TWENTY-FIRST LOMONOSOV
CONFERENCE August, 24-30, 2023
ON ELEMENTARY PARTICLE PHYSICS
MOSCOW STATE UNIVERSITY

Joint Institute for Nuclear Research
SCIENCE BRINGS NATIONS TOGETHER

FUNDAMENTAL PHYSICS WITH REACTOR NEUTRINOS

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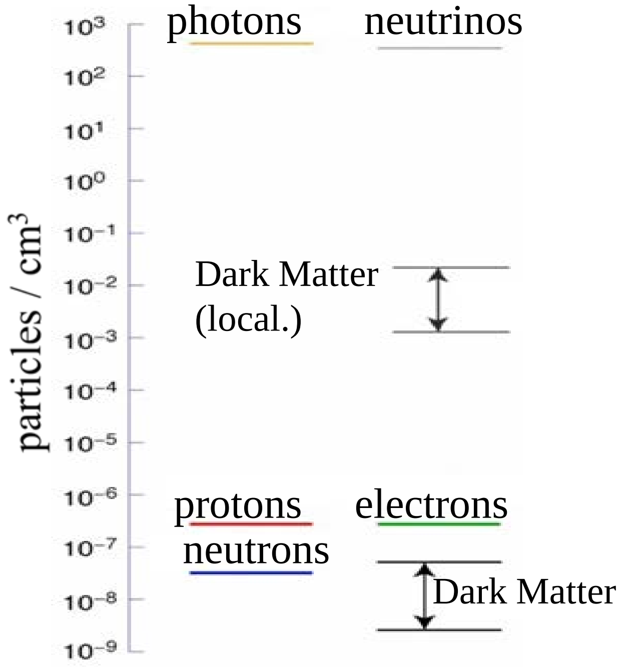
Why neutrinos

- One of the most common yet elusive particles in the Universe (while I was saying that, over 100 trillion neutrinos flew through each of us).

- Contain information about phenomena and the processes that produce them, thus allow us to study events at great distances from us in time (the early Universe) and space (galactic nuclei, stars, including our Sun, the inner part of the Earth, ...). In addition, they allow us to remotely see the operation of a nuclear reactor.

- The properties of that particle itself are unique and their study allows us to understand the fundamentals of physics.

Particle Universe



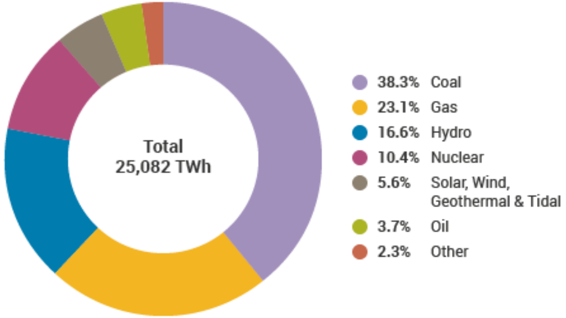
Why reactors

- ❖ On average, 200 MeV of energy is released per fission;
- ❖ On average, 6 $\bar{\nu}_e$ per fission (beta decay of fission products);
- ❖ Working WWER1000 emits 6×10^{20} $\bar{\nu}_e$ each seconds!

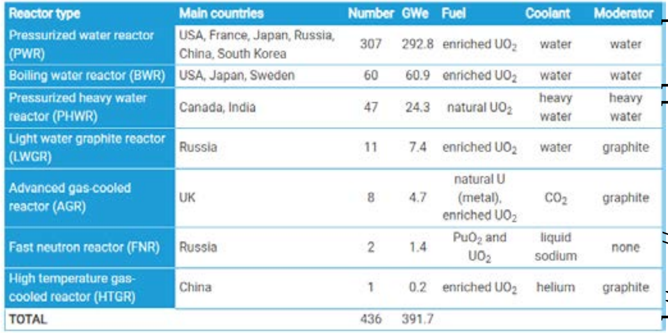
The most powerful artificial neutrino source on Earth!

Today there are about 440 nuclear power reactors in 32 countries, with a combined capacity of about 390 GWe. In 2021 these provided 2653 TWh, about 10% of the world's electricity. About 60 power reactors are currently being constructed;

In addition, about 50 countries have a total of 225 research reactors (used not only for science, but also for medicine, education, isotope production).



Source: IEA Electricity Information 2018

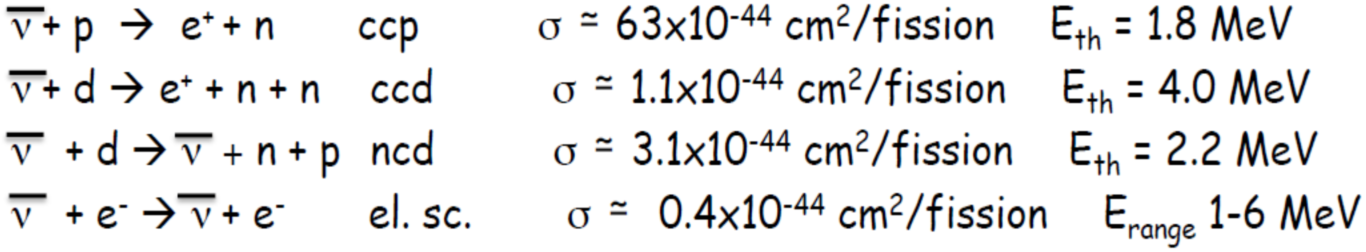


Reactor type	Main countries	Number	GWe	Fuel	Coolant	Moderator
Pressurized water reactor (PWR)	USA, France, Japan, Russia, China, South Korea	307	292.8	enriched UO_2	water	water
Boiling water reactor (BWR)	USA, Japan, Sweden	60	60.9	enriched UO_2	water	water
Pressurized heavy water reactor (PHWR)	Canada, India	47	24.3	natural UO_2	heavy water	heavy water
Light water graphite reactor (LWGR)	Russia	11	7.4	enriched UO_2	water	graphite
Advanced gas-cooled reactor (AGR)	UK	8	4.7	natural U (metal), enriched UO_2	CO_2	graphite
Fast neutron reactor (FNR)	Russia	2	1.4	PuO_2 and UO_2	liquid sodium	none
High temperature gas-cooled reactor (HTGR)	China	1	0.2	enriched UO_2	helium	graphite
TOTAL		436	391.7			

https://www.world-nuclear.org/

Methods for studying reactor neutrinos

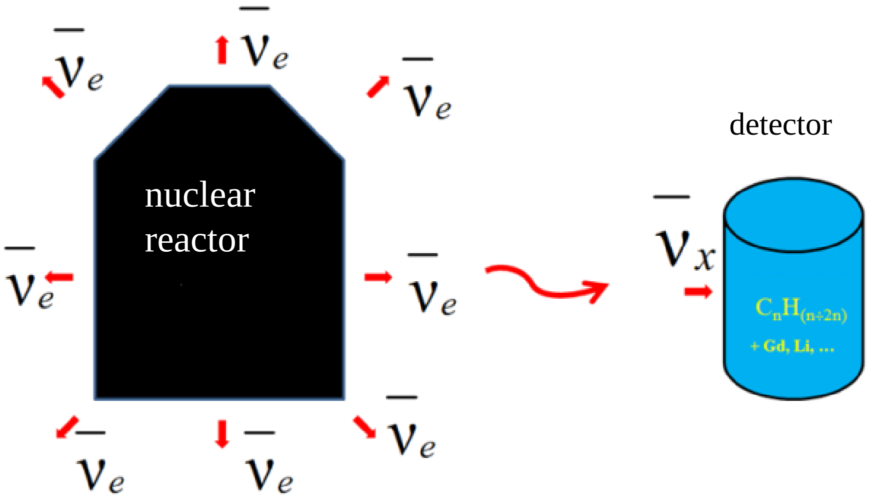
- inverse beta decay;
- electron scattering;
- nuclear scattering (coherent scattering).

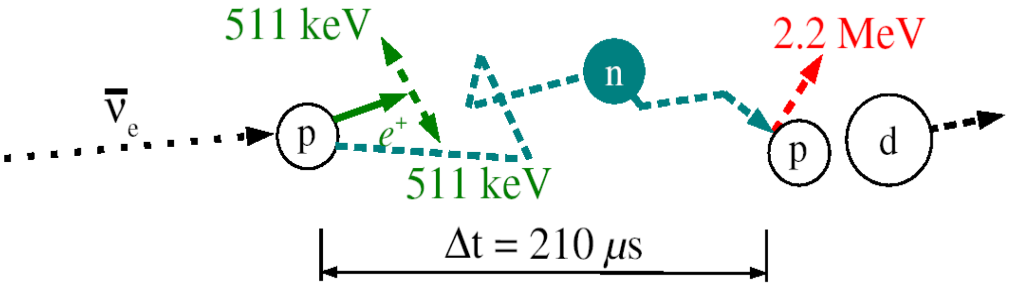


$\overline{\nu} + p \rightarrow e^+ + n$	ccp	$\sigma \simeq 63\mathrm{x}10^{-44}\ \mathrm{cm}^2/\mathrm{fission}$	$E_{th} = 1.8$ MeV
$\overline{\nu} + d \rightarrow e^+ + n + n$	ccd	$\sigma \simeq 1.1\mathrm{x}10^{-44}\ \mathrm{cm}^2/\mathrm{fission}$	$E_{th} = 4.0$ MeV
$\overline{\nu} + d \rightarrow \overline{\nu} + n + p$	ncd	$\sigma \simeq 3.1\mathrm{x}10^{-44}\ \mathrm{cm}^2/\mathrm{fission}$	$E_{th} = 2.2$ MeV
$\overline{\nu} + e^- \rightarrow \overline{\nu} + e^-$	el. sc.	$\sigma \simeq 0.4\mathrm{x}10^{-44}\ \mathrm{cm}^2/\mathrm{fission}$	E_{range} 1-6 MeV

In 1946 Bruno Pontecorvo, proposed the use of the inverse beta process ($\nu + Z \rightarrow e^- + [Z+1]$) to detect neutrinos, pointing to the famous chlorine-argon reaction ($\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$), and noted the Sun and nuclear reactors as significant sources of neutrinos.

$$\boxed{\overline{\nu}_e + p \rightarrow n + e^+}$$





Inverse beta processes

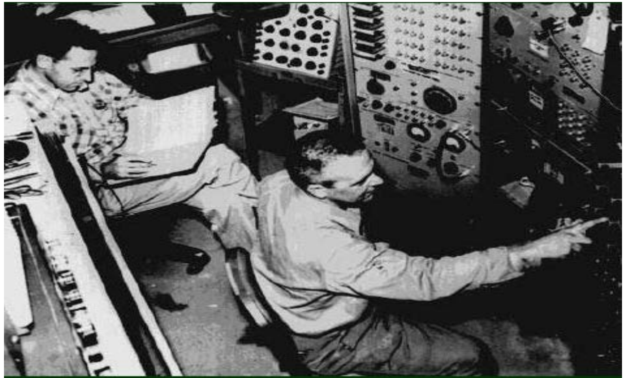
- Experimental discovery of neutrinos (1956);

- Solar neutrinos;

- Search, direct confirmation of neutrino oscillations (solving the problem of solar neutrinos) and determination of oscillation parameters with precision accuracy (1990 - present day);

- Search for sterile neutrinos (our days);

- Reactor monitoring (our days).



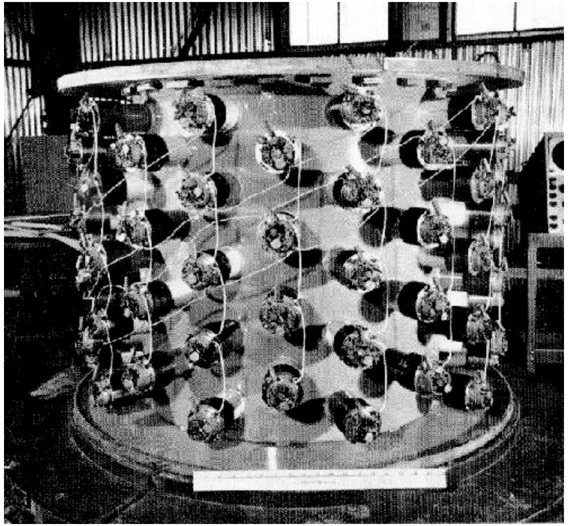
F. Reines and C. Cowan at the Control Center of the Hanford Experiment (1953)

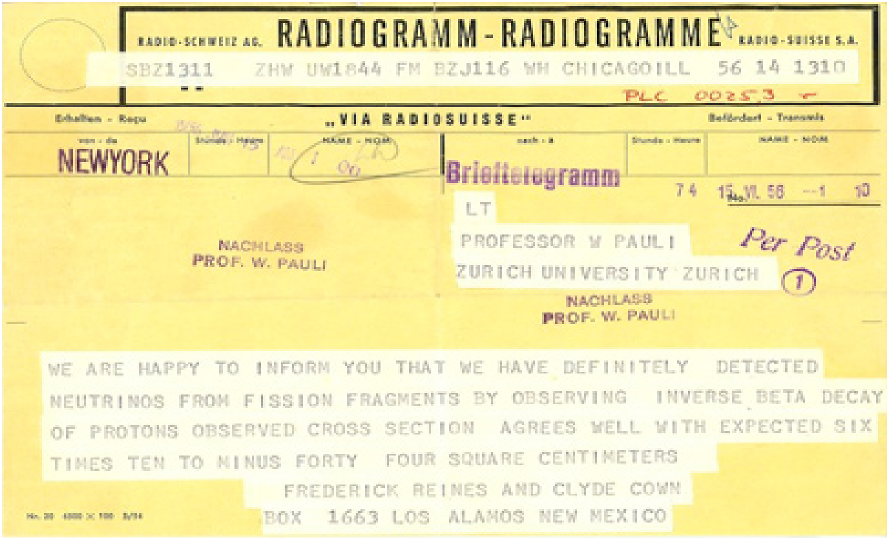
Experimental discovery of neutrinos (1956)

The experiment performed 1953-1956 yy
(Savannah River, South Carolina, USA.)

Reines and Cowan

400 liters of cadmium chloride solution in water.





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Brieftelegramm

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LT

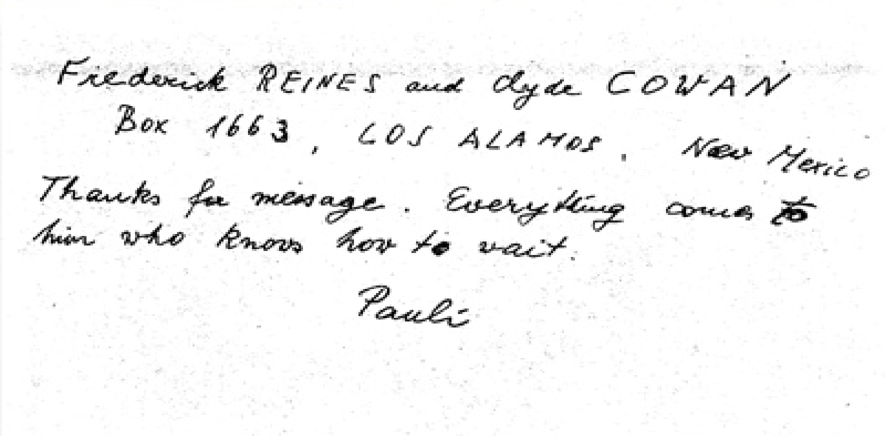
PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH

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



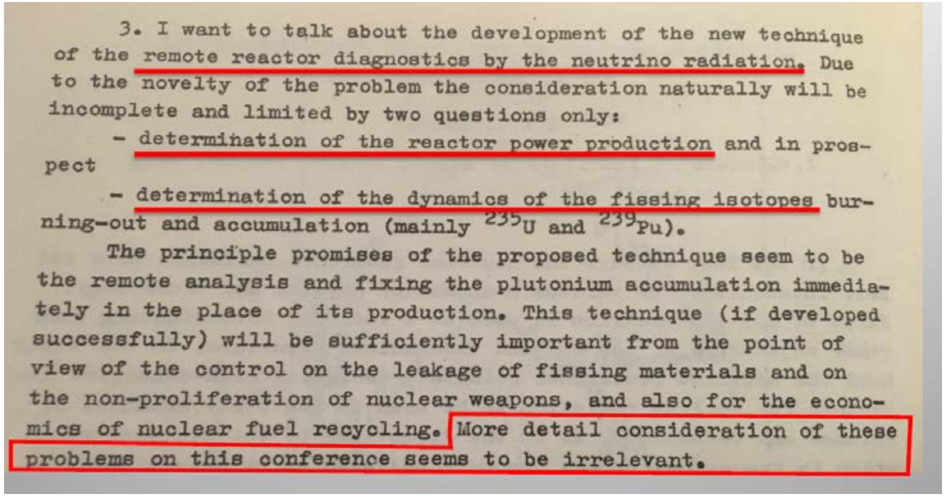
Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to him who knows how to wait.

Pauli

Monitoring reactors with neutrinos

The idea was expressed by L.A.Mikaelian in 1977 during the international conference Neutrino 77 in Baksan.

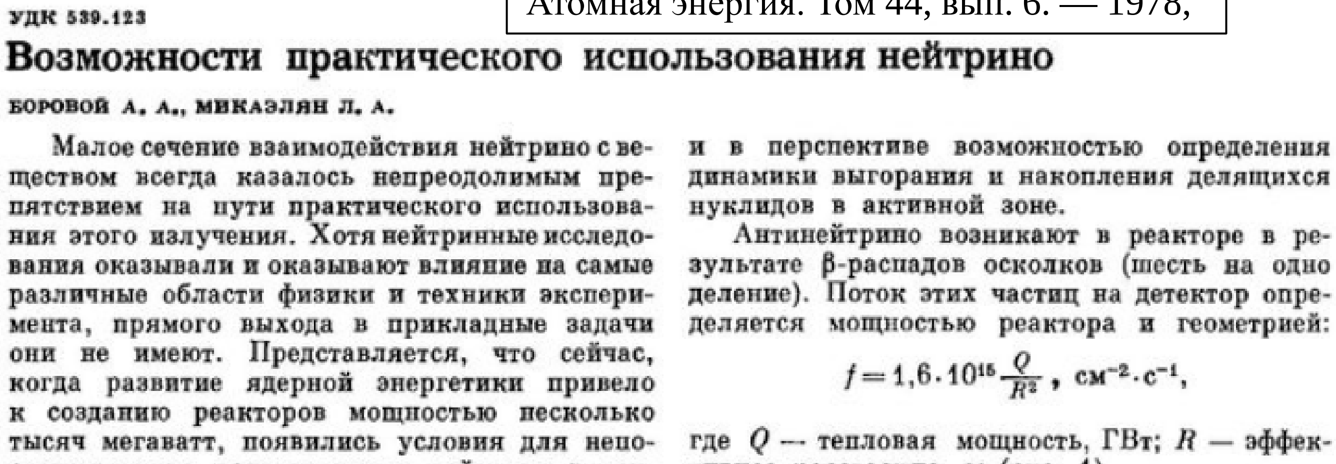


3. I want to talk about the development of the new technique of the remote reactor diagnostics by the neutrino radiation. Due to the novelty of the problem the consideration naturally will be incomplete and limited by two questions only:

- determination of the reactor power production and in prospect
- determination of the dynamics of the fissing isotopes burning-out and accumulation (mainly ^{235}U and ^{239}Pu).

The principle promises of the proposed technique seem to be the remote analysis and fixing the plutonium accumulation immediately in the place of its production. This technique (if developed successfully) will be sufficiently important from the point of view of the control on the leakage of fissing materials and on the non-proliferation of nuclear weapons, and also for the economics of nuclear fuel recycling. More detail consideration of these problems on this conference seems to be irrelevant.

Атомная энергия. Том 44, вып. 6. — 1978,



УДК 539.123

Возможности практического использования нейтрино

БОРОВОЙ А. А., МИКАЭЛЯН Л. А.

Малое сечение взаимодействия нейтрино с веществом всегда казалось непреодолимым препятствием на пути практического использования этого излучения. Хотя нейтринные исследования оказывали и оказывают влияние на самые различные области физики и техники эксперимента, прямого выхода в прикладные задачи они не имеют. Представляется, что сейчас, когда развитие ядерной энергетики привело к созданию реакторов мощностью несколько тысяч мегаватт, появились условия для непо-

и в перспективе возможностью определения динамики выгорания и накопления делящихся нуклидов в активной зоне.

Антинейтрино возникают в реакторе в результате β-распадов осколков (шесть на одно деление). Поток этих частиц на детектор определяется мощностью реактора и геометрией:

$$f=1{,}6\cdot 10^{15}\frac{Q}{R^2}\text{, см}^{-2}\cdot\text{с}^{-1},$$

где Q — тепловая мощность, ГВт; R — эффек-

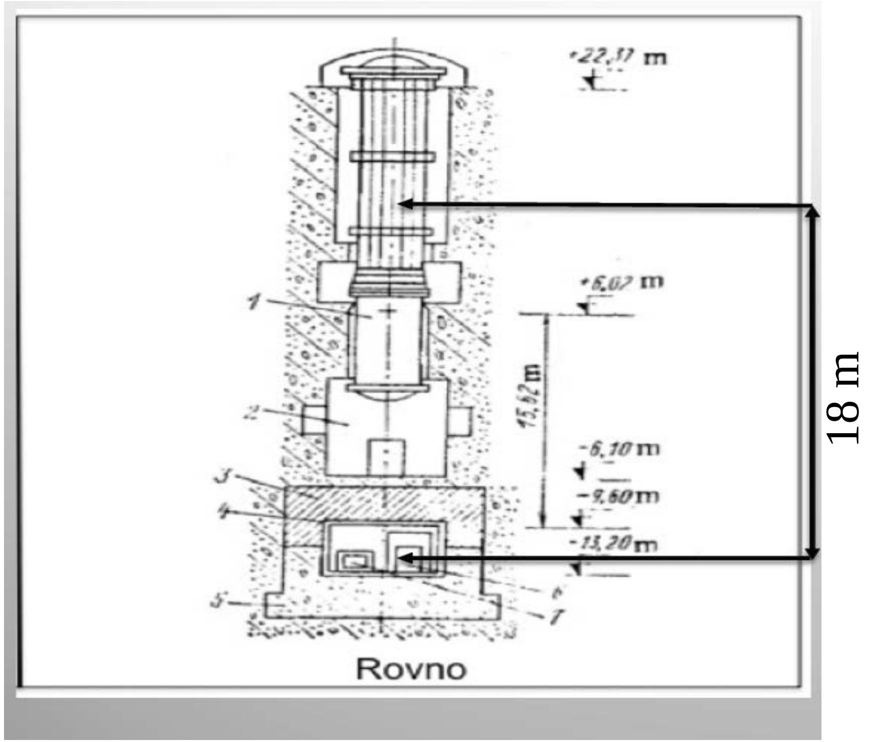
Rovno

WWER440

18 meters from the core

The detector: 500 liters of LS (Gd loaded)

First results: 1984!

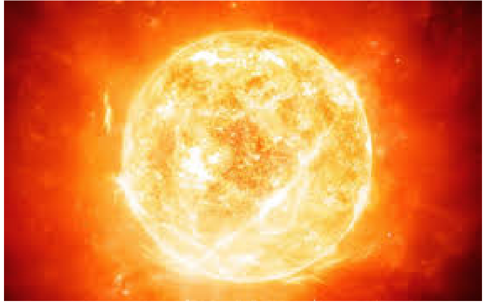


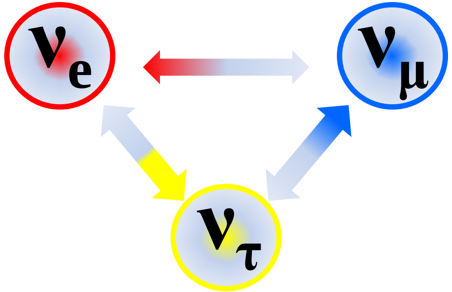
Solar neutrino problem, neutrino oscillations

Since the late 1960s, neutrinos have been detected from the Sun, where they are produced in huge quantities in thermonuclear reactions.

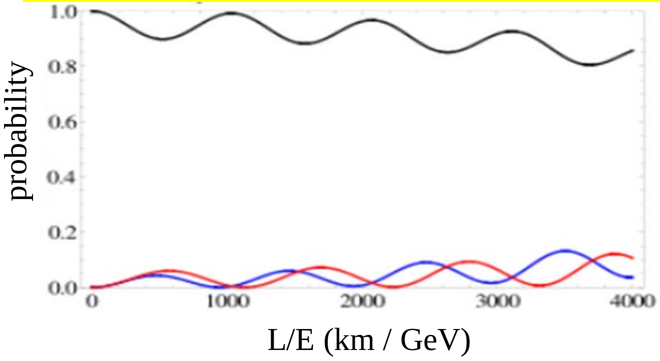
The number of registered neutrinos turned out to be 2-3 times less than expected from the model of the Sun and our knowledge of thermonuclear reactions.

One possible explanation for the neutrino deficit is neutrino oscillations: each neutrino is a superposition of mass states, so the probability of observing a particular type of neutrino, such as an electron neutrino, depends on the distance from the neutrino source.





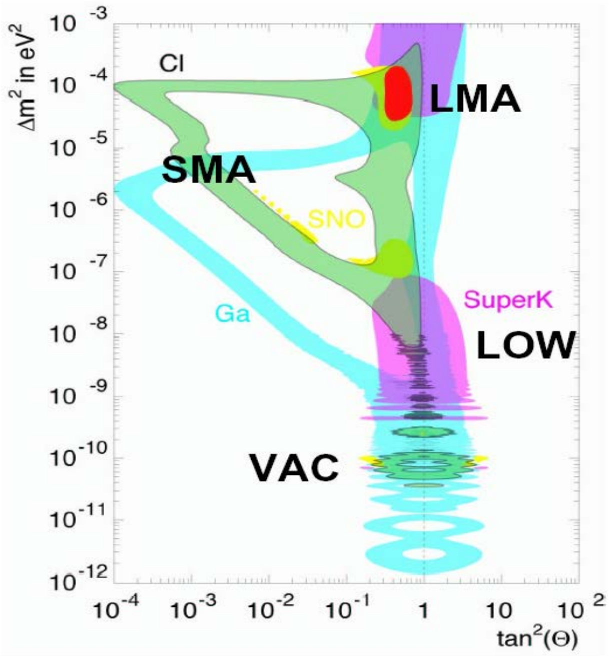
$$P_{\nu_e\to\nu_e} = 1 - \sin^2 2\theta \cdot \sin^2\left(1.27\,\Delta m^2_{12}\frac{L}{E_\nu}\right)$$

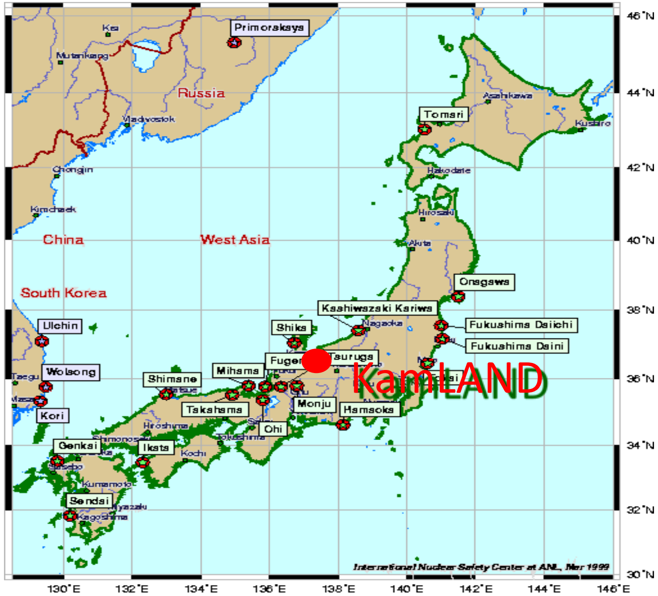


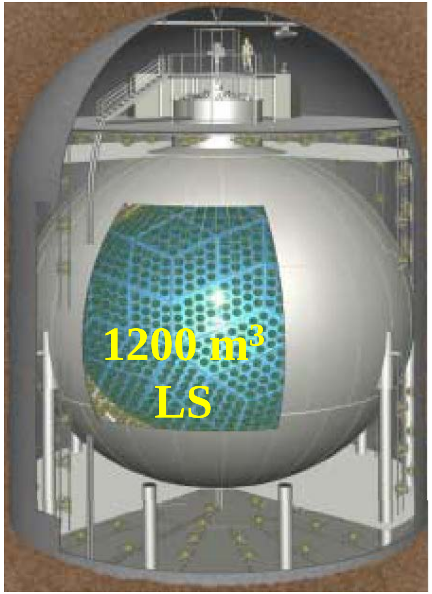
Solar neutrino problem, neutrino oscillations

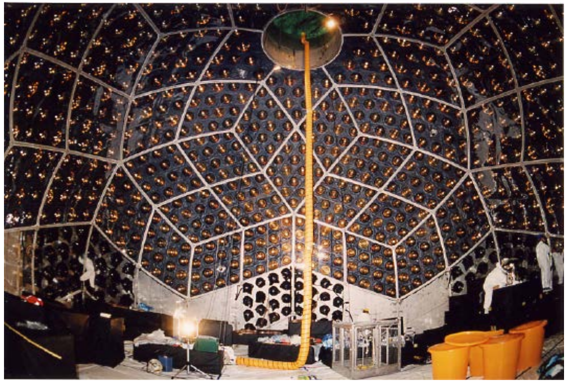
By 2000, a considerable amount of conflicting data from different solar neutrino experiments had accumulated.

The problem was solved using reactor neutrinos in the KamLAND experiment (Japan).

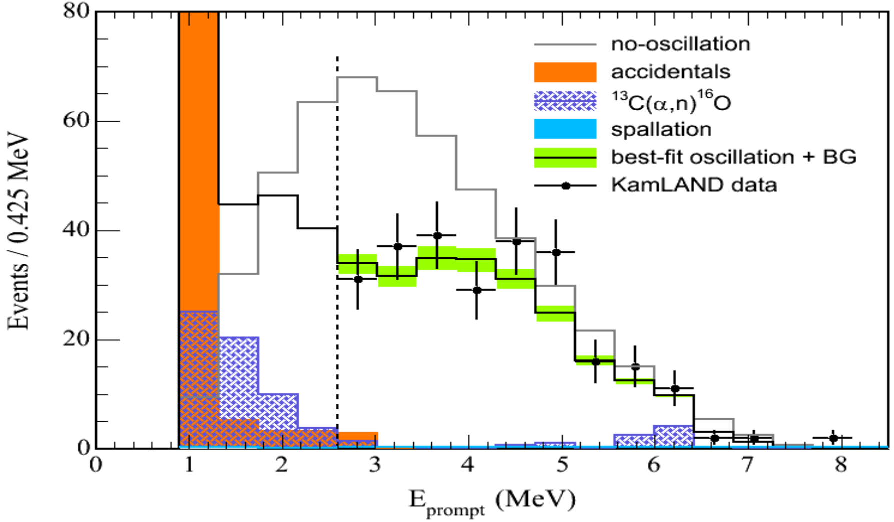


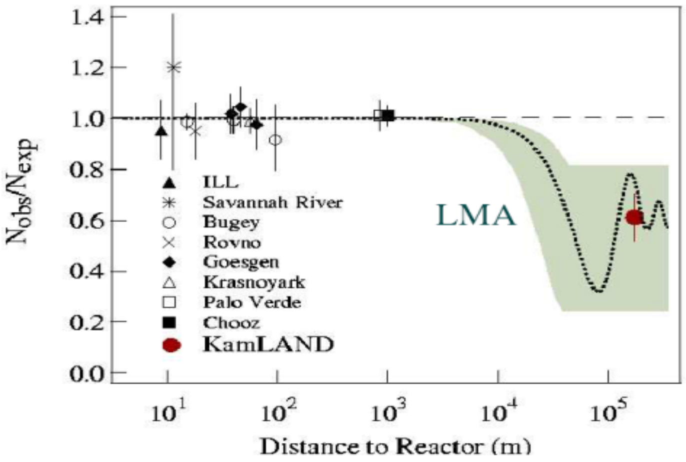


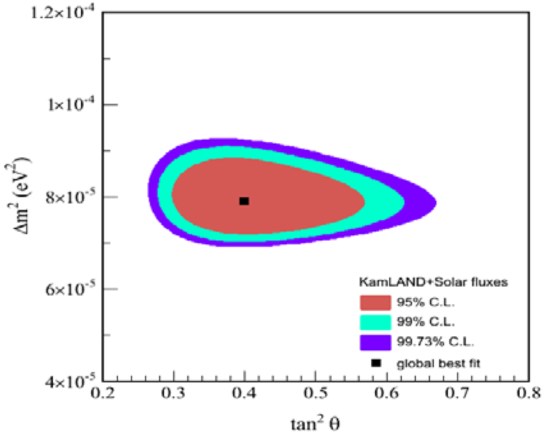


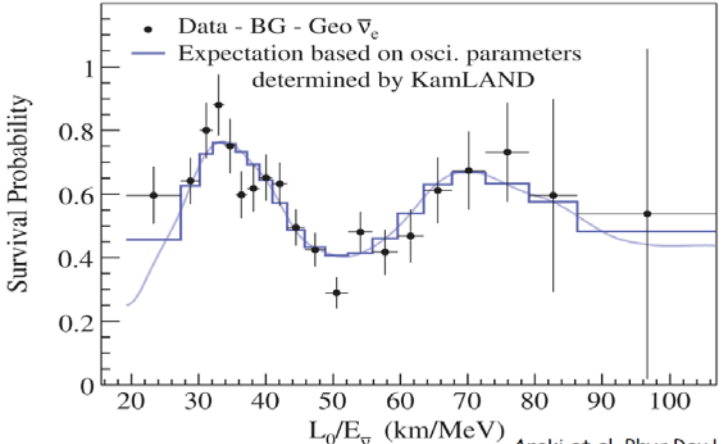


KamLAND







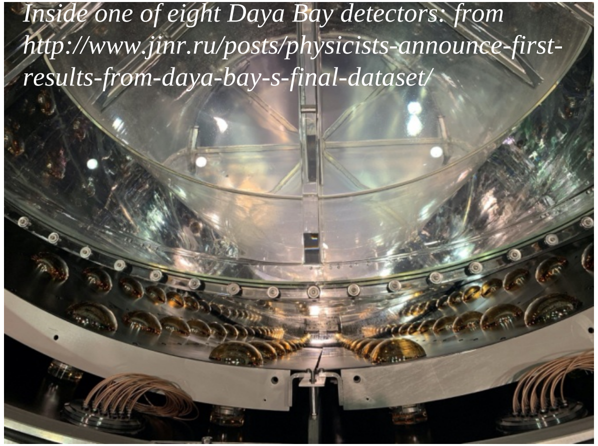


Araki et al. Phys.Rev.Lett.**100**,221803

After KamLAND

Why all mixing angles are large, except θ_{13} ?

The question was answered in reactor neutrino experiments in 2012 Daya Bay, Reno, Double CHOOZ



Inside one of eight Daya Bay detectors: from http://www.jinr.ru/posts/physicists-announce-first-results-from-daya-bay-s-final-dataset/

https://pdg.lbl.gov/2023/

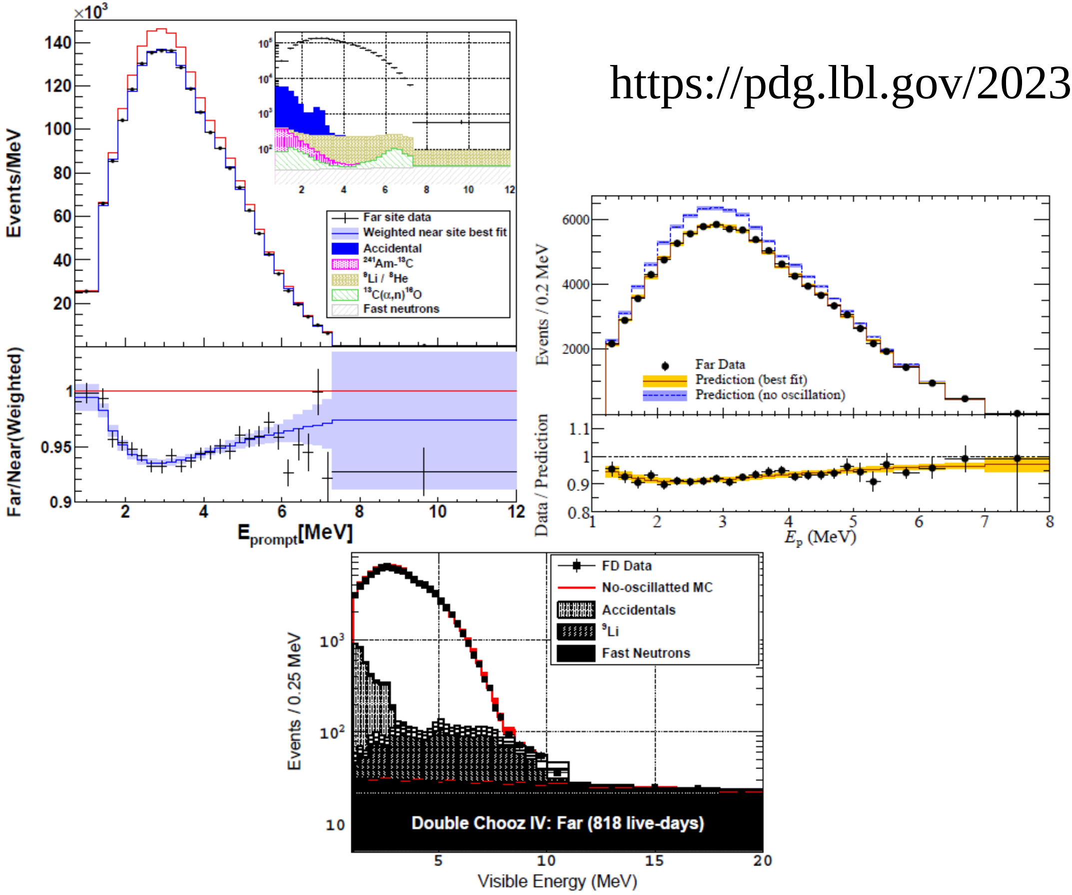


Figure 14.8: Energy spectra for prompt events at the far detectors for Daya Bay [141], RENO [142], and Double Chooz [143].

In all 3 θ_{13} experiments, as well as in the NEOS experiment, an excess of neutrino events over the expected energy spectrum has been observed around 5 MeV.

A search for sterile neutrinos at a nuclear reactor was first proposed by L. Mikaelyan and V. Sinev, Yad. Fiz. 62, 2177 (1999), Phys. At. Nucl. 62, 2008 (1999).

New sterile neutrino(s)?

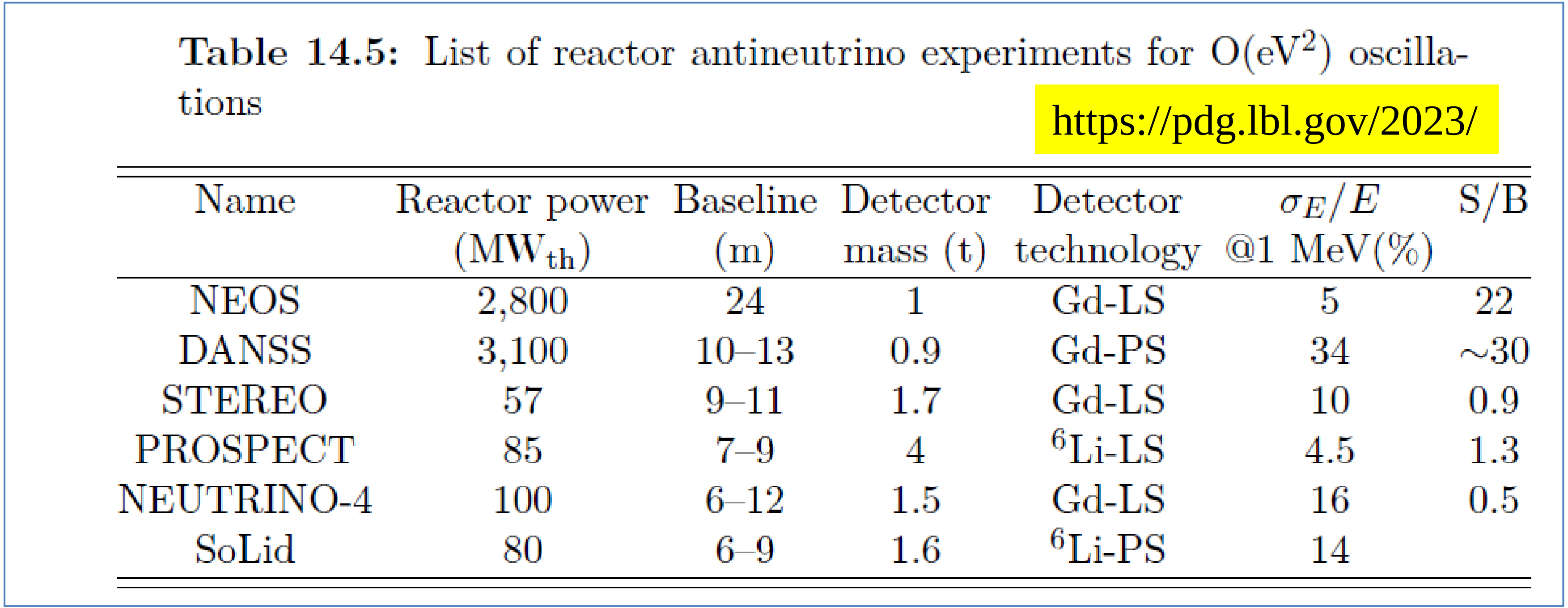


Table 14.5: List of reactor antineutrino experiments for O(eV^2) oscillations

https://pdg.lbl.gov/2023/

Name	Reactor power (MW$_{\text{th}}$)	Baseline (m)	Detector mass (t)	Detector technology	σ_E/E @1 MeV(%)	S/B
NEOS	2,800	24	1	Gd-LS	5	22
DANSS	3,100	10–13	0.9	Gd-PS	34	~30
STEREO	57	9–11	1.7	Gd-LS	10	0.9
PROSPECT	85	7–9	4	^{6}Li-LS	4.5	1.3
NEUTRINO-4	100	6–12	1.5	Gd-LS	16	0.5
SoLid	80	6–9	1.6	^{6}Li-PS	14	

Our days reactor neutrino projects in Russia

Kalinin NPP:
GEMMA (finished)
DANSS, DANSS-2: *next talk*
νGeN: *next talk*,
RED-100 (finished?),
iDREAM

SM-3 reactor (Dimitrovgrad, Russia): Neutrino-4

Novovoronezh NPP:
place for a possible future neutrino project
(excellent background conditions)

What next?

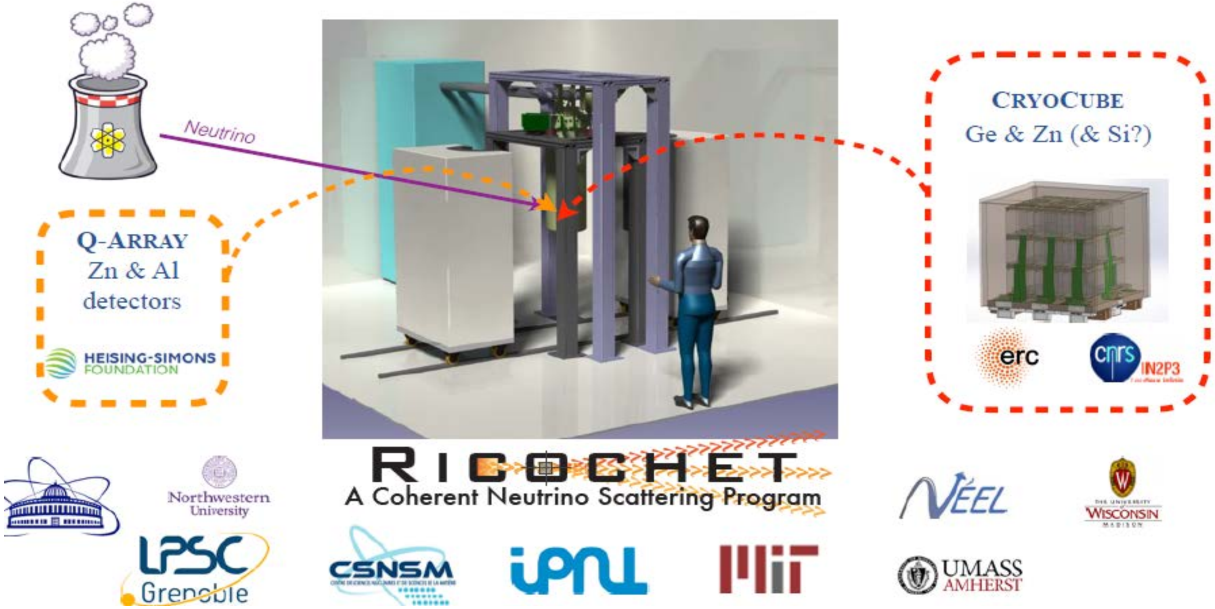
- Mass scale
- Sterile neutrino(s) (Neutrino-4, DANSS-2, etc)
- Mass ordering (JUNO)
- Neutrino-antineutrino difference (JUNO)
- Electromagnetic properties (νGeN, etc)

New physics?

The influence of New Physics is expected to produce spectral distortions in the energy region of recoil nuclei induced by coherent neutrino scattering (CEνNS) below 100 eV.

RICOCHET experiment: New physics with precision measurements of CEvNS at reactors.

RICOCHET aims at building the ultra low-energy **CEνNS neutrino observatory** dedicated to physics beyond the Standard Model



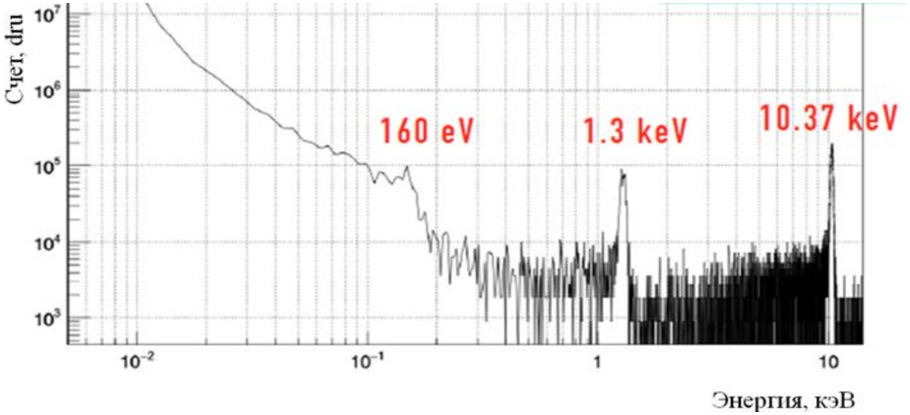
50 eV energy threshold with a 10^3 background rejection down to the threshold

The CRYOCUBE: a compact tabletop size setup

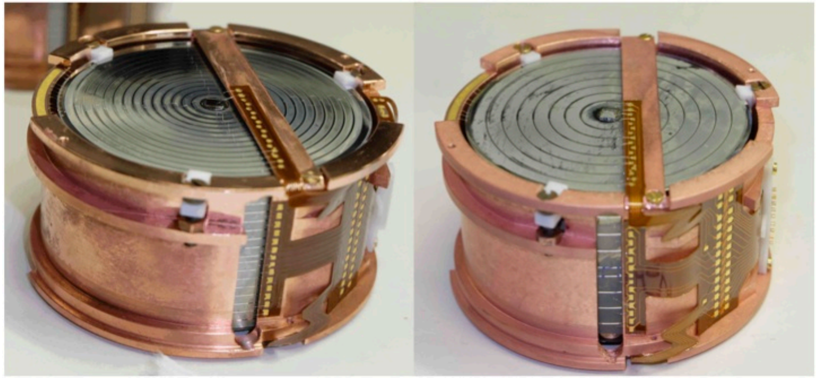
27 x 33 g detectors
8 x 8 x 8 cm^3
radio-pure infrared-tight copper box

The first key feature of the RICOCHET program, compared to other planned or ongoing CEνNS projects, is to aim for a kg-scale experiment with significant background rejection down to the O(10) eV energy threshold.

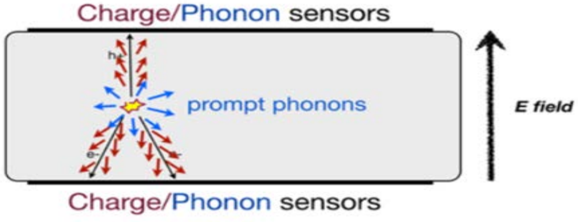
Detector-bolometers developed by Dark Matter search experiment EDELWEISS-LT



An unprecedented **charge resolution of 0.53 electron-hole pairs** (RMS) has been achieved using the Neganov-Trofimov-Luke internal amplification.

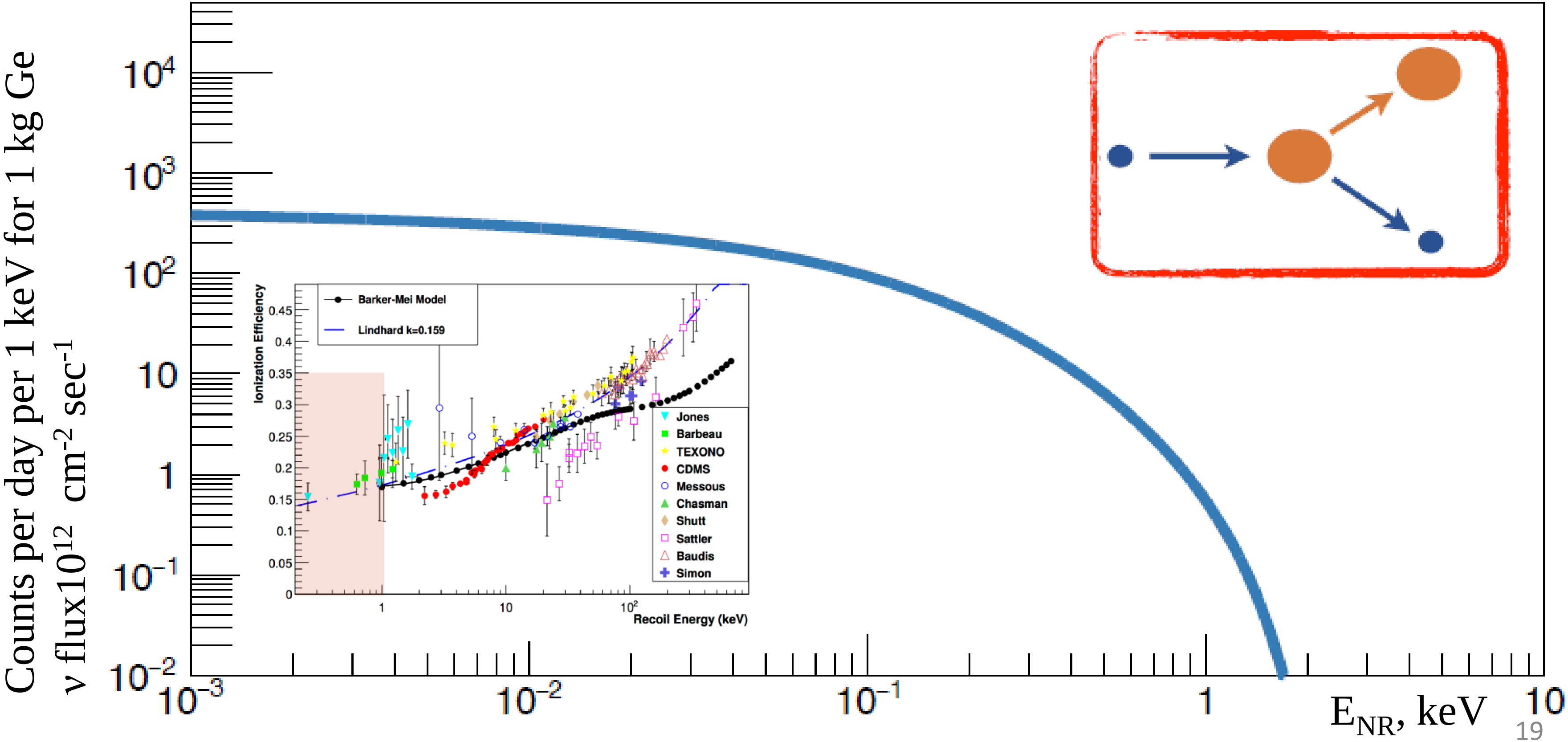


$$E_t = E_r + \frac{1}{3\,eV} E_Q \Delta V$$



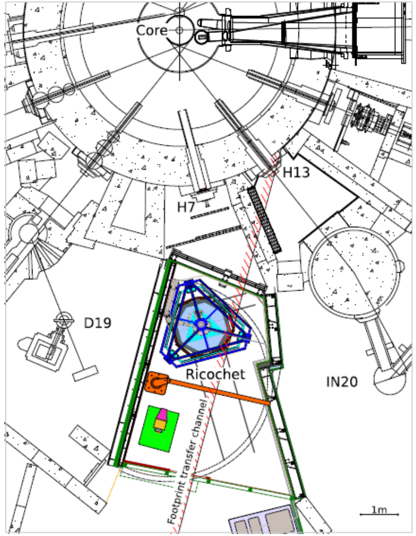
Coherent elastic neutrino-nucleus scattering (CEνNS)

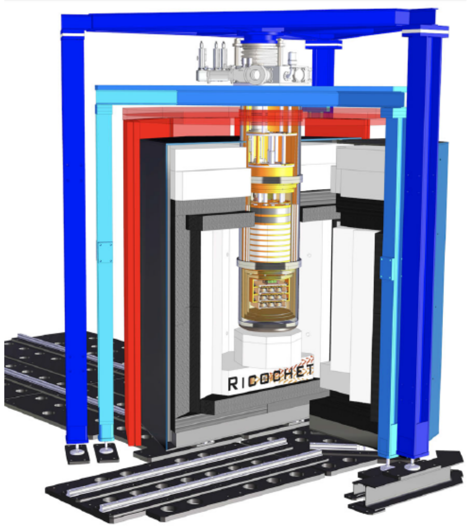
The use of bolometers makes it possible to measure the energy of the nucleus directly (heat signal), in contrast to semiconductor detectors that measure ionization.
This it the way to the precision measurements.

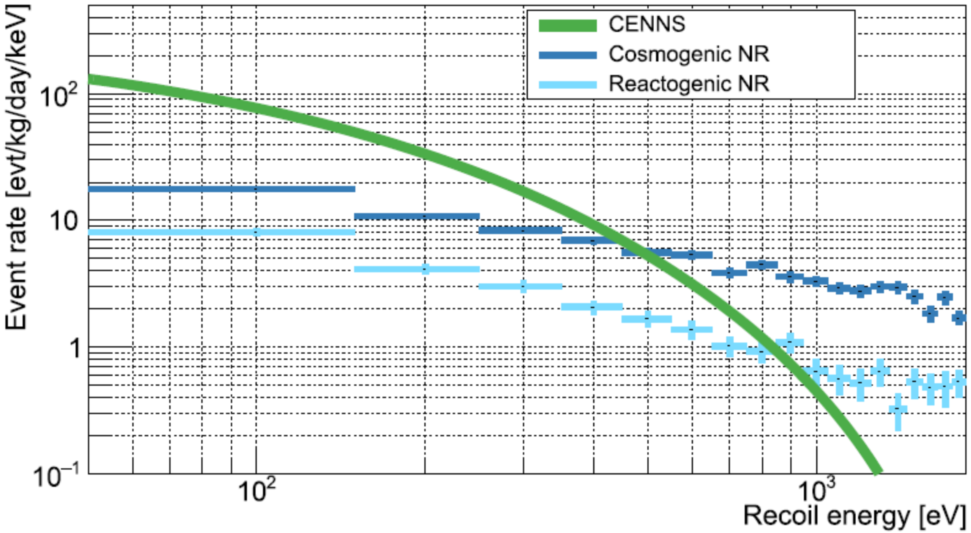


J. Billard et al., JCAP 11 (2018) 016

The experiment will deploy a kg-scale low-energy-threshold detector array combining Ge and Zn target crystals 8.8 m away from the 58MW research nuclear reactor core of the ILL







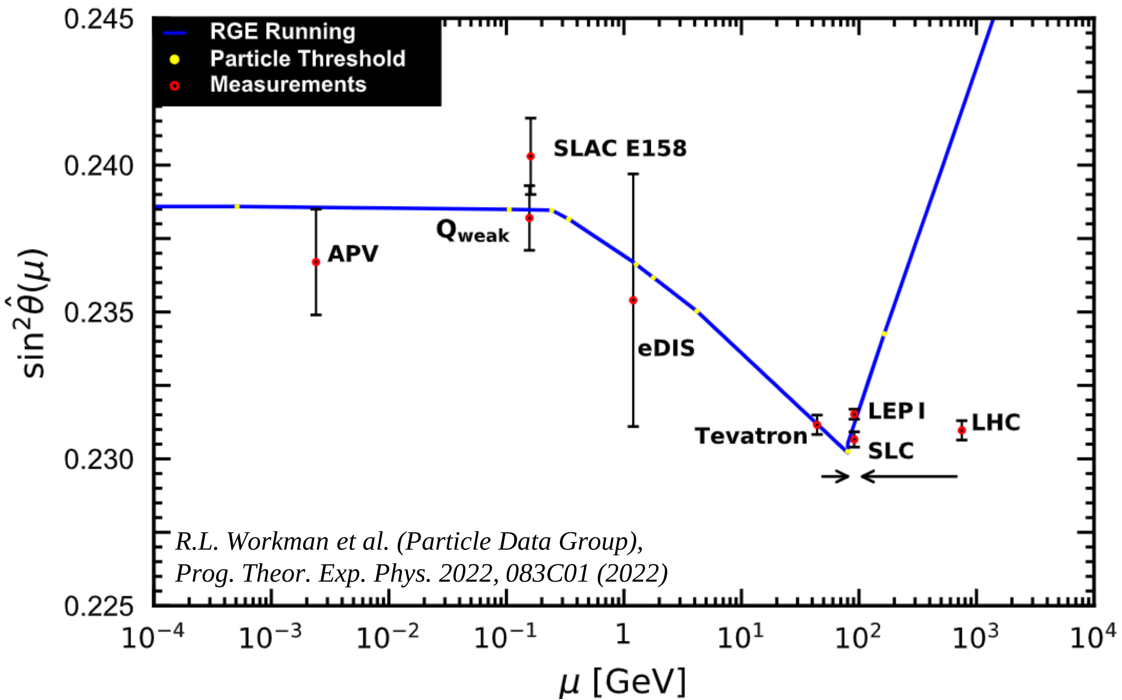
	Cosmogenic	Reactogenic	Total (MC)	CENNS (Ge/Zn)
Nuclear recoils [50 eV, 1 keV] (evts/day/kg)				
No shielding (I)	1554 ± 12	53853 ± 544	55407 ± 545	–
Passive shielding (II)	42 ± 3	2.4 ± 0.3	44 ± 3	–
Passive + μ-veto (III)	7 ± 2		9 ± 2	12.8 / 11.2

The Ricochet experiment should reach a statistical significance of 4.6 to 13.6 σ for the detection of CENNS after one reactor cycle. The start of the data taking in the experiment is planned for 2024.

Why we want precision measurements?

$$\frac{d\sigma(E_\nu, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_w^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F^2(E_r)$$

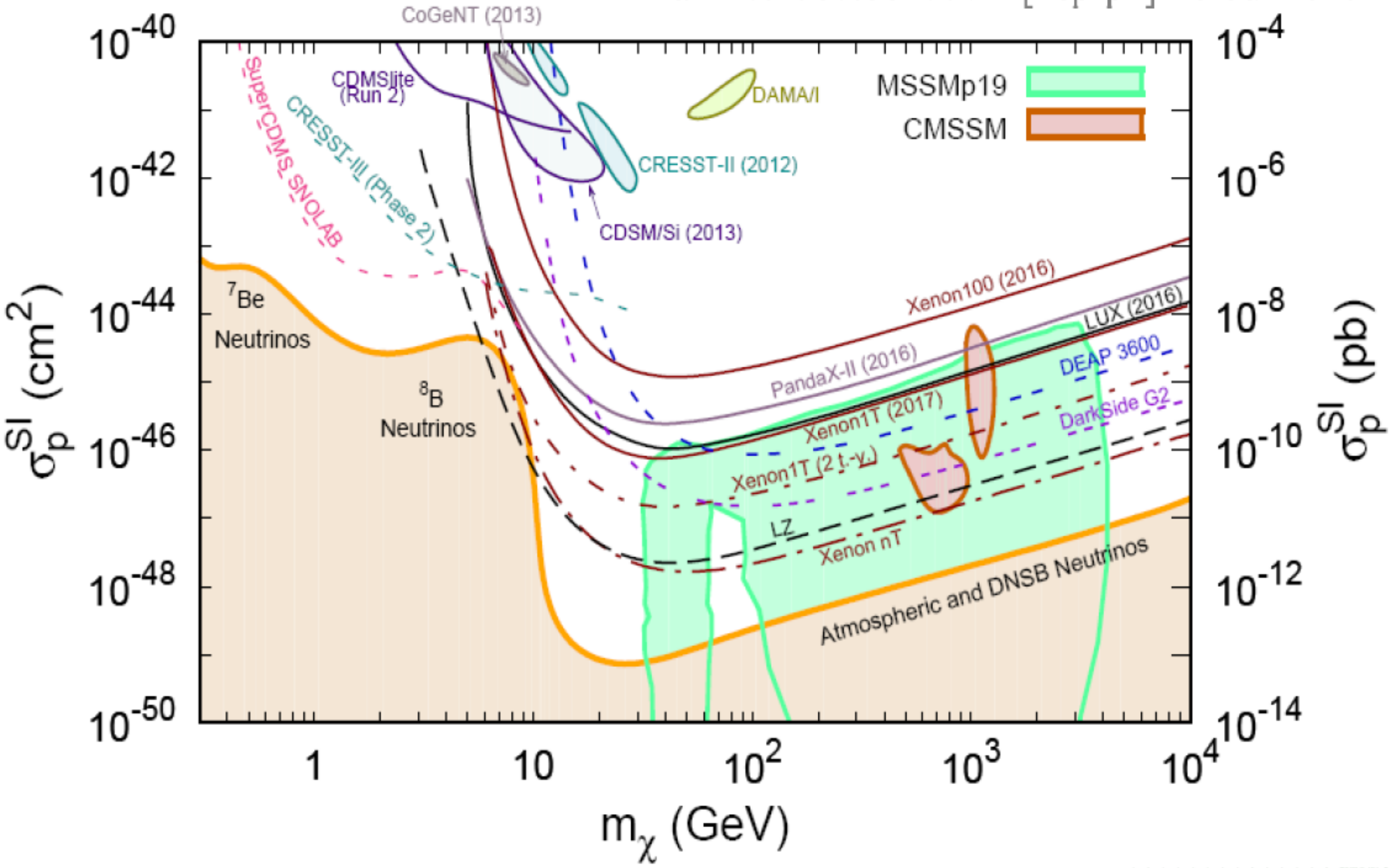
$$Q_w = N - Z(1 - 4\sin^2\theta_w)$$



R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

Why we want precision measurements?

arXiv:1707.06277v1 [hep-ph] 19 Jul 2017



- Neutrino magnetic moment;

- Searching for new massive mediators

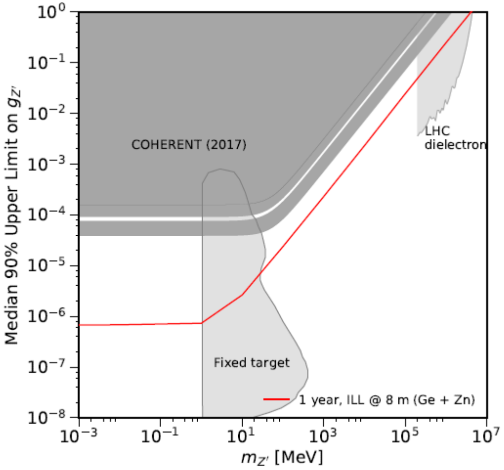
  Some extensions of the SM suggest the presence of an additional vector mediator boson [E. Bertuzzo et al., JHEP 1704, 073 (2017)], that couples both to the neutrinos and the quarks, called Z'.

- Non-Standard Interactions

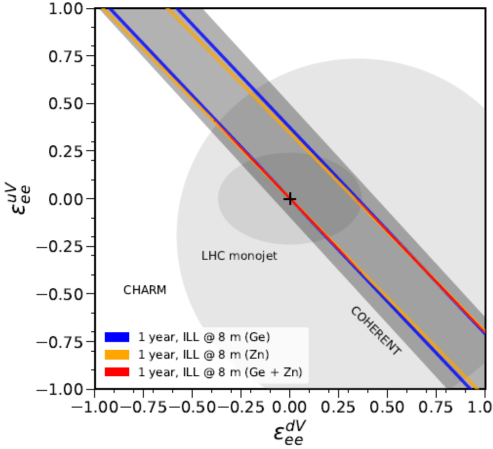
  *New physics that is specific to neutrino-nucleon interaction is currently quite poorly constrained, and is motivated in some beyond-SM scenarios [J. Barranco, O. G. Miranda, and T. I. Rashba, Phys. Rev. D **76**, 073008 (2007)]. In the context of a model-independent effective field theory, the Lagrangian describing the neutrino-nucleon interaction leads to NSI operators, which can either enhance or suppress the CEνNS event rate.*

- Sterile neutrino.

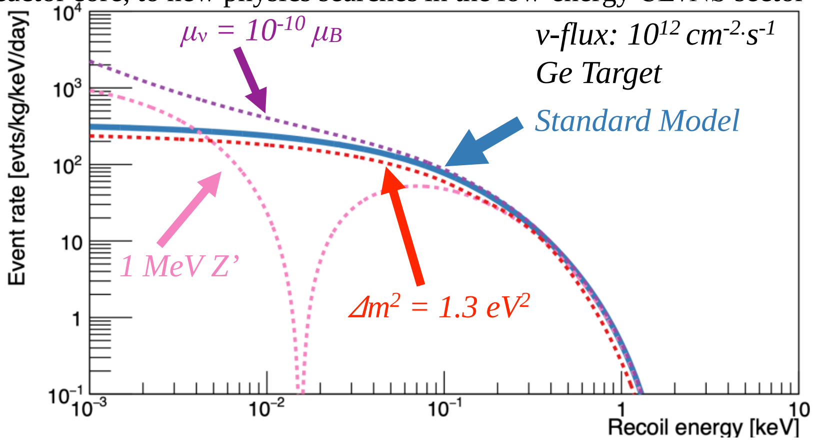
Constraints on Z' searches



Non-Standard neutrino-quark interactions in the neutrino-electron sector.



Projected sensitivities of the Ricochet experiment, located at 8 m from the ILL reactor core, to new physics searches in the low-energy CEνNS sector



New sites in Russia

ROSENERGOATOM
ROSATOM

NOVOVORONEZH NPP

VORONEZH
STATE
UNIVERSITY

JOINT INSTITUTE
FOR NUCLEAR RESEARCH

Motivation / aims:

1) Higher neutrino flux for possible further phases of the RICOCHET or related projects (depends on ILL results);

2) Other neutrino projects.

Unit #6: new 3+ generation WWER-1200

Maximal thermal power is 3212 MW

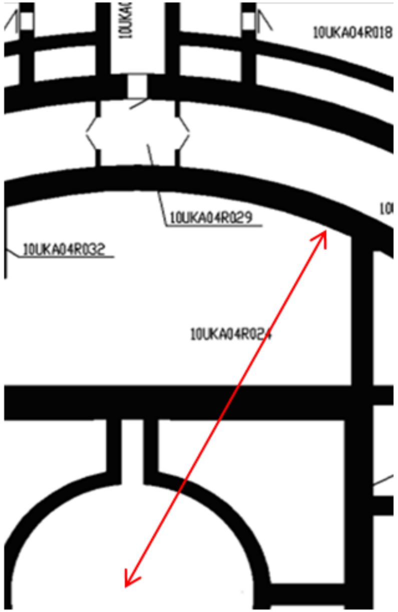
NVNPP has Rosatom international training center, thus access for foreign is possible (important for international collaborations).

Two places were proposed (2020) , both at -5.4 m (underground), strong basement, no noise or vibrations.

One place was checked in beginning of 2020:
- ~25 m from the core, inside of controlled access area;
- Maximal measured muon flux is **16.2 $\mu\ m^{-2}\ sr^{-1}\ sec^{-1}$**, about 7 times less with respect to the max of the sea level, this corresponds to **~50 mwe**, anisotropy (better shielding from the reactor) ;
- Neutrons (fast and thermals): **25-30 times** less with respect to the see level;
- Ionizing radiation is **ok**: at the level of the so-called “natural radiation background” , <20 $\mu Sv\ h^{-1}$.

Work was suspended due to the Covid-19 pandemic.

Estimated distance from the center of the reactor core is ~25 m



Conclusion / outlooks

- The properties of neutrinos are fundamental to particle physics, cosmology and astrophysics.

- A number of fundamental questions have been answered with reactor neutrinos, from the first experimental confirmation of the existence of neutrinos, to the precision measurement of the mixing matrix parameters of neutrino states.

- Advances in experimental techniques have and will continue to allow for new research at the leading edge of science.

- The solution of fundamental problems with neutrino detection leads to the possibility of application of the developed methods for remote control of reactor operation. (see for example talks about the DANSS detector)