EURECA

Evolution of the European strategy for dark matter search with cryogenic (crystal) detectors

Perspective, challenges and plans with:

$CaWO_4$ (CRESST)

Germanium (EDELWEISS)

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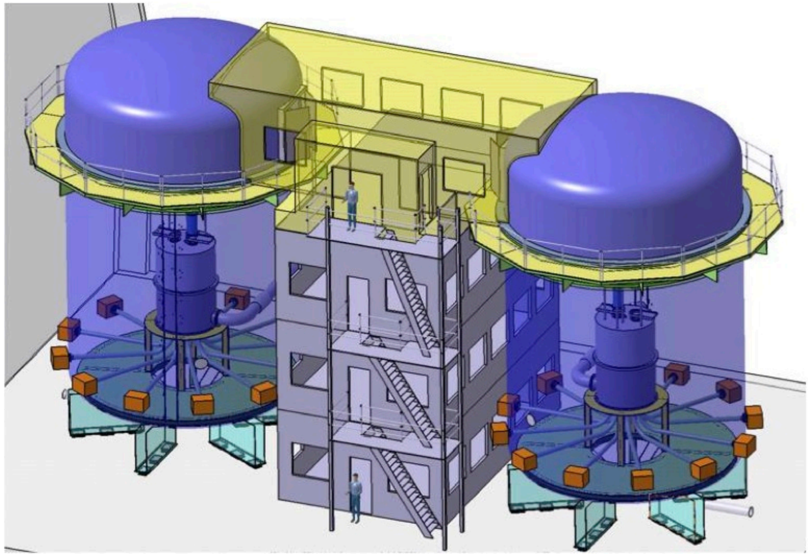
(IPNLyon, Université Lyon 1 + CNRS/IN2P3)

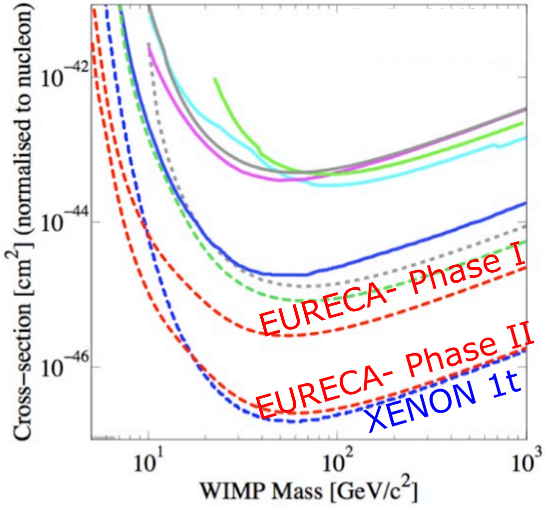
** Thanks to:*
Klaus Eitel (EURECA spokesp.)
Federica Petricca (CRESST spokesp.)

CONTEXT & STRATEGY

EURECA CDR (2014)

- *European Underground Rare Event Calorimeter Array*: Federation of European efforts for direct DM Search with cryogenic experiments
- Conceptual Design Report [Phys. Dark Univ. 3 (2014) 41]
- Goal: 2×10^{-47} pb @ 50 GeV (cMSSM inspired WIMPs)
- Common cryostat for 1-ton size experiment
- <1 evt/keV/ton/y background
- Variety of target: Ge + $CaWO_4$
- Site: LSM (Fréjus tunnel) extension in ~2017



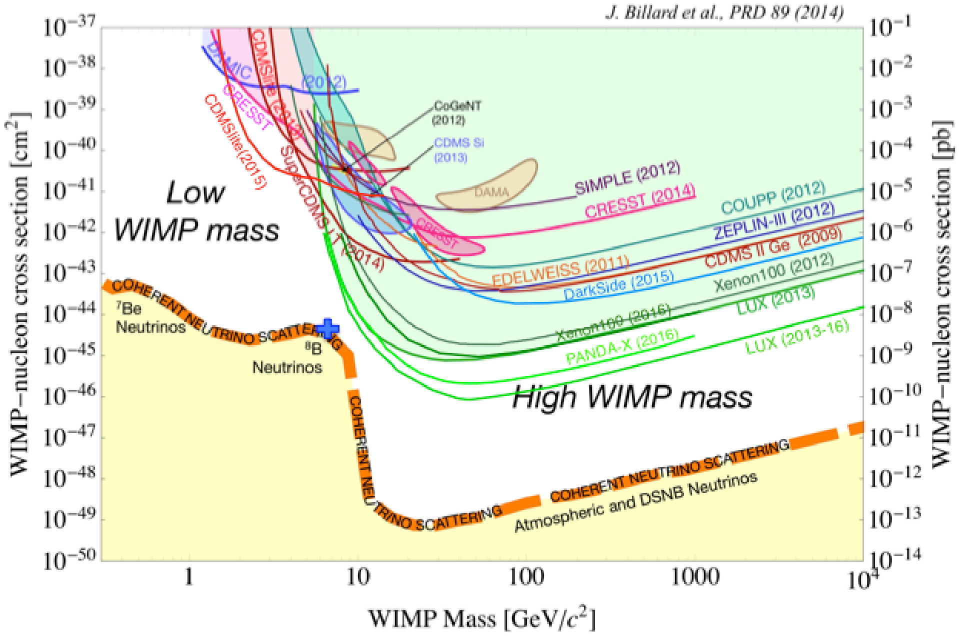


[Phys. Dark Univ. 3 (2014) 41]

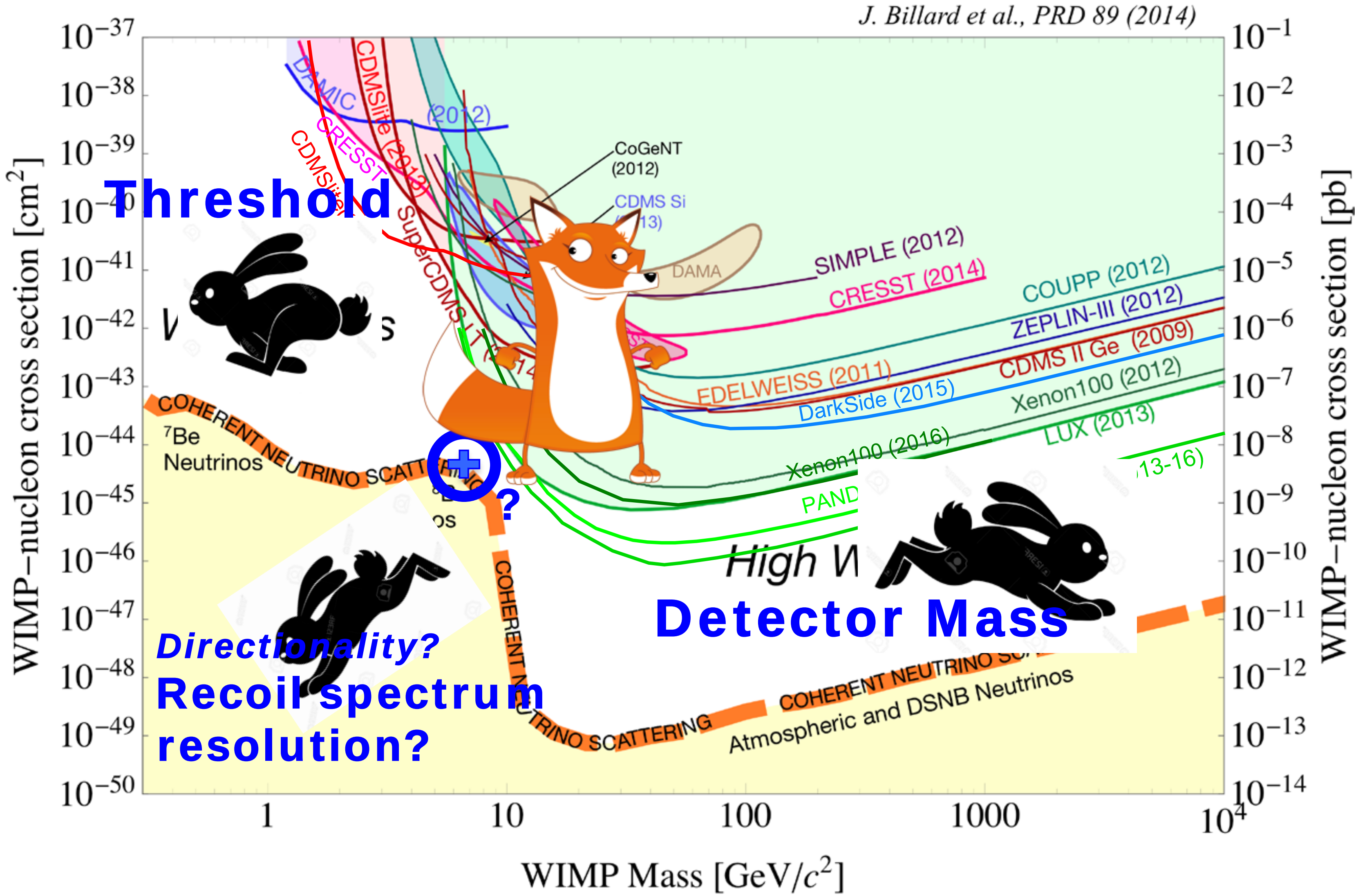
Change of scene since 2014 CDR

- LSM extension delays
- No signs of cMSSM SUSY @LHC: need to widen the search
- Rapid progress of xenon at high mass
- Identification of "Low-WIMP mass" region above the Solar ν floor, ideally suited for low-threshold cryogenic detectors

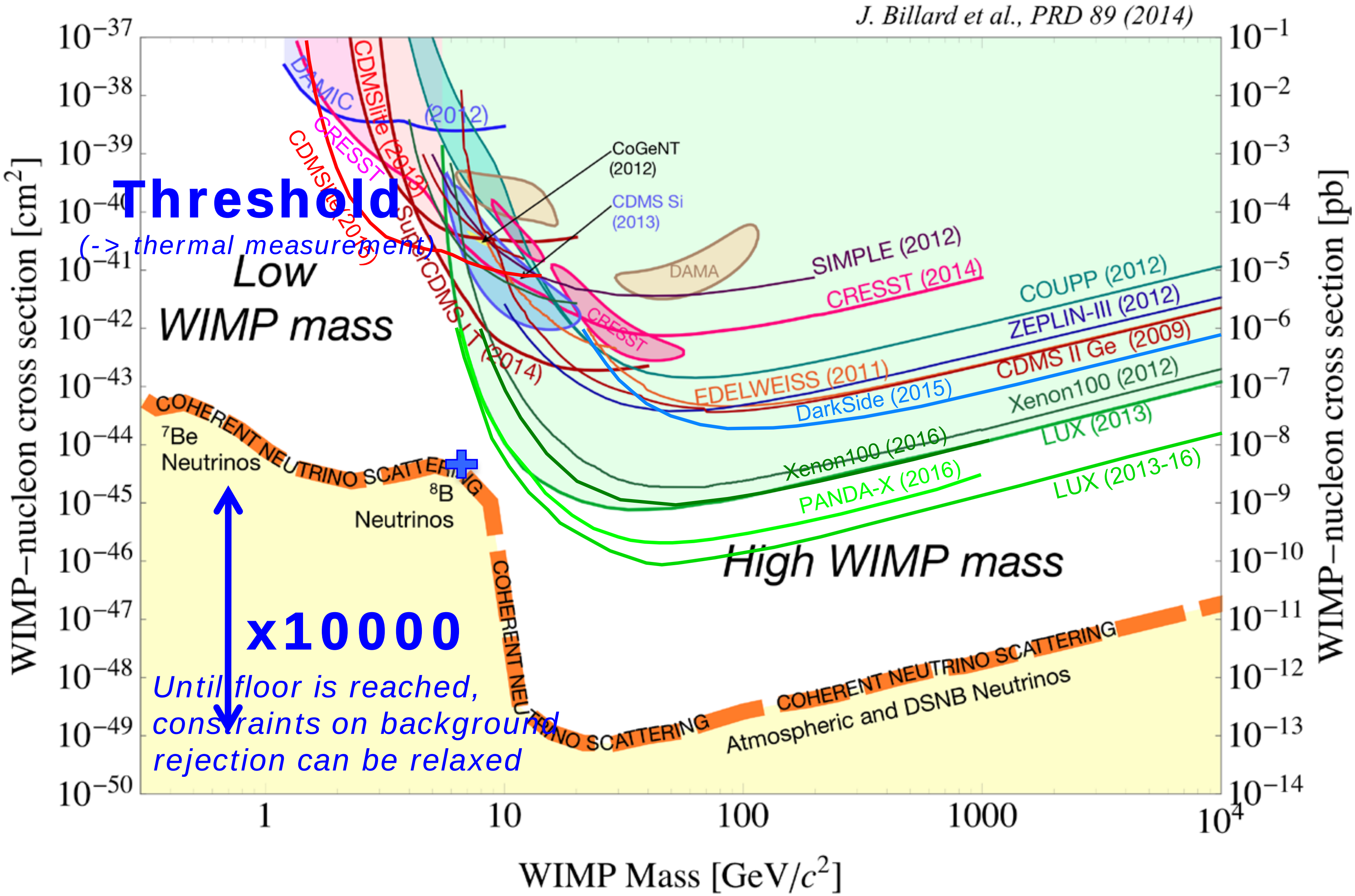
New EURECA strategy targeted at low mass & challenges associated with low thresholds



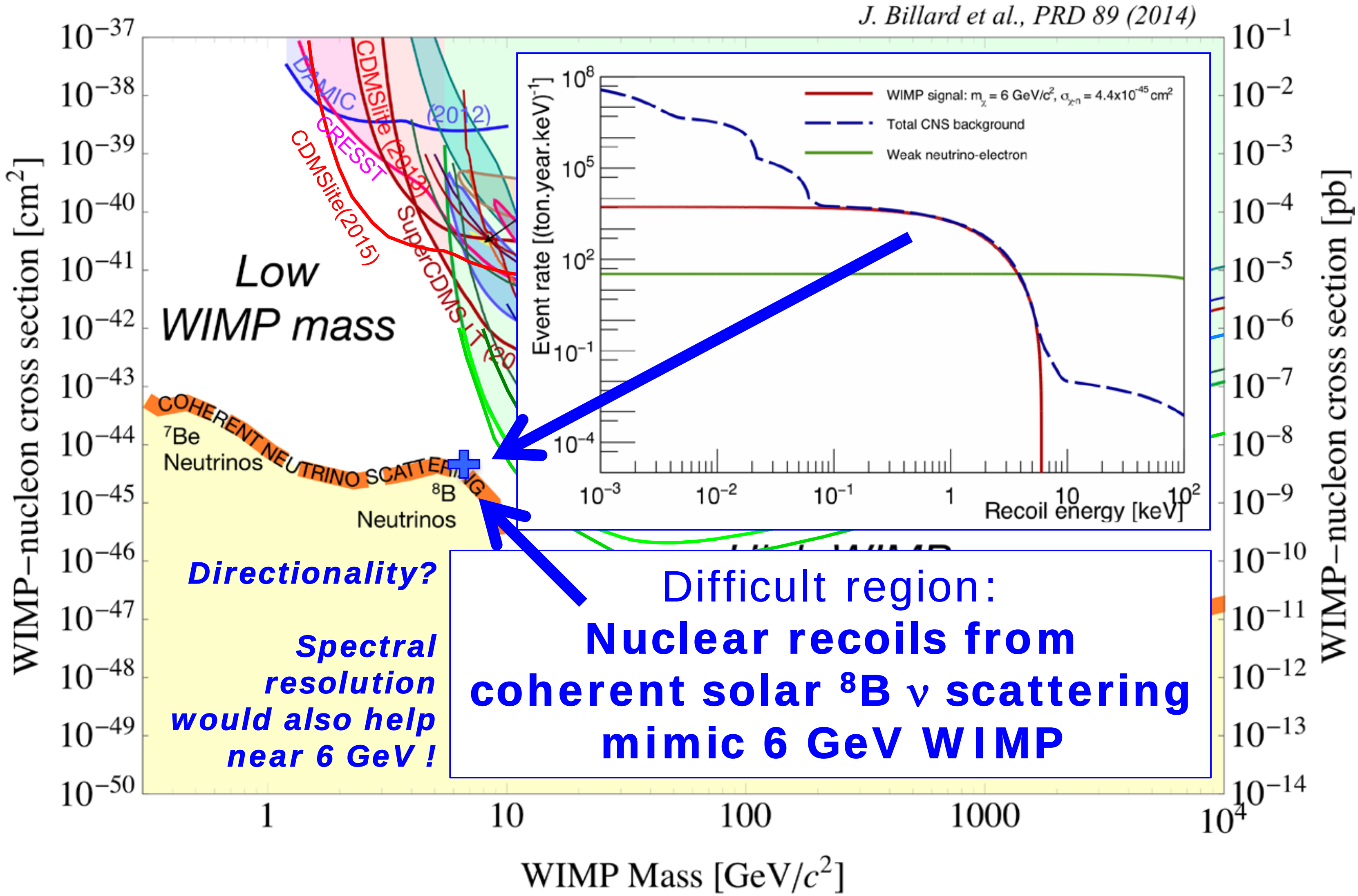
Choice of hunting ground



The GeV region



The ^{8}B region



Directionality?

Spectral resolution would also help near 6 GeV !

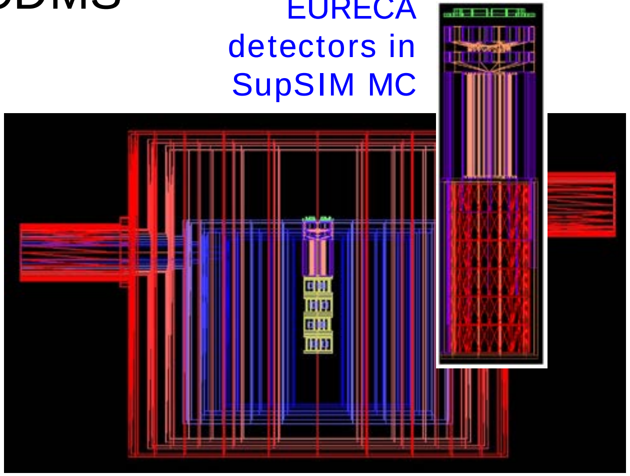
Difficult region:

Nuclear recoils from coherent solar ^{8}B ν scattering mimic 6 GeV WIMP

Updated EURECA strategy

- Aim: 1-20 GeV mass range, ideally suited for cryogenic detectors
- First step: tune the $CaWO_4$ and Ge detectors to fully exploit the full potential for cryogenic detectors for low thresholds
- Exploit current facilities at LSM and LNGS (with few kg) until external radioactive bkgs require major upgrades
- Larger exposure (>1000 kg.day): prepare detector adaptation to very-low background SuperCDMS @ SNOLAB environment currently being designed
  - *Preparation made possible by openness of SuperCDMS to share design info & MC code with EURECA*

EURECA detectors in SupSIM MC



Mockup tower to test detector / tower interface

CRESST DETECTOR CHALLENGES AND PLANS

CRESST Collaboration

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

INFN
Laboratori Nazionali del Gran Sasso

TECHNISCHE UNIVERSITÄT MÜNCHEN

UNIVERSITY OF OXFORD

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

HEPHY
Institut für Hochenergiephysik

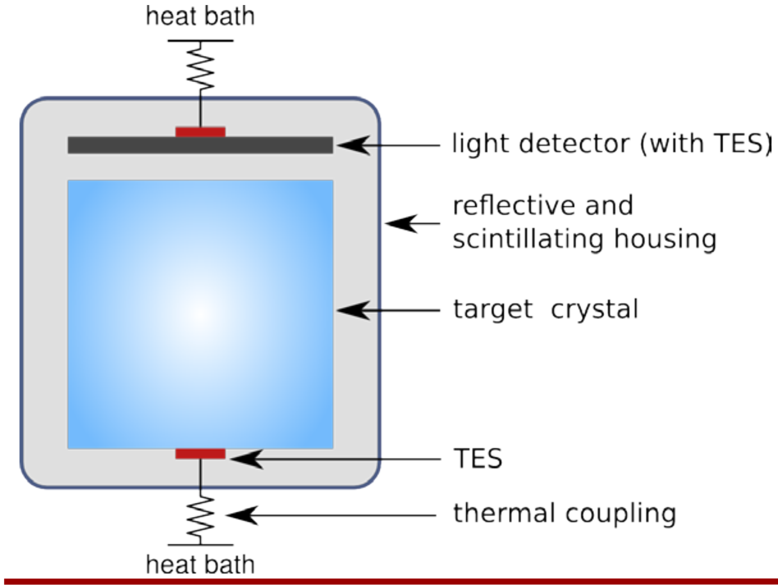
CRESST-II detectors

Cryogenic Rare Event Search with Superconducting Thermometers

Scintillating $CaWO_4$ crystals as target

Target crystals operated as **cryogenic calorimeters** (~15mK)

Separate **cryogenic light detector** to detect the scintillation light signal



Energy deposition:
- mainly phonons

(almost independent of the type of particle)

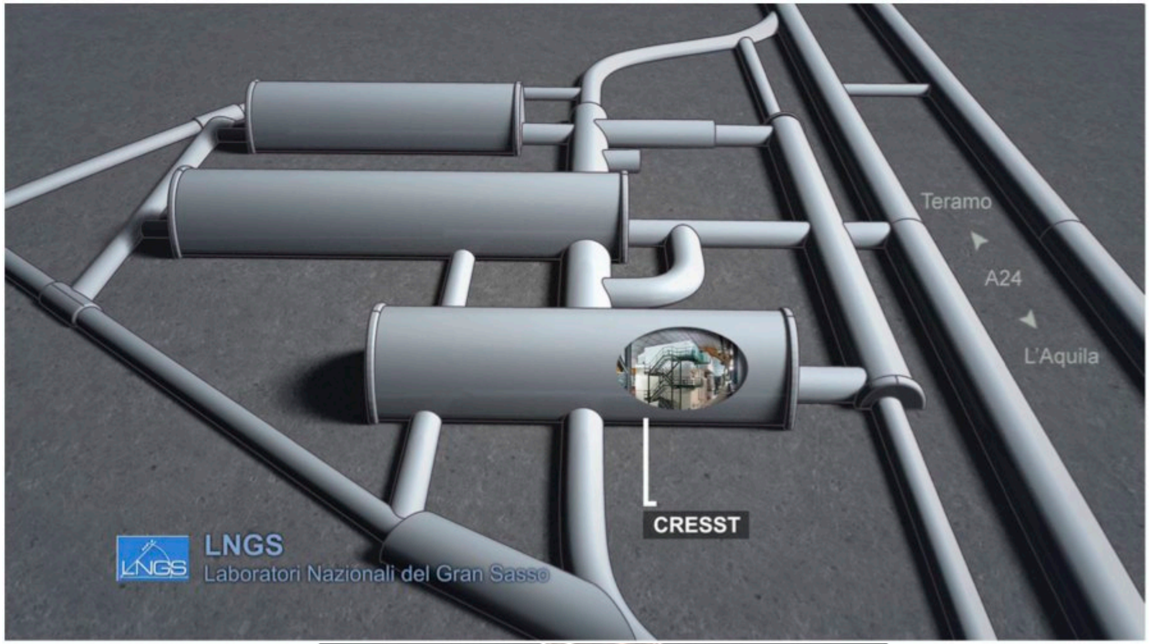
Measurement of deposited energy
- small fraction into scintillation light

(characteristic of the type of particle)

Particle discrimination

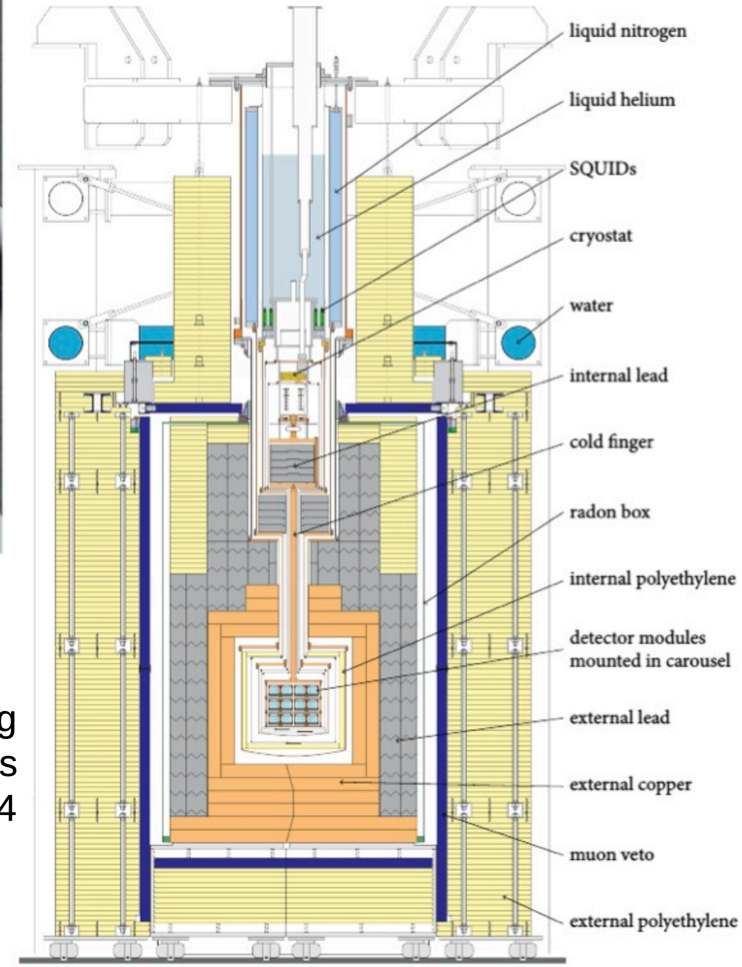
Two simultaneous signals from the two transition edge sensors (TES)

CRESST Experimental setup

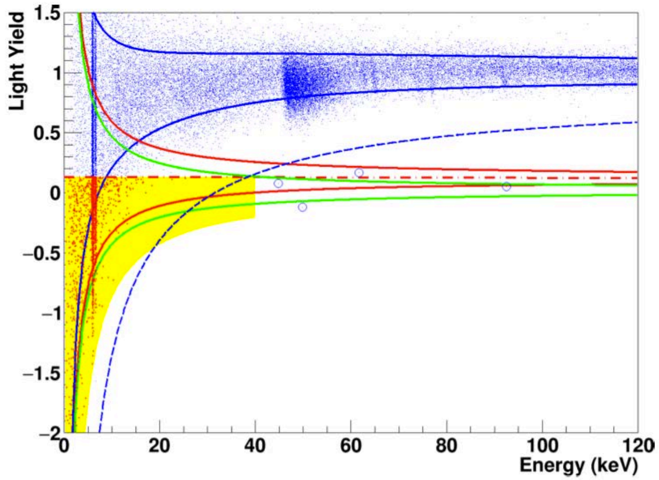


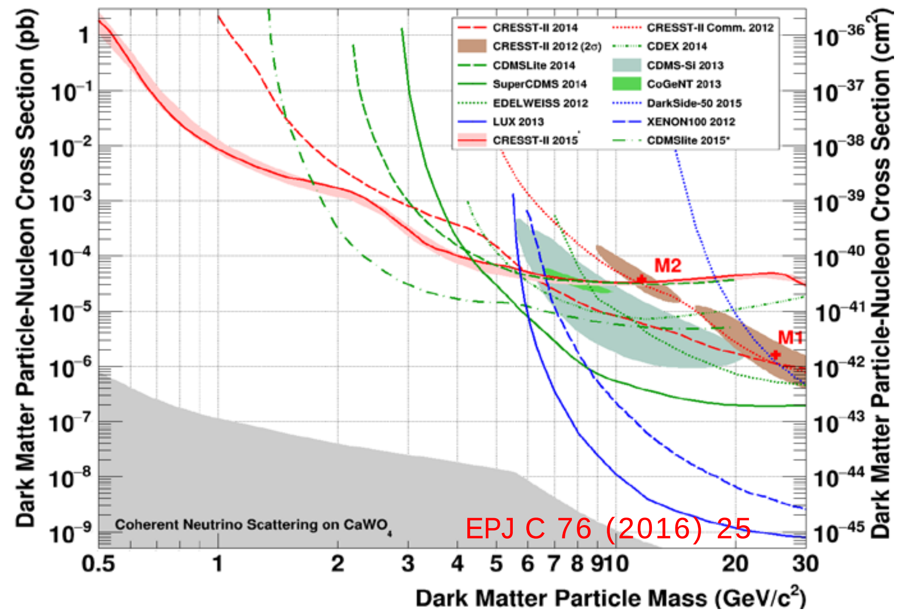
18 300g detectors in 2014

SQUID Readout

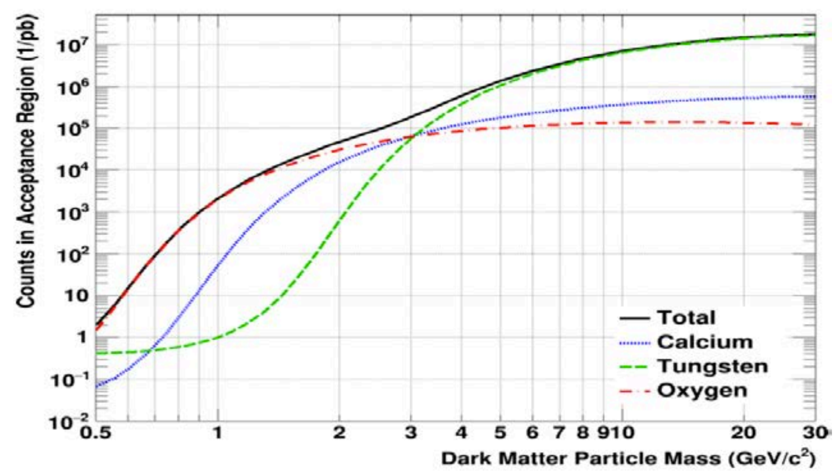


CRESST-II Results





- Based on 300g crystal with best nuclear recoil threshold (307 eV)
- World-leading result for masses below 1.7 GeV/c^2
- First experiment to explore masses in the sub-GeV/c^2 range
- Exploit different sensitivities of O, Ca and W recoils

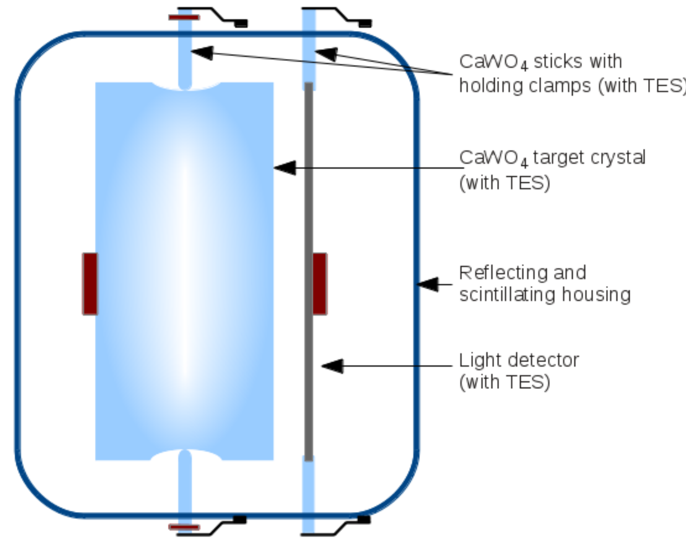


CRESST-III detectors

Change of strategy to improve sensitivity to low masses

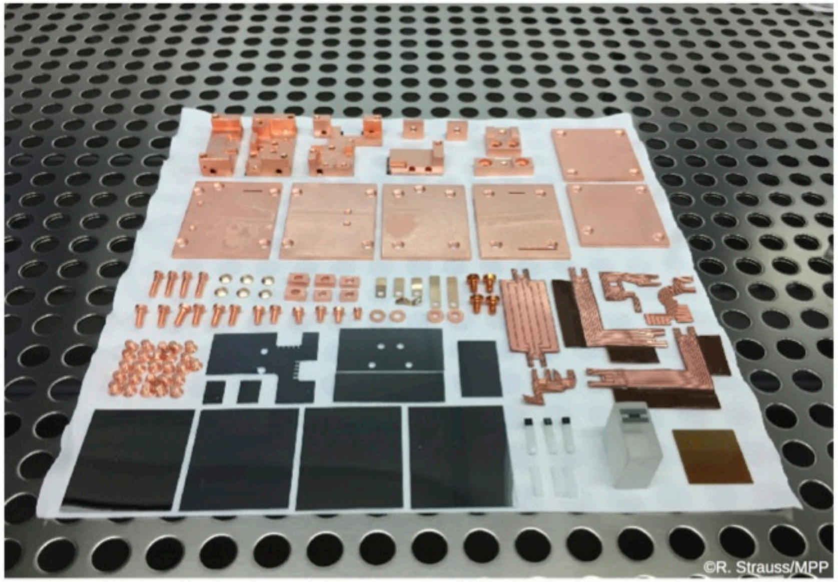
Detector design optimization:

- Clean self-grown crystals
- Small crystals (20x20x10)mm^3 (**25g**)
- 100 eV threshold design goal
- Small light detector (20x20)mm^2
- 6 modules with <**100 eV** threshold running at LNGS

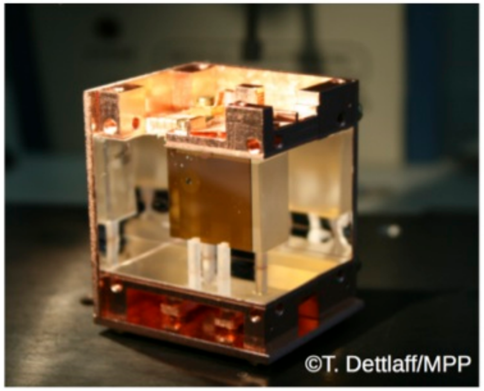


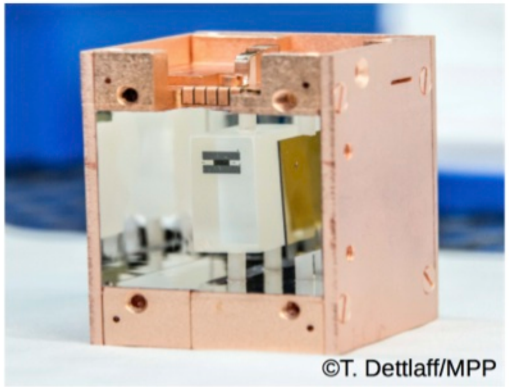
CRESST-III preparation

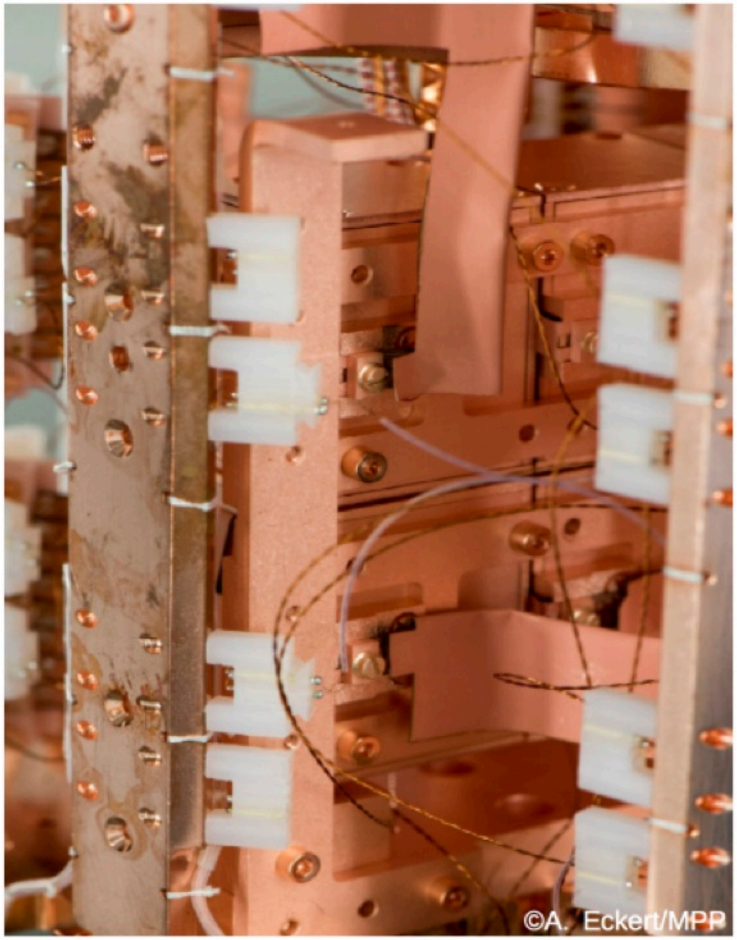
Construction kit for a CRESST-III module



CRESST-III modules during assembly



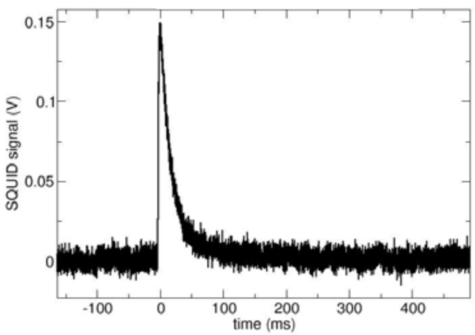




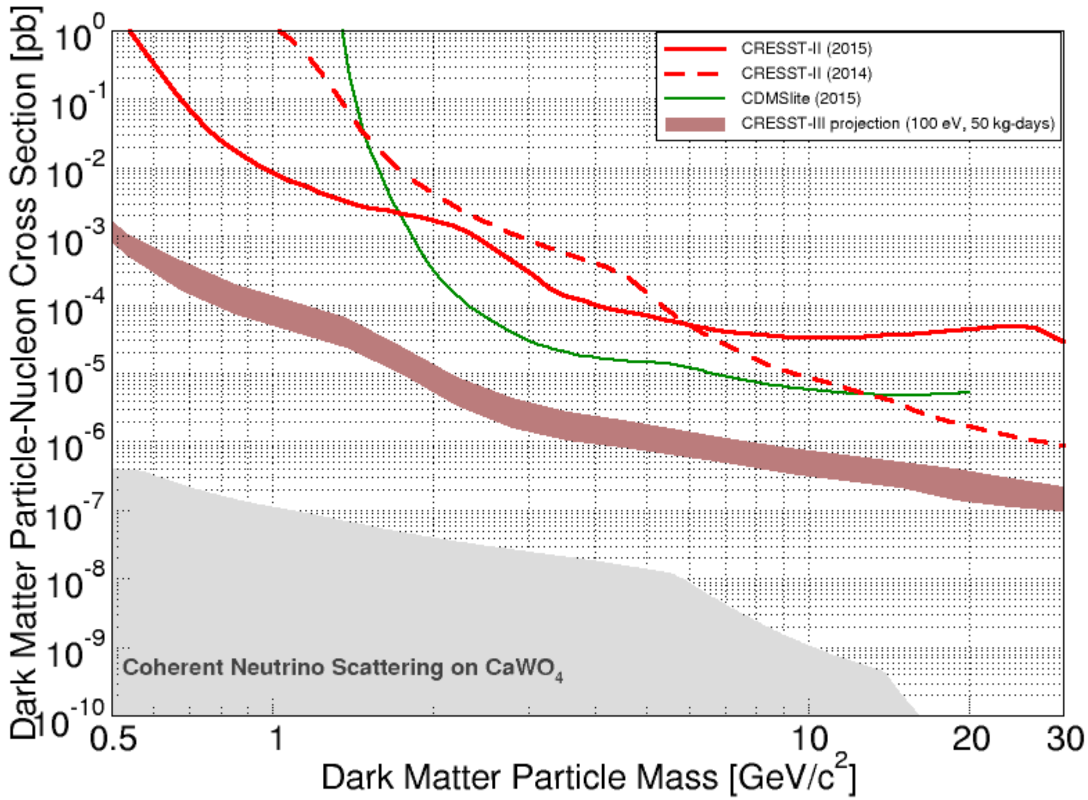
CRESST-III modules installed in the LNGS facility.
Data taking since summer 2016

CRESST-III phase I goals

500eV pulse

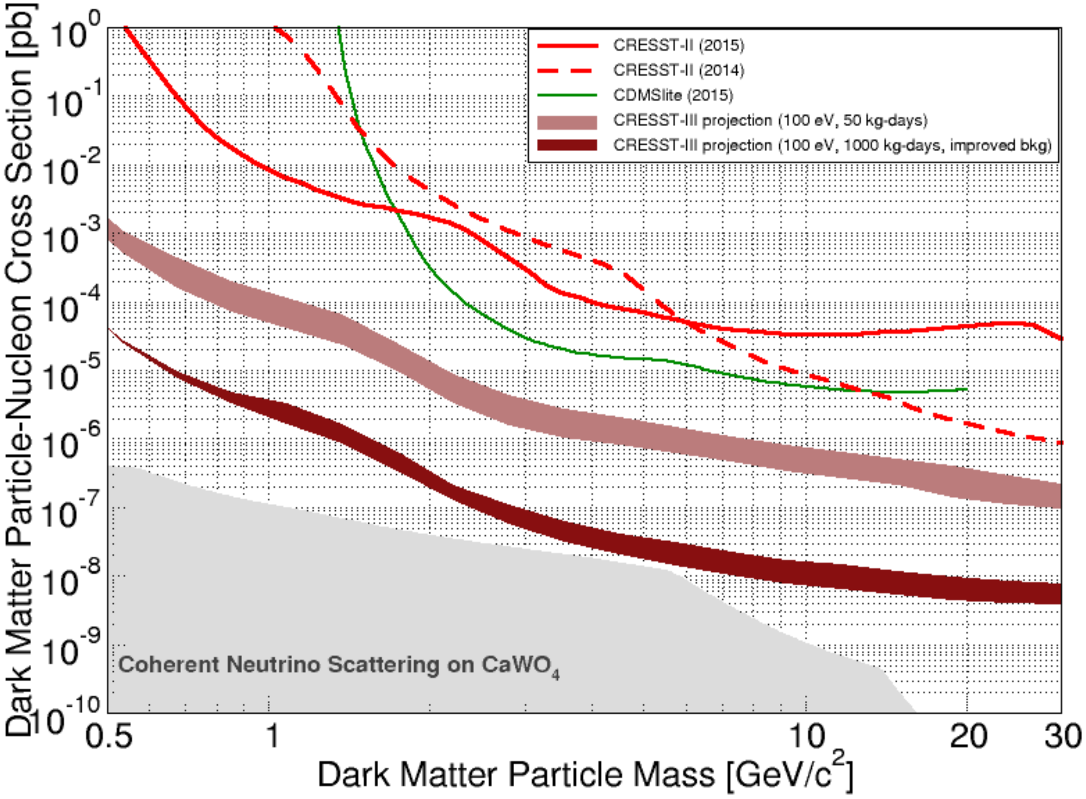


Projected sensitivity for 50kg days (1 year) with design goal threshold (100eV)



CRESST-III phase II

- Material screening and purification of raw material for crystal production
  - Factor 100 reduction of background
- Upgrade of LNGS facility to operate 100 detectors
  - 1000 kg days in 2 years

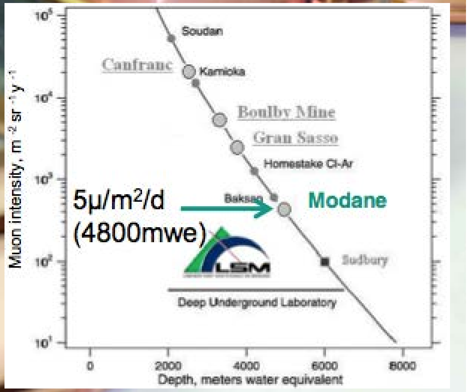


EDELWEISS DETECTOR CHALLENGES AND PLANS

EDELWEISS collaboration

CSNSM	CNRS/IN2P3
iPNL	CNRS/IN2P3
NÉEL institut	CNRS/INP
LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES	CNRS
Irfu	CEA/IRFU
IRAMIS	CEA/IRAMIS
KIT Karlsruher Institut für Technologie	IKP EKP IPE
JINR	JINR DUBNA
UNIVERSITY OF OXFORD	Univ. OXFORD
The University Of Sheffield.	Univ. SHEFFIELD

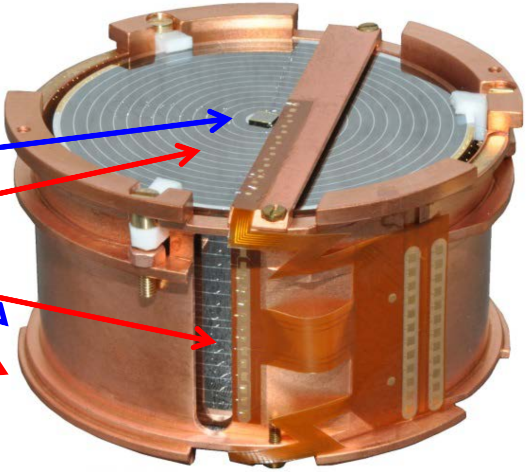
- **Direct detection of WIMPs, germanium target**
- **20 kg Ge total (largest for DM search), 870g units**
- **Ionization + Heat** *PLB 681 (2009) 305*
  - **Position independent (~thermal) heat measurement**
  - **Emphasis on complete e^- + h^+ charge readout** *JINST 11 (2016) 10008*
- **Simple & robust design**
  - **Important for scalability to large arrays**
  - **Initially designed for >20 GeV WIMP search, extended down to 5 GeV given achieved resolutions** *EPJC 76 (2016) 548*
- **Laboratoire Souterrain de Modane**
  - **Deepest in Europe : 5 μ / m² / day**



Fully InterDigitized electrode design

- ~870g detectors (ϕ=70 h=40 mm)
- 2 GeNTDs heat sensor per detector
- Electrodes: concentric Al rings (2 mm spacing) covering all faces
- XeF_2 surface treatment to ensure low leakage current (<1 fA) between adjacent electrodes

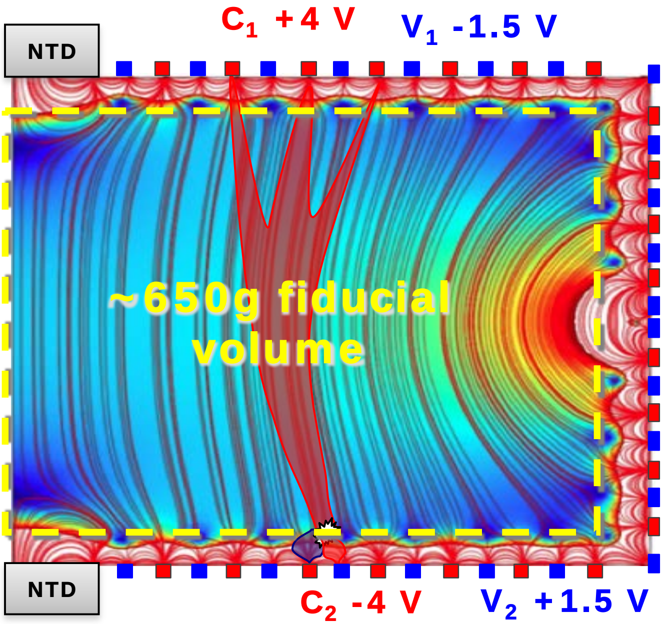
J Low Temp Phys (2014) 176: 182-187



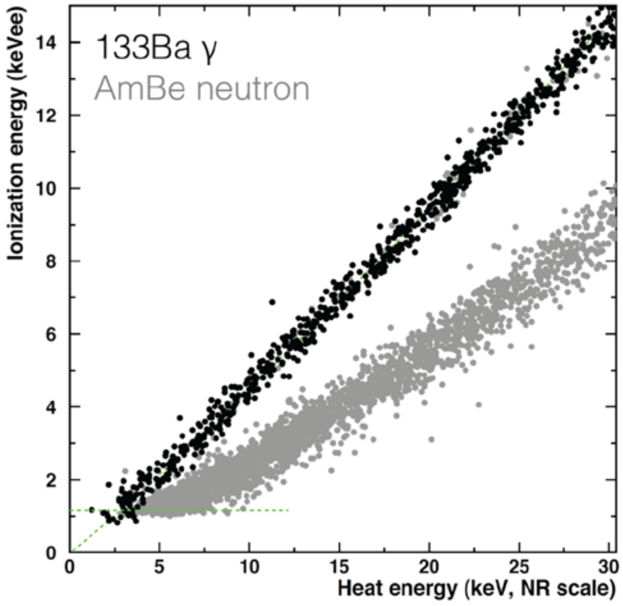
Surface event rejection

Phys Lett B 681 (2009) 305–309

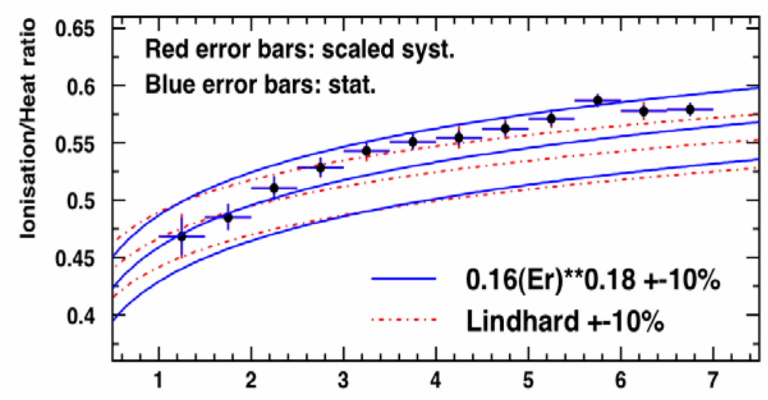
- Bulk event: charges collected by C_1 and C_2 ; V_1 and V_2 act as veto
- Surface events: charges collected by either C_1V_1 or C_2V_2



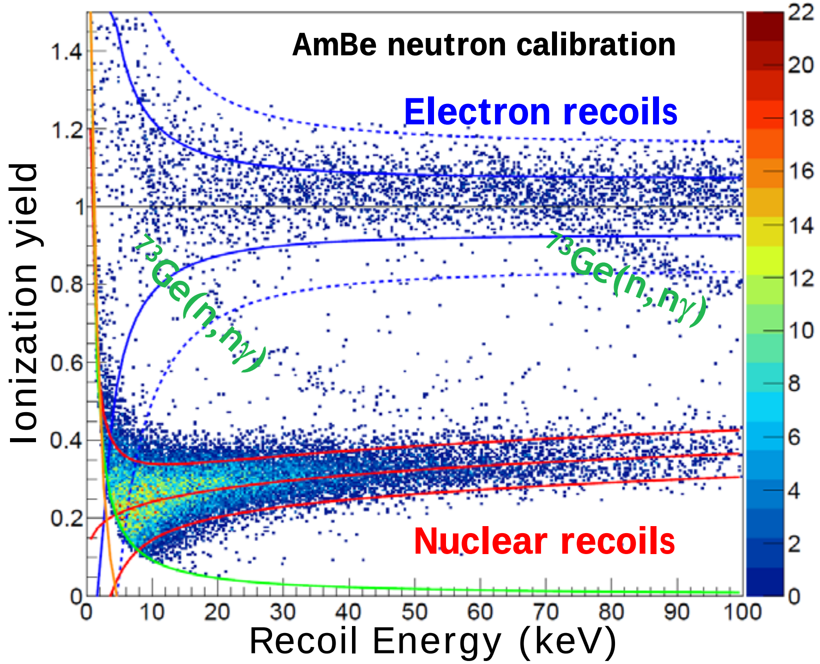
Nuclear recoil calibration + discrimination



- Clear event-by-event separation down to 5 keV energy recoils
- Response to nuclear recoils calibrated down to the analysis threshold for low-mass WIMP searches
  (1 keV$_{ee}$ heat = 2.5 keV nuclear recoil)



Sanglard IDM2016



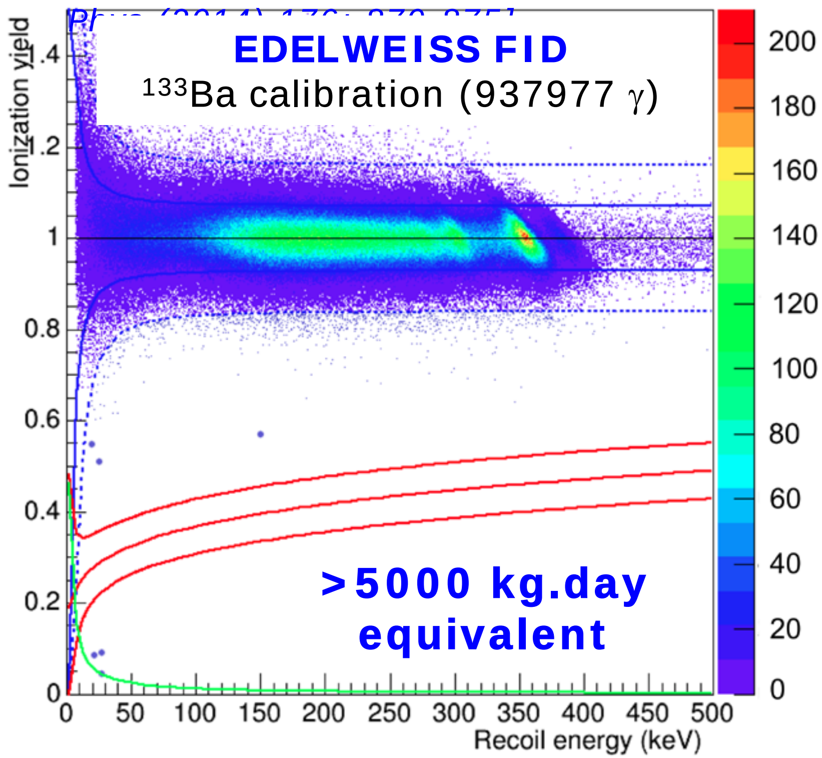
Gamma rejection & Surface rejection

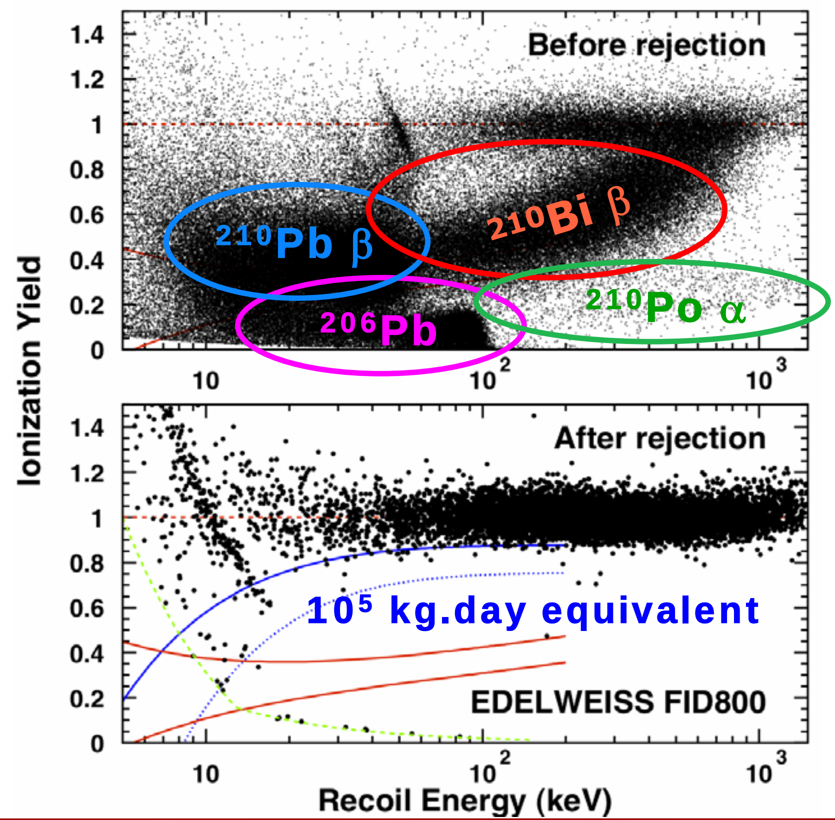
- γ rejection factor: < 5.6 x 10^{-6} *[J Low Temp Phys (2012) 167: 1056-1062]*

  Updated now to < 2.5 x 10^{-6} with additional detectors + statistics

- Surface evts rejection (^{210}Pb+^{210}Bi β, ^{210}Po α, ^{206}Pb recoils): < 4 x 10^{-5}

[J Low Temp Phys (2014) 176: 870-875]

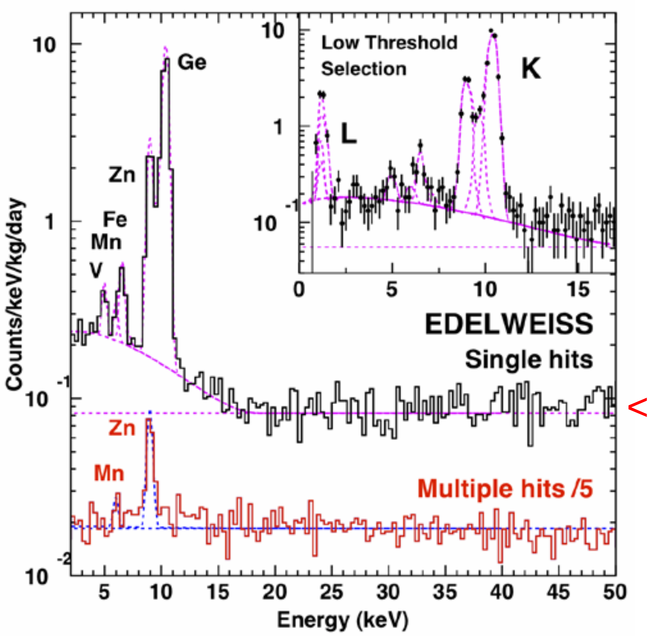




EDELWEISS-III 2014-2015 data taking

- 161 days of physics data with 24 FIDs: >3000 kgd total

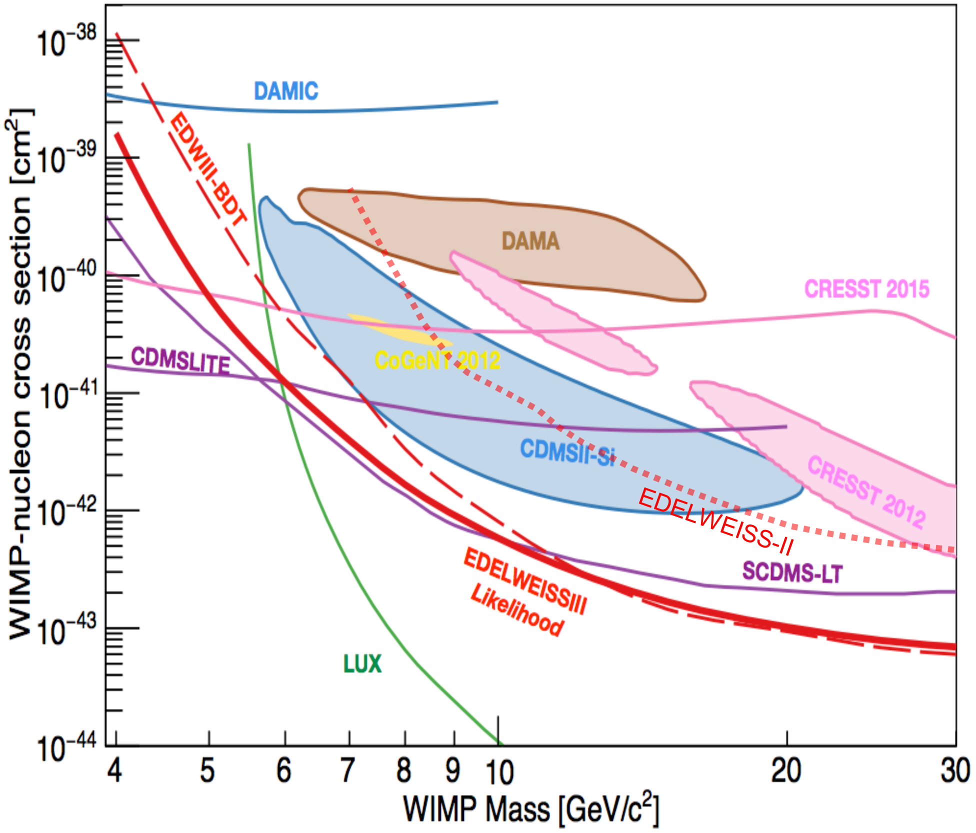
- Low electron-recoil bkg: 19 FIDs used in first measurement of cosmogenic production of ^3H in Ge *[arxiv:1607.04560]*



- *8 lowest threshold FIDs used for low-mass WIMP search*

Low-Mass analysis

- Analysis with Boosted Decision Tree [JCAP05 (2016) 019]
- Analysis with Profile Likelihood [EPJC 76 (2016) 548]



- Improvement by x20 to x150 between 7 and 10 GeV wrt EDELWEISS-II
- Limited by heat-only background: *identification and rejection using the σ=230 eV resolution on ionization*
- Ionization resolution is key for rejection
- Heat resolution is key for low thresholds

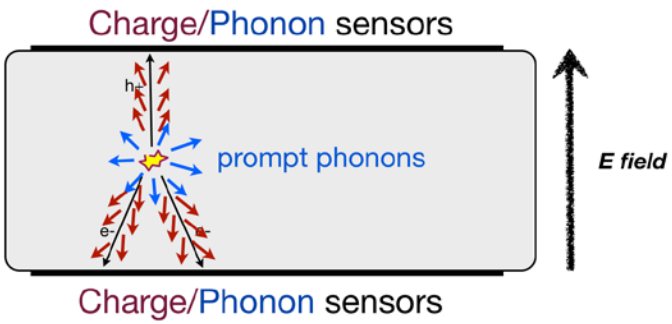
Strategy for low-mass WIMP searches

1. **High Voltage: Amplify heat signal to reduce threshold**
   - *8 V —> 100 V*
2. **Lower the intrinsic heat threshold**
   - *Improved heat sensors*
   - *500 eV (RMS) —> 100 eV (RMS)*
3. **Reduce background from heat-only events**
   - */100 heat only rate*
4. **Extend background ID to lower energy**
   - *Improved ionization measurement*
   - *200 eV (RMS) -> 100/50 eV (RMS)*

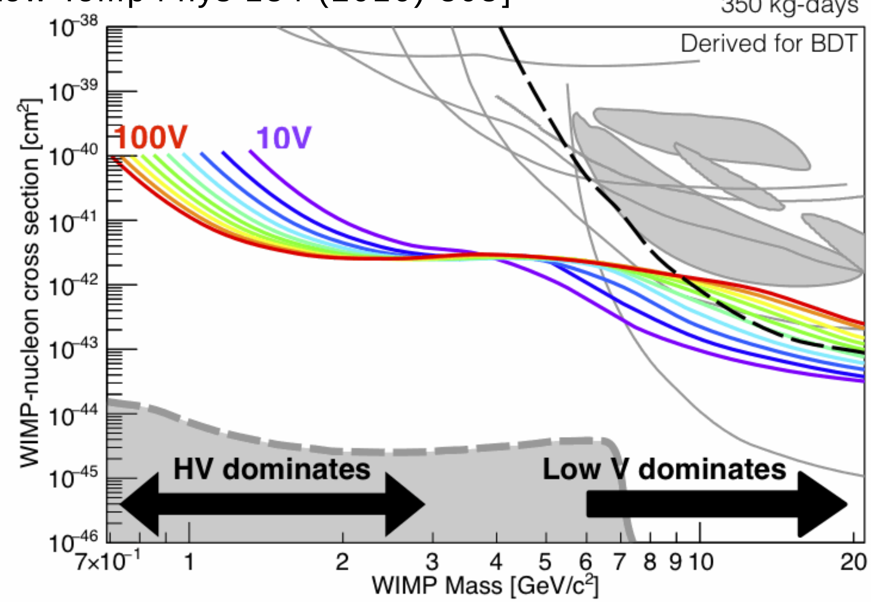
Challenge #1: High-voltage

Heat thresholds improved using larger bias voltages

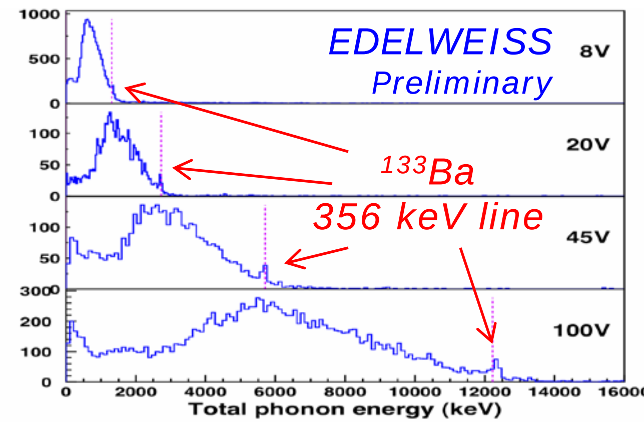
$$E_{TOTAL} = E_{RECOIL} + E_{ION} \frac{\Delta V}{3Volt}$$



[J Low Temp Phys 184 (2016) 308]



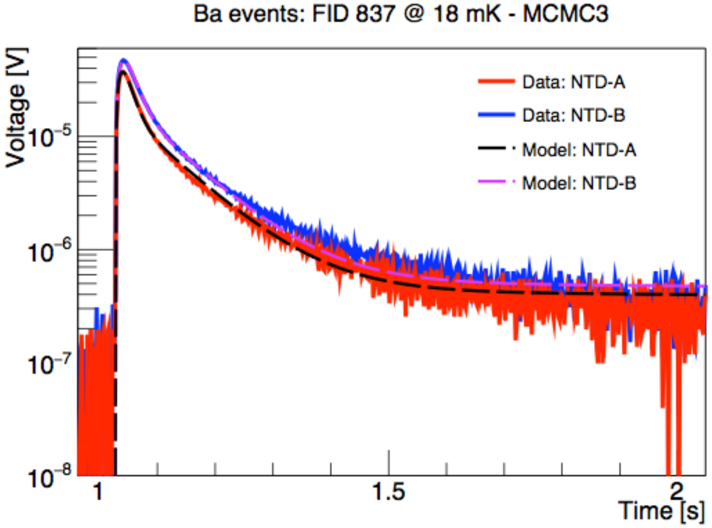
- Heat signal boosted by Neganov-Luke effect (~Joule heating, factor [$1+V_{bias}/3$])
- Loss of ionization-based bkg discrimination: method benefits low-mass searches only



100V bias already achieved

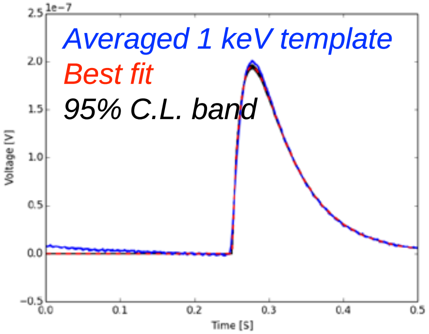
Challenge #2: heat sensor resolution

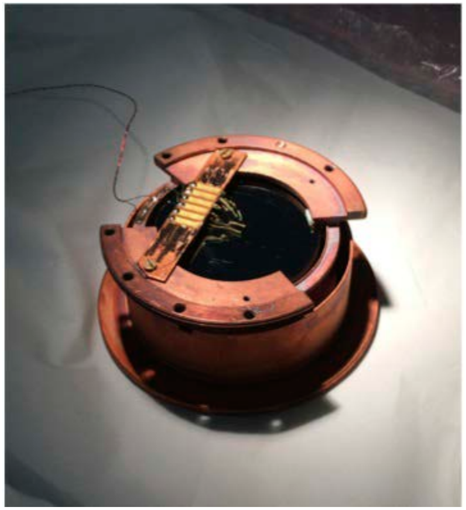
JLTP 184 (2016) 299



- Better understanding of heat signal
  - Thermal modeling of signal, verified with dedicated R&D
  - Identification of sensitivity to ballistic phonons
  - Identification of parasitic heat capacity

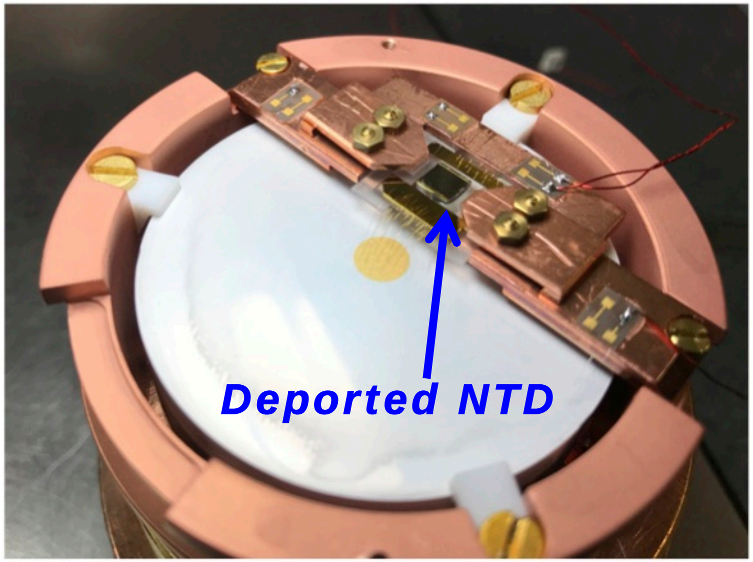
- Sensitivity of 200 nV/keV (x6 wrt present FIDs) achieved on 250 g test detectors



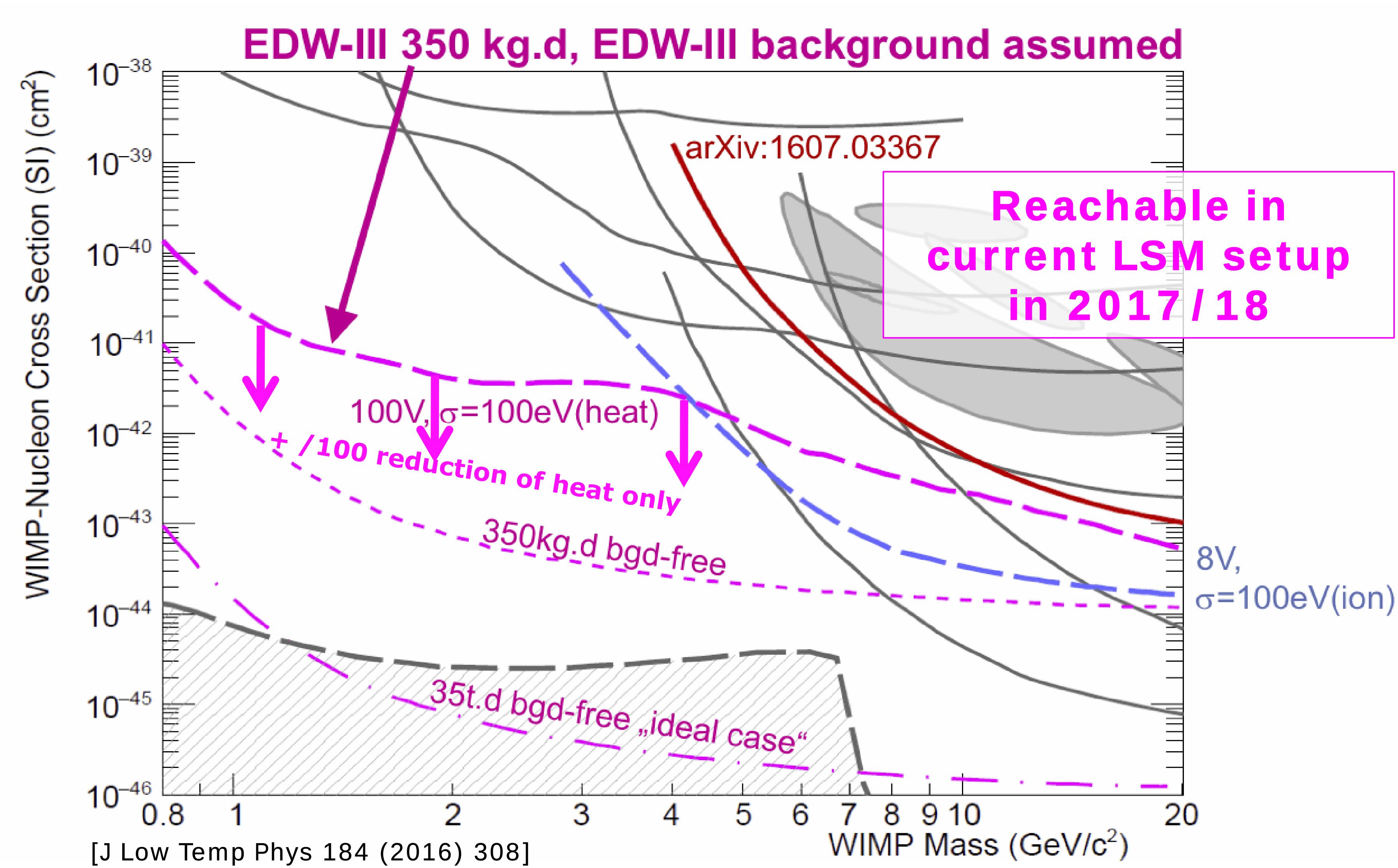


Challenge #3: heat-only events

- Dominant (+reproducible) background at low energy
- Noise, cryogenics, stress from detector suspension: excluded as sources of this background
- Remaining suspect: stress from glueing, avoided via:
- ***Two "deported NTD", glued on separate sapphire wafer***
- ***Photo-lithographied high-Ω NbSi TES, sensitive to athermal phonons***
- Following promising tests, present cool-down @ LSM of 5 detectors with these new designs



GeV-range prospects with goals 1+2(+3)

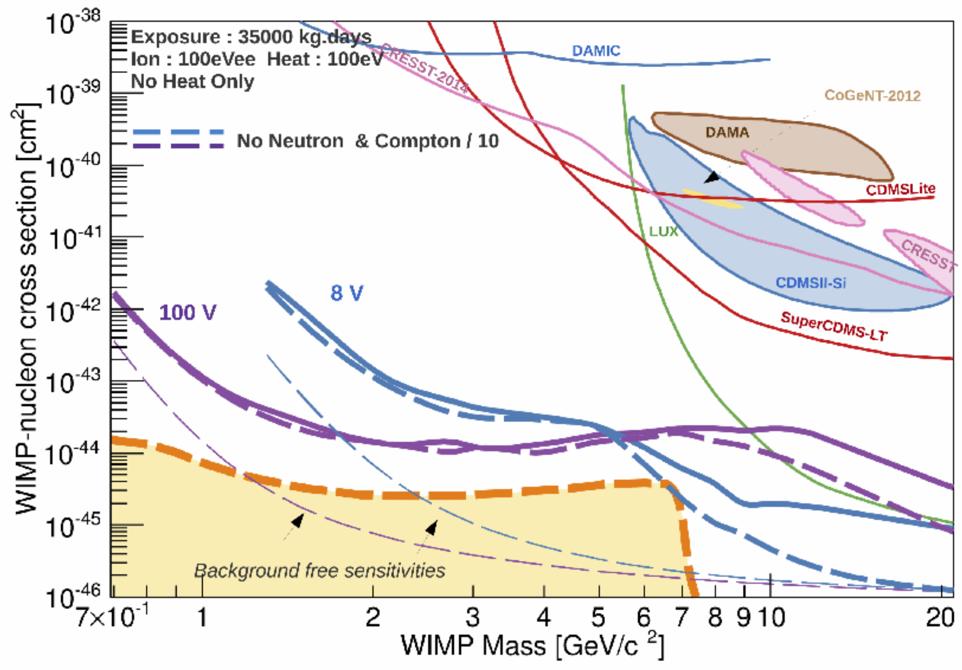


[J Low Temp Phys 184 (2016) 308]

Future: reduce backgrounds, increase mass

- EDELWEISS sensitivity for 35 ton.day = 100 kg x 1 year *[J Low Temp Phys 184 (2016) 308]*
- Suppression of Heat-Only becomes essential in GeV range
- In 5-20 GeV range, need:
  - Improve ionization resolution (for discrimination) from σ=230 to 100 eV
  - reduction of neutron + bulk electron recoils reduction by /10 wrt present setup

    ➔ *achievable in future in SuperCDMS environment planned @SNOLAB*

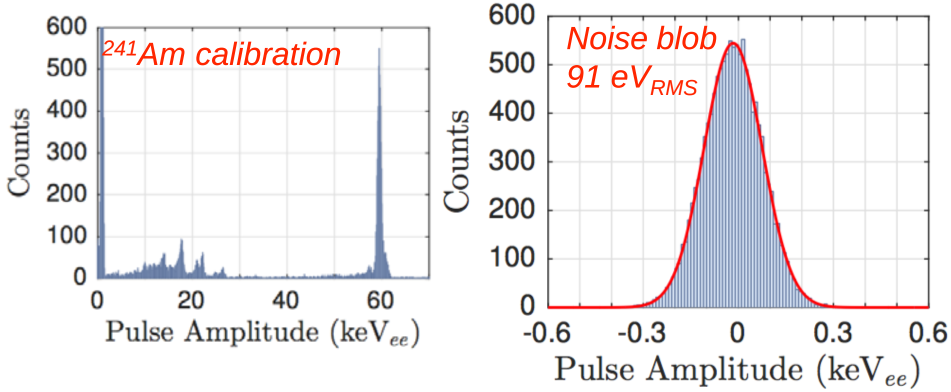


- Study implication of SuperCDMS tower design +HEMT readout on EDELWEISS detectors
- Collaboration on CUTE test facility @SNOLAB
- *Study improvement of charge readout with HEMTs*

Goal 4: ionization resolution

- **Transitioning from JFET to HEMT**
  - Lower intrinsic noise, low heat load
  - Works at 4K: shorter cables reduces capacitance and improves resolution
  - Considered by EDW/HARD (resolution) [*XB+AB NIMA 787 (2015) 51*]
    and SuperCDMS (heat load) [*AP, JLTP 176 (2014) 466 and 911*]
- ***Successful HEMT amplifier with sub-100 eV$_{RMS}$ ion. resolution***
  [A. Phipps, arXiv:1611.09712, collaboration between SuperCDMS and EDW]
- Step#1: Upgrade EDW ionization readout with this new design
- Step#2: Electrode design to reduce detector capacitance to reach 50 eV$_{RMS}$
- **Increase of electrode spacing from 2 to 4 mm already successfully implemented**

A. Phipps et al, arXiv: 1611.09712

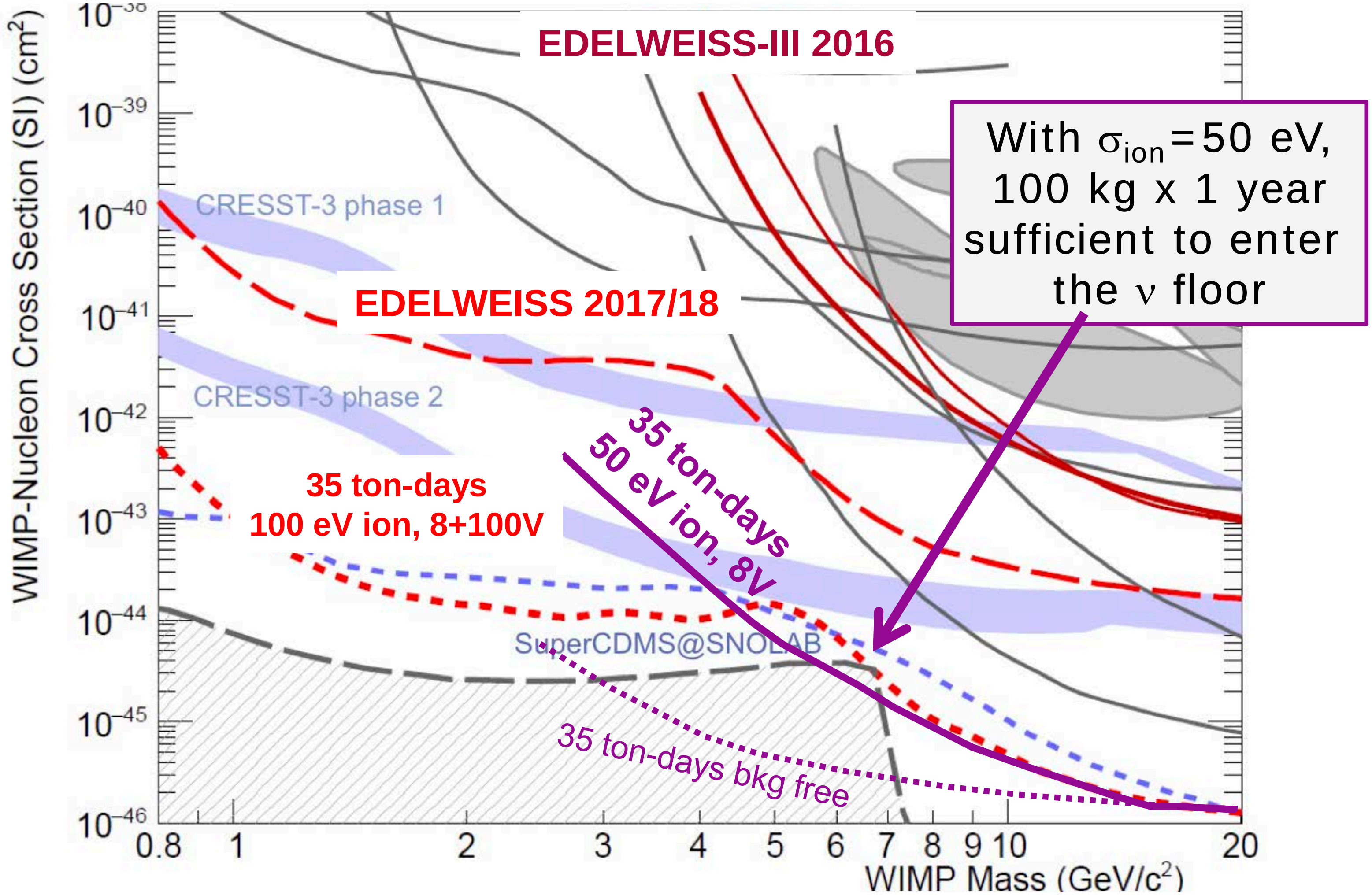


FID842
2 mm spacing

FID824
4 mm spacing

Entering the ^{8}B region

- Projection with σ=100 eV ion. resolution, 100 kg x 1 year



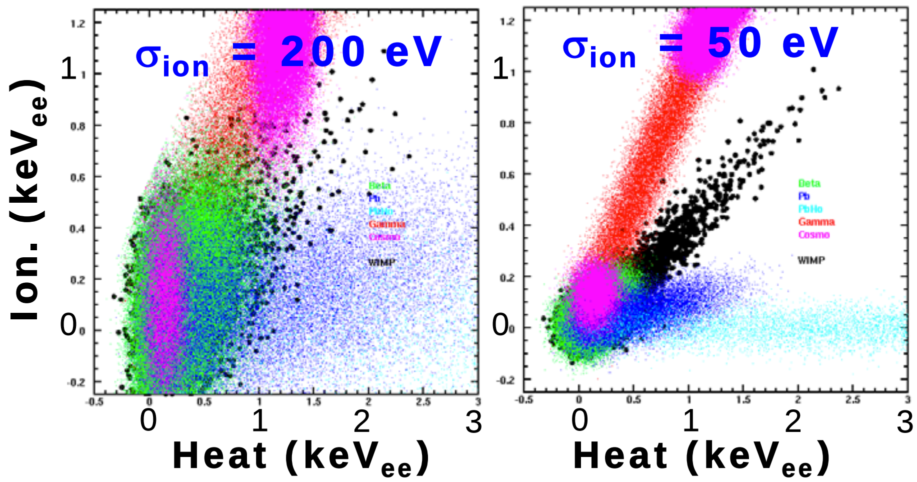
^{8}B region exploration with FID+HEMT

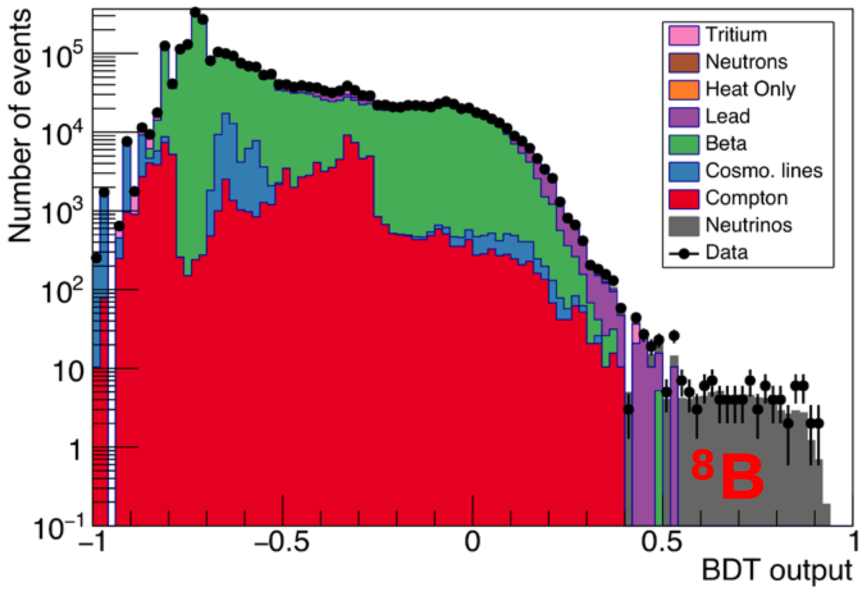
- Separation of ^{8}B CNS signal (~6 GeV WIMP, black) with σ_{ion} = 50 eV (wrt present ~200 eV)

- E resolution: ~10% @ 1 keV_{ee}
  spectral separation for WIMP searches close to 6 GeV

- Simulated BDT analysis:
  78 "bkg-free" ^{8}B events in 1 t.y
  (8 in 100 kg x 1 year)

- Paving the way for a detailed measurement of this important (and yet to be observed) background from ^{8}B ν CNS





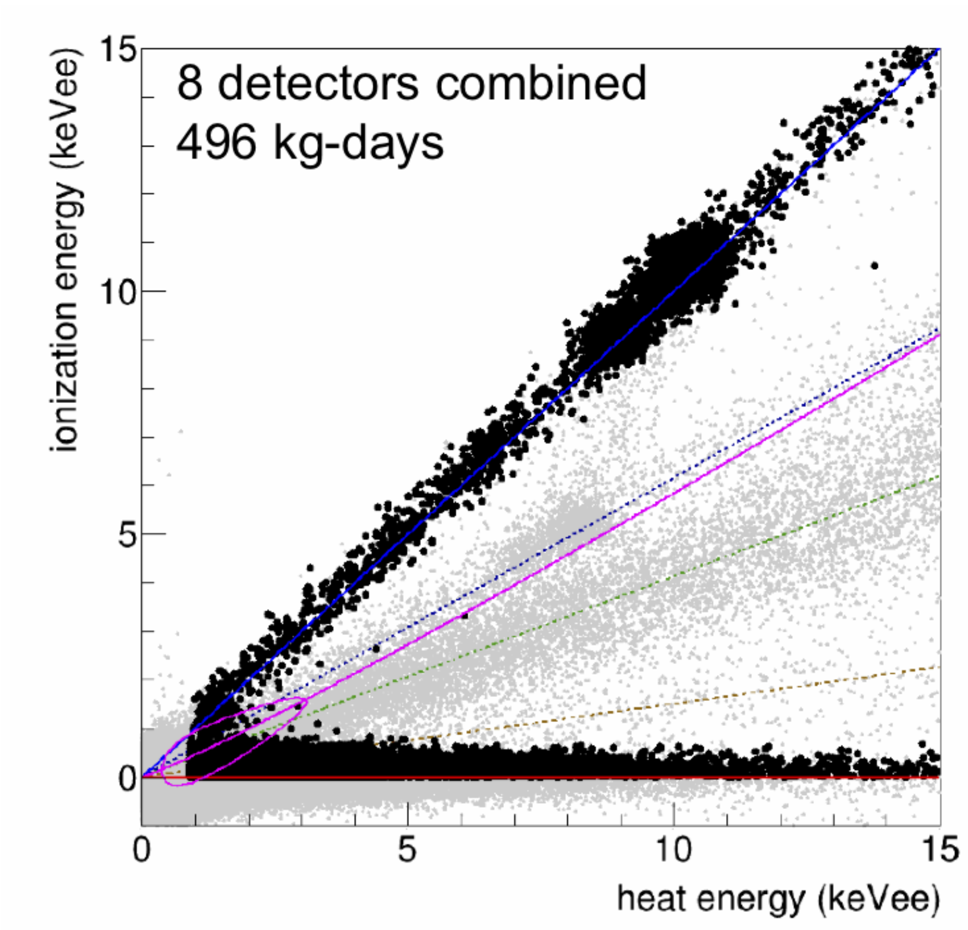
Conclusions

- The European collaboration for cryogenic crystal detectors (EURECA) has updated its objectives relative to its 2014 CDR
- *Emphasis for 1-20 GeV WIMP masses*, for which the detector technology is ideally suited (low threshold on heat signal)
- 2017-2018 prospects in the GeV-WIMP range: 10^{-41} cm^2 @1.5 GeV with both CRESST and EDELWEIS, achievable in present facilities @ LSM and LNGS
  - Factor 10 improvement in a future 1000 kgd CRESST-III phase-II
- Larger exposure with lower external background: collaboration with SuperCDMS@SNOLAB
  - Adaptation to SuperCDMS tower design under study
- Prospects for WIMPs in the ^{8}B region
  - ~100 kg low-capacitance FIDs+HEMTs at SNOLAB to complement nicely the SuperCDMS-SNOLAB reach with clear “bkg-free” ^{8}B CNS signal

BACKUP

Low-Mass analysis

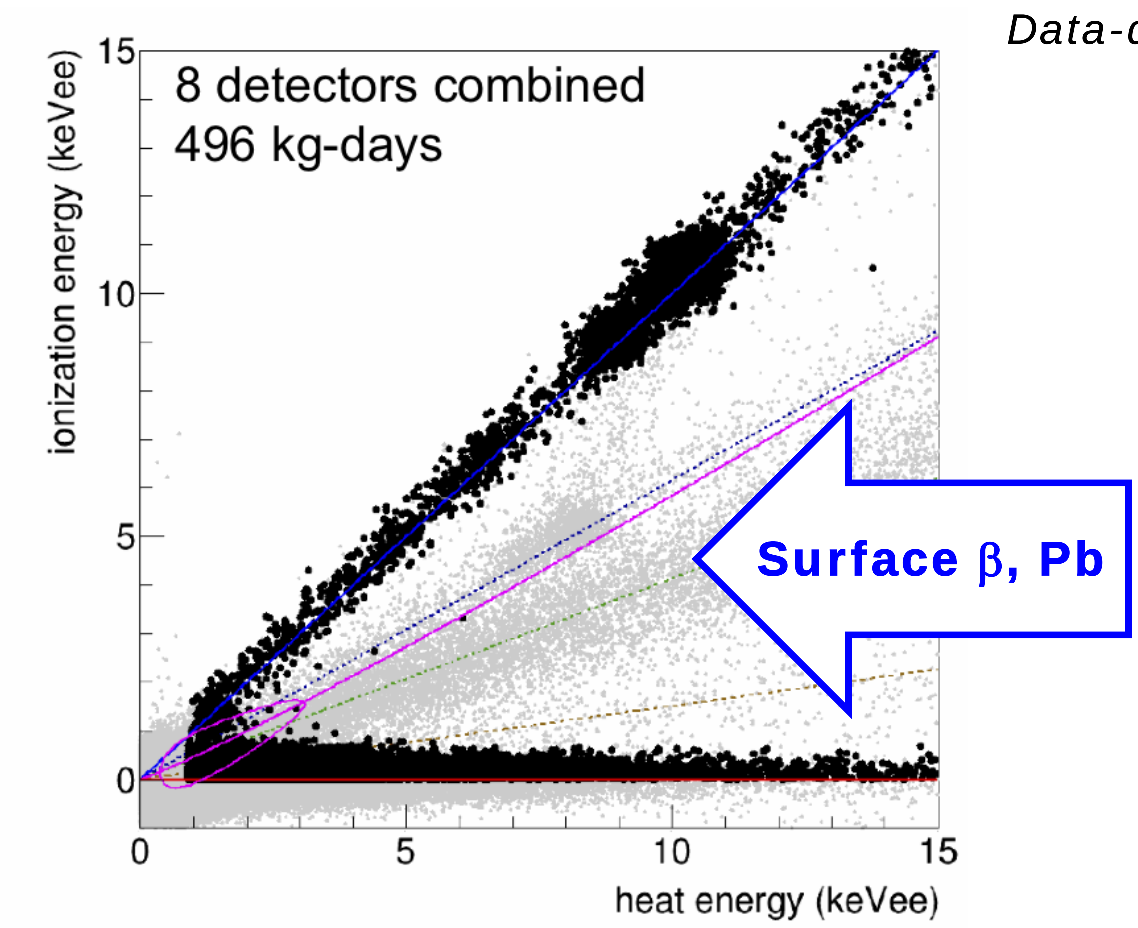
- Analysis with Boosted Decision Tree [JCAP05 (2016) 019]
- Analysis with Profile Likelihood [EPJC 76 (2016) 548]



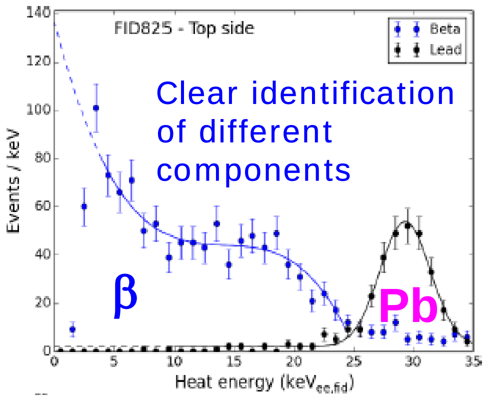
Data-driven background models based on sidebands

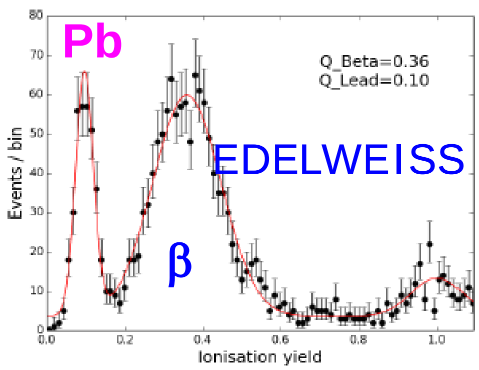
Low-Mass analysis: surface background

- Analysis with Boosted Decision Tree [JCAP05 (2016) 019]
- Analysis with Profile Likelihood [EPJC 76 (2016) 548]



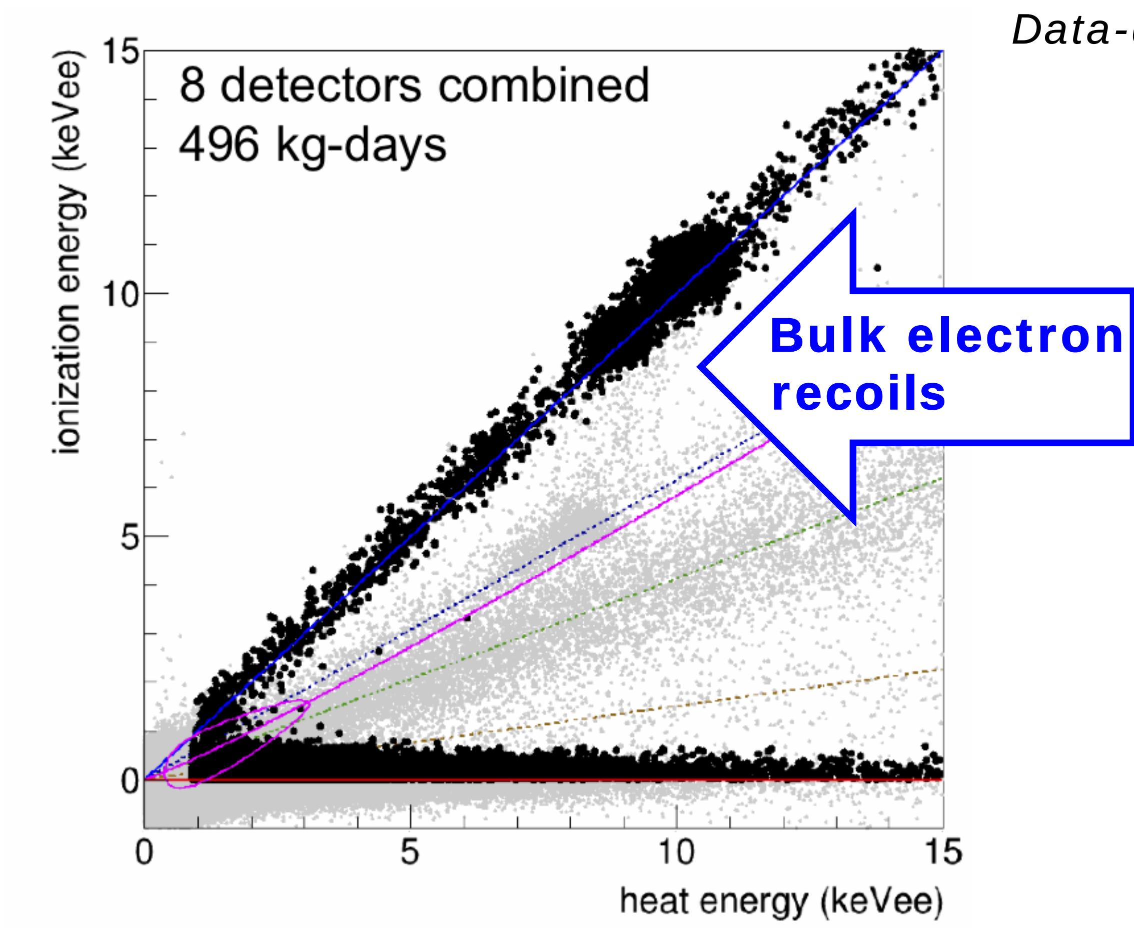
Data-driven background models based on sidebands



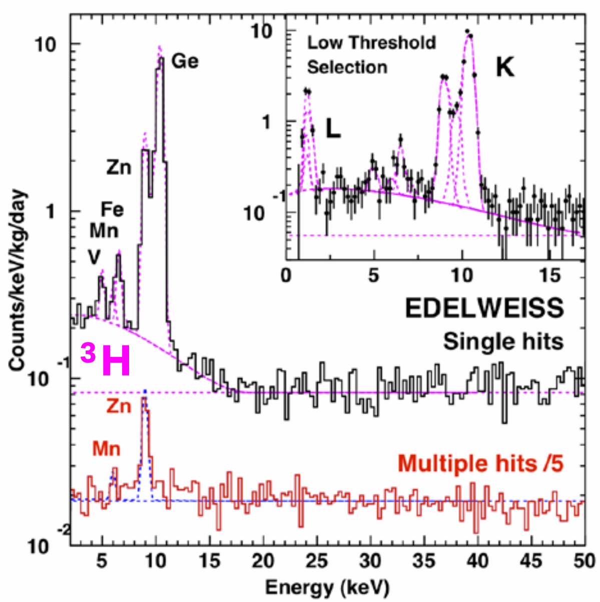


Low-Mass analysis: fiducial electron recoil

- Analysis with Boosted Decision Tree [JCAP05 (2016) 019]
- Analysis with Profile Likelihood [EPJC 76 (2016) 548]



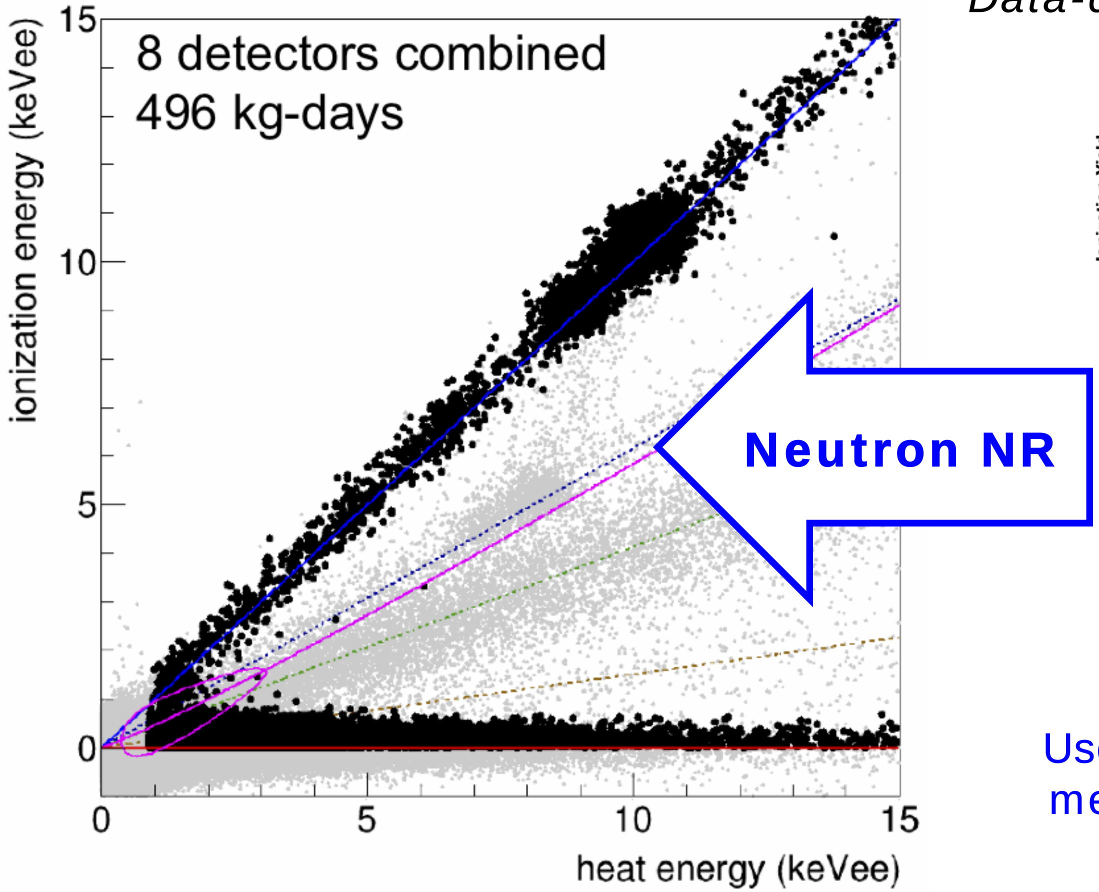
Data-driven background models based on sidebands



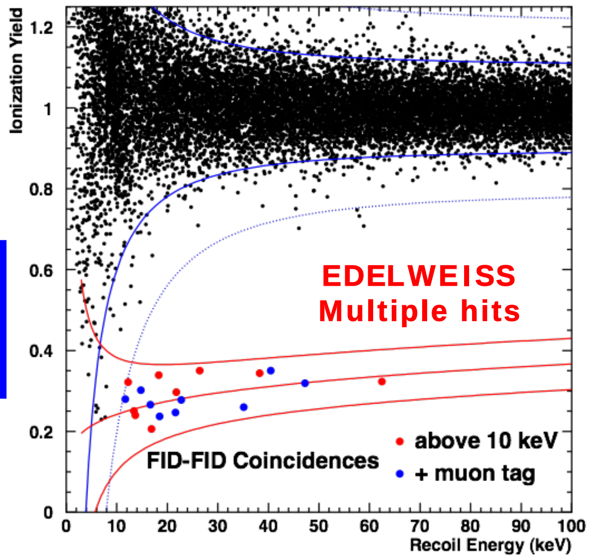
First measurement of cosmogenic production of ^{3}H in Ge [arxiv:1607.04560]

Low-Mass analysis: neutron background

- Analysis with Boosted Decision Tree [JCAP05 (2016) 019]
- Analysis with Profile Likelihood [EPJC 76 (2016) 548]



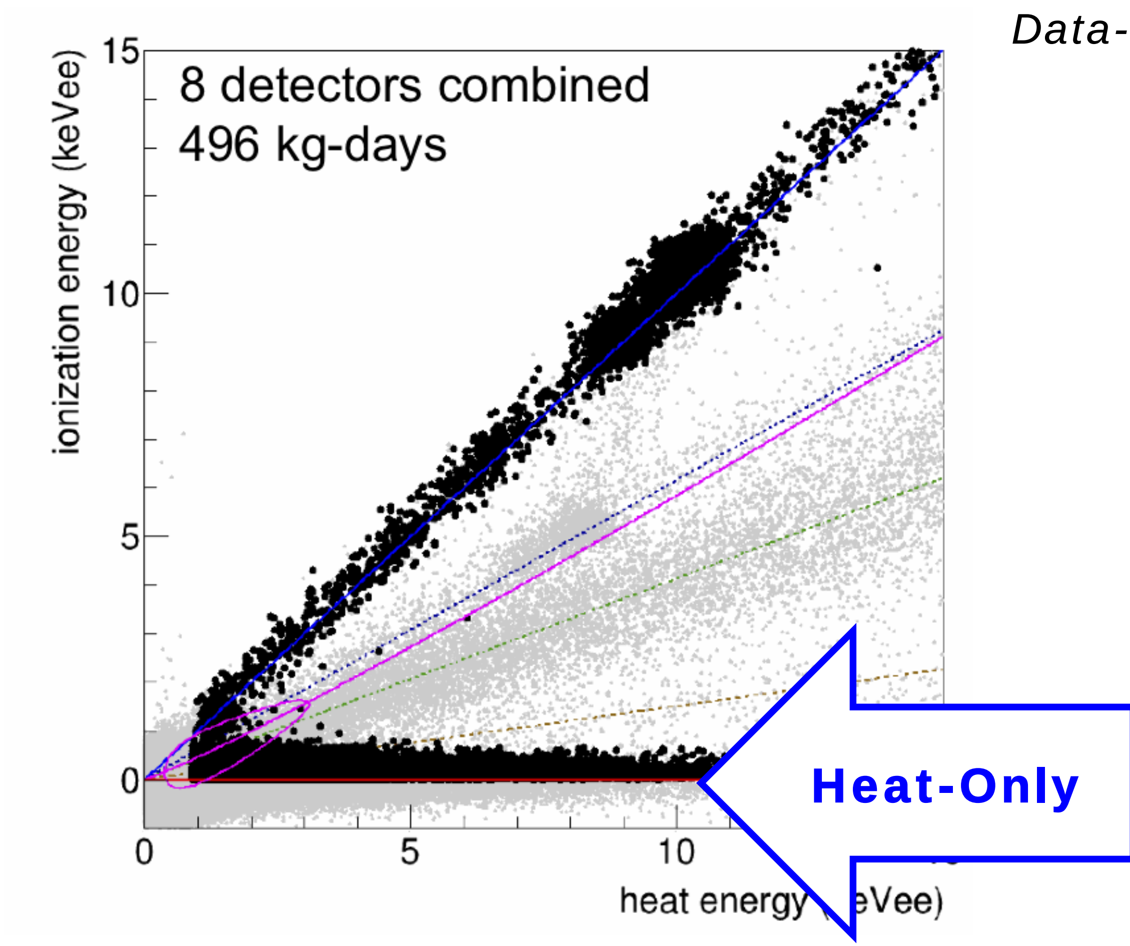
Data-driven background models based on sidebands



Use MC spectrum, scaled by measured rate of coincident nuclear recoil events

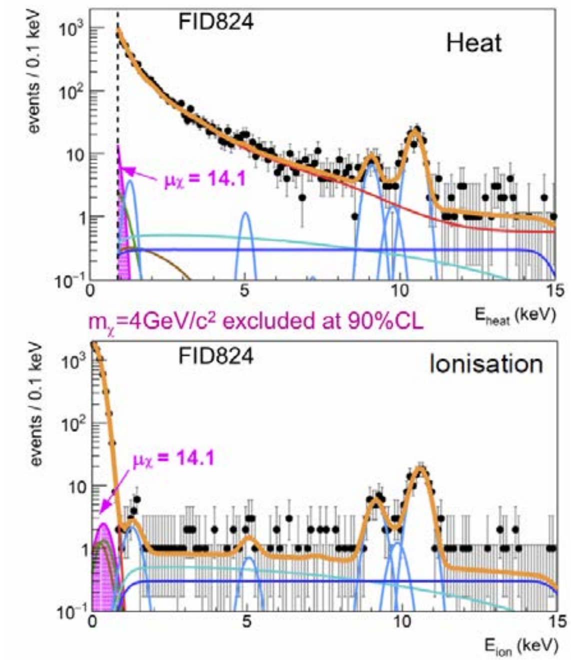
Low-Mass analysis: heat-only background

- Analysis with Boosted Decision Tree [JCAP05 (2016) 019]
- Analysis with Profile Likelihood [EPJC 76 (2016) 548]



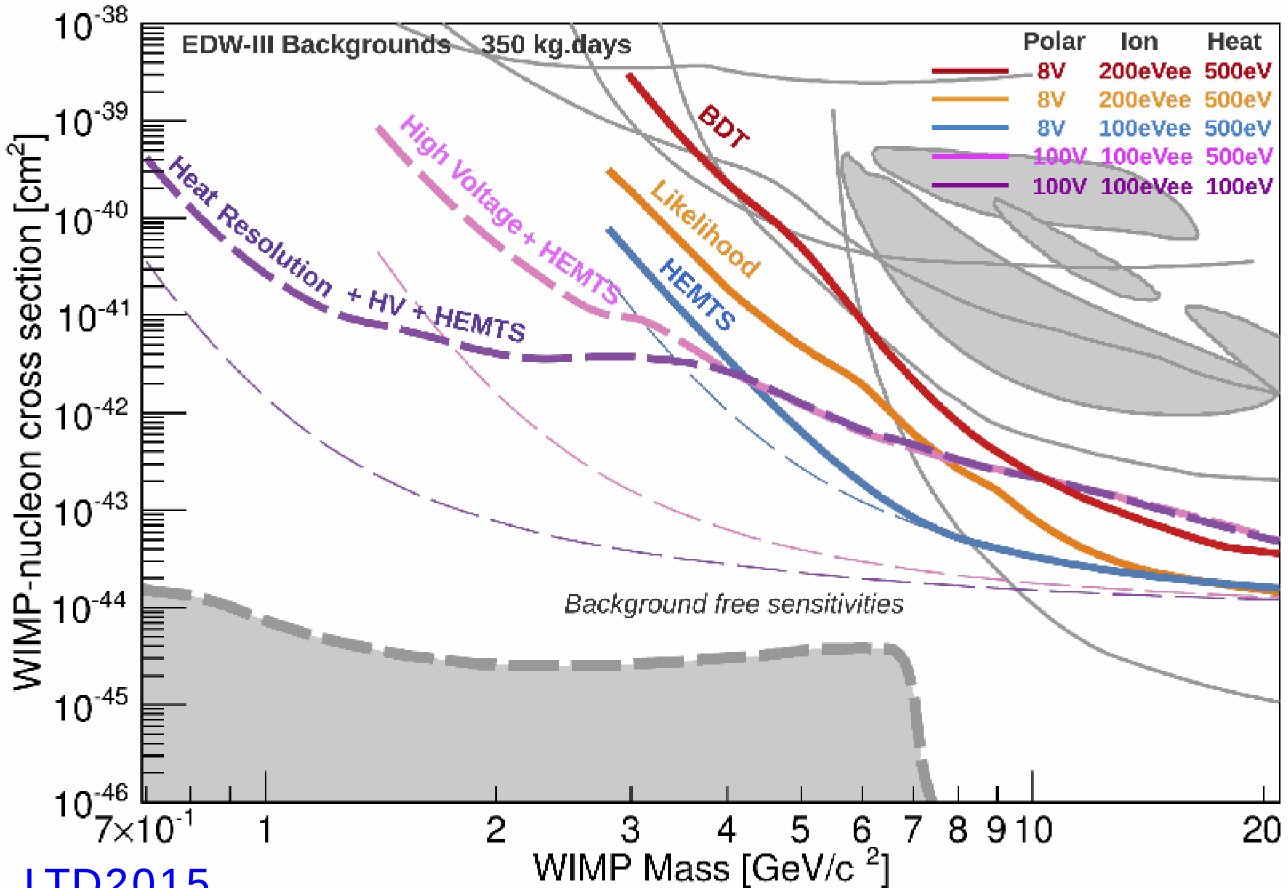
Data-driven background models
based on sidebands

Stable + reproducible bkg
Origin under investigation



What can be done with 1 kgyear Ge

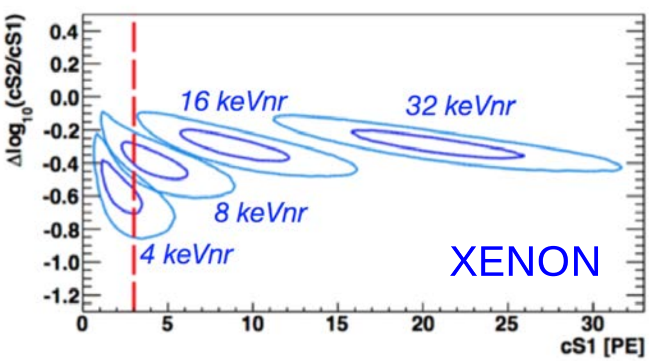
- Calculated assuming present EDELWEISS background (including Heat-only)



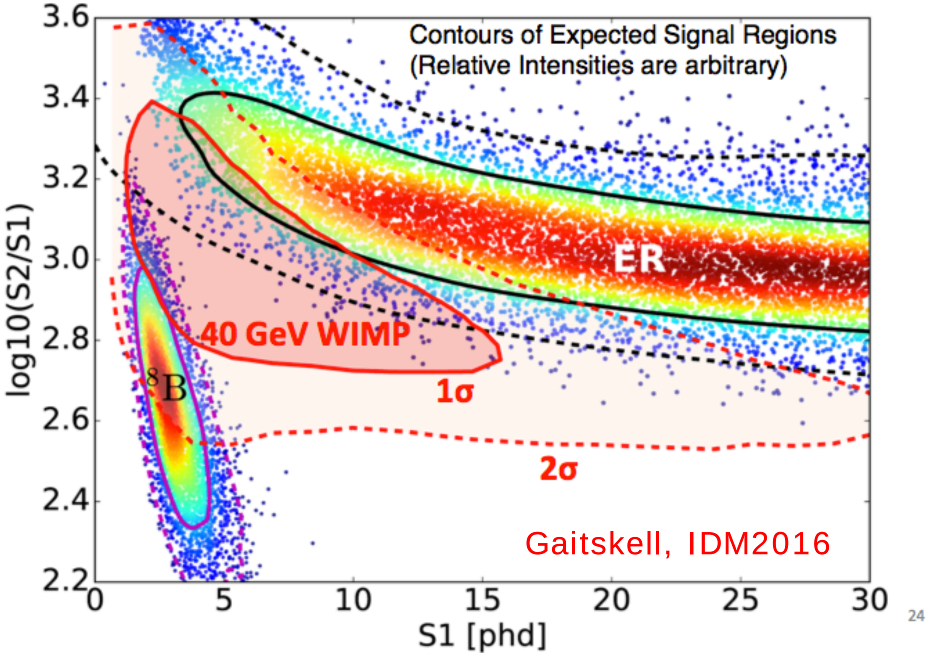
Arnaud, LTD2015

^{8}B region with xenon

- Xenon experiments may reach ^{8}B floor in coming years
  - Very small efficiency limited by photon collection
  - ^{8}B backgrounds difficult to control: very little spectral response



LZ WIMP Signal Region Example
- We must also understand 8B signal



Measurement WITH good energy resolution and background rejection is needed to properly control this background