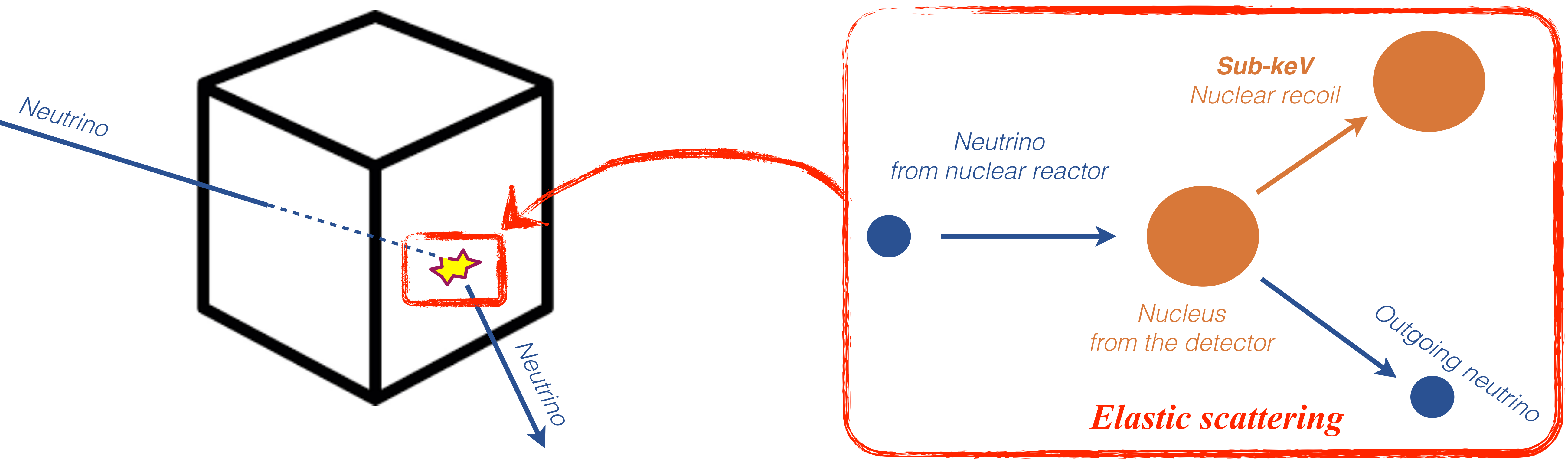
Bolometric detection of CENNS: concept, status and prospects

J. Billard
Institut de Physique des 2 Infinis de Lyon / CNRS / Université Lyon 1

P2IO BSM-Nu workshop, April 11th, 2022

CENNS: *The process*

Coherent **E**lastic **N**eutrino-**N**ucleus **S**cattering (CENNS)



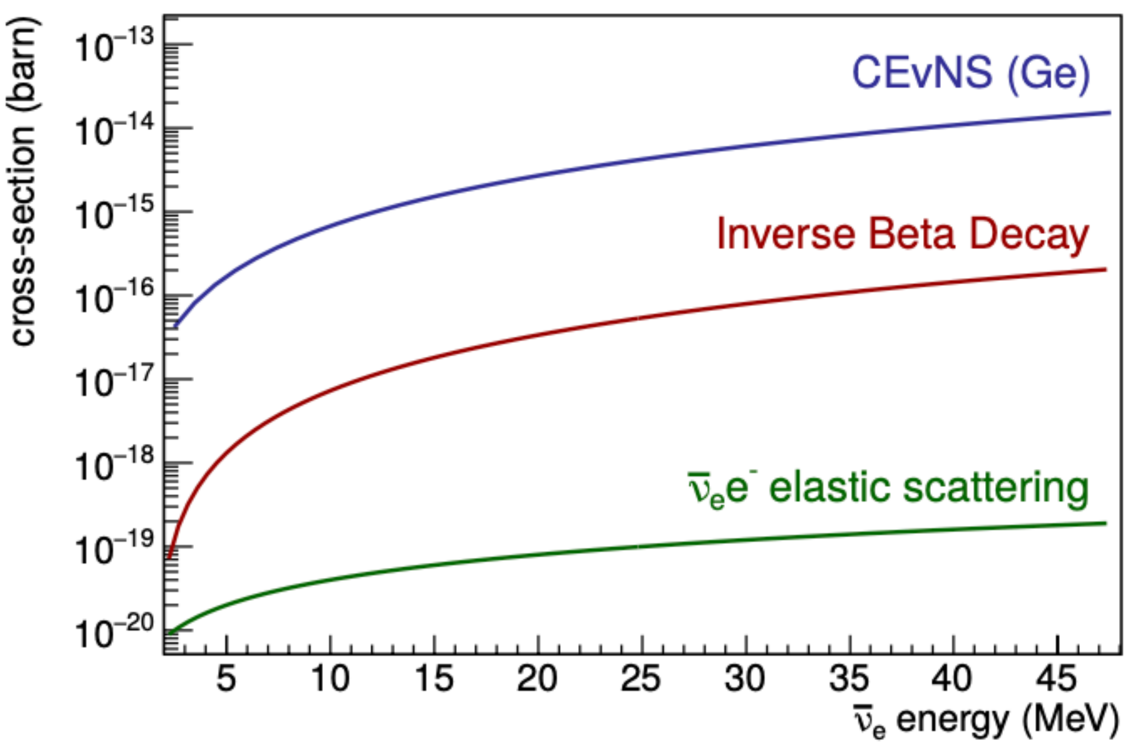
For a recent and detailed review:
*M. Abdhulla et al., « Coherent elastic neutrino-nucleus scattering: Terrestrial and astrophysical applications », arXiv:*2203.07361

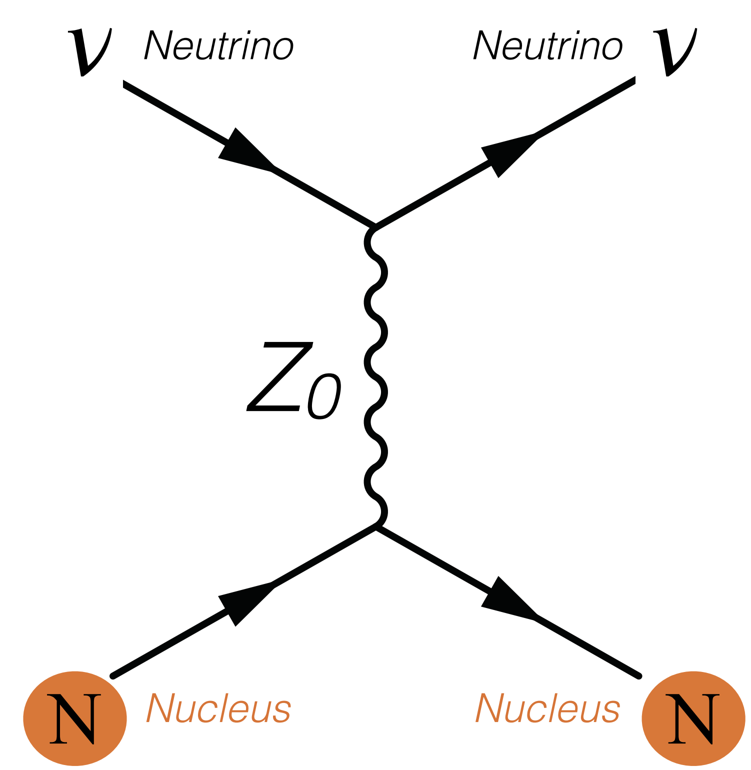
CENNS: *The process*

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

Coherent **E**lastic **N**eutrino-**N**ucleus **S**cattering (CENNS)

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





- CENNS cross-section ***1000 times larger*** than IBD cross-section
- No energy threshold - ***Elastic Scattering***
- From ton-scale to kg-scale neutrino detector payloads

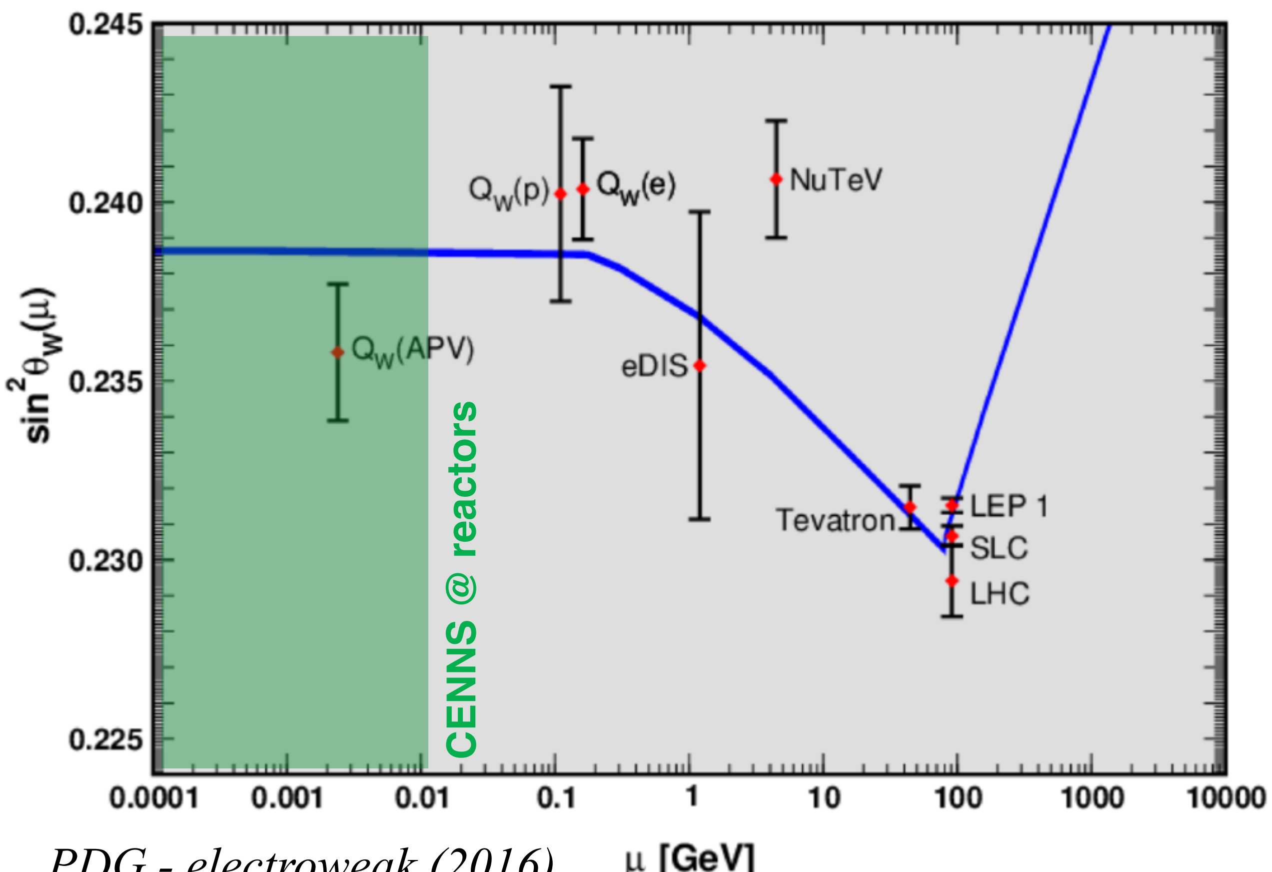
CENNS: *The process*

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

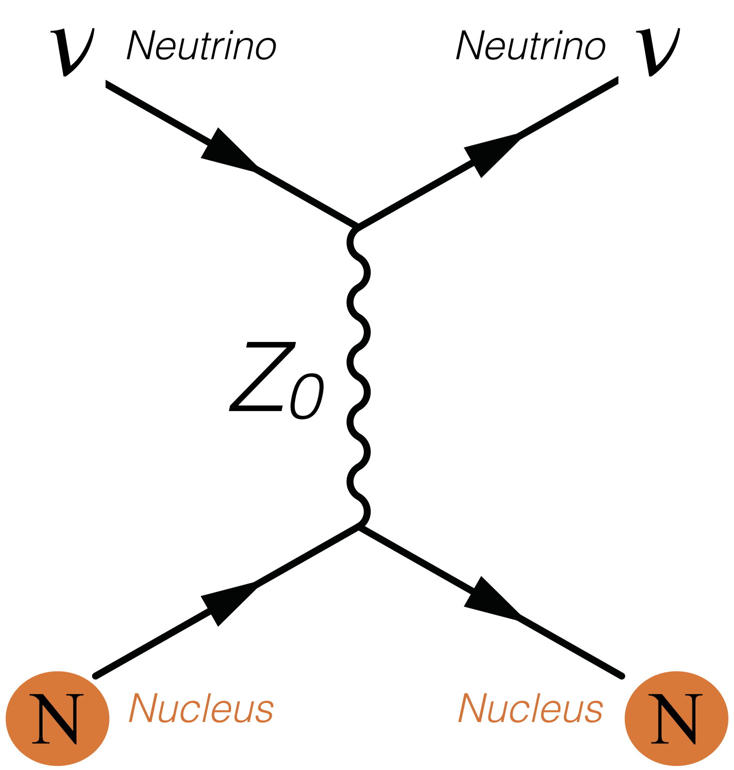
Coherent **E**lastic **N**eutrino-**N**ucleus **S**cattering (CENNS)

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

$$Q_w = N - Z(1 - 4\sin^2\theta_w)$$



PDG - electroweak (2016)

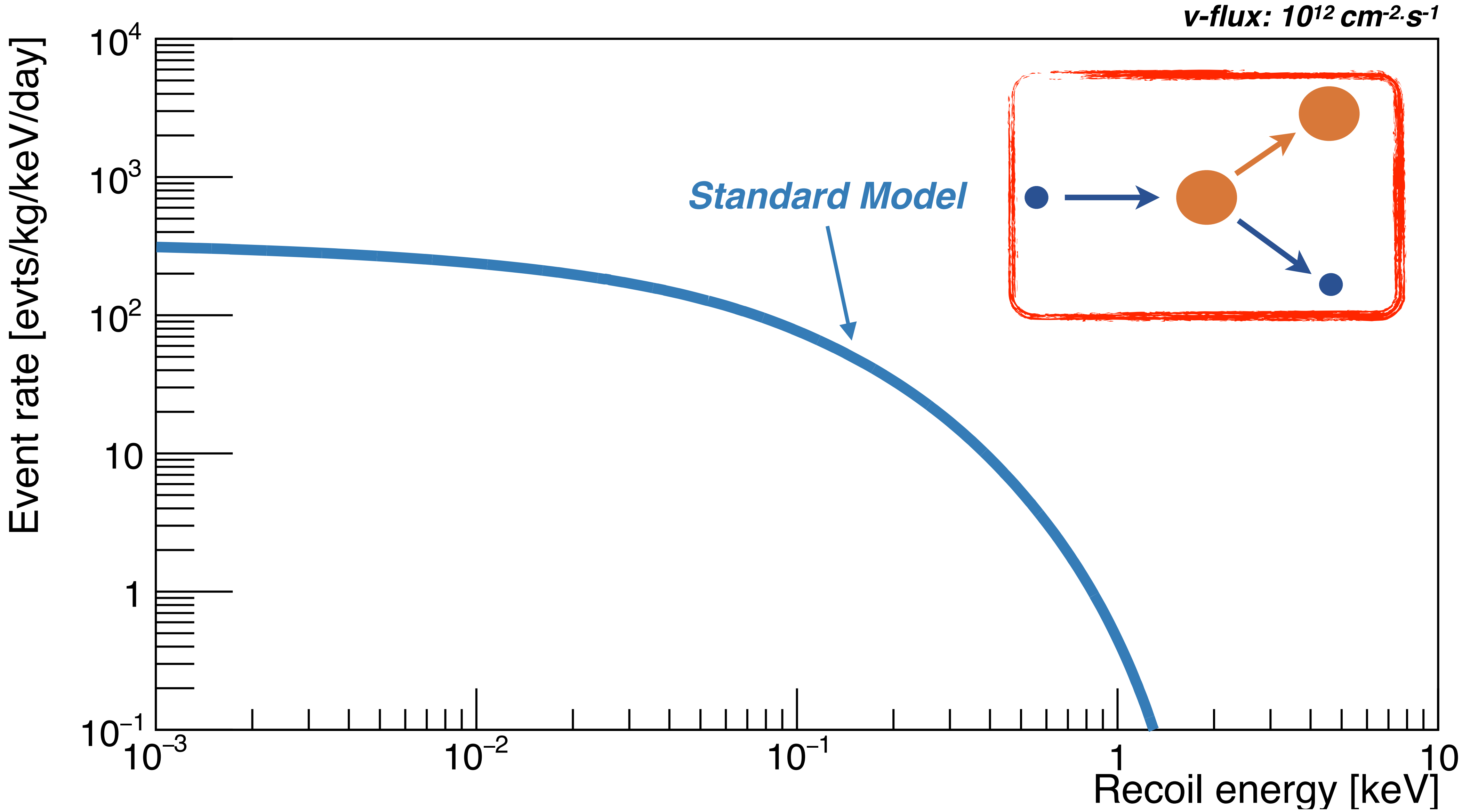


A gateway to new physics:

- Non-Standard Interaction
- Existence of new massive bosons
- Neutrino Magnetic Moment
- …

CENNS: *The signal*

Recoil energy distribution

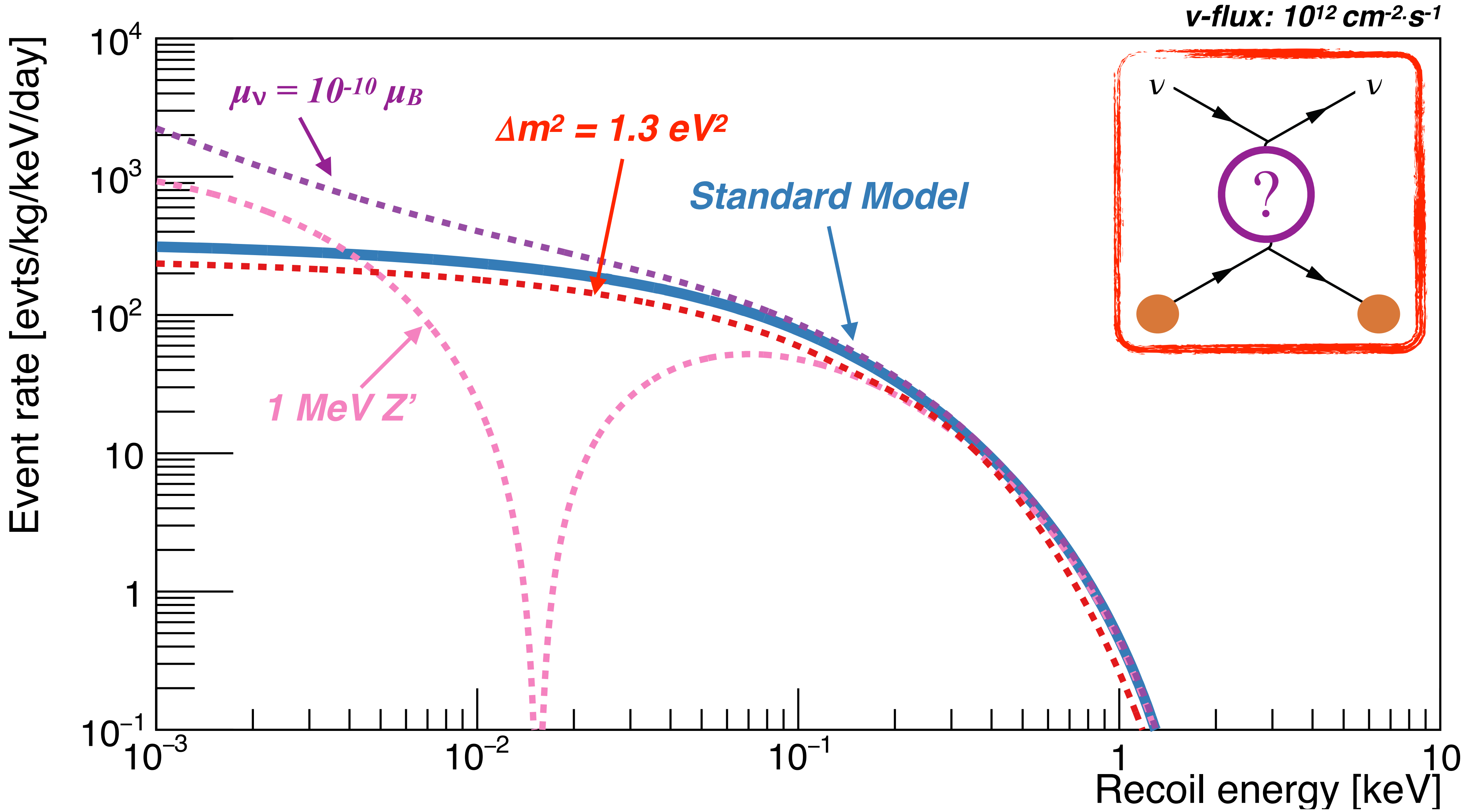


J. Billard, J. Johnston and B. Kavanagh, JCAP (2018)

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 with sub-100 eV threshold***

CENNS: *searching for new physics*

Recoil energy distribution

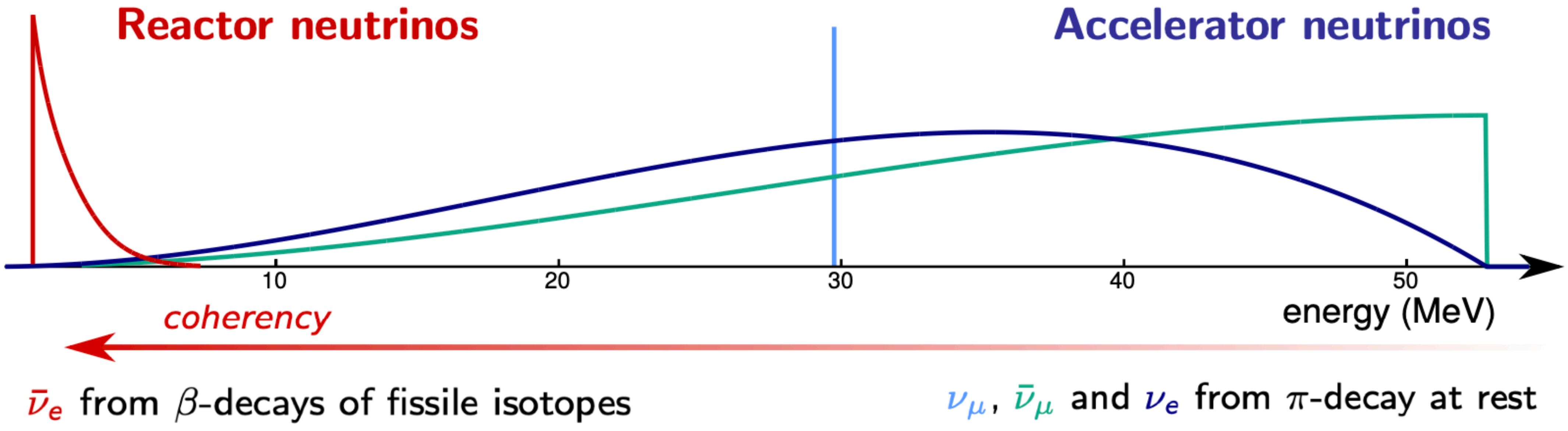


J. Billard, J. Johnston and B. Kavanagh, JCAP (2018)

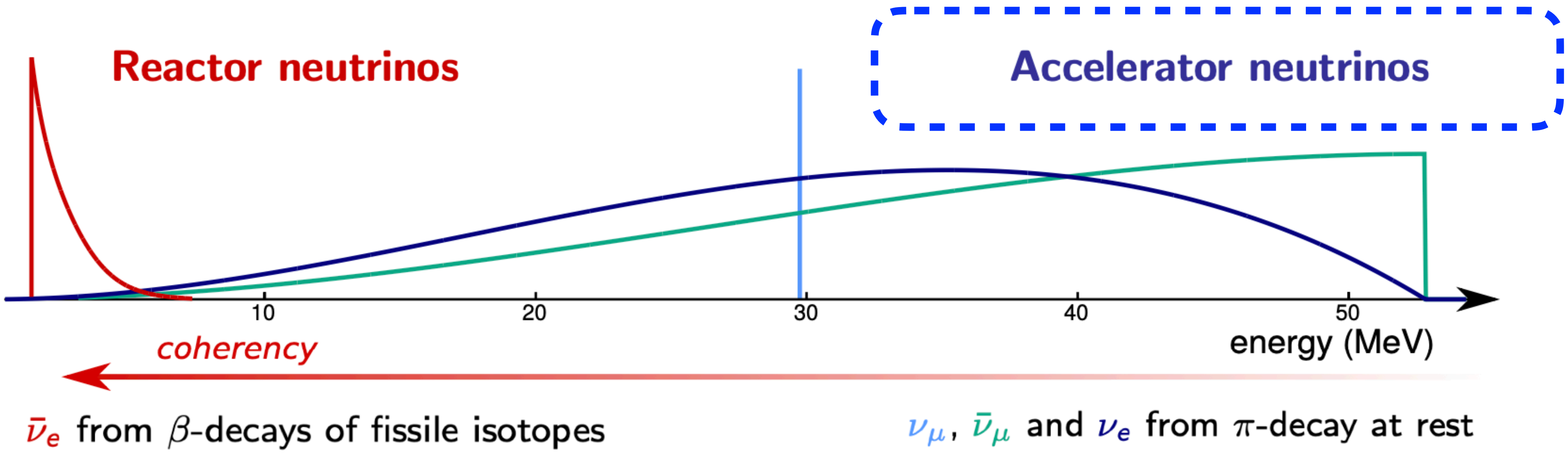
New physics signatures will arise at the lowest energies

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

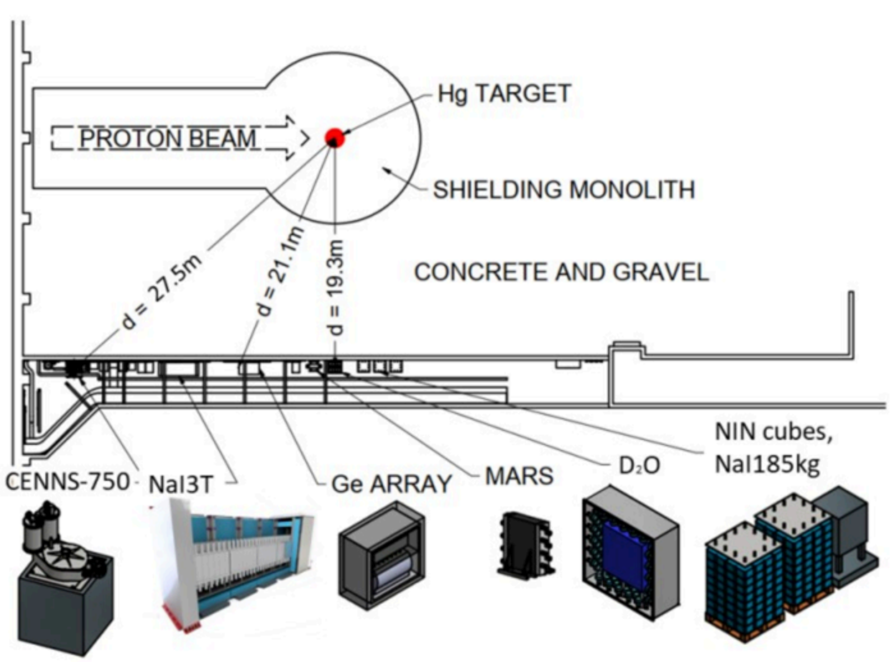
CENNS: *State of the art*

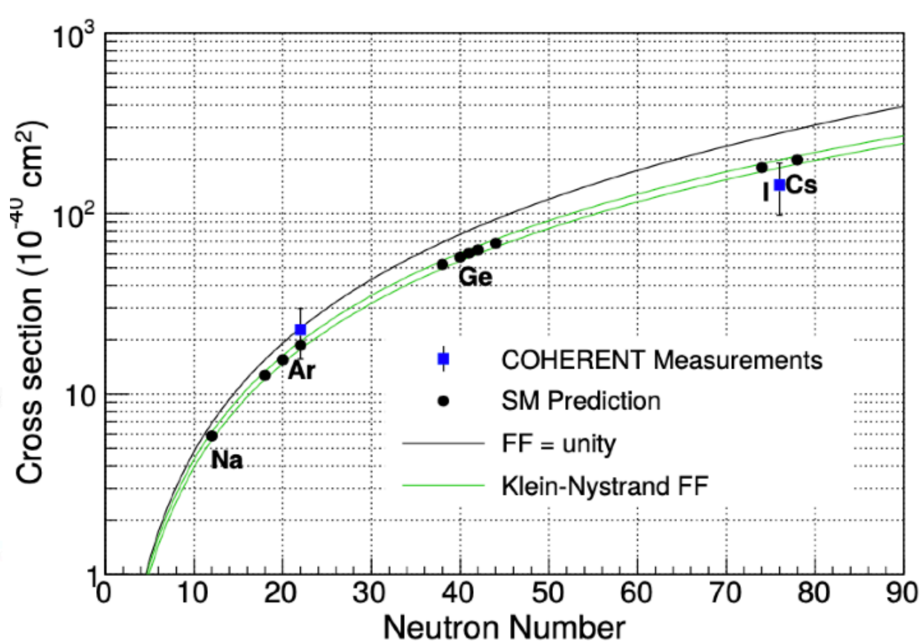


CENNS: *State of the art*



The COHERENT experiment at SNS — The first (two) detections !





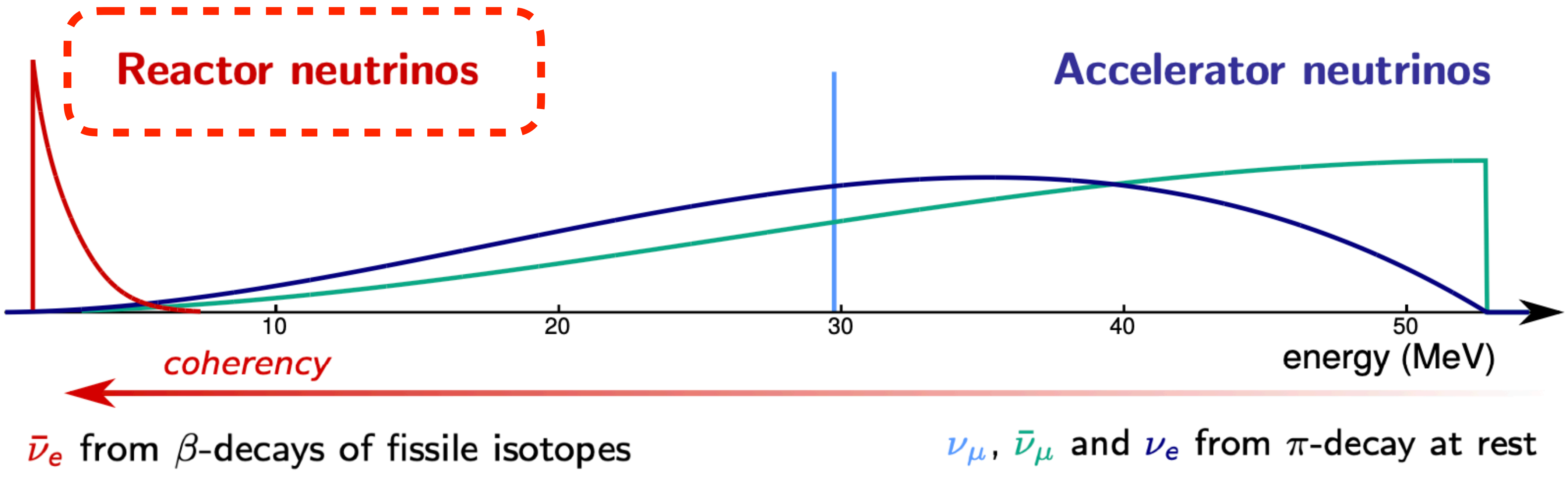
COHERENT at the spallation Neutron Source first observation ! CsI (2017) [1], Ar (2020) [2]

- Combine different targets and technology
  - **Measure the N² dependence**
- Sensitive to nuclear physics (form factor)
- Bounds on BSM physics: **NSI, light mediators,** …

Ongoing proposals for CENNS @ ESS [3]

[1] D.Akimov et al., Science (2017), arXiv:1708.01294
[2] D.Akimov et al., PRL (2021), arXiv:2003.10630
[3] D. Baxter et al., JHEP (2020), arXiv:1911.00762

CENNS: *State of the art*



Reactor neutrino experiments

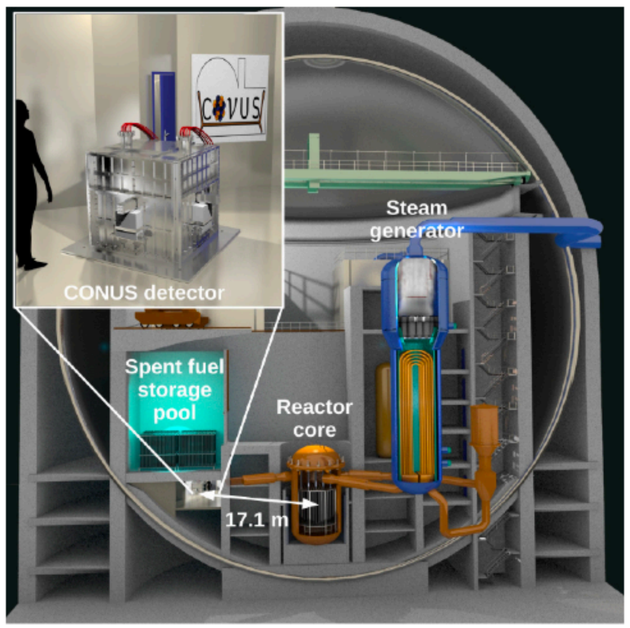
running: CONUS, TEXONO, CONNIE...
future: RICOCHET, NUCLEUS...

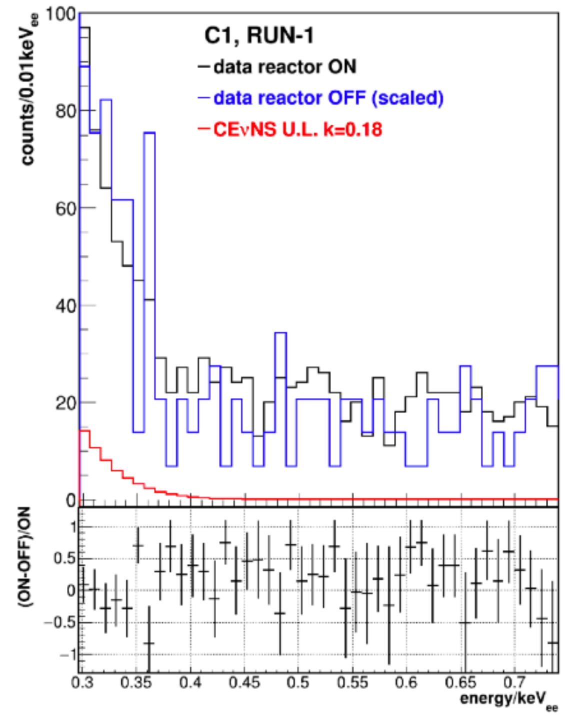
- Full coherent regime
- Sensitive to neutrino magnetic properties
- Bounds on BSM physics
  NSI, light mediators...
- Reactor spectrum investigations

CENNS: *Ionisation-based experiments @ reactors*

CONUS

H. Bonnet et al, CONUS coll., PRL (2021), arXiv:2011.00210

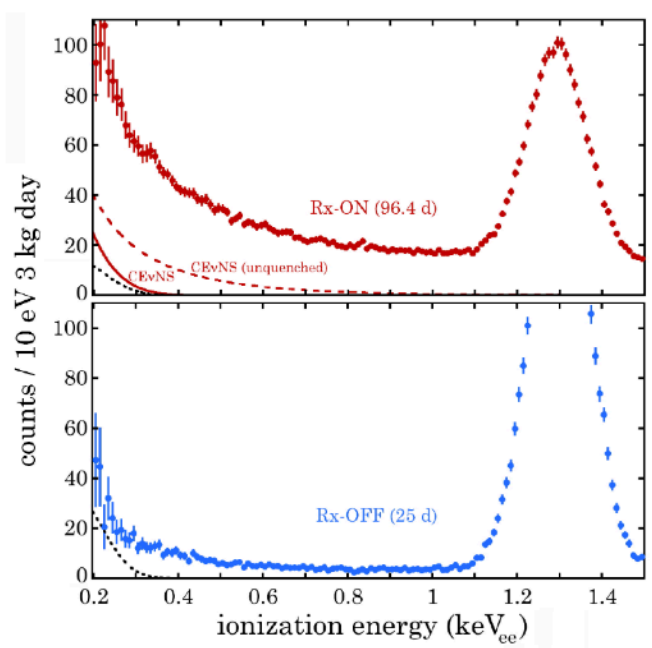




- 17 m from 3.9 GWth Brokdorf reactor
  - neutrino flux: *10^{13} ν/s/cm²*
- 24 m.w.e overburden
- 4 p-type point contact HPGe (1 kg each)
- Baseline resolution: 36 eVee (RMS)
- Threshold: 300 eVee (~1.6 keVnr)
- Background [0.5-1 keVee]: 10 DRU
- **CENNS signal 17x weaker than sensitivity**

Dresden-II

J. Colaresi, J.I. Collar, et al., arXiv:2202.09672



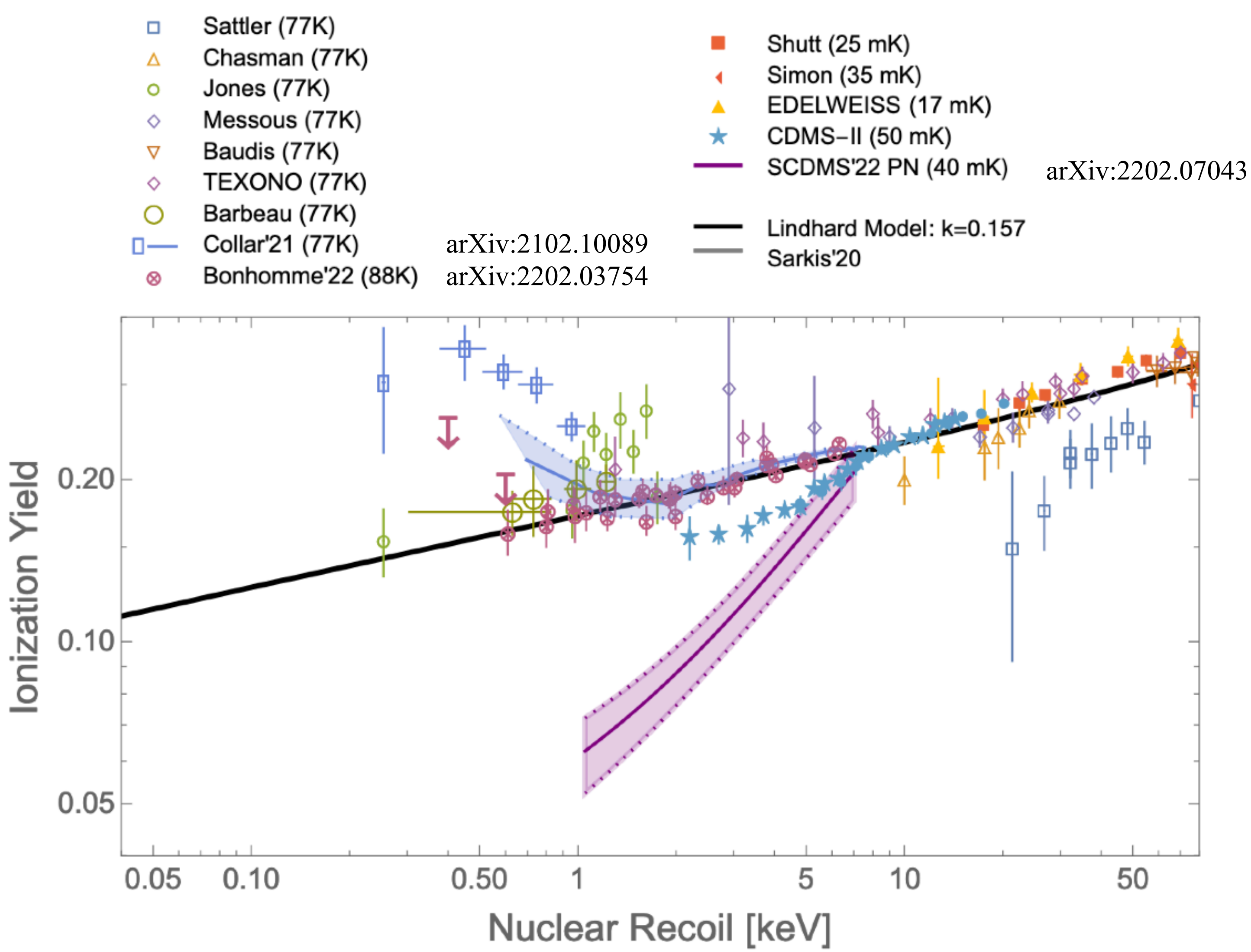
- 8 m from 2.96 GWth Dresden reactor
  - neutrino flux: *$8x10^{13}$ ν/s/cm²*
- 3 m.w.e overburden
- 1 p-type point contact HPGe (3 kg)
- Baseline resolution: 70 eVee (RMS)
- Threshold: 200 eVee (~1.1 keVnr)
- Background [0.5-1 keVee]: 500 DRU (OFF)
- **Suggestive evidence of CENNS detection** BUT requires highly controversial ionisation yield and large reactogenic background subtraction

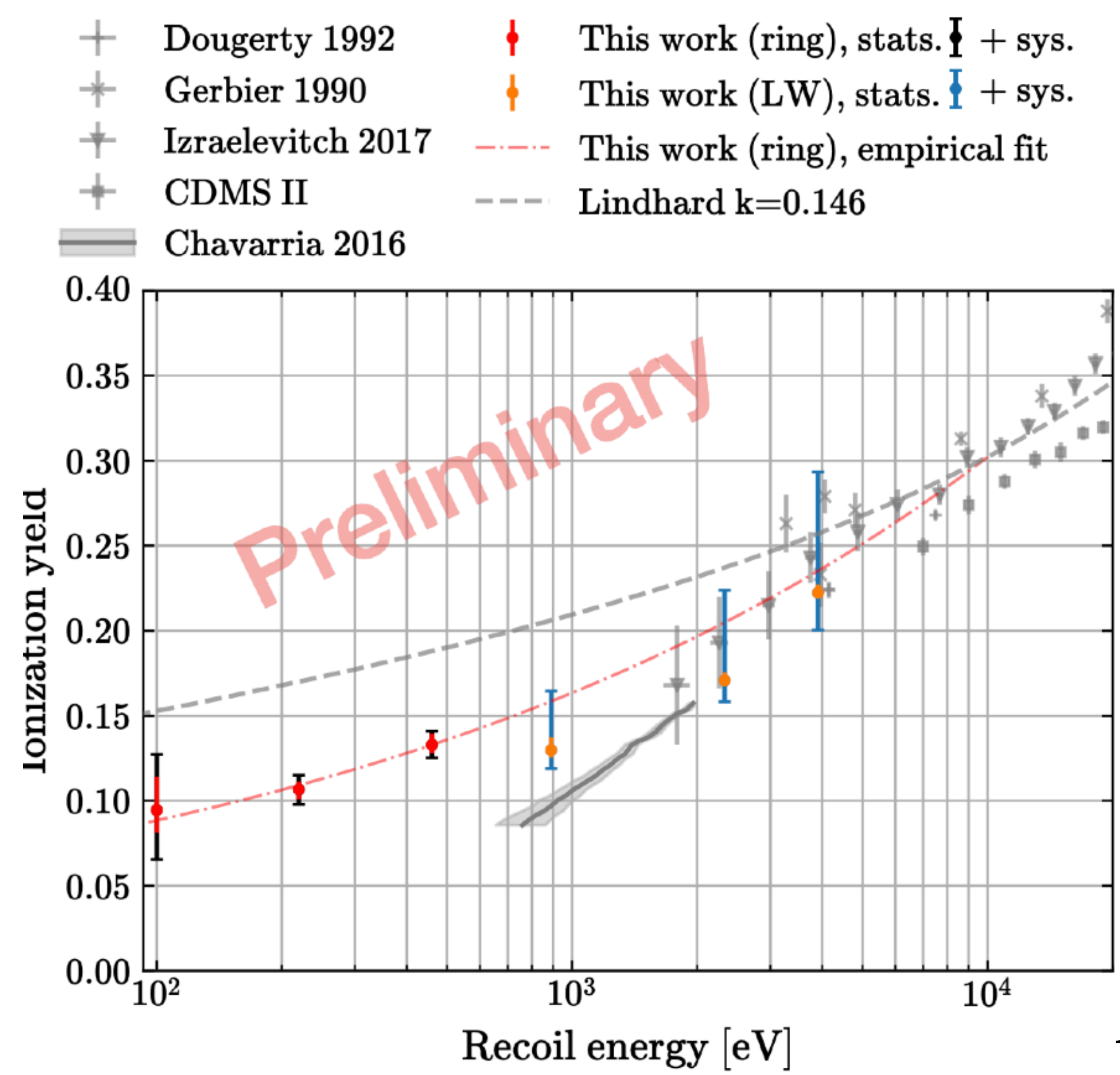
See also interesting results from CONNIE, TEXONO, NuGen, … with no CENNS detection so far

CENNS: *Ionisation-based experiments @ reactors*

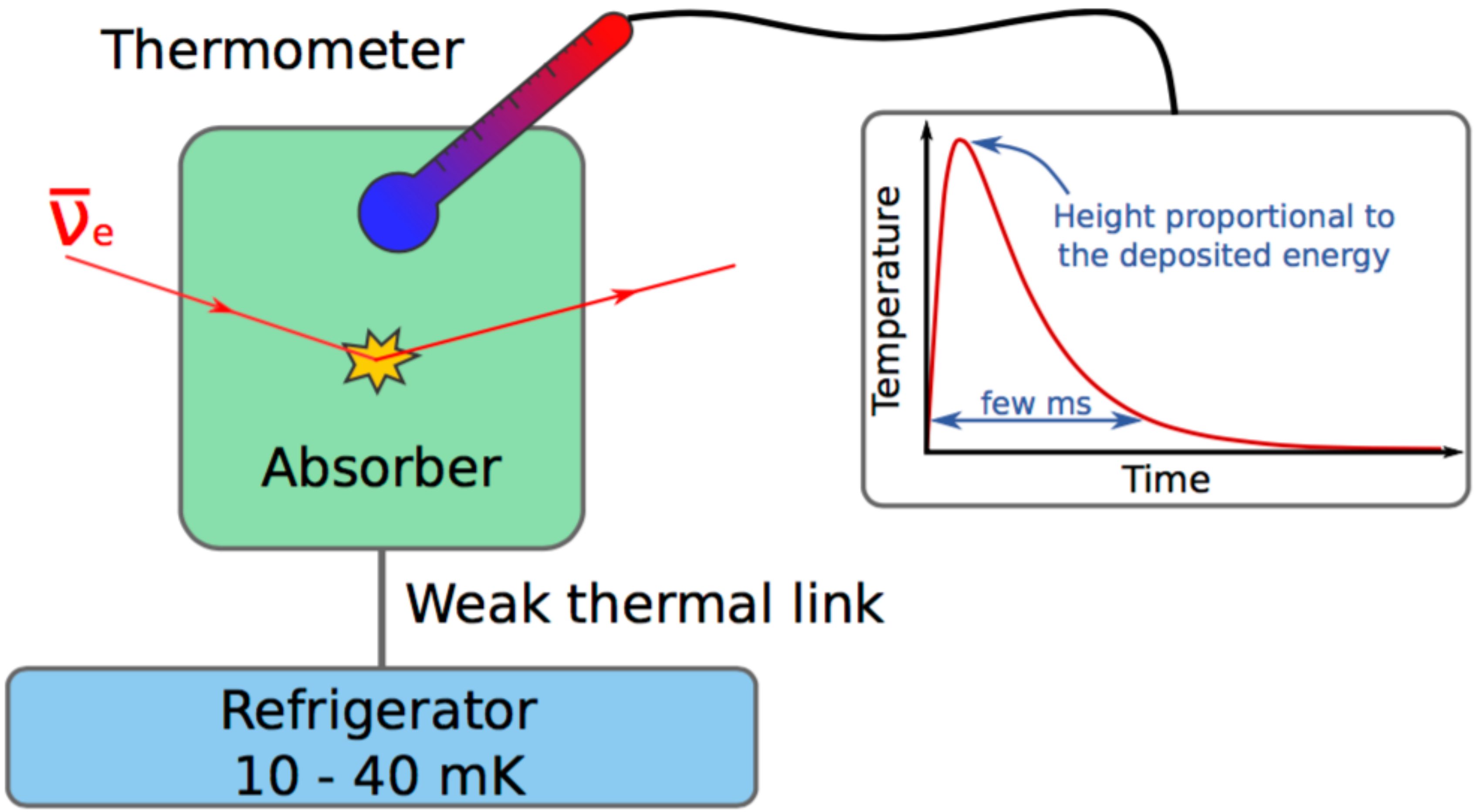
Despite of their exquisite energy resolution, ionisation-only based experiments suffer from **low and uncertain ionisation yield at low energies** where the CENNS signal is expected

- In Ge: Significant discrepancy between latest measurements —> Huge impact on CENNS sensitivity
- In Si: Strong evidence of a lower yield than Lindhard predictions —> Higher threshold than anticipated
  - **Seems highly challenging to reach sub-keVnr threshold with standard (Si-CCD/HPGe) ionisation detectors**





CENNS: *Cryogenic experiments*



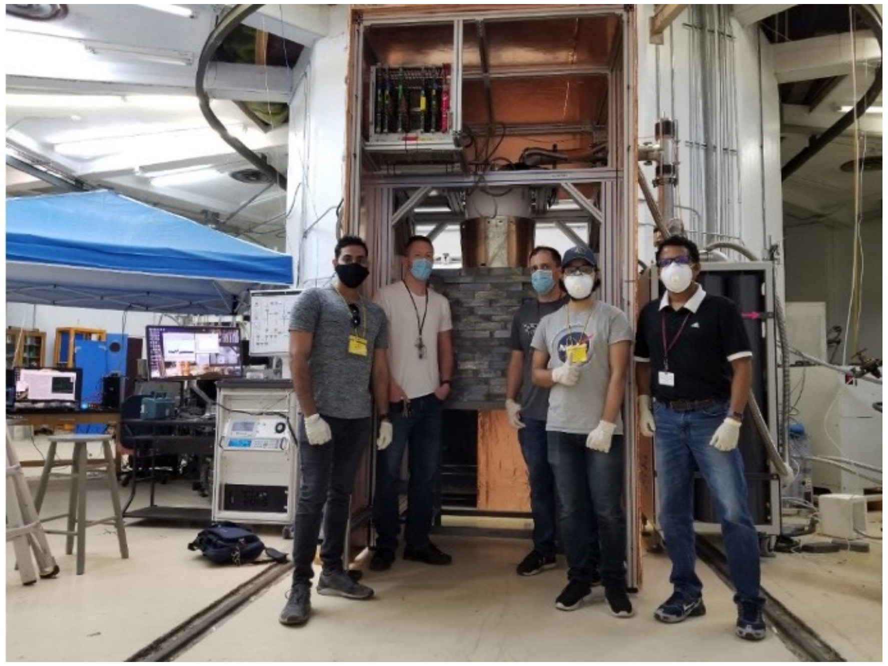
Advantages of a cryogenic phonon readout:

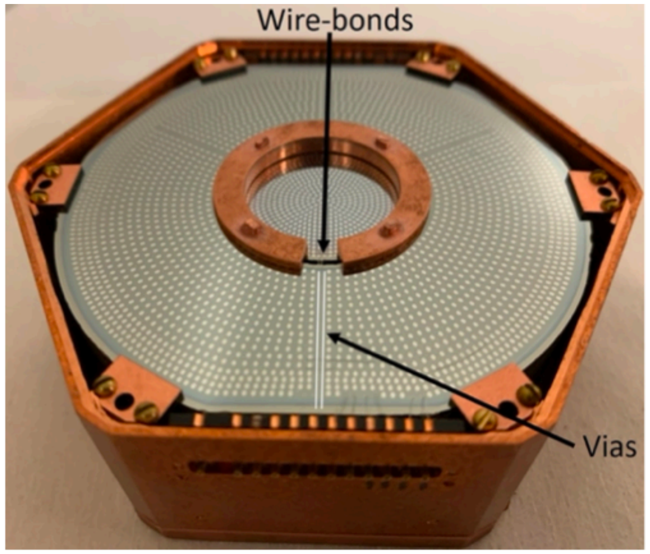
- Direct measurement of the recoil energy, *no quenching involved*
- Almost 100 % of the recoil energy is sensed, *allowing for low-thresholds*
- From thermodynamics, ultimate energy resolution is: **~eV (RMS) for ~ 10 g detectors**
    - ***Calls for the construction of arrays of 10g-scale cryogenic detectors***

Three cryogenic CENNS experiments are about to start their science phase: MINER, NuCLEUS, Ricochet

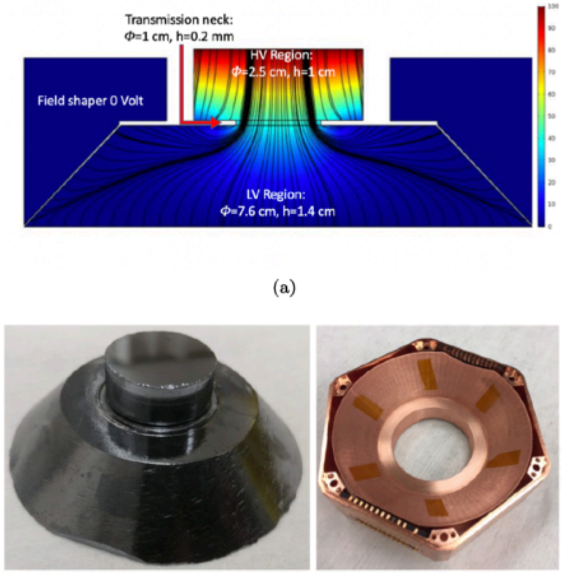
CENNS: *Cryogenic experiments — MINER*

- Located at the Mitchell institute research reactor (1 MWth)
- Movable core from 1-to-10 m from cryostat
- Almost no overburden and limited shielding from reactor core
- Intense and large R&D program based on SCDMS technology (TES):
  - **Full cryogenic active veto:** 25g Ge target detectors with 2.5 cm (4 Pi) active Ge with 200 eV threshold
    - Back. reduction about 10 —> **won't be part of science payload**
  - **Hybrid Ge detector:** with both low- and high-field regions for Luke-Neganov boost based discrimination
    - **ER/NR discrimination demonstrated at the few keVnr scale**
  - **Low threshold 100g sapphire detectors:**
    - Demonstrated 100 eVnr threshold on 100 g sapphire detector with position sensitivity —> **will be used in tower stack**

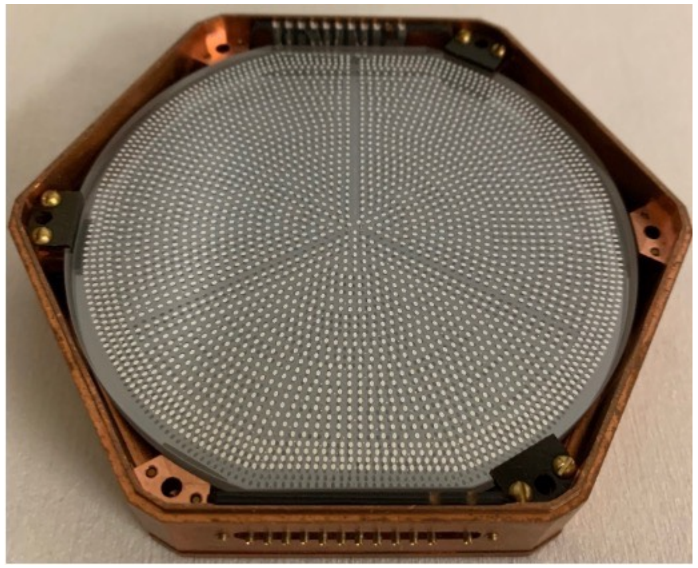




Full cryogenic active veto



Hybrid Ge detector

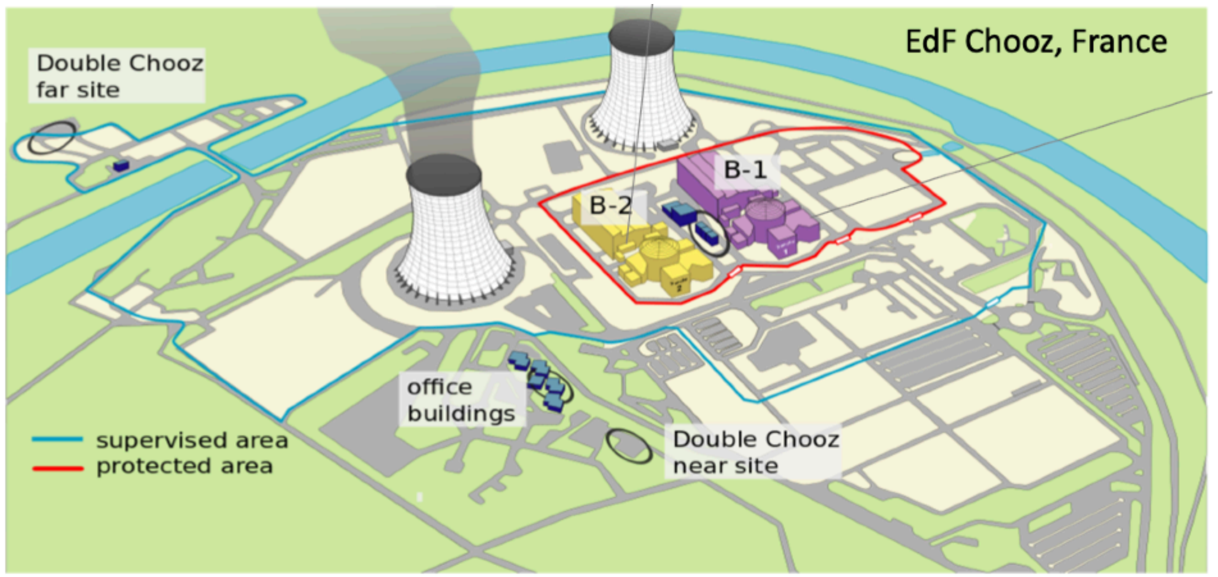


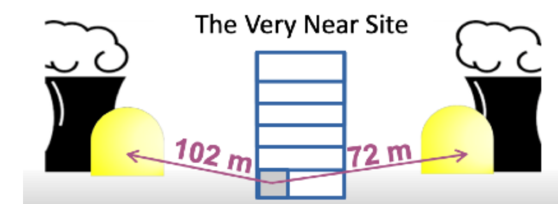
Low threshold 100g sapphire detectors

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

CENNS: *Cryogenic experiments — NUCLEUS*

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





- 2 x 4.25 GW_{th} nuclear power reactors
- New experimental site: the Very Near Site (VNS) is a 24m^2 room in an administrative building
- High average ν-flux*: $1.7 \cdot 10^{12}$ ν/(s cm^2)

* 80% full power: accounts for typical loading + refueling period

Target detectors

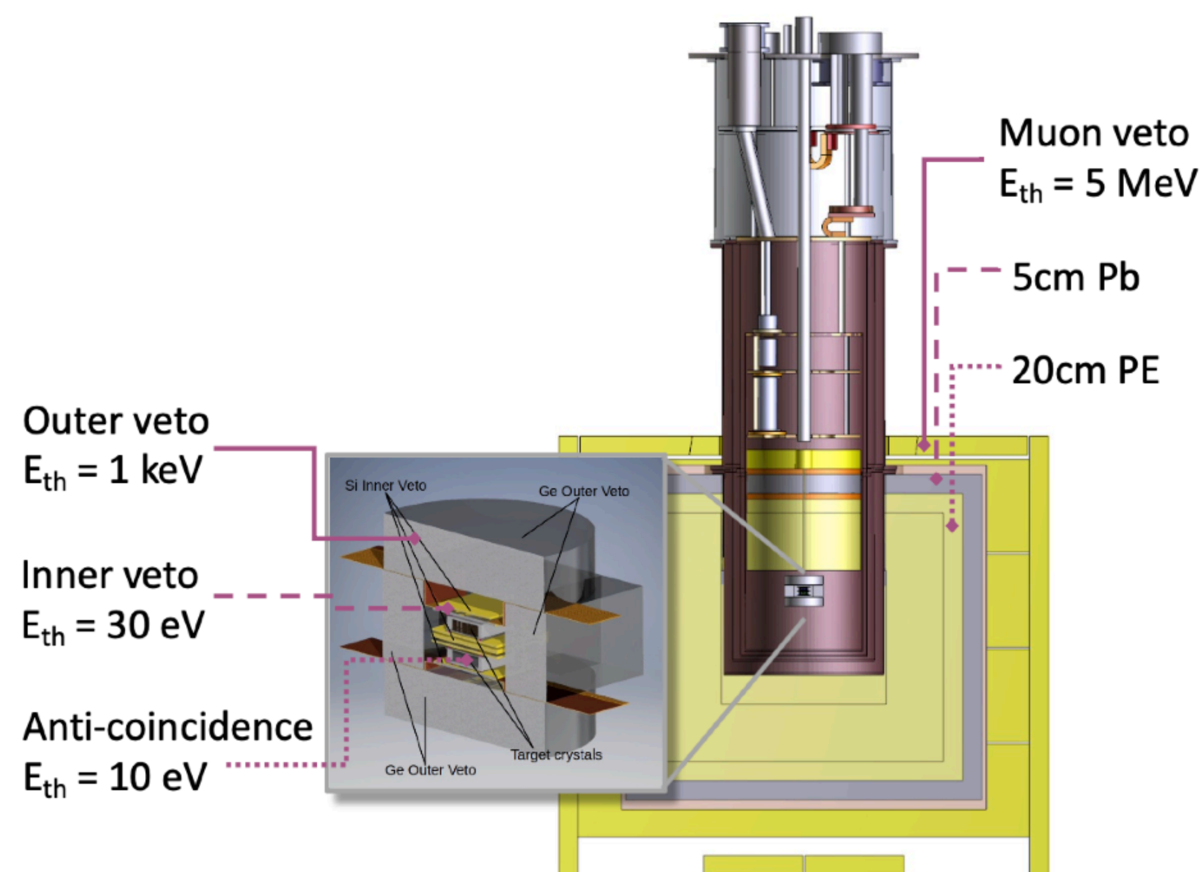
✓ $CaWO_4$ and Al_2O_3 crystals read-out with W-TES

✓ Based on CRESST technology

✓ Al_2O_3 prototype with threshold $E_{th} = (19.7 \pm 0.8)\ eV_{nr}$

✓ No reactor correlated background expected at VNS

- To reach background goal, the shielding needs to be optimized for VNS:
  - Compact passive shielding with footprint of ~1 m^2
  - At 3 m.w.e, a muon veto with ε > 99% is needed

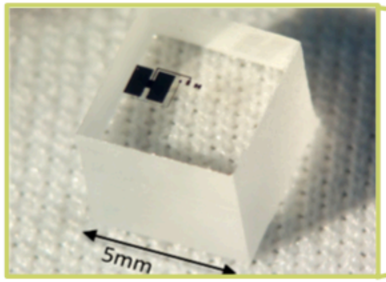


Adapted from V. Wagner, TAUP2021

CENNS: *Cryogenic experiments — NUCLEUS*

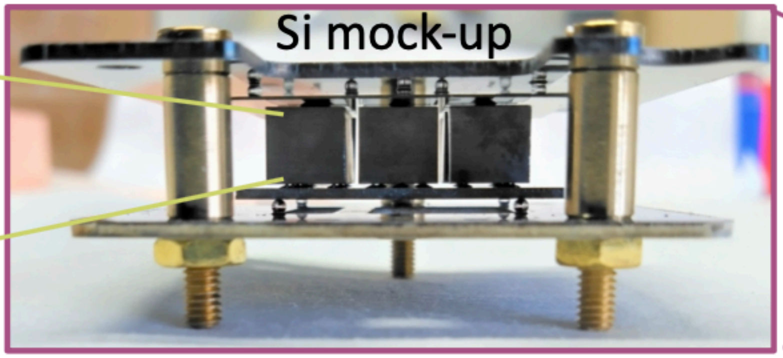
Very innovative active cryogenic detectors holding system designed for surface, gamma and neutron background rejection

Target crystals:
Two 3x3 arrays with a total mass of 6g ($CaWO_4$) + 4g (Al_2O_3)



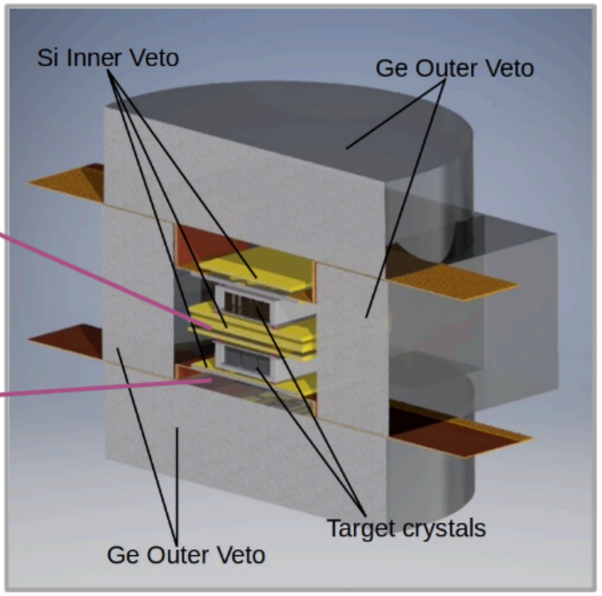
- ✓ Production of detector arrays
- Next steps: testing & cutting

Inner veto: TES-instrumented holder
to reject surface backgrounds and holder-related events



- ✓ Mechanical and thermal test with mock-up
- Next steps:
  - Replacement of 2nd wafer with *beaker* for a 4π-coverage
  - detector operation in inner veto

Germanium outer veto
for active γ/n background rejection

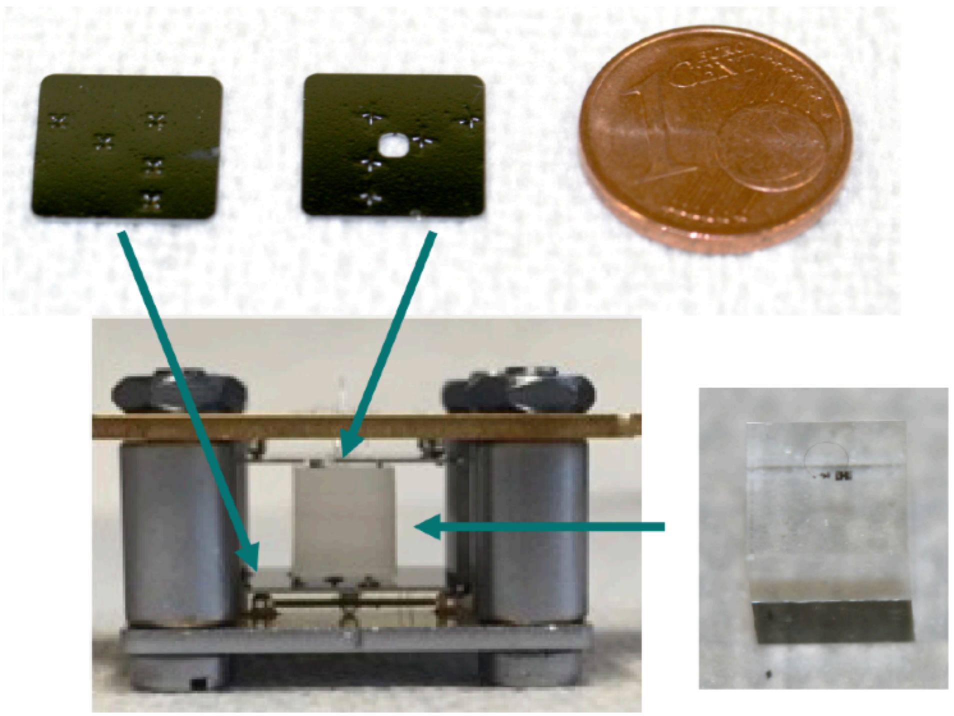


- ✓ Design finished
- ✓ Ongoing prototype test

Adapted from V. Wagner, TAUP2021

CENNS: *Cryogenic experiments — NUCLEUS*

Cryogenic Inner Veto



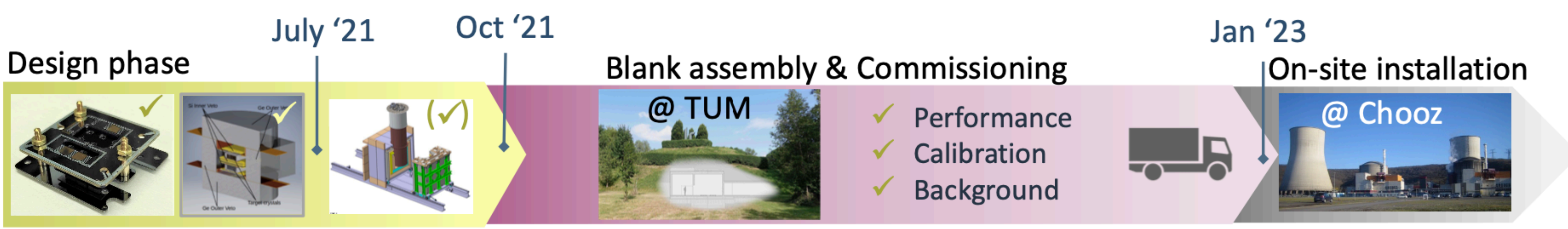
- First results with a single target crystal for proof of concept (from LTD 2019)
- Demonstration of highly efficient background rejection with partial coverage
- Veto threshold demonstrated to be <100 eV
- Some phonon leakage between target and veto detectors observed
- **Next step: Demonstration with full payload**

Cryogenic Outer Veto

- First results with a partial 2.5 cm thick top and bottom Ge detectors with ionisation readout with ~1 keVee (RMS) baseline resolution (not optimised yet)
- Target detector: 50g Li2WO4 detector from BASKET R&D program
- Demonstration of the feasibility to use anti coincidence despite of above ground operation
- Preliminary background reduction of 20% (due to partial coverage) matches expectations !
- **Next steps: Add side Ge crystals for 4-Pi coverage**

CENNS: *Cryogenic experiments — NUCLEUS*

An exciting research program with first CENNS results from NuCLEUS to be expected in the next few years !

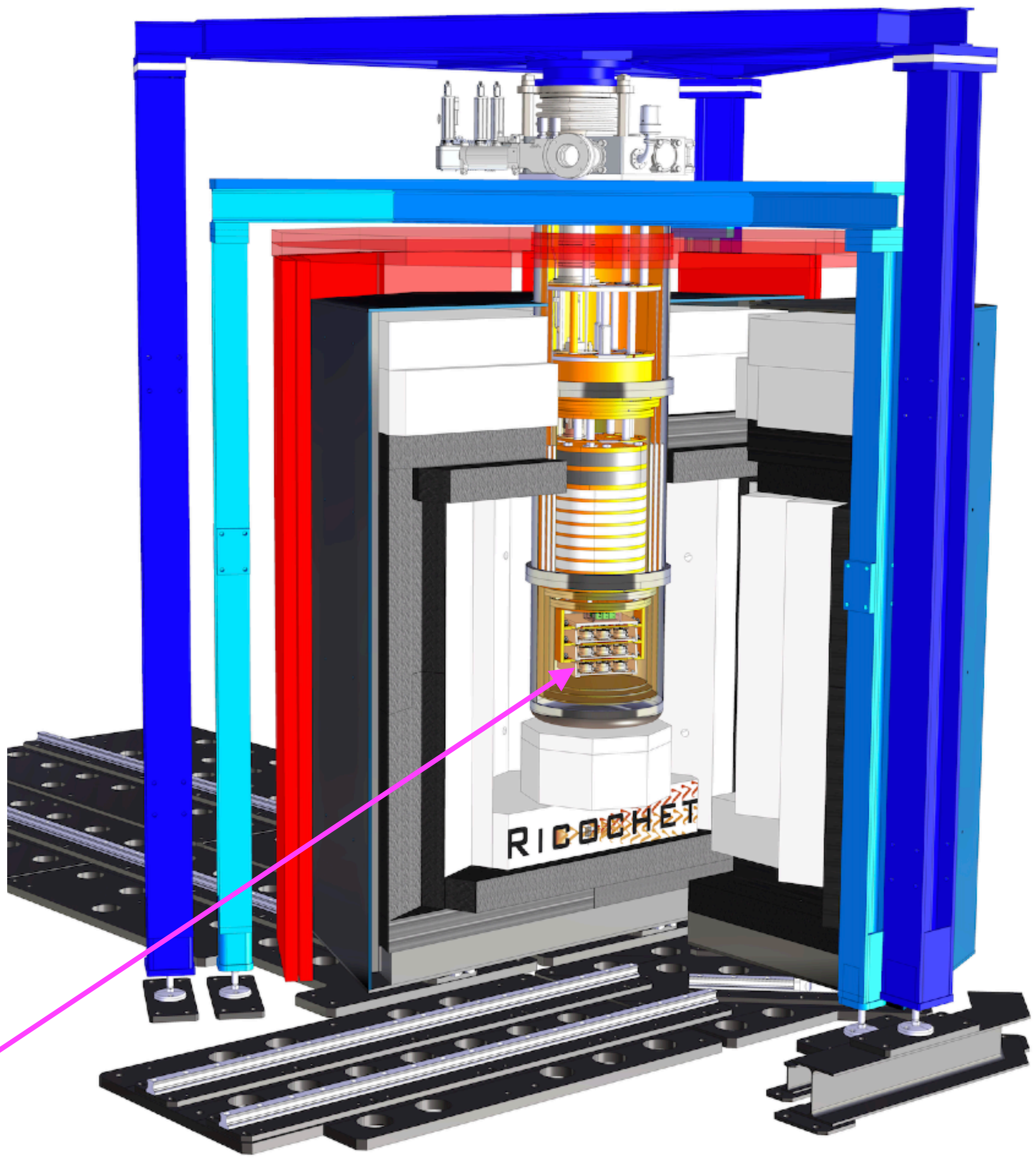


Adapted from V. Wagner, TAUP2021

CENNS: *Cryogenic experiments — RICOCHET*

C. Augier *et al.*, arXiv:2111.06745

- Ricochet will be installed at the ILL-H7 *(previously used by the STEREO experiment)*
- 58 MW nominal thermal power
  - 8.8m from core: 12.8 evts/day/kg *($1.2x10^{12}$ ν/s/cm²)*
- 3 to 4 cycles per year: ***excellent ON/OFF modulation to subtract uncorrelated backgrounds***
- Challenging environment: reactogenic backgrounds, vibrations, and intense magnetic fields
- Significant overburden (~15 m.w.e) to reduce cosmics
- Background simulation studies based on onsite characterization suggest that the **science potential at ILL-H7 is excellent**
- Expect a total background budget of about 100 and 10 evt/kg/day/keV for gamma and neutron induced events respectively
- Pushing for particle identification down to 100 eV with two technologies:
  - Q-Array (Zn pulse shape discrimination)
  - **CryoCube (Ge/Si ionization + heat measurement)**



Inner shielding:
- PE/Cu: 30 cm
- Pb/Cu: 15 cm
- Cryogenic Muon Veto
- Mu-Metal

Outer shielding:
- PE: 35 cm
- Pb: 20 cm
- Muon veto
- Soft iron

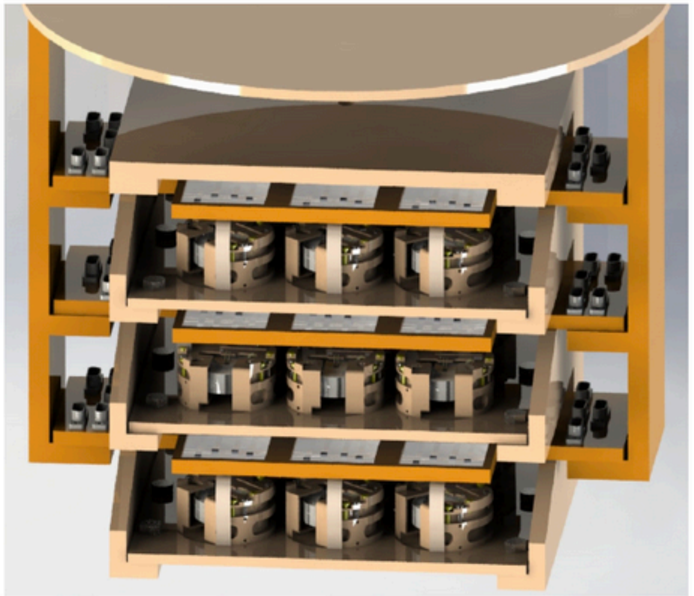
CENNS: *Cryogenic experiments — RICOCHET*

3x3x3 CryoCube

1kg payload

integrated HEMT readout

To be delivered starting mid-2022

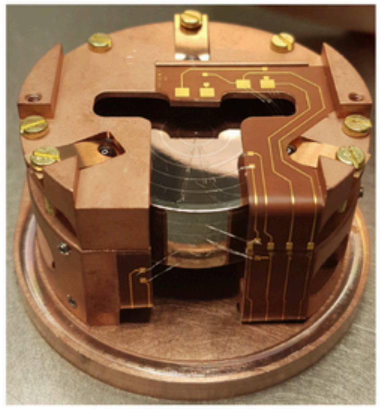


Alternating 15mK/1K layers

Misiak PhD Thesis

Salagnac & al: arXiv:2111.12438

27 x 38g Ge crystals
with NTDs and electrodes
2 optimized designs (COMSOL)
Ongoing validation of the performances.



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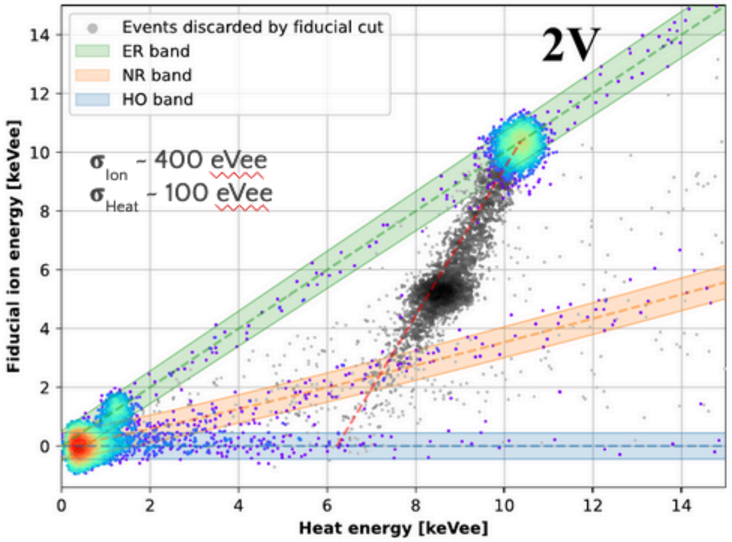
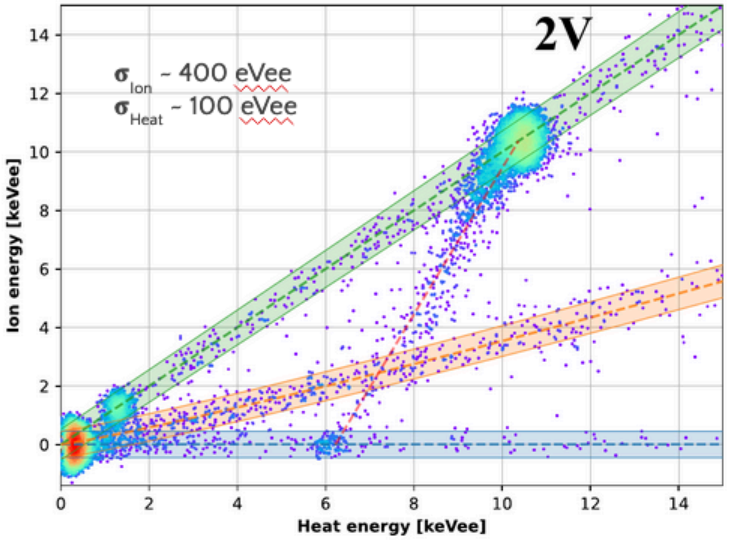
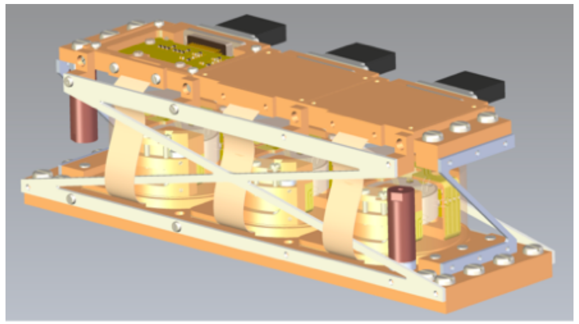


Using FET electronics

PL 38



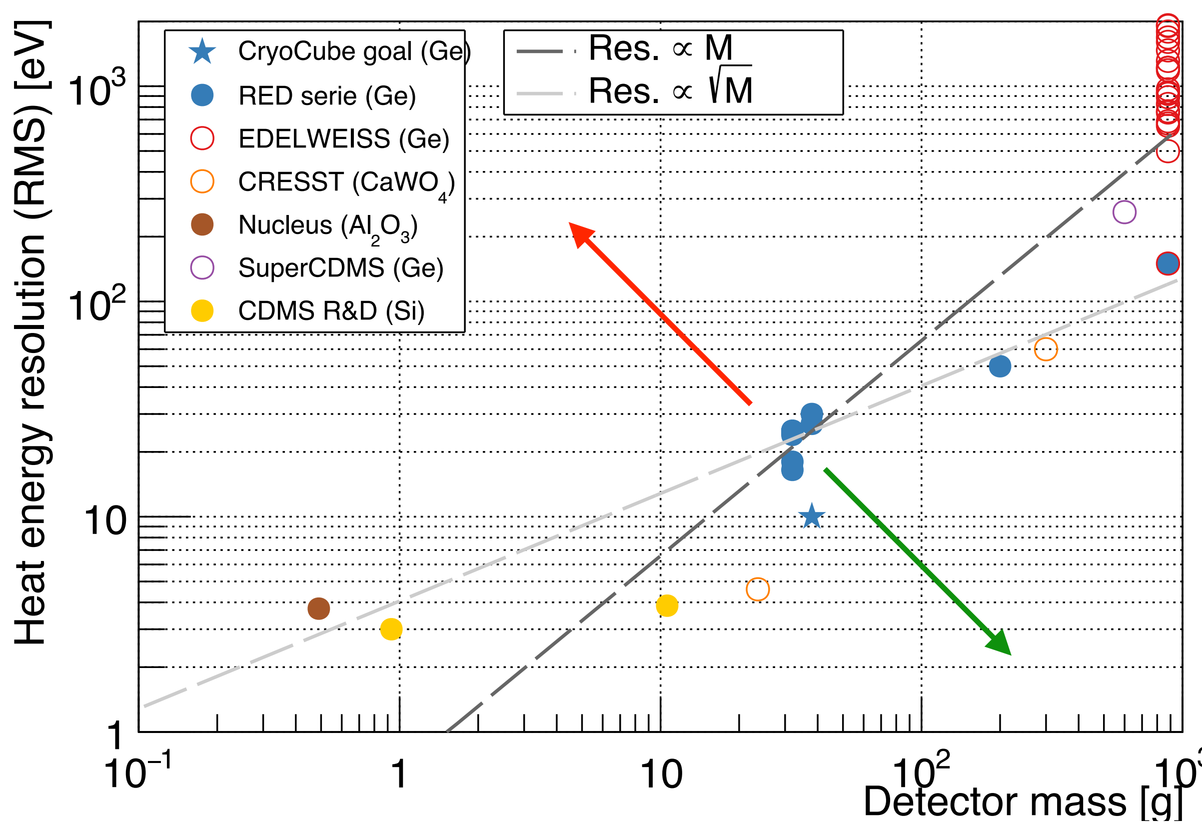


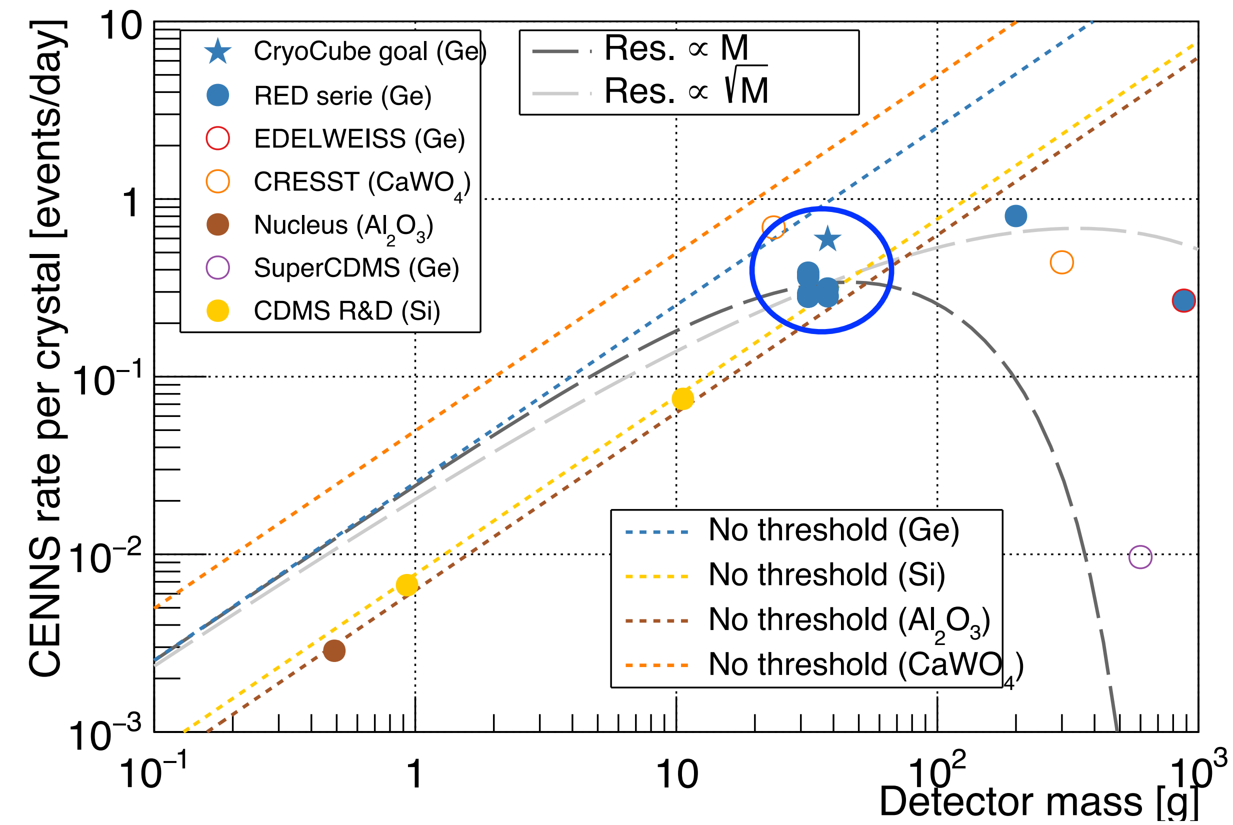
- **CryoCube pathfinder:** MiniCryoCube with 3 detectors and their HEMT electronics
- Validate the thermal decoupling between the 1K and 10mK stages (5cm away)
- Validate the low-capacitance cabling and E&M performance
- Tests will start in April-May 2022 and pave the way to the CryoCube final technological solutions

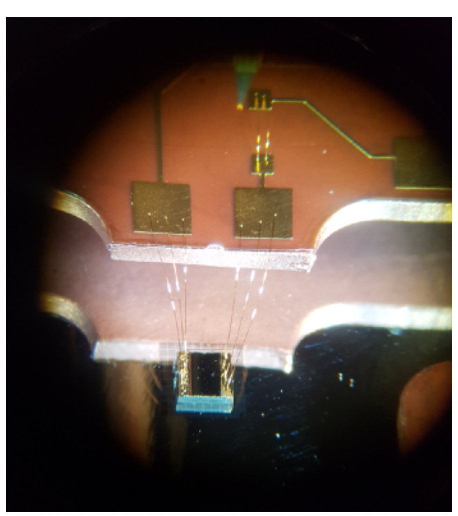
CENNS: *Cryogenic experiments — RICOCHET*

Salagnac & al: arXiv:2111.12438

Threshold defined for all experiments as 5σ

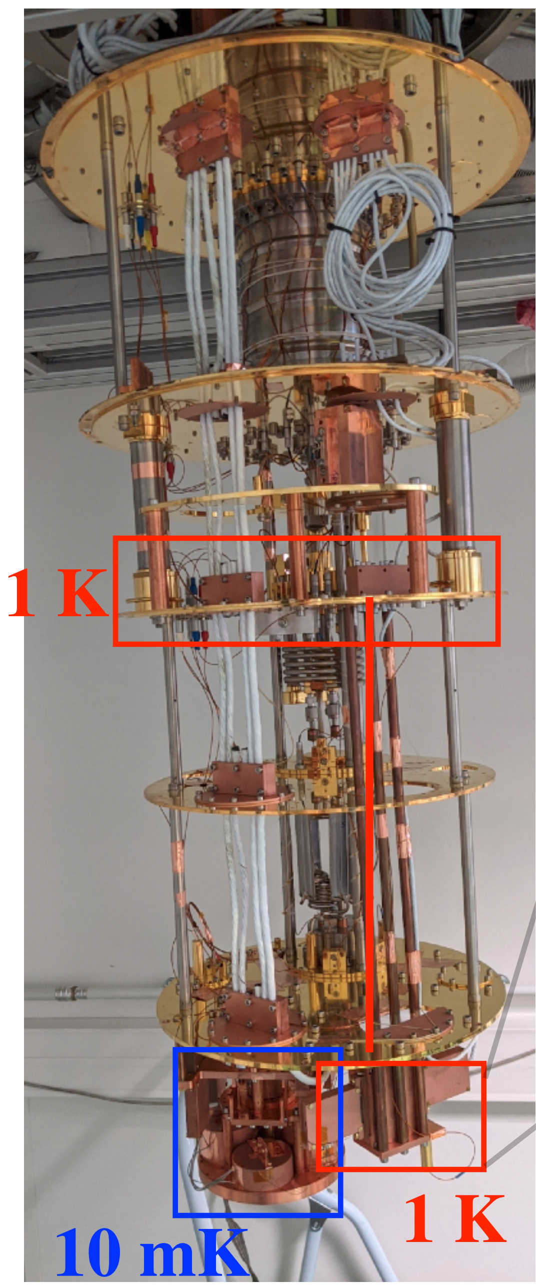




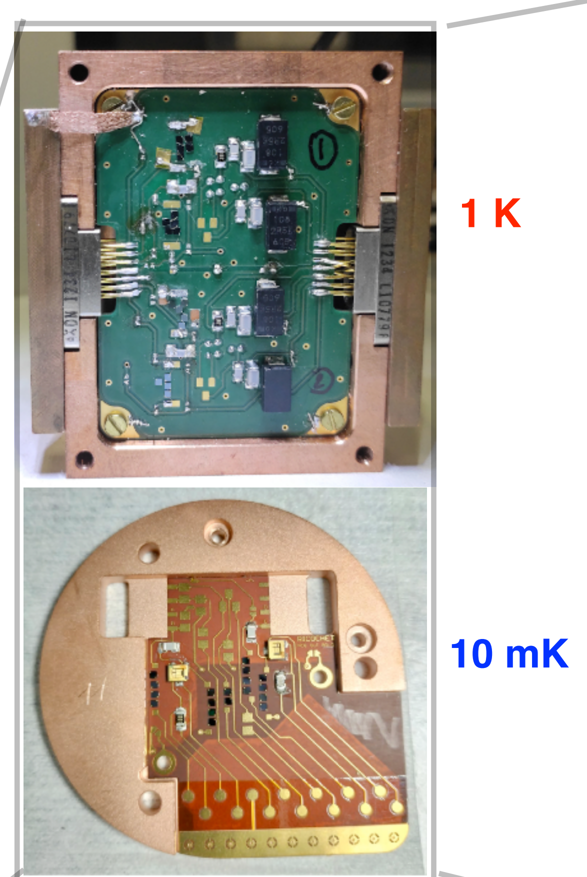


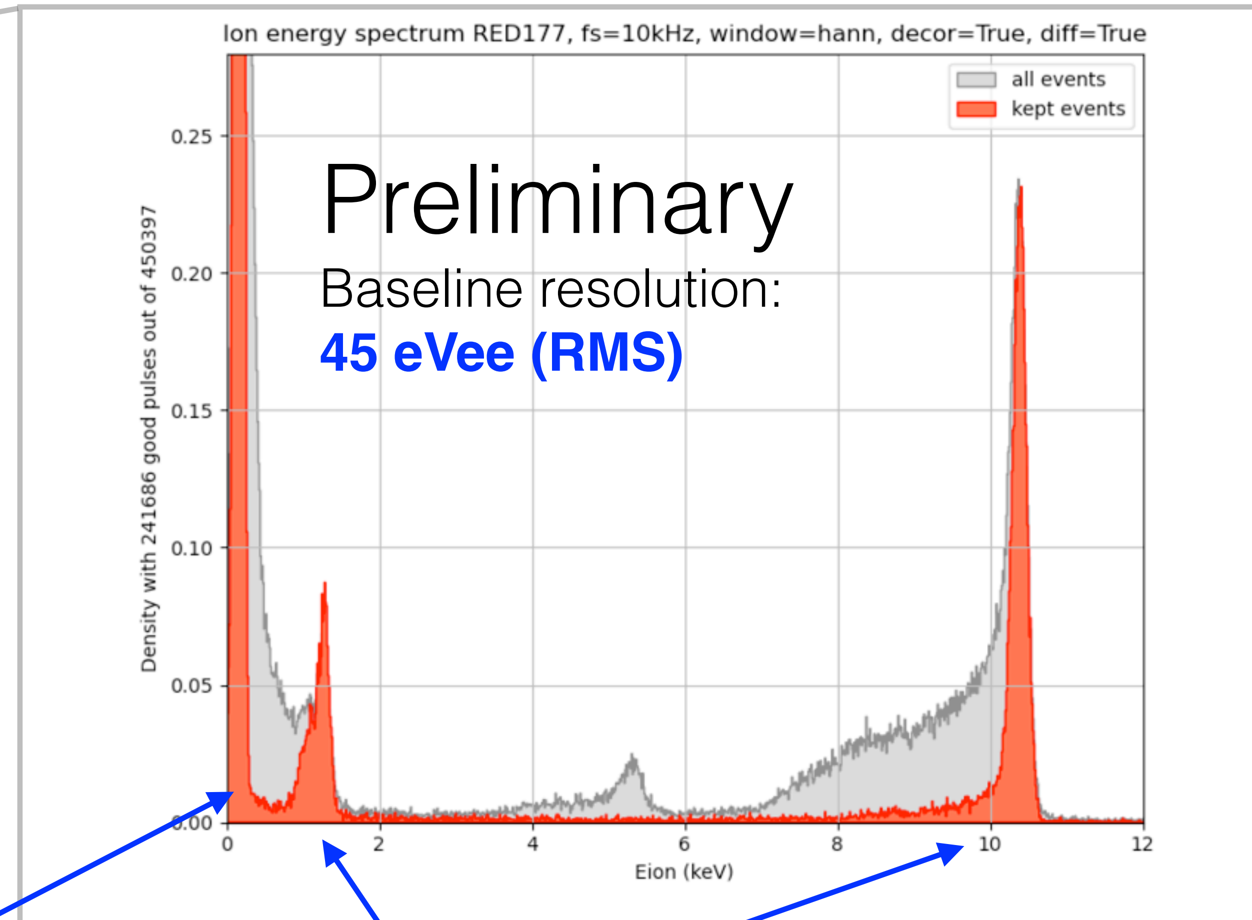
- Achieved an averaged 22-30 eV (RMS) heat resolution on 10 Ge detectors (38 g) with JFET electronics with **a new holder design insensitive to PT-induced vibrations**
- With respect to the community our detectors achieve among the **best resolution-to-mass ratio** and exhibit the **largest CENNS signal strength per crystal** from above ground operation of about 0.3 evt/day (goal 0.6 evt/day) 8.8m away from the ILL reactor.

CENNS: *Cryogenic experiments — RICOCHET*



High Electron Mobility Transistor
[Baulieu & al: arXiv:2111.10308]





Ion. only threshold: 250 eVee

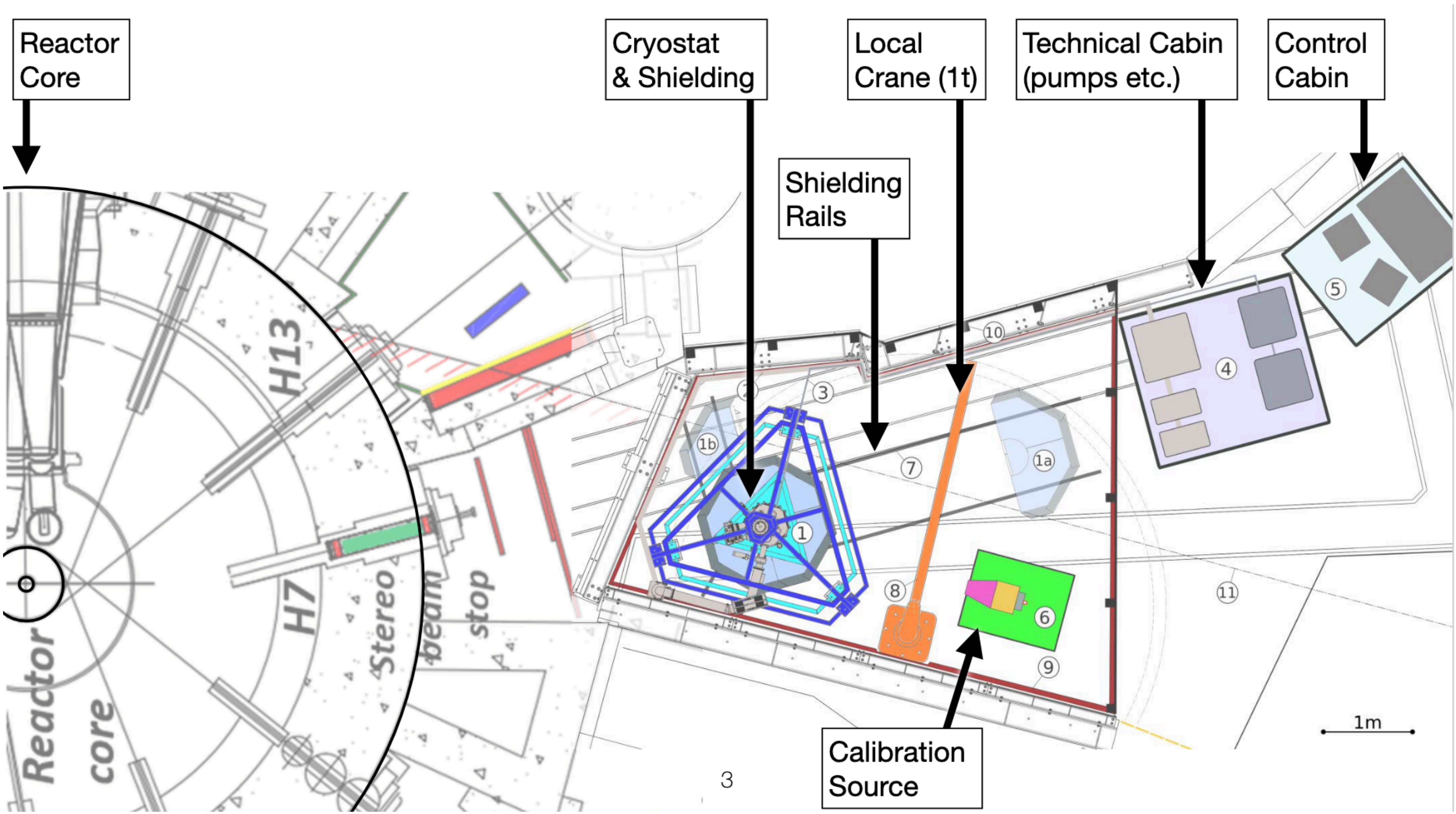
1.3 keV and **10.37 keV** calibration lines

Next step: 100 eVee (CryoCube goal)

- **Already competitive with best HPGe experiments, but with heat readout in addition !**
- Factor of two improvement expected from reduced capacitance cabling and active resets
- HEMT dissipation can be decreased from 100 uW to 3 uW —> **Improve scalability !**

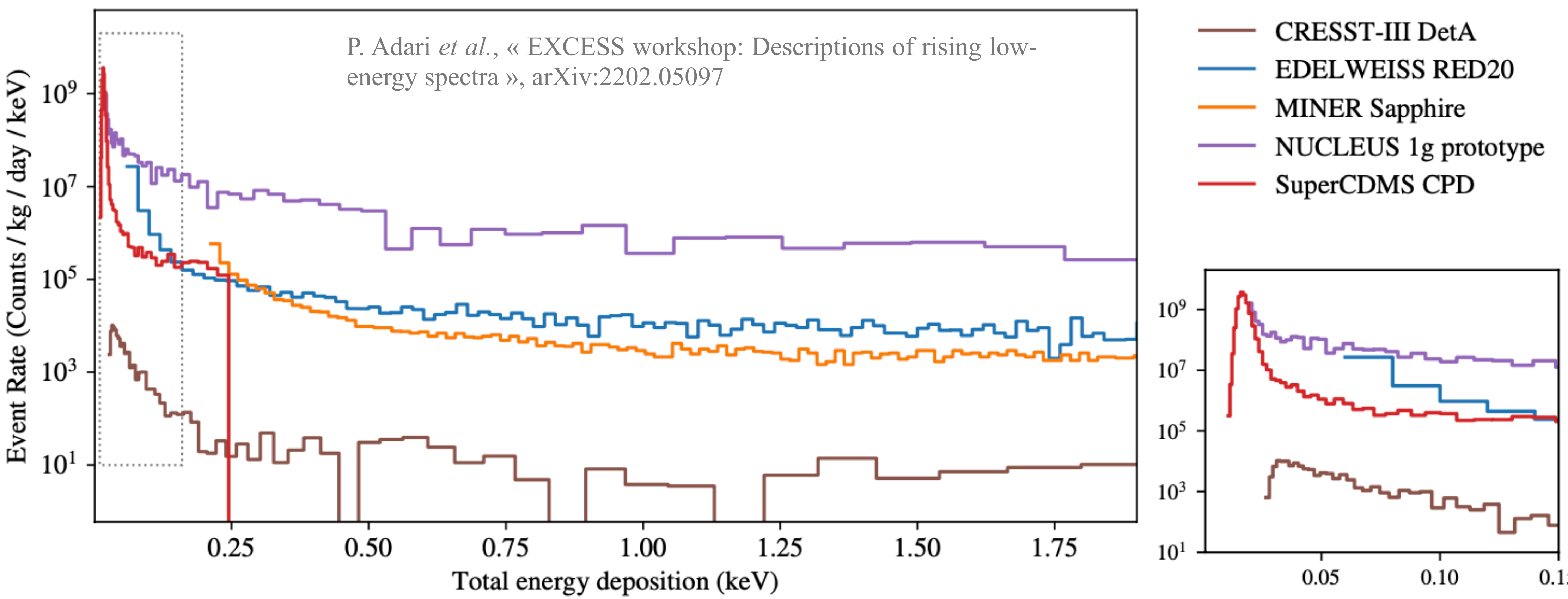
Double heat and ion measurements in the coming months for a first demonstration of a sub-keV ER/NR discrimination

CENNS: *Cryogenic experiments — RICOCHET*



- **Ricochet integration at ILL planned over 2022/2023**

CENNS: *Cryogenic experiments — Low-E excess !*



- Currently, all cryogenic experiments which have reached sub-100 eV thresholds are seeing such an excess
- The lowest excess has been observed by CRESST DetA detector but appears to be an outlier !
- This excess is nowadays fully acknowledge by the international community and a dedicated workshop has been created to exchange ideas and results with experimentalists and theorists (https://indico.cern.ch/event/1013203/)
- Characteristics: time dependent, non-ionising, independent of sites, dependence with holding techniques (?)
- **Particle identification, or any discrimination strategy, could be highly beneficial !**

CENNS: *Cryogenic experiments — Outlook*

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

A very exciting process that will be explored at the lowest energies with MINER, NUCLEUS and RICOCHET in the coming few years:

- 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, …)*
- Required for upcoming precision neutrino oscillation measurements *(Non Standard Interactions)*
- Astrophysics wise: drives supernovae dynamics and the neutrino floor to DM direct searches

One can appreciate the challenge of measuring CENNS at reactors in computing the DM direct detection parallel

- Measuring CENNS at reactors is equivalent at searching for a 2.7 GeV WIMP with a corresponding cross section that depends on the neutrino flux
- We need to better than current DM experiment underground BUT from above ground !
- **Also suggests that future CENNS experiments will tomorrow become leading DM experiments**