Prospects for exploring new physics with Coherent Elastic Neutrino-Nucleus Scattering

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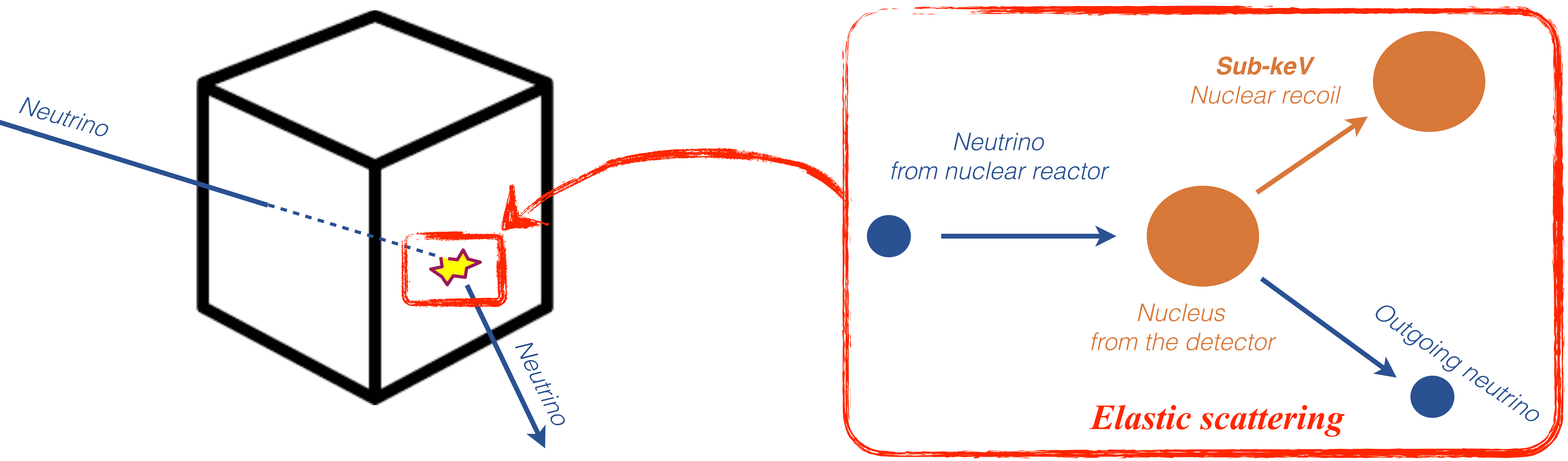
Prospectives IN2P3, October 28th, 2019

CENNS: *The process*

Coherent Elastic Neutrino-Nucleus Scattering (CENNS)



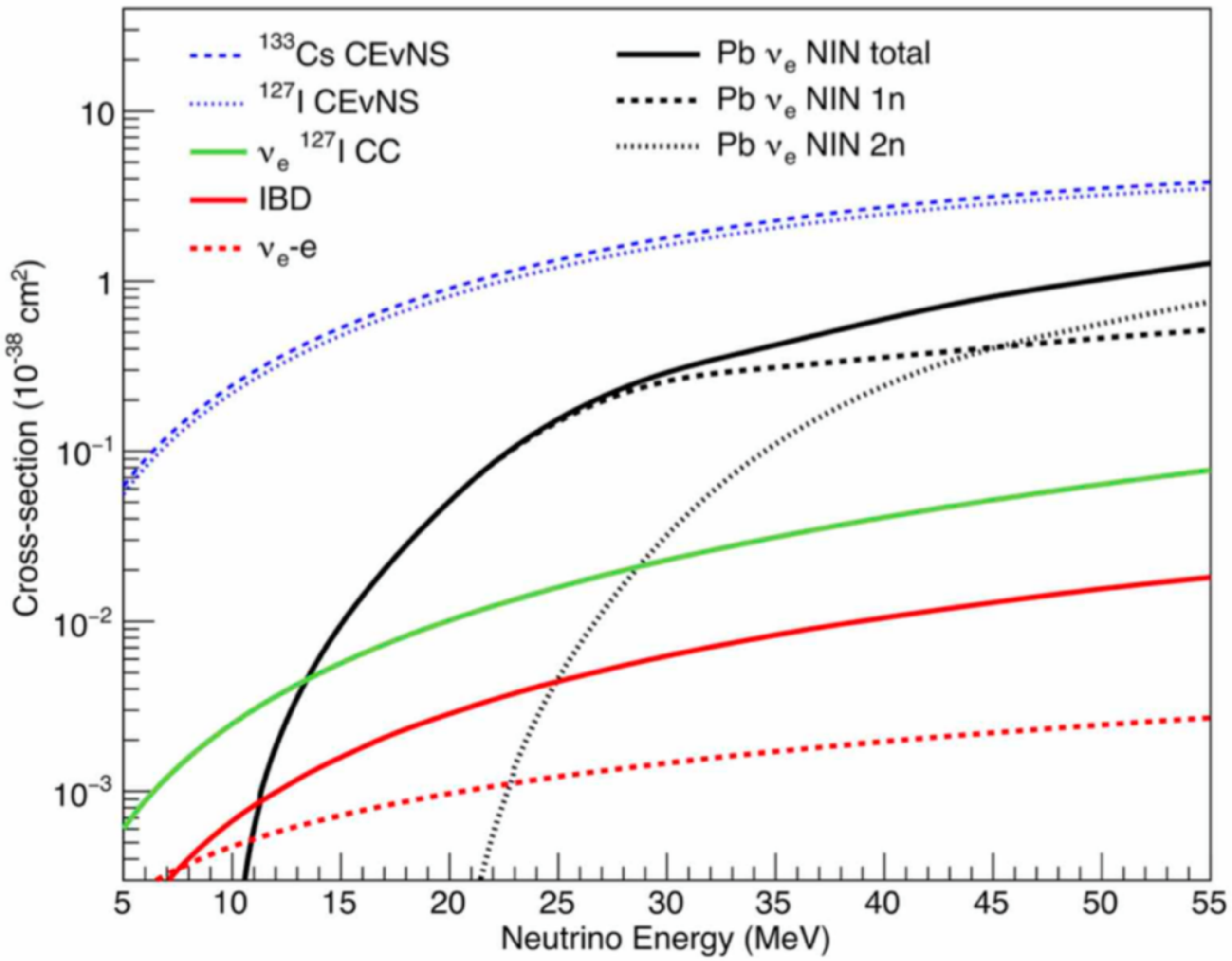
CENNS: *The process*

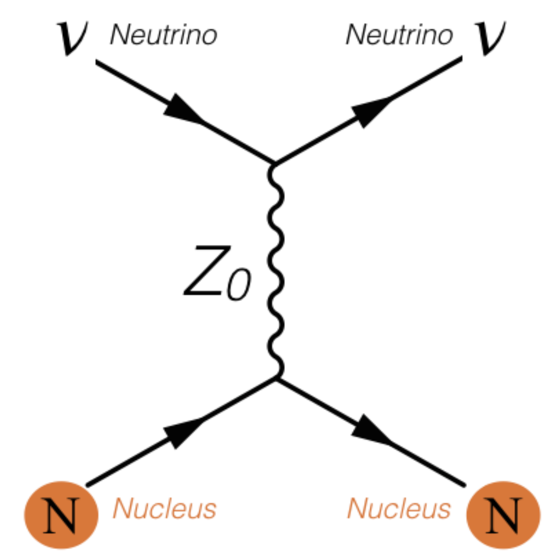
D. Z. Freedman, PRD 9 (5) 1974

Coherent Elastic Neutrino-Nucleus Scattering (CENNS)

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

D. Akimov et al., Science 2017





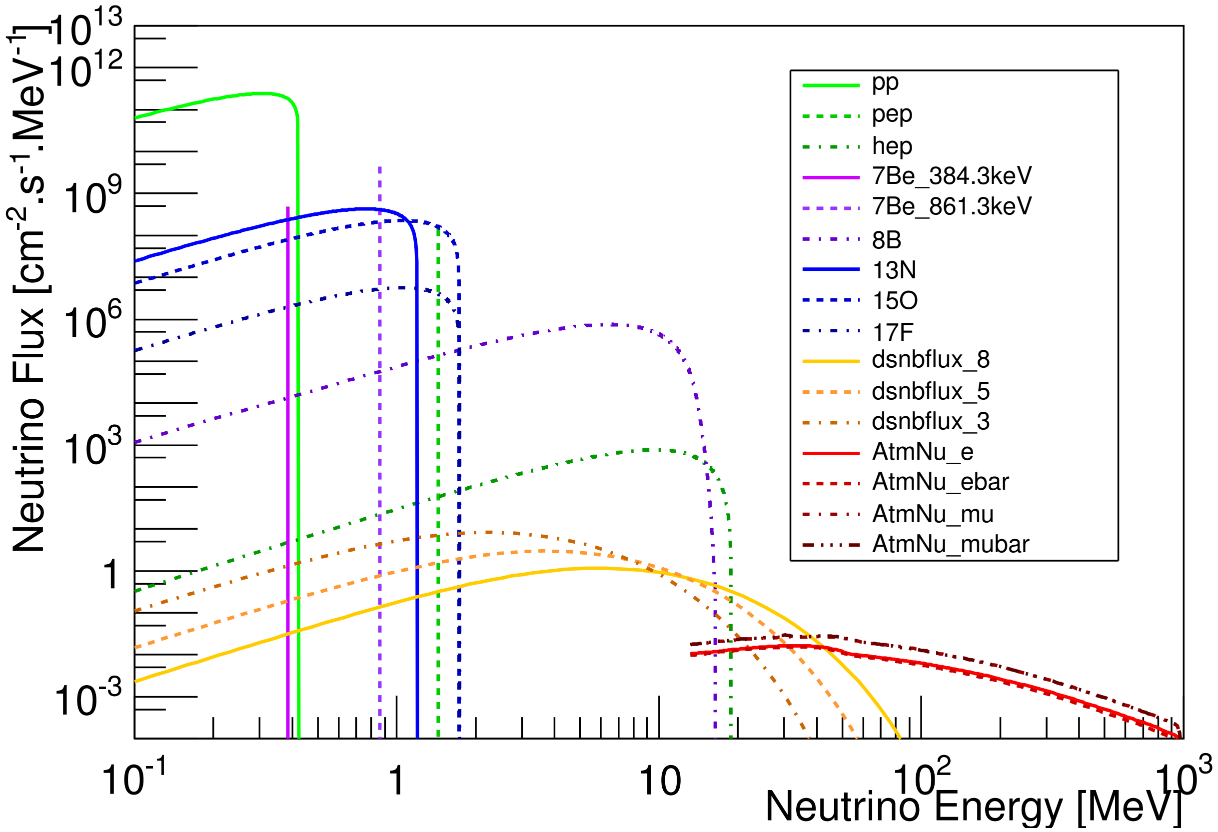
$$E_r \leq 2E_\nu^2 / M_A$$

- Largest neutrino cross section at low energies by few orders of magnitude:
  - *From ton-scale experiments to kg-scale ones !*
- No energy threshold
- Unexplored process offering a new probe for BSM physics

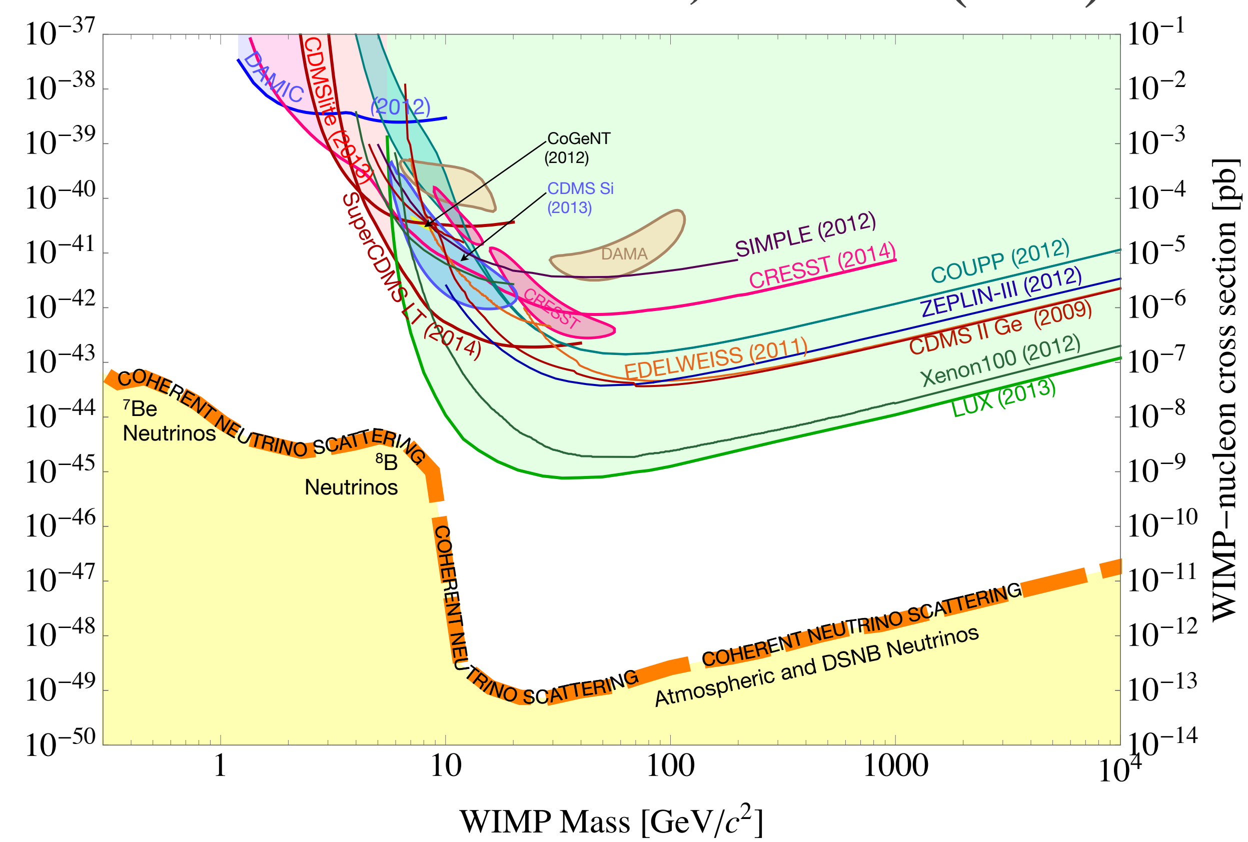
CENNS: *Neutrino sources*

4 sources to consider:

- Cosmic neutrinos: Solar, atmospheric and DSNB
- Electron-capture sources
- Reactors
- Pion Decay-at-rest source (SNS)



J. Billard et al., PRD 89 (2014)



- Cosmic neutrinos will inevitably become the ultimate background to direct detection of Dark Matter
- Calls for reduced uncertainties on the CENNS process to lower the neutrino floor

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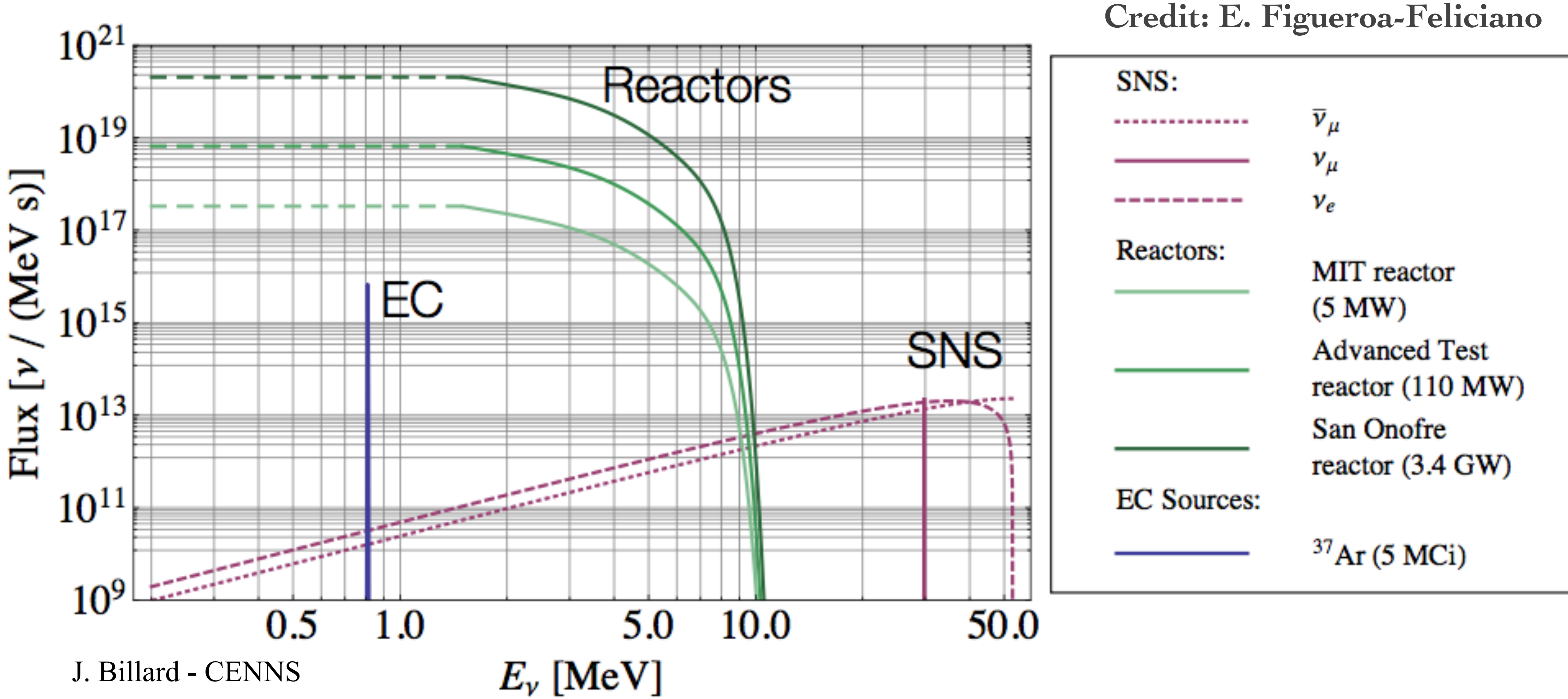
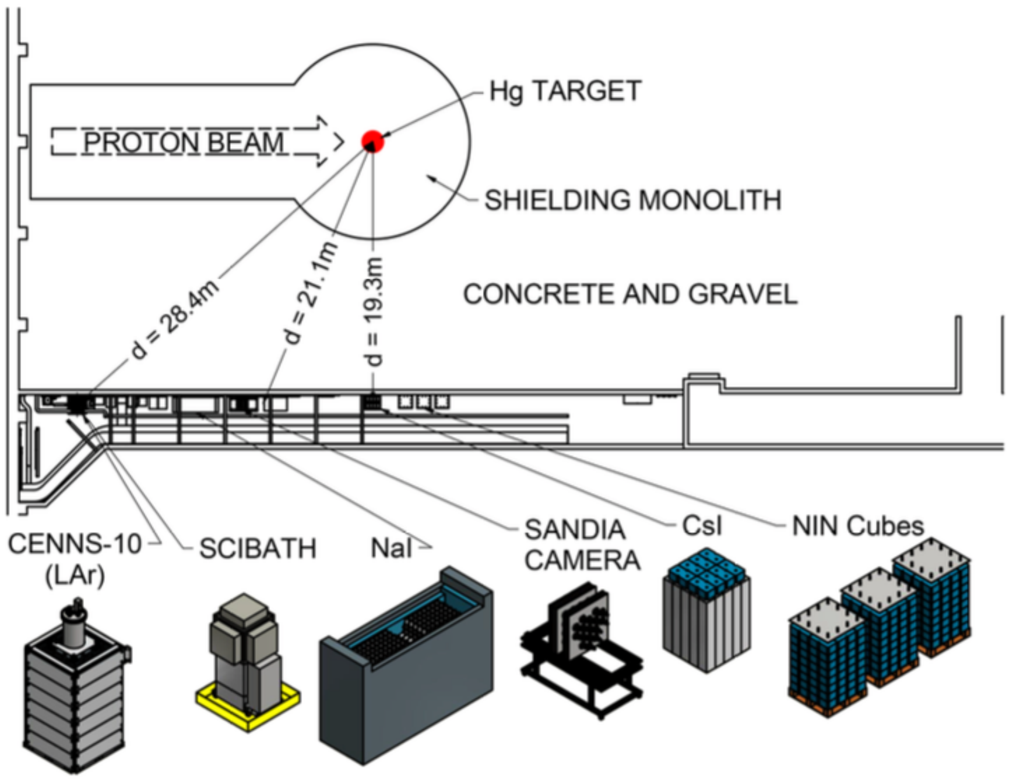
Credit: E. Figueroa-Feliciano

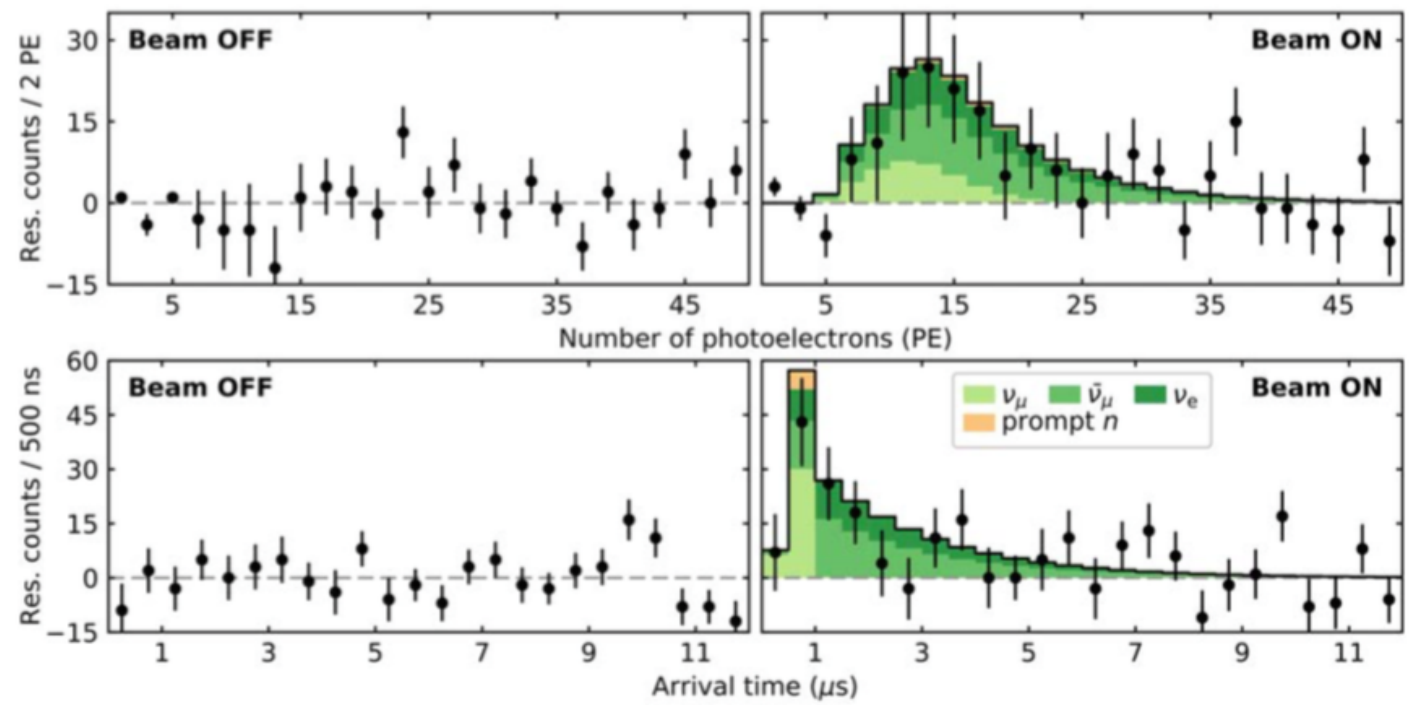


CENNS: *The first detection*

D. Akimov et al., Science 2017

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





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

They observed a clean sample of ~134 ± 22 CEvNS events thanks to their beam ON/OFF residual

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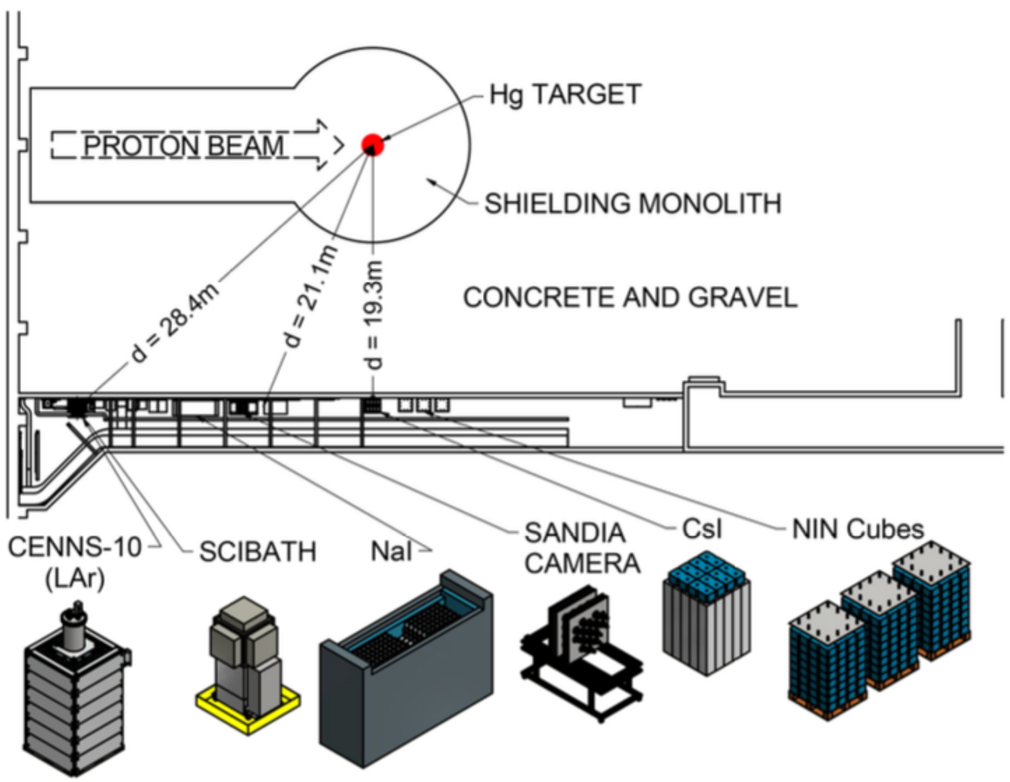

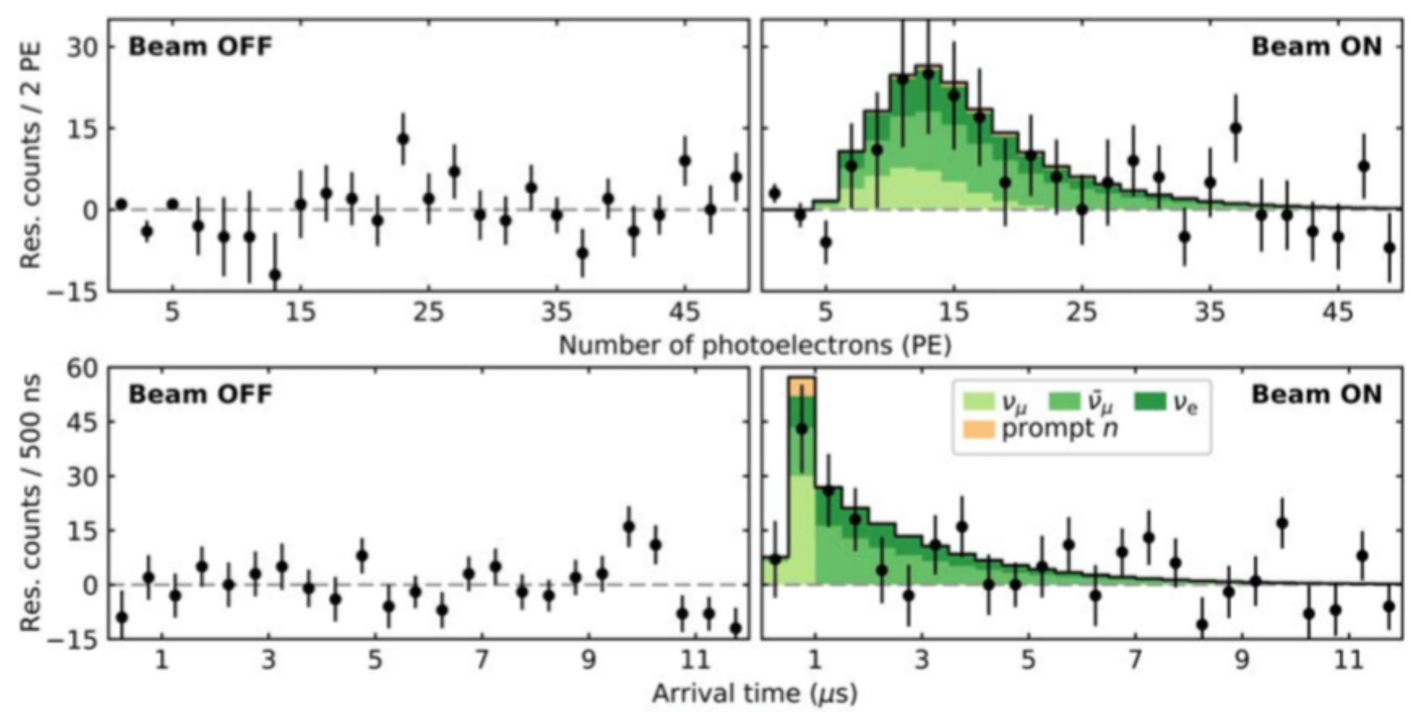

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Change of paradigm: from discovery to a precision measurement @ low-energy

CENNS: *@ reactors*

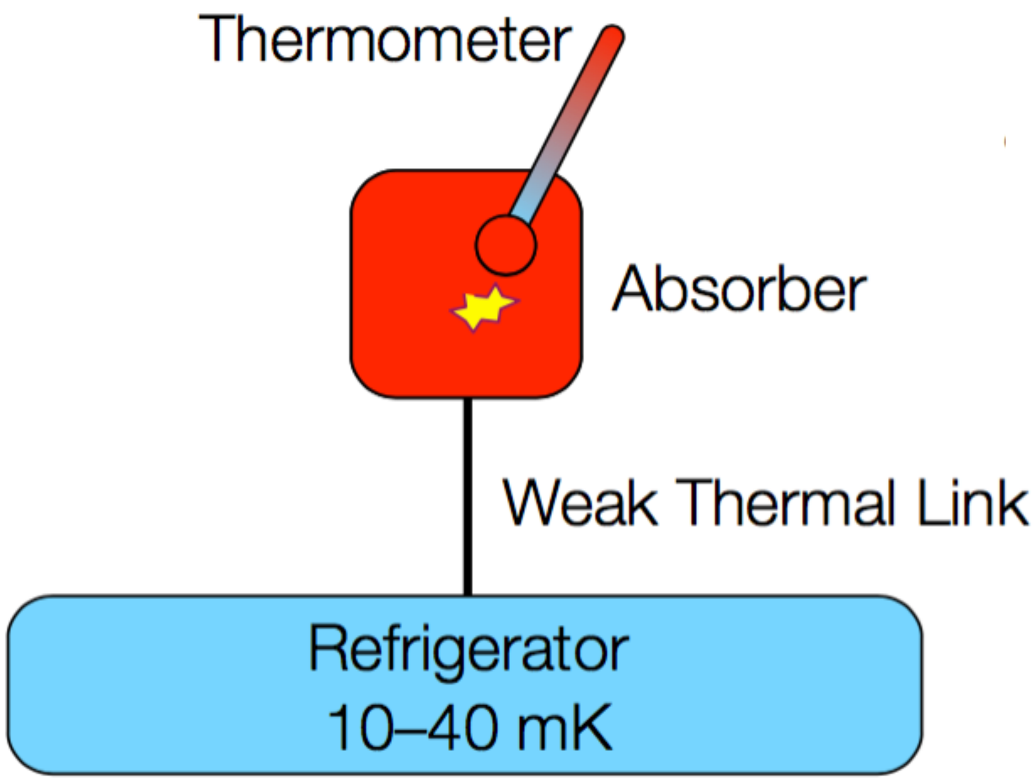
- NuGEN: 1 x 1 kg + 3 x 1.5 kg of germanium — **V. Belov et al 2015 JINST 10 P12011**
- CONUS: 4-100 kg of germanium — JHEP 1703 (2017) 097
- TEXONO: 1kg of germanium — Nucl.Instrum.Meth. A836 (2016) 67-82
- Connie: Si detector at Angra Reactor in Brasil — JINST 11 (2016) P07024
- RED100: Xe detector at Kalinin Reactor — JINST 12 (2017) C06018
- MINER: GeSi at a non-commercial Reactor — Nucl.Instrum.Meth. A853 (2017) 53
- NU-CLEUS — Eur. Phys. J **C77** (2017) 506
- BASKET — **see C. Nones - LTD18**
- BULLKID — **see I. Colantoni - LTD18**

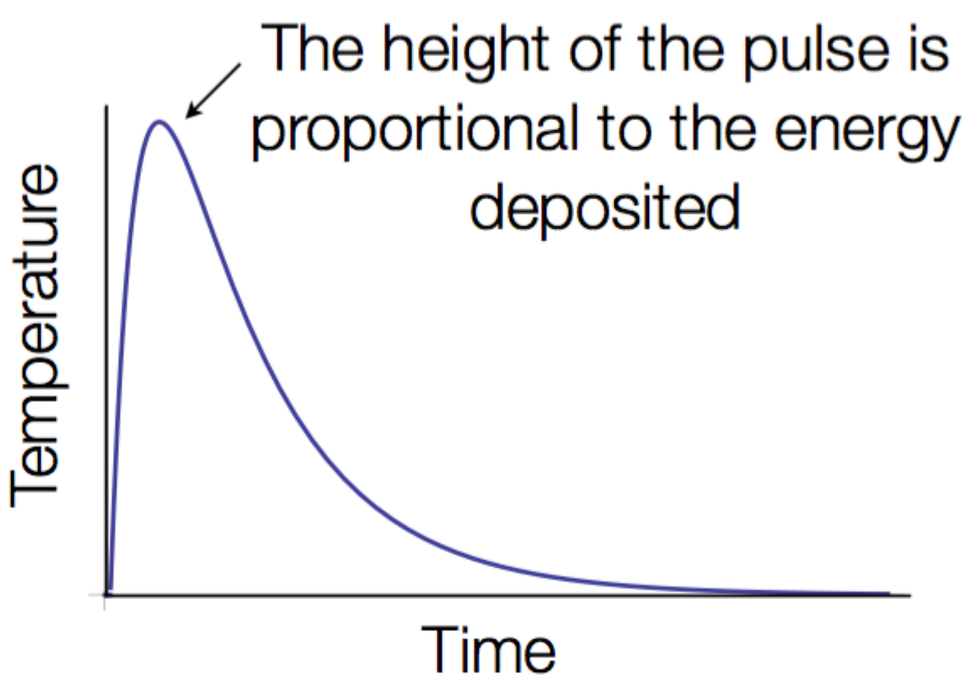
Cryogenic experiment & R&D programs for **sub-100 eV** CENNS measurement

RICOCHET
A Coherent Neutrino Scattering Program

J. Billard et al., J Phys. G (2017)

CENNS: *Cryogenic detectors*





- Advantages of a phonon readout:
  - Direct measurement of the recoil energy, *no quenching involved*
  - ~100 % of the recoil energy is sensed, *allowing for low-thresholds*
  - *No intrinsic threshold (meV)*
  - From thermodynamics, ultimate energy resolution is: **~eV (RMS) for ~ 10 g detectors**

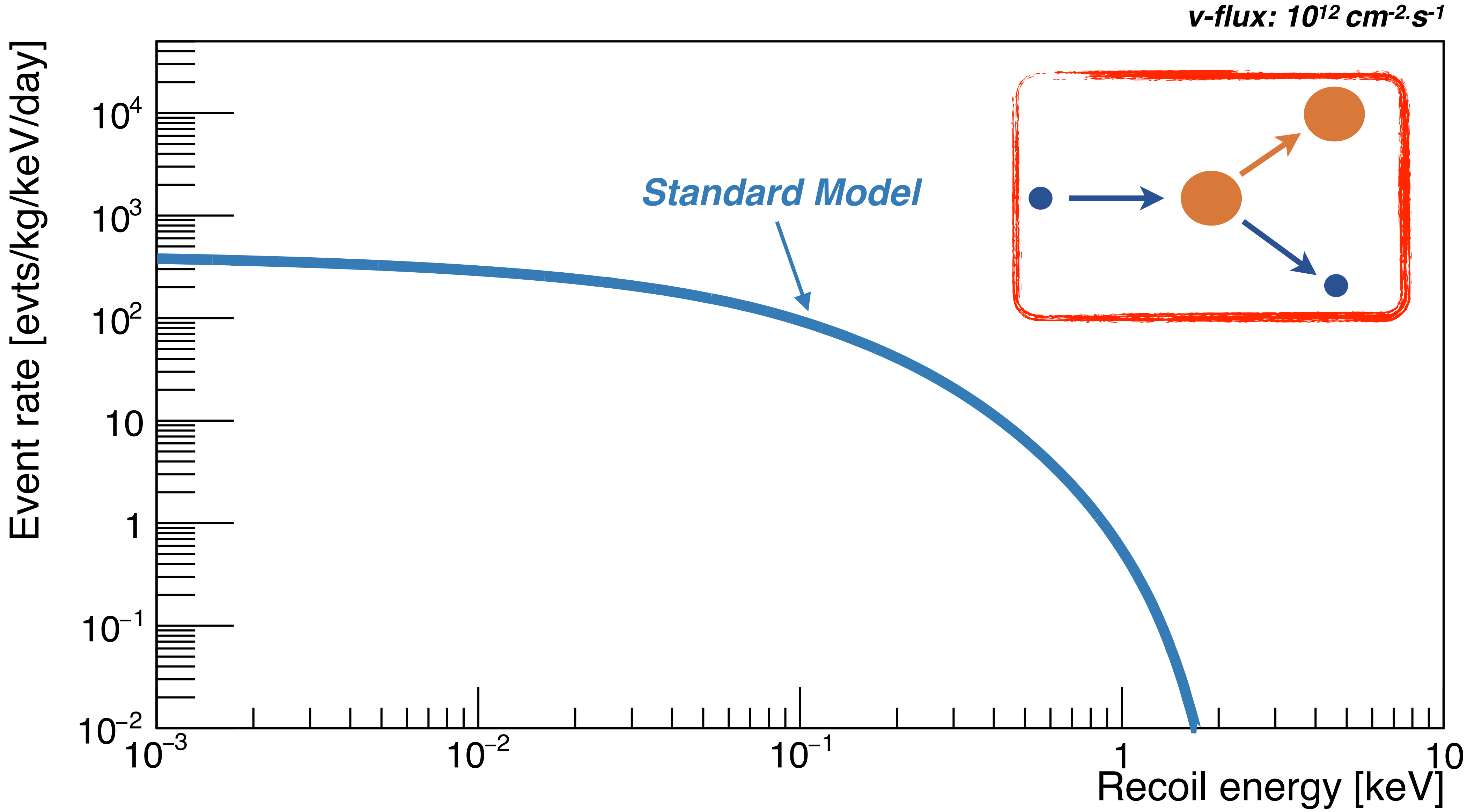
- Phonon readout can be done in two ways:
  - Thermal measurement (EDELWEISS)
  - Athermal measurement (CRESST/SCDMS)

$$E_T \propto M^n_{\mathrm{detector}}$$

Scaling law (n~1) depends on phonon readout

CENNS: *Standard Model prediction*

Recoil energy distribution



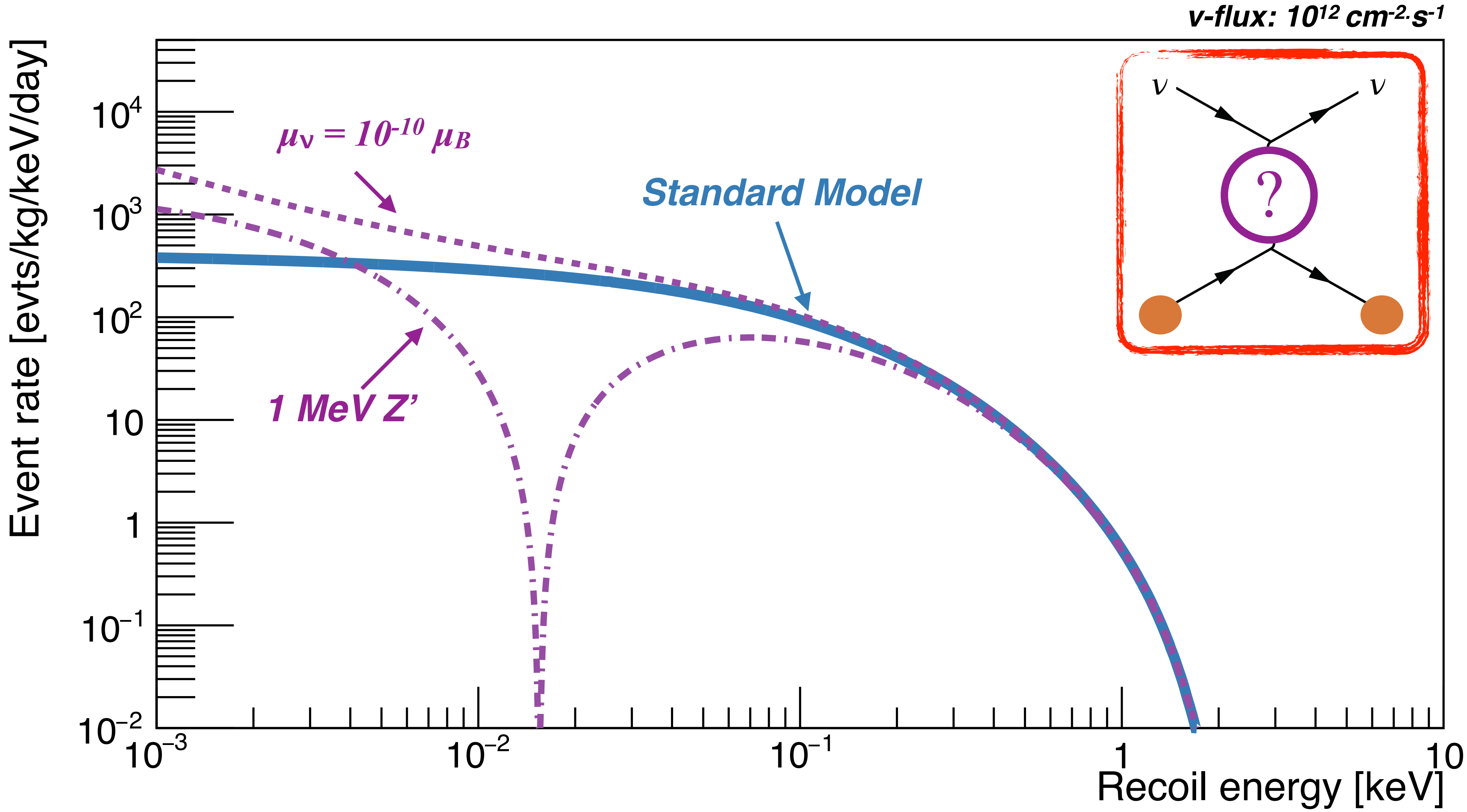
J. Billard, J. Johnston and B. Kavanagh, JCAP (2018)

We expect a few tens of events per day and per kg of detector material

Calls for small total detector mass to reach high-precision: kg-scale

CENNS: *Searching for New Physics*

Recoil energy distribution



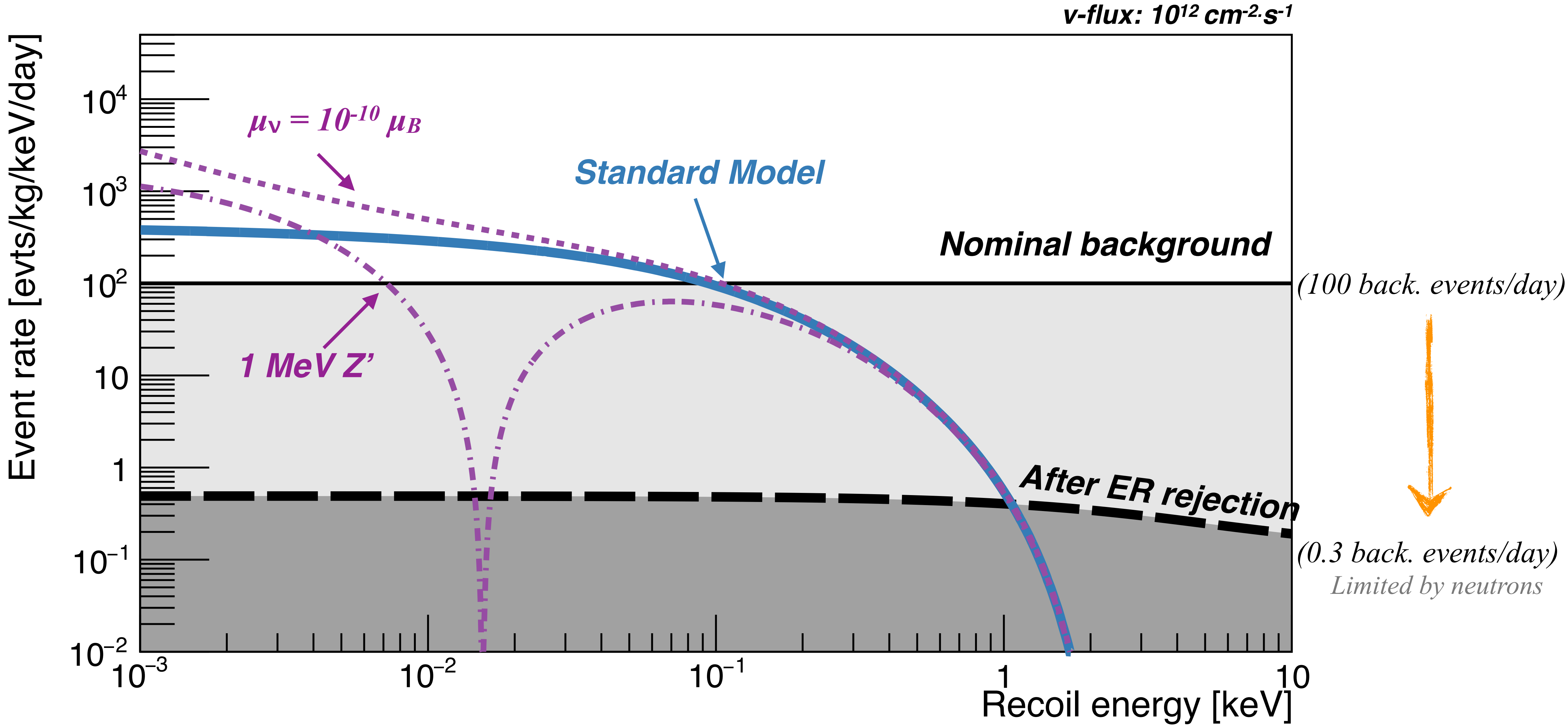
J. Billard, J. Johnston and B. Kavanagh, JCAP (2018)

New physics signatures will arise at the lowest energies

Calls for very low-energy thresholds: O(10) eV

CENNS: *The Background*

Recoil energy distribution



20 CENNS events/day: ***5 sigma CENNS detection in a couple of days !***

1 % precision measurement after one year

CENNS: *Aiming at % precision measurement (by-2024)*

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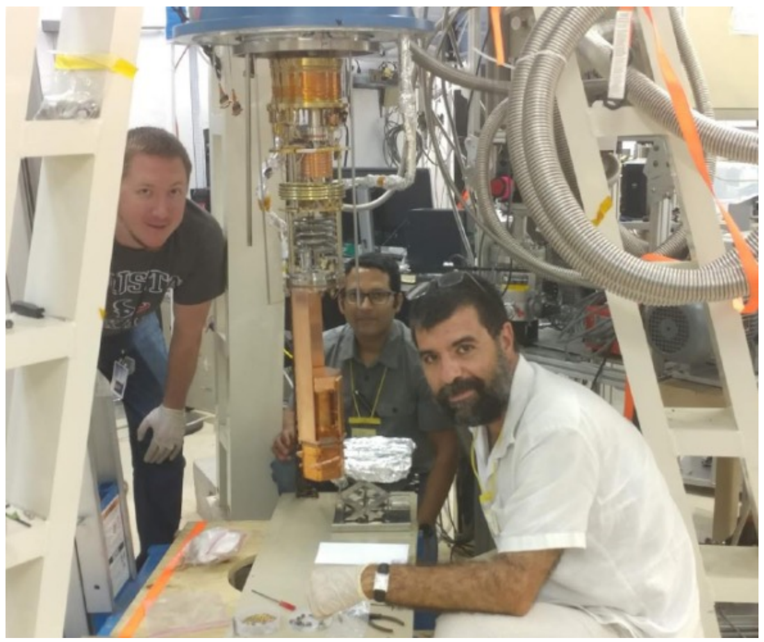
R. Mahapatra *et al.*, NIMA 853 (2017) 53

MINER



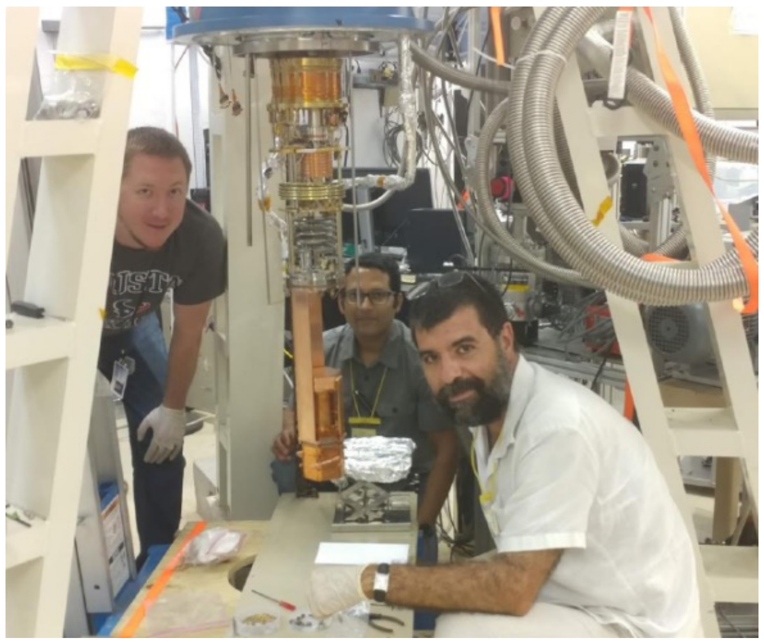
- At the Mitchell Insti. research reactor (1 MW) with movable core
- Use of SuperCDMS Soudan detectors iZIP (625 g Ge) in HV mode
- Aiming for a total payload of 10 kg with ~200 eVnr energy threshold
- Background reduction with passive and active shielding - **No particle identification**
- Science run started, Phase 2 in ~ 1 year

CENNS: *Aiming at % precision measurement (by-2024)*

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

R. Strauss *et al.*, EPJC 77 (2017) 506

MINER



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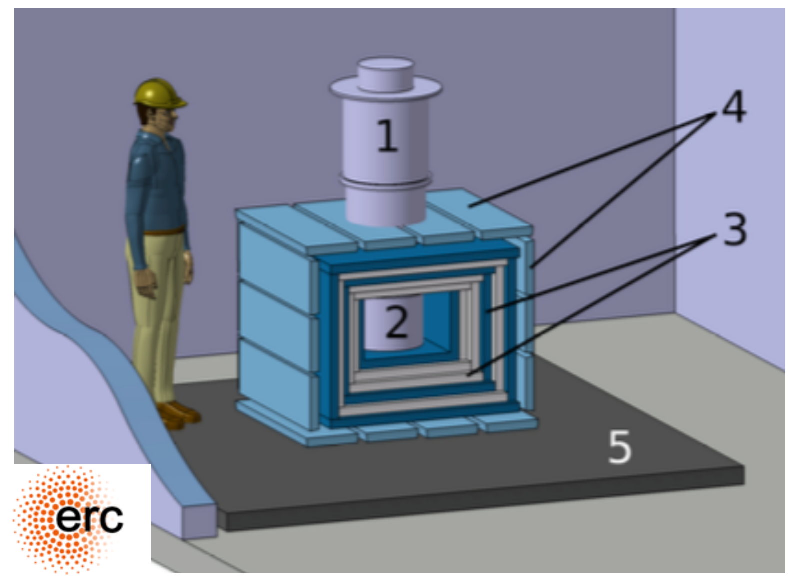
NuCLEUS



- 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 $Al2O_3$,
- ~20 eVnr energy threshold
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- Phase 1 start in 2021, then switch to phase 2 with 10 kg (2000 crystals)

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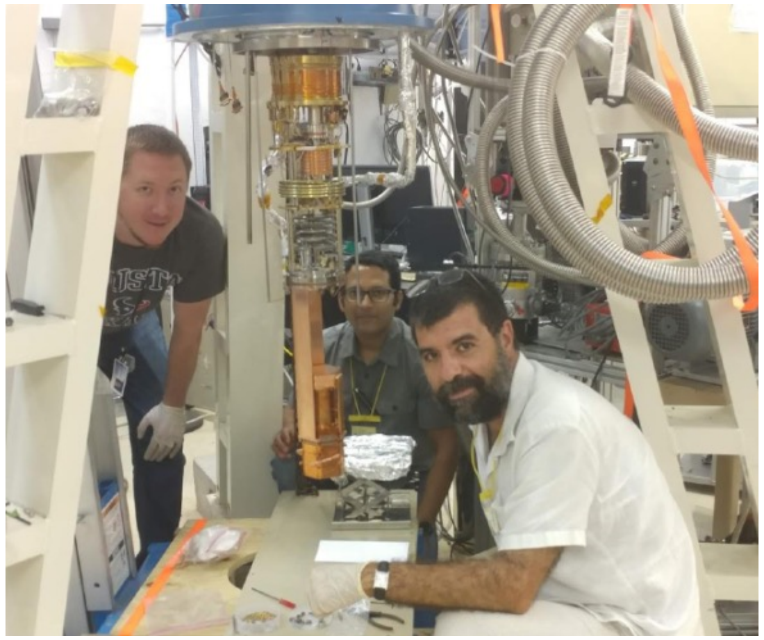

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R. Strauss *et al.*, EPJC 77 (2017) 506

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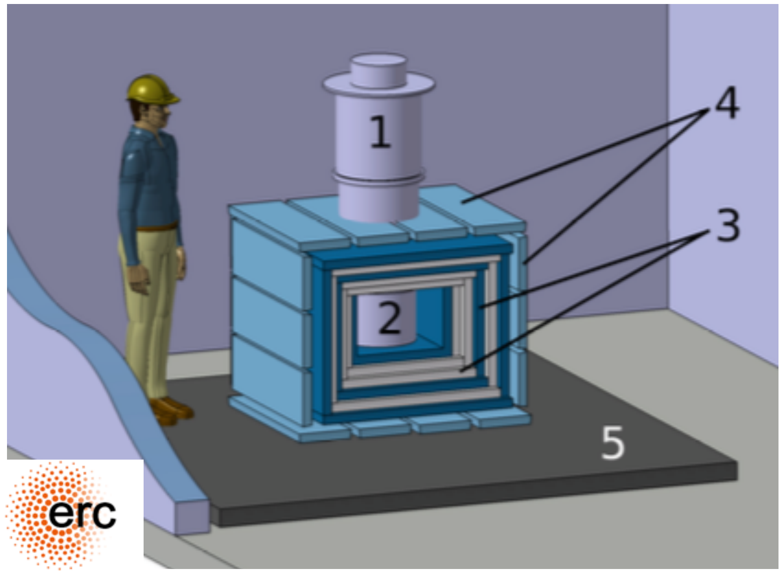

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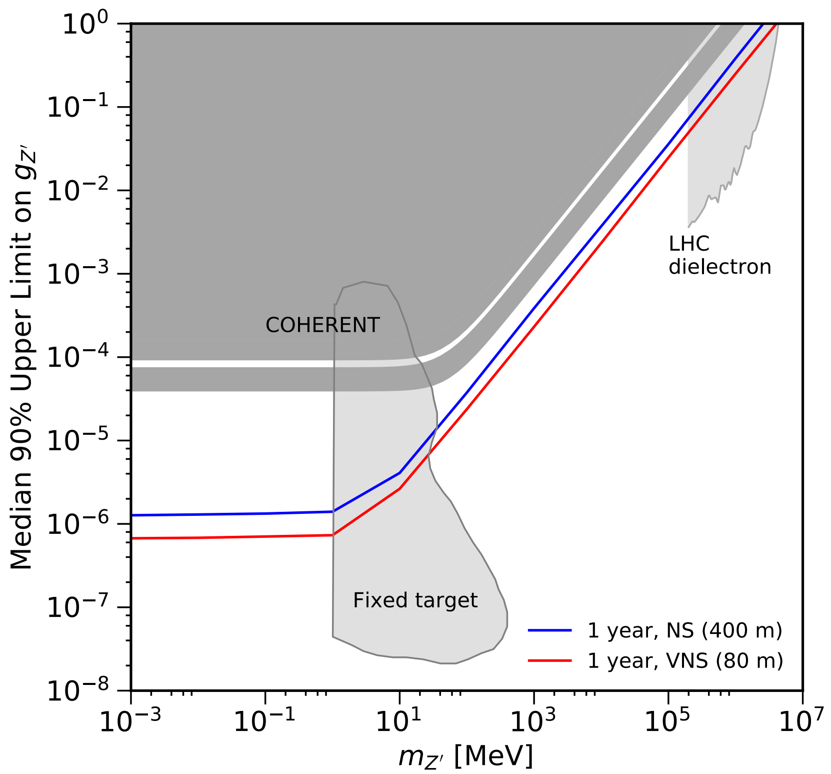
J. Billard *et al.*, JPG 44 (2017) 10

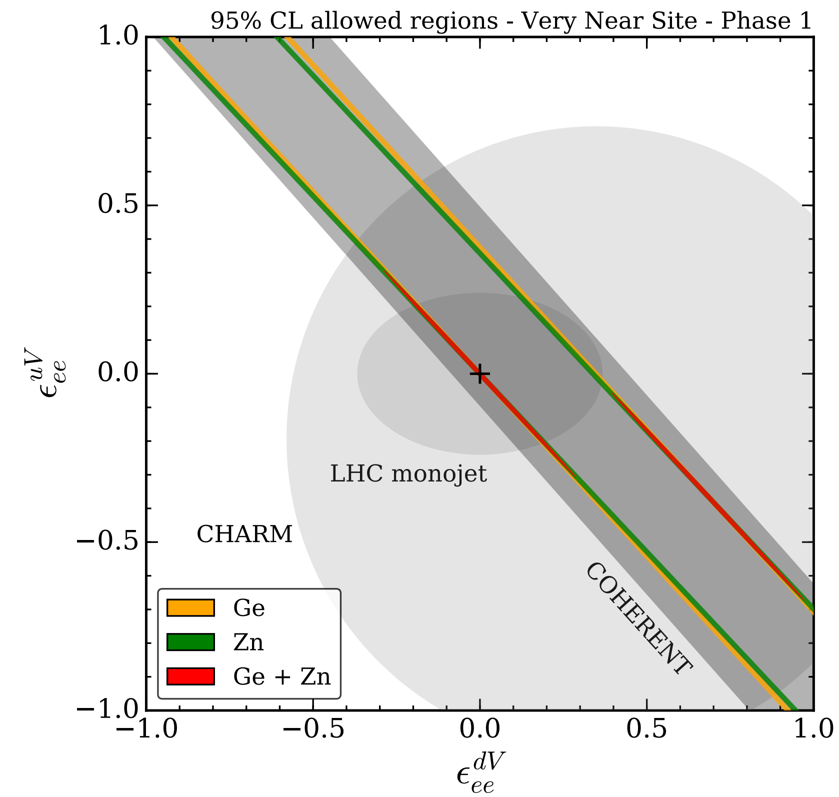
Ricochet

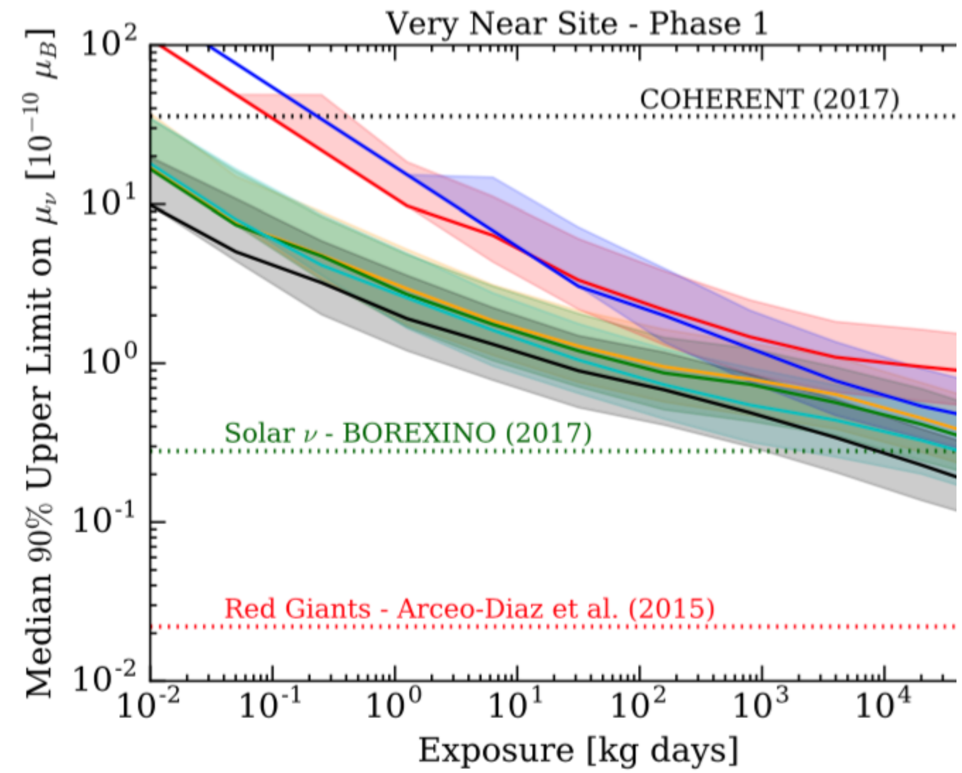
- Nuclear site to be finalized by end-2019
- Two detector technologies both achieving:
    - ***CryoCube***:1 kg array of detectors 30 g (Ge & Zn)
    - ***Q-Array***: 200 g (Zn & Al)
- ~50 eVnr energy threshold
- Background reduction with passive and active shielding + **particle identification**
- First science data taking planned for 2022/2023

CENNS: *Upcoming sensitivities to New Physics*

J. Billard, J. Johnston and B. Kavanagh, JCAP 11 (2018) 016







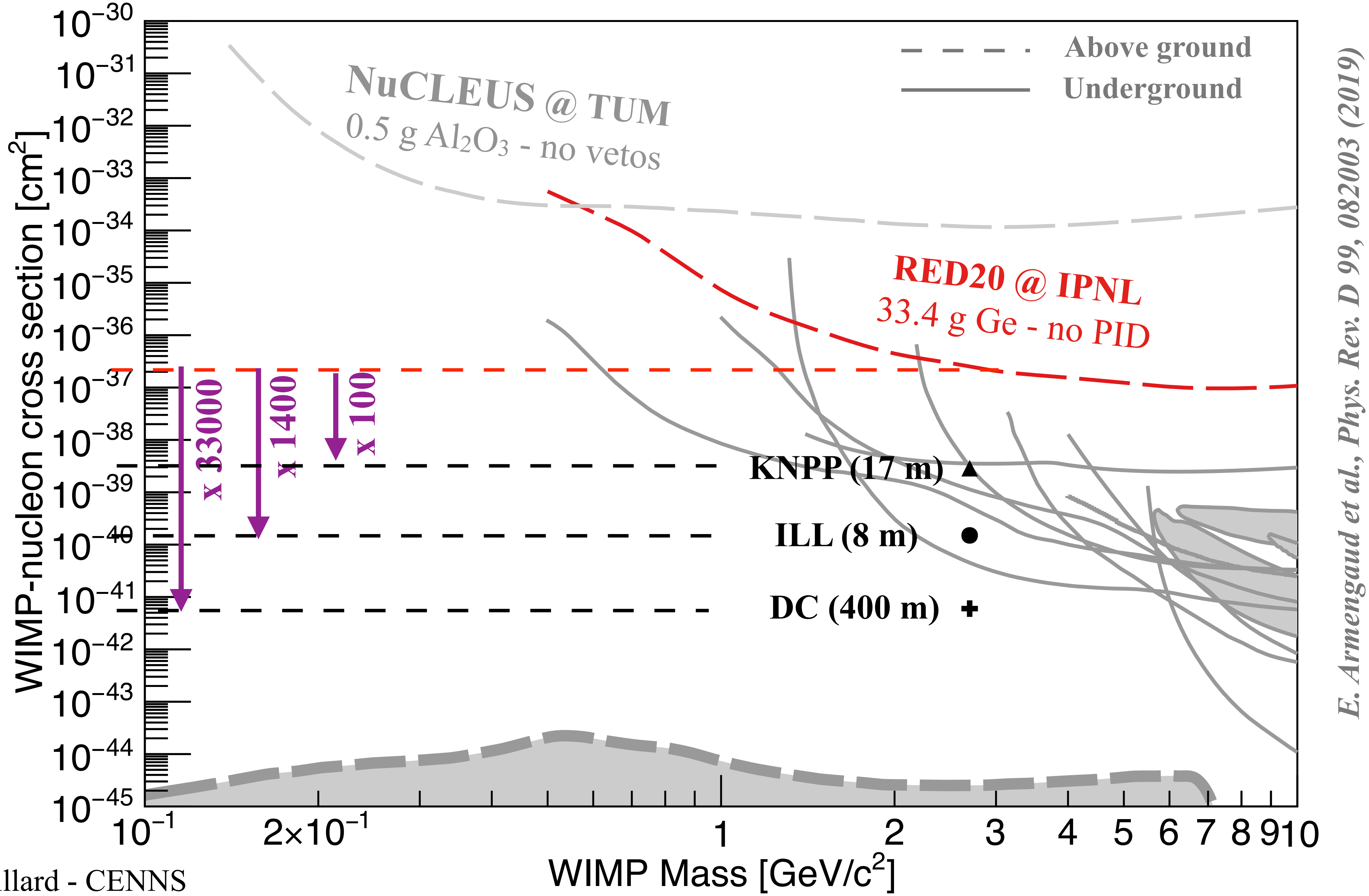
Ongoing or planned sub-100 eVnr CENNS experiment are all aiming for a **percentage level precision measurement (roughly) by the end of 2024 to:**

- Measure the Weinberg angle with a %-precision from 1 to 10 MeV in momentum transfer
- Search for new bosons with a sensitivity **up to two orders of magnitude better than current limits**
- Further constrain the existence of NSI by two orders of magnitude
- Reach a world-leading CENNS-based NMM limit of $\mu_\nu \sim 10^{-11}\ \mu_B$ **at the 90% C.L.**

CENNS: *Present sensitivity (via DM search)*

Sensitivity improvement needed towards CENNS sensitivity @ reactors

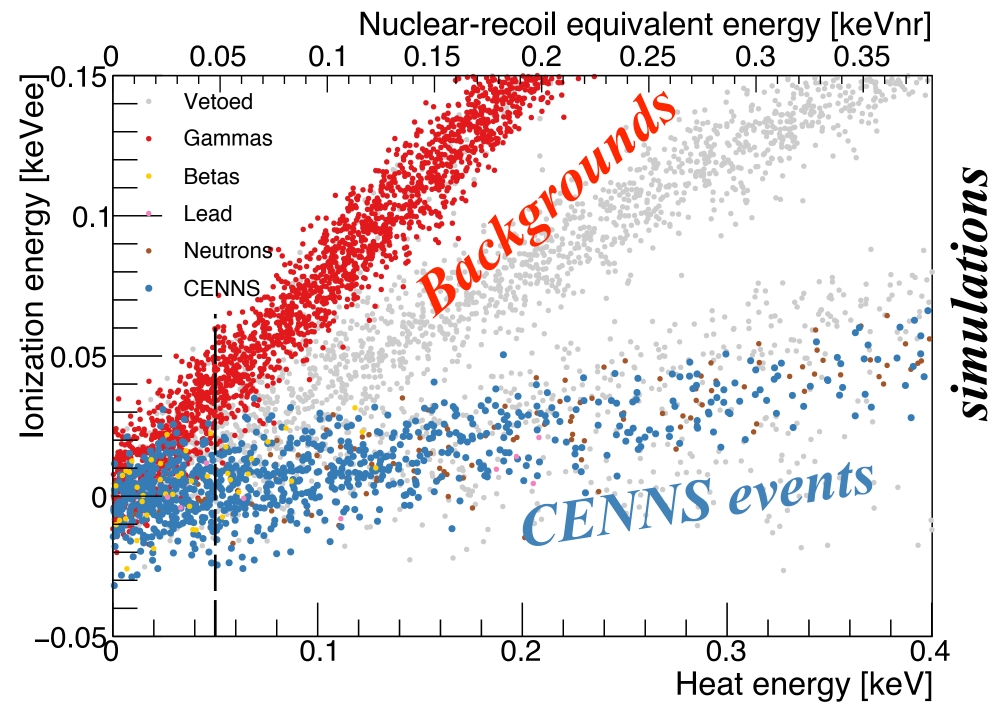
We need to do as well as the best DM experiments but from aboveground !!



CENNS: *Challenging systematics*

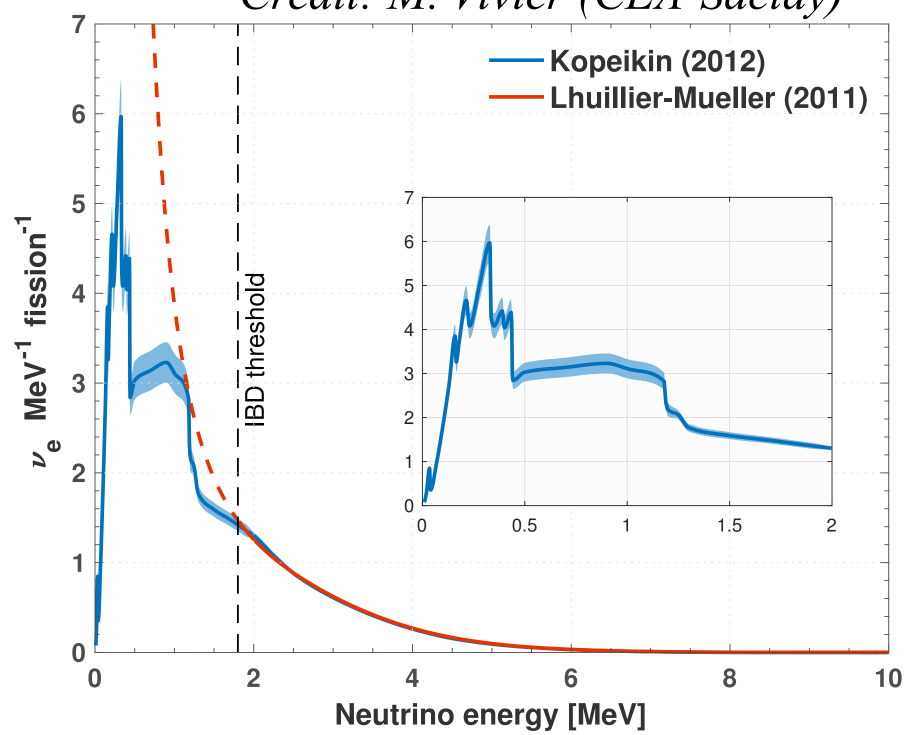
Aiming for a percentage level precision measurement requires a great control of various systematics:

- **Precise energy calibration at the lowest energies**
  - *Development of a dedicated low-energy, mono-energetic and pulsed neutron source for Ricochet*
- **Understanding the backgrounds in a yet unexplored energy region**
  - *Ricochet is pushing for PID down to sub-100 eVnr to model/reject both known and **unknown** backgrounds*



Credit: *M. Vivier (CEA-Saclay)*

- **Accurate knowledge of the reactor neutrino fluxes**
  - Reactor power known at the ~% level at best
  - No experimental data on reactor antineutrino energy spectra below the IBD threshold (1.8 MeV)
  - **NENuFAR** project at CEA *(M. Vivier et al.)*
    - Refined modeling of beta decays in fission products
    - Using an up-to-date nuclear data base and re-evaluation of the systematics' budget
    - Computation of neutrino fluxes at both power and research reactors

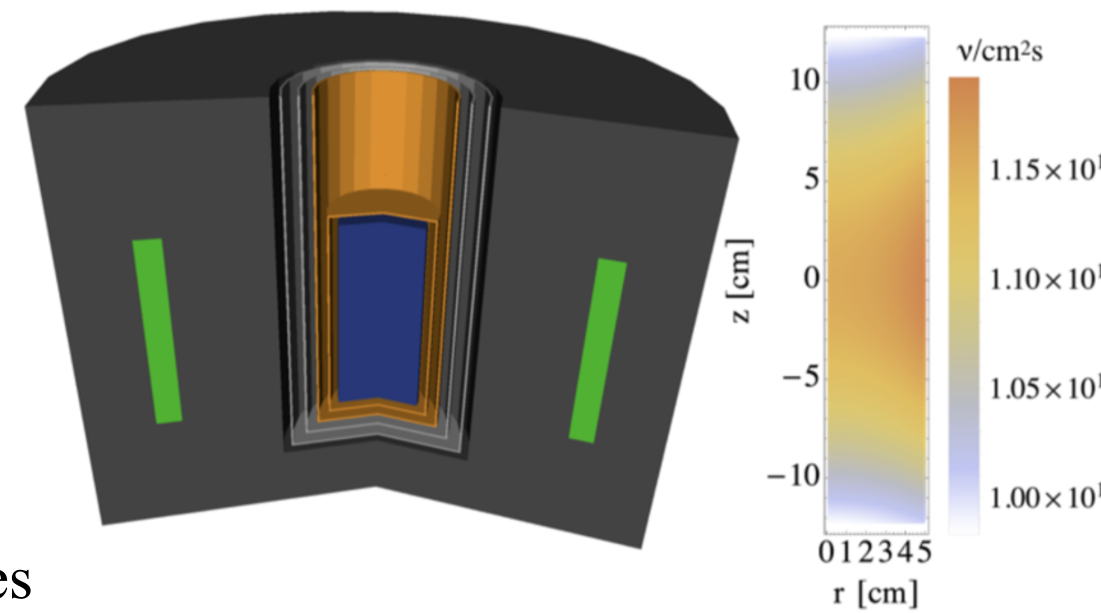


CENNS: *Beyond 2024*

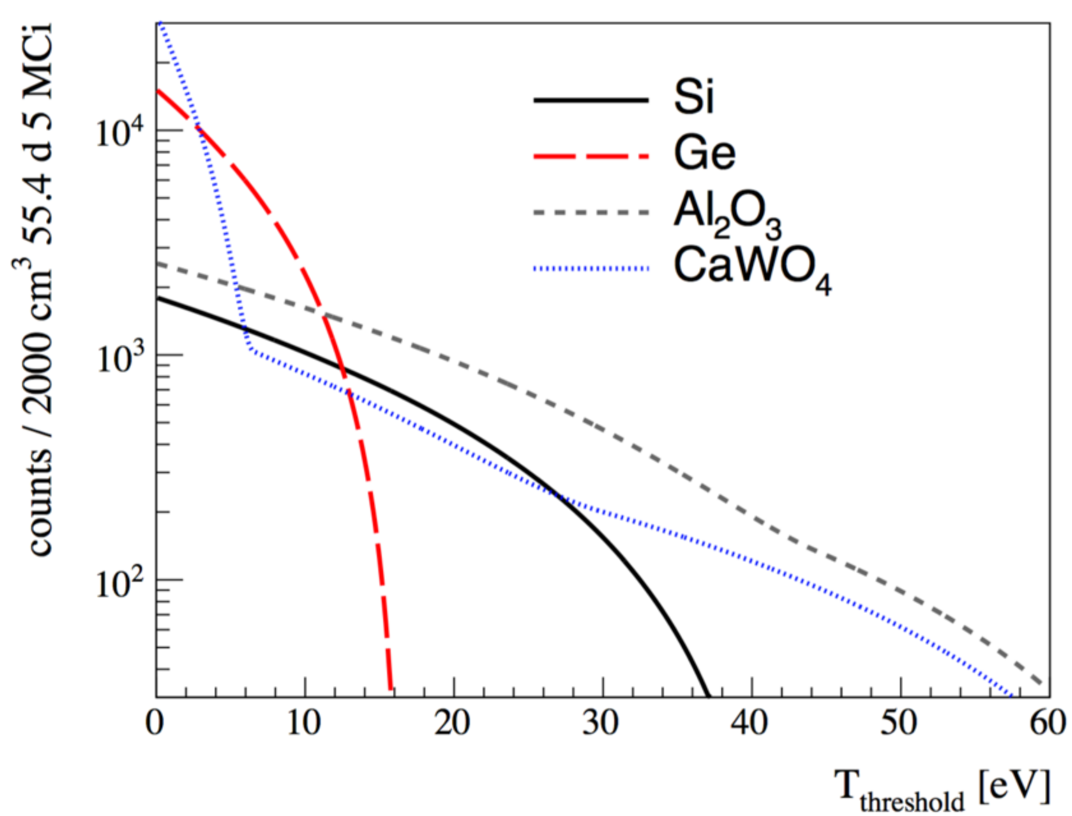
C. Bellenghi *et al.*, EPJC **79** (2019)

Going beyond percentage level precision CENNS measurement will require a completely new strategic approach:

- **Use of artificial radioactive sources such as ^{51}Cr**
  - Idea based on the previous GALLEX (^{51}Cr) and SAGE (^{51}Cr, ^{37}Ar) experiments
  - Perfectly well known neutrino spectrum with the dominating lines at 747 keV (81%) and 752 keV (9%)
  - ^{51}Cr half-life is 55.4 days
  - **Activation at research reactors** with high neutron fluxes
    - 5.10^{14} n/cm^2/s for 24 days leads to a ~5 MCi



- **Experimental challenges**
  - Few ~0.1% precise activity monitoring should be achievable
  - Complex shielding of the source : expect intense gamma background from impurities *(and neutrons ?)*
  - Environmental background: **Go underground ?**
  - Very low energy threshold (sub-10 eV) for large detector payloads (5 to 12 kg) to achieve sub-% precision !



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 at the lowest energies, where signs of New Physics may arise (*NSI, anomalously large NMM, …*), and with strong implications on astrophysics (*SN dynamics, DM direct detection*)

CENNS is a great technology driver for: Detector Innovation, Fundamental Science, and Nuclear Non-Proliferation

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

Ongoing sub-100 eV CENNS experiment are aiming for **percentage-level precision measurement at the horizon of 2024** (5 years from today).

Next generation experiment aiming at sub-% level precision measurement would require:

- Well controlled sources: e.g. artificial ones (ex: 51Cr) ?
- Much larger payloads and lower thresholds: 10 to 100 kg target material / sub-10 eV
- Much lower backgrounds: Similar to that from **DM underground experiments**

Based on its leading role within the Ricochet collaboration, IN2P3 would be particularly well positioned to lead such an ultimate CENNS experiment at the horizon of 2030