The coherent elastic neutrino-nucleus scattering (CEvNS) (Lecture on May 12th, 2025)

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43 YEARS TO BE DISCOVERED

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

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(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

RESEARCH

Science 357, 1123–1126 (2017)

NEUTRINO PHYSICS

Observation of coherent elastic neutrino-nucleus scattering

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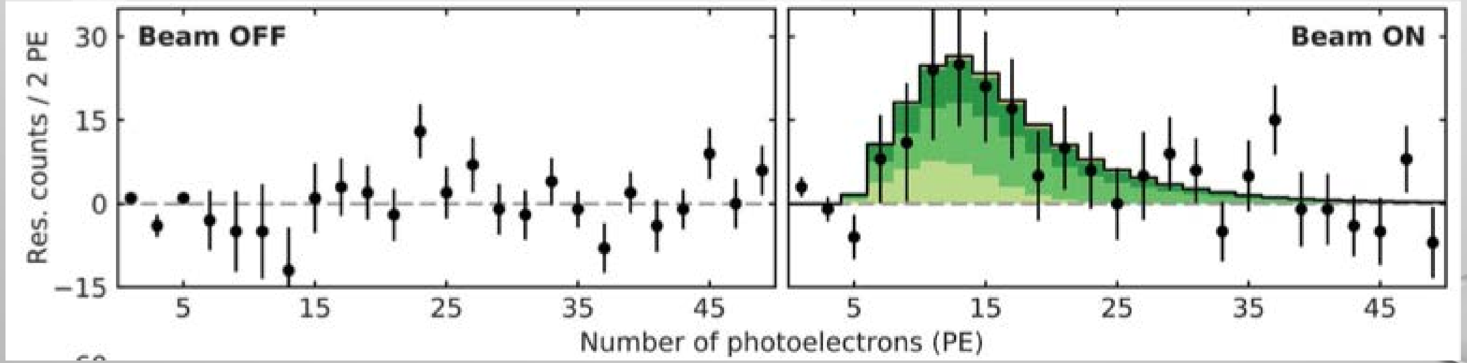
The coherent elastic scattering of neutrinos off nuclei has eluded detection for four decades, even though its predicted cross section is by far the largest of all low-energy neutrino couplings. This mode of interaction offers new opportunities to study neutrino properties and leads to a miniaturization of detector size, with potential technological applications. We observed this process at a 6.7σ confidence level, using a low-background, 14.6-kilogram CsI[Na] scintillator exposed to the neutrino emissions from the Spallation Neutron Source at Oak Ridge National Laboratory. Characteristic signatures in energy and time, predicted by the standard model for this process, were observed in high signal-to-background conditions. Improved constraints on nonstandard neutrino interactions with quarks are derived from this initial data set.

14.6 kg CsI[Na],

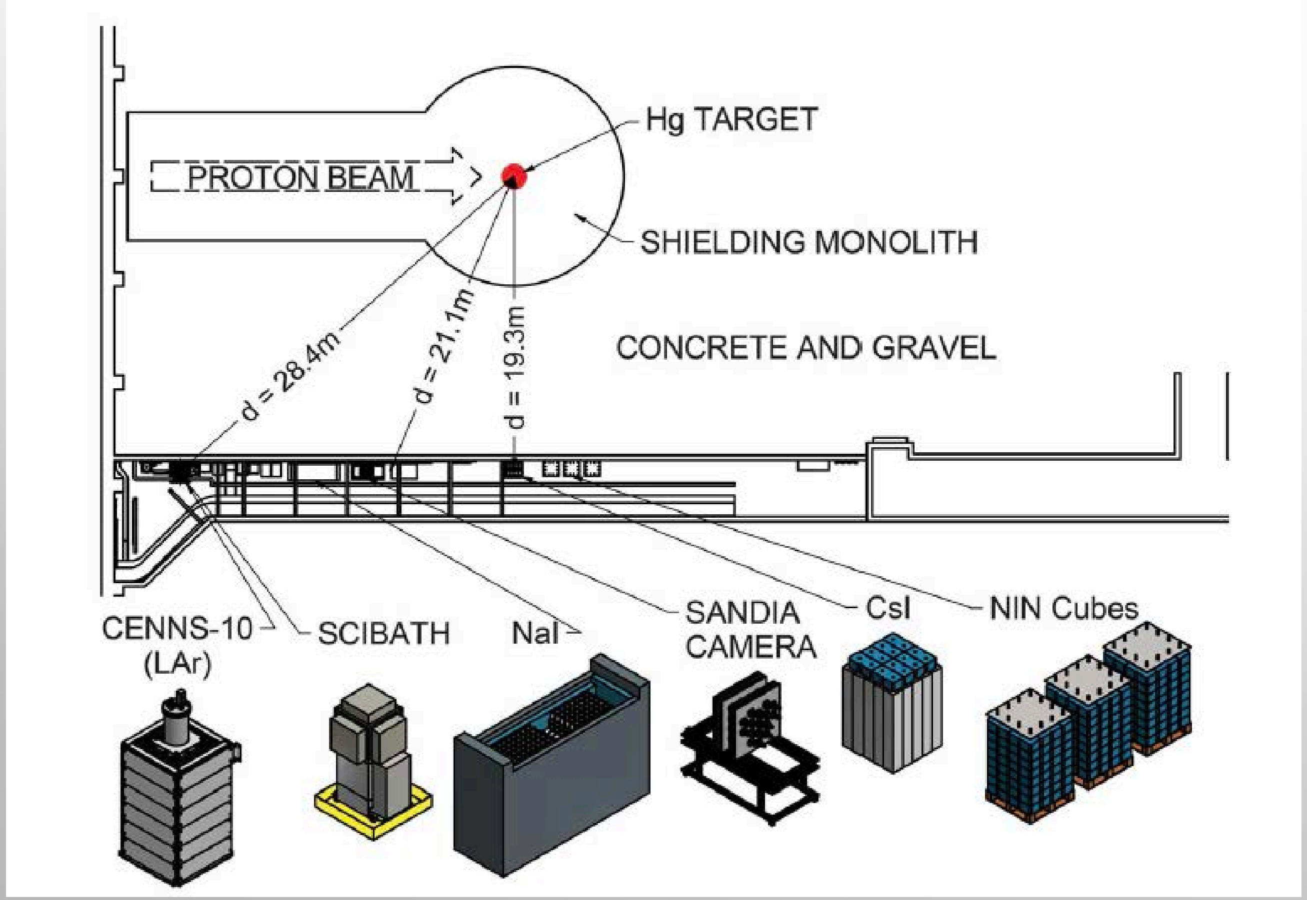
153 days beam off 308 days beam on

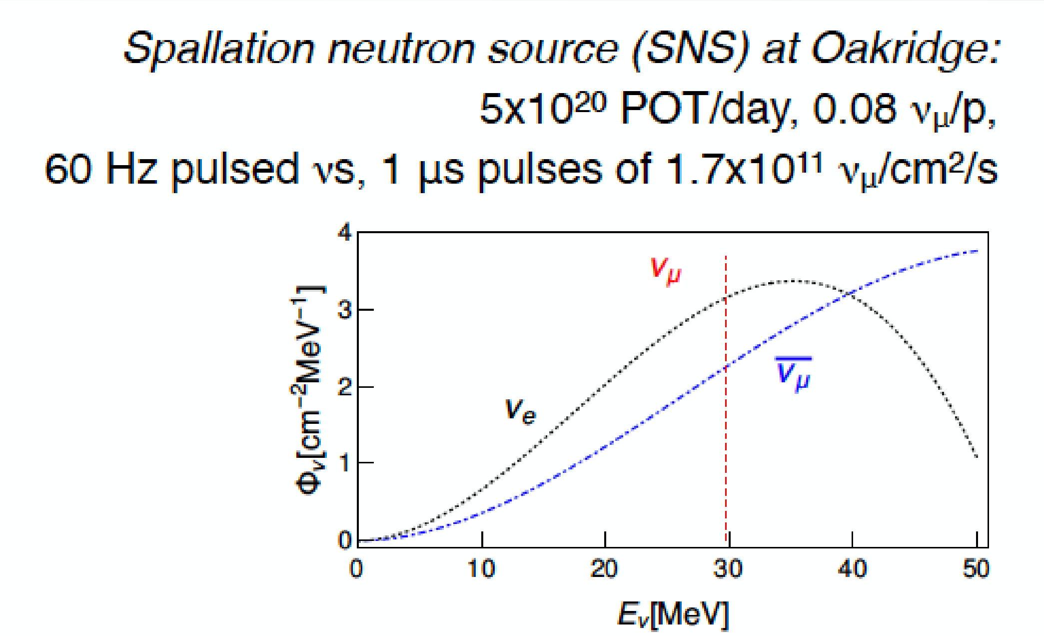


Spallation neutron source at Oakridge

COHERENT EXPERIMENT

- The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory generates intense pulsed neutron beams by the interactions of accelerator-driven high-energy (~1 GeV) protons striking a mercury target.
- Spallation sources create a large yield of neutrinos, generated when pions, by-product of proton interactions in the target, decay at rest;





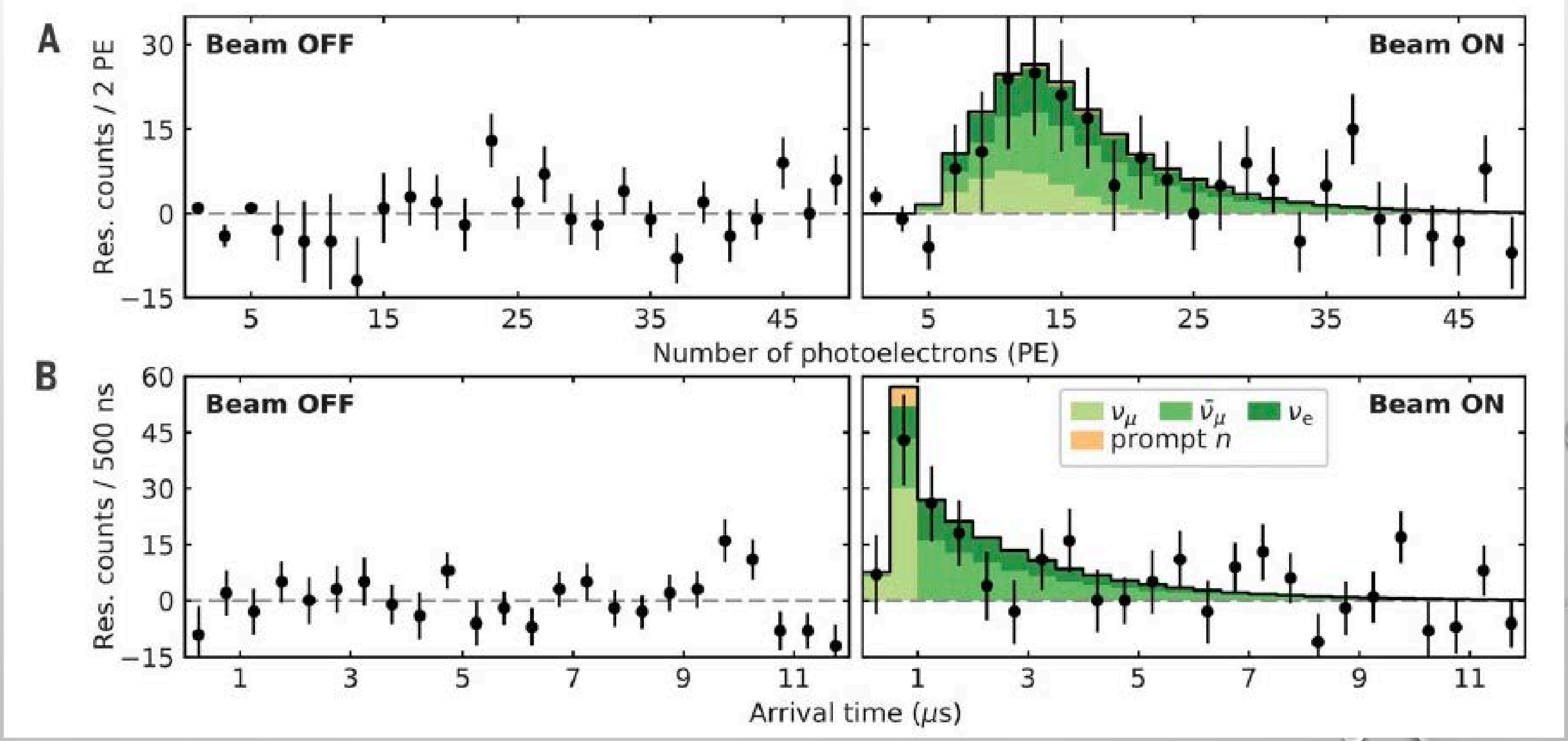
time windows preceding the triggers can be inspected to obtain information about the nature and rate of steady-state backgrounds

COHERENT EXPERIMENT - CsI

- 14.6 kg of CsI(Na) detector
- 19.3 meters from SNS
- 6.7 σ evidence of CEνNS
- $\sim$ 7 keVnr threshold
- Both energy (A) and time information (B)

153.5 live days Beam OFF and 308.1 live days Beam ON

1.17 photoelectrons are expected per keV of Cs or I nuclear recoil energy

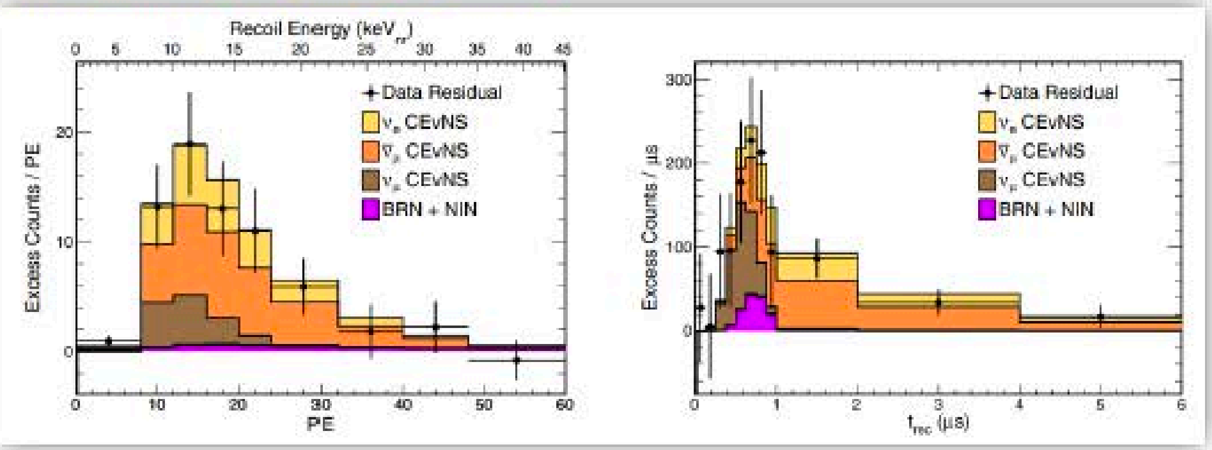


COHERENT EXPERIMENT

CsI Update (2021)

- **2022:** new data release of the CsI detector **with twice the statistics**
- Observed data reject the no-CEvNS hypothesis at **11.6 σ.**
- Data fitted with a **poissonian definition** of the least square function.
- Better understanding of the experimental background.
- **2D** information: time and energy
- About 300 CEνNS events

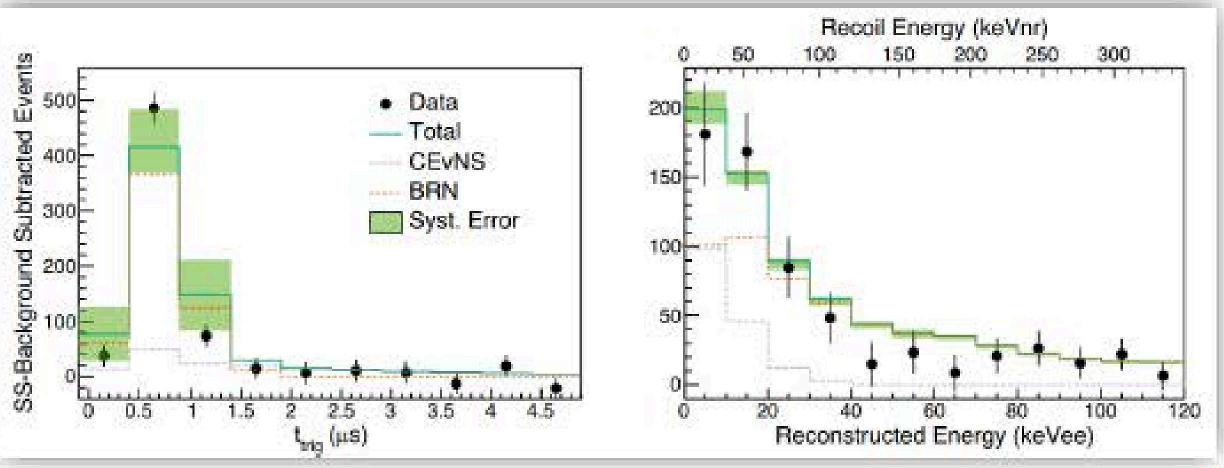
Phys.Rev.Lett. 129 (2022) 8, 081801



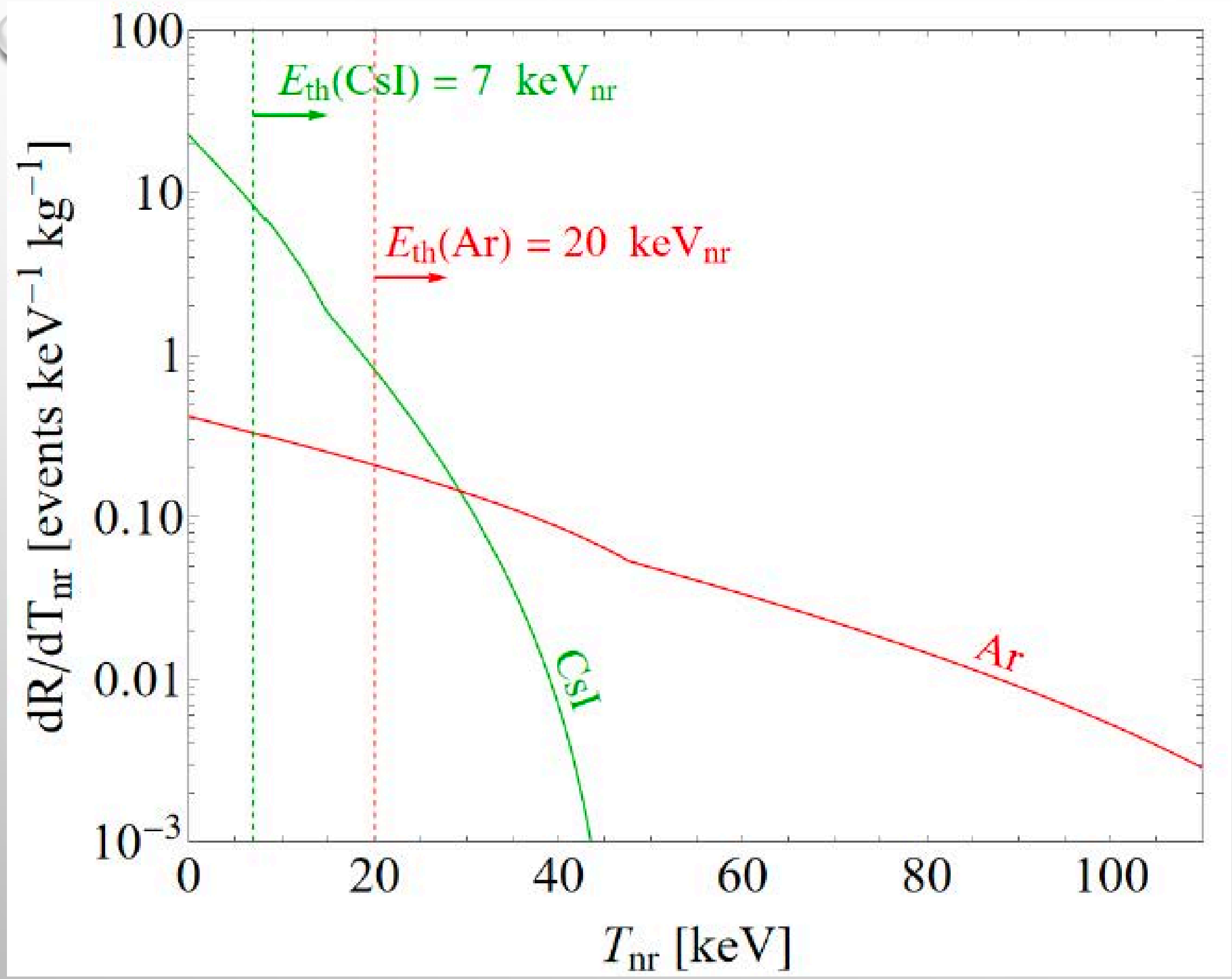
Liquid Argon Data (2020)

- Observation of CEνNS in **2020** with **24 kg LAr** detector **27.5 m** from SNS target
- Single phase detector with 20 keV$_{\mathrm{nr}}$ threshold
- $\mathbf{3.5\ \sigma}$ significance
- Data fitted using the prescription provided in https://zenodo.org/record/3903810#.ZBNRmHbMIQ8
- About 100 CEνNS events
- New data expected soon!

Phys.Rev.Lett. 126 (2021) 1, 01200213



COHERENT EXPERIMENT



- CEνNS differential event rates corresponding to the data taking time accounting for the SNS ν-fluxes
- Lowering the threshold would allow to get more CEνNS events
- Argon: compromise between background rejection power and strong CEνNS signal.
- Upgrade to a 750 kg LAr detector
- Cryogenics technologies under development for CsI

CEνNS experiments in the world

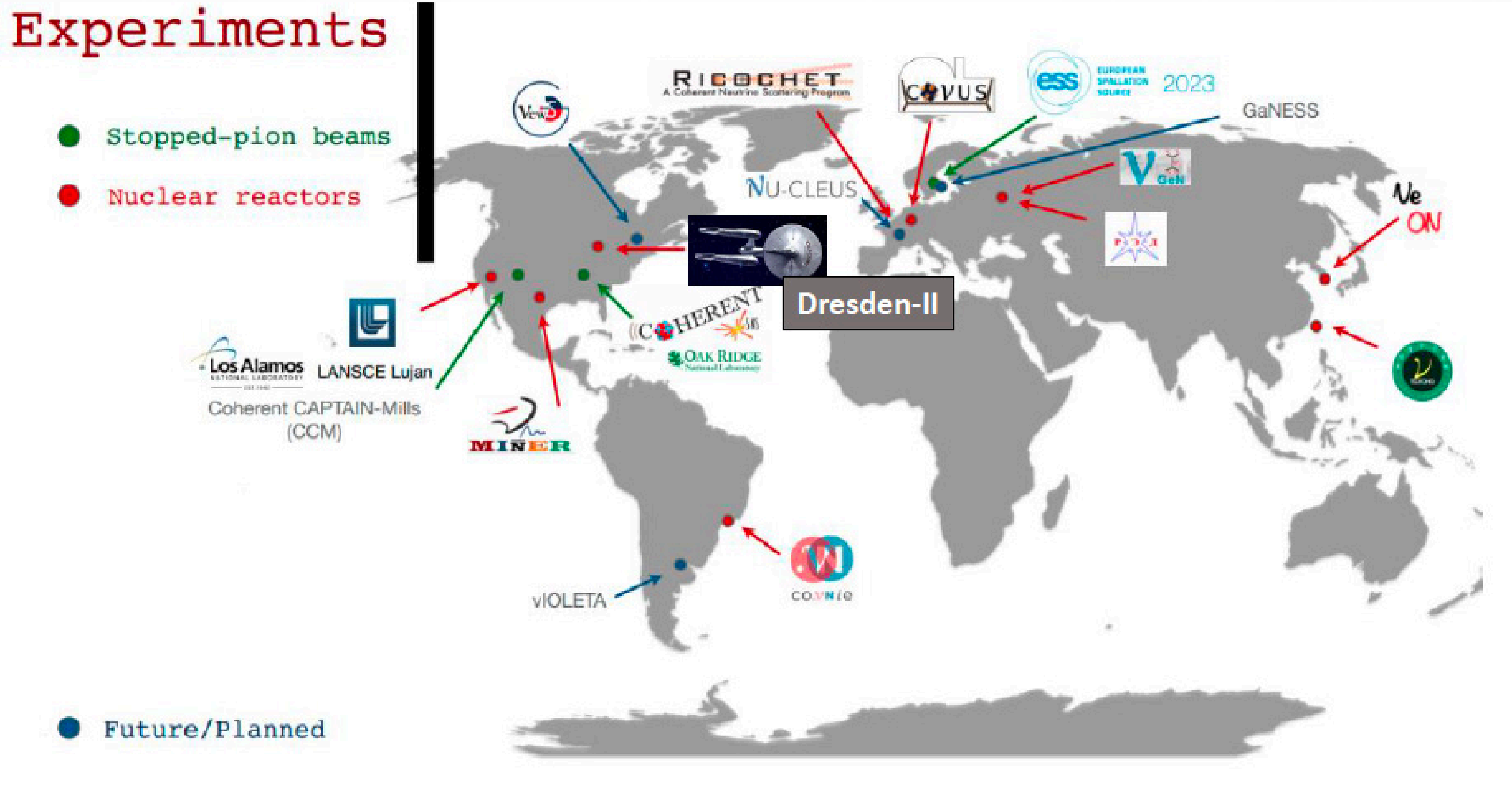
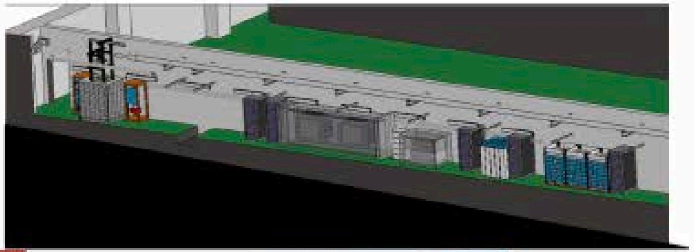
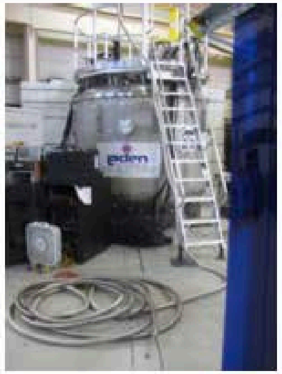
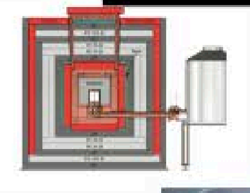
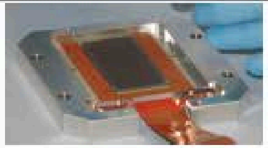
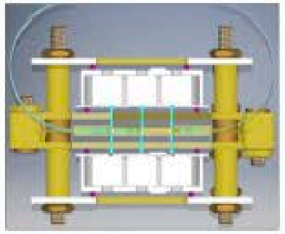
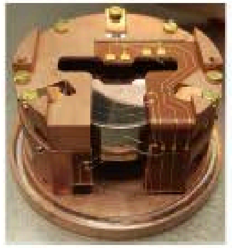
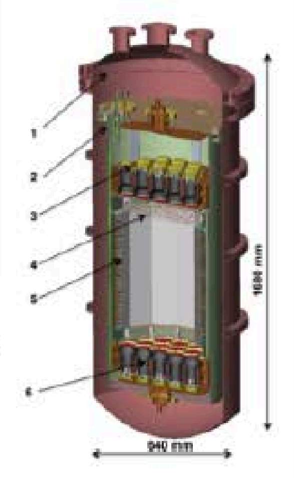
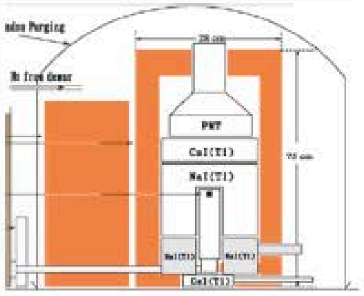


Image from D. Papoulias MPIK, Particle and Astroparticle Theory Seminar, June 20 2022

CEνNS experiments in the world

Experiment	Technology	Location	Source
COHERENT	CsI, Ar, Ge, NaI	USA	πDAR
CCM	Ar	USA	πDAR
ESS	CsI, Si, Ge, Xe	Sweden	πDAR
BULLKID	Si/Ge	Italy	Reactor
CONNIE	Si CCDs	Brazil	Reactor
CONUS	HPGe	Germany	Reactor
NEWS-G	Ar+2%CH4	Canada	Reactor
MINER	Ge/Si cryogenic	USA	Reactor
NEON	NaI(Tl)	Korea	Reactor
NUCLEUS	$CaWO_4$, Al_2O_3 cryogenic	Europe	Reactor
νGEN	Ge PPC	Russia	Reactor
RED-100	LXe dual phase	Russia	Reactor
Ricochet	Ge, Zn, Al, Sn cryogenic	France	Reactor
TEXONO	p-PCGe	Taiwan	Reactor
Dresden II	PCGe	USA	Reactor
SBC	Scintillating Bubble Chamber	Fermilab (R&D)	Reactor

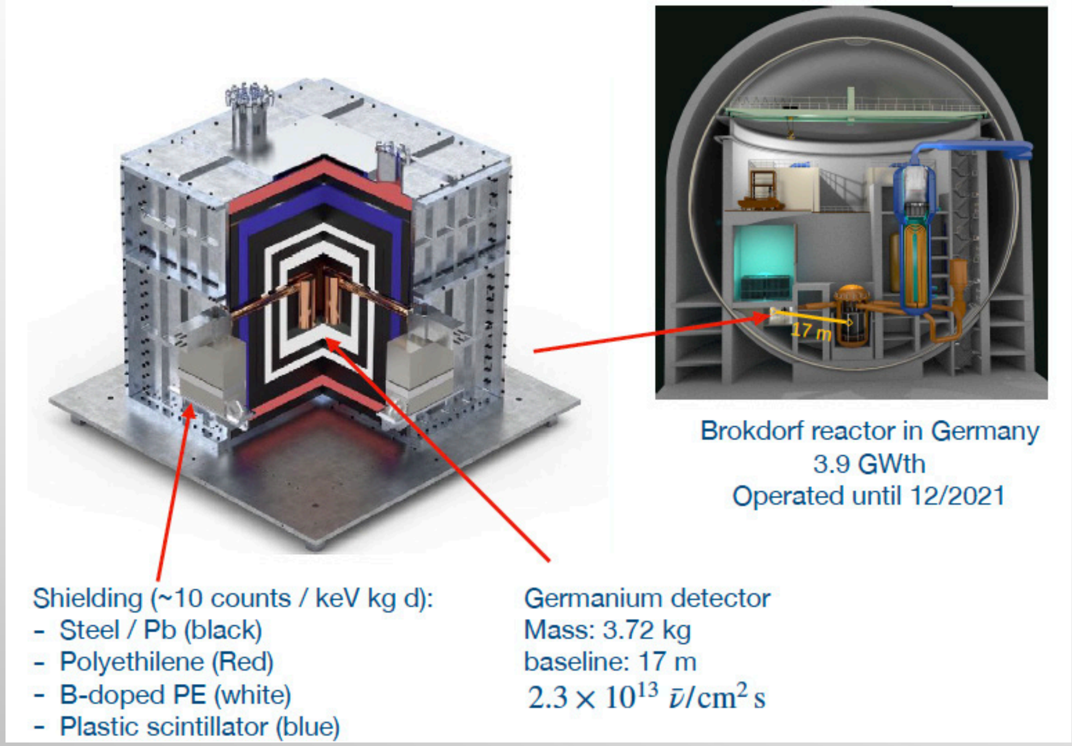








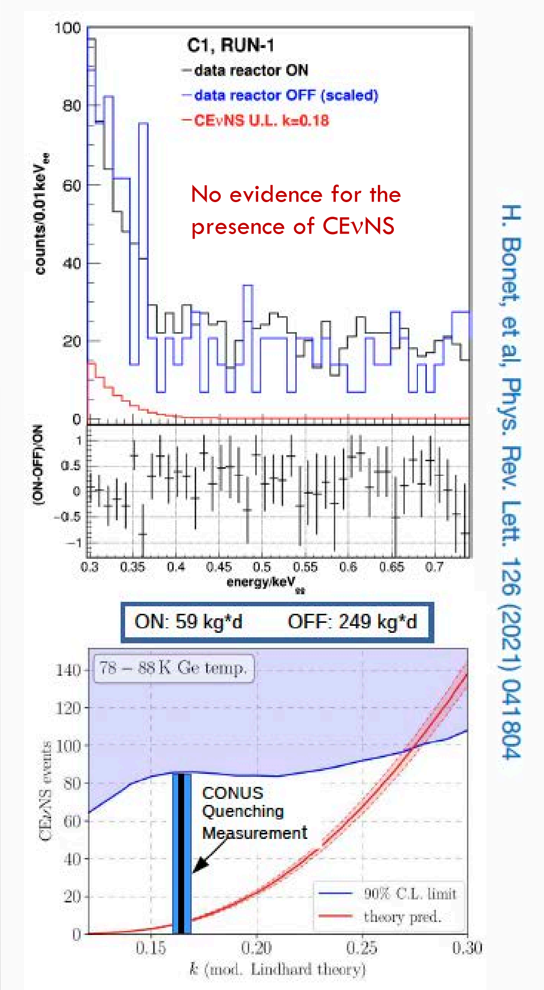


+DM detectors, +directional detectors +Solar/SN detectors…

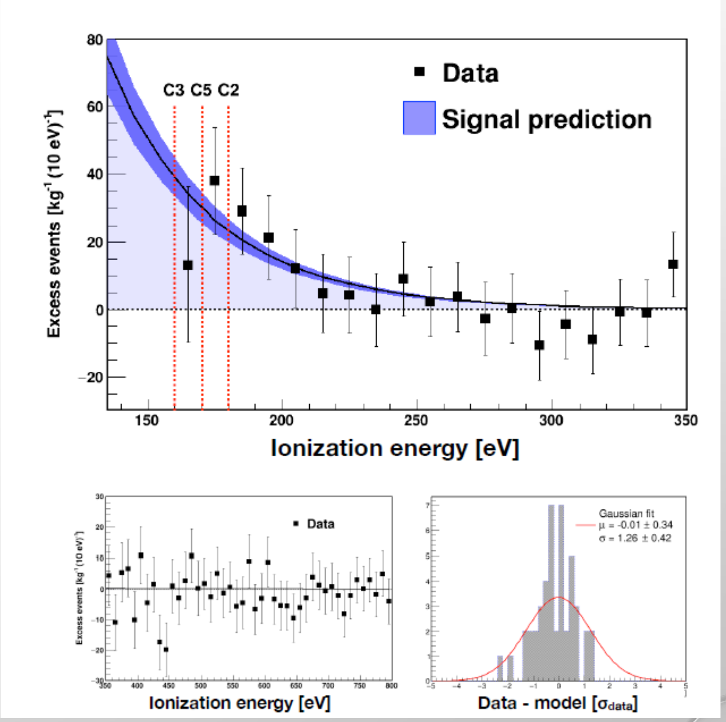
many novel low-background, low-threshold technologies!!

GERMANIUM TARGET : CONUS & CONUS+





CONUS+: Leibstadt nuclear power plant in Switzerland (arxiv.org:2501.05206)

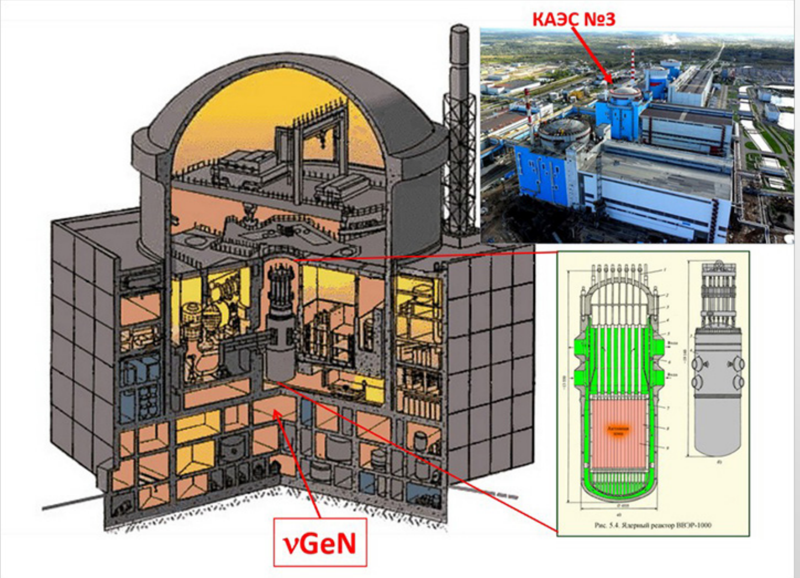


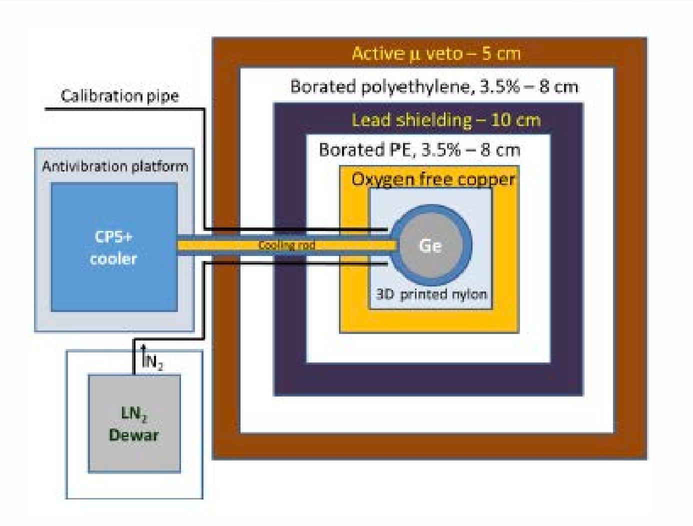
CONUS+: first observation of a neutrino signal with a statistical significance of 3.7 sigma. In 119 days of reactor operation (395±106) neutrinos observed

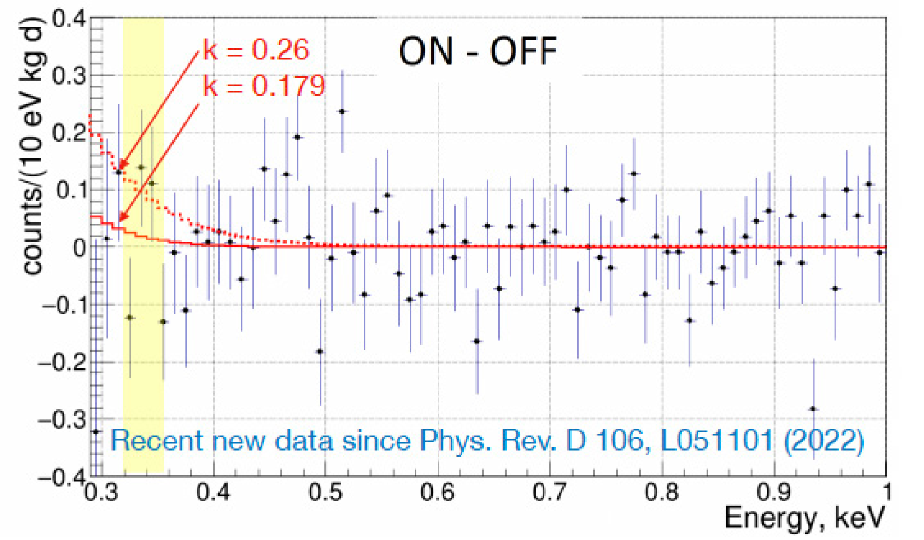
GERMANIUM TARGET : νGeN

The νGeN experimental setup:

- located under Reactor Unit #3 of the Kalinin nuclear power plant
- distance of about 10 m from the centre of the reactor core
- neutrino flux >$5 \cdot 10^{13}$ neutrinos/ ($cm^2 \cdot sec$)







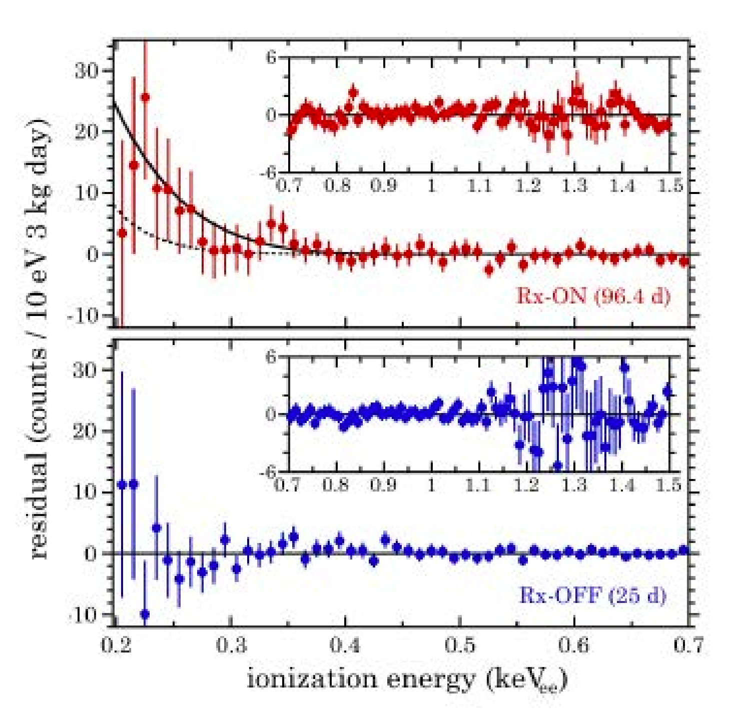
Null result: CEνNS< 0.5 cpd/kg

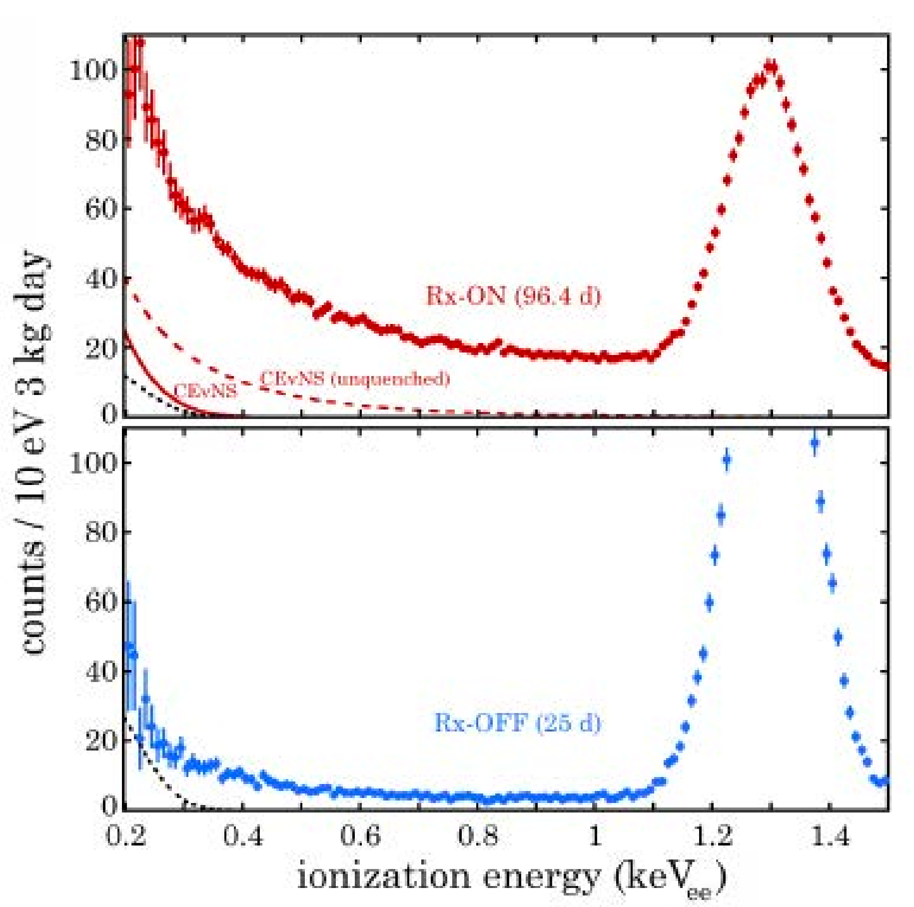
Shielding (~50 counts / keV kg d):
- Pb (black)
- B-doped PE (white)
- muon-veto (brown)
- Copper (yellow)

Germanium detector
Mass: 1.4 kg
baseline: 11 m
$4 \times 10^{13}\ \bar{\nu}/cm^2\ s$

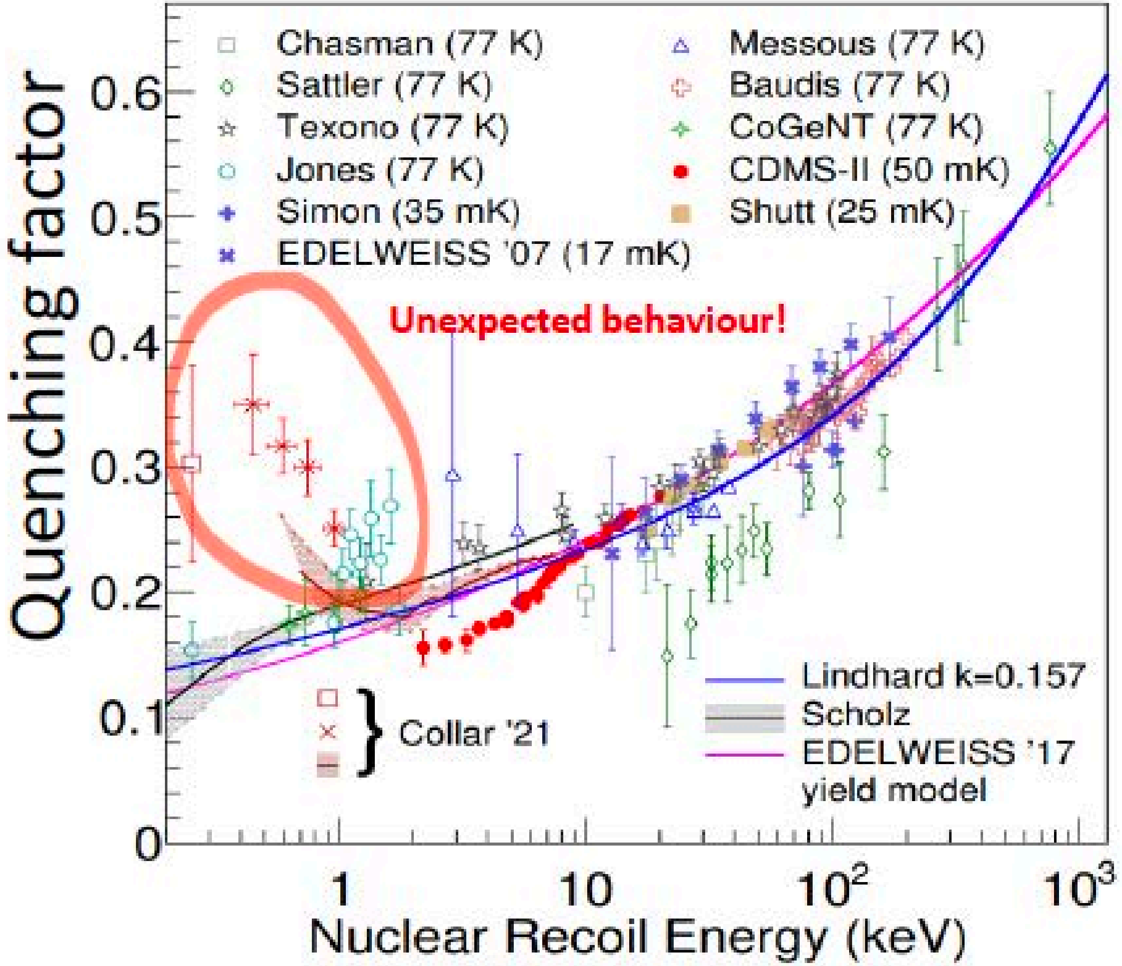
GERMANIUM TARGET : DRESDEN-II

- 96.4 day (**Rx-ON**) exposure of a 3 kg ultra-low noise germanium detector.
- 10.39 m away from the Dresden-II boiling water reactor ($P = 2.96\ \mathrm{GW_{th}}$).
- **Strong preference** ($p < 1.2 \times 10^{-3}$) for the presence of CEνNS.
- This observation is **very controversial** in the CEνNS Community.





QUENCHING FACTOR IN GERMANIUM

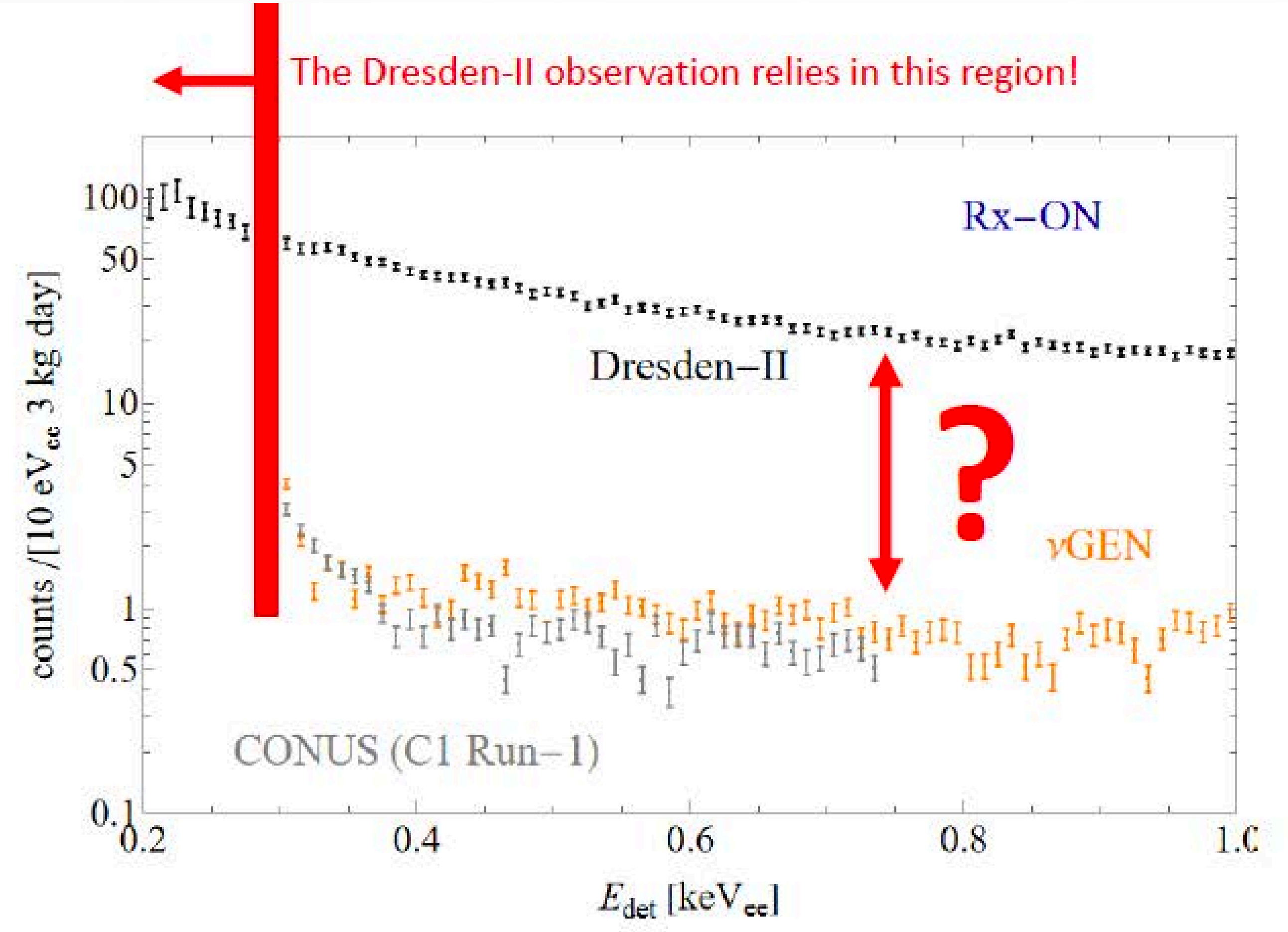


Tension in the available measurements

Key Point

- The new measurements from Dresden-II are **much higher** than expected.
- The new quenching results in a **much higher** CEνNS signal.

COMPARING GE TARGET EXPERIMENTAL RESULTS

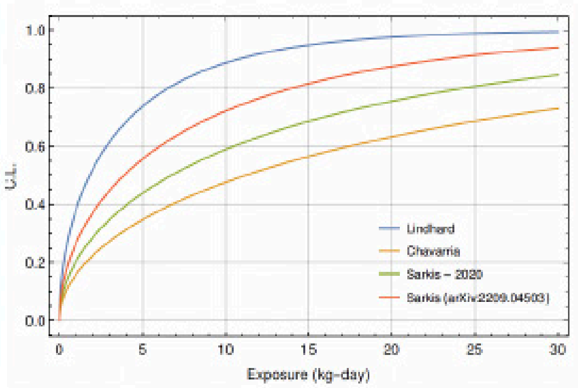


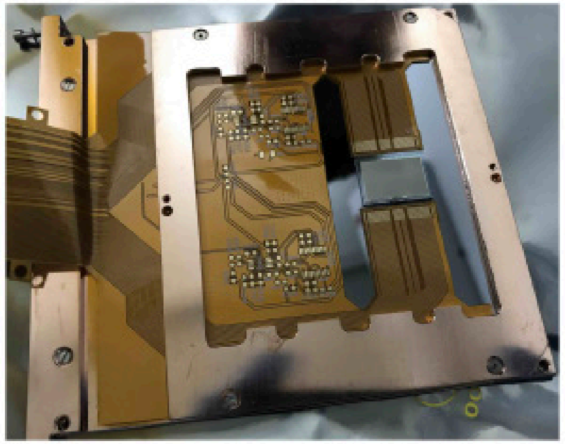
They are all Ge detectors.

- **Dresden-II** Reactor Power: 3.0 GW_{th}; Distance: 10 m; 2.96 kg
- **νGEN** Reactor Power: 3.1 GW_{th}; Distance: 11 m; 1.41 kg
- **CONUS**: Reactor Power: 2.96 GW_{th}; Distance: 17 m; 3.73 kg

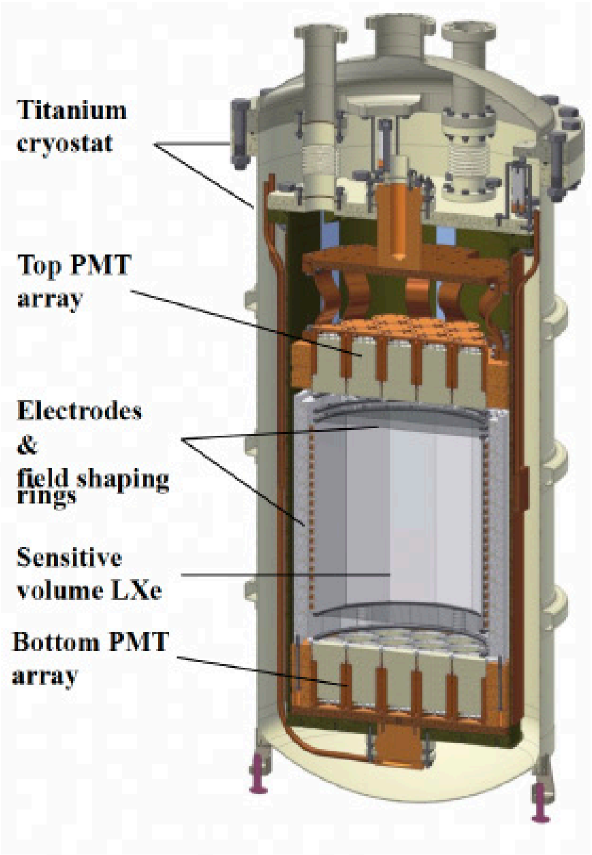
REACTOR EXPERIMENTS

CONNIE
Moved to Skipper CCDs
More CCDs to be installed (1kg)
Move closer to reactor



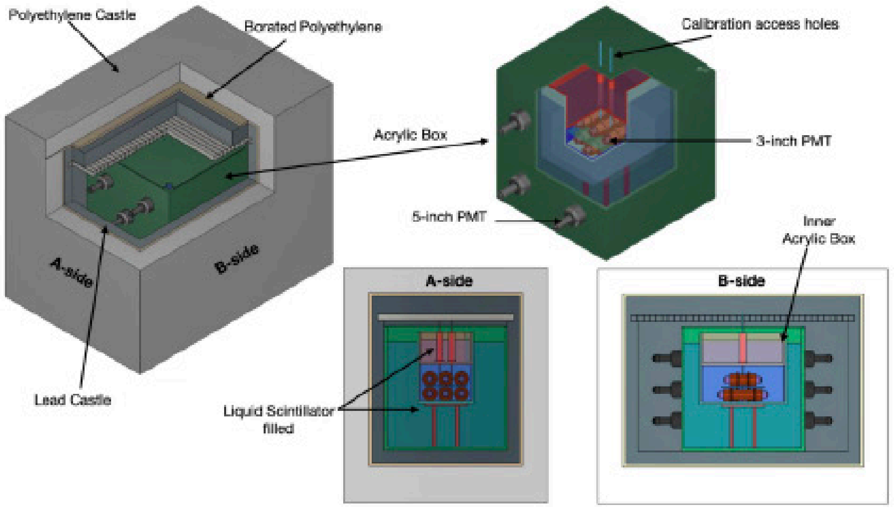


RED-100
Successful Data run with Xe
Moving from Xe to Argon



NEON
16.7 kg NaI(Tl)

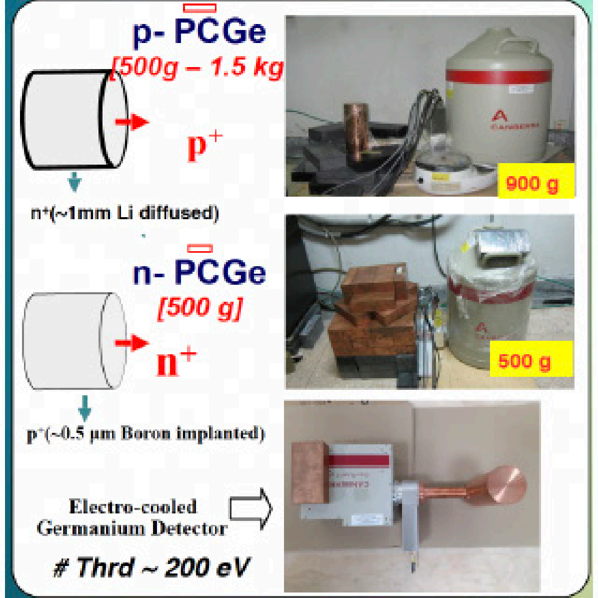
- 6 counts/day/kg/keV (DRU) flat bkg
- 24 NPEs/keV light yield
- 0.2 keV threshold (5 NPE) <- On going!!
- 16.7 kg detector mass
- 1 year reactor on data <- Just wait!!
- 140 days reactor off data



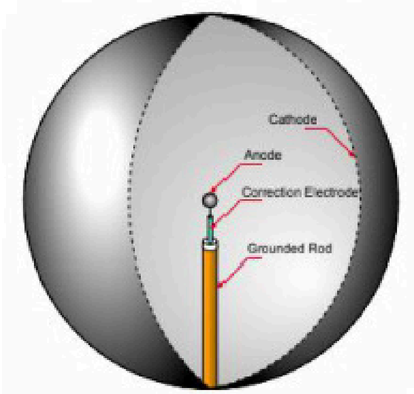
REACTOR EXPERIMENTS

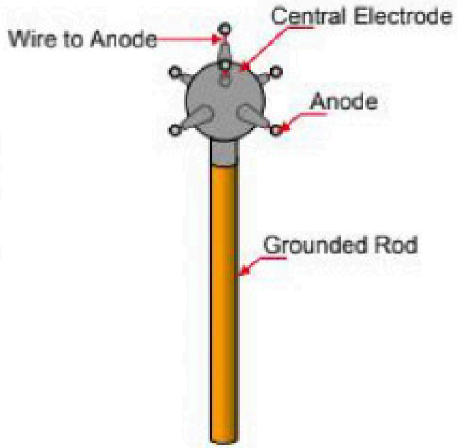
TEXONO
Looking for new site

- **TEXONO** (Taiwan EXperiment On NeutrinO) Experiment is located at Kuo-Sheng Nuclear Power Plant -II on northern shore of Taiwan.
- **Theme:** Low Energy Neutrino Physics and Dark Matter Searches.
- Collaboration with Turkey, China and India.
- The reactor power of 2.9 GW gives 6.35×10^{12} $cm^{-2}\ s^{-1}$ electron anti-neutrinos at a distance of 28 m.
- Collaboration with CDEX Underground Dark-Matter Experiment, China.

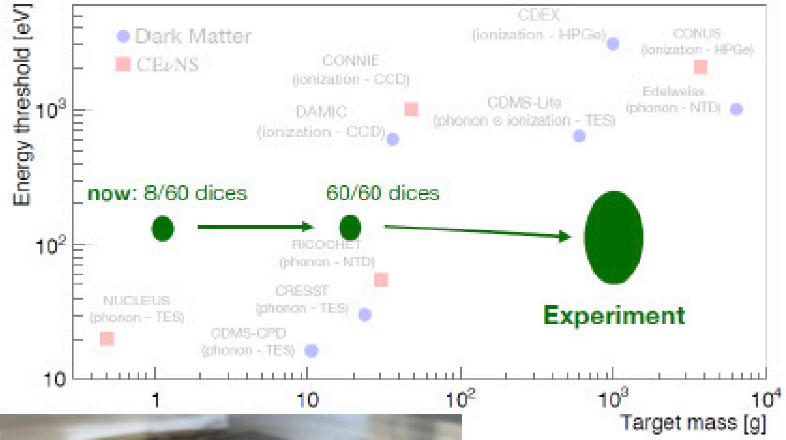


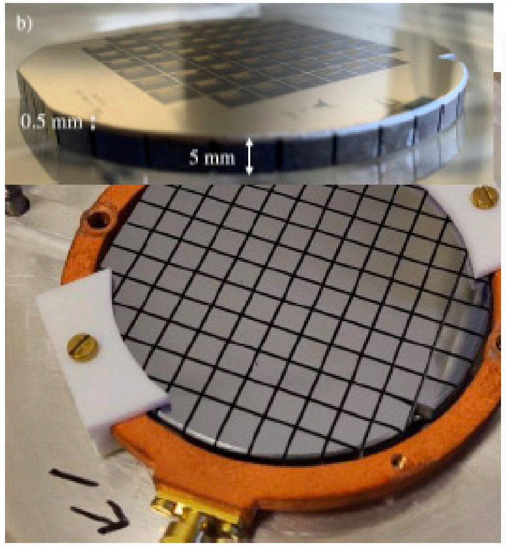
NEWS-G3
Spherical Proportional Counter
Working on final design

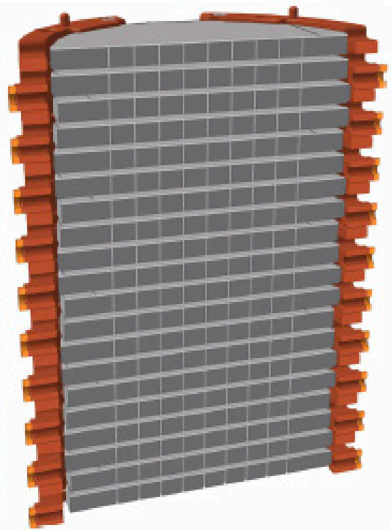




BULLKID
Si/Ge with MKIDS



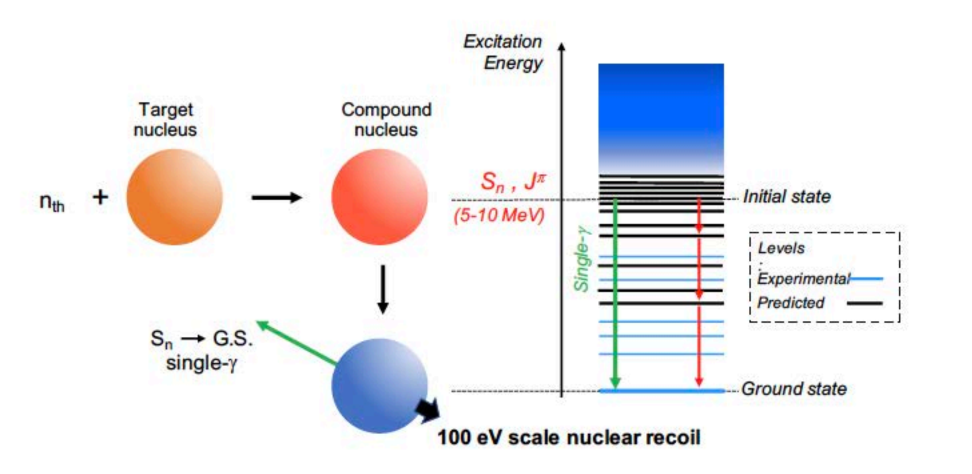


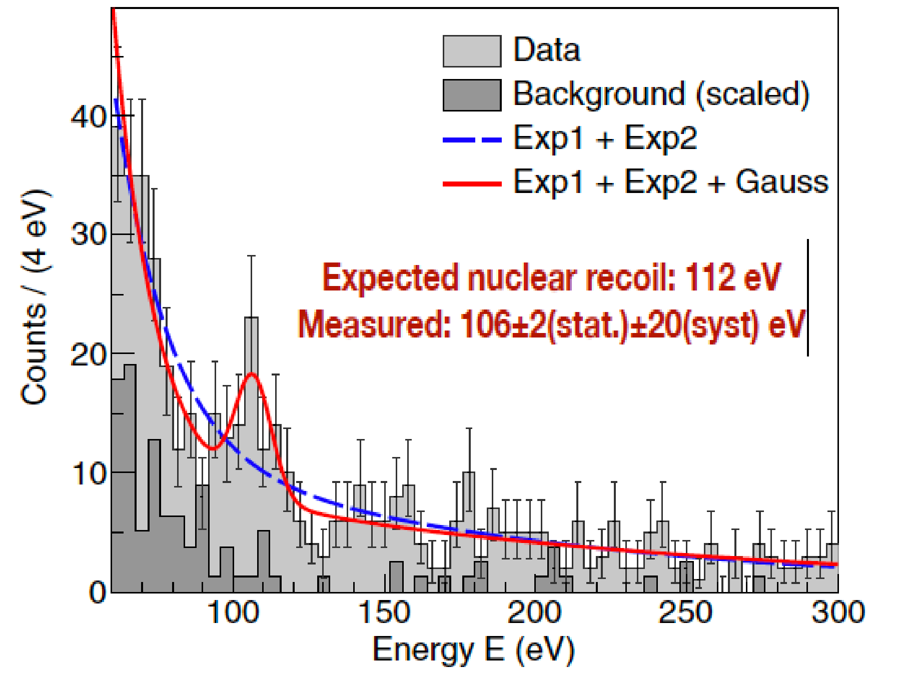


CRYOGENIC DETECTORS FOR CEνNS

- Very low energy threshold
- Small uncertainty in the energy scale
- Low energy recoil calibration feasible

PRL 130, 211802 (2023)





Low energy calibration: nuclear recoils resulting from the γ emission following thermal neutron capture. In particular, several MeV-scale single-γ transitions induce well-defined nuclear recoil peaks in the 100 eV range

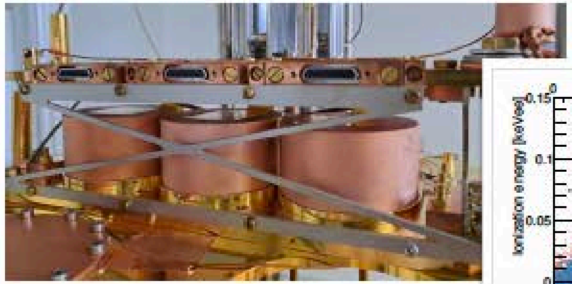
First observation of a nuclear recoil peak at ≈112 eV induced by neutron capture in ^{183}W of a NUCLEUS CaWO4 cryogenic detector exposed to a ^{252}Cf source

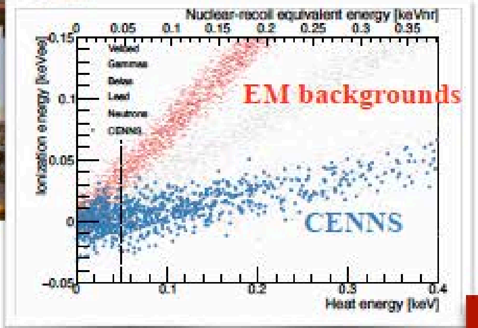
Cryodetectors: RICOCHET

Data taking foreseen in 2024

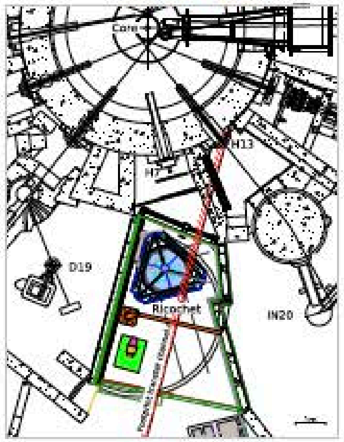
Ge detectors (heat + ionisation)

Target Mass: 42 g x 18/27
baseline: 8.8 m
$1.1 \times 10^{12}\ \bar{\nu}/\text{cm}^2\,\text{s}$





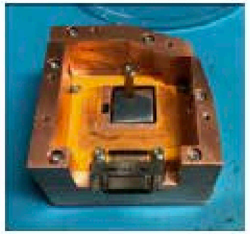
ILL Research reactor in Franche
58 MW_{th}

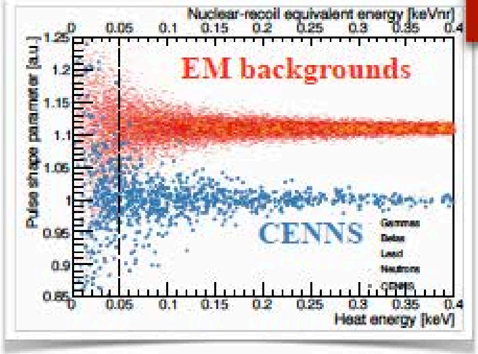


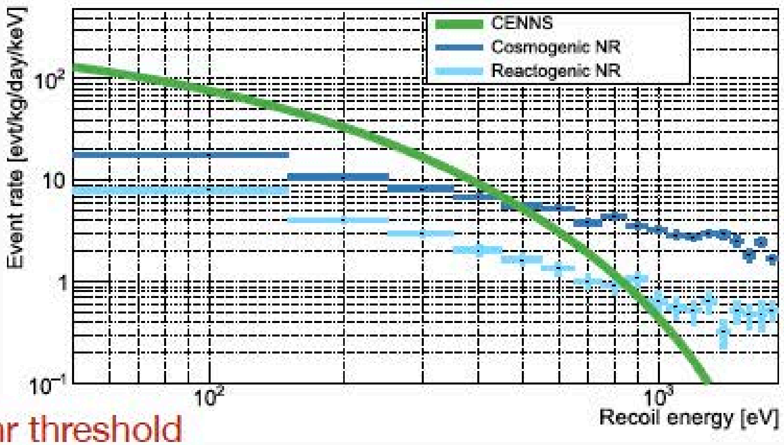
Particle ID @ < 100 eV

Zn detectors (heat only)

Target Mass: 32 g x 9



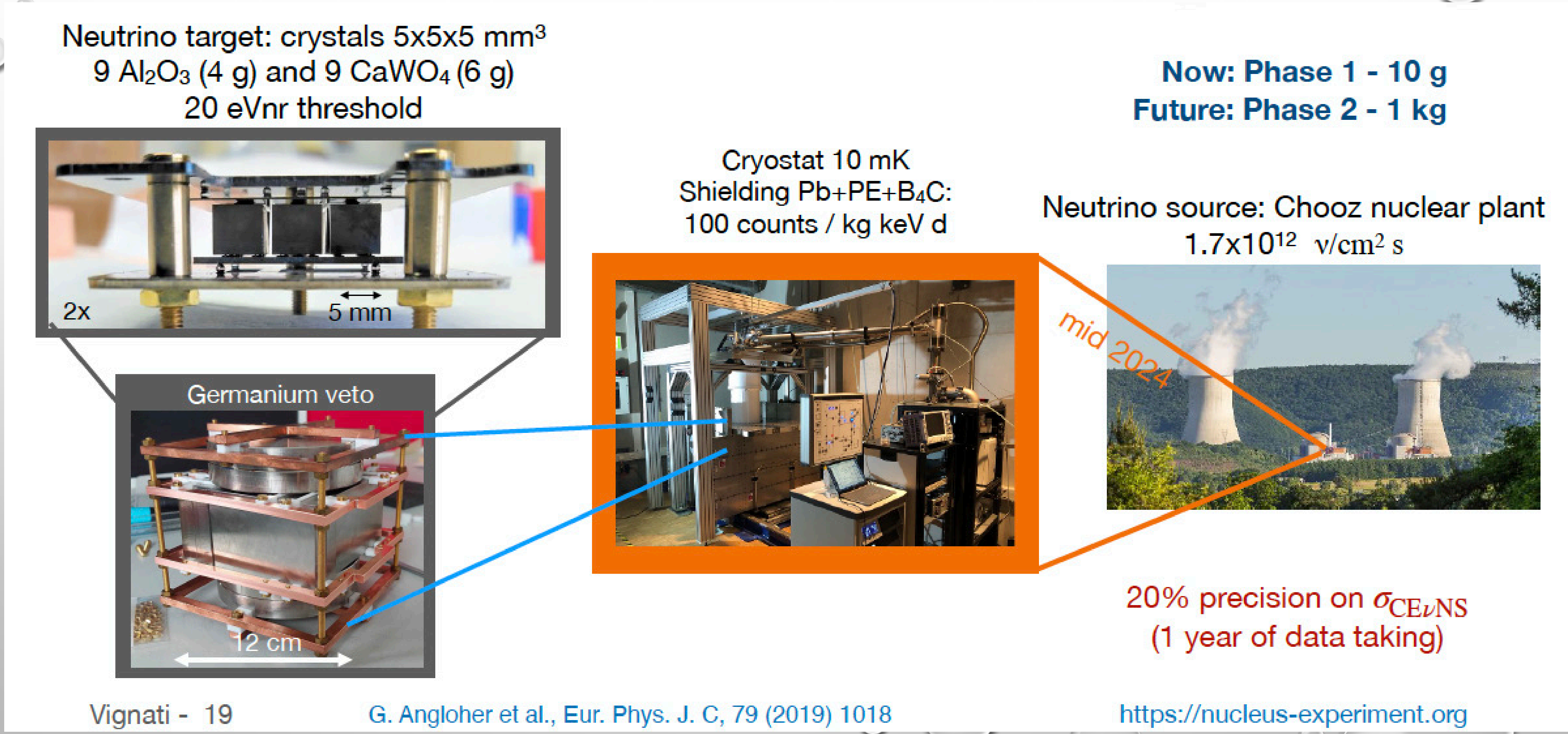




50 eVnr threshold

C. Augier, et al, Eur. Phys. J. C 83 (2023) 20

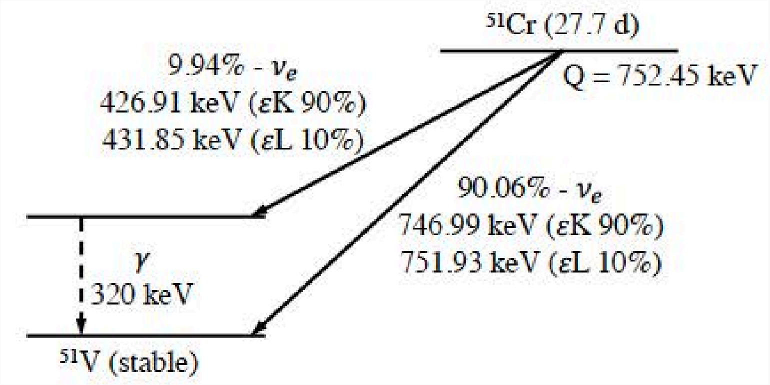
NUCLEUS EXPERIMENT

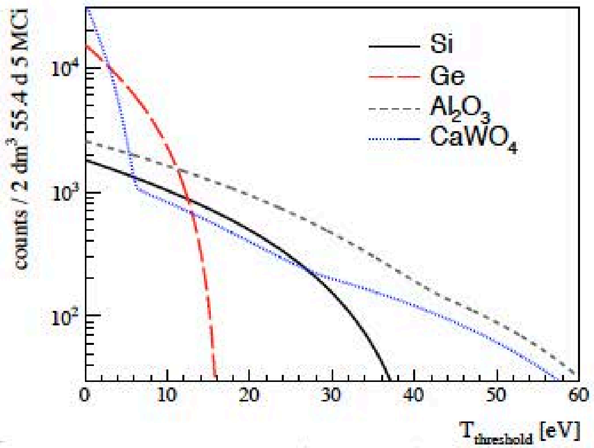


EC NEUTRINO SOURCE

^{51}Cr

C. Bellenghi, et al, Eur. Phys. J. C 79 (2019) 727

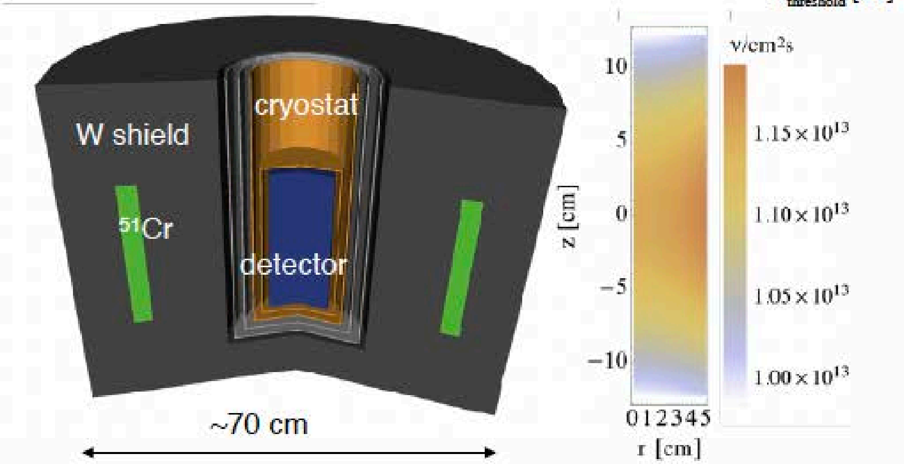




- ✓ Activity monitored with calorimeter < 1 % precision (SOX experience)
- ✓ INFN owns a 36 kg source (GALLEX)

Challenges:

- activation up to 5 MCi
- even lower threshold than reactors



1% precision with 10 kg Ge target in 2 months, but extremely challenging!

NUCLEUS experiment

- Goal: high-precision measurement of the coherent elastic neutrino-nucleus scattering (***CEνNS***) at low energy with cryogenic detectors

- Site: the experiment will operate at the **Chooz B** nuclear power plant in France (operated by EDF)

- Detector: **$CaWO_4$** and **Al_2O_3** gram-scale crystal with ultra-low energy threshold, operating at mK and placed inside active and passive shields

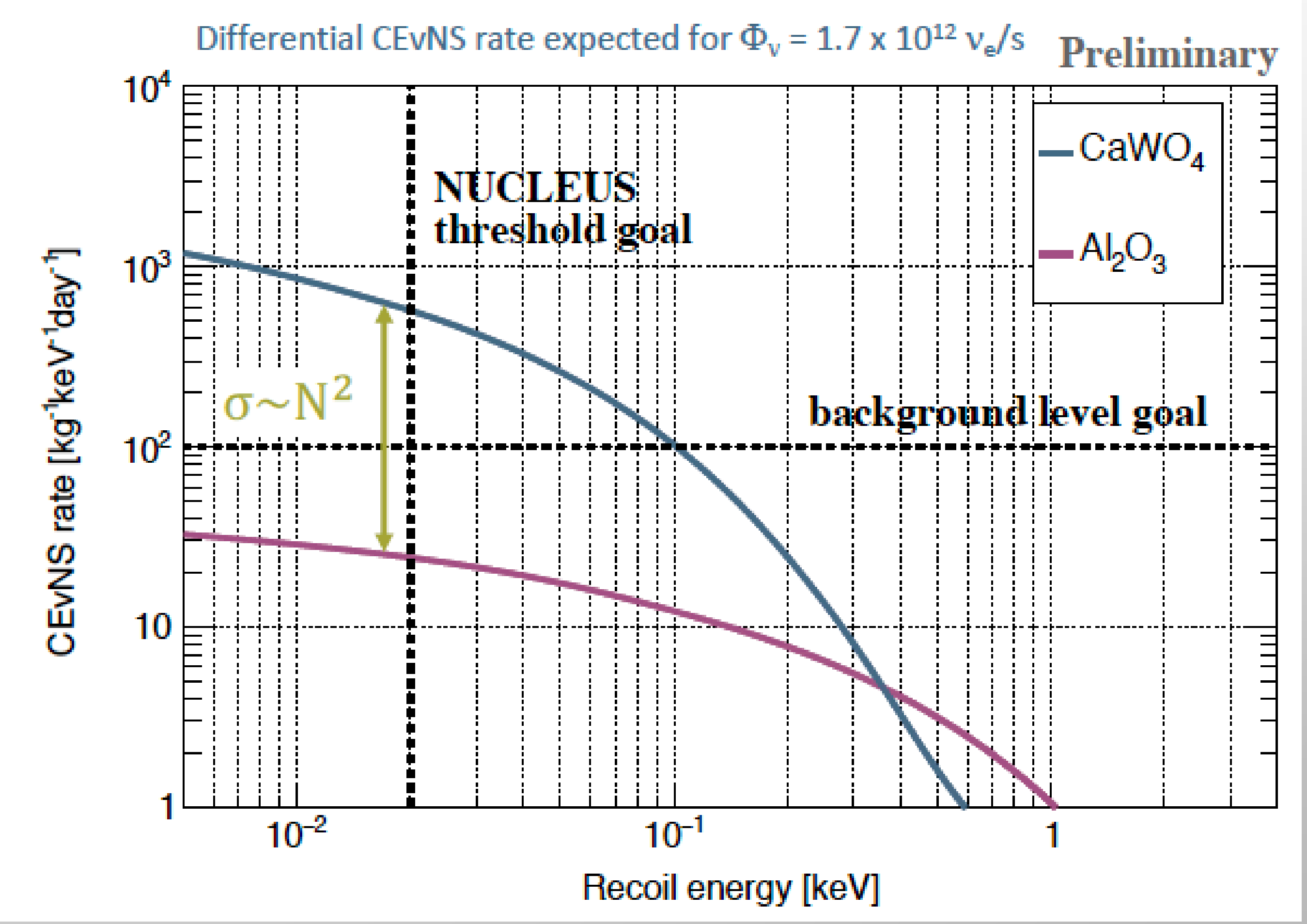
6 Institutions, **40** members

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS · TUM · cea · INFN · TU WIEN · MAX-PLANCK-INSTITUT FÜR PHYSIK

CEνNS signal at nuclear reactors

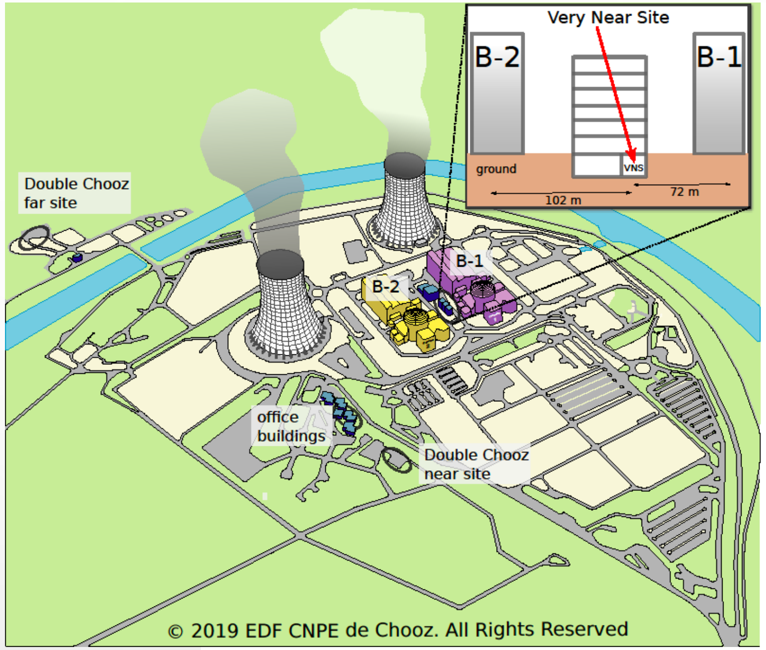
- Nuclear Reactors are intense source of anti-neutrinos; En < 8 MeV (fully coherent domain)
- Induced nuclear recoils for CEνNS interaction are in sub-KeV range
- Low threshold detectors and low background counting rate are required

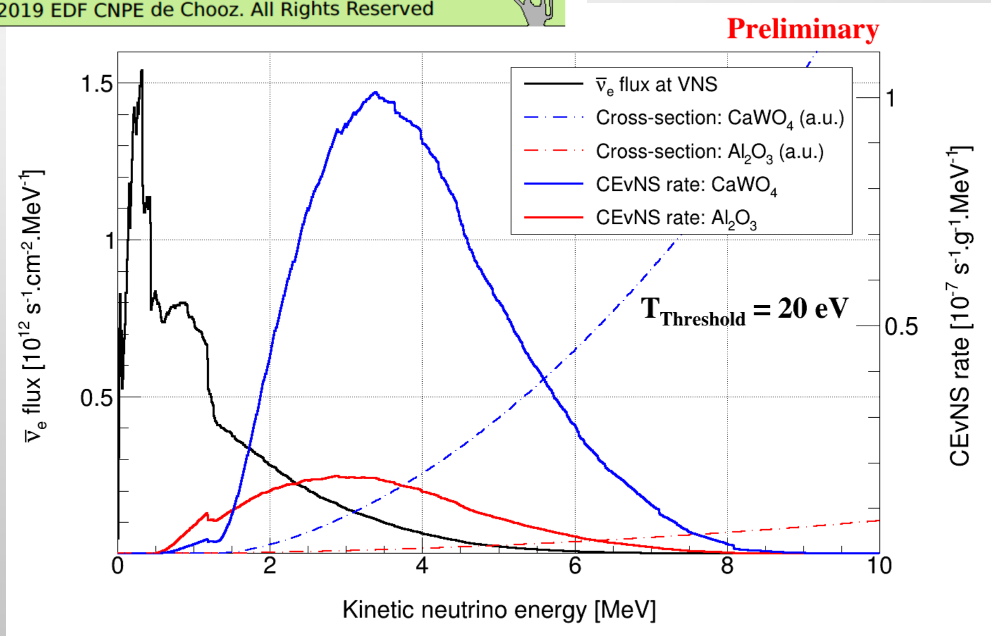
Expected CEνNS signal rate in different target material



VNS at Chooz Nuclear Power Plant

- The experimental site (VNS) is located at 102 m and 72 m from the 2 reactors of the Chooz B plant of EDF, at ≈ 5 m.w.e depth
- Reactor nominal thermal power: 2 x 4.25 GW_{Th}
- The expected average neutrino flux at VNS: $1.7 \times 10^{12}\ \bar{\nu}_e/(s \cdot cm^2)$



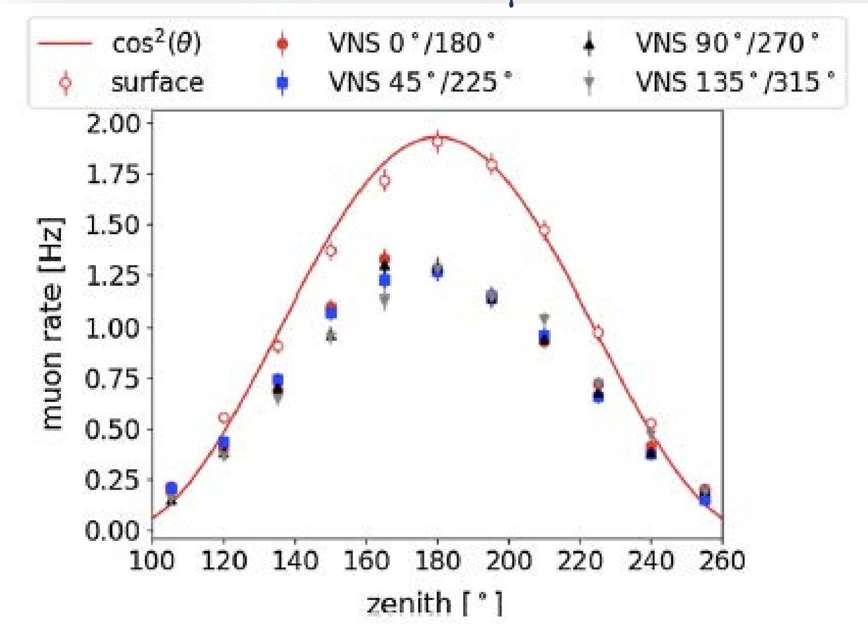


See A. Wex and A. Erhart presentation in the Poster Section

Background at VNS

Eur. Phys. J. C (2019) 79:1018

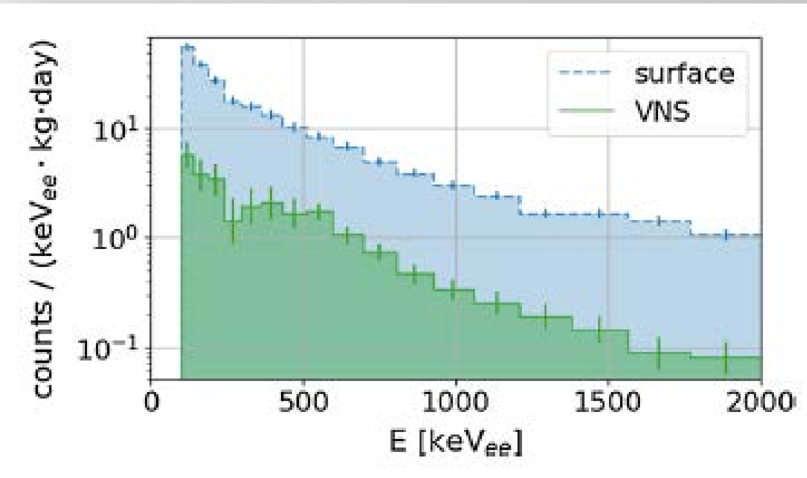
Cosmic μ



Characterization of the VNS site:

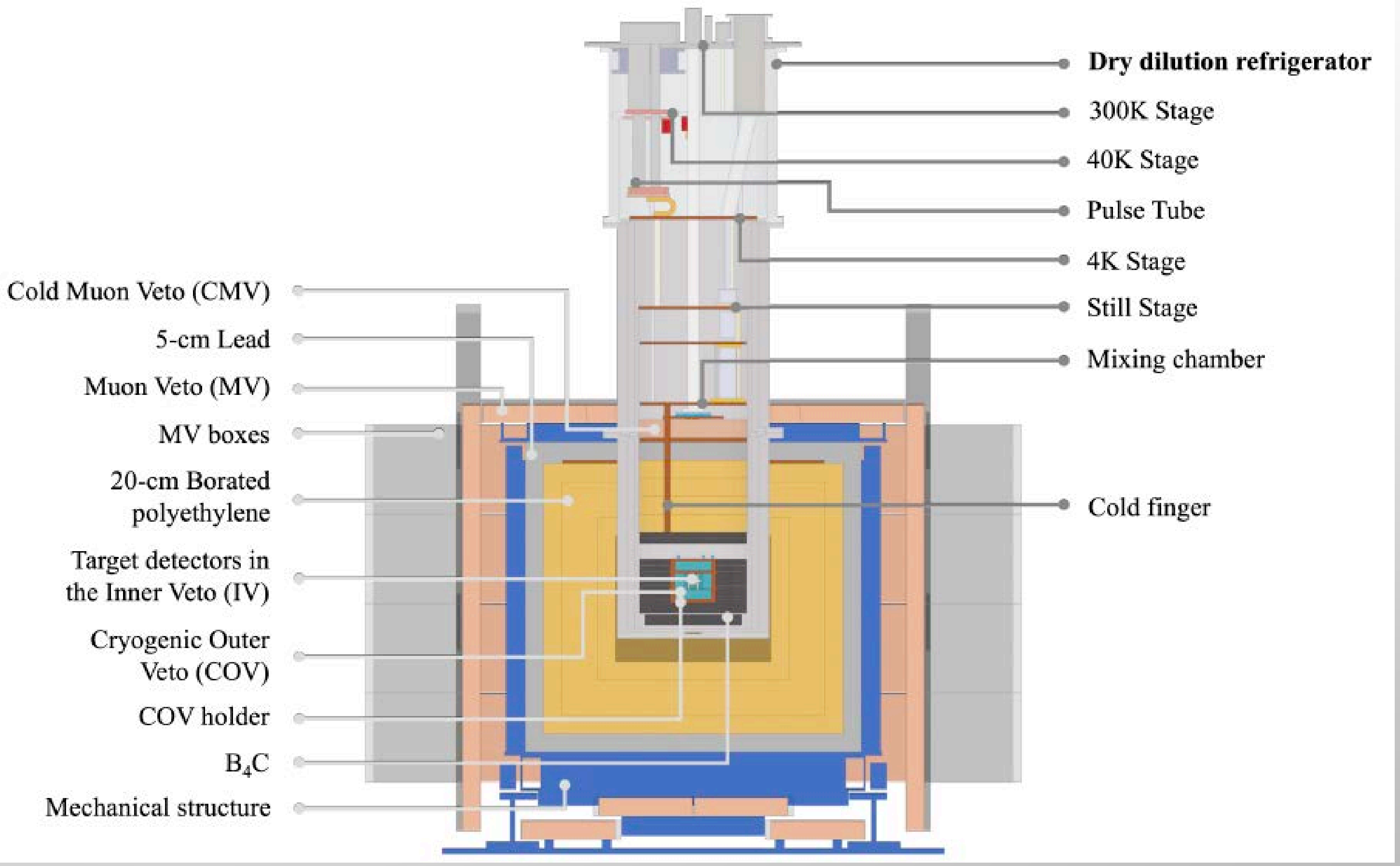
- $\simeq 0.7$ relative reduction of the cosmic muon flux measured at VNS with respect to the surface
- $\simeq 8$ reduction fraction of atmospheric neutrons (up to 2 MeVee)
- gamma background measurement and vibration measurement performed (data under evaluation)
- further neutron background measurements and Radon monitoring foreseen

Fast neutrons



Overview of the NUCLEUS setup

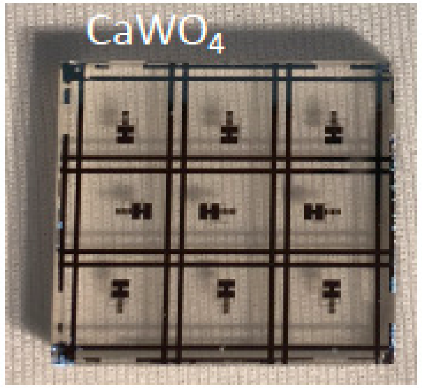
- “Dry” dilution refrigerator from Bluefors
- External 4π **Muon Veto** active shield
- Multi-layer **passive shield** (Lead/Borated PE)
- Inner “cold” shield
- **Ge cryogenic active Veto** surrounding the inner target detectors
- **Si cryogenic active Veto** holding and encapsulating the crystals
- Arrays of 3 x 3 cryogenic crystal calorimeters (9 **$CaWO_4$** and 9 **Al_2O_3**) operating at mK
- **UV-VIS** Calibration system + **radioactive** sources on site



NUCLEUS TARGET DETECTORS

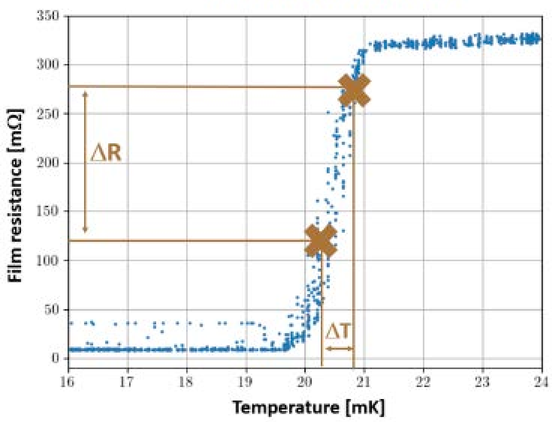
- Two arrays of 3 x 3 cryogenic crystal calorimeters with ultra-low energy threshold, (19.7±0.9) eV for Al_2O_3 are reached [PRD 96, 022009 (2017)]
- Multi target approach: 9 $CaWO_4$ (≃6 g) and 9 Al_2O_3 (≃4 g) crystals operating at mK with transition edge sensors as highly sensitive thermometer
- **UV-VIS** Calibration system

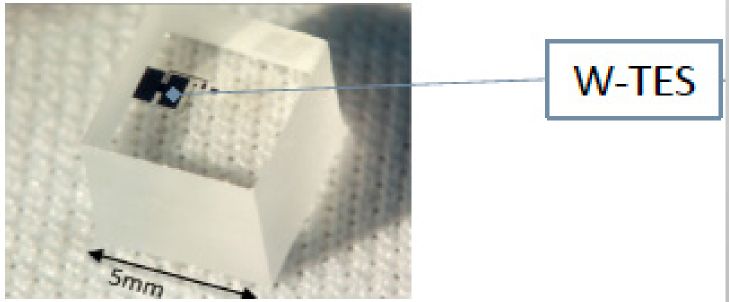
Arrays before cutting with W-TES (20x20x5) mm³



CRESST technology

Transition of W-TES

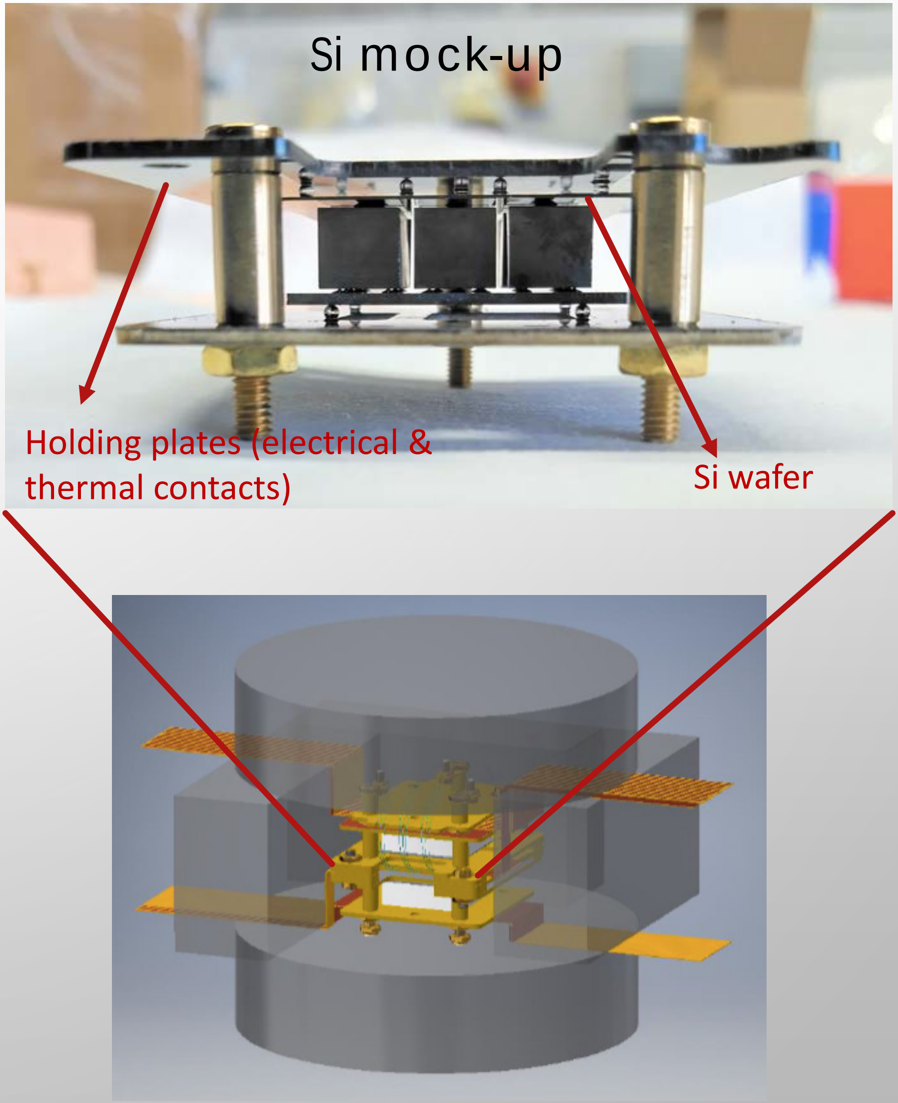




Phys. Rev. D **96**, 022009 (2017)

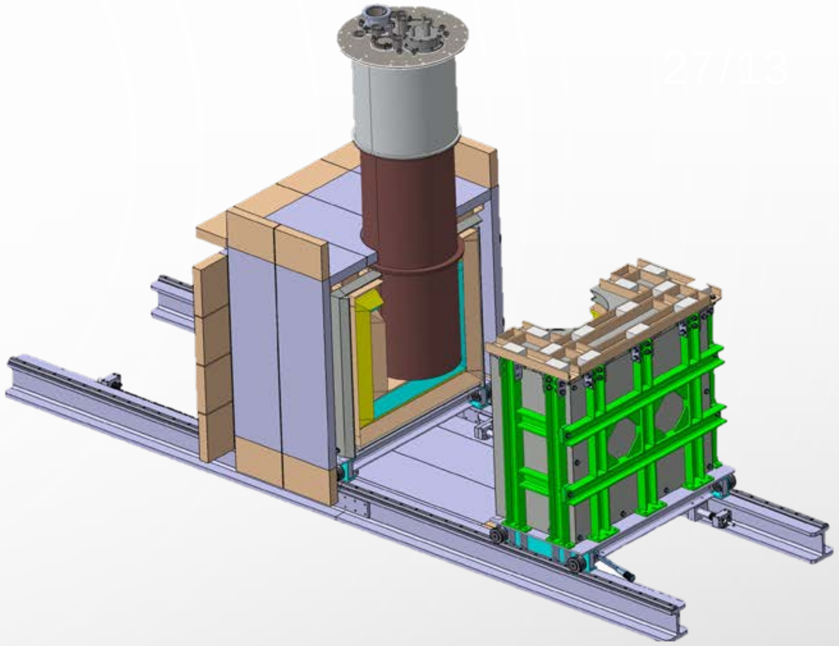
Inner & Outer Cryogenic Veto: 4π coverage of the target detector

- Active inner veto made of a Si beaker to reject surface backgrounds and holder-related events
- Si wafer instrumented with TESs to hold and encapsulate the crystals (mechanical and thermal test concluded)
- Inner veto pressed between 2 Si holding wafer where TES connection and copper cables will be connected
- 4 kg and 2.5 cm thickness HPGe Outer Veto surrounding the inner detectors for active γ/n background rejection (Cylindrical Ge crystals prepared, tested and validated; rectangular crystal in production)



Muon Veto

- 5 cm thick plastic scintillator plates
- SiPM & WLS-fiber readout
- High efficiency for muon detection > 99%
- High uniformity in light collection
- 4π coverage of the set-up
- Cold muon veto: cylindrical shape, thermalized at 800 mK



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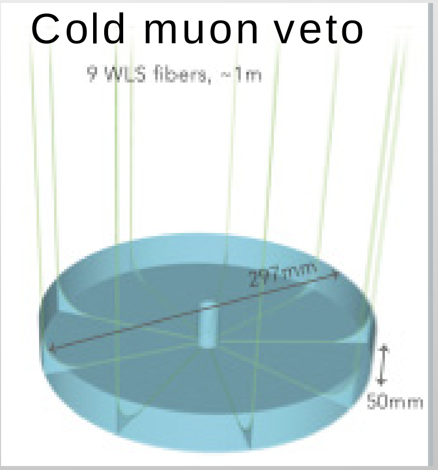
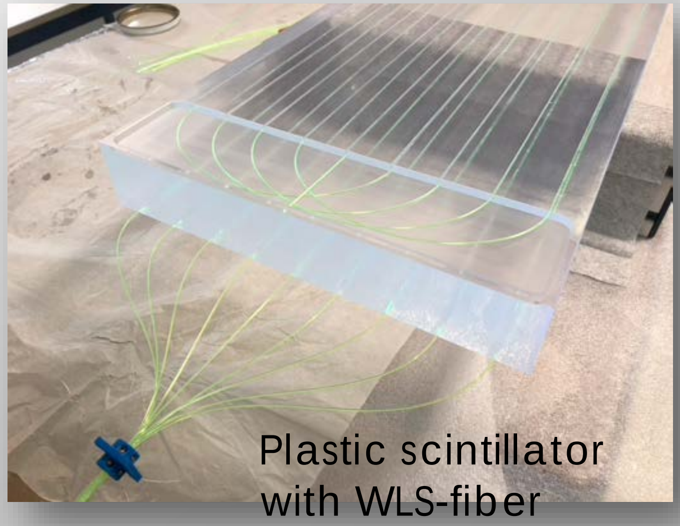
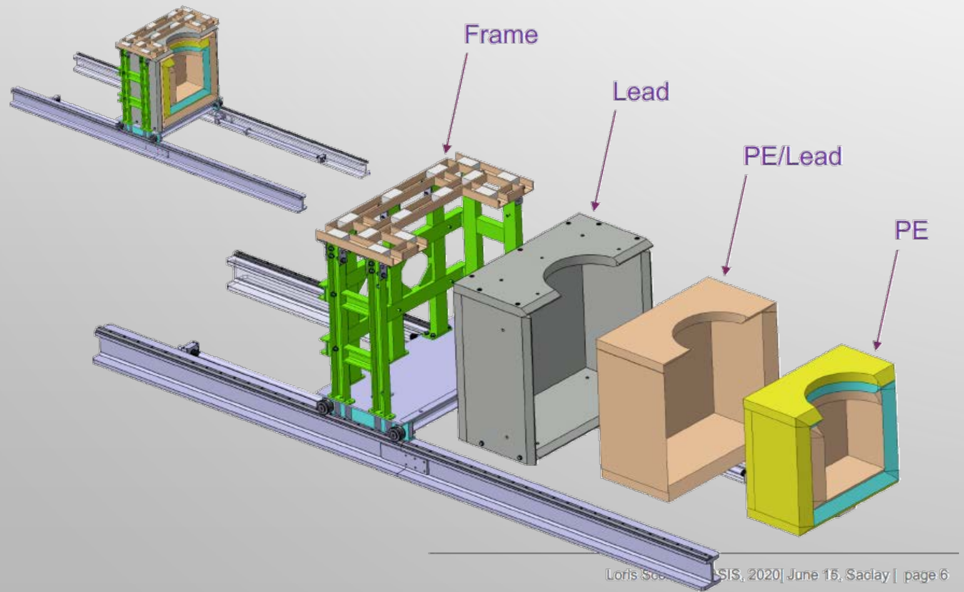


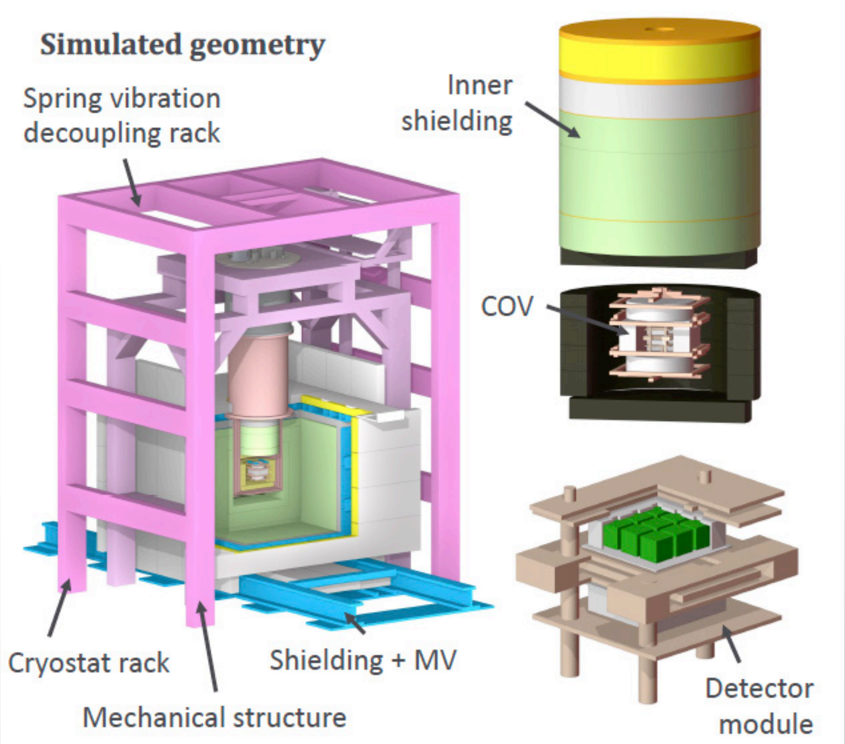


Passive Shield

- Multilayer Passive Shield made of Lead and Polyethylene
- Movable mechanical structure to allow easy opening/closing procedure
- Ambient gamma background reduction
- Attenuation of neutron background (Borated PE and B_4C layer)
- Minimize neutrons in the inner part of the shield induced by μ interaction with shield materials

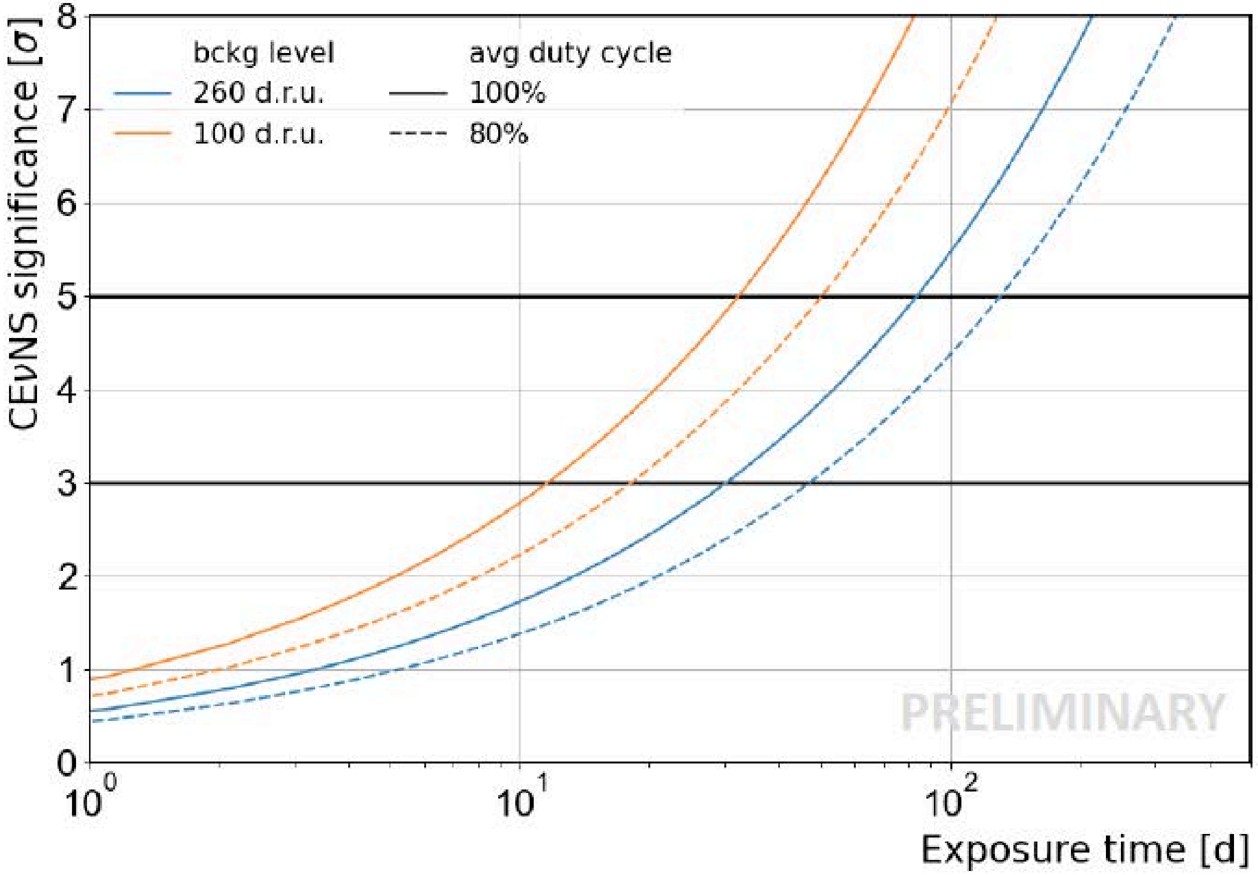


Inner "Cold" shield



- Aligned with external Active and Passive shield
- Just above the detectors to close the external shield
- Muon Veto, Lead, Copper support (acting also as a thermal contact), PE, B_4C
- Thermalized at 600 mK

NUCLEUS 10g sensitivity



S/B ≈ 1

3σ after ~ 50 days
5σ after ~ 140 days

Very strong hypotheses!

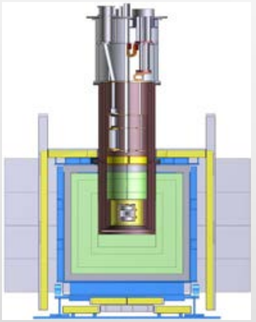
- Flat background
- Target detectors threshold @10 eV
- No EXCESS
- No detector efficiency
- No dead time

⇒ Detailed sensitivity studies are on-going

Excess and its role in the low energy range to be investigated: NUCLEUS veto system can allow to identify different excess components

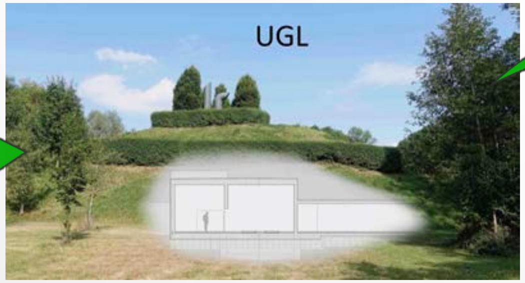
TOWARD THE BLANK ASSEMBLY AND BEYOND

Design (May '22)



- DESIGN FINALIZED

Assembly at TUM (2024)

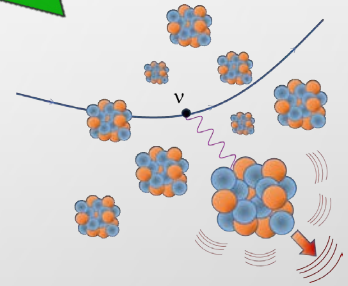


- Installation and commissioning
- Performances
- LED Calibrations
- Neutron Calibration (CRAB) (see G. Soum-Sidikov poster)

Set-up will be moved to CHOOZ (end 2025)

- Installation at Chooz
- Experiment switch on

Physics run (2026)



- Reactor neutrinos measurement

Future: from 10 g to kg scale high-precision measurement

Conclusion

- **The NUCLEUS** experiment aims at the exploration of ***CEνNS*** at low energy with cryogenic detectors
- The experiment will operate at the **Chooz** nuclear power plant in France
- In the 1st stage **10 g** scale target mass will allow to measure the CEνNS signal by using **Al_2O_3** and **$CaWO_4$** cryogenic detectors
- **The NUCLEUS** finally assembled at TUM; long background run foreseen in summer 2024
- In **2025** it will be shipped to **Chooz, installed** and **commissioned**
- A **1 kg** mass scale experiment is foreseen for precision measurement at percent level to explore **physics beyond SM**