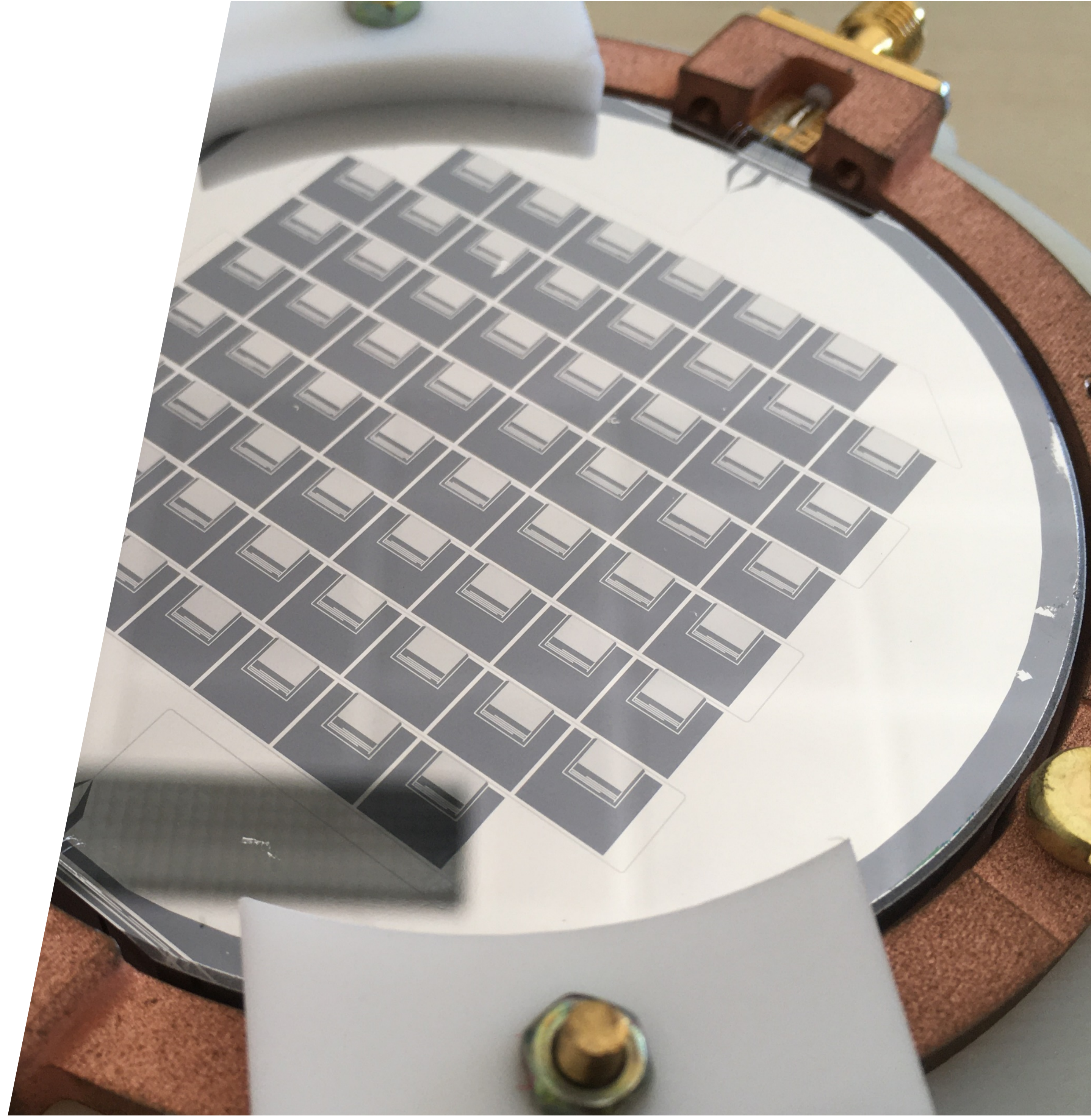
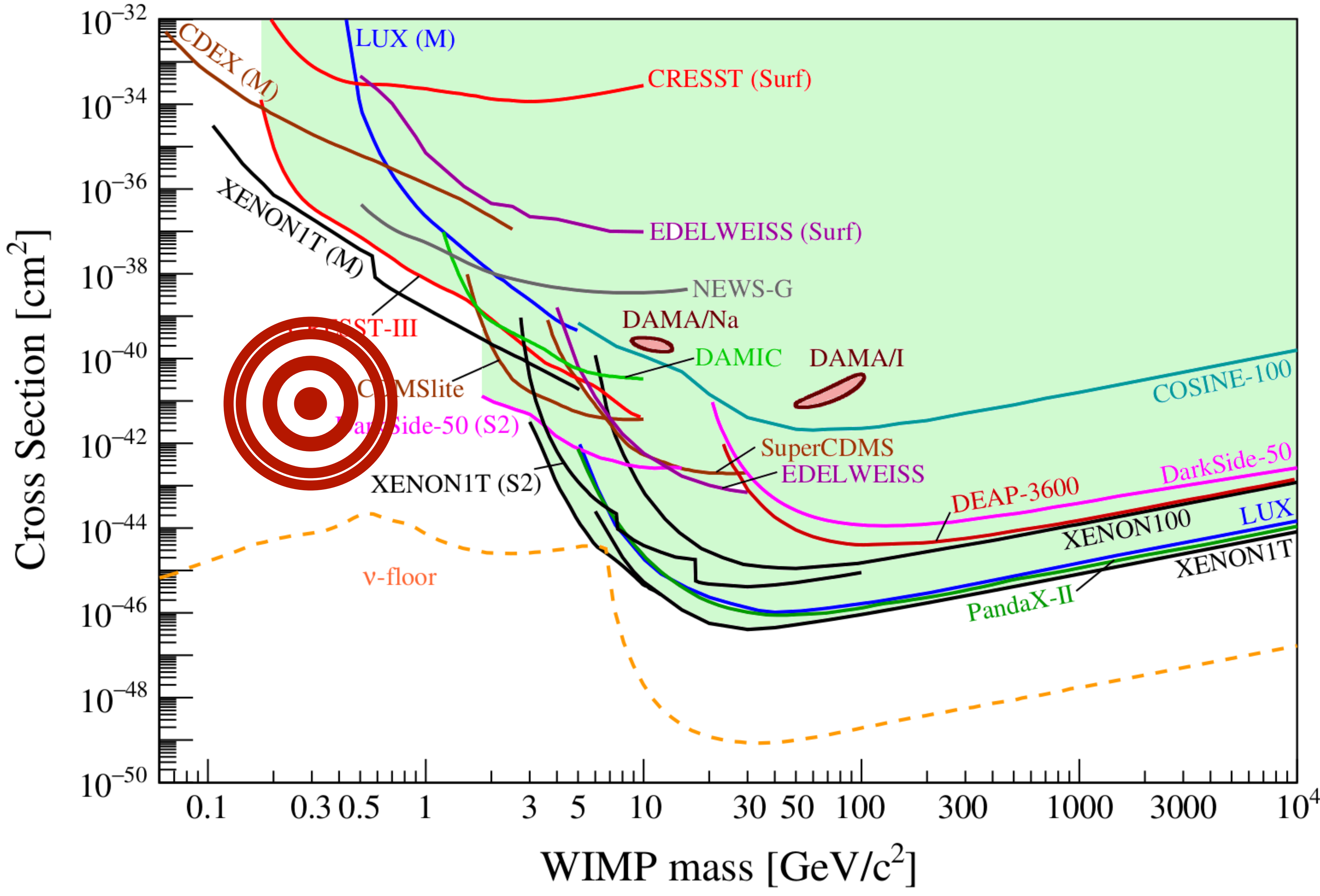
Sapienza Università di Roma
INFN Istituto Nazionale di Fisica Nucleare



Low-mass WIMP Competitors

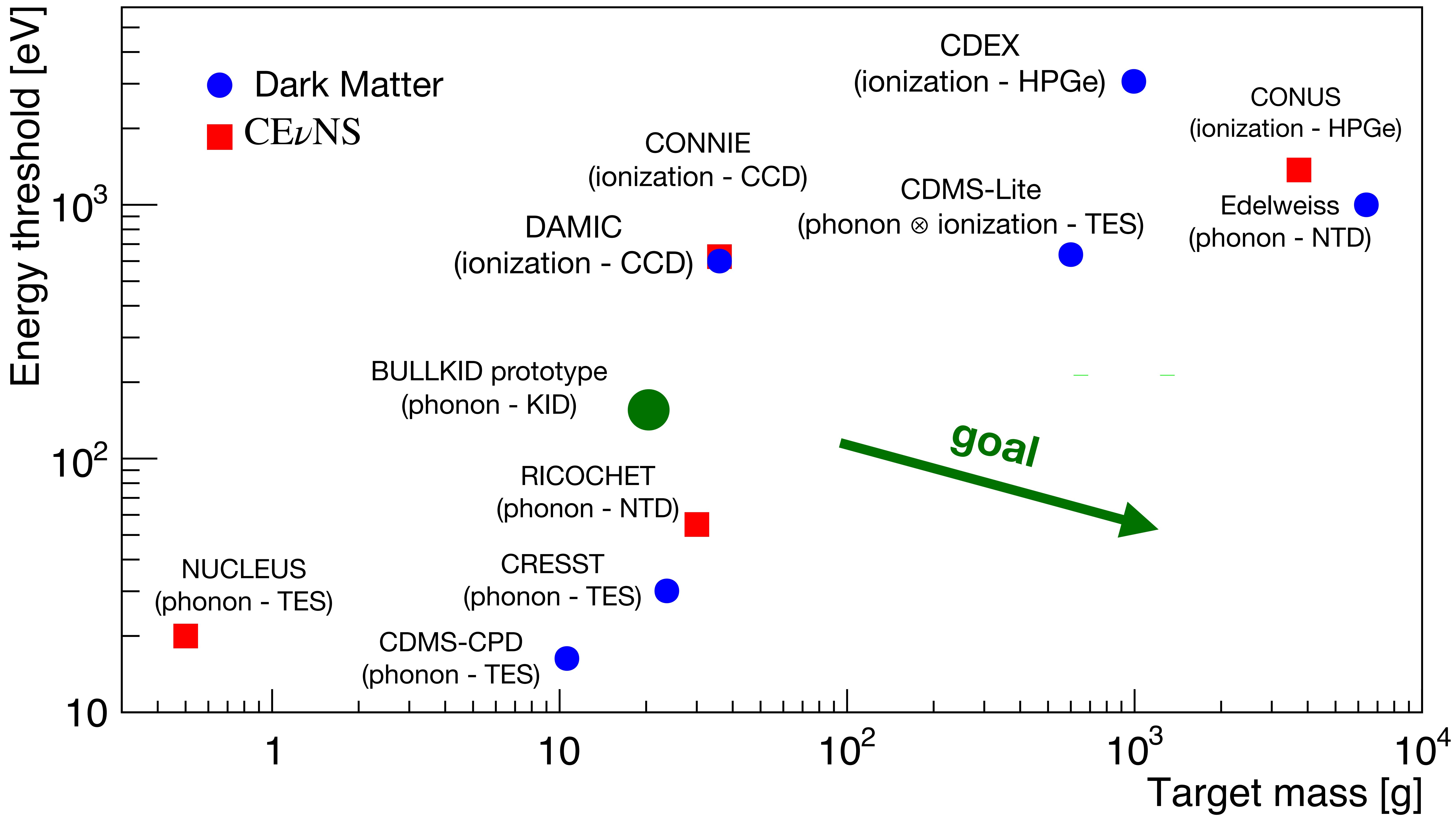


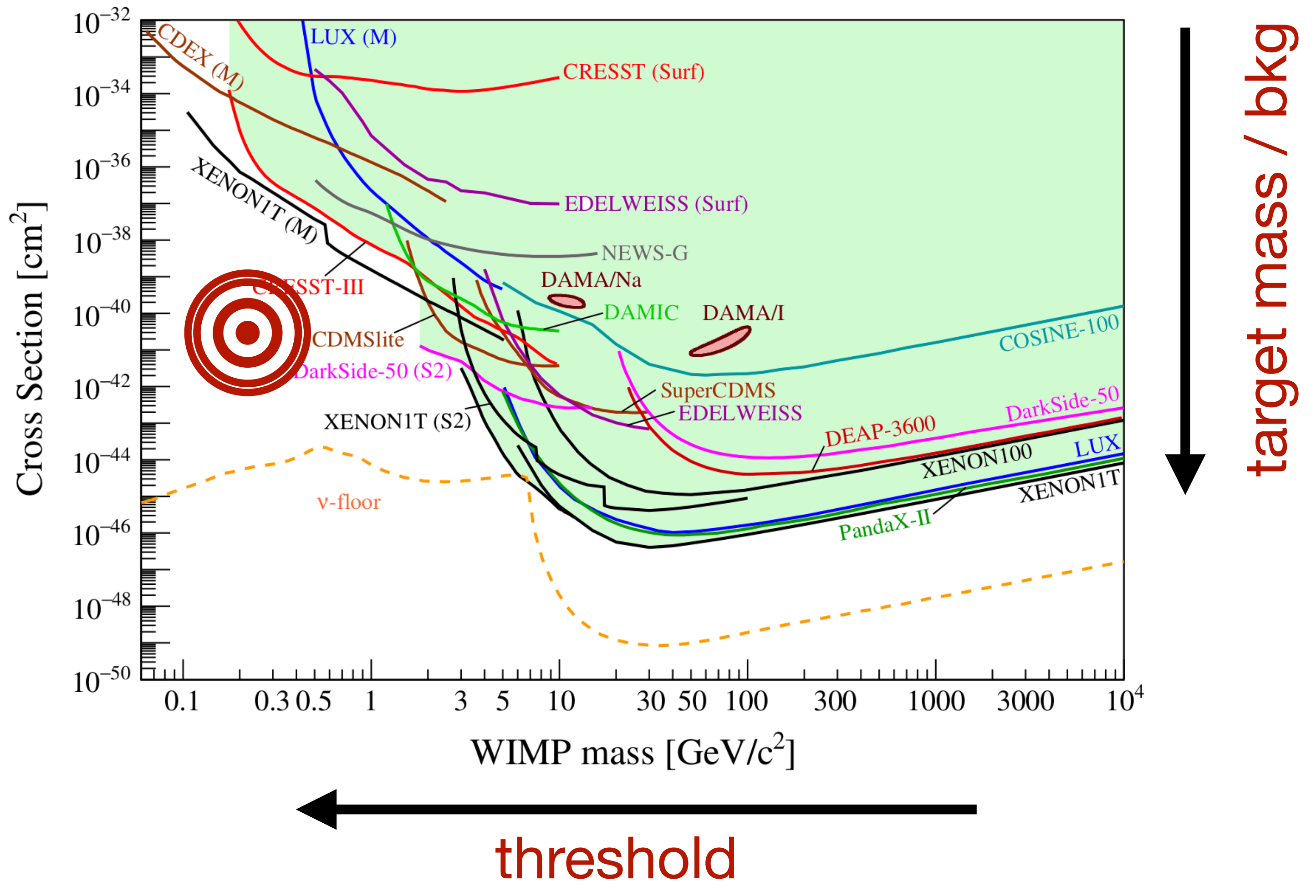
Marco Vignati, LNGS, 19 March 2024

Tentative list of competitors

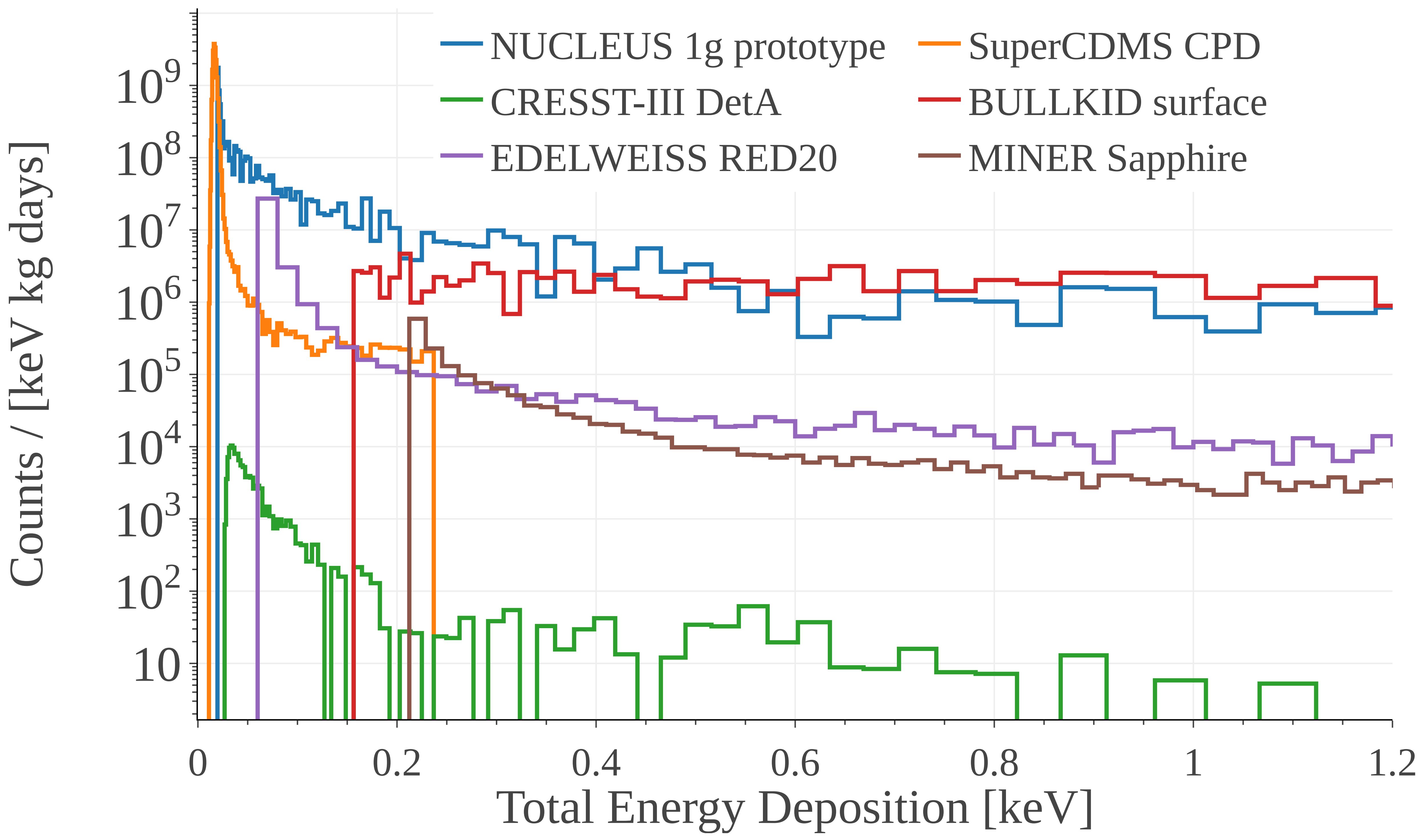
	Detector	Laboratory	Status
CRESST	Phonon-TES	LNGS	Data taking + R&D
TESSERACT	Phonon-TES / Phonon-LHe	LSM	R&D
Super CDMS	Phonon-TES	SNOLAB	Construction
DarkSide (S2 / Migdal)	Liquid scintillator	LNGS	Construction

State of the art (solid-state detectors)





Background issue in phonon experiments

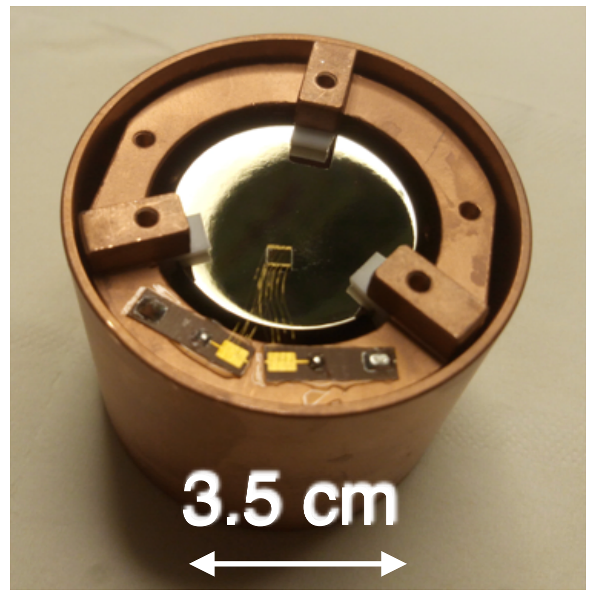


P. Adari, et al.: EXCESS workshop: Descriptions of rising low-energy spectra SciPost Phys. Proc. 9 (2022) 001 + BULLKID 2023

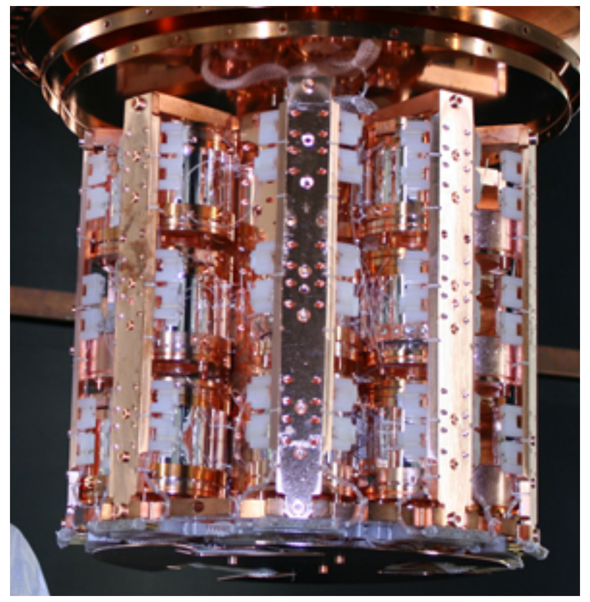
Not understood *excess* background rising at low energies:

- Phonon bursts (crystal-support friction) ?
- Lattice relaxations after cool down?
- Phonon leakage from interactions in the supports?
- ~~Neutrons (cosmic ray induced, radioactivity) ?~~

RED 20 (Ge, 33 g)



CRESST array

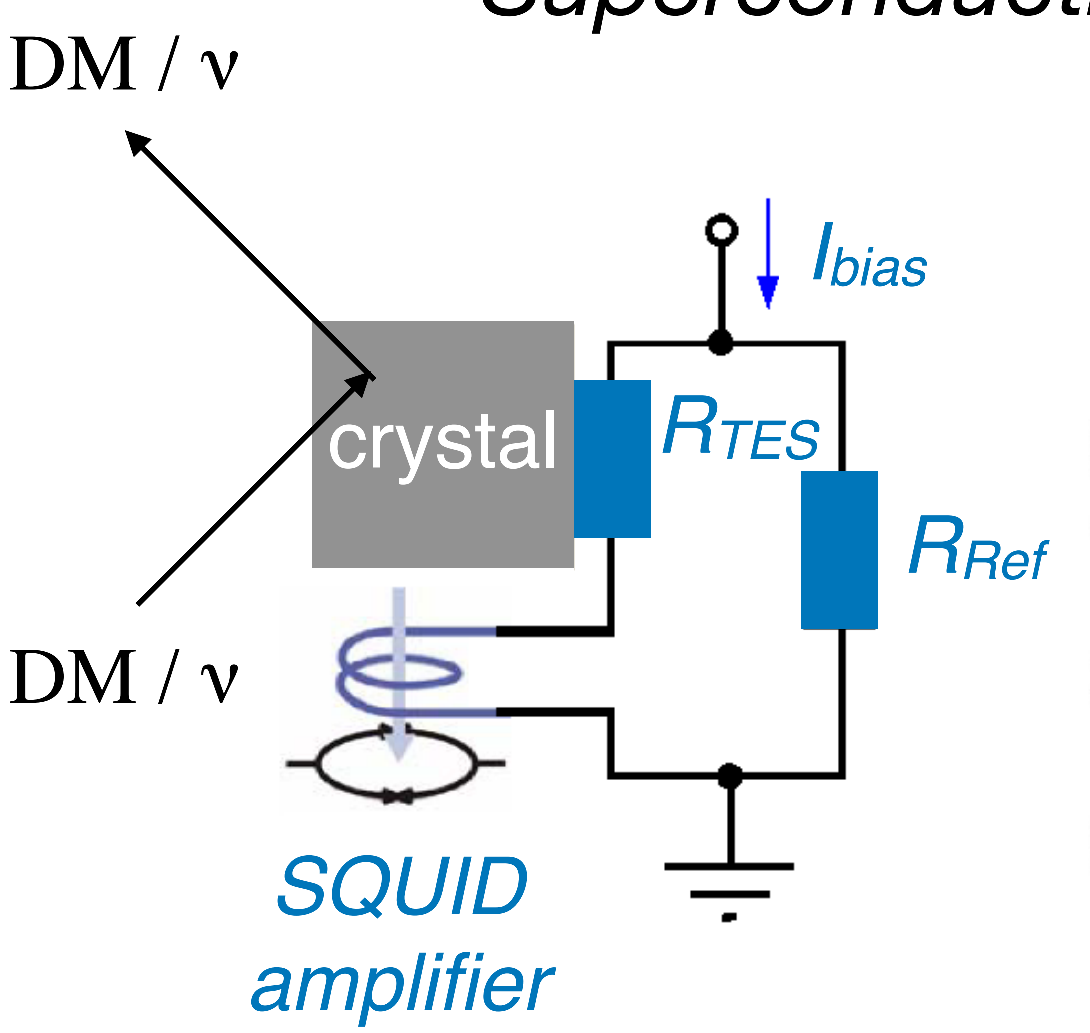


This background limits the sensitivity of present experiments

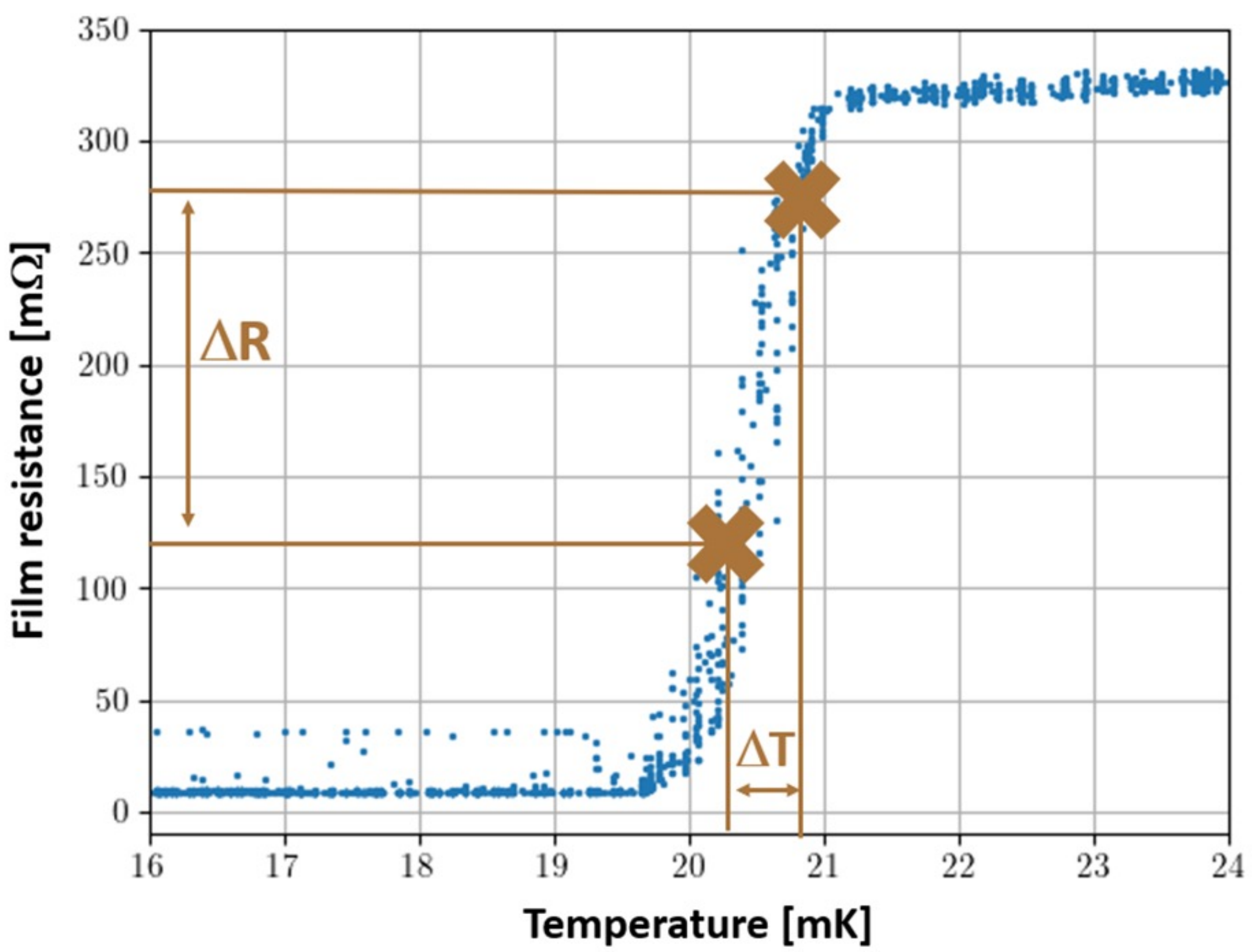
State of the art of phonon detection

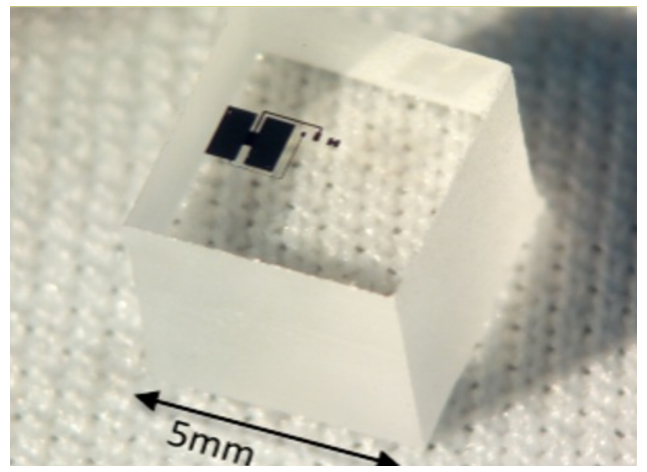
(CRESST/NUCLEUS experiments)

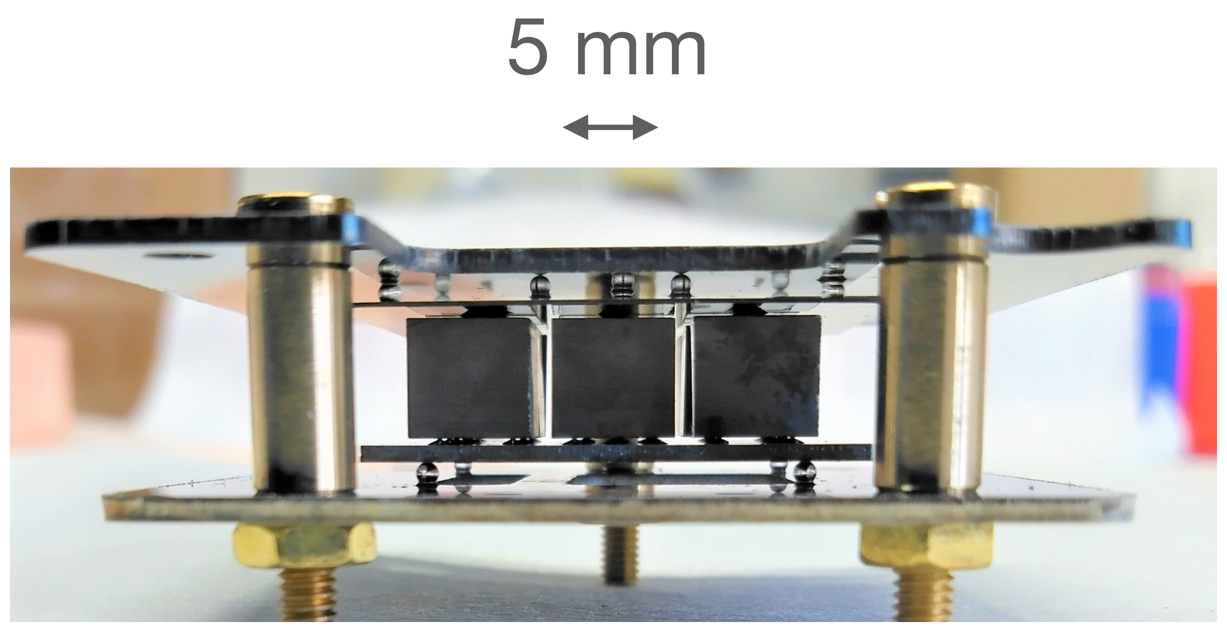
Superconducting thermometers (TES)

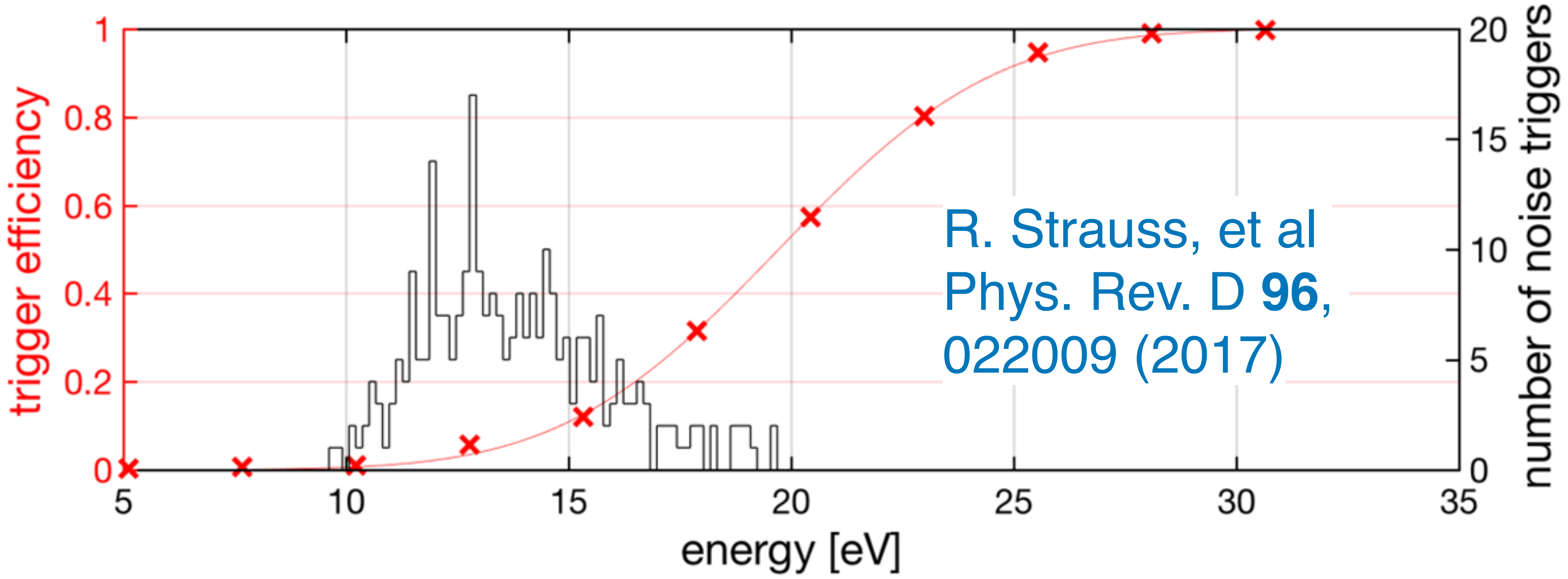


Transition of W-TES









Limitation: individual readout

Pro: record-low energy threshold ~ 20 eV

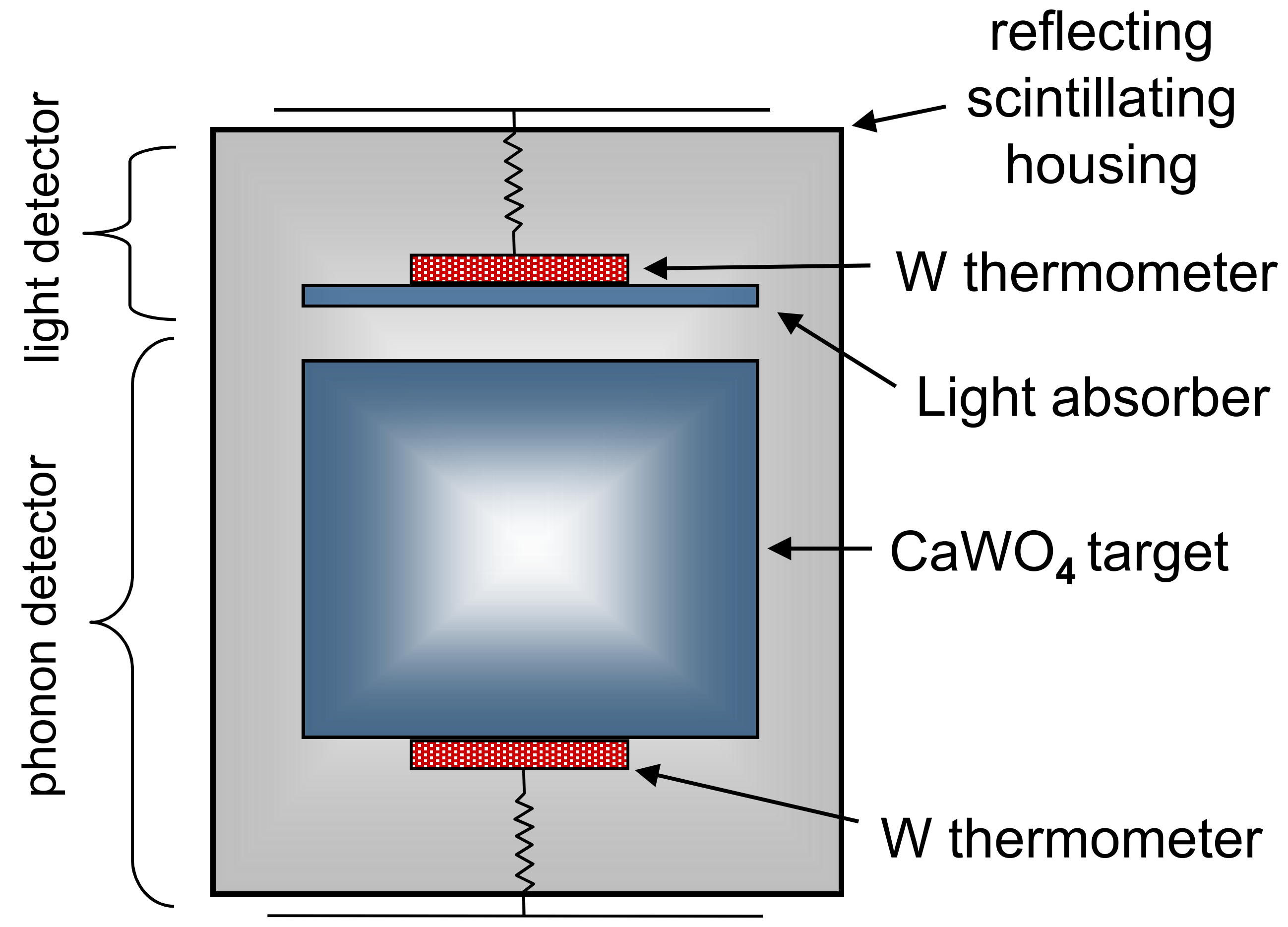
Future experiments point to kg targets (100÷1000 crystals) challenging with this technology

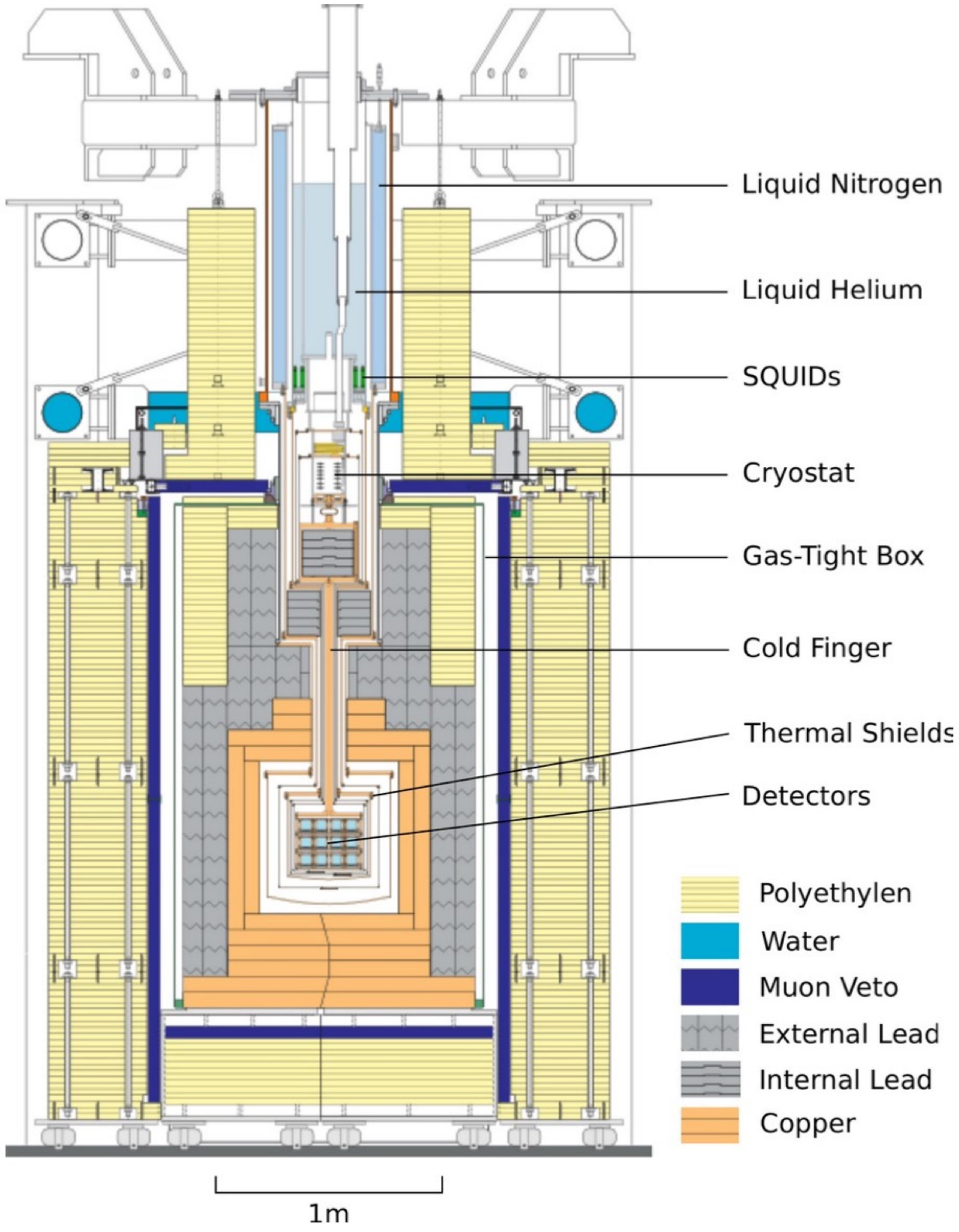
CRESST Experiment @LNGS

$CaWO_4$ crystals (30-300g) operated as bolometers (phonon detectors):

1) detect also scintillation light to discriminate nuclear recoils

2) Multi-target: sensitive to different WIMP masses:





CRESST $CaWO_4$ (2019)

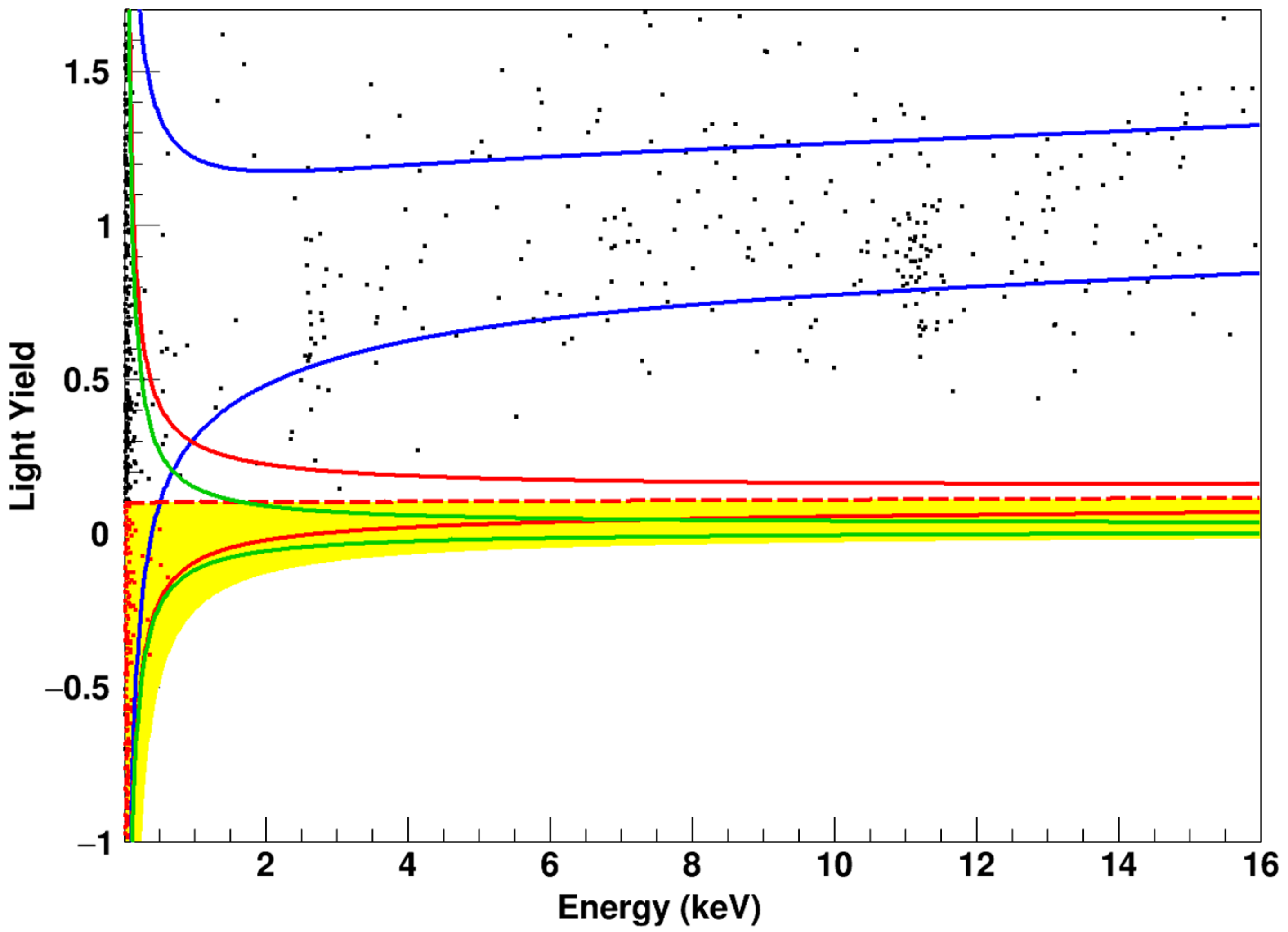


FIG. 5. Light yield versus energy of events in the dark matter data set, after selection criteria are applied (see Sec. III D). The blue band indicates the 90% upper and lower boundaries of the β/γ-band; red and green show the same for oxygen and tungsten, respectively. The yellow area denotes the acceptance region reaching from the mean of the oxygen band (red dashed line) down to the 99.5% lower boundary of the tungsten band. Events in the acceptance region are highlighted in red. The position of the bands is extracted from the neutron calibration data as shown in Fig. 3. A zoom to the low-energy region is given in Appendix A 2.

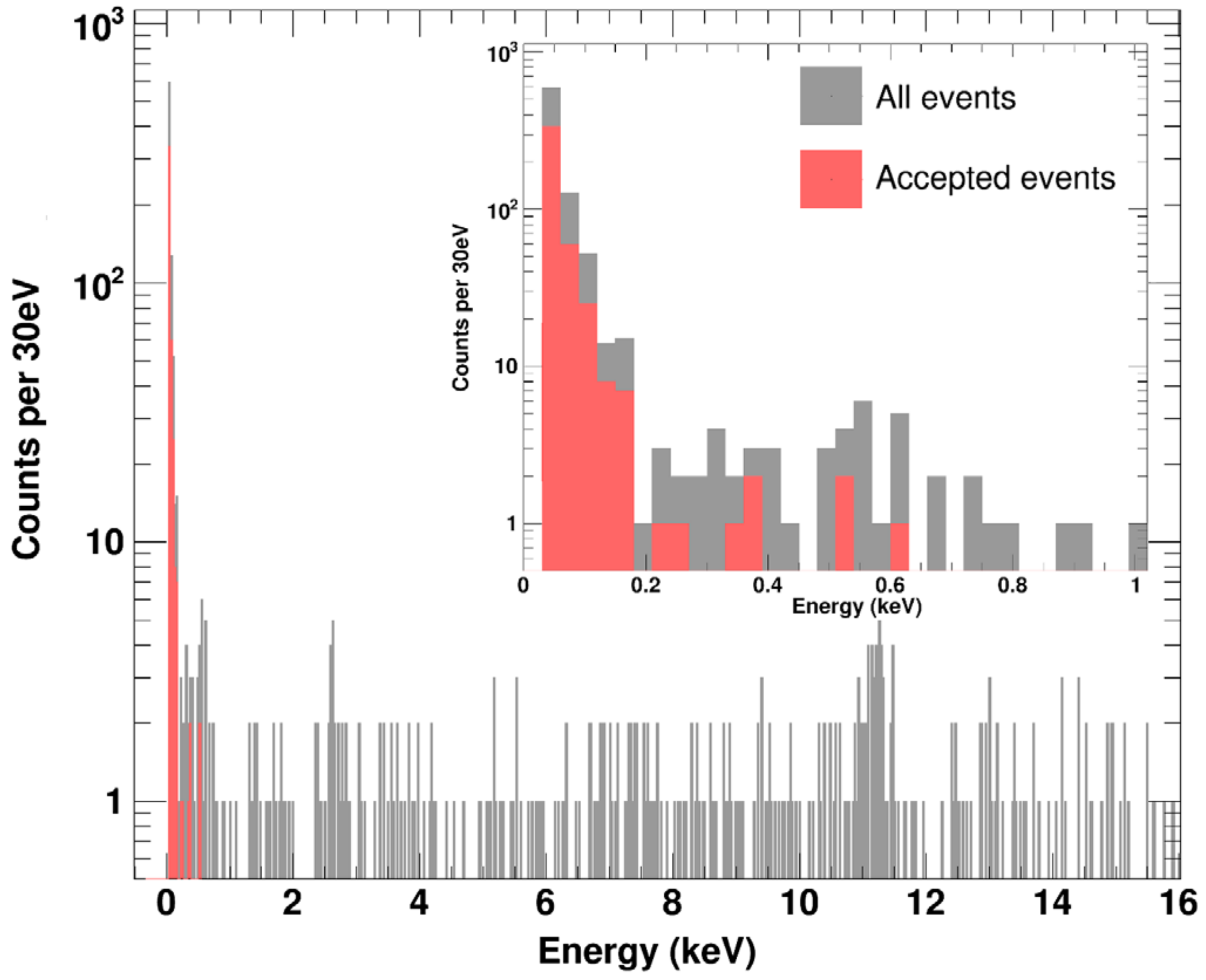
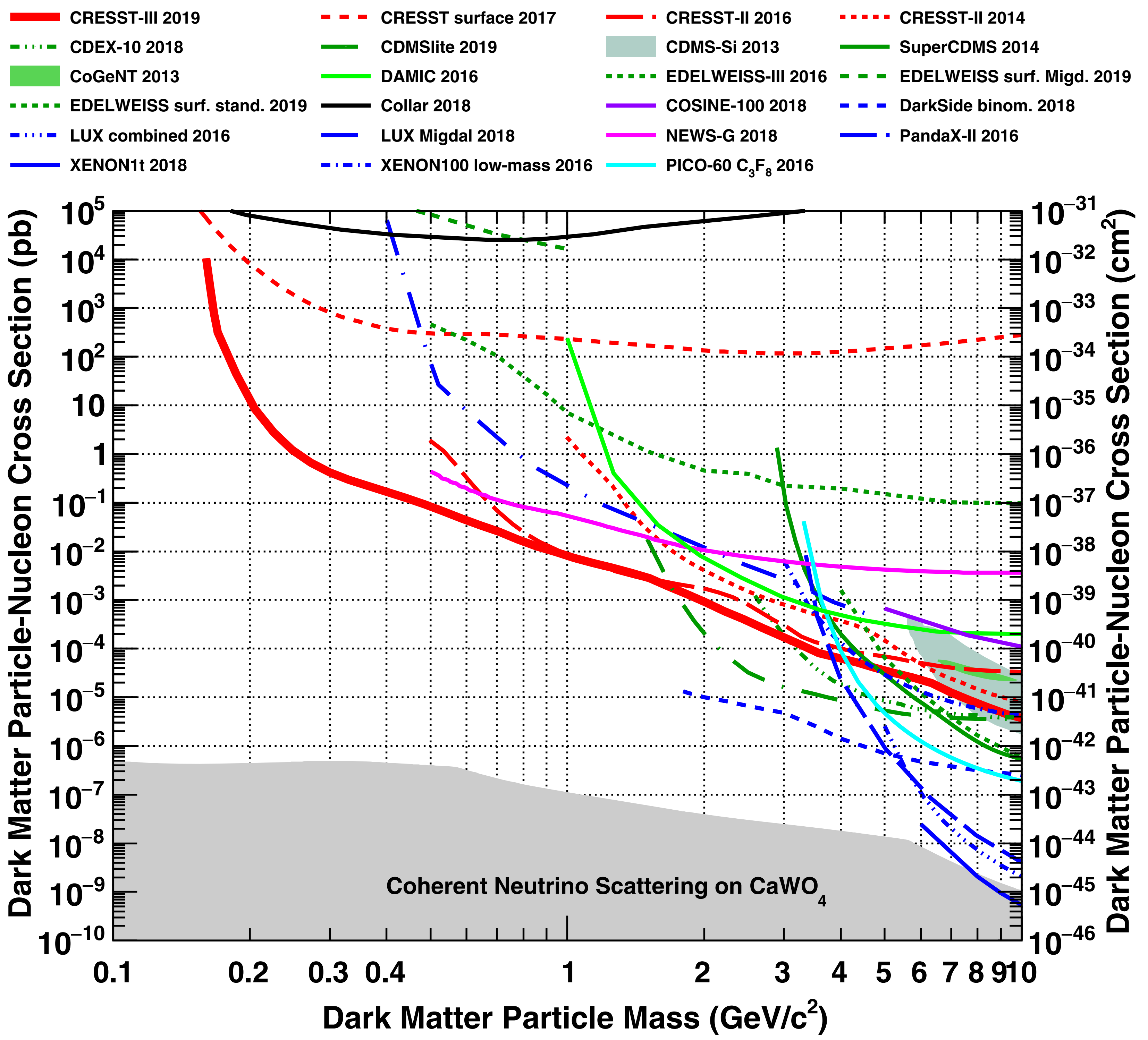


FIG. 6. Energy spectrum of the dark matter data set with lines visible at 2.6 keV and 11.27 keV originating from cosmogenic activation of ^{182}W [16]. Gray is for all events; red is for events in the acceptance region (see Fig. 5).



CRESST Silicon wafer (2022)

Si wafer detector: 0.35 g

Data-taking period: Nov 2020 – Aug 2021

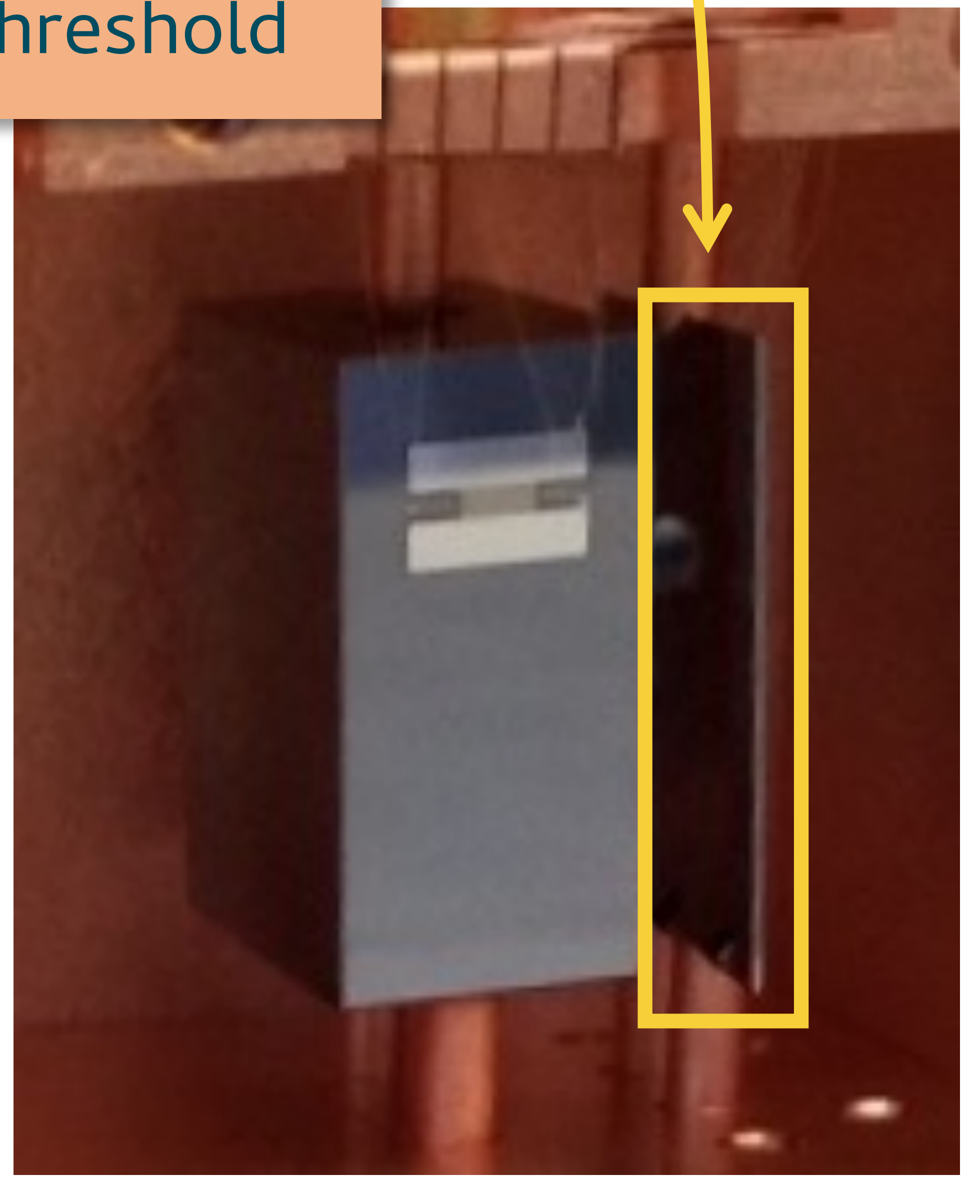
Exposure: 55.06 g · days

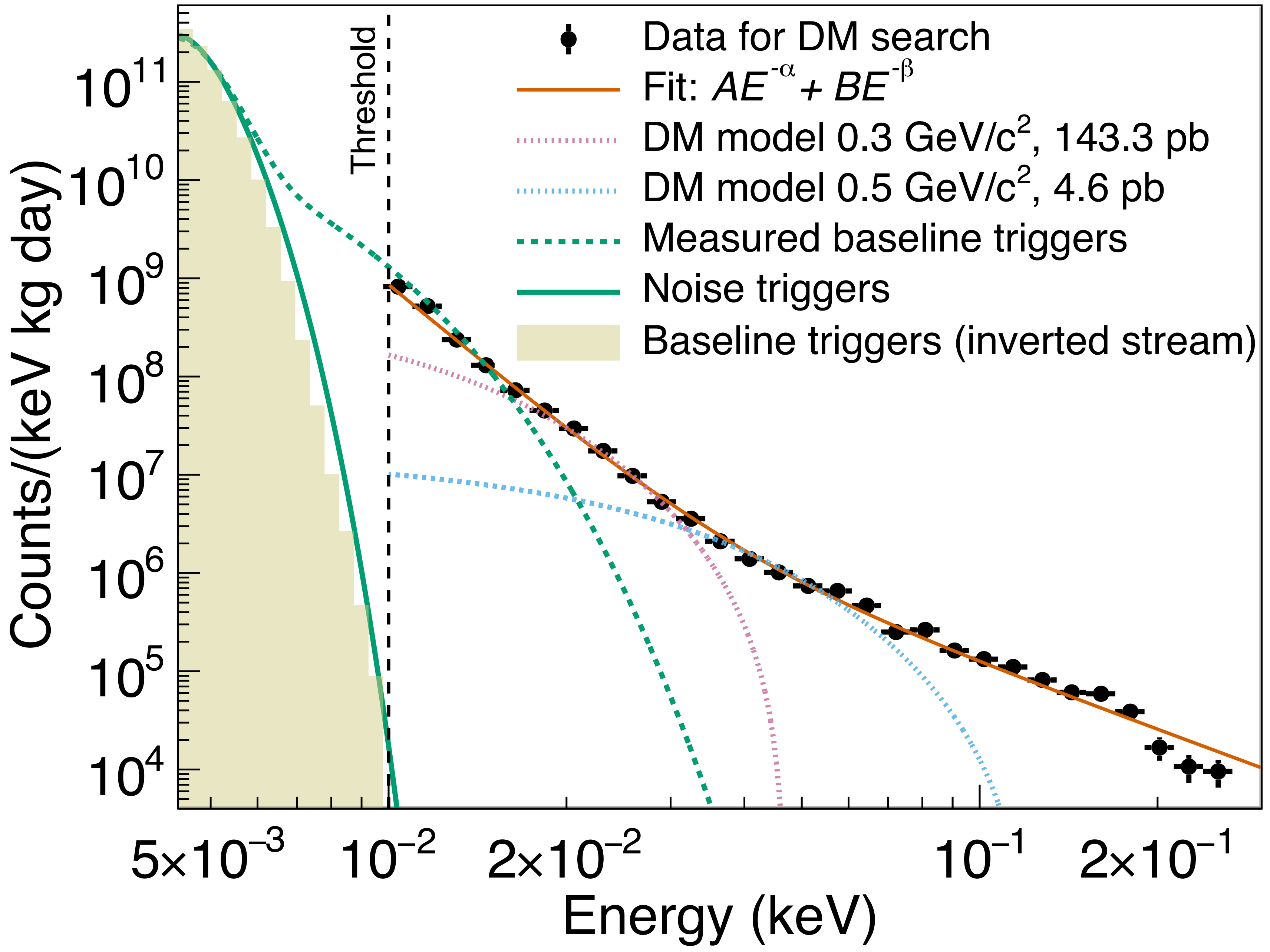
Energy threshold: **10.0 eV**

Thin wafer detector is a target

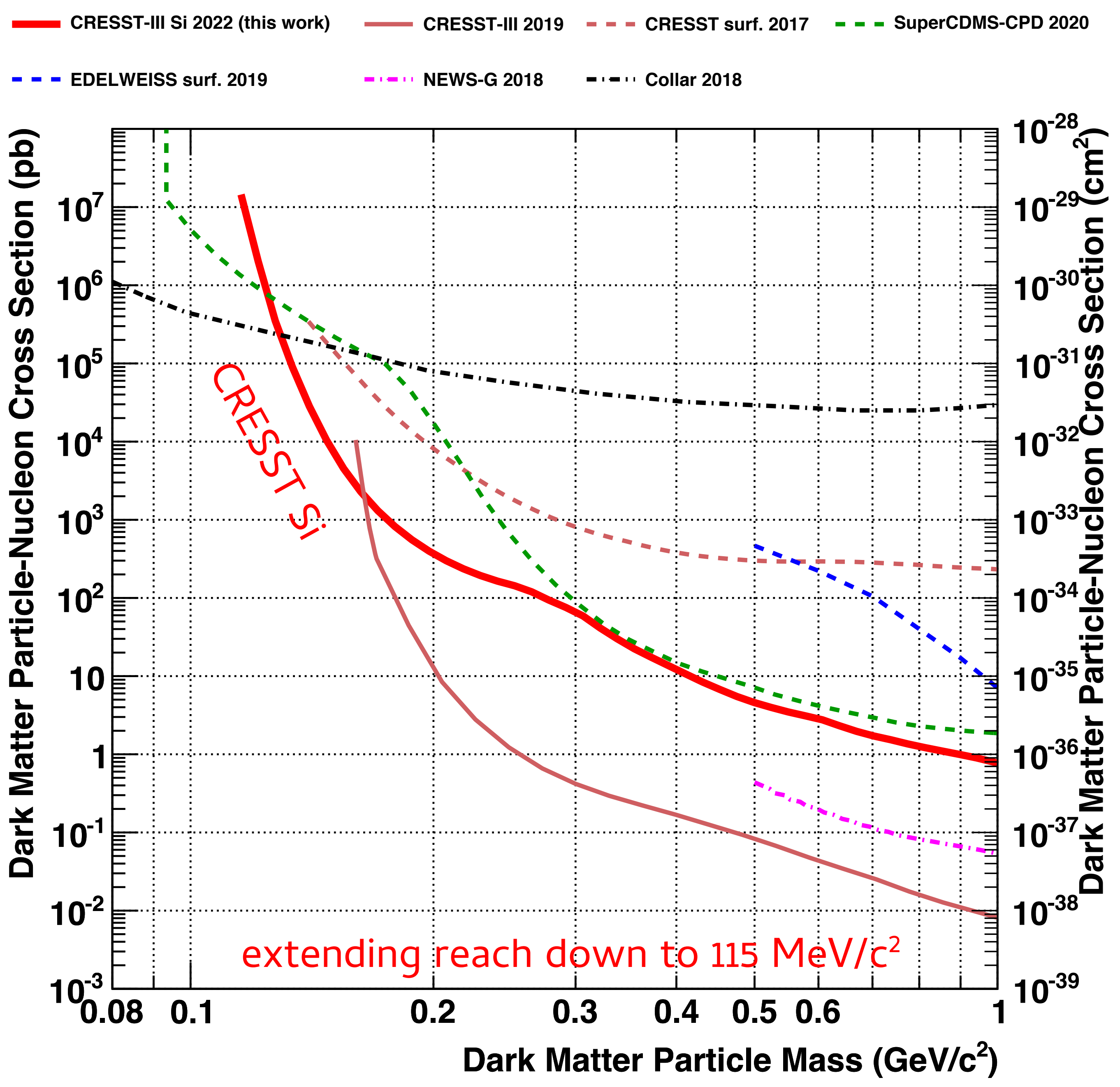
Bulky detector is a veto to remove coincidence events.

10.0±0.2 eV energy threshold





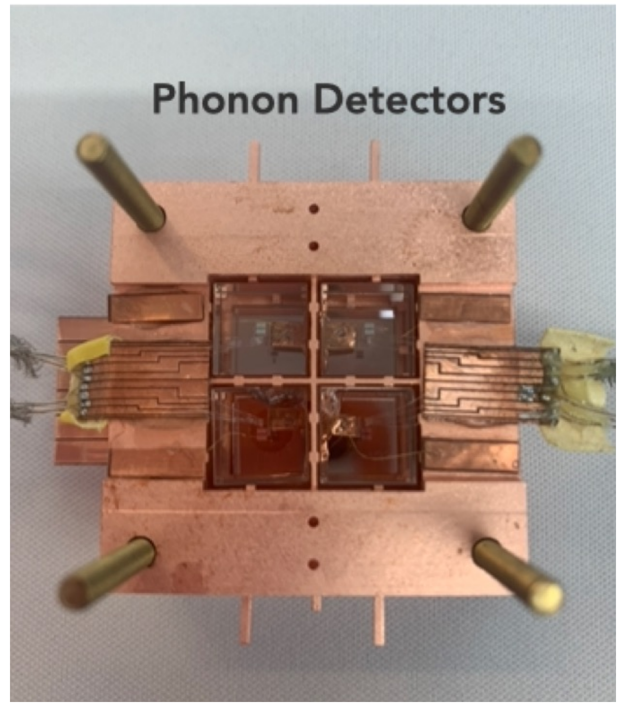
Phys. Rev. D **107**, 122003 / arXiv:2212.12513



CRESST today: study of excess, more chats

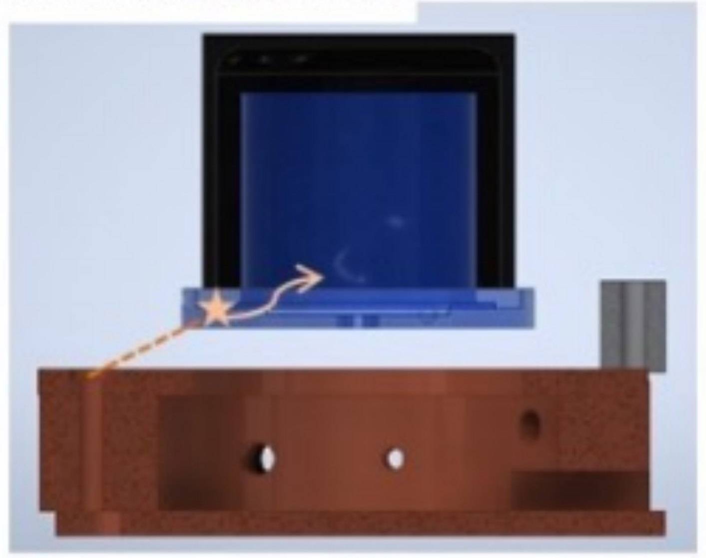
Holding structures

novel stress-free holding structure
-> LEE reduction?



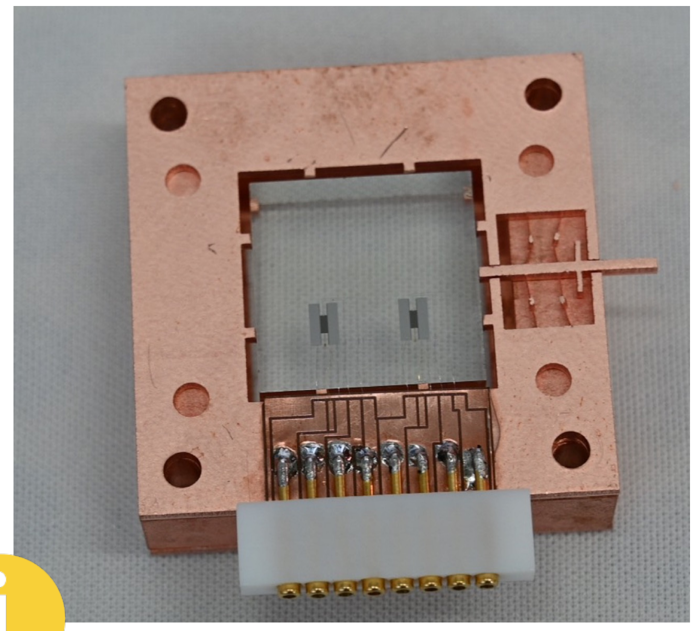
instrumented holders
-> discriminate events transmitted through the holding structure

• transmitted events



Double TES read-out

-> discriminate events in the absorber from events in the TES films or material interfaces



Talk: "Results of doubleTES detectors" by Francesca Pucci at the Excess@TAUP workshop last Saturday

More features

- maximize sensitivity to dark matter recoils
- 4π veto

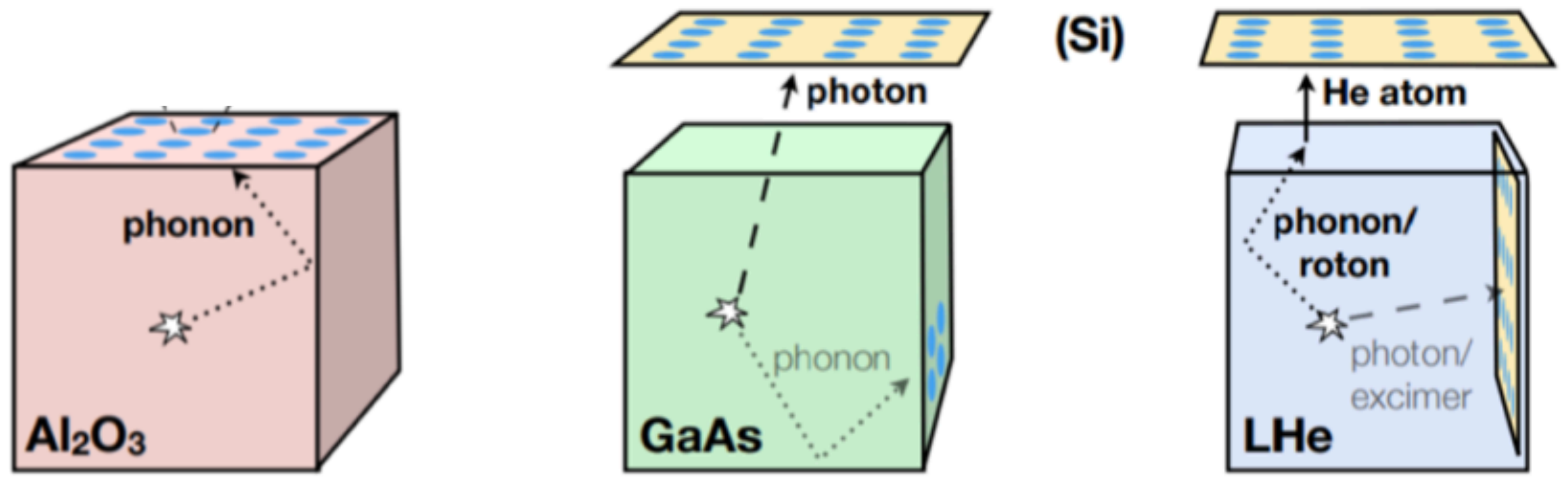
Above-ground measurements show very promising performance!

A **major CRESST setup upgrade** to 288 read-out channels is in preparation:

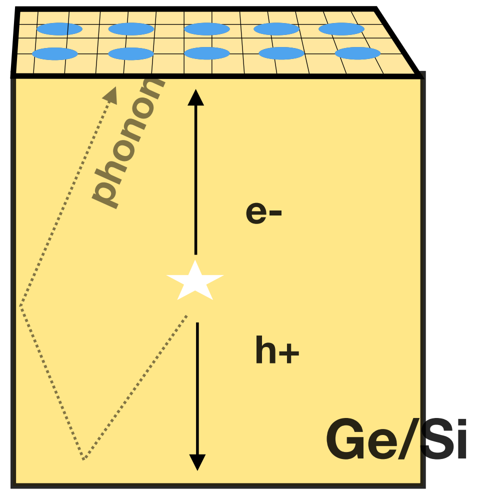
- SQUIDs and wiring are already produced
- new DAQ and bias electronics are designed
- goal: installation at LNGS in 2024

TESSERACT@LSM: Proposal experiment at LSM

Transition Edge Sensors with Sub-Ev Resolution And Cryogenic Targets



- DOE Funding for R&D and project development began in June 2020 (Dark Matter New Initiative)
- One experimental design, and different target materials with complementary DM sensitivity, all using TES
- Includes SPICE (Al_2O_3 and GaAs) and HeRALD (LHe)
- ~40 people from 8 institutions
- **Actively searching for an underground lab**

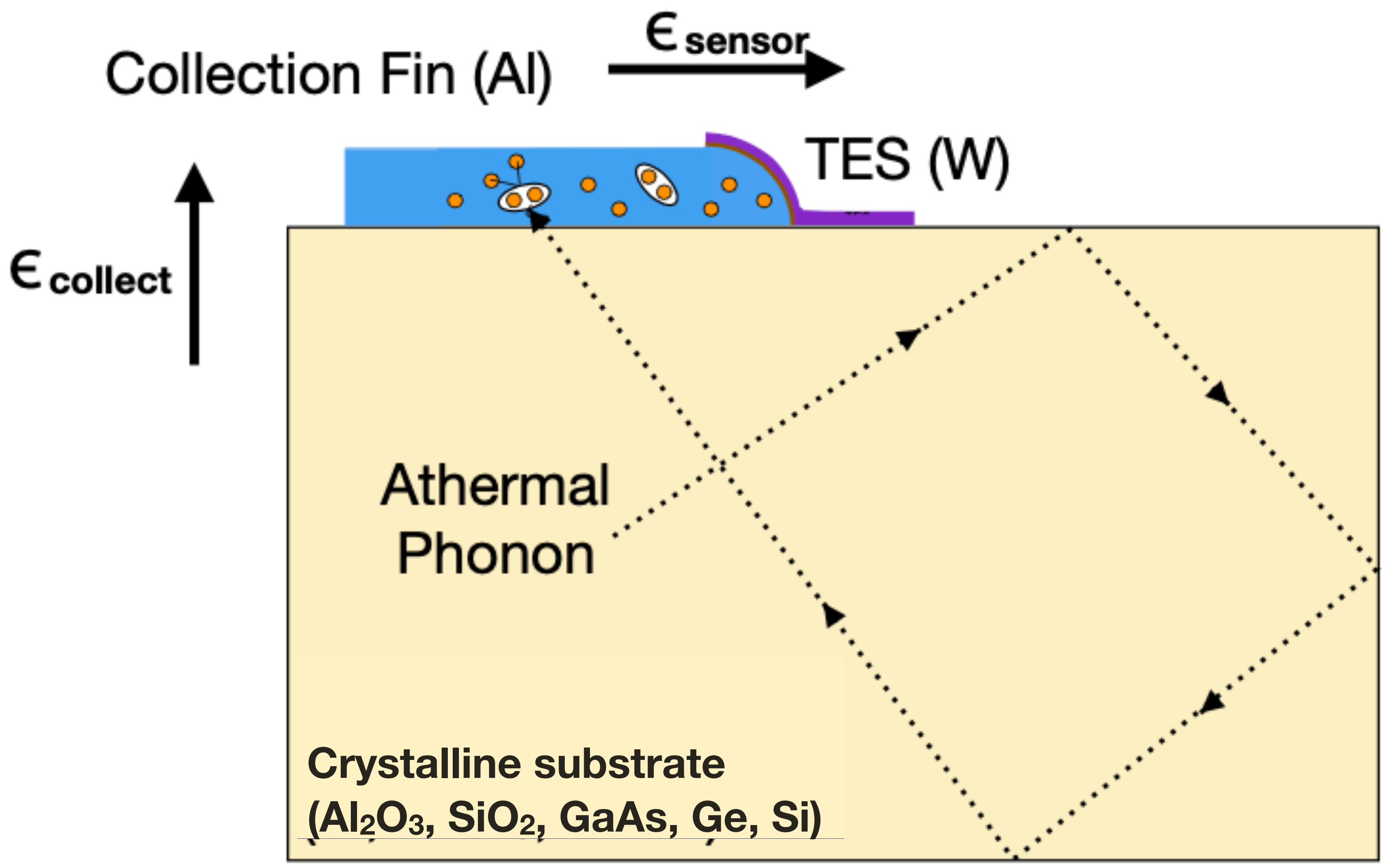


TESSERACT @ LSM proposal:

- Benefit from EDW+Ricochet+CUPID Ge bolometer expertise and low-background cryogenic setup experience to:
  1. **Add the French semiconductor Ge bolometer technology to the TESSERACT science program**
  2. **Deploy the future TESSERACT experiment at LSM**
- Achieve leading light DM sensitivities on short time scales
- Benefit from exchange of technologies with US partners

TESSERACT: New generation TES phonon sensors

TES based athermal phonon sensor technology:

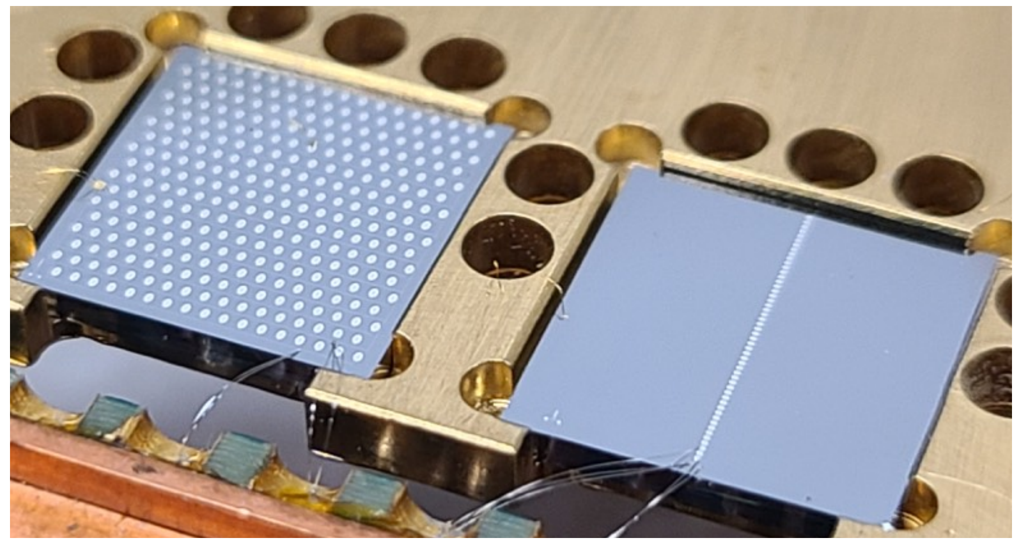


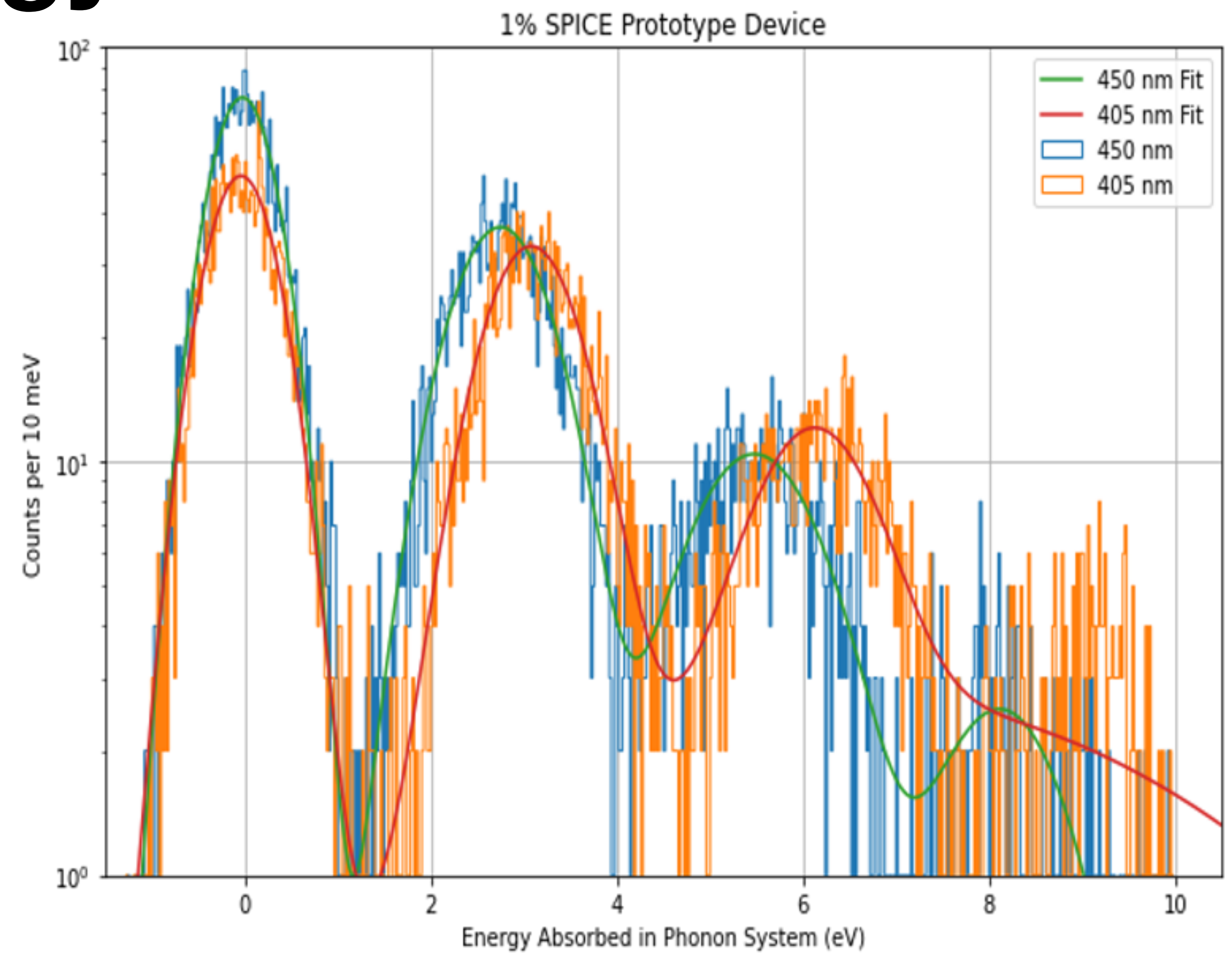
$$\sigma_E \sim \frac{\sqrt{4k_bT_c^2G(\tau_{collect}+\tau_{sensor})}}{\epsilon_{collect}\epsilon_{sensor}}$$

$$\sigma_E \propto V_{det}^{1/2}T_c^3$$

Energy threshold decreases with detector mass

Energy threshold decreases very quickly with Tc



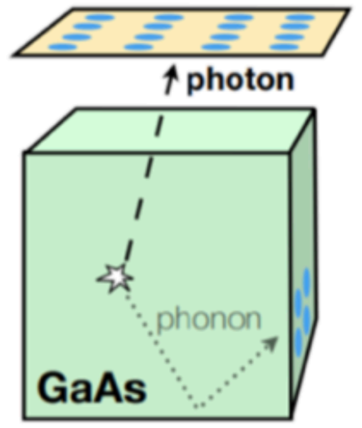


- **273 meV (RMS) leading to eV-scale threshold already achieved** with a 0.2g Si detector and Tc = 50 mK
- Targeted Tc around 15-20 mK recently achieved

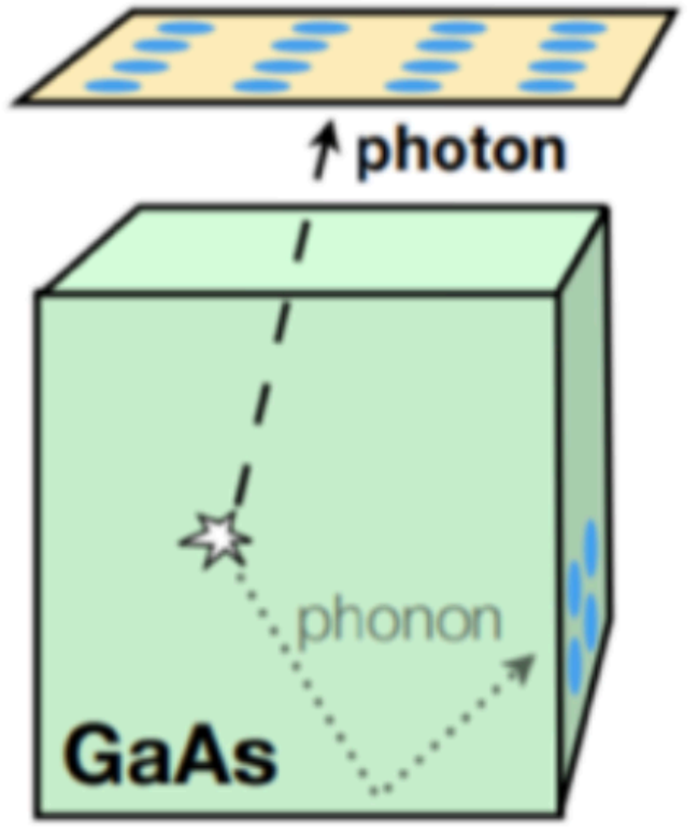
  ~100 meV threshold achievable on 1 cm^3 crystals
- **Next challenge:** parasitic power (vibrations, EMI, IR photons) needs to be <aW to fully reach TES sensitivity

8

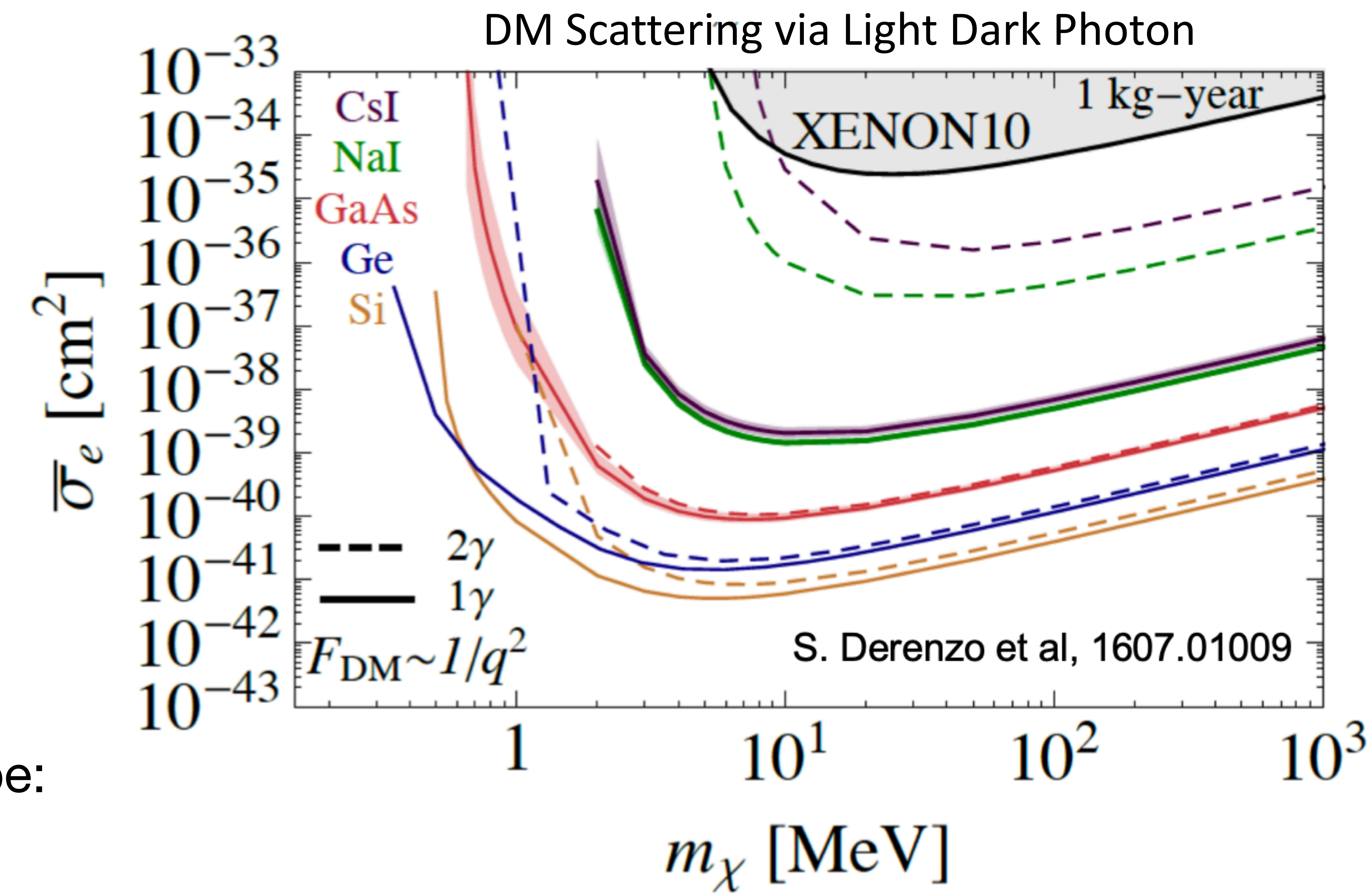
TESSERACT@LSM: SPICE



Sub-eV Polar Interactions Cryogenic Experiment: GaAs

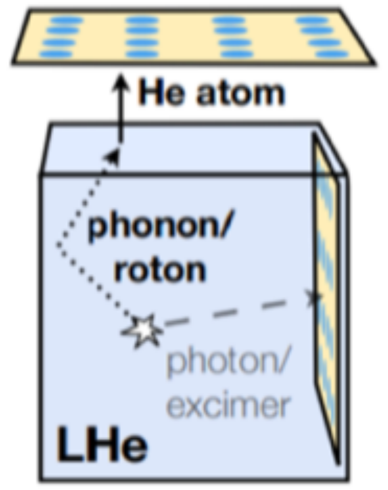


- GaAs has very high scintillation yield (125 ph/keV, arxiv:1904.09362),
- GaAs has a similar ERDM sensitivity than Ge/Si and similarly allows for **control of the backgrounds**:
  - photon:phonon ratio depends on the recoiling particle type: NR/ER discrimination (~10 eV scale)
  - photon/phonon coïncidence in two separate sensors: instrumental background rejection (LEE) (~eV scale)

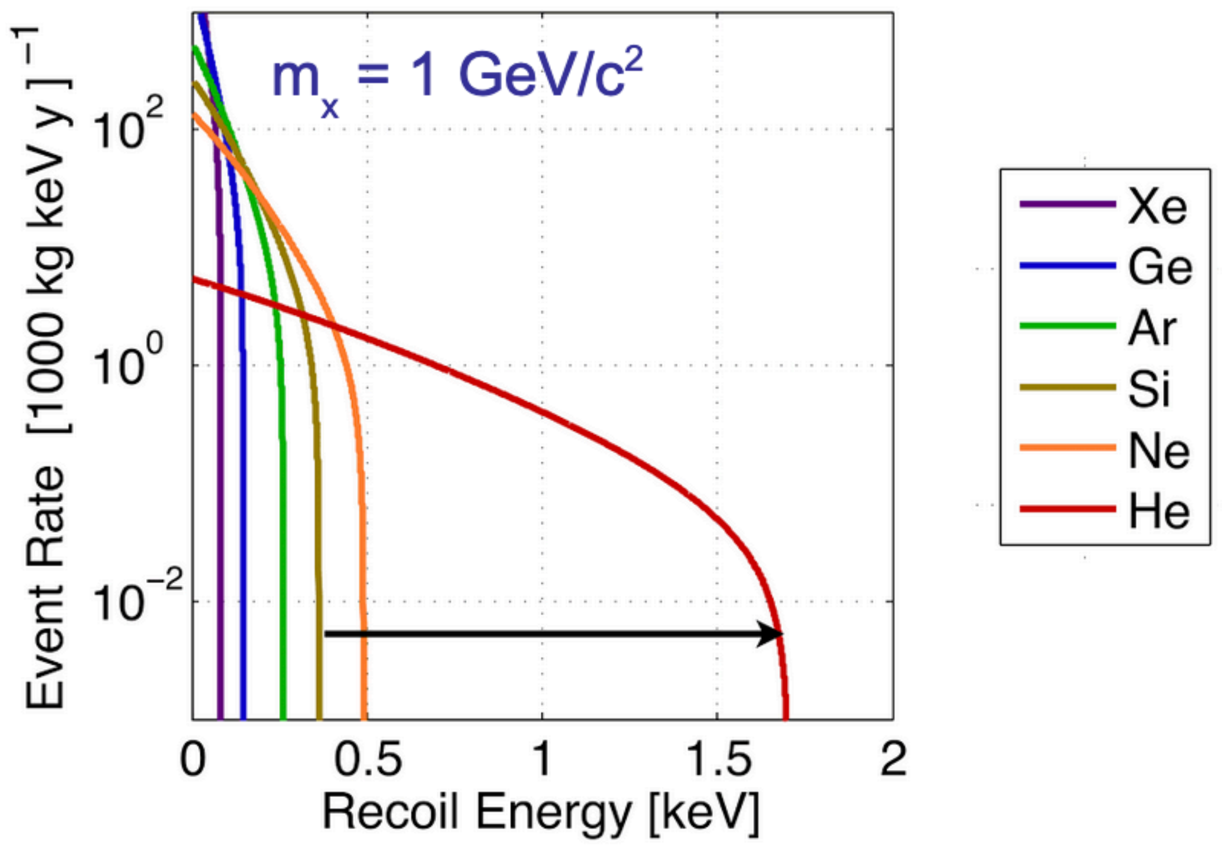


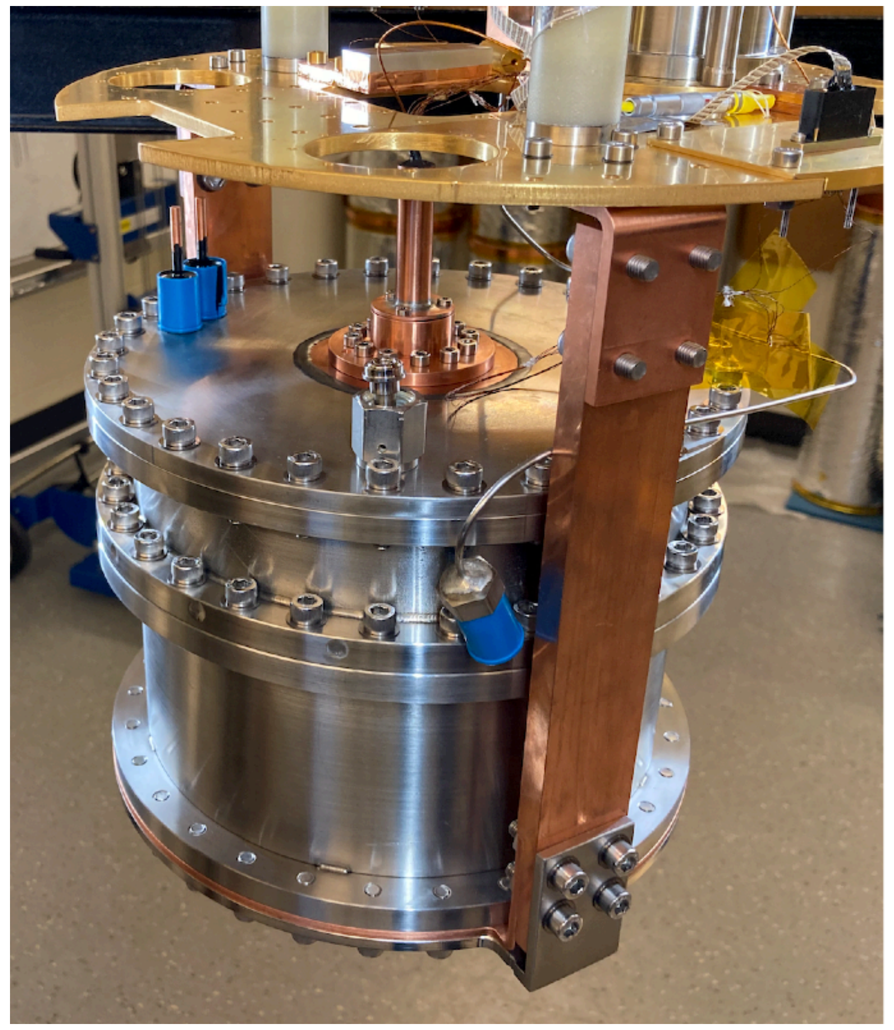
10

TESSERACT@LSM: HeRALD

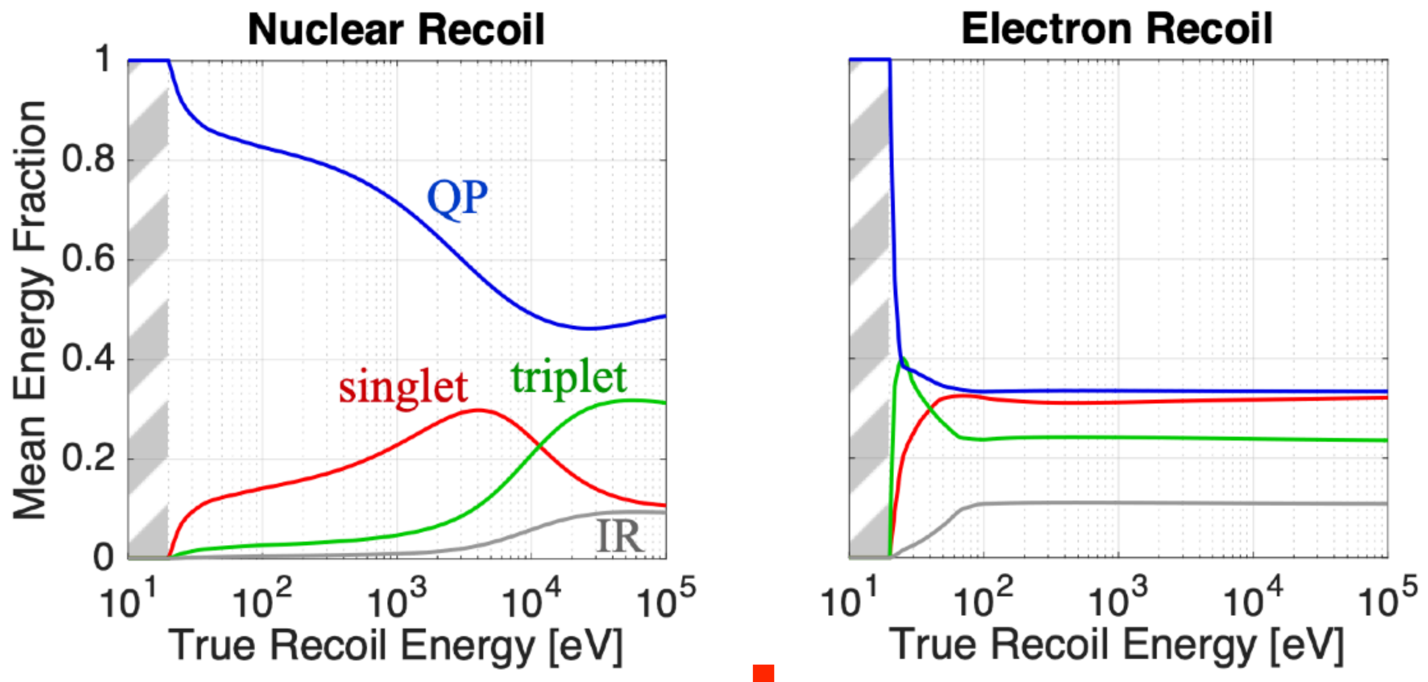


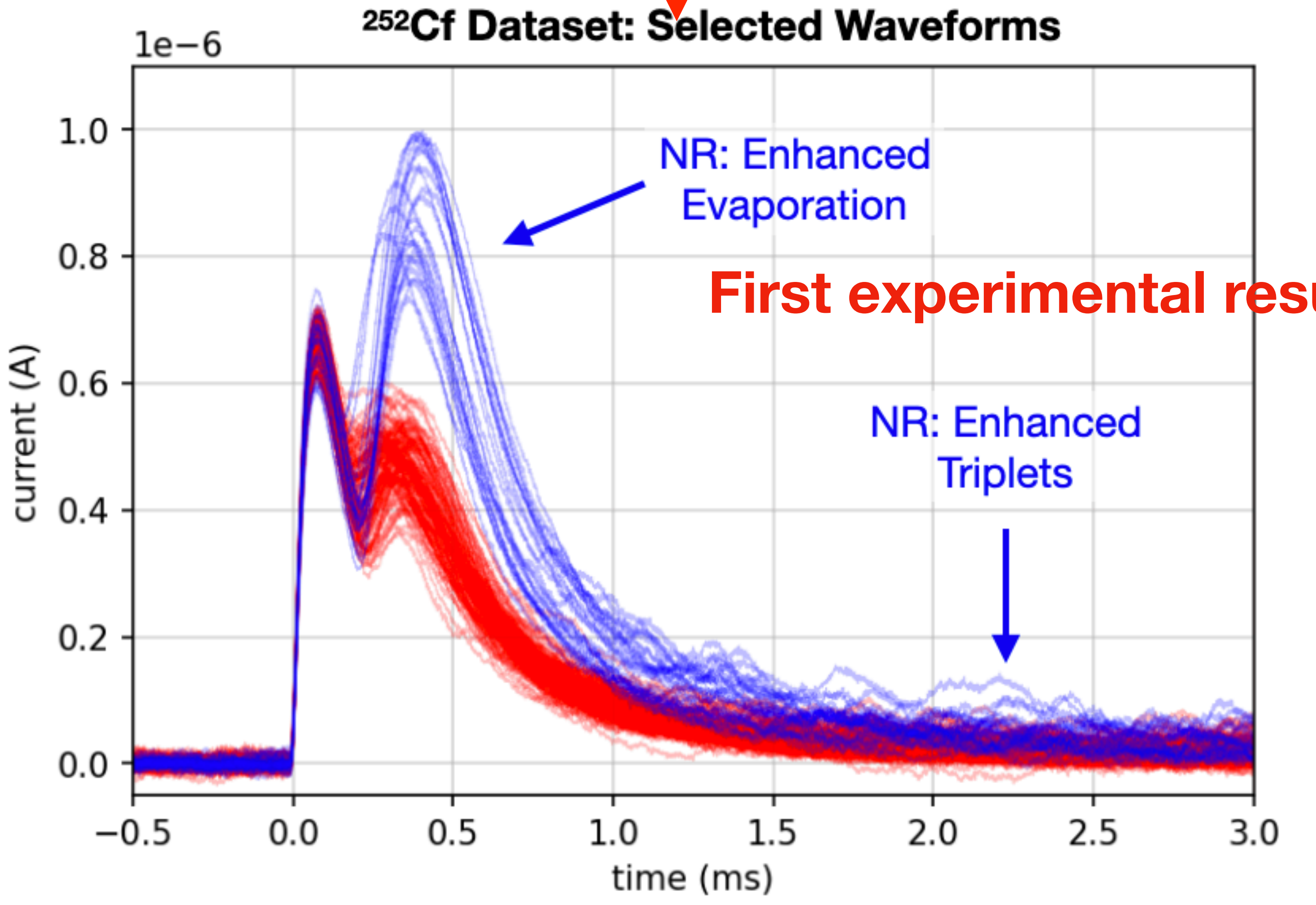
Helium Roton Apparatus for Light Dark matter





R. Anthony-Petersen et al., arXiv:2307.11877





- Well kinetically matched to GeV-scale DM
- Easy to purify, intrinsically radio pure
- Monolithic and scalable
- LHe cell operated at 20-50 mK with wafer-like cryogenic detectors with TES suspended in vacuum
  - UV/IR photons and **He atoms** from qp induced evaporation
- **First evidence of ER/NR discrimination @10 keV**
- **Already achieved ~170 eV threshold on He recoils (300 MeV DM)**

11

SuperCDMS

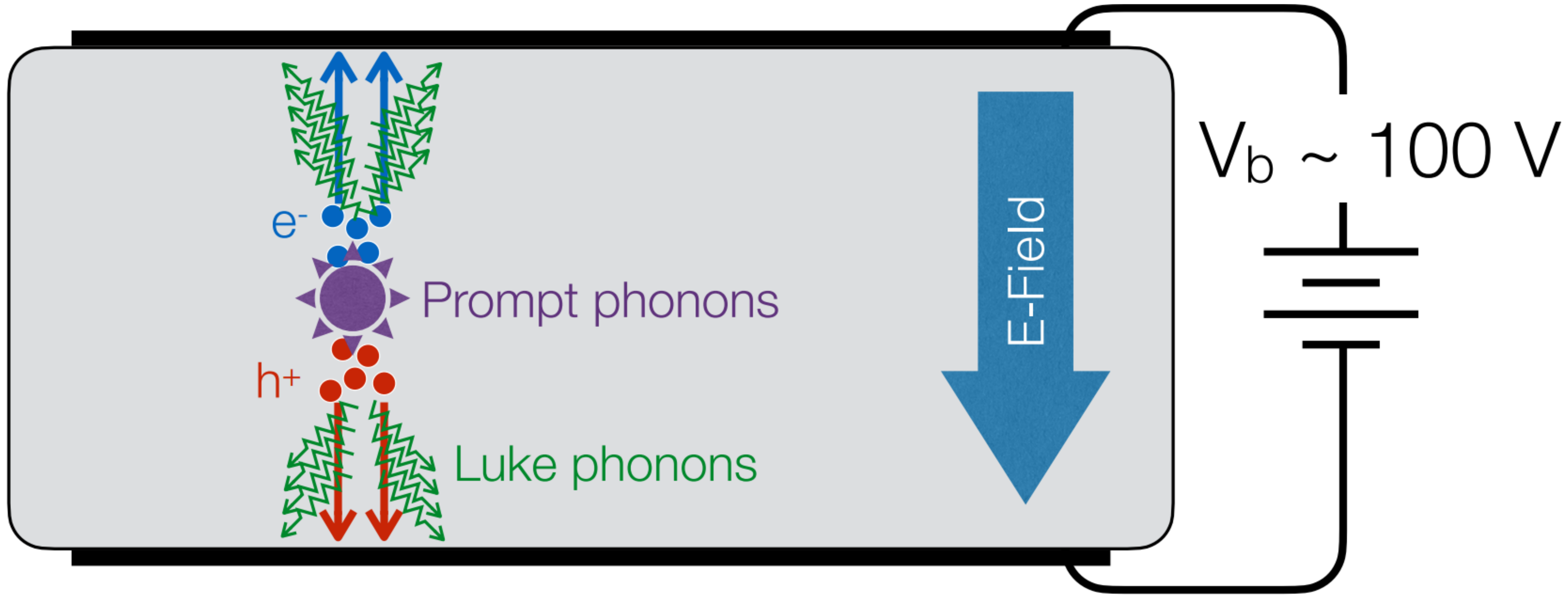
HV detector $\rightarrow$ low threshold

- Drifting charge carriers (e^-/h^+) across a potential (V_b) generates a large number of Luke phonons (NTL effect)
- Trade-off: no NR/ER discrimination

$$E_t = E_r + (N_{eh} \cdot e \cdot V_b)$$

total phonon energy — primary recoil energy — Luke phonon energy

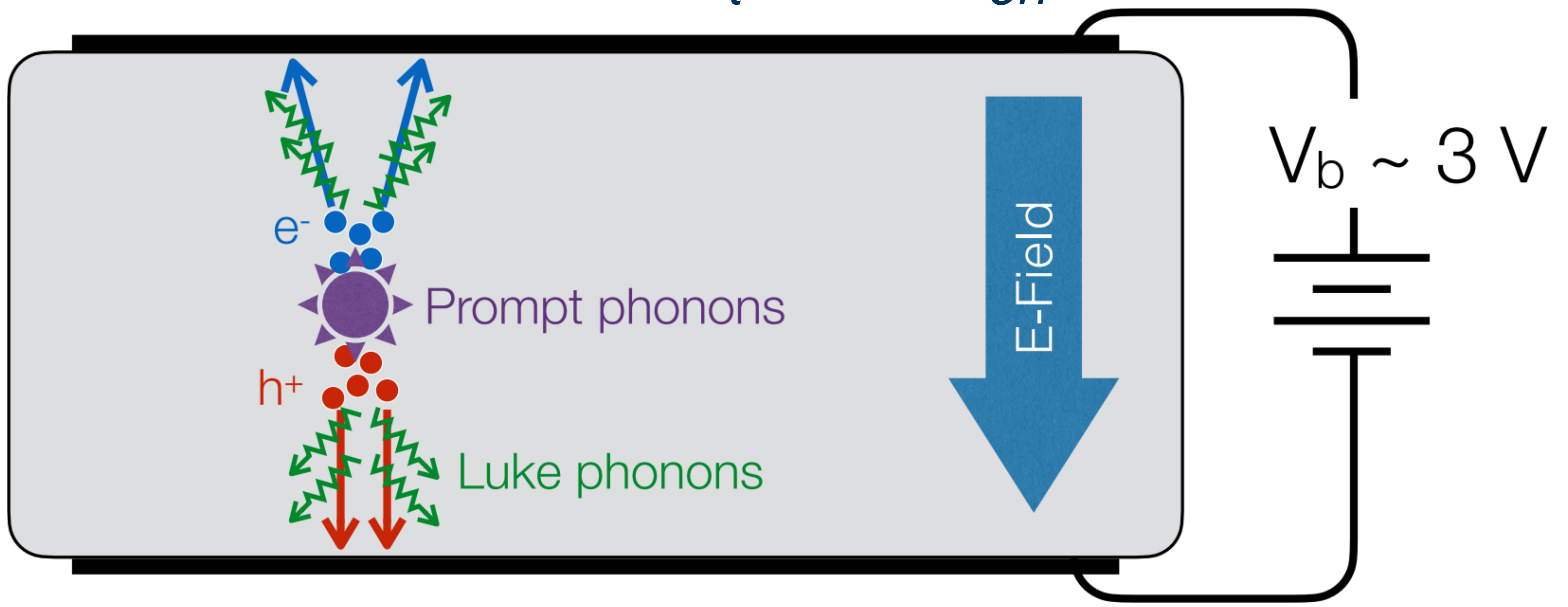
Sensors measure E_t



iZIP detector $\rightarrow$ low background

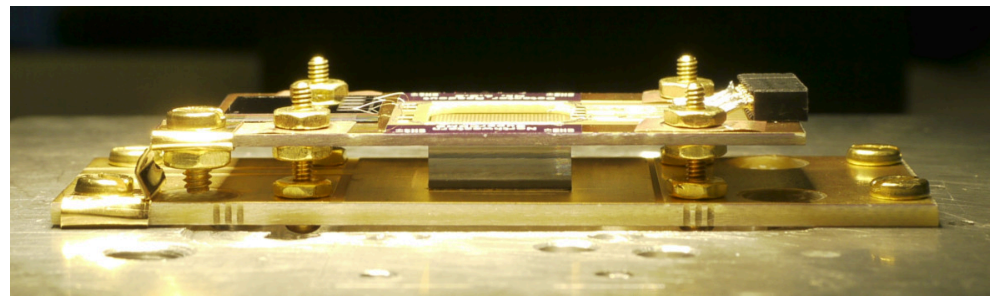
- **I**nterleaved **Z**-sensitive **I**onization and **P**honon detector
- Prompt phonon and ionization signals allow for NR/ER event discrimination

Sensors measure E_t and N_{eh}

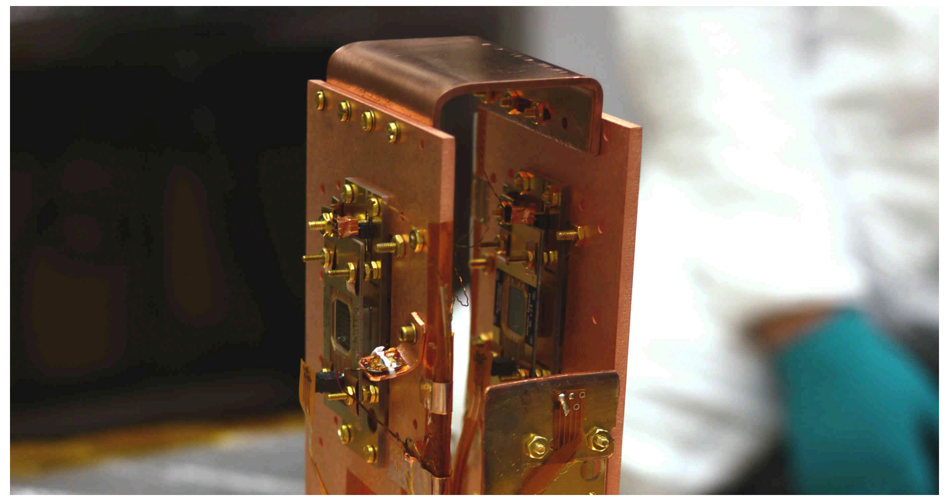


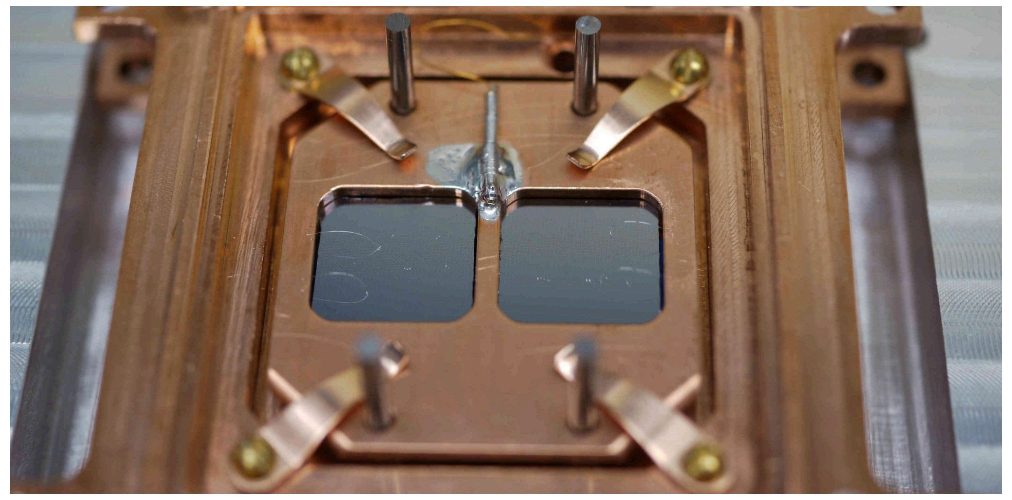
SuperCDMS

Highlights of HVeV R&D detector program



PRD 102, 091101(R), 2020

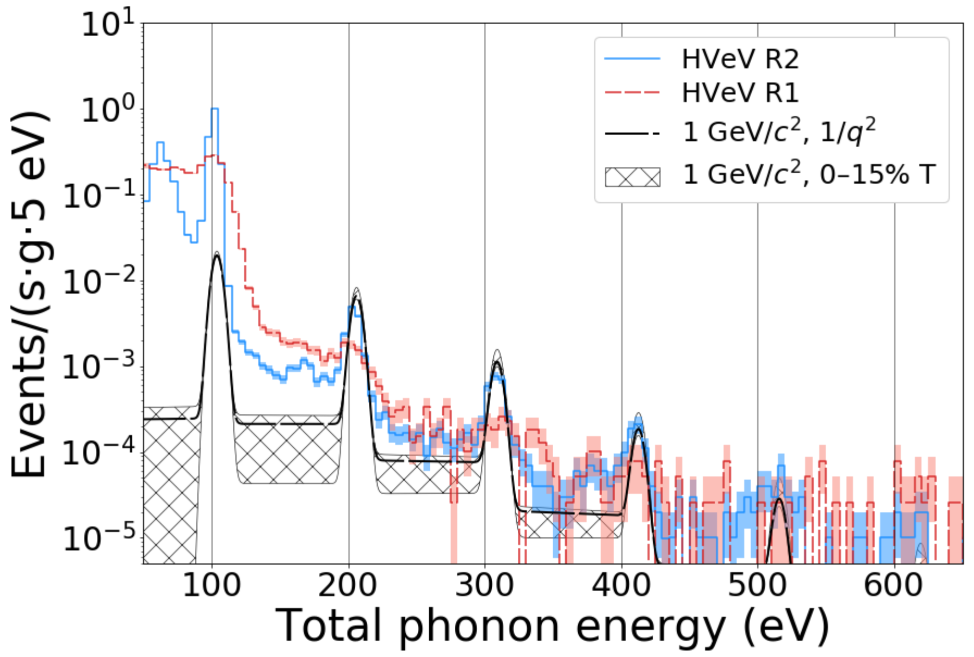




Stay tuned!

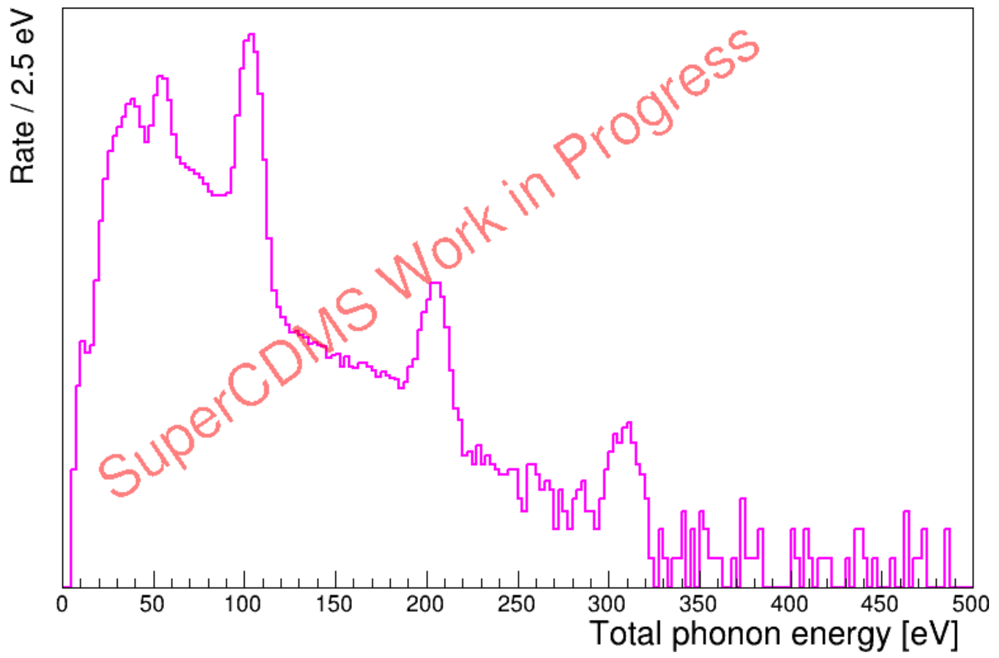
HVeV Run 2

- Detection and study of 1 e^-/h^+ burst events
- Hypothesis: originate in PCB holder



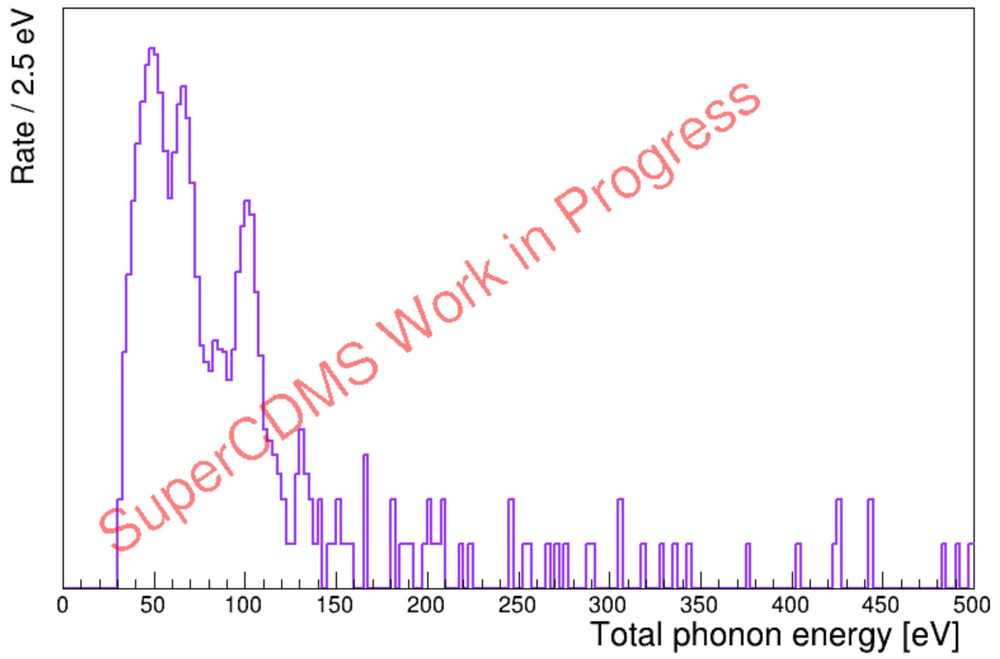
HVeV Run 3

- Coincidence measurement with HVeVs
- Confirmed external origin of burst events



HVeV Run 4

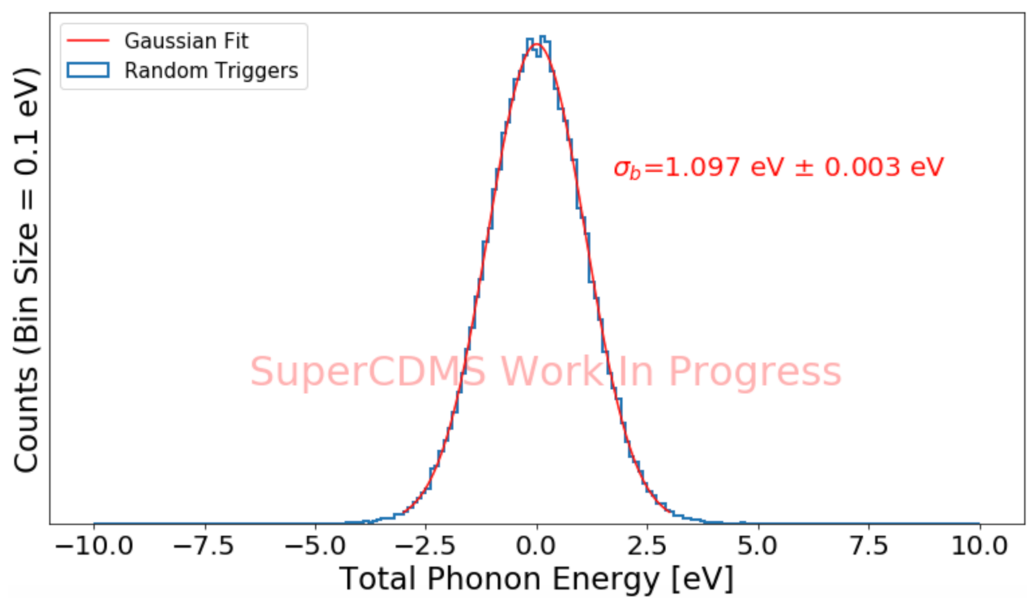
- Replaced PCB + coincidence measurement
- Elimination of higher-order e^-/h^+ peaks



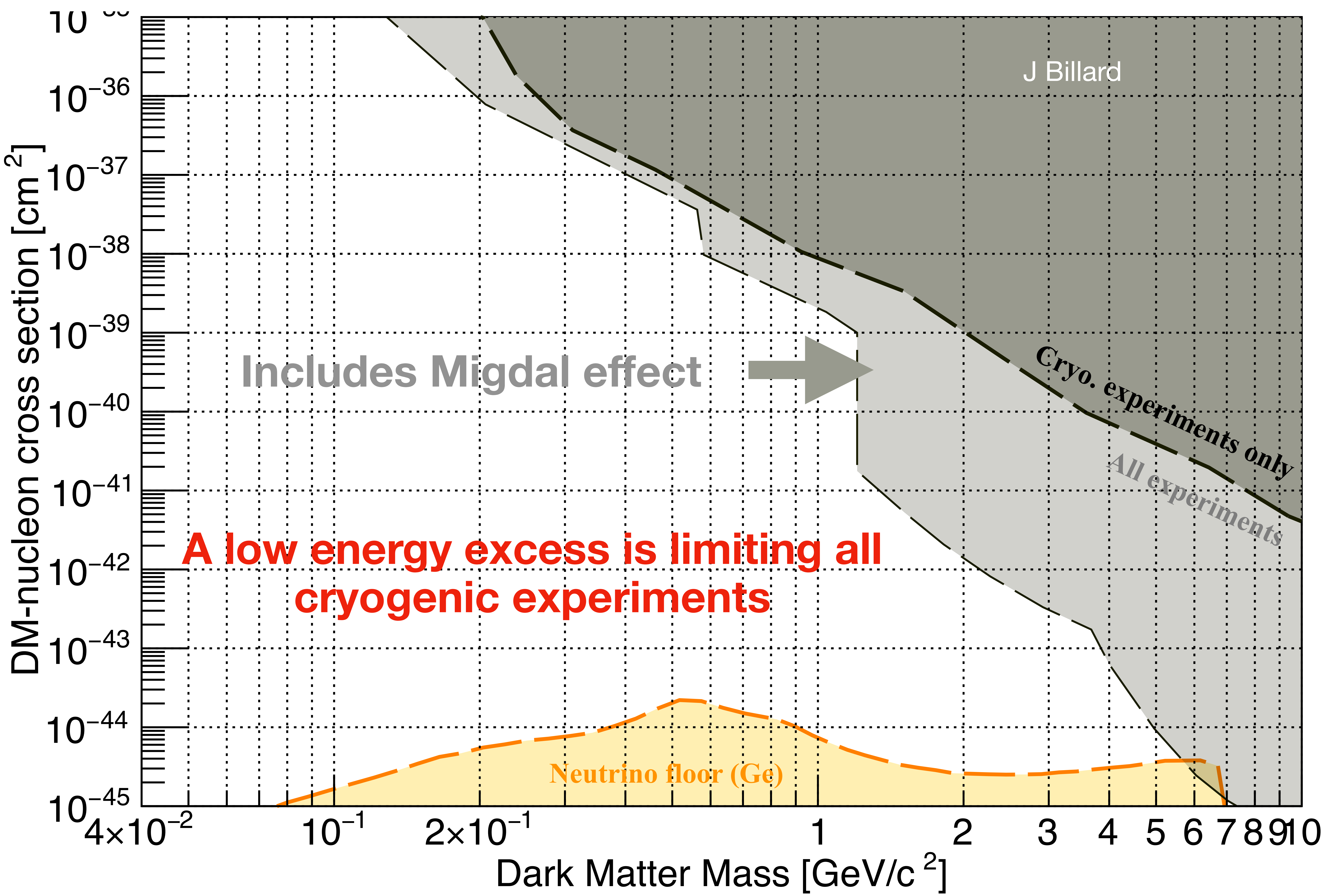
Latest performance

- V3 of HVeV detectors
- Achieved lowest baseline resolution in class!

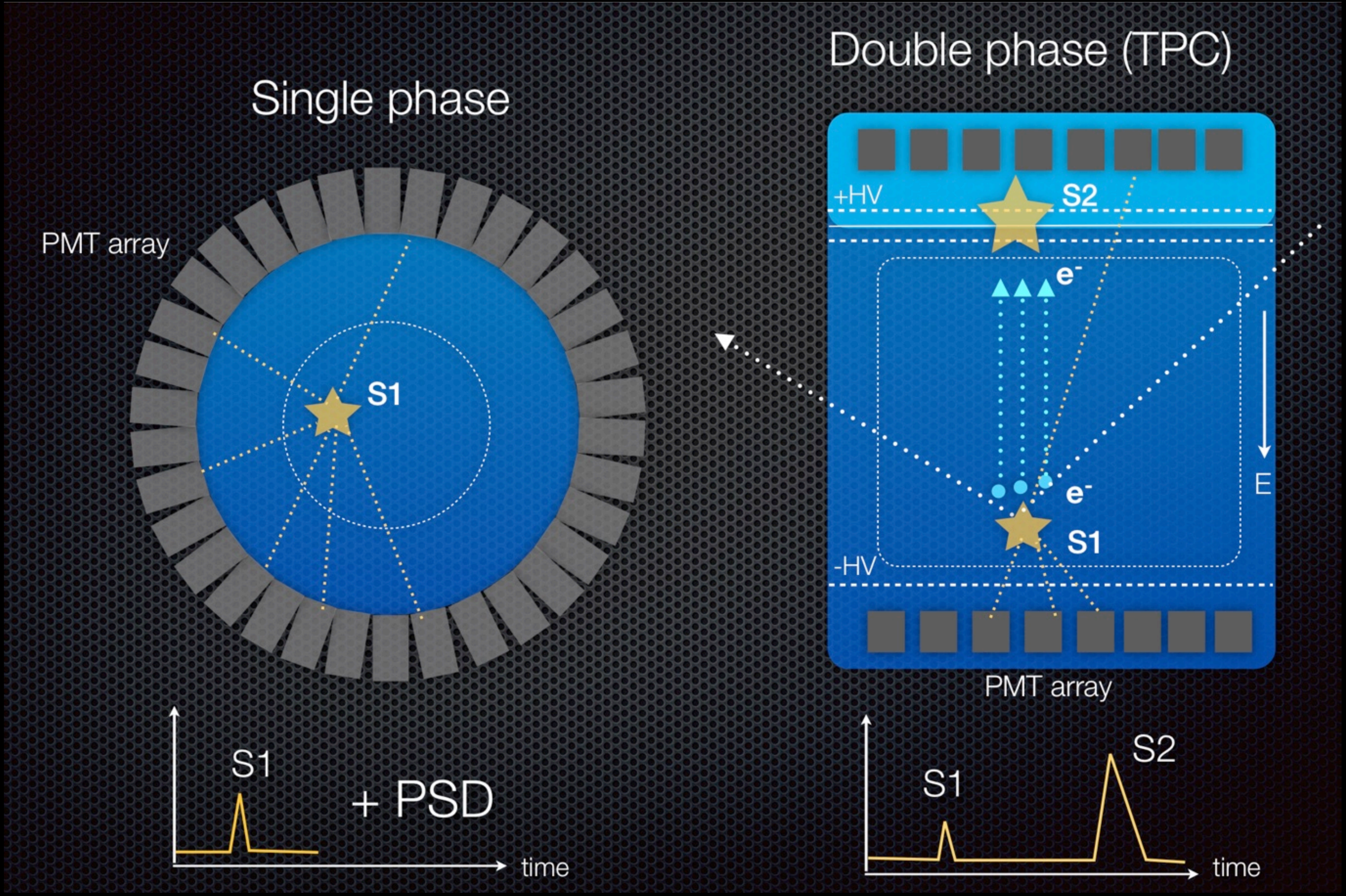
$\rightarrow \sigma_b = 1.097 \pm 0.003$ eV



Main competitors are not phonon experiments!

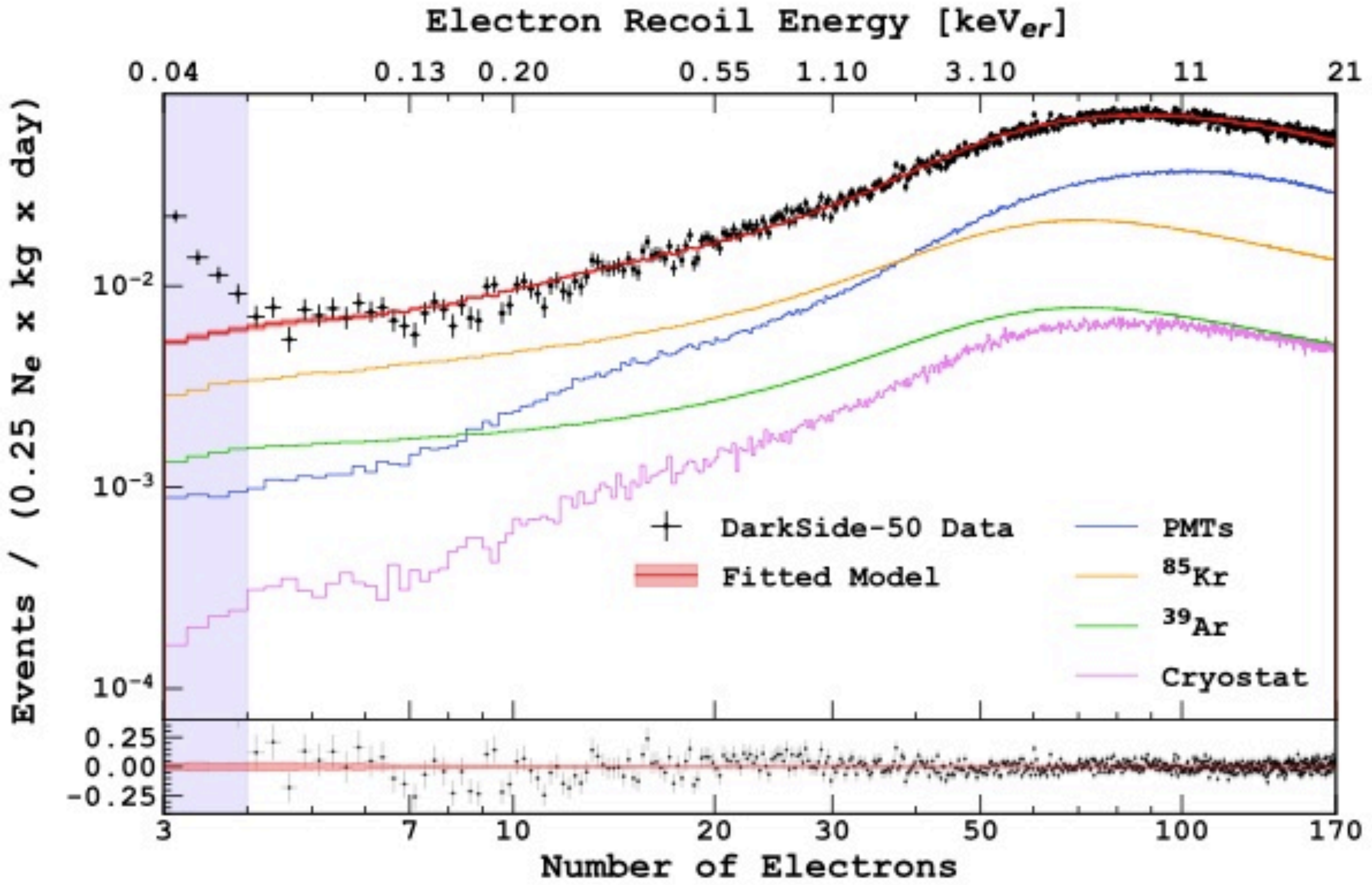


Dark Side

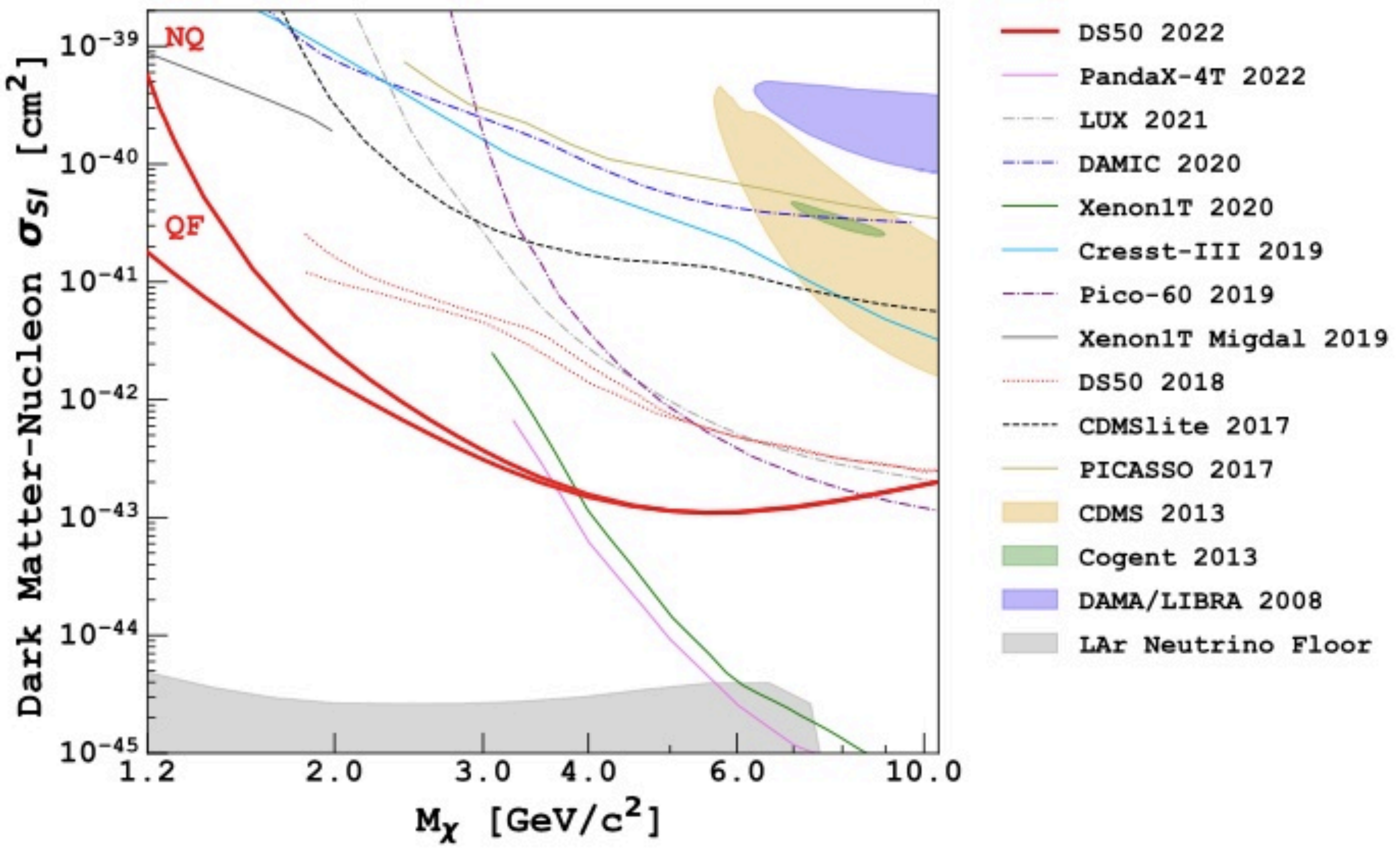


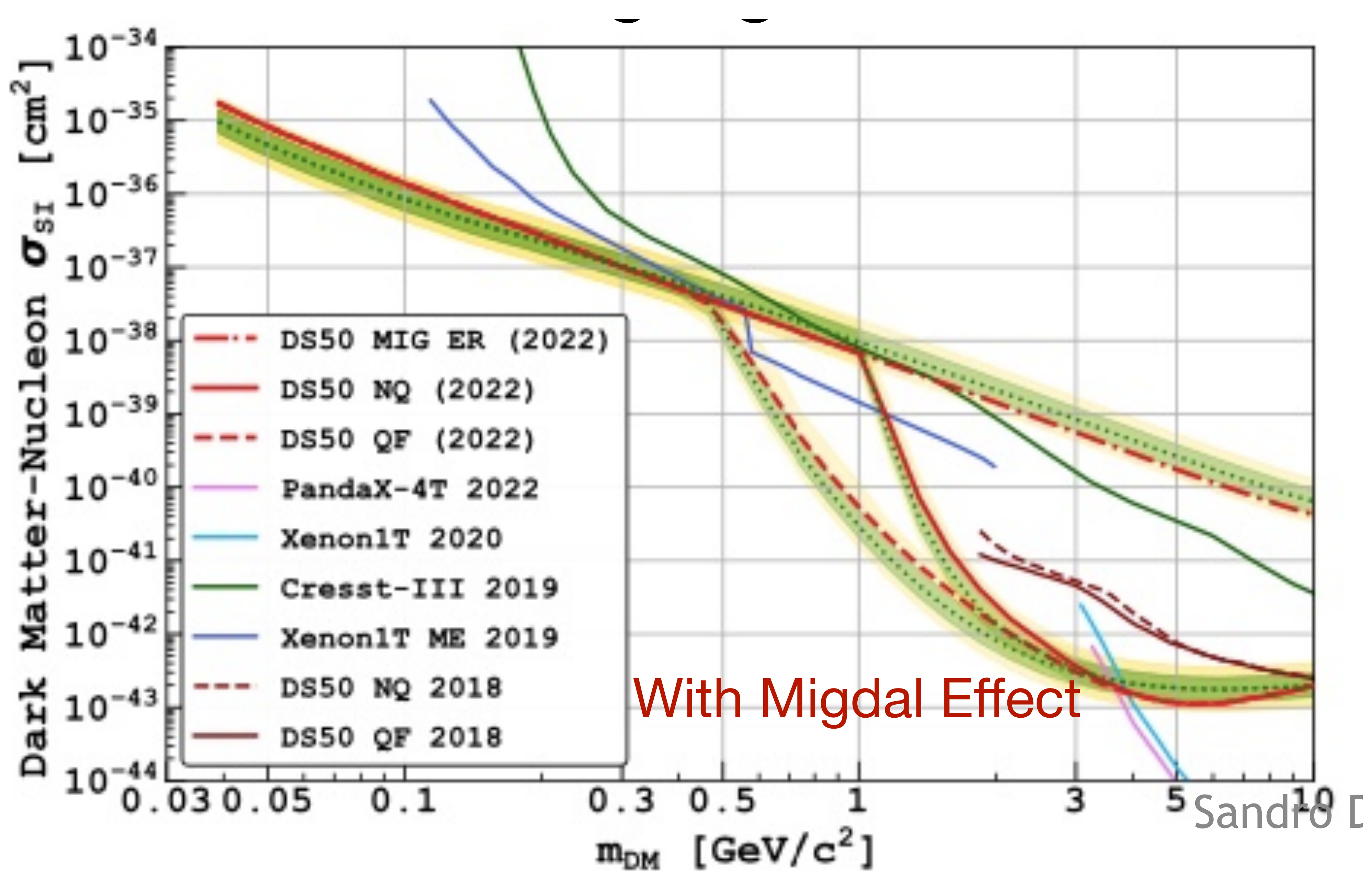
Single phase
PMT array
S1
S1
+ PSD
time
Double phase (TPC)
+HV
S2
e-
e-
S1
-HV
E
PMT array
S1
S2
time

DarkSide 50: electron recoils (S2 only)



DarkSide 50: S2 results

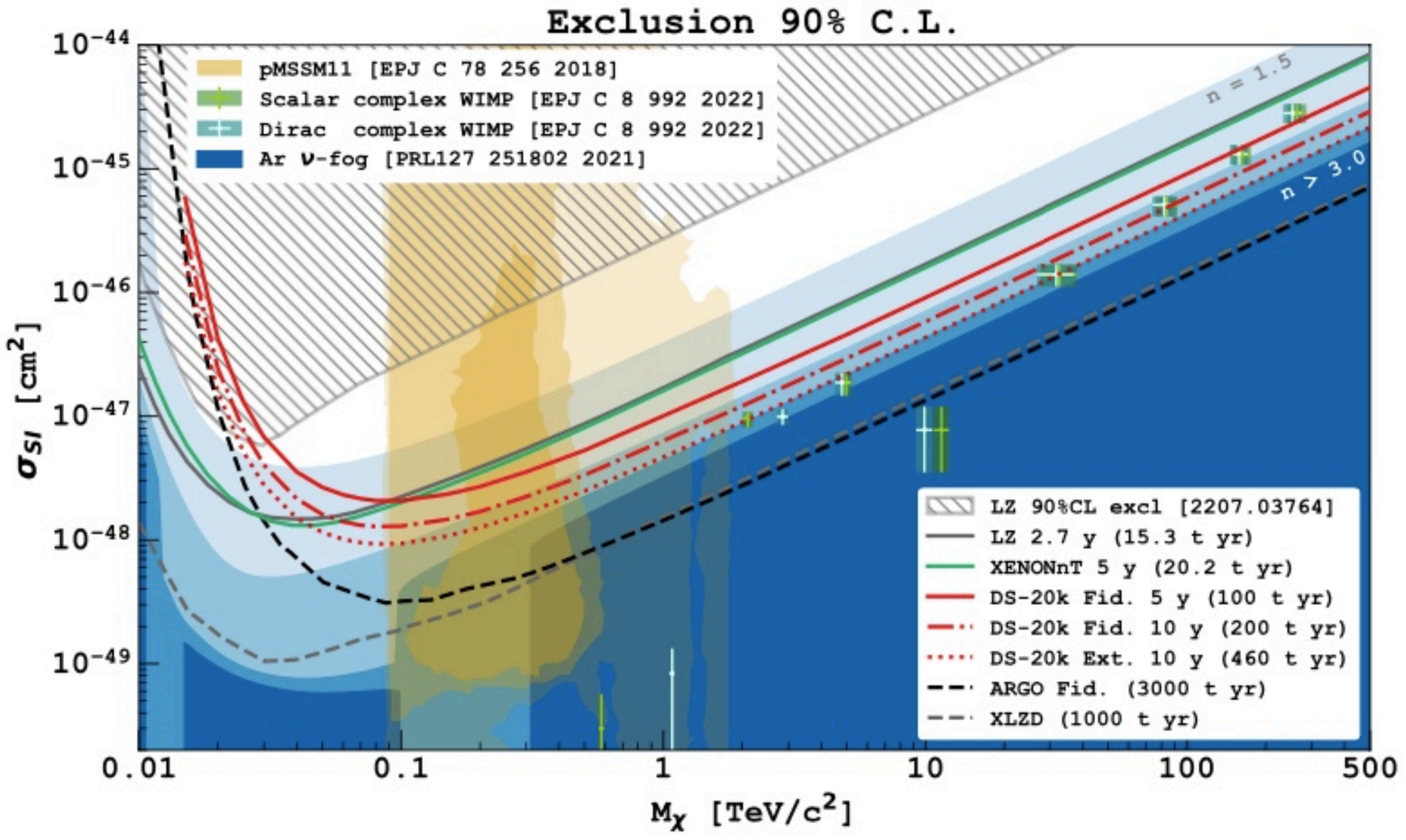




Phys. Rev. D 107, 063001 (2023)
Phys. Rev. Lett. 130, 101001 (2023)
Phys. Rev. Lett. 130, 101002 (2023)

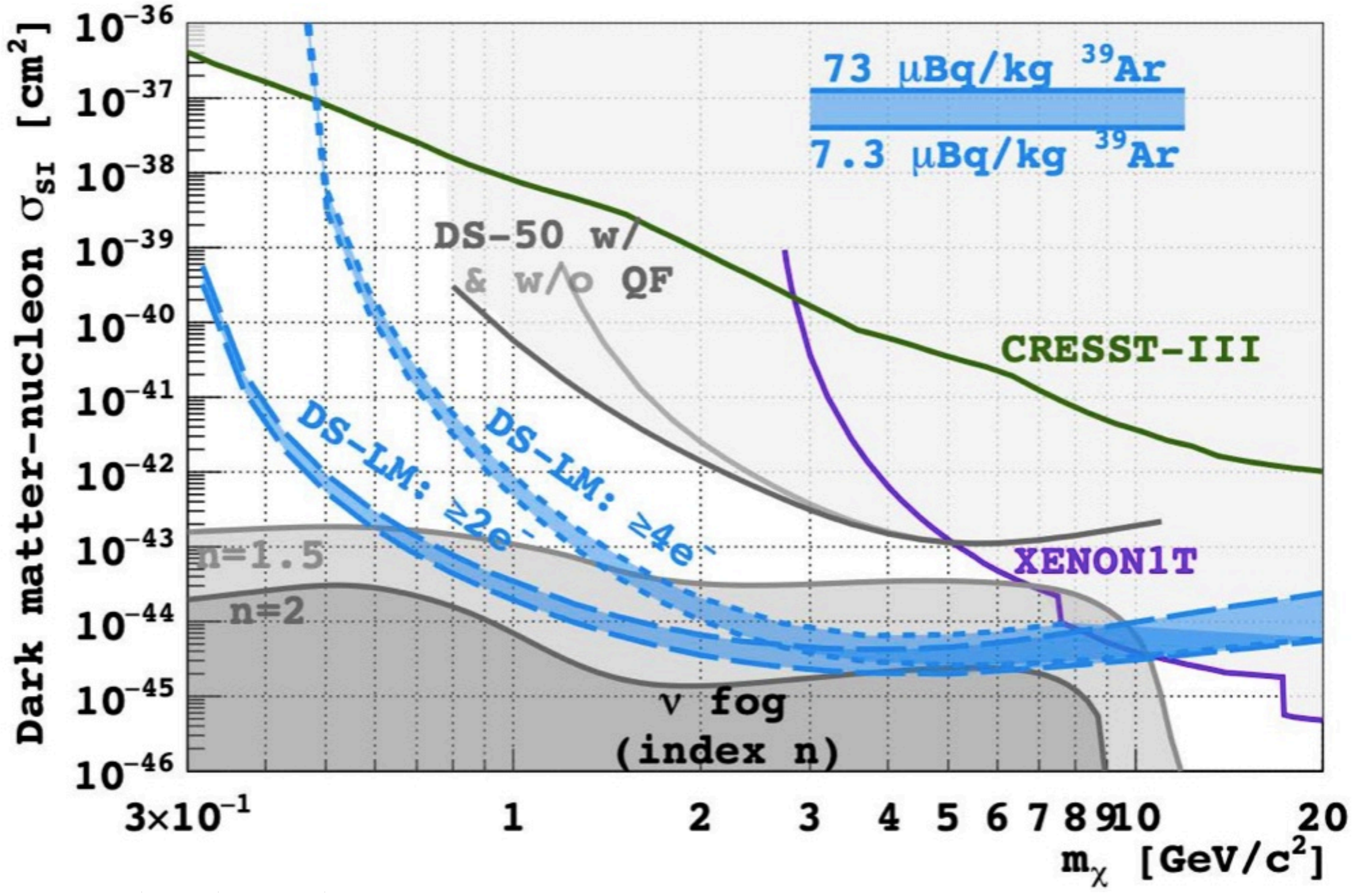
Also:
- ER interpretation of S2 only signature: Axions,dark photons, …
- Baiesian approach with evolved Likelihood including calibration parameters in the fit

DarkSide future: 20k and 1k low-mass?



High mass with 20 T

(Phys.Rev.D 107 (2023) 11, 112006) ***a conceptual low background 1 ton UAr TPC ~ 1 year exposure sensitivity:***

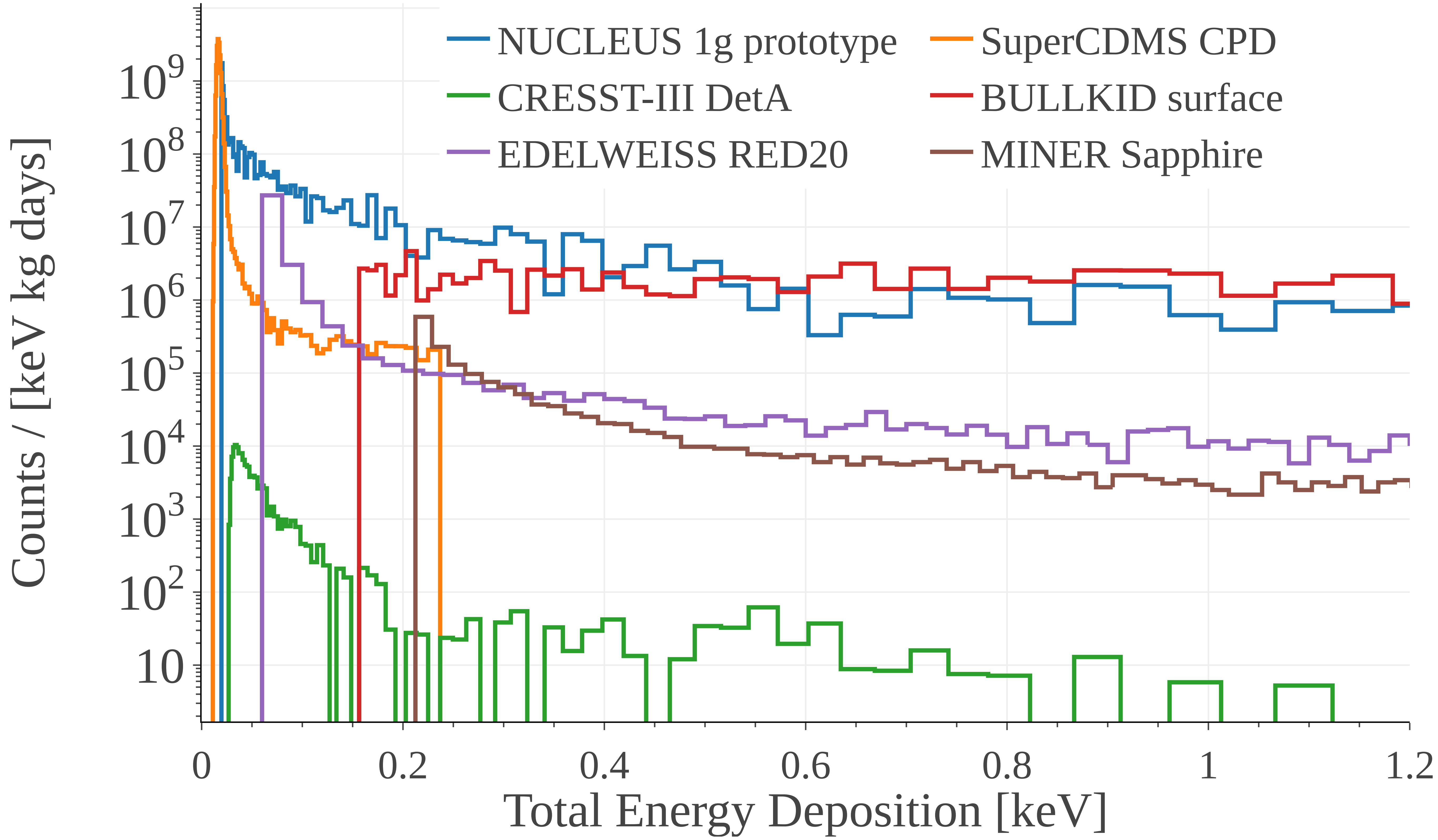


Low-mass with 1 T optimised for S2

Declared timescales

	Detector	Laboratory	Status	Date
CRESST	Phonon-TES	LNGS	Data taking + R&D	
TESSERACT	Phonon-TES / Phonon-LHe	LSM	R&D	2026 (start construction)
Super CDMS	Phonon-TES	SNOLAB	Construction	2025 (start science run)
DarkSide 20k/LM	Liquid scintillator	LNGS	Construction	2026 (end construction)

Who wins? The one who beats the excess



BULLKID already implements all the strategies that other experiments are now beginning implementation:
multi-sensor, instrumented holders
but
this does not ensure that we solved it down to < 1 DRU

Excess workshop in Rome: 6 July 2024 - https://agenda.infn.it/event/39007/