF. W. PAULI		LT PROFESSOR W PAULI ZURICH UNIVERSITY ZURICH		Per Post ①	
		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 x 100 3/54					

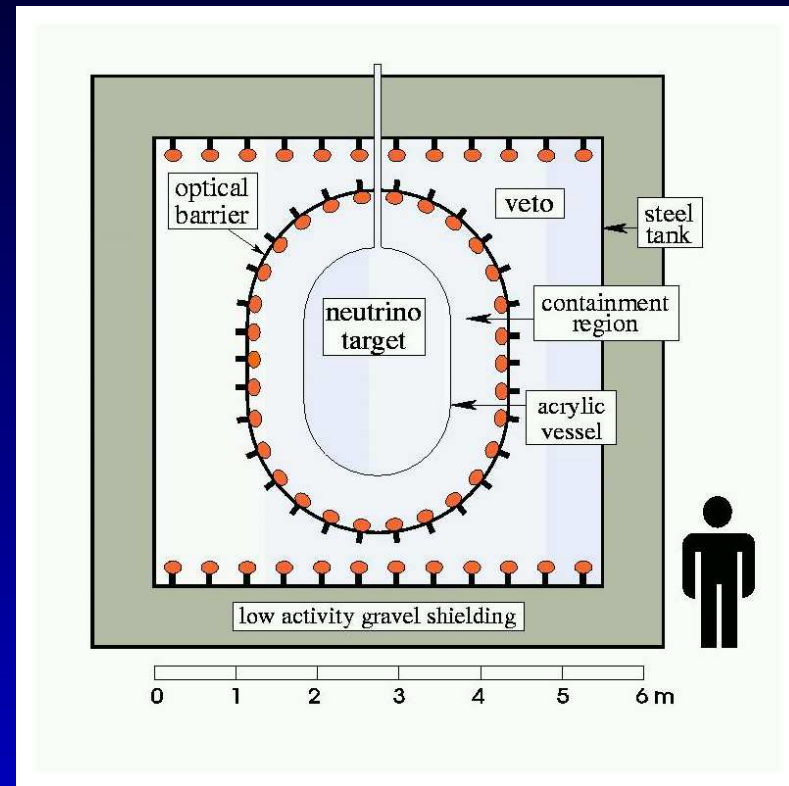
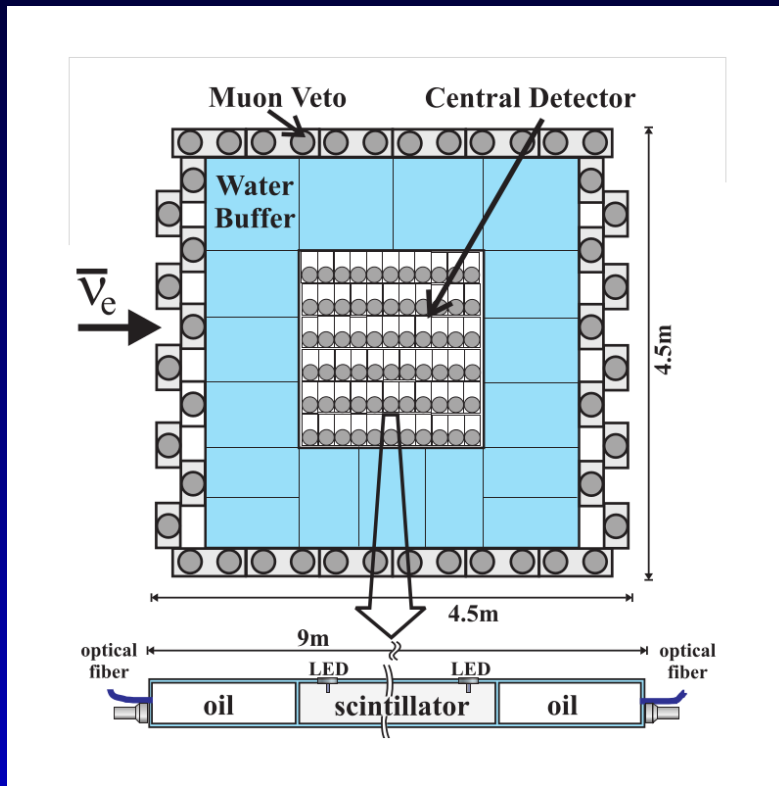
They report a cross section (!) of $6 \times 10^{-44} \text{ cm}^{-2}$.

Long list of SBL experiments

a	Experiment	f_{235}^a	f_{238}^a	f_{239}^a	f_{241}^a	$R_{a,SH}^{\text{exp}}$	σ_a^{exp} [%]	σ_a^{cor} [%]	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-II	0.607	0.074	0.277	0.042	0.907	6.4	} 3.8	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		18
6	Rovno88-2S	0.557	0.076	0.313	0.054	0.949	7.3	} 3.8	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	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	} 3.8	8.76
15	Krasnoyarsk87-33	1	0	0	0	0.925	5.0		32.8
16	Krasnoyarsk87-92	1	0	0	0	0.942	20.4	} 4.1	92.3
17	Krasnoyarsk94-57	1	0	0	0	0.936	4.2		0
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

Palo Verde & CHOOZ

Late 1990's inspired by KamiokaNDE

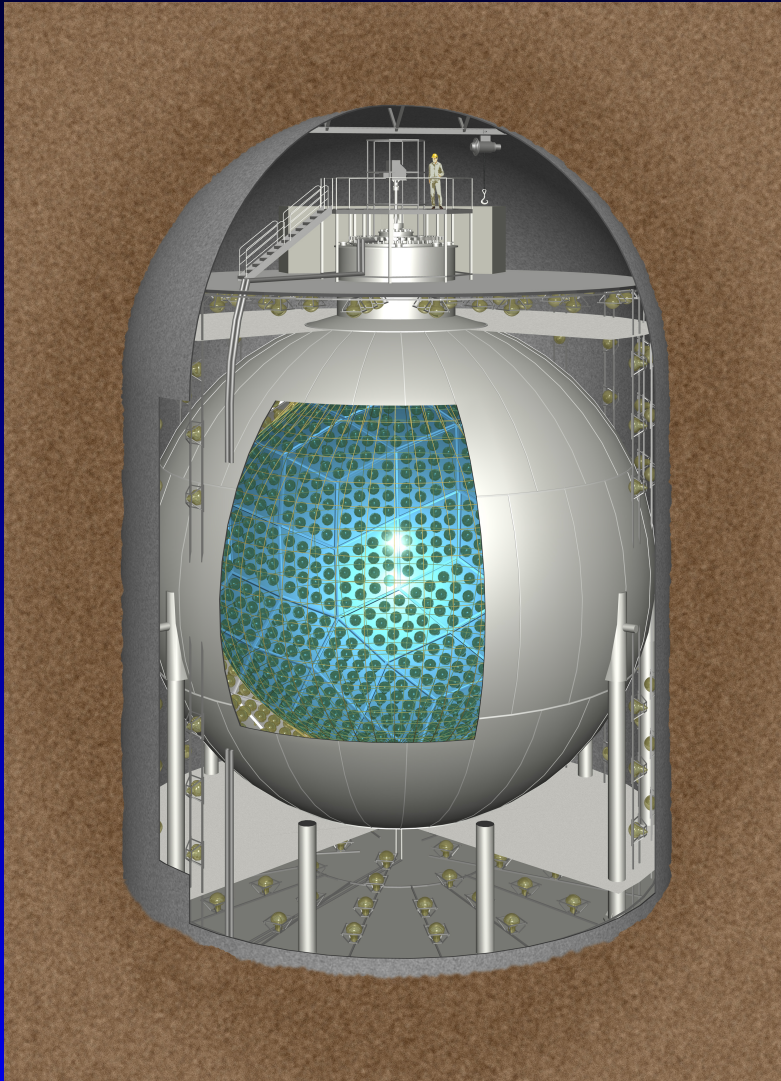


800 m from a commercial reactor

1100 m from a commercial reactor

Null result in both.

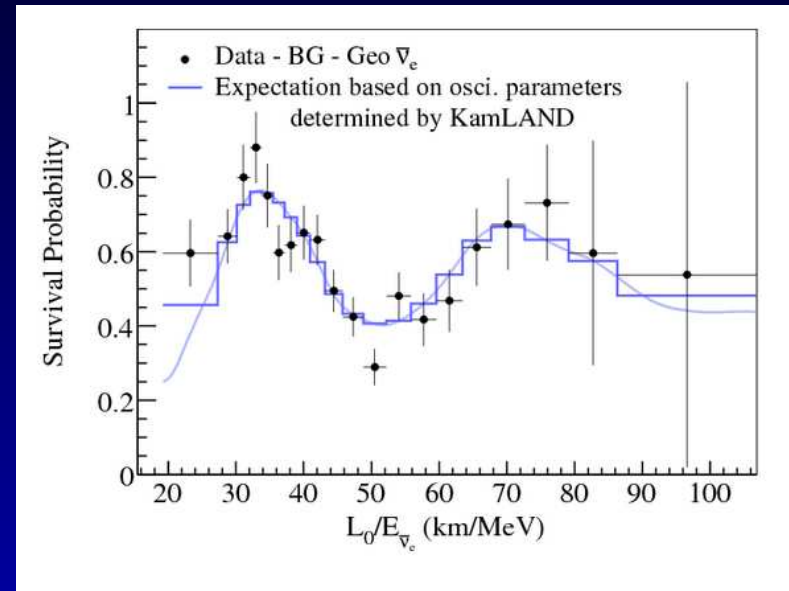
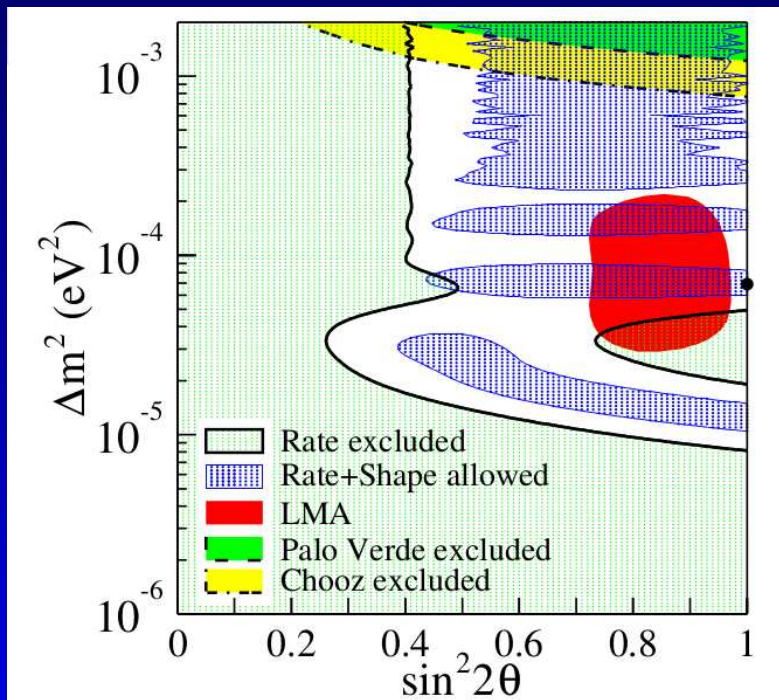
KamLAND – 2002



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

KamLAND – results

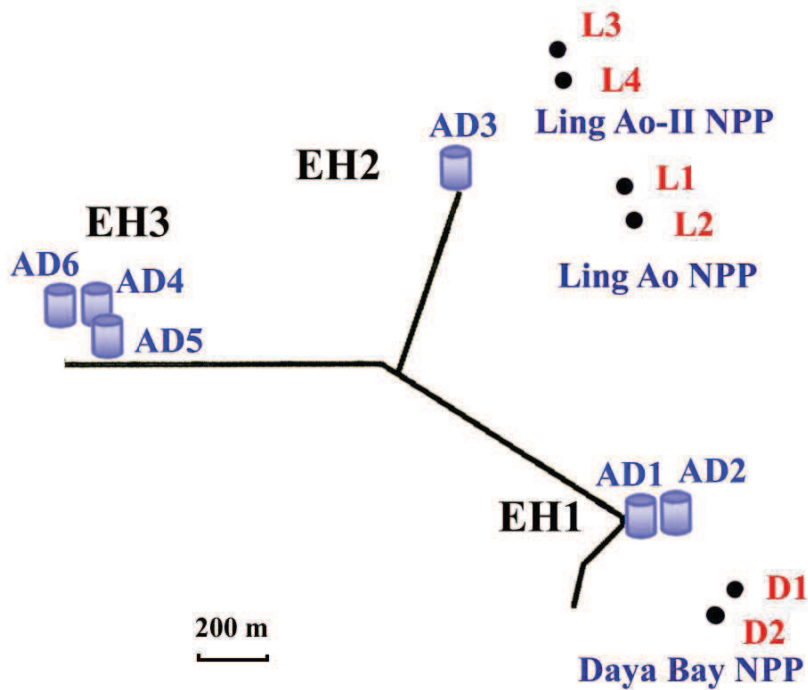
KamLAND confirmed the oscillation interpretation of the solar neutrino results and “picked” the so-called LMA solution.



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

Daya Bay – 2011

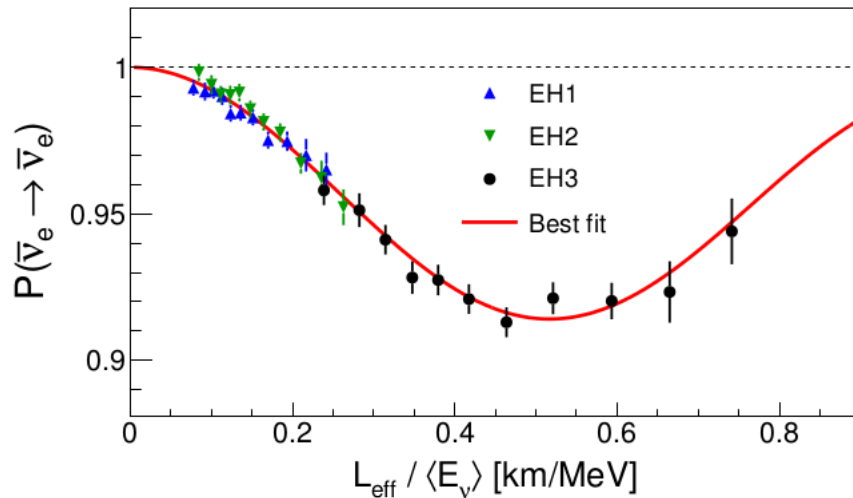
In a 1 reactor, 2 detector setup all flux related errors cancel completely in the near-to-far ratio.



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

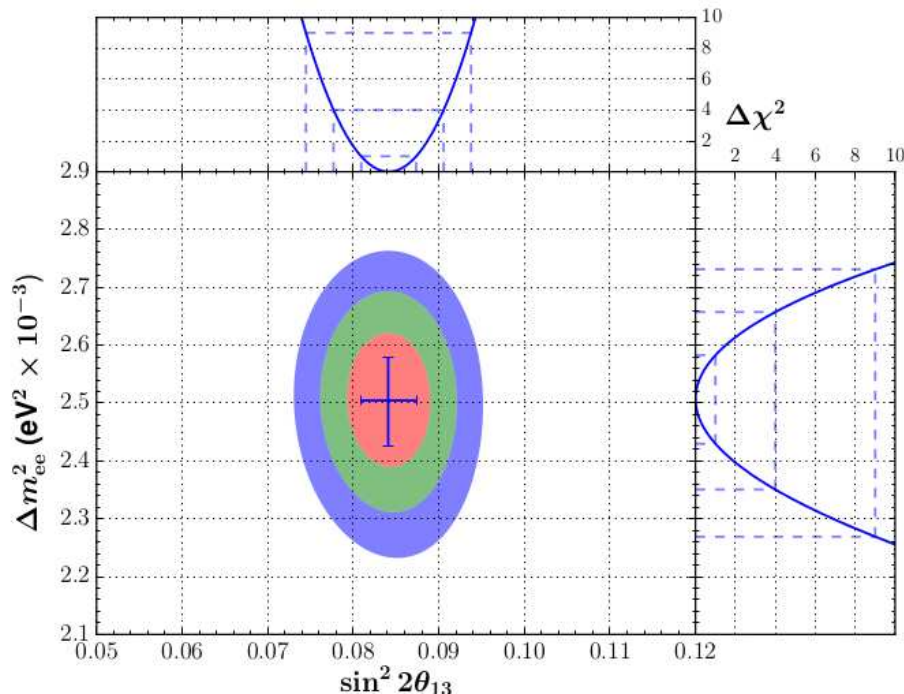
AD3 sees the same ratio of Ling Ao I to Ling Ao II events as do the far detectors.

Daya Bay – results



More than 2.5 million IBD events.

Most precise measurement of θ_{13}

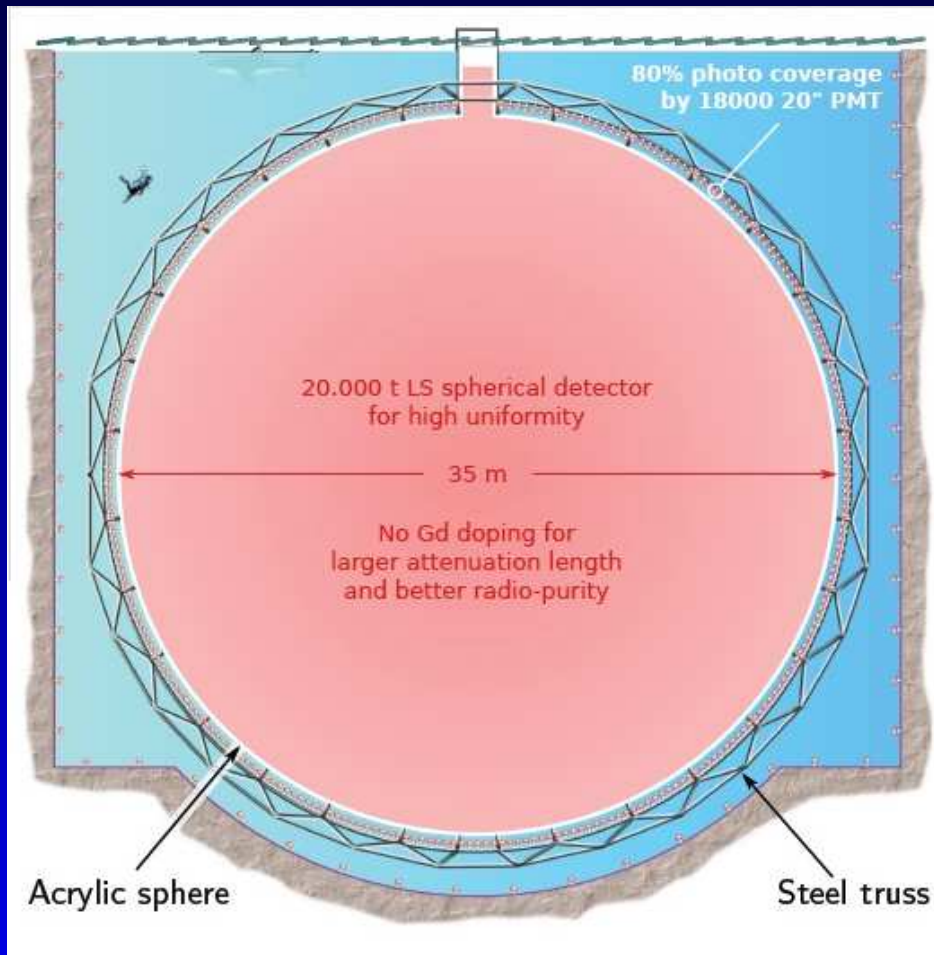


Precise measurement of Δm_{32}^2

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

JUNO – under construction

JUNO – Jiangmen Underground Neutrino Observatory

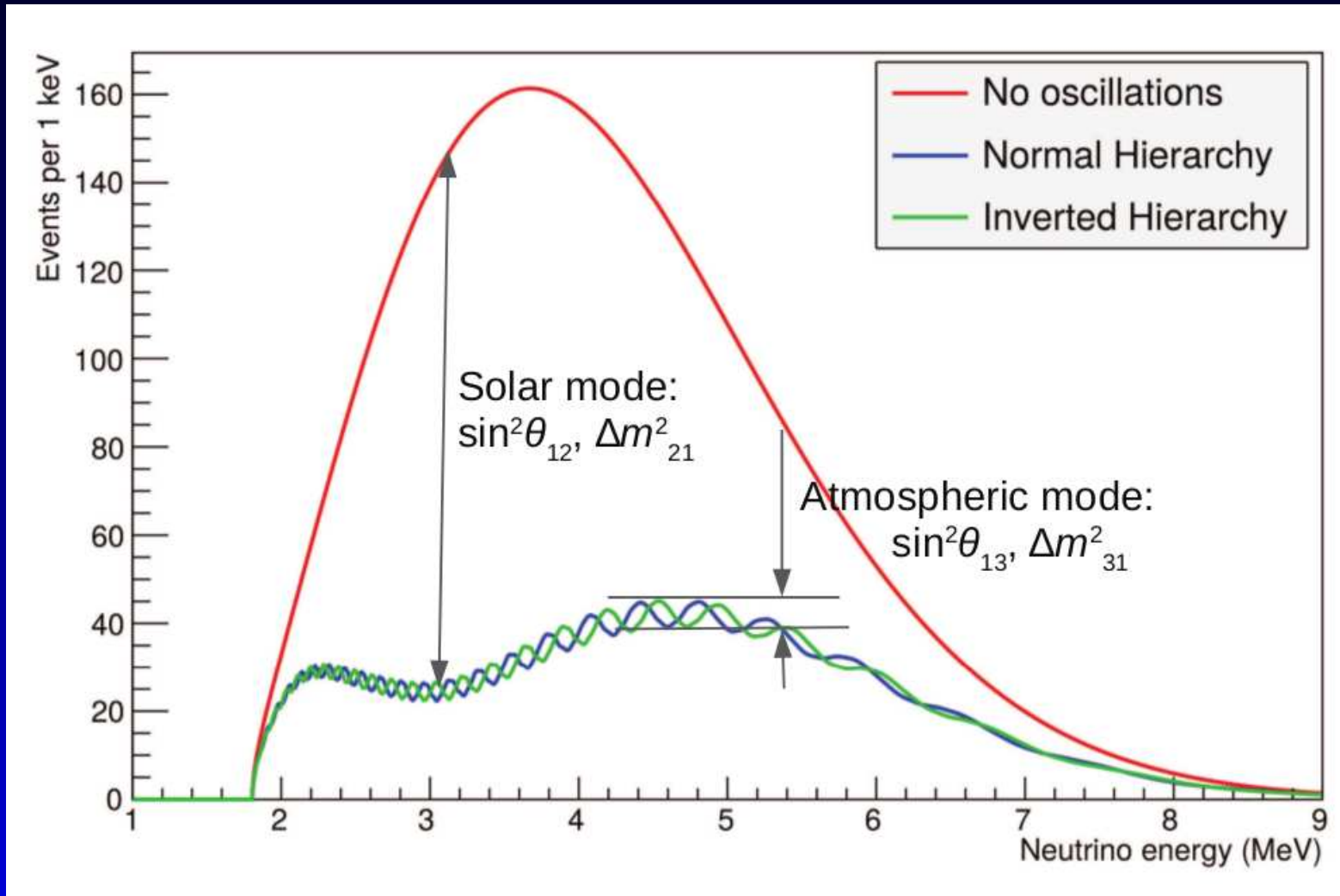


20,000 ton undoped liquid scintillator

53 km from two powerful reactor complexes, 18 GW each

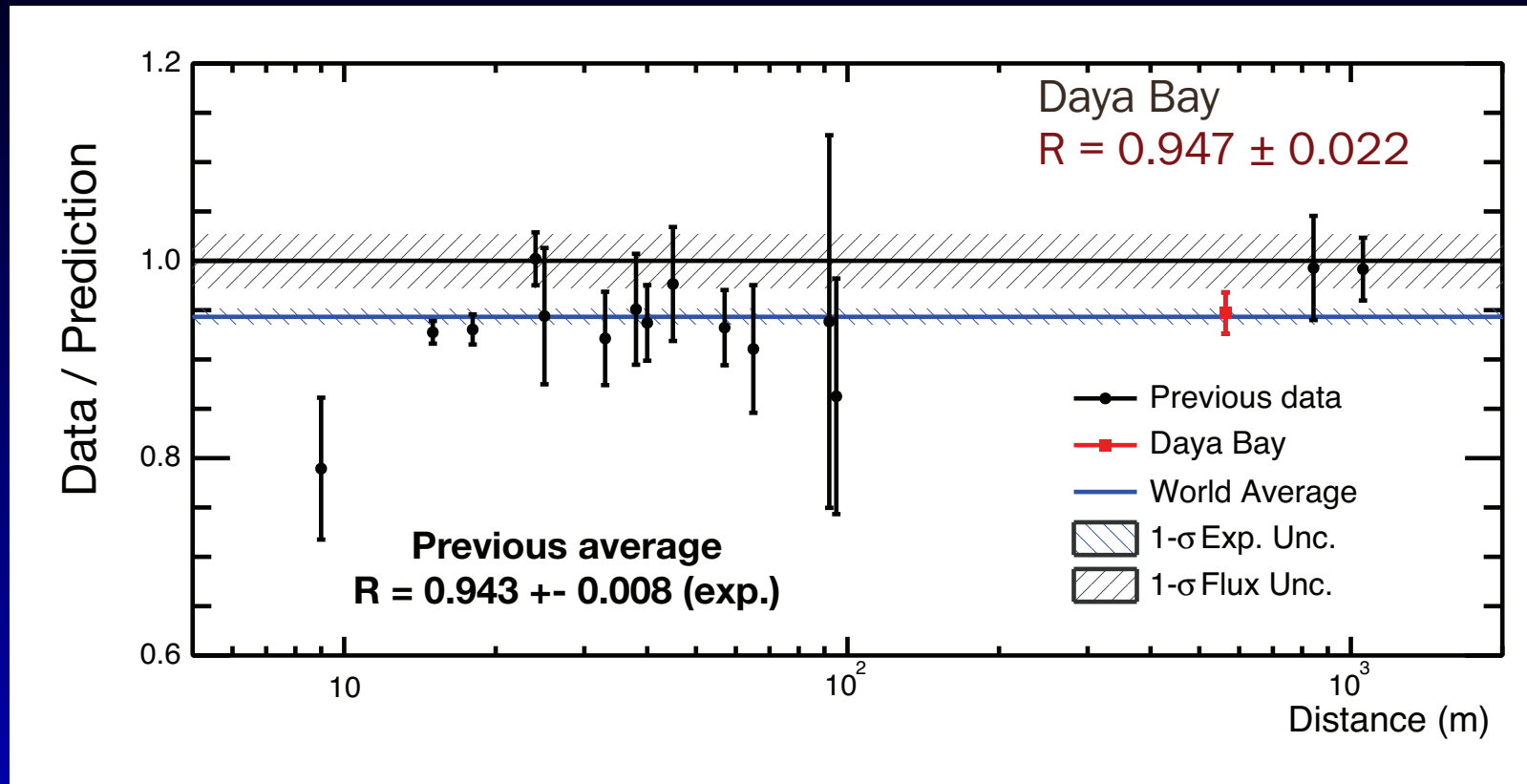
Start of data taking \sim 2024.

JUNO – physics goals



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

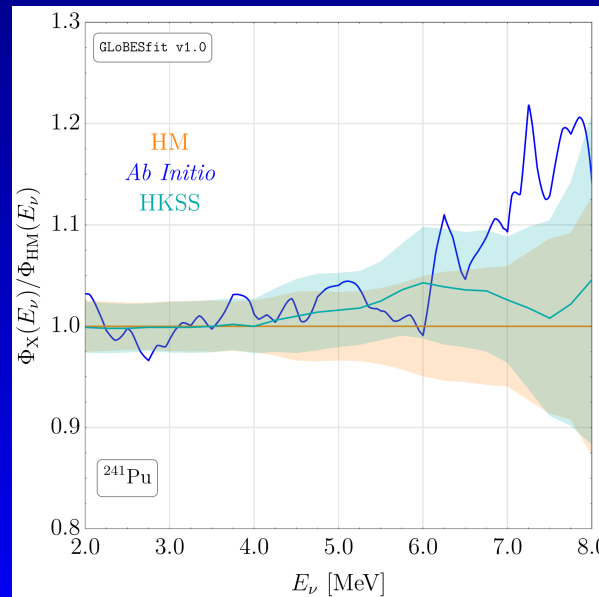
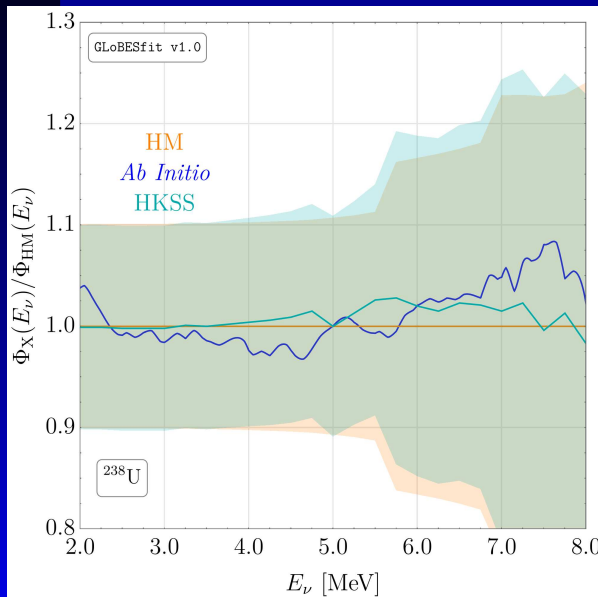
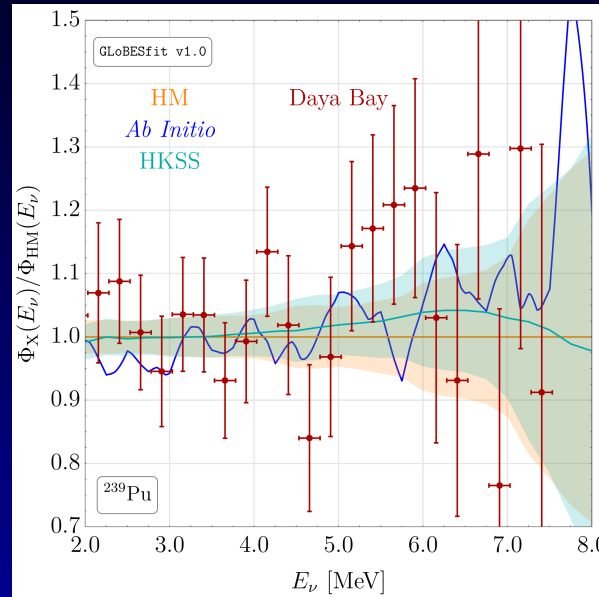
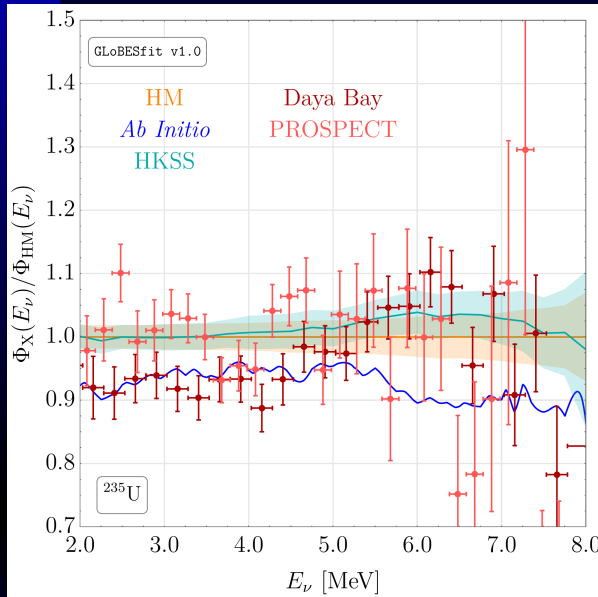
The reactor anomaly



Daya Bay, 2014

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

Status quo early 2021



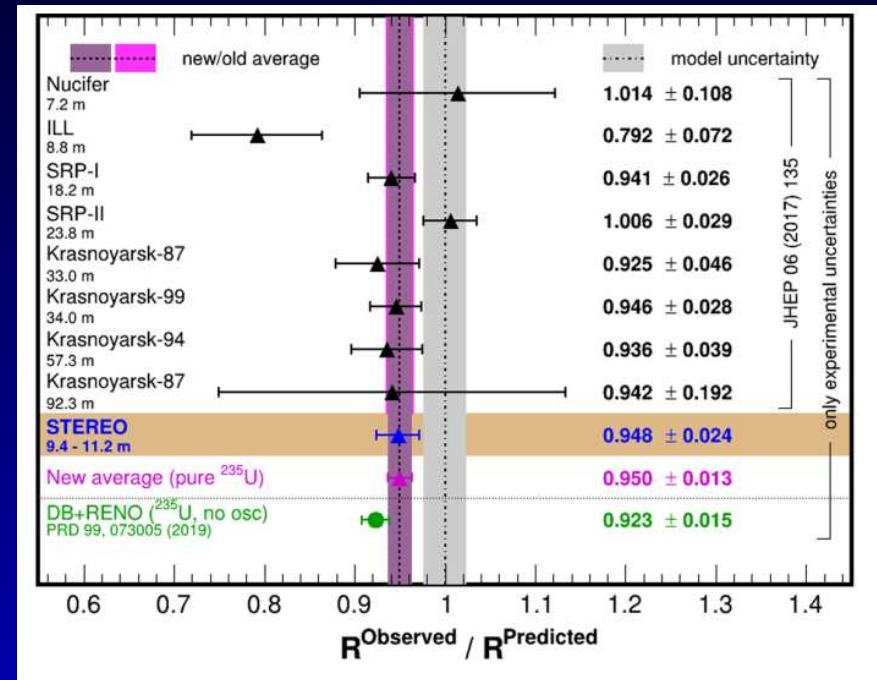
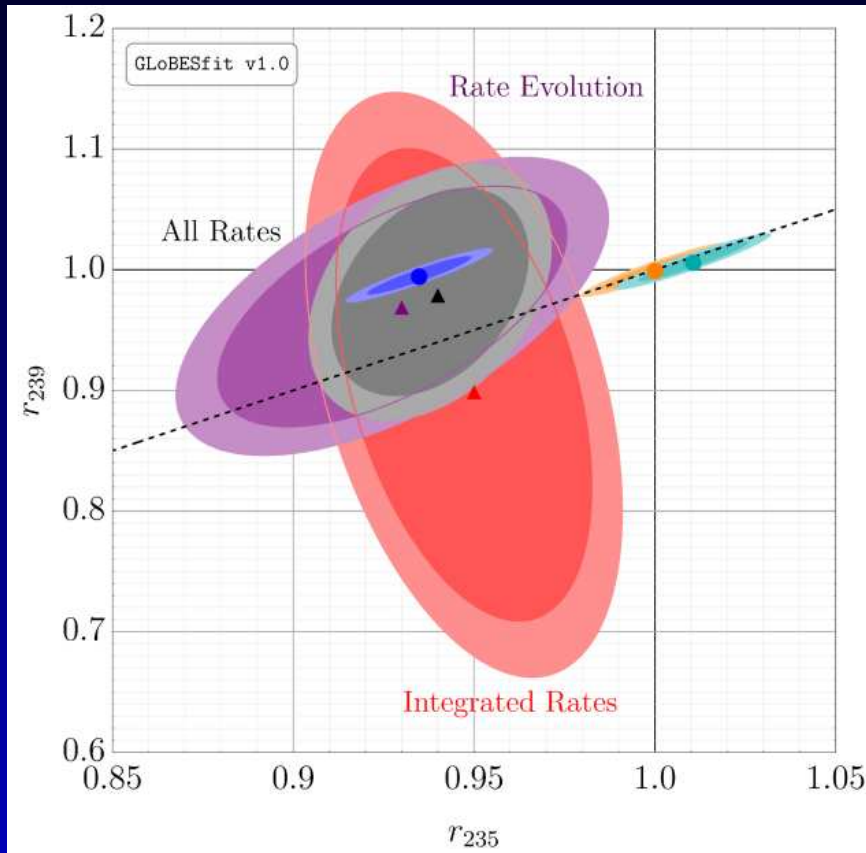
3 different flux models, data from 2 different experiments

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

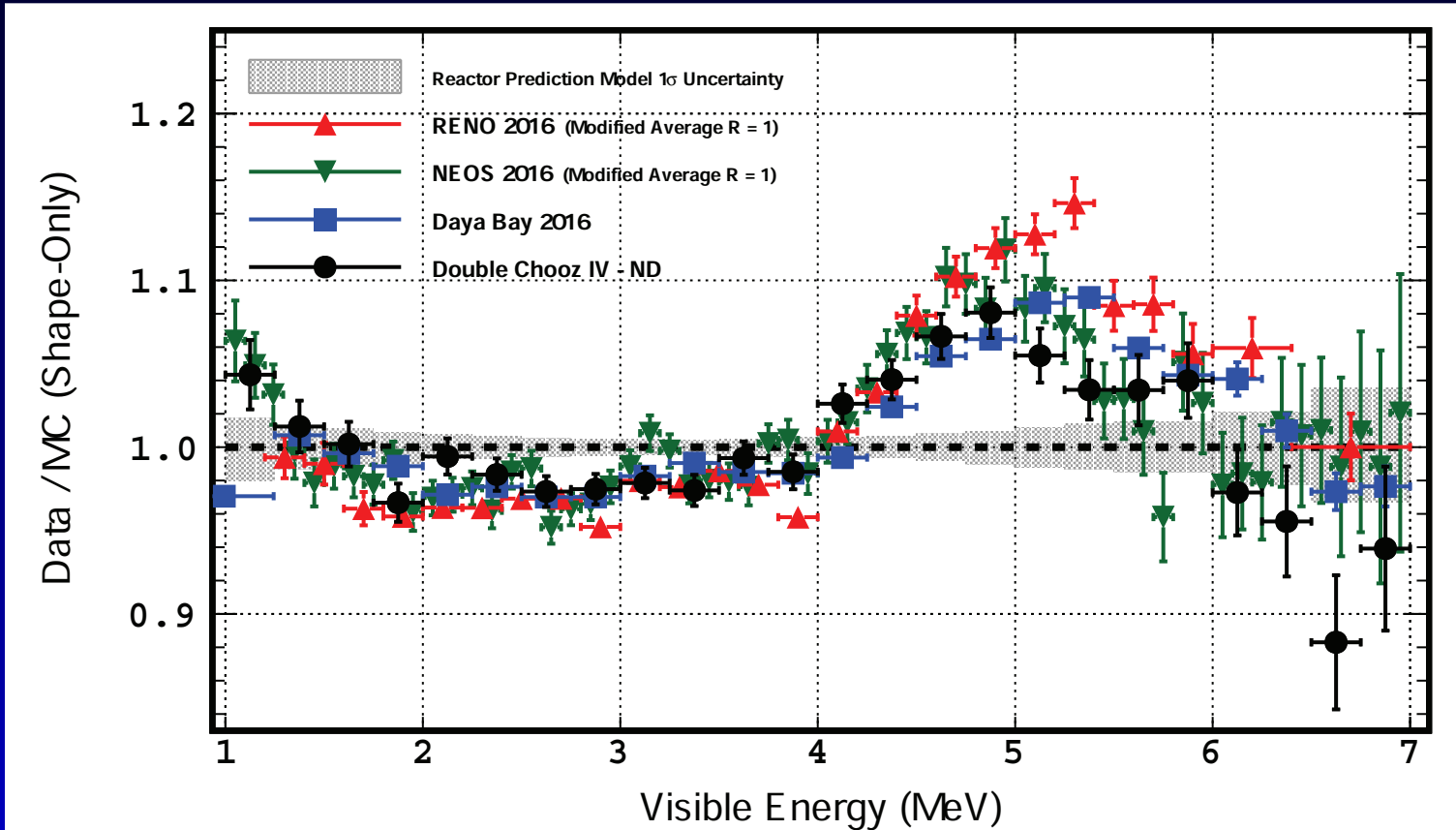


STEREO, 2020

Berryman, PH, 2020

U235 seems to “own” all of the deficit.

The 5 MeV bump

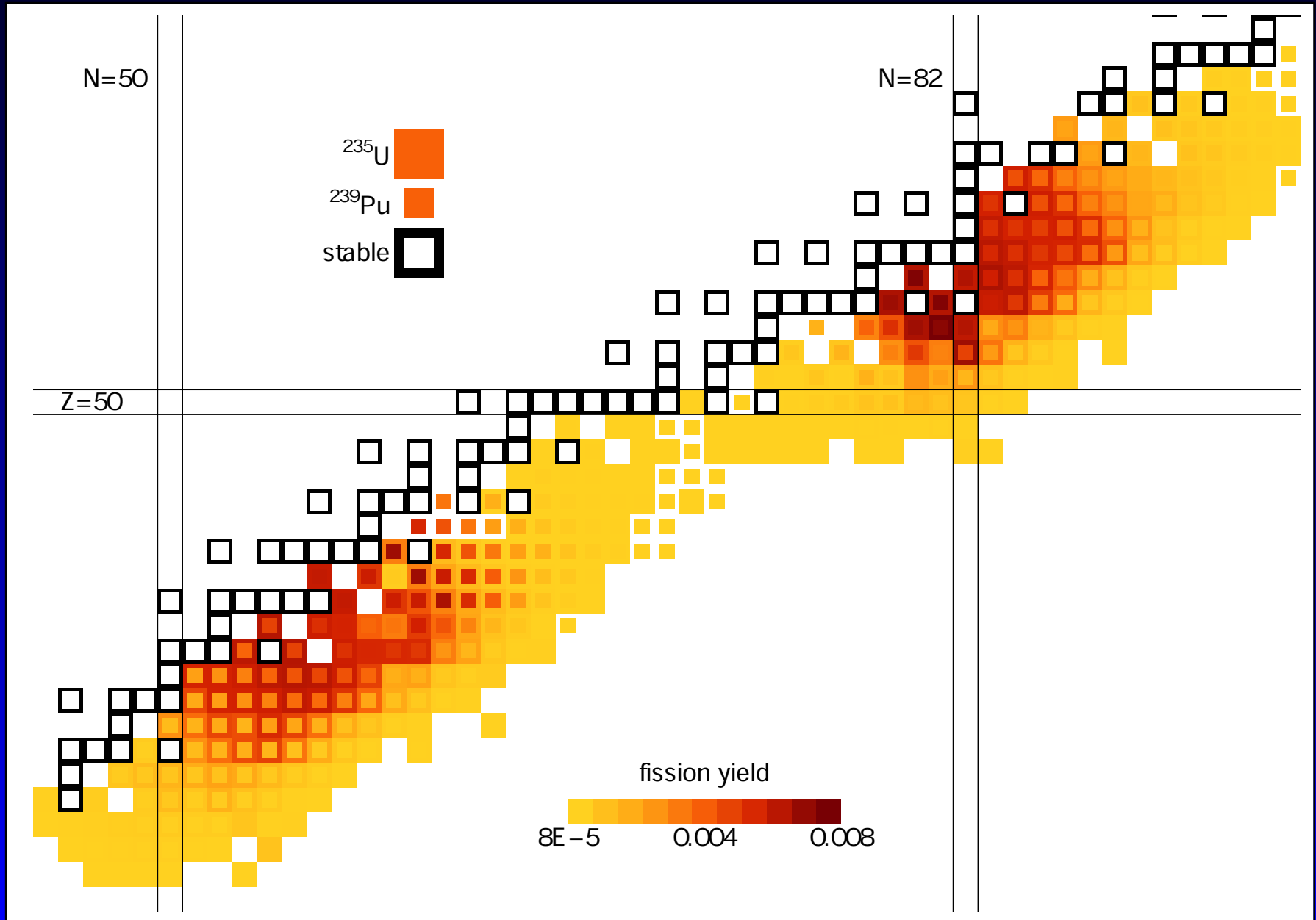


Double Chooz 2019

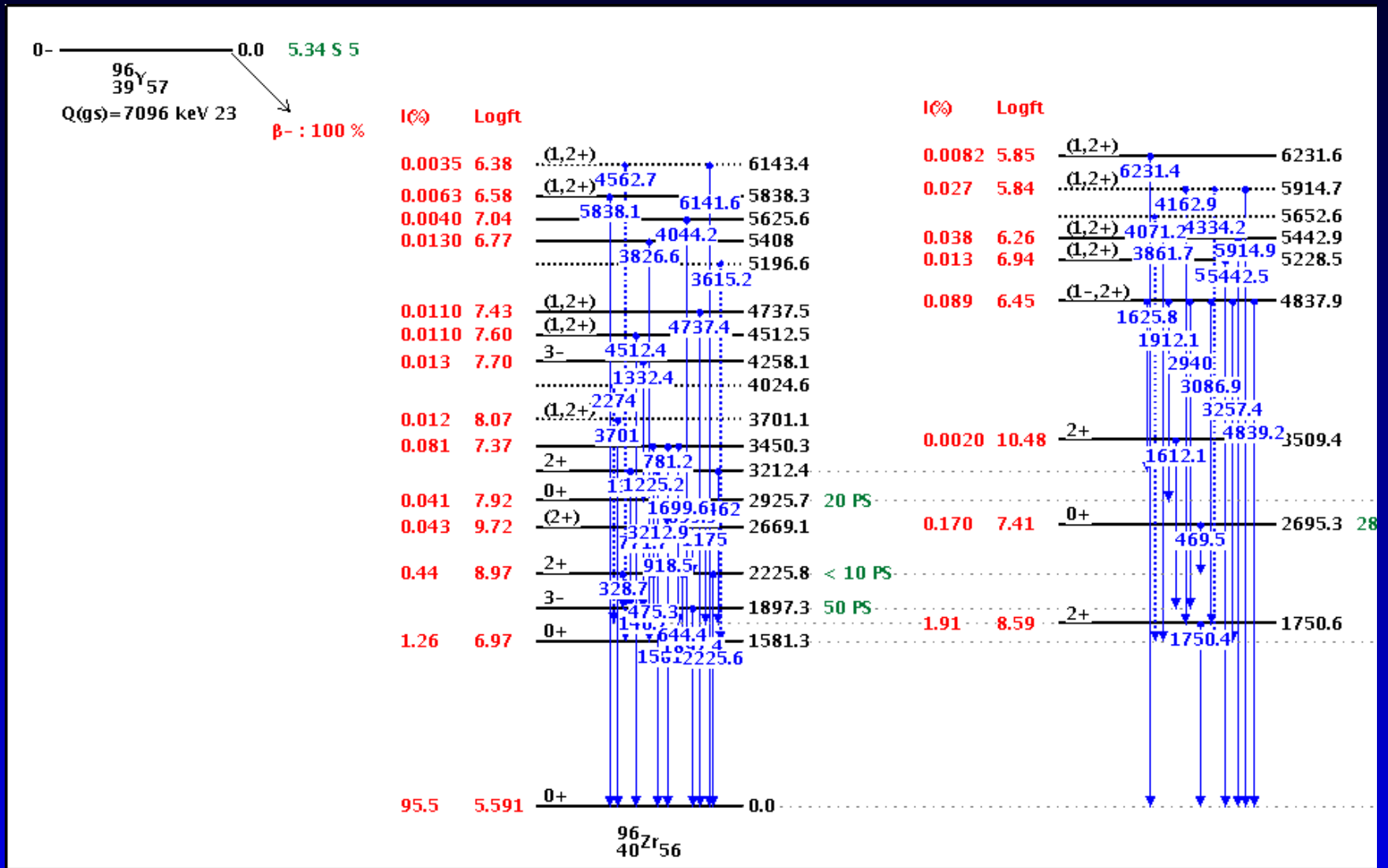
Contains only 0.5% of all neutrino events – not important for sterile neutrinos

Yet, statistically more significant than the RAA!

Why is this so complicated?



β -branches



Two ways to predict

Summation calculations

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:

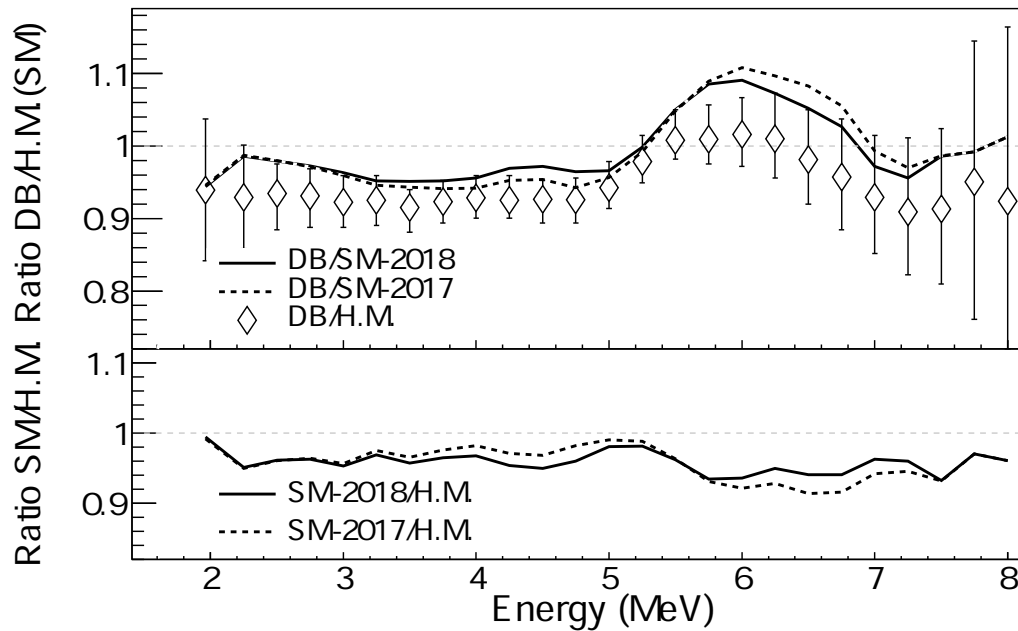
Forbidden decays

Weak magnetism corrections

Non-equilibrium corrections

Structural materials in the reactor

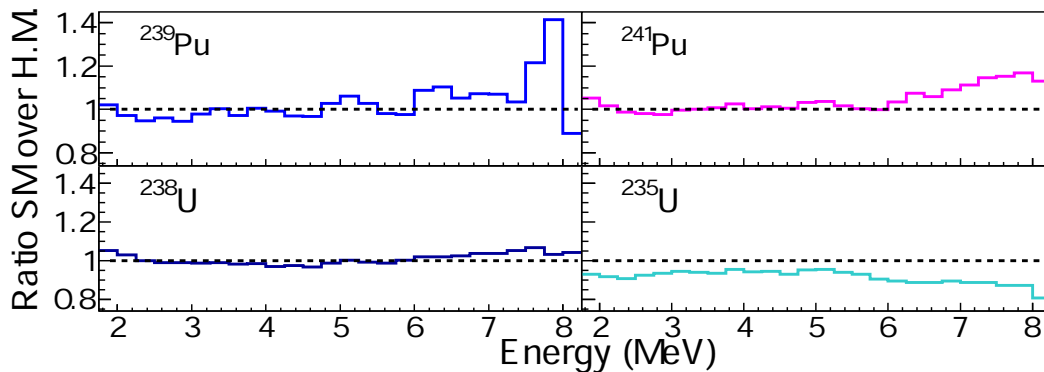
Summation method – EF



Take fission yields from database.

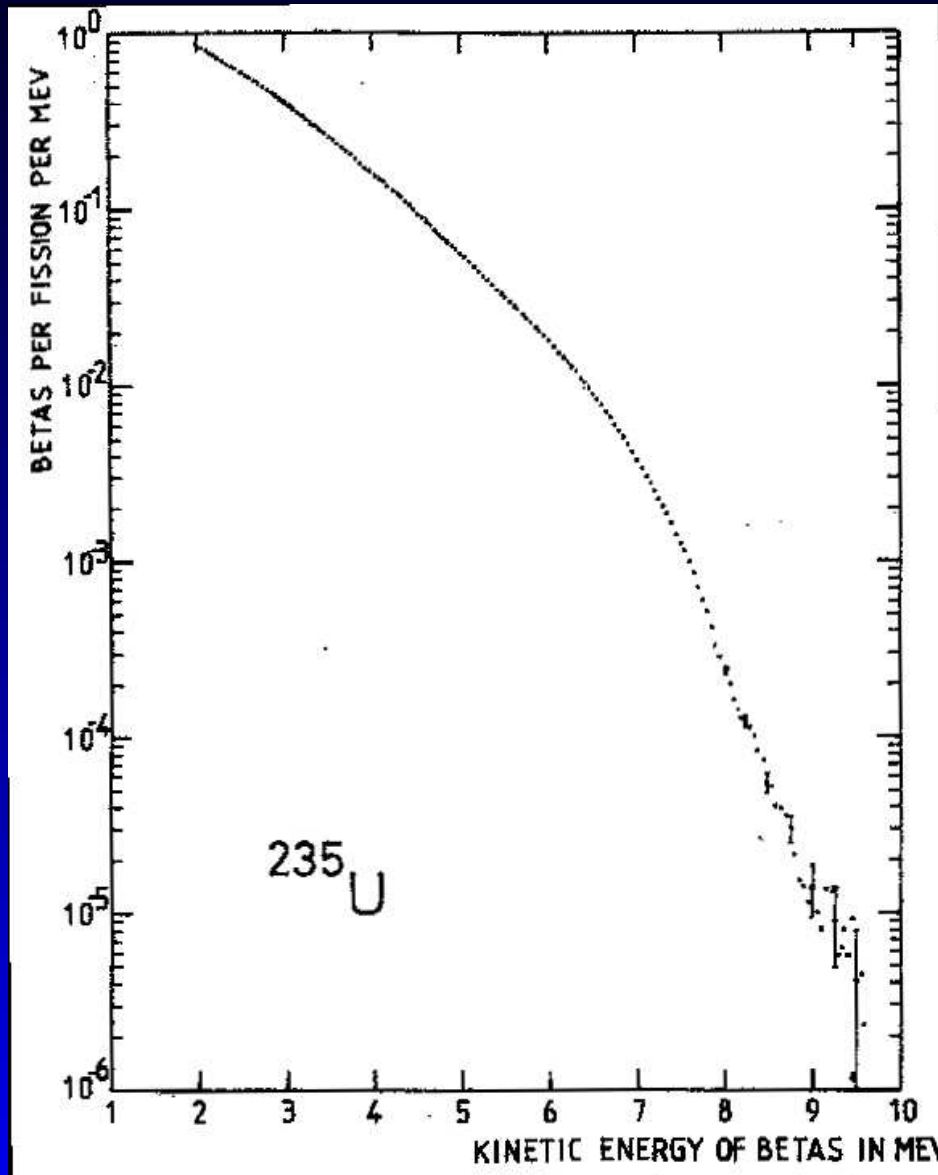
Take beta decay information from database.

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



Estienne *et al.*, 2019

Conversion method – HM



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

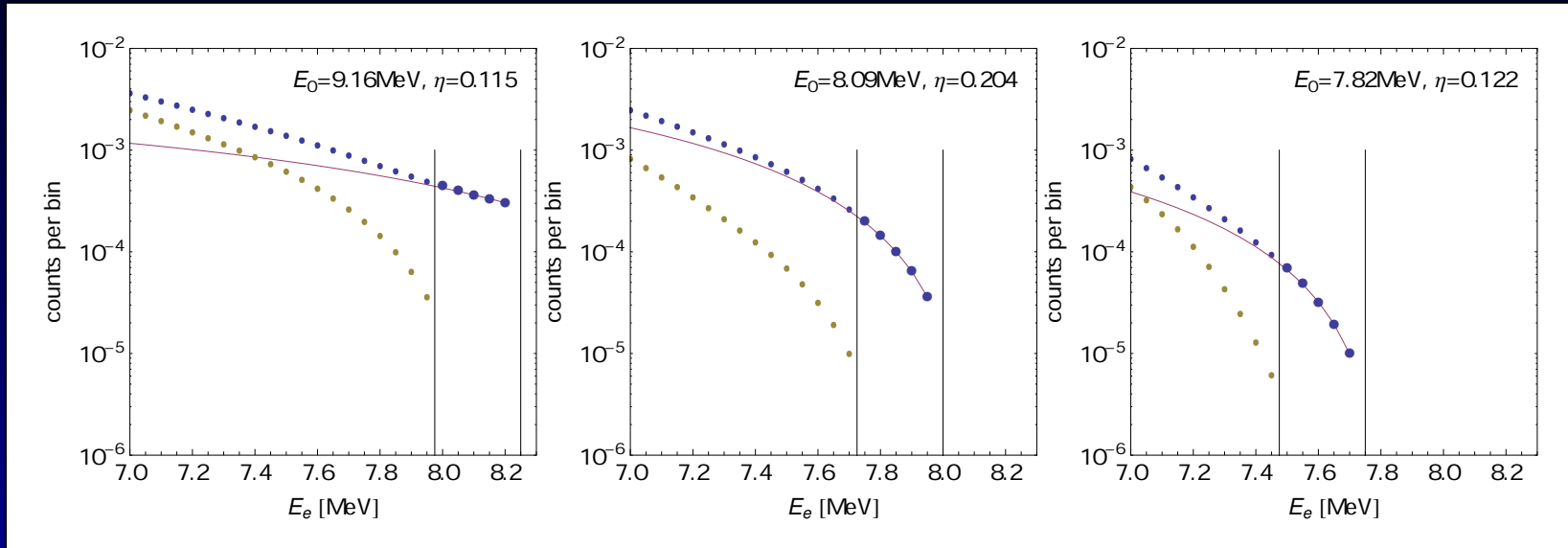
Electron spectroscopy with a magnetic spectrometer

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

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

Schreckenbach, *et al.* 1985.

Virtual branches



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

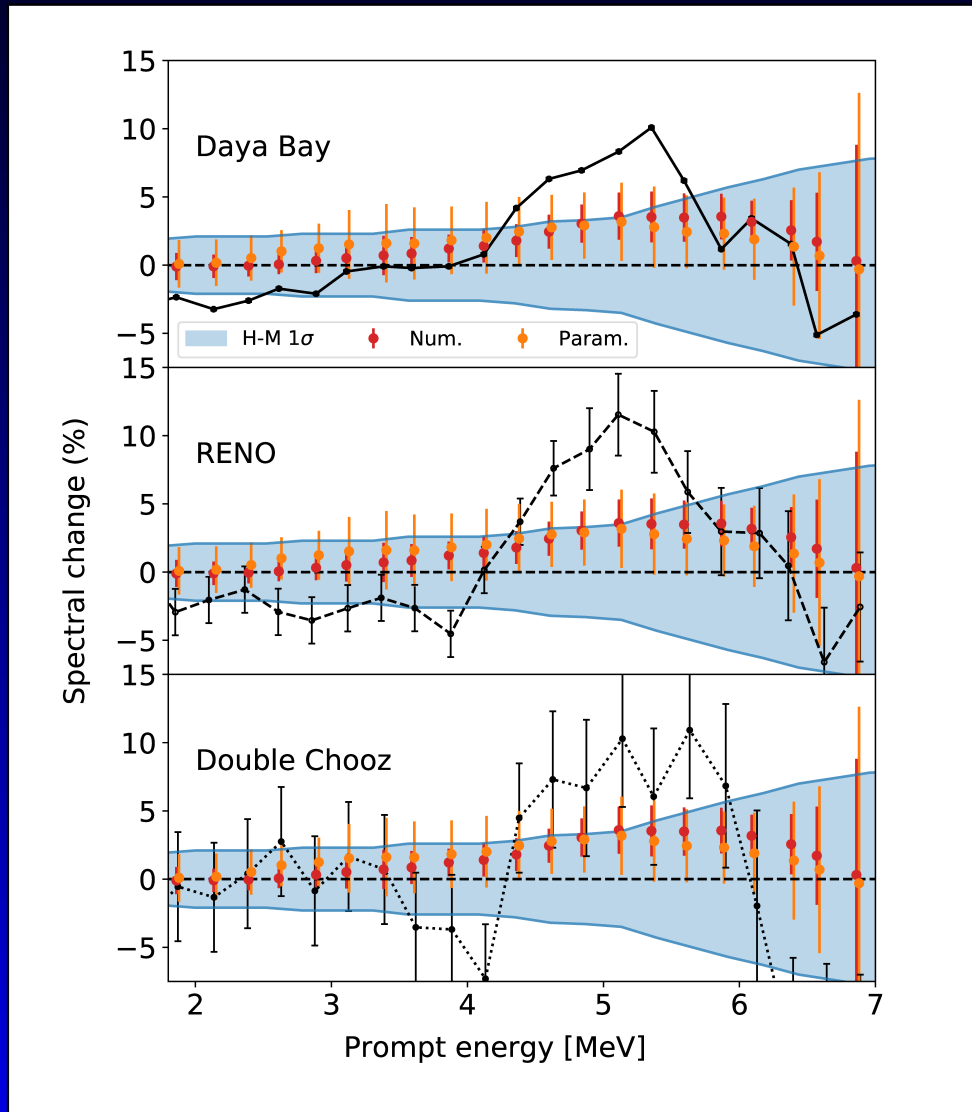
2 – delete the last s data points

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



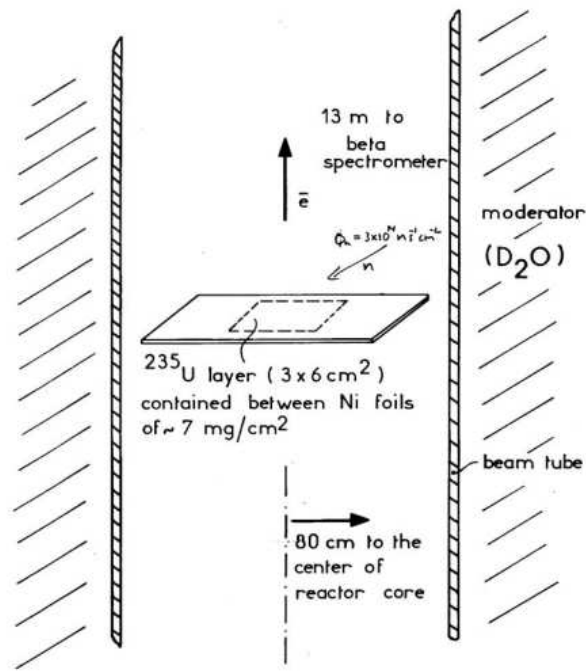
Forbidden decays major source of systematic.

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

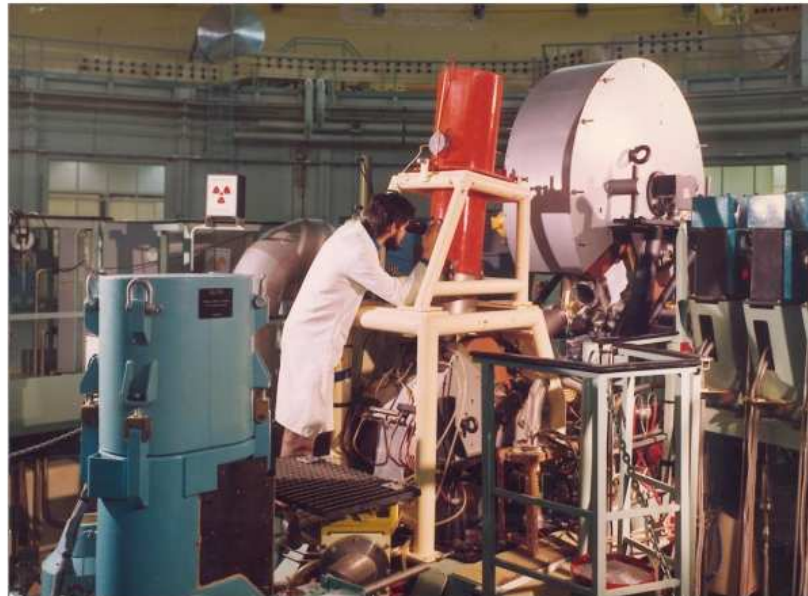
Increases the IBD rate anomaly by 40%, but the uncertainty increases by only 13% relative to HM

Hayen, *et al.* 2019

Kill BILL?



SCHEMATIC VIEW OF THE TARGET SITE



Magnetic BILL spectrometer at ILL, 1972-1991

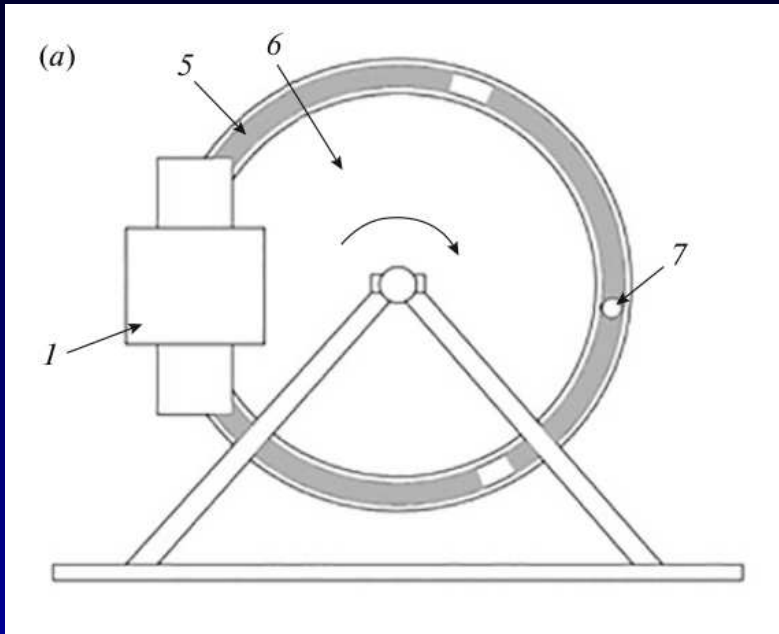
(Electron detector in focal plane: multi chamber proportional counter in transmission, rear mounted scintillator in coincidence)

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

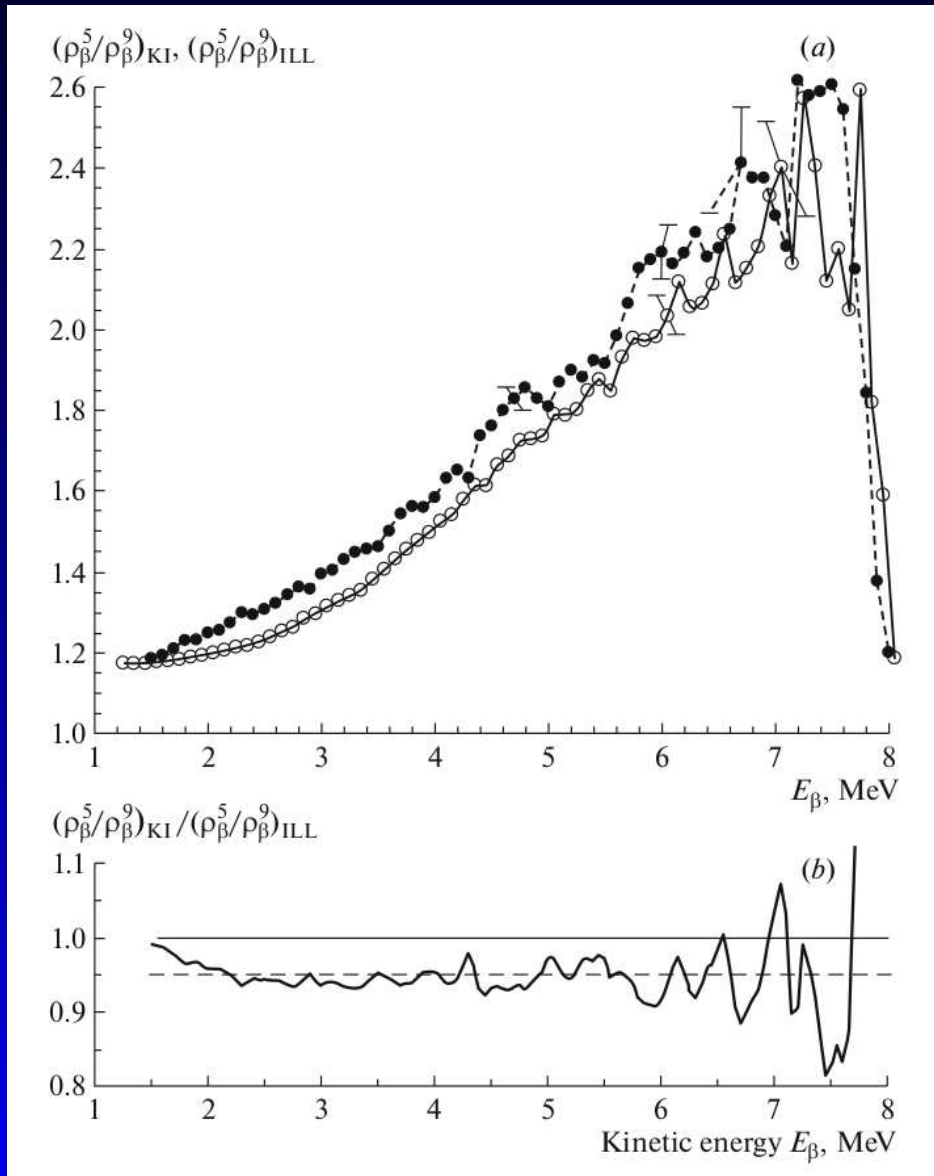


Relative measurement of U235 and Pu239 targets under identical conditions.

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.

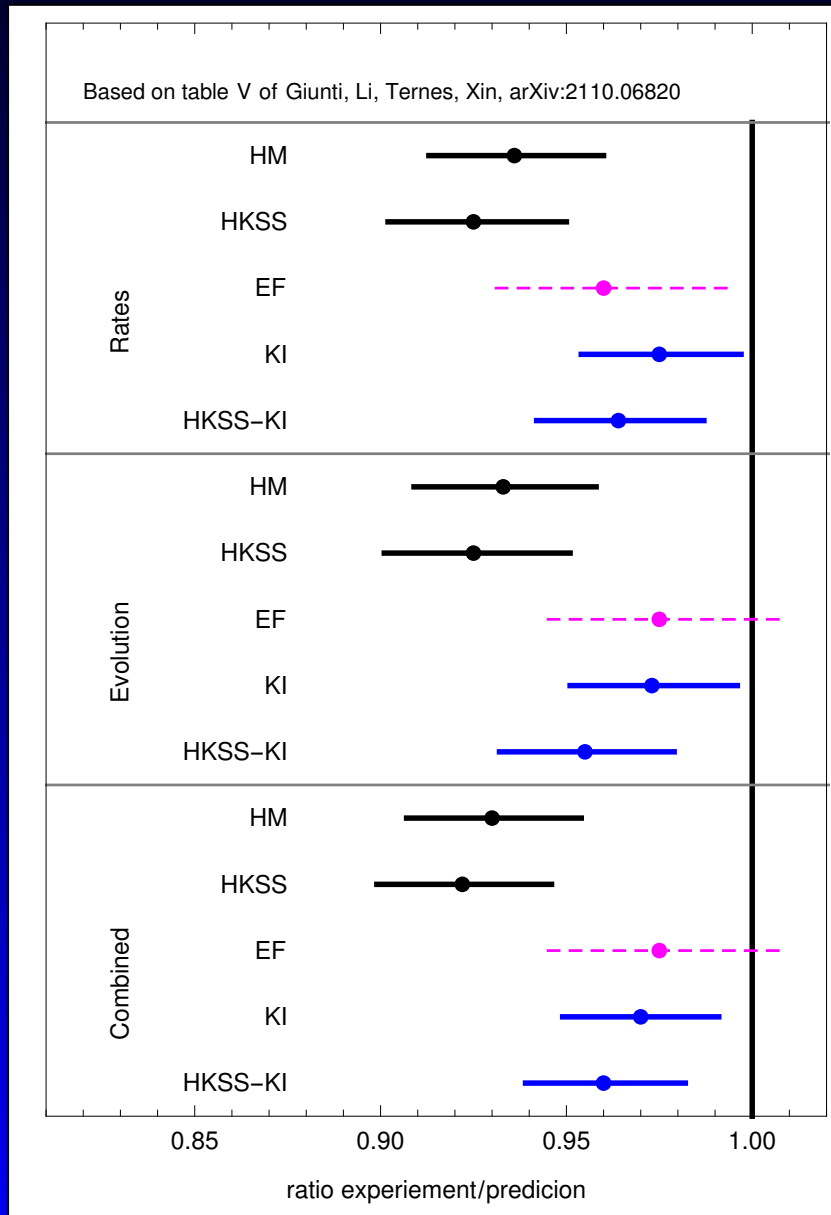
2021 beta results



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

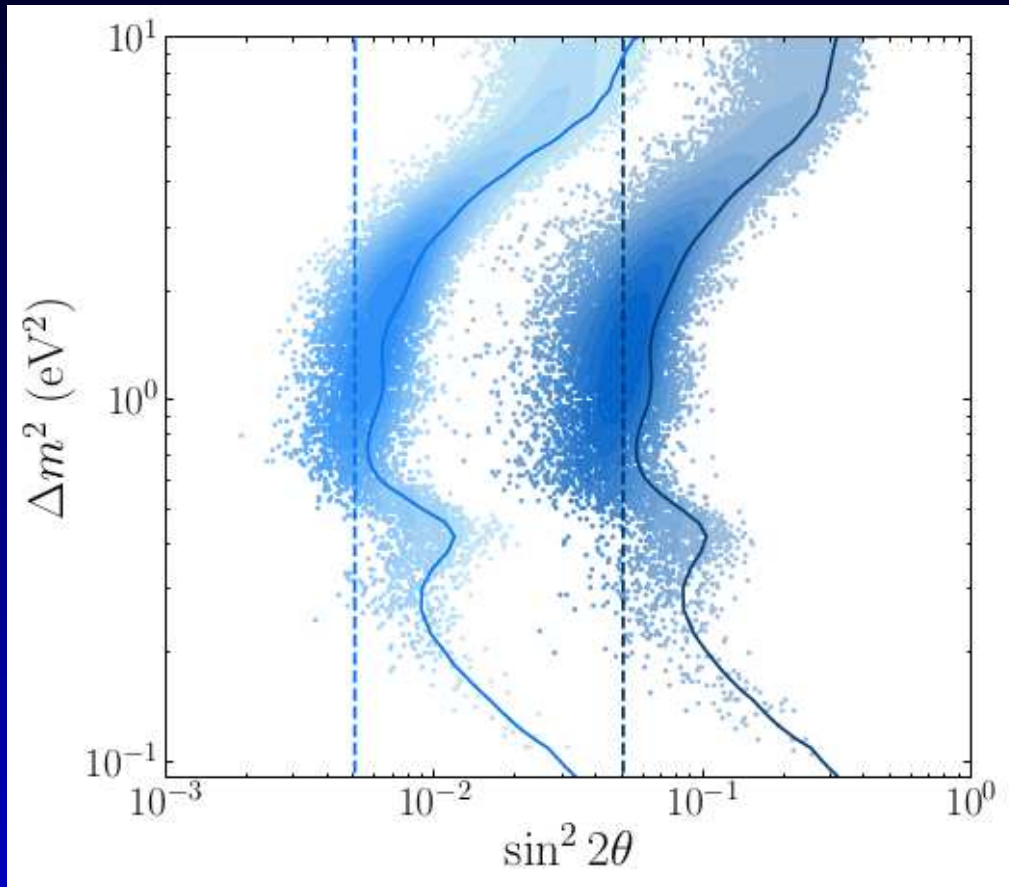


HM – conversion
 HKSS – conversion
 + forbidden decays
 EF – summation
 unclear theory error
 KI – HM + KI data
 HKSS+KI – HKSS +KI

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.

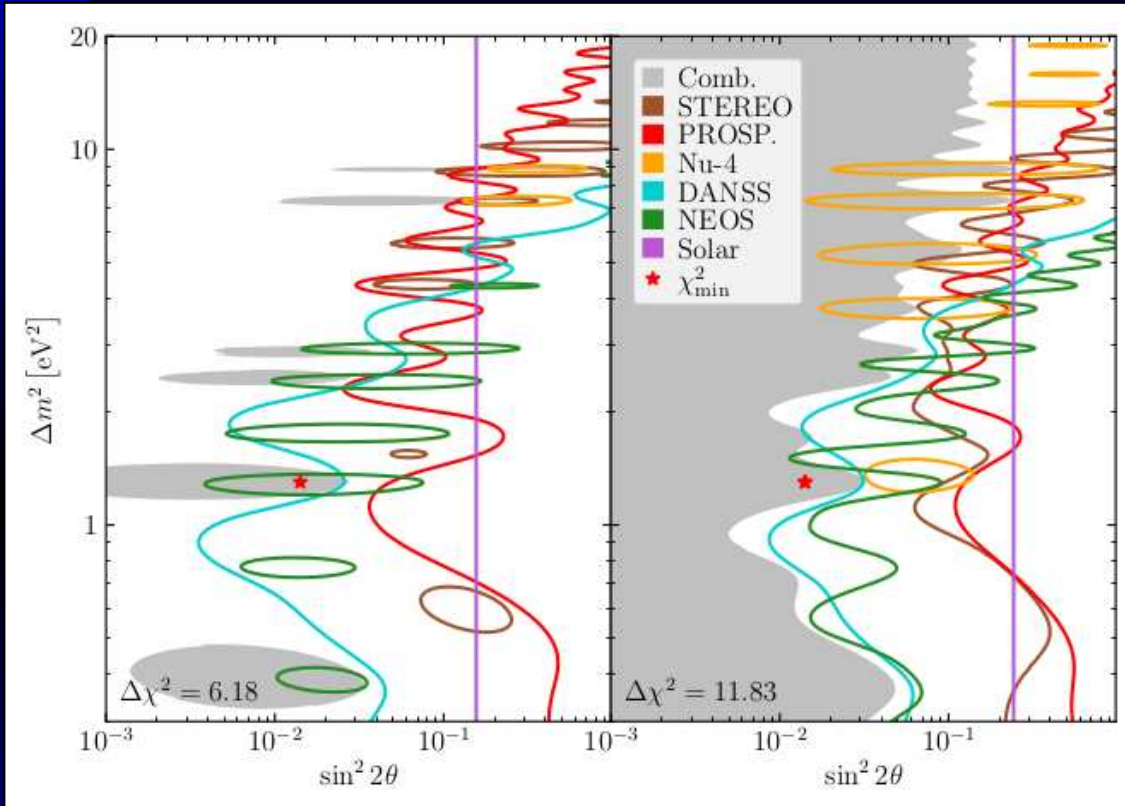
Wilks' theorem does
not apply

Coloma, PH, Schwetz, 2020

Agostini, Neumair, 2019; Silaeva, Sinev, 2020; Giunti, 2020

PROSPECT+STEREO, 2020

Global reactor data



$\Delta\chi^2 = 7.3$ for no-oscillation hypothesis, flux model-independent
Solar data provides a strong constraint at large $\sin^2 2\theta$

Berryman, Coloma, PH,
Schwetz, Zhou 2021

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

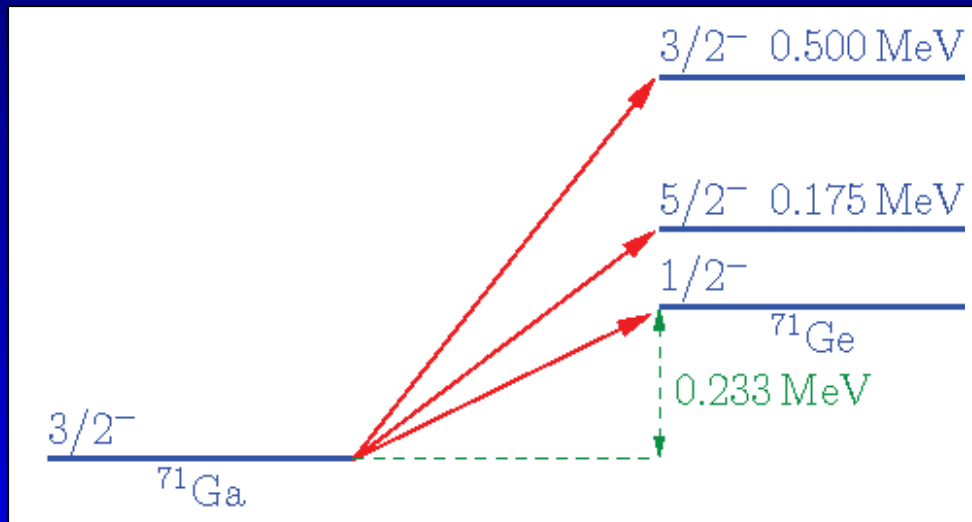
No tension with Neutrino-4

Gallium anomaly

Radioactive source experiments

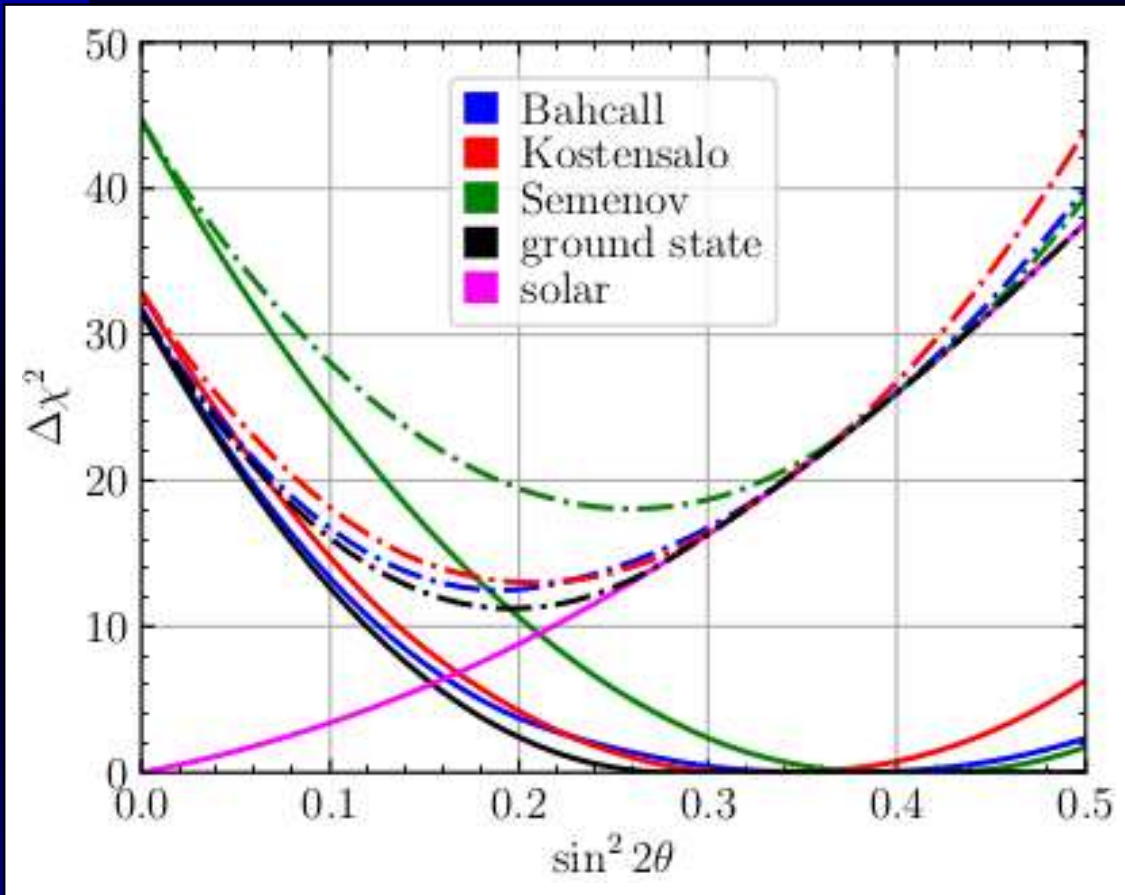
GALLEX	GALLEX	SAGE	SAGE	BEST (inner)	BEST (outer)
0.953 ± 0.11	0.812 ± 0.10	0.95 ± 0.12	0.791 ± 0.084	0.791 ± 0.044	0.766 ± 0.045

Nuclear matrix elements



ground state
follows from beta
decay
excited states?

Gallium and solar

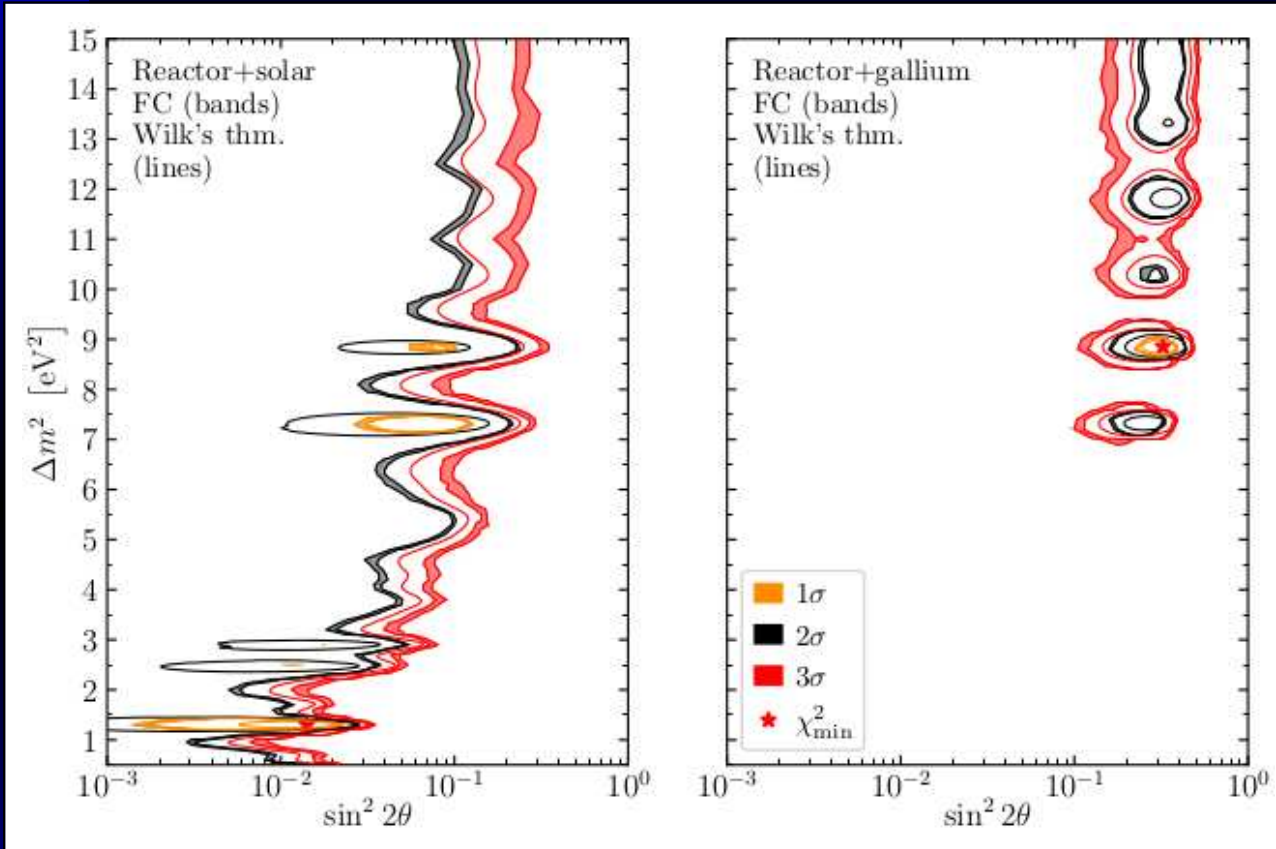


Any model for the matrix element yields than 5σ for the gallium anomaly, even the ground state contribution by itself.

BCHSZ 2021

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

All together now



Full FC analysis

Reactor+solar:
 1.1σ

Reactor+gallium:
 $5.3-5.7\sigma$

BCHSZ 2021

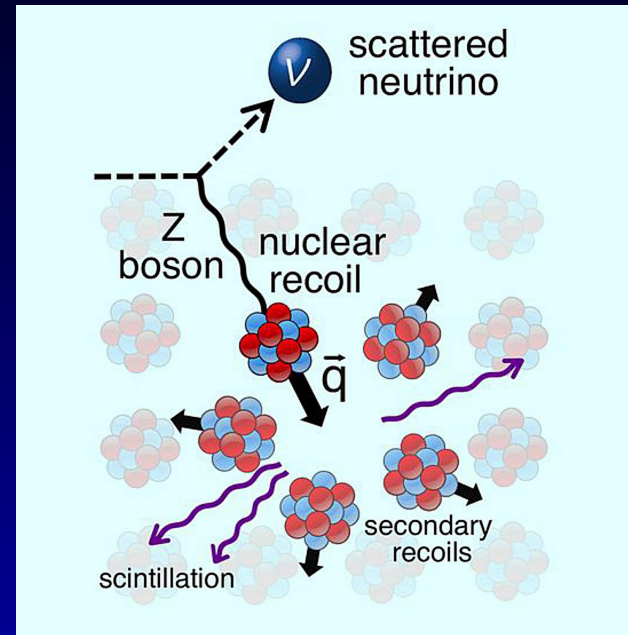
Evidence for neutrino disappearance entirely driven by gallium results, only tension gallium vs solar at $> 3\sigma$.

CE ν NS

Coherent elastic neutrino nucleus scattering (CE ν NS) is threshold-less.

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

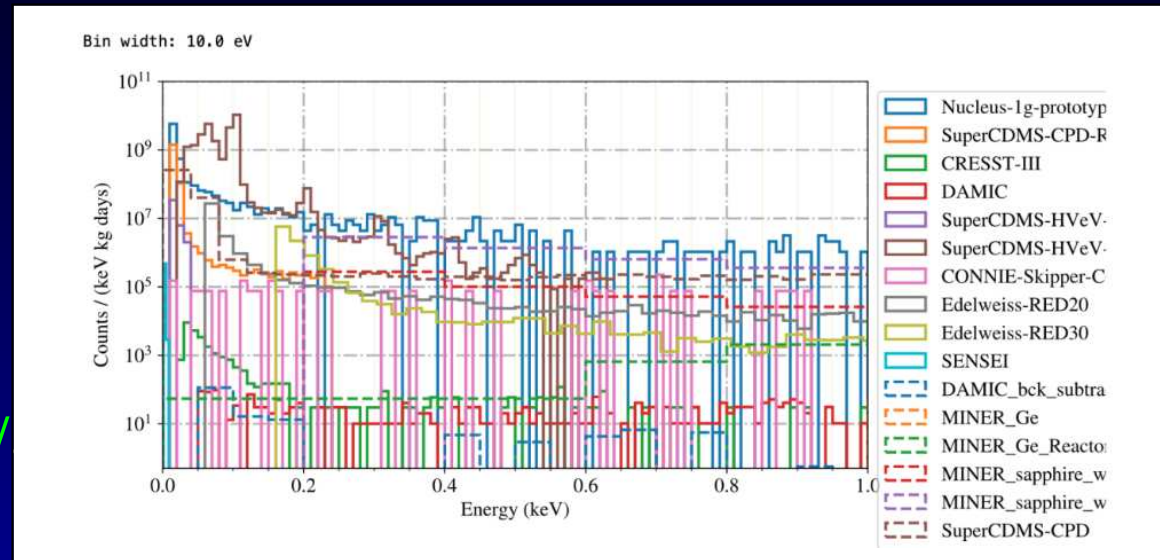
T recoil energy, N neutron number



- 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.

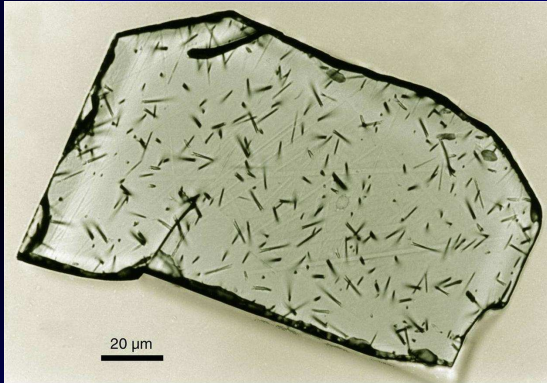
Optical detection of crystal defects as technological alternative? [Goel, Cogswell, PH 2021](#)

Future: CEvNS track detectors

CEvNS cross section is high

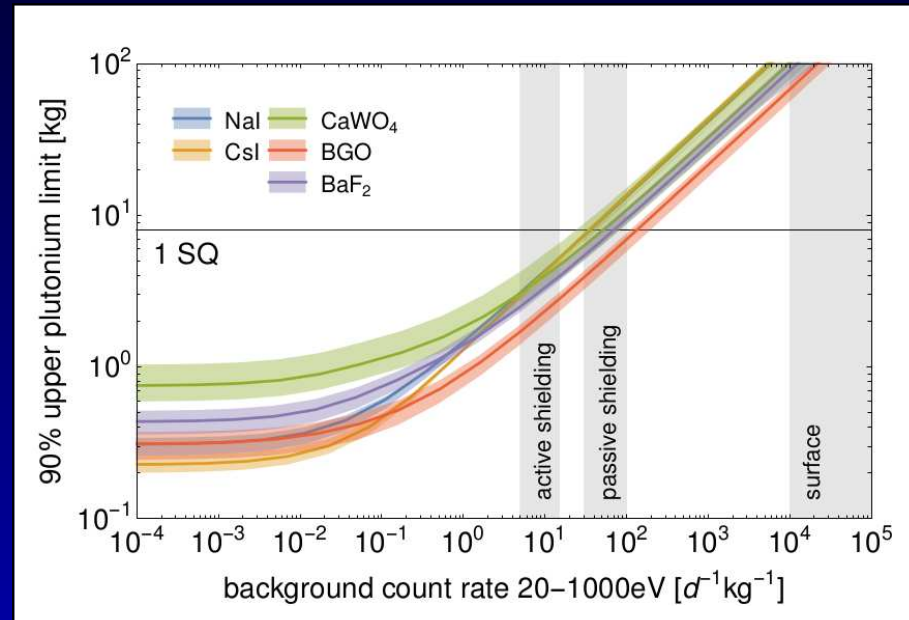
CEvNS results in nuclear recoil

Recoil produces permanent damage to crystal lattice



Fission Track Lab, U. Bergen

Recently Dark Matter searches have triggered strong interest in readout technology based on color centers - connection to QIS



Cogswell, Goel, PH, 2021

100 gram crystal could, with moderate neutron shielding, put a limit on plutonium production.

PALEOCCENE

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¹Center for Neutrino Physics, Physics Department, Virginia Tech, Blacksburg, VA

²University of Zurich, Switzerland

³Lawrence Livermore National Laboratory, Livermore, CA

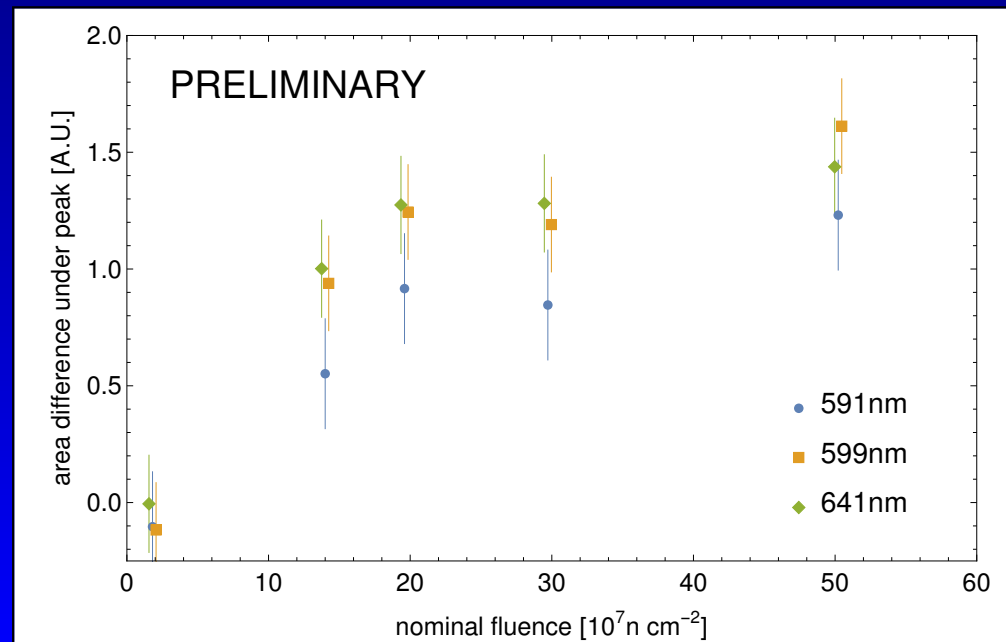
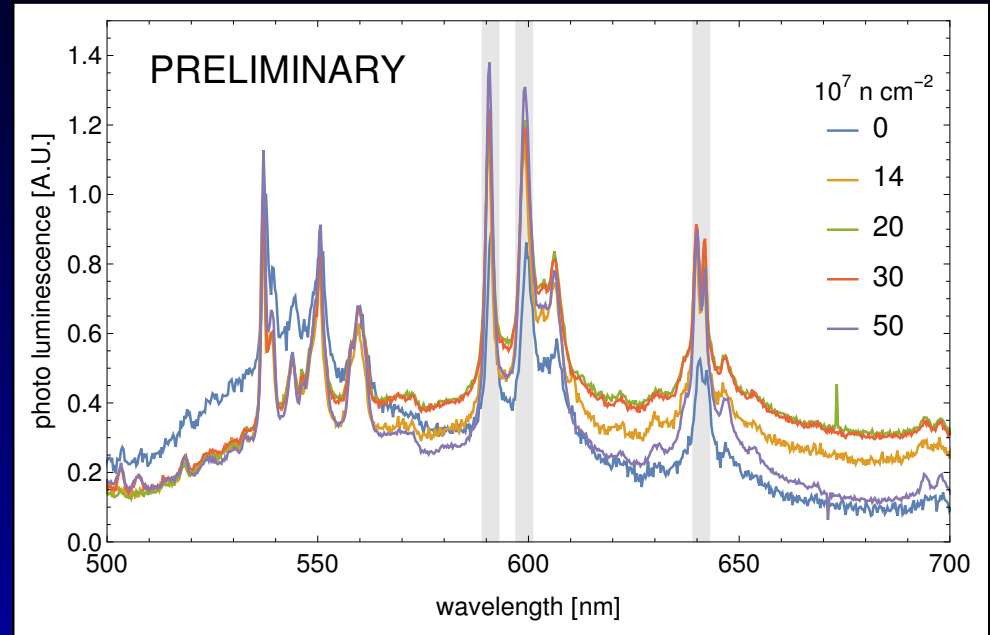
⁴George W. Woodruff School of Mechanical Engineering,
Georgia Institute of Technology, Atlanta, GA, USA

⁵University of New Mexico, Albuquerque, NM

⁶Physics Department, Virginia Tech, Blacksburg, VA

⁷Department of Nuclear Engineering and Radiological
Sciences, University of Michigan, Ann Arbor, MI

CaF₂ samples irradiated with an AmBe neutron source corresponding to only 1% of what was done previously, observation of fluorescence in response to excitation at 488 nm. [arXiv:2203.05525](https://arxiv.org/abs/2203.05525)



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.