# Coherent Elastic Neutrino Nucleus Scattering: Results & Future Prospects

Matthieu VIVIER

CEA Paris-Saclay, IRFU,
91191 Gif-sur-Yvette, FRANCE

Prospects of Neutrino Physics
Kavli IPMU, Kashiwa, Japan
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# Outline

1. Experimental aspects of Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

2. The COHERENT experiment and results

3. CEvNS experiment at reactors

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1. Experimental aspects of Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

2. The COHERENT experiment and results

3. CEvNS experiment at reactors

WORKSHOP
**THE MAGNIFICENT CEvNS**
NOVEMBER 2-3, 2018 CHICAGO, IL USA

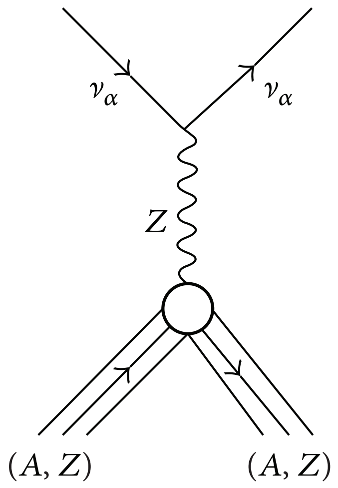
Some of the materials presented here based on presentations given at « THE MAGNIFICENT CEvNS » workshop

https://kicp-workshops.uchicago.edu/2018-CEvNS/index.php

# . Experimental aspects of CEvNS

# Coherent elastic neutrino nucleus scattering

- Neutral current process first predicted by Freedman (1974), which is insensitive to neutrino/antineutrino flavor



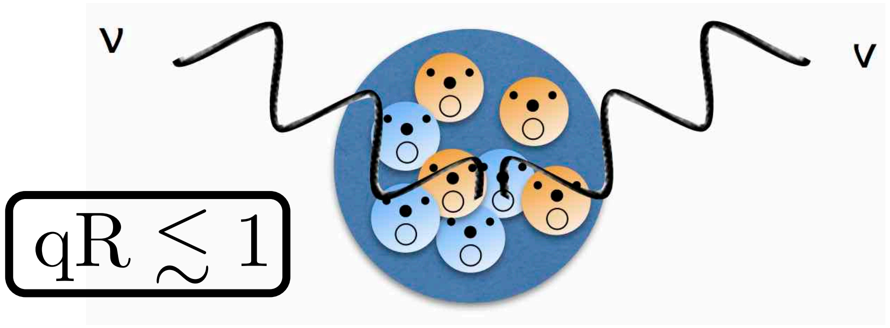

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

**Coherent effects of a weak neutral current**

Daniel Z. Freedman†
*National Accelerator Laboratory, Batavia, Illinois 60510*
*and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790*
(Received 15 October 1973; revised manuscript received 19 November 1973)

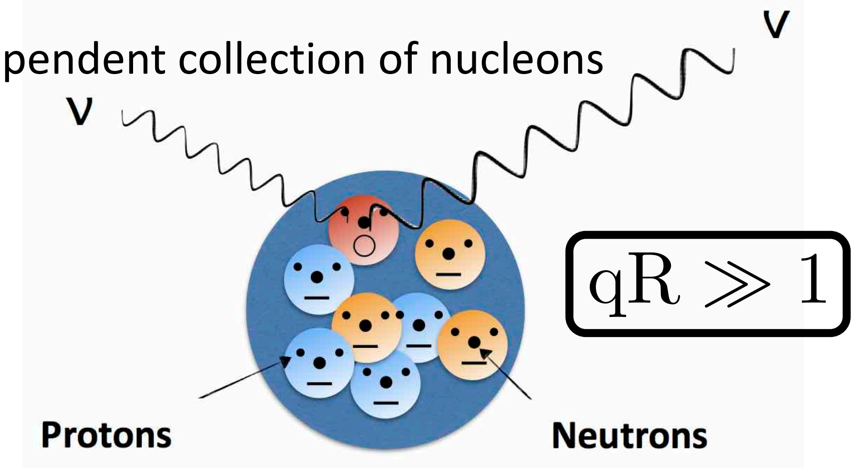
If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The 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 $\nu + A \rightarrow \nu + A^*$ 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.

- **Coherence:** the neutrino sees the nucleus as a whole, and not anymore as an independent collection of nucleons




q: momentum transfer
R: nucleus size

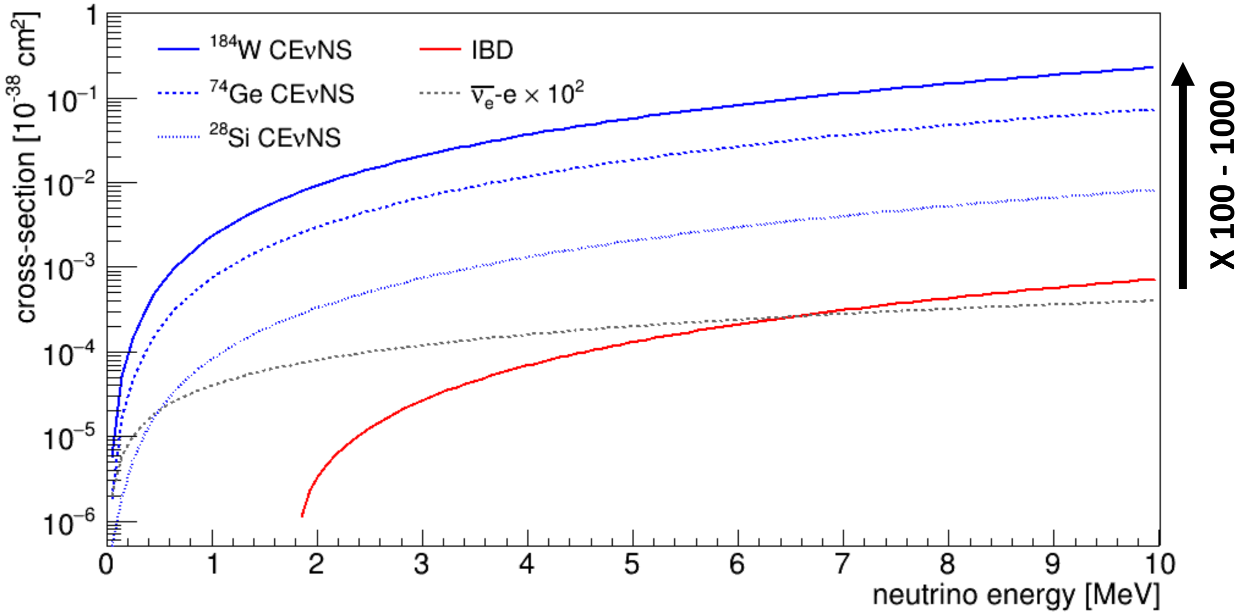
| |
|---|
| **Aluminium: 1/R ≈ 60 MeV** |
| **Lead: 1/R ≈ 30 MeV** |



# Coherent elastic neutrino nucleus scattering

- Cross-section mostly scales with the (number of neutrons)² in the target nucleus:

$$\sigma(E_\nu) \approx \frac{G_F^2}{4\pi}\left[Z\,(4\sin^2\theta_W - 1) + N\right]^2 E_\nu^2 \approx 0.42 \times 10^{-44} N^2 (E/1\,\mathrm{MeV})^2\,\mathrm{cm}^2$$




- No energy threshold
- The heavier the target, the larger the boost in the cross-section but the smaller the recoils…
- Cross-section x 100-1000 with respect to other ν detection channels

**Potential to miniaturize neutrino detectors and perform precision physics with < ton-scale detectors**

# CEvNS physics

- **Particle physics:**
  - New couplings to u & d quarks: non-standard flavor conserving and flavor changing interactions
  - Running of $\sin^2\theta_W$ at low momentum transfers
  - Neutrino electro-magnetic properties
  - Test of the reactor antineutrino anomaly and search for sterile neutrinos

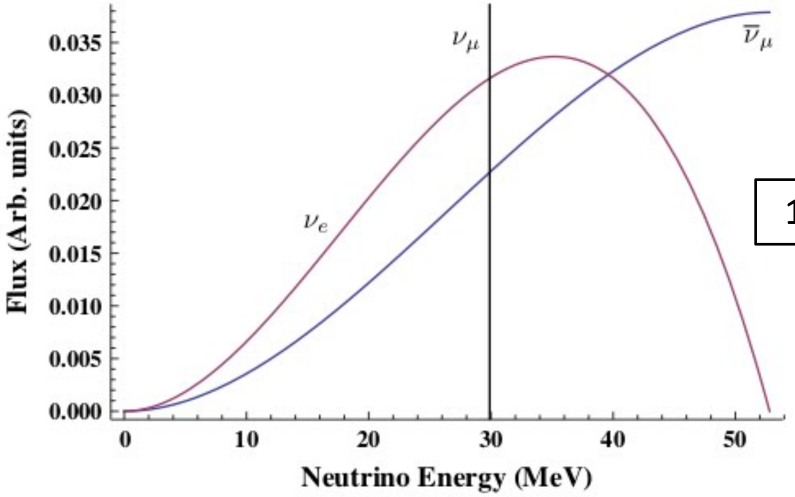
See J. Walker's talk for particle physics perspectives

- **Nuclear physics:** neutron density distributions
- **Interesting for:**
  - Direct dark matter detection → irreducible background
  - Detection of supernovae
  - Solar neutrino physics
  - Nuclear reactor safeguarding

**Need percent-level precision measurements to be competitive with other experiments**

# Man-made neutrino sources for CEvNS

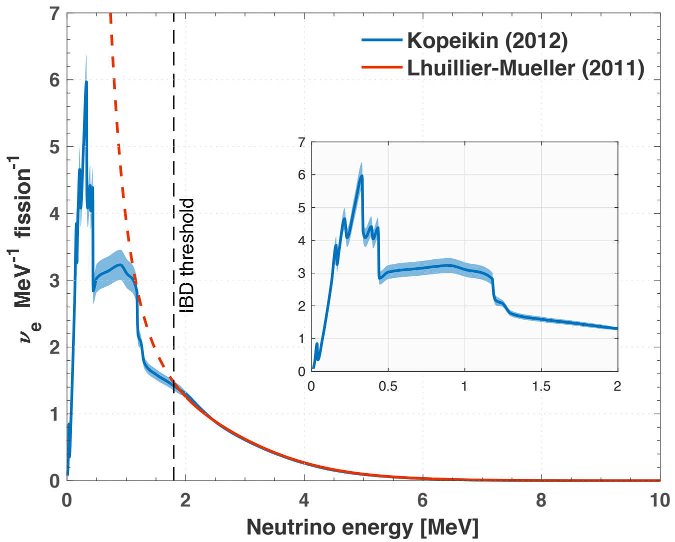
## Low energy neutrinos from accelerators




$10^7$-$10^8$ $cm^{-2}$ $s^{-1}$

- Pion-decay-at-rest (DAR) sources → multiple flavors
- Pulsed sources → high bck discrimination through timing
- Relatively « high » recoil energies ≥ keV
- Close to decoherence
- First observation of CEvNS by COHERENT in 2017

## Reactor antineutrinos



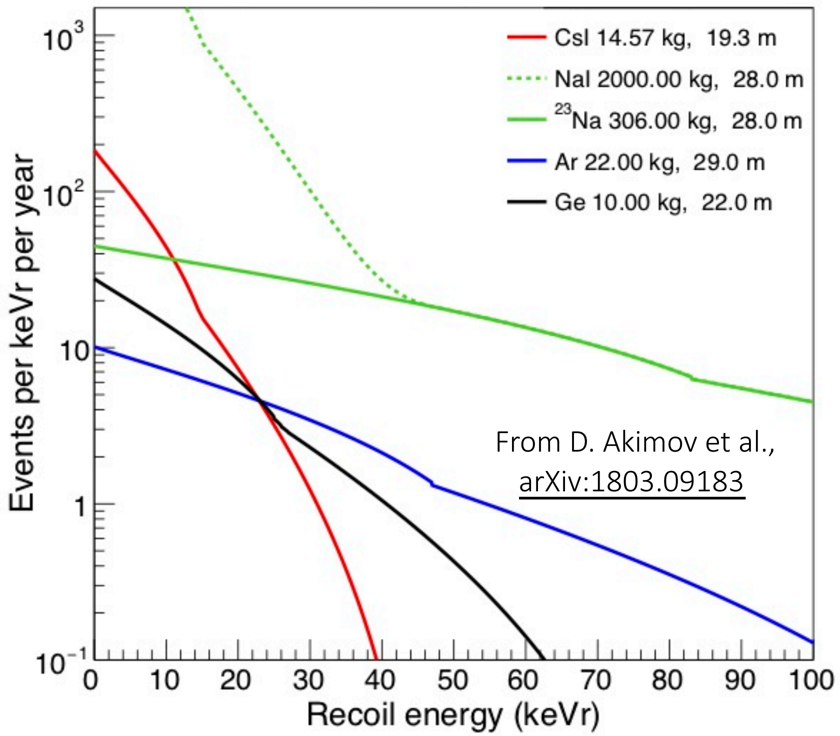

$10^{12}$-$10^{13}$ $cm^{-2}$ $s^{-1}$

- Nuclear fission → single (electronic) flavor
- Lower energies than accelerator → full coherence + smaller recoils
- Lower cross-section but much higher flux
- Continuous source → moderate bck discrimination through timing
- Wealth of on-going and planned experiments: CONUS, CONNIE, MINER, NU-CLEUS, RICOCHET, νGEN, etc…

# Detection: experimental challenges

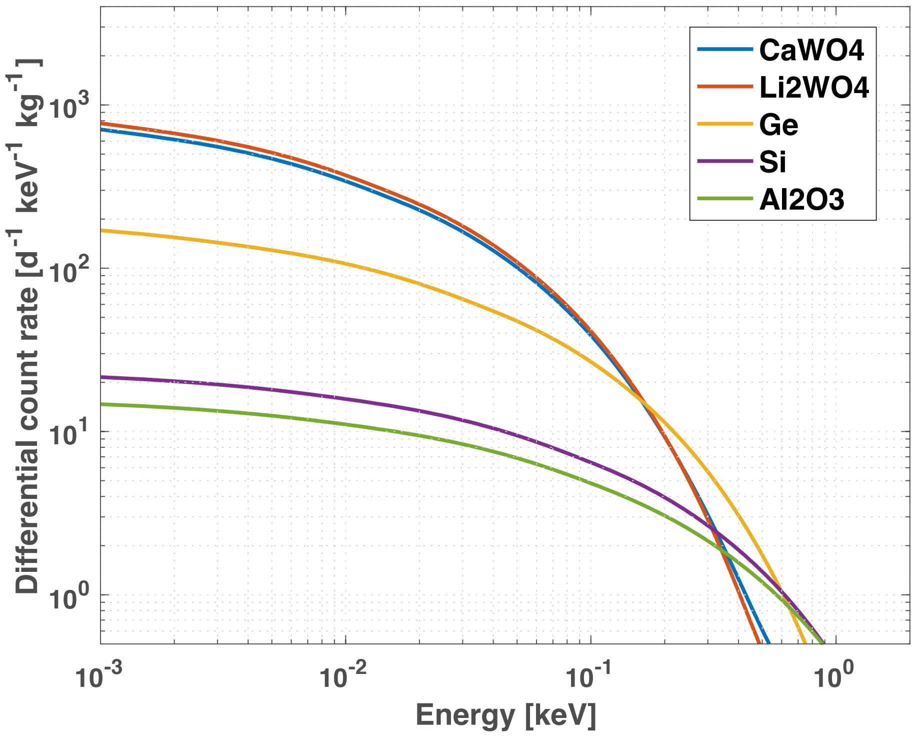
**Reach the lowest possible energies**

## Low energy neutrinos from accelerators




**$E_R \approx$ 10's of keV**

## Reactor antineutrinos

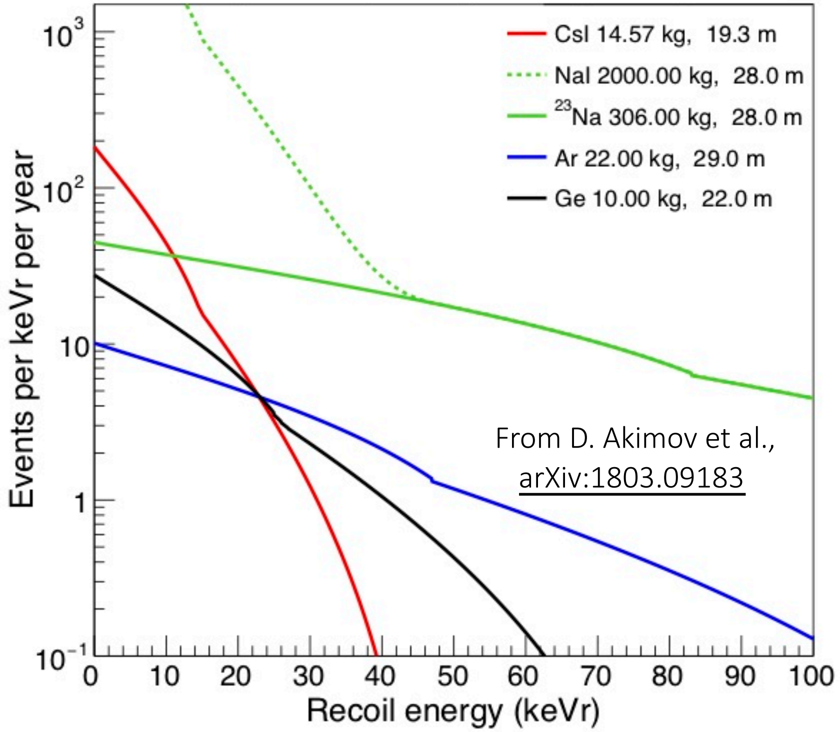



**$E_R \leq 1$ keV**

# Detection: experimental challenges

**Understand and mitigate the backgrounds in a yet unexplored energy regime**

## Low energy neutrinos from accelerators




From D. Akimov et al., arXiv:1803.09183

**$E_R \approx$ 10's of keV**

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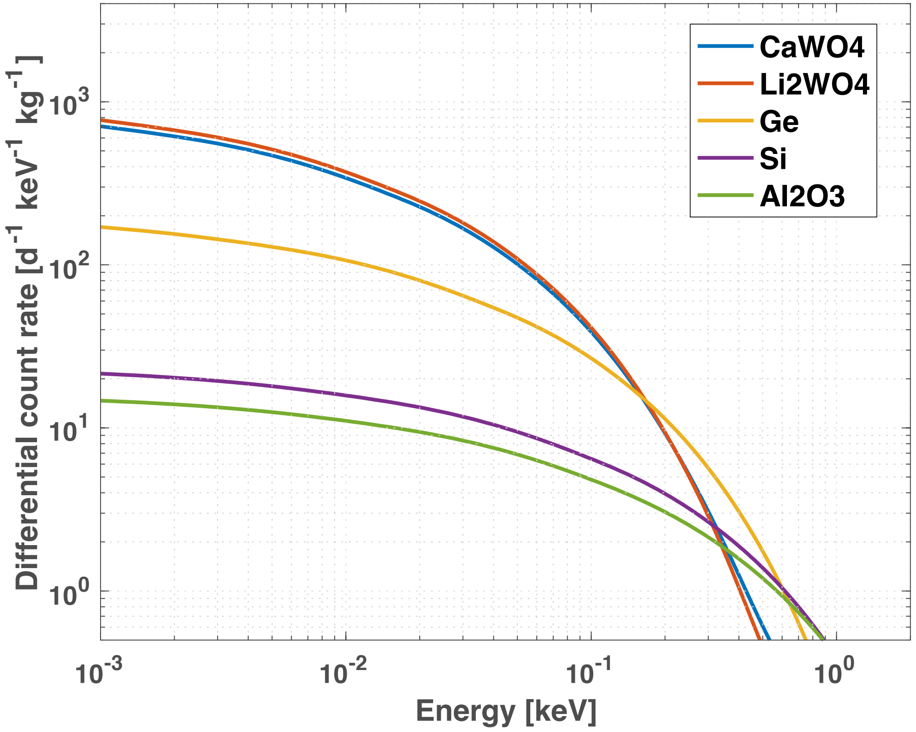
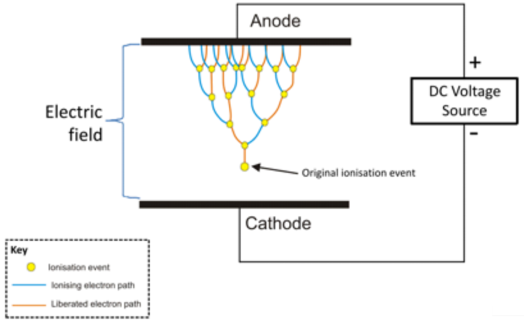



**$E_R \leq 1$ keV**

# CEvNS: what kind of detectors?

## Ionization detectors




- Energy to create an e-/hole pair ≥ 5-10 eV depending on target
- Suitable for ≥ keV nuclear recoils, hard for sub-keV (quenching…)
- Big expertise from DM and 00νβ exp.: **Ge PPCs, Ar/Xe TPCs, Si CCDs**

# CEvNS: what kind of detectors?

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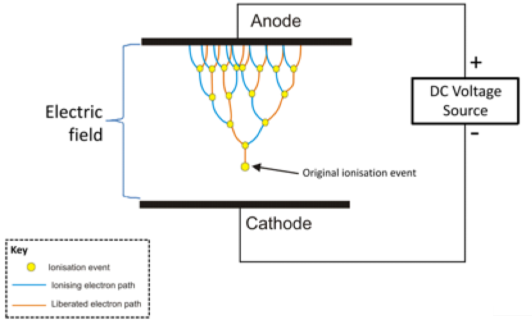


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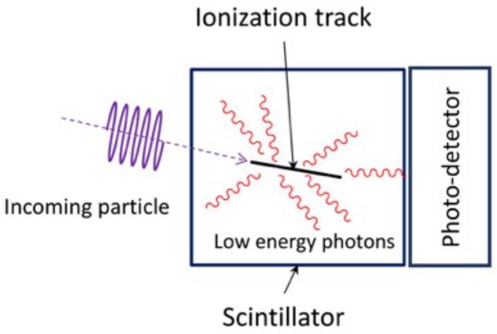
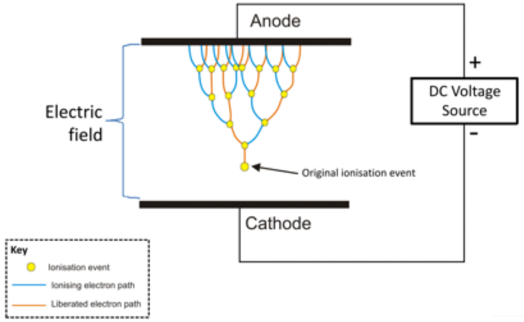
## Scintillation detectors




- Energy to excite fluorescence levels ≈ 10s of eV depending on material
- Suitable for ≥ keV nuclear recoils, very hard for sub-keV (quenching…)
- **Inorganic crystals: CsI, NaI, etc…**

# CEvNS: what kind of detectors?

## Ionization detectors

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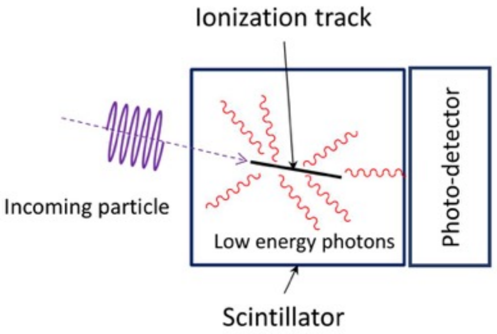


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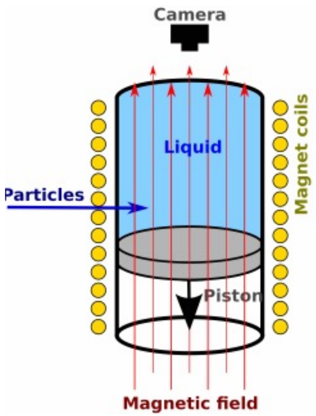
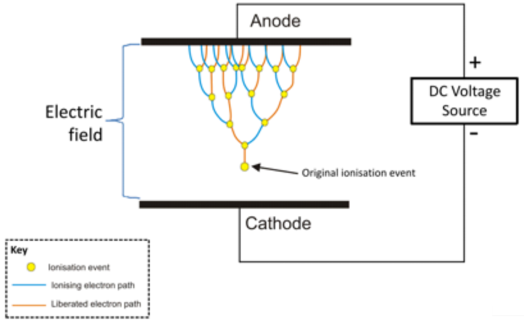
## Bubble chambers




- Energy to nucleate a bubble ≥ keV
- Suitable for ≥ keV nuclear recoils, not possible for sub-keV
- **Superheated liquids: $C_3F_8$, $CF_3I$, Xe**

# CEvNS: what kind of detectors?

## Ionization detectors

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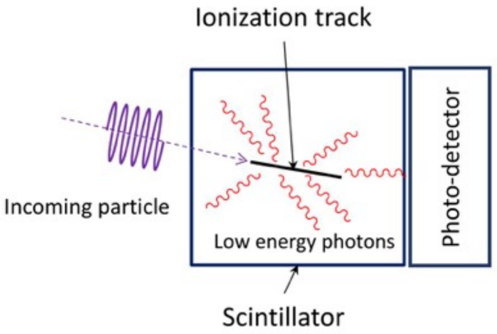


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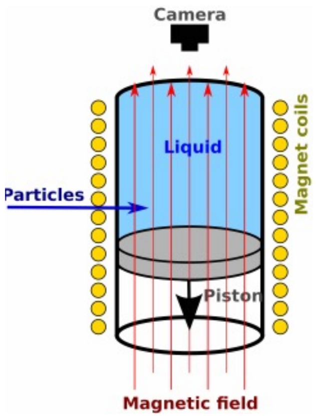
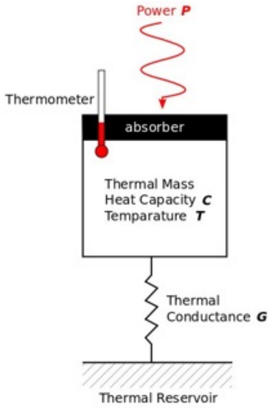
## Bubble chambers




- Energy to nucleate a bubble ≥ keV
- Suitable for ≥ keV nuclear recoils, not possible for sub-keV
- **Superheated liquids: $C_3F_8$, $CF_3I$, Xe**

## Phonon detectors

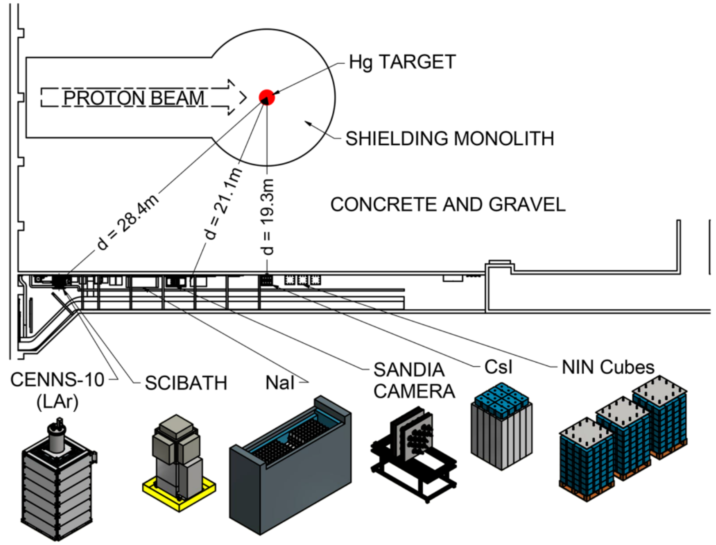



- Energy to create phonon in the μeV range
- Suitable for nuclear recoils below 0.1-1 keV
- Big expertise from DM and 00νβ exp.: **Ge, Si, $CaWO_4$, etc…**

# . The COHERENT experiment and results

# The COHERENT experiment

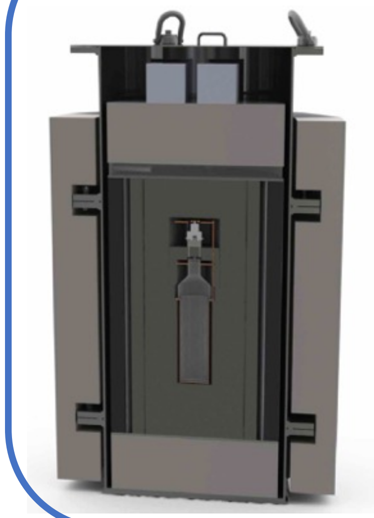
- Multiple detectors placed in the "neutrino alley" at the Spallation Neutron Source facility (Oakridge, Tennessee)
  - 60Hz-pulsed neutron source with $5 \times 10^{20}$ POT/day
  - Neutrino flux ≈ $10^{7}$ cm$^{-2}$ s$^{-1}$ @ 20 m
  - Beam related neutrons shielded by iron & steel monolith around mercury target + 12 m of concrete
- Pragmatic approach, using well-known detector technologies and taking advantage of the pulsed structure of the ν source to detect the "high" energy CEvNS-induced recoils




| Target | Technology | Mass [kg] | Distance [m] | Threshold [$keV_{nr}$] | Data-taking start date |
|---|---|---|---|---|---|
| **CsI[Na]** | Scintillation | 14 | 20 | 4 | Sept. 2015 |
| **Ge PPC** | Ionization | 10 | 22 | ≤ 1 | By summer 2019 |
| **LAr** | Scintillation | 35 | 29 | 20 | June 2017 |
| **NaI[Tl]** | Scintillation | 185 | 28 | 30 | Summer 2016 |

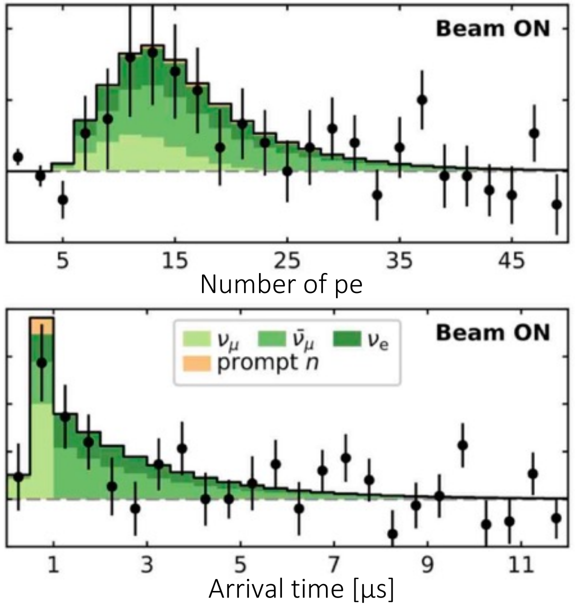
# The COHERENT detection

## CsI[Na] scintillation detector



- 14.6 kg @ 19.3 m from source
- PE + lead passive shielding against neutrons + μ veto
- Energy threshold ≈ 4 keV
- Beam ON/OFF data: 308.1/153.5 live-days

**2015-2017 data**





D. Akimov et al.,
Science 357, 6356 (2017)

**Breakdown of main systematics**

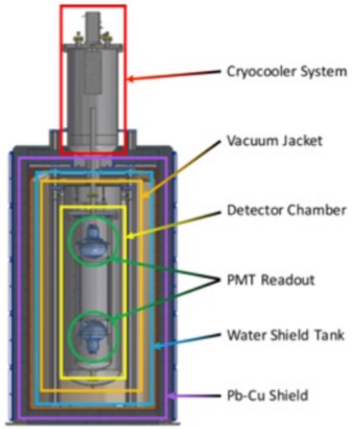
| Source of systematic | Contribution |
|---|---|
| Form factor (in CEνNS cross-section) | 5% |
| **ν flux from SNS** | **10%** |
| **CsI[Na] quenching factor** | **25%** |
| Det. efficiency | 5% |
| Source-detector baseline | Negligible |
| **Backgrounds** | **25%** |

$N_{CE\nu NS}$ = 134 ± 22
6.7σ significance

- Statut of CsI[Na] detector: accumulating data, improving QF measurement & bck characterization

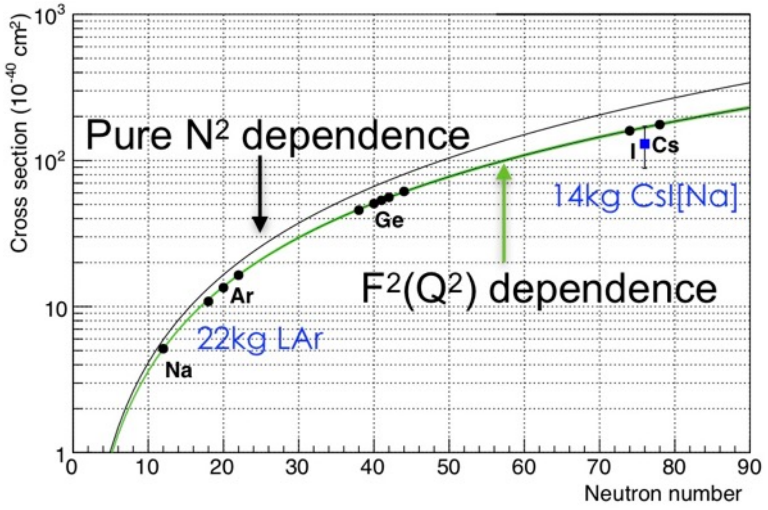
# COHERENT status

## CENNS-10 Liquid argon detector

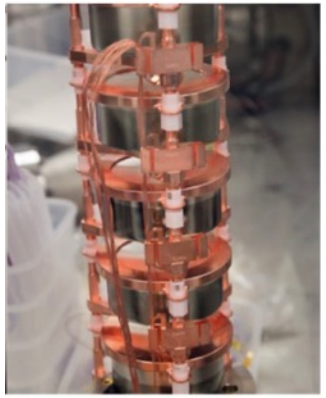



- Scintillation only
- 22 kg fiducial mass, 20 $keV_{NR}$ threshold expected
- Extensive study of backgrounds
- **Accumulating data since June 2017 (100 CEvNS events expected in Nov. 2018)**

Measure $N^2$ dependence of CEvNS cross-section

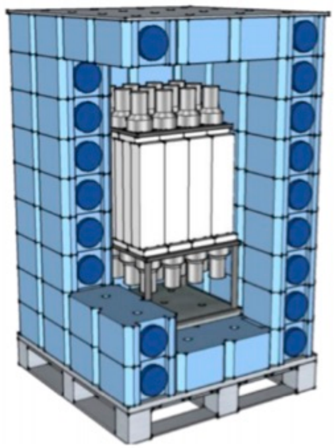



## Ge PPC



- Planning for the deployment of a 10-kg array
- ≤ 1 $keV_{NR}$ demonstrated on the first two 2.5 kg modules
- Data taking to be started by summer 2019

## NaI[Tl]

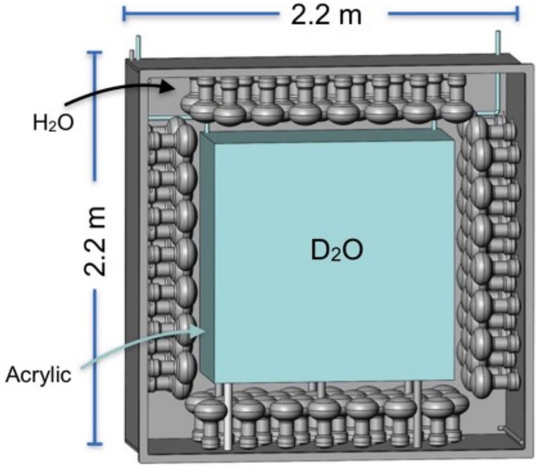


- 185 kg prototype operating since 2016
- Characterization of in-situ backgrounds
- Development of new PMT bases + calibration →energy threshold ≈ 30 $keV_{NR}$
- Working on the final detector design (ton scale) to measure CEvNS on Na

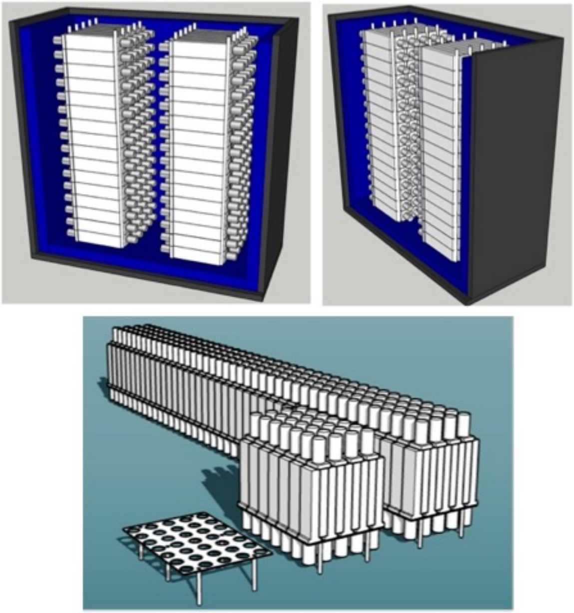
# The future of COHERENT

- My bet for the near future: new results to be released soon with the LAr detector → new CEvNS measurement on Ar
- Huge efforts on measuring the quenching factors of CsI[Na] and other detectors → dominating systematics
- Development of a ton-scale $D_2O$ detector to monitor SNS neutrino flux → reduce systematics
- Detector upgrades under consideration:
  - LAr detector → ton-scale
  - Additional Ge mass in the array of Ge PPCs
  - NaI[Tl] setup → up to 9 tonnes
  - Detectors with other targets, such as Ne and Xe

SNS neutrino flux monitor




Possible setups for a ton-scale NaI detector @ SNS



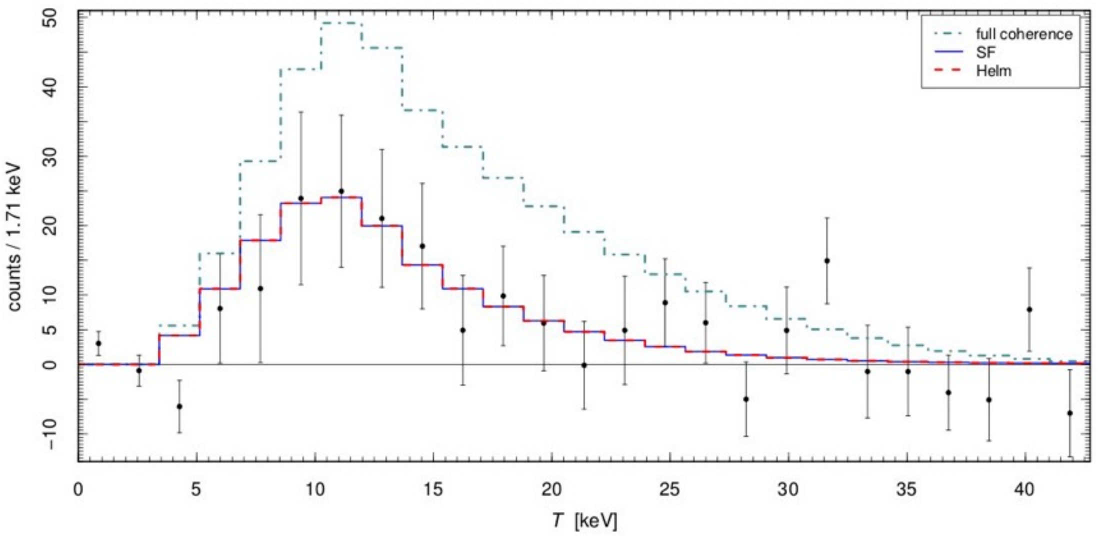
# Cs & I neutron rms radii

$$\frac{d\sigma}{dT} = \frac{G_F^2 (2 g_L^\nu Q_W)^2 F^2(q^2)}{4\pi} M \times \begin{cases} \left(1 - \frac{T}{E_\nu} - \frac{MT}{2E_\nu^2}\right) & \text{for spin } 0 \\ \left(1 - \frac{T}{E_\nu} - \frac{MT}{2E_\nu^2} + \frac{T^2}{2E_\nu^2}\right) & \text{for spin } \frac{1}{2} \end{cases}$$

M. Lindner, W. Rodejohann & X-J. Xu, J. High Energ. Phys. (2017) 2017: 97

$$F(q^2) = \frac{1}{Q_W}\left[N F_n(q^2) - (1 - 4\sin^2\theta_W) Z F_p(q^2)\right]$$

Evidence from departure from full coherence in COHERENT data ($F(q^2) \leq 1$)



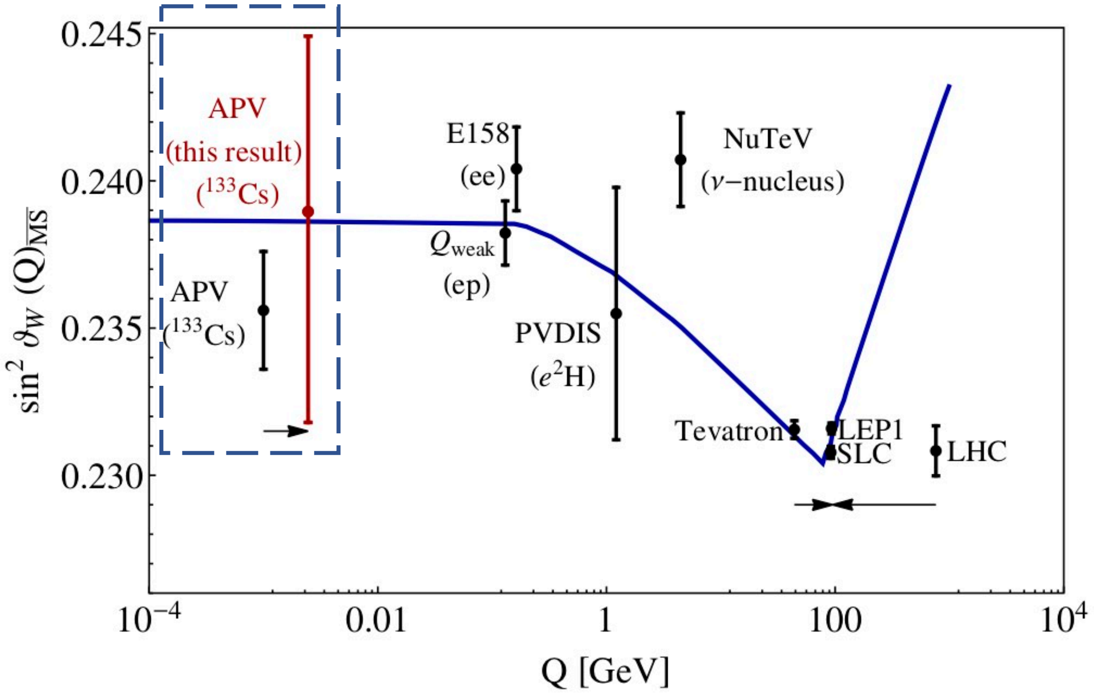

M. Cadeddu, C. Giunti, Y.F. Li & Y.Y Zhang Phys. Rev. Lett. 120, 072501 (2018)

- Proton rms radii are rather well measured, neutron rms radii more seldom and uncertain
- **First measurement ever of neutron rms radii with neutrinos** → very interesting for nuclear physics and astrophysics

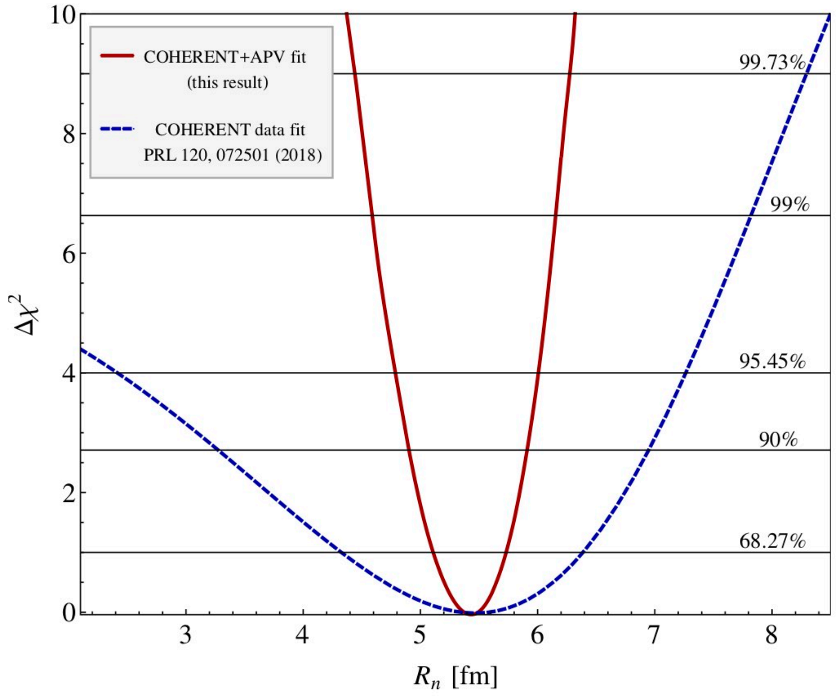
$$R_n = \langle r_n^2 \rangle^{1/2} = 5.5^{+0.9}_{-1.1}\,\text{fm}$$

# Weak mixing angle at low energies

- Using the neutron radius estimate from COHERENT data, APV result on $^{133}$Cs can be reconciled with SM prediction:




M. Cadeddu & F. Dordei
Phys. Rev. D 99, 033010 (2018)




- Combining APV measurement with COHERENT data can further constrain Cs neutron rms radius:

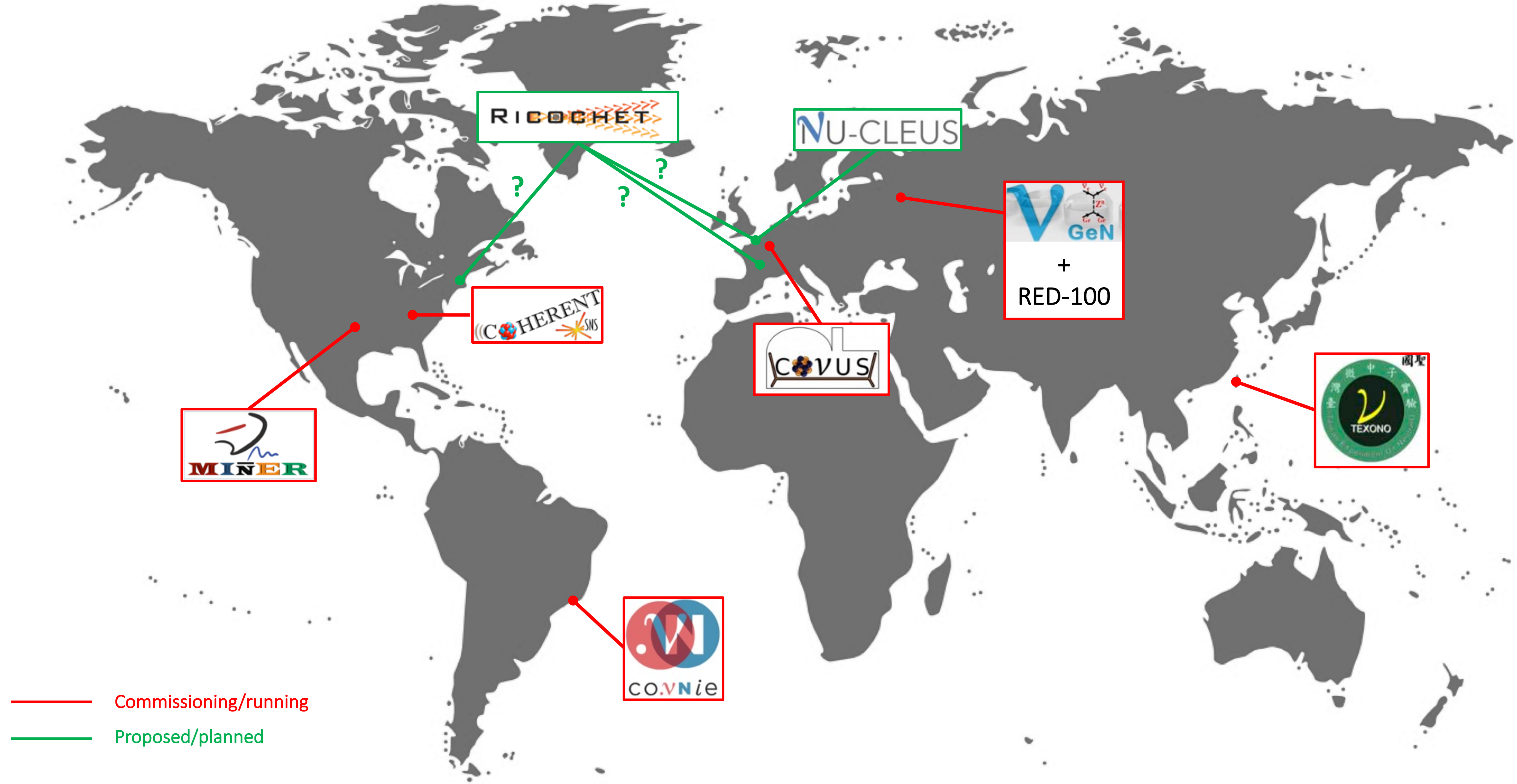
$$\mathrm{R_n} = \langle \mathrm{r_n^2} \rangle^{1/2} = 5.42 \pm 0.31\,\mathrm{fm}$$

1st meaningful value on $^{133}$Cs neutron skin →

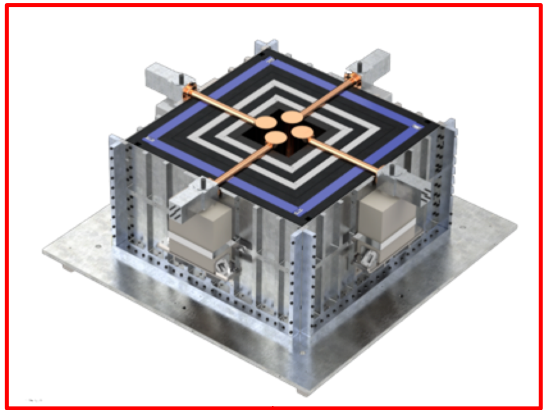
$$\Delta\mathrm{R_{np}} = 0.62 \pm 0.31\,\mathrm{fm}$$

# . Experiments at reactors

# CEvNS experiments worldwide

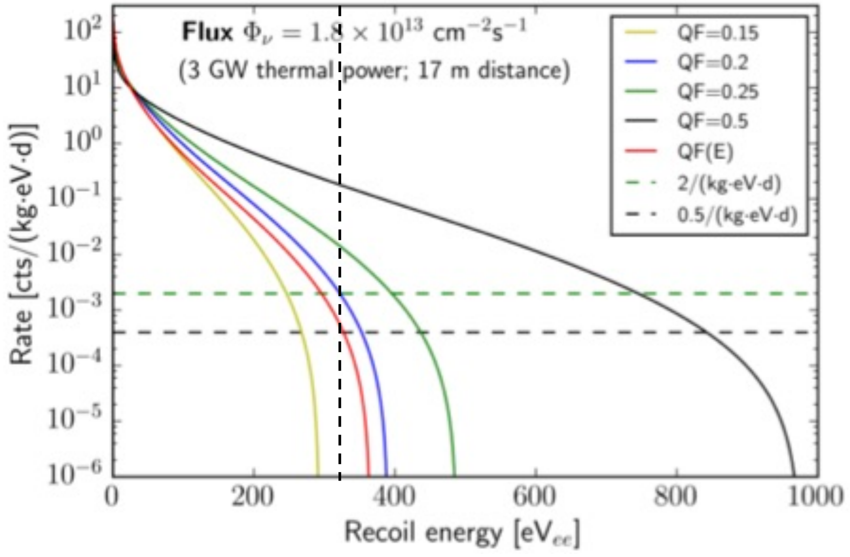


# The CONUS experiment

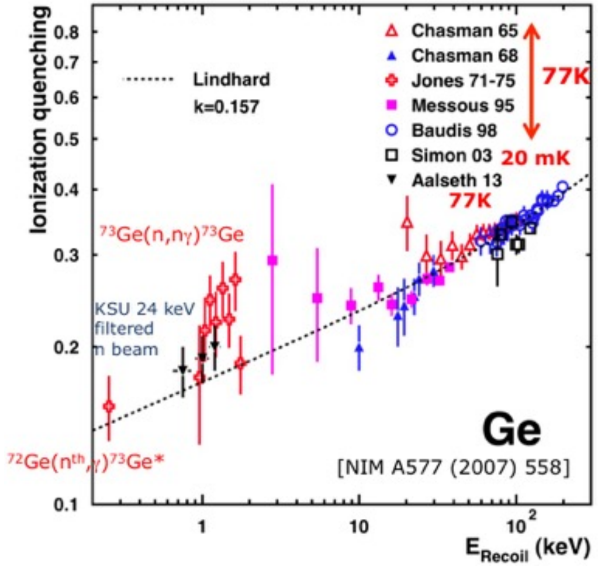


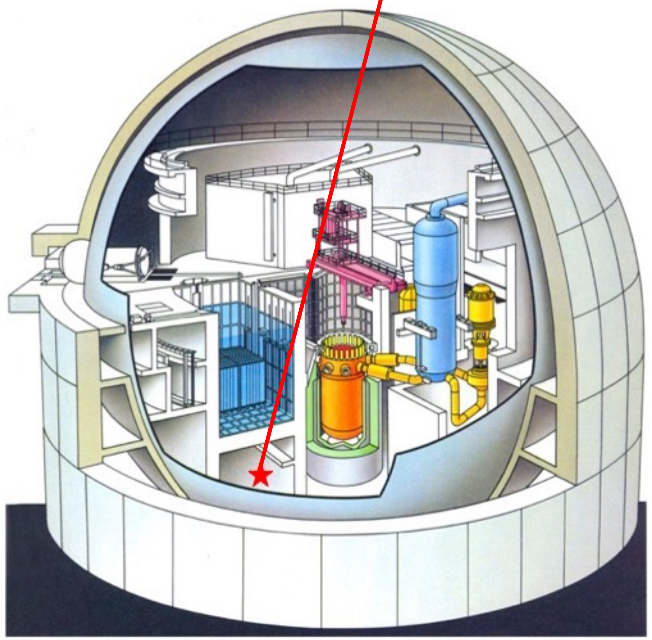
- At Brokdorf reactor (Germany): d = 17 m, $P_{th}$ = 3.9 $GW_{th}$, overburden = 10 m w.e.
- Commercial p-type point HPGe (m ≈ 4 kg) → ionization detector with $E_{th}$ ≈ 300 $eV_{ee}$ ≈ 1-1.5 $keV_{NR}$
- Multi-layered passive shielding + active µ veto → targeted bck. rate in setup: 10 $d^{-1}$ $keV^{-1}$ $kg^{-1}$
- Highly sensitive to ionization quenching, which will define final $E_{th}$ → systematics...

CEvNS recoil spectra as function of Ge ionization quenching



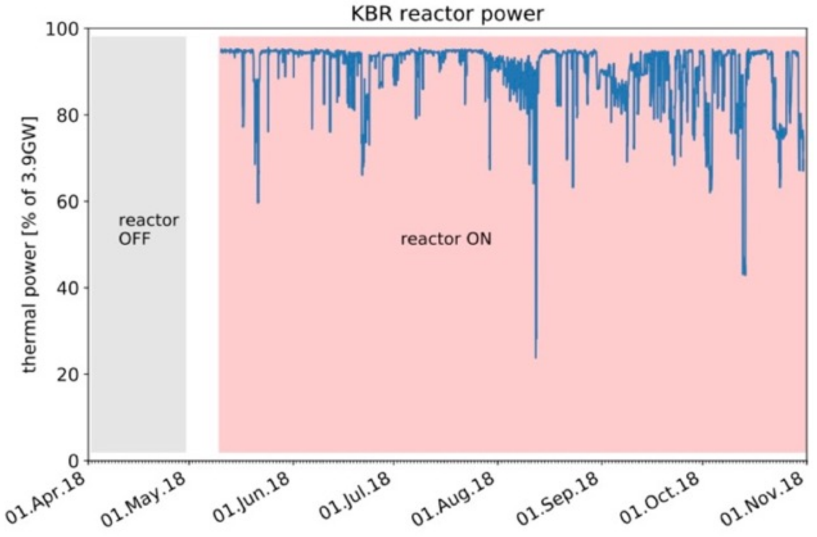

Ge ionization quenching measurements



# CONUS status and future

- Detector construction and commissioning late 2017/beginning 2018
  - Demonstrated radon mitigation, background stability & absence of reactor-correlated background
  - Performed calibration of detector energy response
- Hint for a 2.4σ event excess showed at Neutrino 2018
- **New results** presented at the Moriond 2019 conference:
  - Data from April to November 2018 → downward stat. fluctuation with respect to Neutrino 2018 result.
  - Measurement is background limited: next reactor outage in 2019 (4 weeks), long reactor OFF after 2021
- Future plans for CONUS:
  - Scale up the detector mass to 100 kg → precision physics with CEvNS



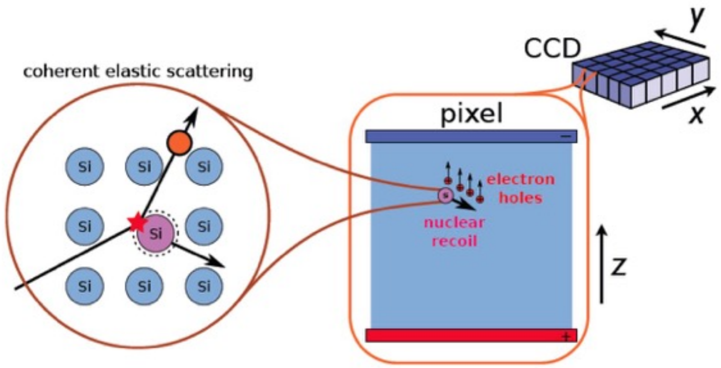

C. Buck @ Moriond 2019

Rate only analysis

| Counting analysis [300-550 keV] | Counts |
|---|---|
| Reactor OFF (65 kg.day) | 354 ± 19 |
| Reactor ON (417 kg.day) | 2405 ± 49 |
| **ON-OFF** | **133 ± 130** |

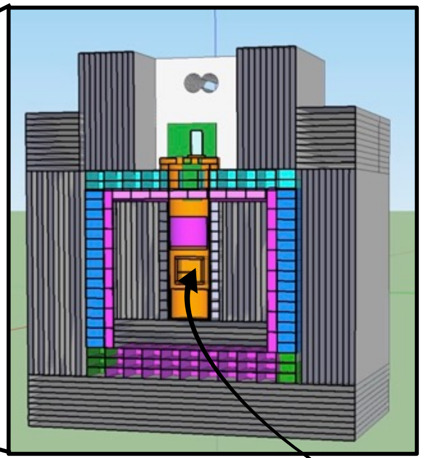
# The CONNIE experiment

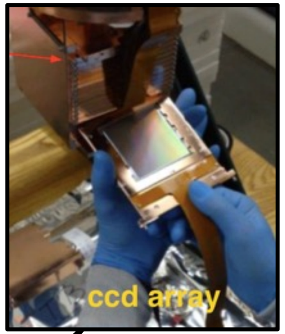
- At Angra nuclear power plant (Brazil): d = 30 m, $P_{th}$ = 3.95 $GW_{th}$, surface
- Ionization detectors mutualized with the DAMIC DM direct detection experiment
  - Mpixels Si CCDs imaging the energy deposition of particles
  - Energy threshold down to 30 $eV_{ee}$ → ≈ 300-400 $eV_{NR}$ taking quenching into account
- Multi-layered passive shielding + active μ veto
- Performed full calibration of quenching at low energy recoils



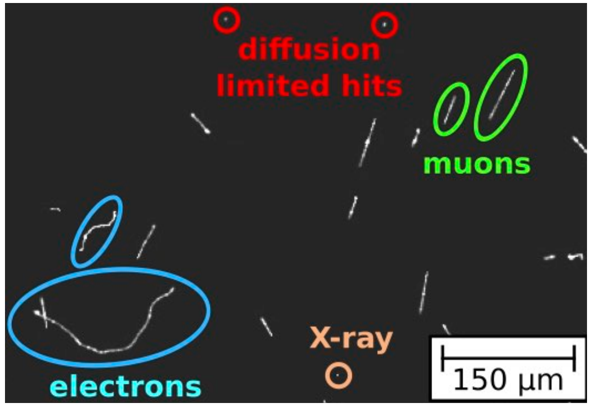

Angra nuclear power plant

Shielding setup






Particle identification capabilities

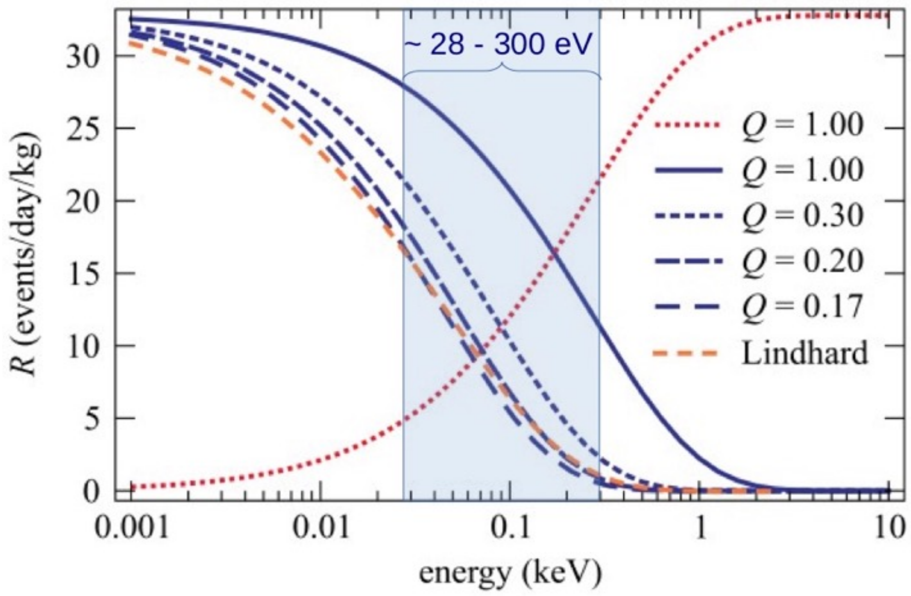


# CONNIE status & future

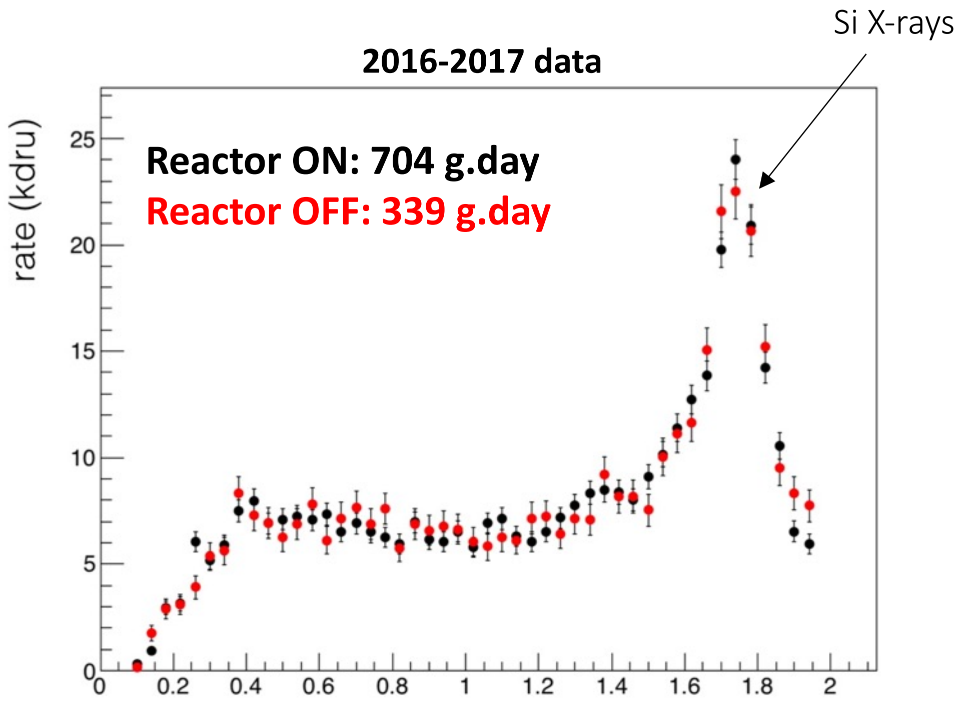
- Engineering run in **2015** with a **1-g active mass** demonstrator → no signal
  - Study of detector response + characterization of backgrounds
- Large detector upgrade in **2016**, data taking with an array of **14 x 6-g CCDs** → analysis on-going, results to be published soon
- Plans for the future:
  - R&D to increase mass by a factor 200 (SkipperCCD for DM and CEvNS)

A. Aguilar-Arevalo et al.
JINST 11 P07024 (2016)

**Integral rate as function of energy threshold**



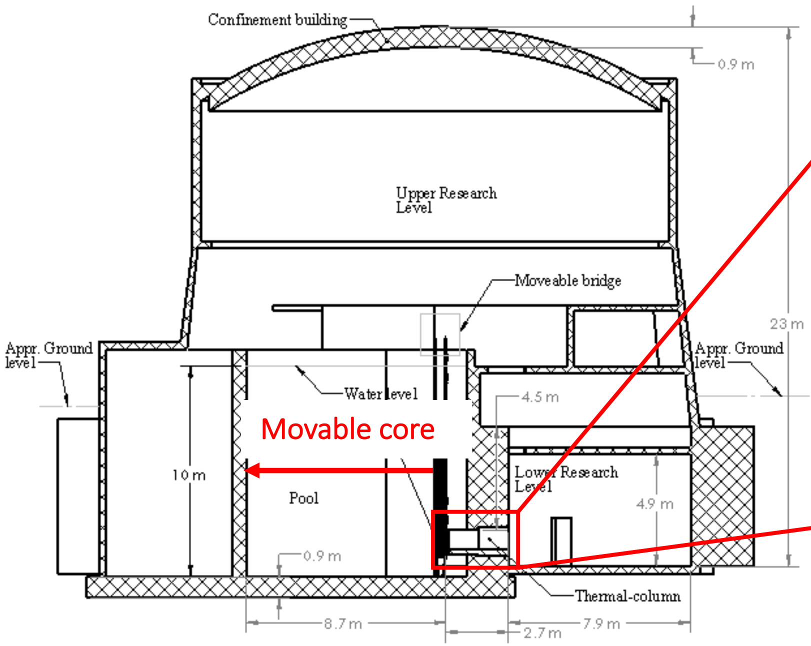

**2016-2017 data**



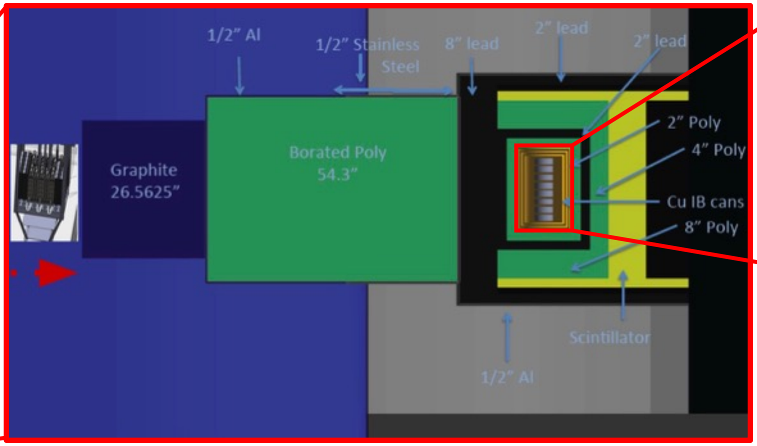

J. Estrada @ Magnificent CEvNS workshop

# The MINER experiment

- At Nuclear Science Center, Texas A&M university, 1-MW TRIGA research reactor (**movable core!**) → baseline 2-10 m → sterile !
- Ionization and/or phonons detectors developed for SuperCDMS DM experiment:
  - Ge & Si iZip detectors with both ionization and phonon readout: particle discrimination - $E_{th} \approx 270/170\ eV_{NR}$ (Ge/Si)
  - High voltage Ge & Si detector with phonon readout only: no particle discrimination – aim at $E_{th} \approx 40/80\ eV_{NR}$ (Ge/Si) using ionization signal amplification (Neganov-Luke)
- Neutron/gamma background at a level of 1000 $kg^{-1}\ d^{-1}\ keV^{-1}$(measurements + simulation)



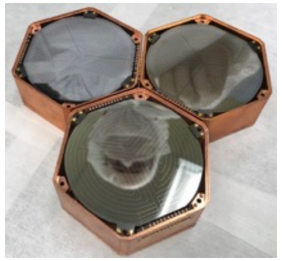

Experimental area + shielding setup




R. Mahapatra @ Magnificent CEvNS workshop

**Detector payload**

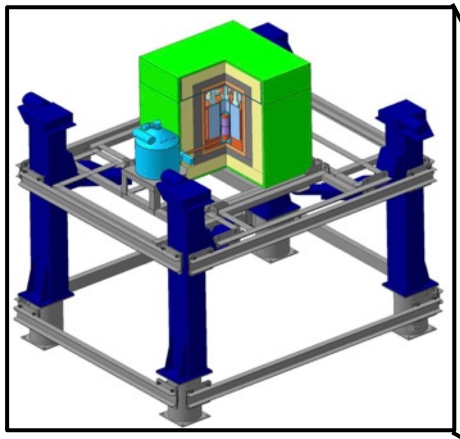
- Phase-1 (now): up to 4 kg
- Phase-2 : 30 kg with new shielding & lower energy threshold



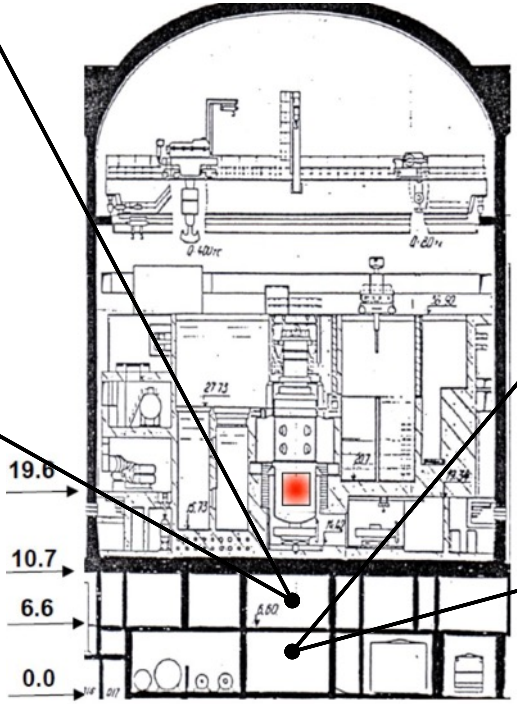
# Experimental efforts in Russia

- Two CEvNS experiments being commissioned/ran at the Kalinin 3 $GW_{th}$ nuclear reactor

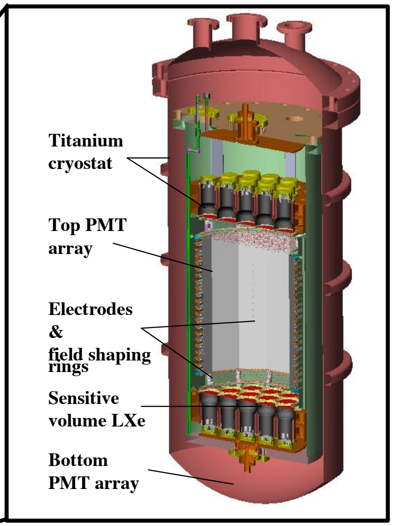
## vGEN HPGe array



- Baseline ≈ 10 → 12 m (lifting mechanism)
- 4 x 0.4 kg detectors: $E_{th}$ ≈ 350 $eV_{ee}$ ≈ 2 $keV_{NR}$
- In-situ background characterization at LSM
- Data taking should be on-going by now



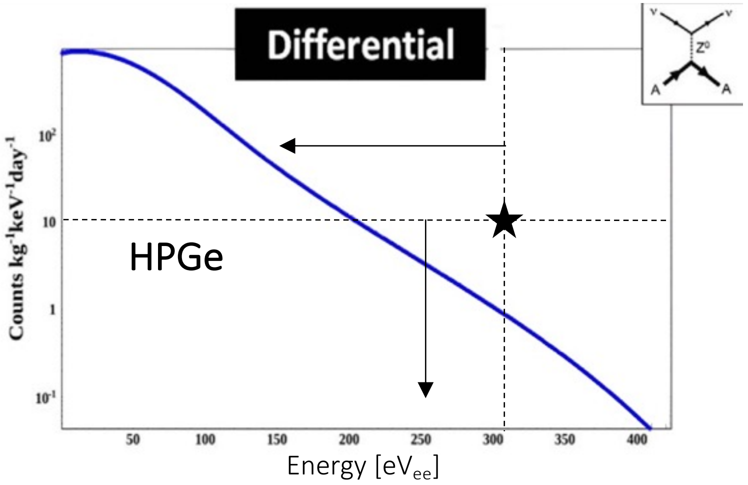

## RED-100 dual phase Xe TPC

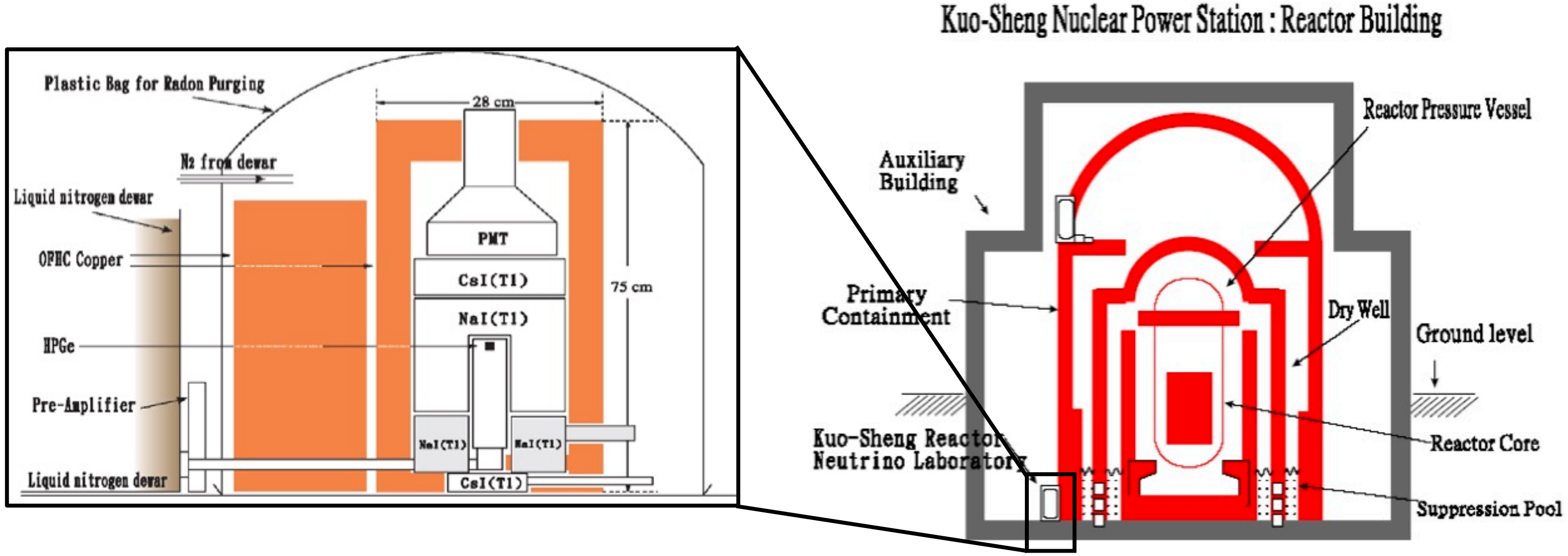



- Baseline ≈ 19 m from reactor core
- Dual readout: ionization and scintillation
- 100 kg fiducial volume - ≤ 1 $keV_{NR}$ threshold
- Installation late 2018

# The TEXONO experiment

- At Kuo-Sheng nuclear reactor (Taiwan): 2.7 $GW_{th}$ – baseline ≈ 28 m
- Neutrino physics program started with $\nu_e$-$e^-$ scattering in CsI[Tl], NaI[Tl] and HPGe detectors → moving now to CEvNS physics



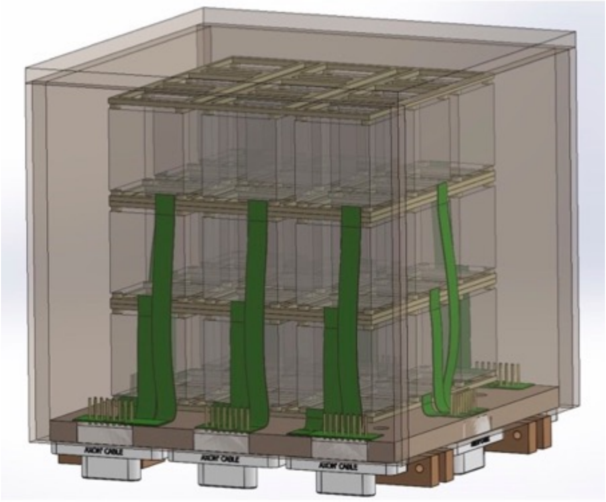




- Achieved $E_{th}$ ≈ 300 $eV_{ee}$ ≈ 1.5 $keV_{NR}$ with bck index of 10 $kg^{-1}$ $d^{-1}$ $keV^{-1}$
- Current focus is on lowering the background (target 1 $kg^{-1}$ $d^{-1}$ $keV^{-1}$) and energy threshold (target 100 $eV_{ee}$)

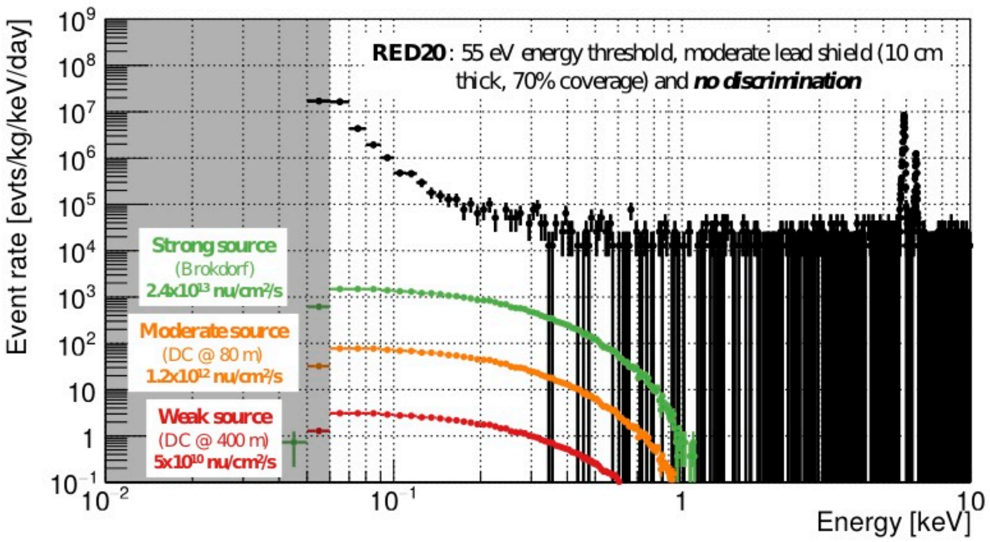
# The Ricochet experiment

- CEvNS physics program at reactors using **low temperature bolometers,** in an R&D stage
- "Cryocube" concept: an array of 27 cubic 32-g detectors → 1-kg payload total mass
  - **Ge bolometers** a la EDELWEISS: ionization + heat for particle identification
  - **Zn metallic superconductors** → PSD to discriminate NRs from ERs (broken cooper pairs have different recombination times)
- Prospecting for an experimental site close to a reactor: Chooz? MIT? RHF Grenoble?

The CryoCube concept



Surface run with a 32-g Ge detector (heat only)



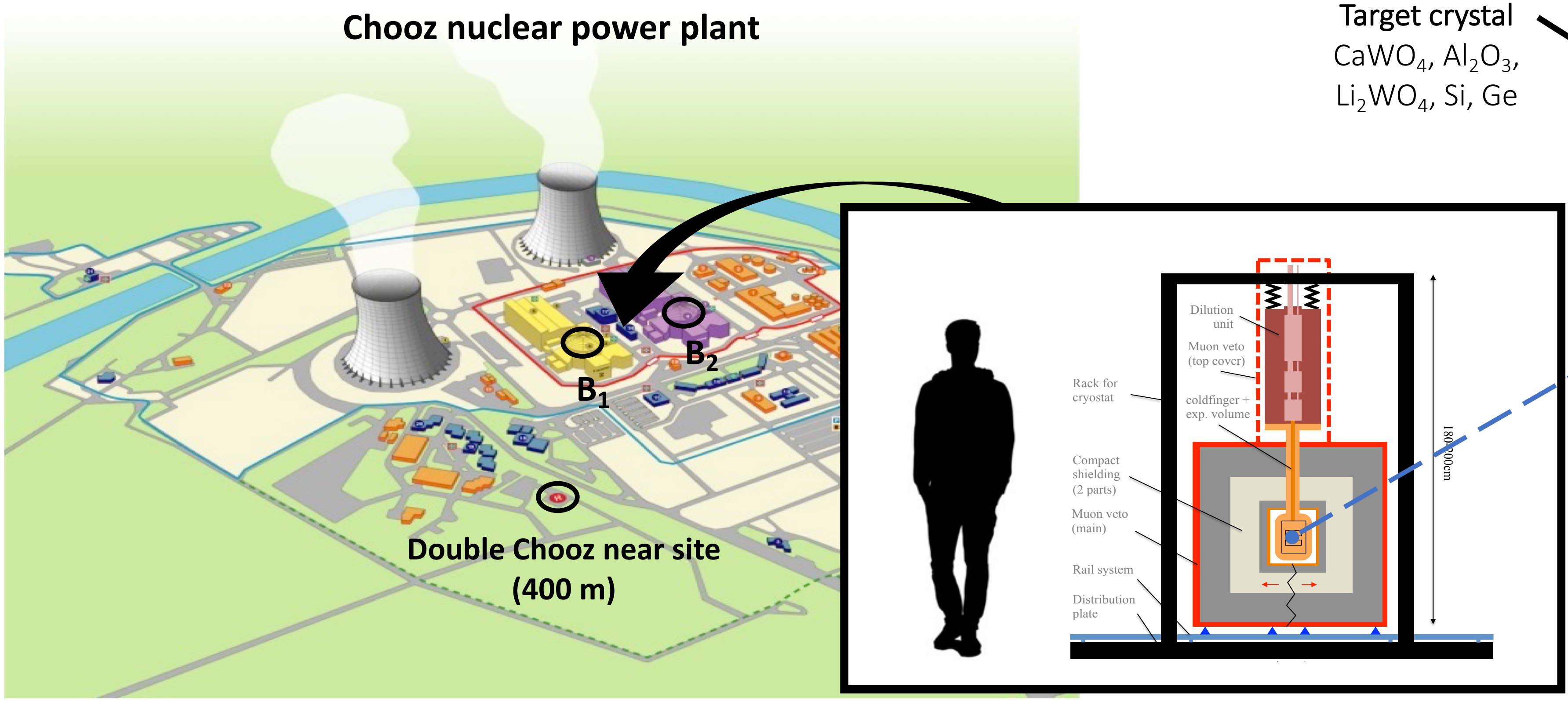

- Operated a 32-g Ge detector in above-ground conditions
- Achieved a 55 $eV_{NR}$ threshold with a heat-only readout
- Need to achieve a > 100 bck discrimination power to be sensitive to CEvNS at reactors

D. Misiak @ Magnificent CEvNS workshop

# The Nu-cleus experiment

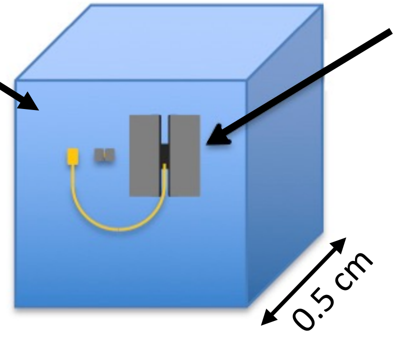
NU-CLEUS

- Proposed reactor CEvNS experiment at the Chooz nuclear power plant (France): very near site identified between the two 4.25 GWth reactor cores with baseline < 100 m → high neutrino flux
- Use of **gram-scale cryogenic calorimeters** achieving unprecedented low energy thresholds: aim at the lowest energies and for high precision




**Target crystal**
$CaWO_4$, $Al_2O_3$, $Li_2WO_4$, Si, Ge

Multi target approach




Transition edge sensor

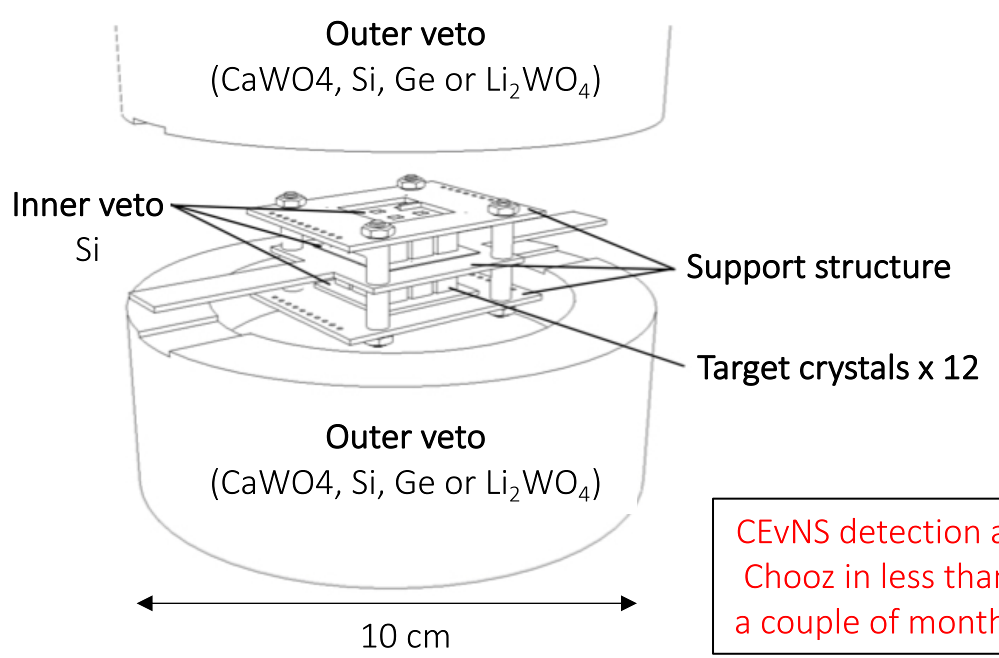
- ➢ Operability above-ground
- ➢ $E_{th} \leq 20$ $eV_{NR}$ (!)

R. Strauss et al.
Eur.Phys.J. C77 (2017) 506

# The Nu-cleus experiment

- Mitigate the external backgrounds with a system of inner & outer vetos: > 100 background discrimination power (simulations)
- Phased approach: 10-g demonstrator then scaling up to 1-kg detector mass

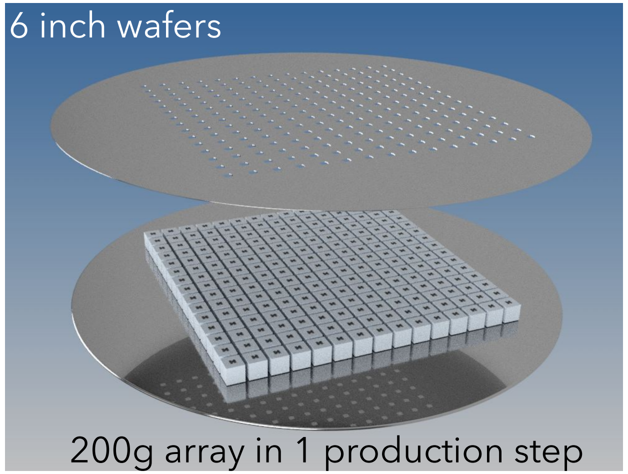
## Nucleus 10-g design




CEvNS detection at Chooz in less than a couple of months

**First CEvNS detection + background comprehension & modeling in the 0.01-1 keV energy regime**

## Nucleus 1-kg

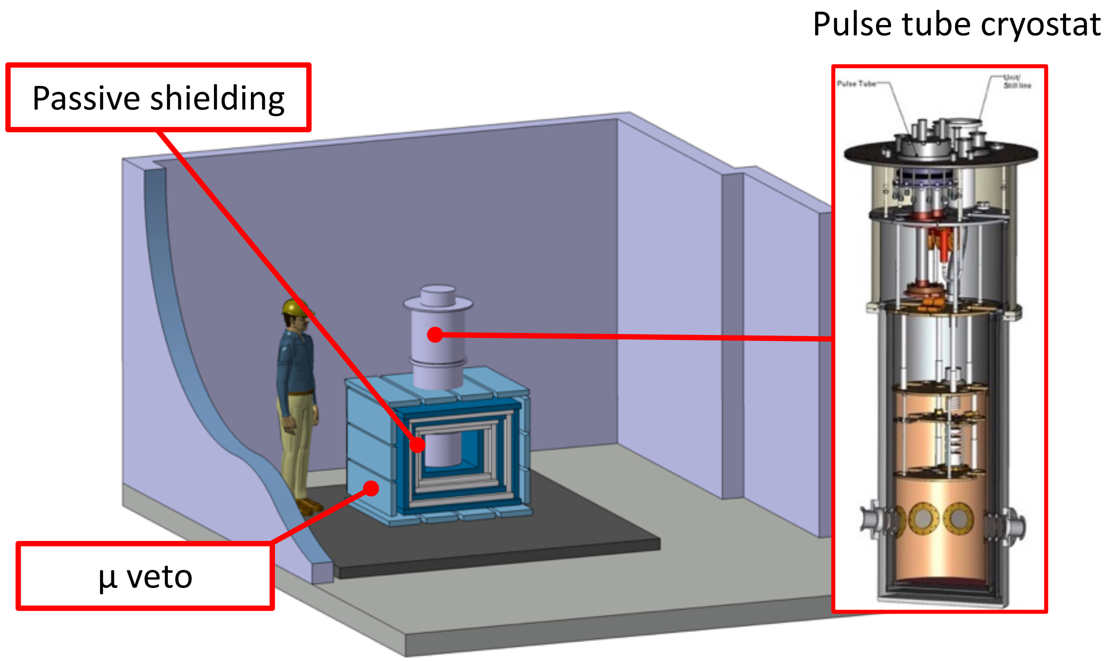


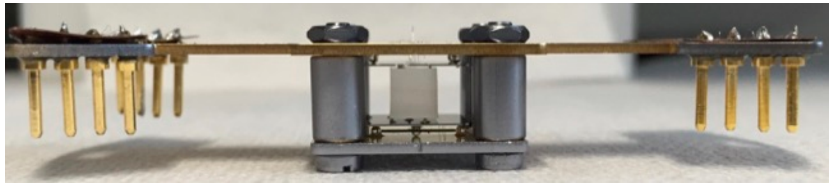

- Exploit semi-conductor technology
- Multiplexing readout (SQUIDs)

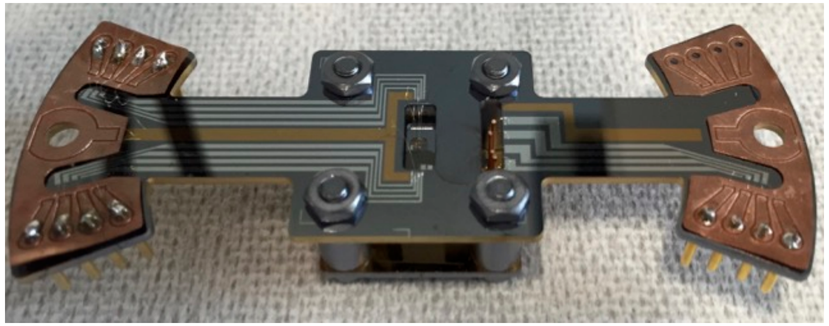
**Aim at a percent-level precision measurement**

# Nu-cleus status

- Very Near Site at Chooz characterized with background measurements in 2018
- Passive + active shieldings are currently being designed & optimized
- First nu-cleus full detector prototype being tested and validated at TUM (Munich)
- **Commissioning of nu-cleus 10-g expected before the end of 2020: stay tuned!**





# Summary

- CEvNS is a new rising field in neutrino physics: new probe for beyond SM physics at the very low energy frontier, applications in nuclear physics & astrophysics
- Experimental programs at accelerators and reactors probe different momentum transfers → complementary
- CEvNS experimental detection techniques closely linked to DM direct detection: same challenges → race towards low energies and backgrounds
- Low temperature bolometers offer a promising opportunity to perform precision physics with kg-scale (!) experiments

**Stay tuned, it's just the beginning…**

# Backup

# Worldwide CEvNS efforts: comparison

| Experiment | ν source | ν flux $[cm^{-2}\,s^{-1}]$ | Overburden [m w.e.] | Technology $E_{th}$ + mass |
|---|---|---|---|---|
| COHERENT | Spallation Neutron Source, Oakridge (USA)<br>Baseline ≈ 20 m | $10^7$ | ≈ 8 | Multiple targets & detectors<br>$E_{th} \geq O(keV)$ – M ≈ 40 kg |
| CONUS | Brokdorf Power Plant (Germany), 3.9 $GW_{th}$<br>Baseline = 17 m | 2.2 x $10^{13}$ | 10 → 45 | Ge ionization<br>$E_{th} \geq$ 1 $keV_{NR}$– M =4 kg |
| CONNIE | Angra dos Reis Power Plant (Brazil) 3.8 $GW_{th}$<br>Baseline = 30 m | 7 x $10^{12}$ | Surface | Si charged couple devices<br>$E_{th} \approx$ 300 $eV_{NR}$ – M ≈ 0.1 kg |
| TEXONO | Kuo-Sheng Power Plant (Taiwan), 2.7 $GW_{th}$<br>Baseline = 28 m | 5 x $10^{12}$ | 30 | Ge ionization<br>CsI[Tl] scintillation<br>$E_{th} \geq$1 $keV_{NR}$ – M≈ kg scale |
| ν-GEN | Kalinin Power Plant (Russia), 3 $GW_{th}$<br>Baseline = 10 m | 5 x $10^{13}$ | ≈ 10 | Ge ionization<br>$E_{th} \geq$ 1 $keV_{NR}$– M = 2 kg |
| RED-100 | Kalinin Power Plant (Russia), 3 $GW_{th}$<br>Baseline = 19 m | $10^{13}$ | ≈ 10 | Liquid Xe TPC<br>$E_{th} \approx O(1\ keV_{NR})$ – M = 100 kg |
| MINER | TAMU research reactor (Texas), 1 $MW_{th}$<br>Baseline = 2-10 m | 4 x $10^{11}$ | 15 | Ge/Si CDMS techno.<br>Aim at $E_{th} \approx$ 40 $eV_{NR}$ – M ≈ 10 kg |
| ν-CLEUS | Chooz (France) 2 x 4.25 $GW_{th}$ @ VNS<br>Baseline = 70-100 m | 2 x $10^{12}$ | ≤ 4 | $CaWO_4$, $Al_2O_3$, $Li_2WO_4$ cryo. cal.<br>$E_{th} \approx$ 20 $eV_{NR}$ – M = 0.01 → 1 kg |
| RICOCHET | Chooz (France) 2 x 4.25 $GW_{th}$ @ NS ? [400 m]<br>MIT research reactor 6 $MW_{th}$ ?<br>ILL research reactor 58 $MW_{th}$ ? [10 m] | 8 x $10^{10}$<br>$10^{11}$<br>9 x $10^{11}$ | 120<br>≈ 10<br>≈ 10 | Ge/Zn cryo. cal.<br>$E_{th} \approx O(50\ eV_{NR})$ - M ≈ 0.5 kg |

Ionization and/or scintillation

Phonons