Institute of High Energy Physics

Direct detection: new results from solid state experiments

Holger Kluck

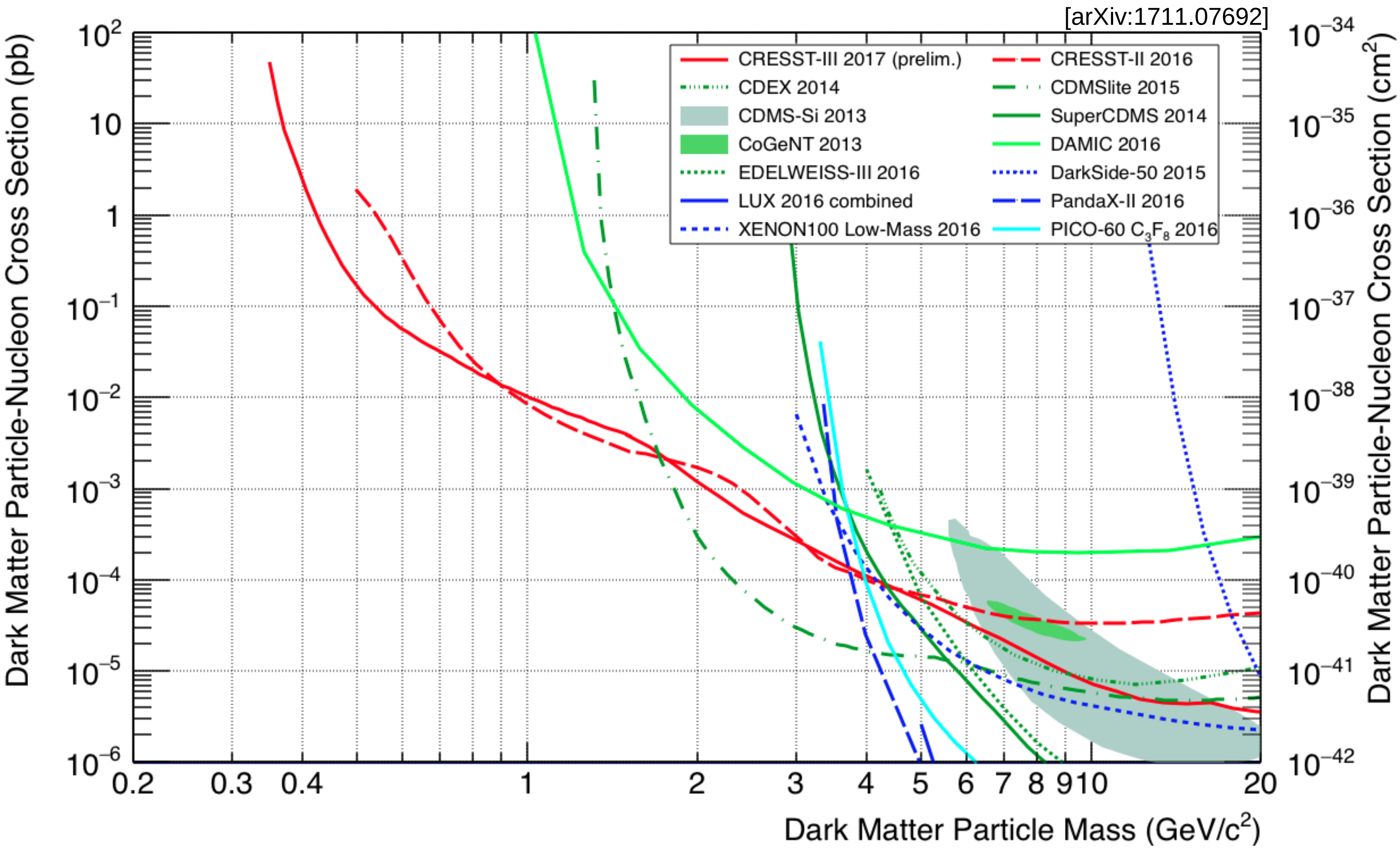
on behalf of the CRESST collaboration

Thanks to: J. Gascon, B. Siebenborn / EDELWEISS; D. Bauer, B. Loer / SuperCDMS; A.E. Chavarria, M. Settimo / DAMIC; T.-T. Yu / SENSEI; H. Shi / DANAE; R. Bernabei, V. Caracciolo / DAMA/LIBRA; M.L. Sarsa / ANAIS; R. Maruyama / COSINE-100; B. Suerfu / SABRE; Y. Takemoto / PICOLON; F. Reindl / COSINUS; S. Kulkarni / HEPHY

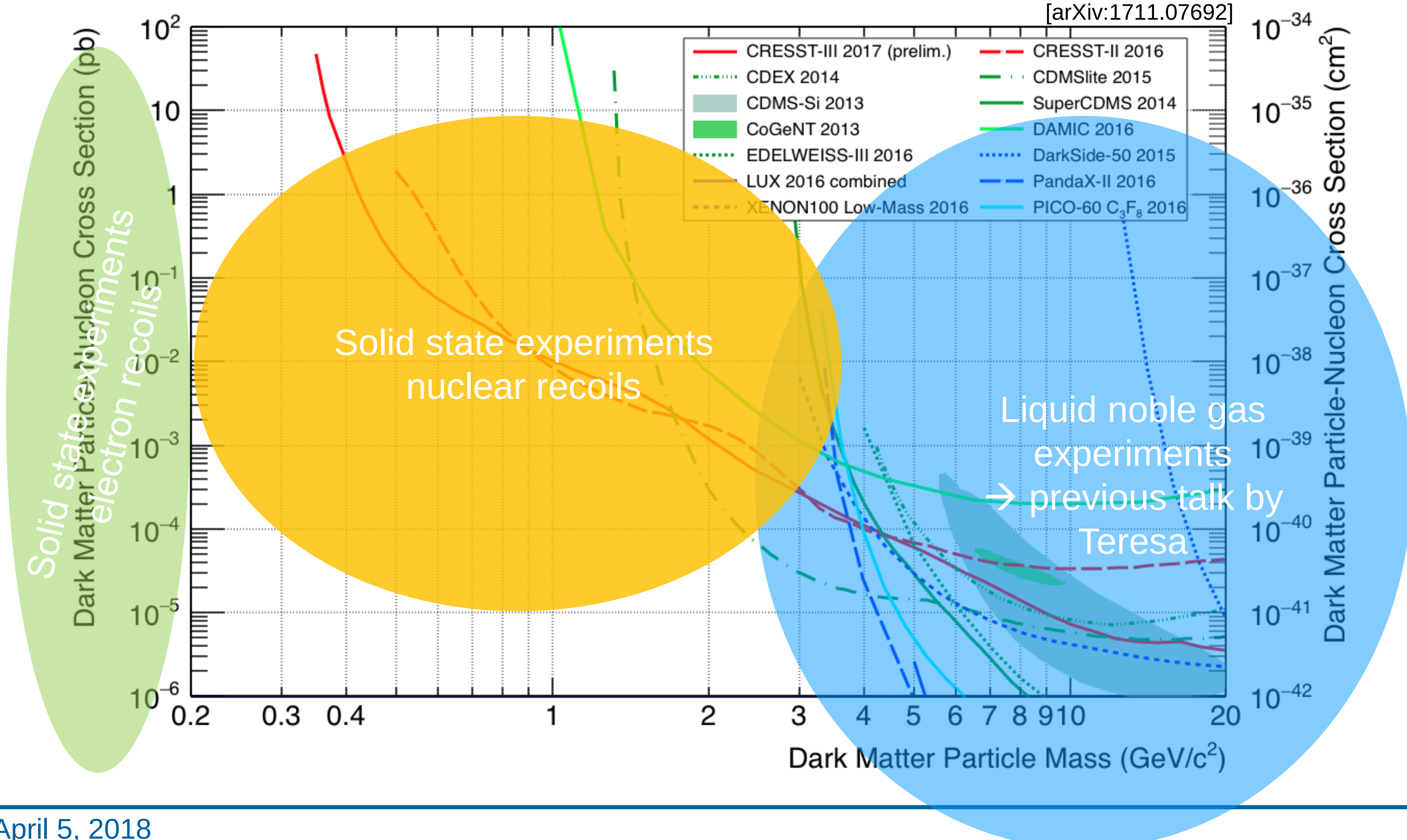
Dark Matter @ LHC 2018
April 3-6, 2018, Heidelberg

April 5, 2018

The parameter space



The parameter space



Outline

Searches for …

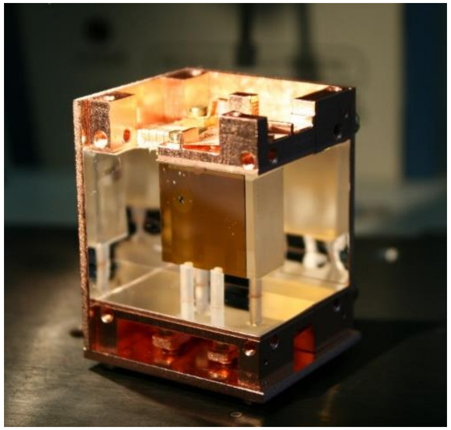
- nuclear recoils
  (CRESST, EDELWEISS, SuperCDMS, DAMIC)

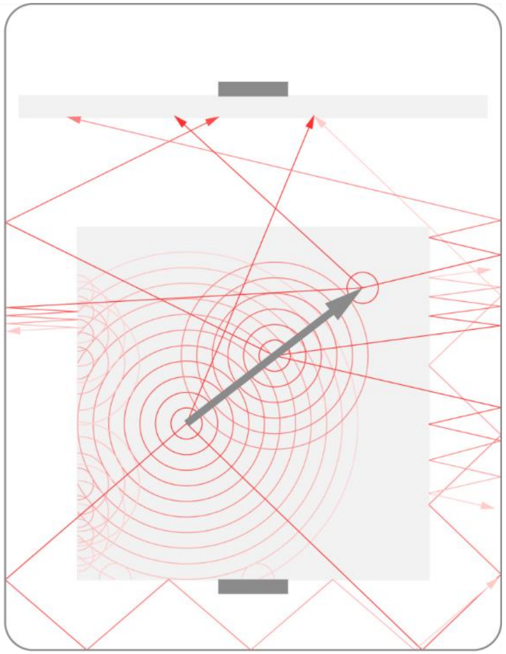
- electron recoils
  (SENSEI, DANAE)

- annual modulations / signal in NaI(Tl)
  (DAMA/LIBRA, ANAIS, COSINE, PICOLON, SABRE, COSINUS)

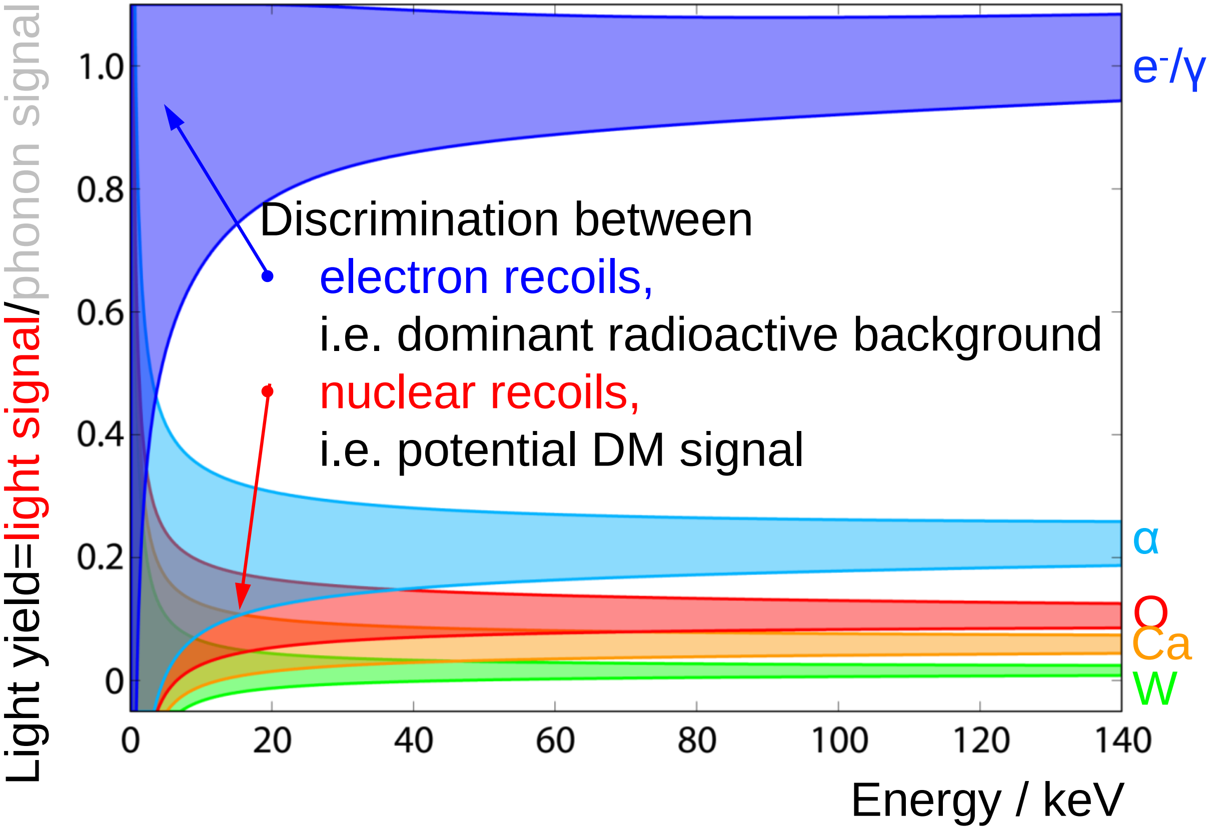
Nuclear Recoils

CRESST

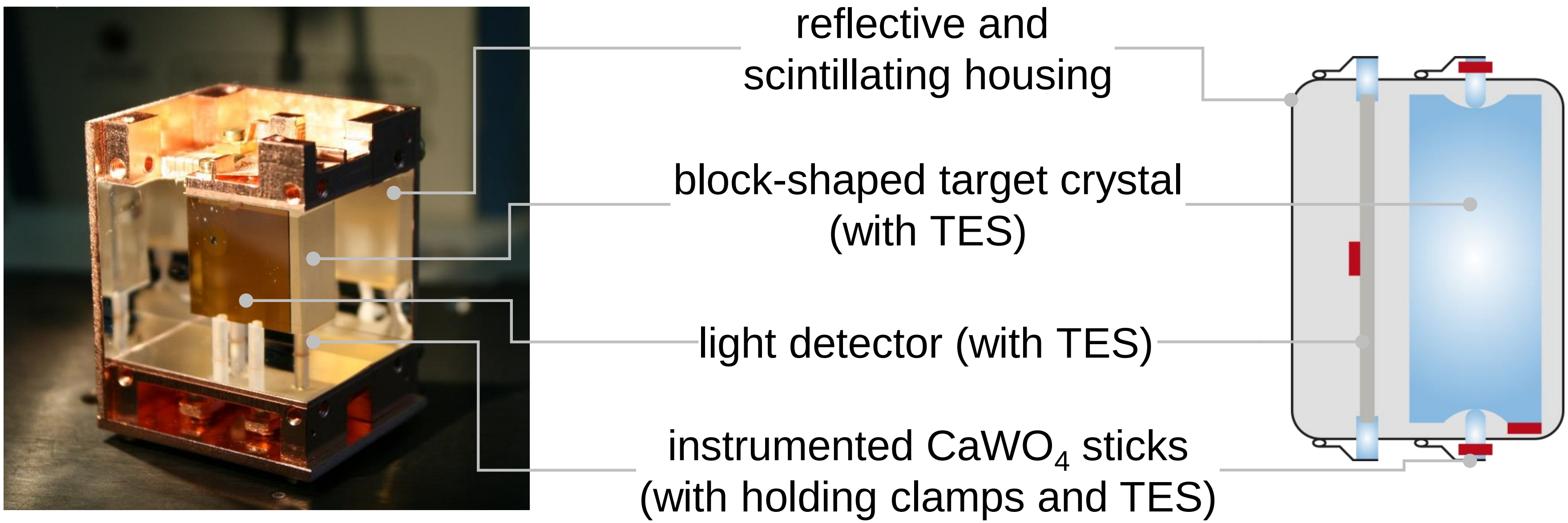




- $CaWO_4$@O(10mK) @ LNGS
- Discriminate nucl./e^- recoil via dual readout of phonon and scintillation
- Veto near-surface α-decays via fully active surrounding



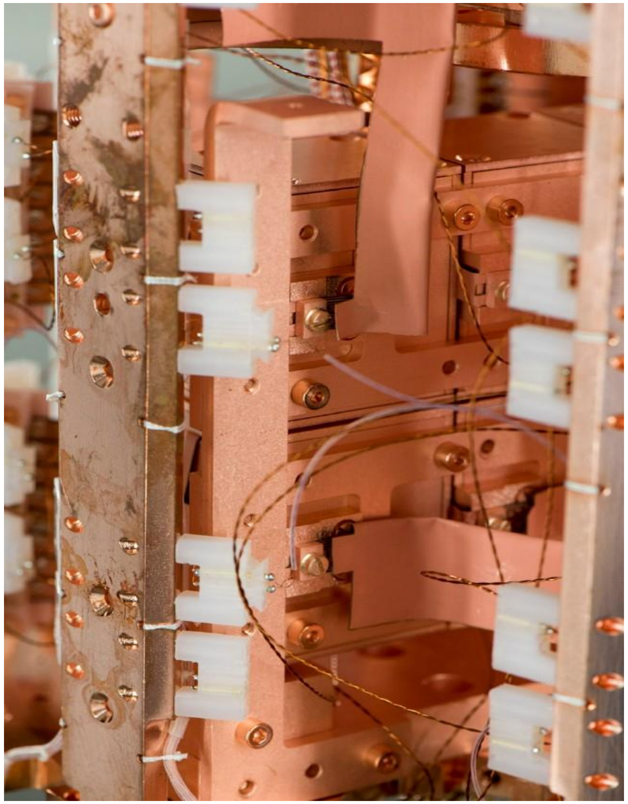
Optimized detector design



Detector design **optimized for low-mass dark matter**:

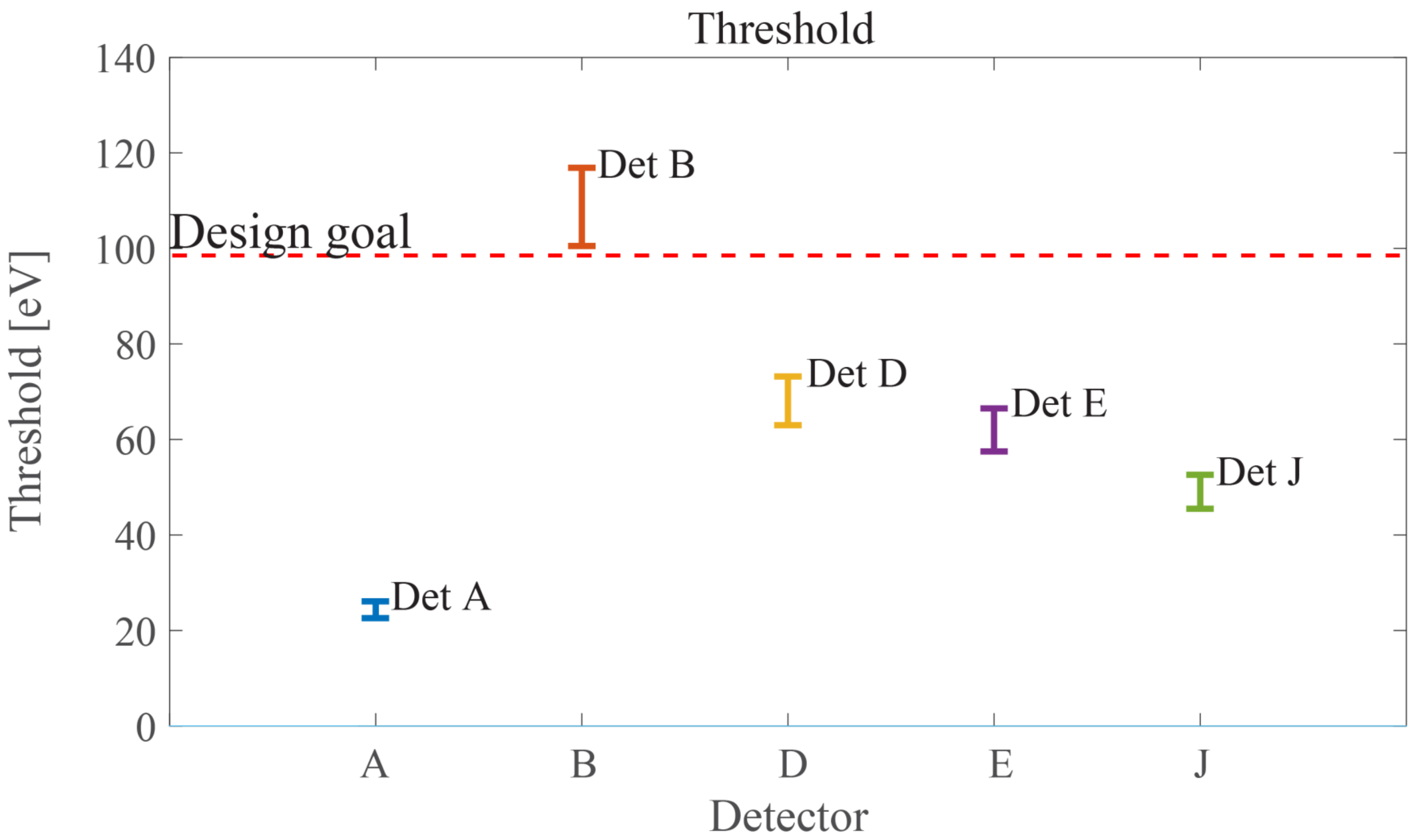
- cuboid crystal with **strongly reduced dimension**: $(20 \times 20 \times 10)\mathrm{mm}^3$ and $\approx 24\mathrm{g}$
- goal: detection **threshold of $100\ \mathrm{eV}$**
- **self-grown crystal** with low total background of $\approx 3\ \mathrm{keV}^{-1}\mathrm{kg}^{-1}\mathrm{d}^{-1}$ in $[1{,}40]\mathrm{keV}$
- **veto against surface related background**: fully scintillating housing + instrumented sticks (“iSticks”)

Status of CRESST-III phase 1

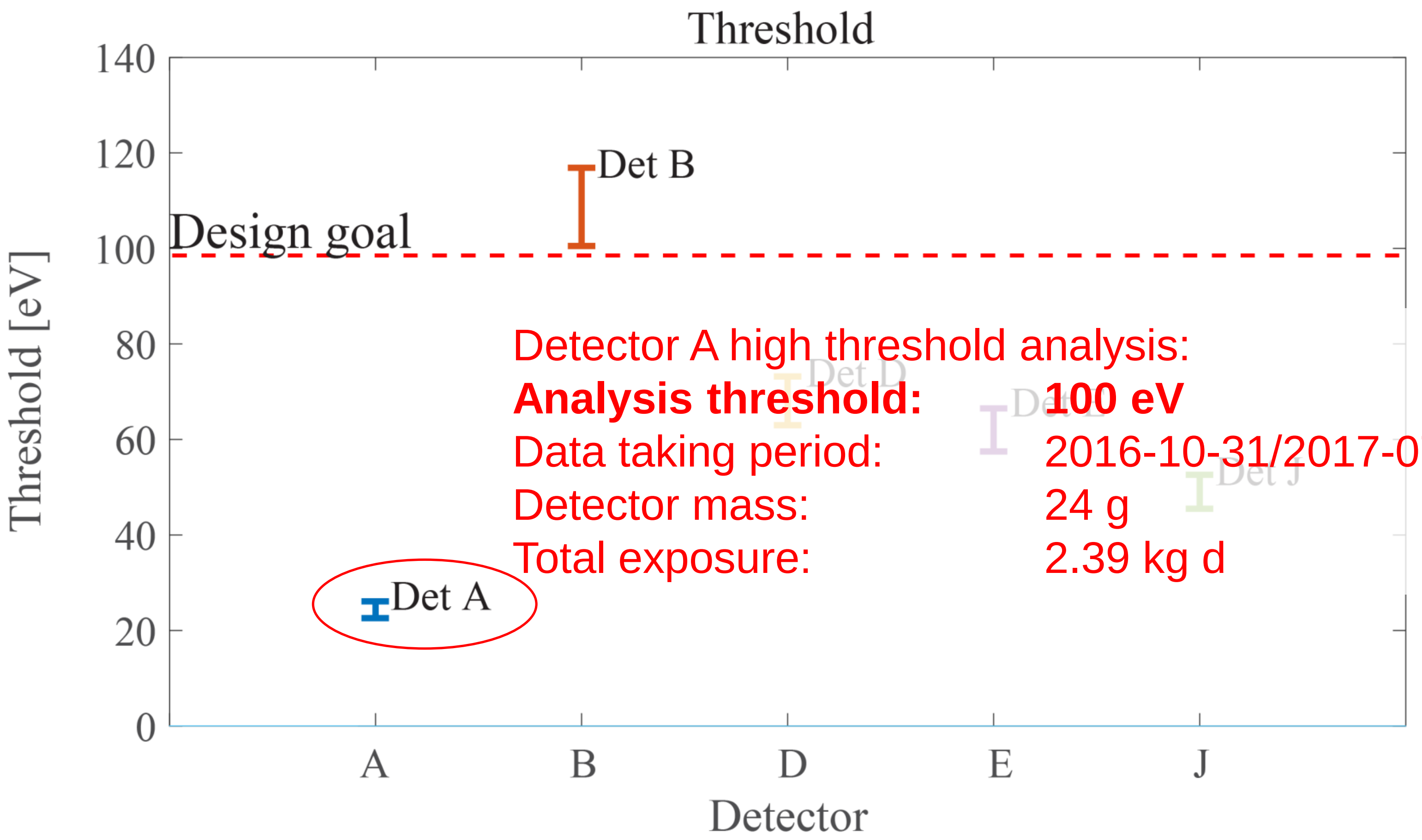


- May 2016:
  10 CRESST-III modules installed
- Oct 2016:
  extensive γ-calibration
- Since Nov 2016:
  data taking (80% blinded, 20% training set)
- ~April 2017:
  extensive n-calibration
- July 2017:
  first results @TAUP2017

First results from CRESST-III phase 1



First results from CRESST-III phase 1

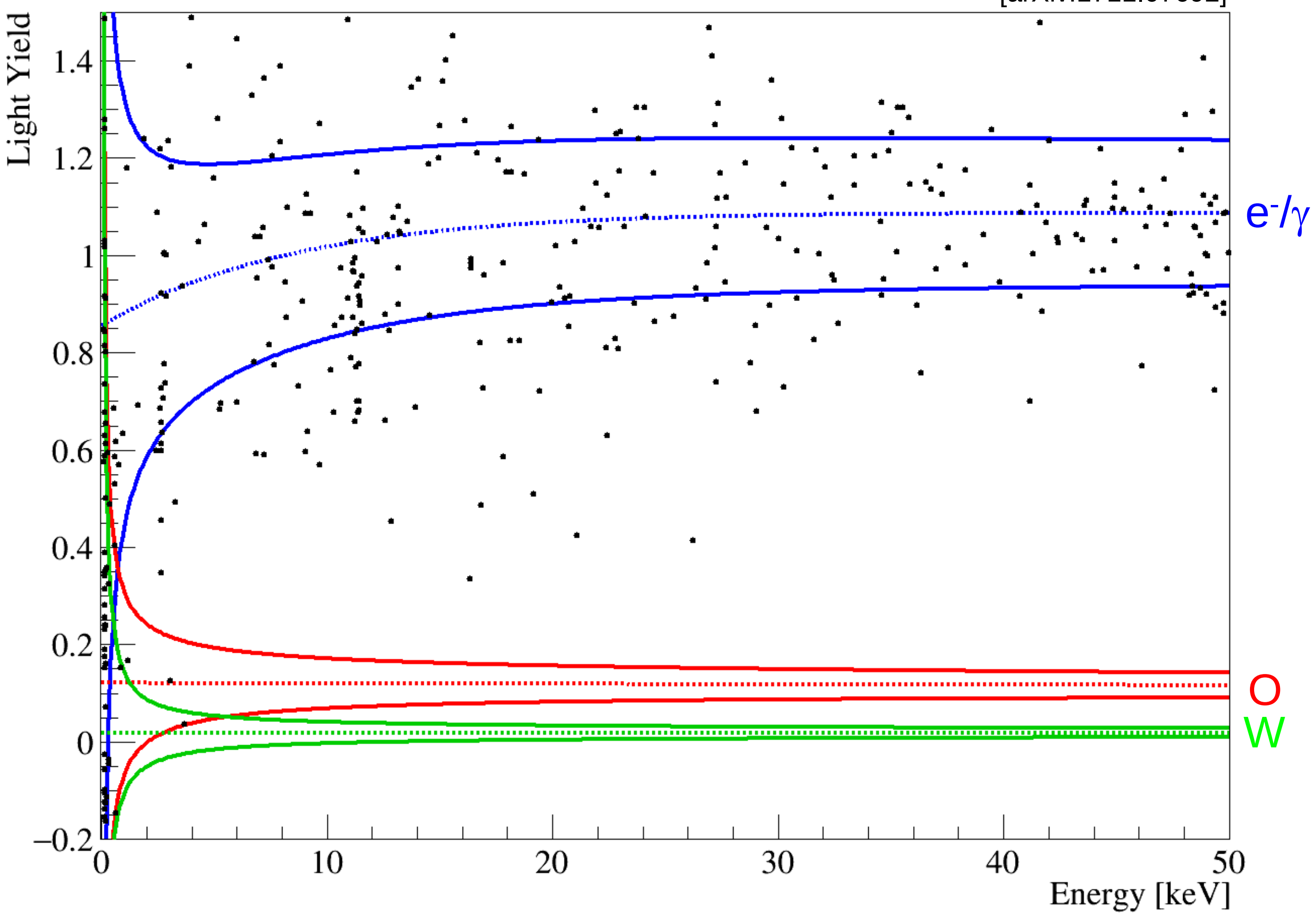


Detector A high threshold analysis:

Analysis threshold:	**100 eV**
Data taking period:	2016-10-31/2017-07-05
Detector mass:	24 g
Total exposure:	2.39 kg d

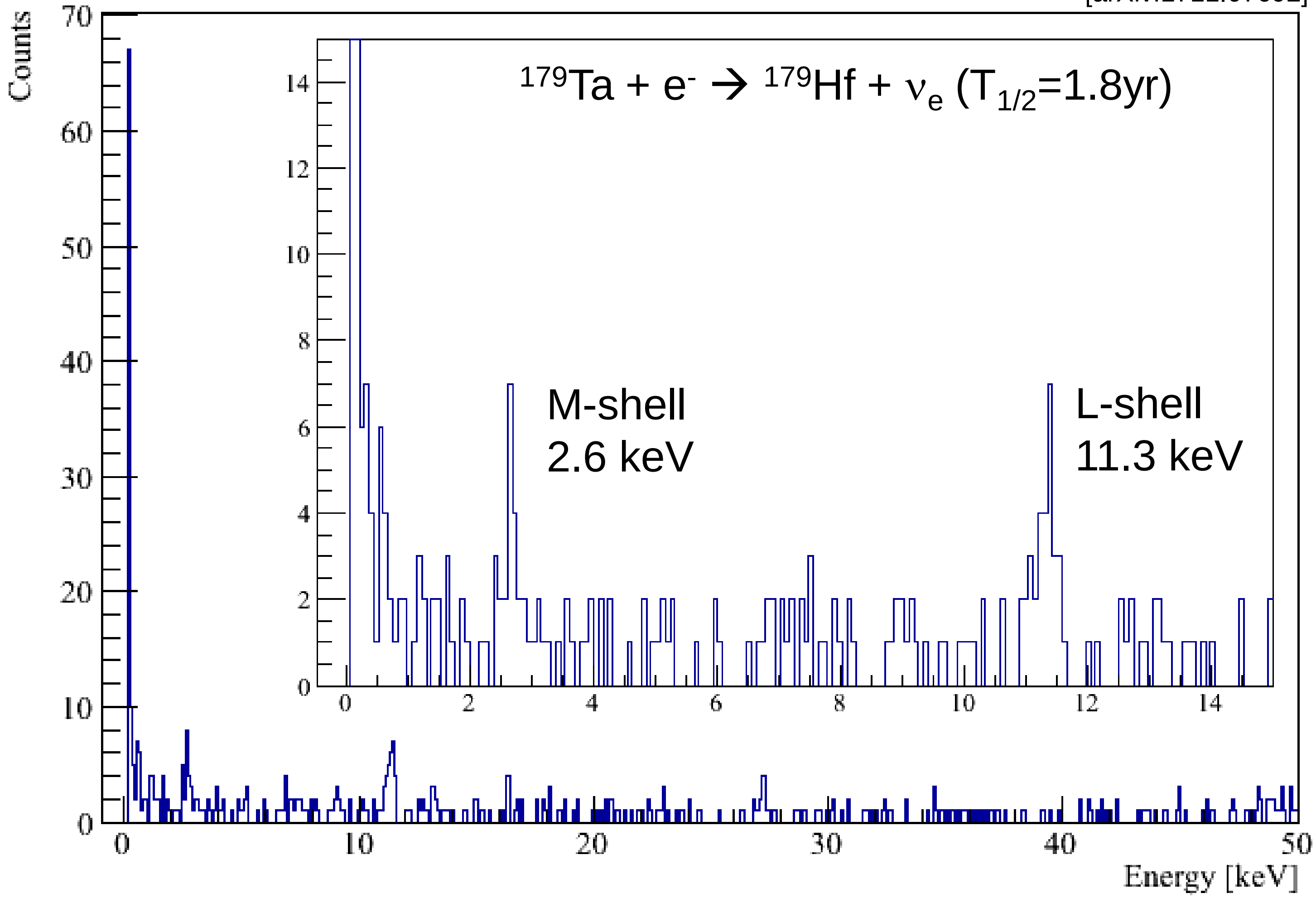
Detector A: physics data

[arXiv:1711.07692]

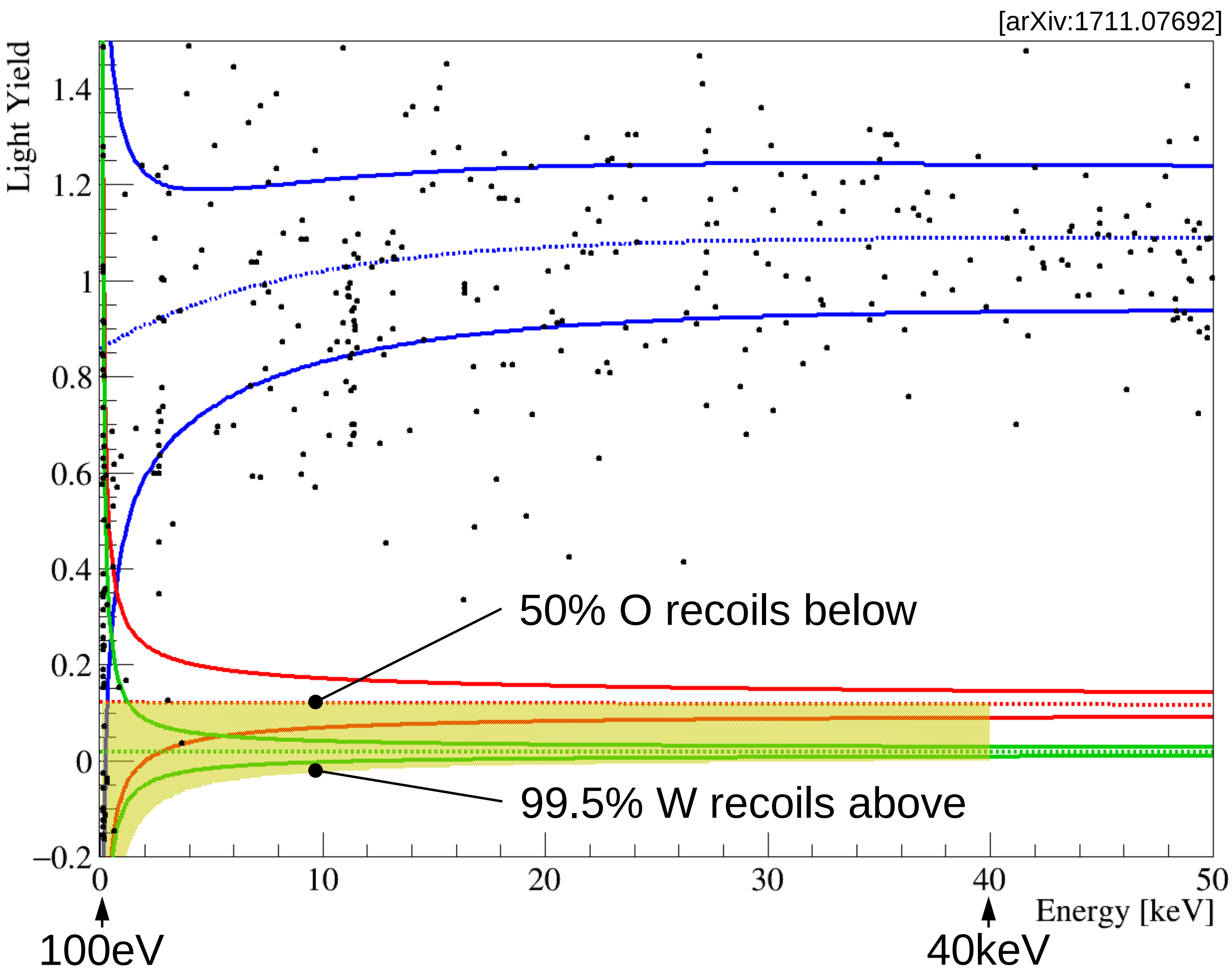


Detector A: energy spectrum

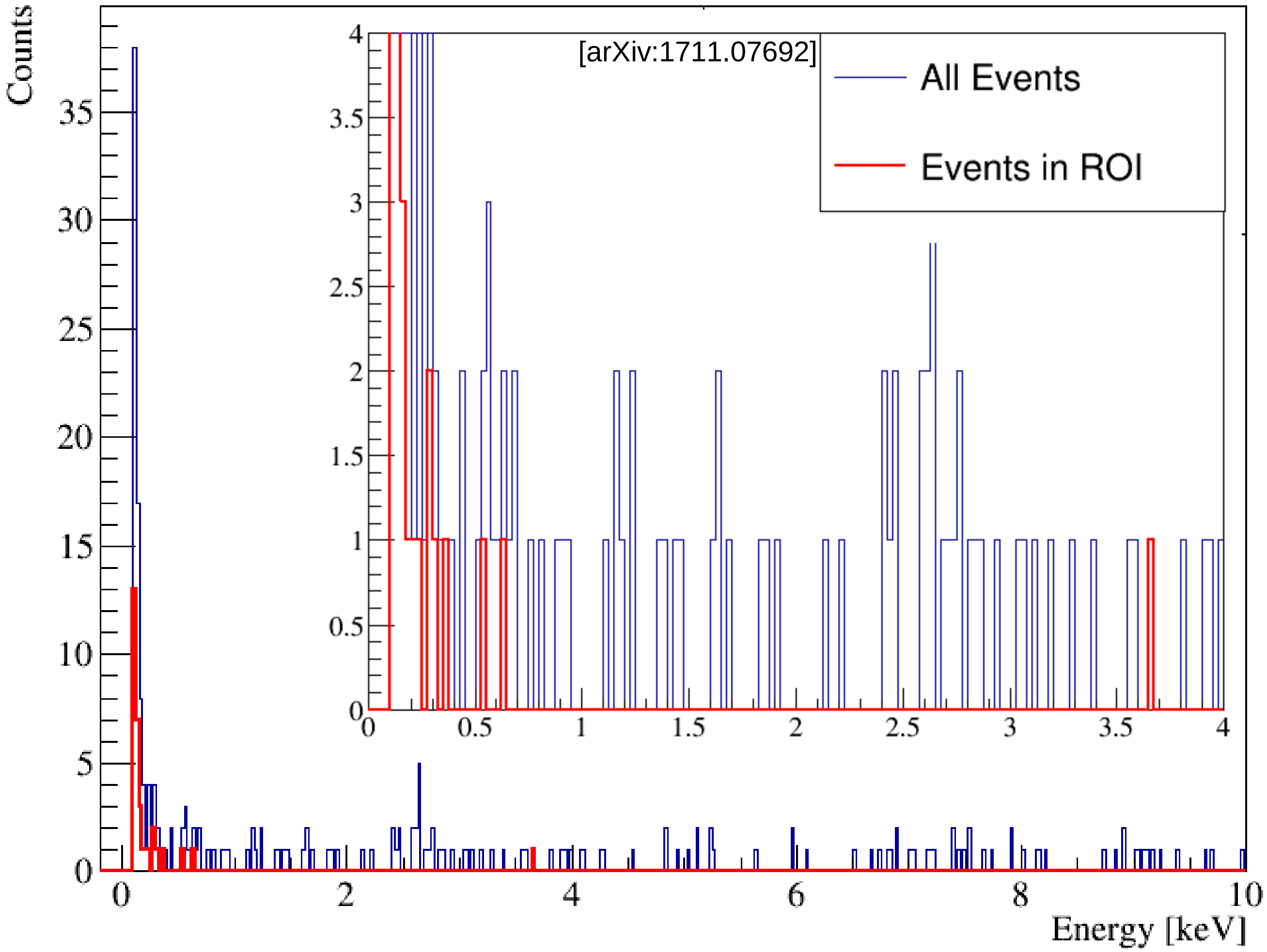
[arXiv:1711.07692]



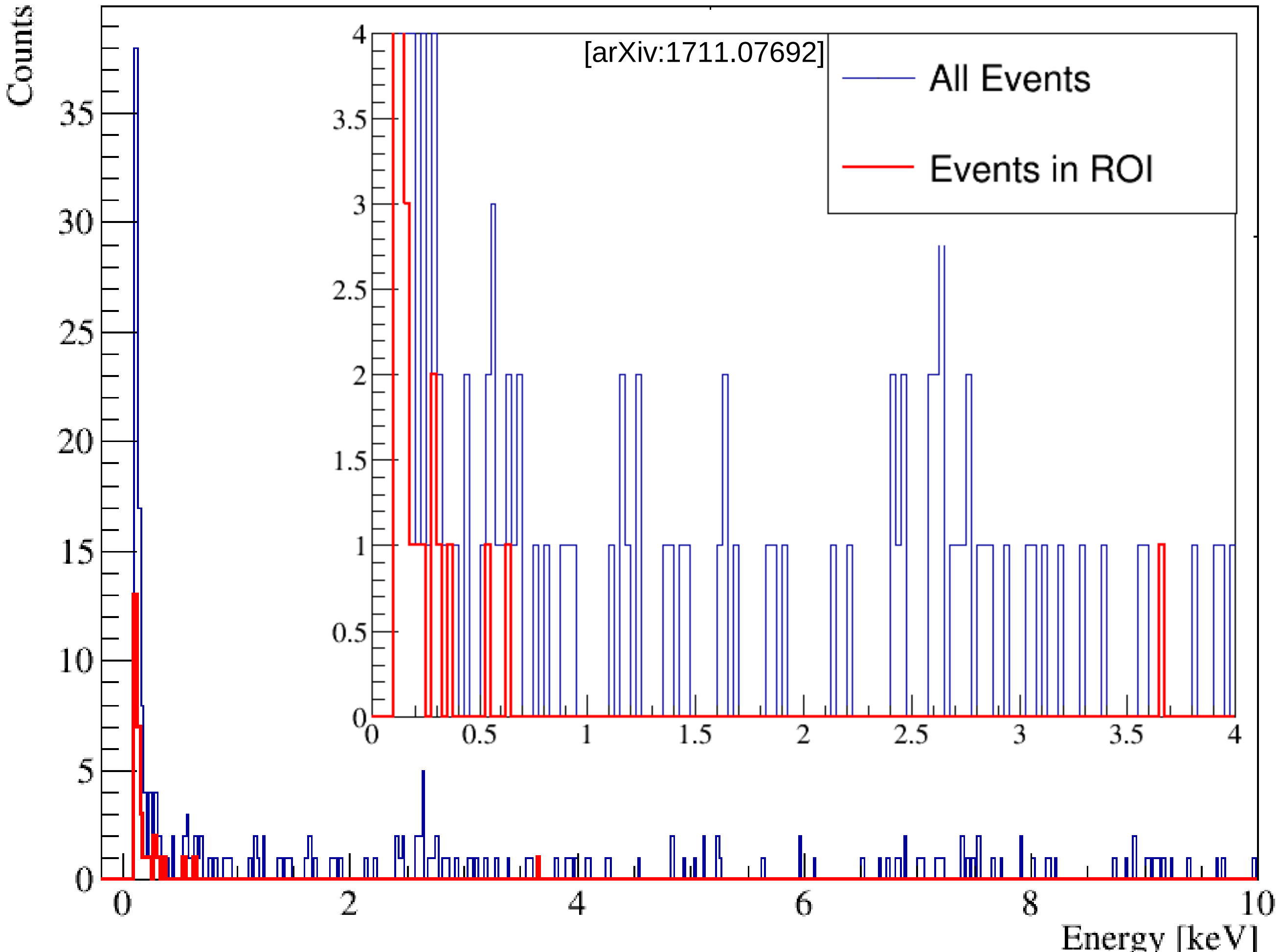
Detector A: acceptance region



Detector A: accepted events



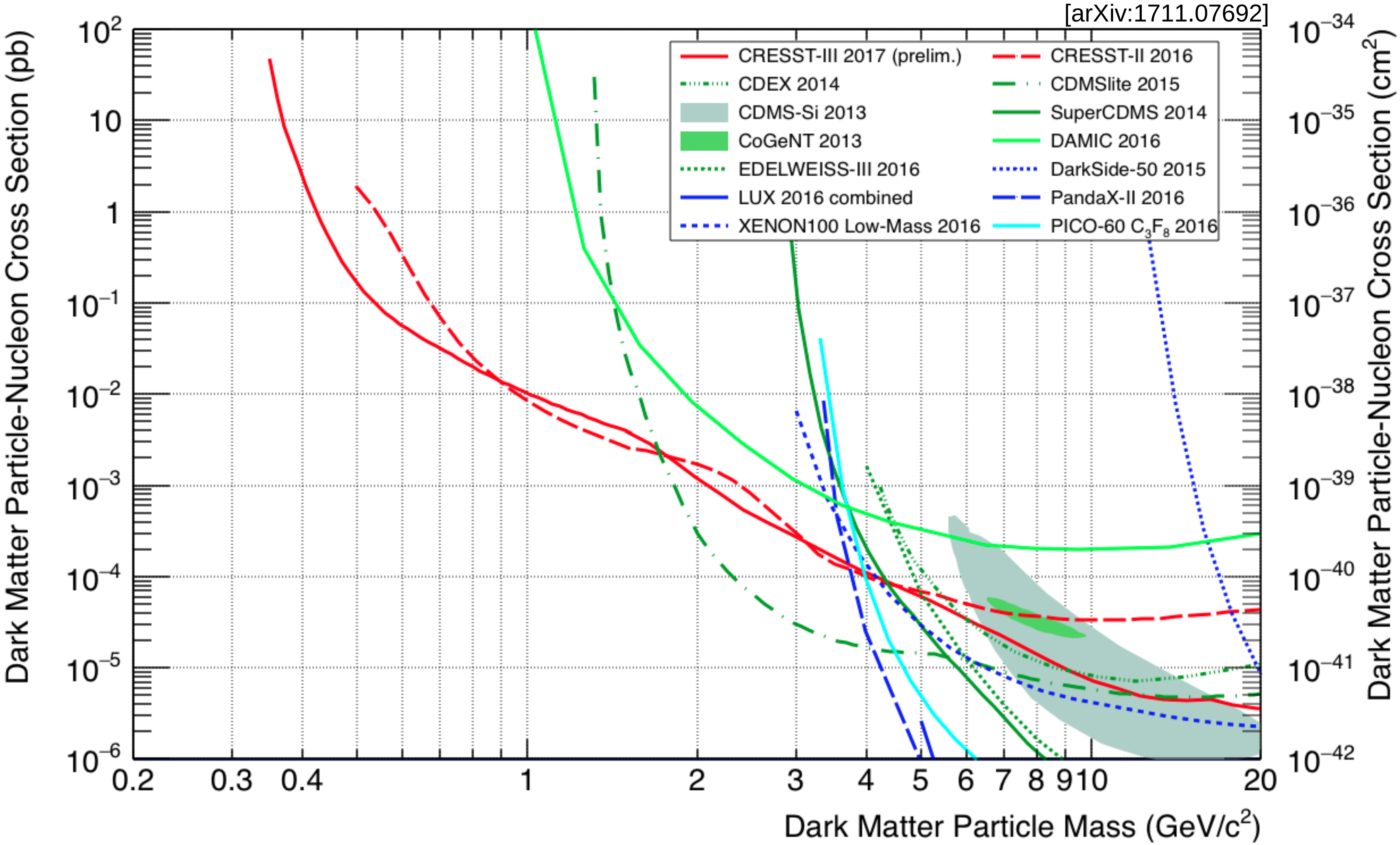
Detector A: accepted events



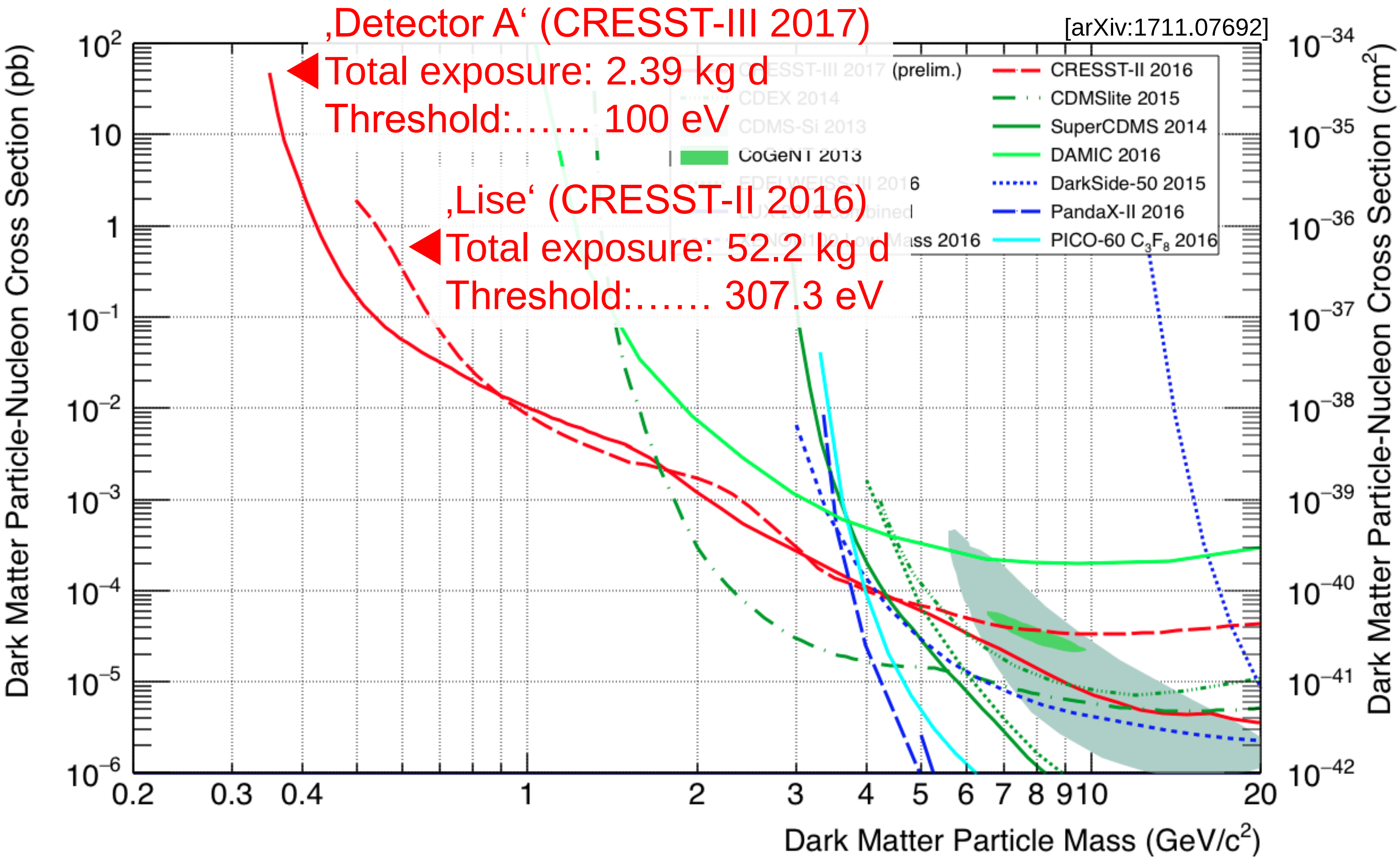
Assume all accepted events are dark-matter caused

→ Use Yellin's optimum interval method to set an exclusion limit

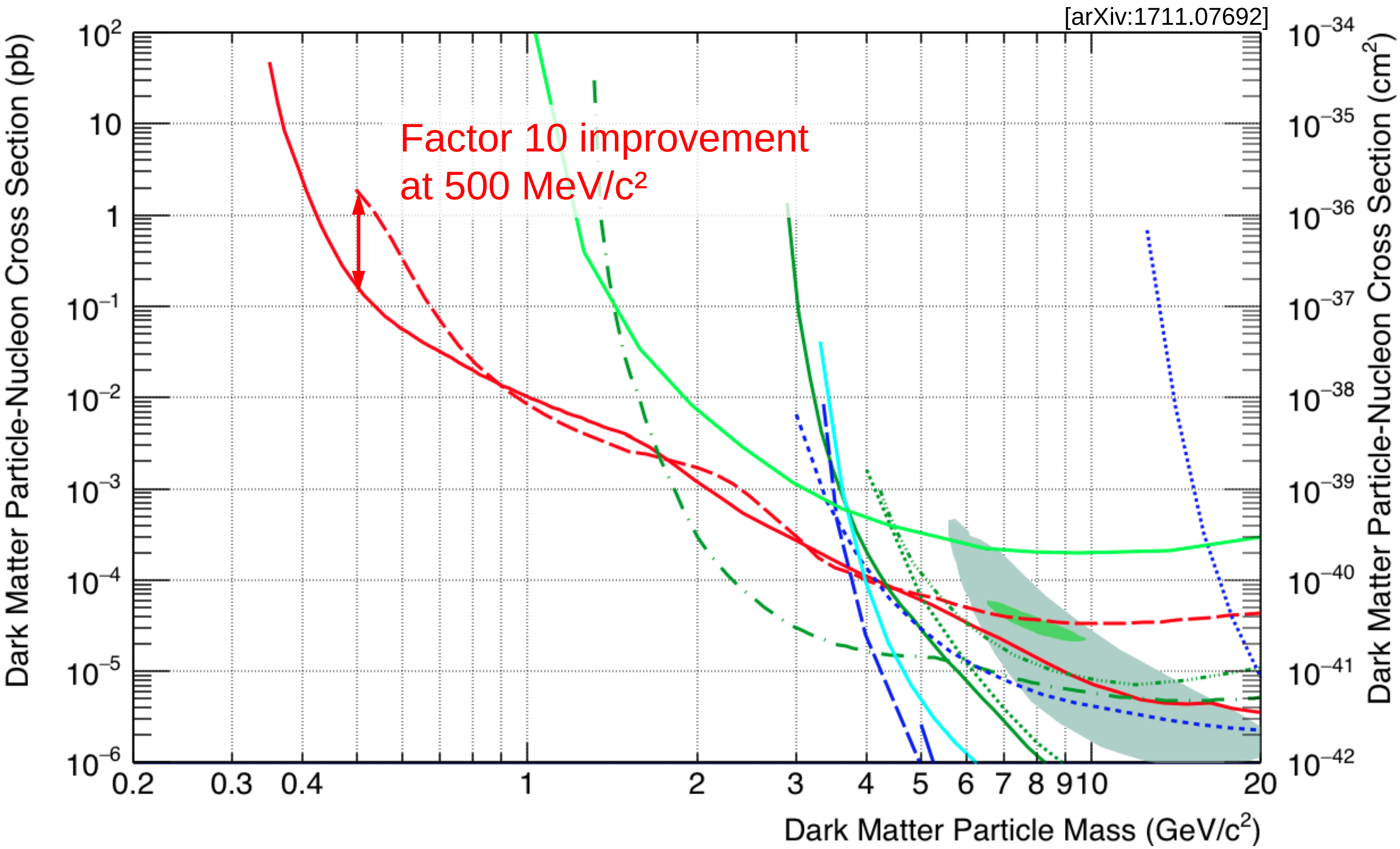
Detector A: exclusion limit



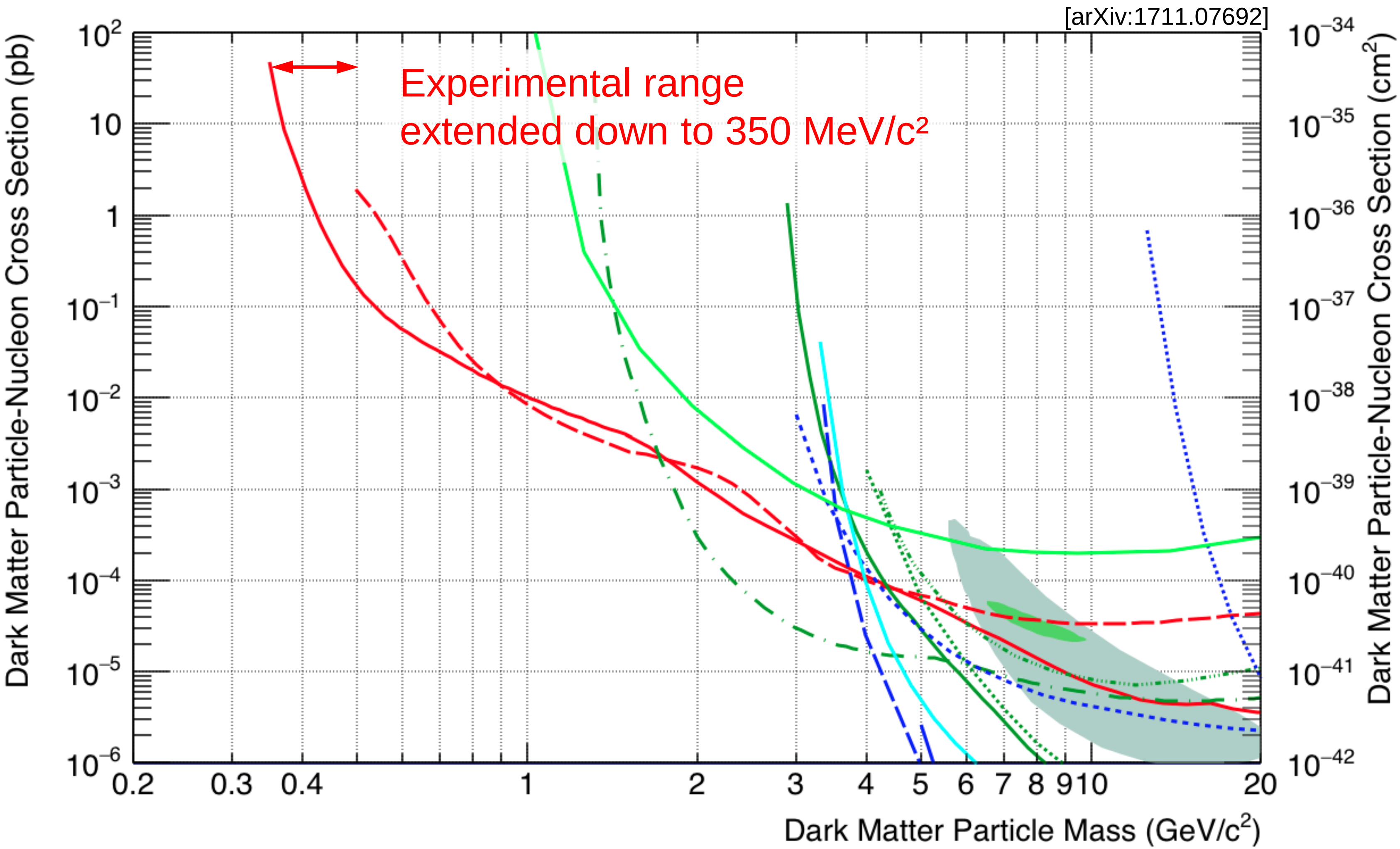
Detector A: exclusion limit



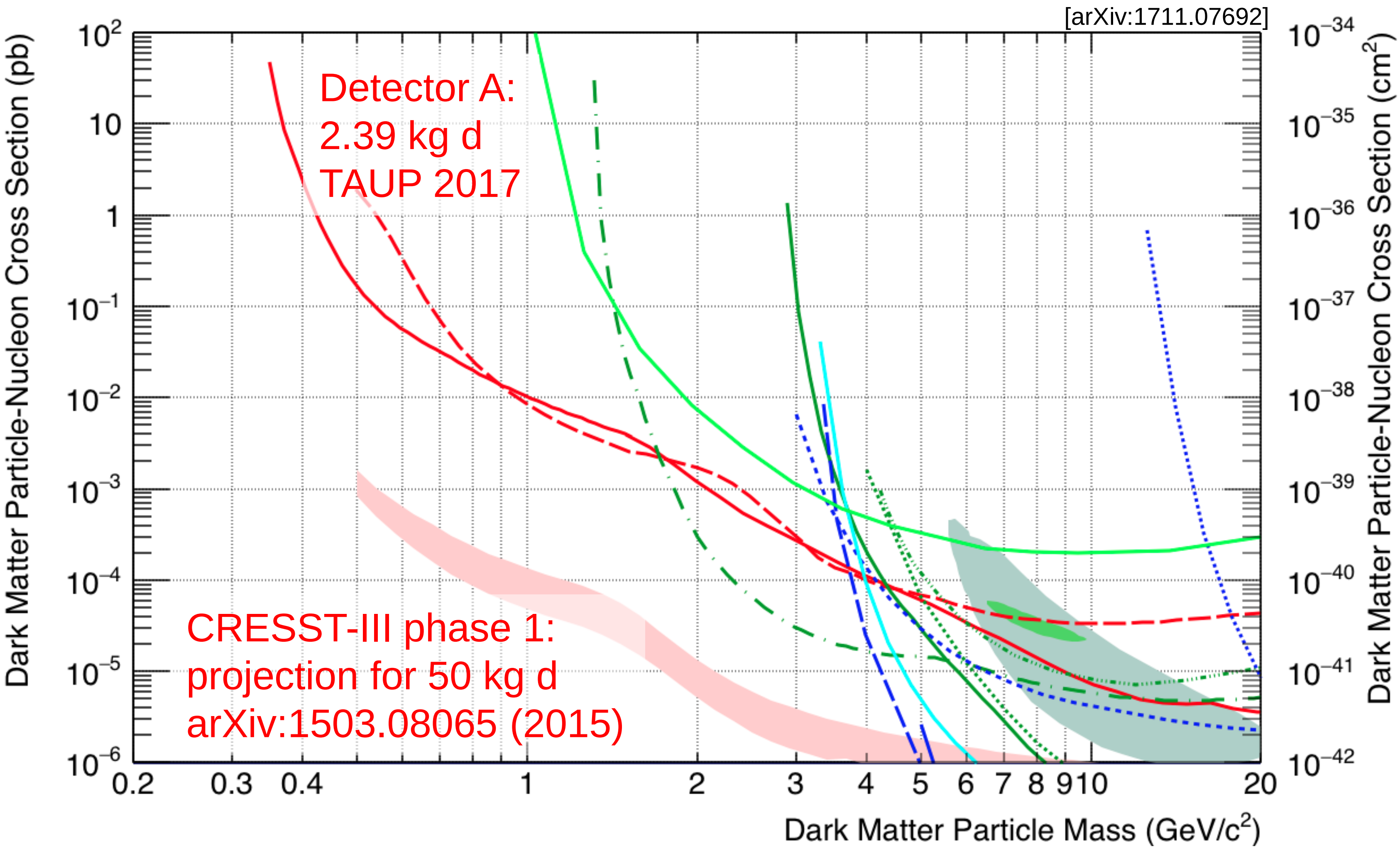
Detector A: exclusion limit



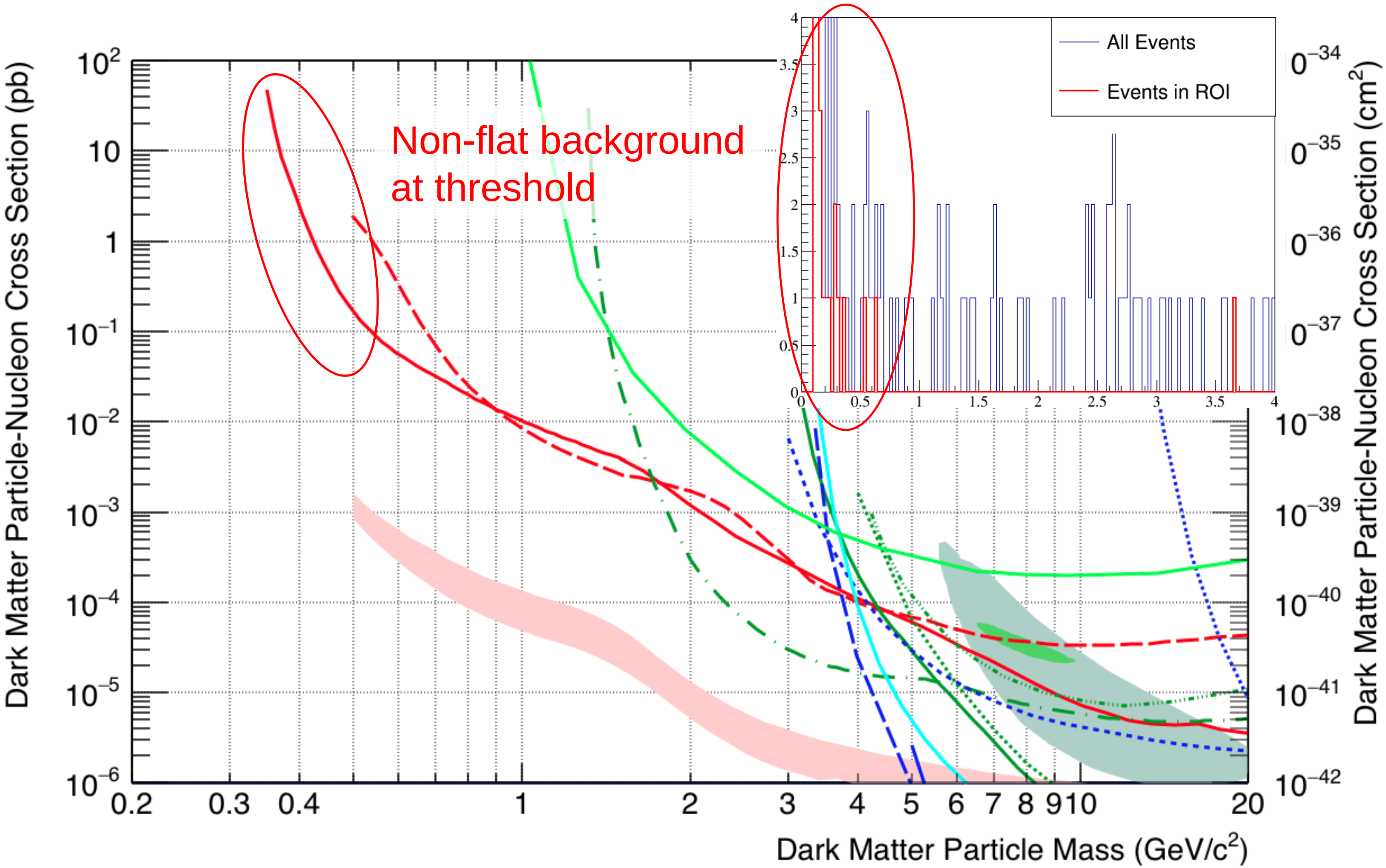
Detector A: exclusion limit



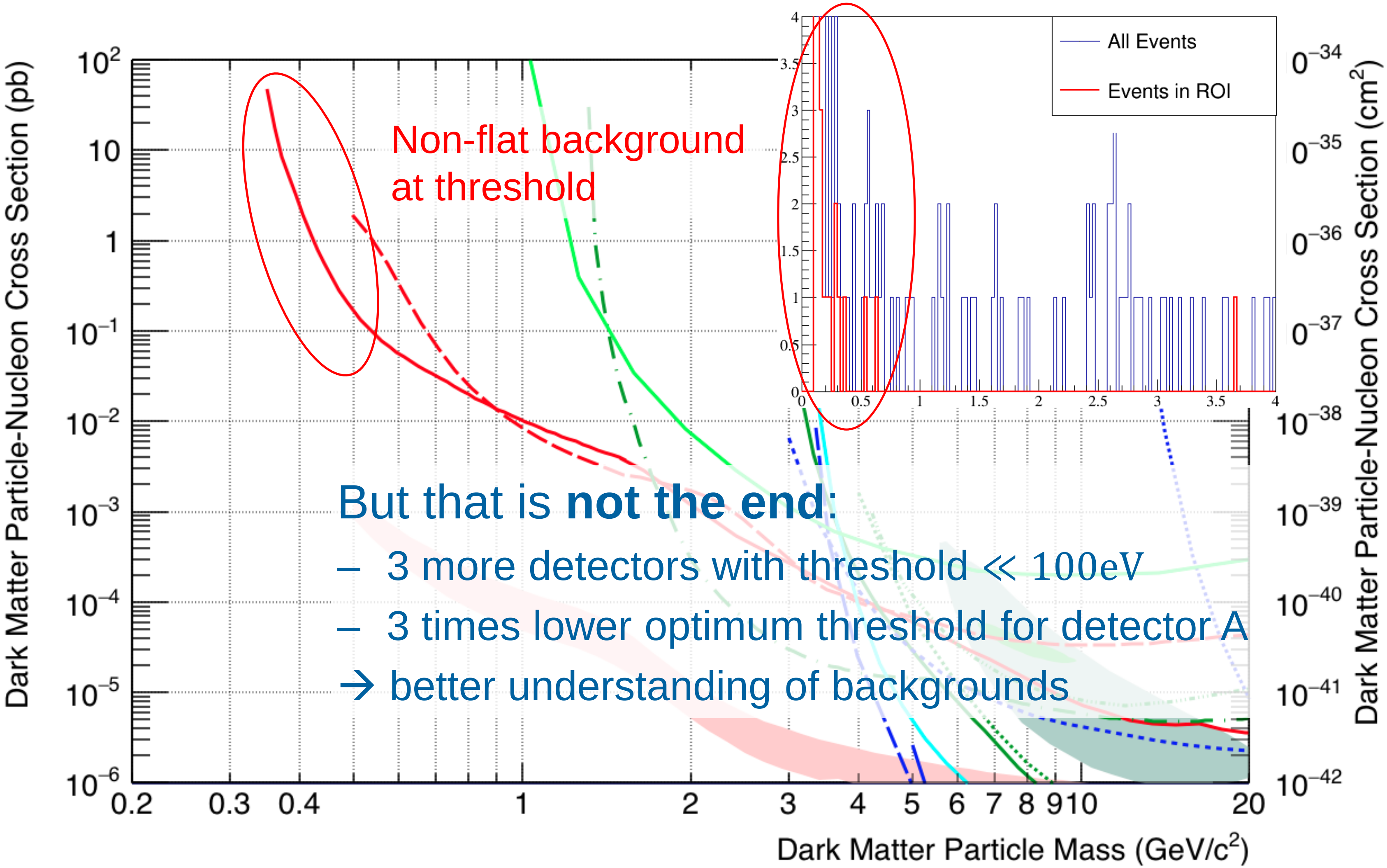
Detector A: limitations



Detector A: limitations



Detector A: limitations

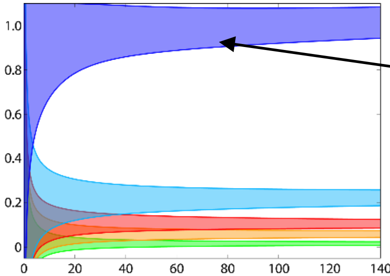


But that is **not the end**:

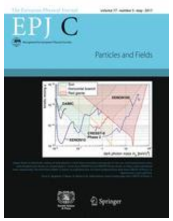
- 3 more detectors with threshold $\ll 100\mathrm{eV}$
- 3 times lower optimum threshold for detector A

→ better understanding of backgrounds

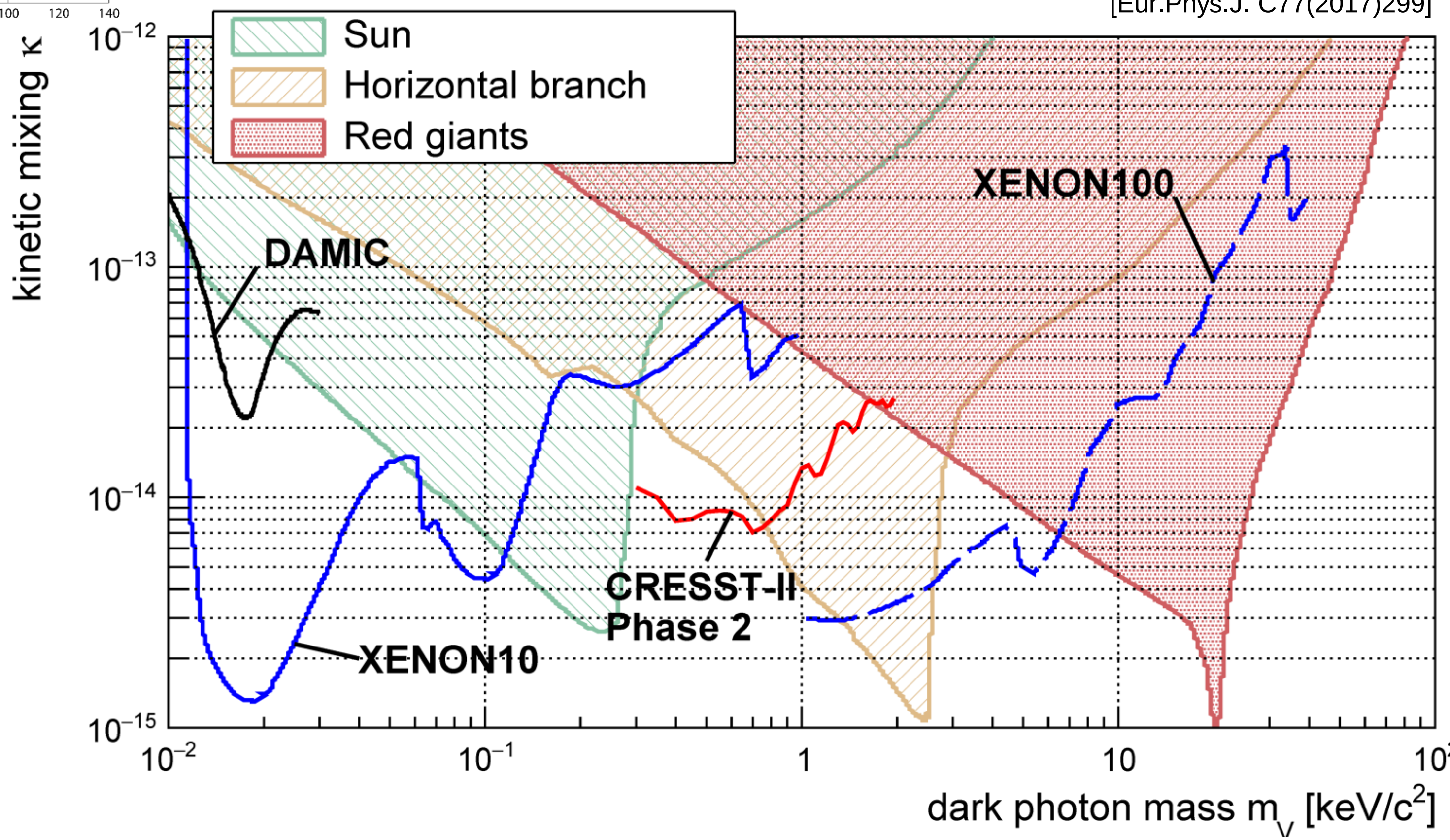
Dark photon limits



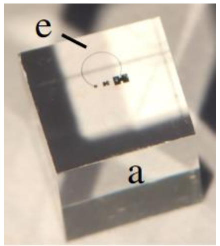
Peak search in the e⁻/γ band



[Eur.Phys.J. C77(2017)299]



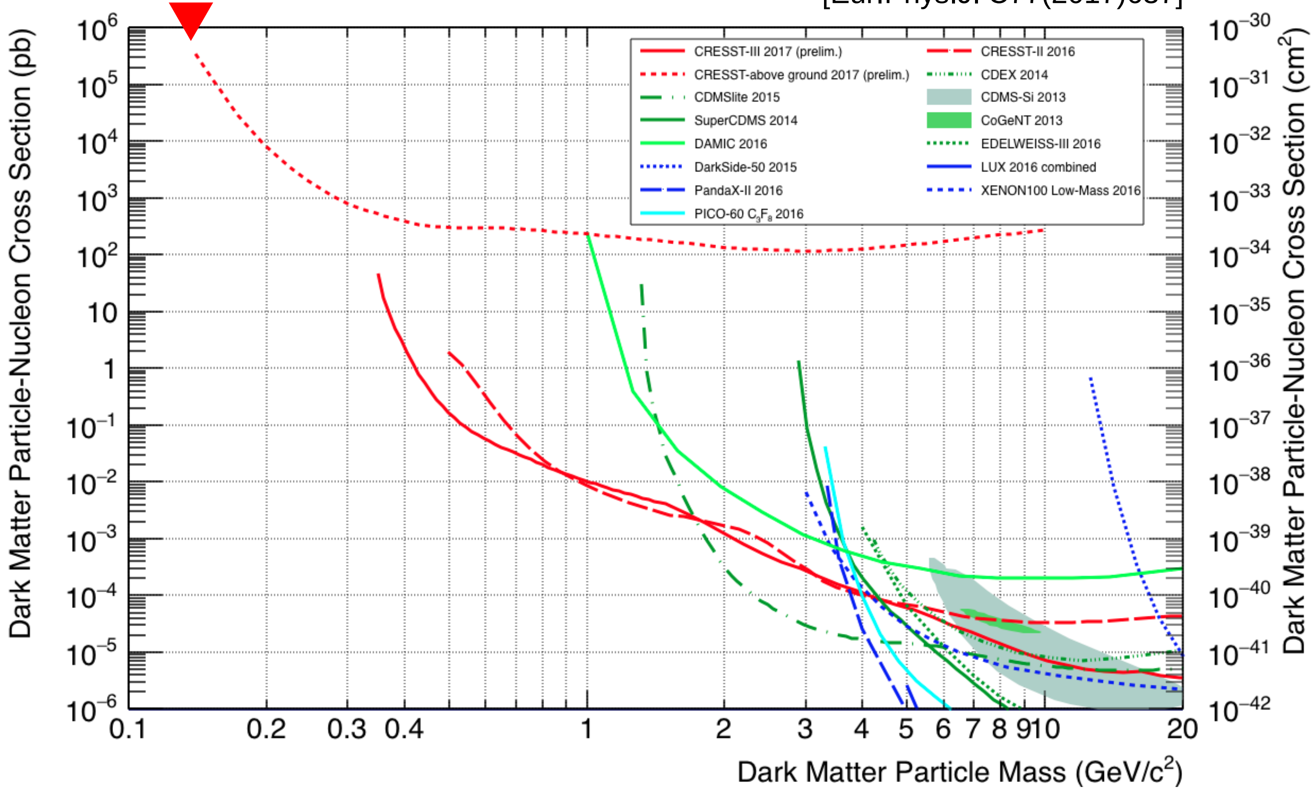
Above ground limit



Target: Al_2O_3
Mass: 500 mg
Threshold: 19.7 eV

140MeV/c²

[Eur.Phys.J. C77(2017)637]

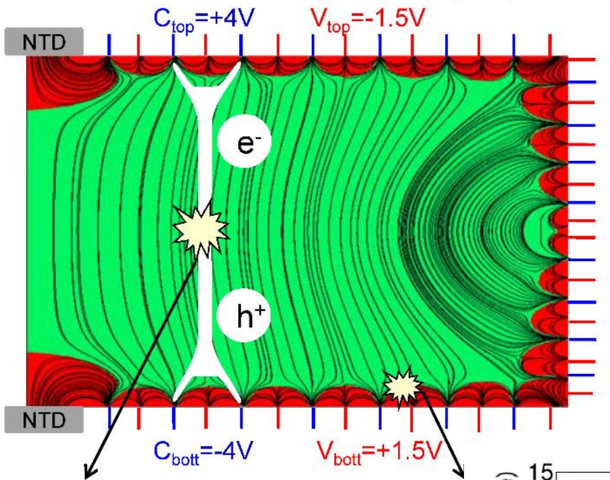


→Also sensitive for SIMPs, e.g [J.H. Davis Phys.Rev.Lett. 119(2017)211302]

EDELWEISS

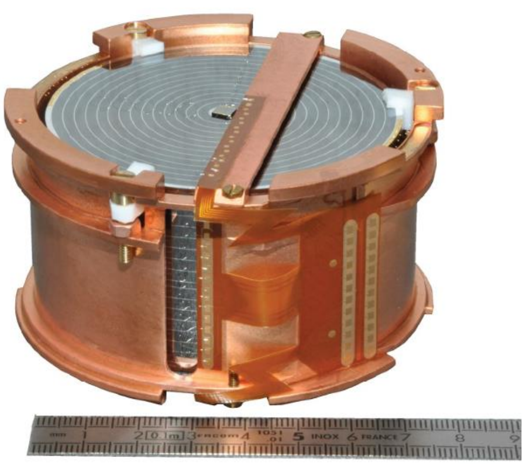
Fully InterDigitized ~870g HPGe detectors

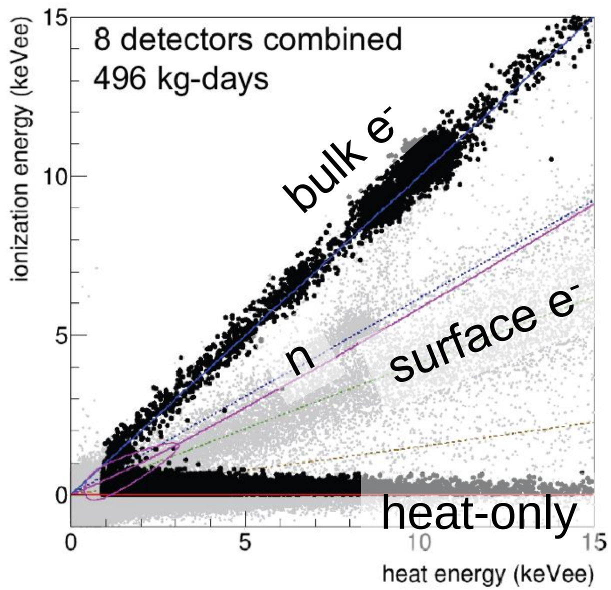
A. Broniatowski et al., Phys Lett B 681 (2009) 305–309

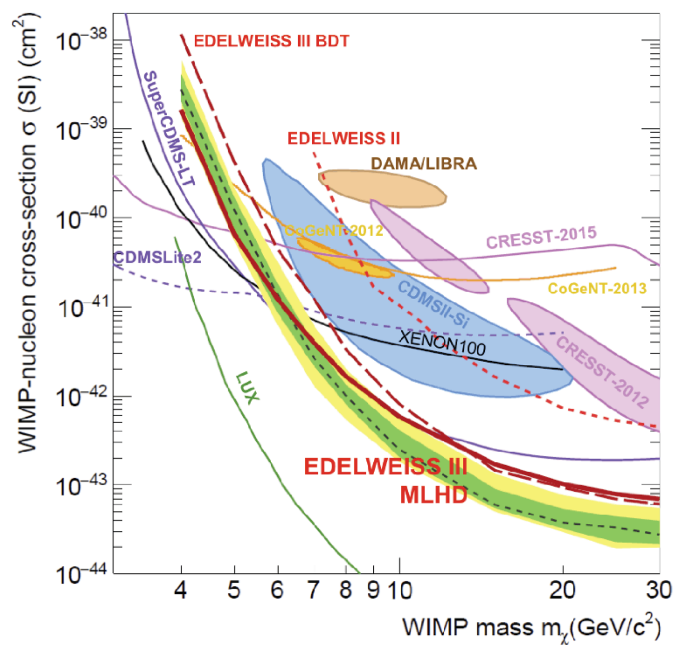


- Ge crystals@~18mK @ LSM
- Discriminate nucl./e⁻ recoil via dual readout of phonon and ionization, FID for fidualization
- EDELWEISS-III (2016): >3000kg.d with 24FIDs
- 8 FIDs with lowest threshold + background model + maximum likelihood analysis → low mass limit

[Eur.Phys.J. C76(2016)548]



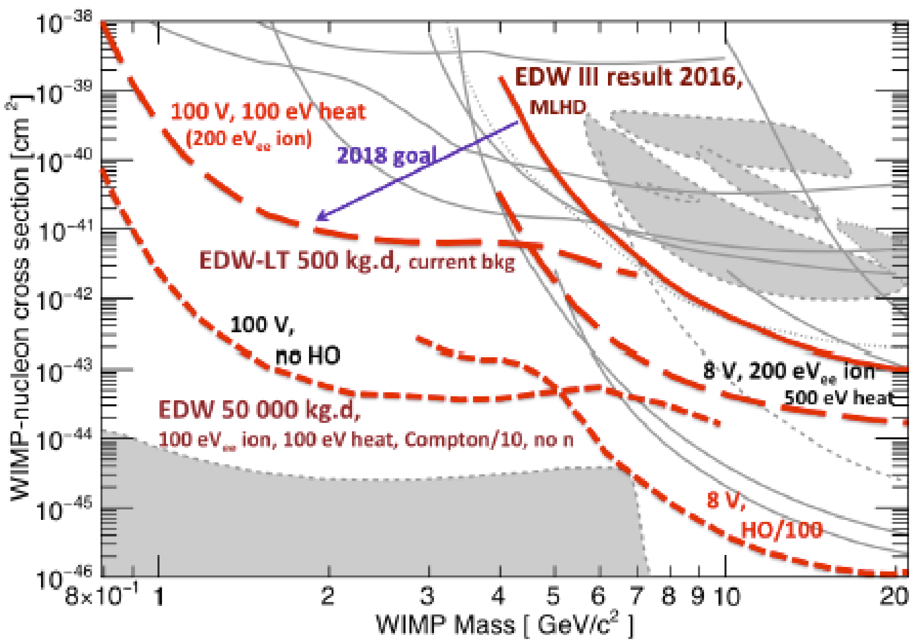




Courtesy of B. Siebenborn / EDELWEISS (Slides from UCLA DM2018)

EDELWEISS

- [ArXiv:1707.04308]: Complete study based on present measured backgrounds and resolutions *vs* possible improvements



1. Use of Luke-Neganov boost to lower thresholds (up to 100V bias)
2. Improve heat resolution σ_{heat} = 500 eV → **100 eV**
   (x5 gain in sensitivity already achieved on 200 g detectors)
3. Reduction x100 of heat-only background
4. Improve ionization resolution σ_{ion} = 200 eV_{ee} → **100/50 eV_{ee}**

Also: effect of improved neutron/ gamma background (+ increased mass) in the environment planned for SuperCDMS at SNOLAB

Courtesy of J. Gascon / EDELWEISS (Slides from TAUP 2017)

EDELWEISS-LT

operation of 4x870g at 100V for 150 day in current LSM background

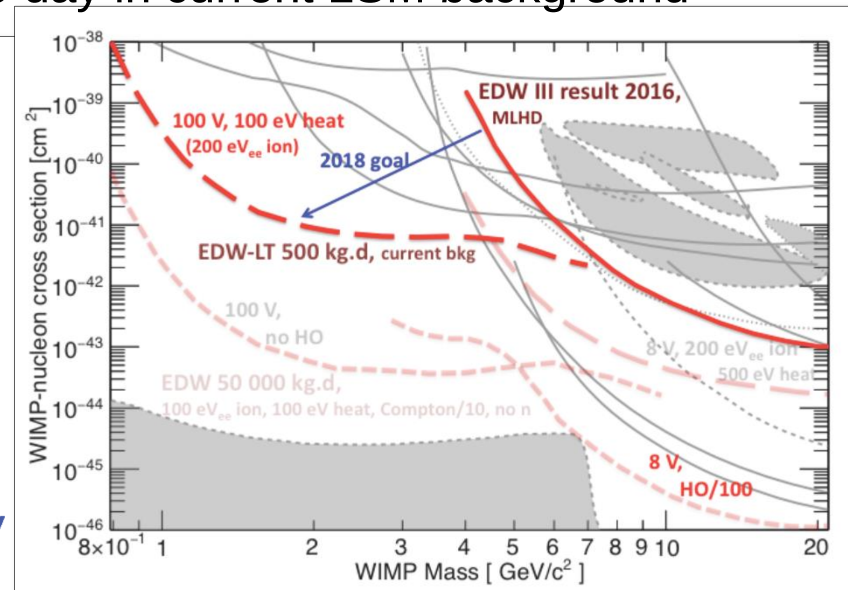
Heat thresholds can be improved by applying larger bias voltages

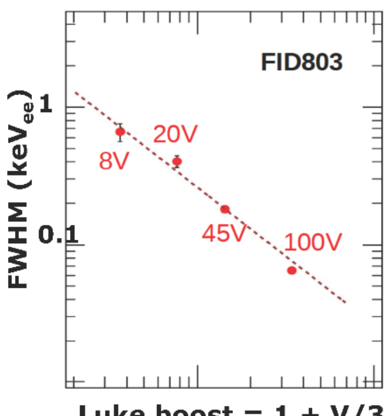
- Heat signal boosted by Neganov-Luke effect (~Joule heating, factor $[1+V_{bias}/3]$)
- Loss of ionization-based bkg discrimination: method benefits low-mass searches only
  → *10^{-41} cm² with 500 kgd and current bkgs*

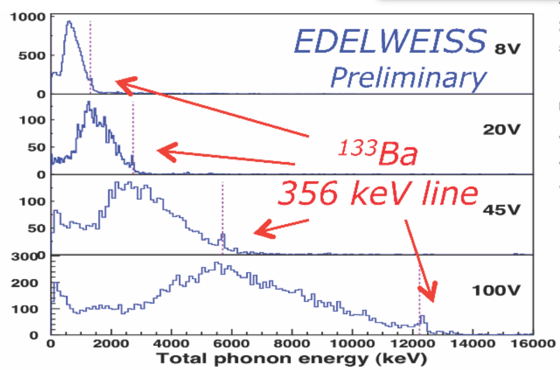
✔ **100V bias already achieved**

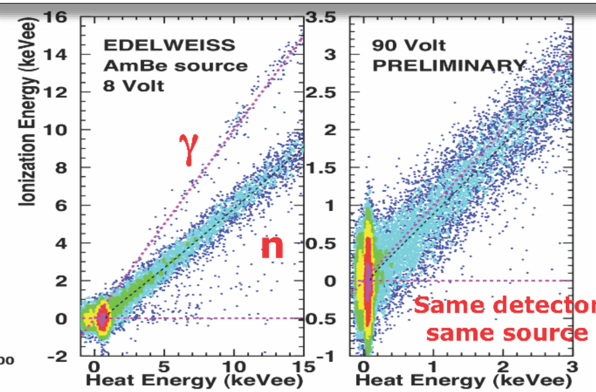
✔ **Observe nucl. recoils down to ~0.1 keV_{ee}**

✔ **First WIMP Data@100V analysis underway**





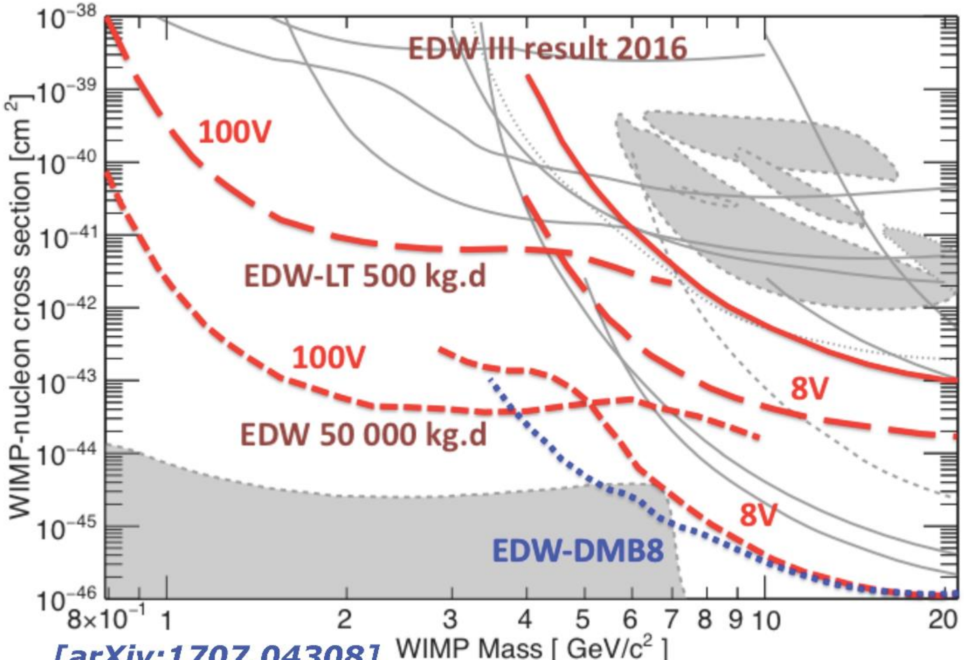




Courtesy of J. Gascon / EDELWEISS (Slides from TAUP 2017)

EDELWEISS-DMB8

- Cold front-end: replace JFET @100K with HEMT (High Electron Mobility Transistor) @4K
- Can be operated at 4K: shorter cabling -> reduced capacitance -> better signal/noise
- Successful HEMT amplifier with sub-100 eV resolution operated on a CDMS-II detector
  [A. Phipps et al., arXiv:1611.09712]
- EDELWEISS electrode design with lower capacitance:
  2 → 4 mm spacing already achieved. Goal: reach 50 eV_{ee}.



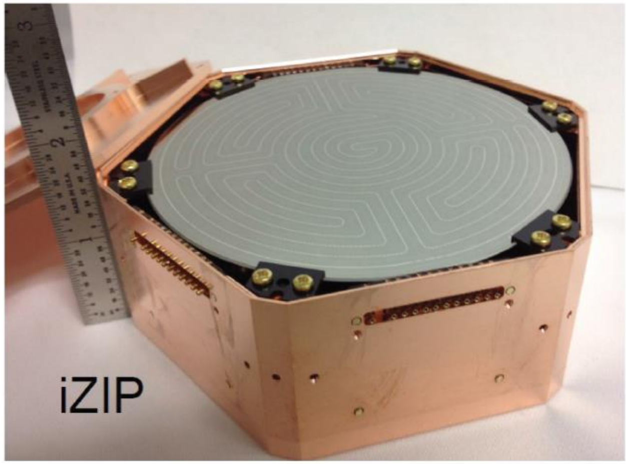
[arXiv:1707.04308]

2 mm spacing → 4 mm spacing

EDELWEISS-DMB8:
Operation of a 200 kg array @8V (with nuclear recoil discrimination) in the improved background environment of SuperCDMS @ SNOLAB

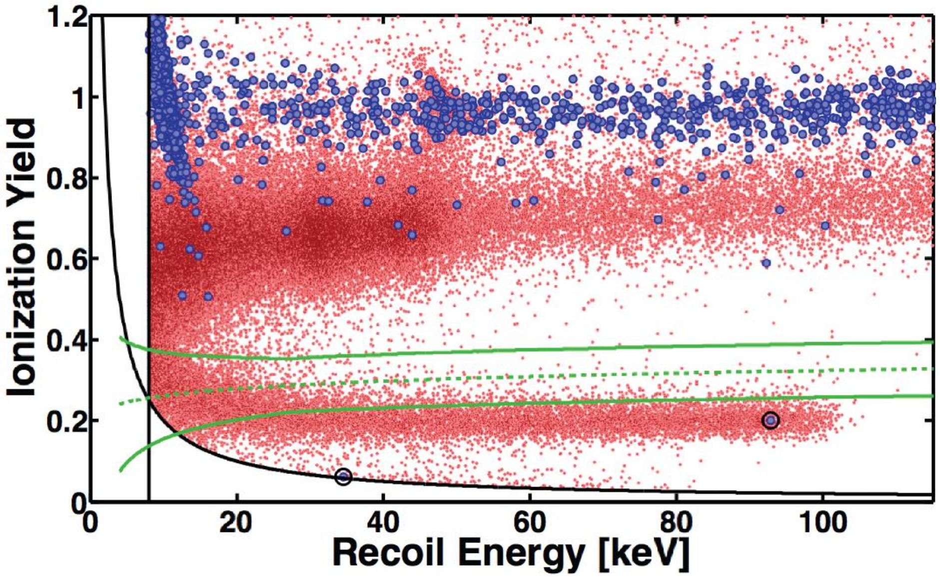
Probing the region of the coherent scattering of ^{8}B solar ν's with resolution and discrimination

Courtesy of J. Gascon / EDELWEISS (Slides from TAUP 2017)

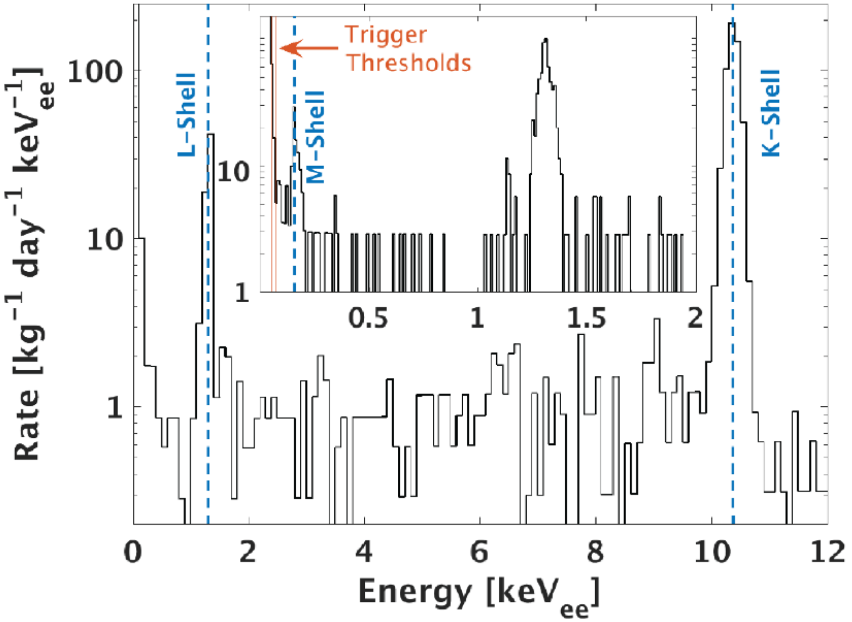


SuperCDMS

- Si, Ge crystals with O(1kg) @ O(10mK)
- iZIP: discriminate nucl./e⁻ recoil via dual readout of phonon and ionization, fidualization
- CDMSlite: Luke-Neganov boosted signal, no discrimination power
- 2011-2015 @ Soudan, → moving to SNOLAB



CDMSlite [Phys.Rev.Lett. 116(2016)071301]



Courtesy of B. Loer / SuperCDMS (Slides from UCLA DM2018)

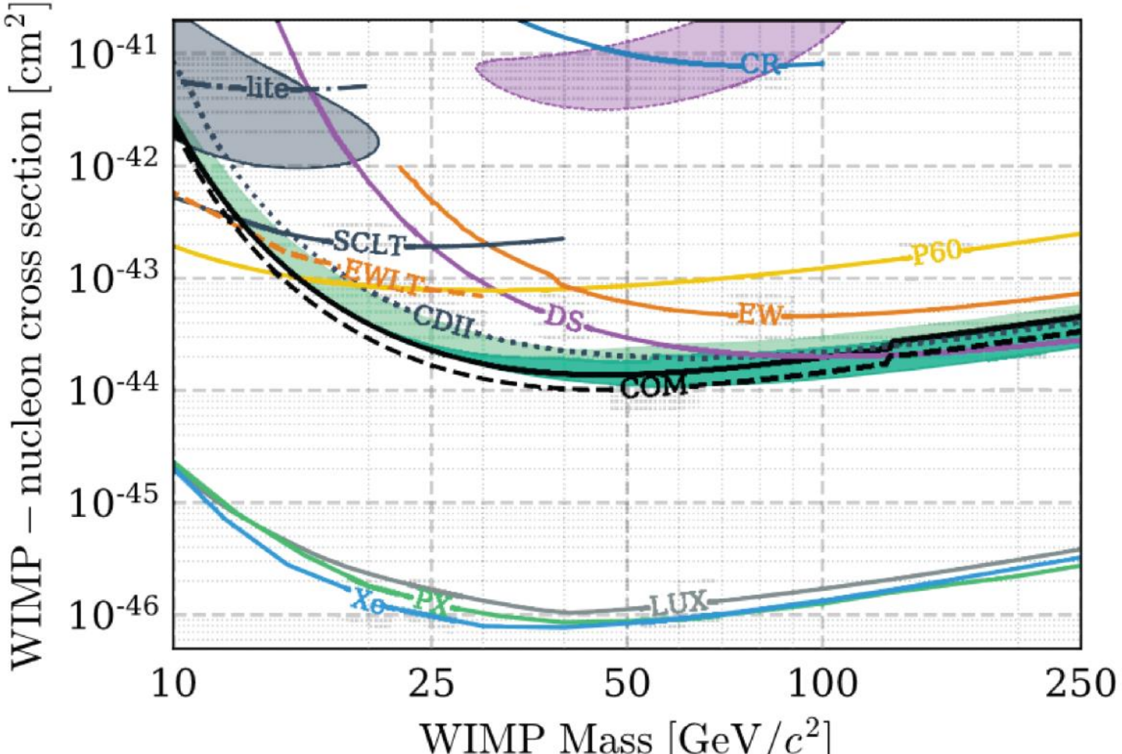
SuperCDMS @ Soudan

Ongoing analysis of Soudan data, e.g.

- Majority of SuperCDMS dataset
- 2 calendar years, ~1700 kg.days

[Phys.Rev.Lett. 120(2018)061802]

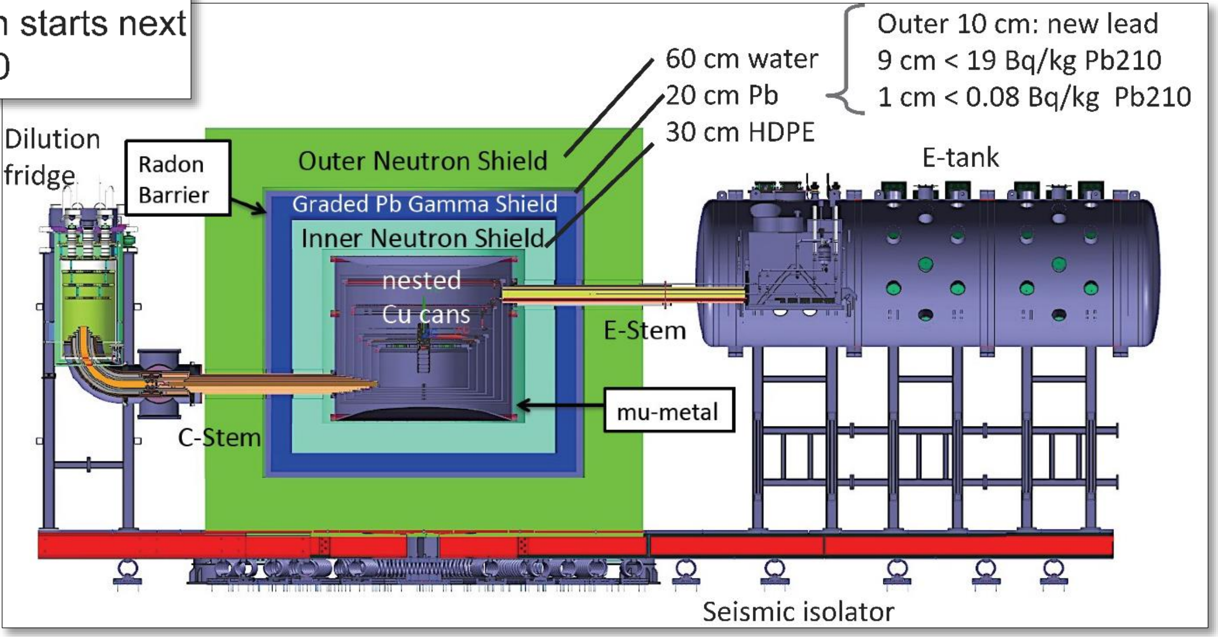
- Few keV threshold
- BDT background discriminant
- Observed 1 event, 0.33 expected



Courtesy of B. Loer / SuperCDMS (Slides from UCLA DM2018)

SuperCDMS @SNOLAB

- Passed CD3 review last month to begin construction
- Underground installation starts next year, completed by 2020

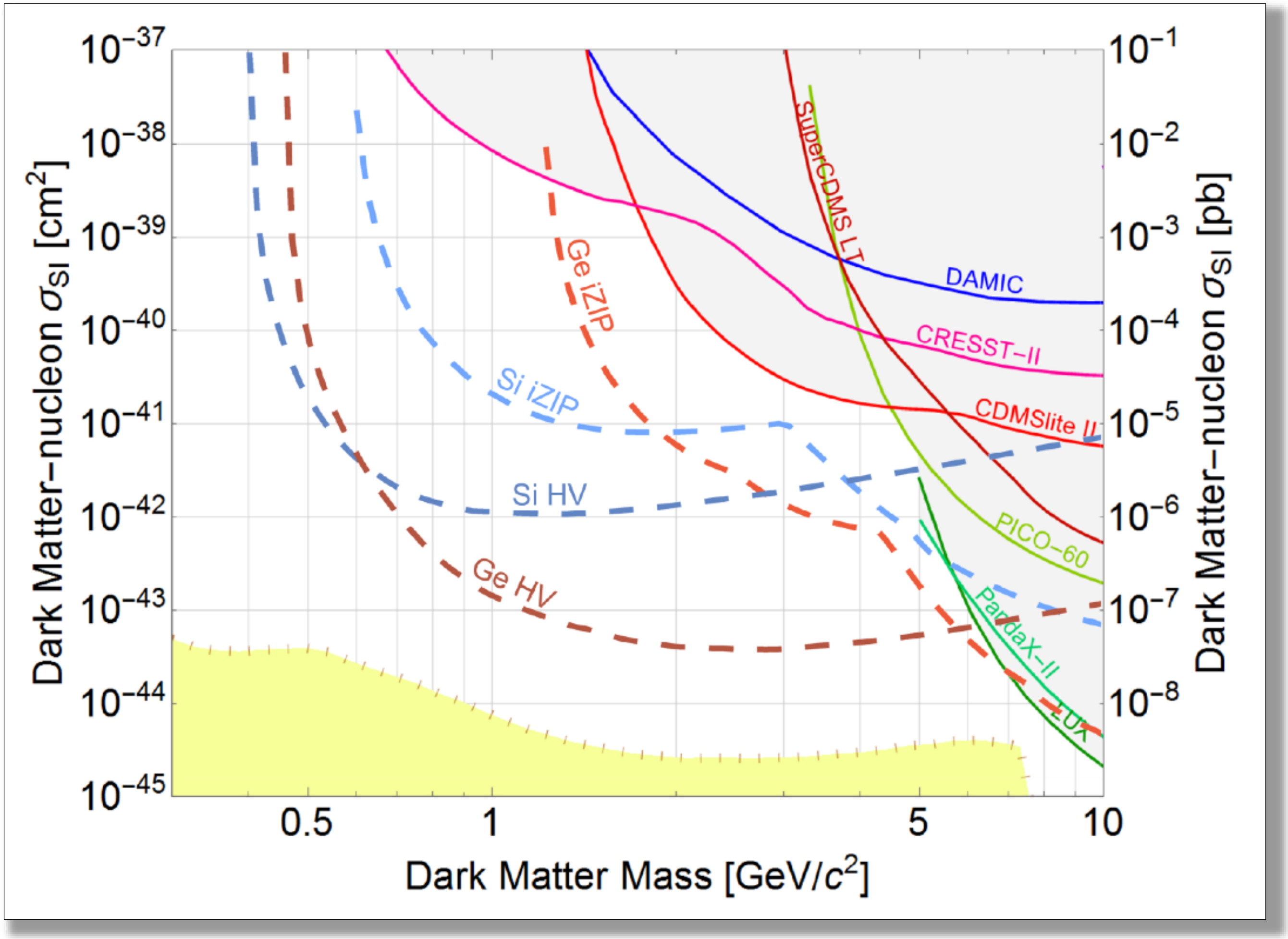


	Soudan	SNOLAB
Phonon resolution, eVt	~250	10 HV, 50 iZIP
HV Bias Voltage, V	70	100
iZIP Charge resolution, eVee	~400	160
HV Threshold, eVnr	300	40

- 4 tower initial payload
  - 2 HV (4 Ge, 2 Si each)
  - 2 iZIP (6 Ge in 1, 4/2 Ge/Si other)
- Fridge, cryostat capable of 31 towers, nominal 15 mK

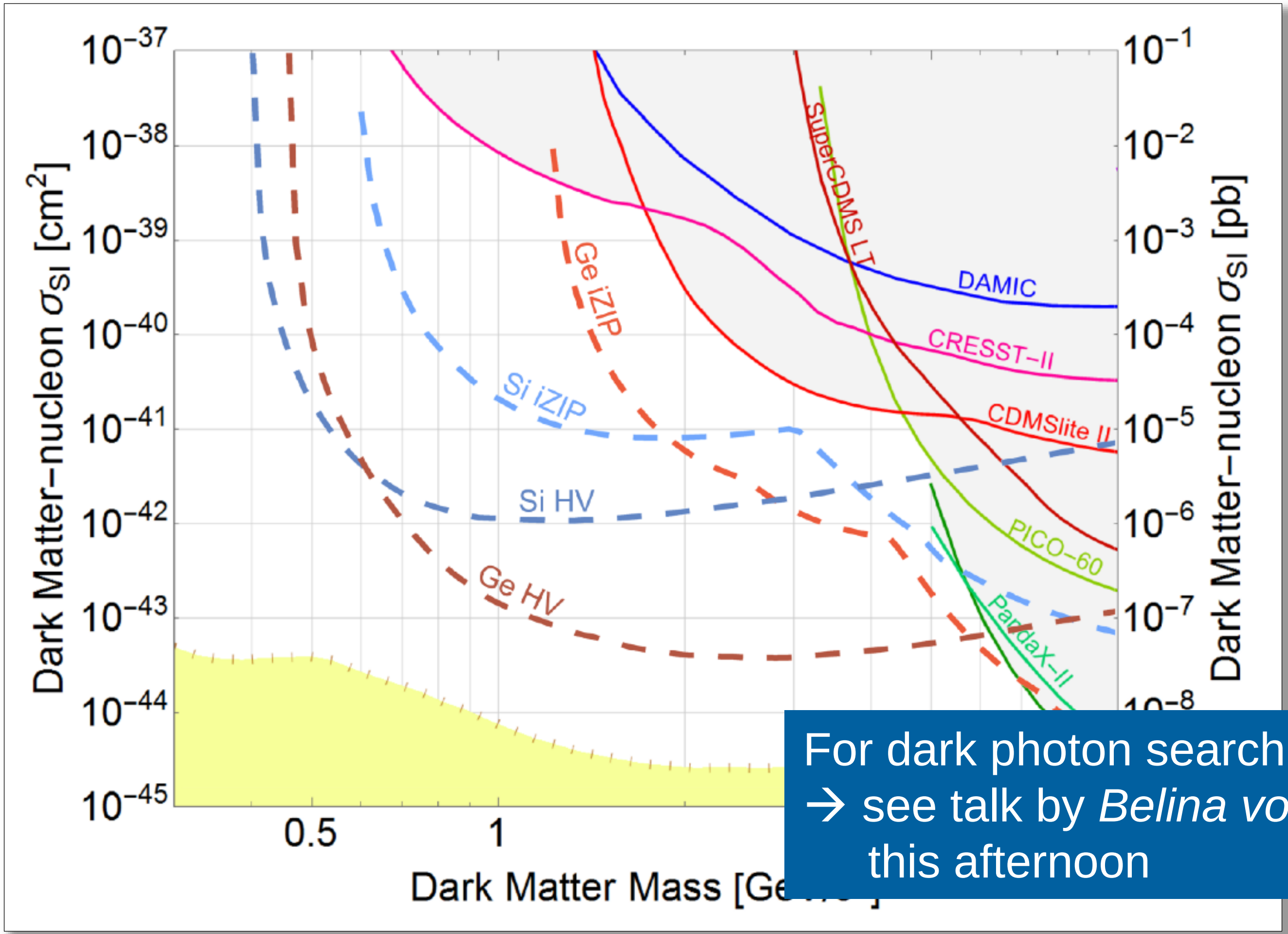
Courtesy of B. Loer / SuperCDMS (Slides from UCLA DM2018)

SuperCDMS



Courtesy of B. Loer / SuperCDMS (Slides from UCLA DM2018)

SuperCDMS

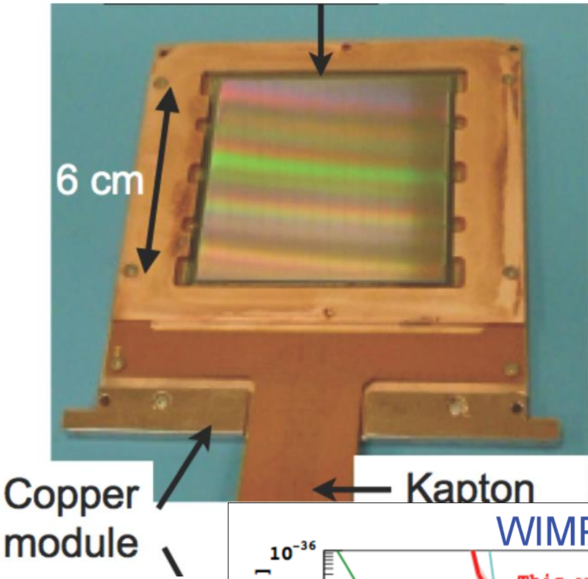


For dark photon search
→ see talk by *Belina von Krosigk* this afternoon

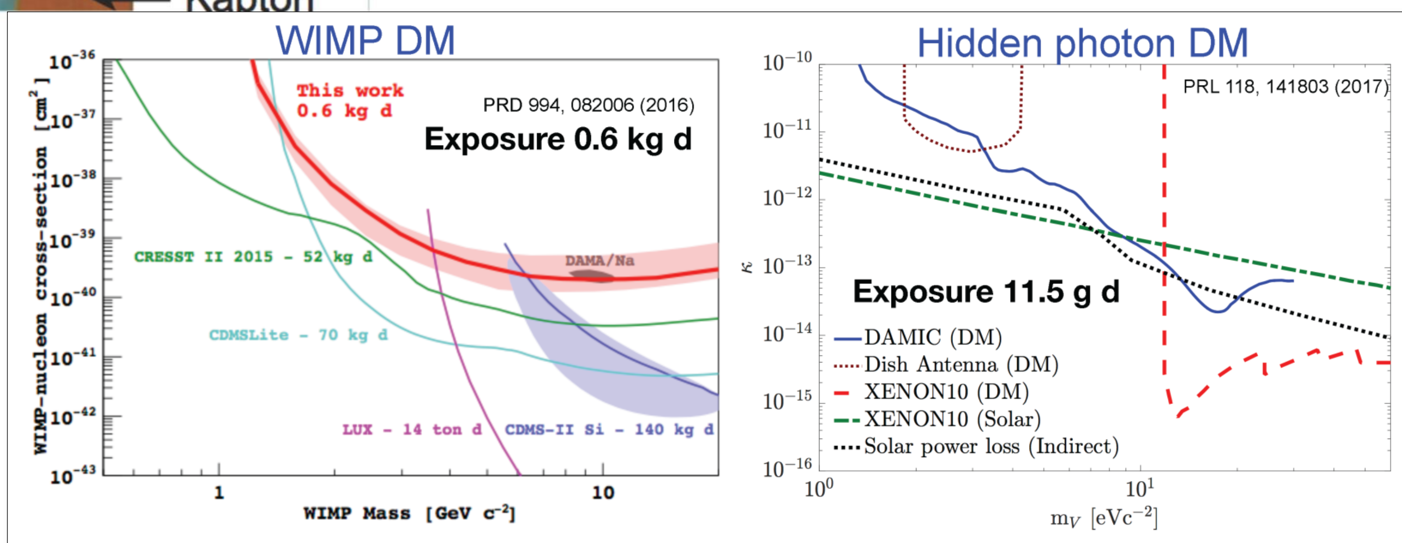
Courtesy of B. Loer / SuperCDMS (Slides from UCLA DM2018)

DAMIC

675 μm thick, 16 Mpix CCD, 6 g



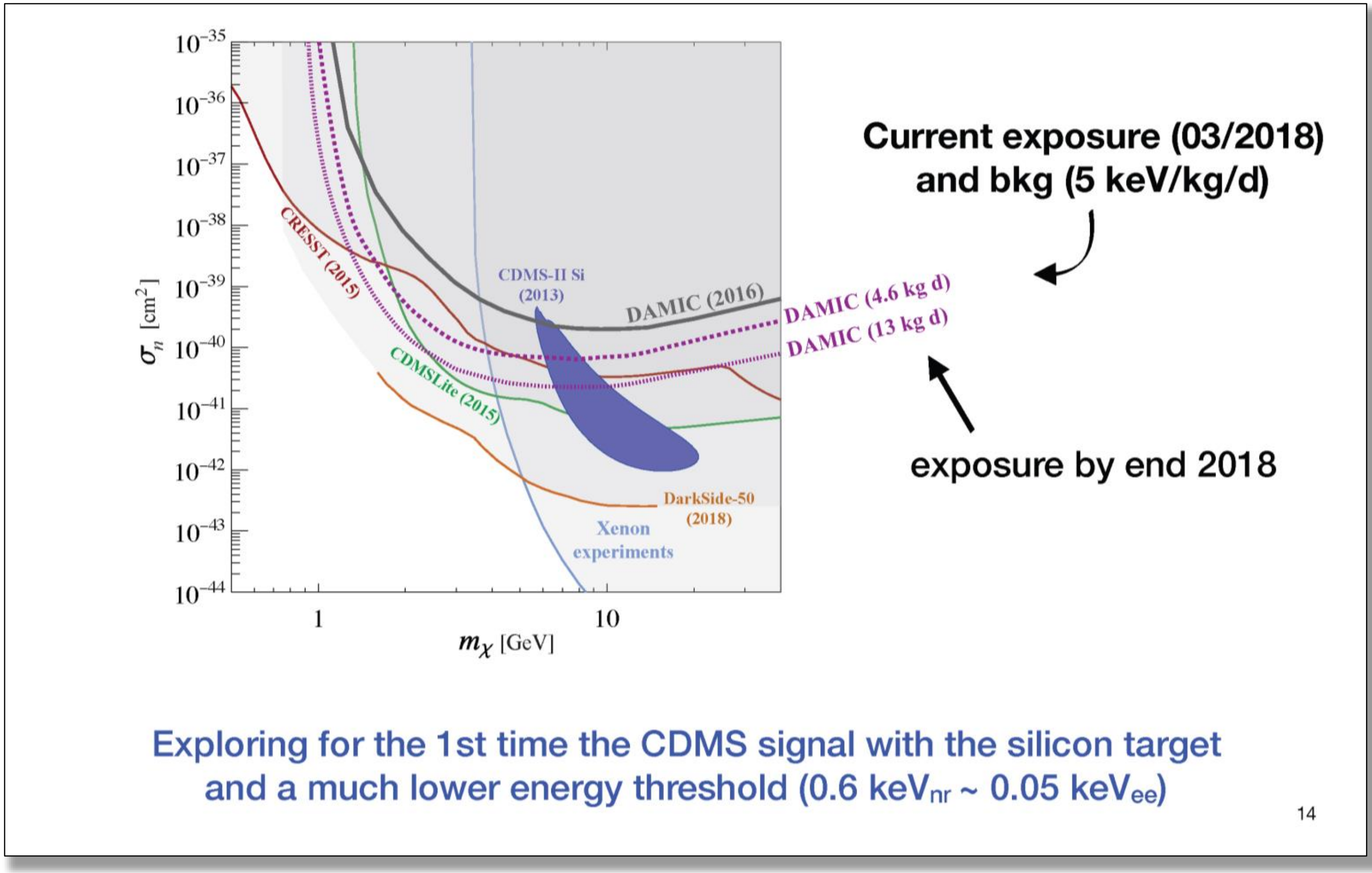
- @ SNOLAB
- 16Mpix CCD, 675µm thick, 6g Si @ 140K
- 7x CCDs stable data taking
- Background reduced by factor of 3-4 to ~5dru
- Threshold as low as 50eVee (=600eVnr)
- 7.6 kg.d background data
- So far, 4.6 kg.d for DM search



Courtesy of A.E. Chavarria / DAMIC (Slides from UCLA DM2018)

DAMIC

Projected sensitivity

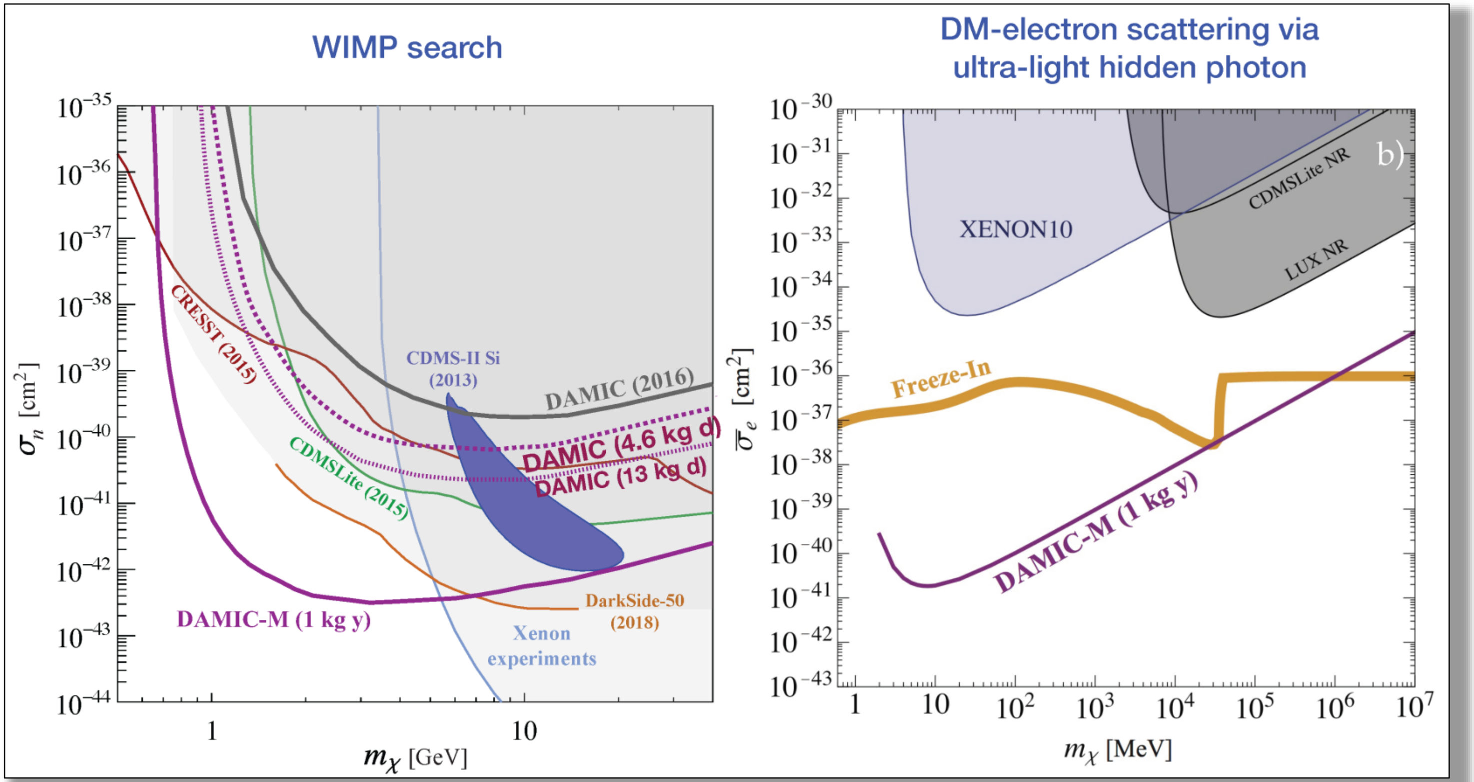


Courtesy of M. Settimo / DAMIC (Slides from 53rd Rencontres des Moriond)

DAMIC-M

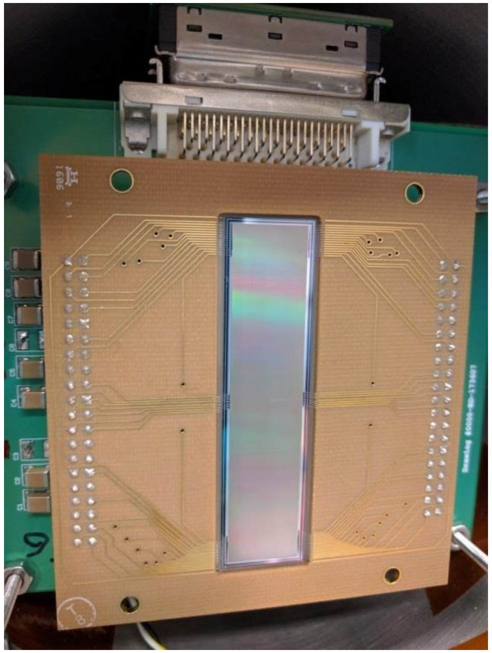
- Next stage @ LSM: 1kg Si
- Skipper readout for sub-eV noise
- 6k x 6k x 1mm CCD, 20g
- Further reduced background

Projected sensitivity



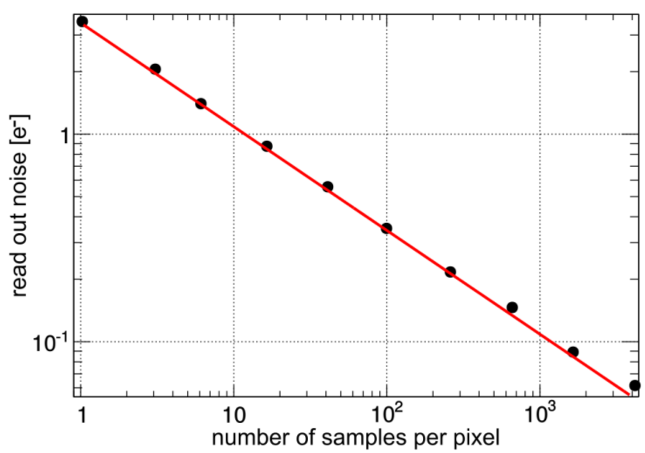
Courtesy of M. Settimo / DAMIC (Slides from 53rd Rencontres des Moriond)

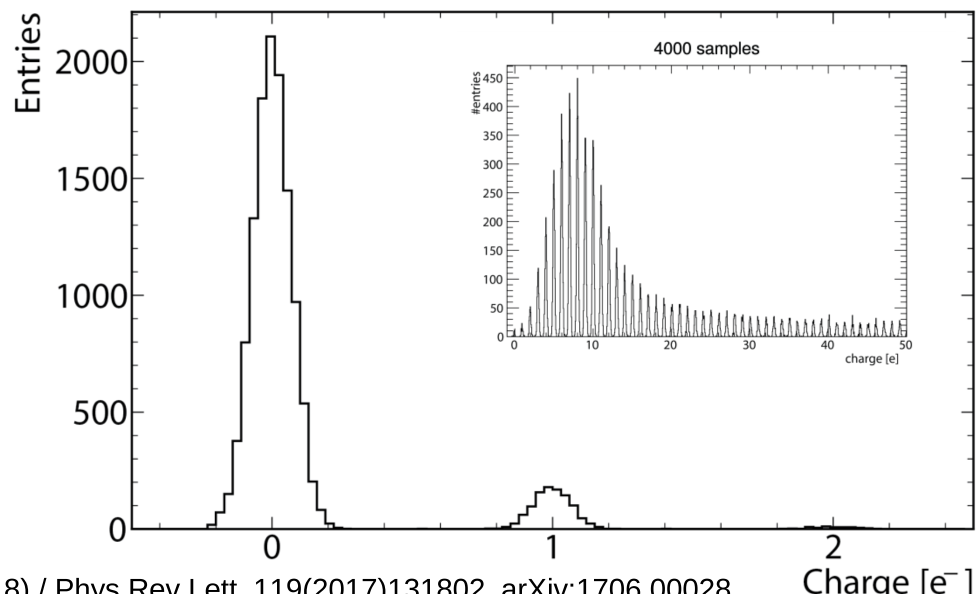
Electron Recoils



SENSEI

- @ Fermi National Accelerator Laboratory (FNAL)
- CCD 724px × 1248px × 200µm, active mass 71mg @ ~130K
- Skipper readout (multiple readouts): $\sigma \propto 1/\sqrt{N}$
- dark current is limiting factor
- $0e^-$ peak: readout noise of 0.068 e^- rms/px
- Currently: FNAL underground (~100m)
- Surface run: 19mg.d



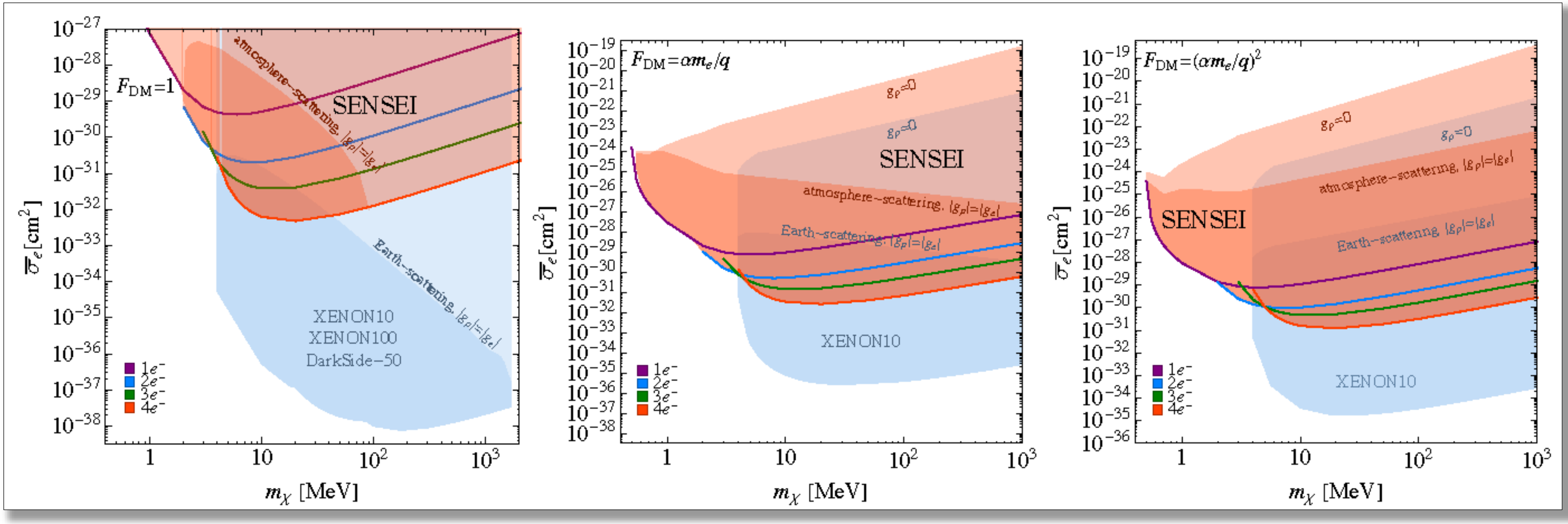


Courtesy of T.-T. Yu / SENSEI (Slides from UCLA DM2018) / Phys.Rev.Lett. 119(2017)131802, arXiv:1706.00028

SENSEI

Results surface run

heavy dark photon   electric dipole moment   ultralight dark photon

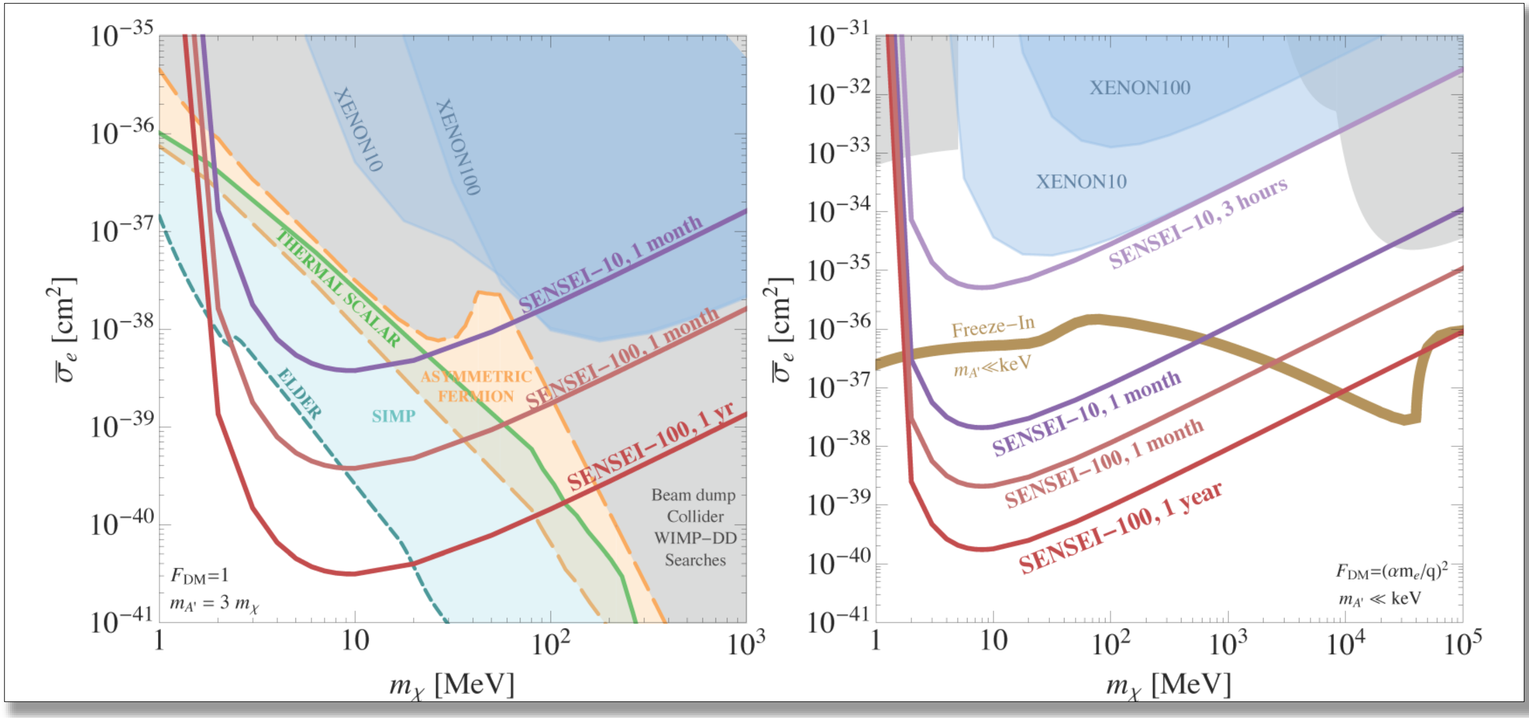


Courtesy of T.-T. Yu / SENSEI

SENSEI

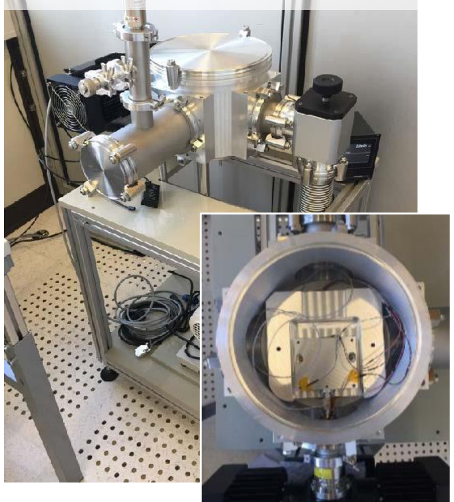
Ultimate goal: 100g Si
Projected sensitivity

heavy dark photon ultralight dark photon



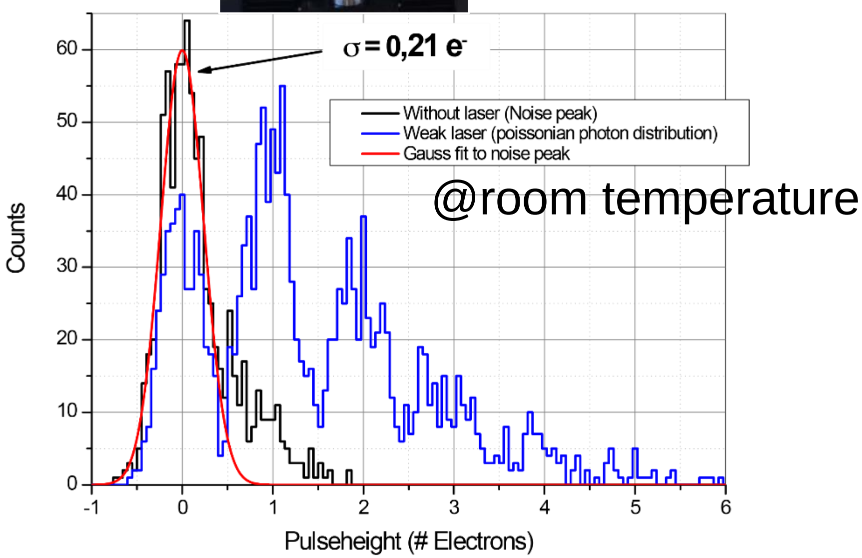
Courtesy of T.-T. Yu / SENSEI (Slides from UCLA DM2018)

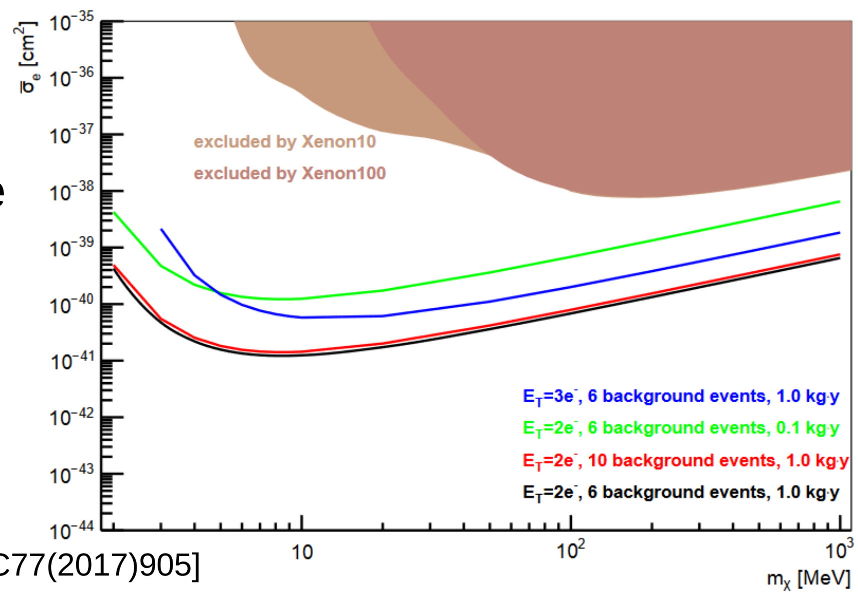
Setup at MPG HLL



DANAE

- Proof-of-principle @ HEPHY, MPG HLL München
- Si DEPFET matrix with multiple readout (DEPFET-RNDR)
- Prototype with 64px x 64px x 450µm
- Fast framerate→ potential to run it with µ-veto
- Single electron separation with 5σ possible
- ← Vacuum and cooling test (@200K) done in March 2018
- Next: readout implementation and tests of the matrix
- Goal for DM search: 1kpx x 1kpx x 1mm, 3.2g/device





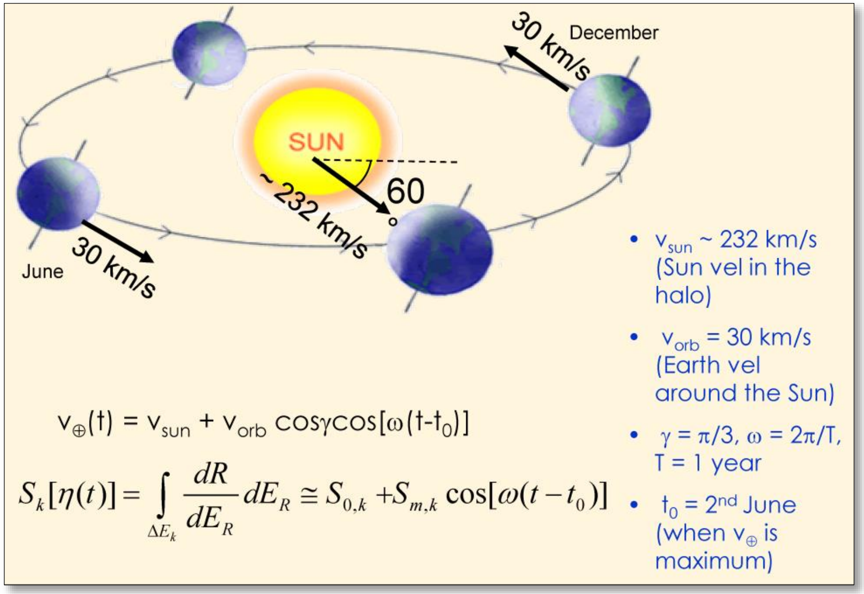
[Eur.Phys.J. C77(2017)905]

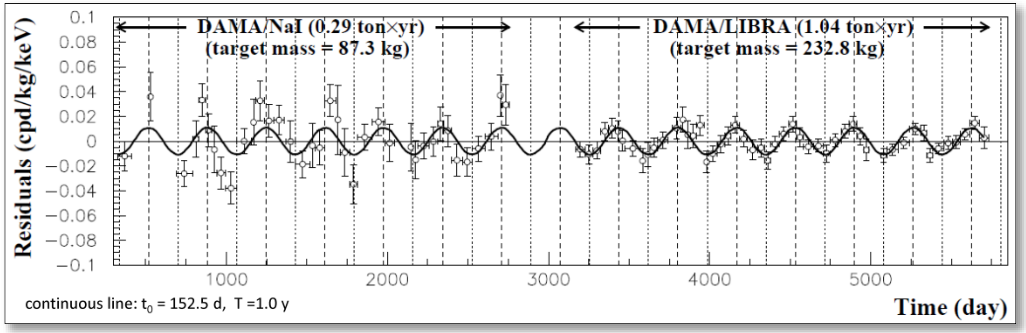
Courtesy of H. Shi / DANAE

Search for annual modulations / signal in NaI(Tl)

DAMA/LIBRA

- @ LNGS
- Scintillating NaI(Tl) crystals
- DAMA/NaI: 100kg NaI(Tl) → 0.29 ton.yr
- Cosinusoidal signal compatible with T=1yr, t_0=June 2[nd]
- DAMA/LIBRA-phase 1: 250kg NaI(Tl), new DAQ, improved purification, → 1.04 ton.yr
- DAMA/LIBRA-phase 2: new PMTs with higher Q.E., trigger threshold down to 1keV



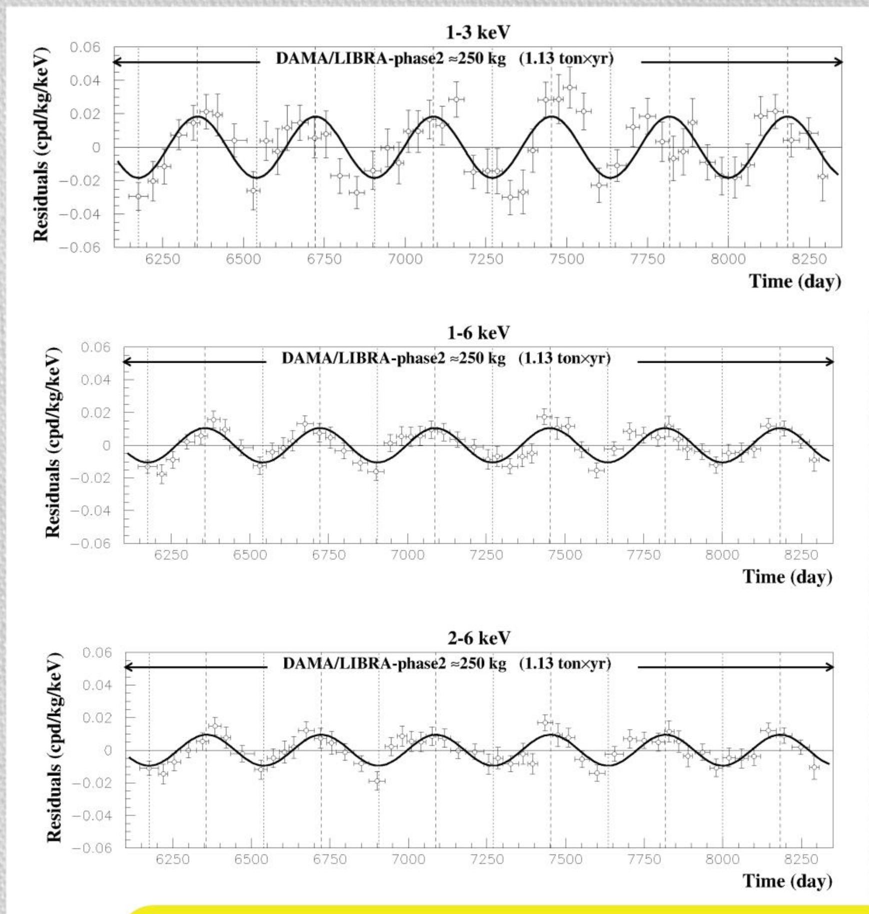


Courtesy of V. Caracciolo / DAMA (Slides from UCLA DM2018)

DM Model Independent Annual Modulation Result

experimental residuals of the single-hit scintillation events rate vs time and energy

DAMA/LIBRA-phase2 (1.13 ton × yr)



Absence of modulation? No

- 1-3 keV: χ^2/dof=127/52 ⇒ P(A=0) = 3×10^{-8}
- 1-6 keV: χ^2/dof=150/52 ⇒ P(A=0) = 2×10^{-11}
- 2-6 keV: χ^2/dof=116/52 ⇒ P(A=0) = 8×10^{-7}

Fit on DAMA/LIBRA-phase2

$A\cos[\omega(t-t_0)]$;
continuous lines: t_0 = 152.5 d, T = 1.00 y

1-3 keV

A=(0.0184±0.0023) cpd/kg/keV

χ^2/dof = 61.3/51 **8.0 σ C.L.**

1-6 keV

A=(0.0105±0.0011) cpd/kg/keV

χ^2/dof = 50.0/51 **9.5 σ C.L.**

2-6 keV

A=(0.0095±0.0011) cpd/kg/keV

χ^2/dof = 42.5/51 **8.6 σ C.L.**

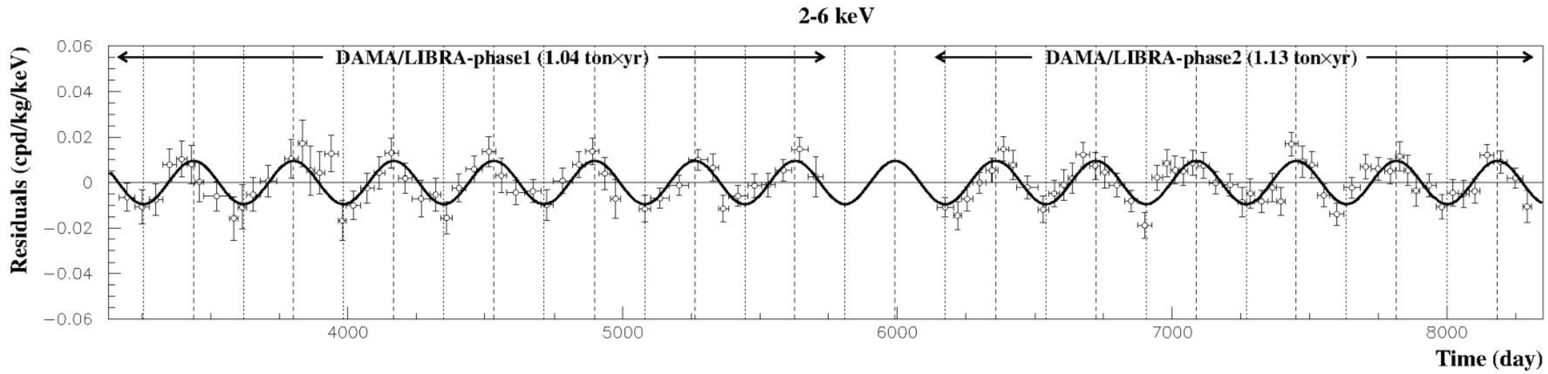
The data of DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 9.5σ C.L.

Courtesy of R. Bernabei / DAMA (Slides from CSLNGS March 26, 2018)

Model Independent DM Annual Modulation Result

experimental residuals of the single-hit scintillation events rate vs time and energy

DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.17 ton × yr)



Absence of modulation? No
- 2-6 keV: χ^2/dof=199.3/102 ⇒ P(A=0) =2.9×10^{-8}

Fit on DAMA/LIBRA-phase1+ DAMA/LIBRA-phase2

$A\cos[\omega(t-t_0)]$;
continuous lines: t_0 = 152.5 d, T = 1.00 y

2-6 keV

A=(0.0095±0.0008) cpd/kg/keV
χ^2/dof = 71.8/101 **11.9σ C.L.**

The data of DAMA/LIBRA-phase1 +DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 11.9 σ C.L.

Courtesy of R. Bernabei / DAMA (Slides from CSLNGS March 26, 2018)

Releasing period (T) and phase (t_0) in the fit

	ΔE	A(cpd/kg/keV)	$T=2\pi/\omega$ (yr)	t_0 (day)	C.L.
DAMA/LIBRA-ph2	(1-3) keV	0.0184±0.0023	1.0000±0.0010	153±7	8.0σ
	(1-6) keV	0.0106±0.0011	0.9993±0.0008	148±6	9.6σ
	(2-6) keV	0.0096±0.0011	0.9989±0.0010	145±7	8.7σ
DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.0096±0.0008	0.9987±0.0008	145±5	12.0σ
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.0103±0.0008	0.9987±0.0008	145±5	12.9σ

$A\cos[\omega(t-t_0)]$

DAMA/NaI (0.29 ton x yr) +
DAMA/LIBRA-ph1 (1.04 ton x yr) +
DAMA/LIBRA-ph2 (1.13 ton x yr)

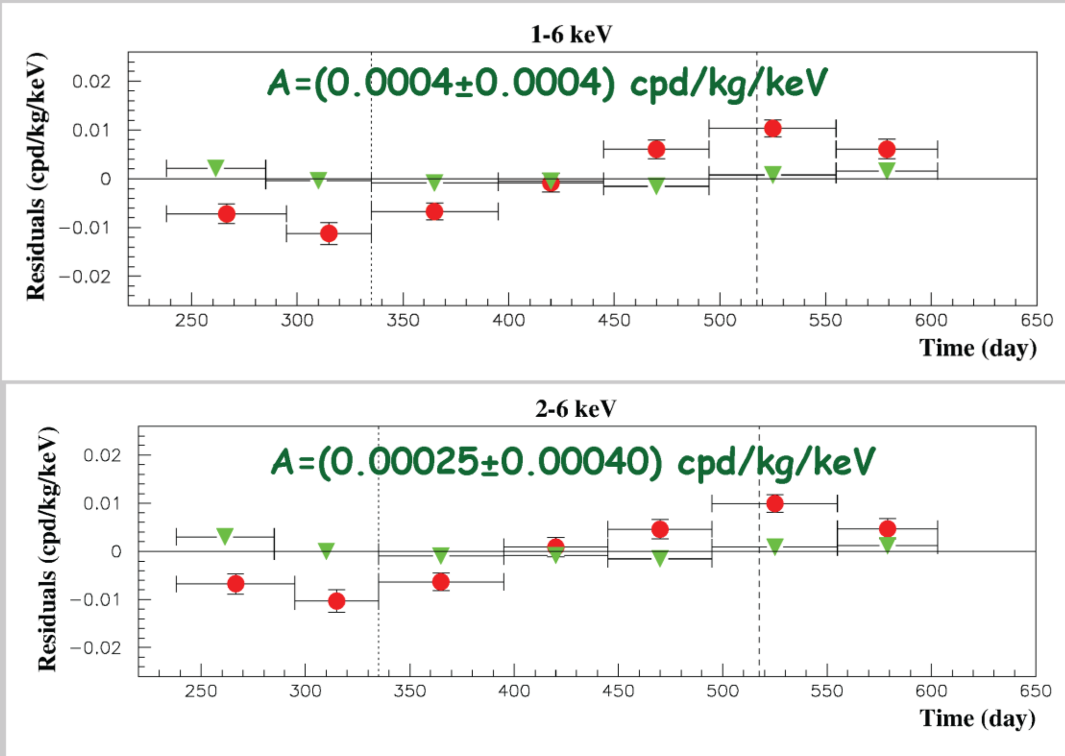
total exposure = 2.46 ton×yr

Courtesy of R. Bernabei / DAMA (Slides from CSLNGS March 26, 2018)

DM Model Independent Annual Modulation Result

DAMA/LIBRA-phase2 (1.13 ton × yr)

Multiple hits events = Dark Matter particle "switched off"



Single hit residual rate (red) vs **Multiple hit residual rate (green)**

- Clear modulation in the single hit events;
- No modulation in the residual rate of the multiple hit events

This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

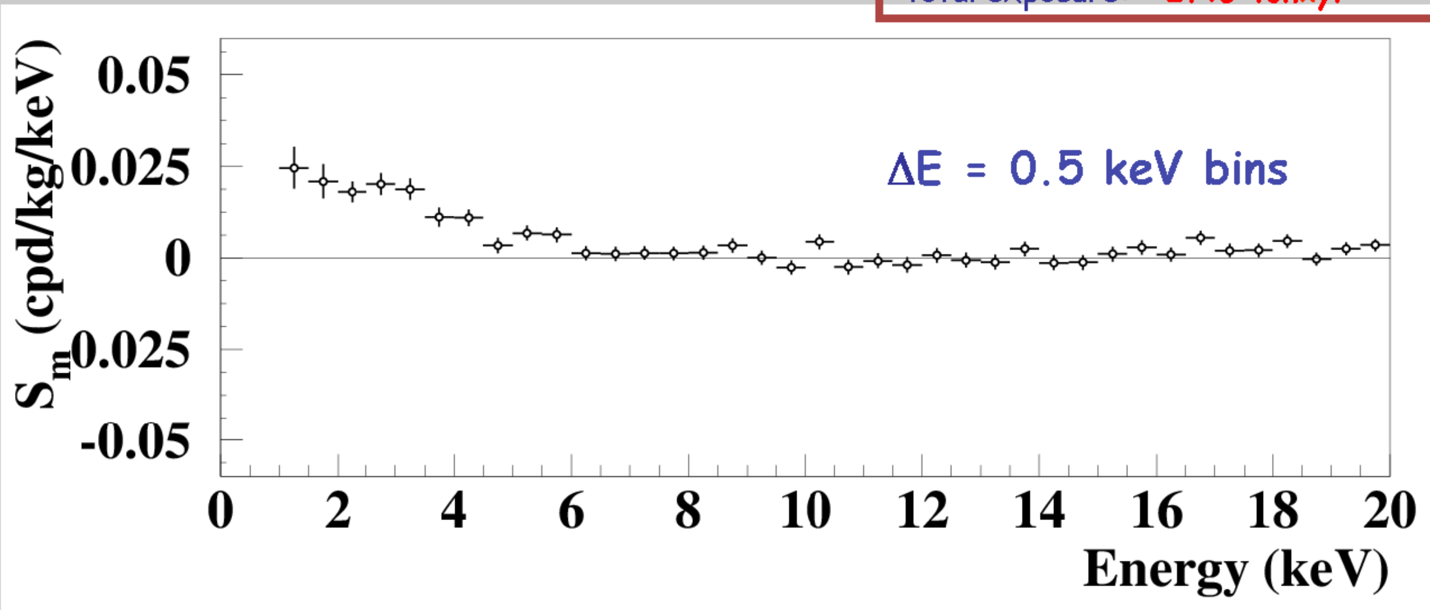
Courtesy of R. Bernabei / DAMA (Slides from CSLNGS March 26, 2018)

Energy distribution of the modulation amplitudes

$$R(t) = S_0 + S_m \cos\left[\omega\left(t - t_0\right)\right]$$

here $T=2\pi/\omega=1$ yr and $t_0= 152.5$ day

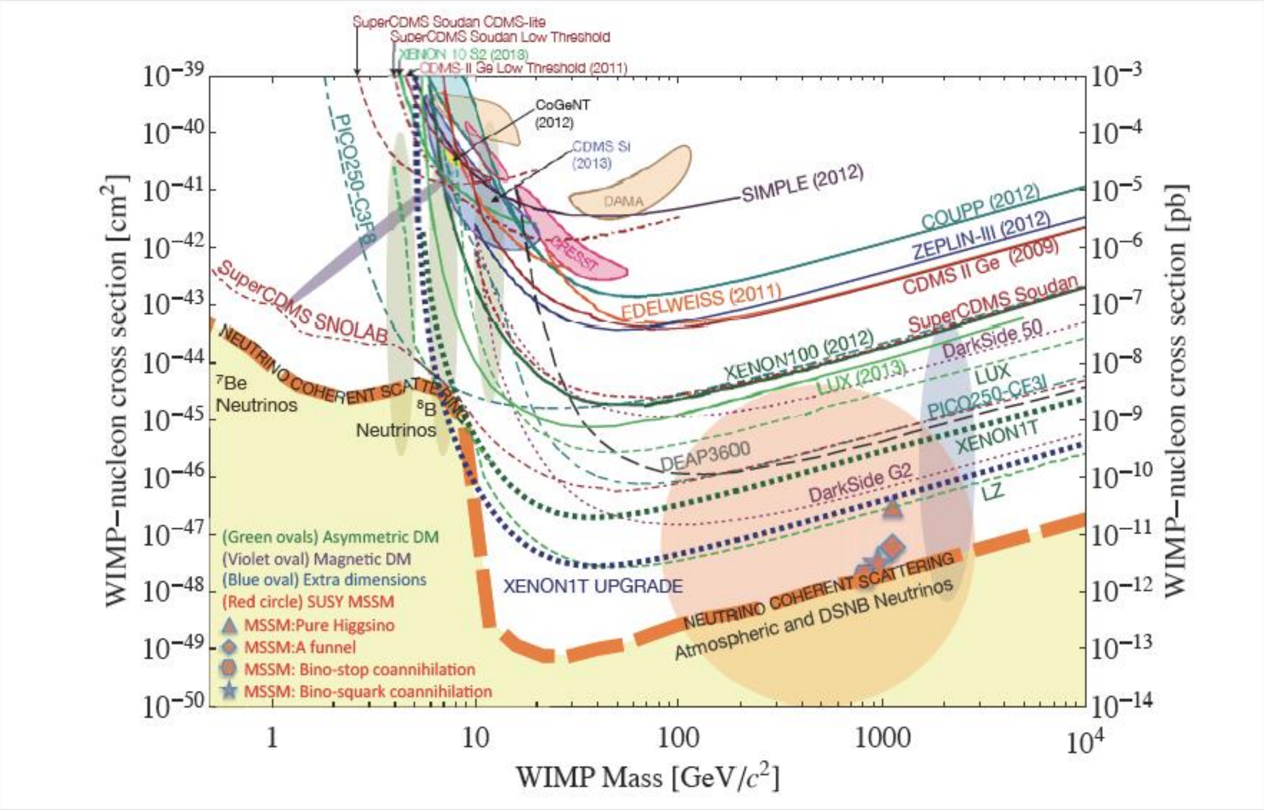
DAMA/NaI
+ DAMA/LIBRA-phase1
+ DAMA/LIBRA-phase2
total exposure: ≈ 2.46 ton×yr



- A clear modulation is present in the (1-6) keV energy interval, while S_m values compatible with zero are present just above
- The S_m values in the (6–14) keV energy interval have random fluctuations around zero with χ^2 equal to 19.0 for 16 degrees of freedom (upper tail probability 27%)
- The S_m values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 42.6 for 28 degrees of freedom (upper tail probability 4%). The obtained χ^2 value is rather large due mainly to two data points, whose centroids are at 16.75 and 18.25 keV, far away from the (1-6) keV energy interval. The P-values obtained by excluding only the first and either the points are 11% and 25%.

Courtesy of R. Bernabei / DAMA (Slides from CSLNGS March 26, 2018)

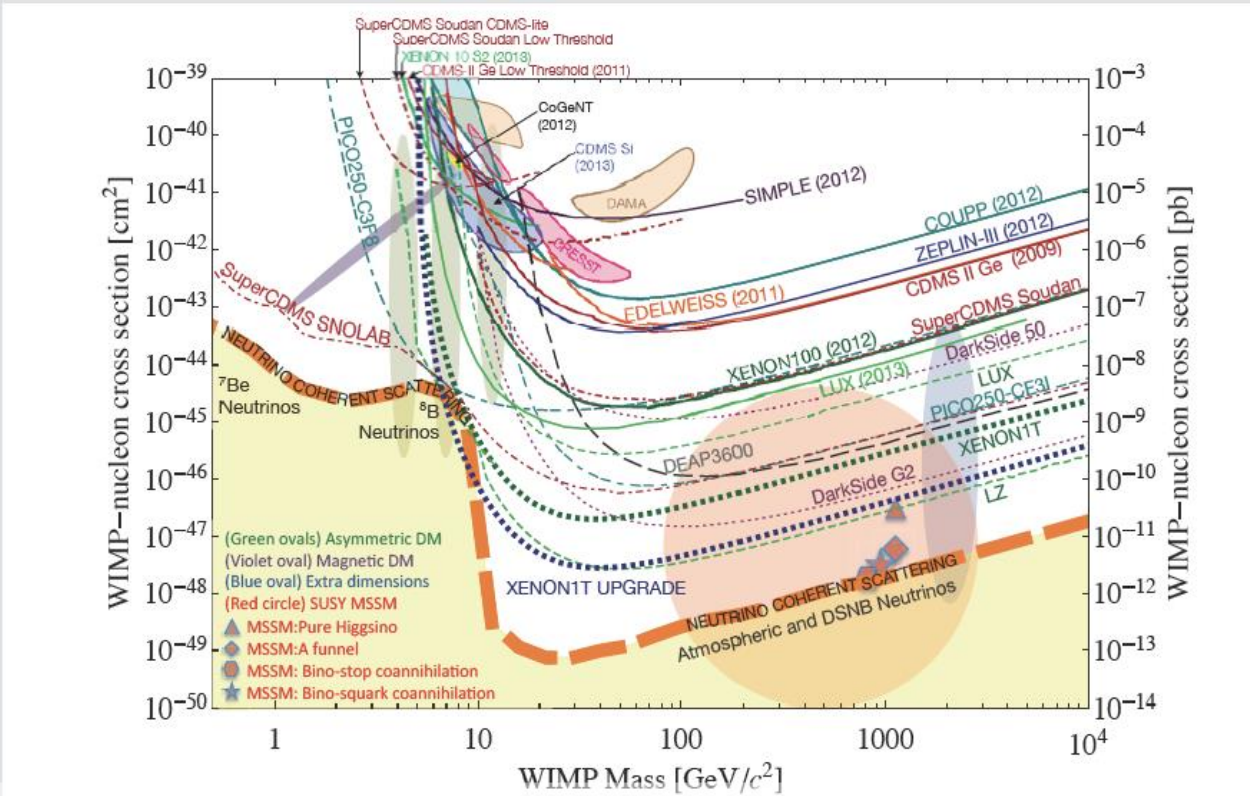
Is it an "universal" and "correct" way to approach the problem of DM and comparisons?



No, it isn't. This is just a largely arbitrary/partial/incorrect exercise

Courtesy of R. Bernabei / DAMA (Slides from CSLNGS March 26, 2018)

Is it an "universal" and "correct" way to approach the problem of DM and comparisons?

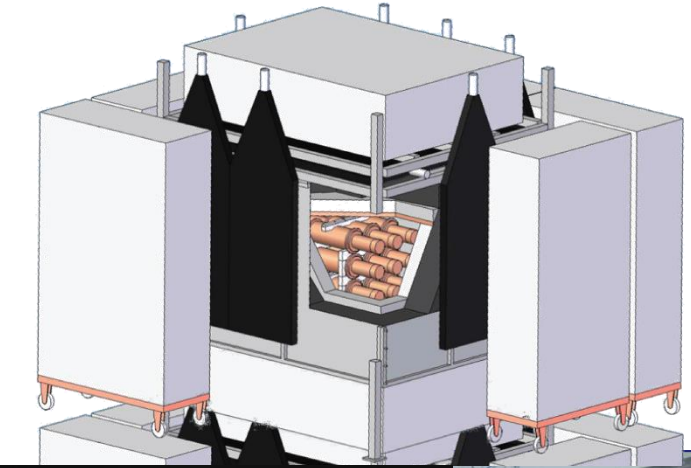


→ As DAMA pointed out, we need a model independent test of the observation

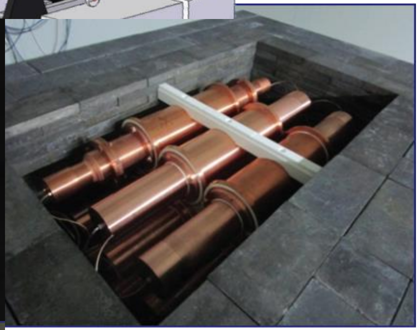
No, it isn't. This is just a largely arbitrary/partial/incorrect exercise

Courtesy of R. Bernabei / DAMA (Slides from CSLNGS March 26, 2018)

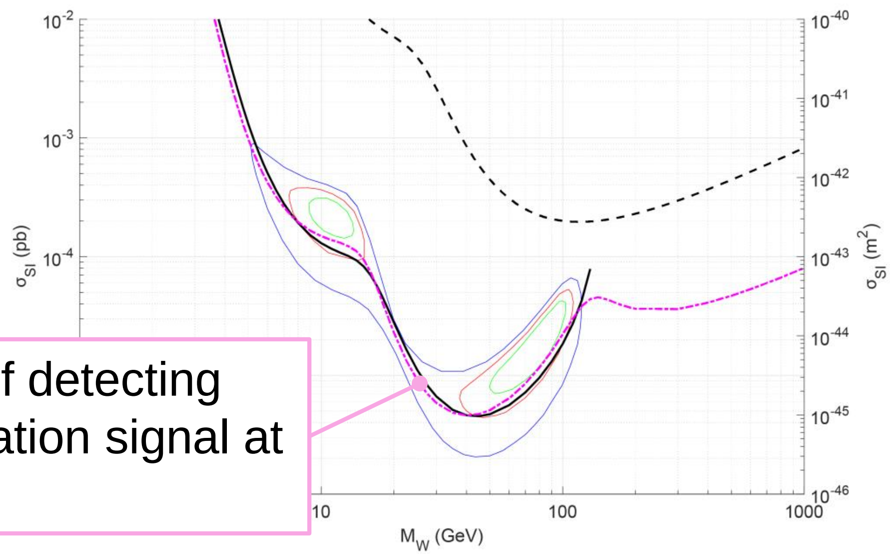
ANAIS



- @ Canfranc (LSC, 2450mwe)
- 3x3 matrix of 12.5kg NaI(Tl) = 112.5kg
- ANAIS-112 DM run started on August 3, 2017
- Triggering down to 1keV$_{ee}$
- 5 years data taking needed for a 3σ result



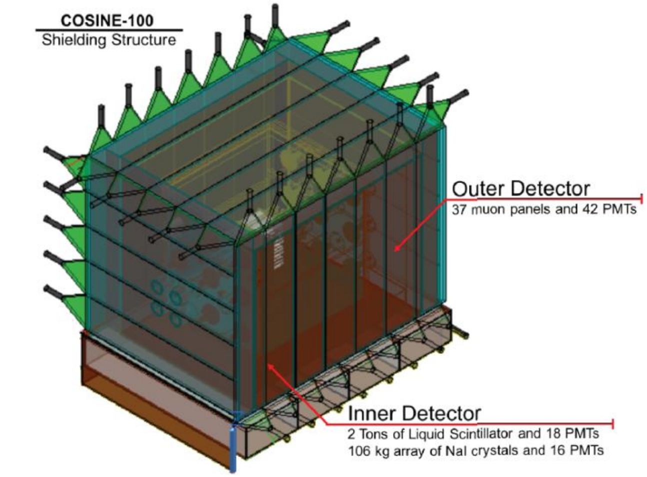
[arXiv:1704.06861]



90% probability of detecting an annual modulation signal at 90% C.L.

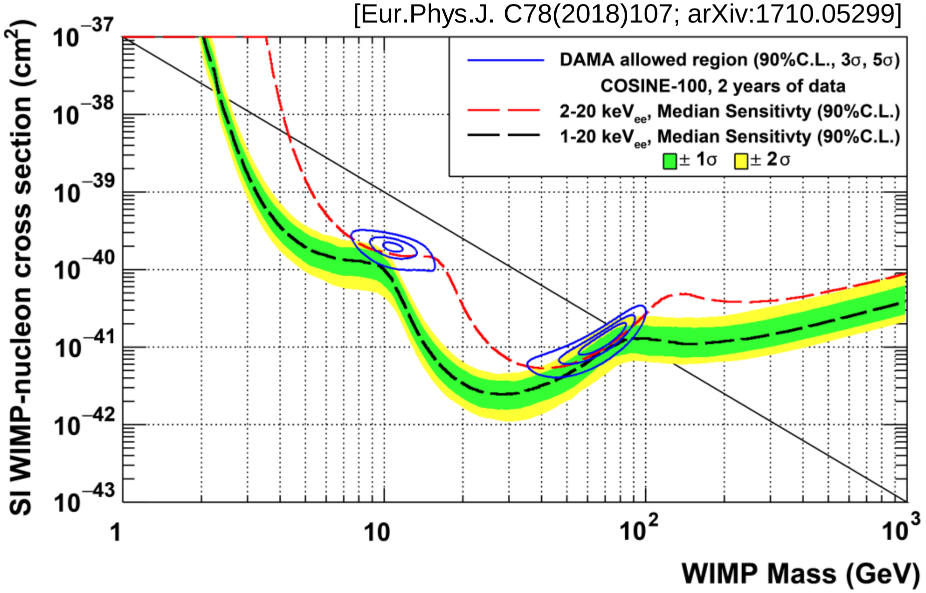
Courtesy of M.L. Sarsa / ANAIS (Slides from UCLA DM2018)

COSINE-100



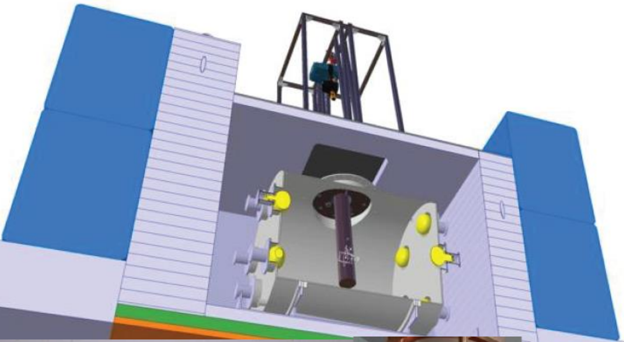
- COSINE100 = DM-Ice + KIMS
- @ YangYang Laboratory (Y2L)
- 8x NaI(Tl) crystals = 106kg
- COSINE-100 running since Sep. 2016
- Background: 2-4 x DAMA avg.
- R&D for higher purity for COSINE-200

[Eur.Phys.J. C78(2018)107; arXiv:1710.05299]



Courtesy of R. Maruyama / COSINE-100 (Slides from UCLA DM2018)

SABRE

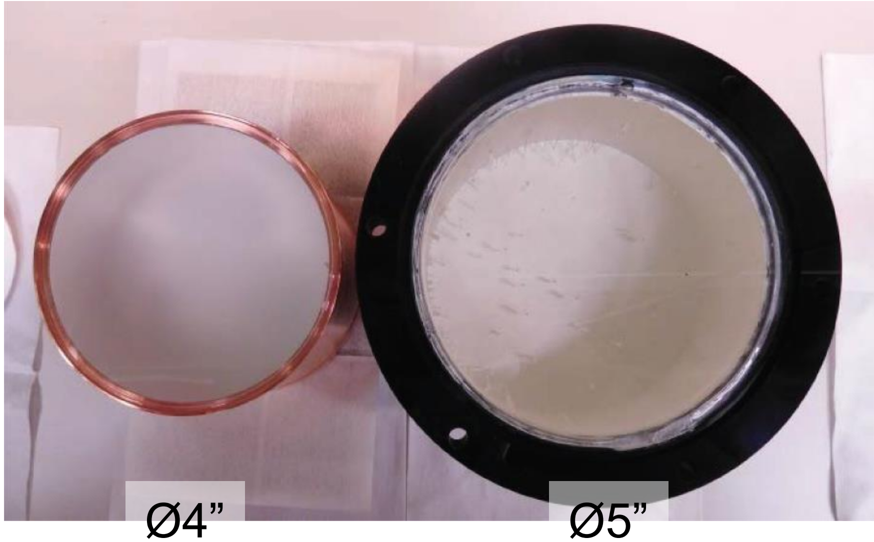


- North and South twin experiments with NaI(Tl) →rule out potential seasonal effects
- Proof-of-principle @LNGS: liquid scintillator vessel, shielding, detector enclosure
- 2015: 2kg crystal with 9ppb ^{40}K, goal: 5kg crystal
- Expect data taking in 2018

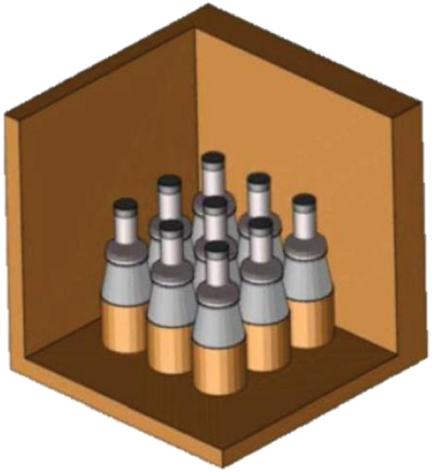
- SABRE in the south (Australia): 50kg NaI(Tl):
- @ Stawell Underground Physics Lab (3000mwe)
- Start vessel tests in 2018, lab ready in early 2019

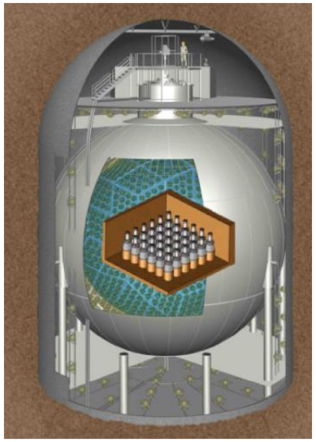
Courtesy of B. Suerfu / SABRE (Slides from UCLA DM2018)

PICOLON

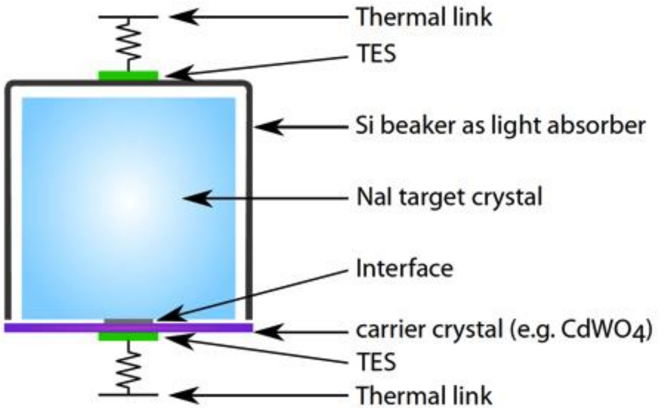


- Project @ Kamioka Underground Observatory
- Ø4” crystals of purified NaI(Tl): U/Th ~ DAMA; ^{40}K, ^{210}Pb > DAMA
- Feb. 2018: 5” x Ø5” crystals of ~5kg NaI(Tl); >230 kg.d background data under evaluation
- Goal: test DAMA with 3x3 array of Ø5” crystals, ~53kg NaI(Tl)
- Future: KamLAN-PICO: 247kg NaI(Tl) inside KamLAND

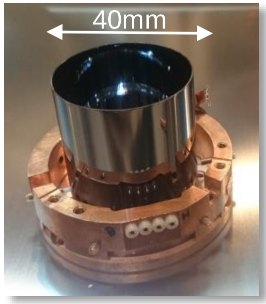




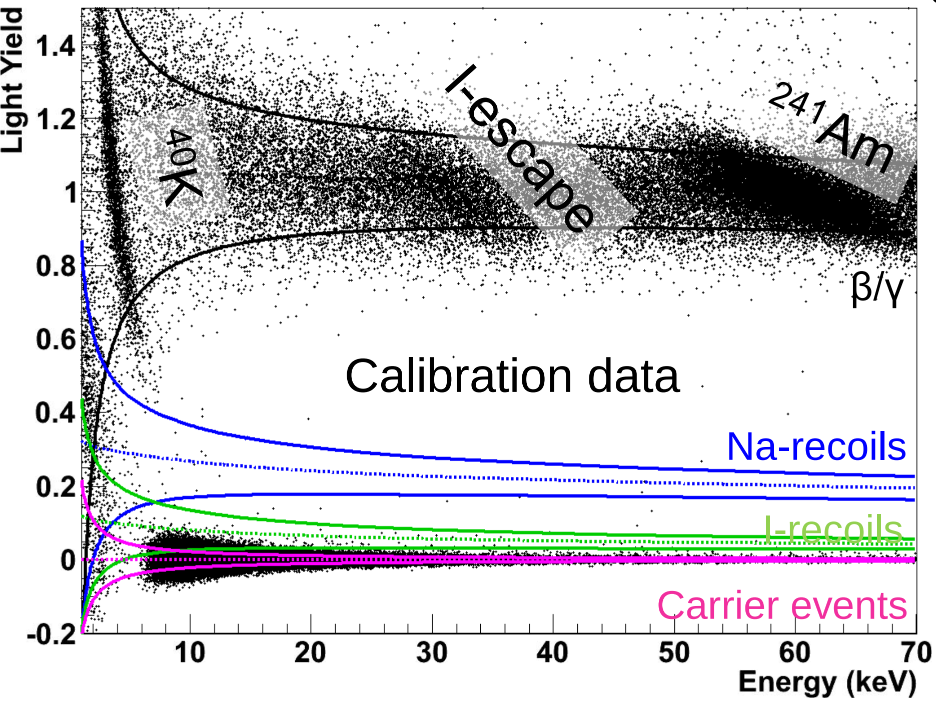
Courtesy of Y. Takemoto / PICOLON (Slides from TAUP2017)

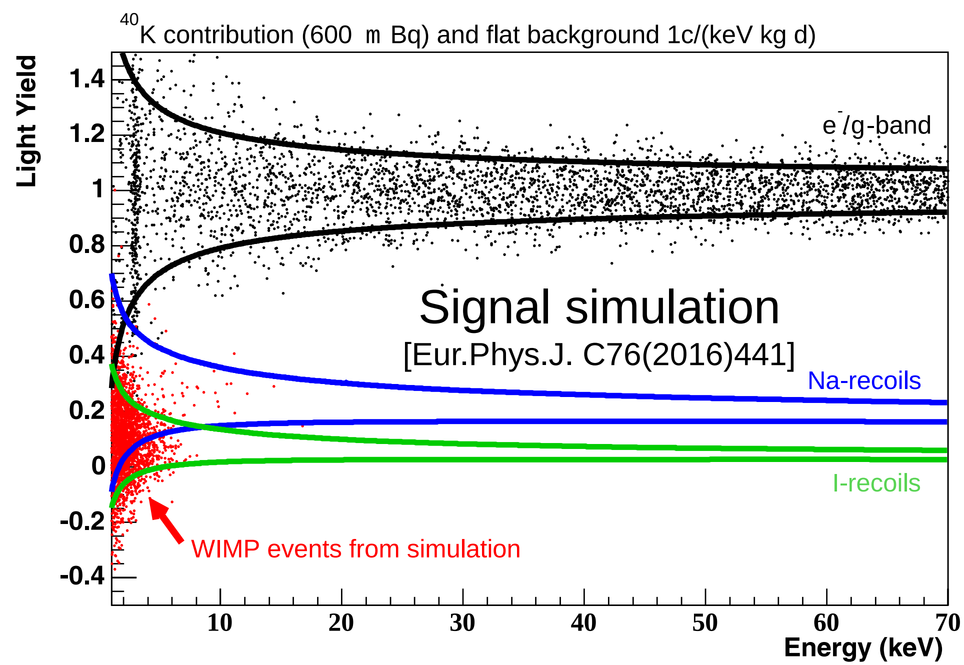


COSINUS



- Proof-of-principle @ LNGS
- Successfully run: 66g NaI @ O(10)mK
- Discriminate between nucl. and e- recoil
- Next: quenching factor measurements; crystals from Astrograde-powder (~4ppb ^{40}K); test NaI(Tl)
- COSINUS-1π: O(100 kg.d) to see DAMA-like nuclear recoils signal





Courtesy of F. Reindl / COSINUS (Slides from TAUP2017)

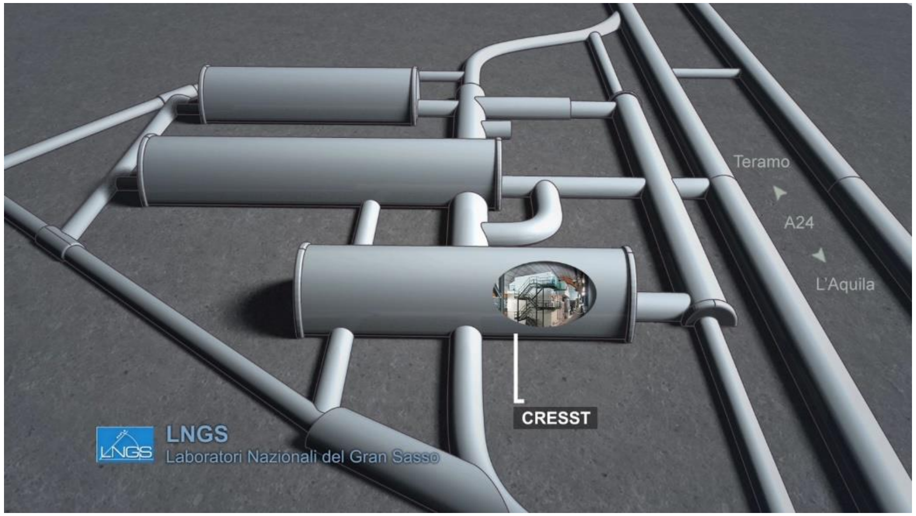
DAMA-like: 10GeV/c², $2 \cdot 10^{-4}$pb [Savage et al.]

Summary

- **Solid state experiment** are multi-purpose tools: sensitive to dark photons, SIMPs (at surface), CNNS (in the future), …
- **DM-nucleon scattering:** solid state experiments are exploring the parameter space well below 1 GeV/c^2 (CRESST down to 350MeV/c^2) or plan to do so in the near future (EDELWEISS, SuperCDMS, DAMIC).
- **DM-electron scattering:** extend sensitivity down to sub MeV-scale (SENSEI).
- DAMA/LIBRA-phase 2 increased the significance of the observed **annual modulation** to 12.9σ. Several experiments are taking data (ANAIS, COSINE-100) or plan to do so to test the DAMA/LIBRA result in a model-independent way.

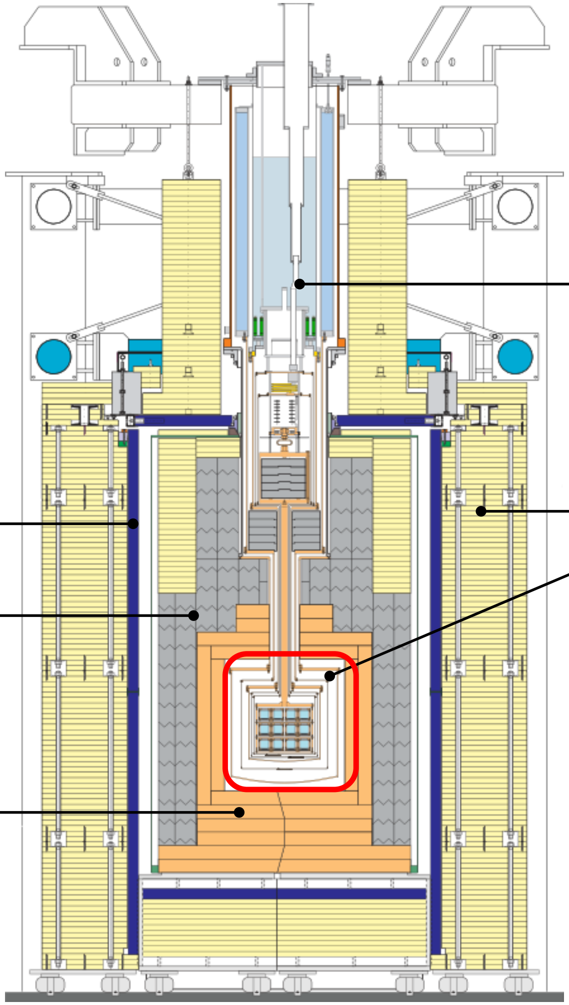
Additional slides

The CRESST experiment



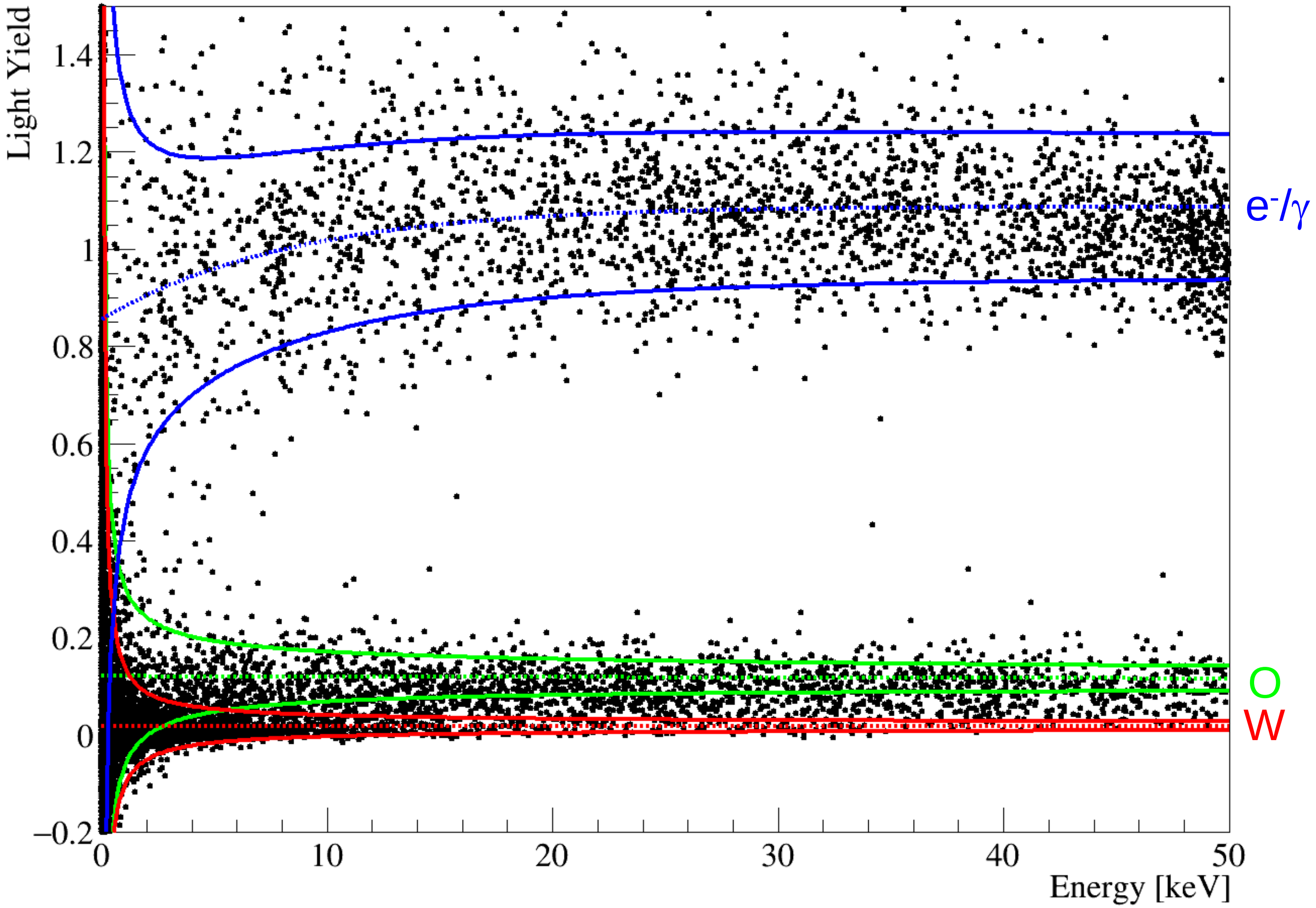
Located in Italy,
under the Gran Sasso mountain,
at the LNGS @ ~3600mwe

μ's $\sim 3 \cdot 10^{-8}\ \mathrm{s}^{-1}\mathrm{cm}^{-2}$
γ's $\sim 7 \cdot 10^{-1}\ \mathrm{s}^{-1}\mathrm{cm}^{-2}$
n's $\sim 4 \cdot 10^{-6}\ \mathrm{s}^{-1}\mathrm{cm}^{-2}$



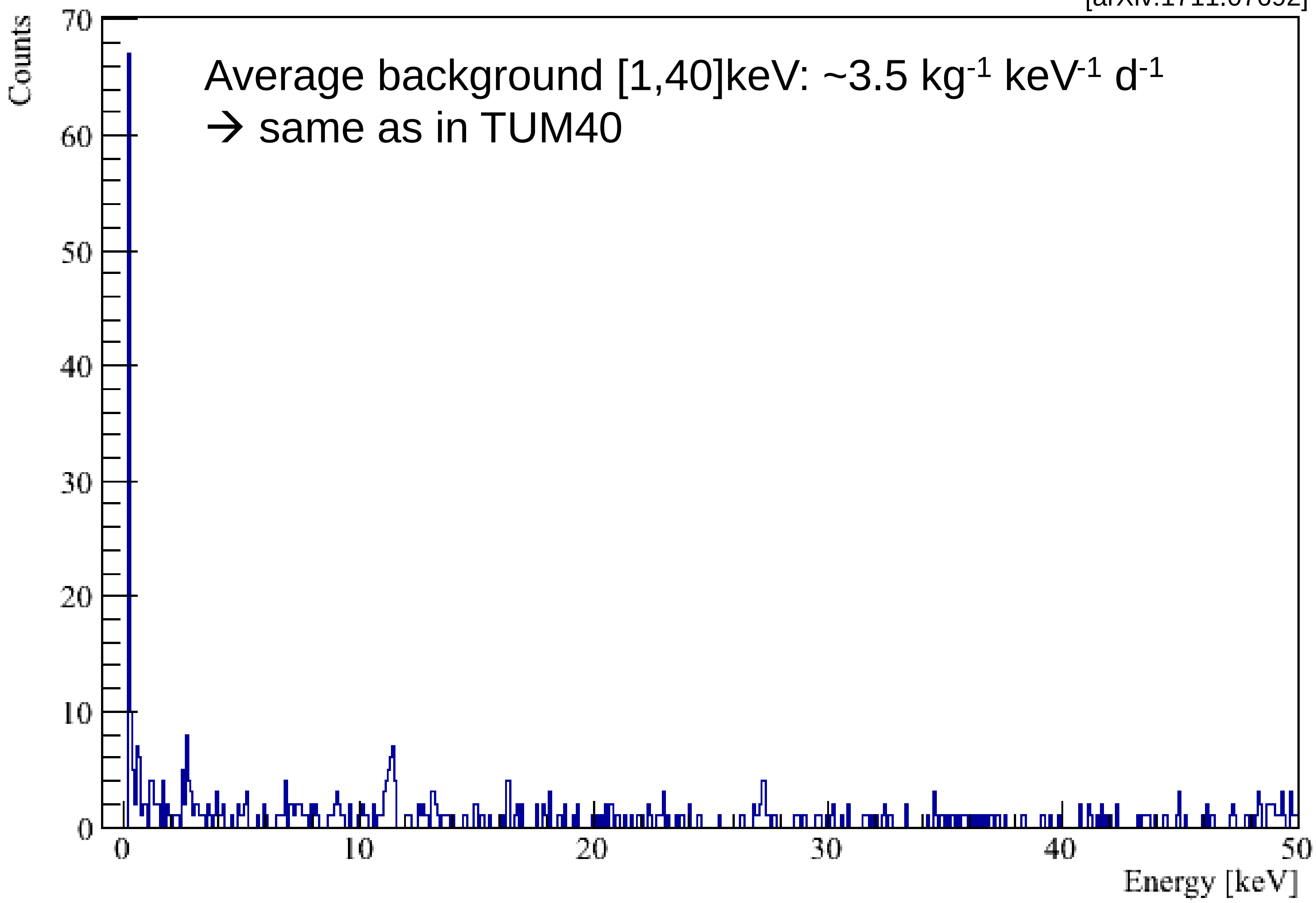
Max-Planck-Institut für Physik

Detector A: neutron calibration

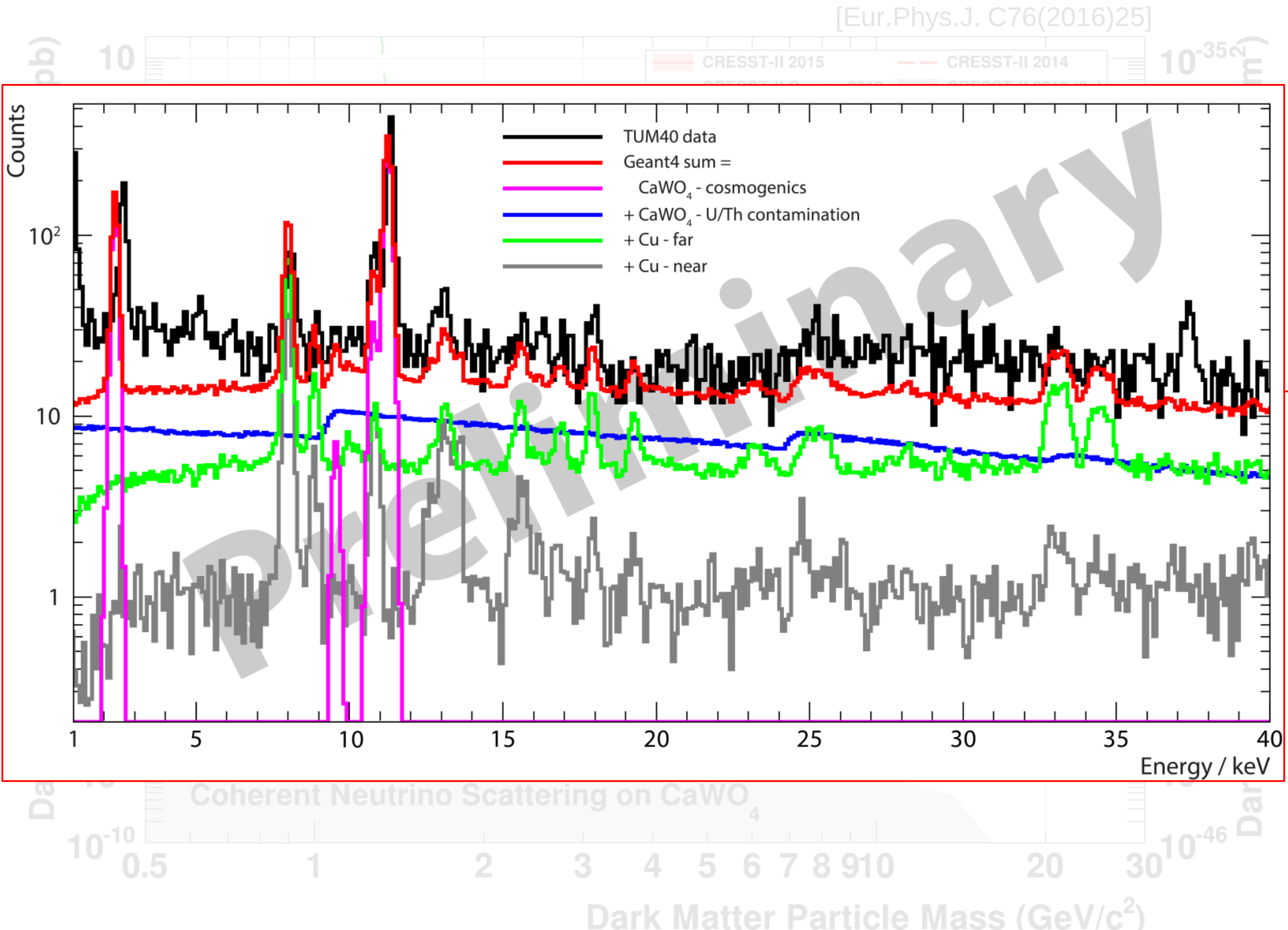


Detector A: energy spectrum

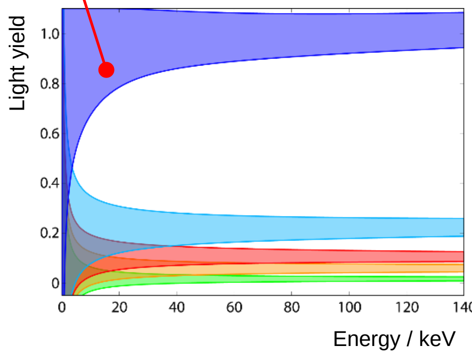
[arXiv:1711.07692]



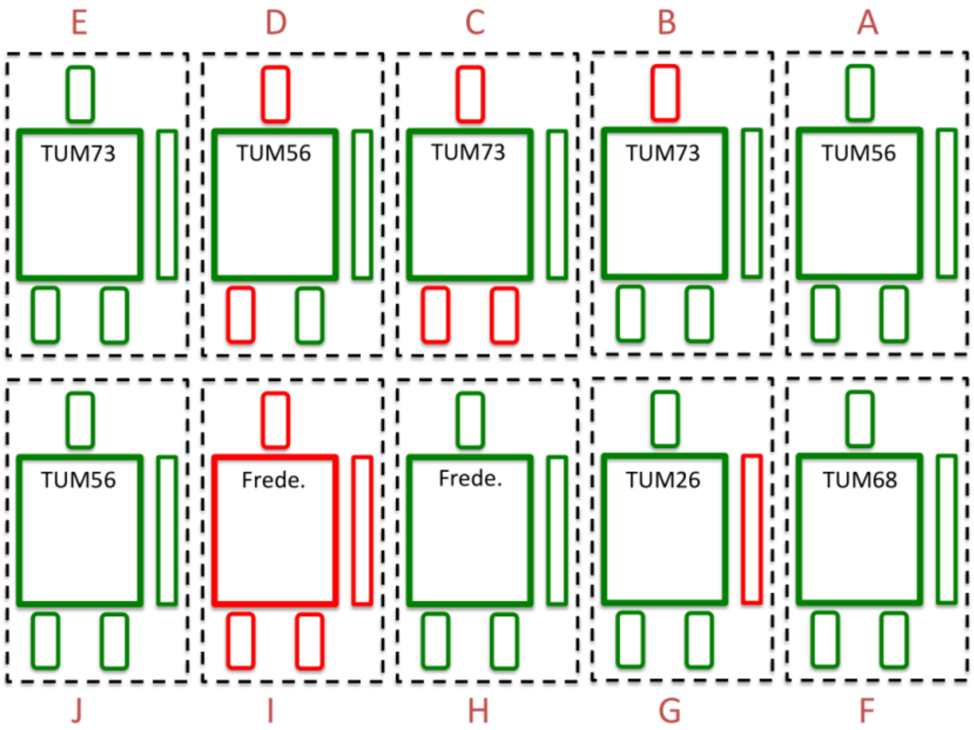
Results of CRESST-II phase 2



- TUM40: successfully reduced intrinsic background
- Ongoing modelling of em. background with Geant4



CRESST-III: detectors



- G-LD: no transition
- I-all: no transitions
- B- one iStick : heater broken cannot be operated
- C and D - iStick system: working, but introduces strong noise on phonon channel

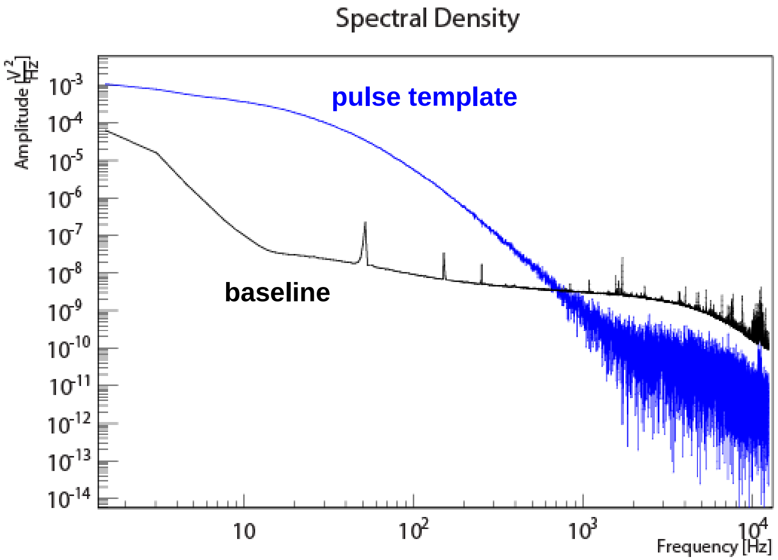
6/50 TES not working (including the 5 of detector I)

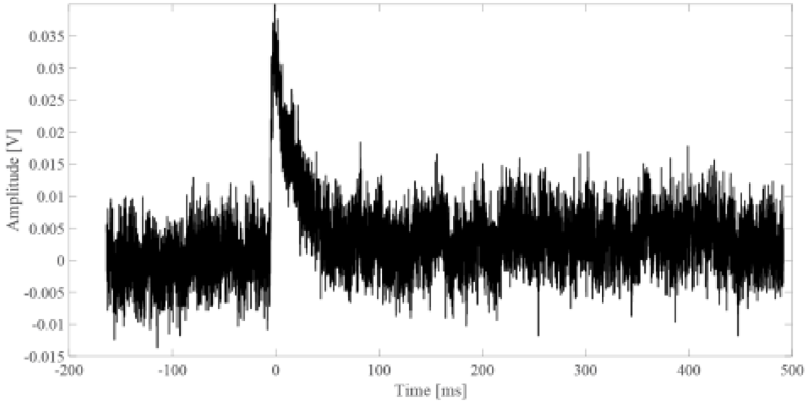
- The wiring is >10 years old
- A TES is a sensitive but challenging device

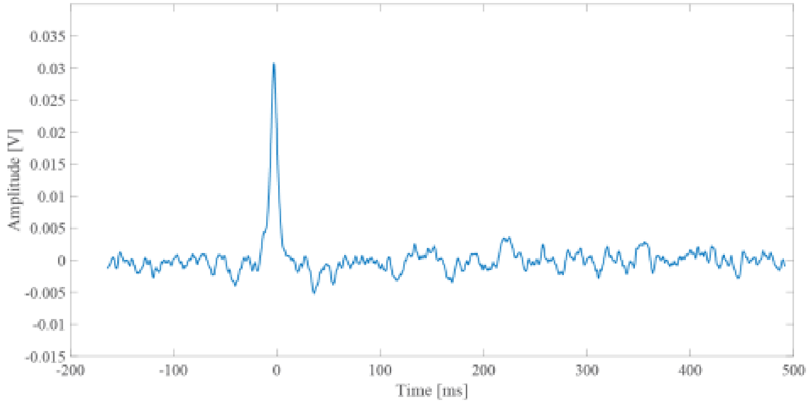
Optimum filter

Pulse-height evaluation
with optimum filter:

The Gatti-Manfredi filter maximize the ratio between the amplitude of the treated pulse and the noise RMS





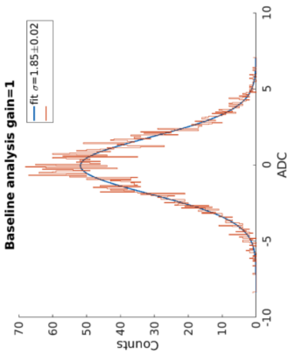


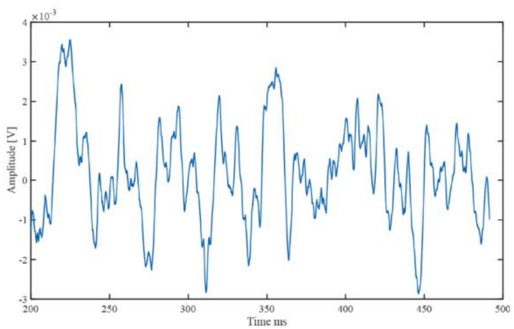
Resolution typically improved by factor 2 to 3

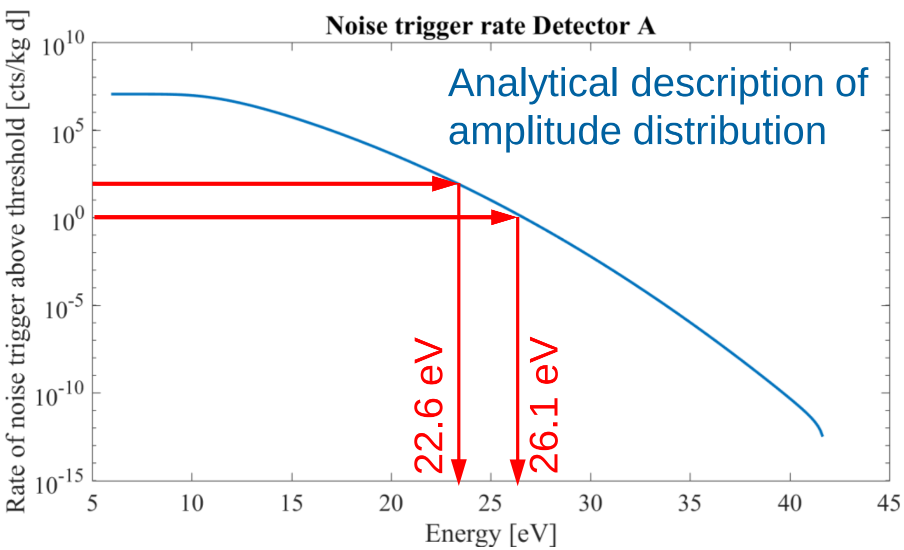
Threshold

- New DAQ in CRESST-III:
  continuous sampling of pulse traces
- Set threshold based on noise distribution after optimum filter

Amplitude distribution of a typical **empty base line pulse trace**



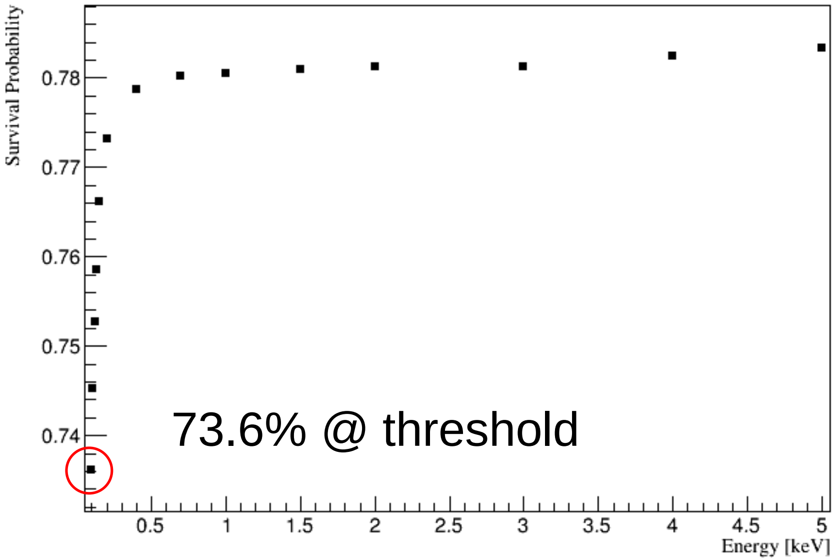




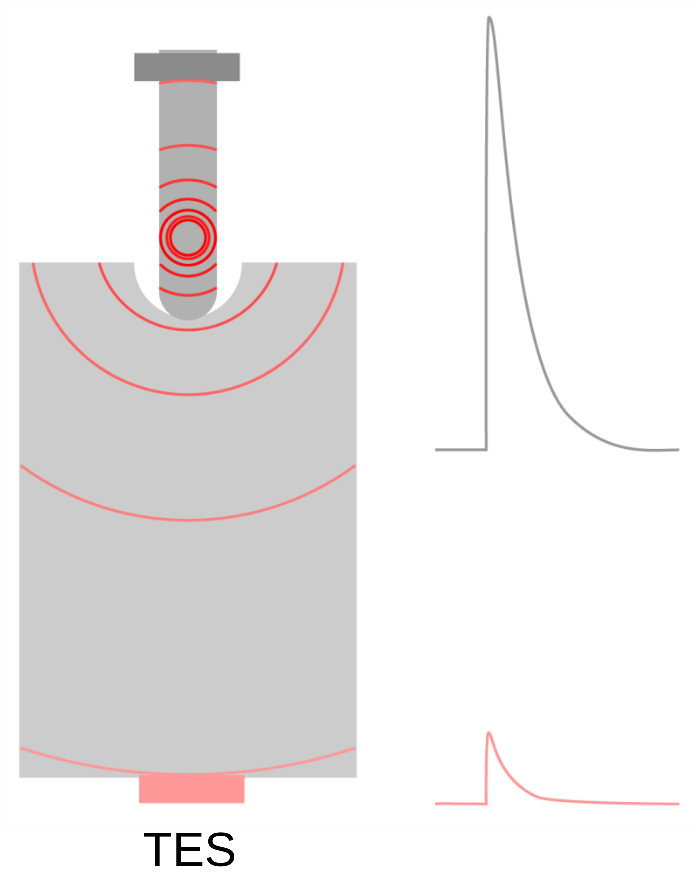
Detector A: selections & efficiencies

Remove pulses where a correct determination of the amplitude is not guaranteed. Designed on non blind data (20% of physics data randomly selected) not included in the final exposure

- Data quality
  events which cannot properly be analyzed
- Pulse shape
  e.g. events in iSticks, pileup
- Coincidences
  here: only with muon veto and iSticks

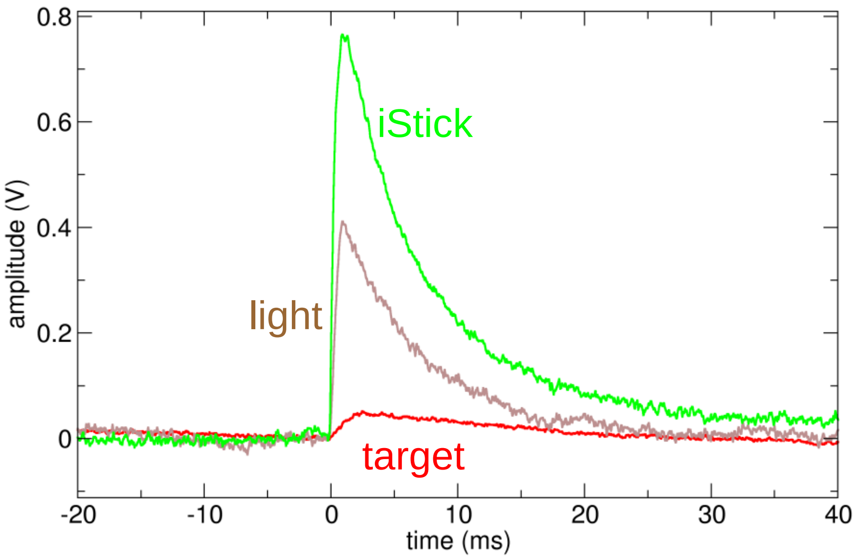


Holder-related backgrounds



- Target is held by $CaWO_4$ sticks
- Event in stick: surface background, relaxation, …
- Signal in instrumented stick (iStick)
- Degraded signal in target

Holder-related backgrounds

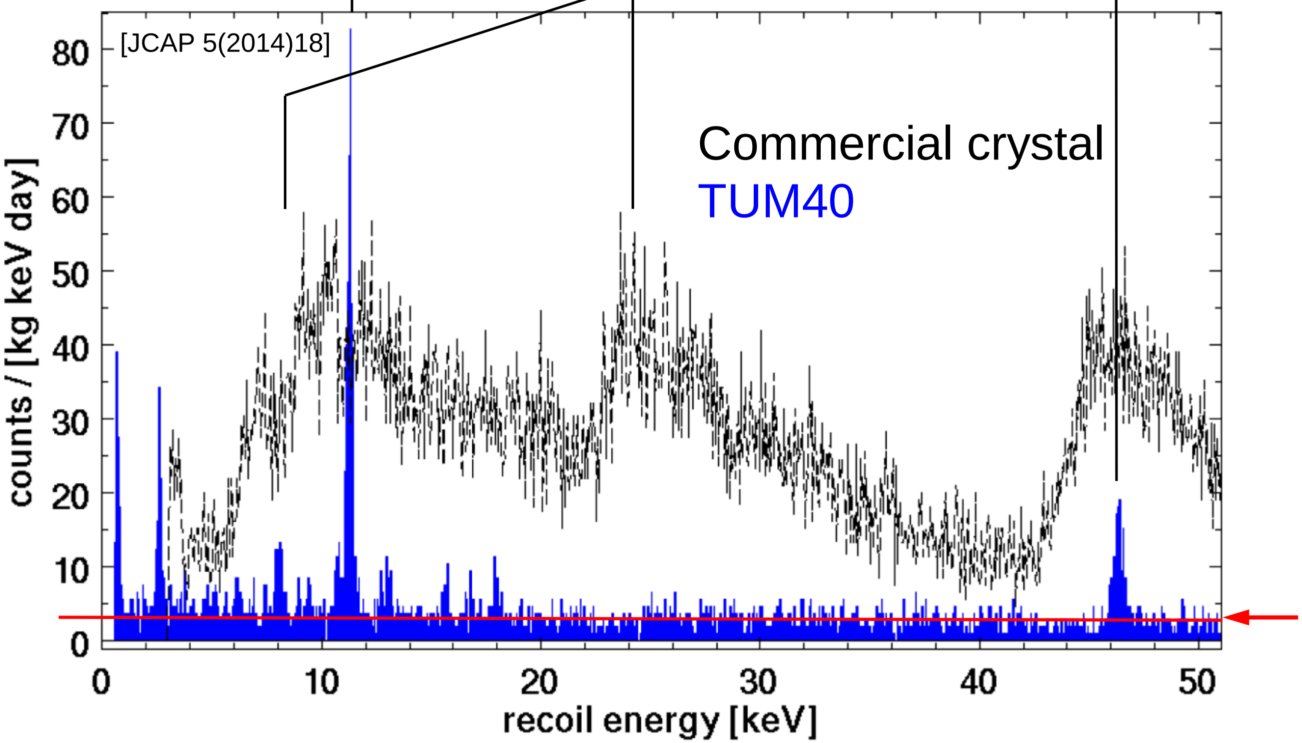


- Target is held by $CaWO_4$ sticks
- Event in stick: surface background, relaxation, …
- Signal in instrumented stick (iStick)
- Degraded signal in target

➔iStick/target is a powerful tool to reject holder-related backgrounds

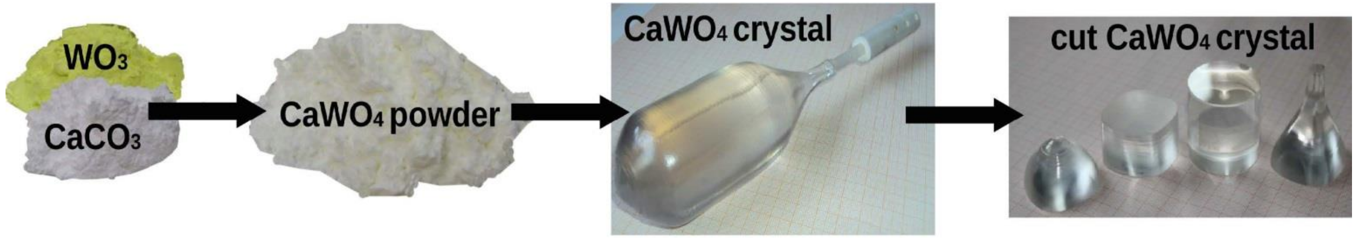
'TUM40' radiopurity

- $CaWO_4$ crystal production at TU Munich
- TUM40: radiopurity improved by factor 2-10

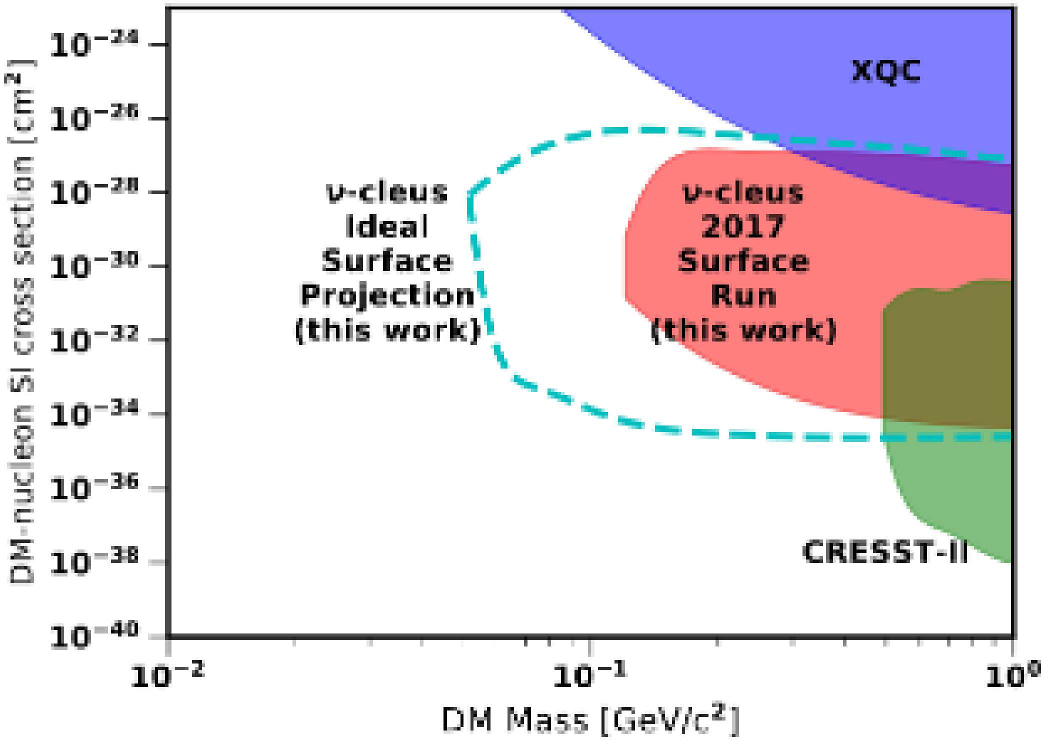


Going beyond 'TUM40' radiopurity

- Cleaning procedure e.g. by re-crystallization, chemical purification of raw materials
- Recently: First steps in chemical purification of $CaCO_3$ powder.
  work by H.H. Trinh Thi, A. Münster, A. Erb
- Measured contamination decreased by …
  - factor 2-7 for Th
  - factor 15-35 for U



CRESST/nu-cleus

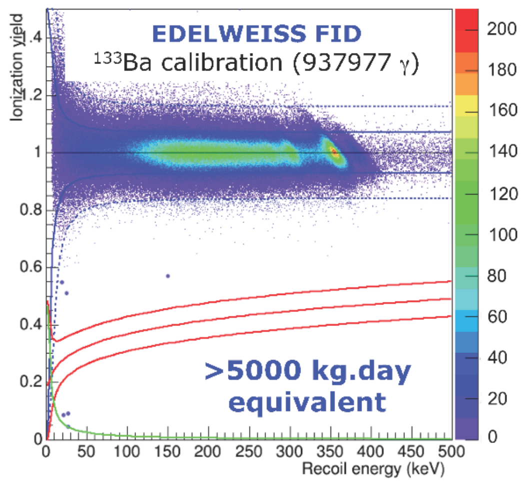


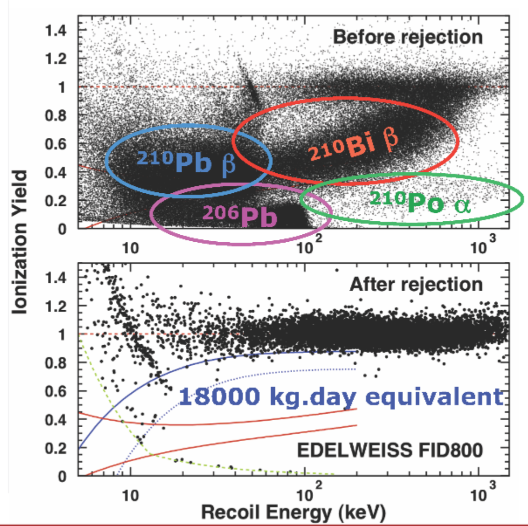
[J.H. Davis Phys.Rev.Lett. 119(2017)211302, arXiv:1708.01484]

EDELWEISS

Gamma rejection & Surface rejection

- Rejection tested with >5000 kgd equivalent samples *[arXiv:1706.01070]*
- γ rejection factor: < 2.5 x 10^{-6}
- Surface evts rejection (^{210}Pb+^{210}Bi β, ^{210}Po α, ^{206}Pb recoils): < 4 x 10^{-5}





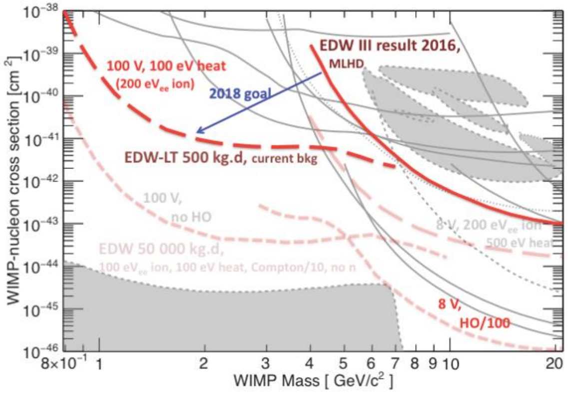
July 24th, 2017 EDELWEISS @ TAUP2017 6

Courtesy of J. Gascon / EDELWEISS (Slides from TAUP 2017)

EDELWEISS

EDELWEISS-LT: Heat-only background

- Standard signals on both NTDs but none on any electrodes
- Many studied hypotheses, none conclusive so far
  - Noise, cryogenics, stress from detector suspension or from glueing, natural radioactivity...
- New detector configurations being tested to study these hypotheses
  - Deported NTD glued on separate sapphire wafer
  - Photolithographed high-impedance NbSi TES sensitive to athermal phonons
- **Dominant at low energy, but sufficiently reproducible for analysis of present 100V data**
  & for EDELWEISS-LT: operation of 4x870g at 100V for 150 days in current LSM backgrounds



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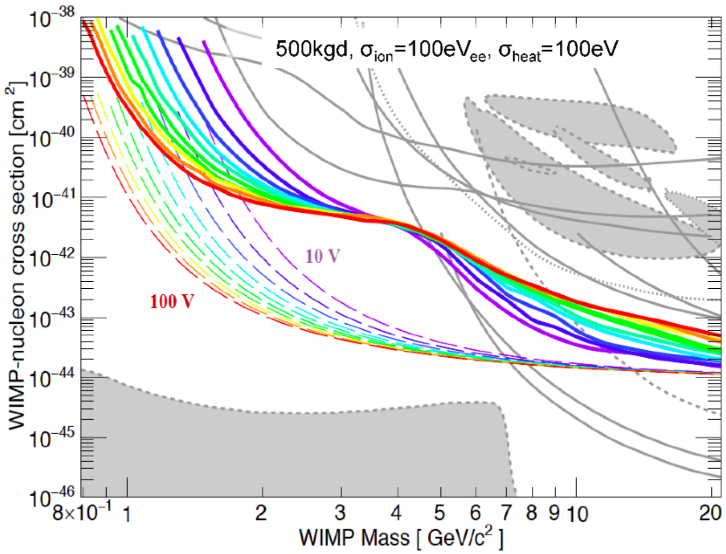
Courtesy of J. Gascon / EDELWEISS (Slides from TAUP 2017)

EDELWEISS

EDELWEISS proj. for different voltages

KIT Karlsruhe Institute of Technology



Phys.Rev.D97,022003(2018)

- Heat signal boosted by Luke effect:
  - ~Joule heating, factor [1+V_{bias}/3]
- Loss of ionization-based bkg discrimination:
  - method benefits low-mass searches only
  - 10^{-41} cm^2 with 500 kgd and current bkgs
- 100 V bias already achieved
- Observe nuclear recoils down to ~0.1 keV$_{ee}$

25 Bernhard Siebenborn EDELWEISS Dark Matter search

Courtesy of B. Siebenborn / EDELWEISS (Slides from UCLA DM2018)

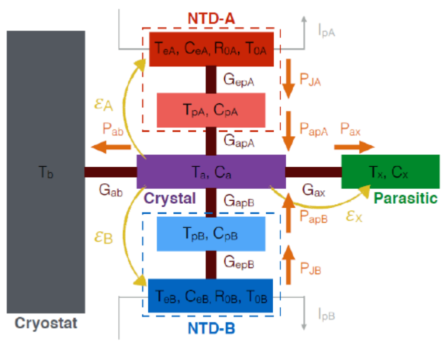
EDELWEISS

Detector R&D: Thermal model & heat sensor

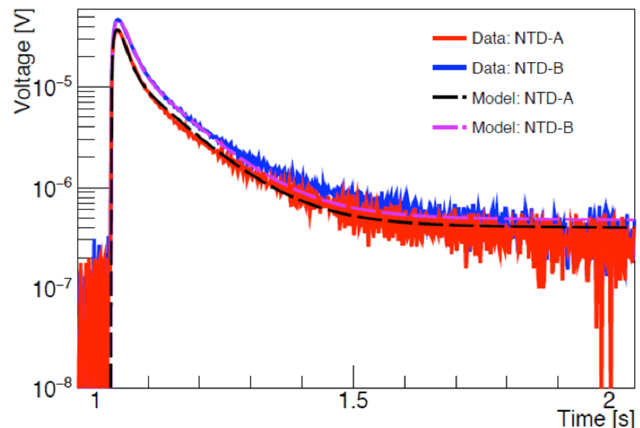
KIT Karlsruhe Institute of Technology

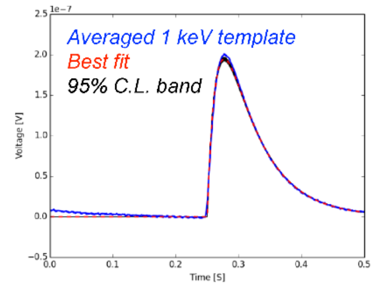
J. Billard et al., JLTP(2016)184:299

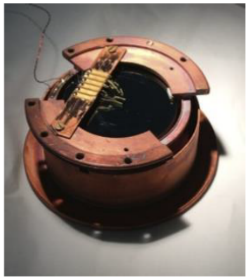
- Better understanding of heat signal
  - Thermal modeling of signal, verified with dedicated R&D
  - Identification of sensitivity to ballistic phonons
  - Identification of parasitic heat capacity



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







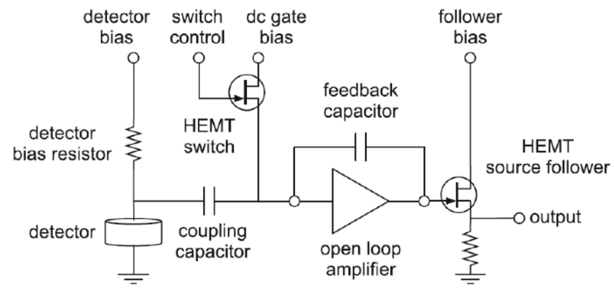
16 Bernhard Siebenborn EDELWEISS Dark Matter search

Courtesy of B. Siebenborn / EDELWEISS (Slides from UCLA DM2018)

EDELWEISS

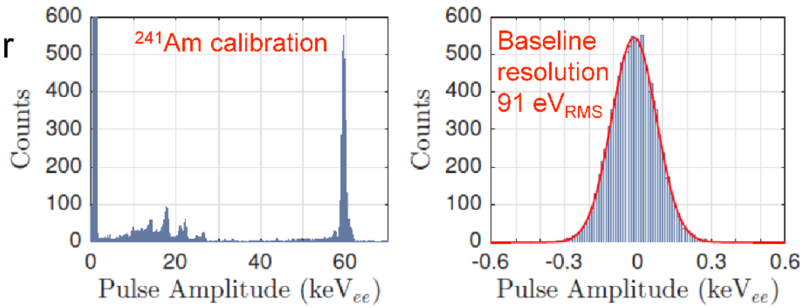
Detector R&D: HEMT read out

- JFET → HEMT
  - Reduced intrinsic noise
  - Lower heat load
  - Operates at 4K stage
    - →shorter cabling
    - Reduced capacitance
    - Better SNR



- Successful HEMT amplifier with sub-100 eV_{RMS} ionization resolution

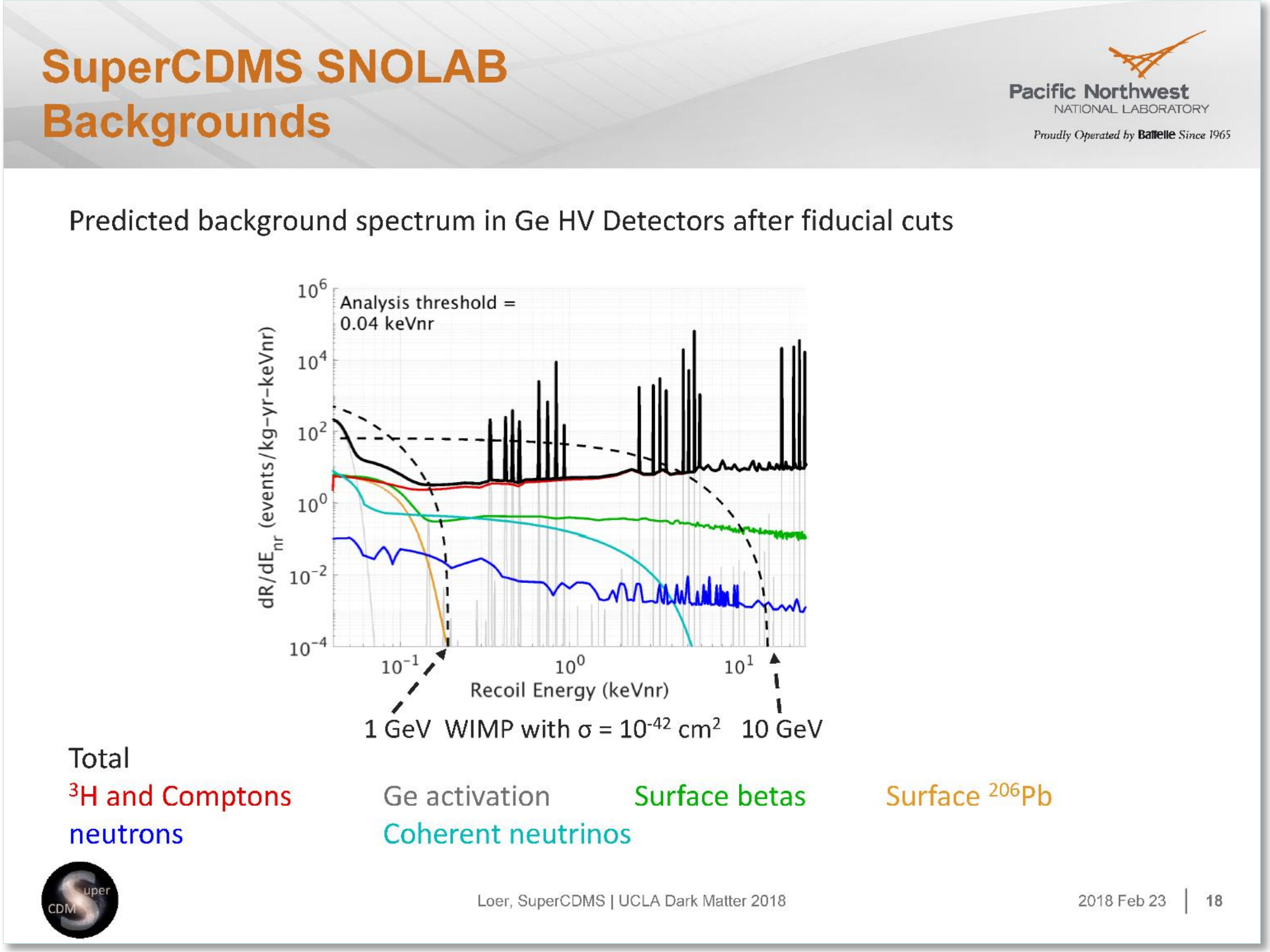
A. Phipps et al., JLTP(2016)184:505
collaboration between SuperCDMS and EDELWEISS



17 Bernhard Siebenborn EDELWEISS Dark Matter search

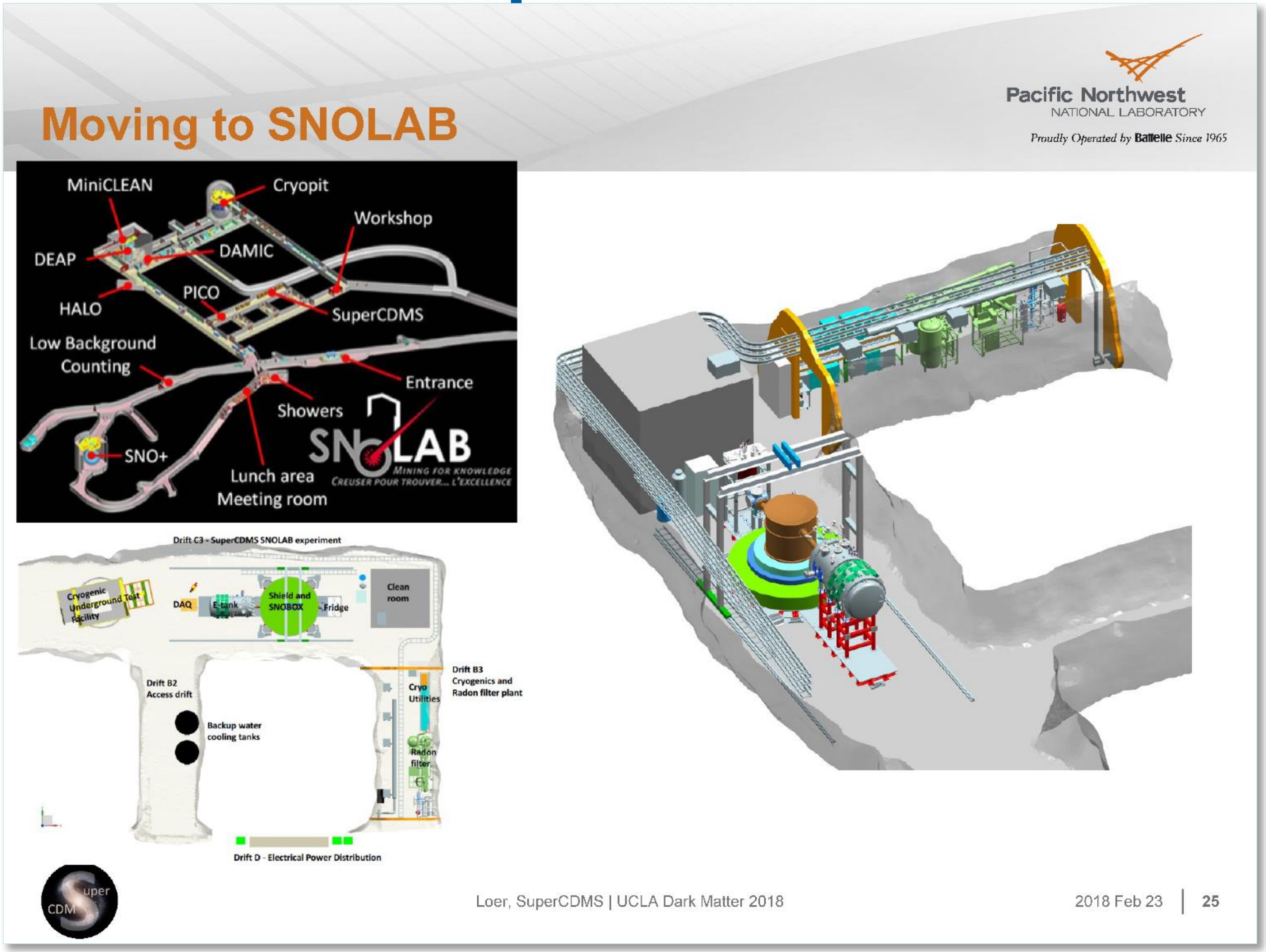
Courtesy of B. Siebenborn / EDELWEISS (Slides from UCLA DM2018)

SuperCDMS



Courtesy of B. Loer / SuperCDMS (Slides from UCLA DM2018)

SuperCDMS



Courtesy of B. Loer / SuperCDMS (Slides from UCLA DM2018)

SENSEI

dark current

	dark current [e^-/pix/day]	$\geq 1e^-$ [pix]	$\geq 2e^-$ [pix]	$\geq 3e^-$ [pix]
measured → [arXiv:1611.03066]	10^{-3}	1×10^{8}	3×10^{3}	7×10^{-2}
	10^{-5}	1×10^{6}	3×10^{-1}	7×10^{-8}
theory prediction →	10^{-7}	1×10^{4}	3×10^{-5}	7×10^{-14}

SENSEI with a 2-electron threshold is a zero-background experiment!

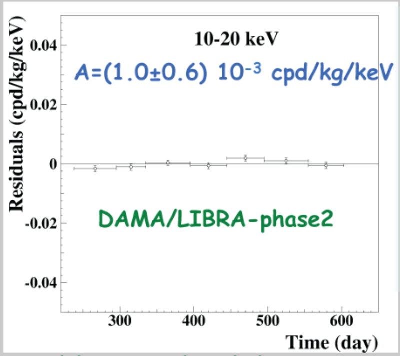
12

Courtesy of T.-T. Yu / SENSEI (Slides from UCLA DM2018)

DAMA/LIBRA

Rate behaviour above 6 keV

- No Modulation above 6 keV



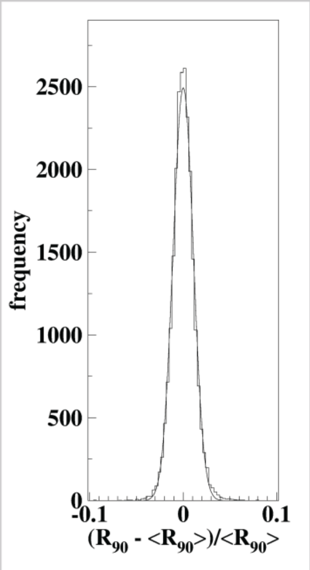
Mod. Ampl. (6-14 keV): cpd/kg/keV
(0.0032 ± 0.0017) DAMA/LIBRA-ph2_2
(0.0016 ± 0.0017) DAMA/LIBRA-ph2_3
(0.0024 ± 0.0015) DAMA/LIBRA-ph2_4
-(0.0004 ± 0.0015) DAMA/LIBRA-ph2_5
(0.0001 ± 0.0015) DAMA/LIBRA-ph2_6
(0.0015 ± 0.0014) DAMA/LIBRA-ph2_7
→ statistically consistent with zero

- No modulation in the whole energy spectrum: studying integral rate at higher energy, R_{90}
- R_{90} percentage variations with respect to their mean values for single crystal in the DAMA/LIBRA running periods
- Fitting the behaviour with time, adding a term modulated with period and phase as expected for DM particles:

consistent with zero

Period	Mod. Ampl.
DAMA/LIBRA-ph2_2	(0.12±0.14) cpd/kg
DAMA/LIBRA-ph2_3	-(0.08±0.14) cpd/kg
DAMA/LIBRA-ph2_4	(0.07±0.15) cpd/kg
DAMA/LIBRA-ph2_5	-(0.05±0.14) cpd/kg
DAMA/LIBRA-ph2_6	(0.03±0.13) cpd/kg
DAMA/LIBRA-ph2_7	-(0.09±0.14) cpd/kg

DAMA/LIBRA-phase2



σ ≈ 1%, fully accounted by statistical considerations

\+ if a modulation present in the whole energy spectrum at the level found in the lowest energy region → R_{90} ~ tens cpd/kg → ~ 100 σ far away

No modulation above 6 keV
This accounts for all sources of bckg and is consistent with the studies on the various components

Courtesy of R. Bernabei / DAMA (Slides from CSLNGS March 26, 2018)

DAMA/LIBRA

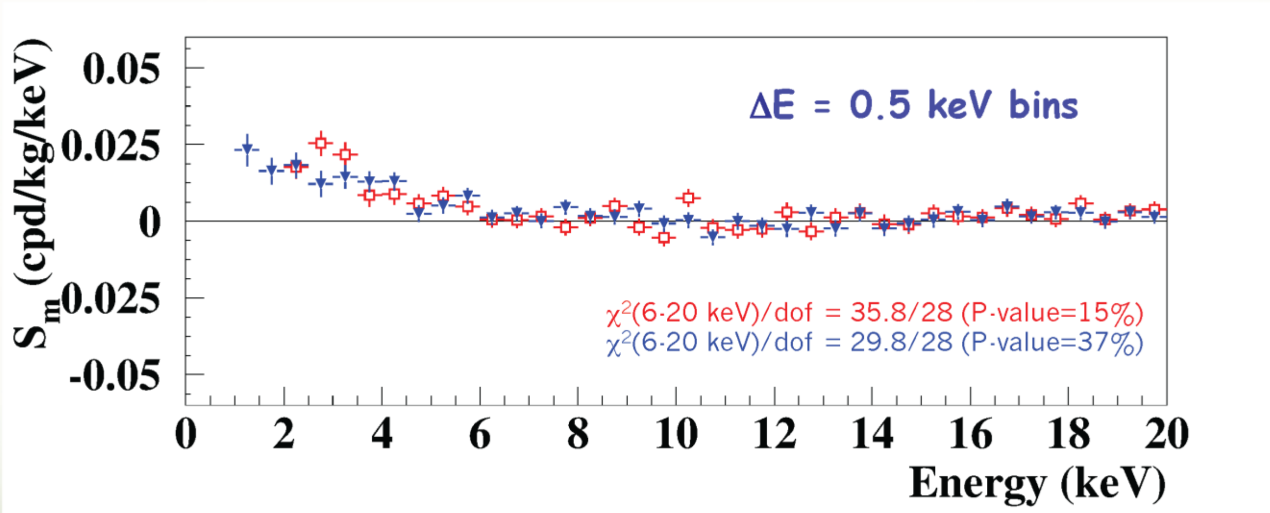
Energy distribution of the modulation amplitudes

Max-likelihod analysis

$$R(t) = S_0 + S_m \cos\left[\omega\left(t - t_0\right)\right]$$

here $T=2\pi/\omega=1$ yr and $t_0= 152.5$ day

DAMA/NaI + DAMA/LIBRA-phase1
vs
DAMA/LIBRA-phase2



The S_m energy distributions obtained in DAMA/NaI+DAMA/LIBRA-ph1 and in DAMA/LIBRA-ph2 are consistent in the (2–20) keV energy interval:

$\chi^2 = \Sigma\,(r_1 - r_2)^2/(\sigma_1^2+\sigma_2^2)$

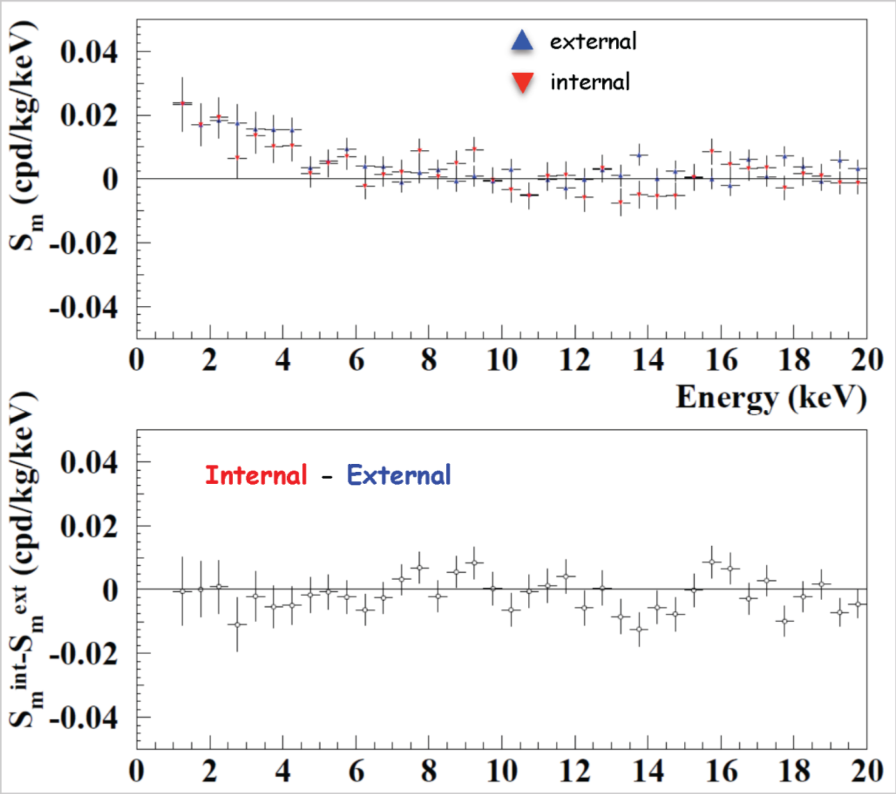
(2-20) keV	χ^2 /d.o.f.=32.7/36	(P=63%)
(2-6) keV	χ^2 /d.o.f.=10.7/8	(P=22%)

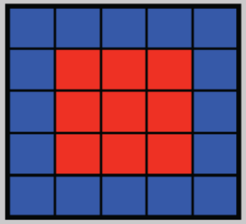
Courtesy of R. Bernabei / DAMA (Slides from CSLNGS March 26, 2018)

DAMA/LIBRA

External vs internal detectors: **DAMA/LIBRA-phase2**

ΔE=0.5 keV





χ^2-Test

1-4 keV χ^2/dof =2.5/6

1-10 keV χ^2/dof =12.1/8

1-20 keV χ^2/dof =40.8/38

Courtesy of R. Bernabei / DAMA (Slides from CSLNGS March 26, 2018)

DAMA/LIBRA

Stability parameters of DAMA/LIBRA-phase2

Modulation amplitudes obtained by fitting the time behaviours of main running parameters, acquired with the production data, when including a DM-like modulation

Running conditions stable at a level better than 1% also in the new running periods

	DAMA/LIBRA-phase2_2	DAMA/LIBRA-phase2_3	DAMA/LIBRA-phase2_4	DAMA/LIBRA-phase2_5	DAMA/LIBRA-phase2_6	DAMA/LIBRA-phase2_7
Temperature (°C)	(0.0012 ± 0.0051)	-(0.0002 ± 0.0049)	-(0.0003 ± 0.0031)	(0.0009 ± 0.0050)	(0.0018 ± 0.0036)	-(0.0006 ± 0.0035)
Flux N_2 (l/h)	-(0.15 ± 0.18)	-(0.02 ± 0.22)	-(0.02 ± 0.12)	-(0.02 ± 0.14)	-(0.01 ± 0.10)	-(0.01 ± 0.16)
Pressure (mbar)	$(1.1 \pm 0.9)\times10^{-3}$	$(0.2 \pm 1.1)\ )\times10^{-3}$	$(2.4 \pm 5.4)\times10^{-3}$	$(0.6 \pm 6.2)\times10^{-3}$	$(1.5 \pm 6.3)\times10^{-3}$	$(7.2 \pm 8.6)\times10^{-3}$
Radon (Bq/m^3)	(0.015 ± 0.034)	-(0.002 ± 0.050)	-(0.009 ± 0.028)	-(0.044 ± 0.050)	(0.082 ± 0.086)	(0.06 ± 0.11)
Hardware rate above single ph.e. (Hz)	$-(0.12 \pm 0.16)\times10^{-2}$	$(0.00 \pm 0.12)\times10^{-2}$	$-(0.14 \pm 0.22)\times10^{-2}$	$-(0.05 \pm 0.22)\times10^{-2}$	$-(0.06 \pm 0.16)\times10^{-2}$	$-(0.08 \pm 0.17)\times10^{-2}$

All the measured amplitudes well compatible with zero
+ none can account for the observed effect
(to mimic such signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also simultaneously satisfy all the 6 requirements)

Courtesy of R. Bernabei / DAMA (Slides from CSLNGS March 26, 2018)

DAMA/LIBRA

- Contributions to the total neutron flux at LNGS;
- Counting rate in DAMA/LIBRA for *single-hit* events, in the (2 – 6) keV energy region induced by:
  - neutrons,
  - muons,
  - solar neutrinos.

$$\Phi_k = \Phi_{0,k}\left(1 + \eta_k cos\omega\left(t - t_k\right)\right)$$
$$R_k = R_{0,k}\left(1 + \eta_k cos\omega\left(t - t_k\right)\right)$$

(See e.g. also EPJC 56 (2008) 333, EPJC 72(2012) 2064, IJMPA 28 (2013) 1330022)

EPJC74(2014)3196

Modulation amplitudes

Source		$\Phi^{(n)}_{0,k}$ (neutrons cm^{-2} s^{-1})	η_k	t_k	$R_{0,k}$ (cpd/kg/keV)		$A_k = R_{0,k}\eta_k$ (cpd/kg/keV)	A_k/S_m^{exp}
SLOW neutrons	thermal n ($10^{-2} - 10^{-1}$ eV)	1.08×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 8 \times 10^{-6}$	[2, 7, 8]	$\ll 8 \times 10^{-7}$	$\ll 7 \times 10^{-5}$
	epithermal n (eV-keV)	2×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 3 \times 10^{-3}$	[2, 7, 8]	$\ll 3 \times 10^{-4}$	$\ll 0.03$
FAST neutrons	fission, $(\alpha, n) \to$ n (1-10 MeV)	$\simeq 0.9 \times 10^{-7}$ [17]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 6 \times 10^{-4}$	[2, 7, 8]	$\ll 6 \times 10^{-5}$	$\ll 5 \times 10^{-3}$
	$\mu \to$ n from rock (> 10 MeV)	$\simeq 3 \times 10^{-9}$ (see text and ref. [12])	0.0129 [23]	end of June [23, 7, 8]	$\ll 7 \times 10^{-4}$	(see text and [2, 7, 8])	$\ll 9 \times 10^{-6}$	$\ll 8 \times 10^{-4}$
	$\mu \to$ n from Pb shield (> 10 MeV)	$\simeq 6 \times 10^{-9}$ (see footnote 3)	0.0129 [23]	end of June [23, 7, 8]	$\ll 1.4 \times 10^{-3}$	(see text and footnote 3)	$\ll 2 \times 10^{-5}$	$\ll 1.6 \times 10^{-3}$
	$\nu \to$ n (few MeV)	$\simeq 3 \times 10^{-10}$ (see text)	0.03342 *	Jan. 4th *	$\ll 7 \times 10^{-5}$	(see text)	$\ll 2 \times 10^{-6}$	$\ll 2 \times 10^{-4}$
	direct μ	$\Phi^{(\mu)}_0 \simeq 20$ μ $m^{-2}d^{-1}$ [20]	0.0129 [23]	end of June [23, 7, 8]	$\simeq 10^{-7}$	[2, 7, 8]	$\simeq 10^{-9}$	$\simeq 10^{-7}$
	direct ν	$\Phi^{(\nu)}_0 \simeq 6 \times 10^{10}$ ν $cm^{-2}s^{-1}$ [26]	0.03342 *	Jan. 4th *	$\simeq 10^{-5}$	[31]	3×10^{-7}	3×10^{-5}

* The annual modulation of solar neutrino is due to the different Sun-Earth distance along the year; so the relative modulation amplitude is twice the eccentricity of the Earth orbit and the phase is given by the perihelion.

All are negligible w.r.t. the annual modulation amplitude observed by DAMA/LIBRA and they cannot contribute to the observed modulation amplitude.

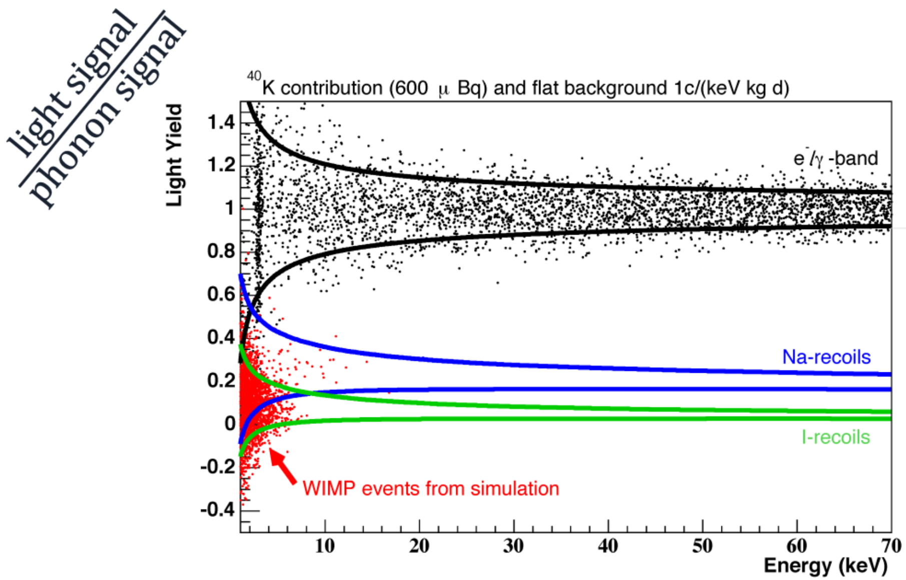
+ In no case neutrons (of whatever origin), muon or muon induced events, solar ν can mimic the DM annual modulation signature since some of the **peculiar requirements of the signature** would fail (and - in addition - quantitatively negligible amplitude with respect to the measured effect).

Courtesy of R. Bernabei / DAMA (Slides from CSLNGS March 26, 2018)

COSINUS

SIMULATION

100 KG-DAYS BEFORE CUTS



WIMP events

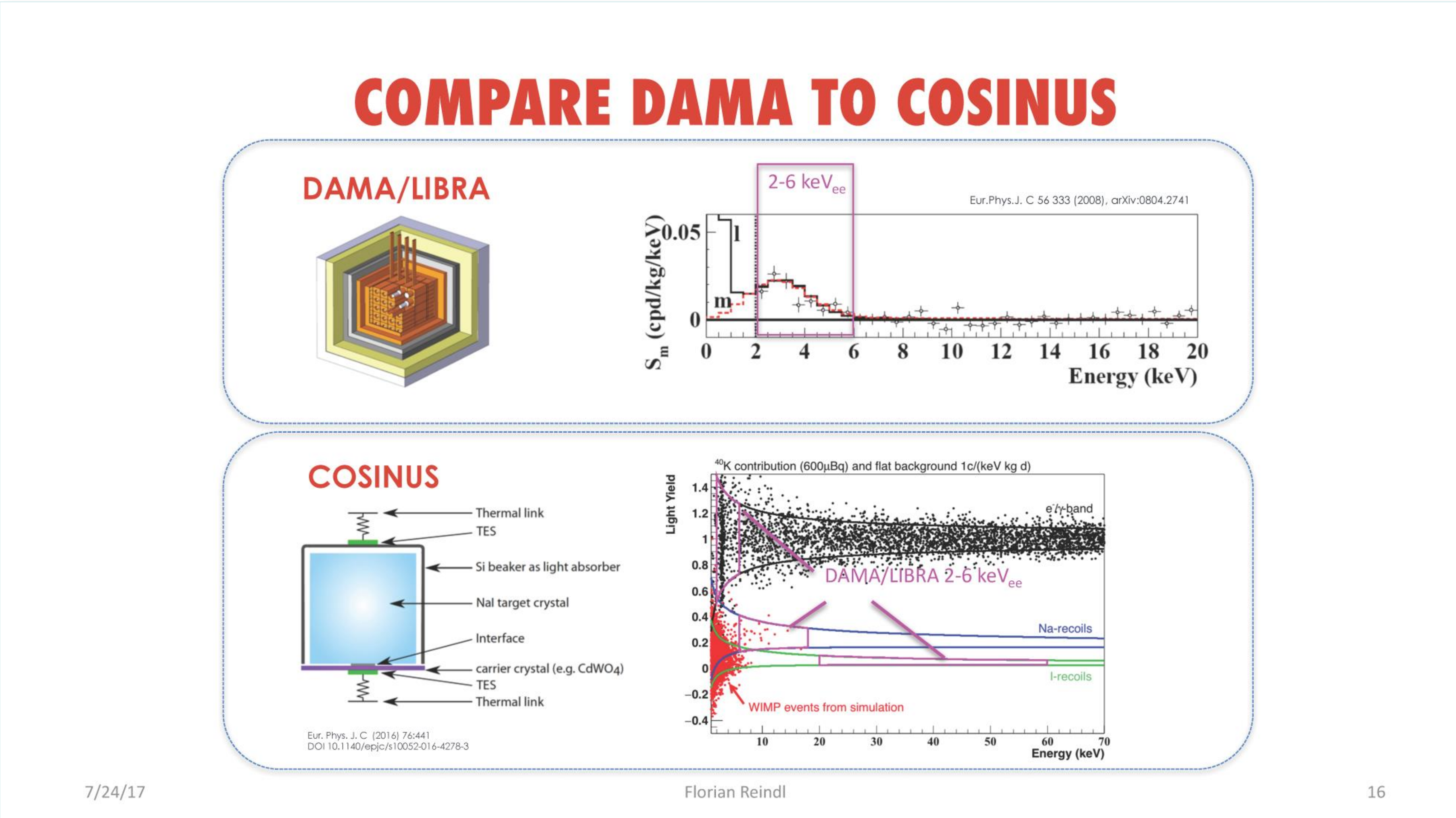
Energy	# Events	Fraction
1-2 keV	1078	45 %
2-6 keV	1262	53 %
> 6 keV	46	2 %
TOTAL	**2386**	**100 %**

Eur. Phys. J. C (2016) 76:441
DOI 10.1140/epjc/s10052-016-4278-3

7/24/17 Florian Reindl 13

Courtesy of F. Reindl / COSINUS (Slides from TAUP DM2017)

COSINUS



Courtesy of F. Reindl / COSINUS (Slides from TAUP DM2017)