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

**J. Billard**
Institut de Physique Nucléaire de Lyon / CNRS / Université Lyon 1

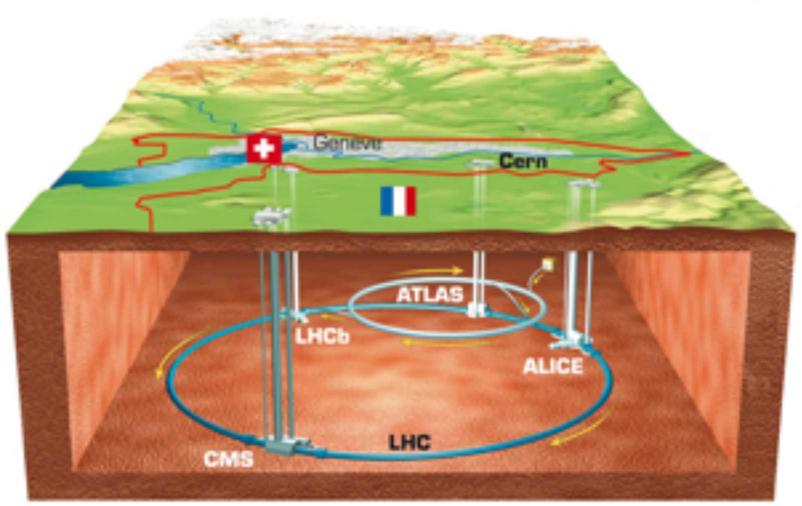
IPPP, May 16th, 2019

# Introduction

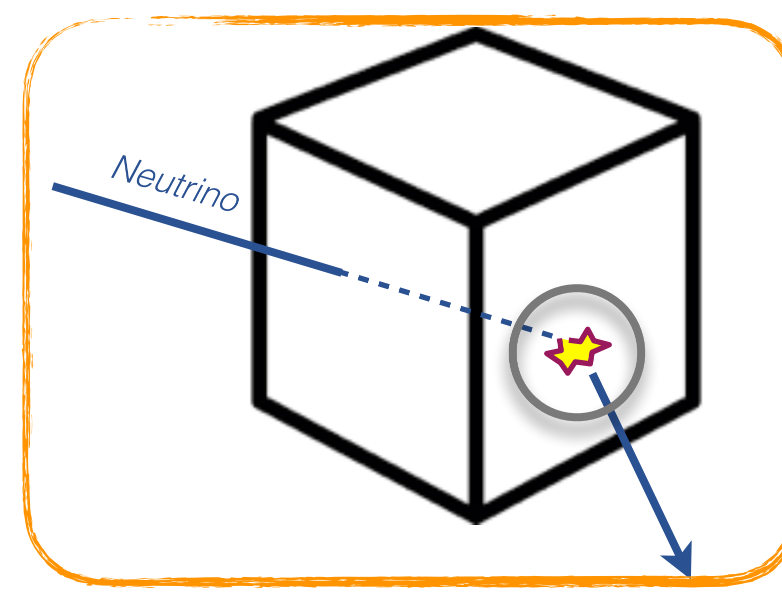
***Despite the brilliant success of***
***the Standard Model of Particle Physics***
***it remains incomplete***

## ***New Physics***

*HIGH ENERGY FRONTIER*

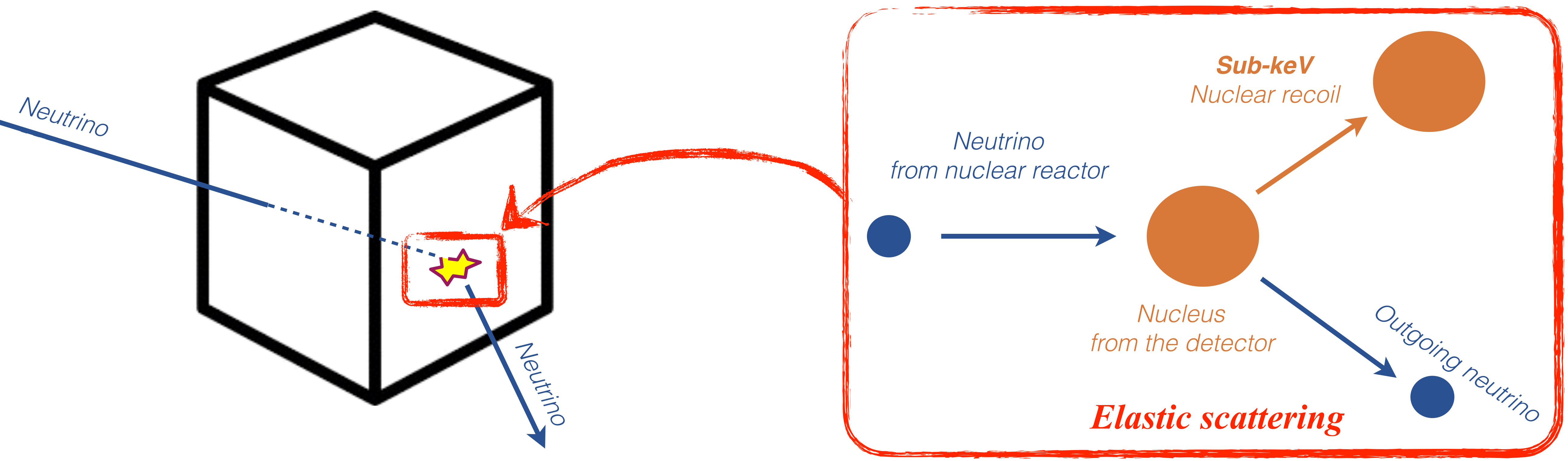



***LOW ENERGY FRONTIER***



# CEvNS: The process

## **C**oherent **E**lastic **N**eutrino-**N**ucleus **S**cattering (CENNS)



# CEvNS: The process

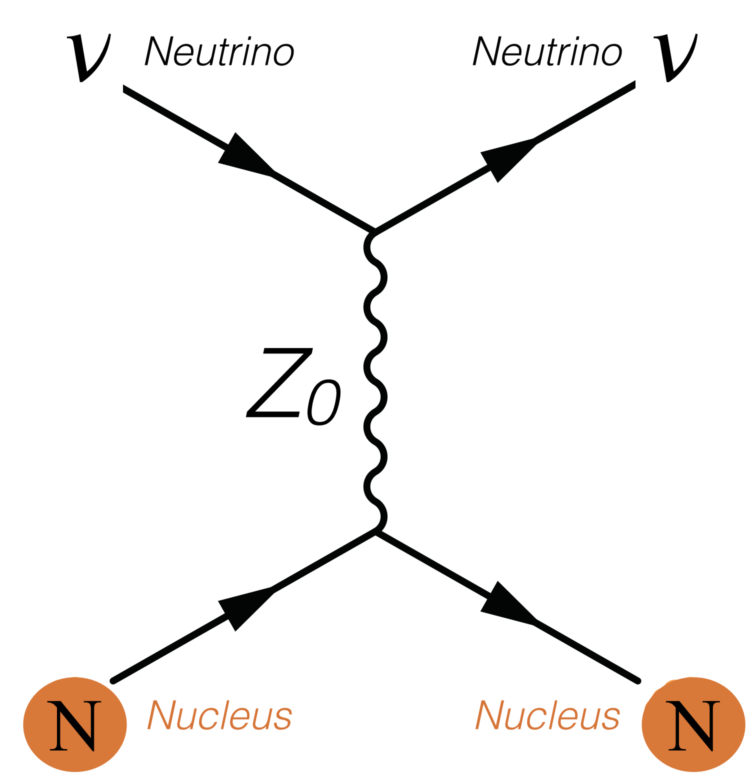
D. Z. Freedman, PRD 9 (5) 1974

## Coherent Elastic Neutrino-Nucleus Scattering (CENNS)

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

- $\sigma$: Cross Section
- $E_r$: Recoil Energy
- $E_\nu$: Neutrino Energy
- $G_f$: Fermi Constant
- $Q_W$: Weak Charge
- $m_N$: Atomic Mass

- Neutrino scatters coherently off all Nucleons
  —> ***Cross section promotional to $N^2$***
- Initial and final states must be identical
  —> ***Neutral Current elastic scattering***
- Nucleons must recoil in phase
  —> ***Low momentum transfer (qR<1)***




***Neutral current***

No flavor-specific terms!!!
Same rate for $\nu_e$, $\nu_\mu$, and $\nu_\tau$

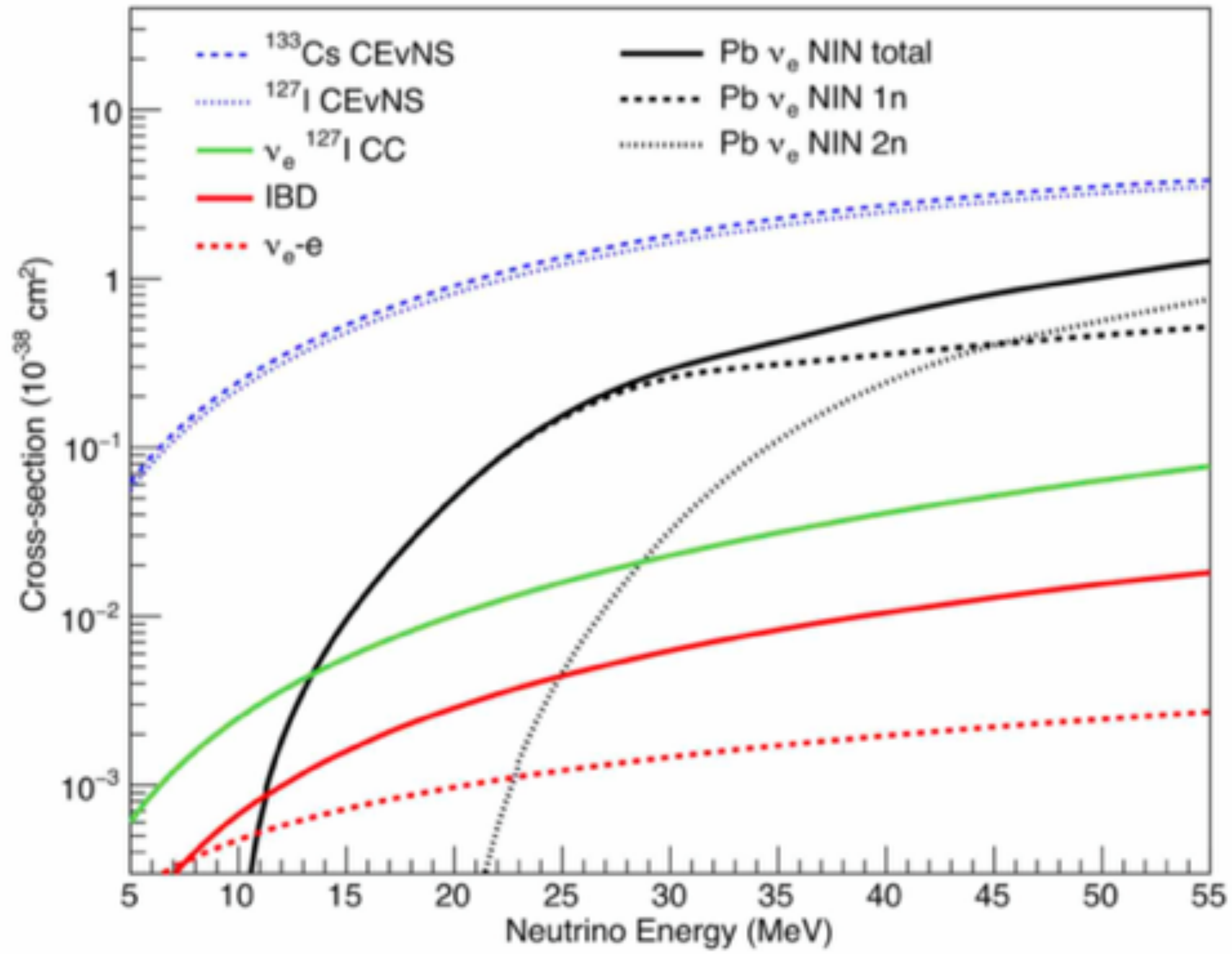
# CEvNS: The process

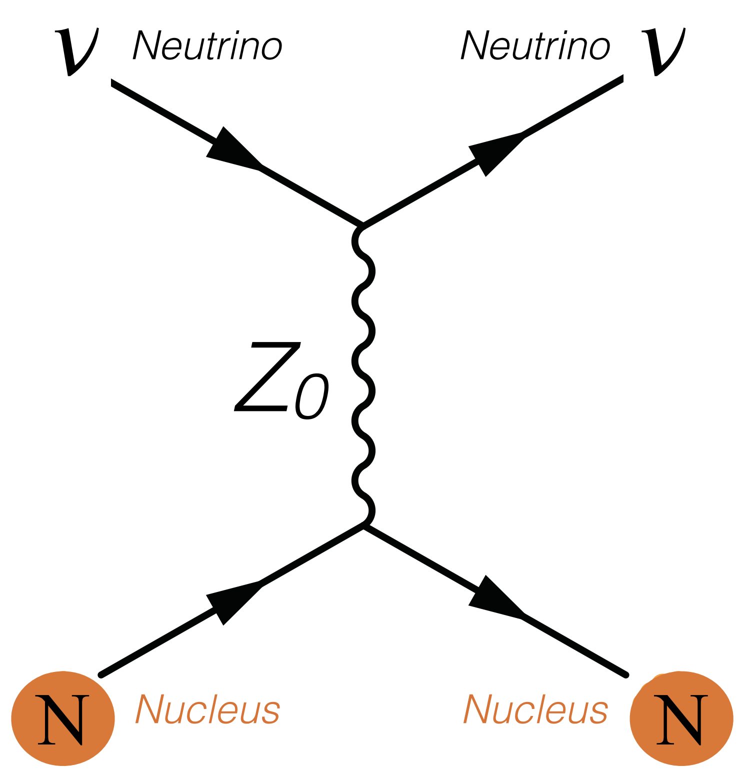
D. Z. Freedman, PRD 9 (5) 1974

## **C**oherent **E**lastic **N**eutrino-**N**ucleus **S**cattering (CENNS)

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

D. Akimov et al., Science 2017




- Largest neutrino cross section at low energies by few orders of magnitude:
  - *From ton-scale experiments to kg-scale ones !*
- No energy threshold

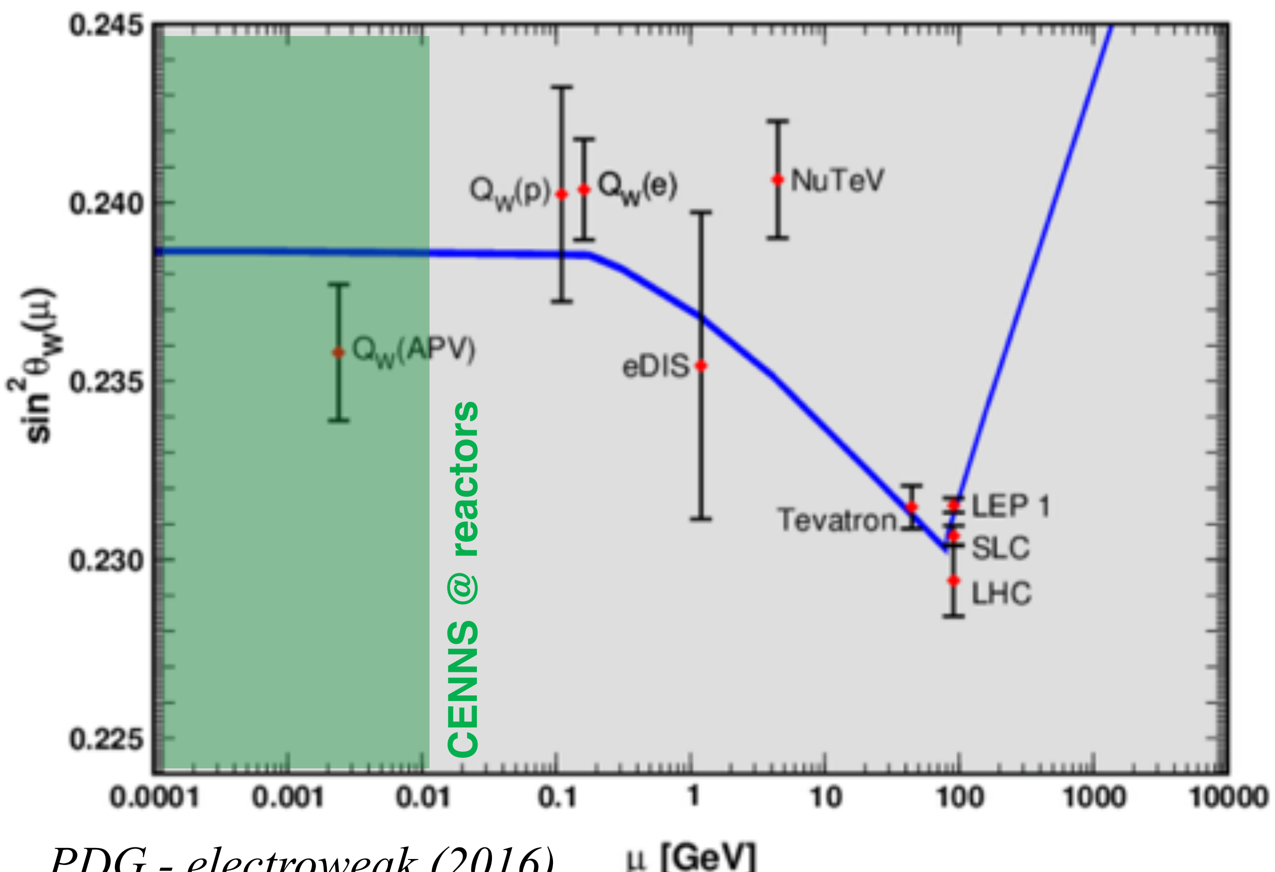
# CEvNS: The process

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

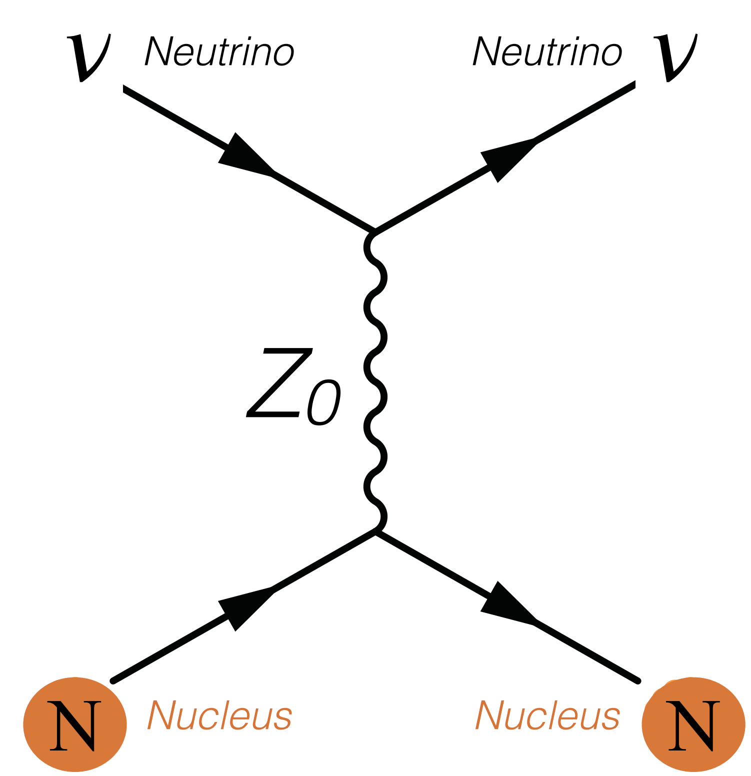
## **C**oherent **E**lastic **N**eutrino-**N**ucleus **S**cattering (CENNS)

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

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



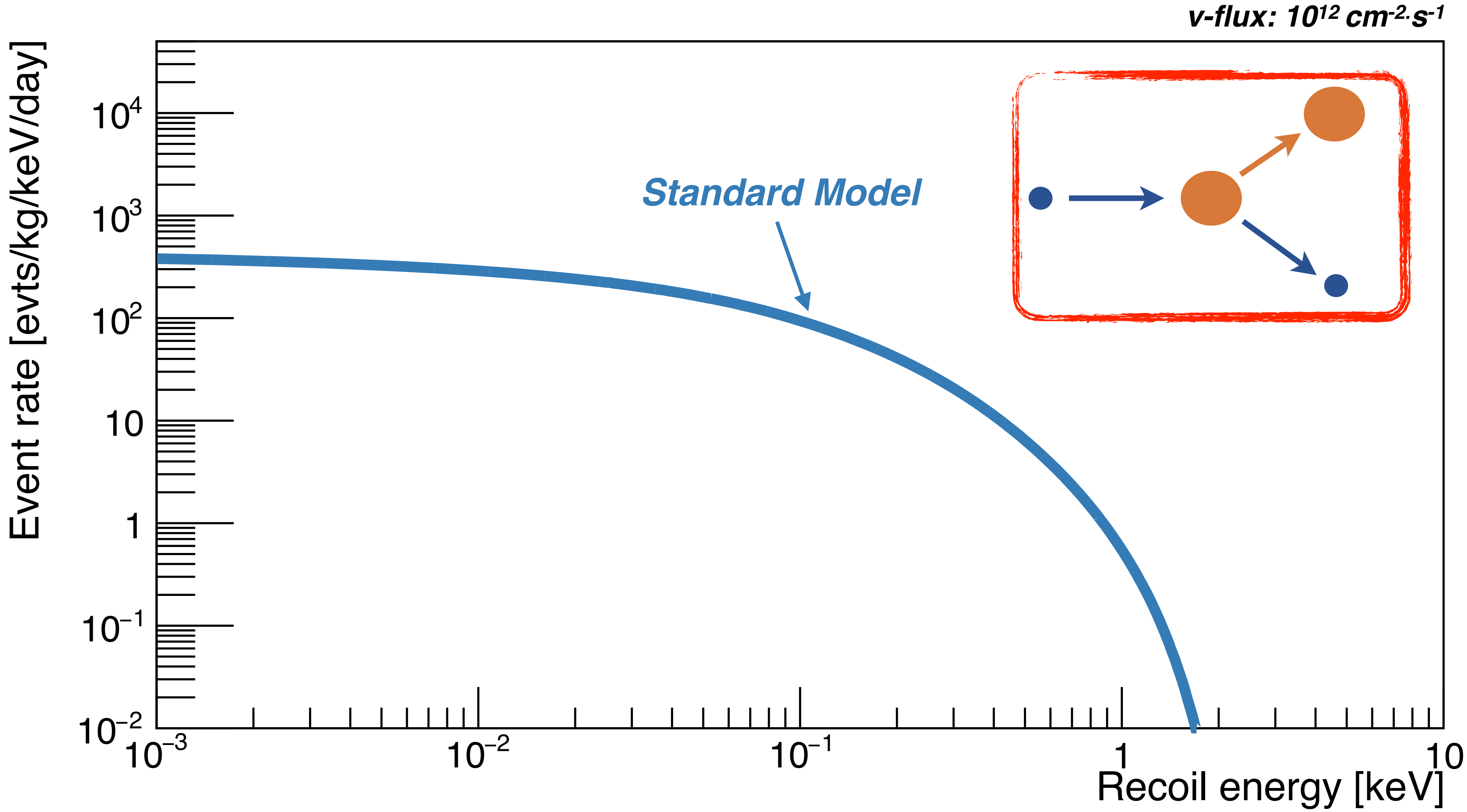

*PDG - electroweak (2016)*




- Need a %-level measurement to be competitive with other experiments
- Will probe the running of the weak mixing angle down to the lowest momentum transfer ***where new physics may arise***

# CEvNS: The process

*Recoil energy distribution*




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

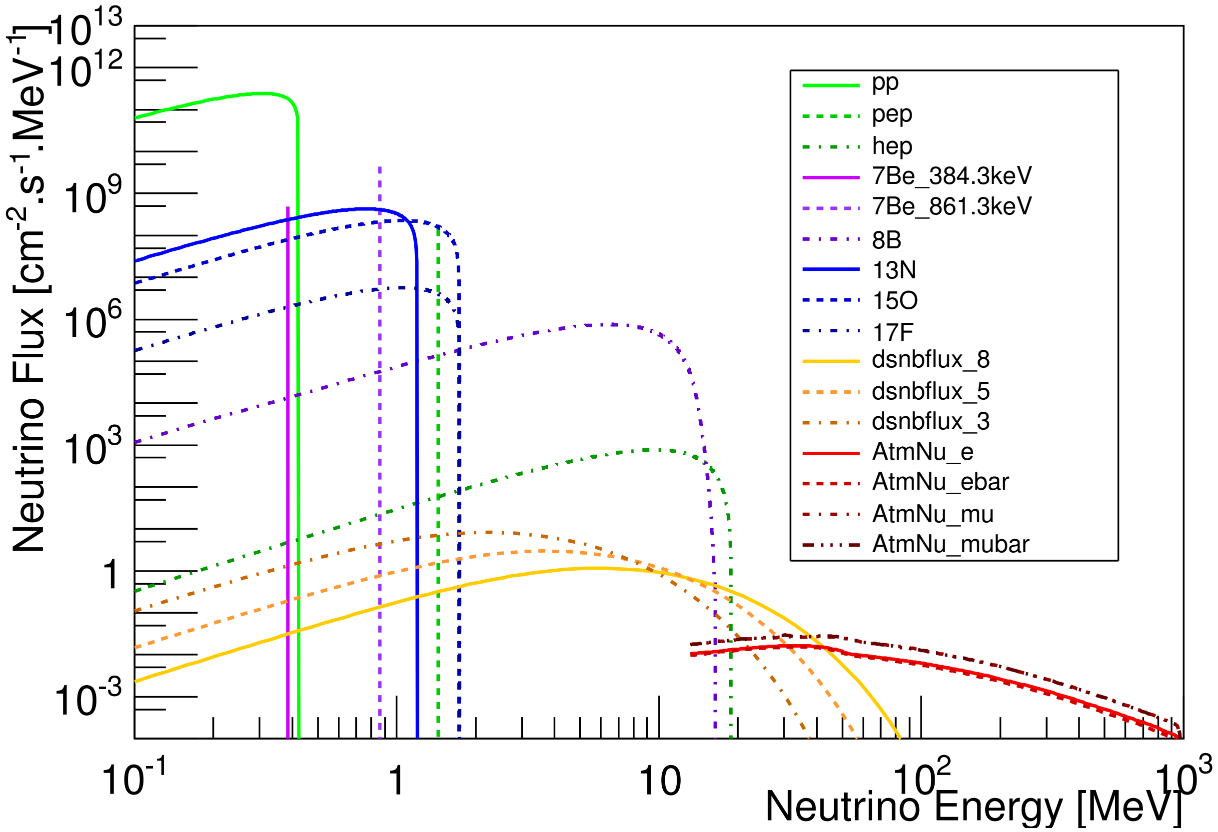
*We expect a few tens of events per day and per kg of detector material*

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

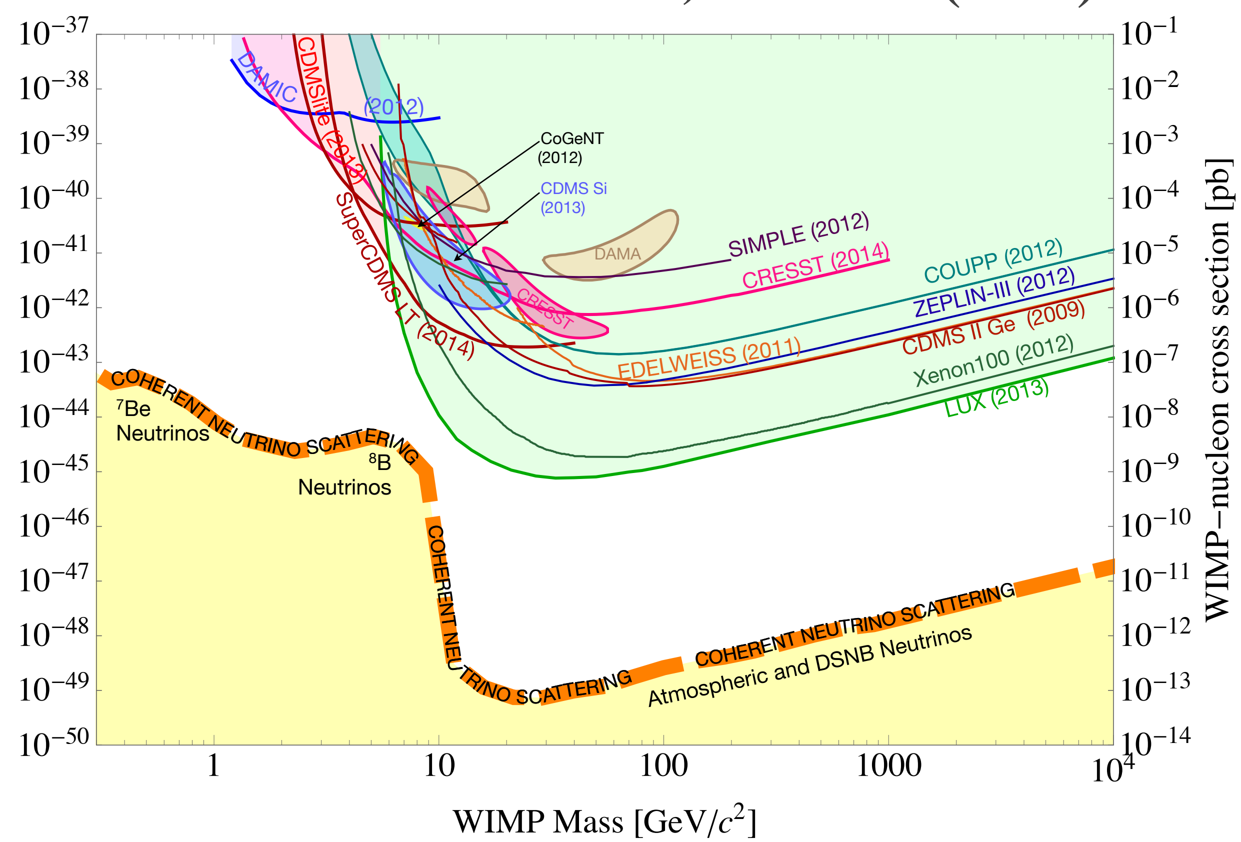
# CEvNS: Neutrino sources

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)

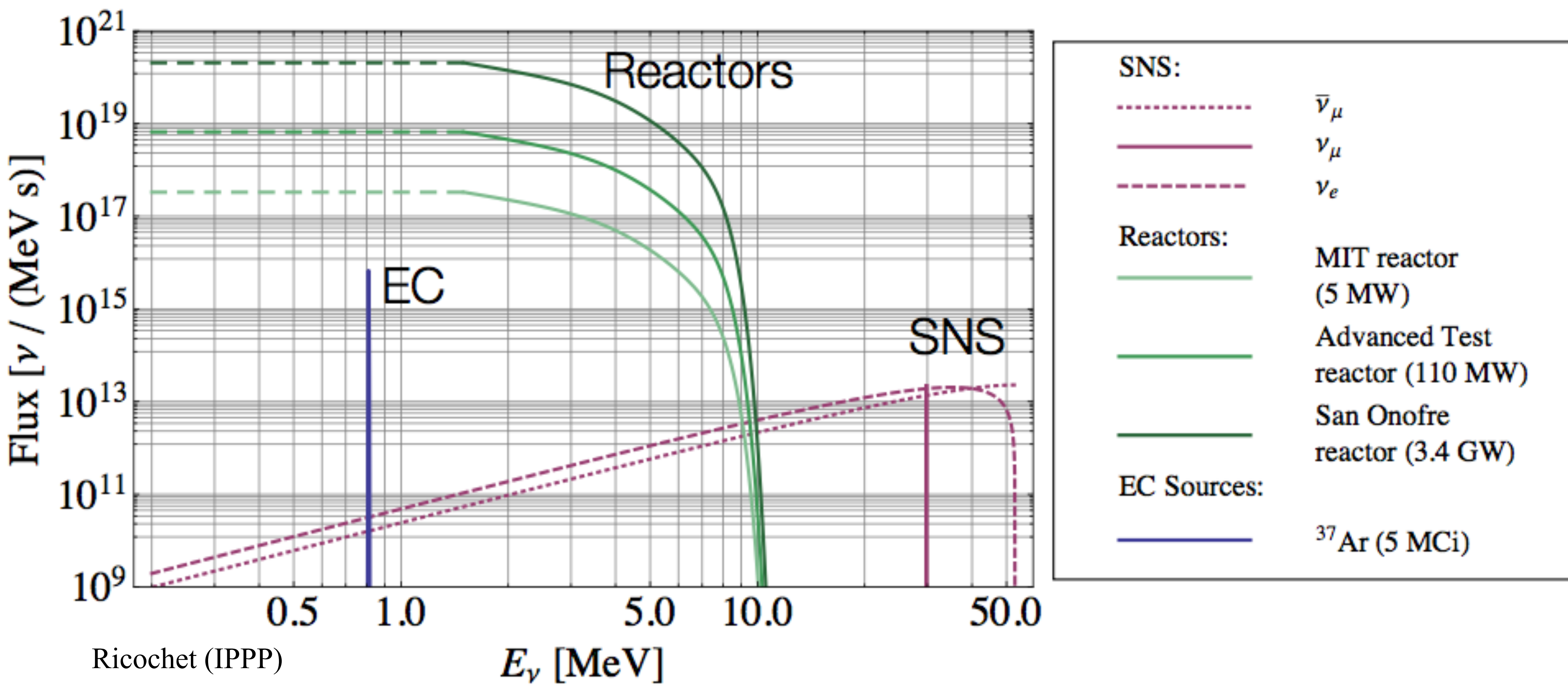



- Cosmic neutrinos will inevitably become the ultimate background to direct detection of Dark Matter
- Calls for reduced uncertainties on the CENNS process to lower the neutrino floor

# CEvNS: Neutrino sources

4 sources to consider:

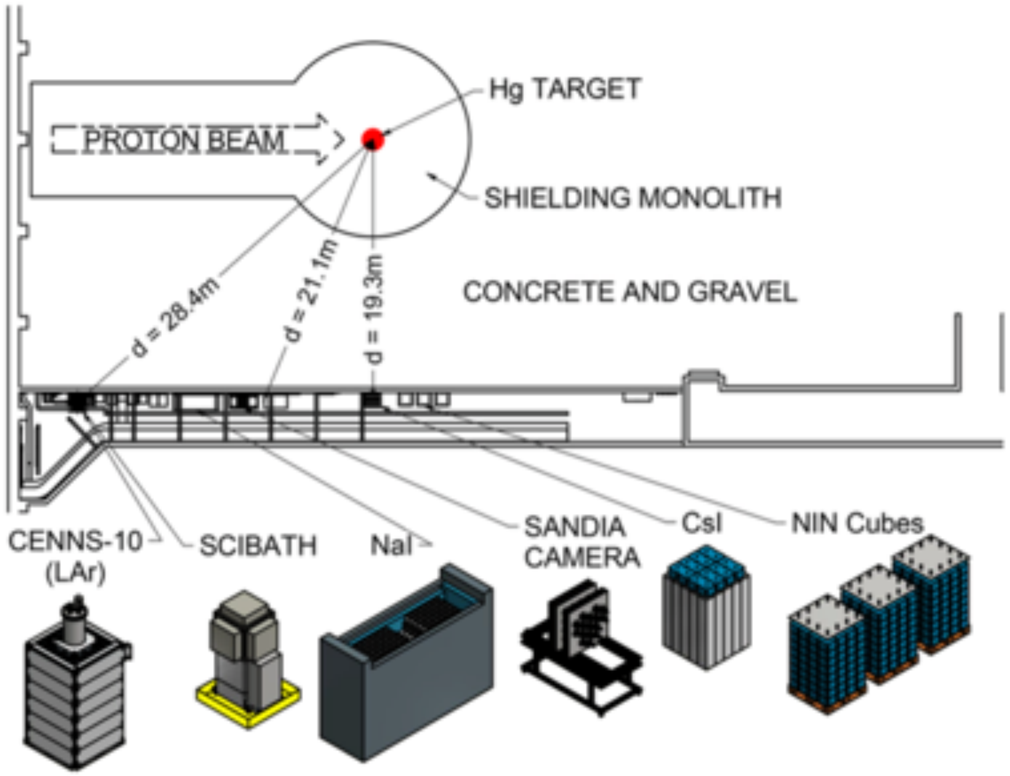
- Cosmic neutrinos: Solar, atmospheric and DSNB
- Electron-capture sources
- Reactors
- Pion Decay-at-rest source (SNS)

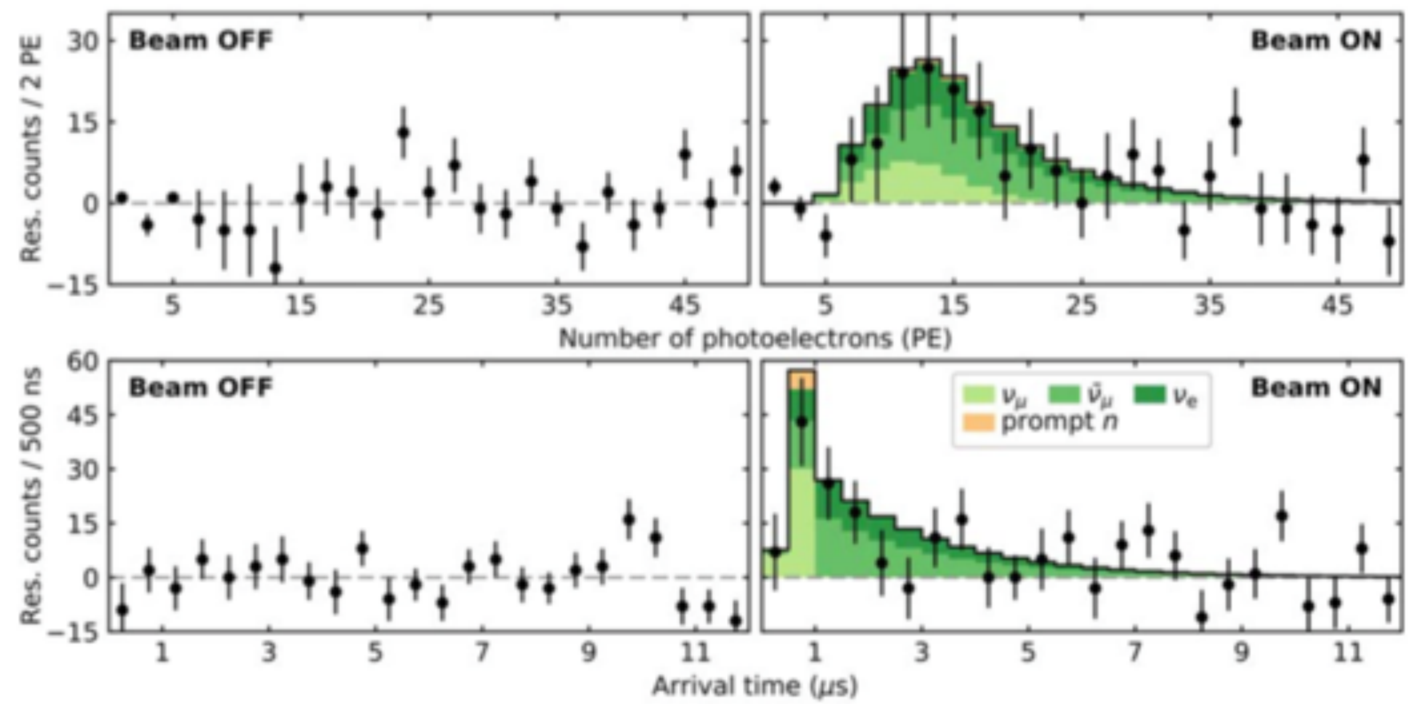


# CEvNS: The first detection

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

**<u>Change of paradigm:</u> from discovery to a precision measurement @ low-energy**

# CEvNS: @ reactors

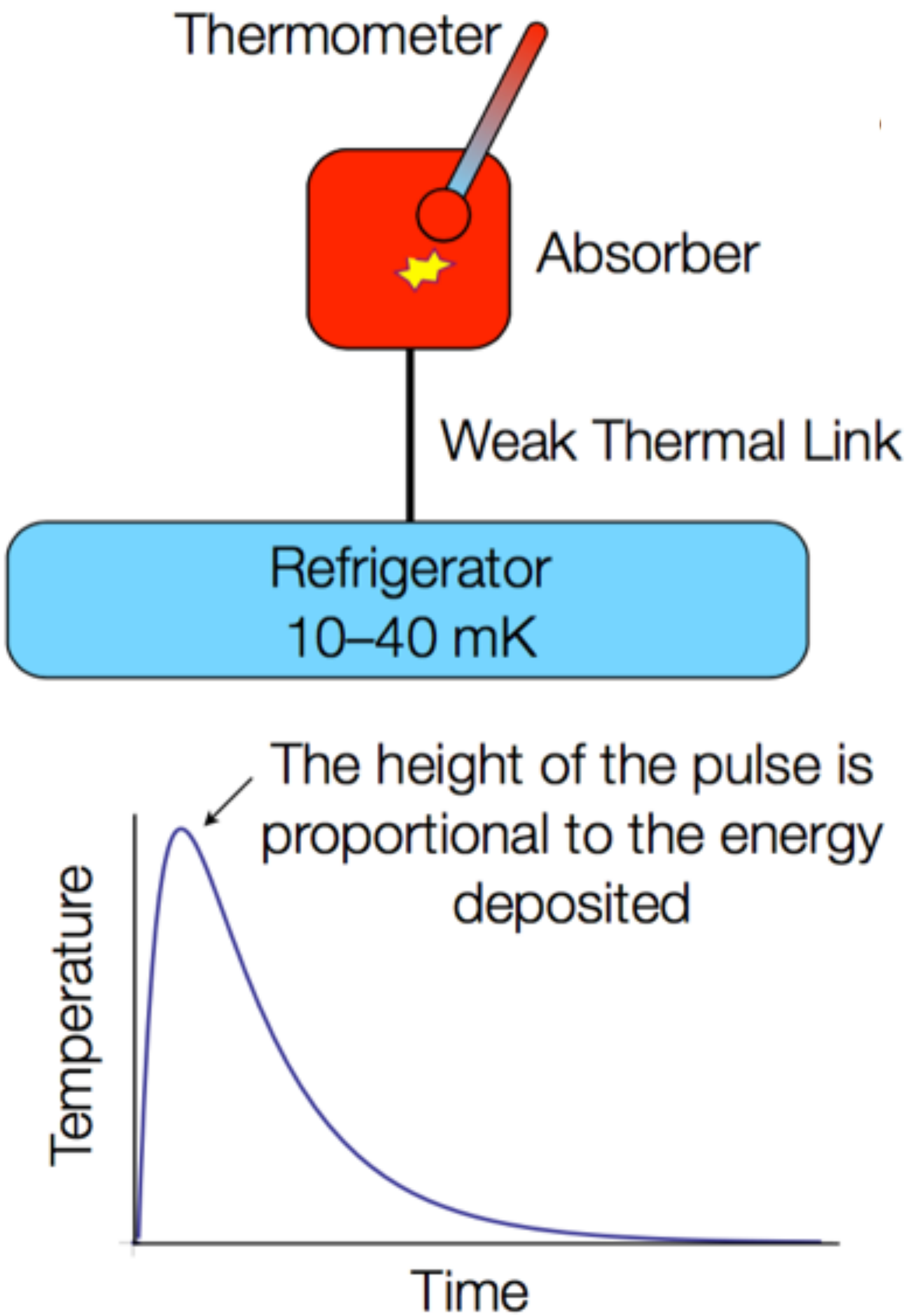
- NuGEN: 1 x 1 kg + 3 x 1.5 kg of germanium — **V. Belov et al 2015 JINST 10 P12011**
- CONUS: 4-100 kg of germanium — JHEP 1703 (2017) 097
- TEXONO: 1kg of germanium — Nucl.Instrum.Meth. A836 (2016) 67-82
- Connie: Si detector at Angra Reactor in Brasil — JINST 11 (2016) P07024
- RED100: Xe detector 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

Cryogenic experiment for **sub-100 eV** CENNS measurement → RICOCHET

RICOCHET
A Coherent Neutrino Scattering Program

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

# RICOCHET: *Cryogenic detectors for CENNS*




Ricochet (IPPP)

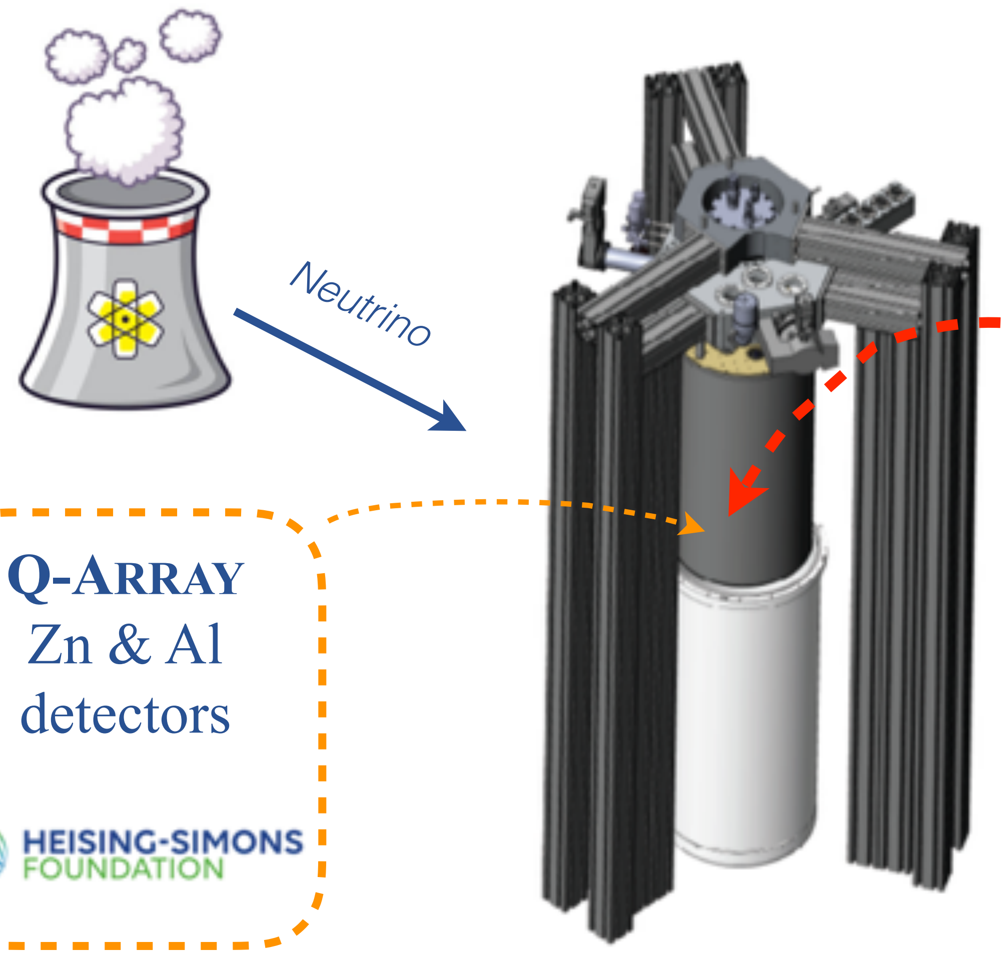
- Advantages of a phonon readout:
  - Direct measurement of the recoil energy, *no quenching involved*
  - ~100 % of the recoil energy is sensed, *allowing for low-thresholds*
  - *No intrinsic threshold (meV)*
  - From thermodynamics, ultimate energy resolution is: **~eV (RMS) for ~ 10 g detectors**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

# RICOCHET: *A future low-energy neutrino observatory*

« The first low-energy kg-scale CENNS neutrino observatory combining multi-target and multi-technology cryogenic detectors » Proposal paper: *J. Billard et al., J. Phys. G (2017)*




**Q-ARRAY**
Zn & Al
detectors

HEISING-SIMONS FOUNDATION

**CRYOCUBE**
Ge & Zn (& Si?)

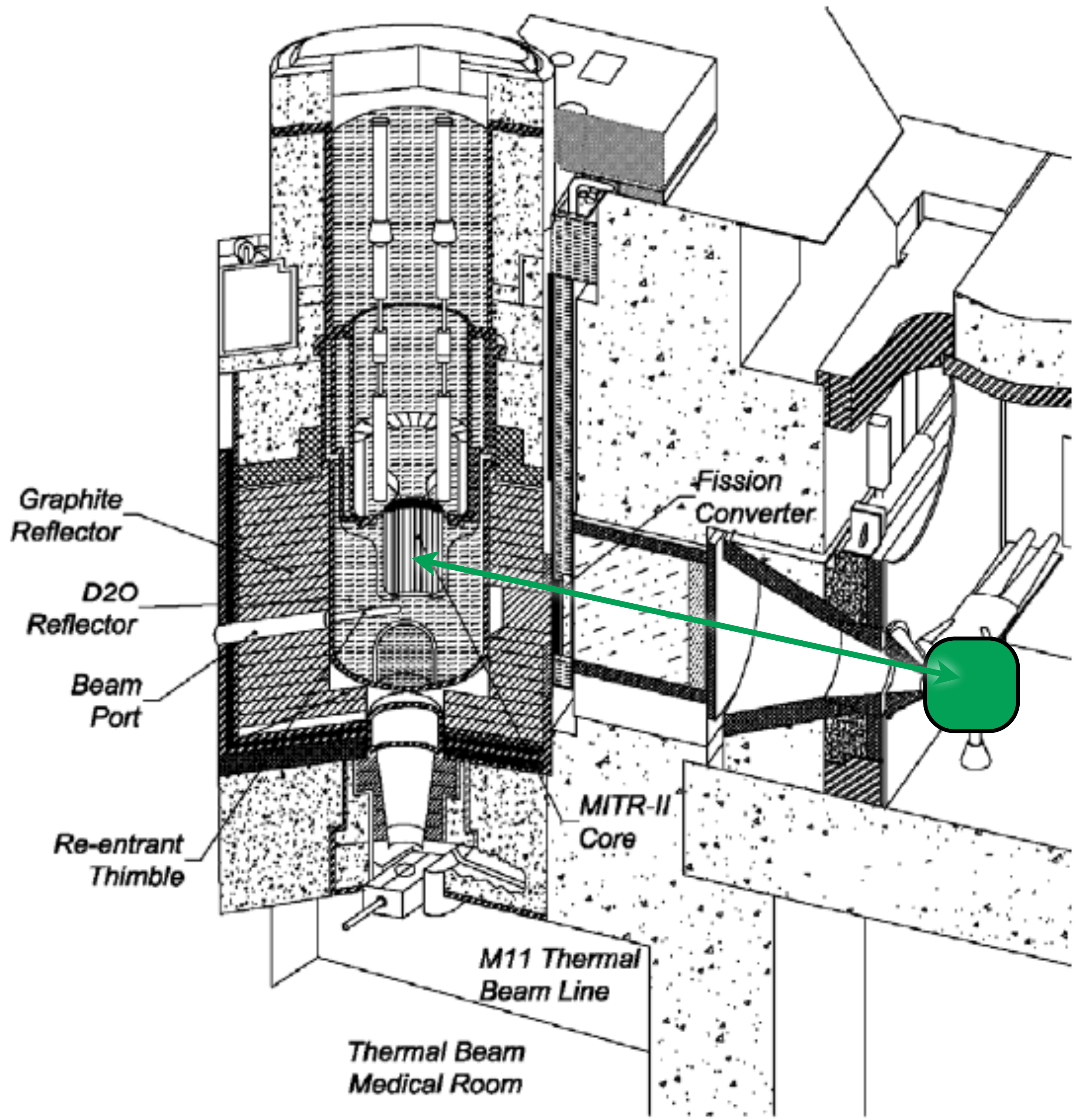
erc
cnrs IN2P3 Les deux infinis

Northwestern University
MIT
IPNL
CSNSM
LPSC Grenoble
NÉEL
The University of Wisconsin Madison
UMASS AMHERST

# RICOCHET: *Searching for nuclear reactor site - MITR*

- 5.5 MW thermal tower
- $1 \times 10^{18}$ ν/s
- $4.5 \times 10^{11}$ ν/cm²/s @ 4 meter from core
- 4 weeks on, 1 week off operating cycle
- PROs: Ideal for sterile neutrino searches
- CONs: practically no overburden, reactogenic background is very large

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



# RICOCHET: *Searching for nuclear reactor site - DC*

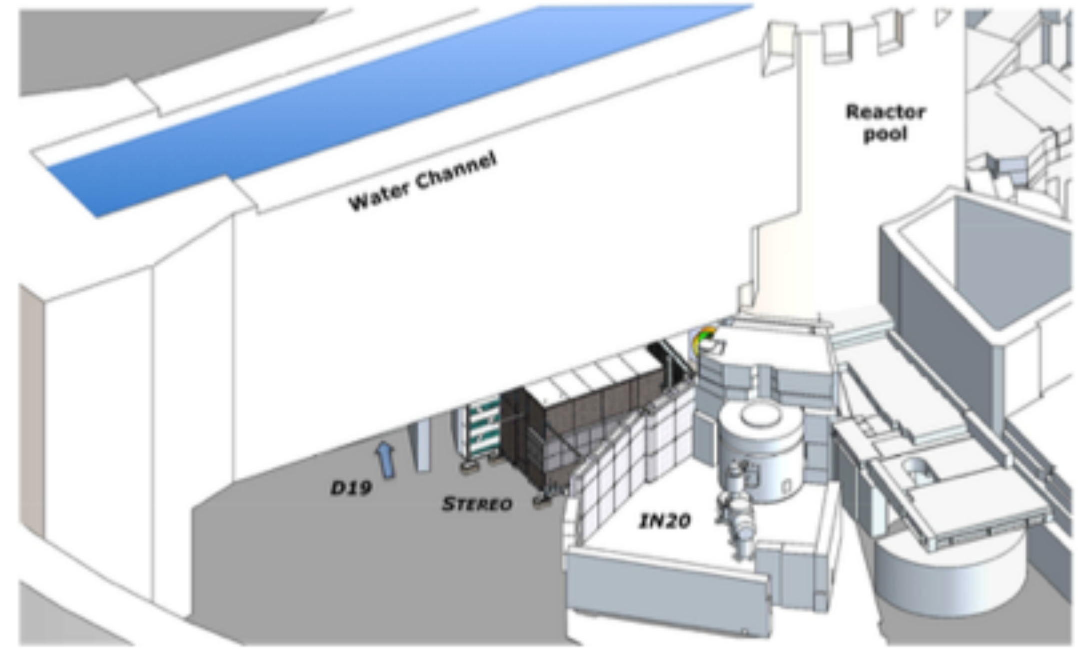
- 2 X 4.25 GW Thermal Power
- Near detector lab about 400 meters away may be available soon !
- ~$5 \times 10^{10}$ ν/cm²/s @ detectors
- Thermal power oscillates over the course of the year:
  - 60% two reactors ON
  - 40 % only one reactor ON
- No « reactogenic » backgrounds !!!
- 120 m.w.e overburden allows for significant reduction of cosmogenic backgrounds
- Rather low CEvNS rate
- Not optimal for sterile search

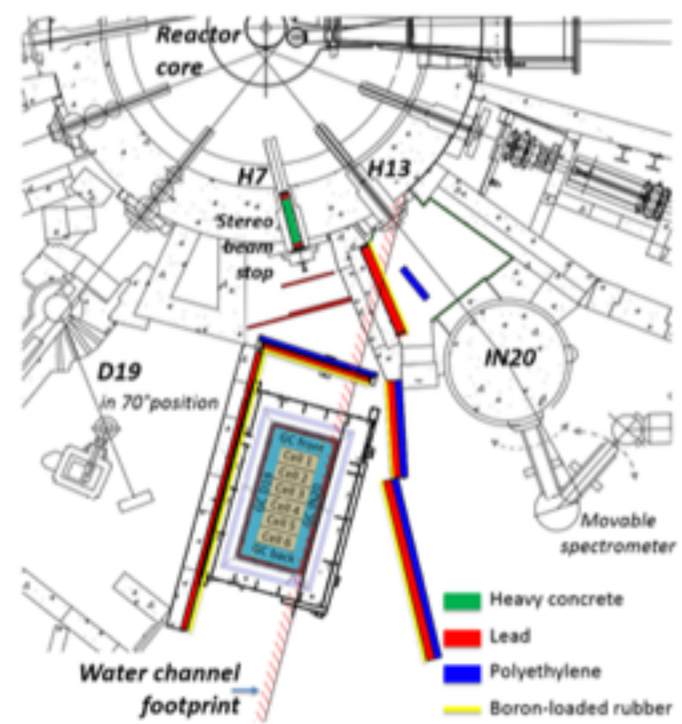

**J. Billard et al., J. Phys. G 2017**

# RICOCHET: *Searching for nuclear reactor site - ILL*

- 58 MW nominal thermal power
- Large neutrino flux: ~$1 \times 10^{19}$ ν/s
  - 5m from core: 40 evts/day/kg *($3.2 \times 10^{12}$ ν/s/cm²)*
  - 7m from core: 20 evts/day/kg *($1.6 \times 10^{12}$ ν/s/cm²)*
- 3 to 4 cycles per year: ***excellent ON/OFF modulation to subtract uncorrelated backgrounds***
- Significant overburden (~15 m.w.e)
- Ricochet could make use of STEREO casemate after its dismantling (2021 - 2022)
- Ricochet would benefit from the strong STEREO experience and background characterization
- Monte Carlo studies ongoing to estimate the expected backgrounds:
  - ***reactogenic*** and ***cosmogenic***
- ***LoI submitted to ILL directors end-Feb 2019***

STEREO Coll., JINST 2018



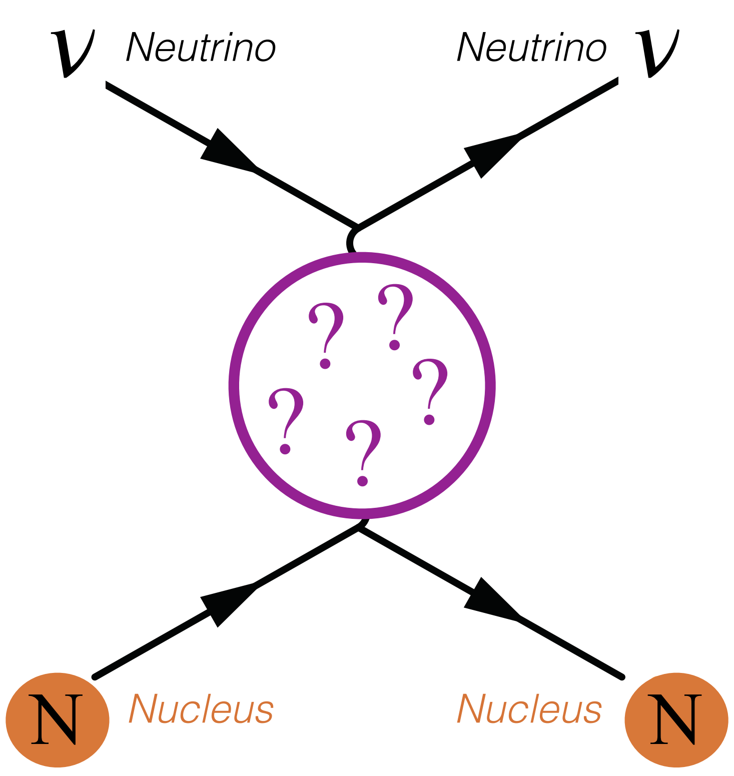
# Ricochet: *searching for new physics*

PROBING NEW PHYSICS WITH **CENNS** AND THE FUTURE RICOCHET EXPERIMENT

***ERC Starting Grant - CENNS***
*(2019 - 2024)*

- ***Sterile neutrino***
- ***New boson searches***
- ***Non-Standard Interactions***
- ***Neutrino Magnetic Moment***

see review: *J. Billard, J. Johnston and B. Kavanagh*, JCAP (2018)

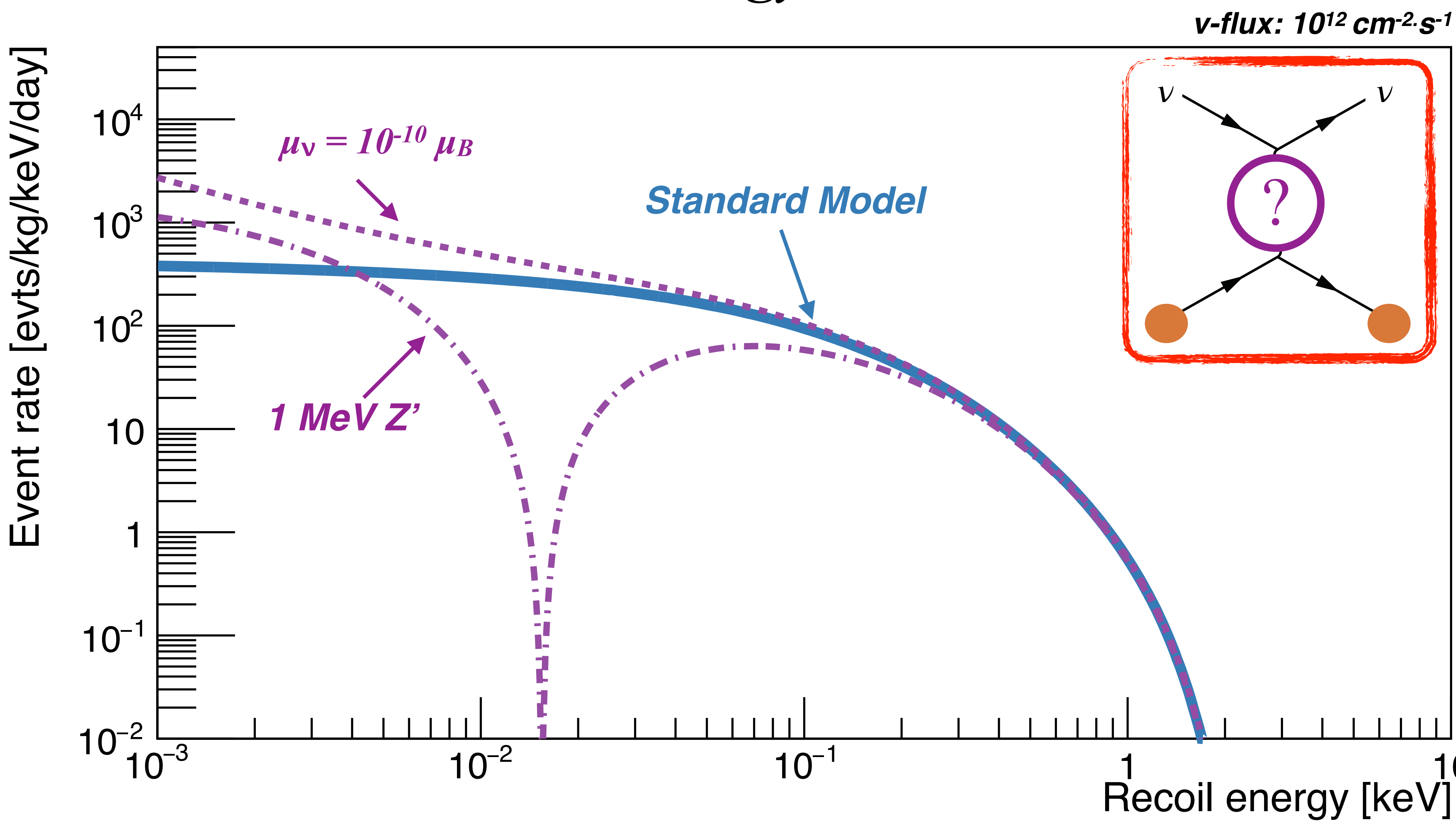



***« A few percent deviation from the Standard Model***
*would be*
***an unambiguous proof of New Physics »***

*Snowmass report (2013)*

# Ricochet: *searching for new physics*

*Recoil energy distribution*

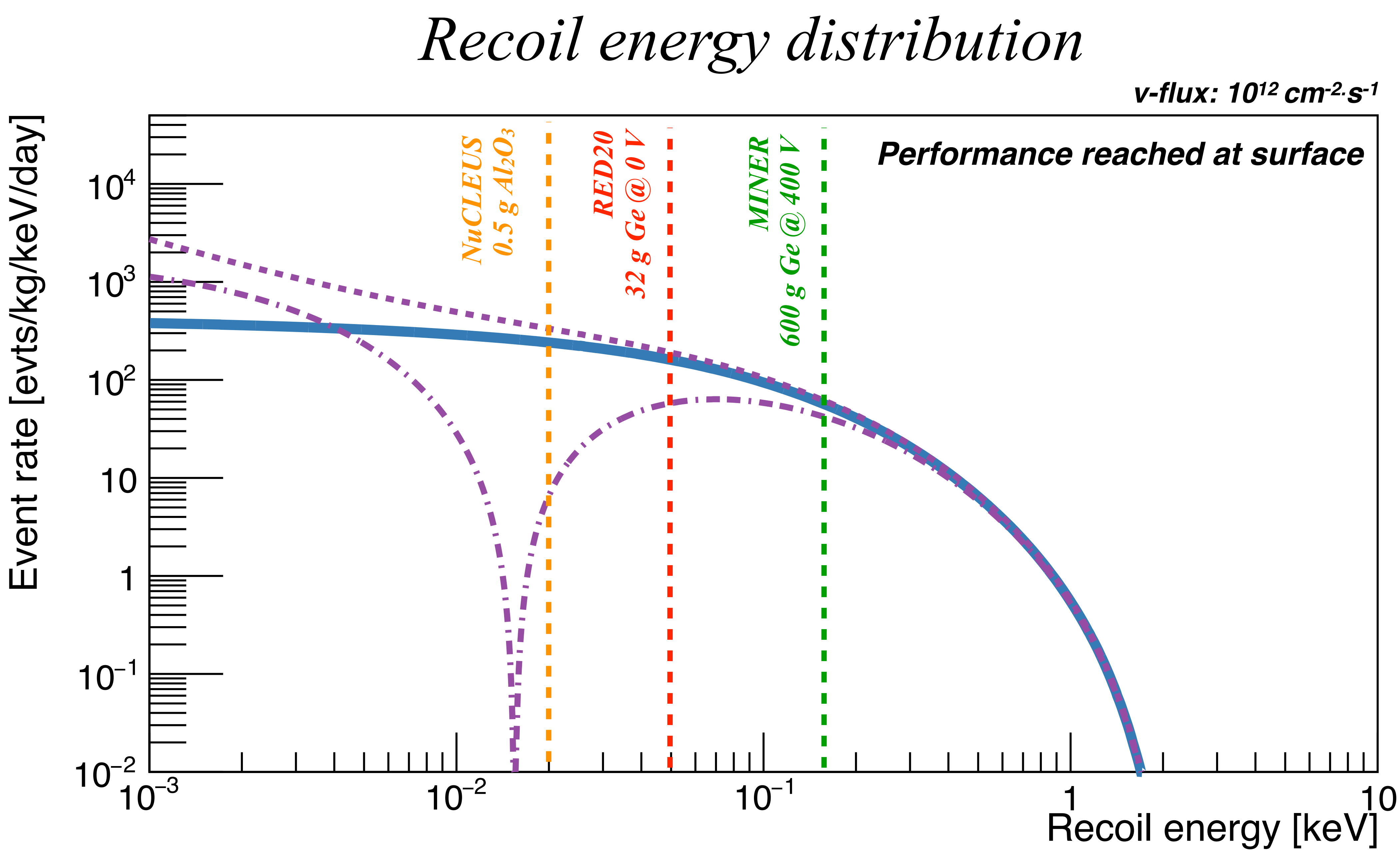



*J. Billard, J. Johnston and B. Kavanagh, JCAP (2018)*

*New physics signatures will arise at the lowest energies*

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

# Ricochet: *searching for new physics*



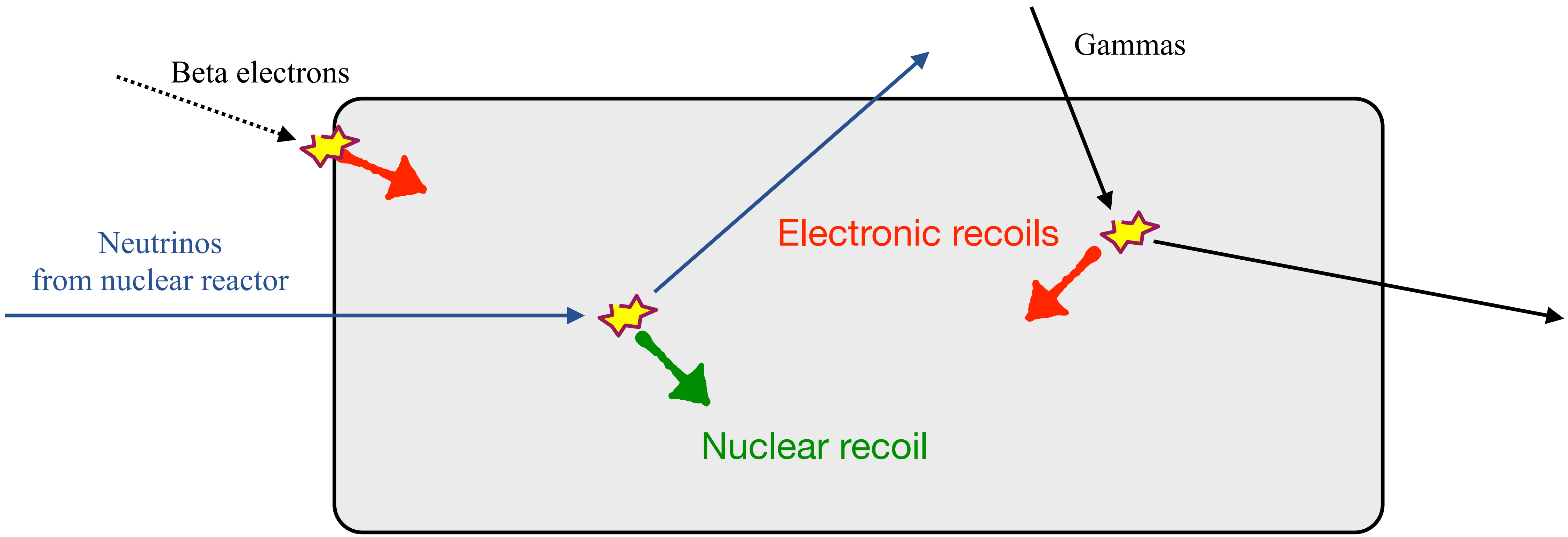

J. Billard, J. Johnston and B. Kavanagh, JCAP (2018)

*New physics signatures will arise at the lowest energies*

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

# Ricochet: *searching for new physics*

## Backgrounds, backgrounds, backgrounds, …

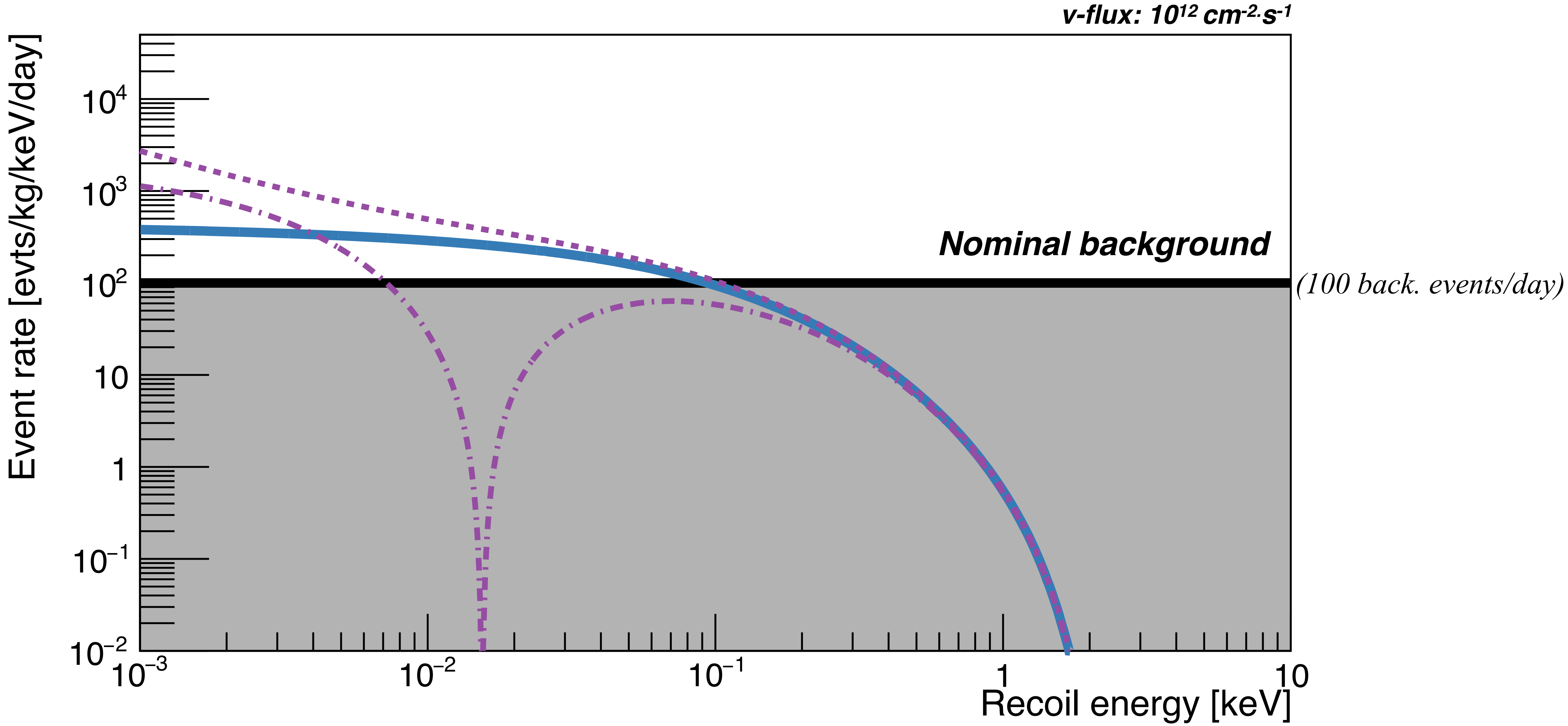



Expect two populations of events:

- **Nuclear recoils:** **CENNS signal** and neutrons
- **Electronic recoils:** gammas and beta electrons from surrounding radioactivity

# Ricochet: *searching for new physics*

## Backgrounds, backgrounds, backgrounds, …

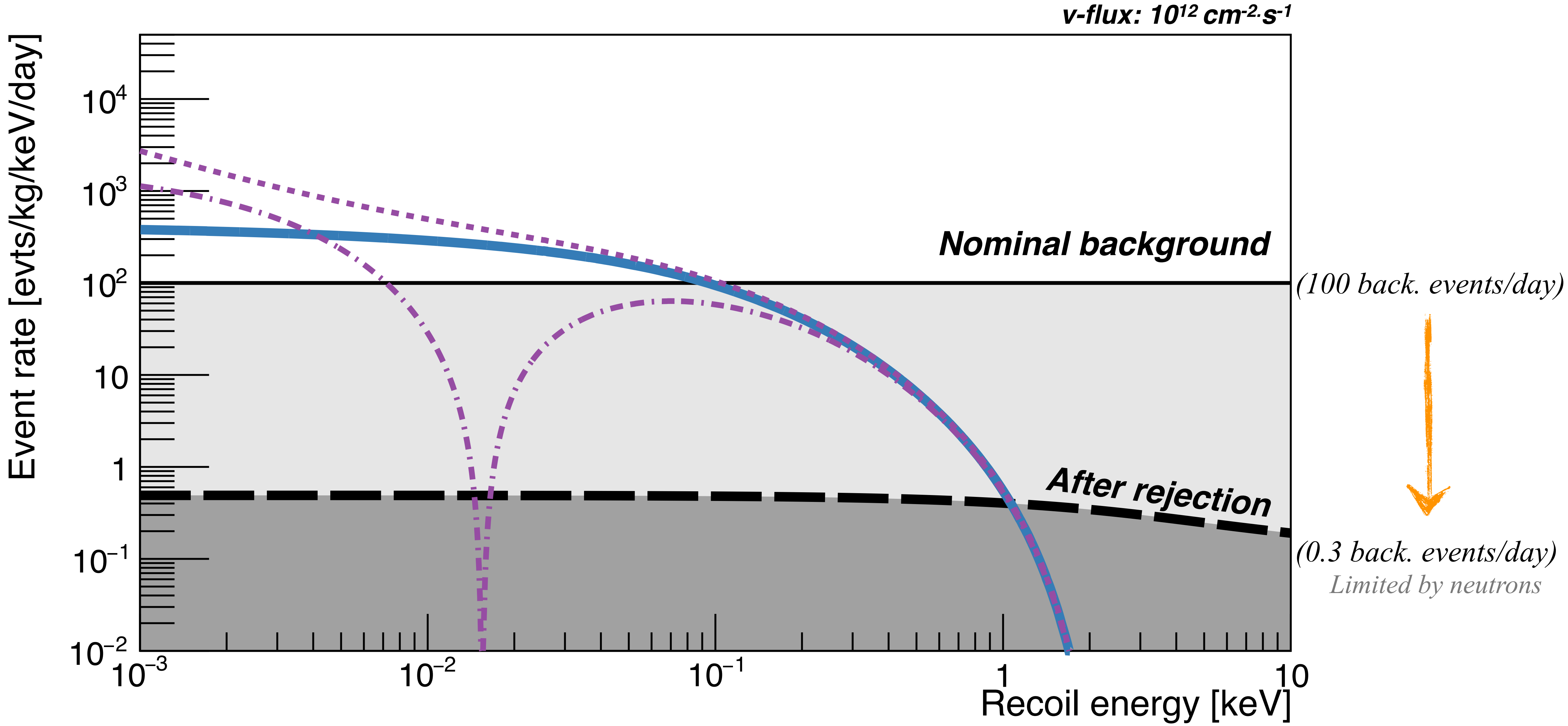



*Expect to be overwhelmed by the backgrounds*

***Calls for particle identification to reach background rejection: >10³***

# Ricochet: *searching for new physics*

## Backgrounds, backgrounds, backgrounds, …

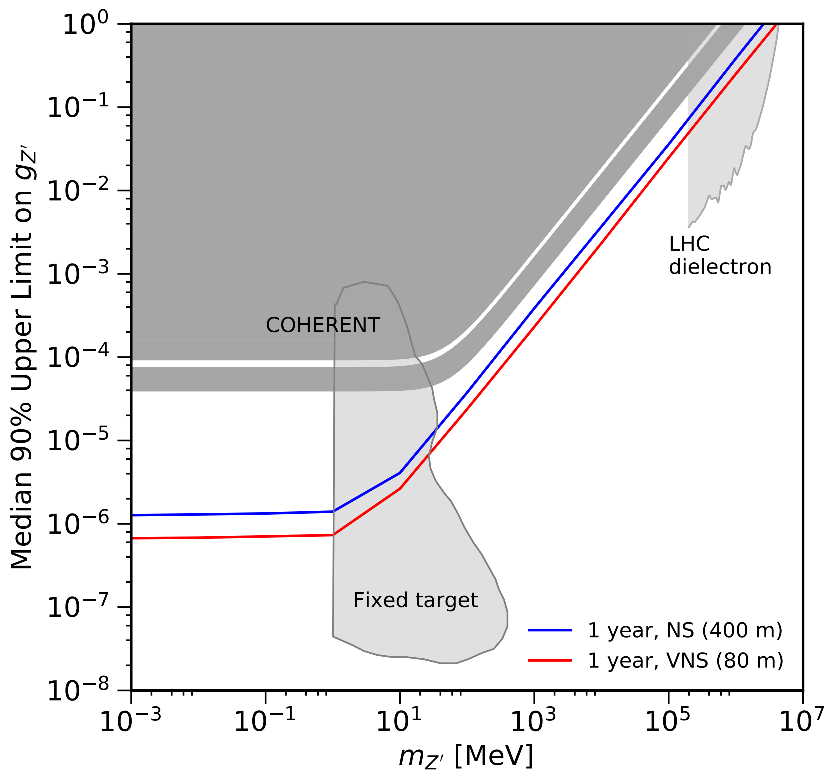


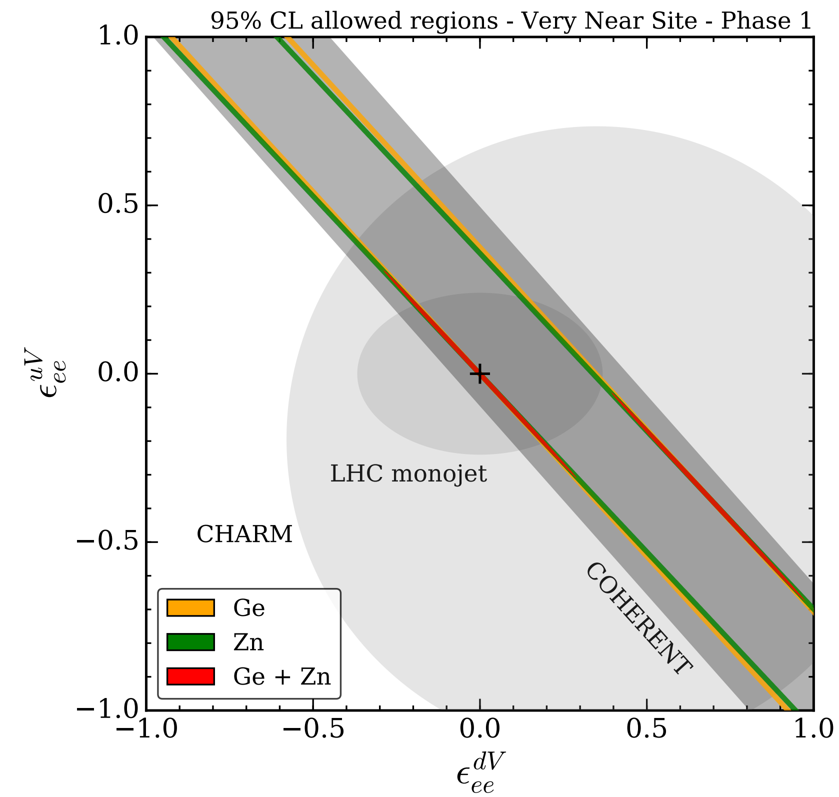

20 CENNS events/day: ***5 sigma CENNS detection in a couple of days !***

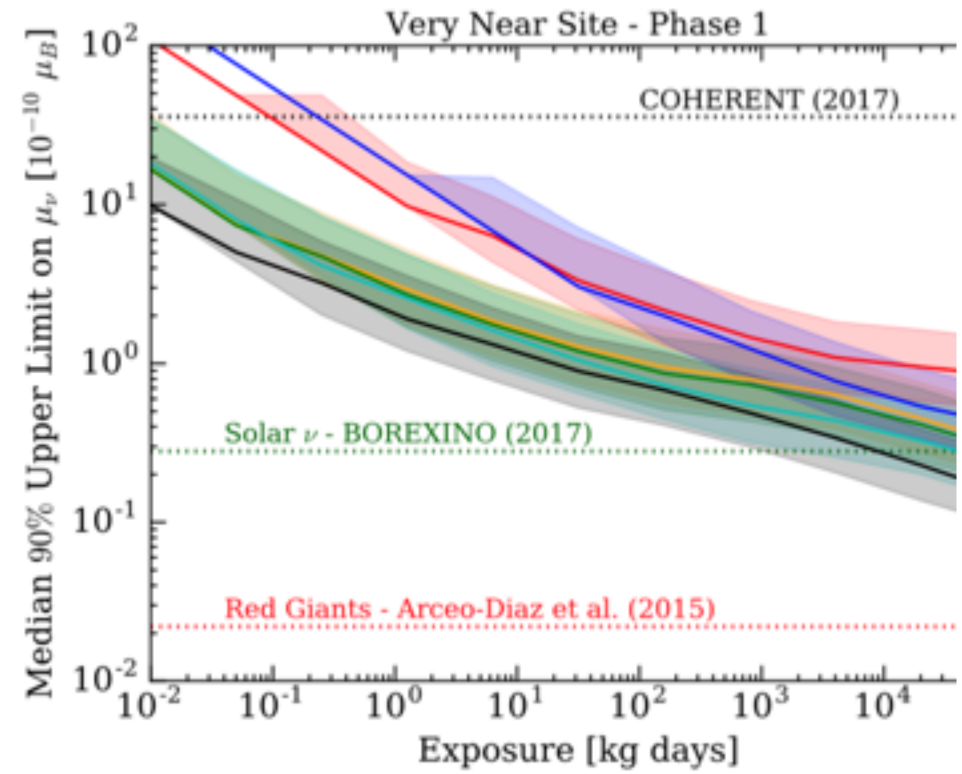
***1 % precision measurement after one year***

# Ricochet: *searching for new physics*

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




The scientific goal is to deliver a low-energy and high precision CENNS measurement at the **percentage level 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 $\mathbf{\mu_\nu \sim 10^{-11}\ \mu_B}$ **at the 90% C.L.**

# Ricochet: *Detector technology innovation (CryoCube)*

***Detector wish list:***

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

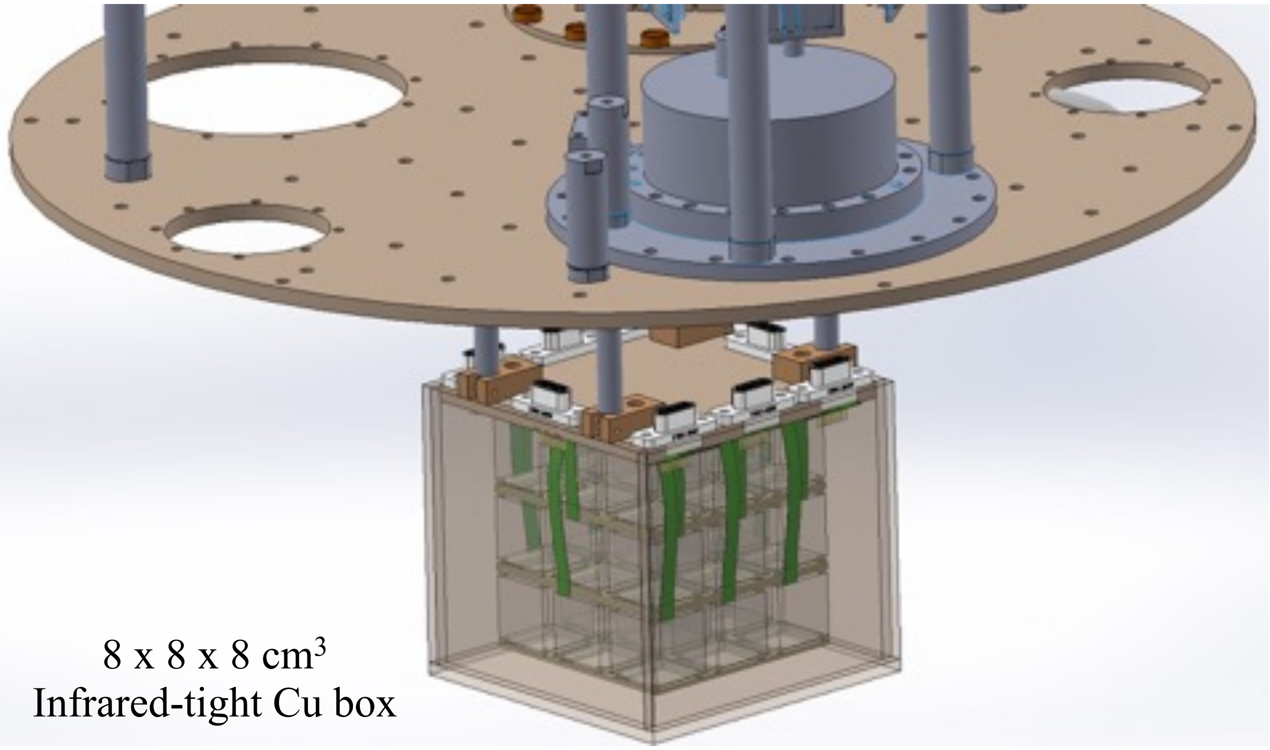
*WORK PACKAGE 1 & 2:* **CRYOCUBE**

An array of 27 x 30 g cryogenic detectors (20 mK)

- 50 % of Ge (& Si ?) semiconductors
- 50 % of Zn superconductors ***(new technology)***

**Total: 1 kg with a minimum level of complexity**

***2019 to 2022***

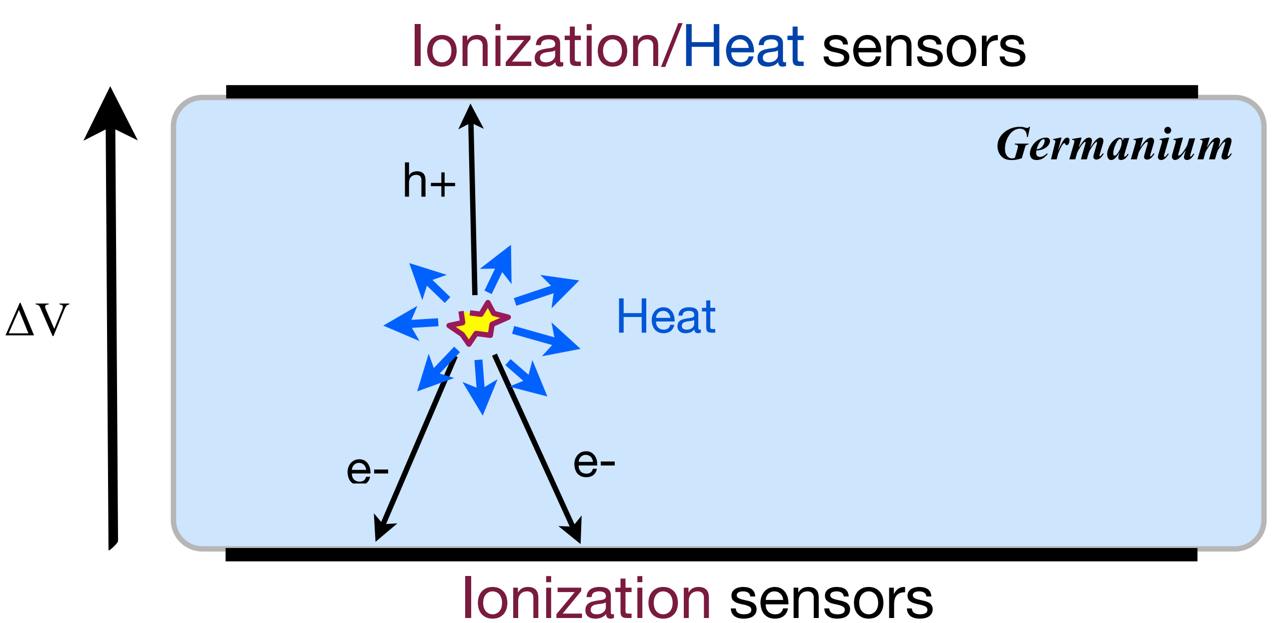


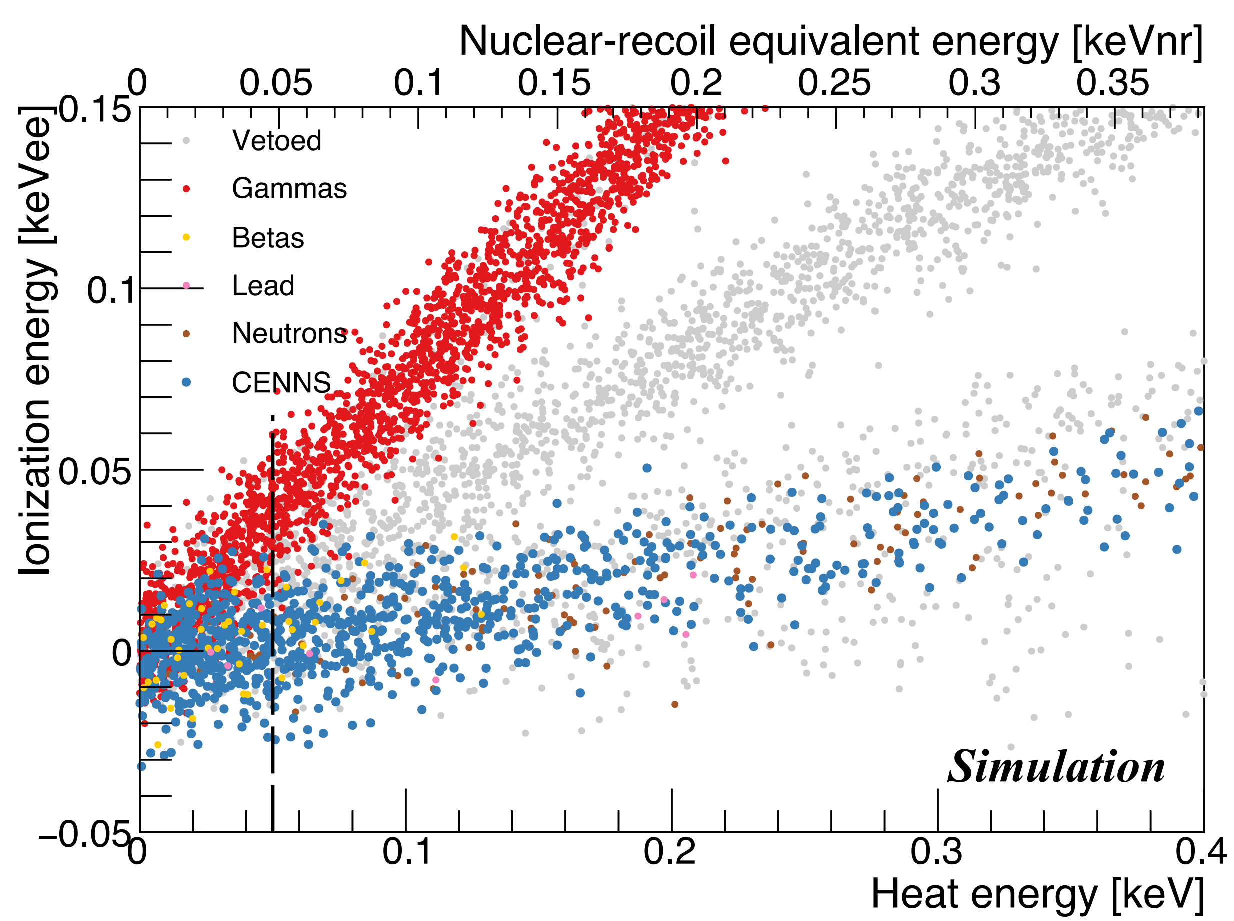
# Ricochet: *Detector technology innovation (CryoCube)*

**Technological key features of the CryoCube detector technology:**

- *Achieve* ***Particle Identification*** *down to O(10) eV with a rejection >$10^3$*
- *Two different cryogenic detector technologies:* ***Ge and Zn***

***Germanium semicondutor***



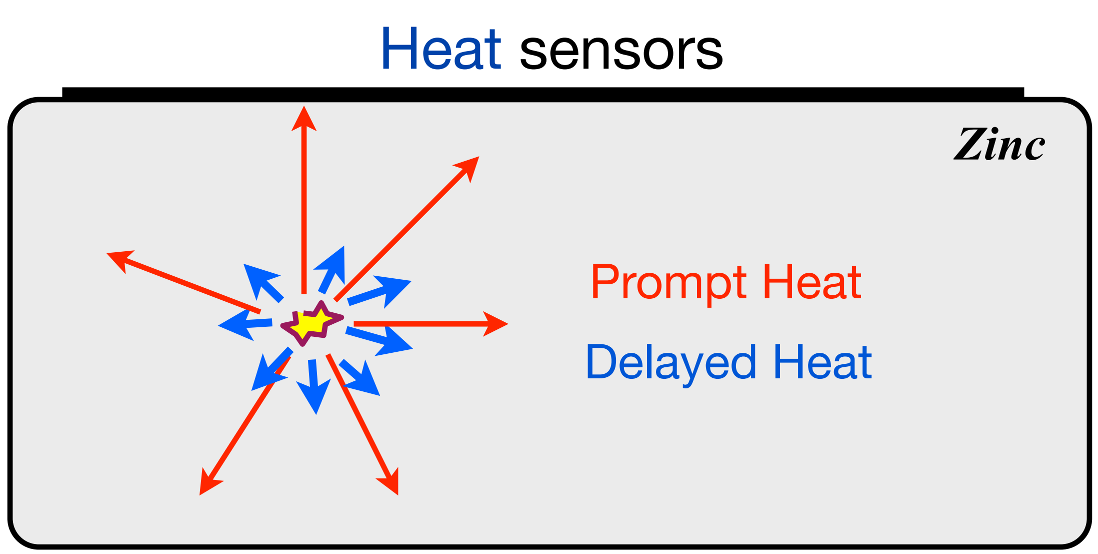

- **Ionization / heat** ratio depends on the particle type
- **Achieve an unprecedented 10 eV ionization resolution**

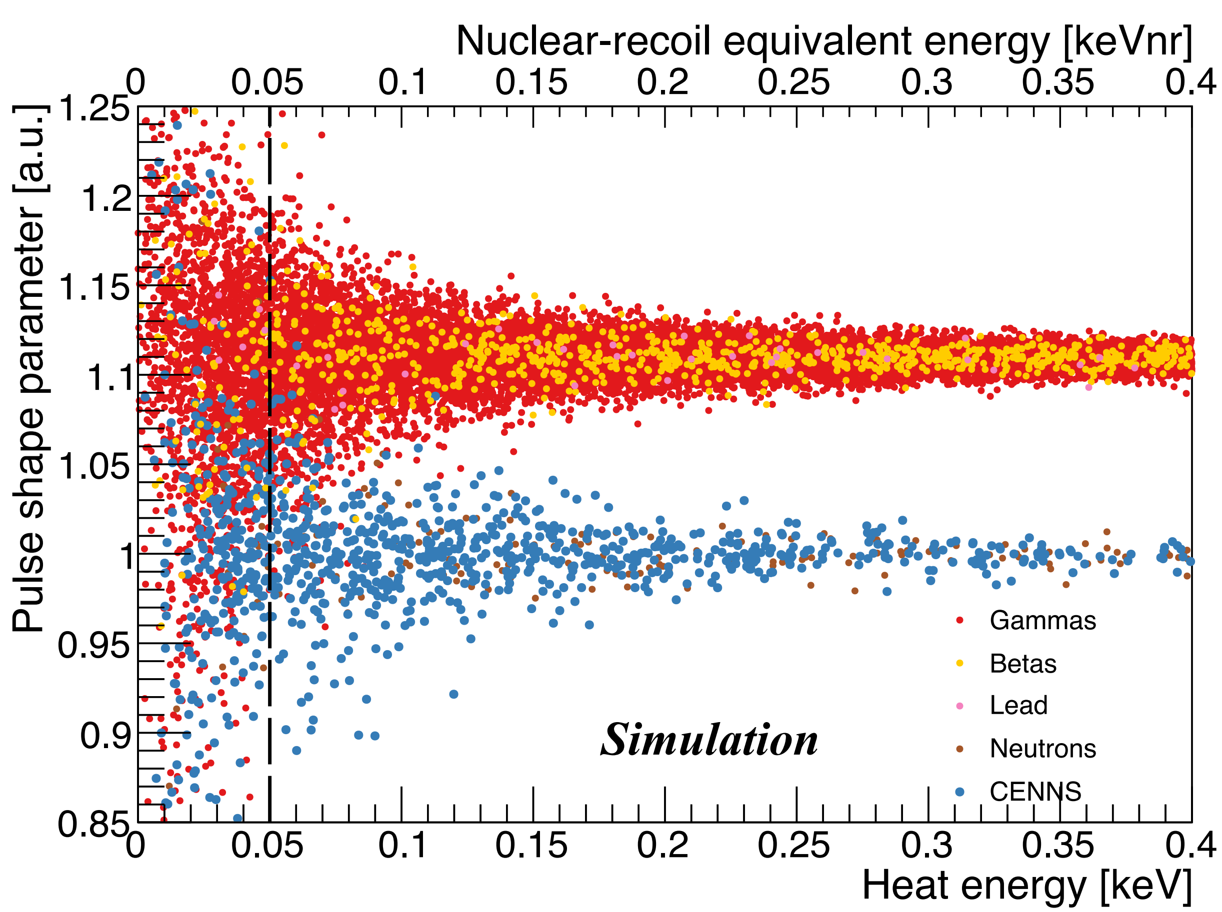
# Ricochet: *Detector technology innovation (CryoCube)*

**Technological key features of the CryoCube detector technology:**

- *Achieve* ***Particle Identification*** *down to O(10) eV with a rejection >$10^3$*
- *Two different cryogenic detector technologies:* ***Ge and Zn***

***Zinc superconducting metal***

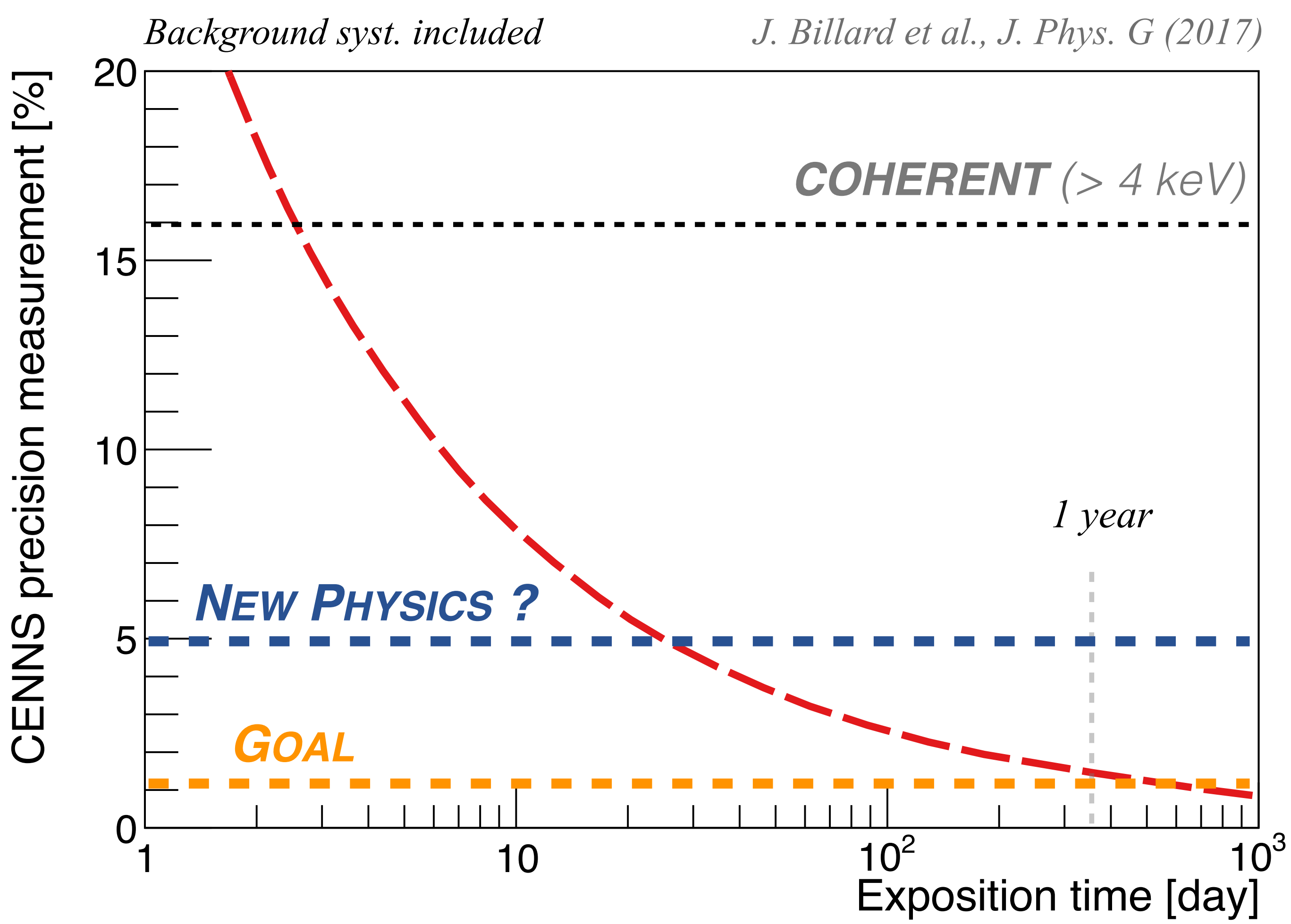



- **Prompt / delayed** heat signals depend on the particle type
- ***NEW*** **technology that may achieve meV threshold**

# Ricochet: *Detector technology innovation (CryoCube)*

***Science Goal**: Reach unprecedented sensitivity to physics Beyond the Standard Model*



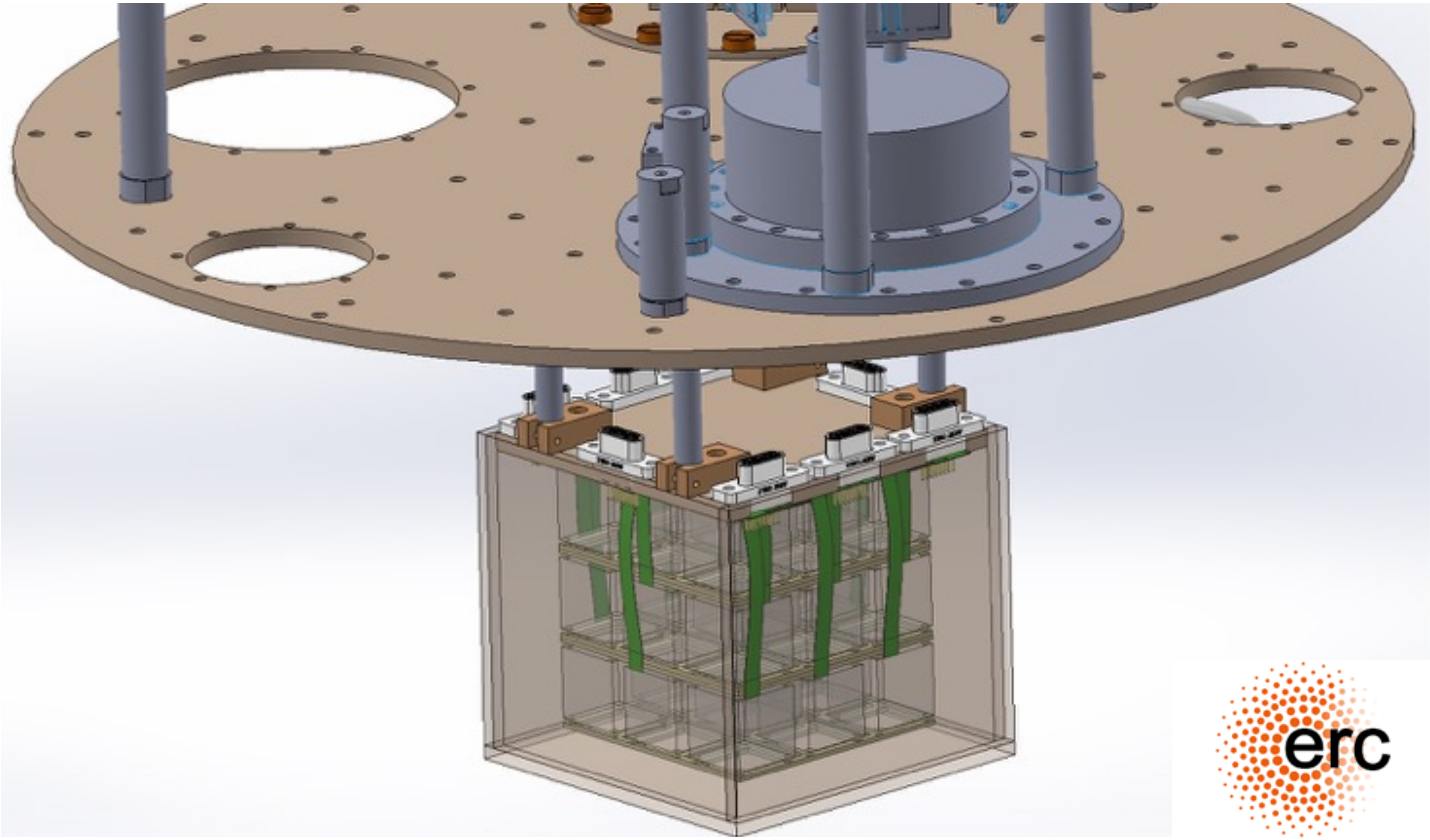

### WORK PACKAGE 3: CENNS SCIENCE

*Aiming for a percentage-level measurement*

- Accurate control of systematics: ***commissioning***
- 1 year of on-site science data taking
- Advanced data analysis techniques

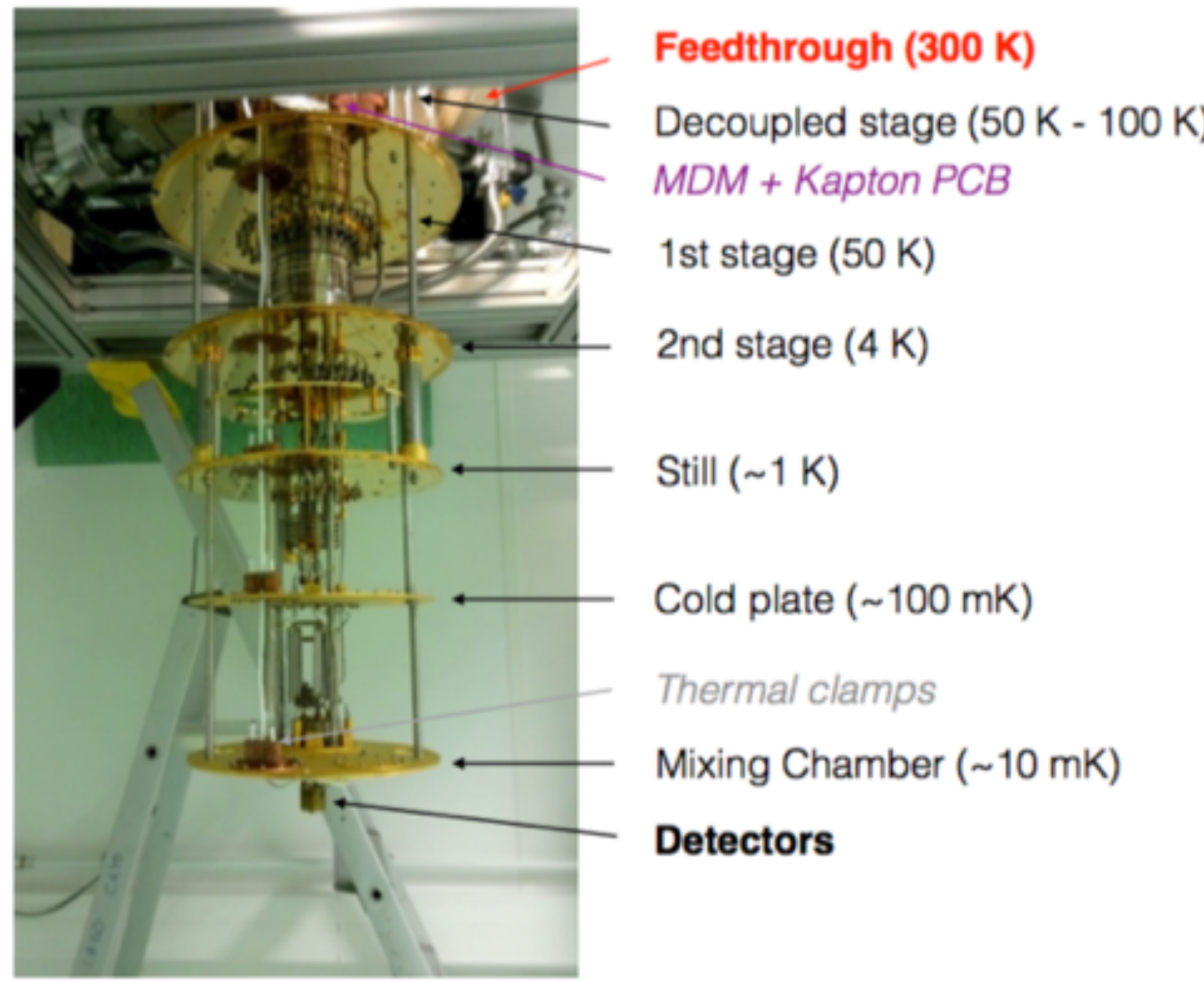
***2022 to 2024***

# Ricochet: *Ongoing R&D effort (CryoCube)*



# CryoCube: *The test facility*

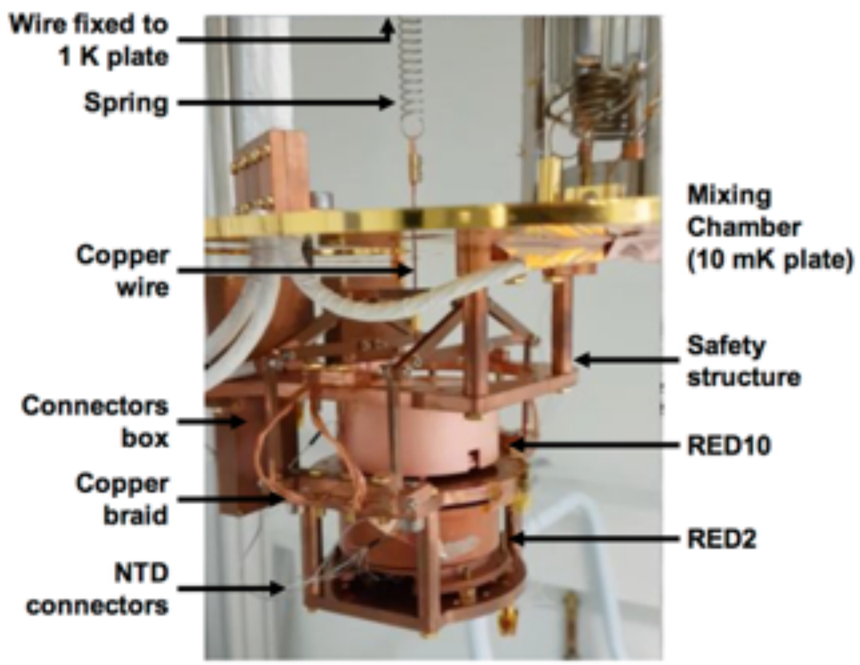
Ricochet (IPPP)

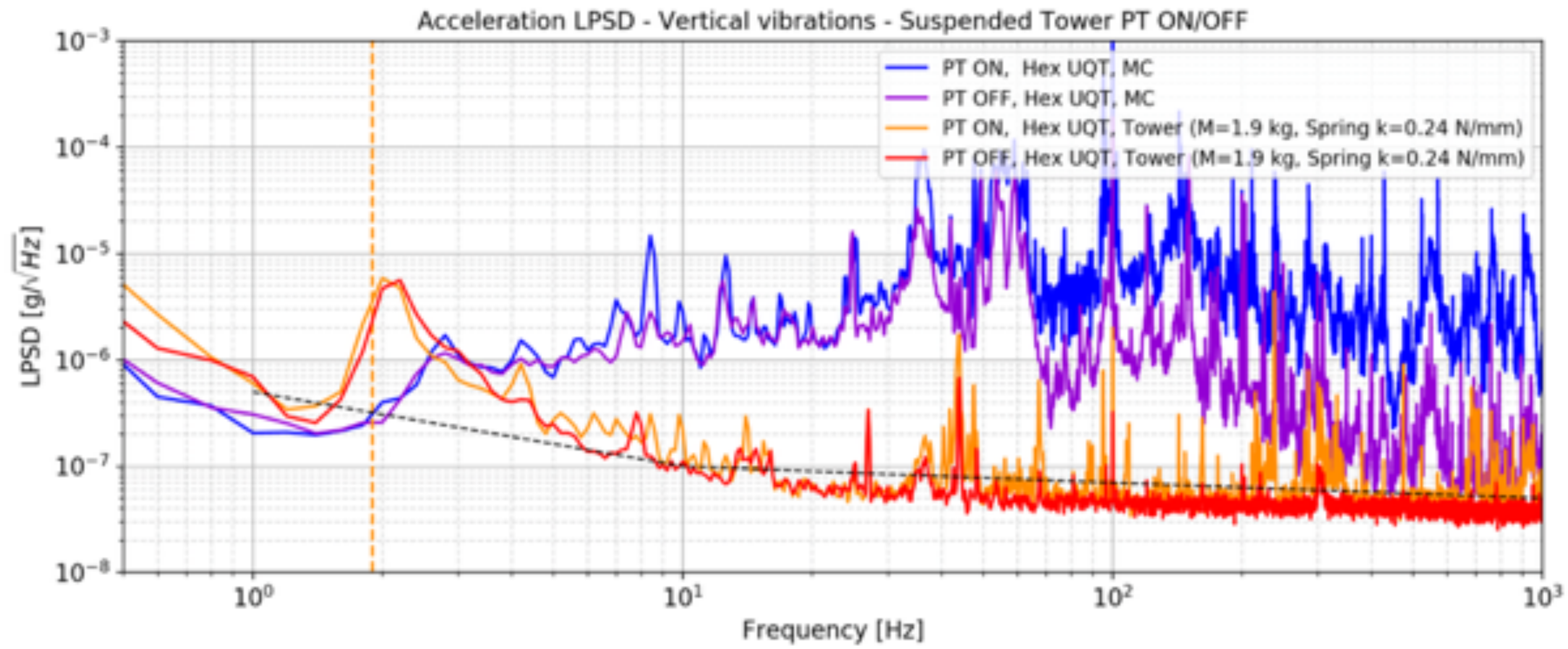


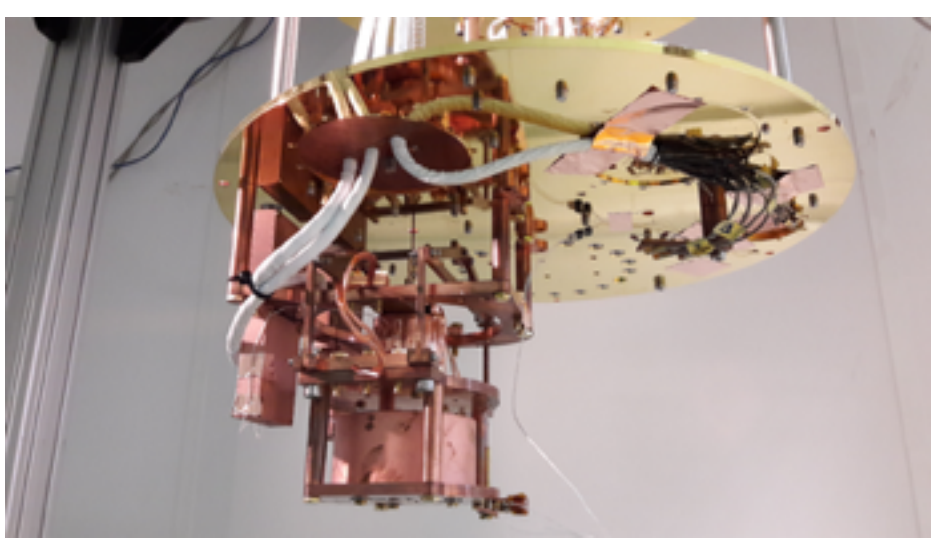

- First ***complete*** cold-head decoupling demonstrated
  *E. Olivieri, J. Billard, M. De Jesus et al, NIMA (2017)*
- An experiment of a similar size is envisioned for Ricochet *(small scale neutrino experiment)*

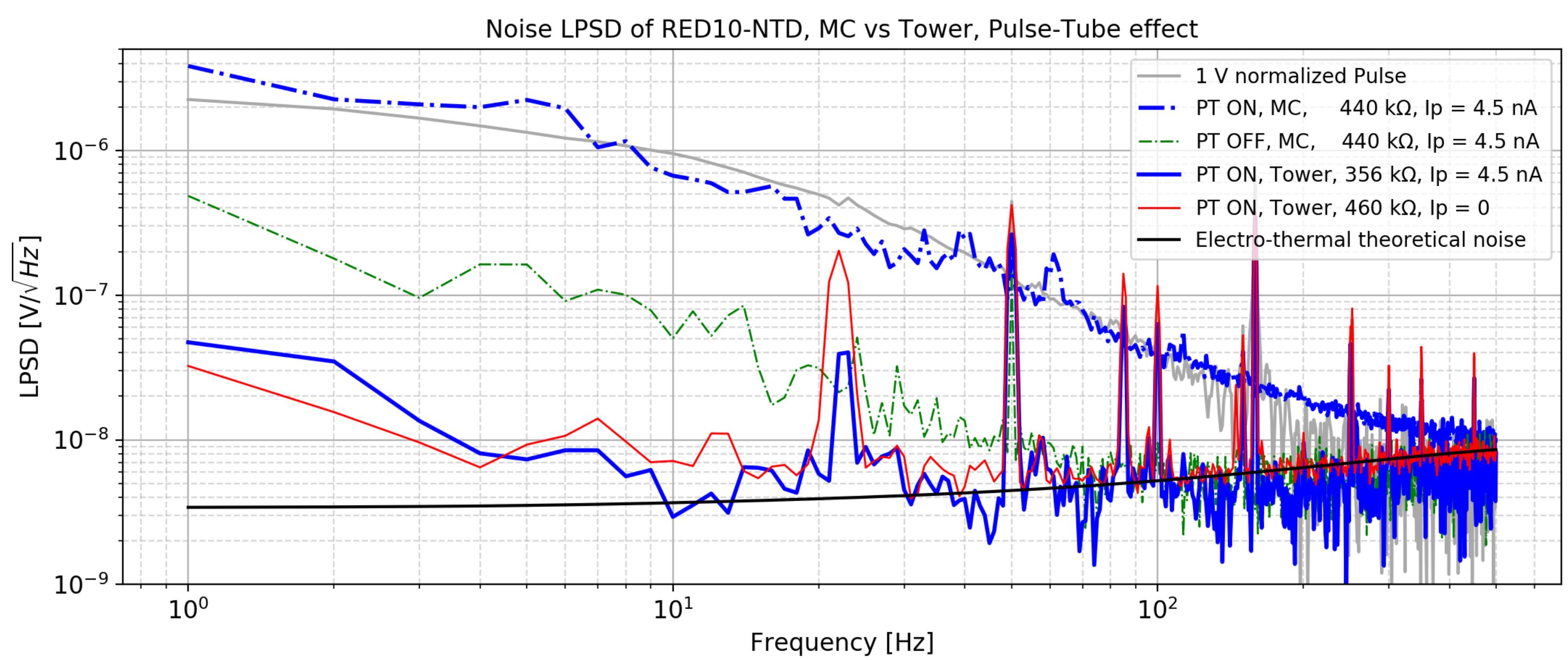
# CryoCube: *Suspension system*

*R. Maisonobe et al.*, JINST **2018**



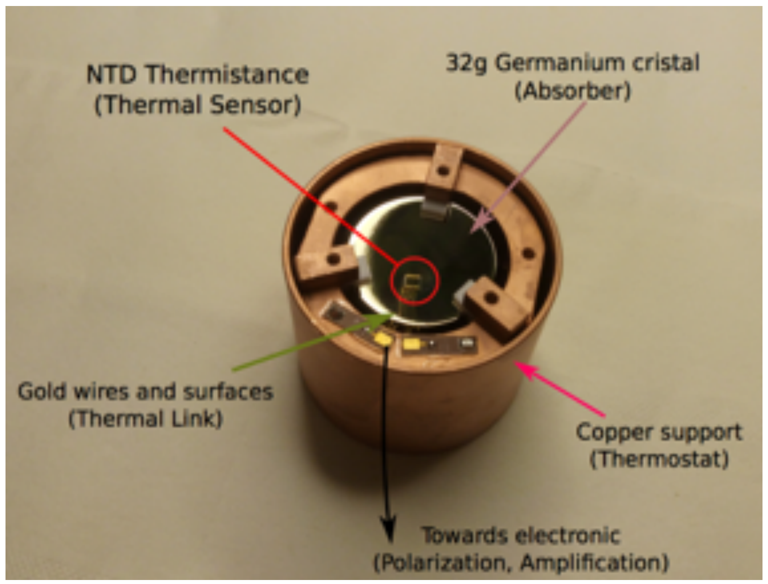



- Suspended tower to reach nanometer-scale vibration levels (RMS): ***CryoCube holding solution***
- Bolometers are now only limited by their intrinsic thermodynamic noise or electronics

# CryoCube: *Energy threshold*

*From the EDELWEISS R&D*

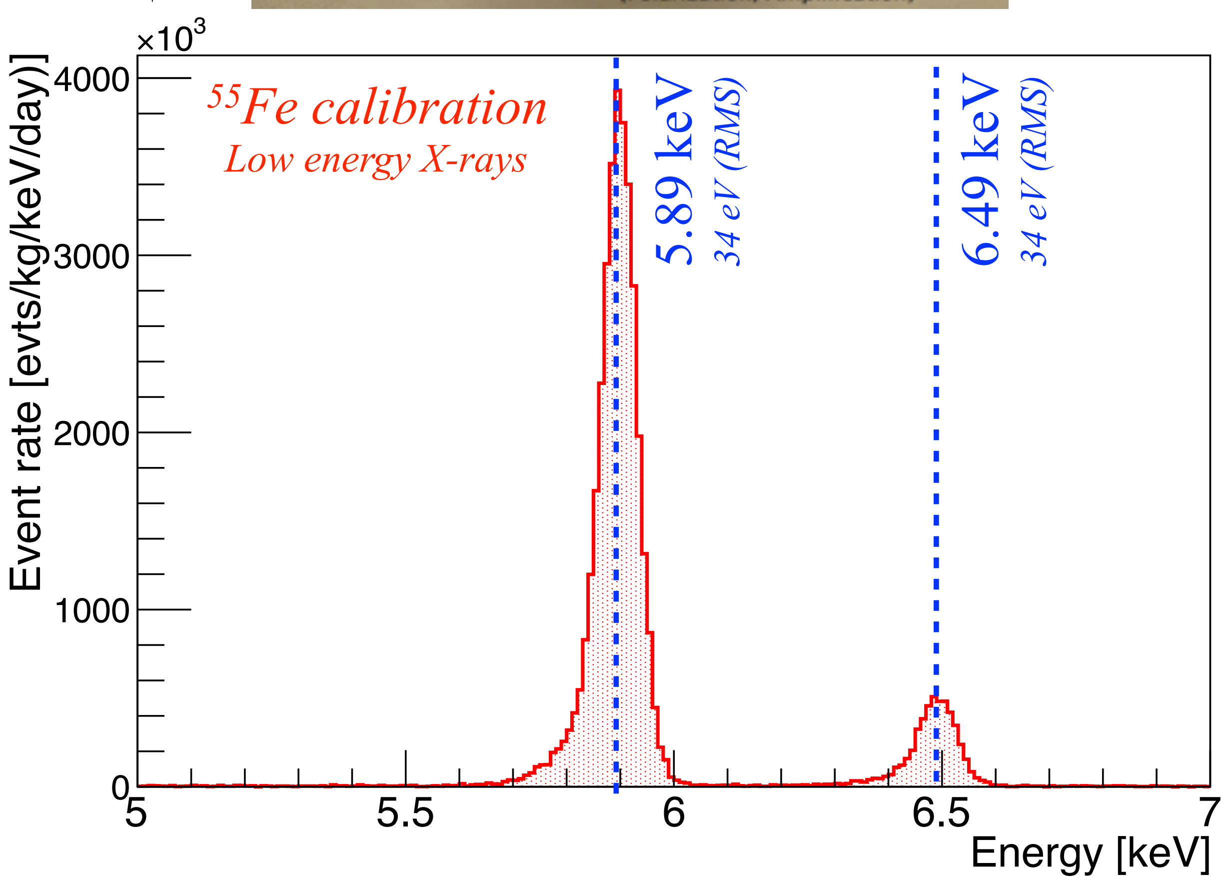
*RED20: 17 eV heat, no electrodes*

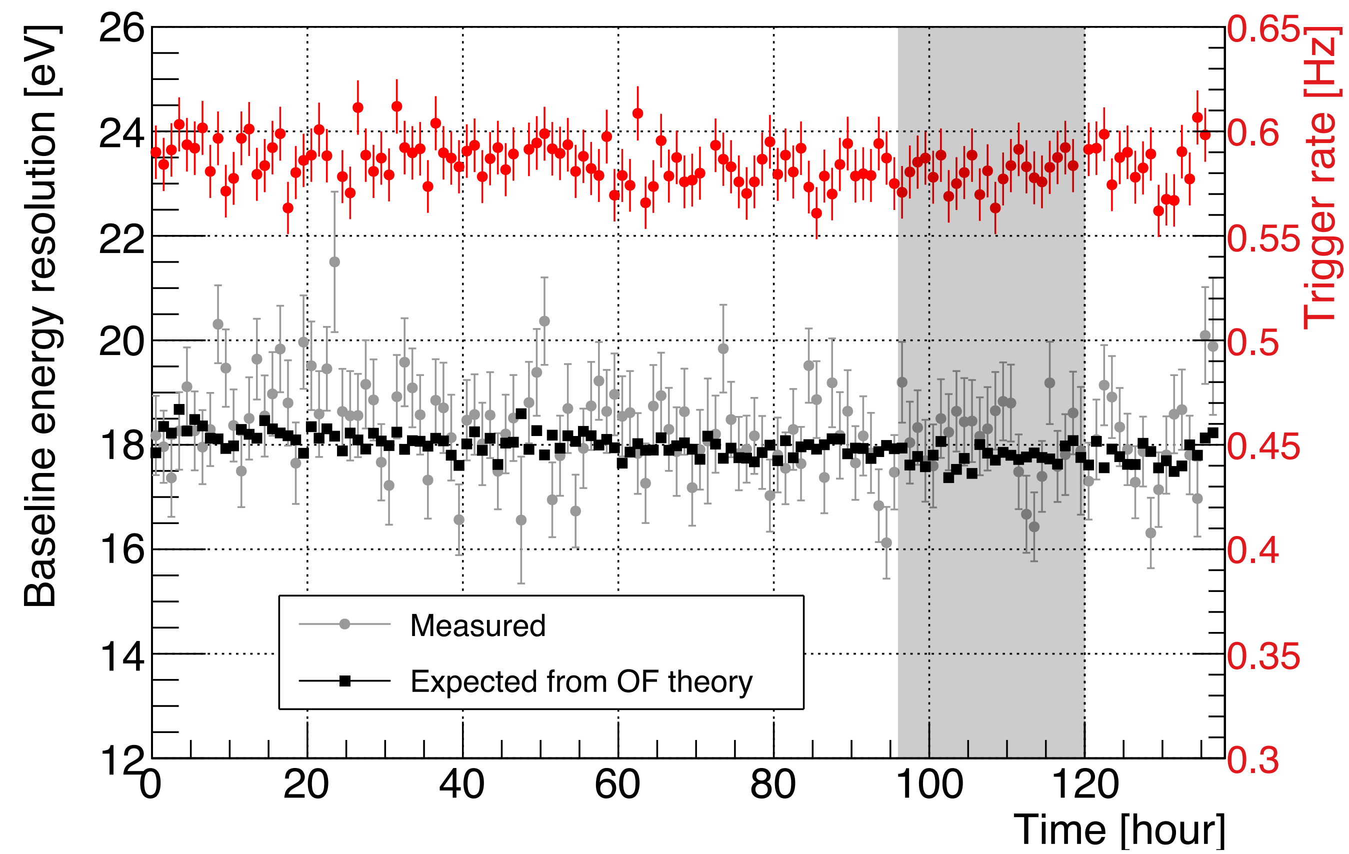



*E. Armengaud et al., Phys. Rev. D 99, 082003 (2019)*

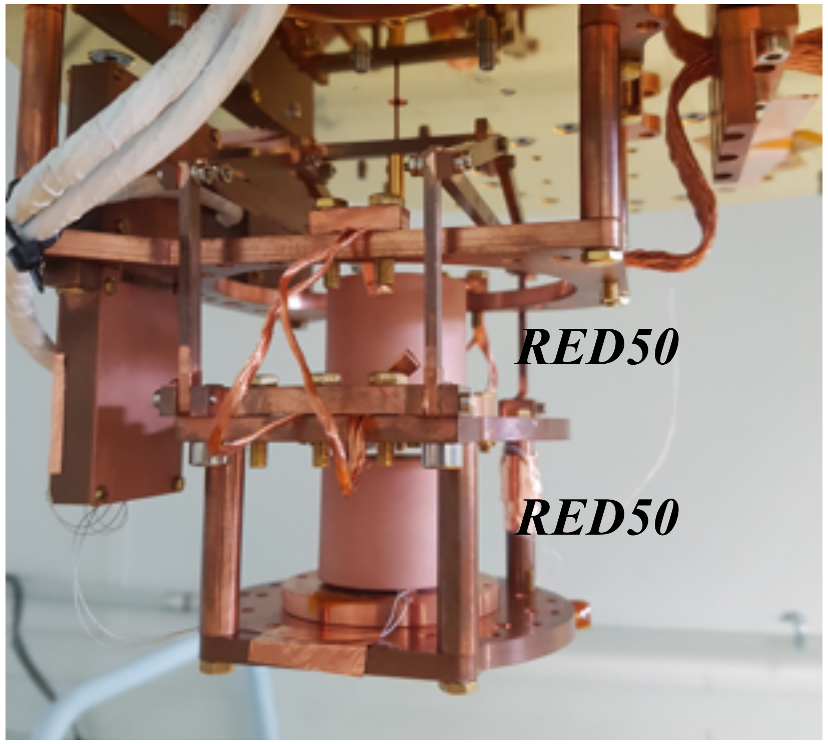
World leading results: **18 eV energy resolution** (RMS)
**55 eV energy threshold**
with a **33 g detector** (Ge)
**near perfect stability (~%)**

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

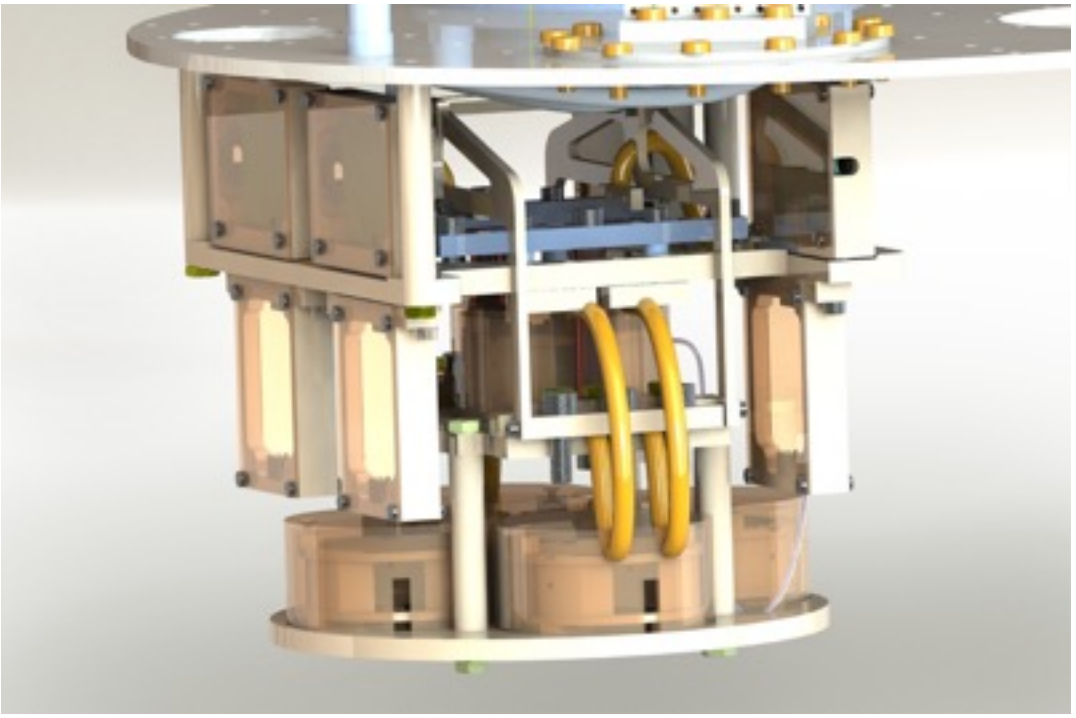


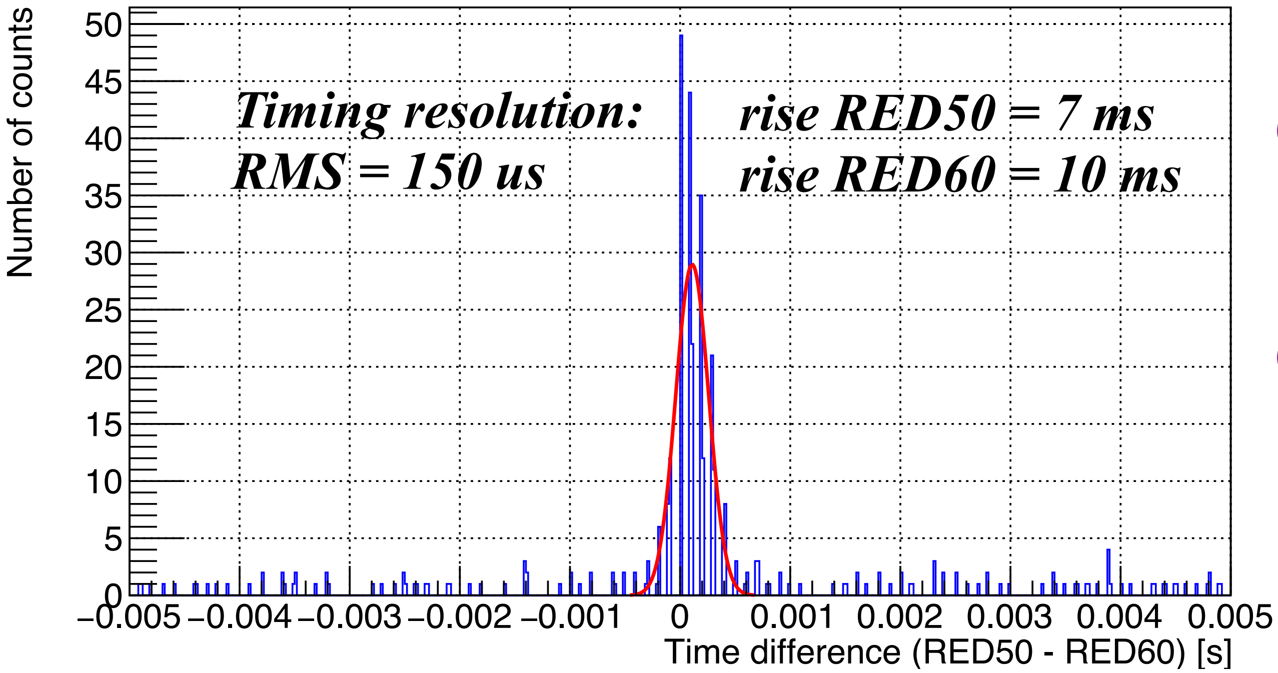
# CryoCube: *Scalability - Towards 1 kg payload*




***~60 g payload***



***~200 g payload***




***Question #1: Scalability ?***

*Observed similar performance (25 eV) with 2 Ge -> **OK***

*Tower of 4-6 bolometers to be tested this summer*

***Question #2: Can we handle a muon veto of ~1m² ?***

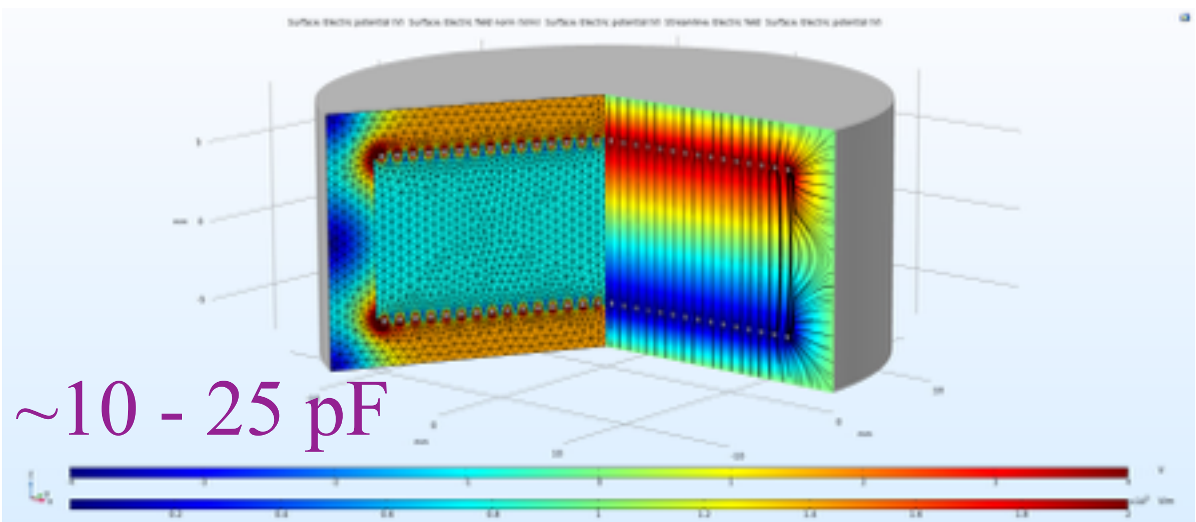
*150 us time resolution between two bolometers despite slow rise times -> **OK***



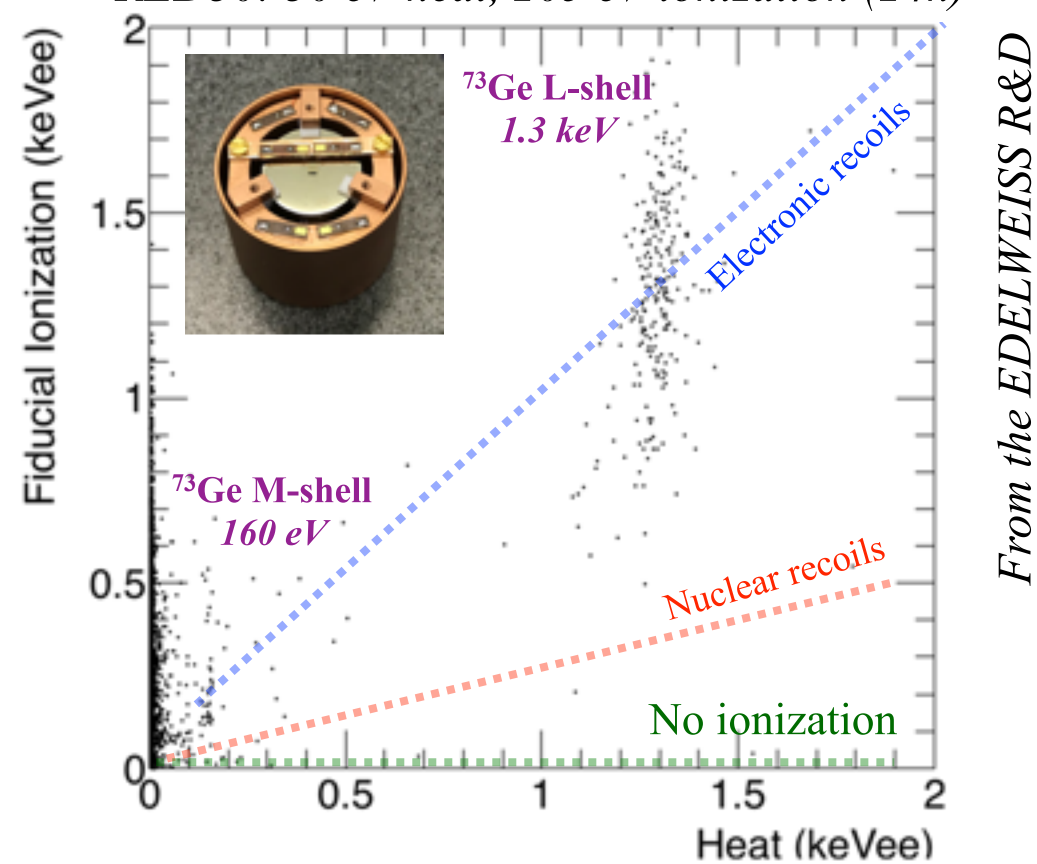
Julien Billard

# CryoCube: *Particle Identification (Ge)*

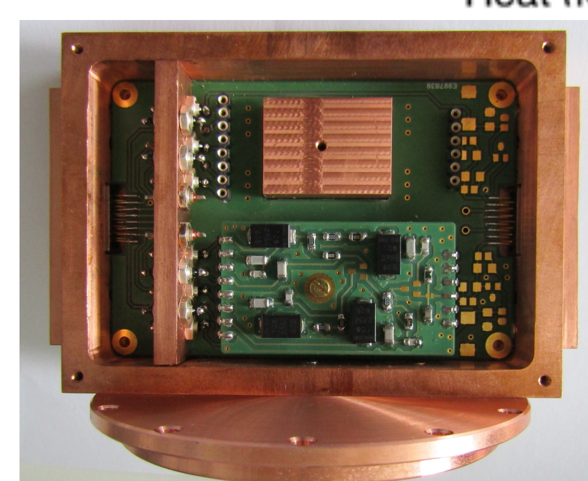
***10 eV ionization resolution: HEMT preamplifiers + new electrode design***




*RED30: 30 eV heat, 205 eV ionization (24h)*

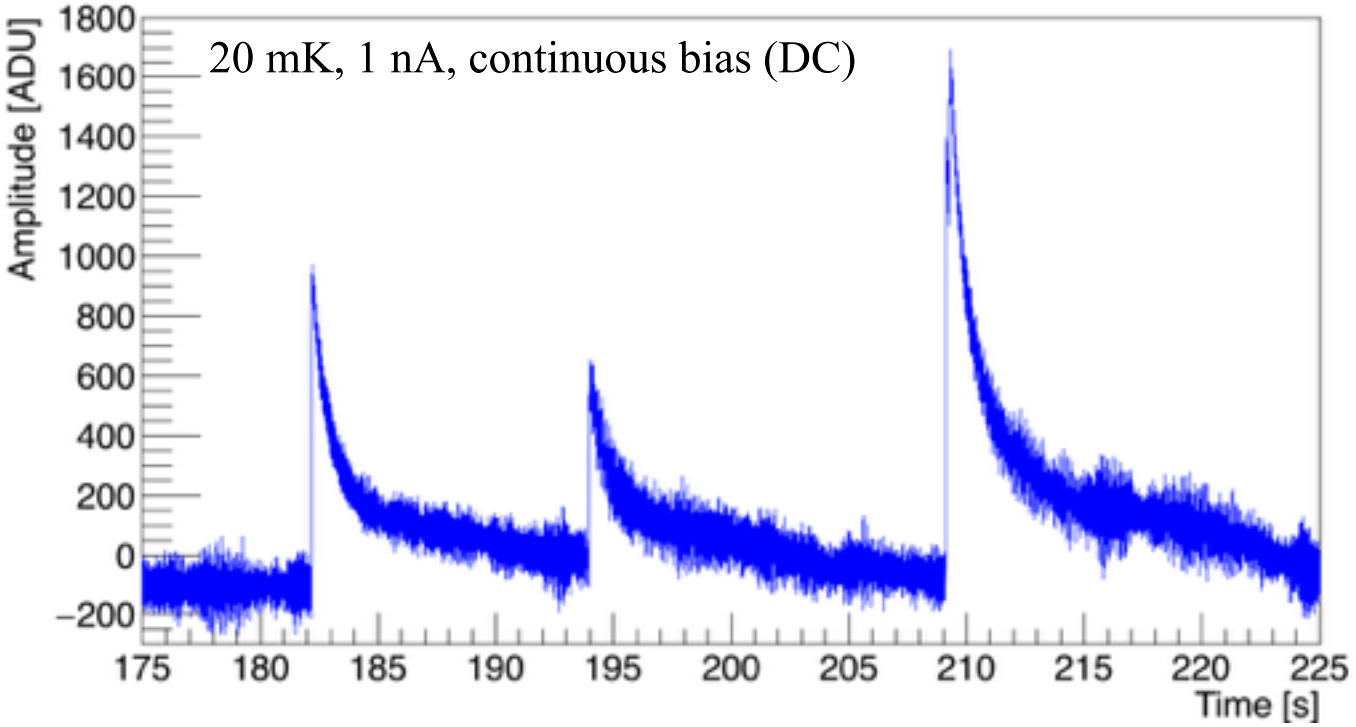



- ER/NR discrimination limited only by ionization resolution (200 eV). **Need to reach 20 eV**
  - best achieved 90 eV *(arXiv:1611.09712)*.
- Design of new electrode scheme: ***ongoing***
- *New cold electronics:* ***ongoing***
- HEMT have lower intrinsic noise than JFET
- Work @ 4/1 K => reduced stray capacitance
- *O*(10) eV resolution achievable with 10 pF input
- **First Cryo HEMT preamp being tested in Lyon**
- Synergie with EDELWEISS collaboration



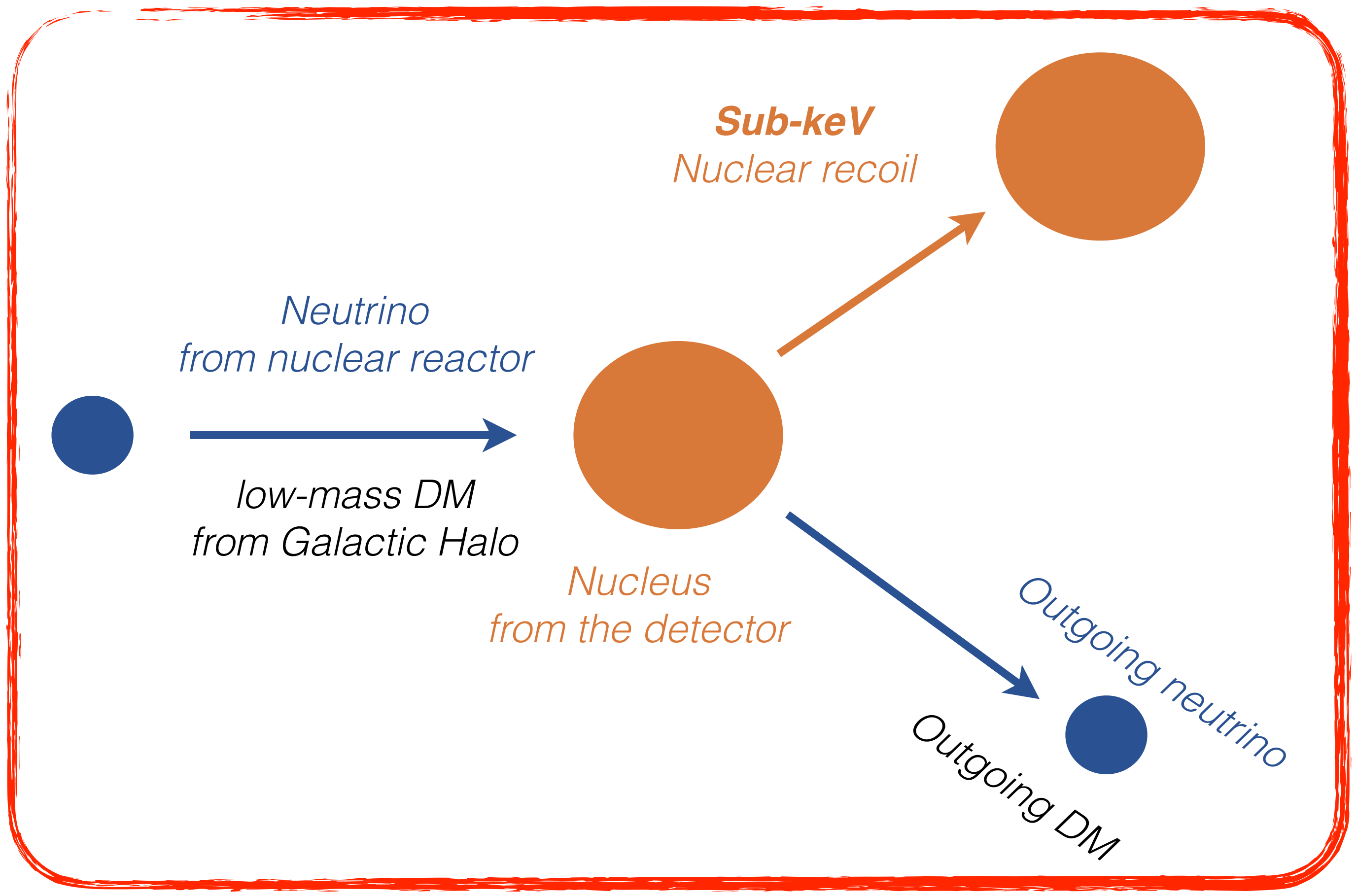
# CryoCube: *Particle Identification (Zn)*

**DBZ - 30 g Zn with NTD**



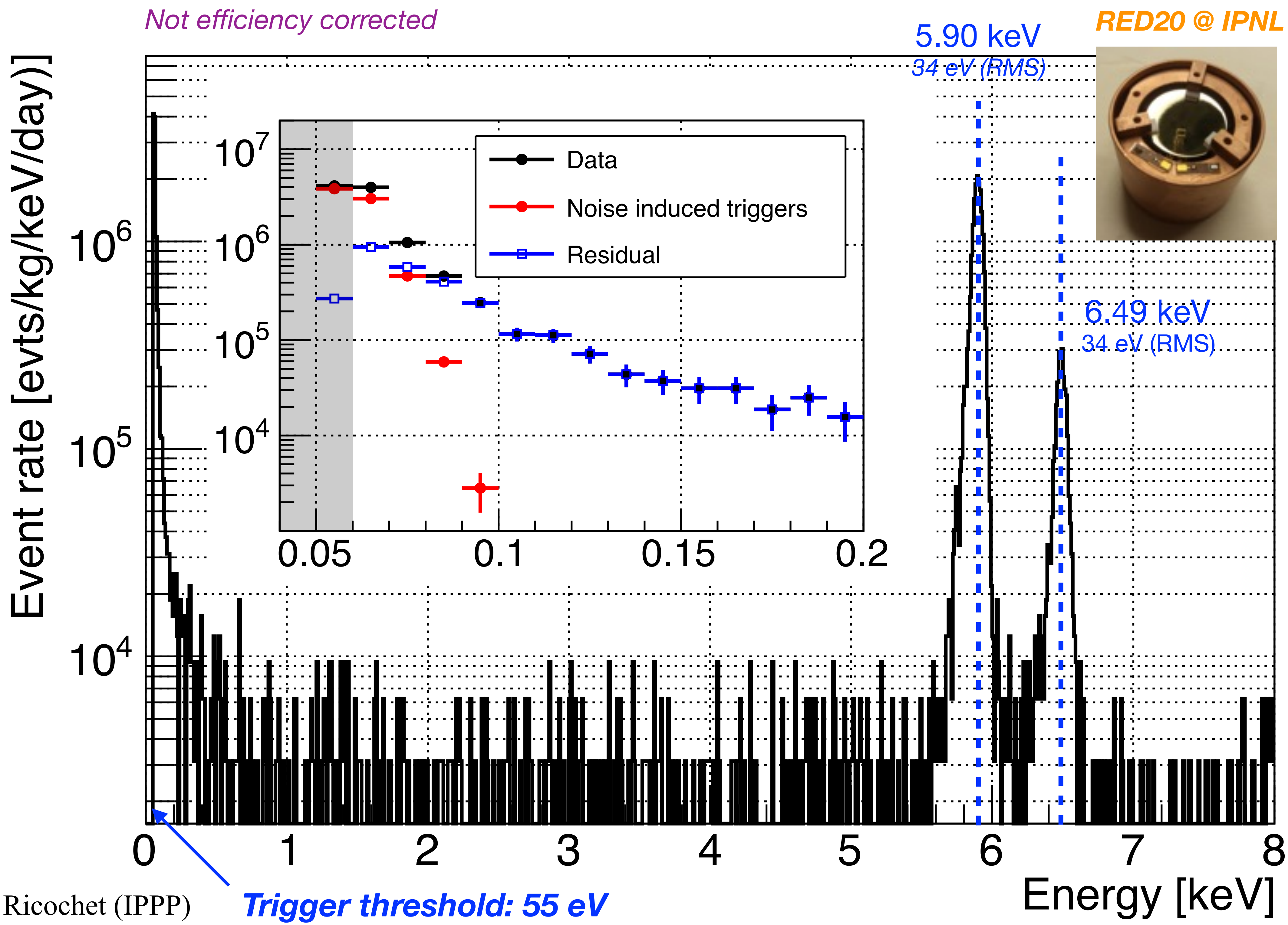

- Thanks to collaborative effort between MIT, CNSM and IPNL, first 30g Zn detector tested
- ***Clear detection of particles !***
- ***Clear evidence of two time constants (fast & slow) !***
  - *Evidence of vanishing quasiparticle-phonon coupling required for PSD ?*
- Next steps:
  - Characterize the crystal purity and heat capacity
  - Design a dedicated pulse shape sensitive data processing software
  - Neutron and gamma calibrations *(cross checked with Ge detector)*

# CryoCube: *Present sensitivity to CENNS*




*Estimating the CENNS sensitivity via DM searches*

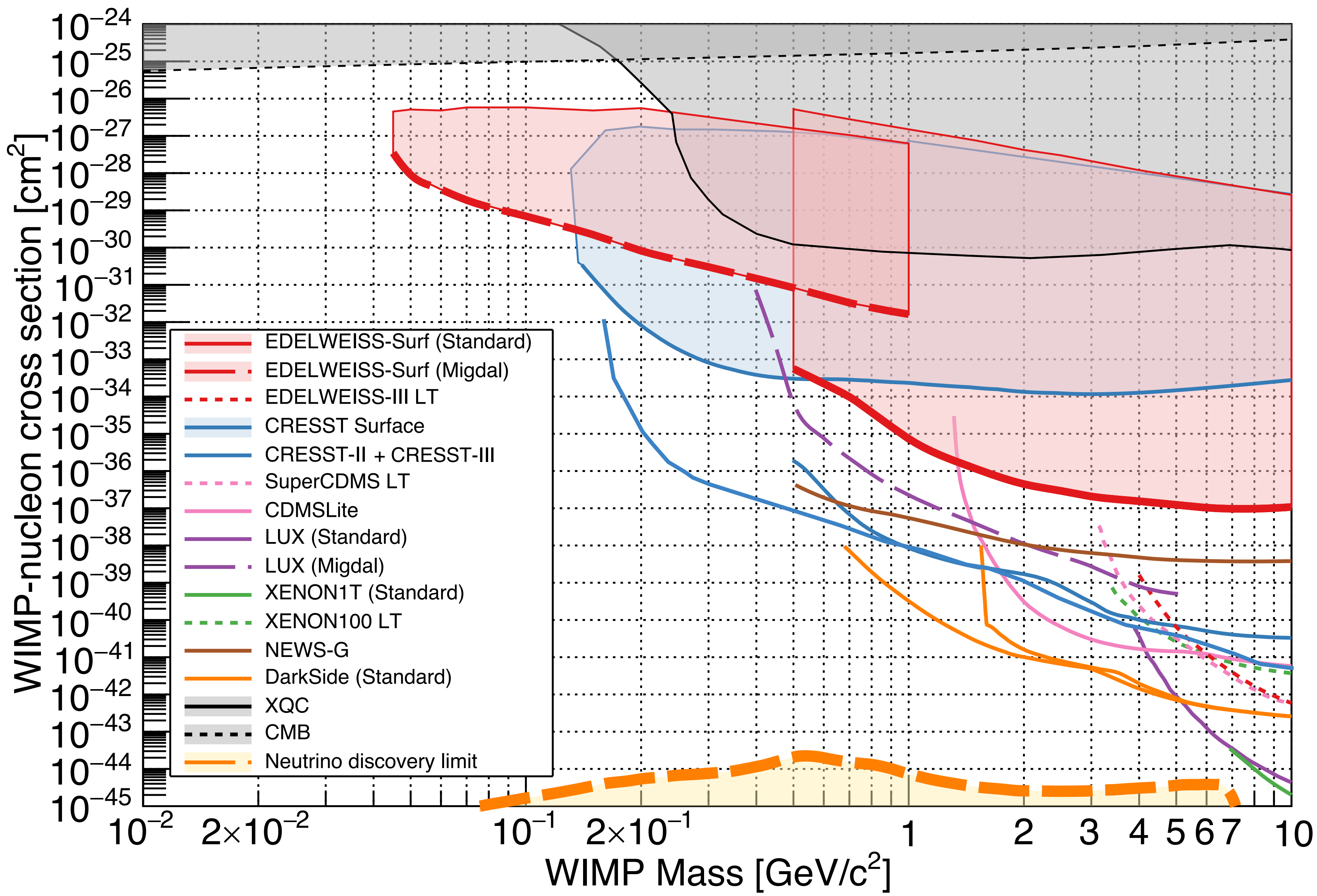
# CryoCube: *Present sensitivity to CENNS*




**RED20 @ IPNL**

E. Armengaud et al., Phys. Rev. D 99, 082003 (2019)

# CryoCube: *Present sensitivity to CENNS*




*E. Armengaud et al., Phys. Rev. D 99, 082003 (2019)*

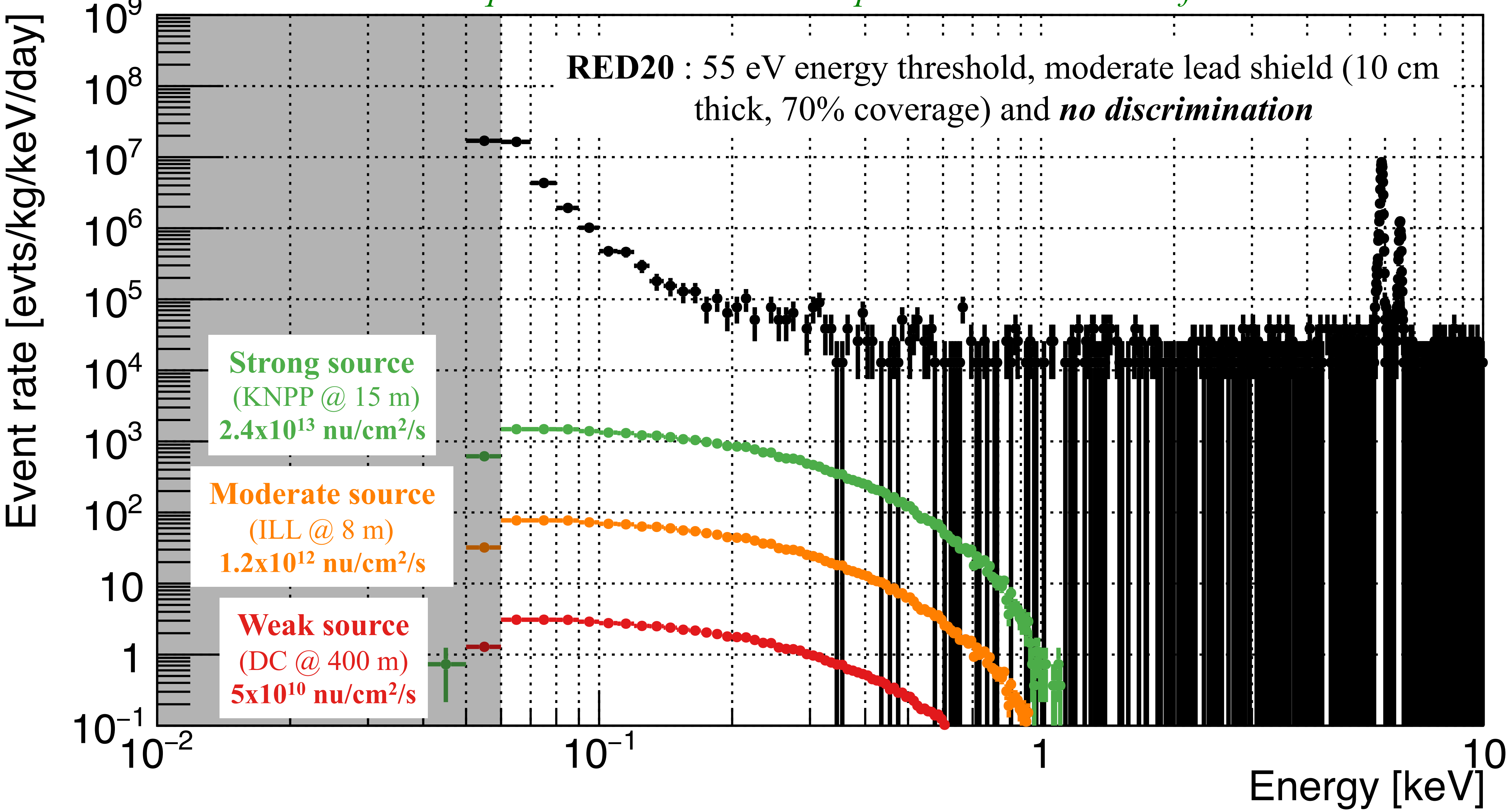
- ***DM - Nucleus interaction:*** first Ge-based limit below 1.2 GeV and best above ground limit down to 600 MeV
- ***Migdal effect***: first DM limit down to 45 MeV limited by Earth-Shielding effect *(B. Kavanagh, 2017)*, which becomes significant > $10^{-31}$ cm$^2$ *(plans to measure this effect with the EDELWEISS experimental setup)*
  - ***Upcoming results from EDELWEISS***: Exploring DM-electron/nucleus couplings with near single-electron sensitivity with massive bolometers operated underground

# CryoCube: *Present sensitivity to CENNS*

*Neutrino-WIMP equivalent model* ***independent of target material***

***CENNS signal from reactor neutrino is similar to a 2.7 GeV WIMP !!***

*The equivalent cross section depends on the neutrino flux*

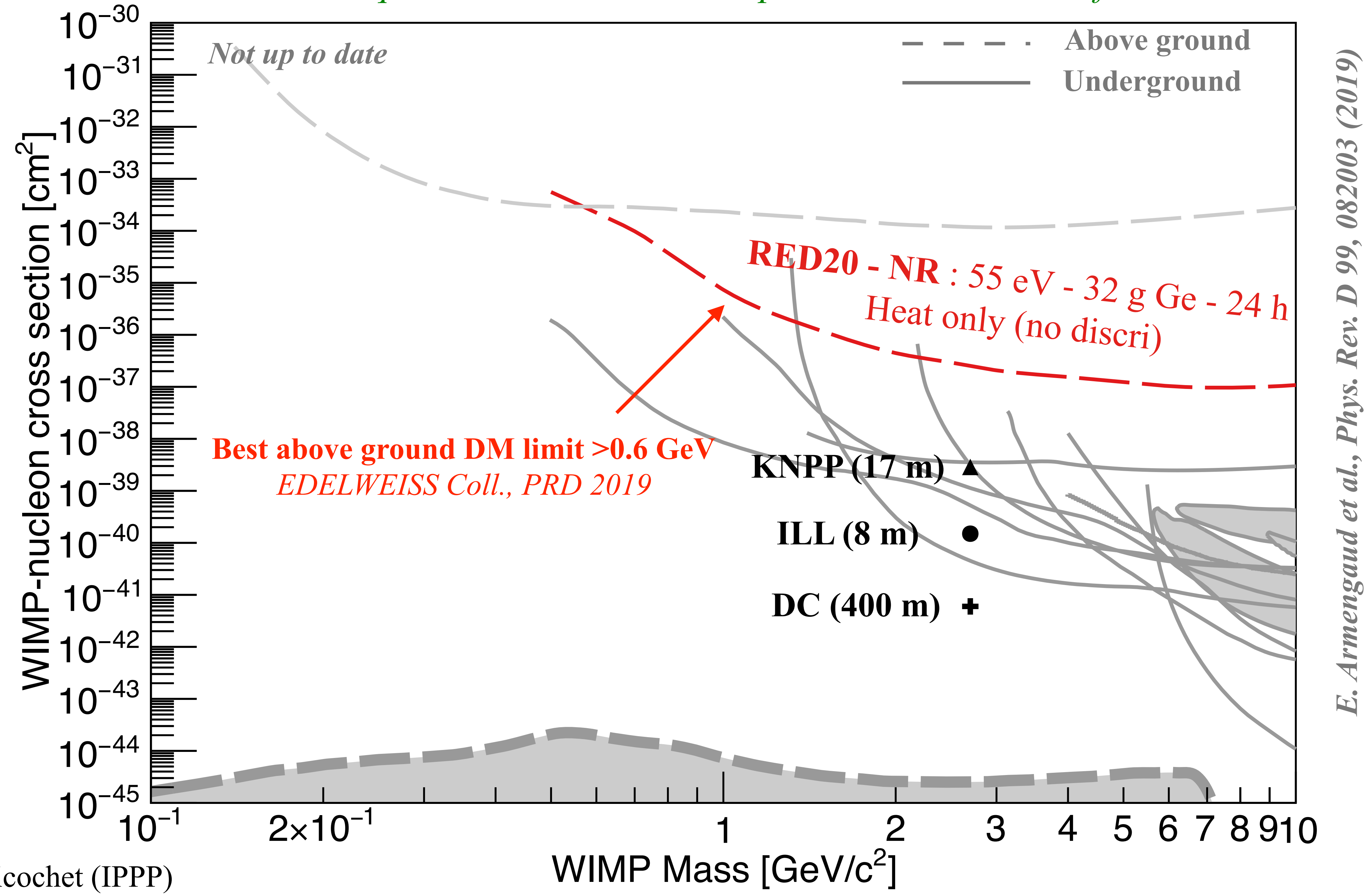


# CryoCube: *Present sensitivity to CENNS*

*Neutrino-WIMP equivalent model* ***independent of target material***

***CENNS signal from reactor neutrino is similar to a 2.7 GeV WIMP !!***

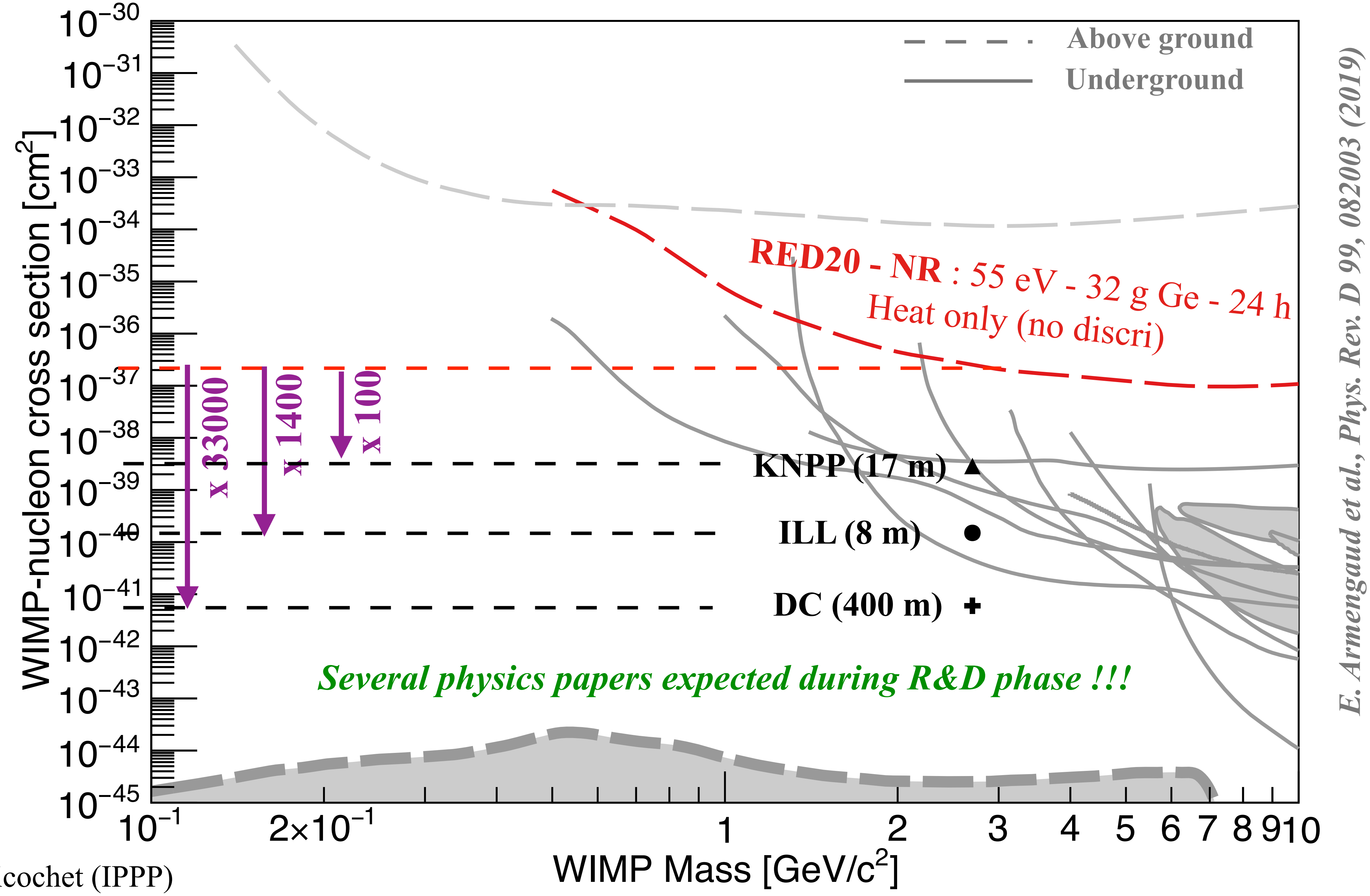
*The equivalent cross section depends on the neutrino flux*



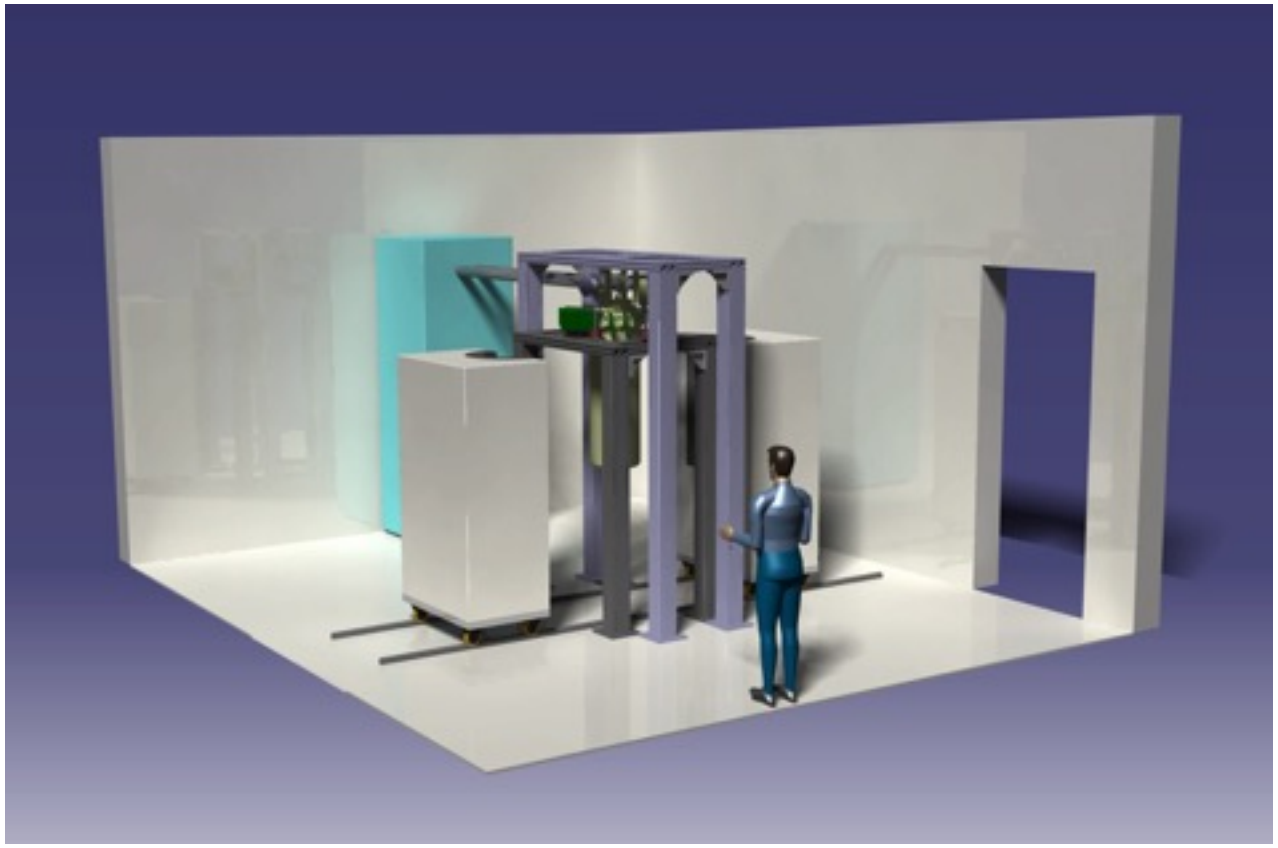
# CryoCube: *Present sensitivity to CENNS*

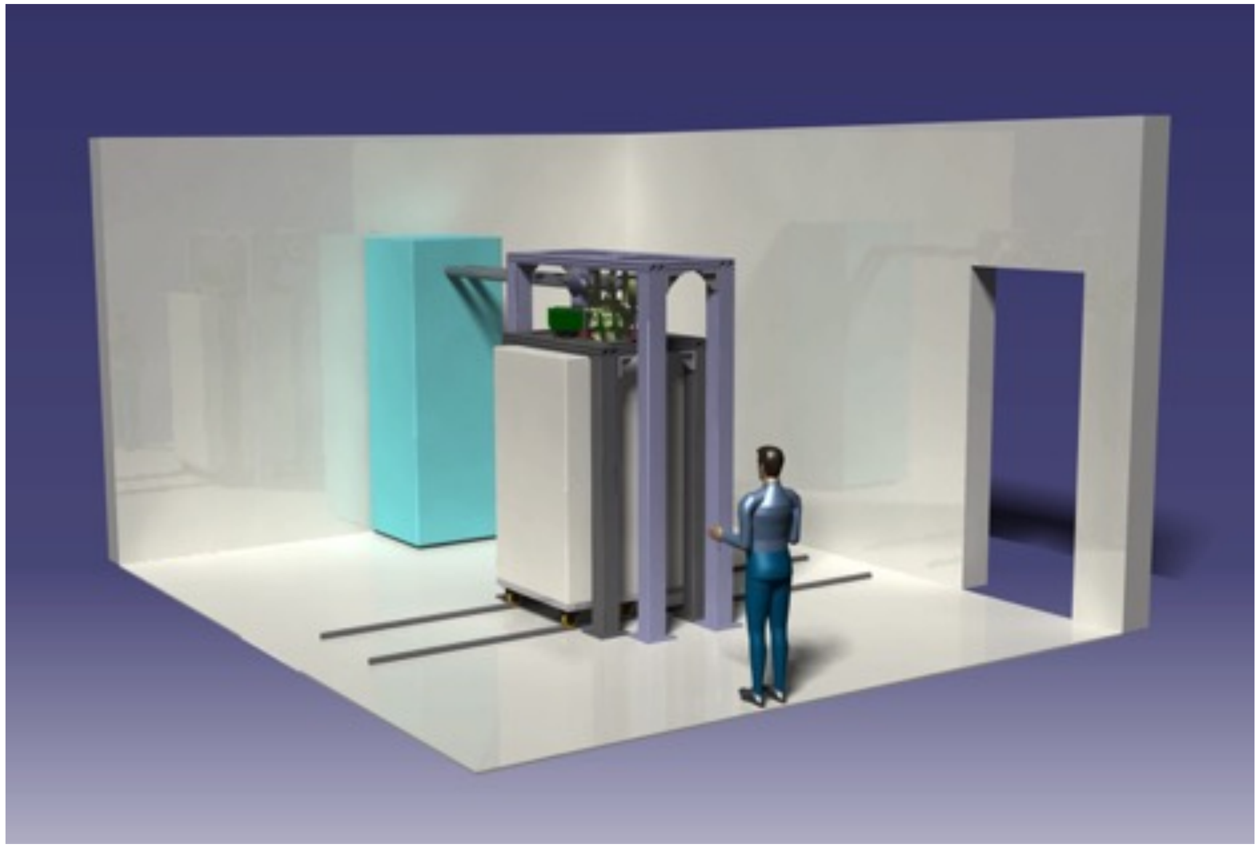
***Sensitivity improvement needed towards CENNS sensitivity @ reactors***

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



# RICOCHET: *The experimental setup*

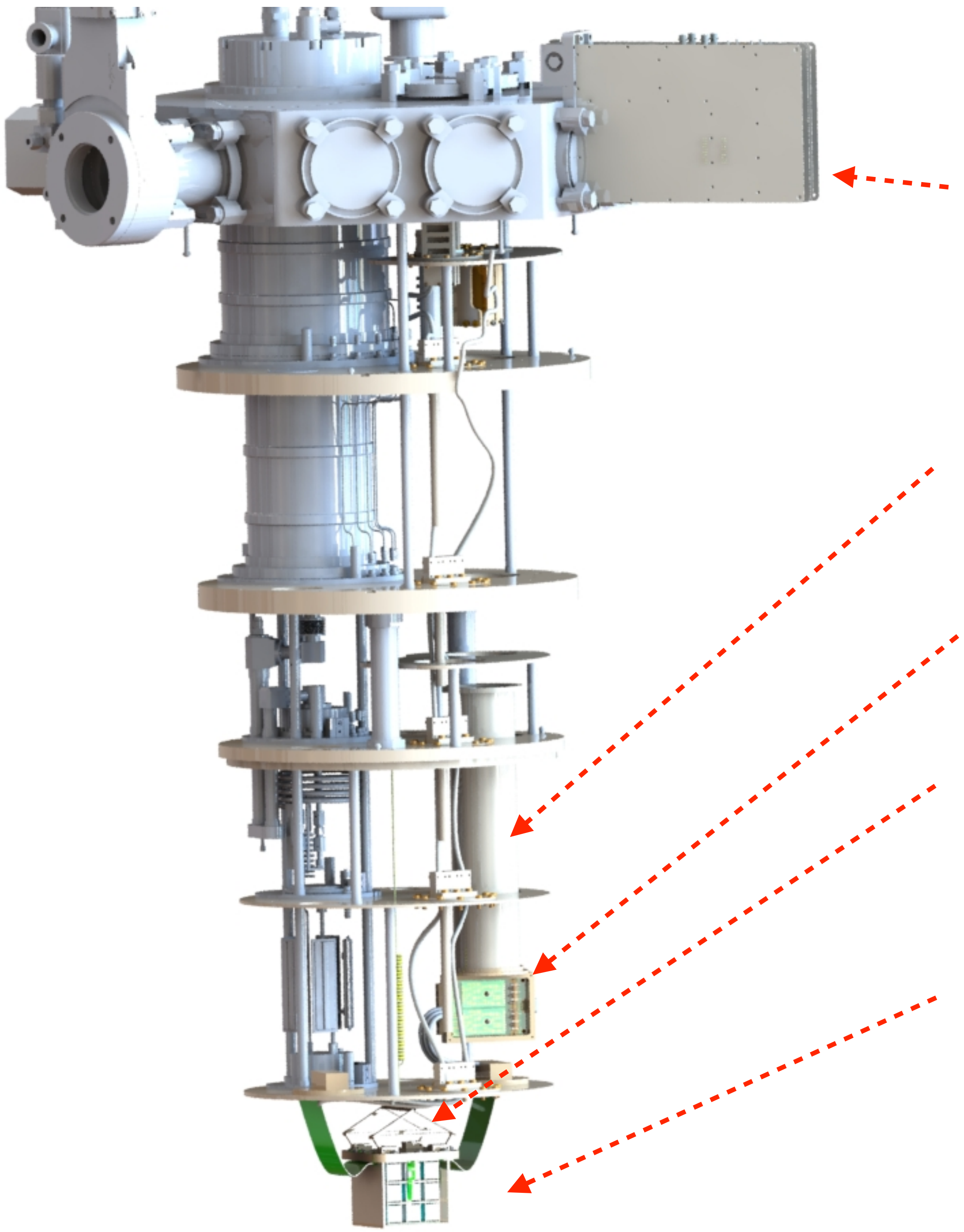




- **A very compact neutrino experiment**
- Use of a double frame: one for thermal machine (PT410) and one for the dilution unit
- Movable shields for a clear access to the cryostat and detectors
- Shields made of lead, ancient lead, high-density polyethylene, borated polyethylene and muon veto *(design under optimization with Geant4 simulations)*. Anticipated load of ~20 tons over 2 $m^2$
- Gas handling system *(pumps, He3/He4 tank and tubing, shown in cyan)*, should be in an adjacent room.

Preliminary

# RICOCHET: *The experimental setup*



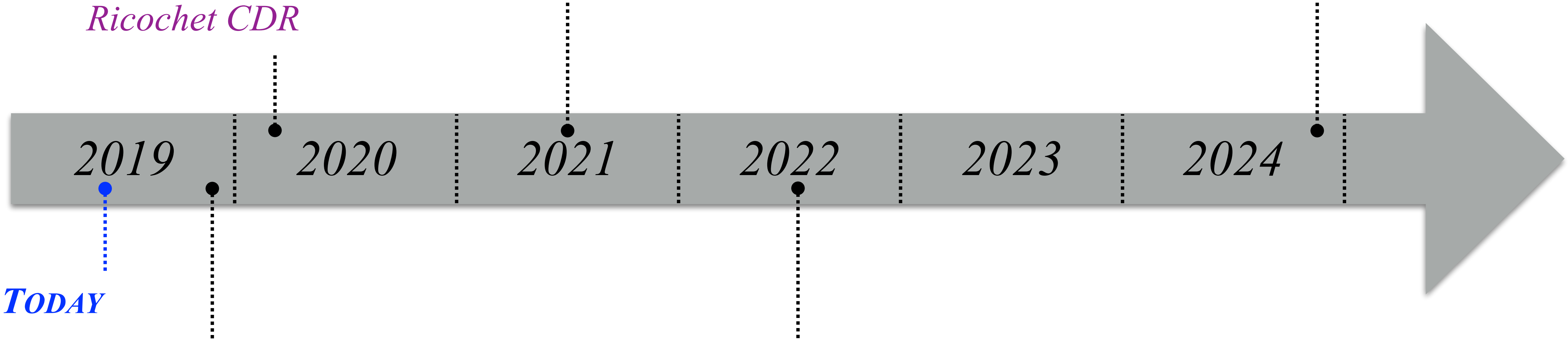
- **Design based on IPNL and MIT test facilities' results**
- Warm electronics (300 K): DC/DC converter + warm preamplifiers + ADC converter + optical fiber output
- Cold finger from 4K to the MC plate (10 mK)
- Front-end electronics: HEMT-Preamplifiers
- Suspended tower design to host both the CryoCube and the Multiplexed-TES detector arrays
- CryoCube detector array (8 x 8 x 8 $cm^3$)
- *Cold shielding (Pb and Polyethylene), and thermal screens not shown here*

# RICOCHET: *Anticipated timeline*

**2021:**
Ricochet's technical design completed (mechanics, cryostat, cabling, and warm elec.).
*Single crystal design completed (threshold & PID)*

**2024:**
Deliver the first low-energy (sub-100 eV) high-precision (%-level) CENNS measurement after 1 year of data taking

**2020:**
*Ricochet CDR*




**End-2019:**
Nuclear site decision and first version of Ricochet's experimental setup

**2022:**
Deployment of the Ricochet experiment at the chosen nuclear reactor site.
*CRYOCUBE delivery date*

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

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.***

***Onsite integration anticipated in 2022*** following the ongoing intense R&D phase to extend particle identification in a yet-to-be explored energy region.

# CENNS: *Probing new physics in the EW sector*

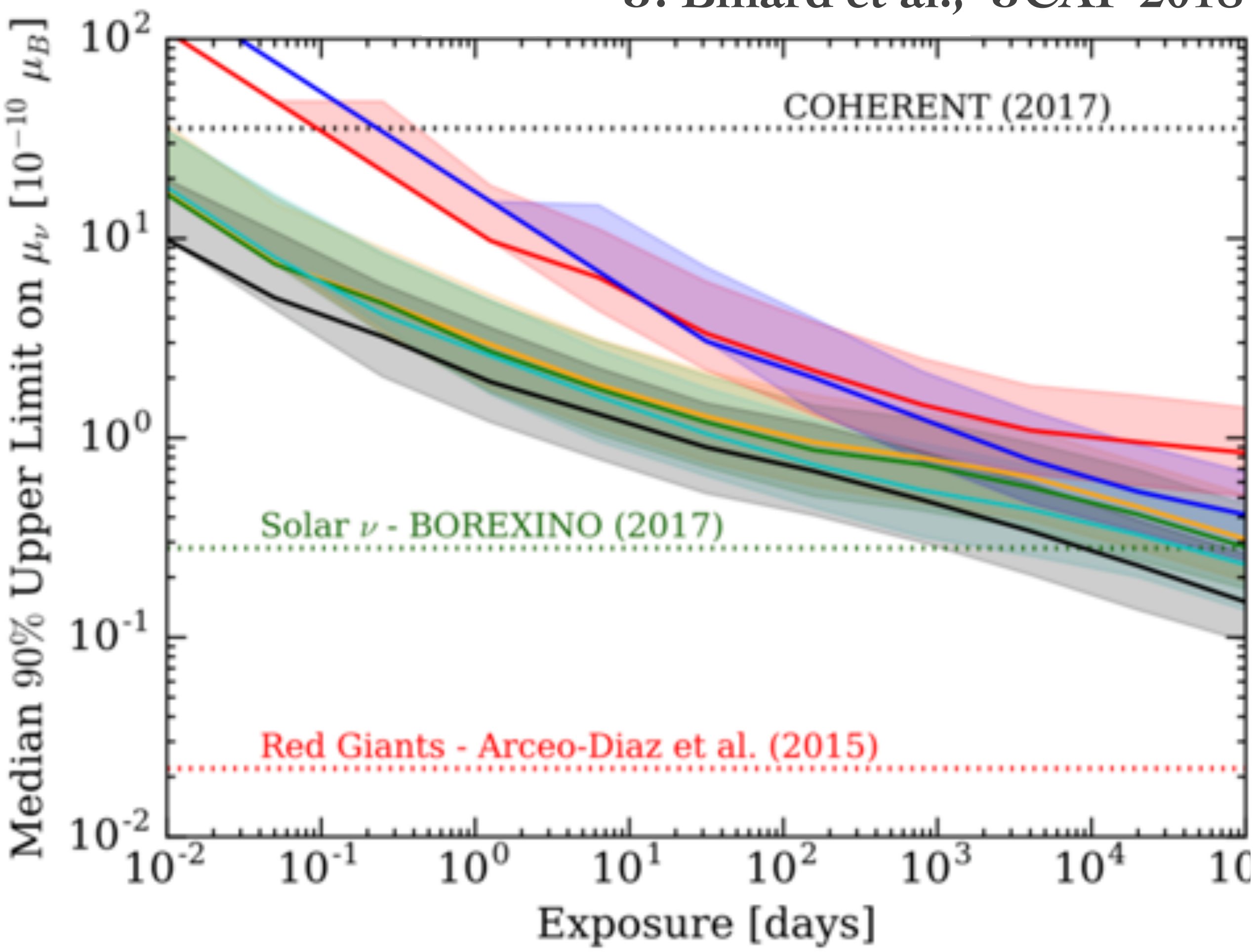
***Anomalously large neutrino magnetic moment:***

- A massive neutrino may acquire a magnetic moment due to radiation correction to its mass
- Such magnetic moment would enhance the neutrino-nucleus cross section via a charge-dipole interaction proportional to $Z^2$ as:

$$\frac{d\sigma^{\text{mag.}}_{\nu-N}}{dE_R} = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2}\left(\frac{1}{E_R} - \frac{1}{E_\nu} + \frac{E_R}{4E_\nu^2}\right)F^2(E_R)$$

- SM prediction for neutrino magnetic moment is tiny: $\mu_\nu \sim 3.2 \times 10^{-19}\mu_B$
  ***Essentially unobservable!***
- Strongest lab constraint comes from GEMMA:
  $\mu_\nu \lesssim 3.1 \times 10^{-11}\mu_B$
  **A. G. Beda et al., PPNL 10 (2013)**
- Contributions from loops of new heavy particles (e.g. in SUSY) can enhance to
  $\mu_\nu \sim \mathcal{O}(10^{-12})\mu_B$
  **Aboubrahim et al., PRD 89 (2014)**
- Evidence of an anomalously large NMM:
  - **There is new physics !**
  - **Neutrinos are Majorana**

**J. Billard et al., JCAP 2018**



# CENNS: *Probing new physics in the EW sector*

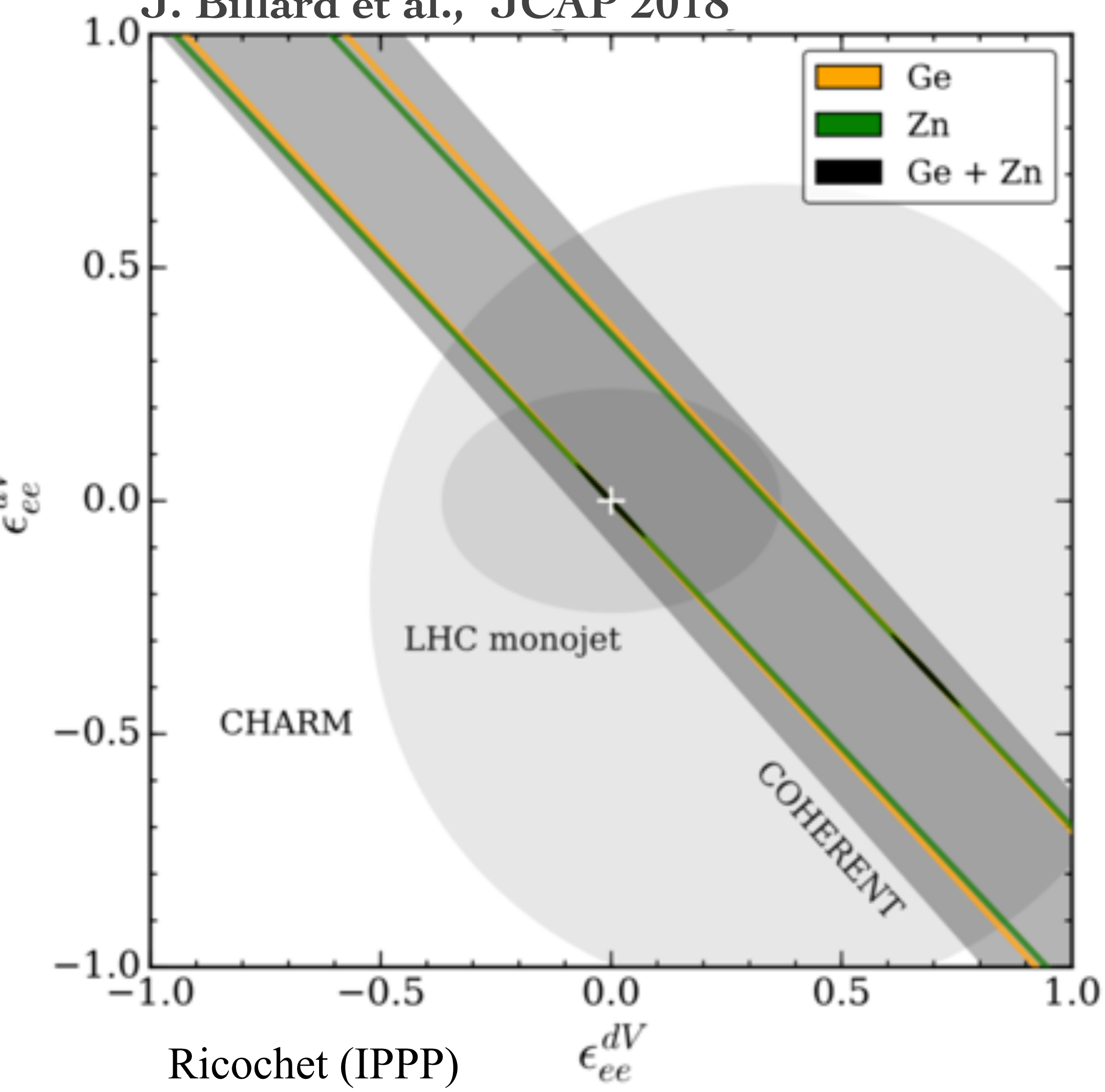
***Non Standard Neutrino Interactions***

- At low-energy, non-standard neutrino interactions are described by a point-like 4-fermion interactions:

$$\mathcal{L}^{\rm NSI} = -\epsilon_{\alpha\beta}^{qV} 2\sqrt{2} G_F (\overline{\nu}_\alpha \gamma_\mu \nu_\beta)(\overline{q}\gamma^\mu q)$$

**S. Davidson et al., JHEP 03 (2003)**

**J. Billard et al., JCAP 2018**




Ricochet (IPPP)

Existence of NSI could affect the measurement of neutrino oscillation parameters and is therefore necessary to alleviate the degeneracies among them

They naturally arise in many extensions of the Standard Model

Thanks to target complementarity, we will improve by ~2 orders of magnitude the constraints on NSI

**CHARM -** High energy neutrino scattering

**J. Dorenbosch et al., PLB 180 (1986)**

**LHC monojet -** constraints on $p + p \rightarrow \overline{\nu}_e + \nu_e$

**A. Friedland et al., PLB 714 (2012)**

# CENNS: *Probing new physics in the EW sector*

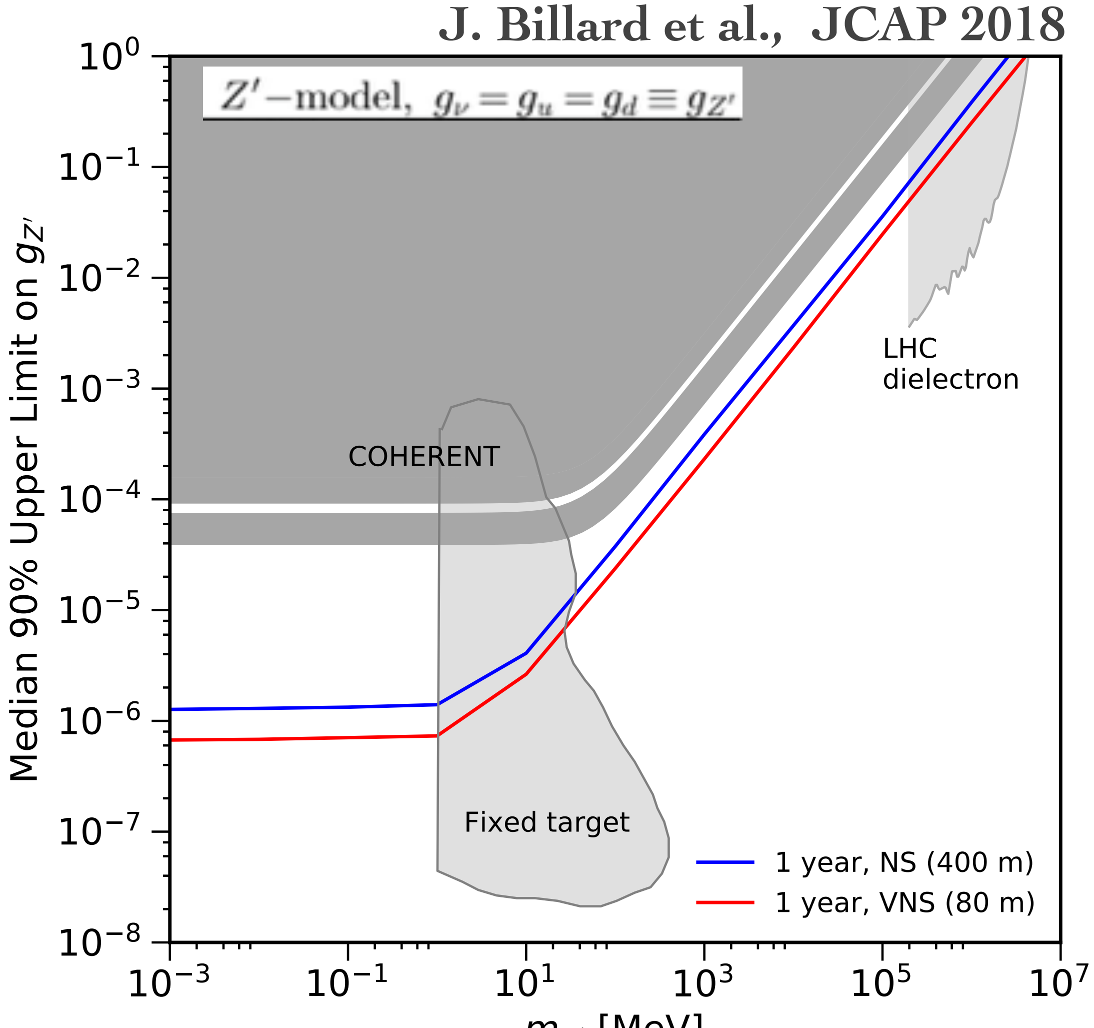
***New massive mediators***

- Add a new vector mediator *Z'* to the Standard Model

$$\mathcal{L}_{Z'} = Z'_\mu \left[g_\nu(\overline{\nu_e}\gamma^\mu\nu_e) + g_\ell(\bar{e}\gamma^\mu e) + g_u(\overline{u}\gamma^\mu u) + g_d(\bar{d}\gamma^\mu d)\right]$$

- Induce an *energy-dependent* modification of nuclear charge

J. Billard et al., JCAP 2018




Ricochet (IPPP)

$$Q_W \to Q_W - \frac{\sqrt{2}}{G_F}\frac{Q_{Z'}}{q^2 + m_{Z'}^2}$$

- Interference with SM Z-boson may increase or decrease recoil rate, and change the energy spectrum
- Competitive over all mass range
- Two orders of magnitude improvement with respect to COHERENT
- Similar results also for scalar mediator

ATLAS dielectron resonances    Fixed target beam dumps

ATLAS, PLB 761 (2016)    R. Harnik et al., JCAP 1207 (2012)