New mK-temperature Germanium detectors for Dark Matter direct search and for precision measurements of CEvNS

Evgeny Yakushev, JINR, Dubna

Two very interesting directions: Neutrino Physics and Dark Matter

The Universe

~5% NORMAL MATTER

~25% DARK MATTER

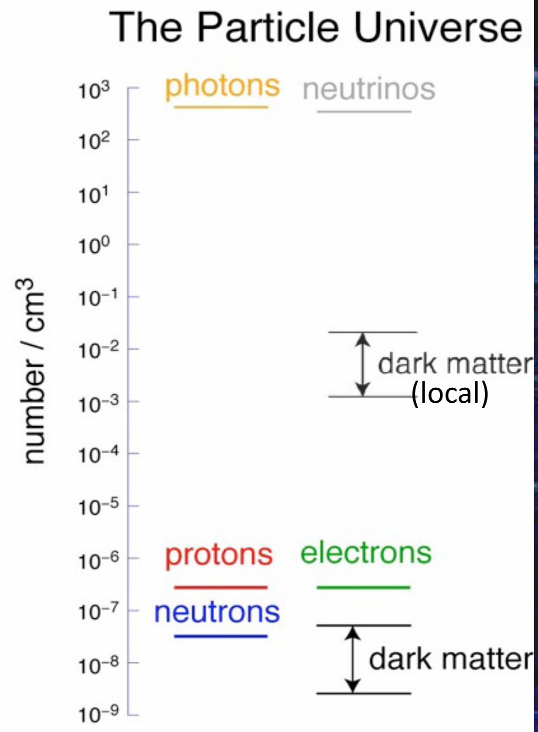
DARK ENERGY

DARK ENERGY

~70%

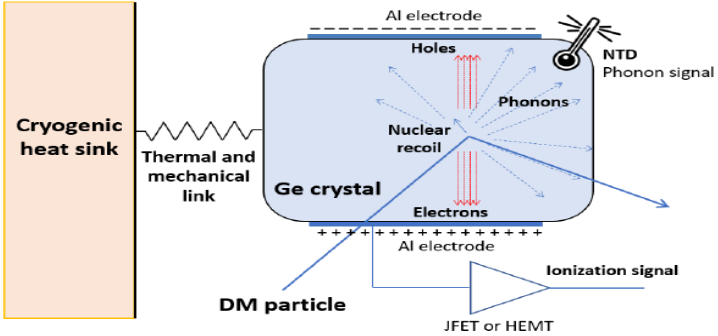
DARK ENERGY

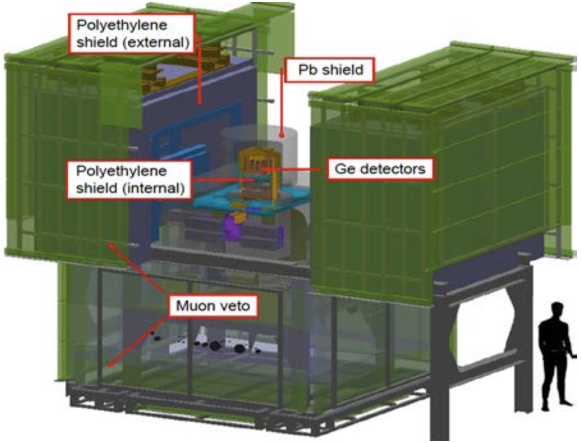
DARK ENERGY

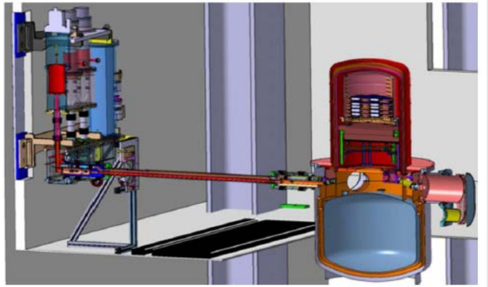


The Particle Universe

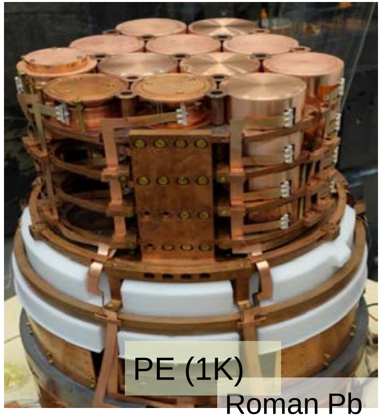
EDELWEISS (Heat and ionization HPGe bolometers)

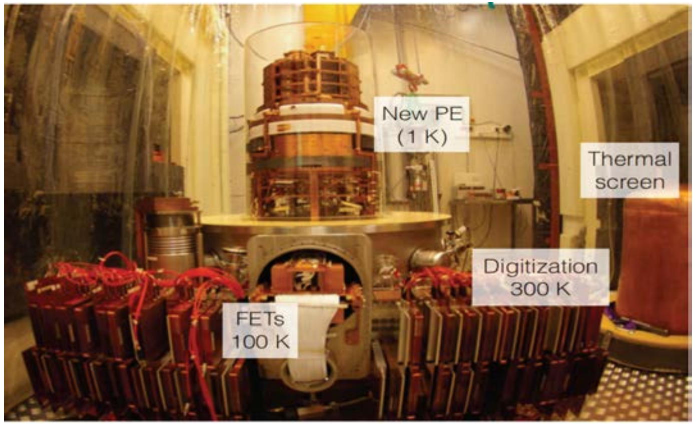






- LSM underground laboratory (France), 4800 mwe
- Clean room + deradonized air
  Rn monitoring down to few mBq/m^3
- Active muon veto (>98% coverage)
- External (50 cm) + internal polyethylene shielding
  Thermal neutron monitoring with ^{3}He detector
- Lead shielding (20 cm, incl. 2 cm Roman lead)
- Selection of radiopure material
- Cryostat can host up to 40 kg detector, at 18 mK



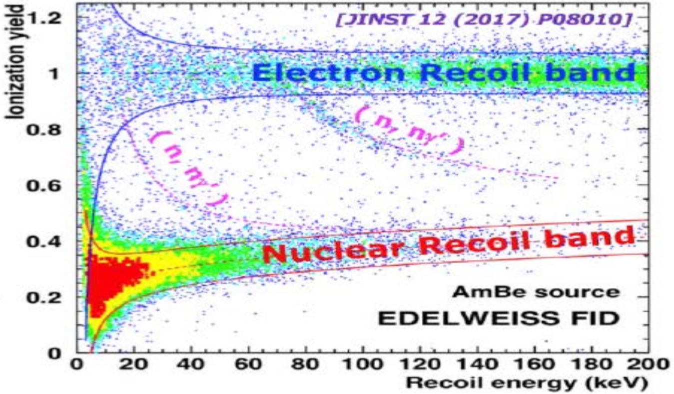


EDELWEISS (Heat and ionization Ge bolometers)

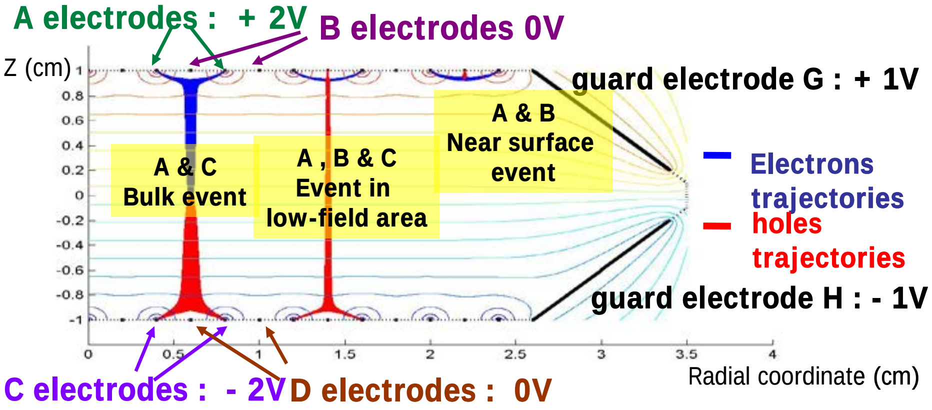
Edelweiss
Expérience pour DEtecter Les WIMPs En SIte Souterrain

Using of *Heat* and *Ionization* HPGe detectors, running in ^{3}He-^{4}He dilution cryostat (<20 mK)

Ratio $E_{ionization}/E_{recoil}$ is
=1 for electronic recoil
≈0.3 for nuclear recoil
⇒Event by event identification of the recoil
⇒Discrimination g/n > 99.99%


[JINST 12 (2017) P08010]

Detectors with special concentric planar electrodes for active rejection of surface events (miss-collected charge)


A electrodes : + 2V

B electrodes 0V

guard electrode G : + 1V

A & C
Bulk event

A , B & C
Event in
low-field area

A & B
Near surface
event

Electrons trajectories

holes trajectories

guard electrode H : - 1V

C electrodes : - 2V

D electrodes : 0V

Direct detection of Dark Matter, germanium target, LSM deep underground laboratory

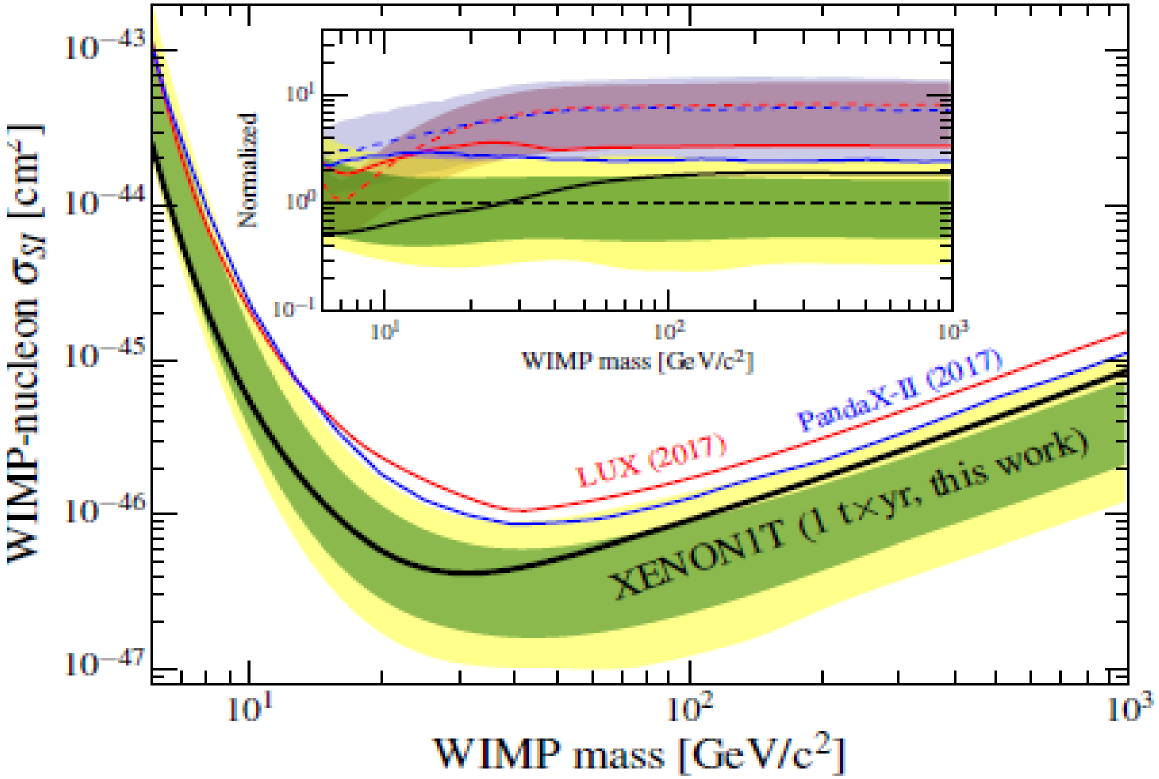
For the past 25 years EDELWEISS is the leading experiment for direct Dark Matter search with Germanium detectors.

Unique, continuously developing technology of ultra-low temperature HPGe detectors-bolometers operated at low background environment.

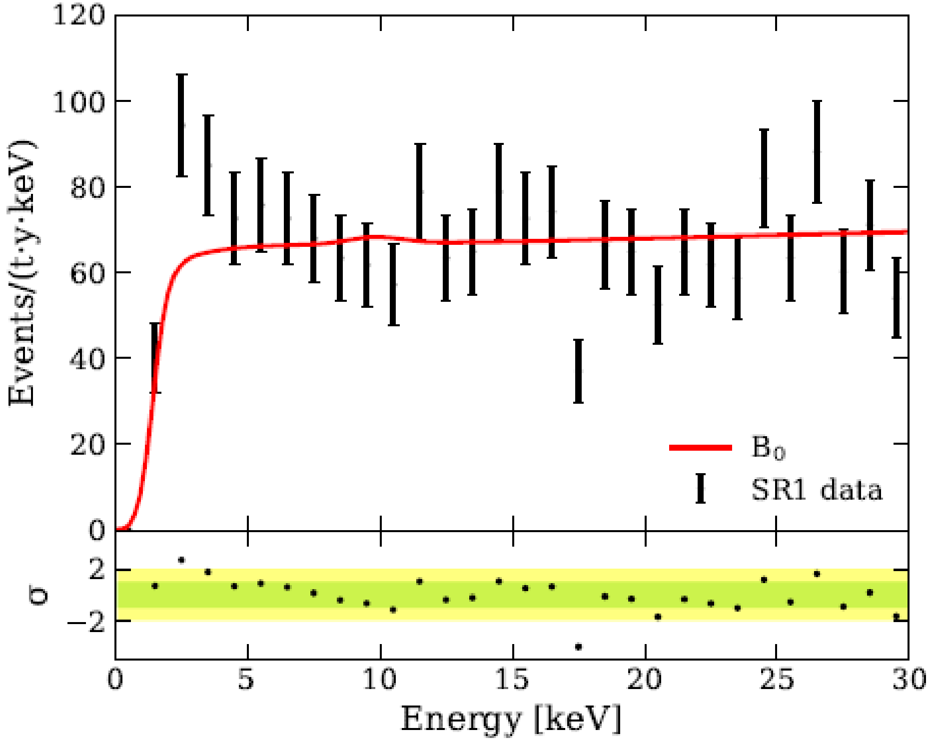
Thanks to the excellent energy resolution, the experimental program is shifted in the energy region inaccessible by other technologies (Ar/Xe based).

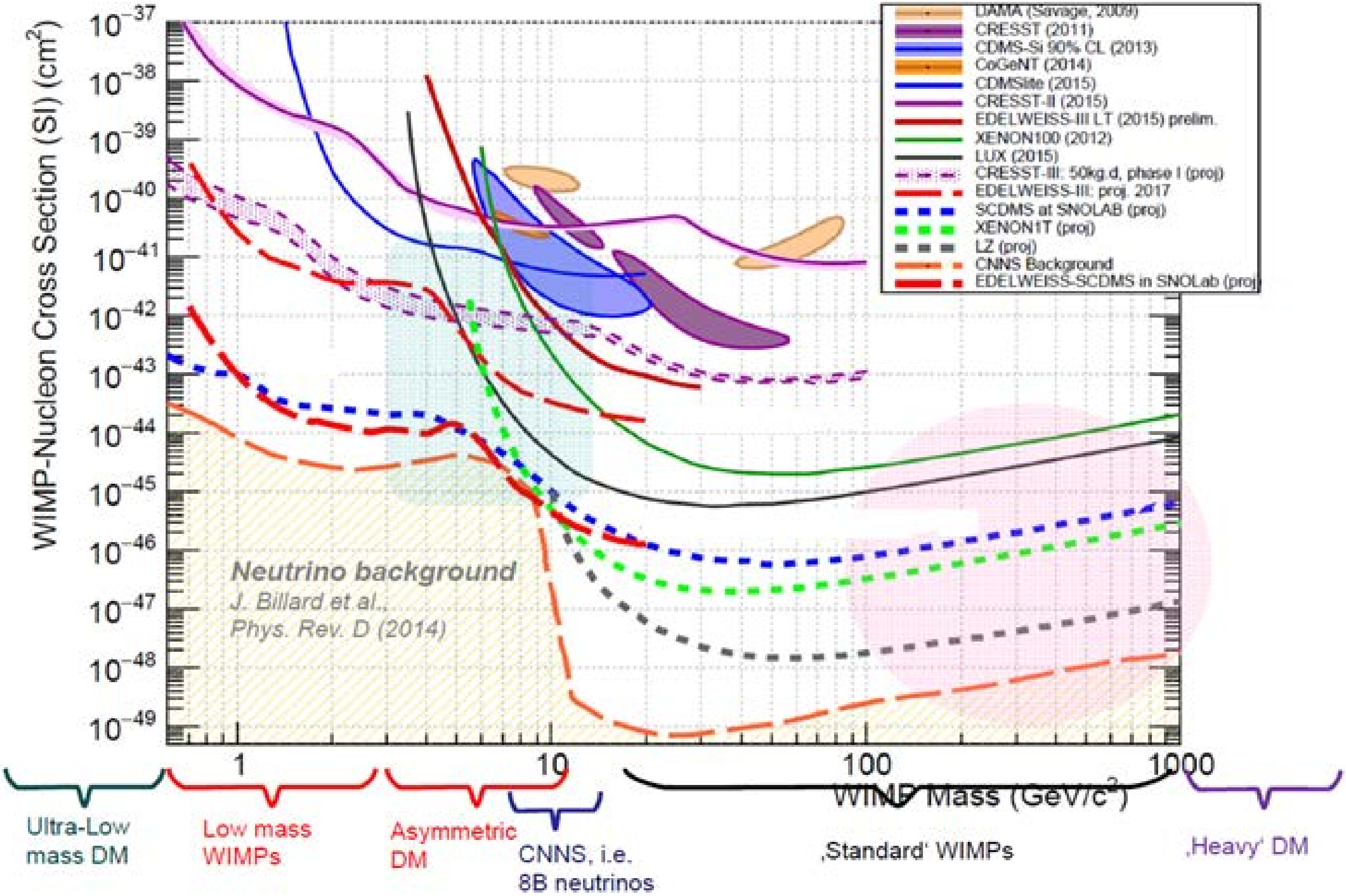
An increasing gain of interest for the search of low-mass, very-heavy WIMPs, other possible condidates

- Non evidence yet for SUSY at the LHC;
- New theoretical approaches favoring lighter candidates;
- No WIMP signals in the “expected” region;
- Controversial results in the region around and below of 10 GeV/c².



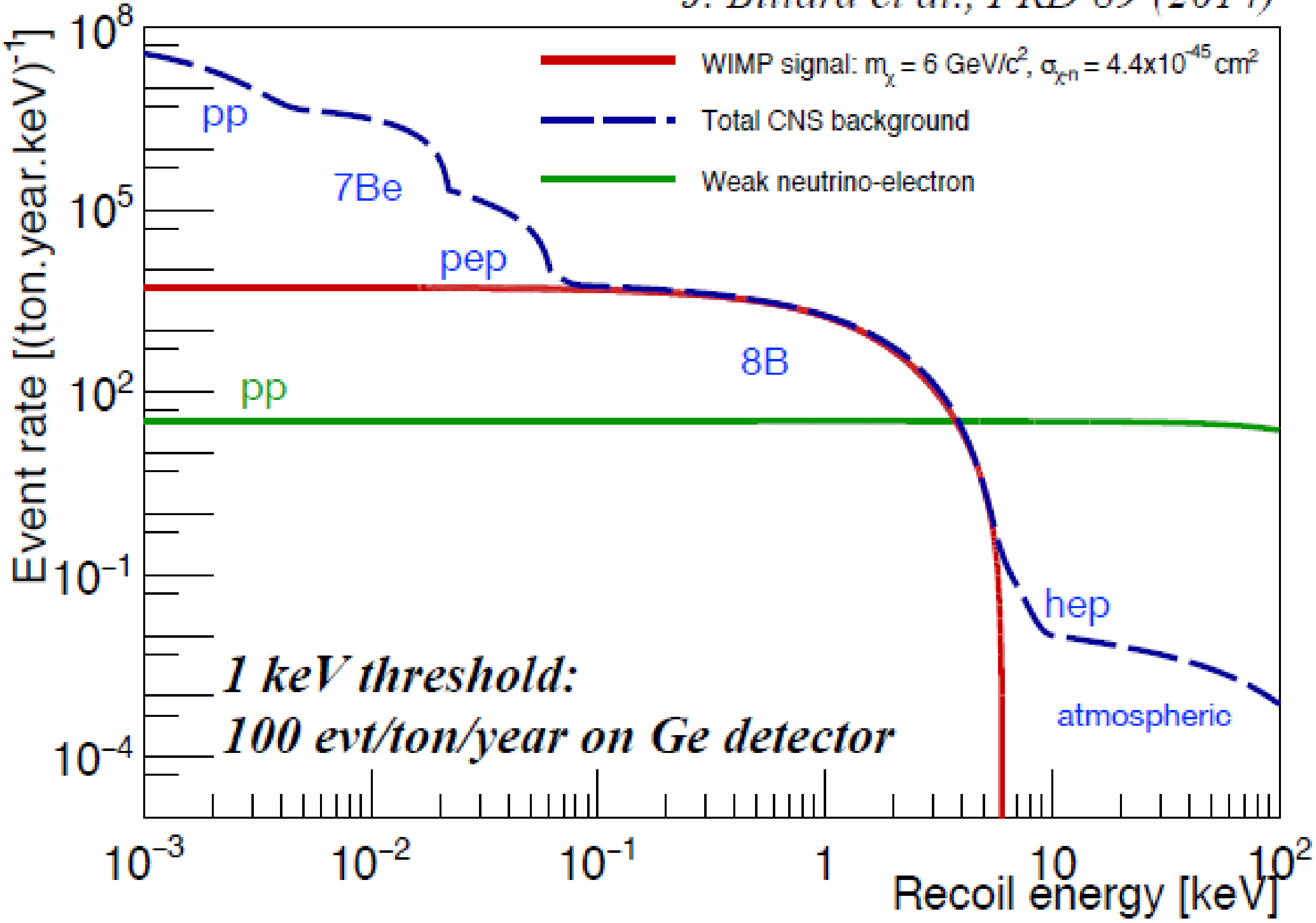
Observation of Excess Electronic Recoil Events in XENON1T

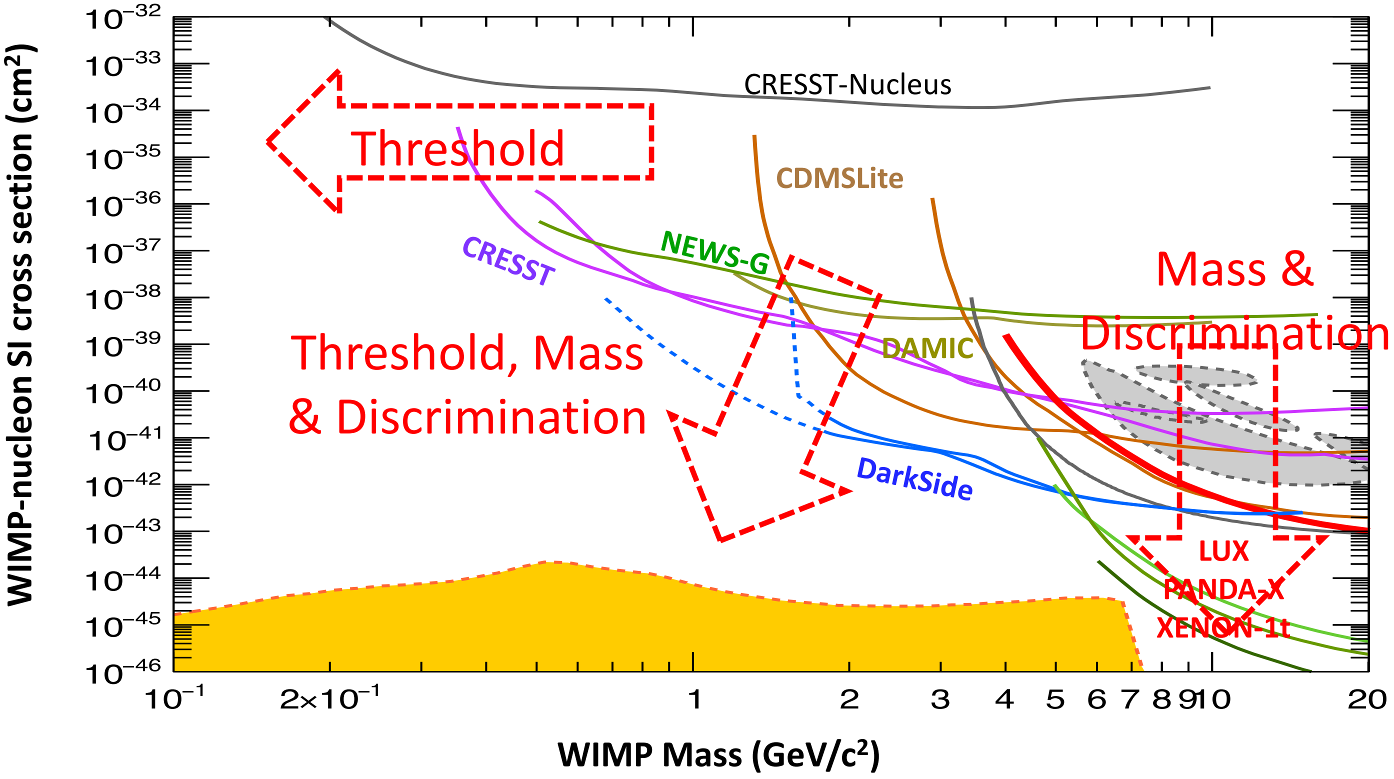




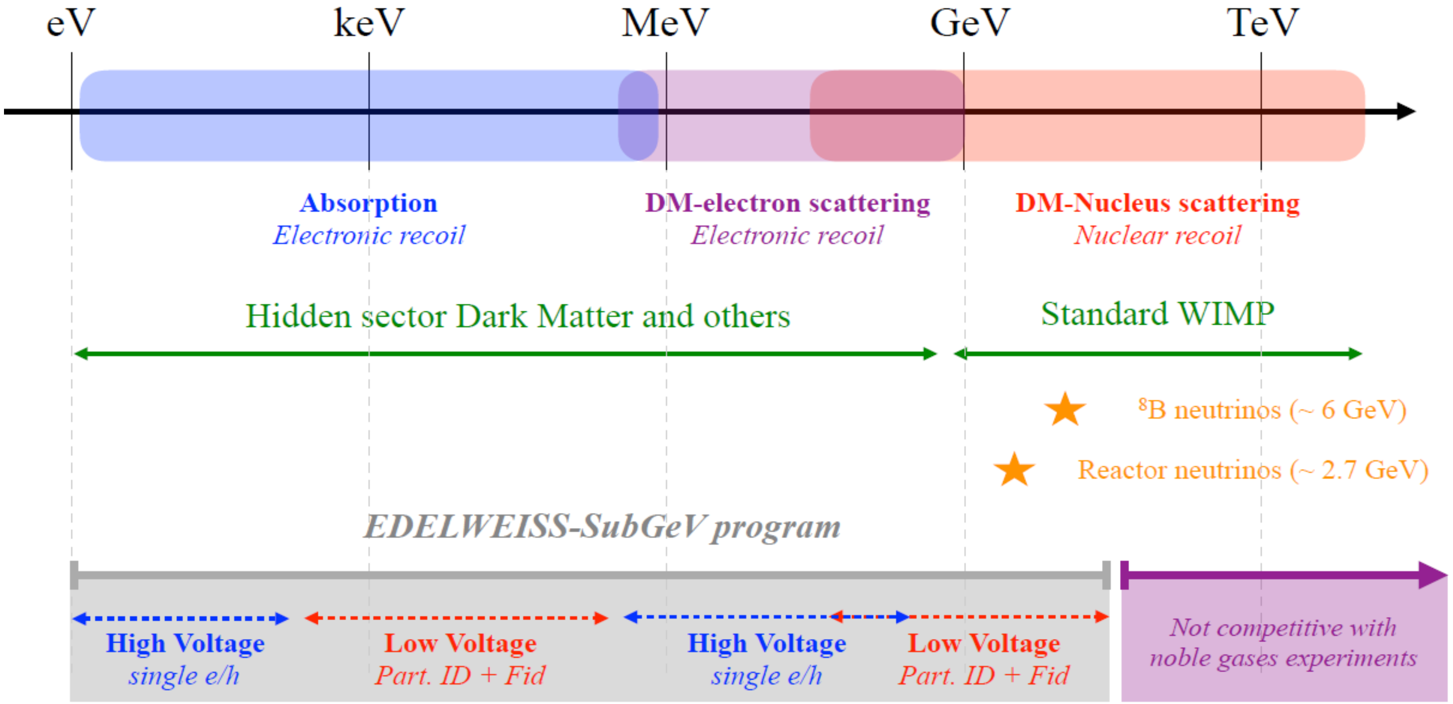
DAMA (Savage, 2009)
CRESST (2011)
CDMS-Si 90% CL (2013)
CoGeNT (2014)
CDMSlite (2015)
CRESST-II (2015)
EDELWEISS-III LT (2015) prelim.
XENON100 (2012)
LUX (2015)
CRESST-III: 50kg.d, phase I (proj)
EDELWEISS-III: proj. 2017
SCDMS at SNOLAB (proj)
XENON1T (proj)
LZ (proj)
CNNS Background
EDELWEISS-SCDMS in SNOLab (proj)
WIMP-Nucleon Cross Section (SI) (cm^2)
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
Neutrino background
J. Billard et al.,
Phys. Rev. D (2014)
1
10
100
1000
WIMP Mass (GeV/c^2)
Ultra-Low mass DM
Low mass WIMPs
Asymmetric DM
CNNS, i.e. 8B neutrinos
‚Standard‘ WIMPs
‚Heavy‘ DM

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




WIMP-nucleon SI cross section (cm²)
10⁻³²
10⁻³³
10⁻³⁴
10⁻³⁵
10⁻³⁶
10⁻³⁷
10⁻³⁸
10⁻³⁹
10⁻⁴⁰
10⁻⁴¹
10⁻⁴²
10⁻⁴³
10⁻⁴⁴
10⁻⁴⁵
10⁻⁴⁶
10⁻¹
2×10⁻¹
1
2
3
4
5
6
7
8
9
10
20
WIMP Mass (GeV/c²)
CRESST-Nucleus
Threshold
CDMSLite
NEWS-G
CRESST
DAMIC
Threshold, Mass
& Discrimination
DarkSide
Mass &
Discrimination
LUX
PANDA-X
XENON-1t

EDELWEISS-SubGeV: *Scientific context*



Absorption
Electronic recoil

DM-electron scattering
Electronic recoil

DM-Nucleus scattering
Nuclear recoil

Hidden sector Dark Matter and others

Standard WIMP

★ ^{8}B neutrinos (~ 6 GeV)

★ Reactor neutrinos (~ 2.7 GeV)

EDELWEISS-SubGeV program

High Voltage
single e/h

Low Voltage
Part. ID + Fid

High Voltage
single e/h

Low Voltage
Part. ID + Fid

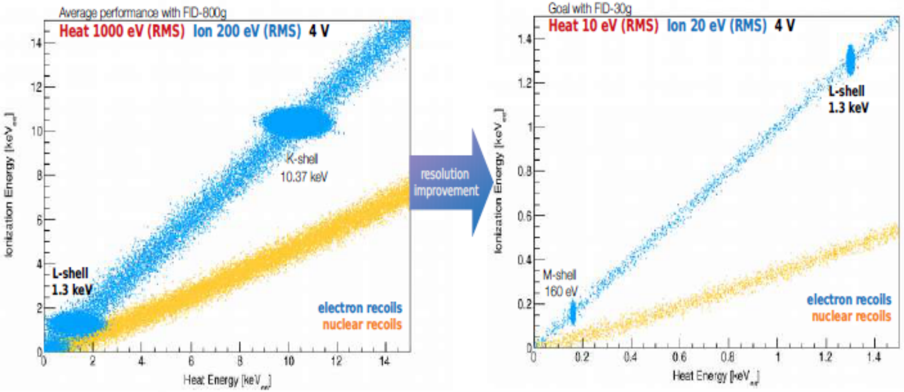
Not competitive with noble gases experiments

EDELWEISS SubGeV two modes

Low Voltage Objectives

- 10 eV (RMS) Heat energy resolution
- 20 eV (RMS) Ionization energy resolution

Particle identification & surface event rejection down to 50 eV



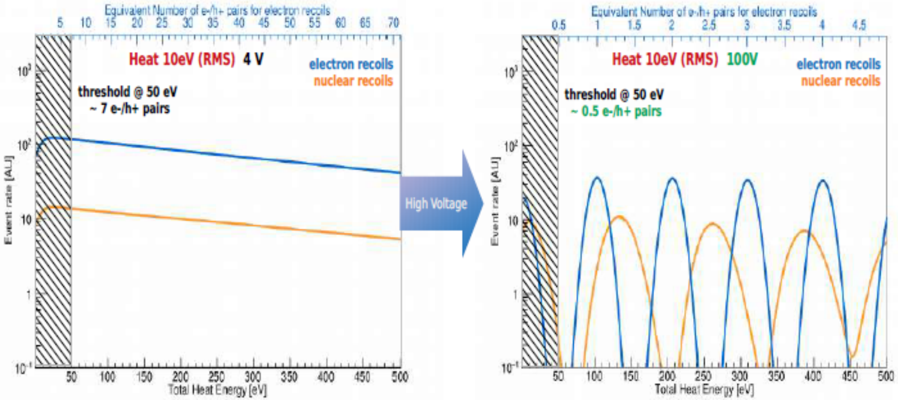
Low-voltage objectives are part of a common effort with the Ricochet collaboration, dedicated to studying CENNS at reactors supported by the ERC-CENNS Starting Grant (2019-2024)

High Voltage Objectives

- 10 eV (RMS) Heat energy resolution
- 100 V with signal amplification only

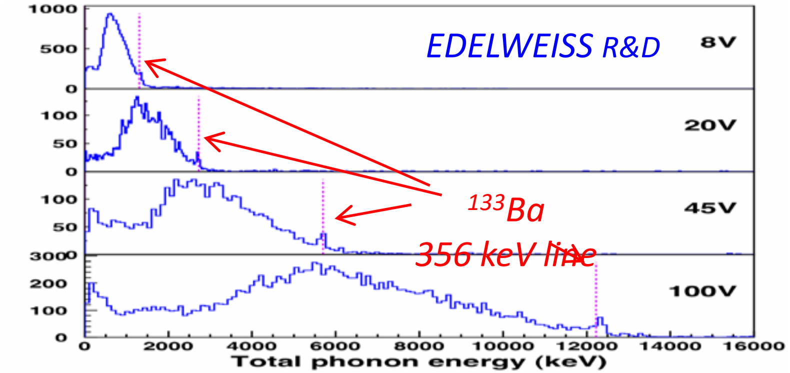
Single-e/h pair sensitivity with massive (~30g) bolometers

Single **ELE**ctron **N**uclear recoil **DIS**crimination
SELENDIS



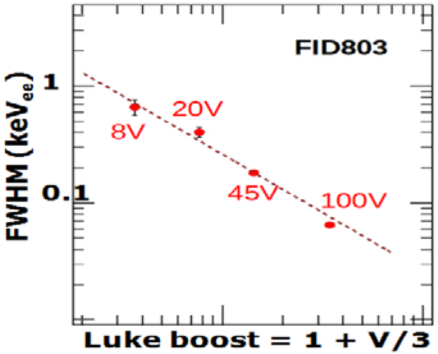
SELENDIS project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 838537

HV: Neganov-Trofomov-Luke effect for internal amplification of the heat signals.

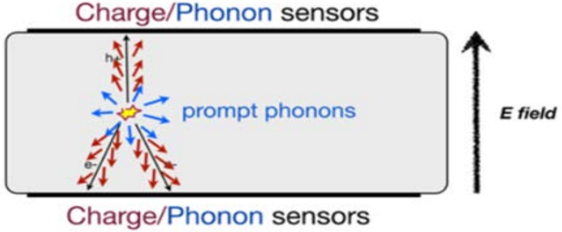


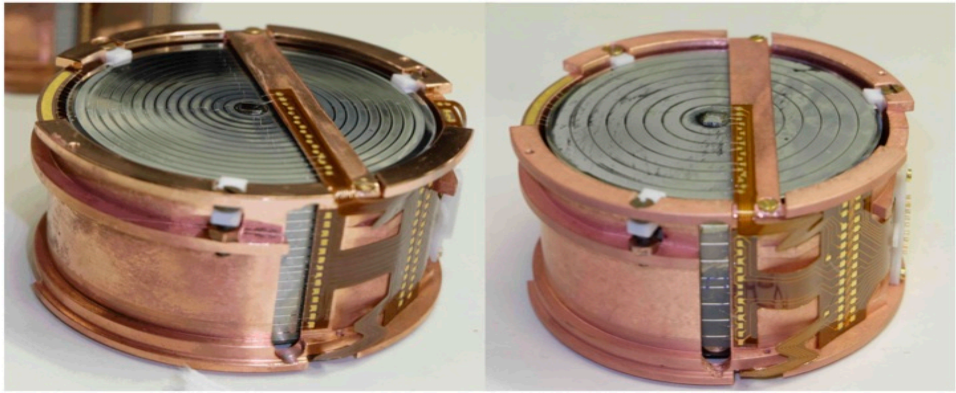
EDELWEISS R&D

^{133}Ba
356 keV line



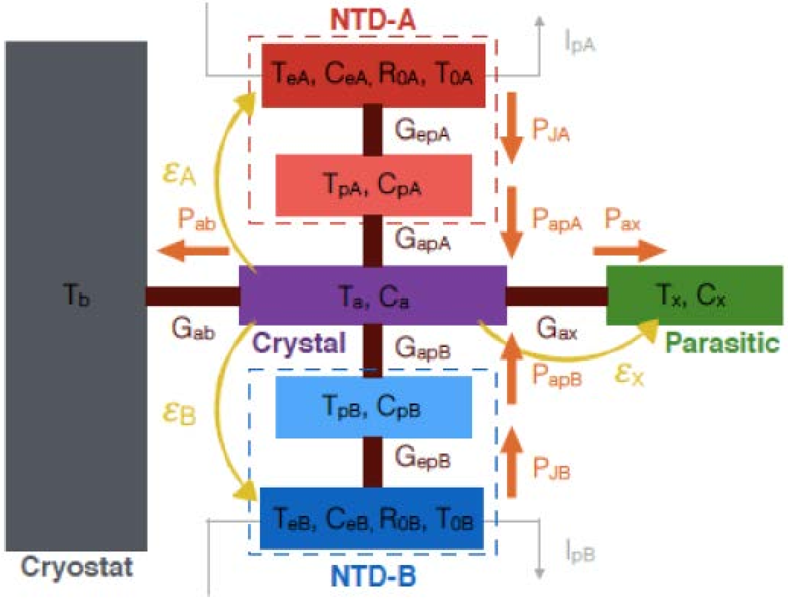
$$E_t = E_r + \frac{1}{3\ eV} E_Q \Delta V$$





How to improve resolution (decrease noise)

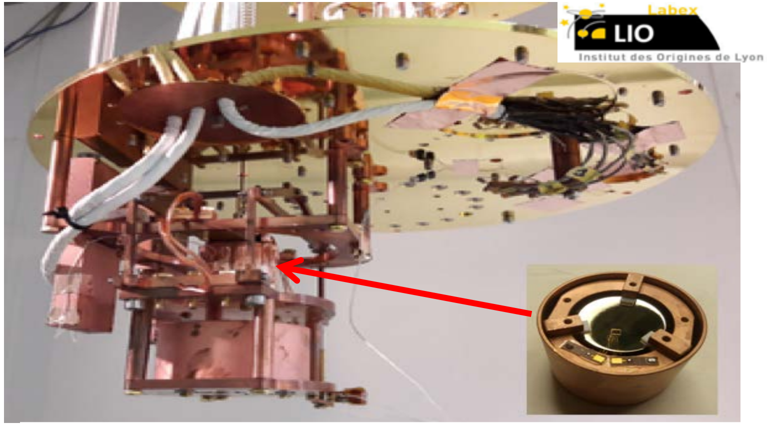
- Intense R&D on NTD sensors
- Detailed thermal model: optimization of the best configuration
- Test of different glues
- Alternative sensors: NbSi superconductive transition edge sensors
- First amplification: JFET at 100K to HEMTs at 4K

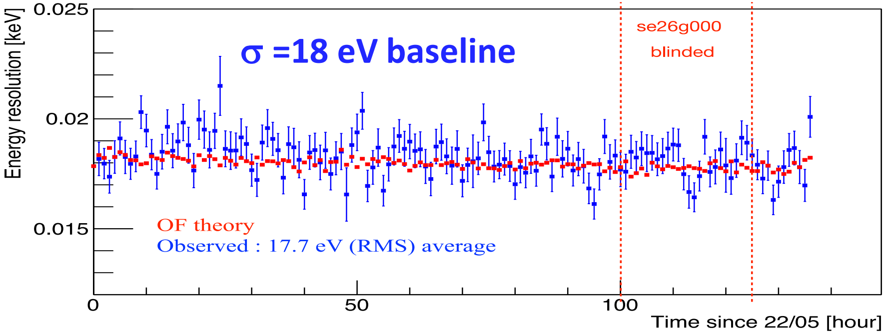


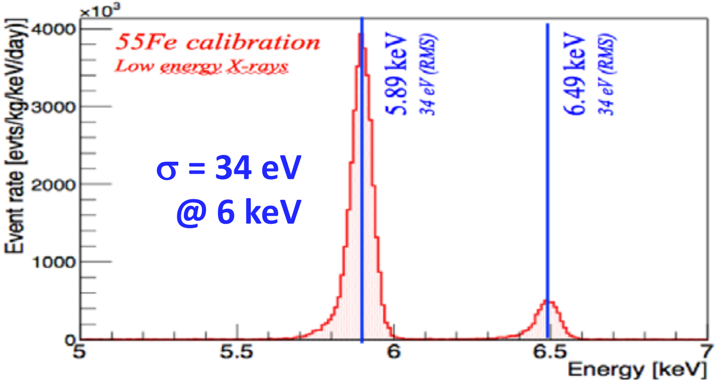
- **JFET to HEMT**
  - Lower intrinsic noise, low heat load
  - Works at 4K: shorter cables reduces capacitance and improves resolution
- ***Successful HEMT amplifier with sub-100 eV_{RMS} ion. resolution*** *[A. Phipps, arXiv:1611.09712, collaboration between SuperCDMS and EDELWEISS]*
- Step#1: Upgrade EDELWEISS ionization readout with this new design
- Step#2: Electrode design to reduce detector capacitance to reach 50 eV_{RM}

Resolution improvements on a 32g detector

- R&D with 32 g combined with the objective of testing the above-ground sensitivity to sub-GeV WIMPs
- *Optimized* NTD heat sensor on a 32g crystal, no electrodes
  (i.e. 1 keV = 1 $\mathrm{keV_{NR}}$)
- Kept at 17 mK in low-vibration dilution fridge
  [ArXiv:1803.03463]
- Stable σ = 18 eV baseline resolution
- DM search in [0-2] keV region

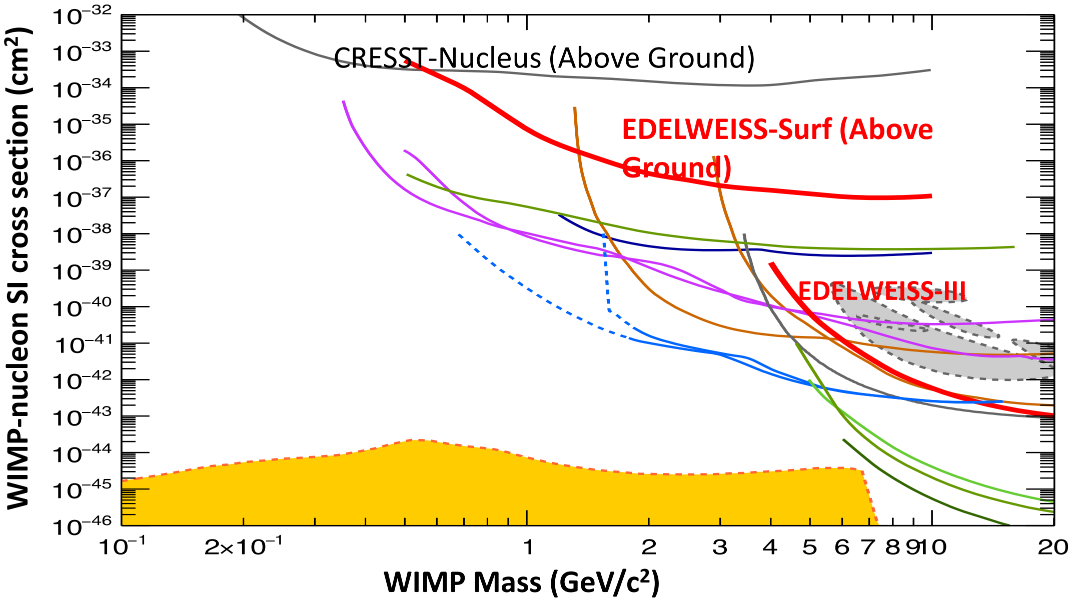






Surface limit

- Achieved resolution on a smaller detector exceeds by x5 the original LT goal with 800 g detectors
- Best above-ground limit down to 600 MeV/c^2: SIMP
- First sub-GeV limit with Ge, down to 500 MeV/c^2
- Opens the way for the 0.1 – 1 GeV/c^2 range



Edelweiss

Expériences pour DEtecter Les WIMPs En Site Souterrain

Run at LSM underground laboratory:

Continuous running at <21 mK since January 2019 to June 2020

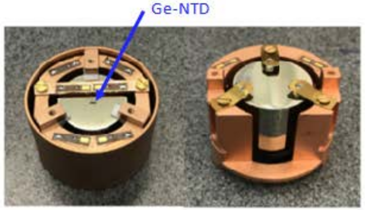
11 different Ge detectors

Rest of cryostat used for joint physics run with CUPID-Mo 0v2β search.

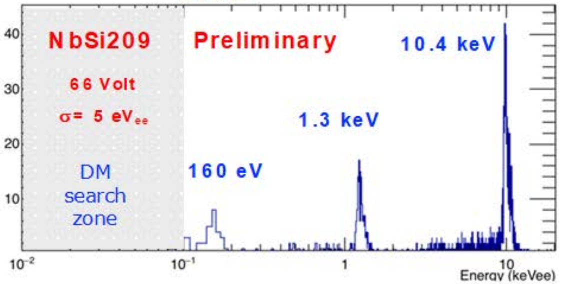
Compare detector physics in 32g, 200 g and 800g detectors. Compare performance of NTD and NbSi-TES heat sensors.

Obtaining near single-electron sensitivity on 33 and 200 g detectors: exploration of DM interactions with electrons and nuclei.

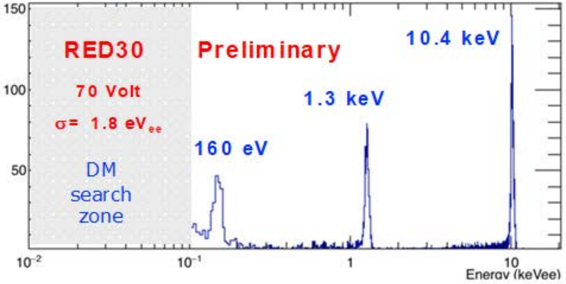
Study of low-energy backgrounds in Ge detectors operated with large Neganov-Trofimov-Luke amplifications.



- NbSi209: 200g Ge with TES thermal sensor

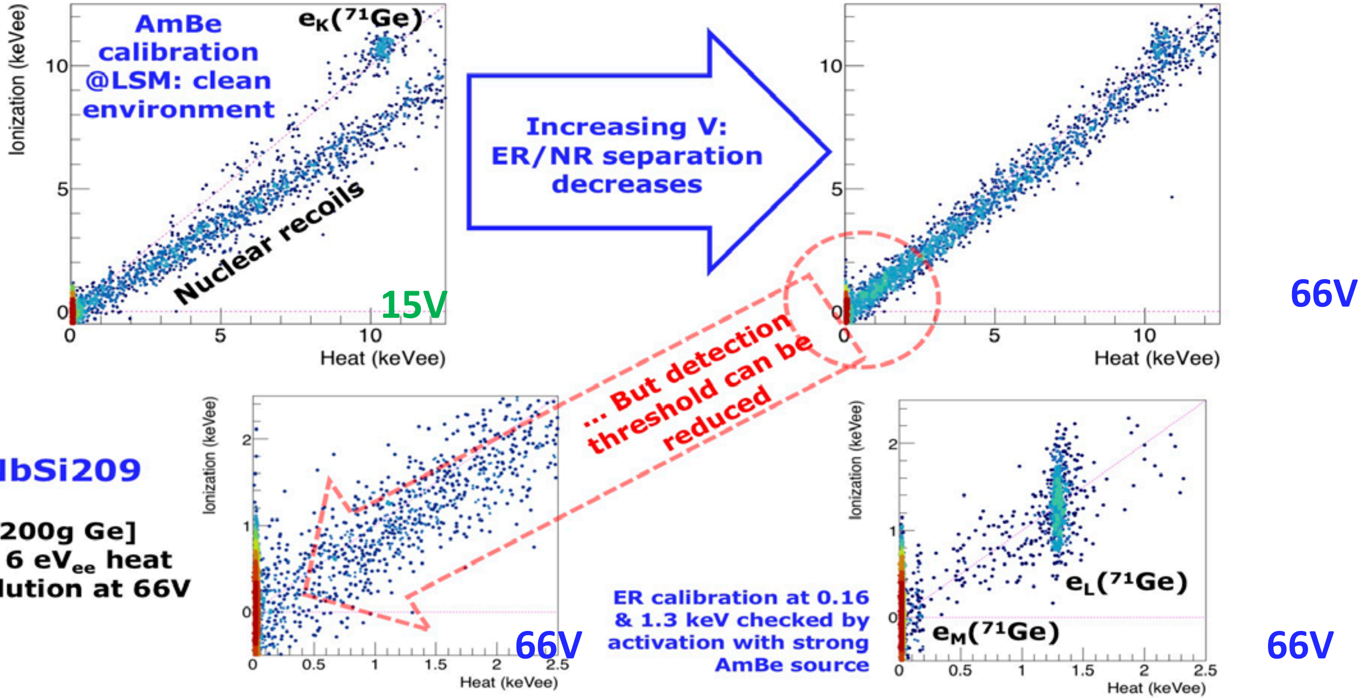


- RED30 : 33 g Ge Al electrodes, NTD thermal sensor



EDELWEISS has been able to obtain at LSM the lowest radioactive background levels below 10 keV in massive Ge detectors (~0.1 evt/kg/day/keV)

- Current run @ LSM : obtaining *near* single-electron sensitivity on 33 and 200 g detectors: *Calibration of nuclear recoils down to low thresholds*



AmBe calibration @LSM: clean environment

Increasing V: ER/NR separation decreases

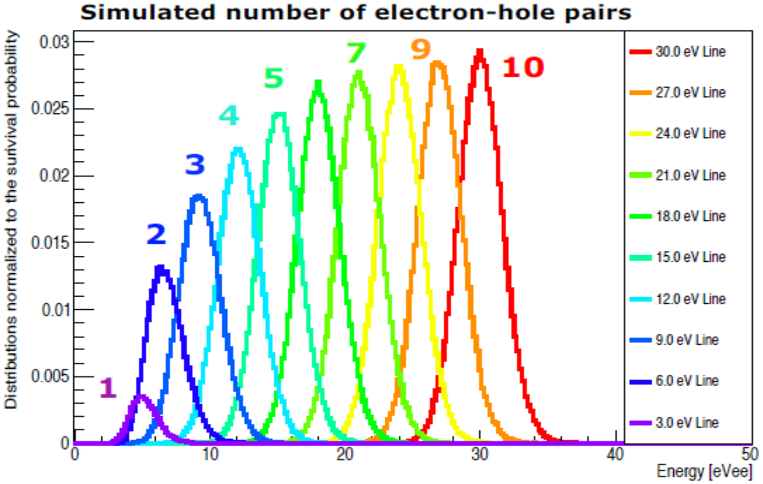
… But detection threshold can be reduced

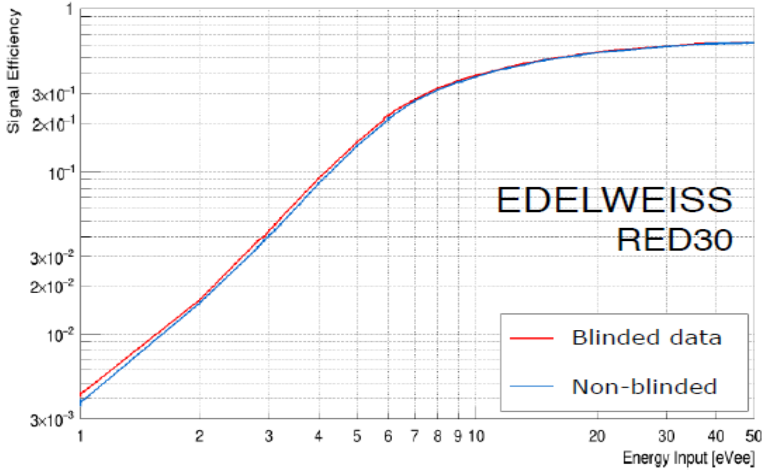
NbSi209

[200g Ge]
σ = 6 eV$_{ee}$ heat resolution at 66V

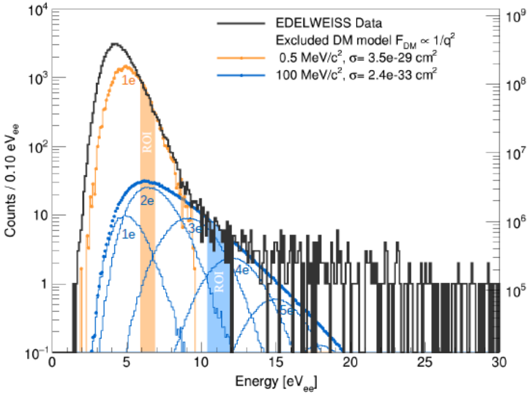
ER calibration at 0.16 & 1.3 keV checked by activation with strong AmBe source

- Efficiency determined by injecting pulses at random time in the recorded data streams
- The injected pulses are actual ^{71}Ge K-line events (from the activation that immediately followed the search), rescaled to the desired energy
- Some sensitivity to 1 electron-hole pair signal

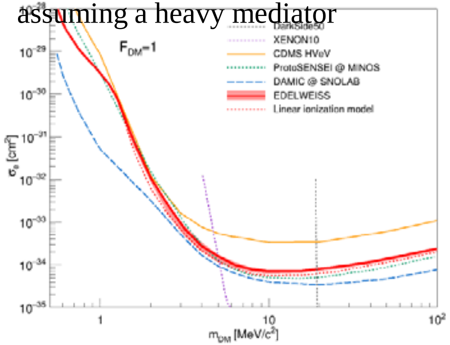

Simulated number of electron-hole pairs



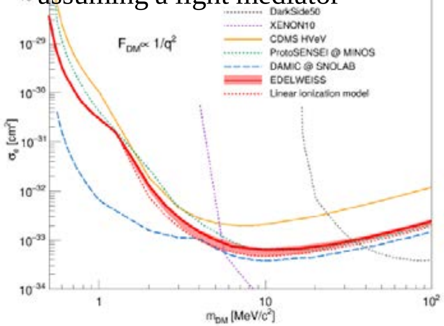
New 2020 EDELWEISS results



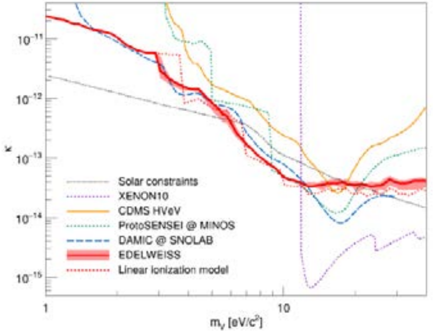
Scattering of DM particles on electrons assuming a heavy mediator



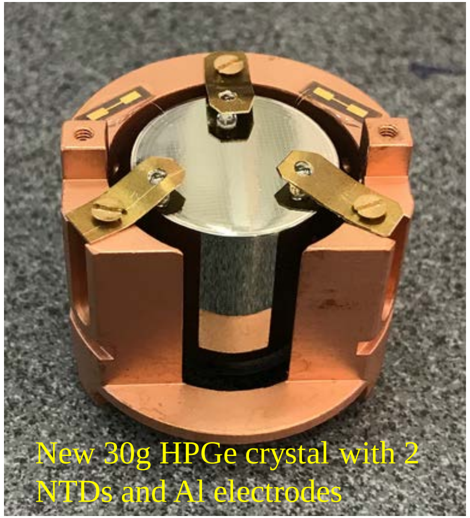
Scattering of DM particles on electrons assuming a light mediator



Kinetic mixing ***k*** of a dark photon



An unprecedented **charge resolution of 0.53 electron-hole pairs** (RMS) has been achieved using the Neganov-Trofimov-Luke internal amplification. We set the first Ge-based constraints on sub-MeV/c^2 DM particles interacting with electrons, as well as on dark photons down to 1 eV/c^2. These are competitive with other searches and demonstrate the high relevance of cryogenic Ge detectors for the search of DM interactions producing eV-scale electron signals.

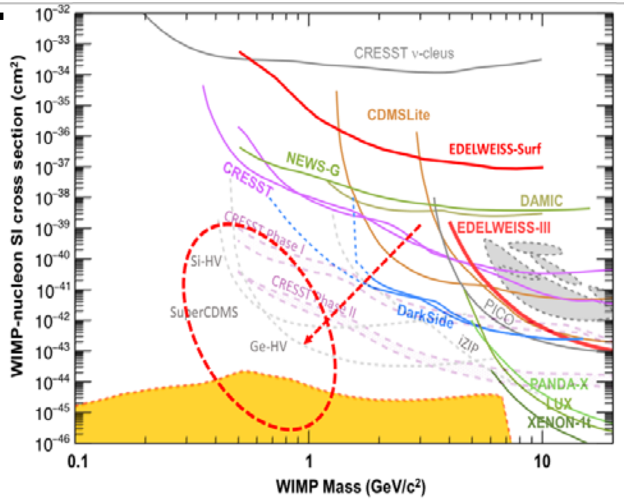


New 30g HPGe crystal with 2 NTDs and Al electrodes

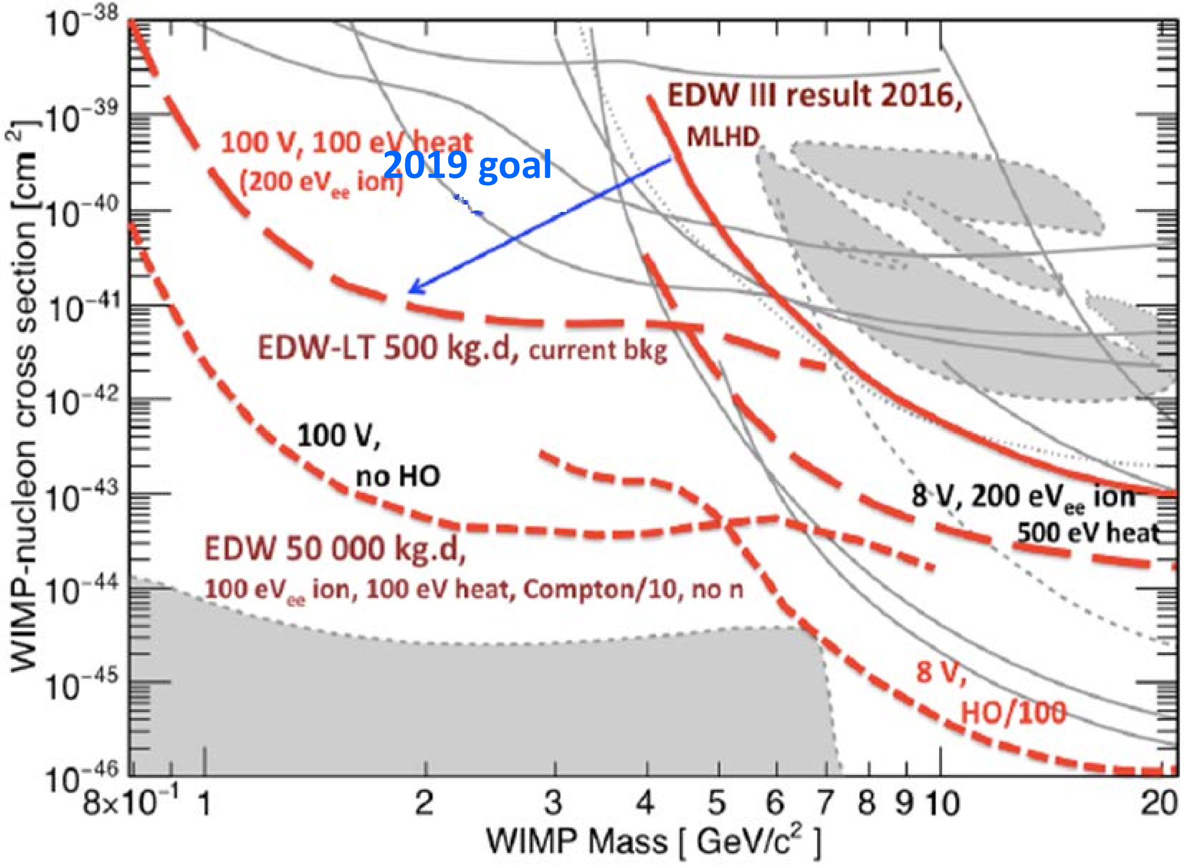
In new class of light DM models the interaction with normal matter comes from the coupling of a Dark Sector photon with the normal photon.

How to detect: DM-electron scattering

Theory predictions: complete coverage (10^{-40} cm^2) possible with 1 kg year exposure of a detector sensitive to the single electron in the absence of any background

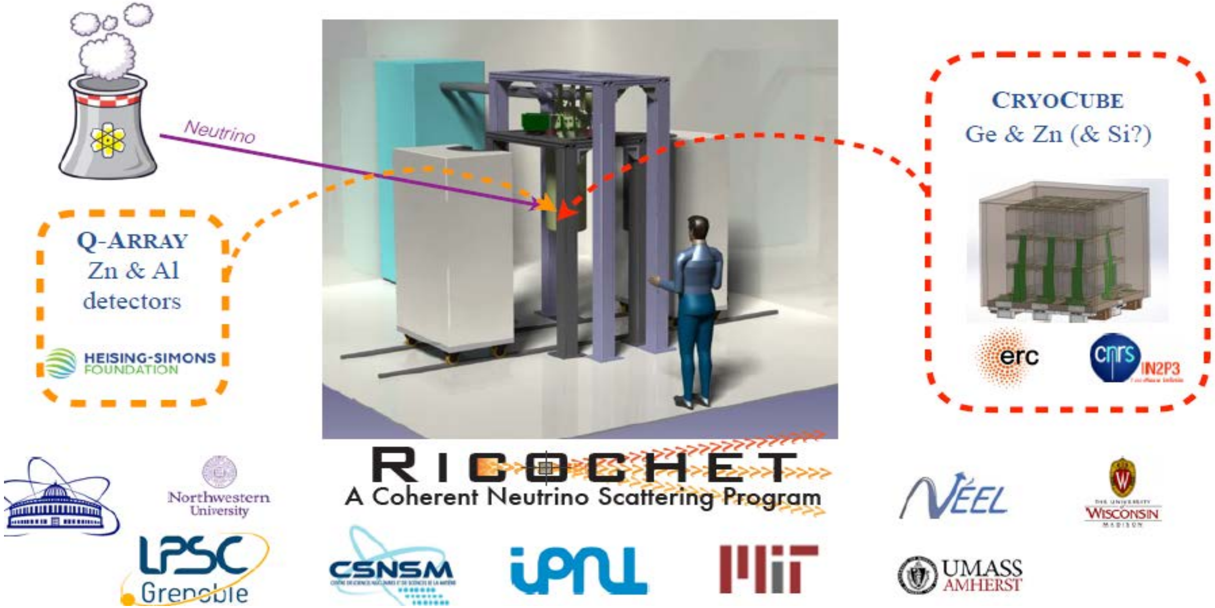


Expected future results



Bolometers - Not only DM

RICOCHET aims at building the ultra low-energy CEνNS neutrino observatory dedicated to physics beyond the Standard Model

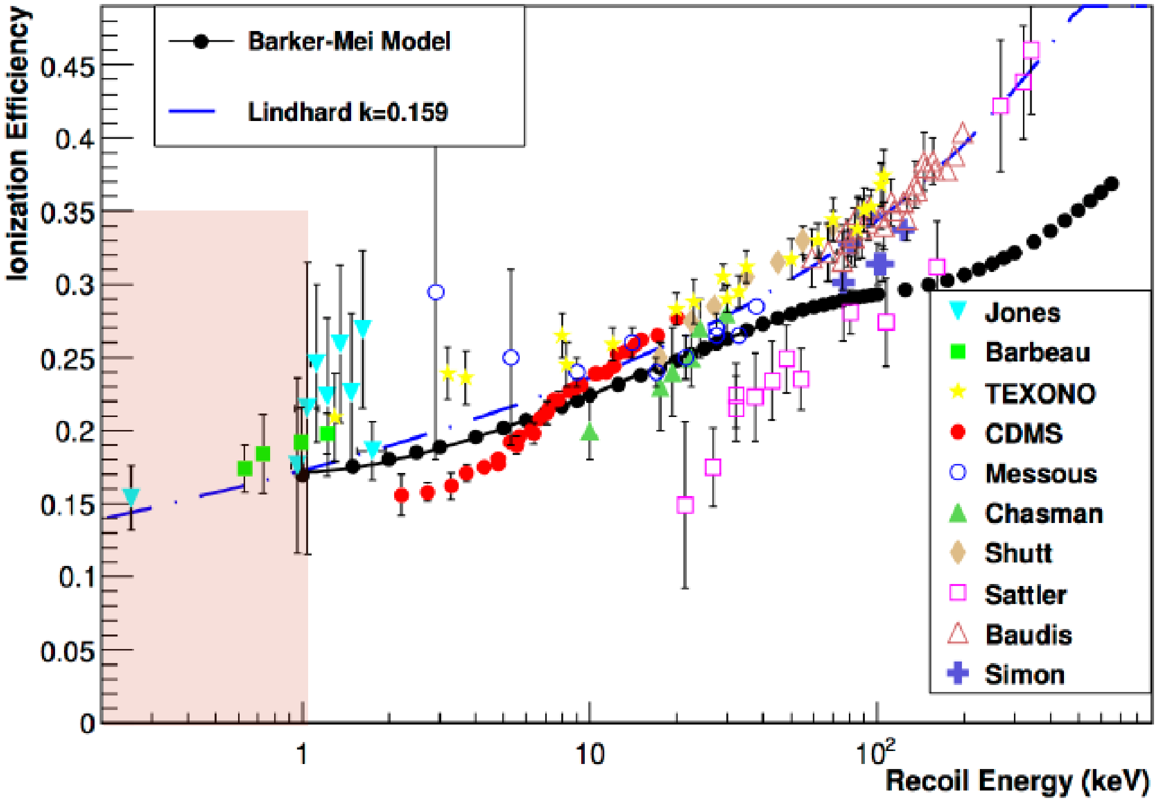


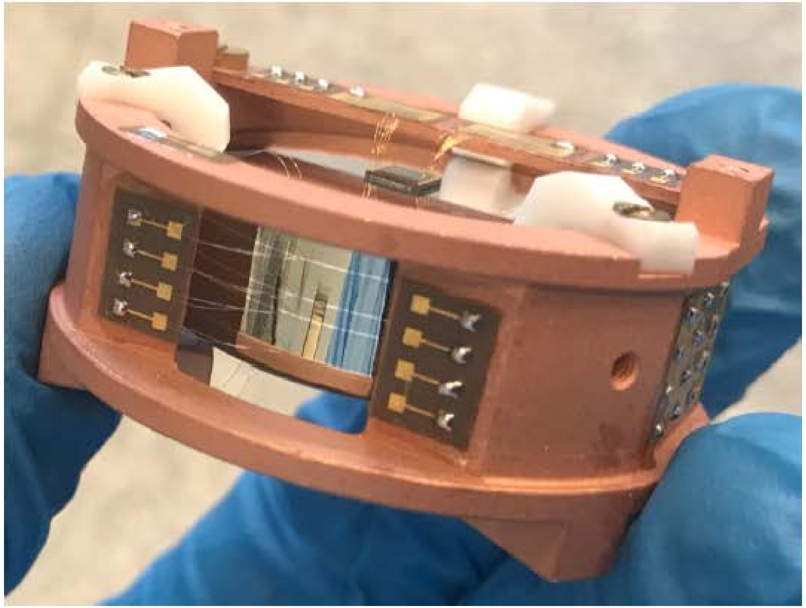
50 eV energy threshold with a 10^3 background rejection down to the threshold

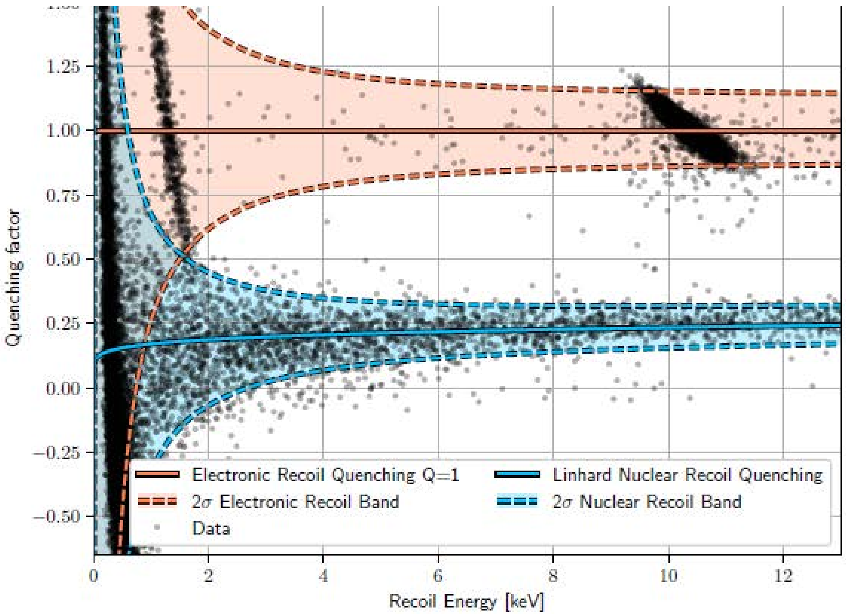
The first key feature of the RICOCHET program, compared to other planned or ongoing CEνNS projects, is to aim for a kg-scale experiment with significant background rejection down to the O(10) eV energy threshold.

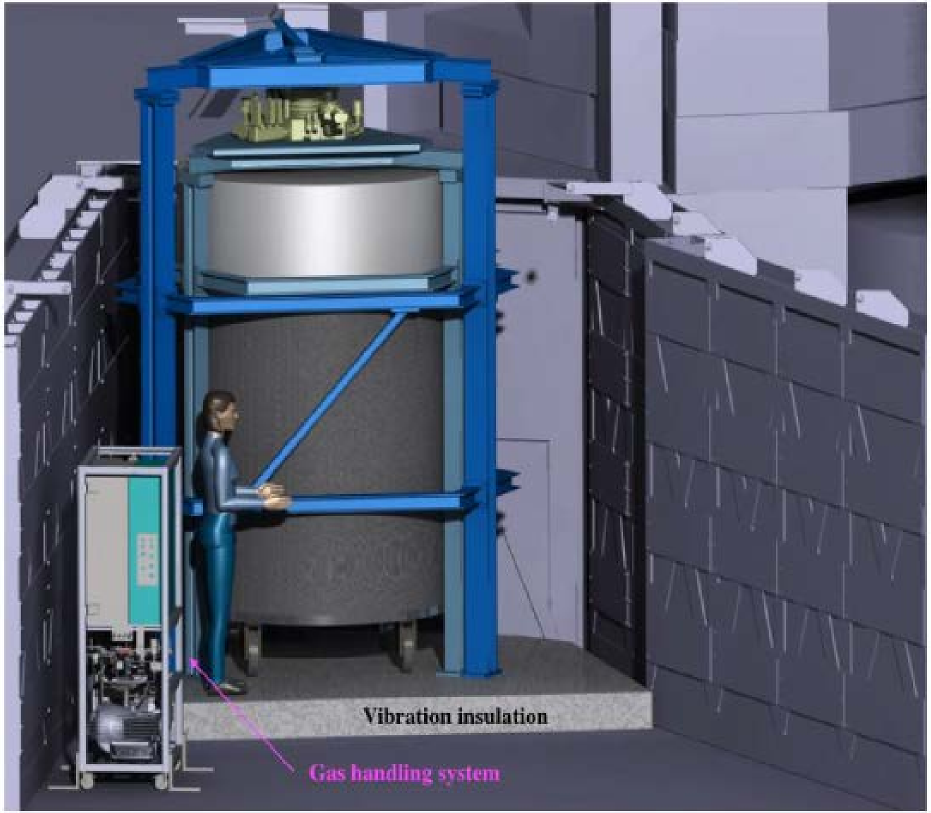
The CRYOCUBE: a compact tabletop size setup

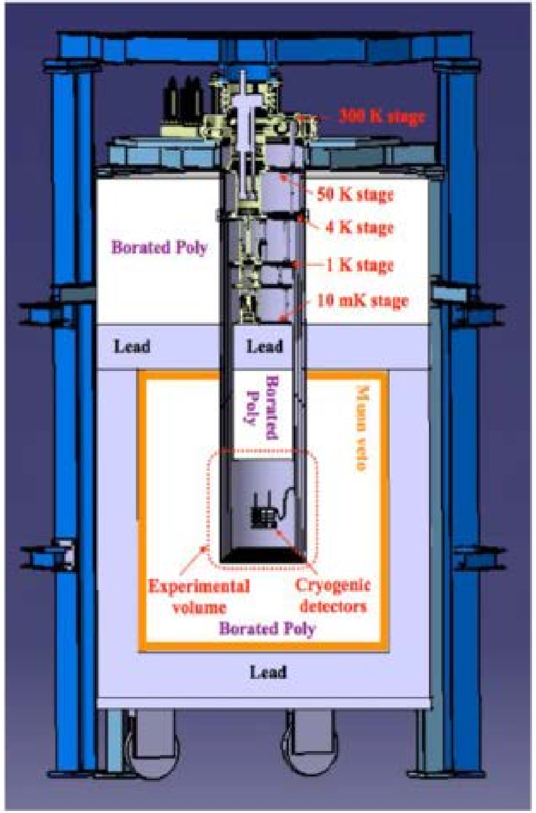
27 x 33 g detectors
8 x 8 x 8 cm^3
radio-pure infrared-tight copper box

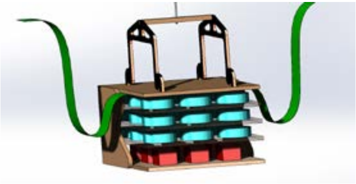

Ionization Efficiency
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
1
10
10^2
Recoil Energy (keV)
Barker-Mei Model
Lindhard k=0.159
Jones
Barbeau
TEXONO
CDMS
Messous
Chasman
Shutt
Sattler
Baudis
Simon

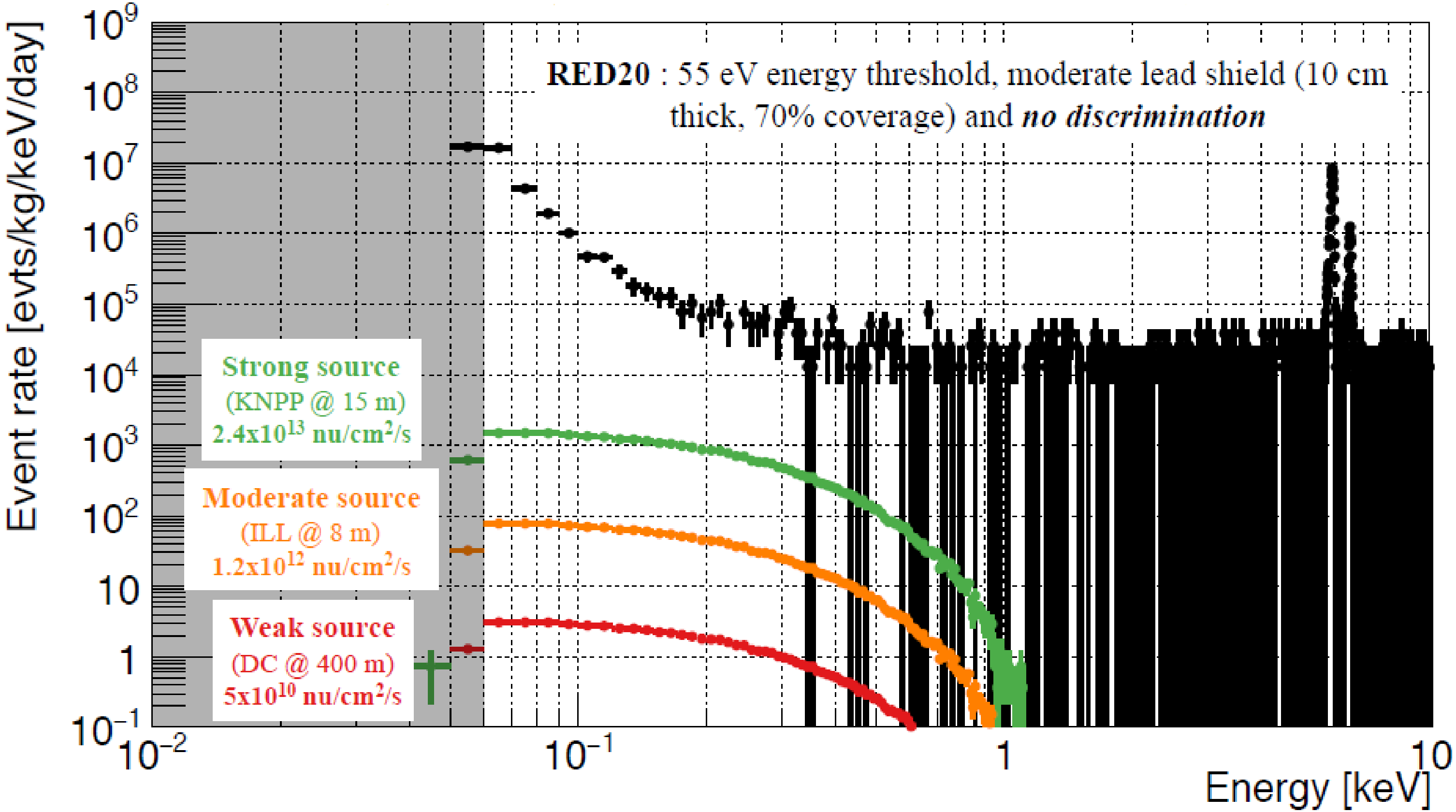



Quenching factor
1.25
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
0
2
4
6
8
10
12
Recoil Energy [keV]
Electronic Recoil Quenching Q=1
2σ Electronic Recoil Band
Data
Linhard Nuclear Recoil Quenching
2σ Nuclear Recoil Band


Vibration insulation
Gas handling system

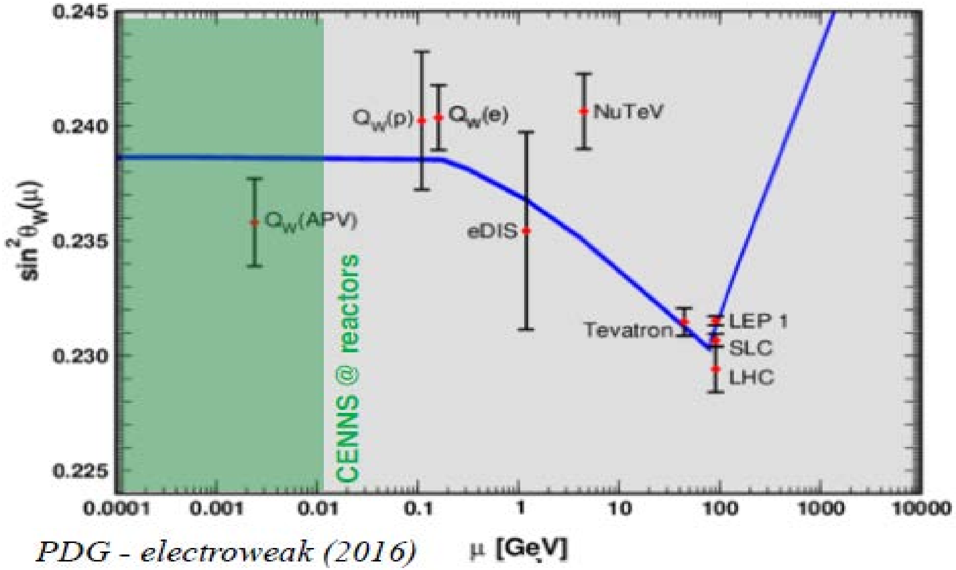

300 K stage
50 K stage
4 K stage
1 K stage
10 mK stage
Borated Poly
Lead
Lead
Borated Poly
Muon veto
Experimental volume
Cryogenic detectors
Borated Poly
Lead



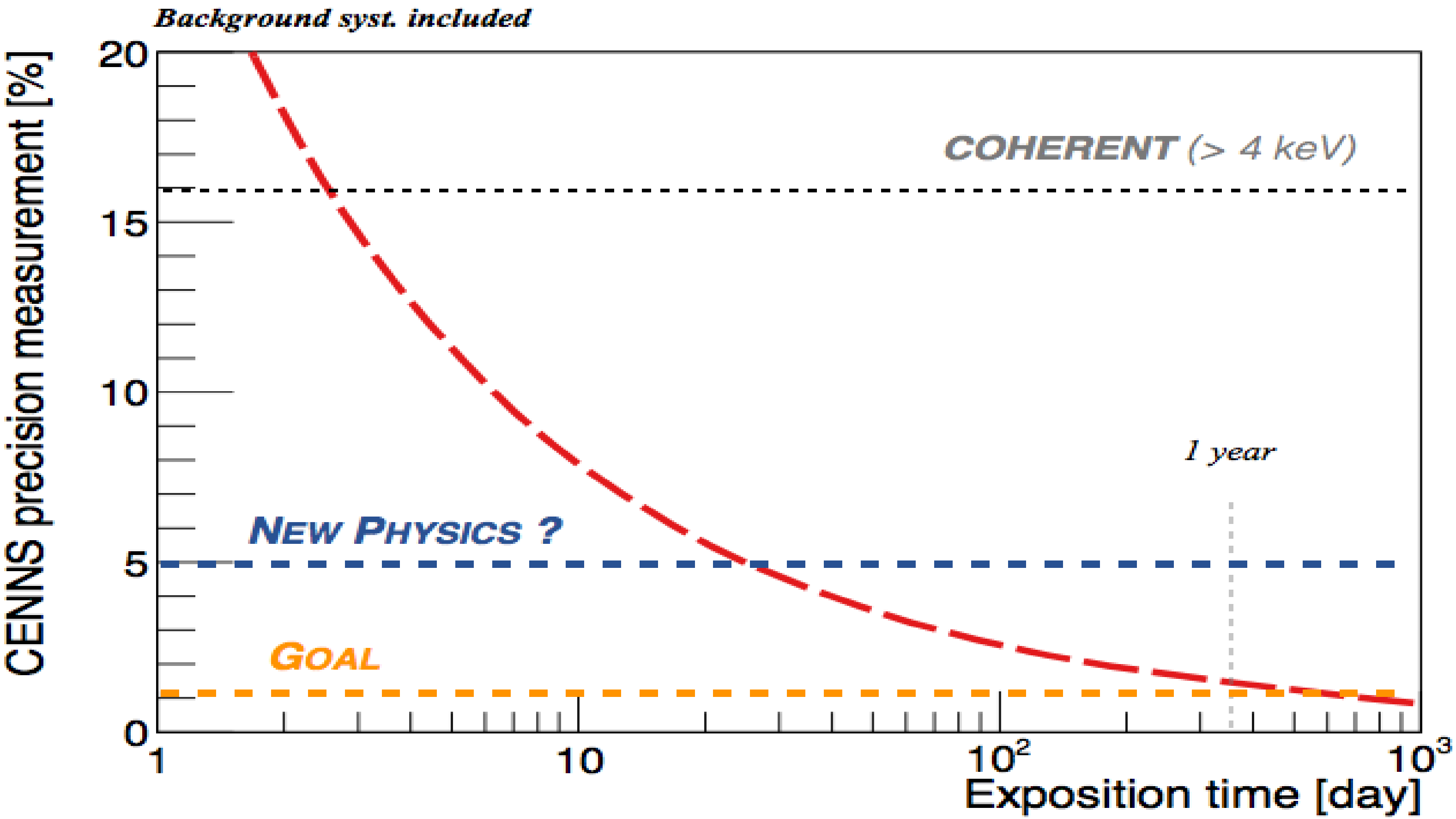

RED20 : 55 eV energy threshold, moderate lead shield (10 cm thick, 70% coverage) and ***no discrimination***
Strong source
(KNPP @ 15 m)
2.4x10^13 nu/cm^2/s
Moderate source
(ILL @ 8 m)
1.2x10^12 nu/cm^2/s
Weak source
(DC @ 400 m)
5x10^10 nu/cm^2/s
Event rate [evts/kg/keV/day]
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-1
1
10
Energy [keV]

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

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



PDG - electroweak (2016)

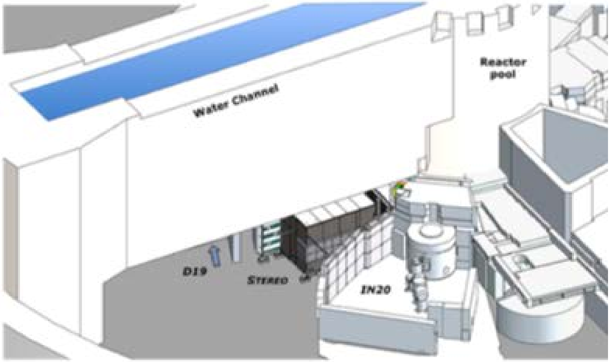

Background syst. included
CENNS precision measurement [%]
20
15
10
5
0
COHERENT (> 4 keV)
1 year
NEW PHYSICS ?
GOAL
1
10
10^2
10^3
Exposition time [day]

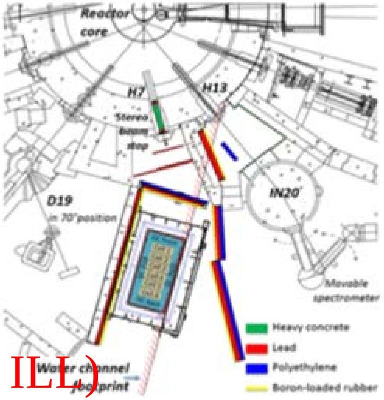
RICOCHET: *Searching for nuclear reactor site - ILL*

- 58 MW nominal thermal power
- Large neutrino flux: ~1x10^{19} ν/s
  - 5m from core: 40 evts/day/kg
  - 7m from core: 20 evts/day/kg
- 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***

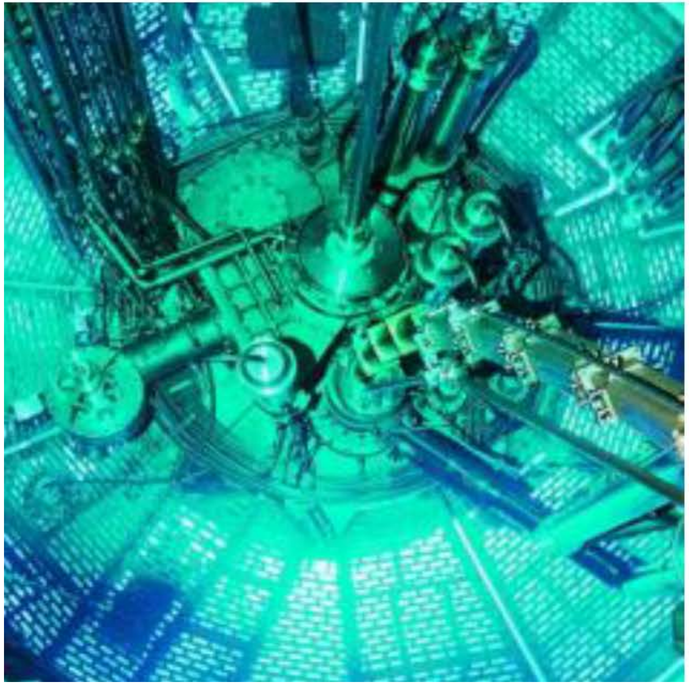
Just approved (640 kEuro for installation at ILL)

STEREO Coll., JINST 2018





Optimised for extraction of intense neutron beams



High-(neutron)flux reactor of the ILL

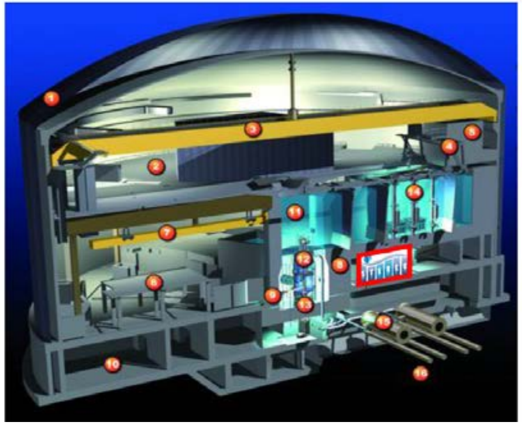
- 58.3 $\mathrm{MW}_{\text{thermal}}$
- Single compact fuel element:
  - ◇ Ø40 cm × 80 cm
  - ◇ Highly enriched fuel: ^{235}U (93%)
  - ◇ 1 cycle ~50 days
  - ◇ 3-4 cycles/year
- Heavy-water moderated
- Flux in moderator: 10^{15} n/cm^{2}s

THE EUROPEAN NEUTRON SOURCE

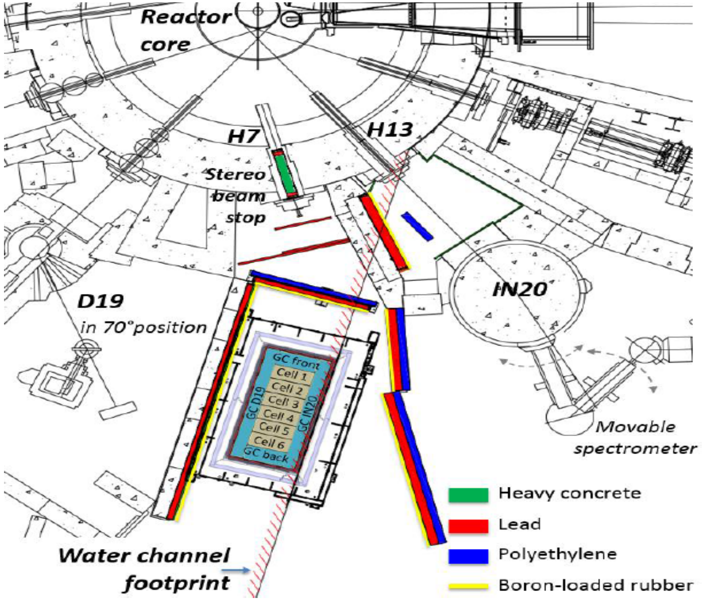
NEUTRONS FOR SCIENCE

Site H7

Antineutrino source and site



- Baseline: ≥ 8m
- Overburden: 15 m.w.e.
- Shielding improved for STEREO
- H6-H7 beam tube removed, or closed by plug

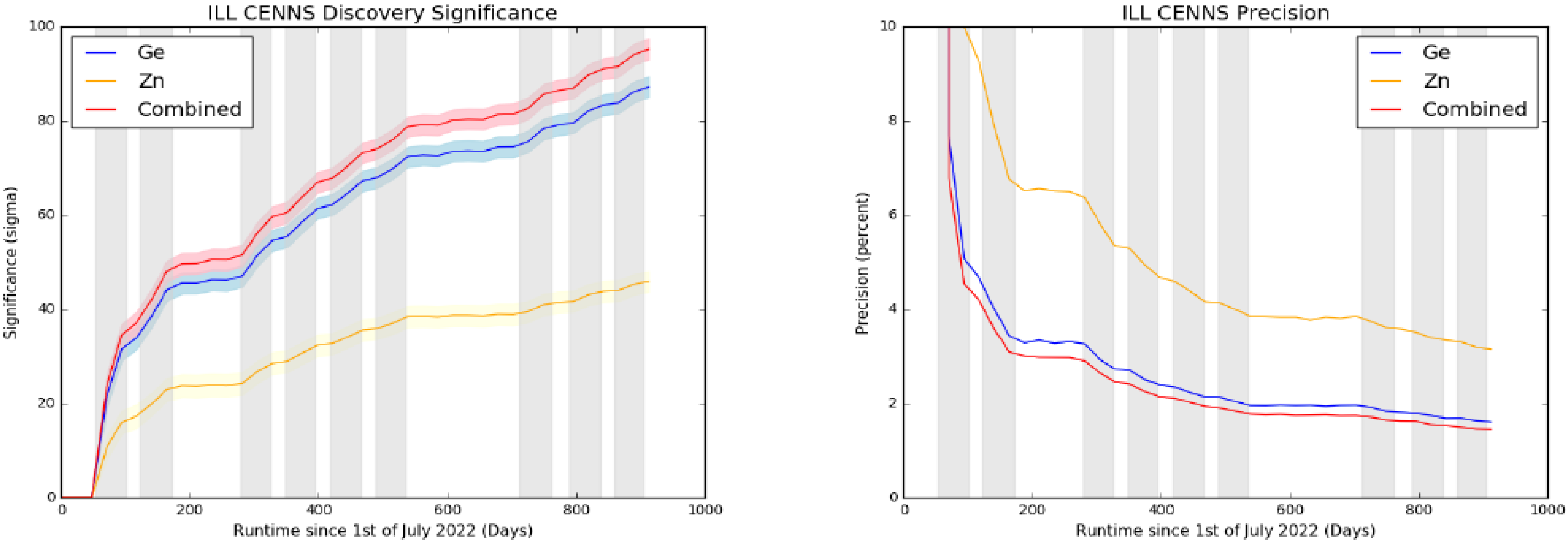


Advantages

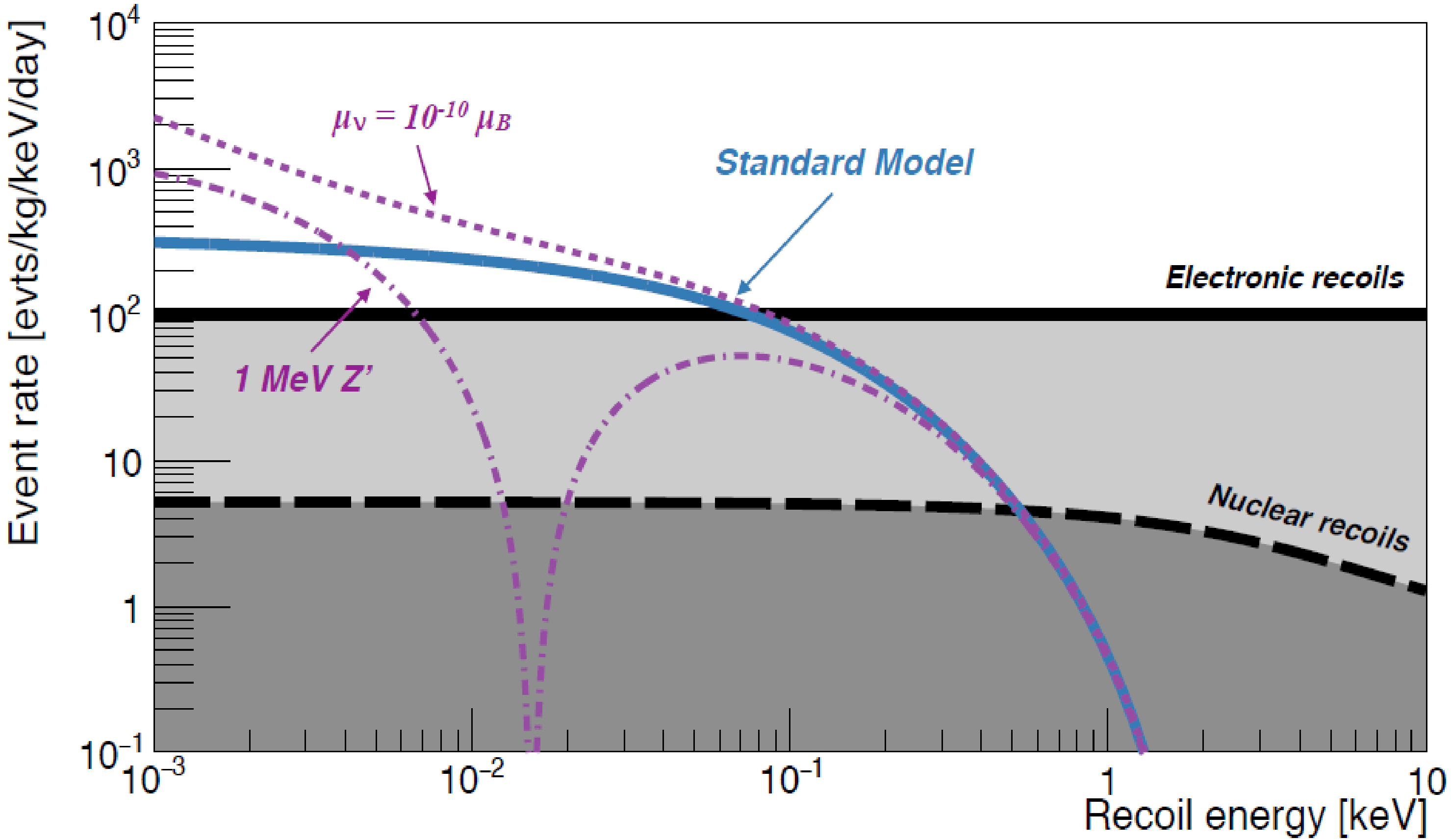
- Pure ^{235}U spectrum, compact core
- Frequent on-off changes
- 15 m.w.e. overburden
- Profit from STEREO (site prep, reactor spectrum)
- Scientific environment and technical support

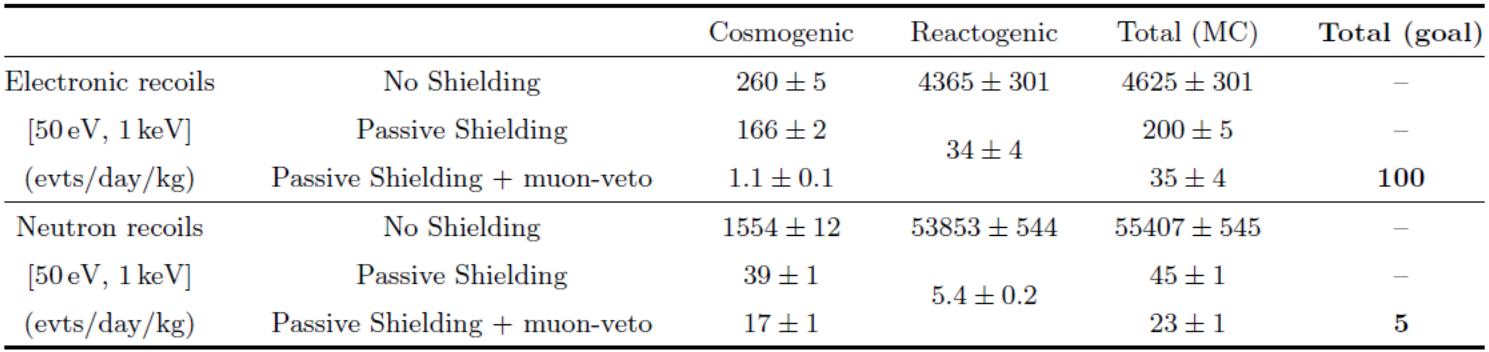
Disadvantages

- Need to be close to core for high flux → Signal/ReactorBG?
- Backgrounds from neighbour instruments
- Limited crane access

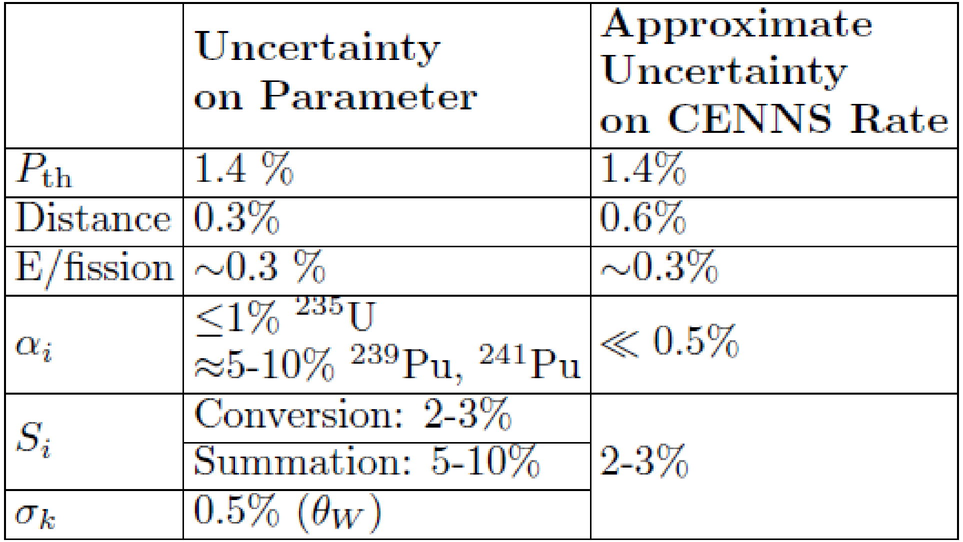


CEνNS discovery significance and precision as a function of exposure. Median significance and precision (and 95% confidence level bands) for the discovery of CEνNS using Ge (blue), Zn (yellow), and the combination of the two (red).


Event rate [evts/kg/keV/day]
10^4
10^3
10^2
10
1
10^{-1}
10^{-3}
10^{-2}
10^{-1}
1
10
Recoil energy [keV]
$\mu_\nu = 10^{-10}\,\mu_B$
Standard Model
Electronic recoils
1 MeV Z'
Nuclear recoils



		Cosmogenic	Reactogenic	Total (MC)	**Total (goal)**
Electronic recoils	No Shielding	260 ± 5	4365 ± 301	4625 ± 301	–
[50 eV, 1 keV]	Passive Shielding	166 ± 2	34 ± 4	200 ± 5	–
(evts/day/kg)	Passive Shielding + muon-veto	1.1 ± 0.1		35 ± 4	**100**
Neutron recoils	No Shielding	1554 ± 12	53853 ± 544	55407 ± 545	–
[50 eV, 1 keV]	Passive Shielding	39 ± 1	5.4 ± 0.2	45 ± 1	–
(evts/day/kg)	Passive Shielding + muon-veto	17 ± 1		23 ± 1	**5**



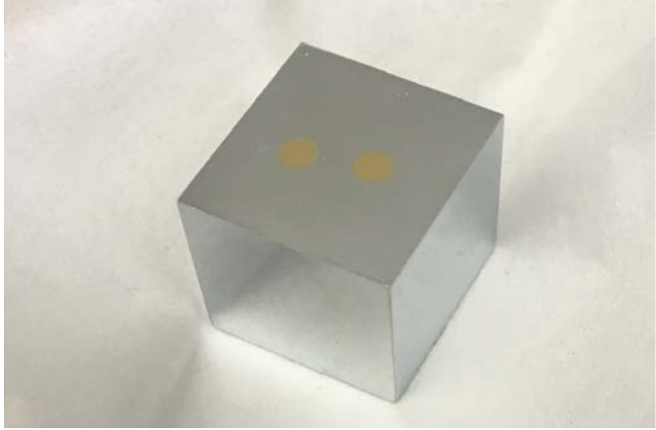
	Uncertainty on Parameter	**Approximate Uncertainty on CENNS Rate**
P_{th}	1.4 %	1.4%
Distance	0.3%	0.6%
E/fission	~0.3 %	~0.3%
α_i	$\leq$1% ^{235}U $\approx$5-10% ^{239}Pu, ^{241}Pu	$\ll$ 0.5%
S_i	Conversion: 2-3%	2-3%
	Summation: 5-10%	
σ_k	0.5% (θ_W)	

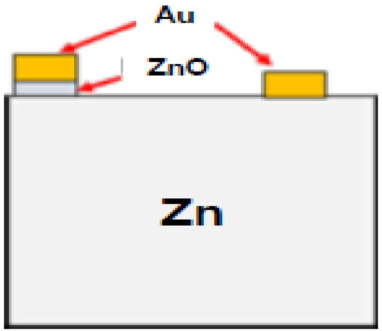
32 gram zinc bolometer

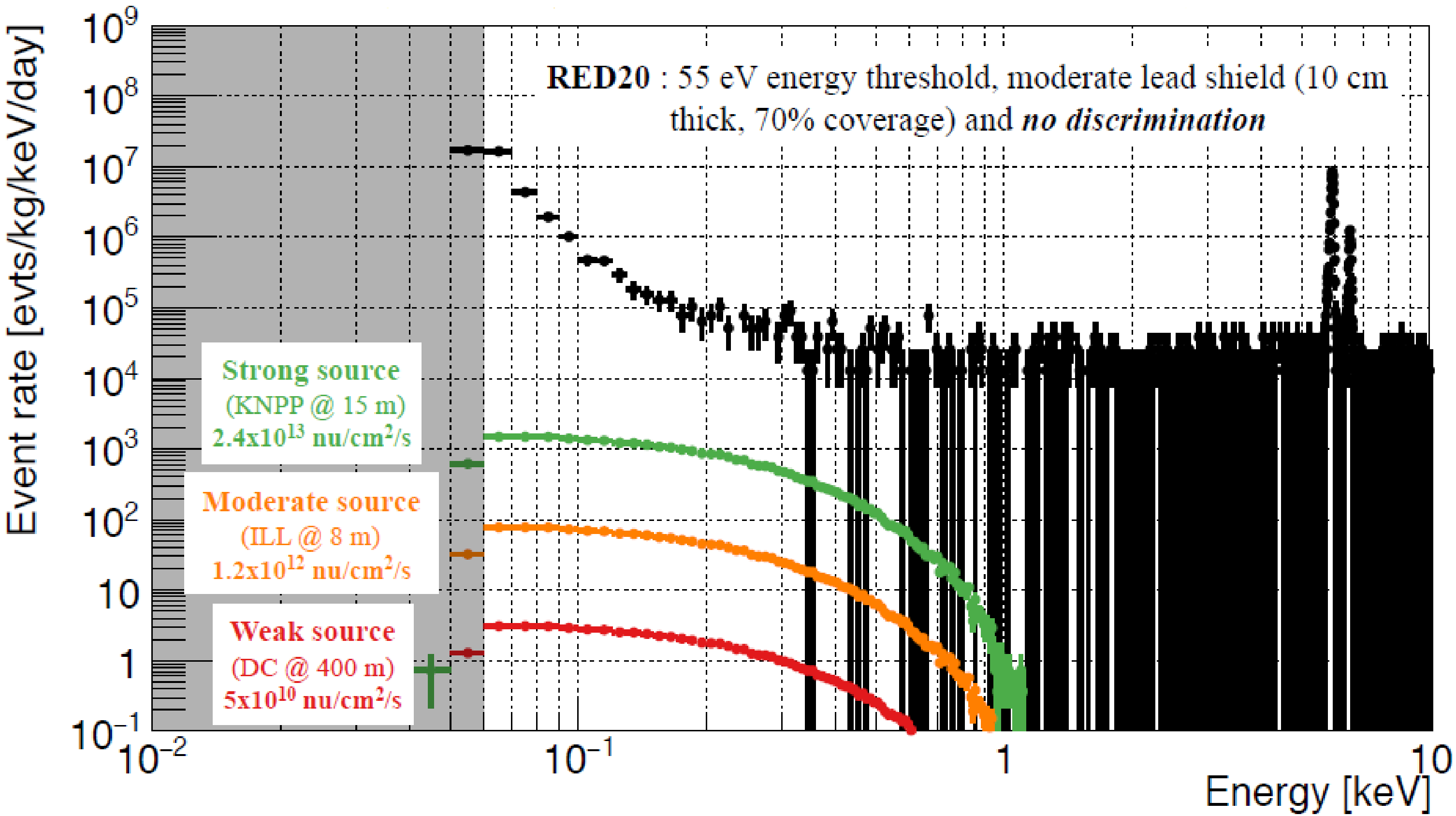
The zinc absorber was instrumented with an NTD thermal resistor and cooled to 15 mK.

Each detector is instrumented with two gold pads, one in direct contact with the zinc absorber, the other having a 50-100 nm ZnO layer in between the two metals.

Such a configuration will allow one to simultaneously measure the phonon and the phonon+quasi-particle population from a given particle energy deposition.



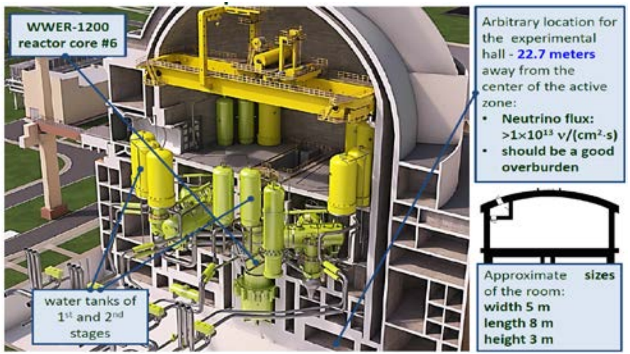



RED20 : 55 eV energy threshold, moderate lead shield (10 cm thick, 70% coverage) and ***no discrimination***
Strong source
(KNPP @ 15 m)
2.4×10^{13} nu/cm^2/s
Moderate source
(ILL @ 8 m)
1.2×10^{12} nu/cm^2/s
Weak source
(DC @ 400 m)
5×10^{10} nu/cm^2/s
Event rate [evts/kg/keV/day]
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-1}
1
10
Energy [keV]

Unit #6 of Novovoronezh NPP

new 3+ generation WWER-1200

Maximal thermal power is 3212 MW



WWER-1200
reactor core #6

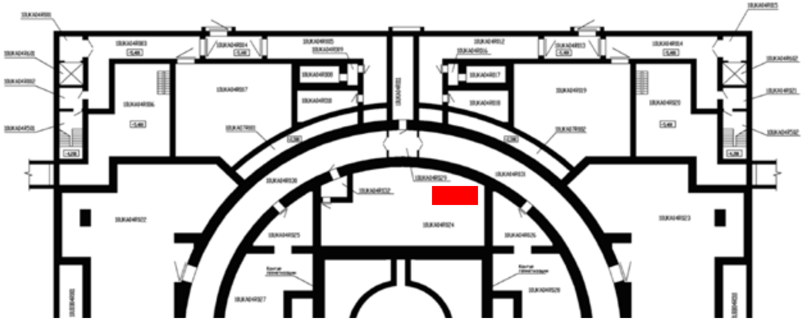
water tanks of
1st and 2nd
stages

Arbitrary location for the experimental hall - 22.7 meters away from the center of the active zone:

- **Neutrino flux: $>1\times10^{13}$ ν/(cm²·s)**
- **should be a good overburden**

Approximate sizes of the room:
width 5 m
length 8 m
height 3 m

First place proposed
-5.4 m (underground)
Strong basement,
No noise or vibrations



Maximal registered muon flux is 16.2 μ m^{-2} sr^{-1} sec^{-1},
About 7 times less with respect to the max of the sea level,
This corresponds to ~50 mwe.

There is expected anisotropy (better shielding from the reactor)

Measured neutron flux: $<10^{-5}$ m^{-2} sec^{-1},
More than 20 times less with respect to the max of the sea level.

RICOCHET: *Timeline*

The Ricochet timeline is the following:

- **End-2019:** Nuclear site decision and first version of Ricochet's Conceptual Design Report (CDR) to ask for funding of the setup at the chosen nuclear site to various agencies.
- **2021:** Ricochet's Technical Design Report (TDR) completed, including the mechanical infrastructure, the cryostat and tubing, the cabling and the warm electronics. The cold cabling, below the 4 K stage, is already being designed in the context of the ongoing CryoCube and Q-array R&D for which the fundings are fully and partially secured for the former and the latter respectively.
- **2022:** Deployment of the Ricochet experiment at the chosen nuclear reactor site.
- **2024:** Deliver the first low-energy (sub-100 eV) high-precision (%-level) CENNS measurement after one year of data taking leading to unprecedented sensitivities to various new physics scenarios.

Two main conclusions:

- In general, all modern methods of nuclear physics have to be applied to achieve the sensitivity levels that are interesting now for particle physics;

- Direct measurement of energy deposition and the excellent energy resolution provided by the bolometric technique are base for its further use for investigation of rear processes.