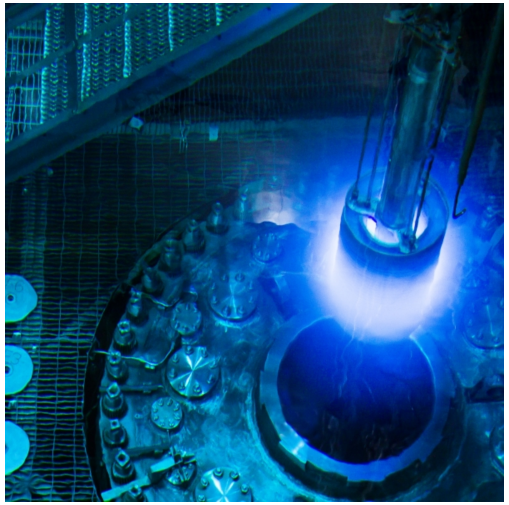


History of reactor neutrino experiments

WoNDRAM

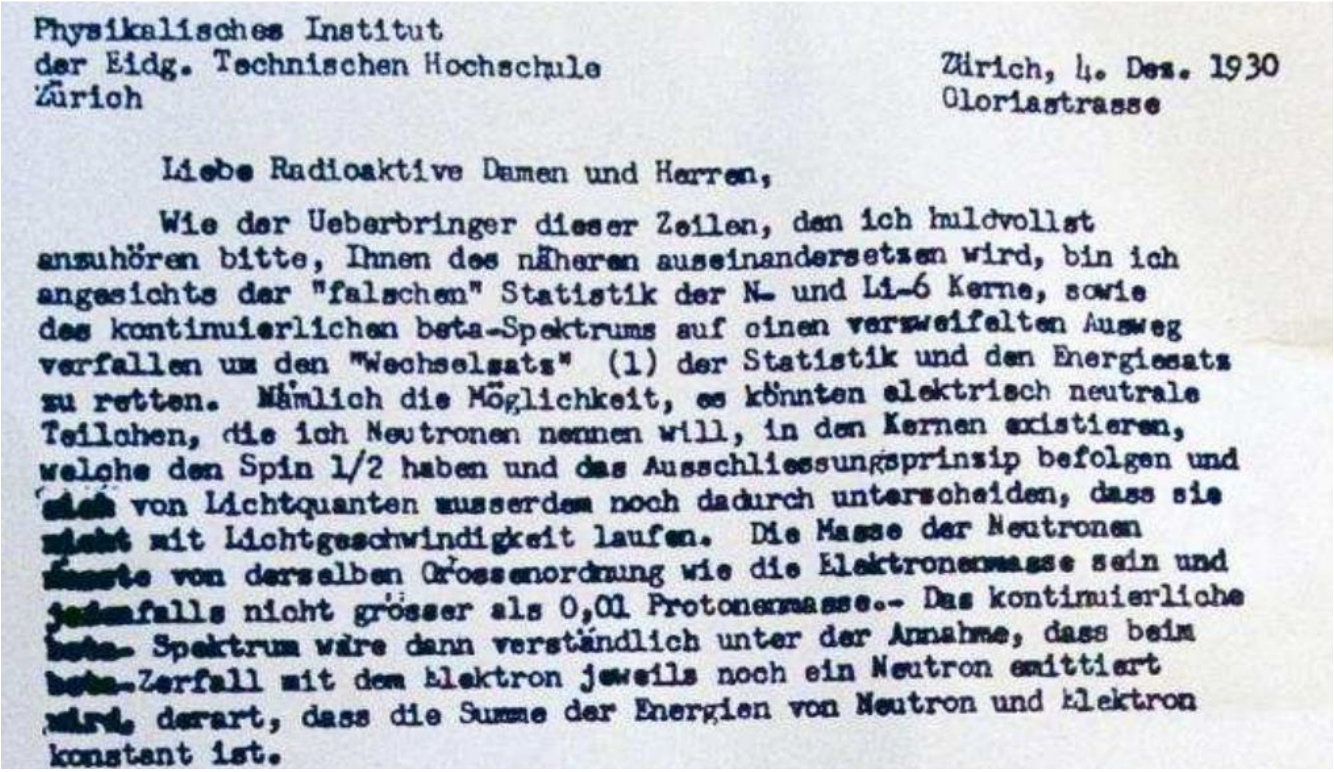
06/21-24 2021

P. Huber

Center for Neutrino Physics at Virginia Tech

Early history of the neutrino

- Neutrino postulated in Pauli's famous letter in 1930.
- Fermi theory of beta decay in 1933.
- Bethe and Peierls estimate detection cross section in 1934 to be $E_\nu^2\, 10^{-43}\, \mathrm{cm}^2$
- and conclude that the neutrino is practically invisible.



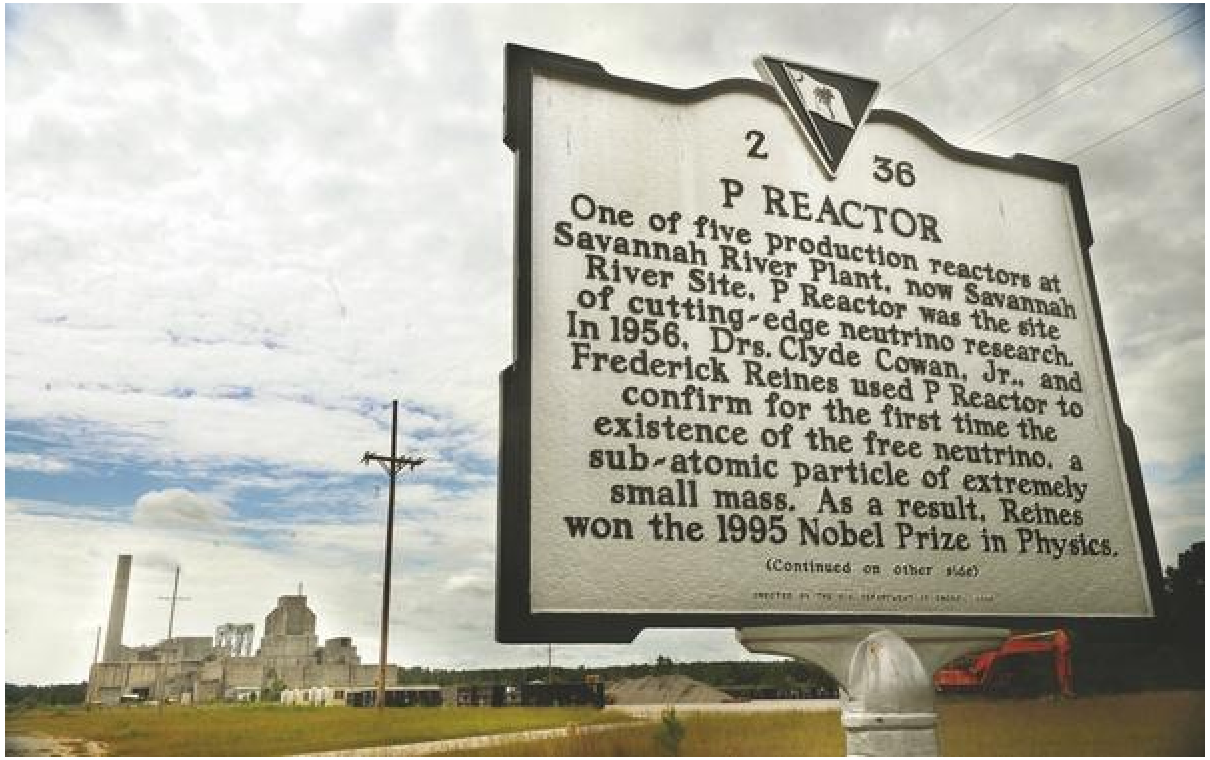
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

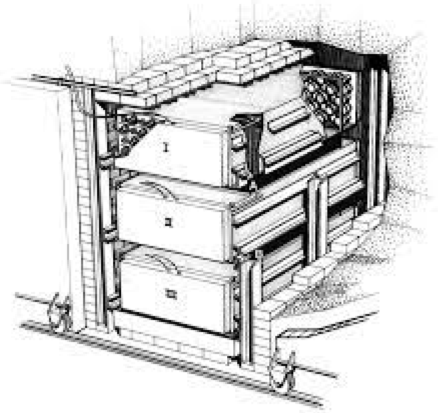
Zürich, 4. Des. 1930
Gloriastrasse

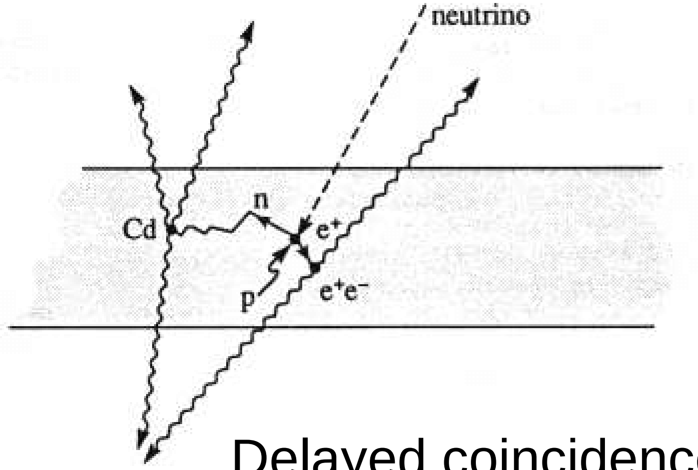
Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst ansuhören bitte, Ihnen des näheren auseinandersetsen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen versweifelten Ausweg verfallen um den "Wechselsats" (1) der Statistik und den Energiesats su 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 Ausschliessungsprinsip 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 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.

How neutrinos were discovered







1956

Delayed coincidence allowed them to use a reactor, instead.

All reactor neutrinos to date have been detected based on the same principles.

On to science

Many experiments aimed at neutrino oscillation throughout the 1980s and 90s at less than 100m from the reactor.

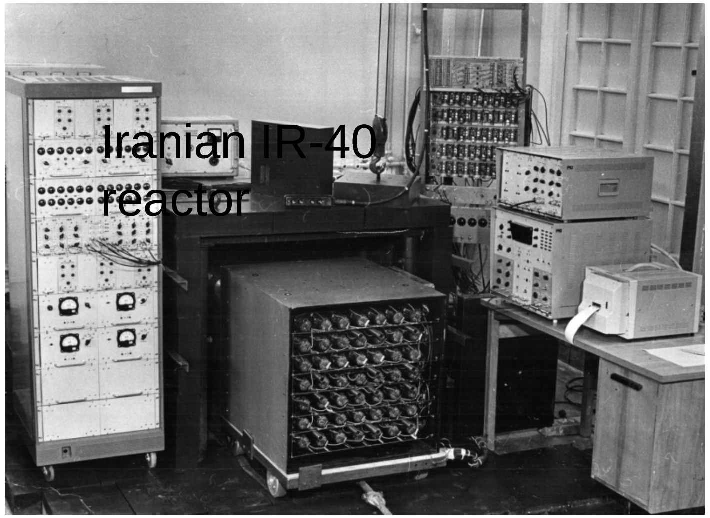
Multi-baseline measurements to avoid dependence on flux predictions.

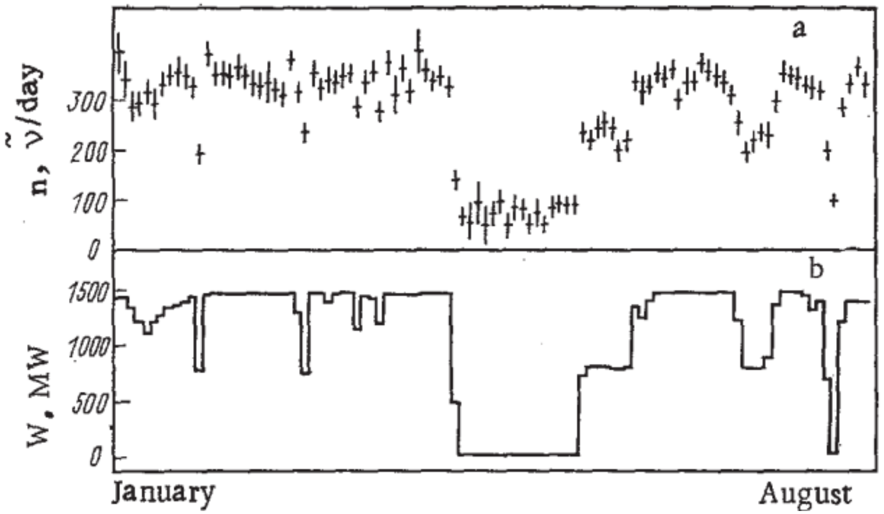
Chooz and Palo Verde inspired by the atmospheric neutrino anomaly started to probe the range around 1km.

a	Experiment	f^a_{235}	f^a_{238}	f^a_{239}	f^a_{241}	$R^{\text{exp}}_{a,\text{SH}}$	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	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	2.2	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		15
9	Bugey-3-40	0.538	0.078	0.328	0.056	0.942	4.3	4.0	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		37.9
12	Gosgen-46	0.584	0.068	0.298	0.050	0.981	5.4	2.0	45.9
13	Gosgen-65	0.543	0.070	0.329	0.058	0.915	6.7	3.8	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

Table from C. Giunti, Phys. Lett. **B** 764 (2017) 145.

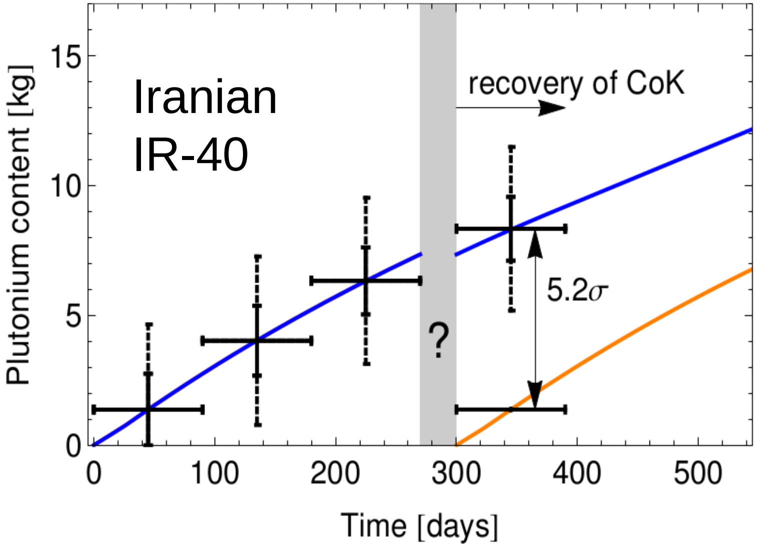
Neutrino reactor monitoring





Korovkin *et al.* Atomic Energy 76 (1994) 123–127.

Christensen, PH, Jaffke, Shea,
Phys. Rev. Lett. 113 (2014) 042503.



First proposed by Borovoi & Mikaelyan in 1978
Soviet Atomic Energy 44 (6), 589–592.

Proof of concept at the Rovno power plant in the 1980s.

Long line of detectors: SONGS, Nucifer, PANDA, VIDARR, CHANDLER, iDREAM, IMRAN, ...

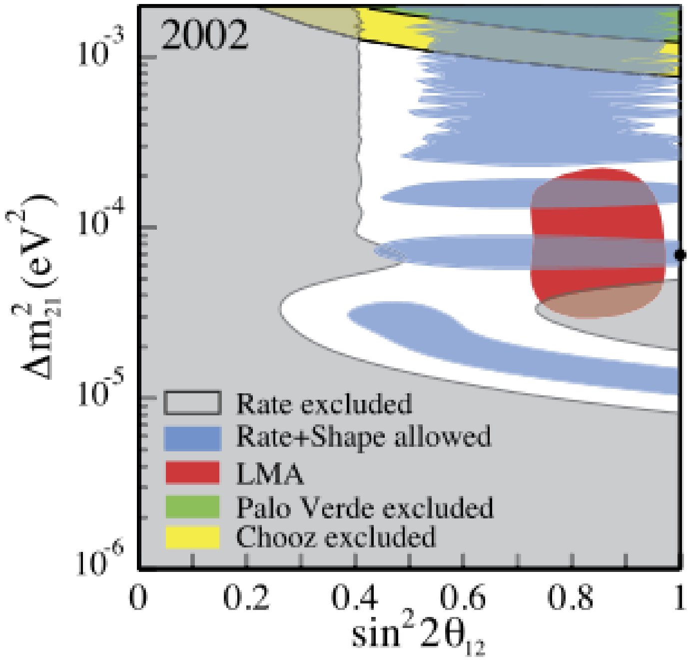
Relevant capabilities may exist for several use cases.

NuTools study sponsored by NNSA DNN R&D will release its final report in July 2021.

https://nutools.ornl.gov/

Discoveries!

Phys.Rev.Lett. 90 (2003) 021802.

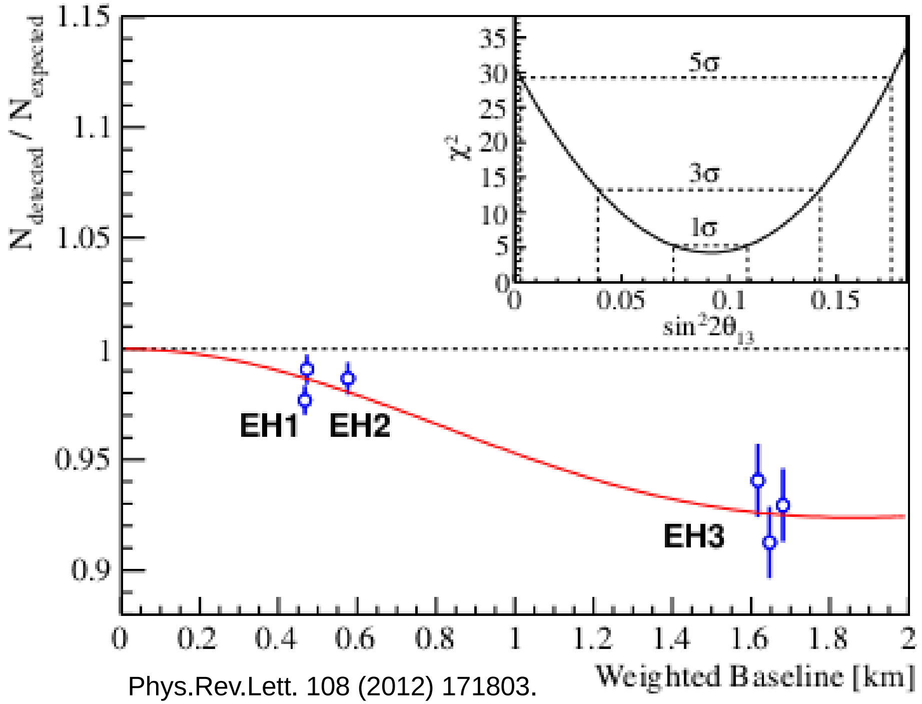


KamLAND, a 1kt liquid scintillator exeriment in Japan was built to look for solar neutrinos and instead observed neutrinos from reactors 200km away and confirmed the solar neutrino anomaly.

Provides to date the best determination of that mass squared difference.

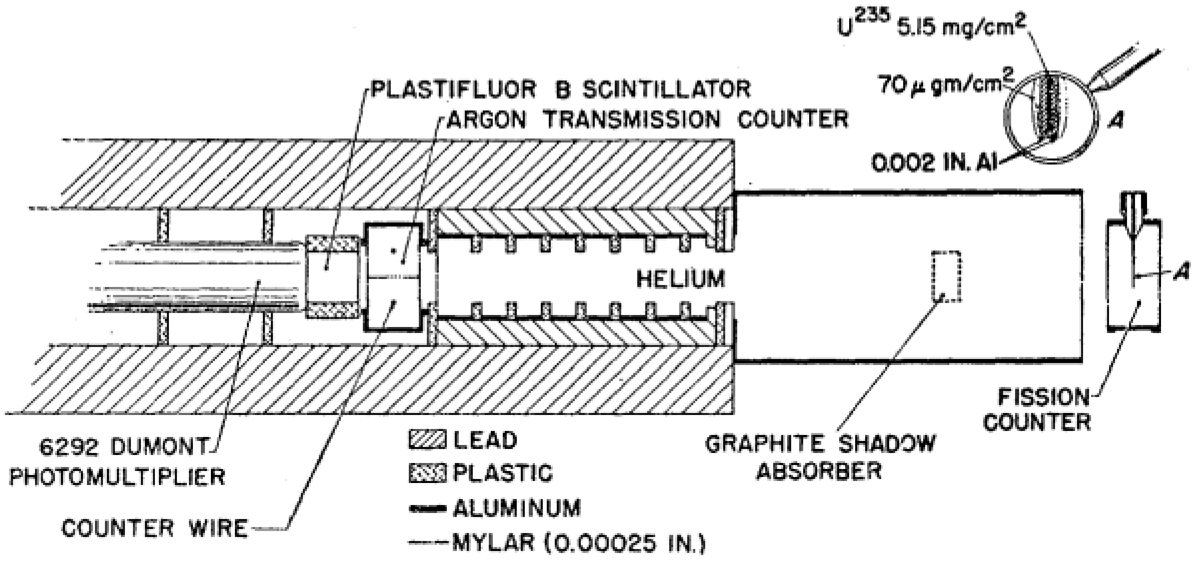
In 2012, following hints from T2K and Double Chooz, the Daya Bay experiment observed oscillations at a distance of 1.6km corresponding to the atmospheric oscillation frequency.

And provides to date the most precise determination of the theta13 mixing angle.



Phys.Rev.Lett. 108 (2012) 171803.

Neutrino flux predictions

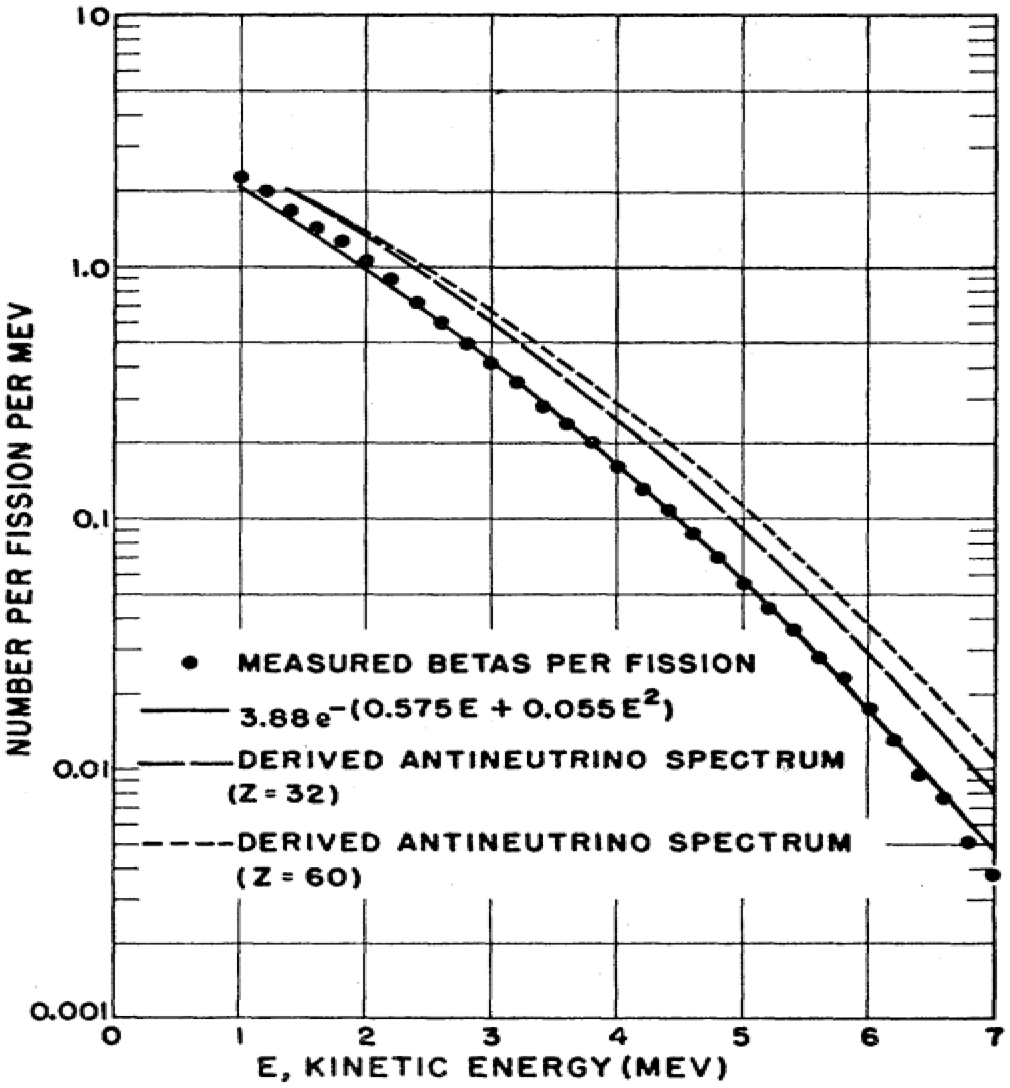


Carter, Reines, Wagner, Wyman, Phys. Rev. **113** (1959) 280.

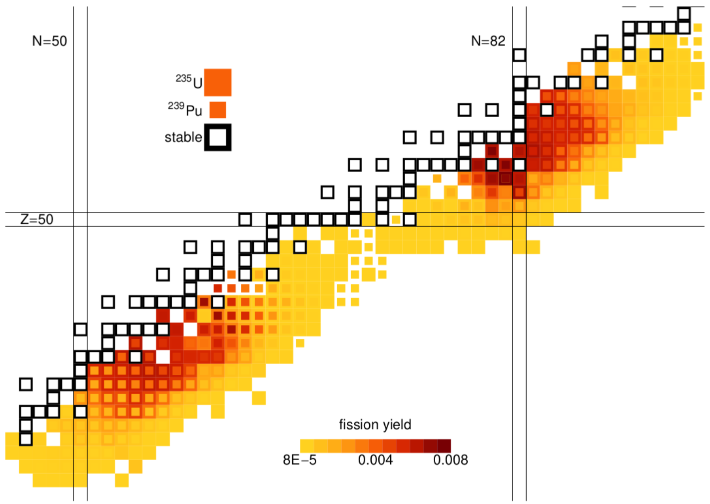
Measure total beta spectrum from **all** fission fragments at once. Convert to neutrino spectrum:

$$N_{\bar{\nu}}(E) = N_\beta(E - 511keV - 50keV) \cdot k(E)$$

50keV average Coulomb correction, 1-k(E)~5% correction from summation calculation



Summation calculations



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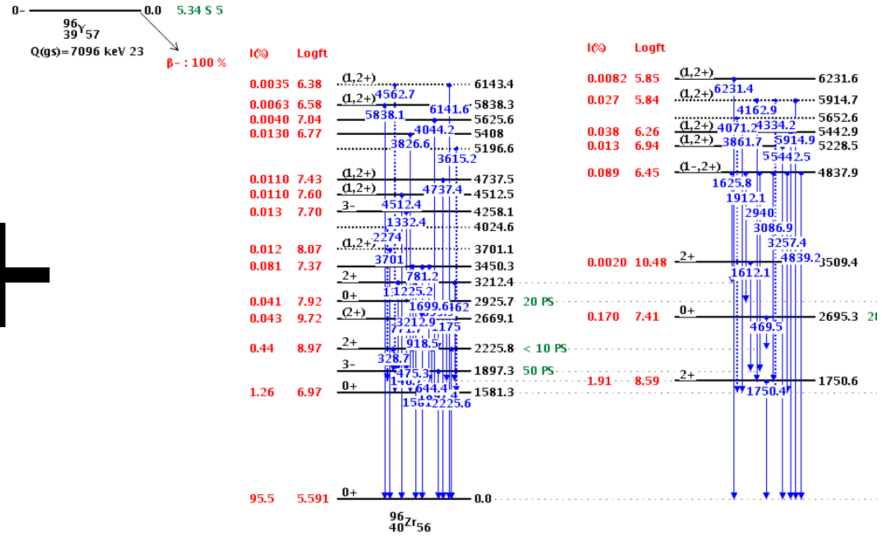

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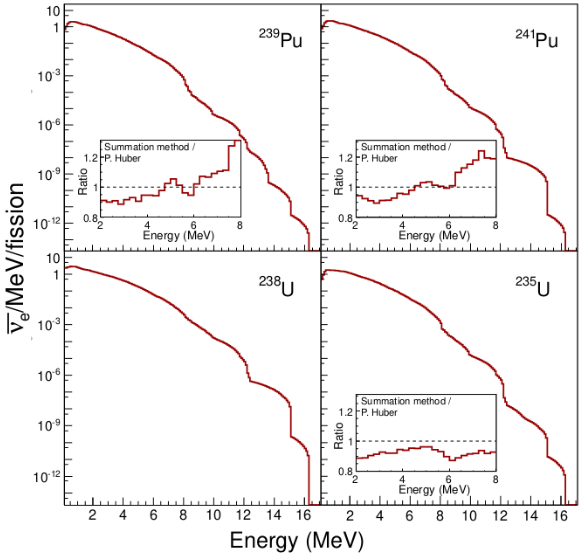


Fallot *et al.* Phys. Rev. Lett. **109** (2012) 202504.
Estienne *et al.*, Phys. Rev. Lett. **123** (2019) 2, 022502.

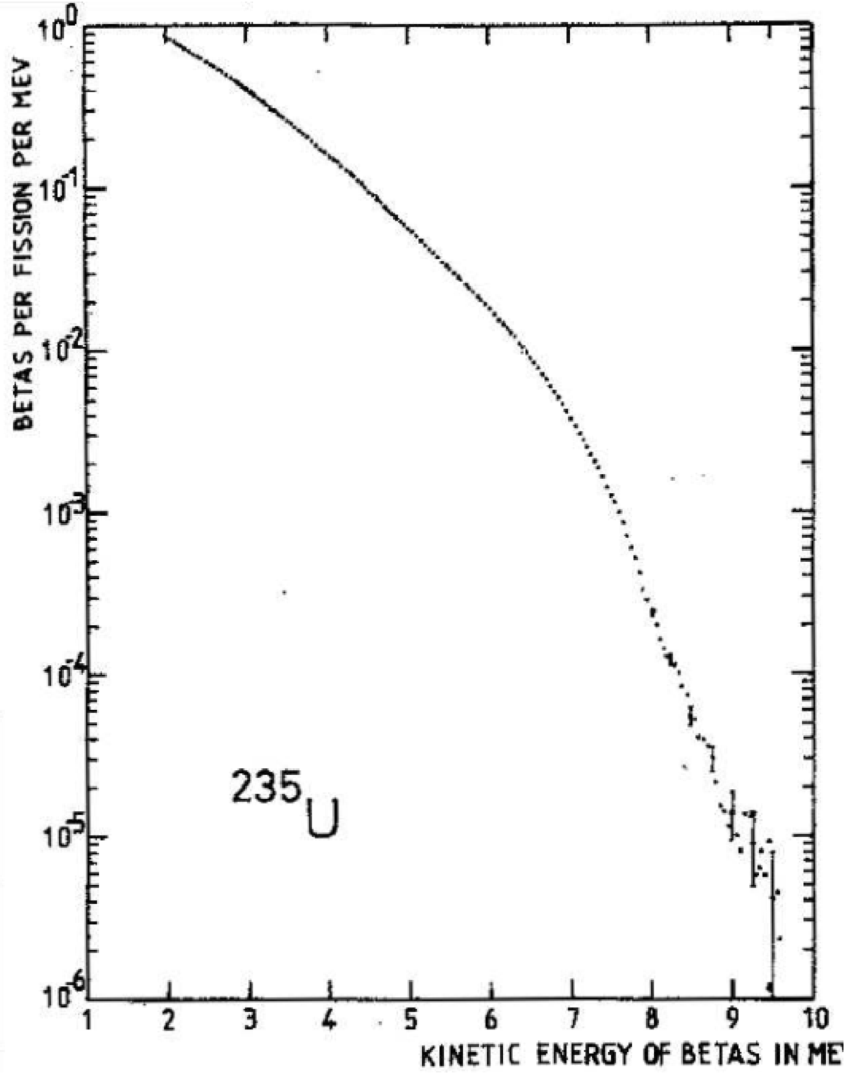
Summation calculations have been done since 1970s.

Play an important role for computing corrections in the conversion method.

~800 fission fragments
~10,000 beta branches

Crucial tool to study novel reactors and systematic uncertainties.

The ILL measurements



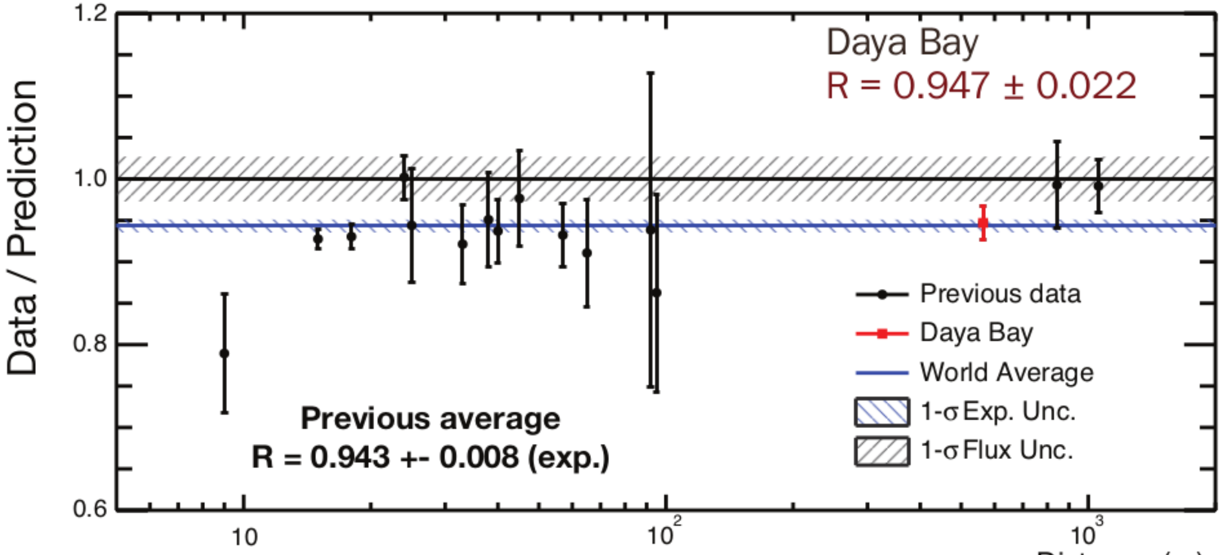
Schreckenbach *et al.* Phys. Lett. B 160 (1989) 325.

Form the basis for flux predictions in the past 3 decades.

Major reevaluation in 2011 lead to the so-called Huber-Mueller model

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

and the so-called reactor antineutrino anomaly.



Phys. Rev. Lett. 116, 061801 (2016).

Sterile neutrinos

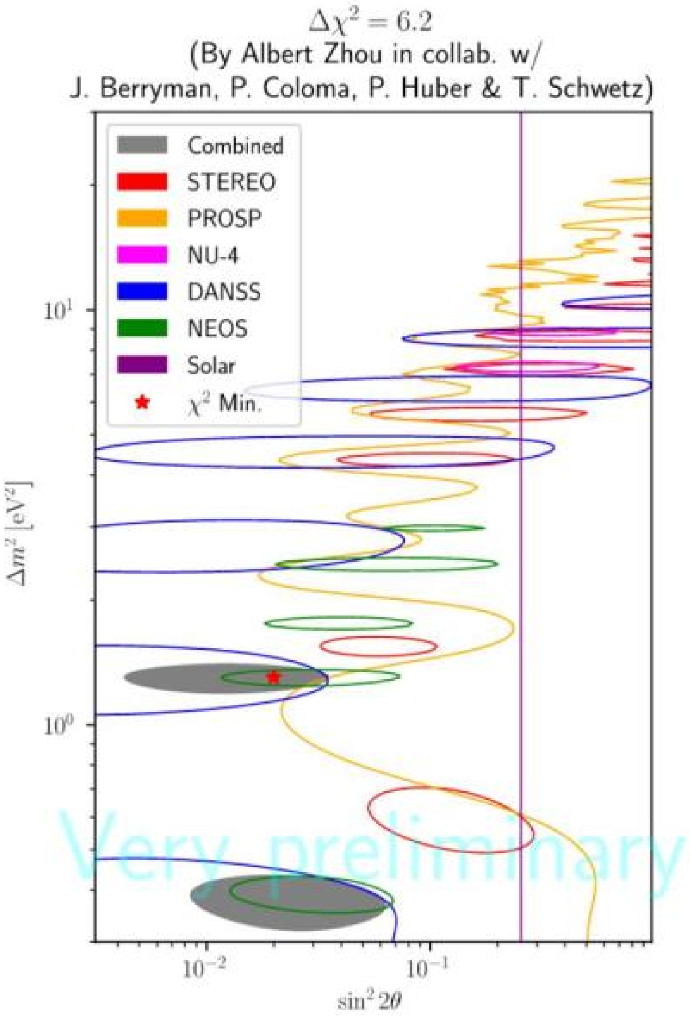
The reactor antineutrino anomaly triggered many short-baseline experiments.

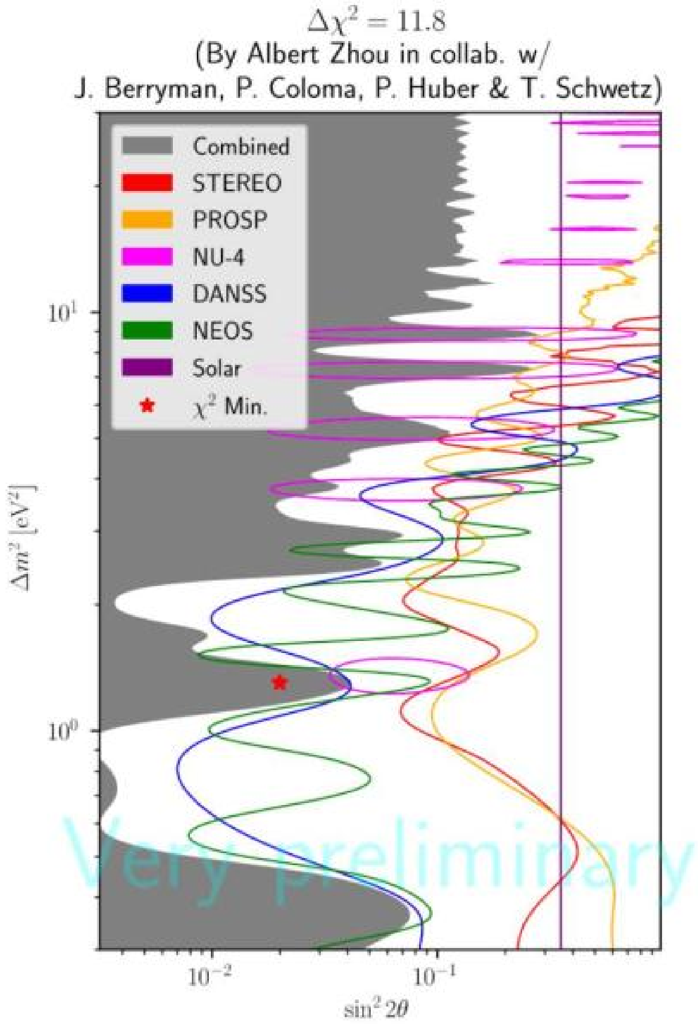
Many different detector designs and materials.

Results in synopsis are inconclusive, global preference for oscillation:

$$\Delta\chi^2 = 9.9$$

Independent of flux predictions!



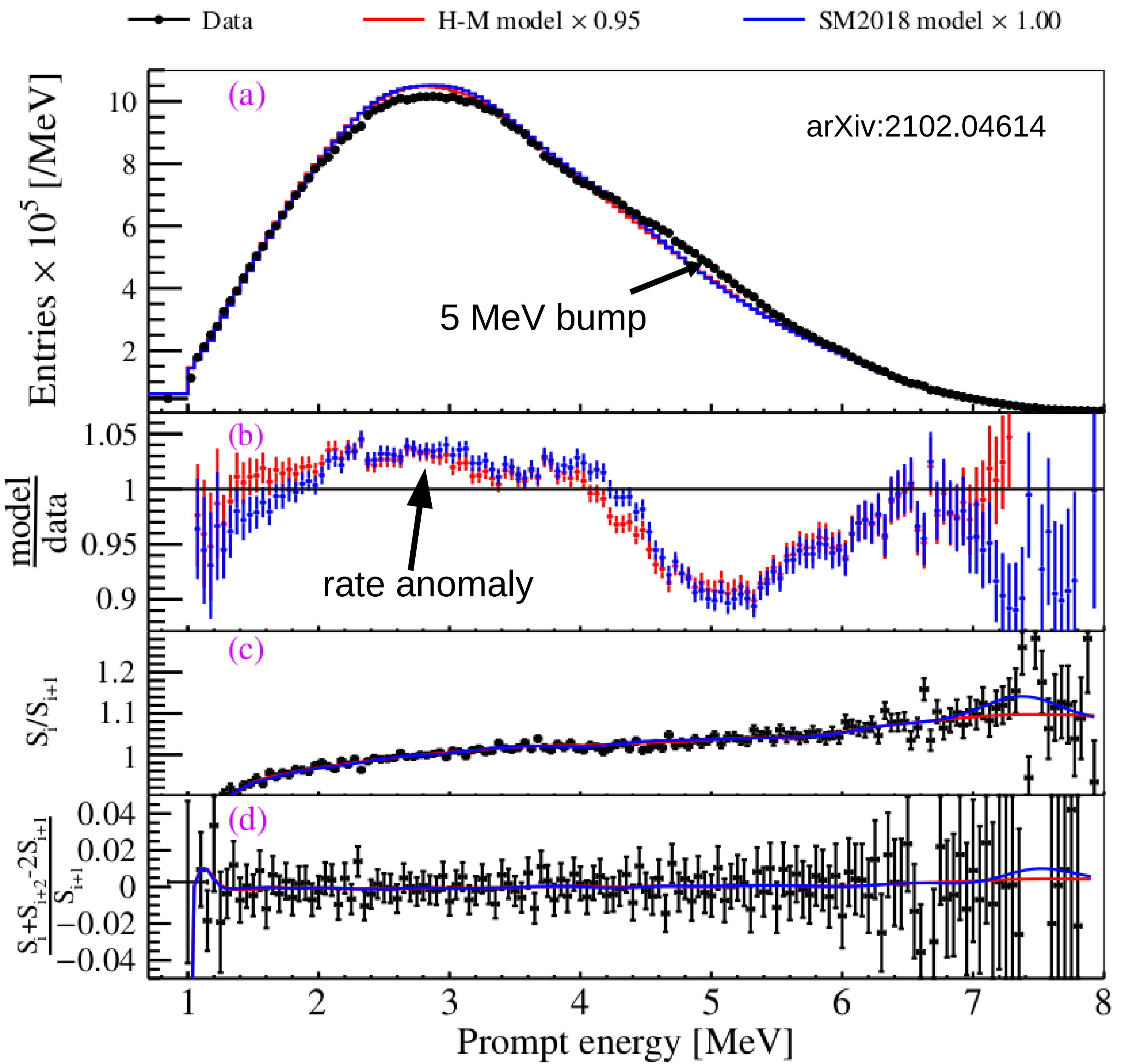


Daya Bay flux measurements

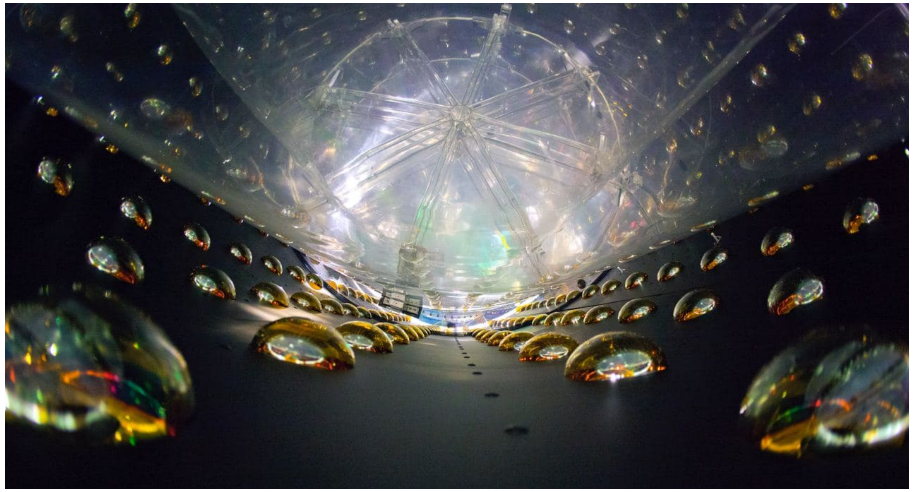
3.5 million inverse beta decay events.

Conversion (HM) prediction does **not** agree in total rate with the data or the summation calculation.

Conversion (HM) and summation (SM) prediction agree on shape with each other, but **not** with the data.



Neutrino detectors as of today



Daya Bay, Double Chooz, RENO: single volume, 10-20ton target, Gd-doped liquid scintillator with a few 100 meter water equivalent overburden 200-2000m from reactor.

PROSPECT
liquid scintillator

CHANDLER, solid scintillator

100-4000kg scale detectors, segmented (2D/3D), Li as neutron capture agent. Liquid and solid scintillator possible. Operation w/o overburden at the surface 10-100m from reactor.

Summary

Neutrino detectors

- Mature, precision technology
- Still improving, active R&D
- 5-10% energy resolution
- 2% absolute normalization
- <0.5% relative normalization
- Surface operation
- Potential applications to reactor monitoring

Neutrino science

- Standard oscillation physics well constrained and independent of fluxes
- Sterile neutrinos unclear, but independent of fluxes
- Open questions around rate & spectrum