Probing new physics with Coherent Elastic Neutrino-Nucleus Scattering and the future Ricochet experiment

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On the behalf of the Ricochet collaboration

GDR Neutrino 2019
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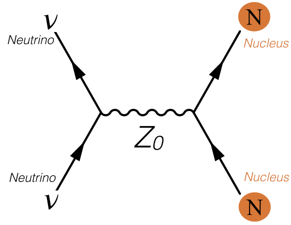
Coherent Elastic Neutrino-Nucleus Scattering

CEνNS: **C**oherent **E**lastic **N**eutrino-**N**ucleus **S**cattering



arXiv: 1708.01294

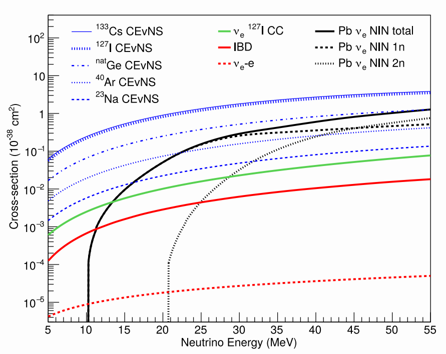
- Cross-section scale as N^2 (N: number of neutrons)

$$\frac{d\sigma}{d\cos\theta} = \frac{G^2}{8\pi}[Z(4\sin^2\theta_w - 1) + N^2]E^2(1 + \cos\theta)$$

  → Allow small target of heavy elements

- No intrinsic threshold
  → Interesting to detect neutrinos at low energy

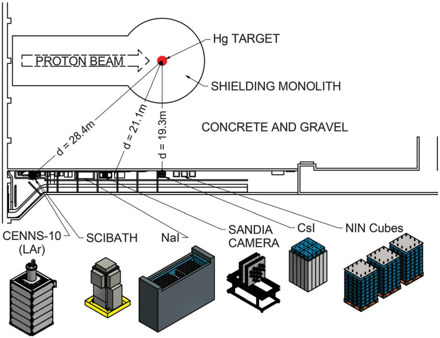
- Small nuclear recoil energy: sub-keV
  → Hard to detect in practice

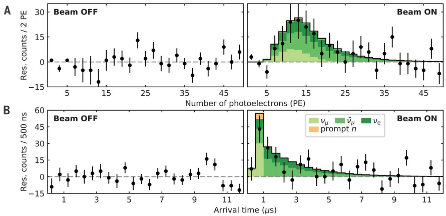


COHERENT: First unambiguous detection of CEνNS

The COHERENT experiment consists in multiple detectors placed in the "neutrino alley" at the SNS emitting high energy neutrinos (~ 50 MeV)

arXiv: 1708.01294





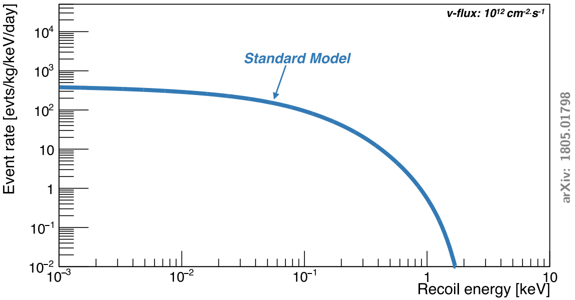
In August 2017, they reported the first unambiguous CEνNS detection at the 6.7 σ confidence level with their 14 kg CsI[Na] detector and a 4.25 keV energy threshold.

They observed a clean sample of $\sim 134 \pm 22$ CEνNS events thanks to their beam ON/OFF residual.

Change of paradigm: from discovery to a precision measurement at low-energy

Probing CEνNS with reactor neutrino

Example: Nuclear recoil spectrum inside 1kg Ge target at ~ 8 m of the 58 MWth ILL reactor



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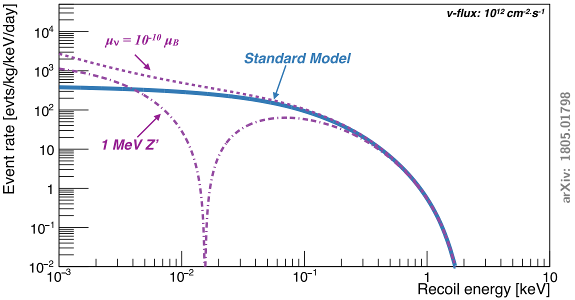

Looking for physics beyond the Standard Model in the electro-weak sector:

- Anomalous large neutrino magnetic moment (NMM)
- New massive mediator: Z' boson
- Non standard neutrino interactions (NSI) at low energy

Probing CEνNS with reactor neutrino

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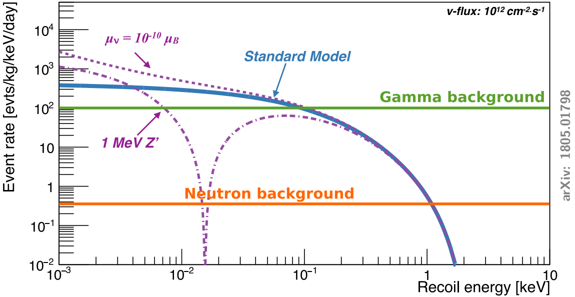

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- Anomalous large neutrino magnetic moment (NMM)
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Projection for new physics using CEνNS

Detector performances:

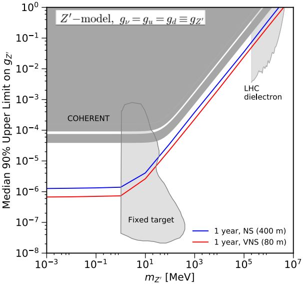
- Low energy threshold $\sim 50\,eV$
- Low energy resolution $\sim 10\,eV$
- EM background rejection of $> 10^3$

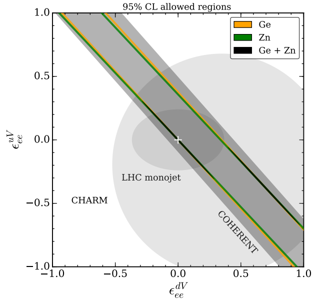
20 CEνNS events/day

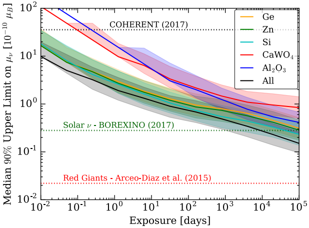
$\Rightarrow$ 5 σ CEνNS detection in a couple of days !

$\Rightarrow$ 1 % precision measurement after one year

arXiv: 1805.01798



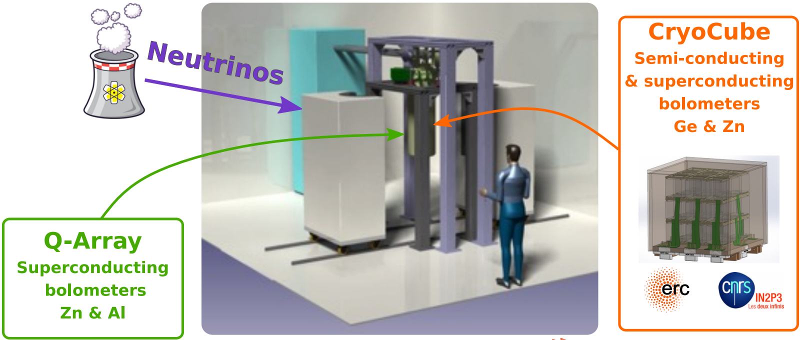




- Measure the Weinberg angle with a %-precision from 1 to 10 MeV in momentum transfer
- Search for new bosons with competitive and complementary sensitivity
- Further constrain the existence of NSI by two orders of magnitude : need different targets
- Reach a world-leading CEνNS-based NMM limit of $\mu_\nu \sim 10^{-11}$ μB at the 90% C.L.

The Ricochet experiment

Proposal paper: "The first low-energy kg-scale CEvNS neutrino observatory combining multi-target and multi-technology cryogenic detectors", J. Billard et al., J. Phys. G (2017) [arXiv: 1612.09035]



UMASS AMHERST — RICOCHET: A Coherent Neutrino Scattering Program — NÉEL institut

The University of Wisconsin Madison — Northwestern University — MIT — JINR — IPNL — LPSC Grenoble — CSNSM

Reactor site candidates for Ricochet

MITR: A. Leder *et al.*, JINST 2018

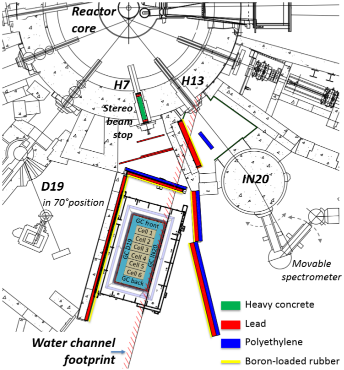
- 4 m from 5.5 MWth core
  $\rightarrow 4.5 \times 10^{11}$ ν/cm²/s at the detector
- Low overburden :
  $\rightarrow$ high cosmic background
- High level of correlated reactor background
- 4 weeks ON and 1 week OFF cycles

ILL: STEREO Collab., JINST 2018

- 7 m from 58 MWth core
  $\rightarrow 1.6 \times 10^{12}$ ν/cm²/s at the detector
- 15 m.w.e overburden :
  $\rightarrow$ reduction factor 2 to 3 of muon flux
- 3 or 4 cycles of 50 days
  $\rightarrow$ good ON / OFF ratio
- Close to reactor and neighboring experiments
  $\rightarrow$ High level of reactor correlated background
- Use Stereo casemate
  $\rightarrow$ Benefit from Stereo experience and background characterization

Chooz – Near Site: J. Billard, *et al.*, J. Phys. G 2017

- 400 m from two 4.25 GWth cores
  $\rightarrow \sim 5 \times 10^{10}$ ν/cm²/s at the detector
- No reactogenic background
- Uniquely high overburden: 120 m.w.e
- Rare OFF reactor periods



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ILL: STEREO Collab., JINST 2018 $\Rightarrow$ **LOI send to ILL**

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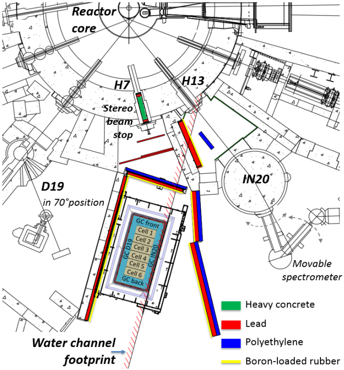
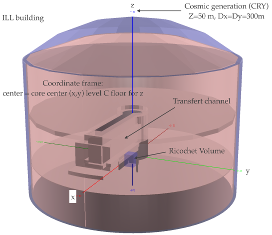
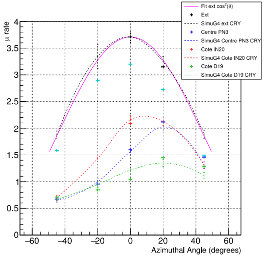


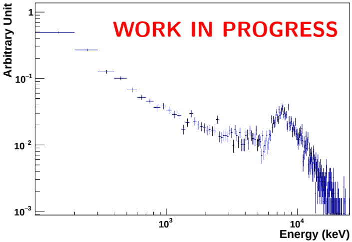
Cosmic simulation at ILL

- Cosmic simulation from STEREO based on CRY (for atmospheric shower) and Geant4
- Good agreement between muon flux measurement and MC simulation from STEREO simulation
- Goal of cosmic simulation:
  - Estimate gamma background
  - Estimate neutron background from muon spallation
  - Define shielding geometry and materials
  - Design μ-Veto
- Cosmic simulation are ongoing
- Reactor correlated background studies will be started soon in parallel

STEREO Collab., JINST 2018







⇒ Background simulation to validate the ILL site are ongoing
⇒ Vibration measurements plan on site in July

Specification of the Ricochet detectors

Detector specifications:

1. Very low energy threshold $O(10)$ eV
2. EM background rejection $> 10^3$
3. Significant target mass 1 kg
4. Target complementary: Ge and Zn

Array of 27×32 g bolometers:

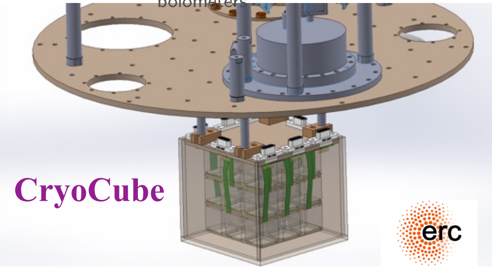
- $8 \times 8 \times 8$ cm^3
- $50\,\%$ of Ge semiconducting bolometers
- $50\,\%$ of Zn superconducting bolometers

Q-Array

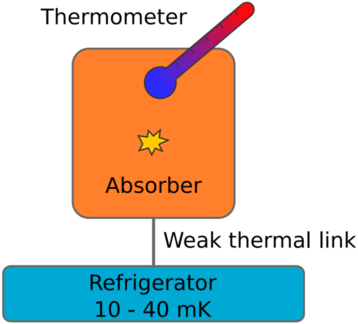
Superconducting bolometers

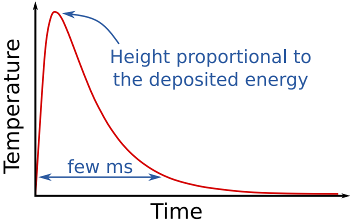
Zn & Al

HEISING-SIMONS FOUNDATION



Cryogenic detector





Advantage of a phonon readout:

- Direct measurement of the recoil energy, no quenching
- $\sim 100\%$ of the recoil energy is sensed, allowing for low thresholds
- No intrinsic threshold (meV)
- From thermodynamics, ultimate energy resolution is:

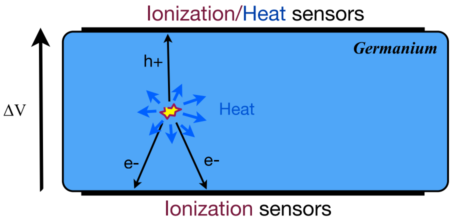
  ∼eV (RMS) for 10g detectors

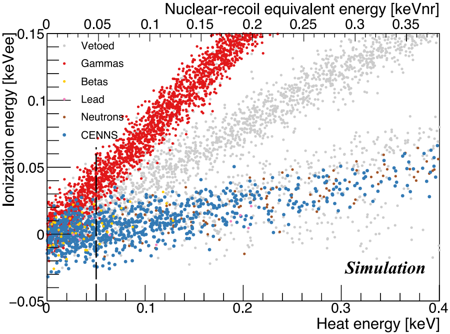
Particle identification with Ge

Technological key features of the Ricochet detector technology:

- Achieve Particle Identification down to $\mathcal{O}(10)$ eV with a rejection $> 10^3$
- Two different cryogenic detector technologies: semi- and super-conductors

Germanium (and silicon ?) semiconductors: CryoCube only





- Ionization/Heat ratio depends on the particle type
- Need to achieve an unprecedented ~ 10 eV ionization resolution

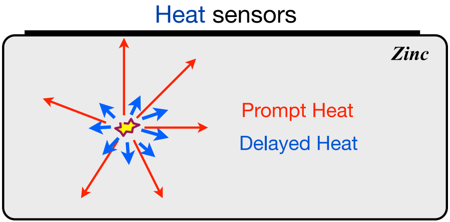
Inspired from the FID800 success of EDELWEISS-III

Particle identification with Zn

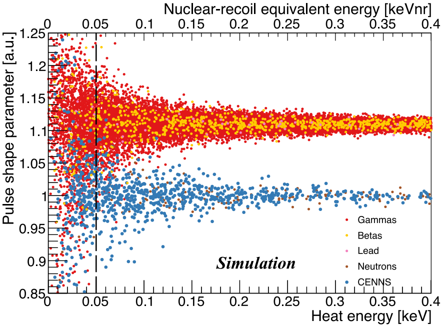
Technological key features of the Ricochet detector technology:

- Achieve Particle Identification down to $\mathcal{O}(10)$ eV with a rejection $> 10^3$
- Two different cryogenic detector technologies: semi- and super-conductors

Zinc (and aluminum ?) superconducting metals: CryoCube and Q-Array

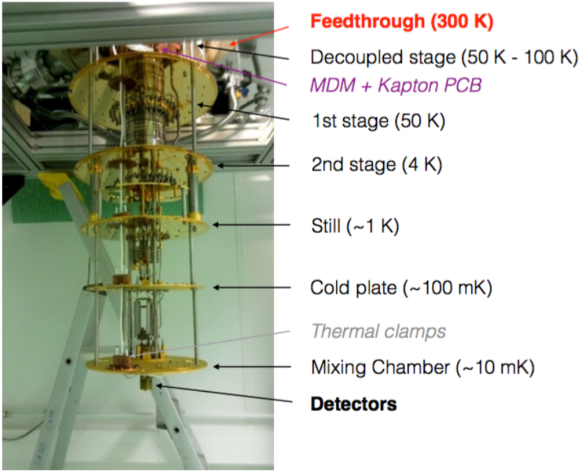


- Prompt / delayed heat signals depend on the particle typeZ
- High risk / high reward



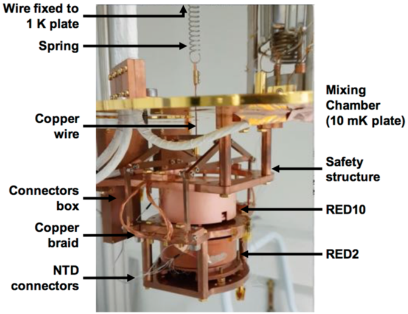
R&D cryostat facility

- R&D laboratory at IPNL hosting a dry cryostat
- R&D shared with the Edelweiss experiment
- Cryostat from Cryoconcept, design similar to the future Ricochet cryostat
- Use a cylindrical lead sheilding of 10 cm thickness
- First complete cold-head decoupling demonstrated: Olivieri *et al*, NIM 2017
- Many detector prototypes and setup have been already tested

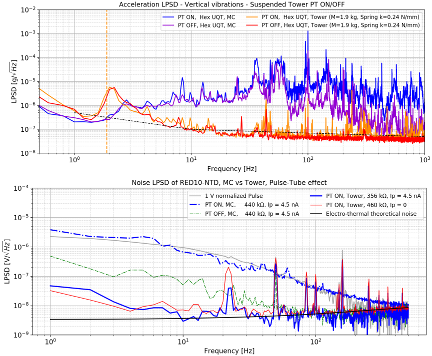


Very low microphonic noise

- High impedance sensors (NTD, NbSi TES and electrodes) are highly sensitive to microphonics
- Highly efficient cryogenic suspension system designed to host kg-scale payloads:
  $\rightarrow$ sub $\mu g/\sqrt{\text{Hz}}$ level over the detector bandwidth (limited by accelerometer sensitivity)
- Detectors are now running in optimal conditions, **only limited by thermodynamic and electronic noises**



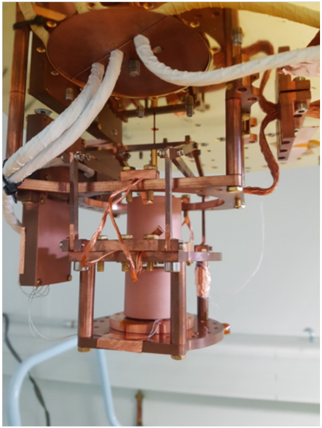
R. Maisonobe, JINST 2018

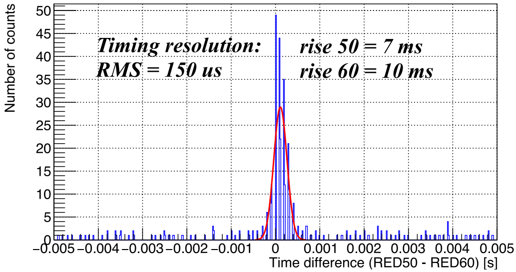


Detector scalability

R&D for the structure and cabling are ongoing:

- Run with 2 x 30g bolometers have been performed already
- Next step is 4 – 6 bolometers at the same time





Time resolution of 100 μs, up to 10 keV despite slow pulse (ms)

- All the pulse is fitted with a template
- Start time of the pulse estimated with fit

Time resolution is decisive for Veto-muon design:

- Deadtime vs Veto-muon surface
- Geant4 studies ongoing to determine feasibility

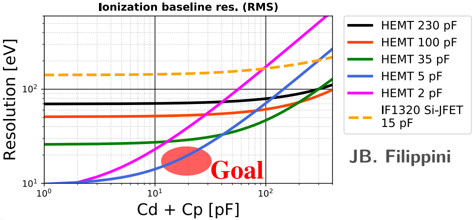
Improving particle discrimination

Particle discrimination is right now limited by the ionization resolution (200 eV)

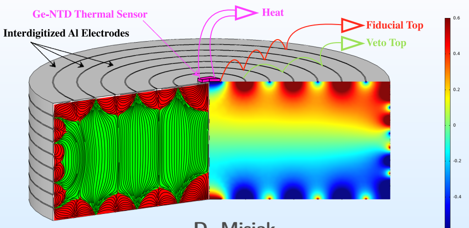
Goal: reach a ionization resolution below 20 eV

HEMT preamplifier: High Molity Electron Transistor

- Lower intrinsic noise than JFET (Junction Field Effect Transistor)
- HEMT Noise Model: goal implies a 20 pF total capacitance (detector & cabling)
- Low temperature threshold $\sim$4 K, closer to detector, less cable capacitance
- R&D ongoing, HEMT are being characterized



JB. Filippini



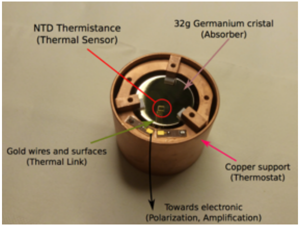
D. Misiak

New electrode design:

- Good charge collection, for event reconstruction
- Large fiducial volume (75%)
- High surface event rejection efficiency (FID)
- Minimized capacitance: Cdet $\sim 10\,\mathrm{pF}$
- Studies ongoing : multiple design simulated with COMSOL and data driven model

Toward a heat baseline resolution of 10 eV

From EDELWEISS R&D: Armengaud, E. *et al.*, Phys. Rev. D 2019



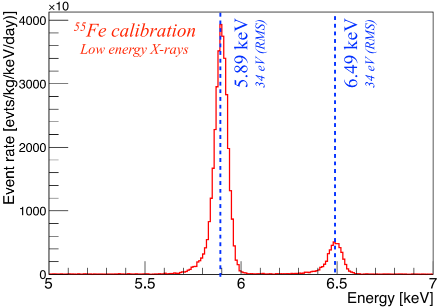
Major accomplishments: with 32 g Ge detector

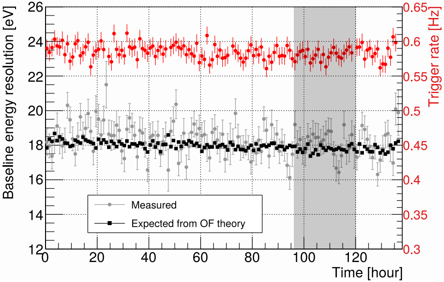
- 18 eV baseline energy resolution (RMS)
- 55 eV energy threshold
- %-level stability over a week

Reproducible: similar results on 3 other ~ 30 g bolometers

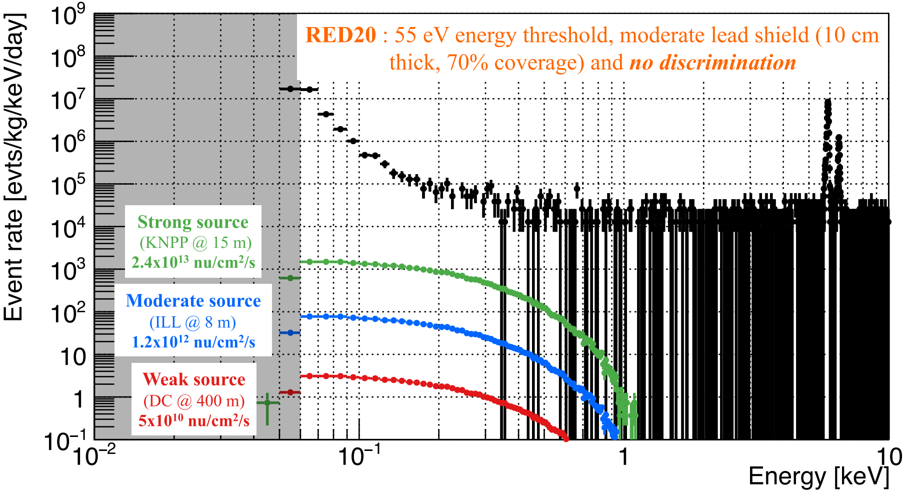
⇒ Validates the choice of 30 g crystals as individual detectors for the CryoCube array

→ **Expect a factor 2 of improvement with HEMT**

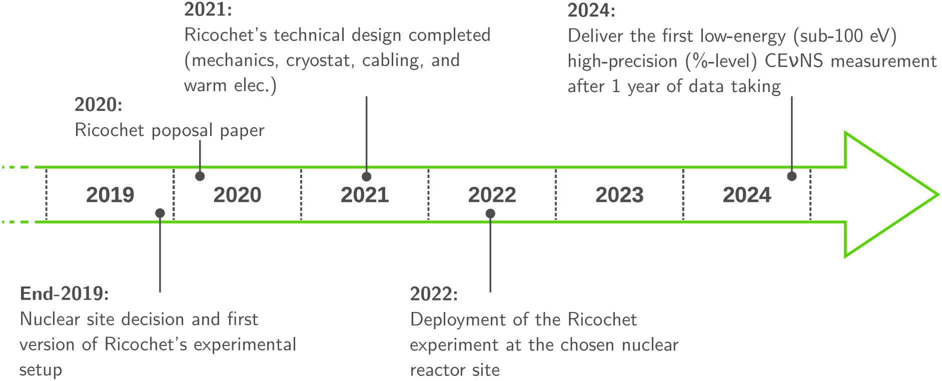




Present sensitivity to CEνNS



Ricochet timeline



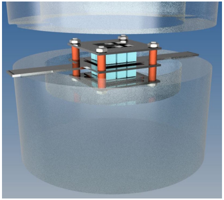
Other experiments probing CEvNS in the sub-100 eV region

MINER

- At the Mitchell Insti. research reactor(1 MW) with movable core
- Use of SuperCDMS Soudan detectors iZIP (625 g Ge) in HV mode
- Background reduction with passive and active shielding - No particle identification $< 1\,\text{keV}$
- Science run started, Phase 2 in 1 year

R. Mahapatra *et al.*, NIMA 853 (2017) 53

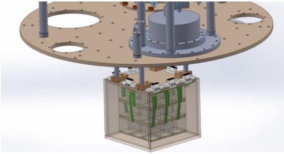
NuCLEUS



- 80 meters away from Chooz reactors (2 x 4.25 GW)
- Phase 1: total target mass of 10 g - 9 x 0.8 g CaWO 4 and 9 x 0.5 g Al2O 3
- Background reduction with passive and active shielding (w. bolometers) - no particle identification
- Phase 1 start in 2020, then switch to phase 2 with 10 kg (2000 crystals)

G. Angloher *et al.*, arXiv:1905.10258 (2019)

Ricochet - CryoCube



- Nuclear site to be finalized by end-2019
- Two detector technologies:
  - CryoCube: 1 kg array of detectors 30g (Ge & Zn)
  - Q-Array: 100 g (Zn & Al)
- Background reduction with passive and active shielding + particle identification
- First science data taking planned for 2023

J. Billard *et al.*, JPG 44 (2017) 10

Conclusion

- Since its first detection by the COHERENT collaboration in July 2017, CENNS has become a burgeoning field of research

- A very exciting process that has yet to be explored:
  - From ton-scale to kg-scale neutrino experiments (ideal for nuclear reactor monitoring)
  - New probe for physics beyond the SM (new massive mediators, anomalously large NMM, ...)

- Growing interest in measuring this process in Europe: Ricochet, NuCLEUS are forming a consortium. Both supported with ERC Starting Grants.

- Ricochet is the only sub-100 eV CENNS experiment investigating particle identification to provide a decisive %-level CENNS measurement by 2024.

- RED20 results from EDELWEISS R&D, show near specification performances for the heat channel for Ge bolometers and indicates that expected detector performances are reachable

- Ricochet has been presented at IN2P3 Scientific Council in October 2018 and positively reviewed.

- Final site decision expect in end-2019