NEUTRINO PHYSICS AT NUCLEAR REACTORS

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НАУКА
СБЛИЖАЕТ
НАРОДЫ

SCIENCE
BRINGING
NATIONS
TOGETHER

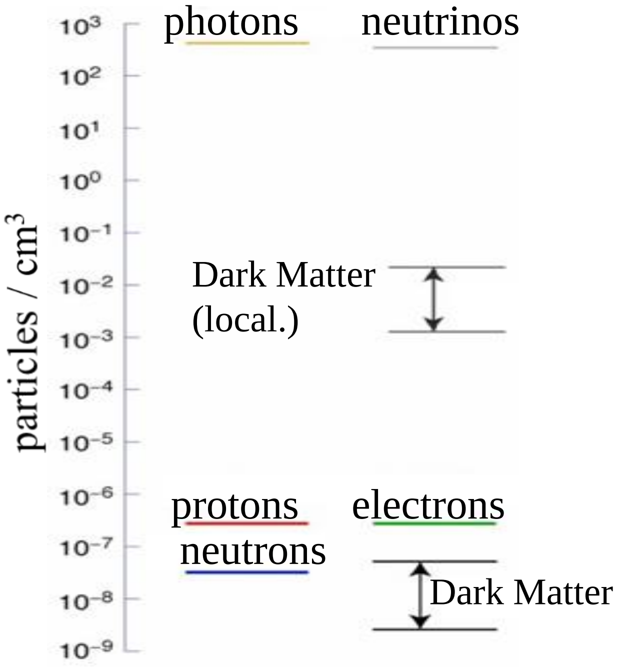
Why neutrinos

• 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

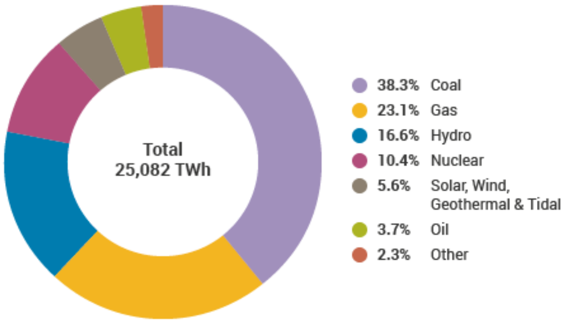
❖ On average, 200 MeV of energy is released per fission;

❖ On average, 6 $\bar{\nu}_e$ per fission (beta decay of fission products);

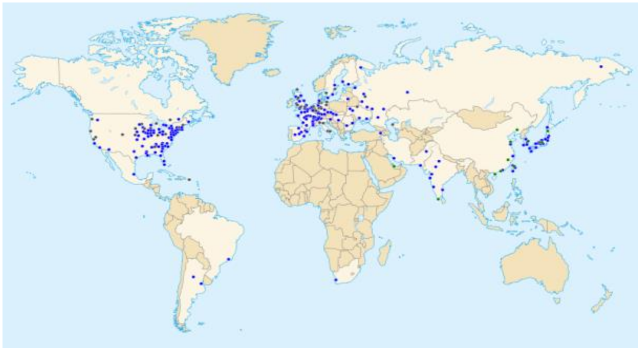
❖ Working WWER1000 emits 6×10^{20} $\bar{\nu}_e$ each seconds!
The most powerful artificial neutrino source on Earth!

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			

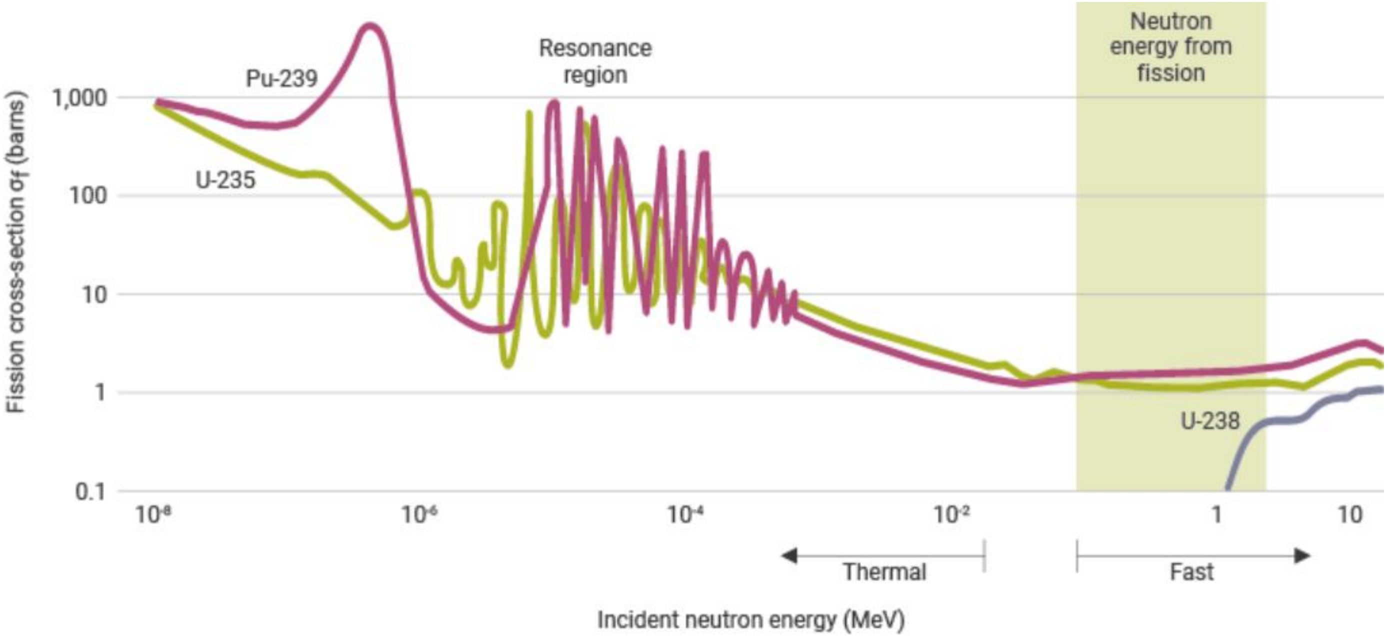
https://www.world-nuclear.org/

Nuclear fission

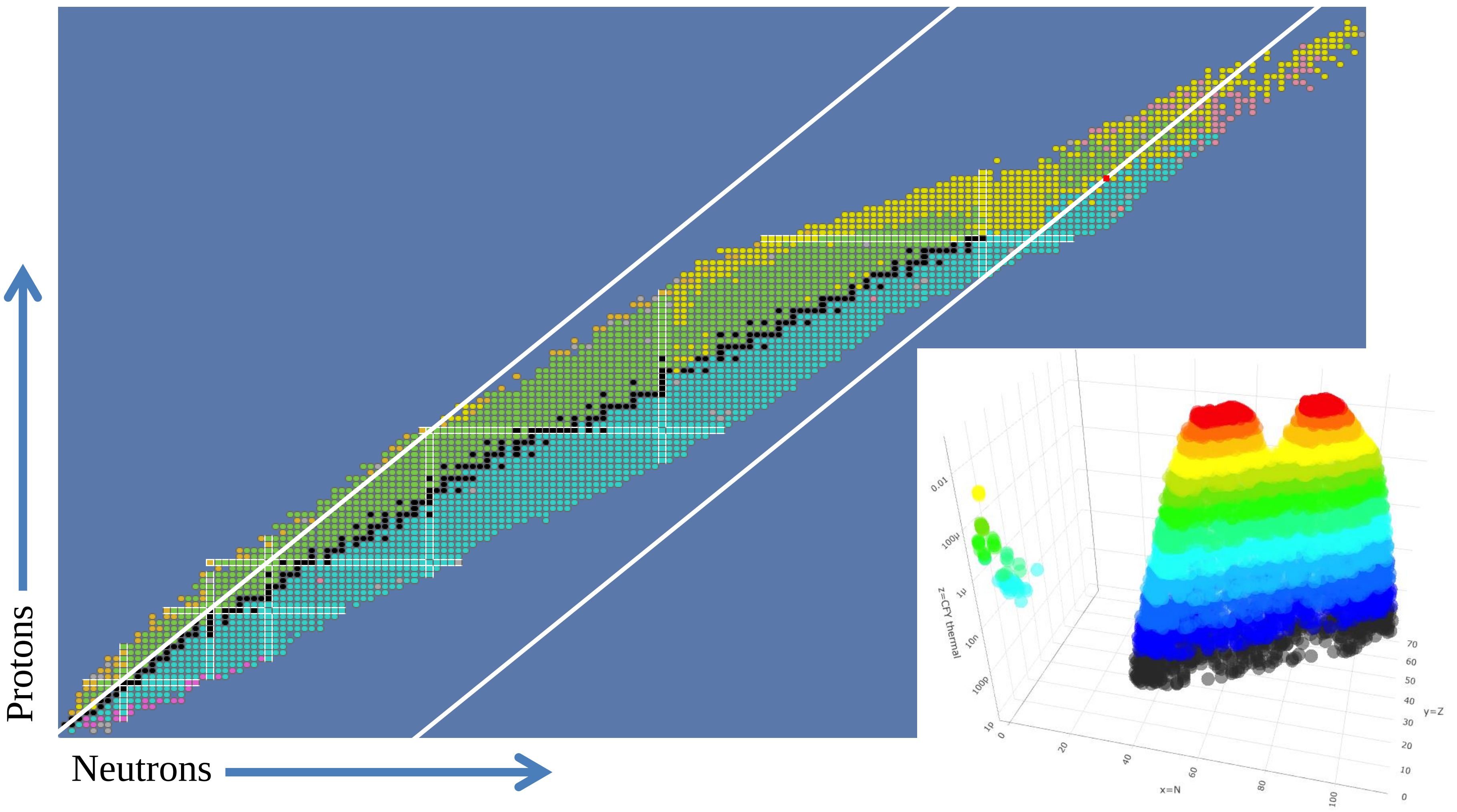
$^{235}U + n \rightarrow {}^{144}Ba + {}^{90}Kr + 2n +$ about 200 MeV

$^{235}U + n \rightarrow {}^{141}Ba + {}^{92}Kr + 3n + 170$ MeV

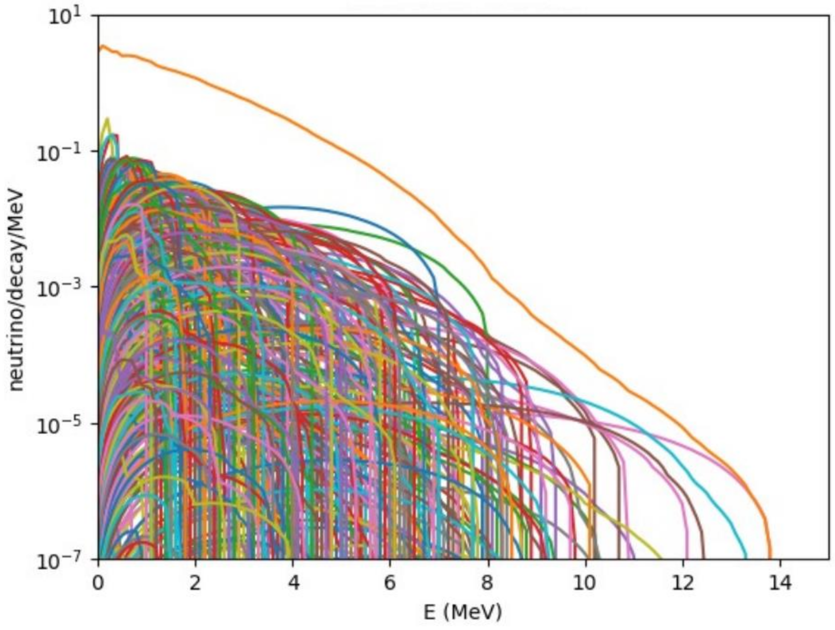
$^{235}U + n \rightarrow {}^{94}Zr + {}^{139}Te + 3n + 197$ MeV

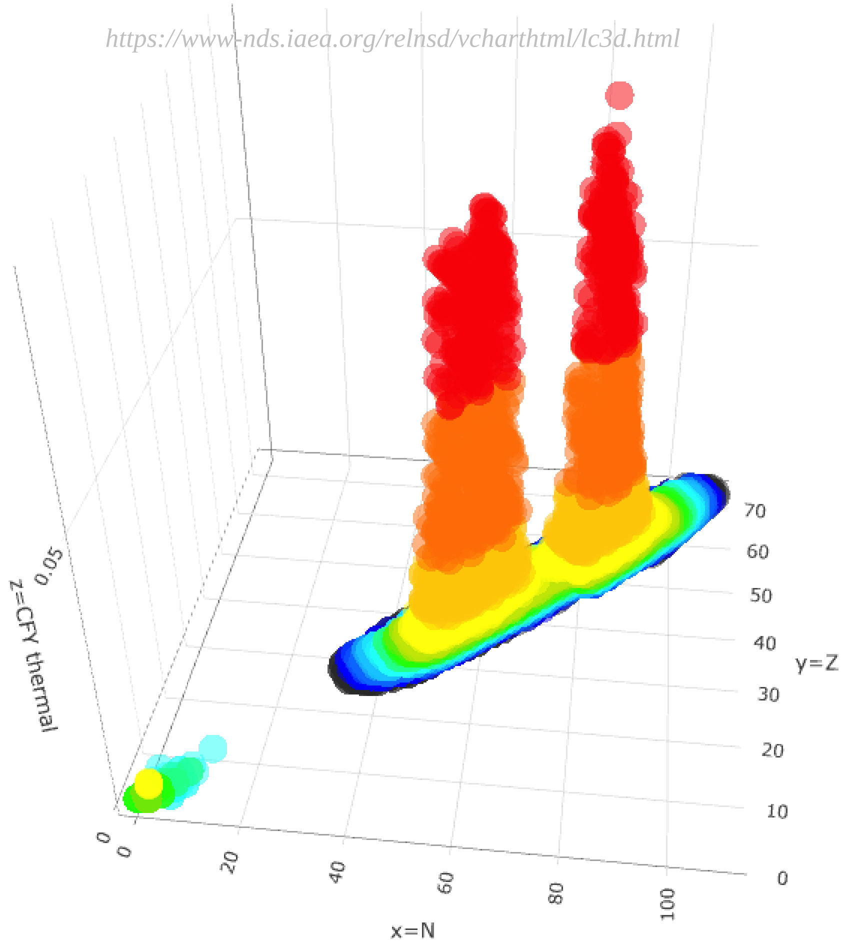


Note that both scales are logarithmic.
Source: NEA, Plutonium fuel – an assessment (1989); Taube, Plutonium – a general survey (1974)



Protons
Neutrons
0.01
100μ
1μ
10n
100p
1p
z=CFY thermal
x=N
y=Z

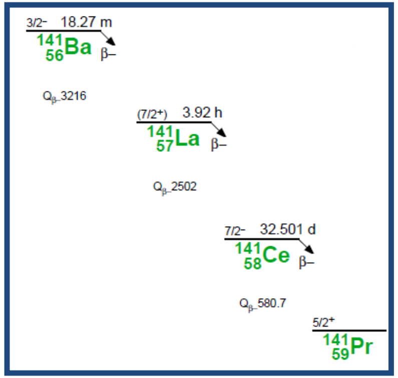


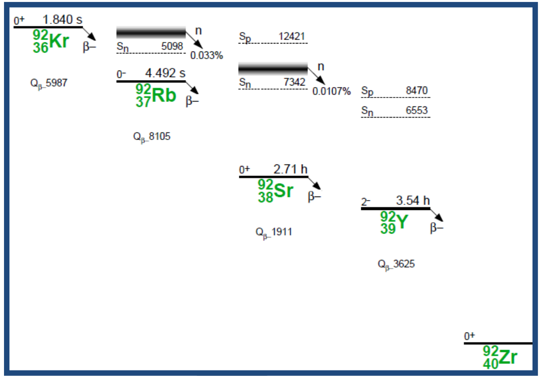


- Antineutrinos come from several thousands of beta decay branches

- Huge uncertainty in decay schemes, especially for high energy levels (short time living isotopes)

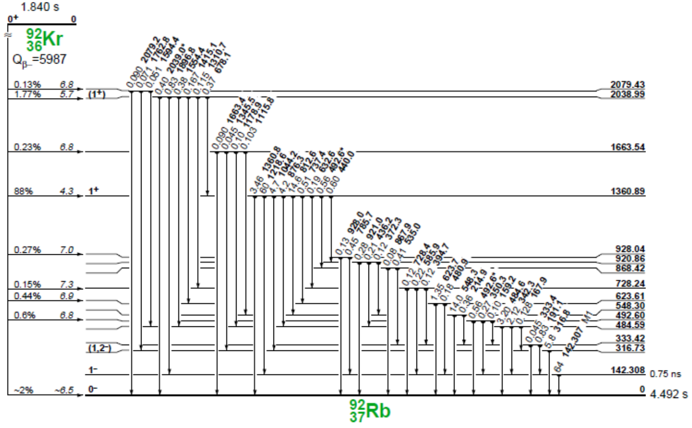
$^{235}U + n \rightarrow {}^{141}Ba + {}^{92}Kr + 3n + 170\ MeV$

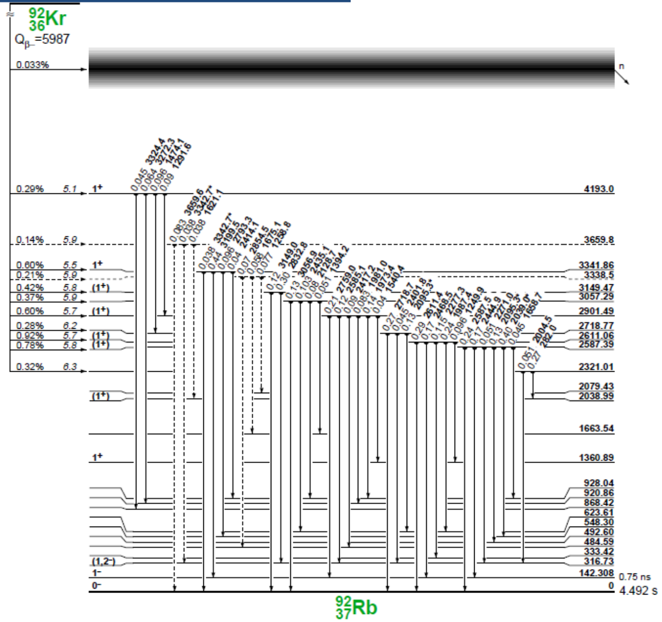


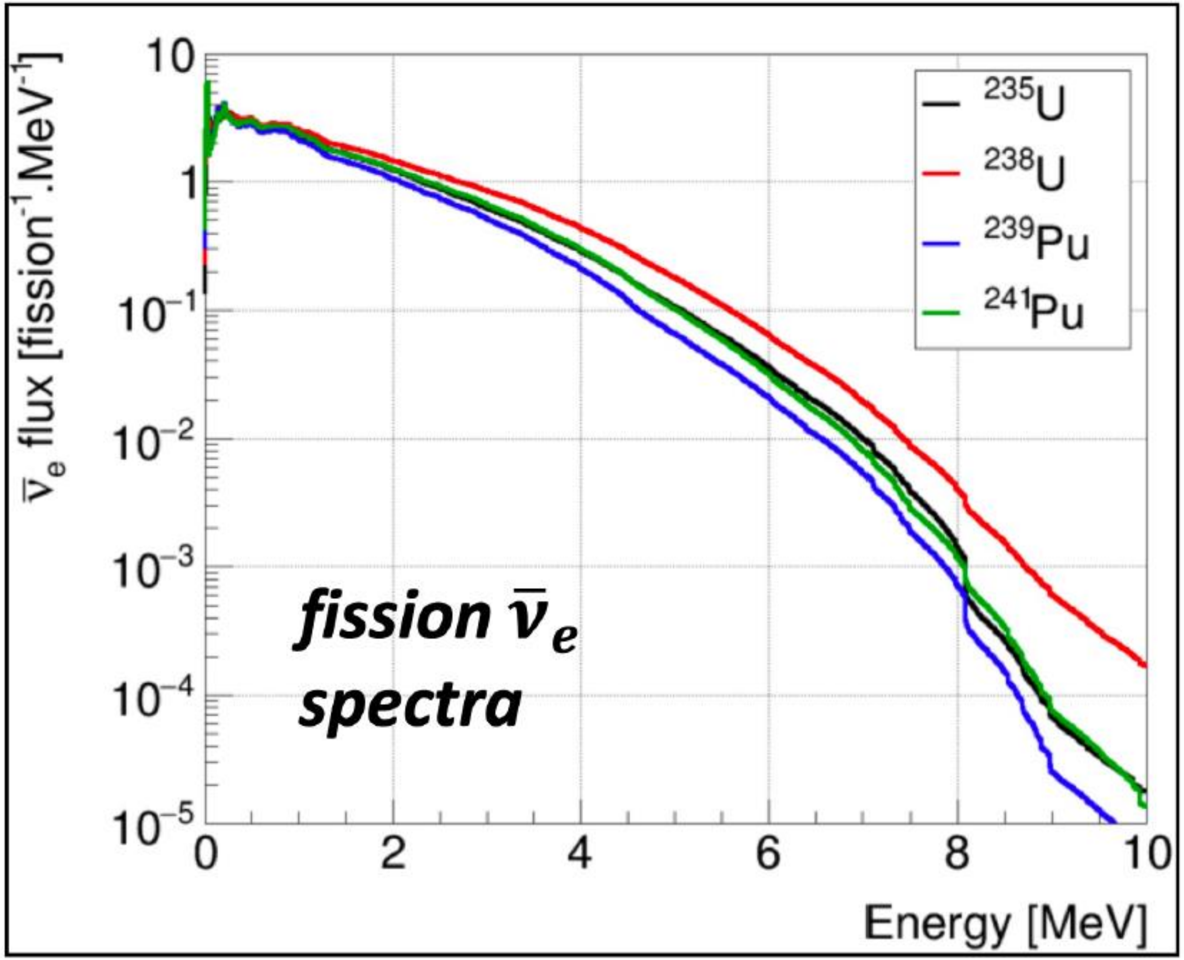


Part 2 of 2

Part 1 of 2







$\overline{\nu}_e$ flux [fission^{-1}.MeV^{-1}]
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
2
4
6
8
10
Energy [MeV]
^{235}U
^{238}U
^{239}Pu
^{241}Pu
fission $\overline{\nu}_e$ spectra

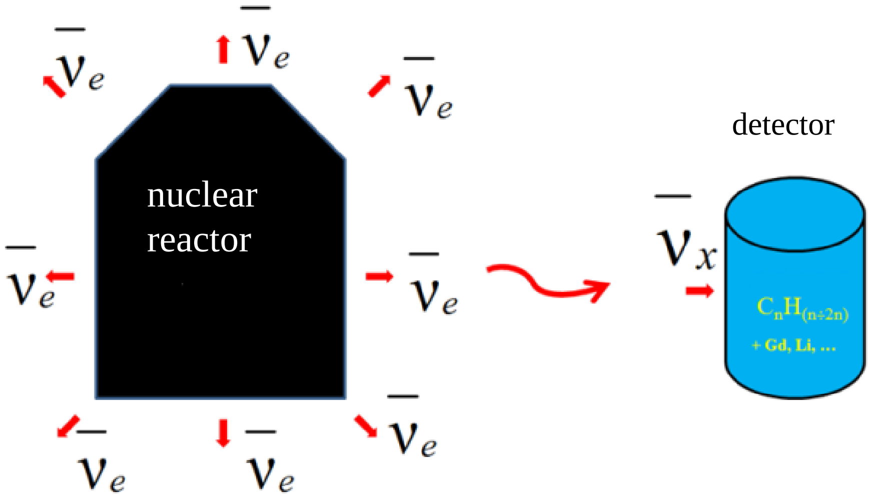
Methods for studying reactor neutrinos

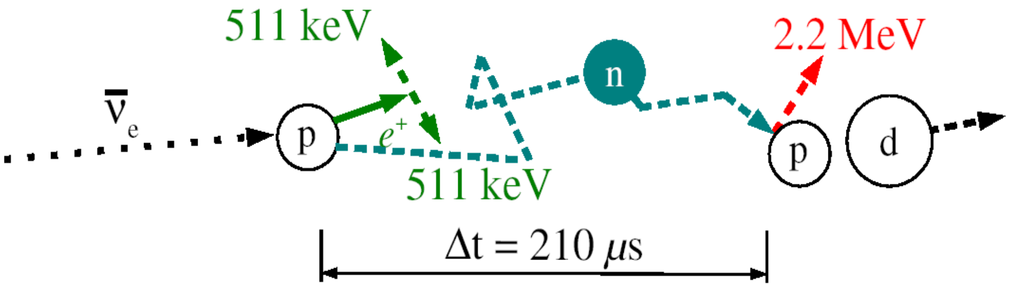
- inverse beta decay;
- electron scattering;
- nuclear scattering (coherent scattering).

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

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





Inverse beta processes

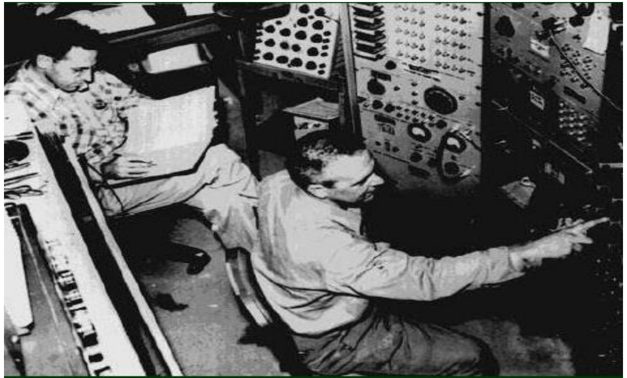
• Experimental discovery of neutrinos (1956);

• 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).



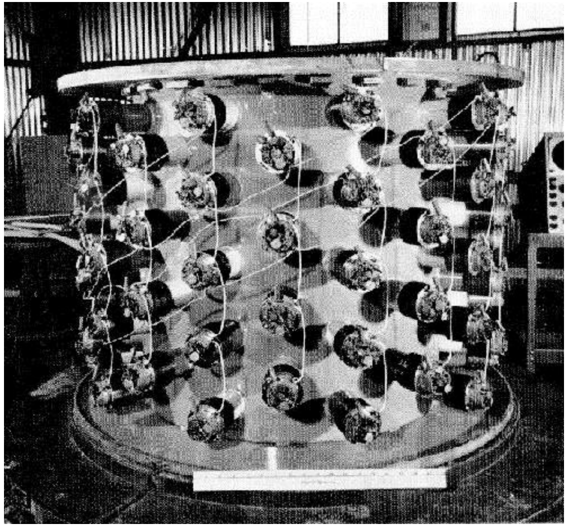
F. Reines and C. Cowan at the Control Center of the Hanford Experiment (1953)

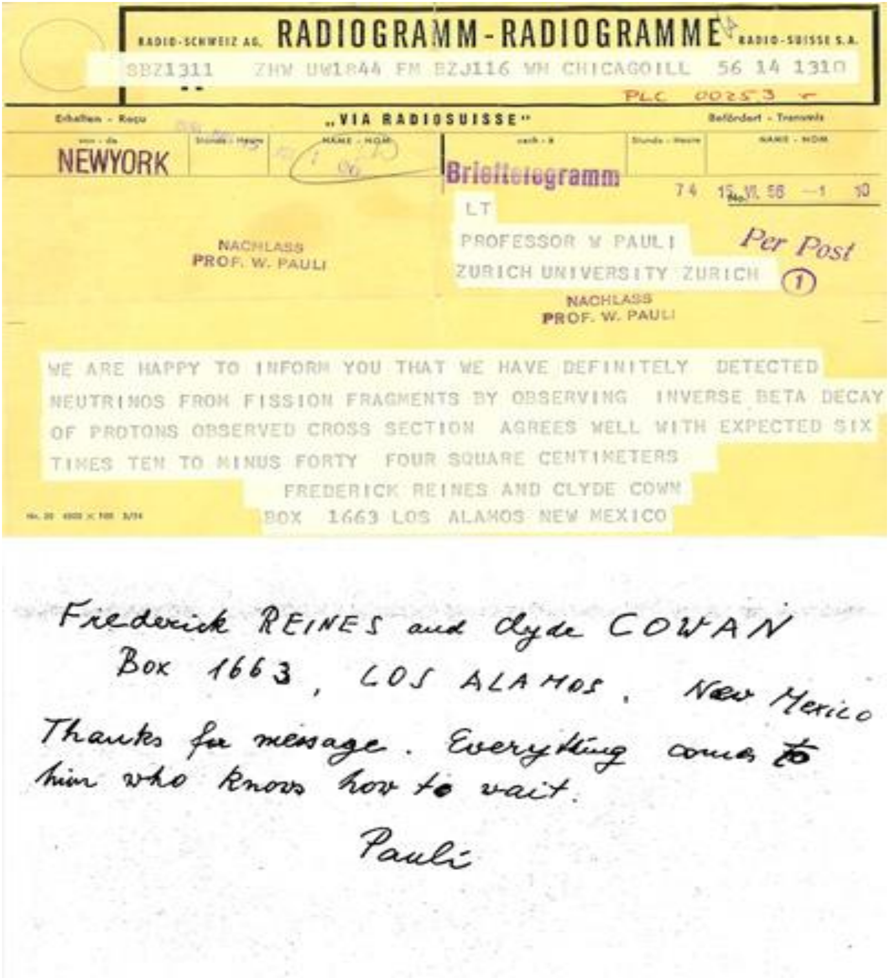
Experimental discovery of neutrinos (1956)

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

Reines and Cowan

400 liters of cadmium chloride solution in water.





RADIO-SCHWEIZ AG. RADIOGRAMM-RADIOGRAMME RADIO-SUISSE S.A.
SBZ1311 ZHW UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310
„VIA RADIOSUISSE"
NEWYORK
Brieftelegramm
LT
PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH
Per Post
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:

$$j = 1{,}6\cdot10^{15}\frac{Q}{R^2}, \text{ см}^{-2}\cdot\text{с}^{-1},$$

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

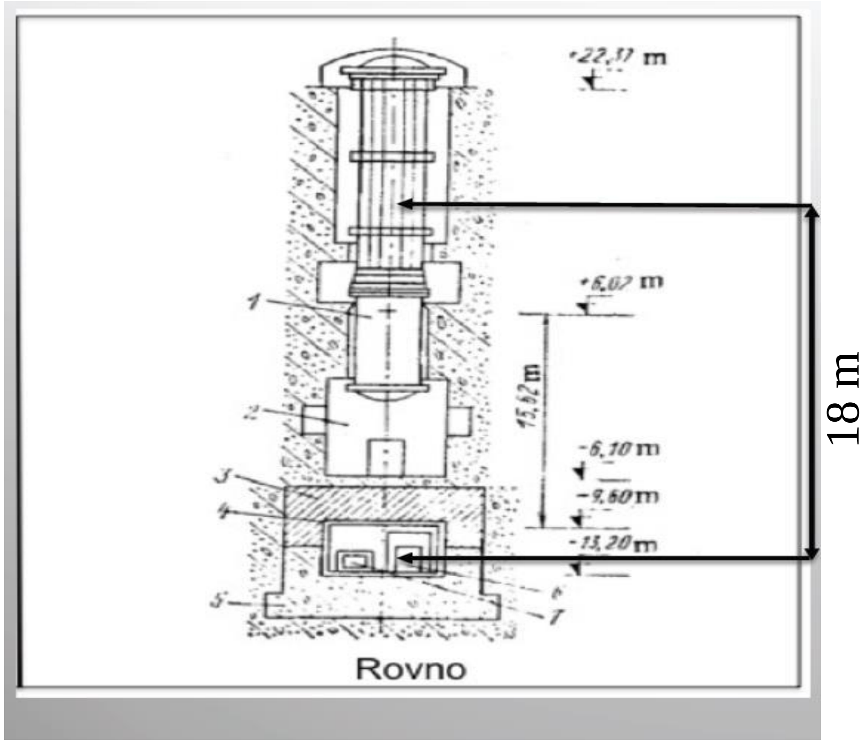
Rovno

WWER440

18 meters from the core

The detector: 500 liters of LS (Gd loaded)

First results: 1984!

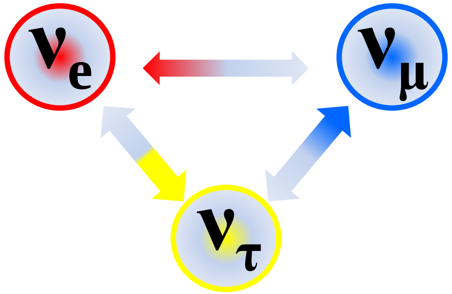


Solar neutrino problem, neutrino oscillations

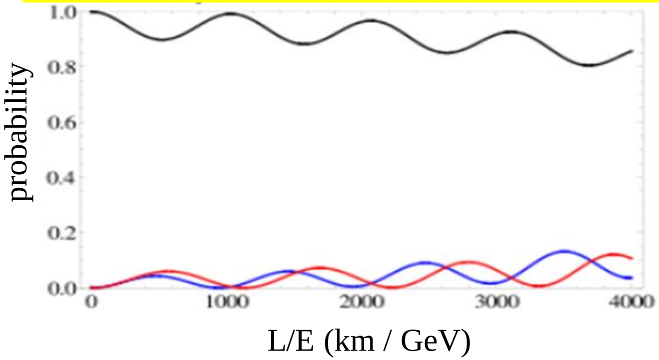
Since the late 1960s, neutrinos have been detected from the Sun, where they are produced in huge quantities in thermonuclear reactions.

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.



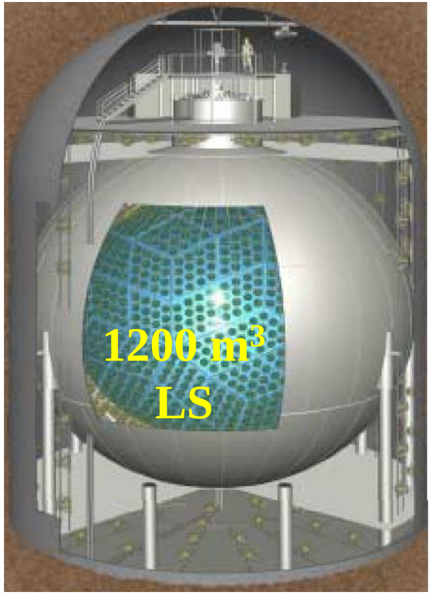
$$P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta \cdot \sin^2\left(1.27\,\Delta m^2_{12} \frac{L}{E_\nu}\right)$$

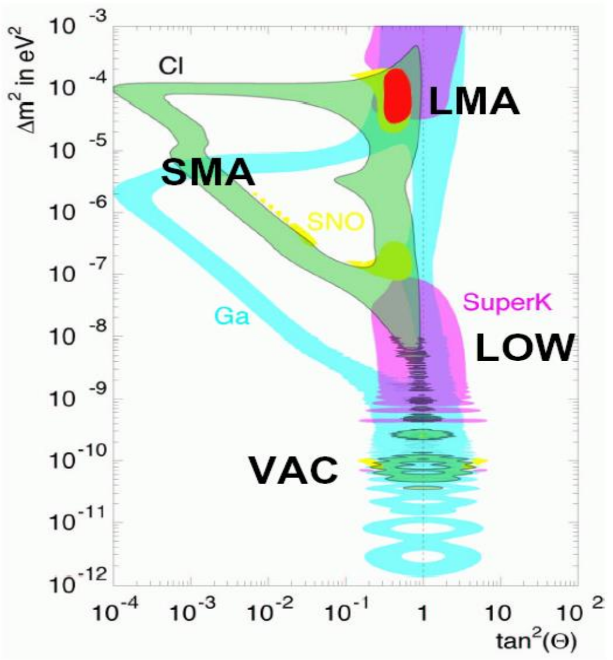


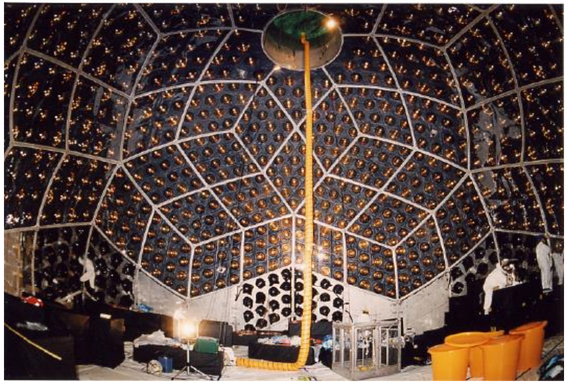
Solar neutrino problem,
neutrino oscillations

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

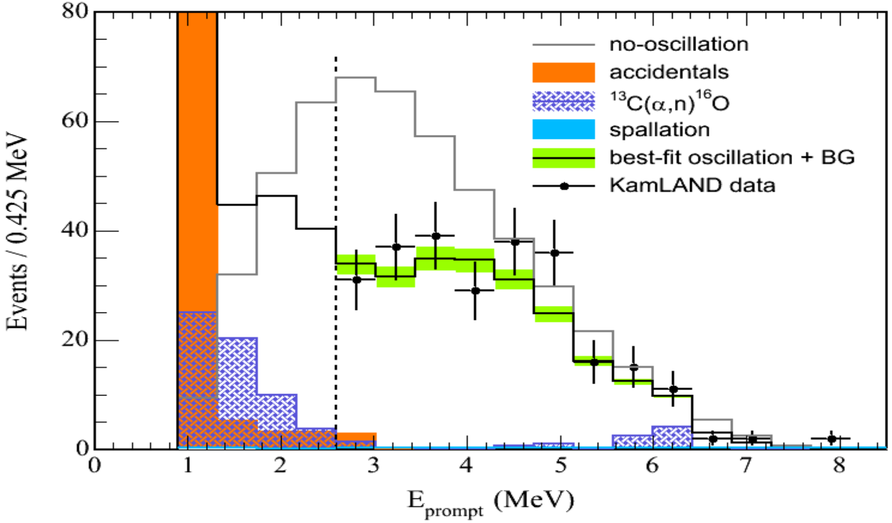
The problem was solved using reactor neutrinos in the KamLAND experiment (Japan).

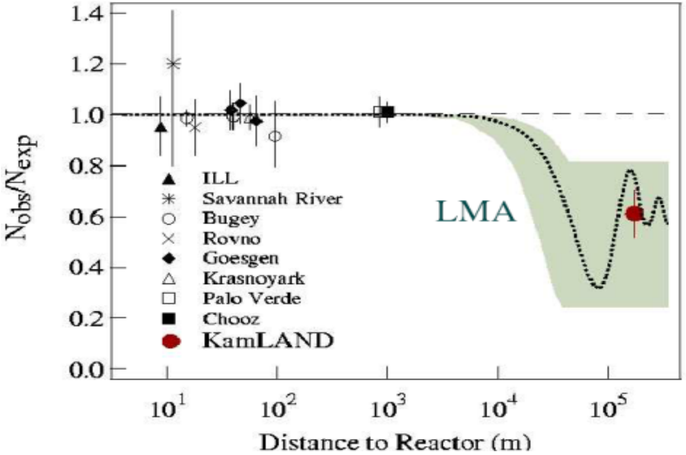


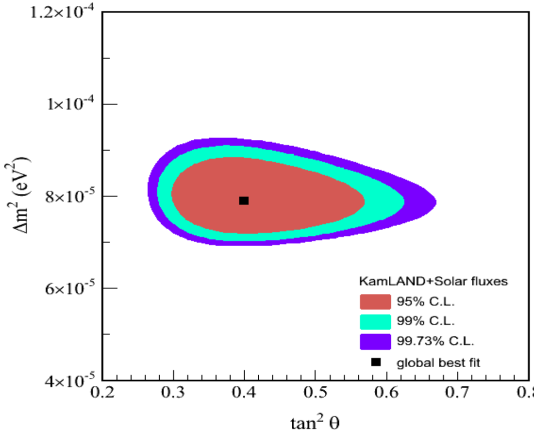


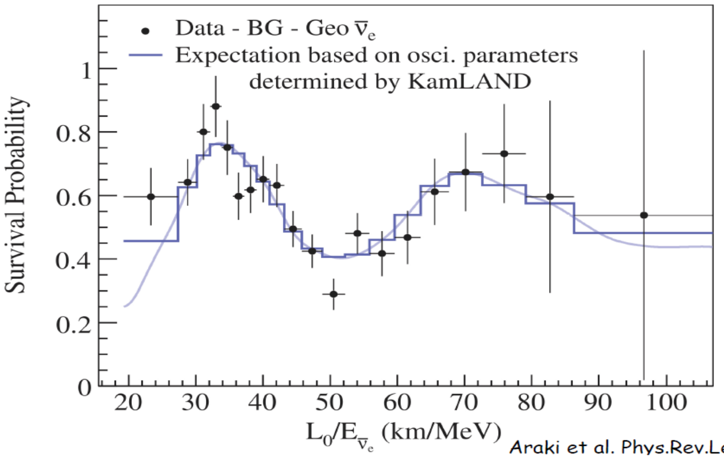


KamLAND









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

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

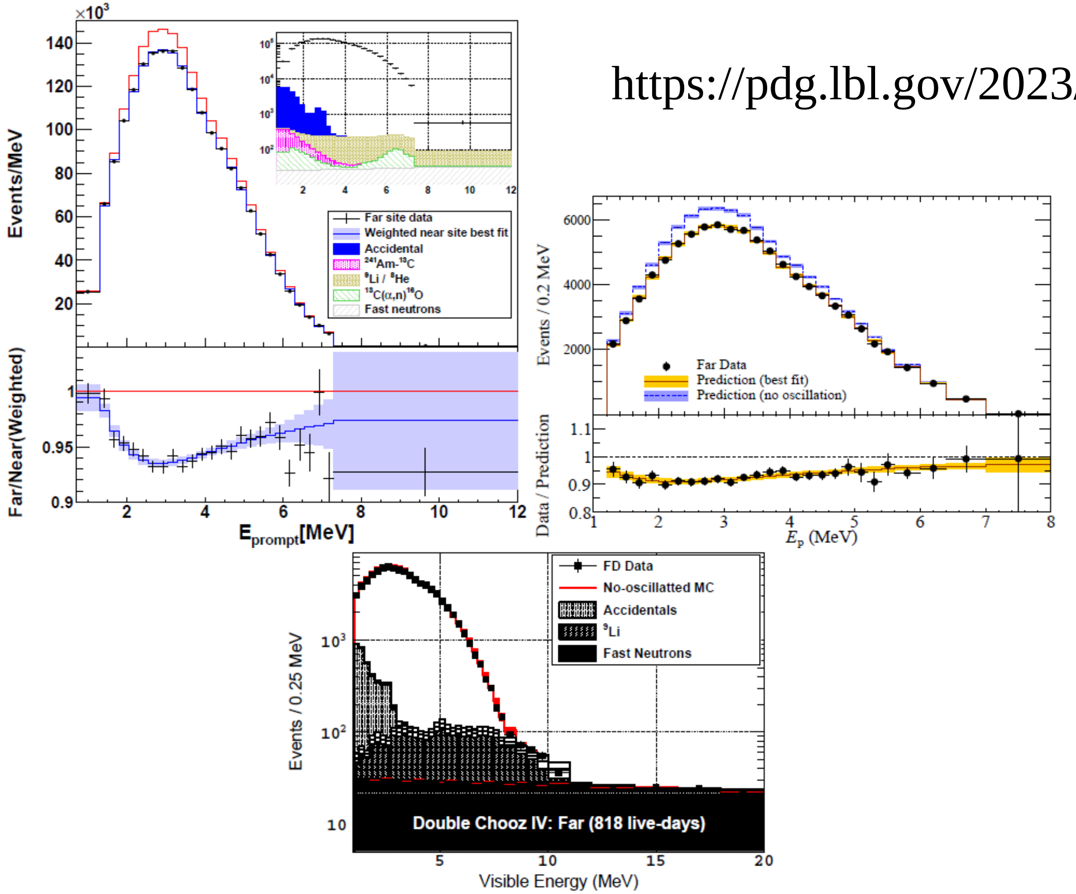


Figure 14.8: Energy spectra for prompt events at the far detectors for Daya Bay [141], RENO [142], and Double Chooz [143].

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

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

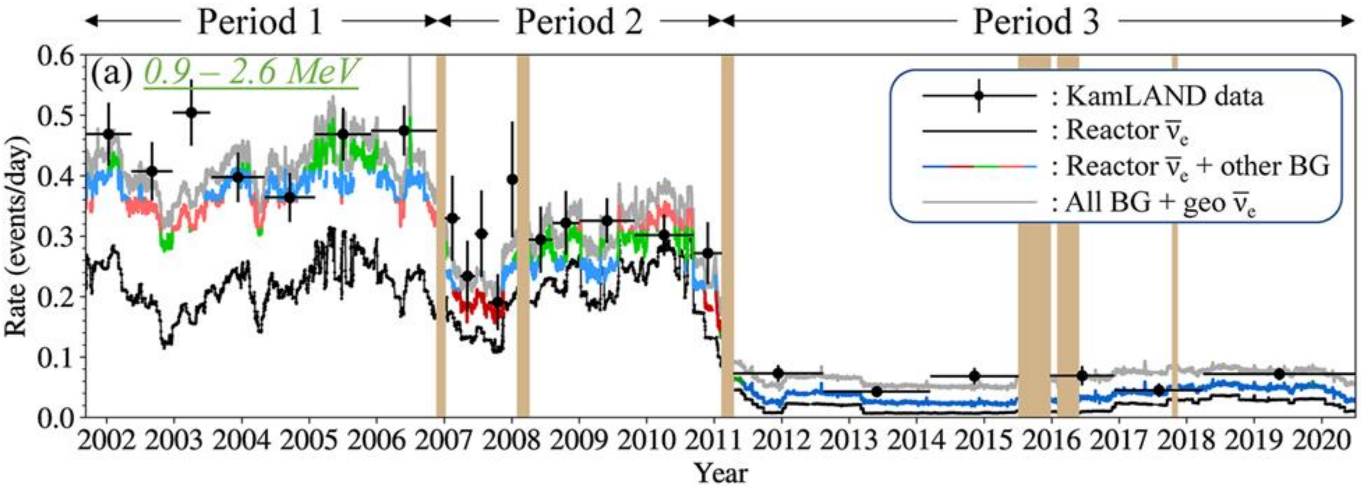
https://pdg.lbl.gov/2023/

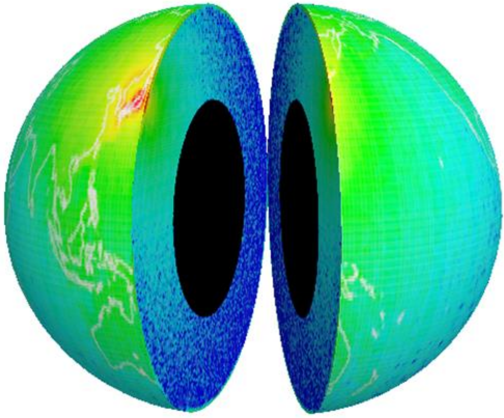
Name	Reactor power (MW_{th})	Baseline (m)	Detector mass (t)	Detector technology	σ_E/E @1 MeV(%)	S/B
NEOS	2,800	24	1	Gd-LS	5	22
DANSS	3,100	10–13	0.9	Gd-PS	34	~30
STEREO	57	9–11	1.7	Gd-LS	10	0.9
PROSPECT	85	7–9	4	^{6}Li-LS	4.5	1.3
NEUTRINO-4	100	6–12	1.5	Gd-LS	16	0.5
SoLid	80	6–9	1.6	^{6}Li-PS	14	

Geo reactor

Total Earth heat flux is 47±2 TW

Sources: gravitation, radioactive elements, geo-reactor (?)





Abe, S., et al. Geophysical Research Letters, 49, e2022GL099566. : The hypothesis that there may exist a natural nuclear fission reactor in the Earth's interior, a so-called georeactor (Herndon, 2003), can be tested using KamLAND data. The energy spectra are fit by adding a constant flux from the hypothetical georeactor assuming a fission ratio of commercial power reactors with the averaged oscillation effect. The geoneutrinos from U and Th are allowed to vary for the spectrum fitting.

The KamLAND data give a limit **on the georeactor power of <1.26 TW at 90% C.L.**

Our days reactor neutrino projects in Russia

Kalinin NPP:
GEMMA: neutrino electromagnetic properties
DANSS, DANSS-2: reactor monitoring, sterile neutrino
νGeN: CEνNS
RED-100: CEνNS
iDREAM: reactor monitoring

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

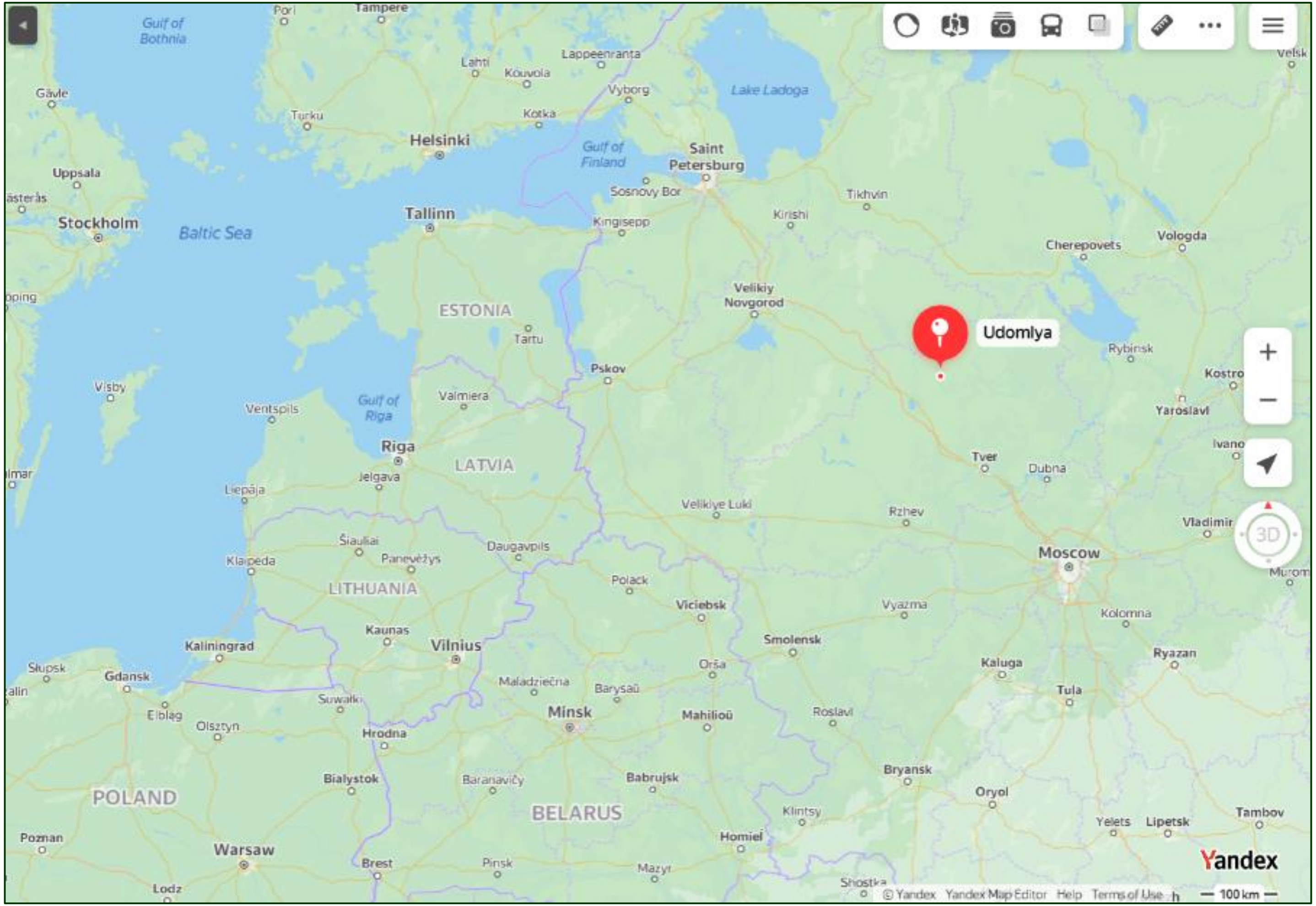
Novovoronezh NPP:
place for new projects

What next?

- Mass scale
- Sterile neutrino(s) (Neutrino-4, DANSS-2, etc)
- Mass ordering (JUNO + others)
- Neutrino-antineutrino difference (JUNO + others)
- 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.


Gulf of Bothnia
Pori
Tampere
Lahti
Kouvola
Lappeenranta
Vyborg
Lake Ladoga
Gävle
Turku
Kotka
Helsinki
Gulf of Finland
Saint Petersburg
Uppsala
Sosnovy Bor
Tikhvin
Tallinn
Kingisepp
Kirishi
Stockholm
Baltic Sea
Cherepovets
Vologda
Velikiy Novgorod
ESTONIA
Tartu
Udomlya
Rybinsk
Pskov
Kostro
Visby
Valmiera
Ventspils
Gulf of Riga
Yaroslavl
Riga
LATVIA
Ivano
Tver
Dubna
Jelgava
Liepāja
Velikiye Luki
Rzhev
Vladimir
Šiauliai
Daugavpils
Panevėžys
Klaipeda
Moscow
LITHUANIA
Polack
Murom
Viciebsk
Vyazma
Kolomna
Kaunas
Kaliningrad
Vilnius
Smolensk
Orša
Ryazan
Kaluga
Słupsk
Gdansk
Maladziečna
Barysaŭ
Tula
Suwałki
Minsk
Roslavl
Elbląg
Mahilioŭ
Olsztyn
Hrodna
Bryansk
Bialystok
Babrujsk
Baranavičy
Oryol
POLAND
BELARUS
Klintsy
Tambov
Yelets
Lipetsk
Poznan
Homiel
Warsaw
Yandex
Brest
Pinsk
Mazyr
Shostka
Lodz
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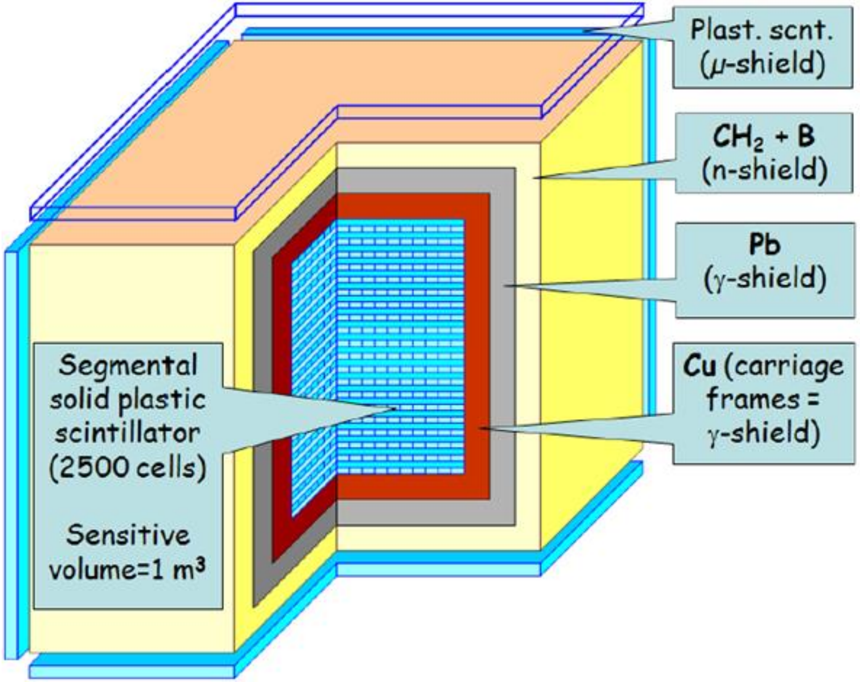
100 km

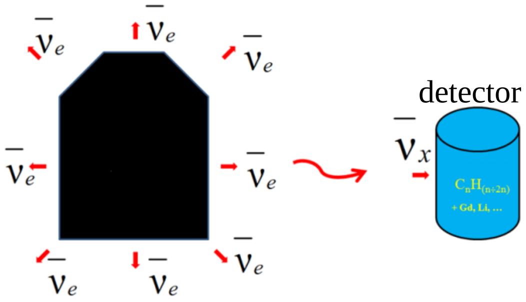
DANSS

Investigations of reactor antineutrinos at the KNPP with an inverse beta decay detector



Compact (1 m^3) highly segmented (2500 plastic scintillator plates) neutrino spectrometer DANSS aims at searching for oscillations in sterile neutrinos, as well as monitoring with neutrinos the reactor power and the composition of nuclear fuel.

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

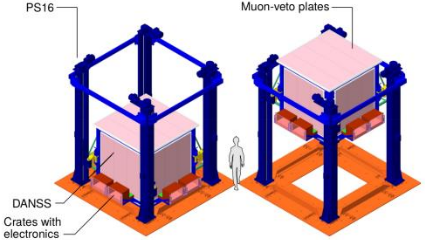


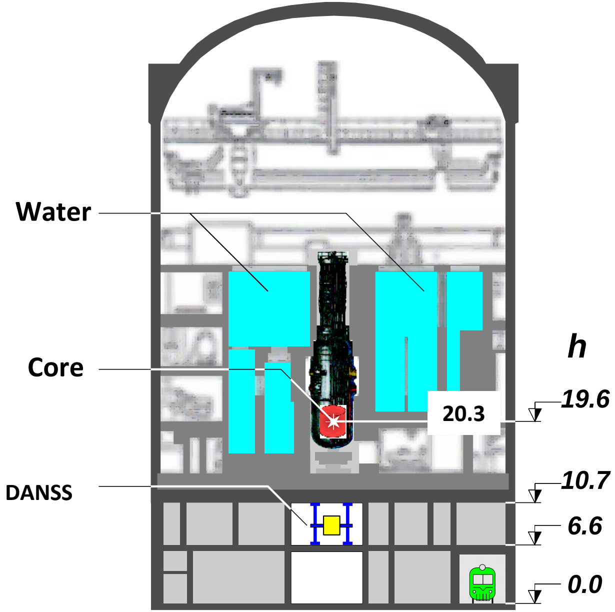
DANSS is installed on a movable platform under 3.1 GW WWER-1000 reactor at Kalinin Nuclear Power Plant

(Core:h=3.7m, ∅=3.1m) at Kalinin NPP.

~50 mwe shielding => μ flux reduction ~6!

No cosmic neutrons!





Detector distance from reactor core 10.9-12.9m (center to center) is changed 2-3 times a week

Trigger: ΣE(PMT)>0.5-0.7MeV=>Read 2600 wave forms (125MHz), look for correlated pairs offline.

Fuel fission fractions: average, start and end of campaign [%]

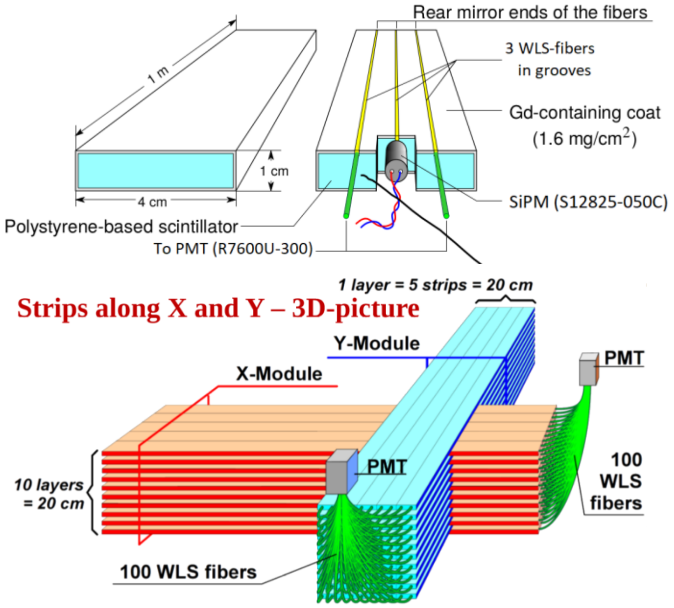
235U	54.1	63.7	44.7
239Pu	33.2	26.6	38.9
238U	7.3	6.8	7.5
241Pu	5.5	2.8	8.5

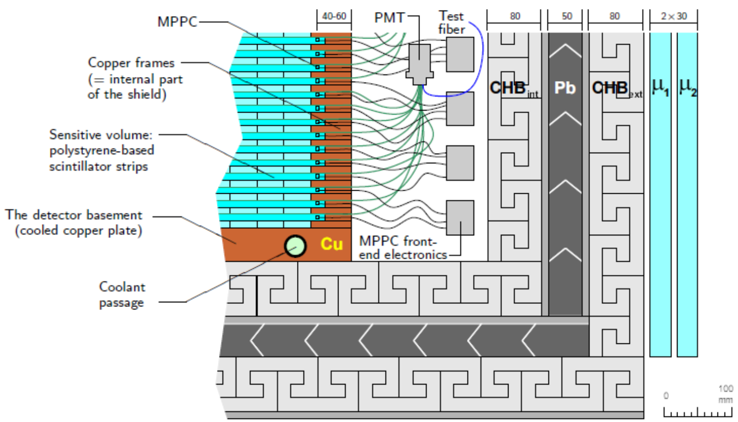
(for a typical campaign)

Main tasks: search for short-range neutrino oscillations and remote monitoring of

DANSS Detector design

JINST 11(2016)no11,P11011

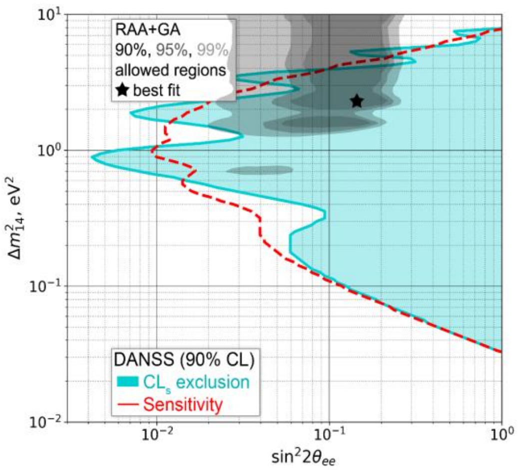




- 2500 scintillator strips with Gd containing coating for neutron capture
- Light collection with 3 WLS fibers
- Central fiber read out with individual SiPM
- Side fibers from 50 strips make a bunch of 100 on a PMT cathode = Module

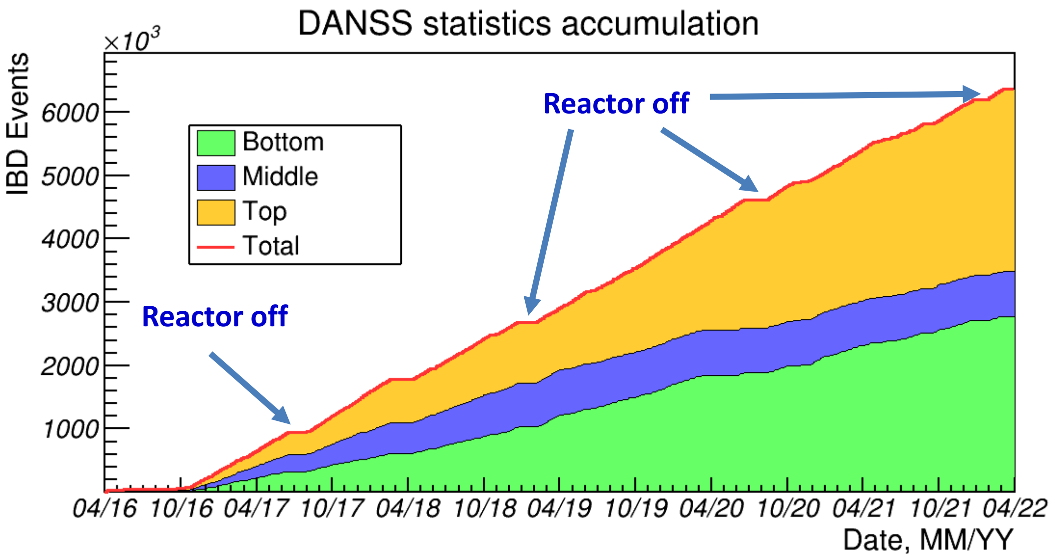
- Two-coordinate detector with fine segmentation – spatial information
- Multilayer closed passive shielding: electrolytic copper frame ~5 cm, borated polyethylene 8 cm, lead 5 cm, borated polyethylene 8 cm
- 2-layer active μ-veto on 5 sides

DANSS status

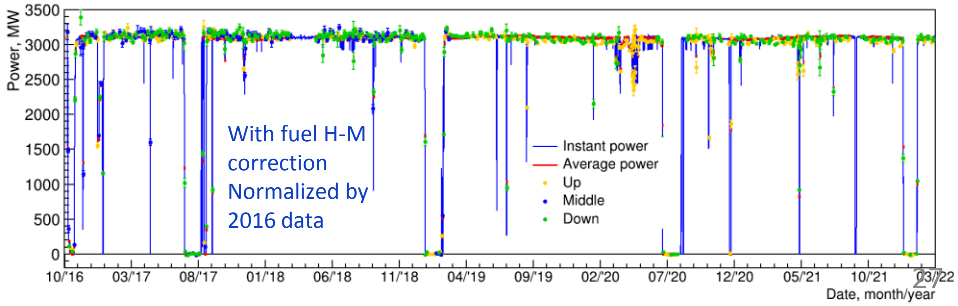


- Exclusion region was calculated using Gaussian CLs method for E_{e+} in 1.5-6 MeV region
- The most stringent limit reaches $\sin^2 2\theta < 4x10^{-3}$ level.
- A very interesting part of 4ν parameters is excluded.
- The most probable point of RRA+GA is excluded at >5σ confidence level already in 2018

Total statistics accumulated is **6M IBD-events in 6 years** and 4 reactor off periods (4.4M events in oscillation analysis)



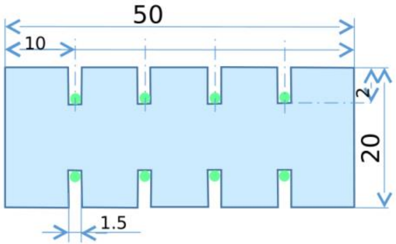
Neutrino reactor power monitoring with 1.5% accuracy in 2 days during 6 years

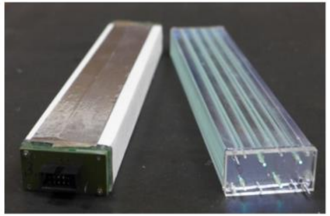


DANSS upgrade

New scintillator strips

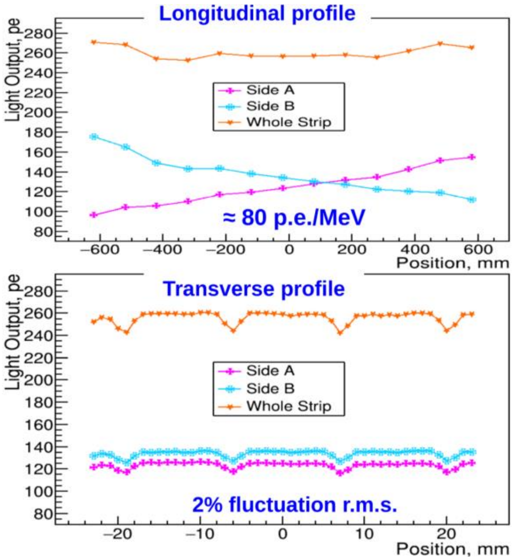
Main goal:
to reach resolution **13%/√E**
current very resolution is 34%/√E.

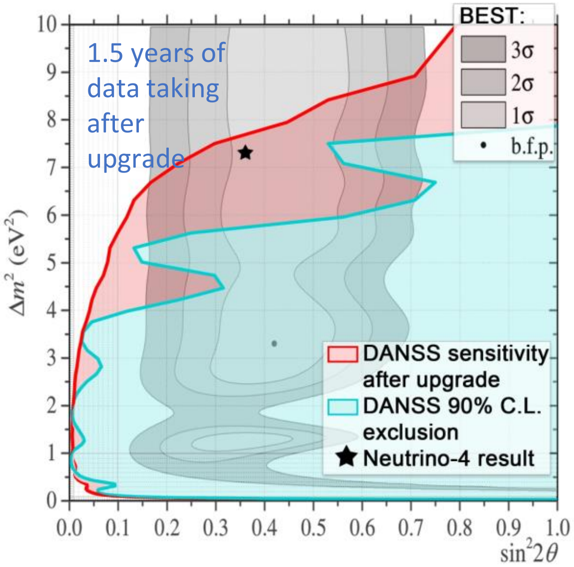




WLS fiber positions were optimized for better uniformity of response
New fast (4ns decay time) YS2 fiber will be used

New geometry:
Strips: 2x5x120 cm,
2-side 4SiPM readout
Structure: 60 layers x 24 strips: – **1.7 times larger fiducial volume**
Setup uses the same shielding and moving platform.
Gd is in foils between layers.



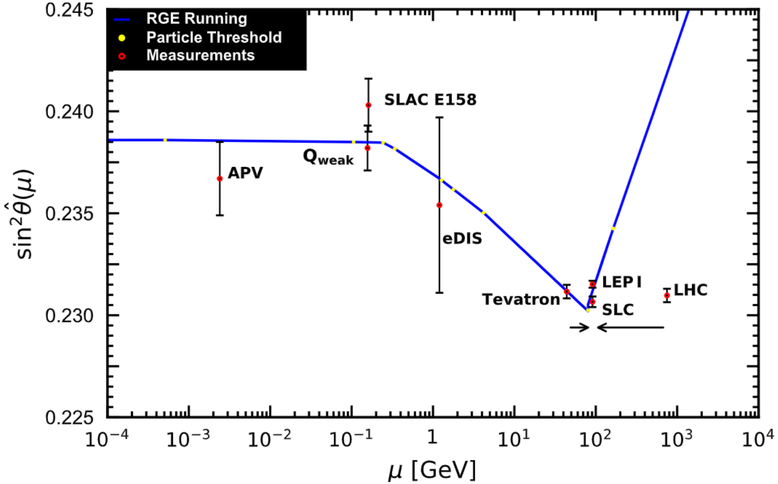


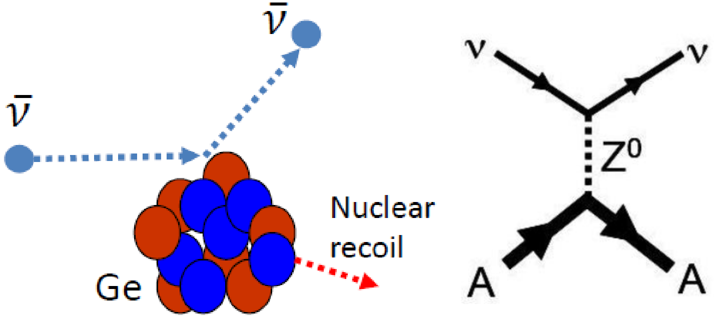
Coherent elastic neutrino nucleus scattering (CEνNS)

For low energy the cross section is 2-3 orders above of other channels

- Astrophysics and cosmology (early Universe, SN)
- The background for DM search

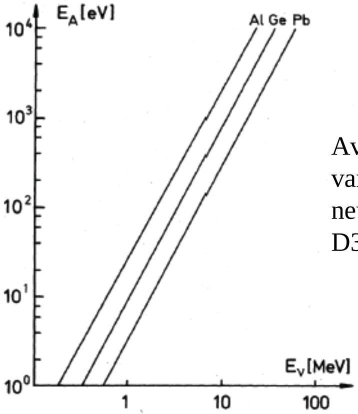
- Parameters of the Standard model
- Search for New physics





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

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



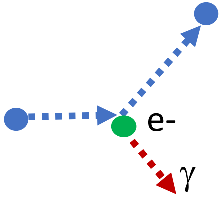
Average recoil energy, E_A, for various nuclei as a function of neutrino energy, from Phys. Rev. D30, 1984, p2295

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.

νGeN experiment: search for CEνNS and other rare processes

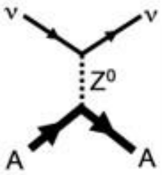
The experiment νGeN is aimed at studying the properties of reactor's antineutrinos. The search for the coherent elastic neutrino-nucleus scattering (CEνNS) and other rare process (search for neutrino magnetic moment, etc) is performed. The projects is conducted mostly by JINR group.

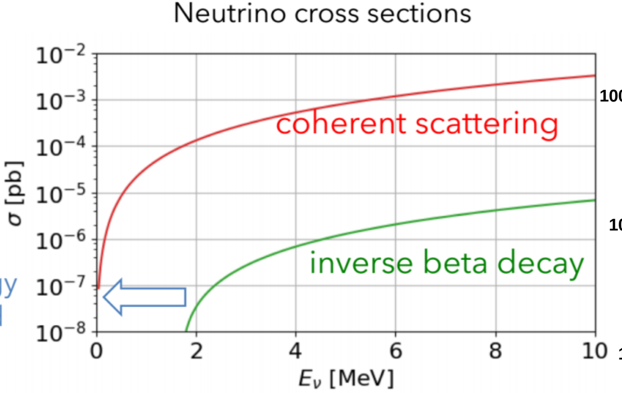
- CEνNS is a process for low energy neutrino, $E_\nu < 50$ MeV (full coherency below ~ 30 MeV)
- Cross section is enhanced by several orders of magnitude
- Proportional to the number of neutrons squared, N^2
- Recoil energy is very low – less than few keV
- Often only a small part of recoil energy can be detected due to quenching (<25% for HPGe).

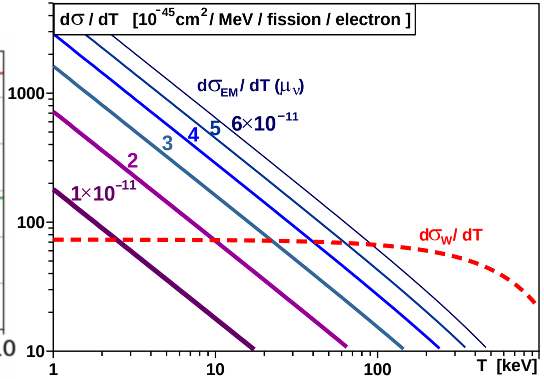


Additional EM component

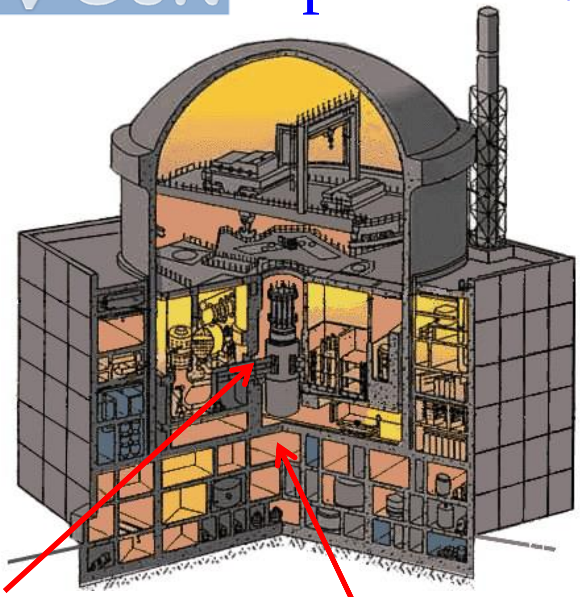
A $\bar{\nu}$ magnetic moment is a fundamental parameter of neutrino and its investigation may lead to results beyond the standard concepts of elementary particle physics and astrophysics. The observation of NMM above $\mathbf{10^{-14}}$ $\boldsymbol{\mu_B}$ would be a New Physics beyond the SM and indicate Majorana nature of neutrino.

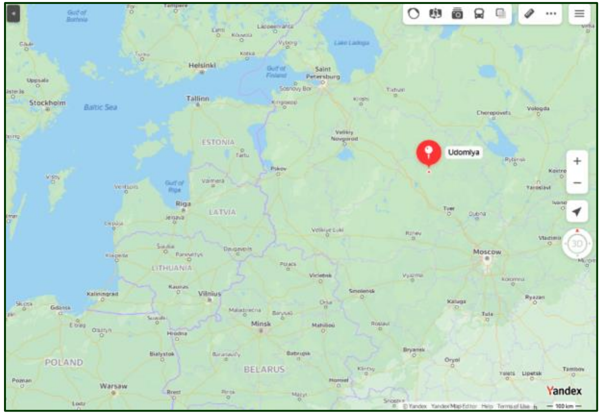






νGeN experiment: search for CEνNS and other rare processes





The experiment νGeN is aimed at studying the properties of antineutrinos from the reactor of the Kalinin NPP (Udomlya, Russia). The search for the coherent elastic neutrino-nucleus scattering and other rare process (like search for neutrino magnetic moment) is performed.

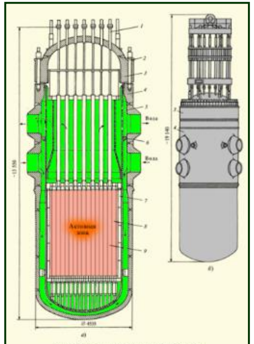
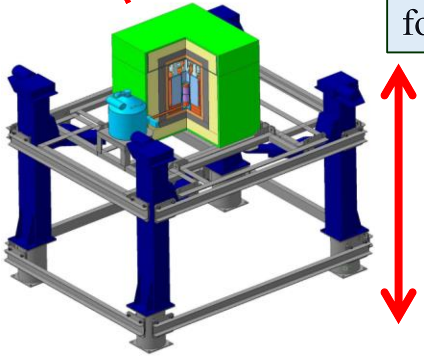


Рис. 5.4. Ядерный реактор ВВЭР-1000

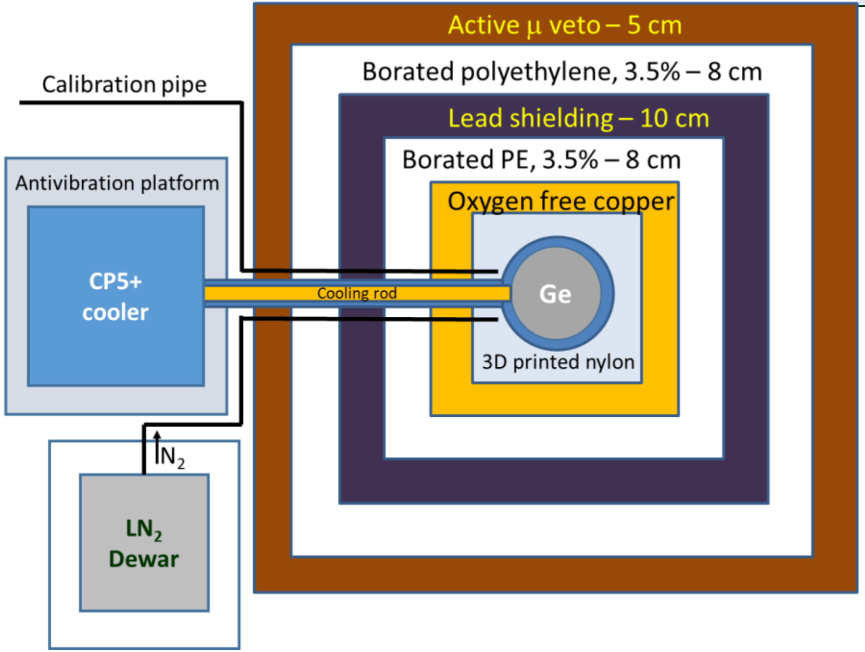


Distances to the center of reactor core: 11.1 – 12.5 m

- Spectrometer **νGeN** is located under the reactor unit #3 (3.1 GW_{th} – thermal power)
- Distance to the center of the reactor core is about 11 m, this gives **~ $4 \cdot 10^{13}$ ν/(sec·cm^2)**
- Overburden **~ 50 m w.e.** – good shielding against cosmic radiation due to reactor's surrounding

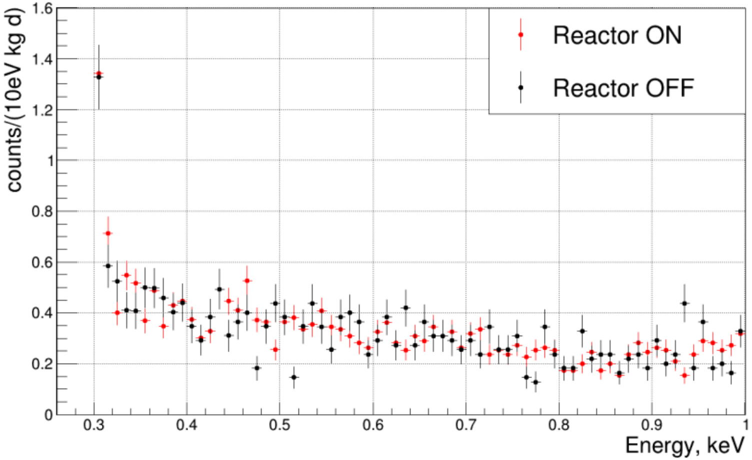
νGeN experiment: search for CEvNS and other rare processes

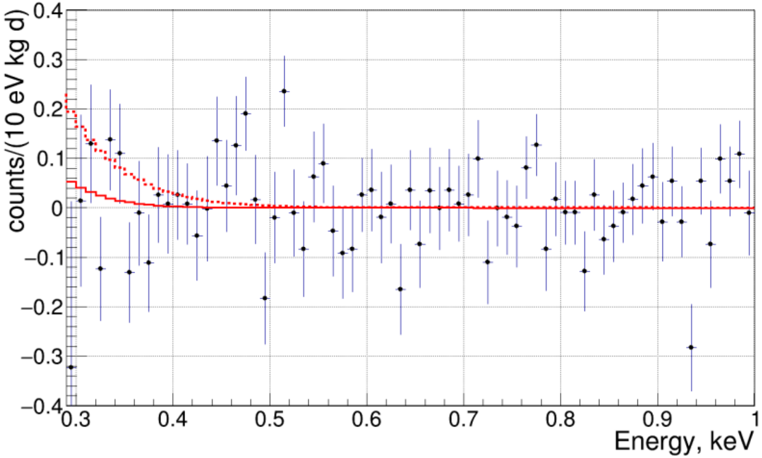
To detect signals from neutrino scattering we use a specially produced by CANBERRA (Mirion, Lingosheim) low-threshold, low-background HPGe detectors. At the moment, only one detector with a mass of 1.4 kg and e-cooling is used for the detection at KNPP.



The passive and active shielding has been organized in order to suppress background from surrounding. Additional systems to suppress radon background and microvibrations were developed. Special acquisition system has been developed to detect weak signals.

νGeN experiment: search for CEνNS and other rare processes





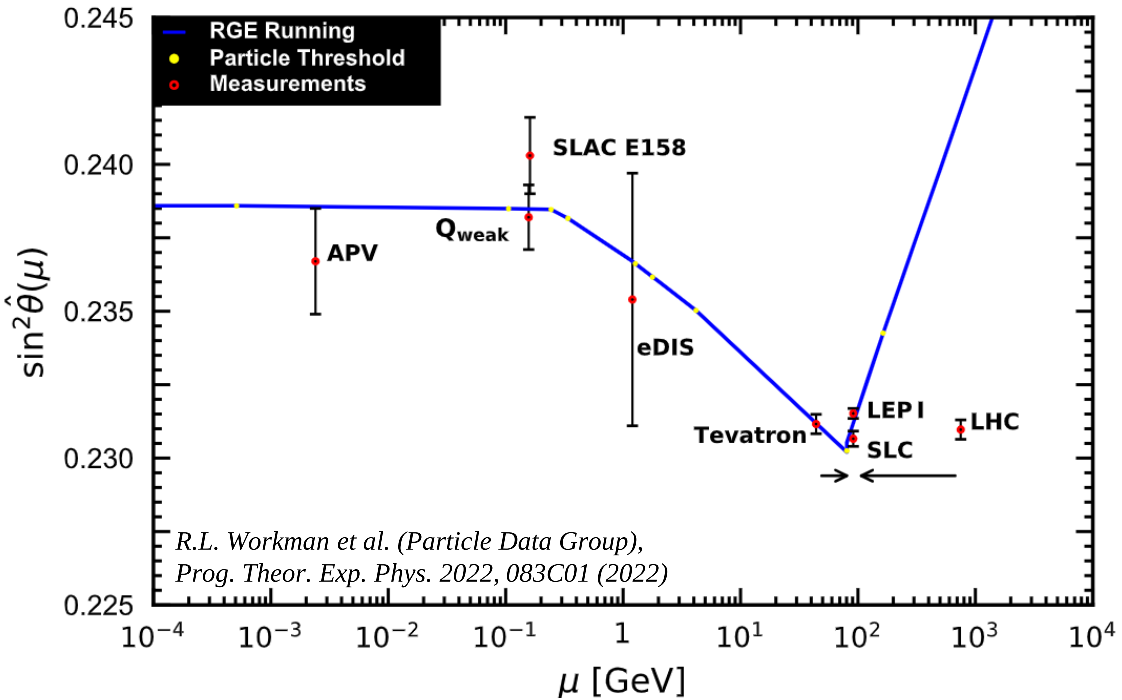
Analysis of the first data shows no significant difference in background level during reactor ON and OFF regimes. No excess at low energy connected with the CEνNS has been observed. The upper limit on the quenching parameter **k < 0.26** with 90% CL has been obtained (dashed line). Red solid line for quenching parameter k = 0.179.

- Measurements with the νGeN spectrometer at Kalinin Nuclear Power Plant are ongoing.
- First results have showed that achieved background level allows to search for CEνNS at KNPP. No significant difference between regimes with reactor ON and OFF has been observed so far.
- More than 1200 kgd of data has been accumulated so far. Since 09/2022 the data taking are performed at reduced distance to the reactor core.
- The optimization of data taking is performed as well. New results with more statistics are expected soon.

Why we want precision measurements?

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

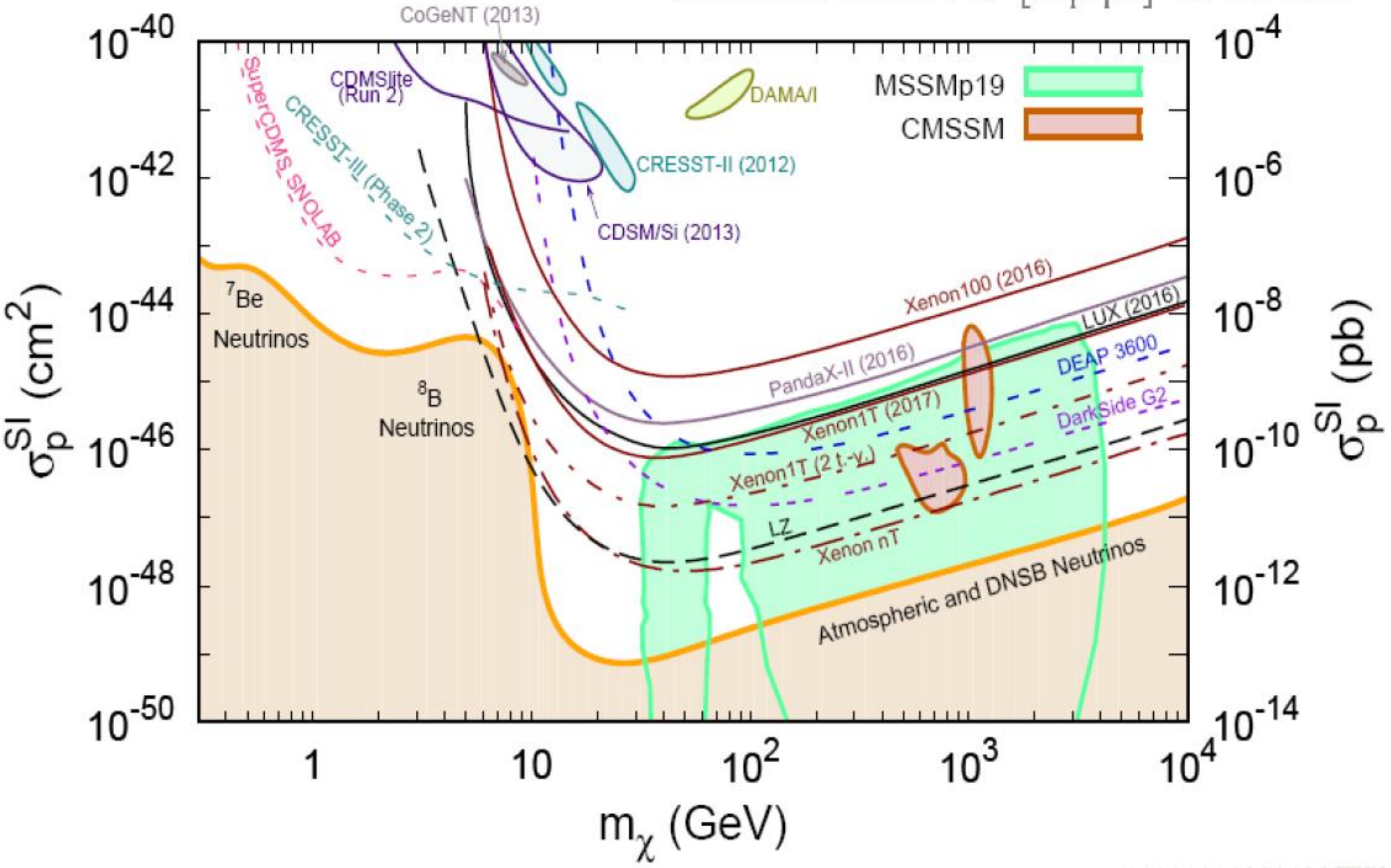
$$Q_w = N - Z(1 - 4\sin^2\theta_w)$$

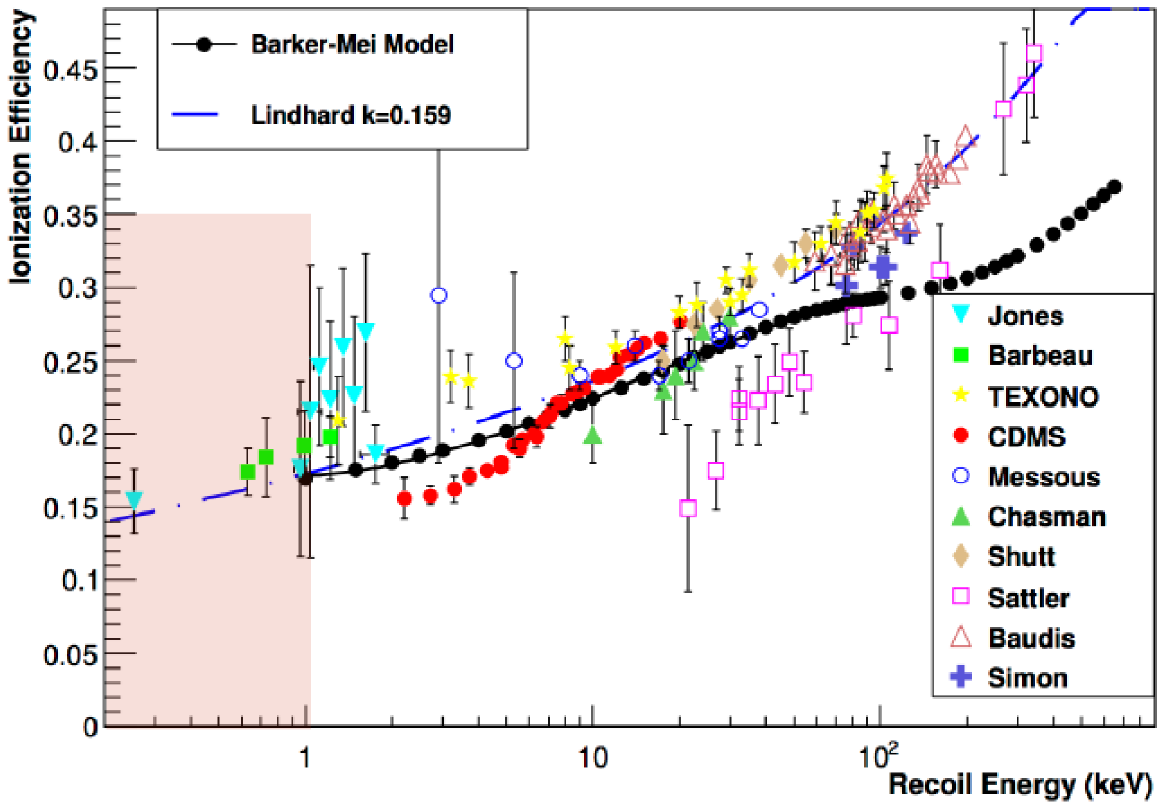


R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

Why we want precision measurements of neutrinos from reactor?

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

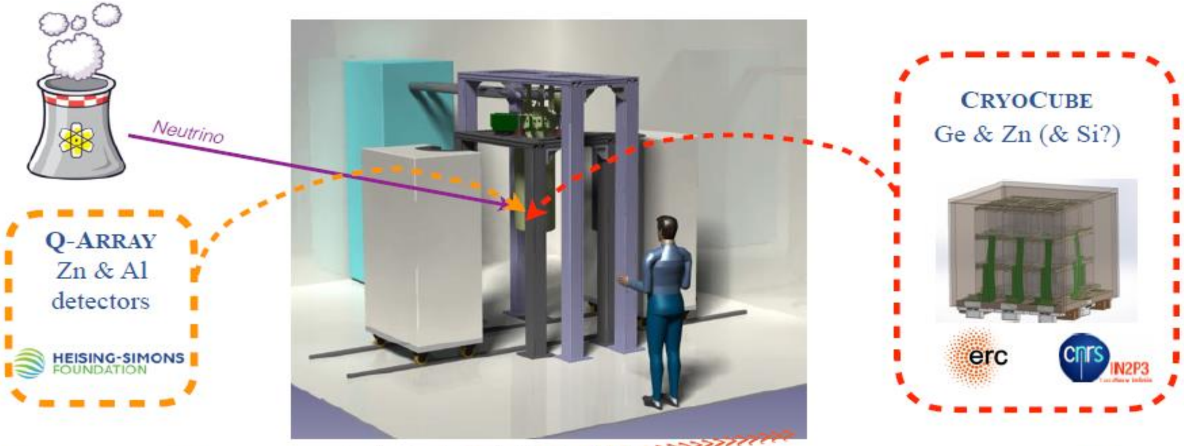




Barker-Mei Model
Lindhard k=0.159
Ionization Efficiency
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1
10
10^2
Recoil Energy (keV)
Jones
Barbeau
TEXONO
CDMS
Messous
Chasman
Shutt
Sattler
Baudis
Simon

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

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



RICOCHET
A Coherent Neutrino Scattering Program

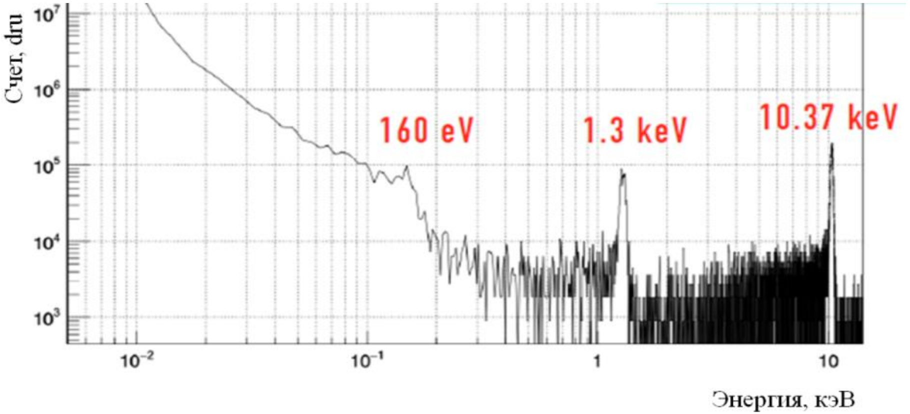
50 eV energy threshold with a 10^3 background rejection down to the threshold

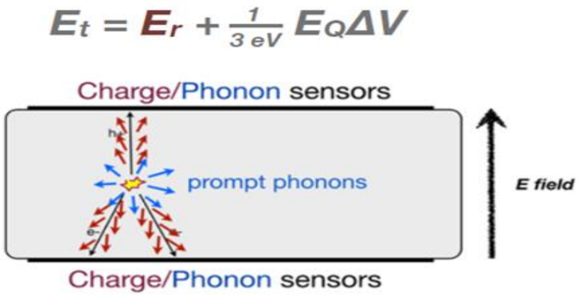
The first key feature of the RICOCHET program, compared to other planned or ongoing CEvNS projects, is to aim for a kg-scale experiment with significant background rejection down to the O(10) eV energy threshold.

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

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



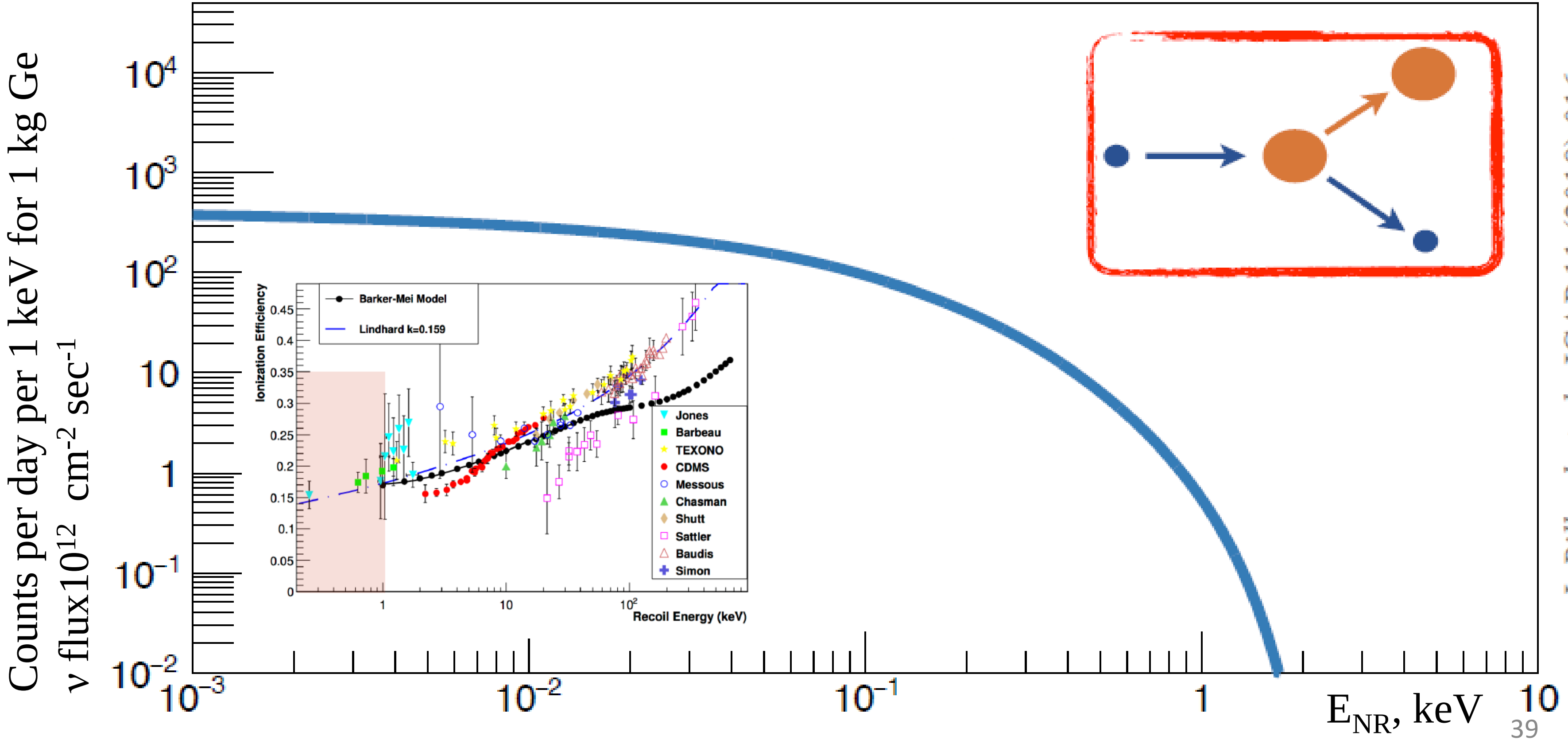


An unprecedented **charge resolution of 0.53 electron-hole pairs** (RMS) has been achieved using the Neganov-Trofimov-Luke internal amplification.

Coherent elastic neutrino-nucleus scattering (CEνNS)

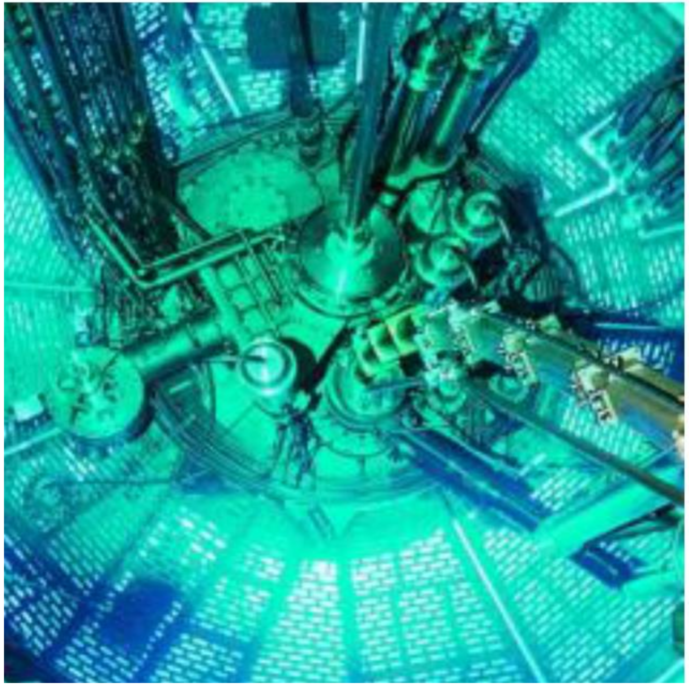
The use of bolometers makes it possible to measure the energy of the nucleus directly (heat signal), in contrast to semiconductor detectors that measure ionization.

This it the way to the precision measurements.



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

Optimised for extraction of intense neutron beams



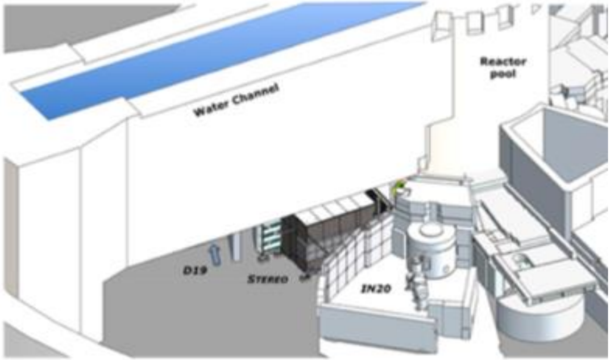
High-(neutron)flux reactor of the ILL

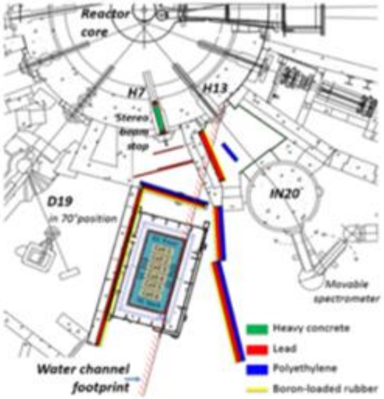
- 58.3 $MW_{thermal}$
- Single compact fuel element:
  - ◇ Ø40 cm × 80 cm
  - ◇ Highly enriched fuel: ^{235}U (93%)
  - ◇ 1 cycle ~50 days
  - ◇ 3-4 cycles/year
- Heavy-water moderated
- Flux in moderator: 10^{15} n/cm^2s

RICOCHET: *Searching for nuclear reactor site - ILL*

- 58 MW nominal thermal power
- Large neutrino flux: ~1x10^{19} ν/s
  - 5m from core: 40 evts/day/kg
  - 7m from core: 20 evts/day/kg
- 3 to 4 cycles per year: ***excellent ON/OFF modulation to subtract uncorrelated backgrounds***
- Significant overburden (~15 m.w.e)
- Ricochet could make use of STEREO casemate after its dismantling (2021 - 2022)
- Ricochet would benefit from the strong STEREO experience and background characterization
- Monte Carlo studies ongoing to estimate the expected backgrounds:
  - *reactogenic* and cosmogenic
- ***LoI submitted to ILL directors end-Feb***

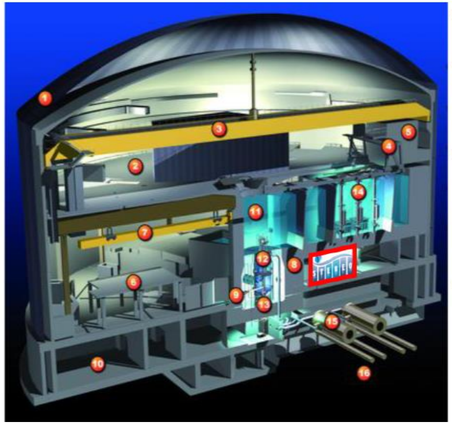
STEREO Coll., JINST 2018



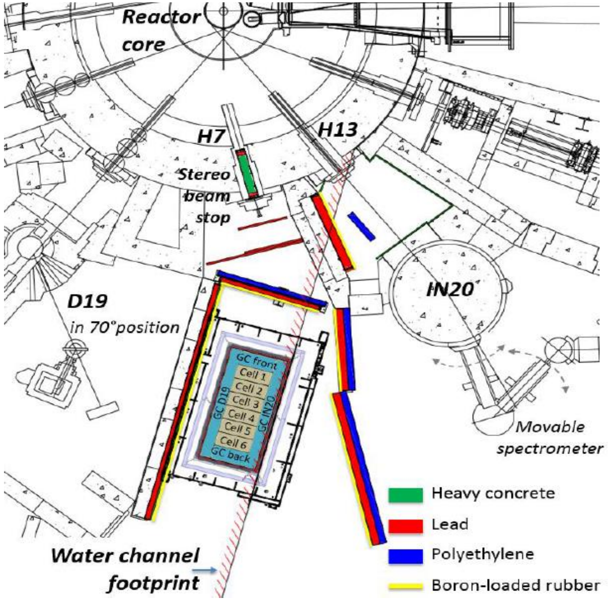


Site H7

Antineutrino source and site



- Baseline: ≥ 8m
- Overburden: 15 m.w.e.
- Shielding improved for STEREO
- H6-H7 beam tube removed, or closed by plug



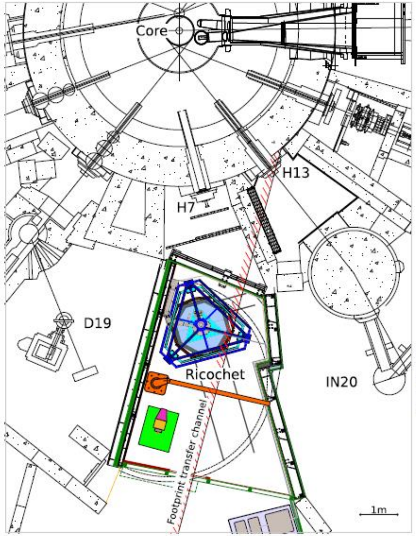
Advantages

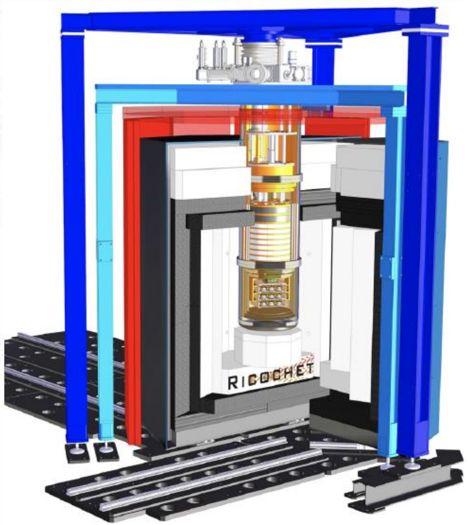
- Pure ^{235}U spectrum, compact core
- Frequent on-off changes
- 15 m.w.e. overburden
- Profit from STEREO (site prep, reactor spectrum)
- Scientific environment and technical support

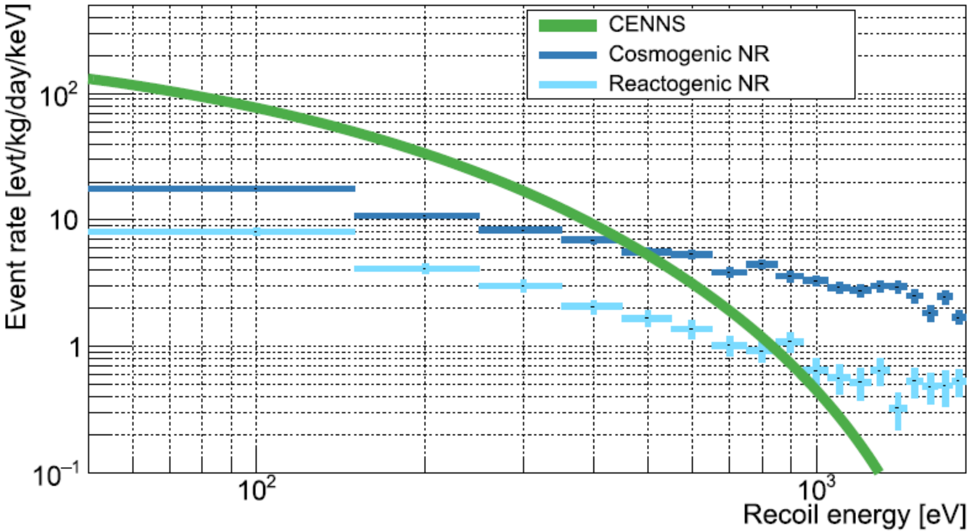
Disadvantages

- Need to be close to core for high flux → Signal/ReactorBG?
- Backgrounds from neighbour instruments
- Limited crane access

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

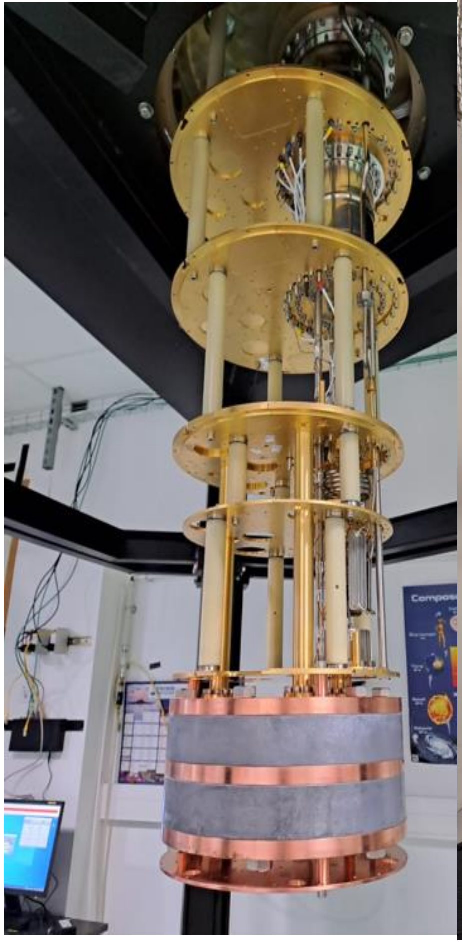


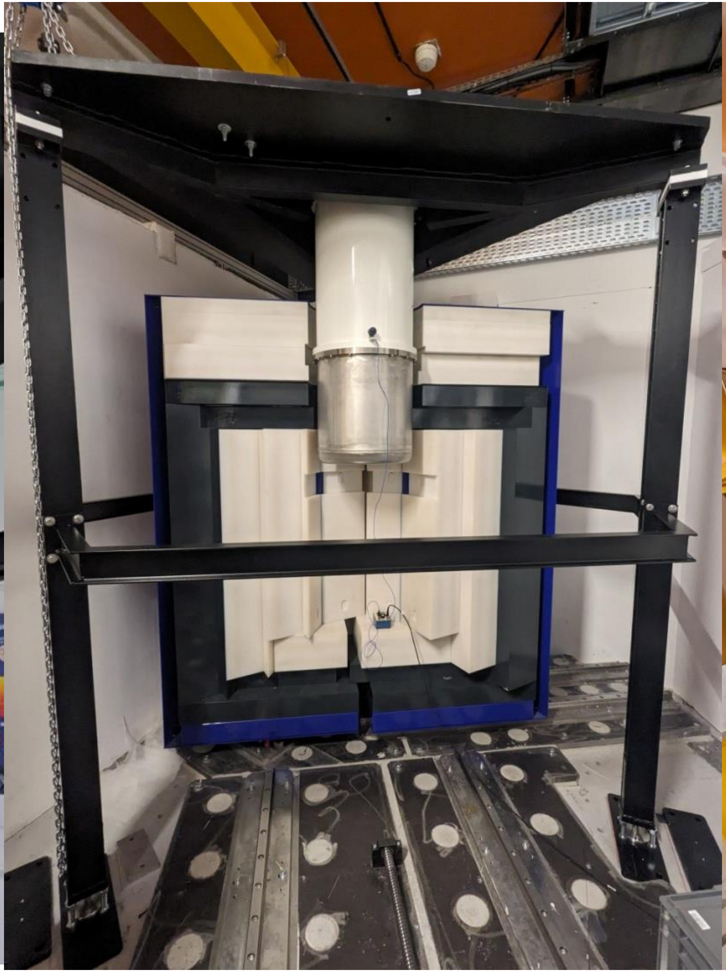


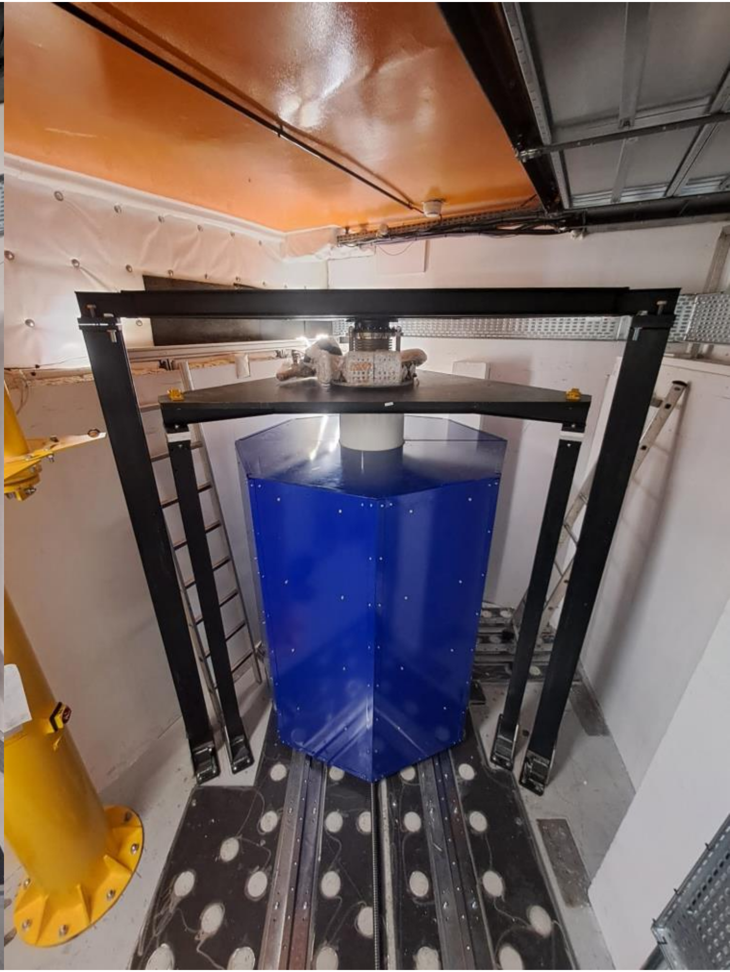


	Cosmogenic	Reactogenic	Total (MC)	CENNS (Ge/Zn)
Nuclear recoils [50 eV, 1 keV] (evts/day/kg)				
No shielding (I)	1554 ± 12	53853 ± 544	55407 ± 545	–
Passive shielding (II)	42 ± 3	2.4 ± 0.3	44 ± 3	–
Passive + μ-veto (III)	7 ± 2		9 ± 2	12.8 / 11.2

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.







- Neutrino magnetic moment;

- Searching for new massive mediators

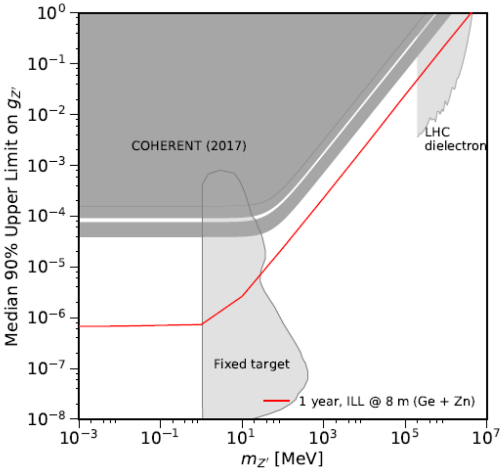
  Some extensions of the SM suggest the presence of an additional vector mediator boson [E. Bertuzzo et al., JHEP 1704, 073 (2017)], that couples both to the neutrinos and the quarks, called Z'.

- Non-Standard Interactions

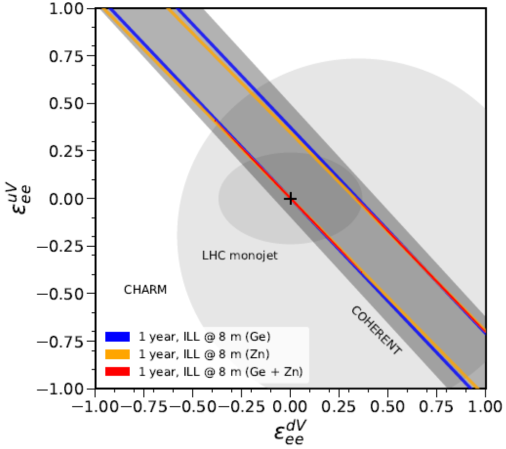
  *New physics that is specific to neutrino-nucleon interaction is currently quite poorly constrained, and is motivated in some beyond-SM scenarios [J. Barranco, O. G. Miranda, and T. I. Rashba, Phys. Rev. D **76**, 073008 (2007)]. In the context of a model-independent effective field theory, the Lagrangian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

- Sterile neutrino.

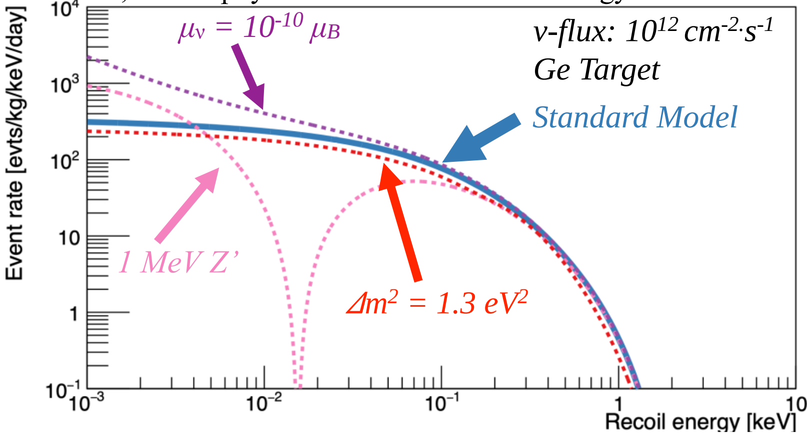
Constraints on Z' searches



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

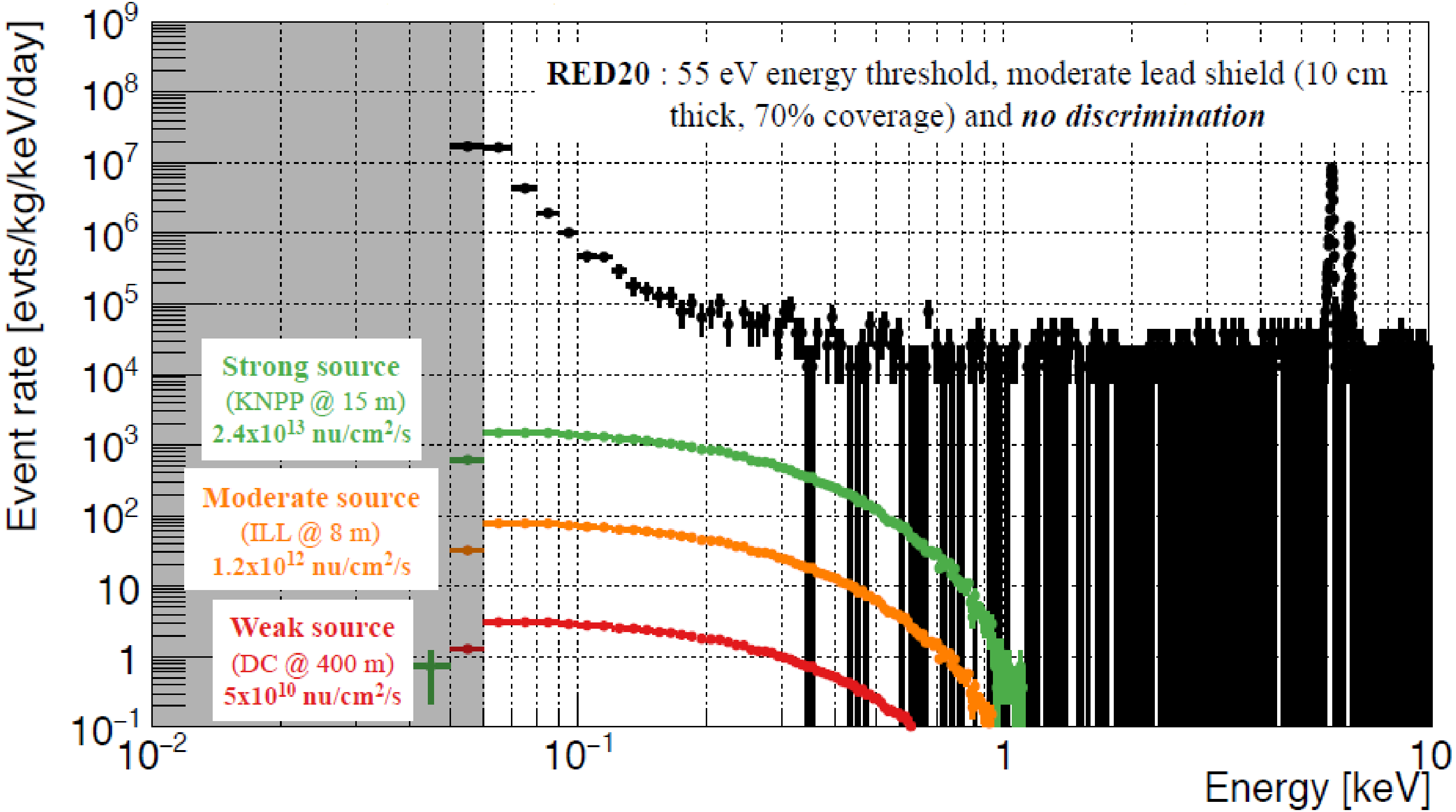


Projected sensitivities of the Ricochet experiment, located at 8 m from the ILL reactor core, to new physics searches in the low-energy CEνNS sector



Precision measurements

	Uncertainty on Parameter	Approximate uncertainty on CEνNS Rate
The thermal power P_{th}	1.4%	1.4%
Distance	0.3%	0.6%
E/fission	~0.3%	~0.3%
fission fractions α_i	≤1% for ^{235}U 5-10% ^{239}Pu, ^{241}Pu	<< 0.5%
fission spectra S_i	Conversion: 2-3%	2-3 %
	Summation: 5-10%	
CEνNS cross section σ_k	0.5% (θ_w)	

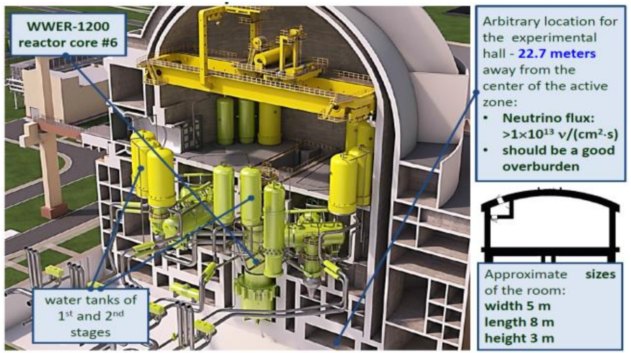


RED20 : 55 eV energy threshold, moderate lead shield (10 cm thick, 70% coverage) and no discrimination
Strong source
(KNPP @ 15 m)
2.4x10^13 nu/cm^2/s
Moderate source
(ILL @ 8 m)
1.2x10^12 nu/cm^2/s
Weak source
(DC @ 400 m)
5x10^10 nu/cm^2/s
Event rate [evts/kg/keV/day]
Energy [keV]
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-1
1
10

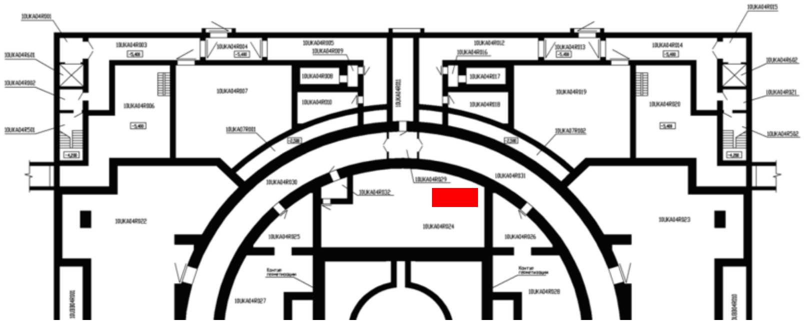
Unit #6 of Novovoronezh NPP

new 3+ generation WWER-1200

Maximal thermal power is 3212 MW



First place proposed
-5.4 m (underground)
Strong basement,
No noise or vibrations



Maximal registered muon flux is 16.2 μ m^{-2} sr^{-1} sec^{-1},
About 7 times less with respect to the max of the sea level,
This corresponds to ~50 mwe.

There is expected anisotropy (better shielding from the reactor)

Measured neutron flux: $<10^{-5}$ m^{-2} sec^{-1},
More than 20 times less with respect to the max of the sea level.

Neutrons

n + ^{3}He → p + ^{3}H + 764 keV

For thermal neutrons σ=5333 ± 7 barns

For fast neutrons, the reaction has cross section ~1 barn.

There are also elastic scattering, (n,D) reaction, etc.

Study of ambient neutrons with He-3 detectors is only possible when detector's intrinsic α-background is low.

Example of interaction of 2.5 MeV monoenergetic neutrons with He-3

PHYSICAL REVIEW VOLUME 122, NUMBER 6

Interaction of Neutrons with He^3†

A. R. SAYRES, K. W. JONES,* AND C. S. WU
Columbia University, New York, New York
(Received February 7, 1961)

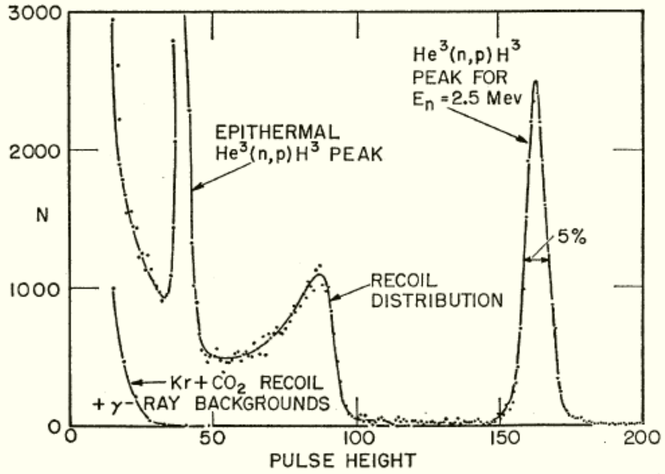
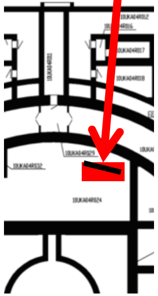
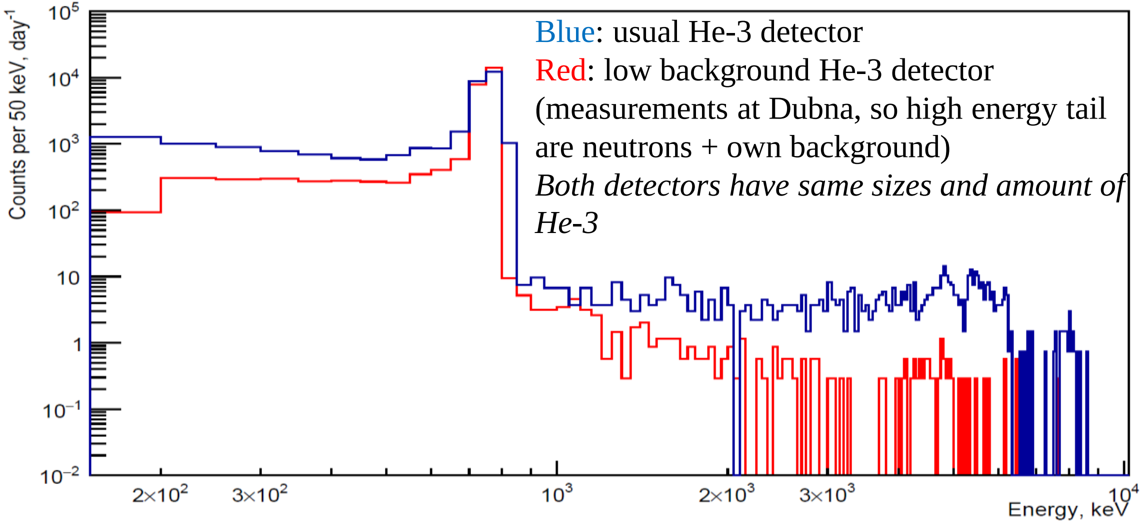


FIG. 3. Neutron spectrum observed with the He^3-filled proportional counter using 2.5-Mev neutrons from the H^3(*p*,*n*)He^3 reaction. Backgrounds in the absence of He^3 are also shown. The curves shown are the differences between runs taken with a collimator and a solid cylinder.

Low background He-3 proportional counter

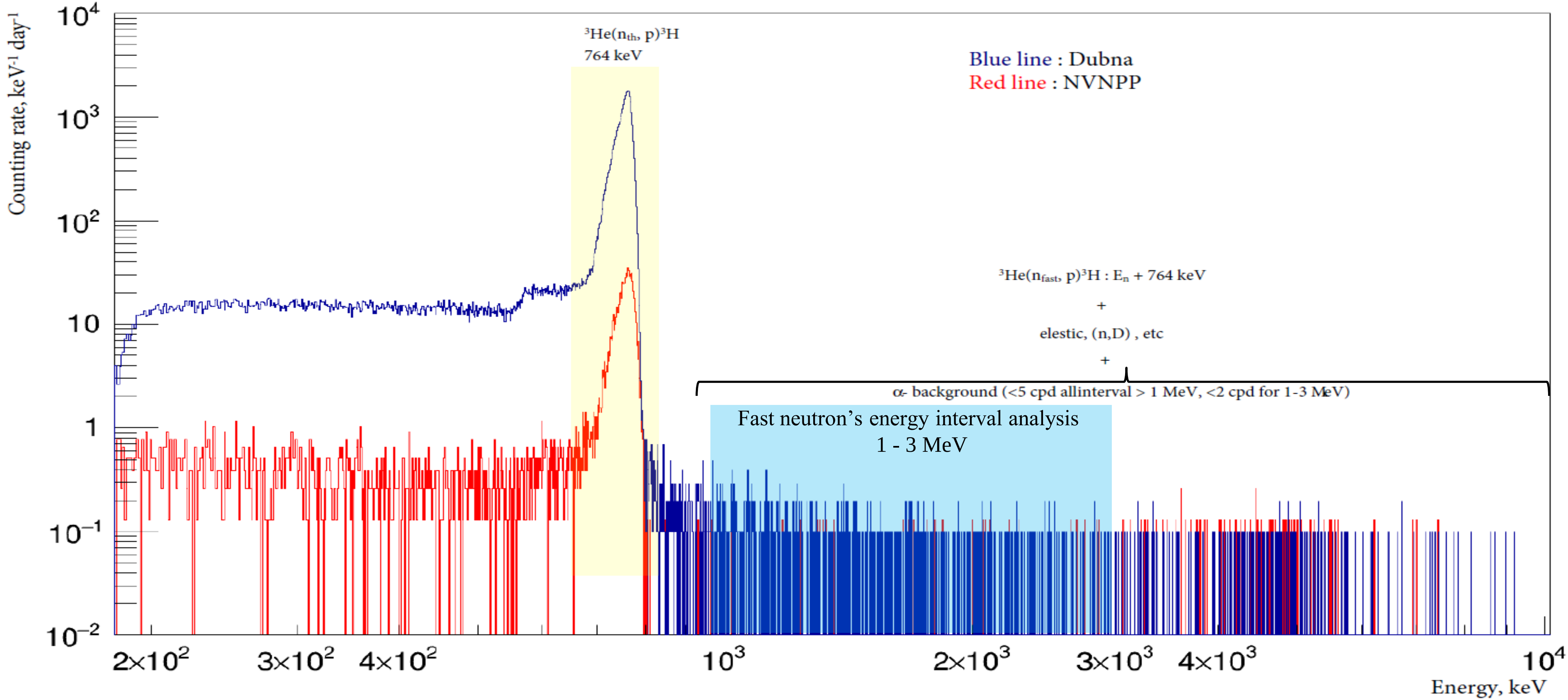
Why low background detector is needed is demonstrated on the figure below (measurements at Dubna)





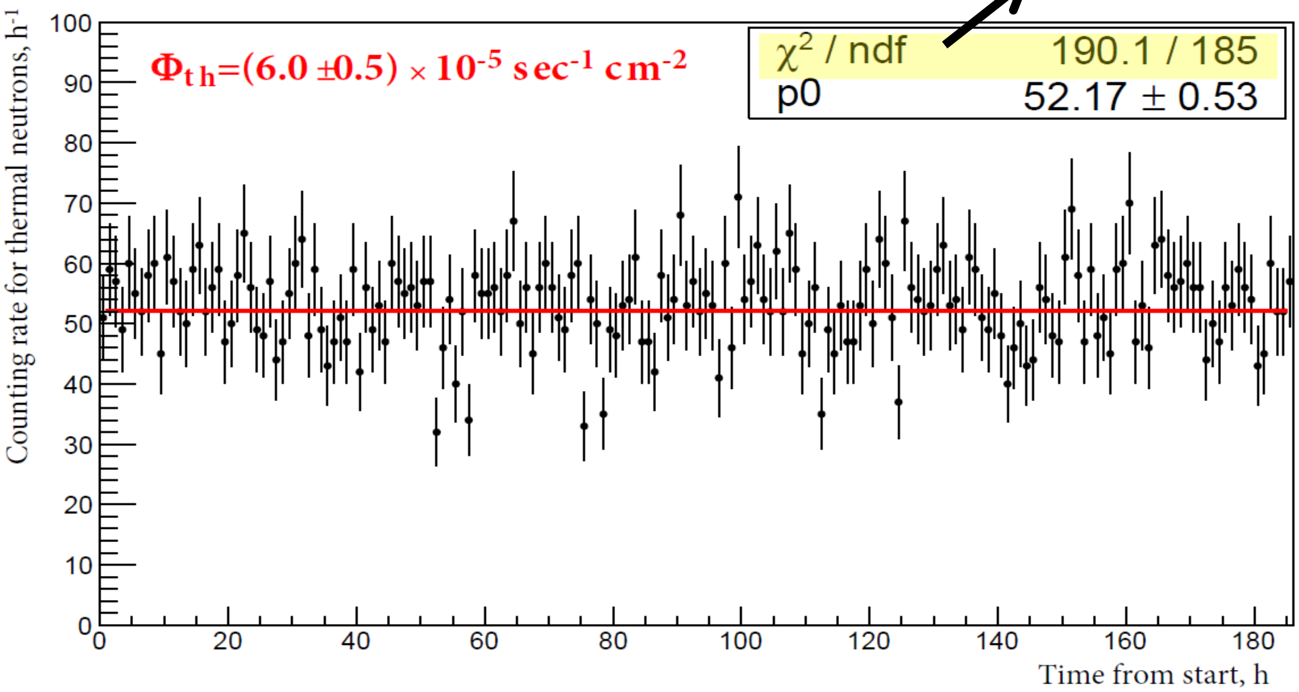
Neutrons at NVNPP, results

Energy spectrum accumulated for 8 days, all measurements performed during reactor ON



Thermal neutrons (764 keV ROI: 660-830 keV)

Statistically, the flux is stable



Place	Thermal neutron flux, 1 sec^{-1} cm^{-2}	Ratio to Dubna
Dubna	2×10^{-3}	1
NVNPP	**6×10^{-5}**	**33**
ILL, reactor ON, place 1	1.2×10^{-1}	0.02
LSM	2×10^{-6}	~1000

Fast neutrons

Place	Counts above background (LSM) for 1 – 3 MeV, day^{-1}	Ratio to Dubna
Dubna	50	1
NVNPP	**2 (30 counts for 7.7586 d, and assuming bkg=1.8)**	**25**
ILL, reactor ON, place 1	55	0.9
ILL, reactor OFF	6.8	7
IP2I	40	1.25
LSM	0 (assume all 1.8 cpd are background)	-

Thus, in agreement with low muon flux we found significant reduction factors for both fast and thermal neutrons

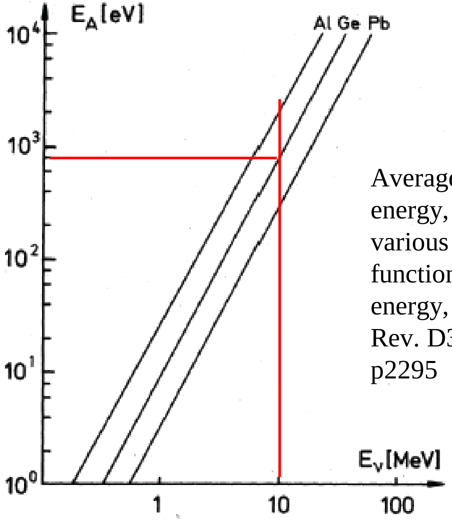
Neutrinos from pulse reactor

- Aim – signal/background discrimination;
- Neutrinos come from beta radioactive isotopes;
- Short living isotopes == high energy

  Maximal recoil energy $2E_\nu^2/M$
  for Ge ~2.5 keV (10 MeV), 6 keV (15 MeV)
  i.e. ionization ~ 0.5 keV and 1.2 keV

- High energy ≠ high energy neutrinos

Background (shield from cosmogenic radiation)
Distance from reactor (i.e. flux).



Average recoil energy, E_A, for various nuclei as a function of neutrino energy, from Phys. Rev. D30, 1984, p2295

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.


С Новым 2024
Годом !!!