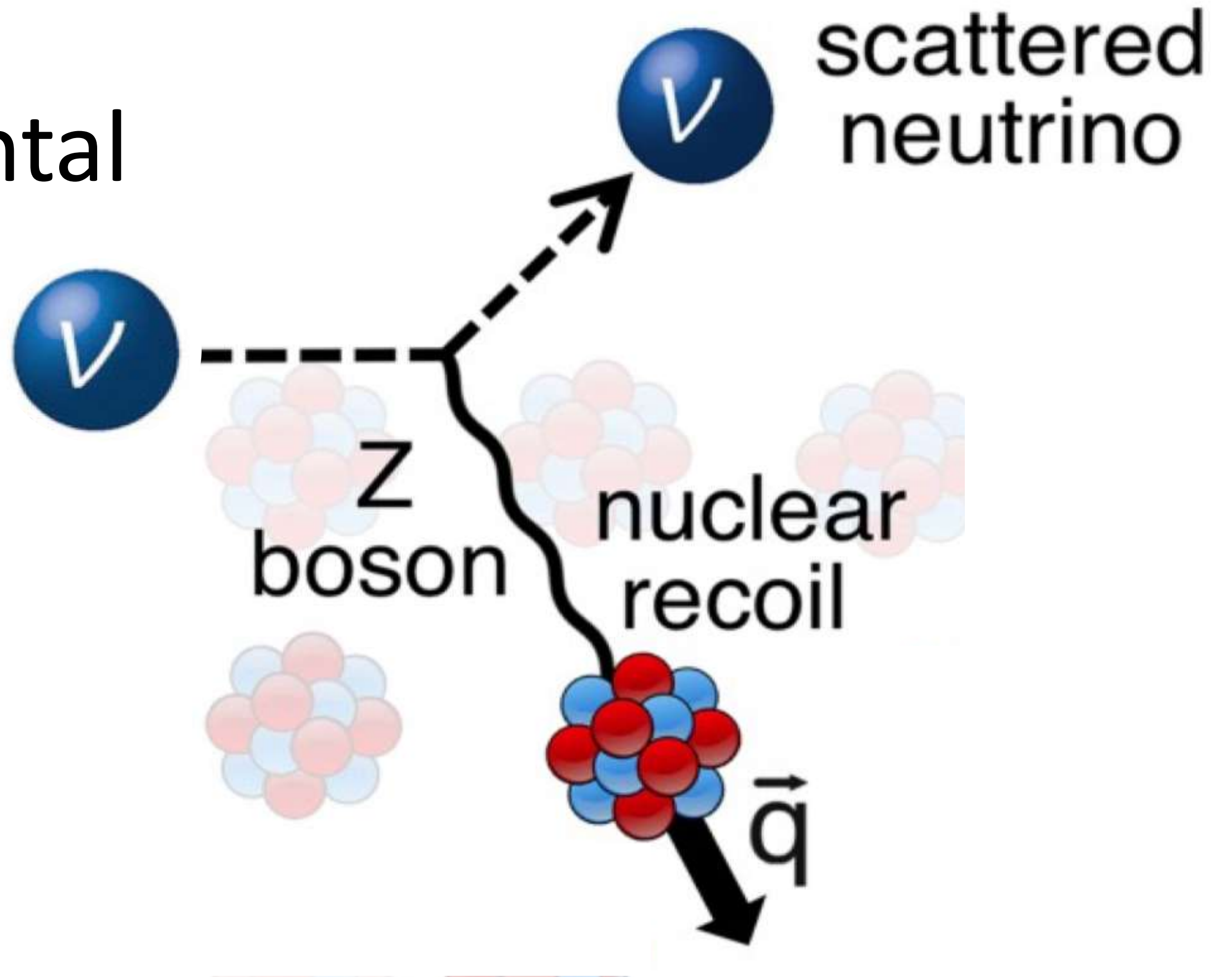
Worldwide experimental study of CEvNS

Dmitry Akimov
NRNU MEPhI

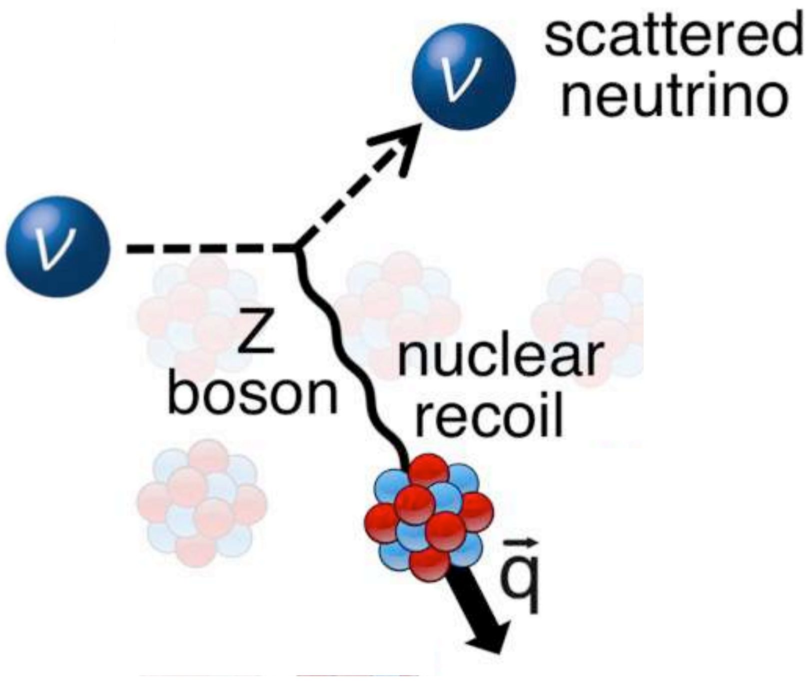


21-st Lomonosov Conference on Elementary Particle Physics, Moscow, August 24-30, 2023

Coherent elastic neutrino-nucleus scattering (CEνNS): $\boldsymbol{\nu} + A \Rightarrow \boldsymbol{\nu} + A$

It was predicted theoretically almost 50y ago by:
D.Z. Freedman, Coherent effects of a weak neutral current, Phys. Rev. D 9 (1974) 1389. **USA**
&
Kopeliovich V B, Frankfurt L L JETP Lett. 19 145 (1974); Pis'ma Zh. Eksp. Teor. Fiz. 19 236 (1974). **USSR**

shortly after the discovery of a neutral current in neutrino interactions in the Gargamelle experiment at CERN. *Phys. Lett. B* 46, 138–140 (1973).



The effect of coherency takes place when $qR \ll 1$, where R – nucleus radius, q – transferred momentum: **the phases of scatter amplitudes A_i at different scatter centers inside the nucleus are close to each other**

$$\Rightarrow A = \Sigma A_i \Rightarrow \sigma \sim N^2$$

$qR \sim 1$ for $E_\nu \sim 50$ MeV

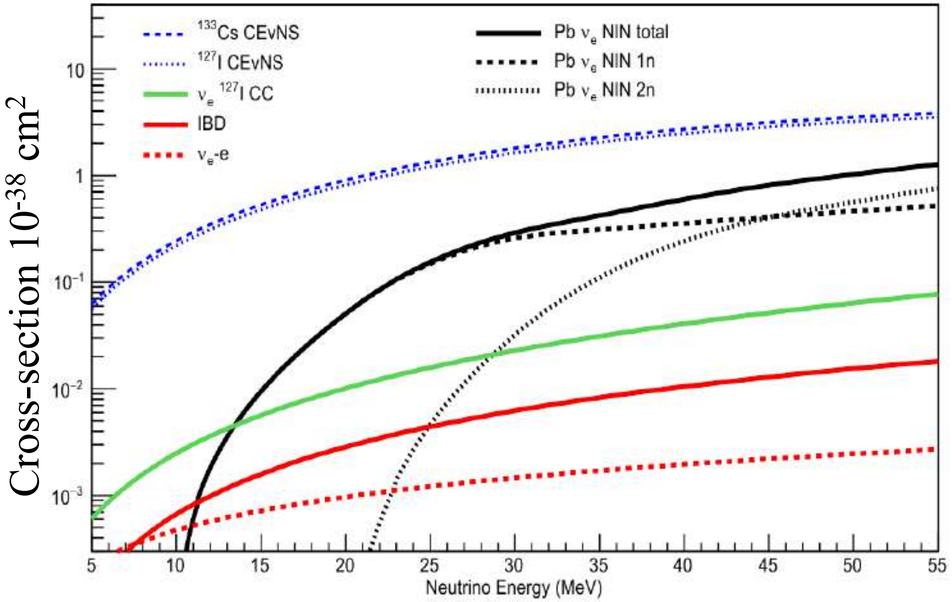
CEvNS has never been observed experimentally until recently (2017, by COHERENT collaboration) because of the very small energy transfer to the nucleus (keV- and sub-keV- recoil energies)
The situation is even worse because of a so-called quenching factor, which reduces the signal

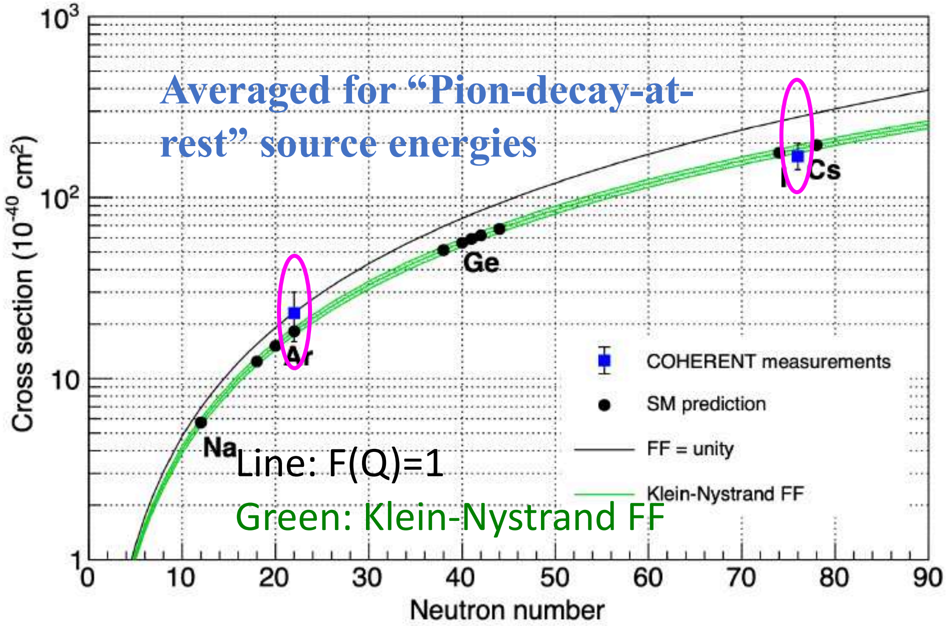
CEvNS cross-section

$$\frac{d\sigma}{dT}_{coh} = \frac{G_F^2}{4\pi} M Q_W^2 \left(1 - \frac{MT}{2E_\nu^2}\right) F_{nucl}^2(Q^2)$$ where T – nucl. recoil energy, F – nuclear FF

$Q_W = [Z(1-4\sin^2\theta_W) - N] \approx N$ – weak nucl. charge

$\sin^2\Theta_W \sim 0.25$ ⟹ $\frac{d\sigma}{dT}_{coh} \sim N^2.$





Experimental points by **COHERENT**: PRL vol. 129 081801 (2022) **Cs & I**

PRL vol. 126 012002 (2021). **Ar**

For heavy nuclei (Cs, I, Xe):

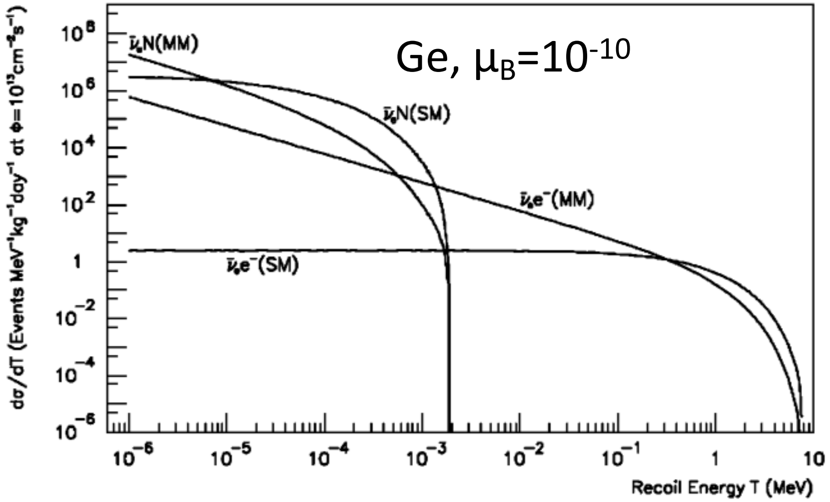
$\langle\sigma\rangle \sim$ **10^{-40}** cm^2 (averaged for the reactor antineutrinos: 0 – ~10 MeV)

$\langle\sigma\rangle \sim$ **10^{-38}** cm^2 (averaged for the "Pion-decay-at-rest" neutrinos: 0 – ~50 MeV)

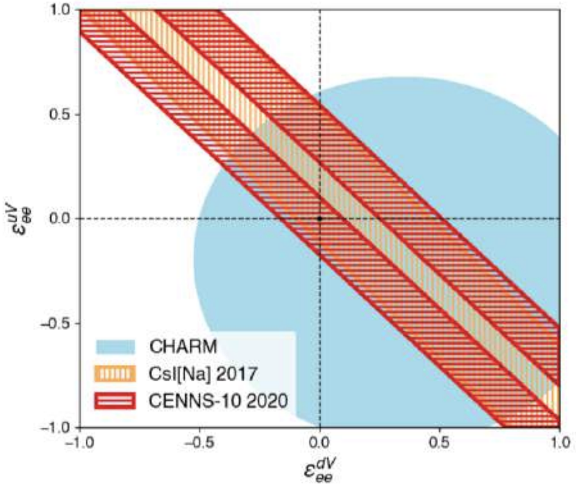
Motivation of experiments

- “Non-standard” physics:

ν magnetic moment

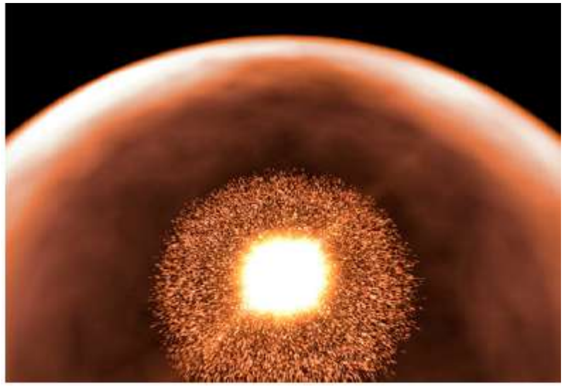


ν-quark interaction



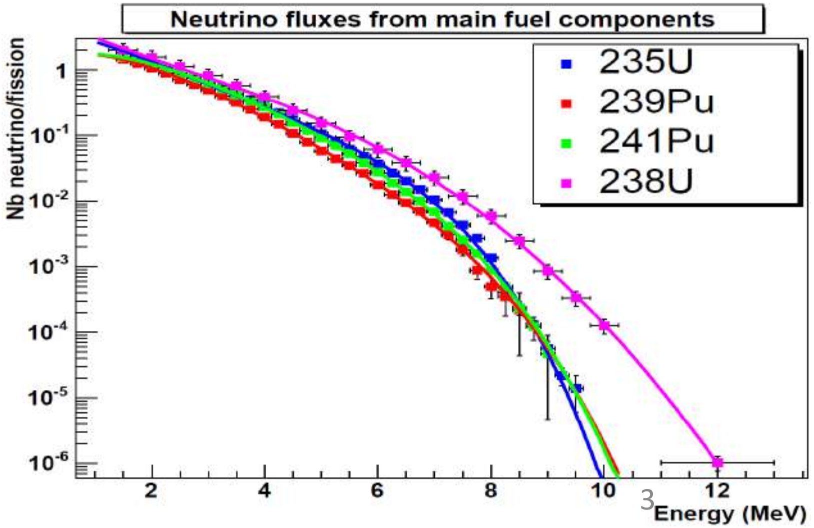
- Very important role of CEvNS in astrophysics:

significantly affects supernova dynamics



99% of gravitational binding energy goes to ν!

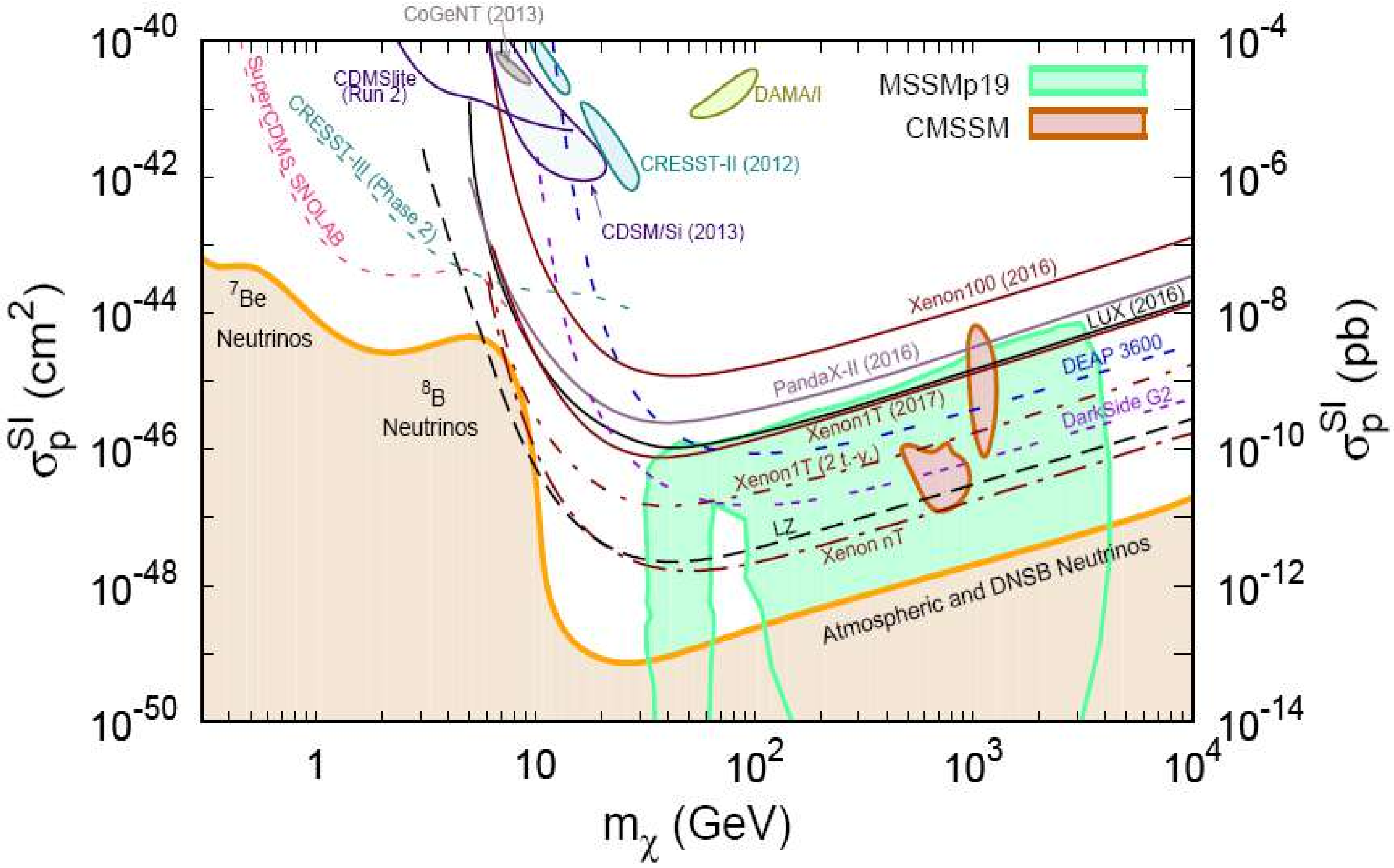
- Monitoring of nuclear reactors



- A tool for study of nucl. structure:

measurement of nuclear form-factors

CEνNS is irreducible background floor for DM experiments

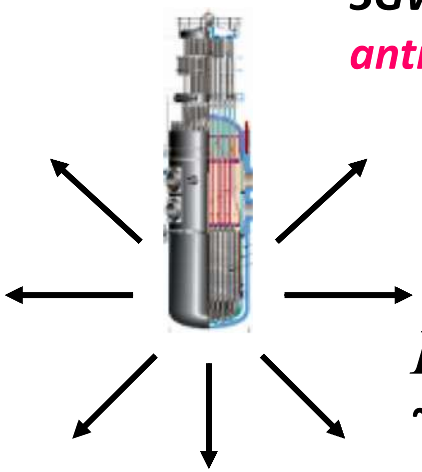


arXiv:1707.06277v1 [hep-ph] 19 Jul 2017

Sources of ν

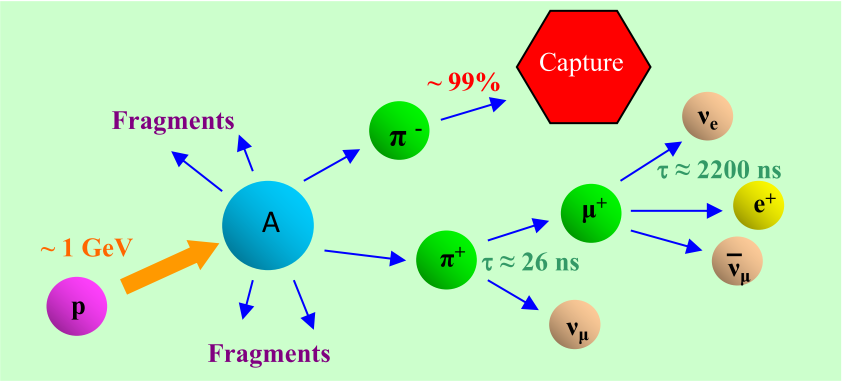
3GW NPP reactor –
antineutrino $\bar{\nu}_e$

~ $6 \cdot 10^{20}$ c^{-1}

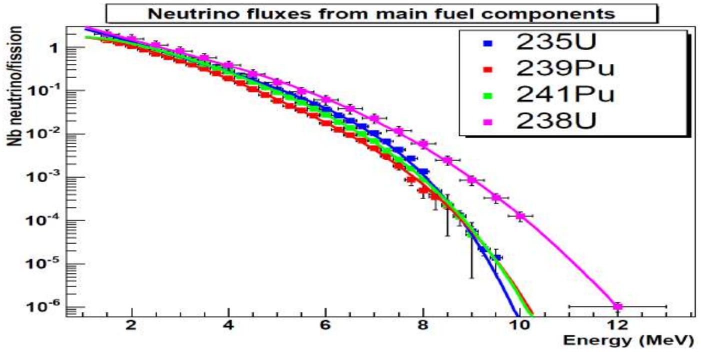


***Flux** @20m*
~ $1.2 \cdot 10^{13}$ cm^{-2}c^{-1}

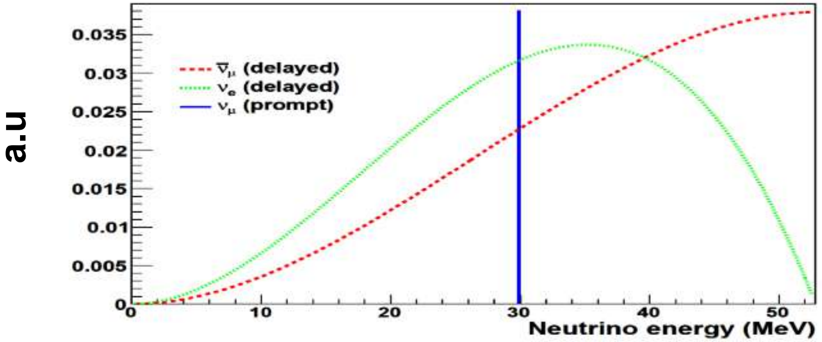
πDAR **- pion Decay At Rest -** $\nu_\mu, \bar{\nu}_\mu, \bar{\nu}_e$

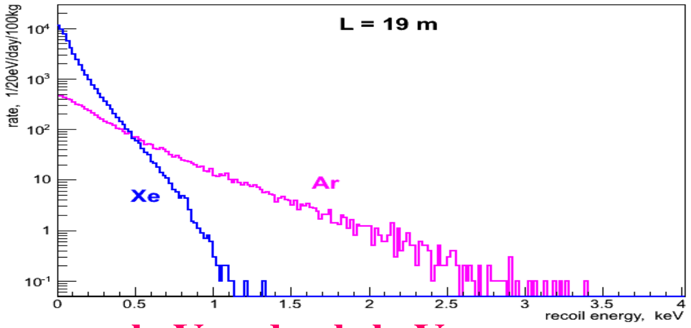


ν flux is lower by 10^6, σ by 10^2 higher



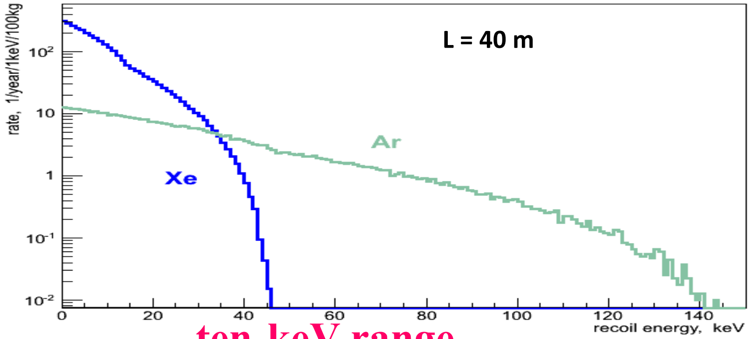
Energy spectra ν





Nucl. recoil spectra

(Xe and Ar)



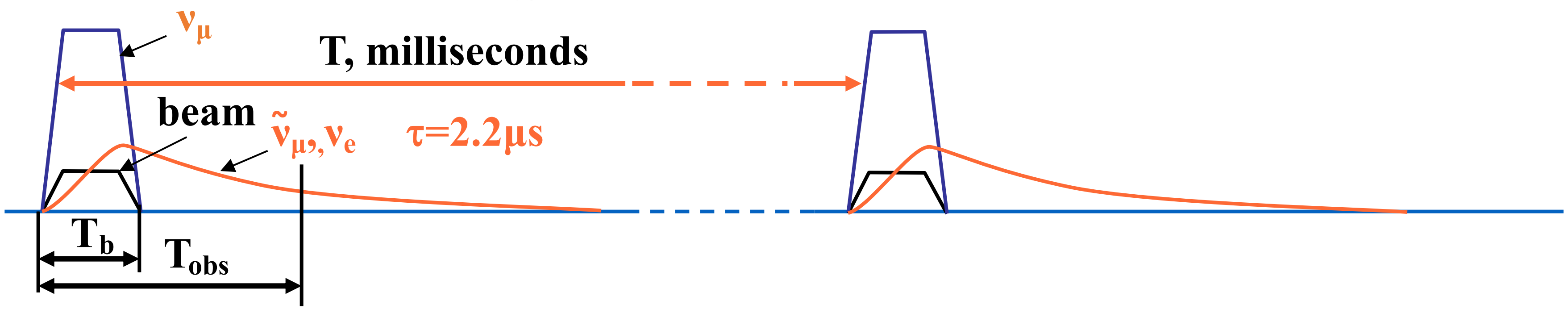
keV and sub-keV range

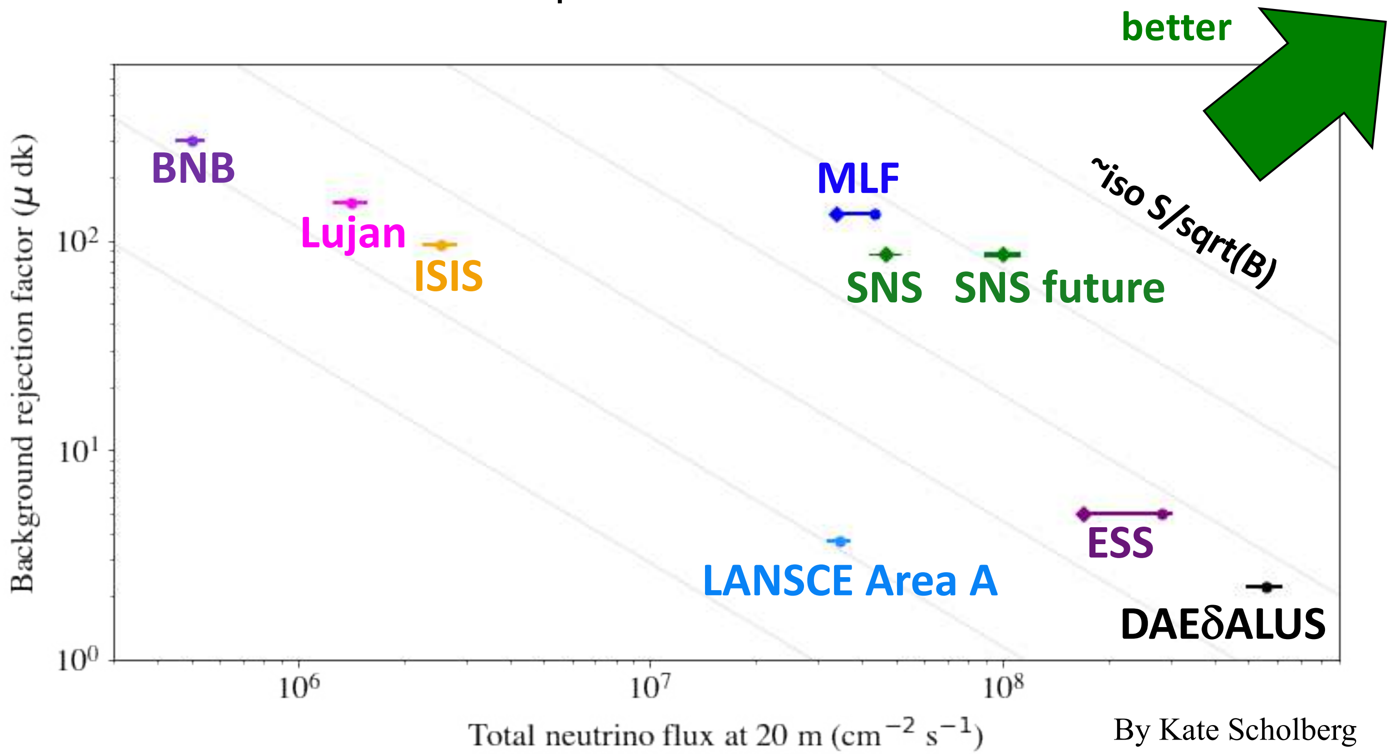
ten-keV range

Accelerator - π Decay At Rest source

Pulsed beam of an accelerator is an essential factor of background reduction (~1/Duty factor)!

Duty factor = $T_{obs}/T \sim 10^{-1} \div 10^{-5}$





By Kate Scholberg

Lujan	US (LANL)
ISIS	UK (RAL)
BNB	US (FNAL)
SNS	US (ORNL)
MLF	Japan (J-PARC)
LANSCE Area A	US (LANL)
ESS	Sweden (planned)
DAEδALUS	US (planned)

The 1-st proposal of experiment on CEνNS detection

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky

Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany

(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small ($10-10^3$ eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

The idea has never been realized

However, it stimulated the development of new direction of low-threshold, low-background detectors to search for dark matter.

The detector idea

-Micron size metastable superconductive granules in a colloidal system placed in magnetic field

-The temperature is tuned so that some granules loose conductivity when the very small energy deposition happens in the detector

-This results to the measurable change of the magnetic field

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten

Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

List of experiments on CEvNS detection

Experiment	Mass, kg	Technology	Location	ν Source
CoGeNT	**0.5**	HPGe PPC	USA, San Onofre	Reactor
TEXONO	**1.0**	HPGe PPC	Taiwan, Kuo-Sheng	Reactor
νGEN	**1.4**	HPGe PPC	Russia, Kalinin NPP	Reactor
CONUS	**4.0**	HPGe PPC	Germany, Brokdorf	Reactor
Dresden-II	**3.0**	HPGe PPC	USA, Dresden NPP	Reactor
CONNIE	**0.04**	Si CCDs	Brazil, Angra dos Reis	Reactor
MINER	**10**	Ge/Si bolometers	USA, TRIGA	Reactor
ν–cleus	**0.01**	$CaWO_4$, Al_2O_3 bolometers	France, Chooz NPP	Reactor
Ricochet	**1/0.3**	Ge, Zn bolometers	France, ILL-H7	Reactor
NEON	**13.3**	Scintillator NaI	South Korea, Hanbit	Reactor
RED-100	**100**	LXe two-phase	Russia, Kalinin NPP	Reactor
COHERENT		CsI, Ar, Ge, NaI	USA, SNS	πDAR
CCM	**10000**	LAr	USA, Lujan	πDAR

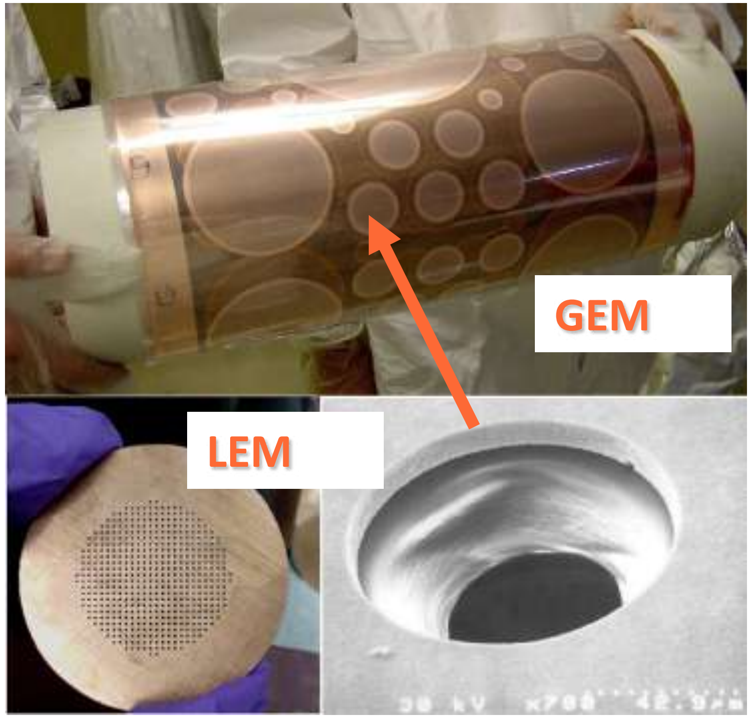
The 1-st attempts started from gas detectors

Such detectors are attractive because potentially they may have the very low energy threshold (< 100 eV)

The gas detectors with microstructures and gas amplification:

P. S. Barbeau et al., IEEE Trans. on Nucl. Sci., V. 50 (2003), no. 5, 1285

J.I. Collar, Y. Giomataris, **Possible low-background applications of MICROMEGAS detector technology**, Nuclear Instruments and Methods in Physics Research A 471 (2001) p. 254.

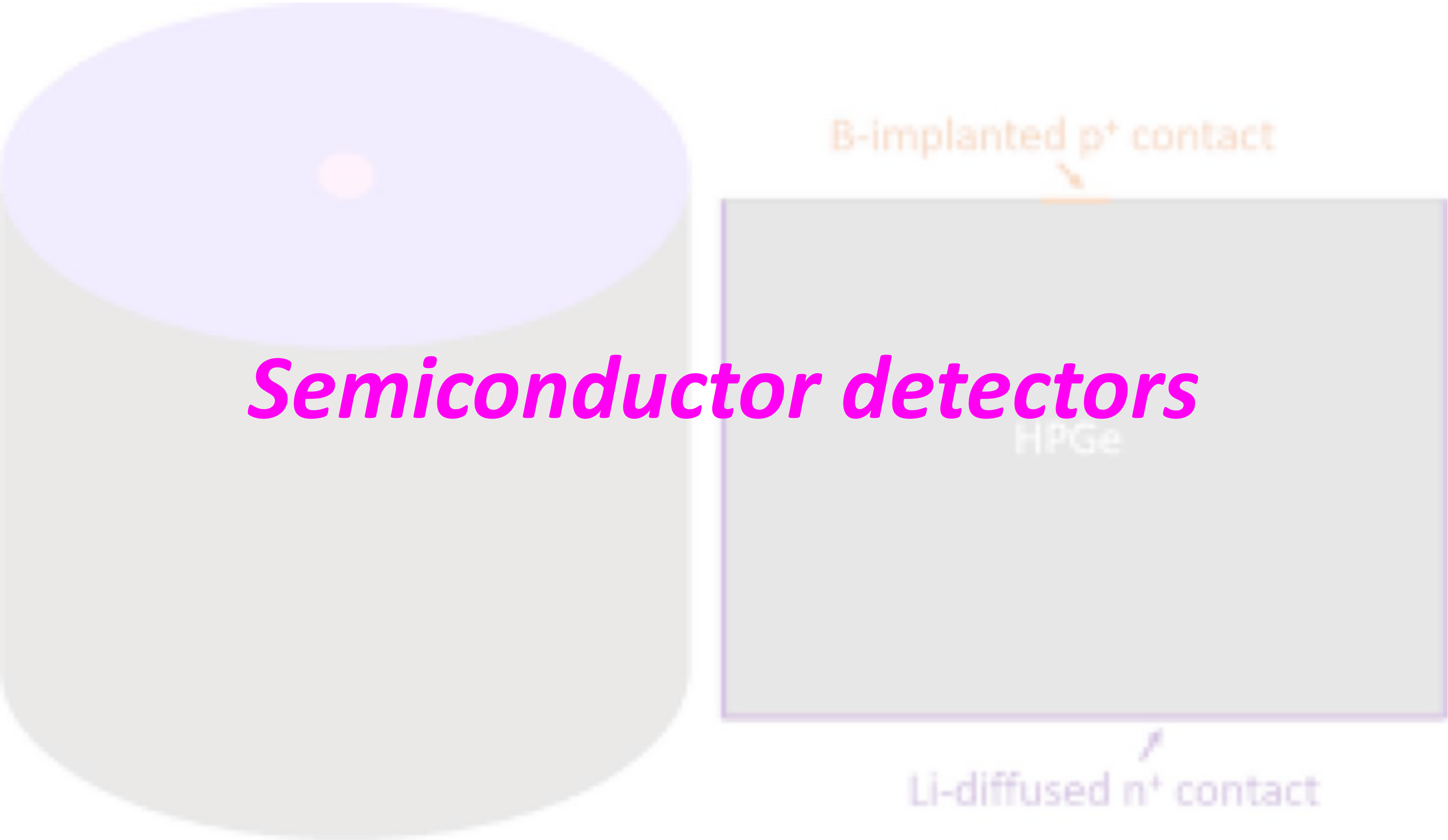


The array of cylindrical proportional counters:

A. V. Kopylov et al., **Gaseous Detector with sub keV Threshold to Study Neutrino Scattering at Low Recoil Energies**
Advances in High Energy Physics V. 2014 (2014), Article ID 147046

The main drawback: very low mass !

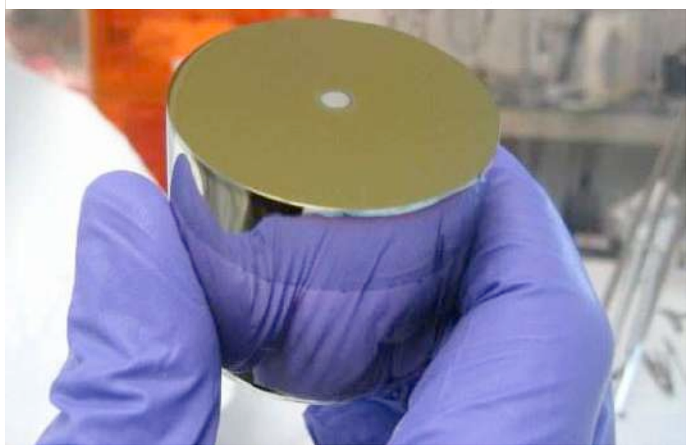
Semiconductor detectors



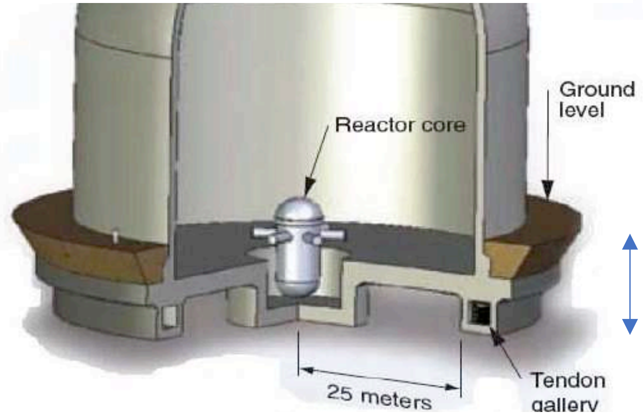
CoGeNT (USA)

p-type point contact (PPC) Ge detector (in fact, a new type of semicond. detectors):

The energy threshold is significantly reduced (<1 keV) due to very low capacitance; excellent energy resolution!



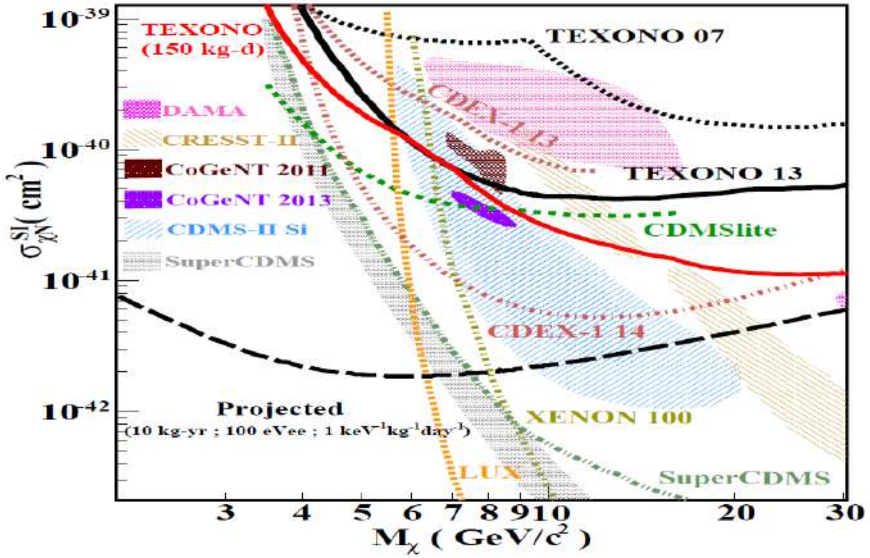
CoGeNT - San Onofre Nuclear Power Reactor, USA, 2009



Energy threshold turned to be too high: ~400 eV_{ee}

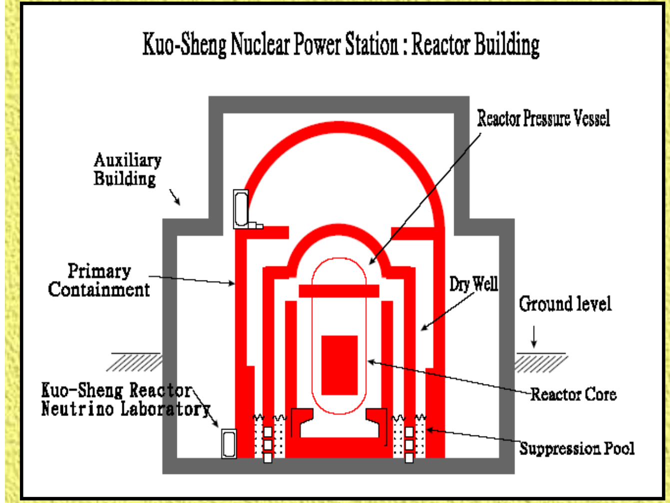
~ 30 mwe

Then the CoGeNT group switched to the DM search for where the threshold requirement is softer:

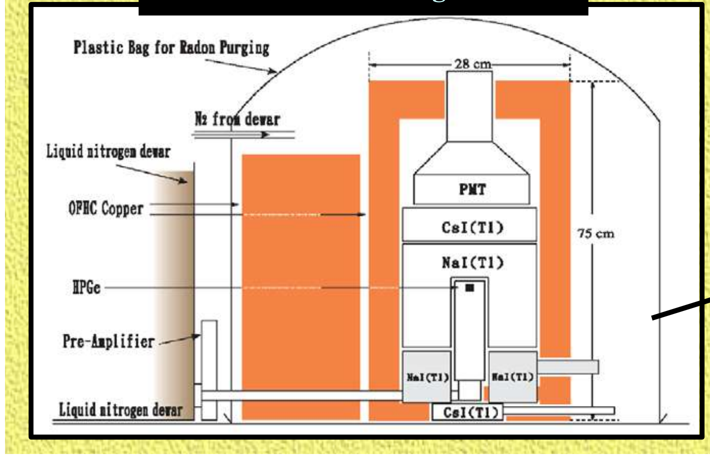


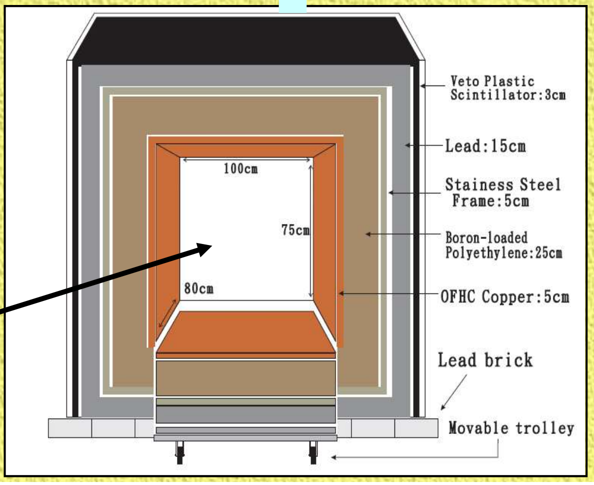
TEXONO (Taiwan)

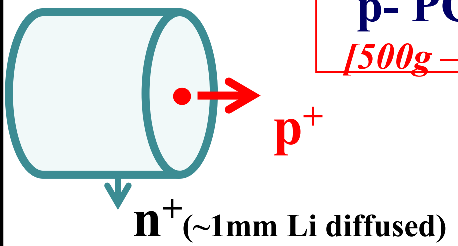
at Kuo-Sheng Reactor Neutrino Laboratory (KSNL) in Taiwan



Baseline Design



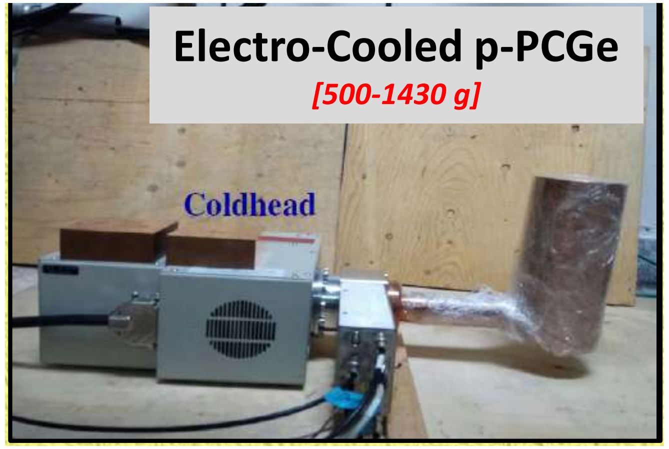




p- PCGe
[500g – 1 kg]

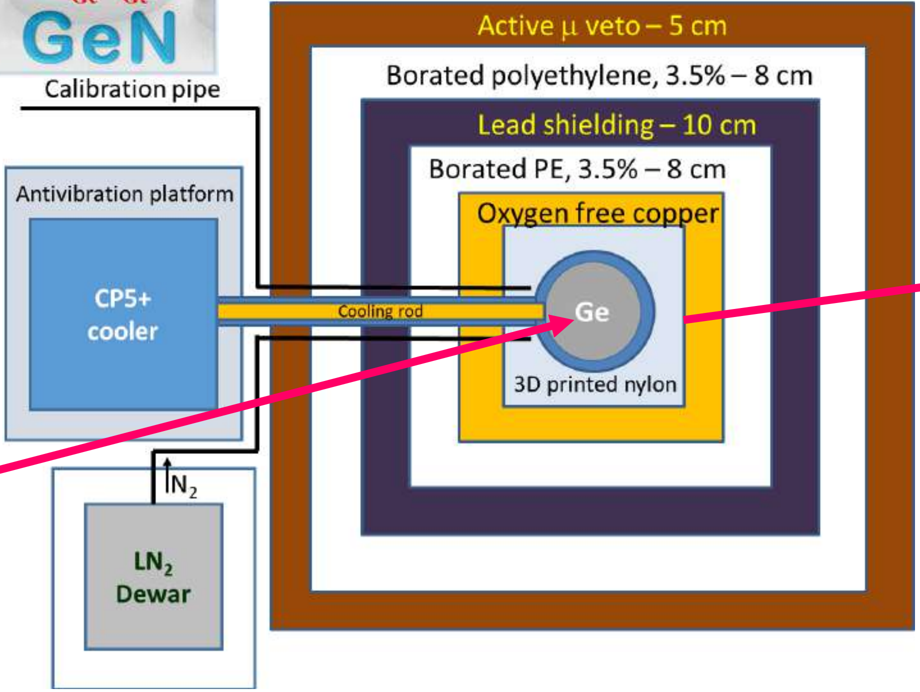
or **n- PCGe**

Threshold 300 eV_{ee} with LN_2 cooling

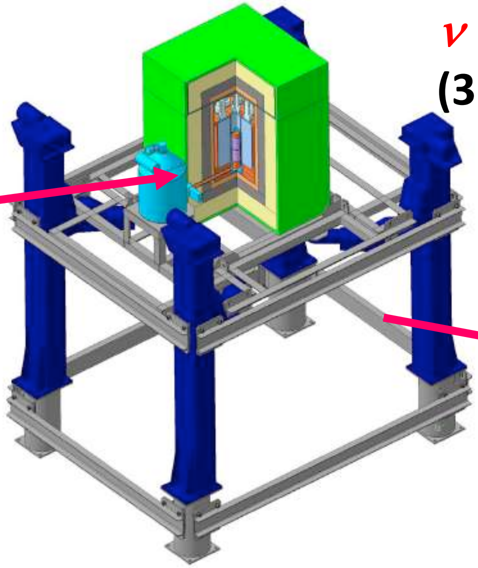


Threshold 200 eV_{ee} with electro-cooling

ν GEN

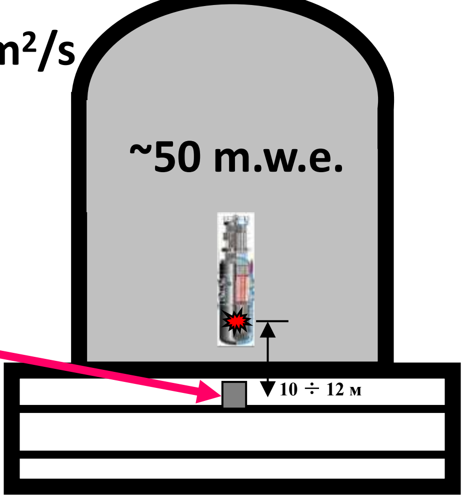


p-PC Ge
1.4 kg

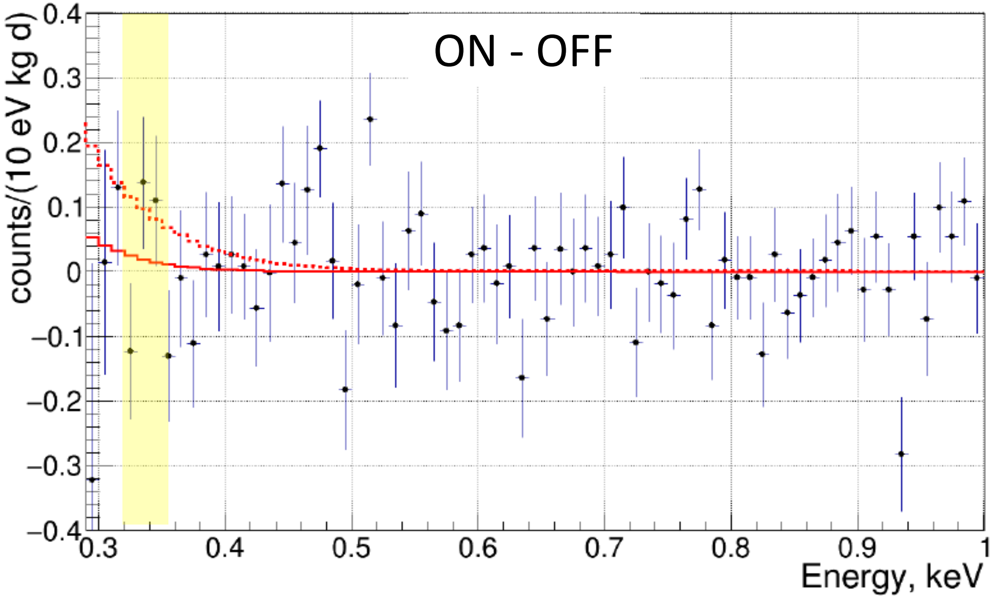


ν flux:
(3.6-4.4) 10^{13} ν/cm²/s

10 ÷ 12 m



•*Phys.Rev.D* 106 (2022) 5, L051101



From A.Lubashevskiy talk @M7, 22.03.2023

	Counts in region [320..360] eV	Measurement time, days	Counts per kgd (stat. error only)
Reactor ON	251	94.5	2.32 ± 0.15
Reactor OFF	126	47.1	2.34 ± 0.21
ON-OFF			-0.017 ± 0.255
CEνNS, k = 0.26	55		0.46

—— k=0.179
⋯⋯ k=0.26
quenching factor

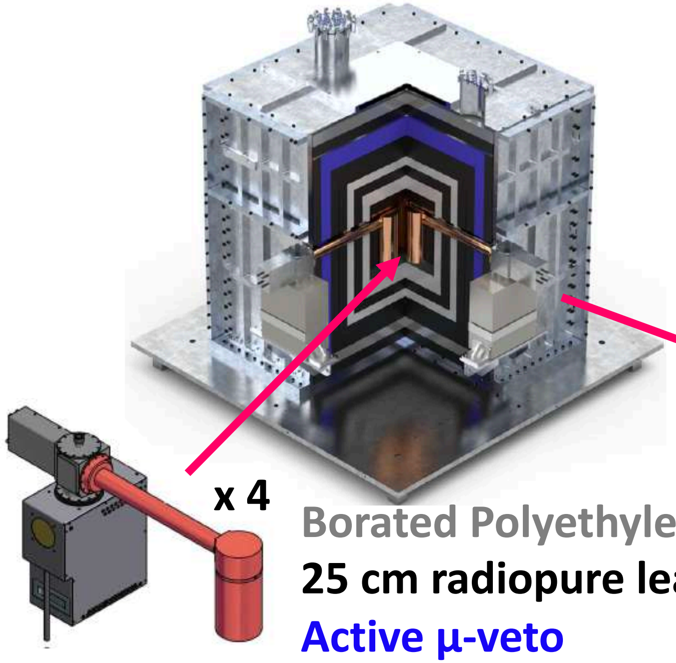
Current status - D.Ponomarev talk this afternoon

CONUS

Max-Planck-Institut für Kernphysik

NPP Brokdorf , Germany

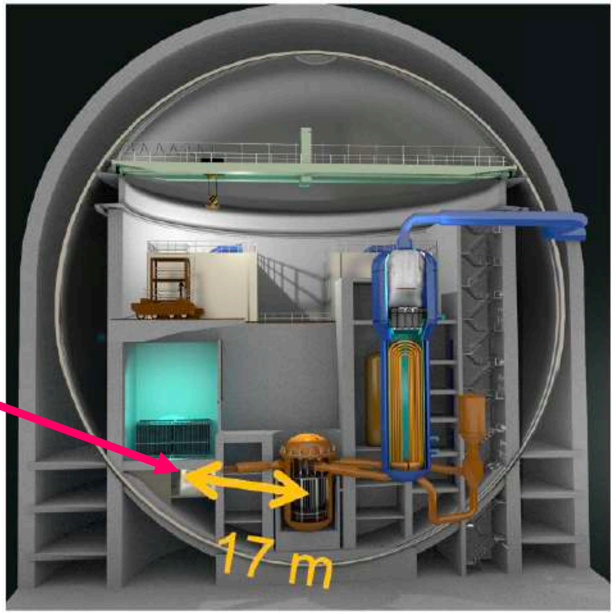
3.9 GW reactor



Borated Polyethylene

25 cm radiopure lead

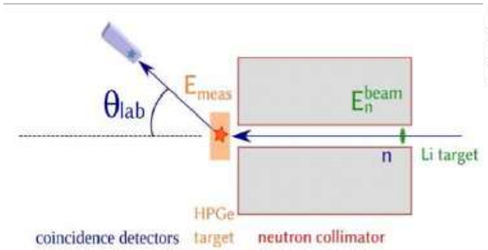
Active μ-veto



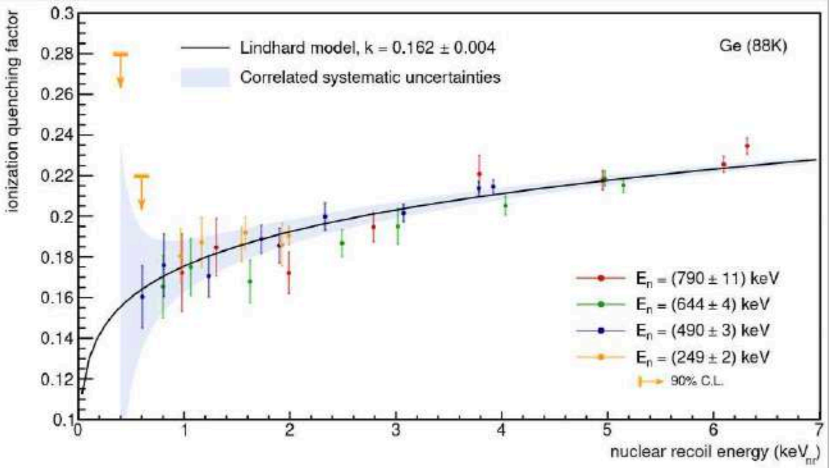
5 years of successful operation
4 x 1 kg Ge detectors @17 m
Φ=2.3 x 10^{13} ν/cm^2/s
Energy threshold ~200 eV$_{ee}$
Ultra-low bckg in ROI ~ 10 cpd/kg

From W. Maneschg talk @M7, 22.03.2023%

Careful QF (k) measurements

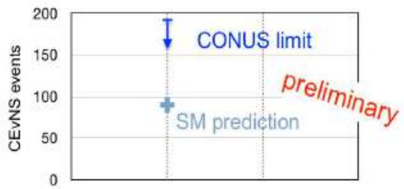


In ROI k=0.162+-0.004 (stat.+syst.)



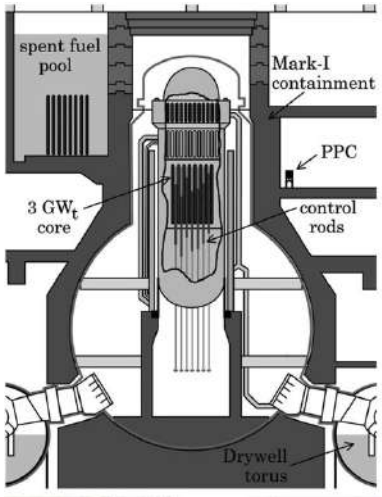
Preliminary results:

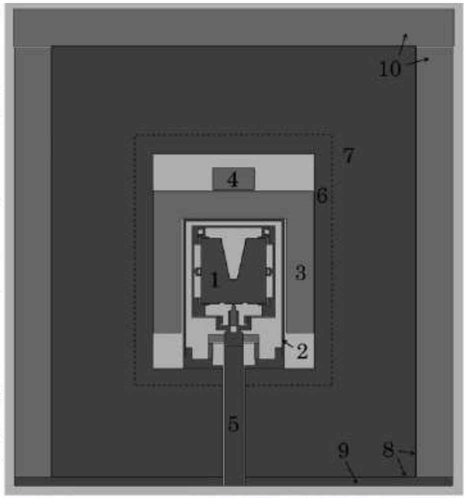
- so far, statistical likelihood ratio test
- all Conus detectors do not find a signal
- combined limit (90% C.L.): factor ~2 above predicted CEvNS based on Lindhard quenching with k=0.162
- further slight improvements expected (PSD, additional statistics,…)



Now moving to Leibstadt NPP (KKL) in Switzerland (CONUS+)

Dresden-II (NCC-1701) @Dresden NPP USA



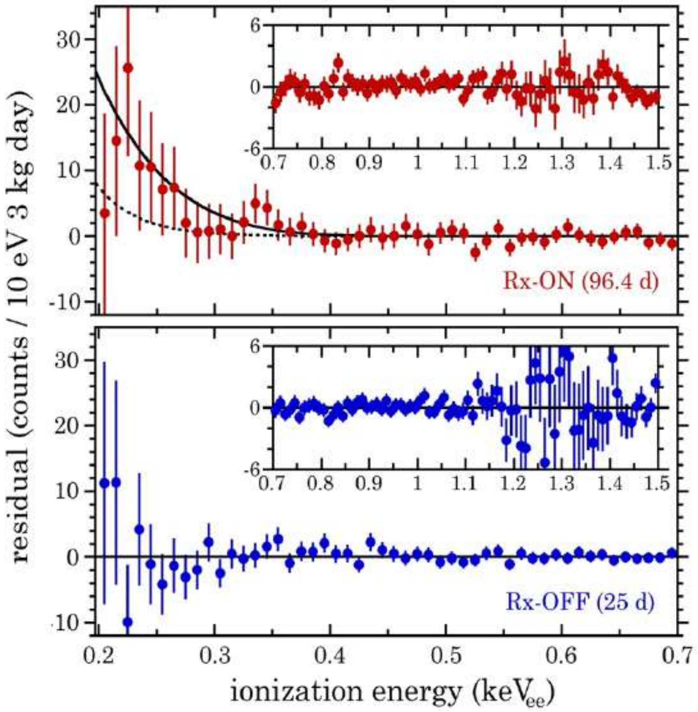


Very close to the reactor core:
10.39 m center-to-center

Very high $\overline{\nu}_e$ flux: 4.8×10^{13} $\overline{\nu}_e$/cm^{2}s
But, practically no overburden

p-PC Ge 2.9 kg, 200 eVee threshold

Claimes observation of CEvNS (consistent with SM prediction)!
arXiv:2202.09672
Phys. Rev. Lett. **129** (2022), 211802



Residual betw. the data and bckg model

However, there is a criticism from the CEvNS community:

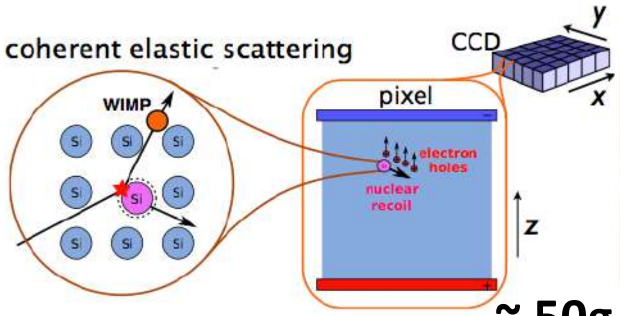
see Enectali Figueroa-Feliciano talk @M7, 22.03.2023:

- Claimed about strong preference (p<1.2·10^{-3}) for the presence of CEvNS.
- Similar to nuGeN antineutrino flux from reactor (4.8 10^{13} ν/cm2/sec)
- Sideway location gives almost no overburden (cosmogenic background).
- Almost no shielding against fast neutrons.
- Different shielding during reactor ON and OFF
- Big difference in background levels during reactor ON and OFF
- Moderate energy resolution > 160 eV (FWHM) (in nuGeN – 101.6(5) eV)

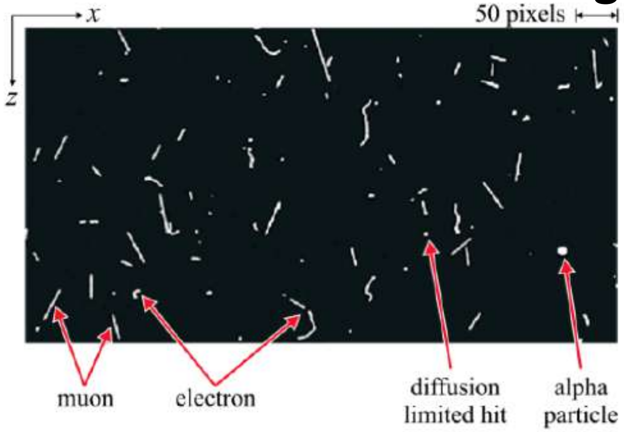
- **and measured QF is by >2 higher! arXiv:2102.10089**

CONNIE (Coherent Neutrino Nucleus Interaction Experiment)

Si CCDs

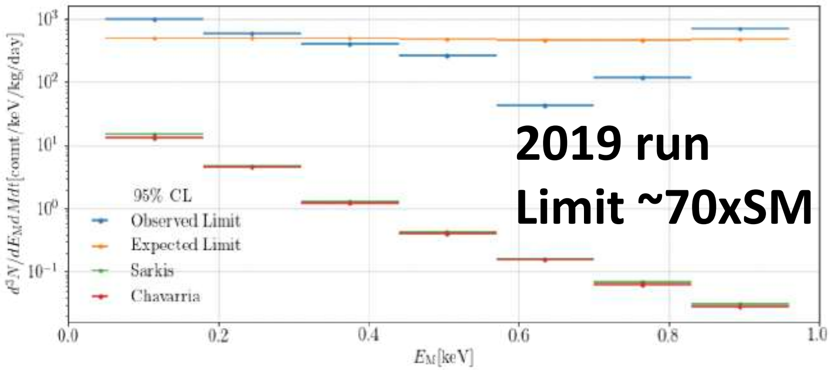


~ 50g



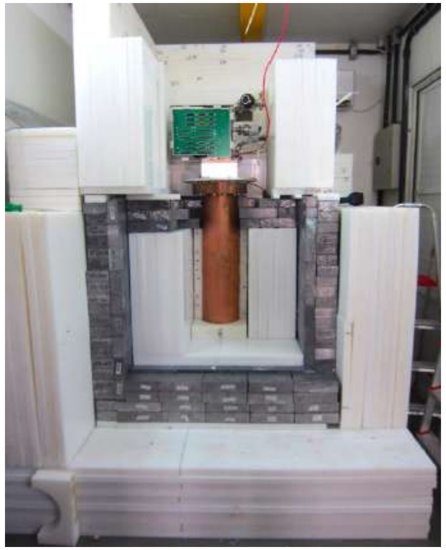
Rejection of ER interactions
and acception of only point-like NR events
Threshold ~ 50eV

arXiv:1608.01565, 2110.13620



2019 run
Limit ~70xSM

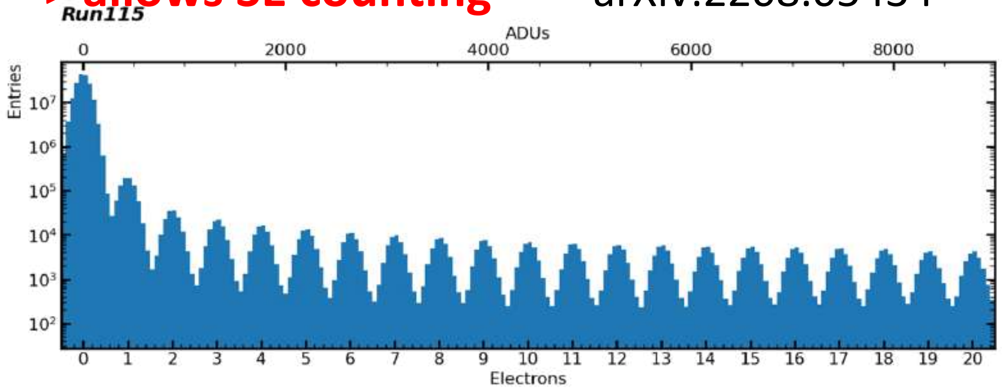
Angra dos Reis NPP, Brazil



Now testing the new technology – Skipper CCD

Allows to improve s/n ratio by multiple measurement (>1000 times!) of each cell charge

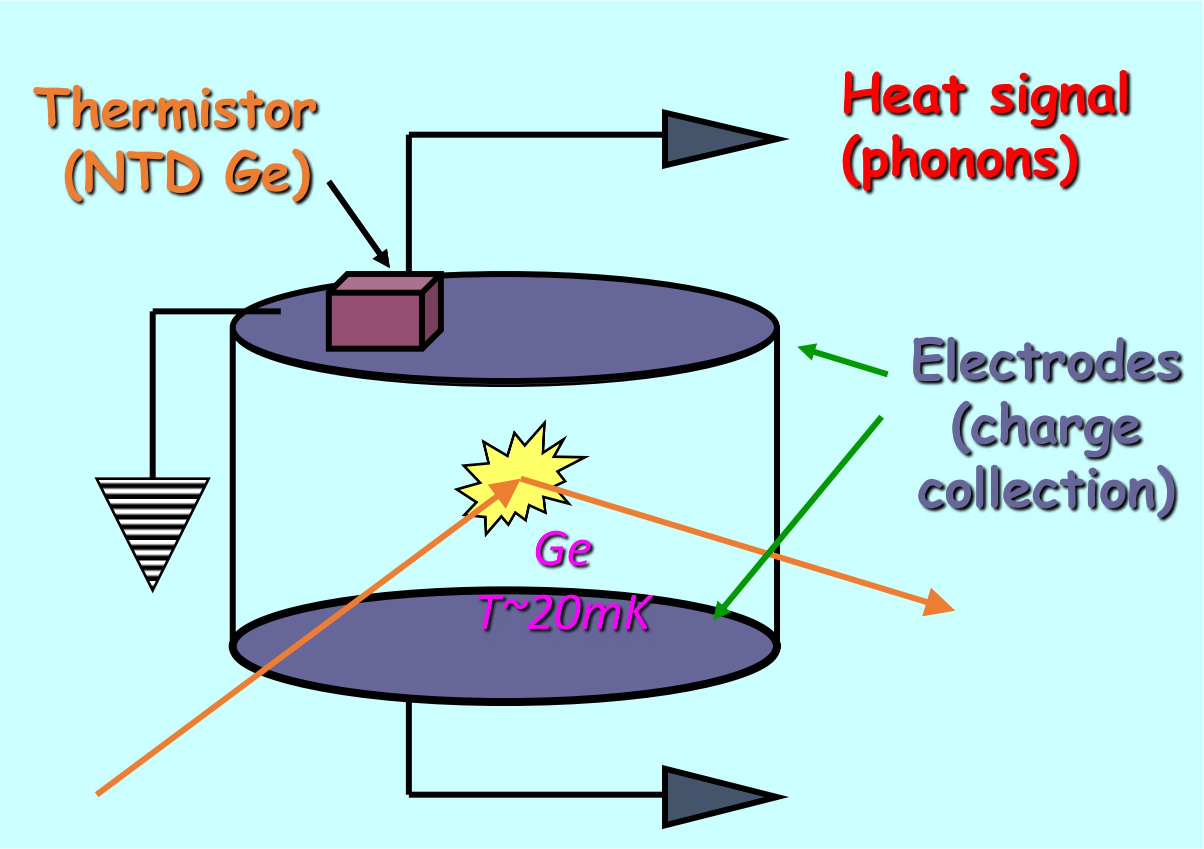
=> allows SE counting arXiv:2208.05434



Threshold => ~ 20 eV

Cryogenic bolometers

Principle of operation



At the low temperature, the specific heat capacitance C becomes very small:

$$C \sim T^3$$

For example,
$C_{Ge} \sim 1$ keV/mol/μK
@T ~ 20 мК

Very slow
But E_{thr} is down to tens eV

RICOCHET

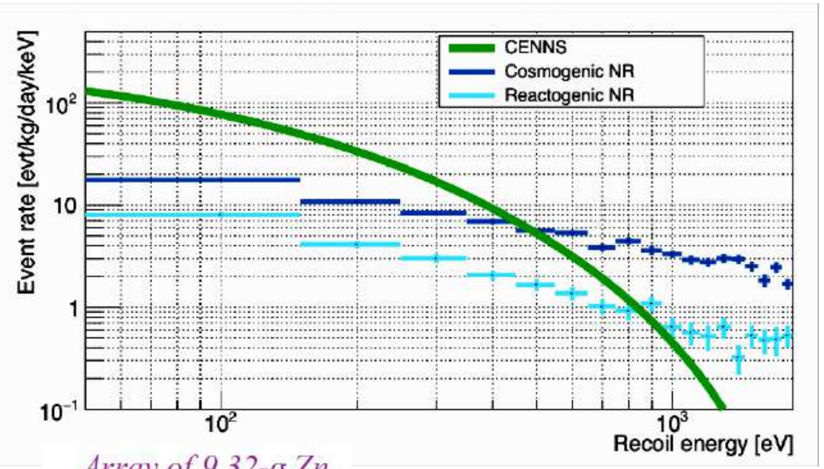
France, USA and Russia collaboration

58 MW ILL research reactor, **France**,
8.8 m from the core

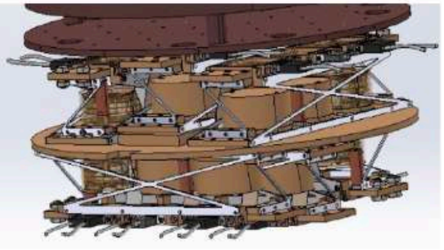
Eur. Phys. J. C (2023) 83:20

$1.1\times10^{12}\ \bar{\nu}_e/cm^2s$ significant overburden ~ 15 mwe

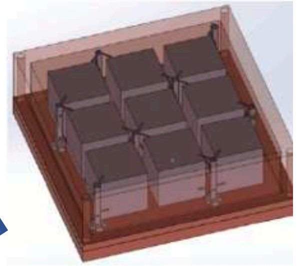
Expected CEvNS event rate of approximately 12.8 and 11.2 events/kg/day with a **50 eV** energy threshold and **Ge** and **Zn** targets crystal, respectively



Array of 18-to-27 42-g Ge detectors

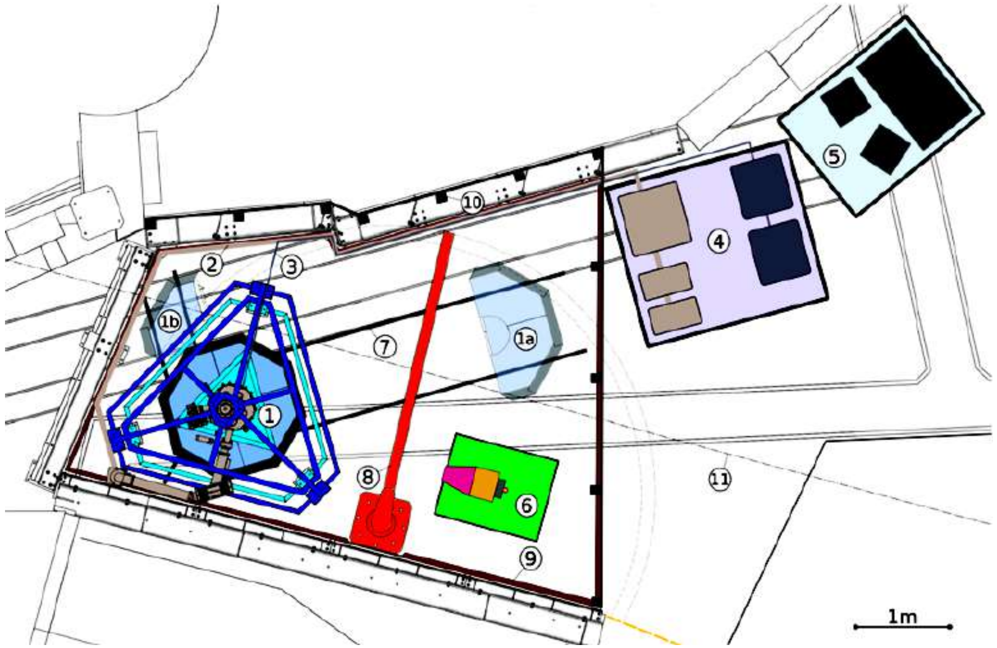


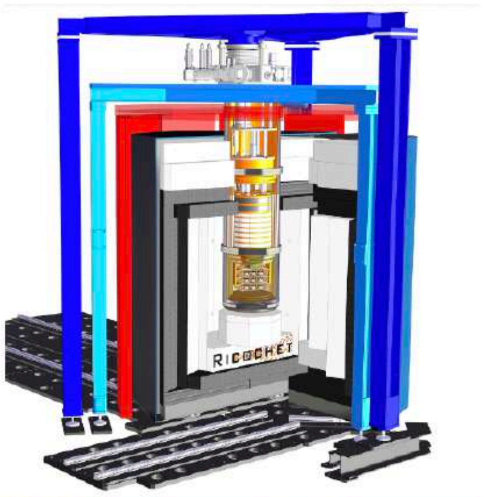
Array of 9 32-g Zn detectors



Detector construction is ongoing

First ν data mid-2024



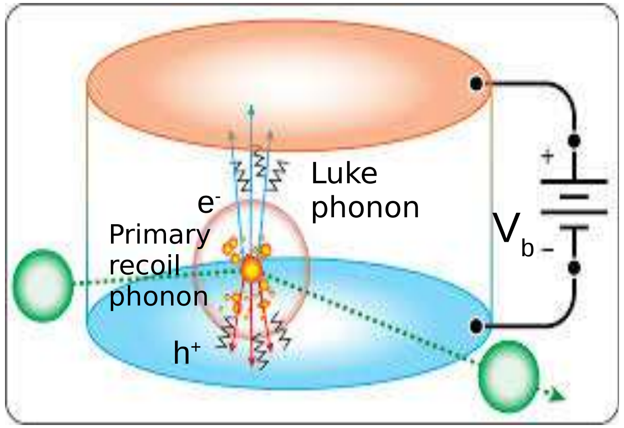


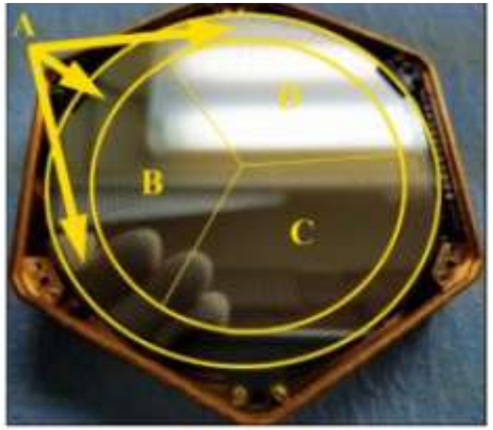
MINER

Texas A&M University

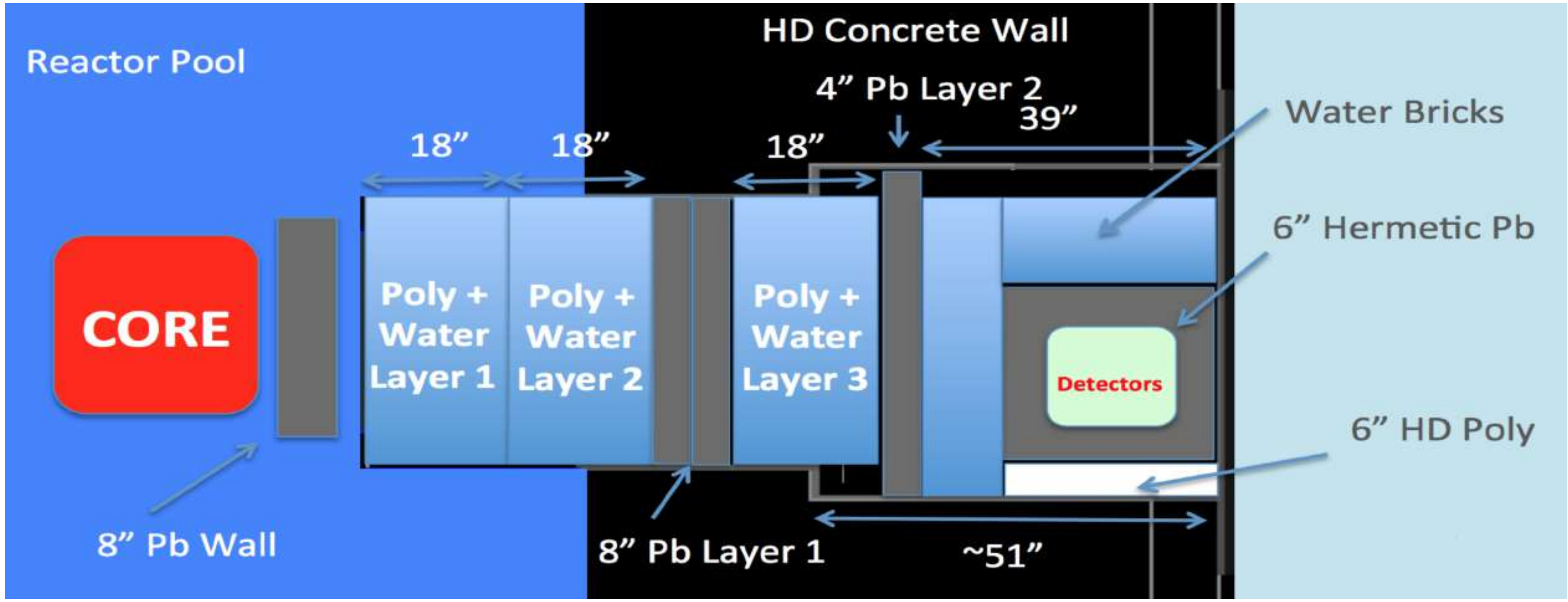
Mitchell Institute Neutrino Experiment at Reactor;
Detector – low-temperature bolometer with the use of Neganov-Trofomov-Luca phonon amplification effect
This allows to achieve ~ 10 eV energy threshold!

TRIGA 1 MW reactor (Training, Research, Isotopes, General Atomics)





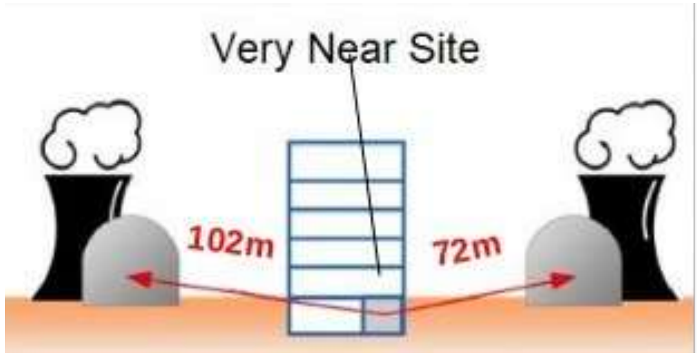
But very close - ~ 4.5 m



Currently, caring out engineering runs on site

NUCLEUS *(collaboration of 9 institutions)*

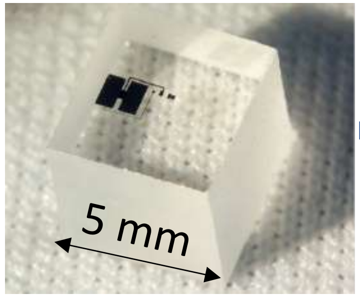
Chooz NPP, France



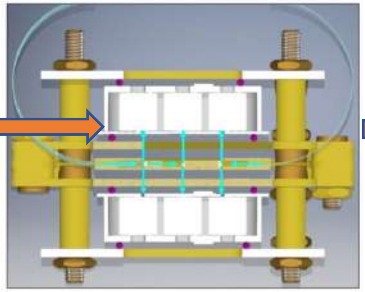
24 m² basement room (~3 m.w.e)
2x4.25 GWth nuclear reactors at the Chooz NPP
Baselines of 72 m and 102 m
expected antineutrino flux of 1.7×10^{12} ν/(s cm²)

1 gr-scale cryogenic calorimeters (bolometers)

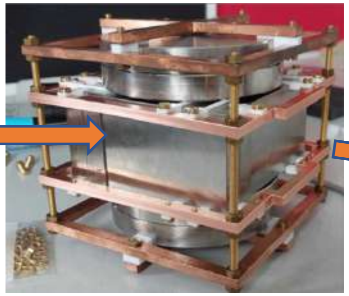
Basic idea: very small crystals => very low threshold (down to 20 eV_{NR}) & excellent energy resolution (~10 eV)



Al_2O_3, $CaWO_4$
CRESST experience of use

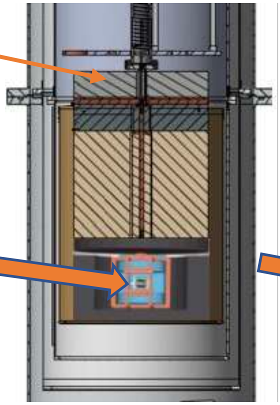


2x3x3 crystals arrays:
9x Al_2O_3, 9x $CaWO_4$

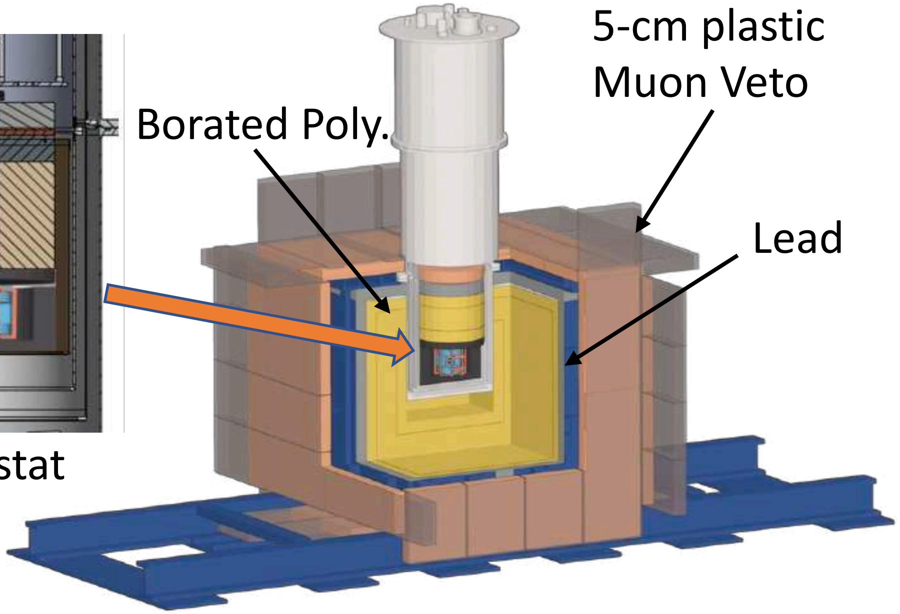


Active 4π veto:
4 HPGe crystals
4 kg in total

Cryogenic Muon Veto



Cryostat



Commissioning of the full setup @TUM University this year, move to Chooz in 2024

Noble gas detectors, two-phase

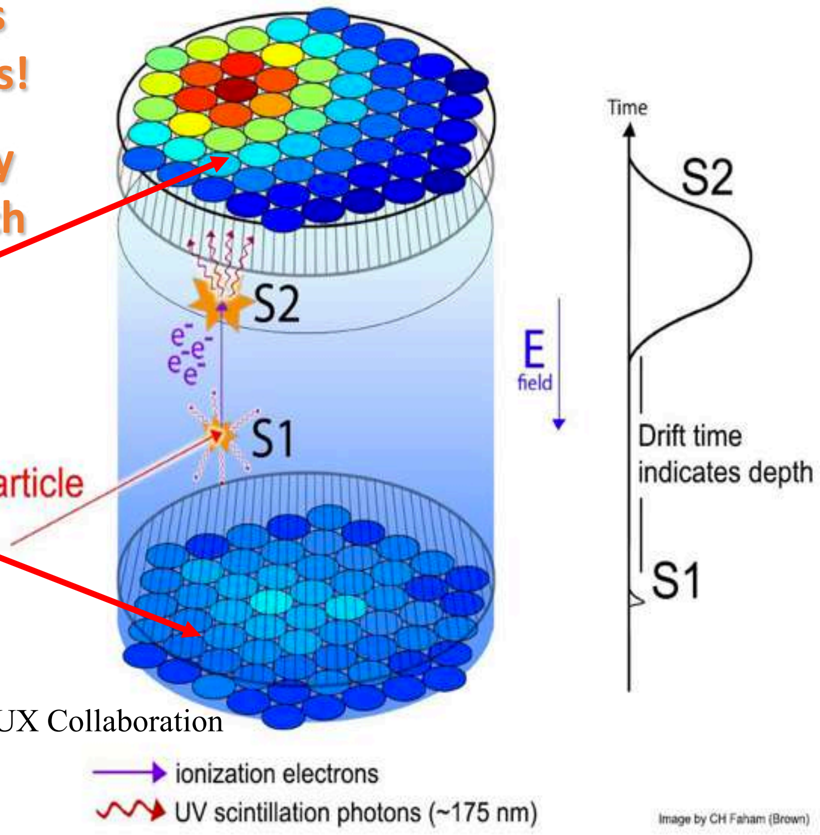
Two-phase method was proposed by Russian scientists in MEPhI in 1970s!

Later, successfully used in DM search

Emission two-phase detector

Photodetectors

(photomultipliers)



Picture by LUX Collaboration

The produced charge is extracted from the liquid to the gas phase

A two-phase method combines the advantages of gas detectors: the possibility of proportional or EL amplification, 3D positioning, SE counting, with the possibility to have the large mass (in the liquid phase)!

The progress in setting limits on SI WIMP-proton cross-section RAPIDLY increased with the use of two-phase detectors

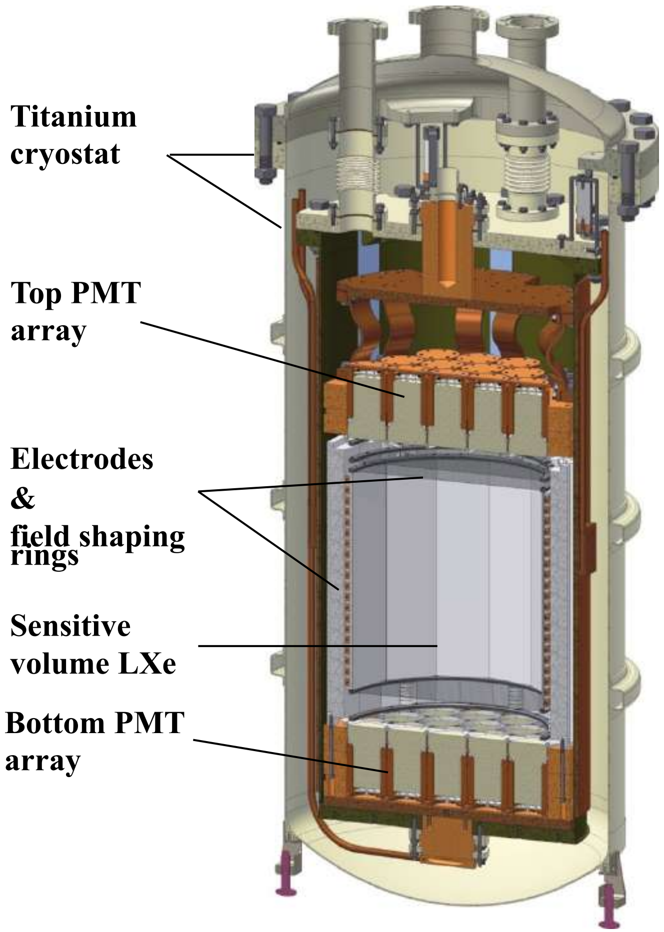
1-st proposal for CEvNS detection was by C.Hagmann & A.Bernstein (LAr):

IEEE Transactions on Nucl. Science V.51, no.5, p2151

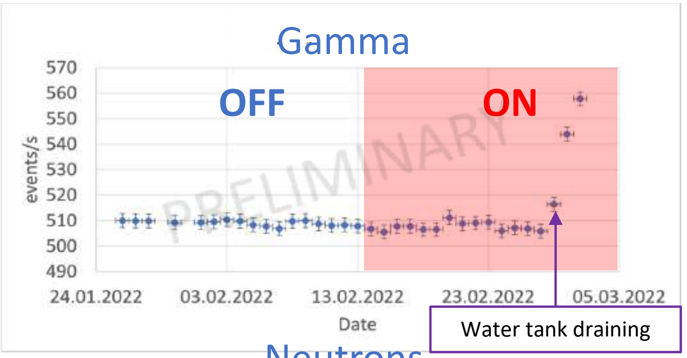
LXe: RED-100

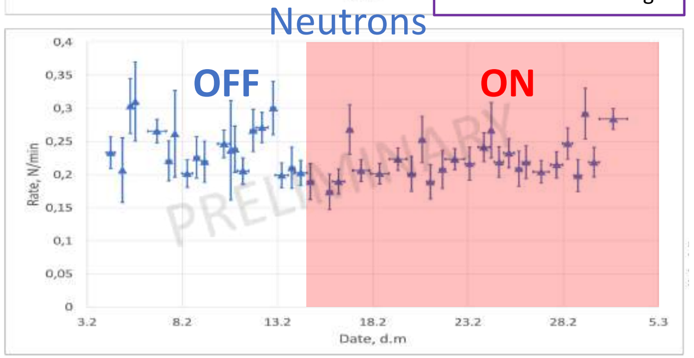
19 m from the core, ~50 mwe
ν flux:
1.35 10^{13} ν/cm^2/s

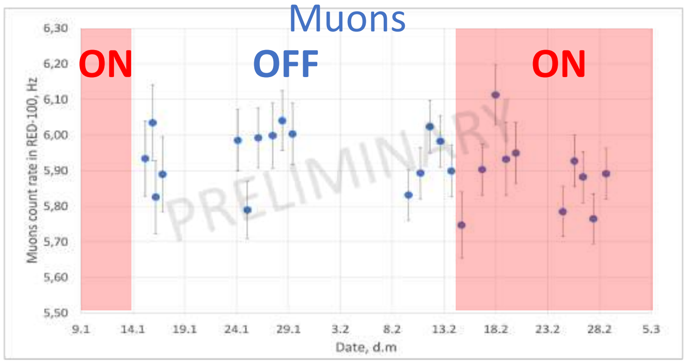
- 26 PMTs Hamamatsu R11410-20 (19 in top PMT array, 7 in bottom PMT array)
- Contains ~200 kg of LXe (~ 100 kg in FV)



Stable bckg during ON-OFF !







Data taking run with LXe target:
mid Jan 2022–beg Mar 2022
2022 JINST 17 T11011 – technical description

Analysis ongoing: more details in **O.Razuvaeva talk this evening**

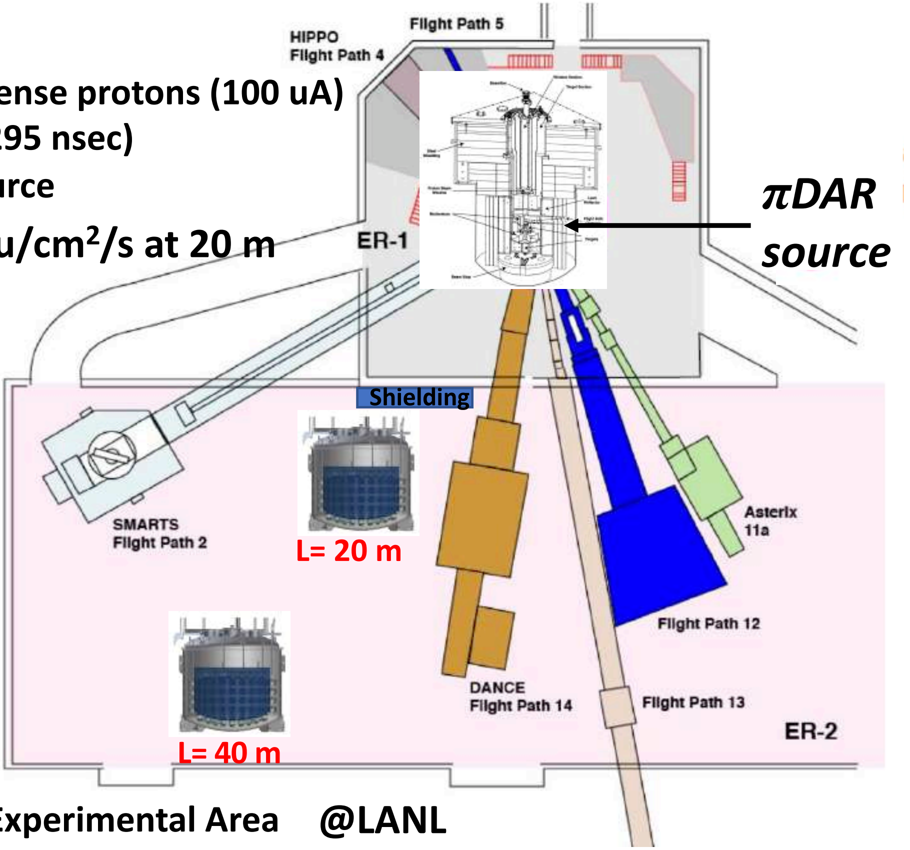
Current status: **lab tests with LAr target**

CCM: Coherent Captain Mills @ Lujan: single-phase LAr

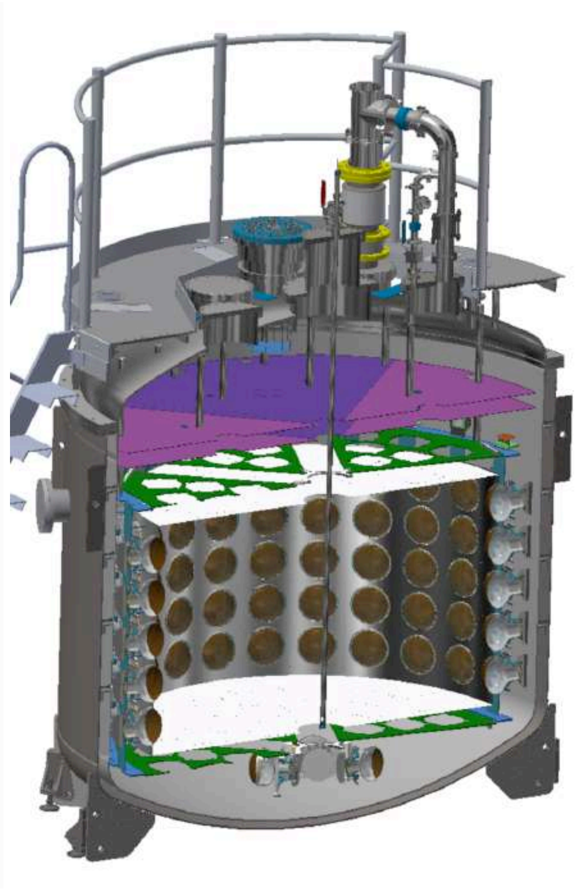
Lujan Target

- 800 MeV intense protons (100 uA)
- Fast Beam (295 nsec)
- Compact source

ν_μ 4.74x10^5 nu/cm^2/s at 20 m



Lujan Experimental Area @LANL



CCM200: 10 ton Liquid Argon (LAr) detector instrumented with 200 8” PMT’s

CCM200: taking data now

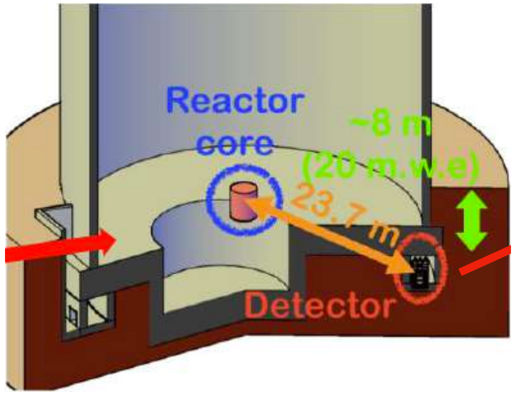
Expected No of CEvNS events:

Reaction	L = 20 m (events/yr)	L = 40 m (events/yr)
Coherent ν_μ (E = 30 MeV)	2709	677
Coherent $\nu_e + \bar{\nu}_\mu$	9482	2370

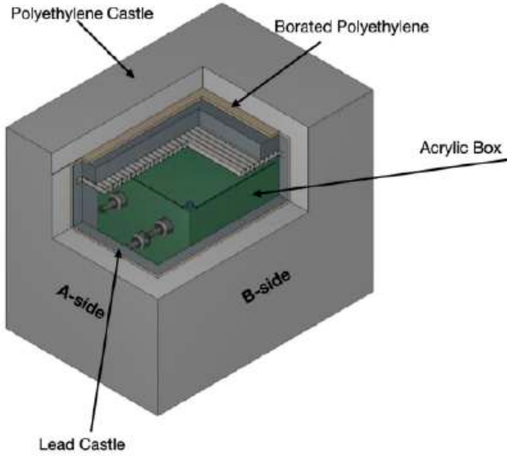
NEON

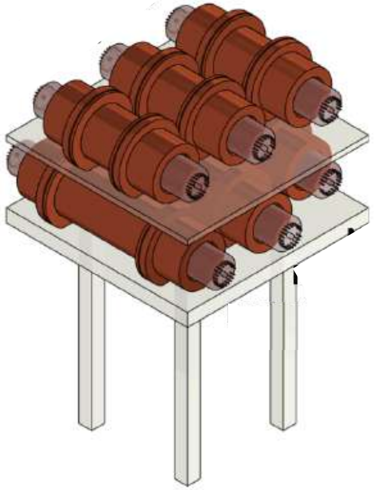
Neutrino Elastic scattering Observation with NaI

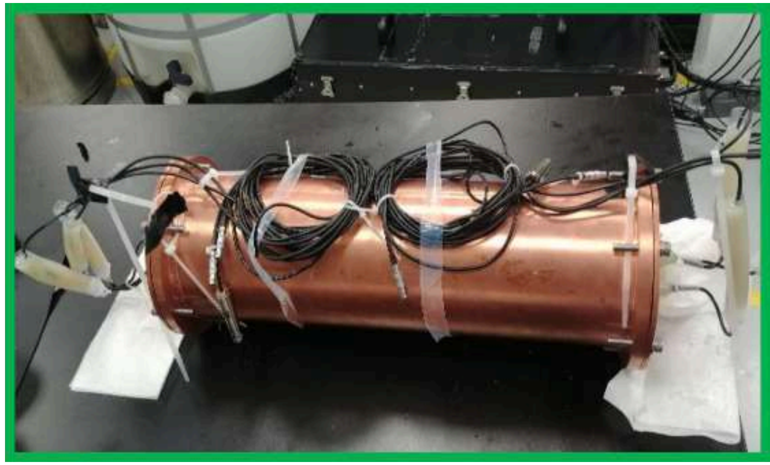
Hanbit nuclear reactor, South Korea.

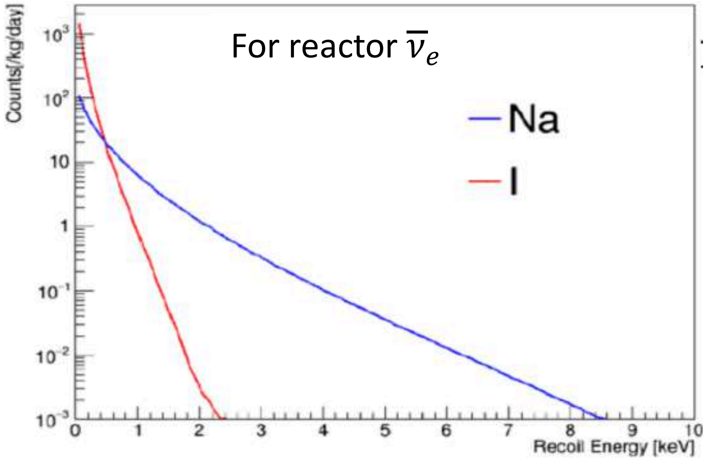


In tendon gallery (20 m.w.e.), 23.7 m from reactor









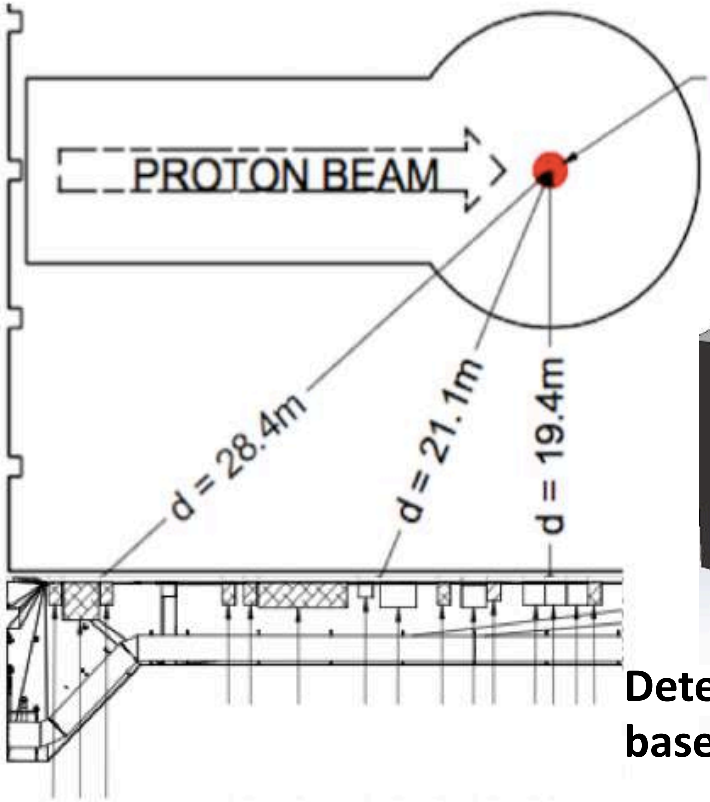
Detector mass 16.7 kg total
Very high light collection eff. – 24 phe/keV

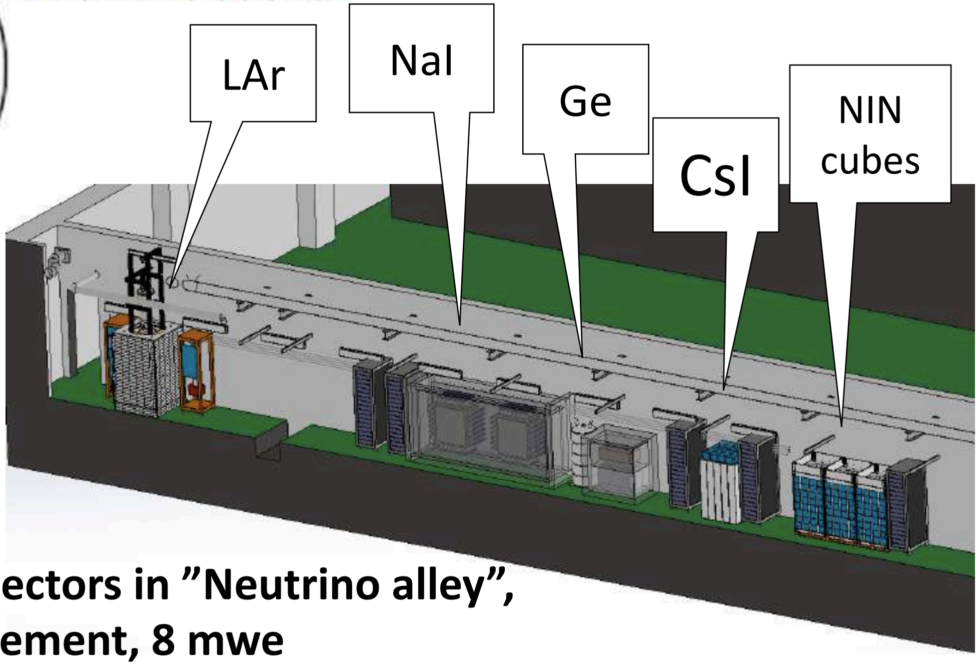
Low threshold – 0.2 keV_{ee}

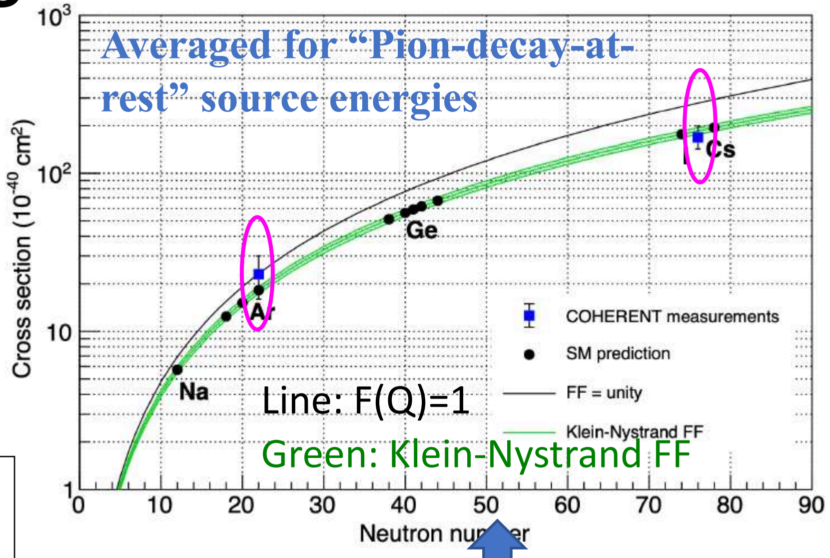
140 day OFF data collected
Now, collecting 1-y ON data

COHERENT – multidetector experiment with different targets

Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target







Detectors in "Neutrino alley", basement, 8 mwe

CENNS-750 (750-kg LAr) is under construction

More details in next talk by A.Konovalov

Till now, COHERENT is the only experiment that provided measured CEvNS cross-sections.

First observation in 2017

CONCLUSION

- **Experiments on CEvNS detection and study are ongoing.**
- **For the moment, CEvNS is reliably detected, and cross-section is measured only at πDAR source (by COHERENT at SNS for Ar and Cs&I).**
- **More results are expected very soon**