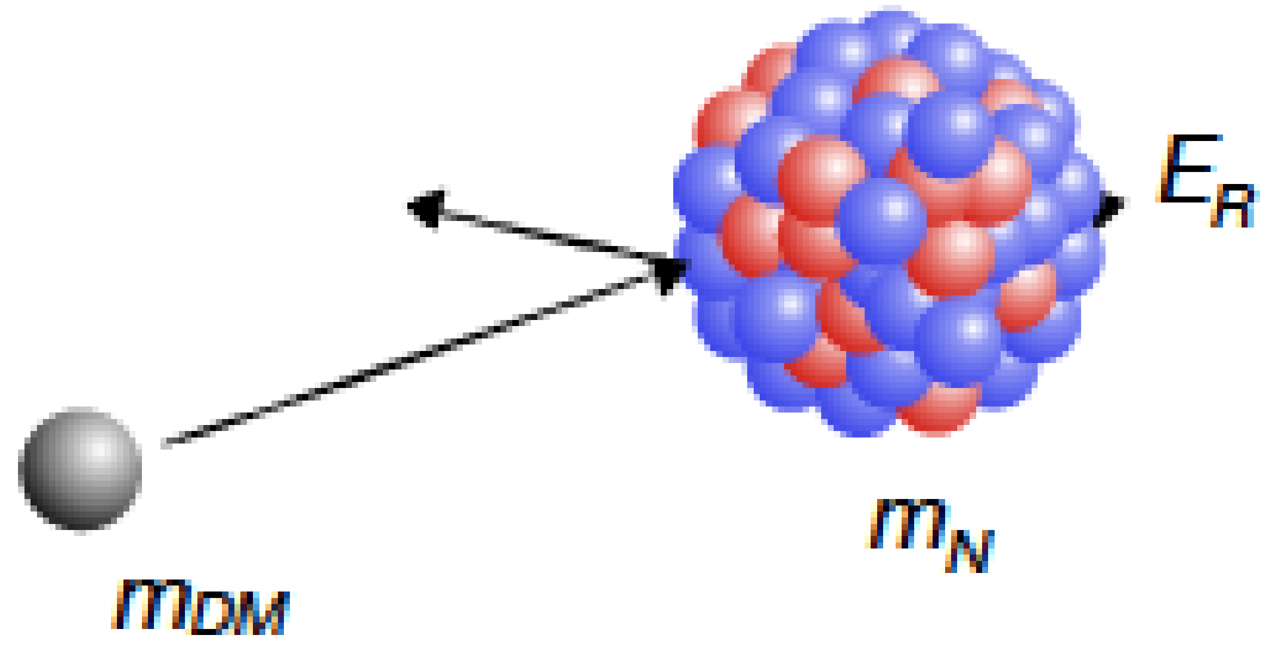
2024/10/16

Direct Searches for Sub-GeV Dark Matter

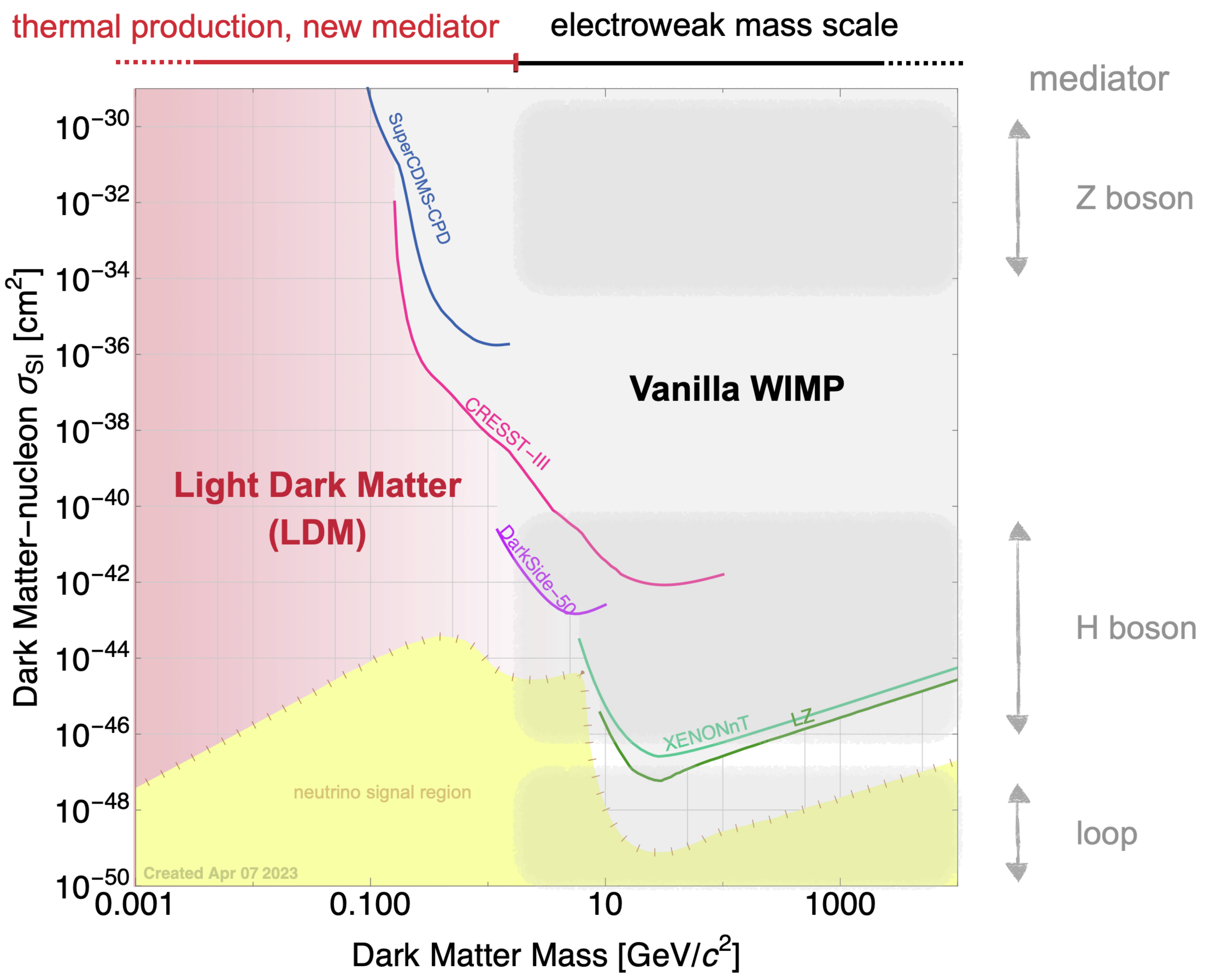
Jodi Cooley
Executive Director | SNOLAB
Professor of Physics | Queen’s University
Adjunct Research Professor SMU

Direct Detection Landscape



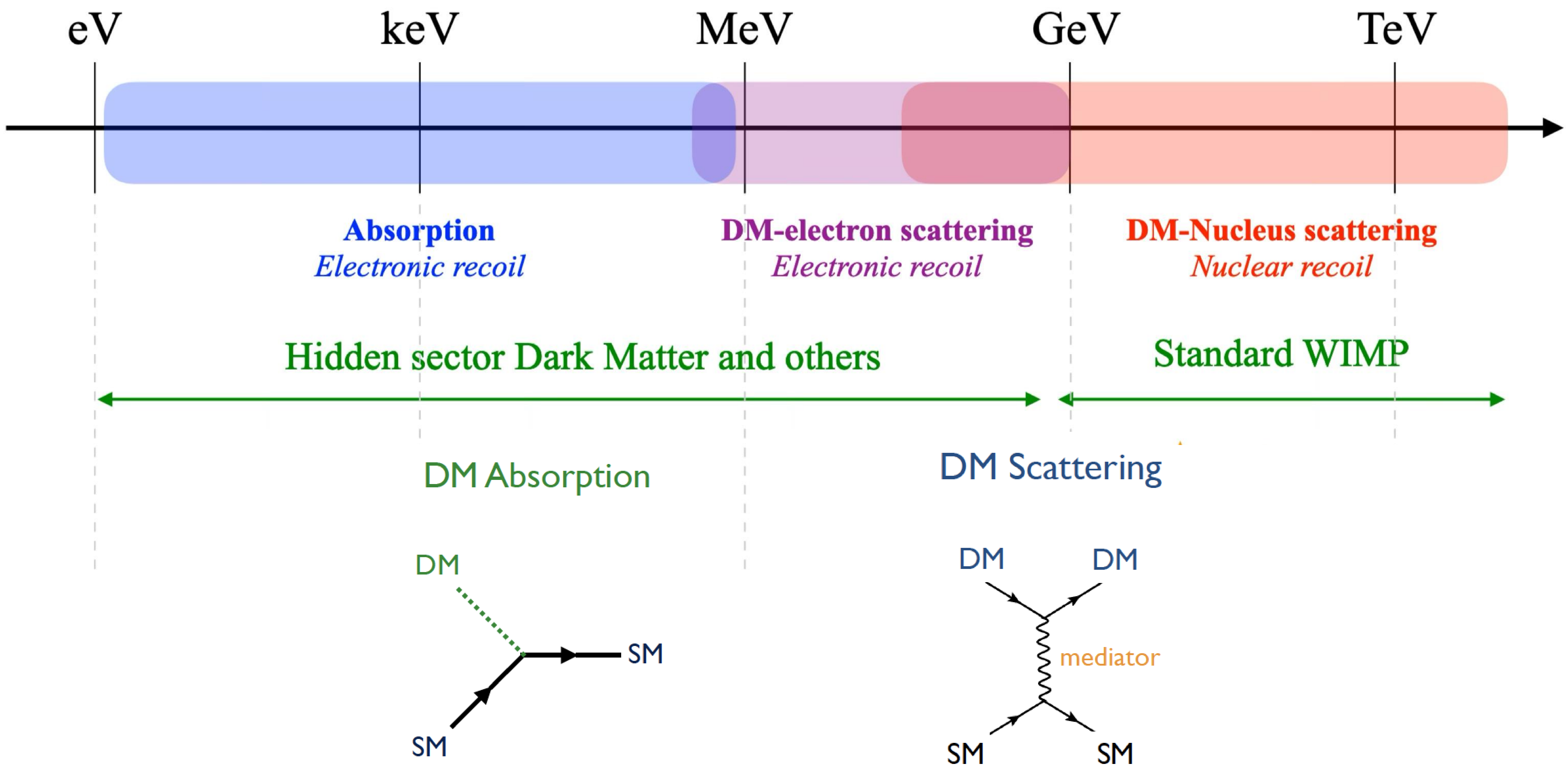
Observable recoil energy:

$$E_R = \frac{1}{2}\frac{\Delta p^2}{m_N} \lesssim \frac{2\, m_{\rm DM}^2 v_{\rm DM}^2}{m_N}$$



Sub-GeV searches require…

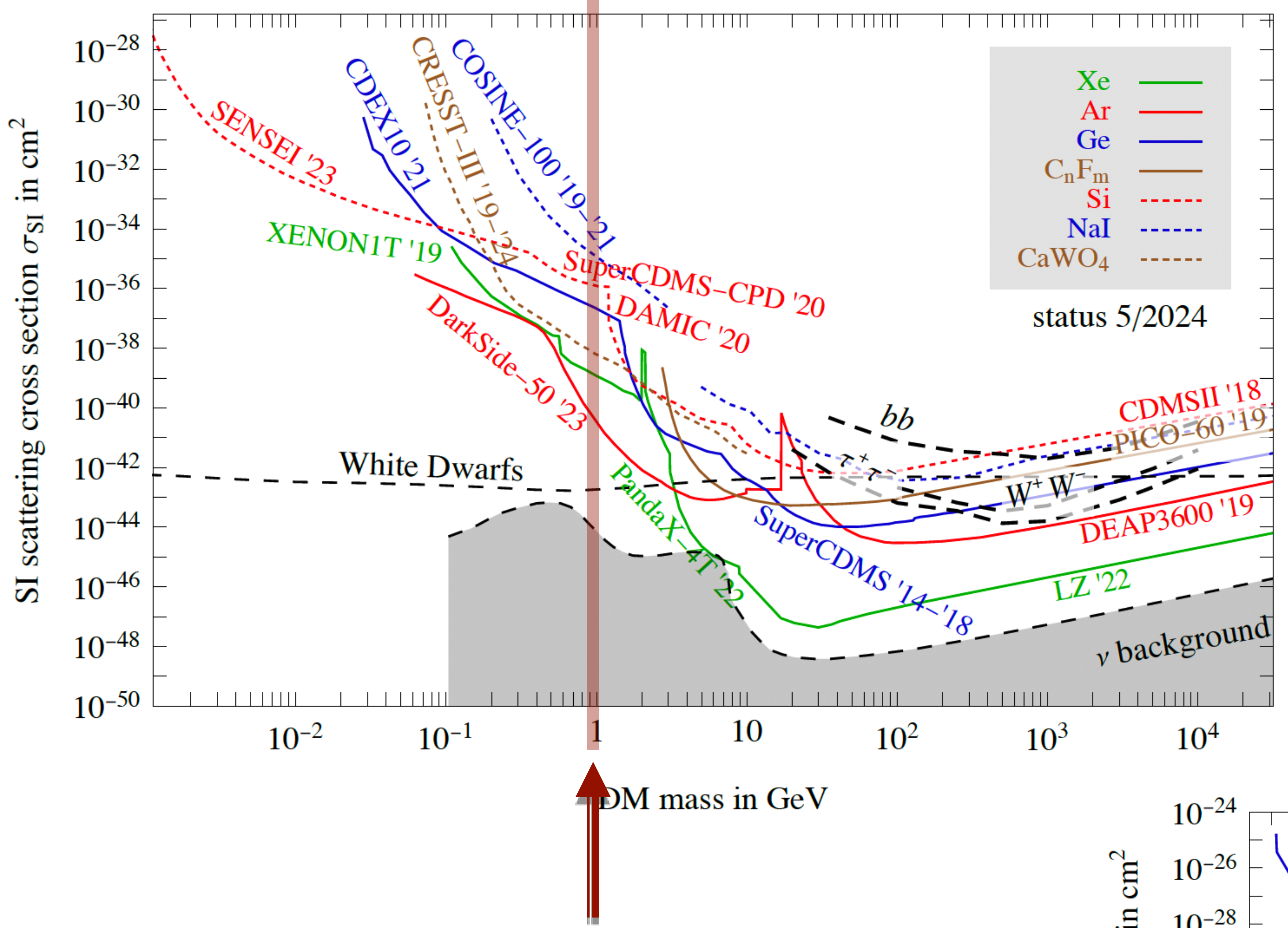
- ultra-low energy thresholds and/or
- light scattering partners and/or
- interaction channels beyond scattering



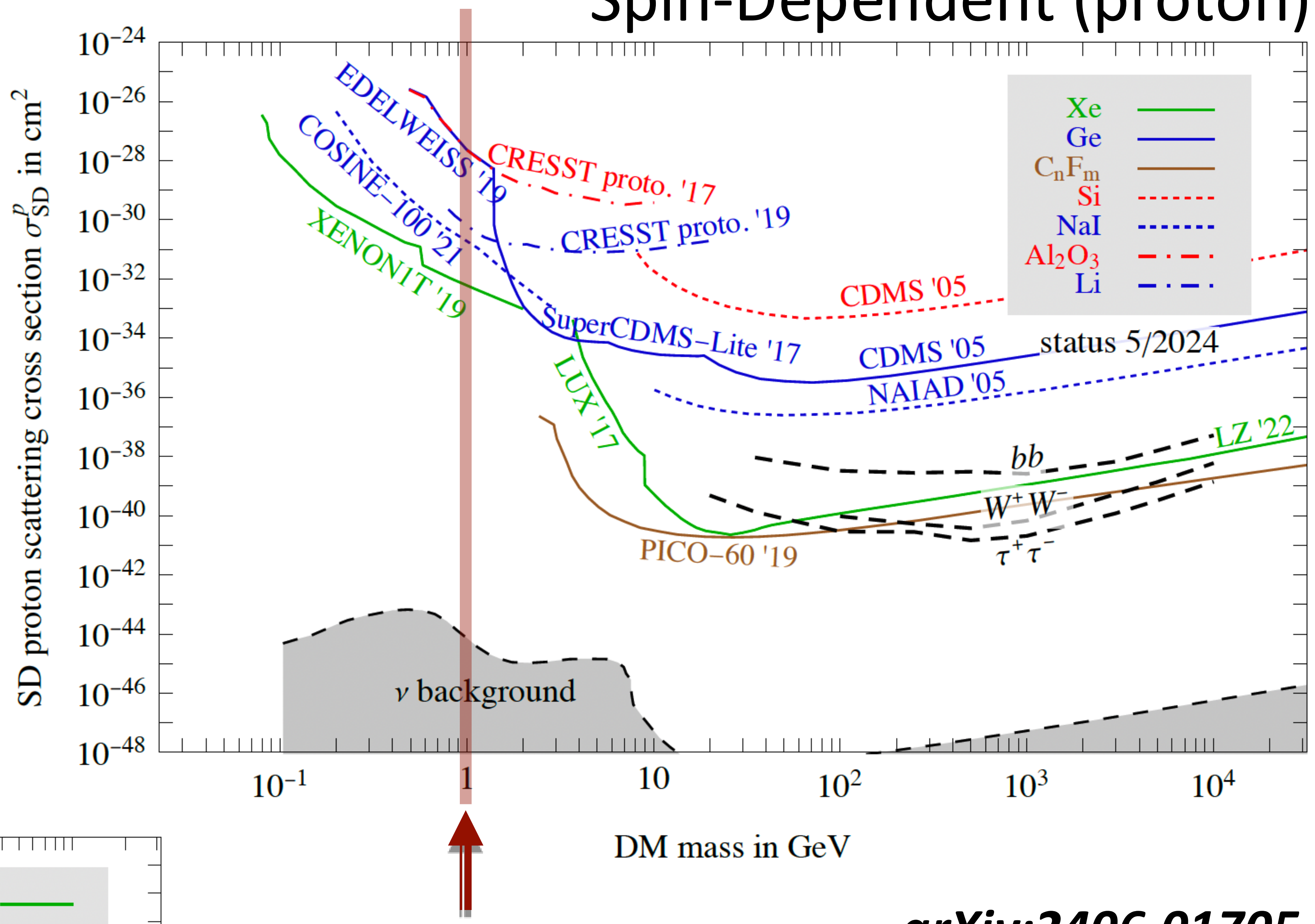
DM – Nucleon Scattering

Current Status: DM-Nucleon Scattering

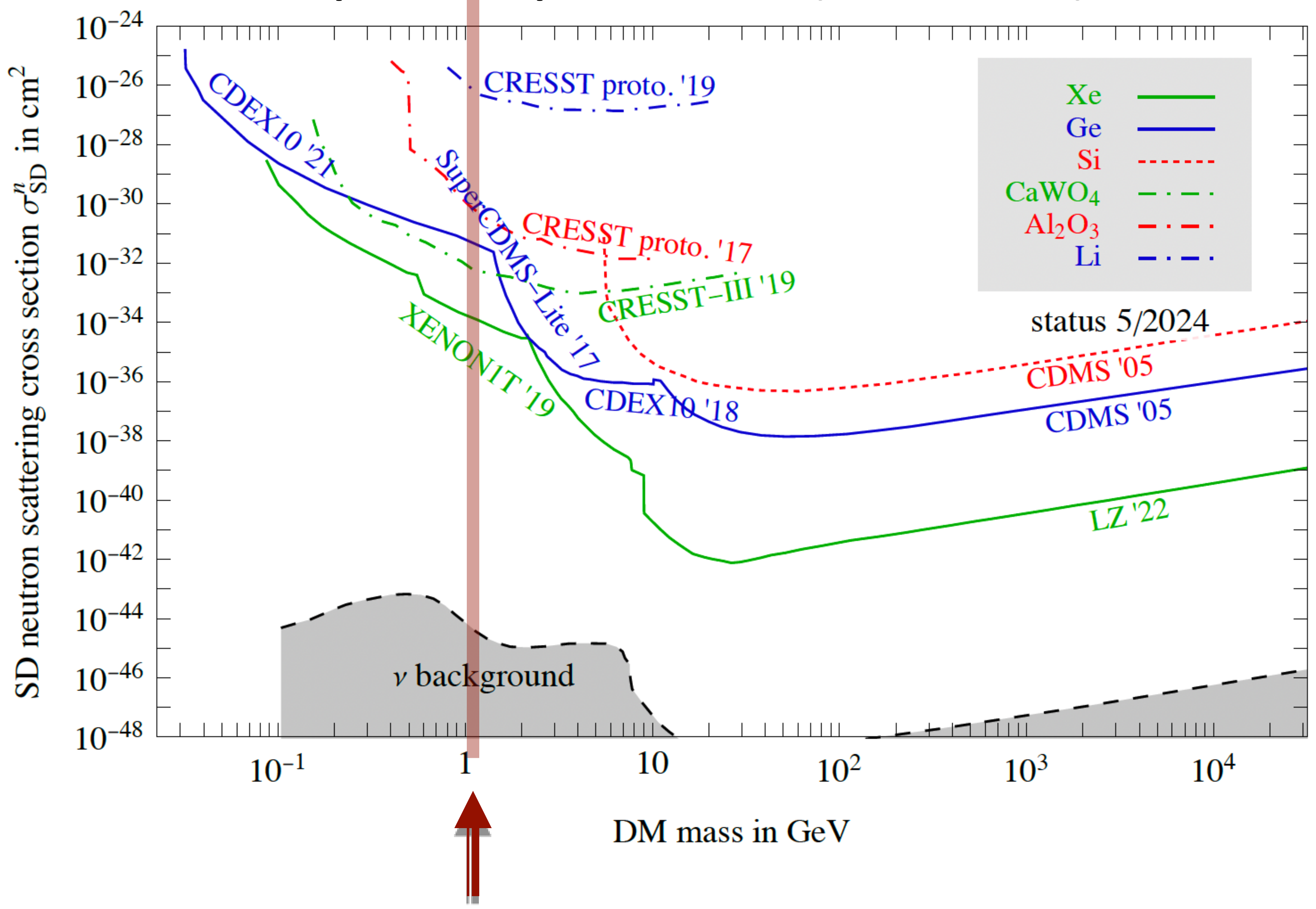
Spin-Independent



Spin-Dependent (proton)



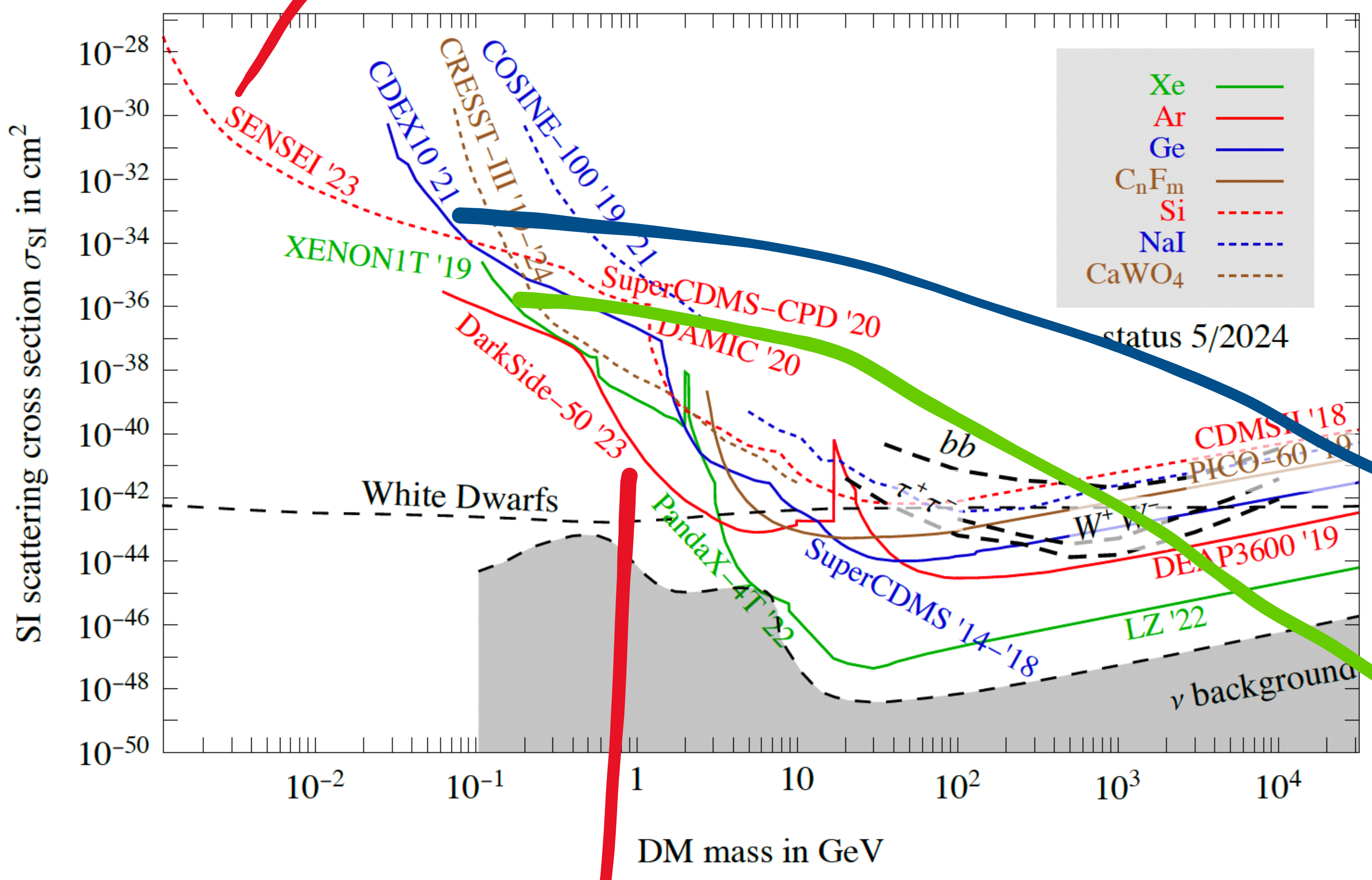
Spin-Dependent (neutron)



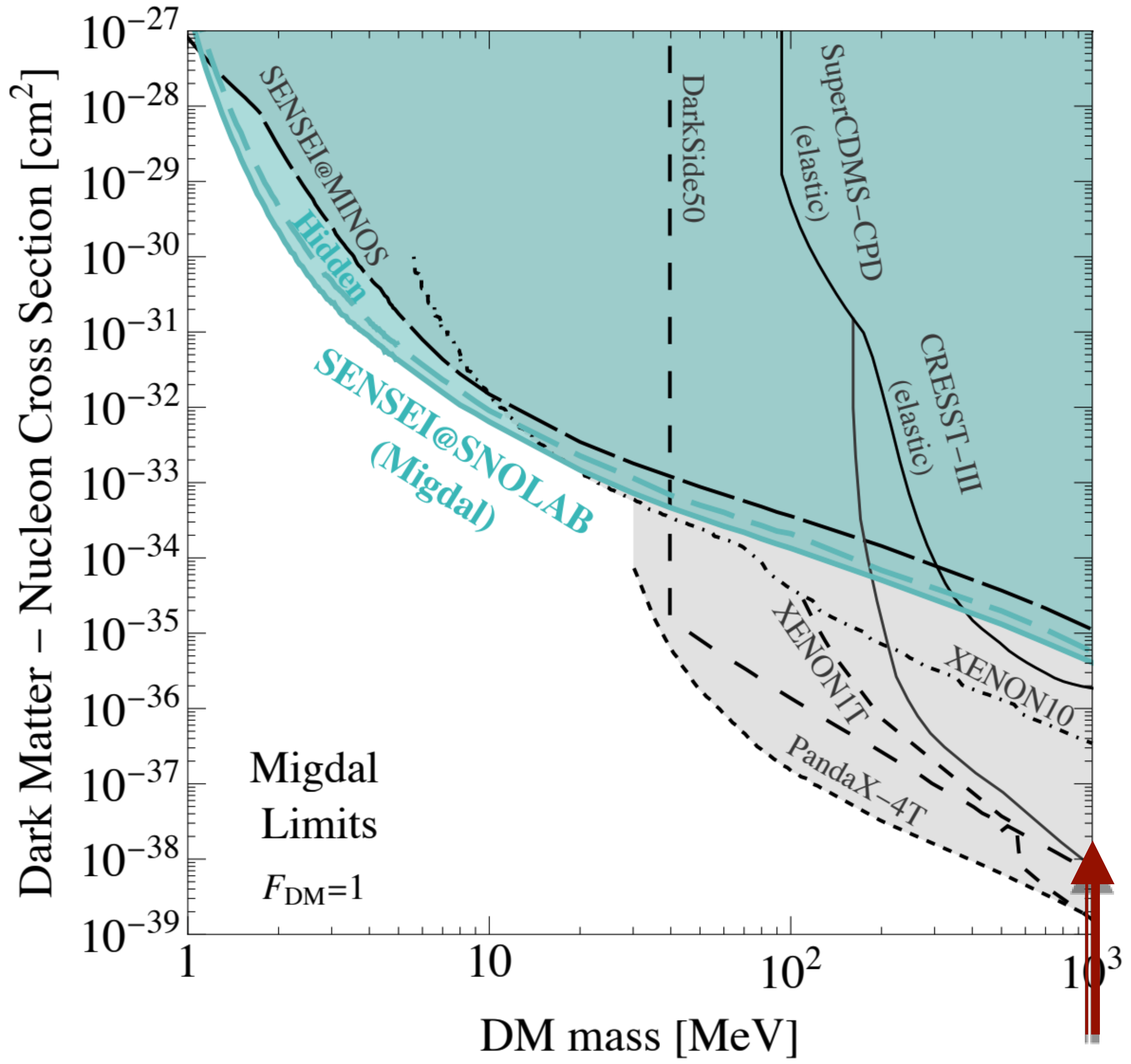
arXiv:2406.01705

There is quite a bit of activity below 1 GeV!

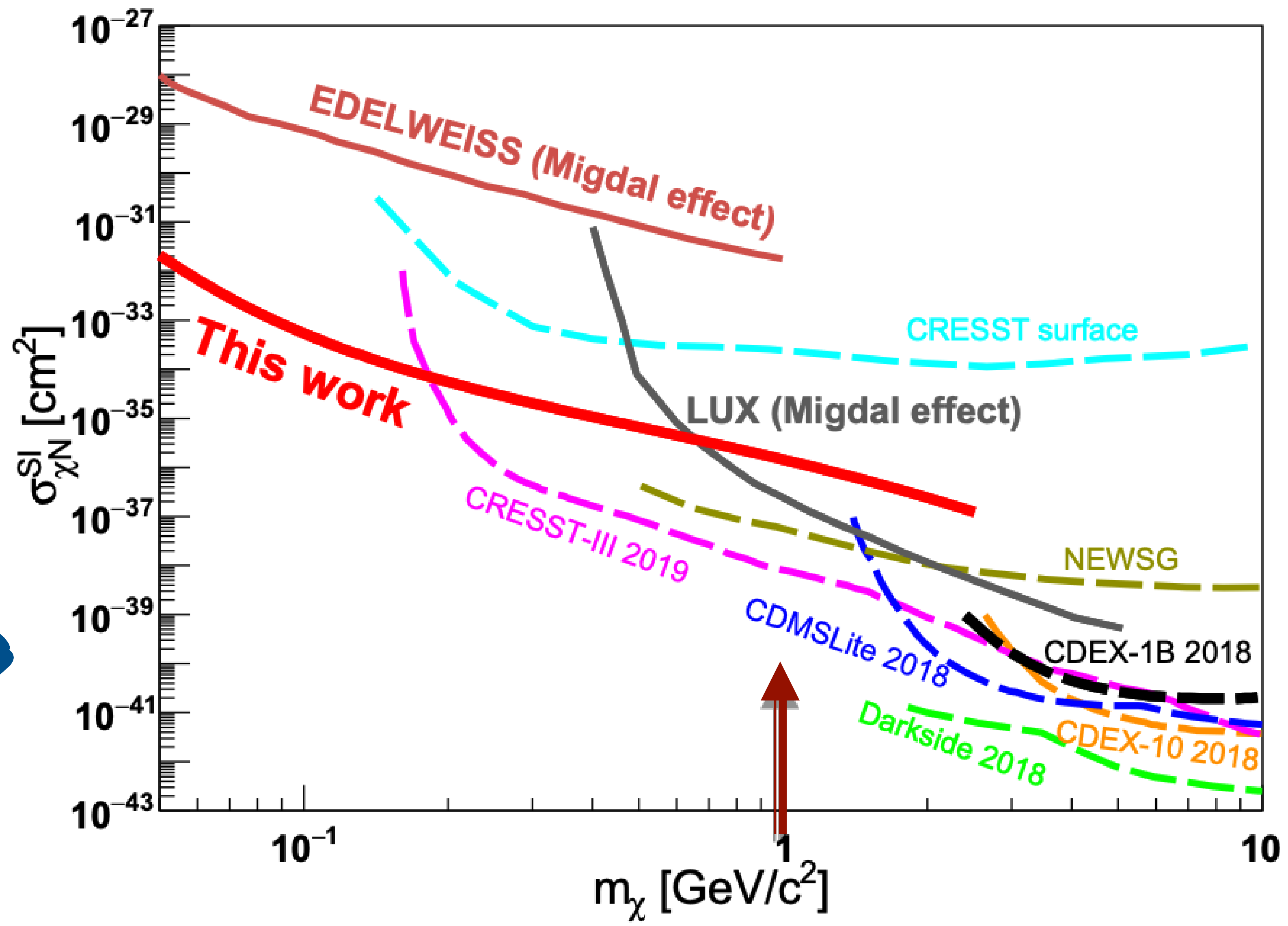
… but it is NOT all elastic scattering!



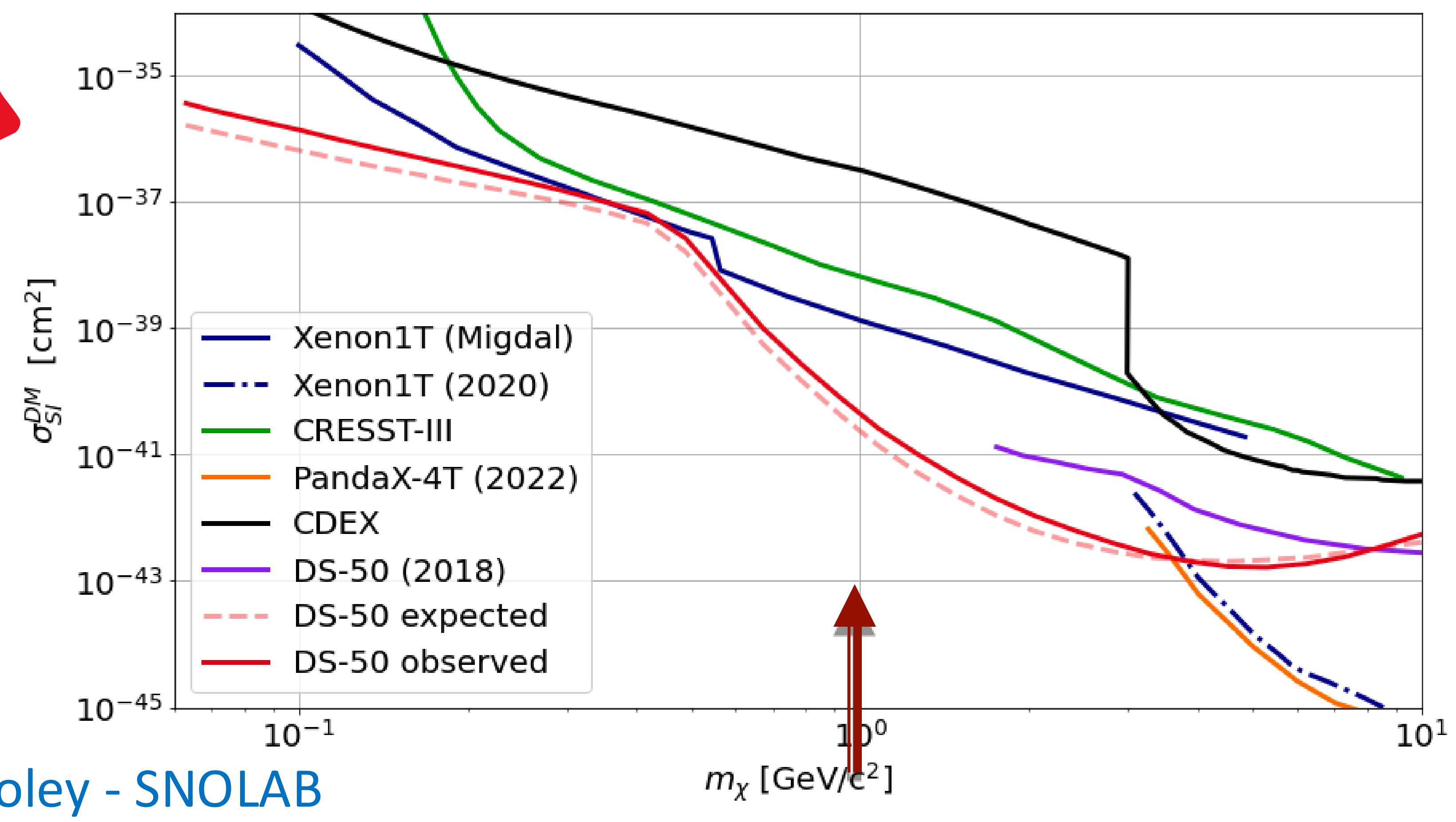
SENSEI, arXiv:2312.13342



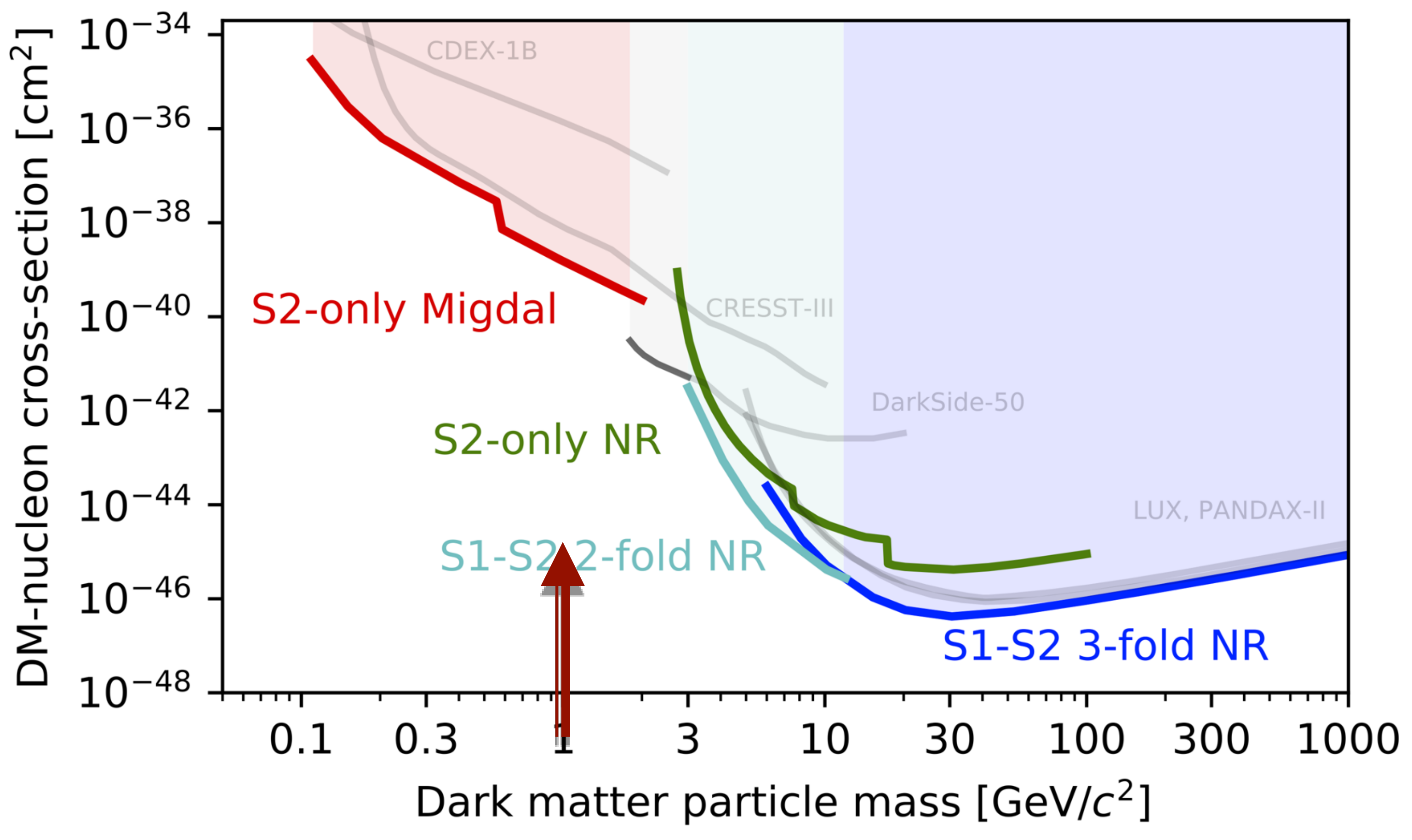
CDEX, Phys. Rev. Lett. 123, 161301



DarkSide-50, Eur. Phys. J. C 83, 322



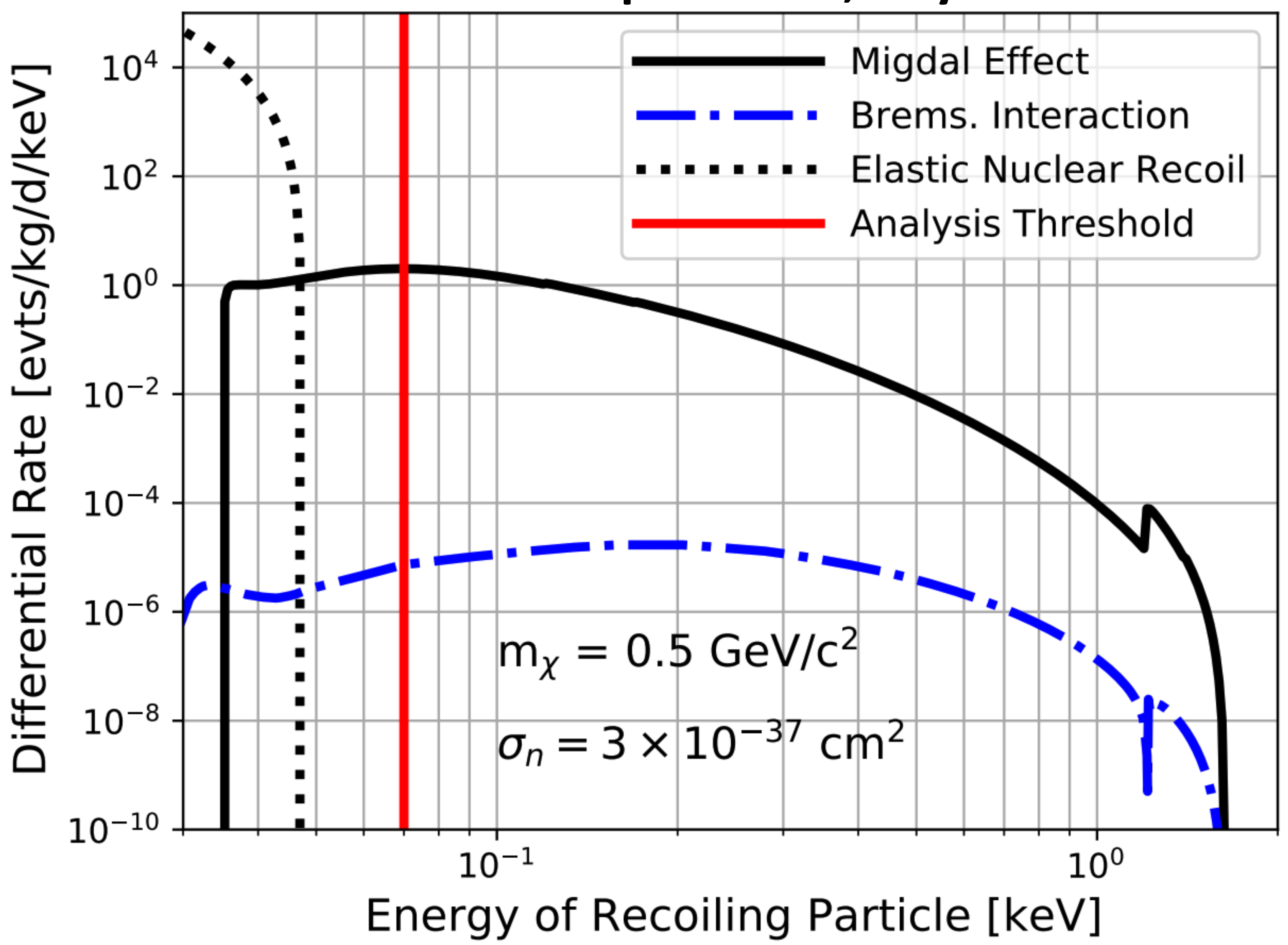
XENON1T, Phys. Rev. D 102, 072004

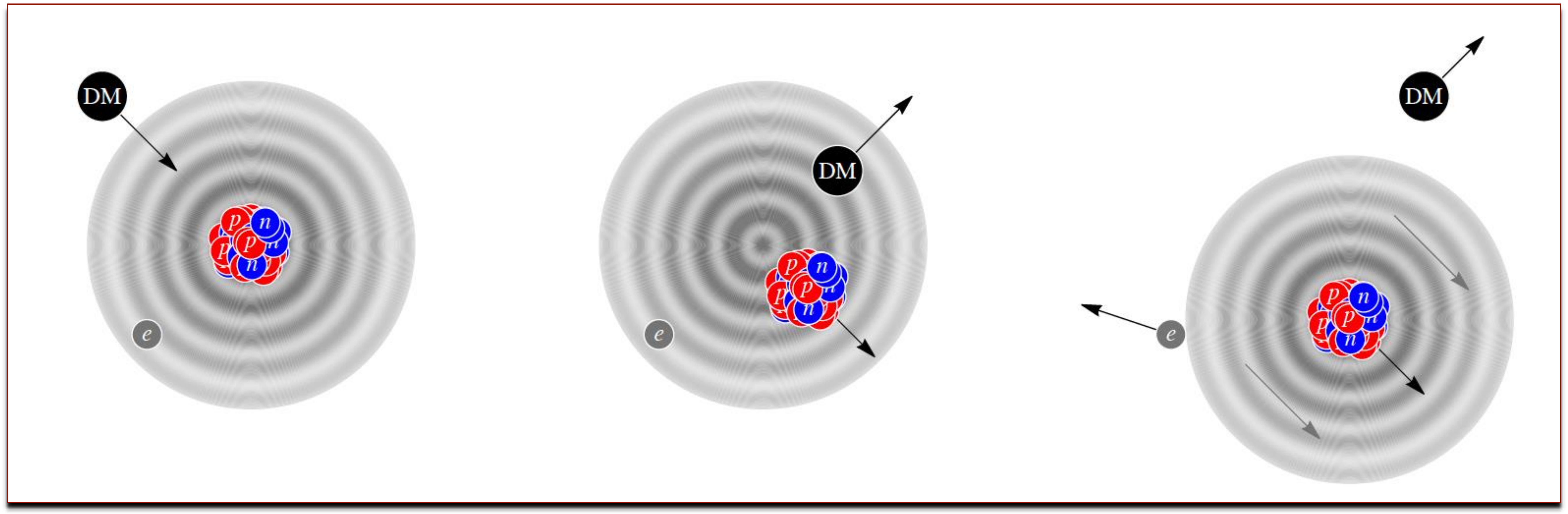


Migdal Effect

- DM first scatters on nucleus
  → nucleus recoils
- Perturbation is transferred to electron cloud
  → an electron is kicked out

SuperCDMS, Phys. Rev. D 107

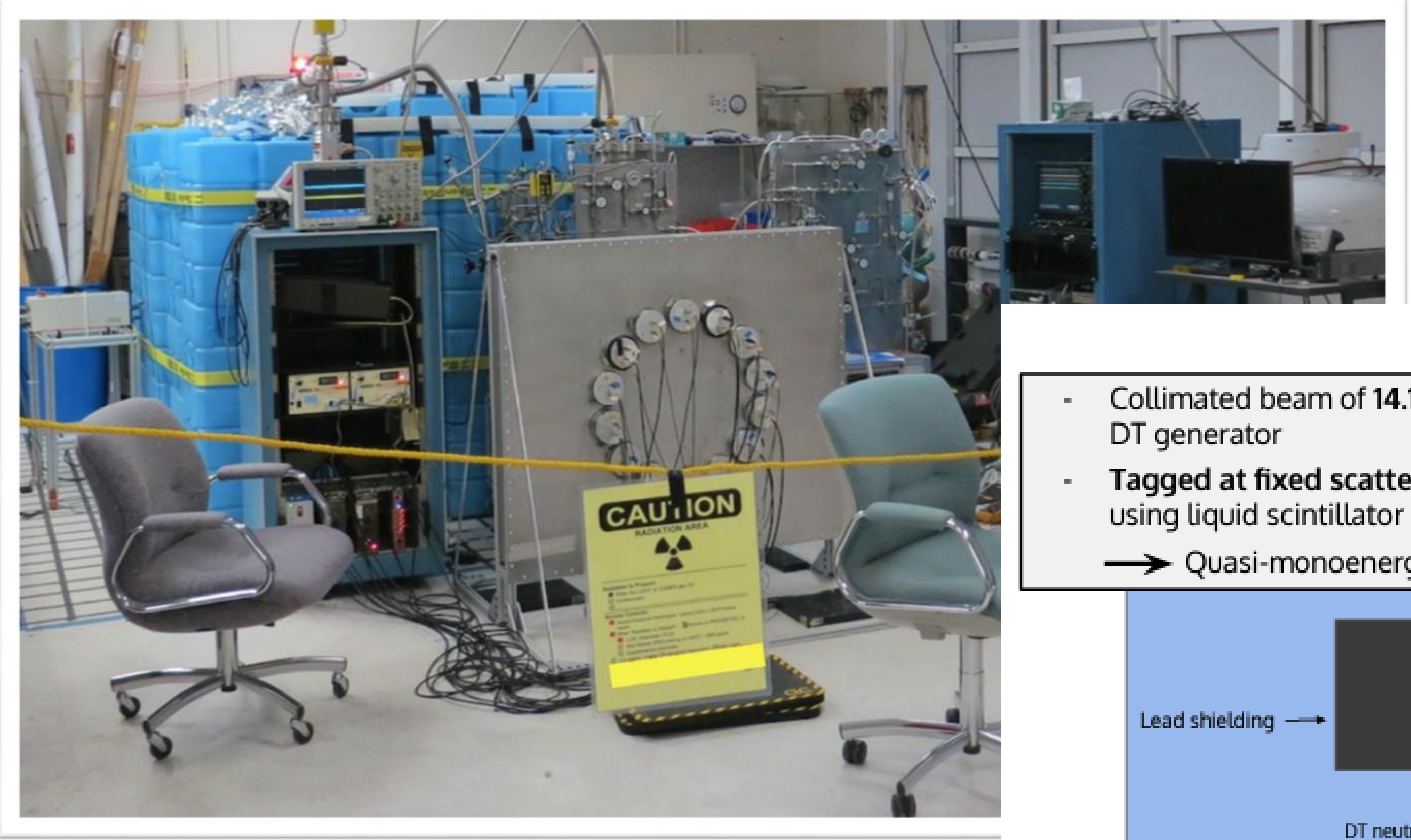




arXiv:2406.01705

- Migdal atomic relaxation can lead to keV electron recoil energy for sub-keV nuclear recoils.
- ***This process has not yet been observed in nuclear recoiling events!***

Search for Migdal Effect in LXe

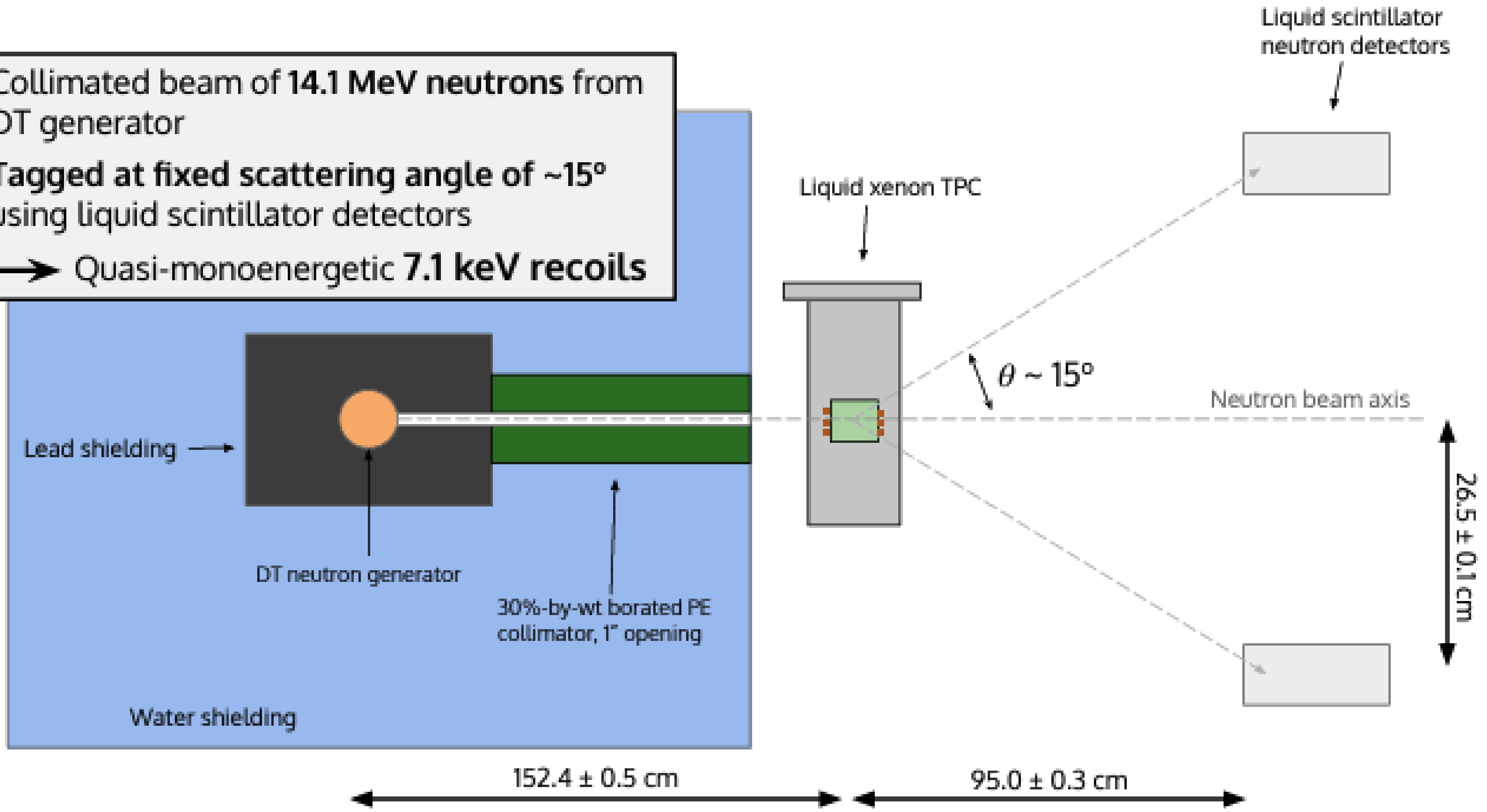


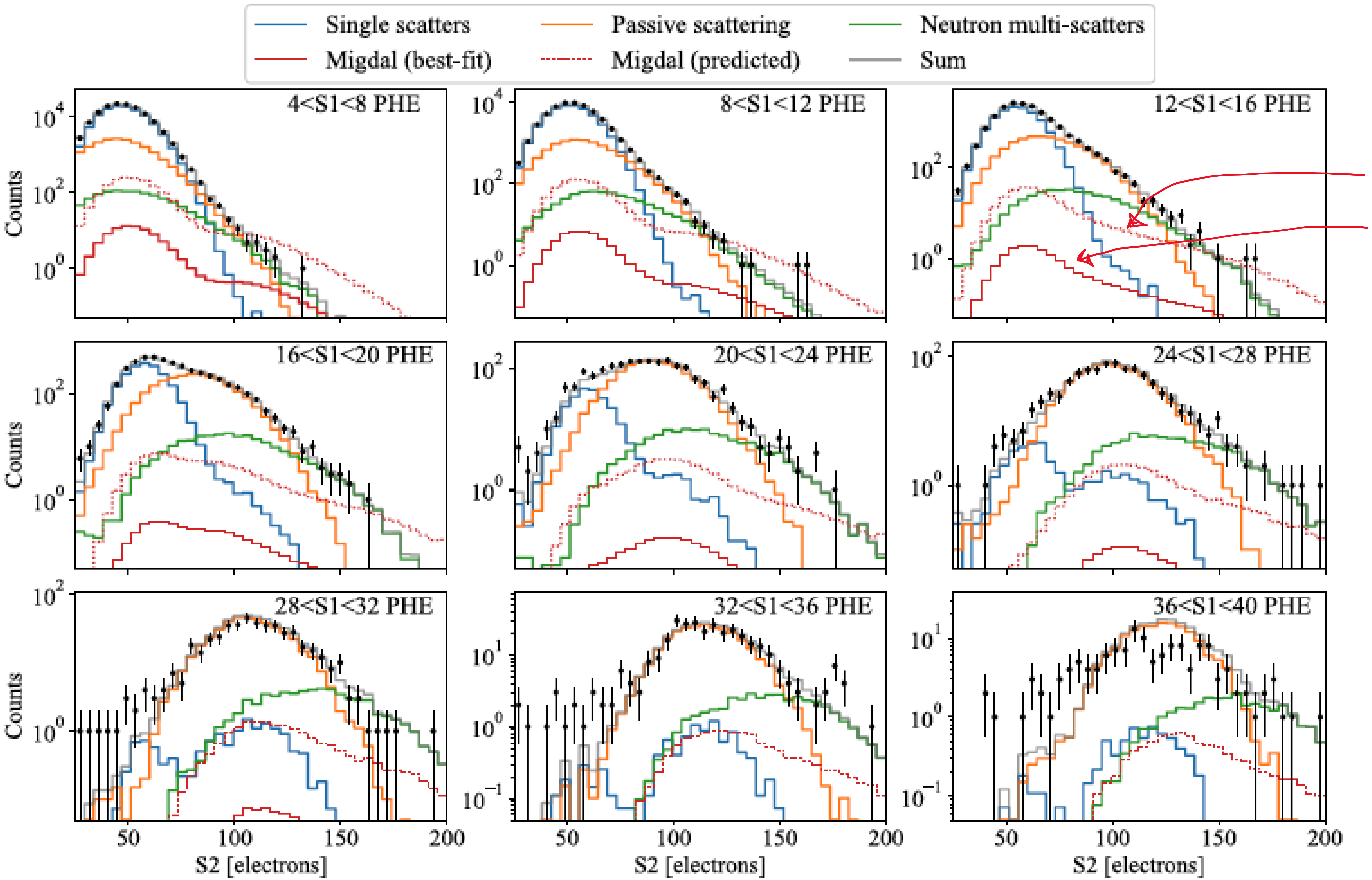
Experimental setup at LLNL

Phys. Rev. D 109, L051101 (2024)

- Collimated beam of **14.1 MeV neutrons** from DT generator
- **Tagged at fixed scattering angle of ~15°** using liquid scintillator detectors

⟶ Quasi-monoenergetic **7.1 keV recoils**



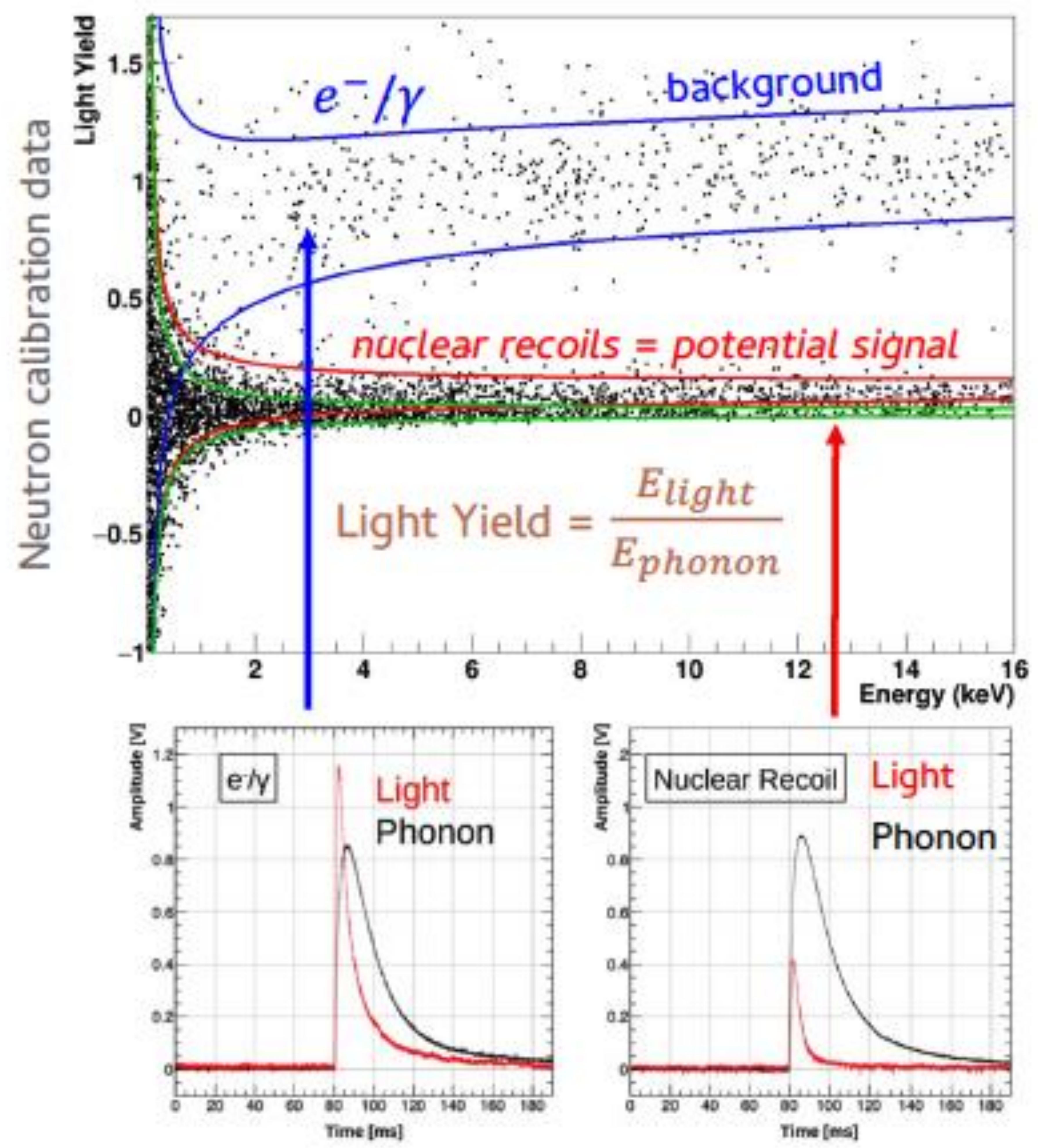


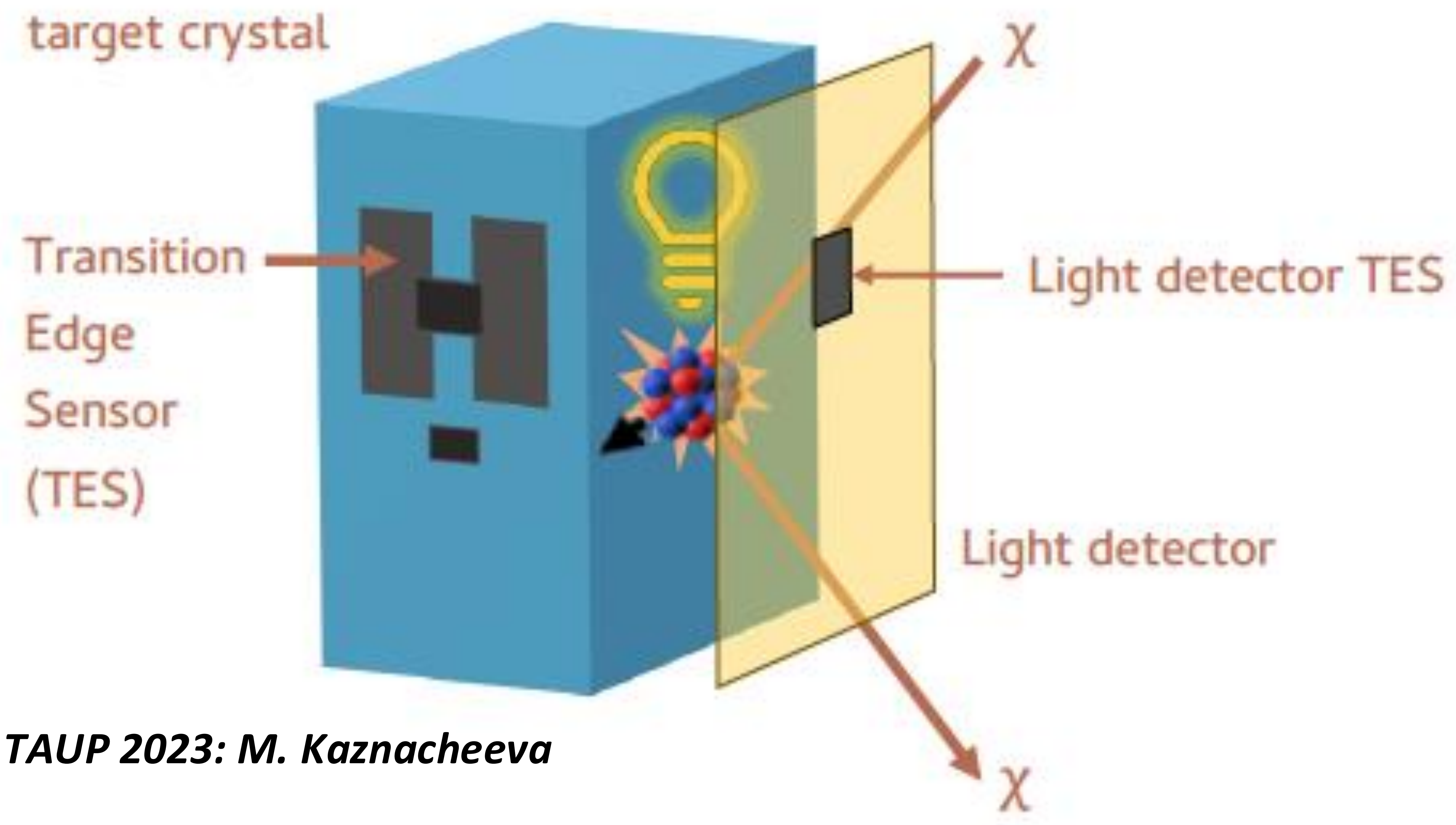
Possible explanations:

- *Overestimate of the rate of Migdal ionization in liquid xenon?*
- *Enhanced electron-ion recombination in the liquid xenon?*

A number of groups aim to measure this effect using a variety of targets.

Phonon and Scintillation Signal - CRESST





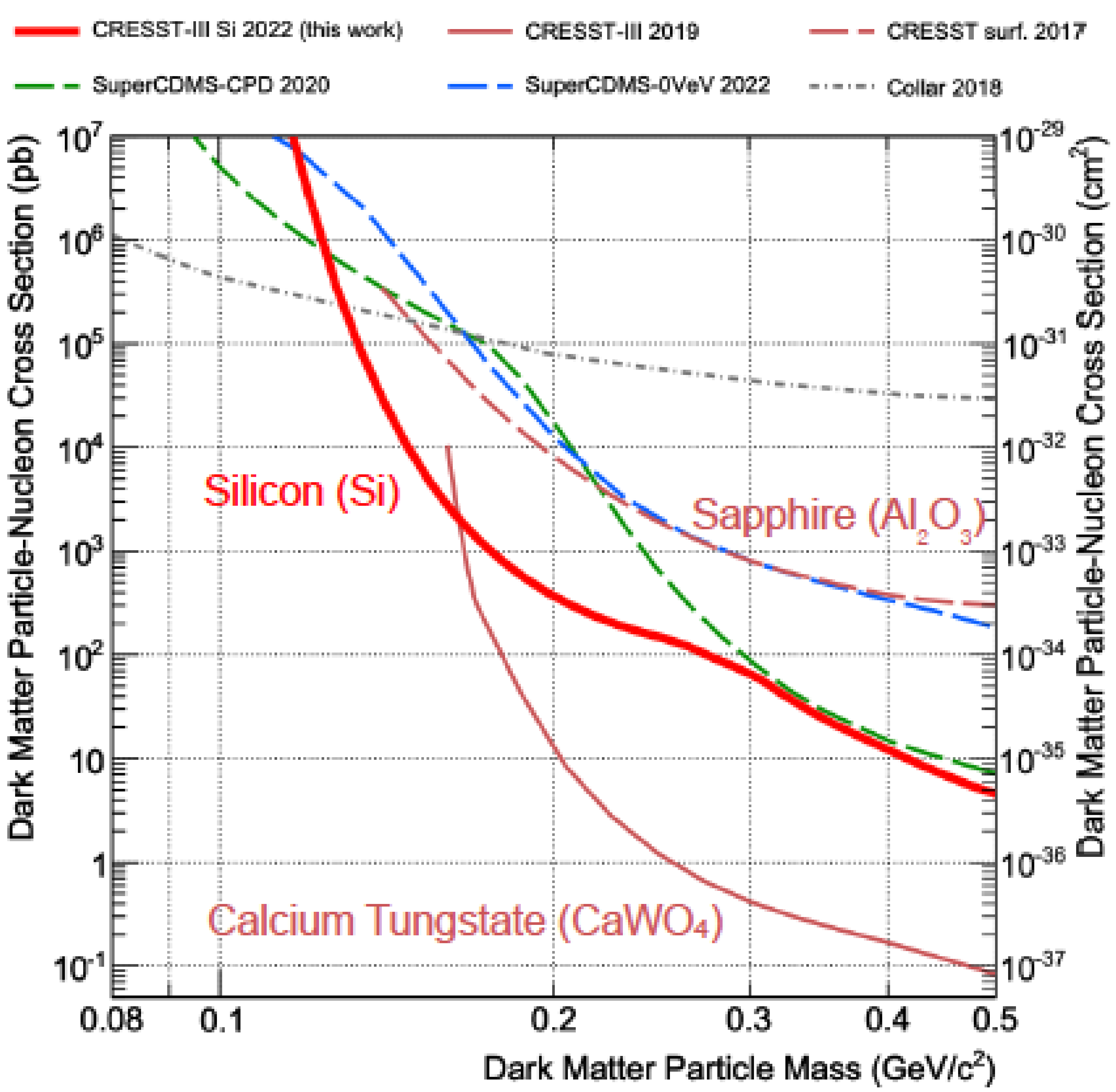
TAUP 2023: M. Kaznacheeva

Target: various crystal materials ($CaWO_4$, Al_2O_3, $LiAlO_2$, Si)

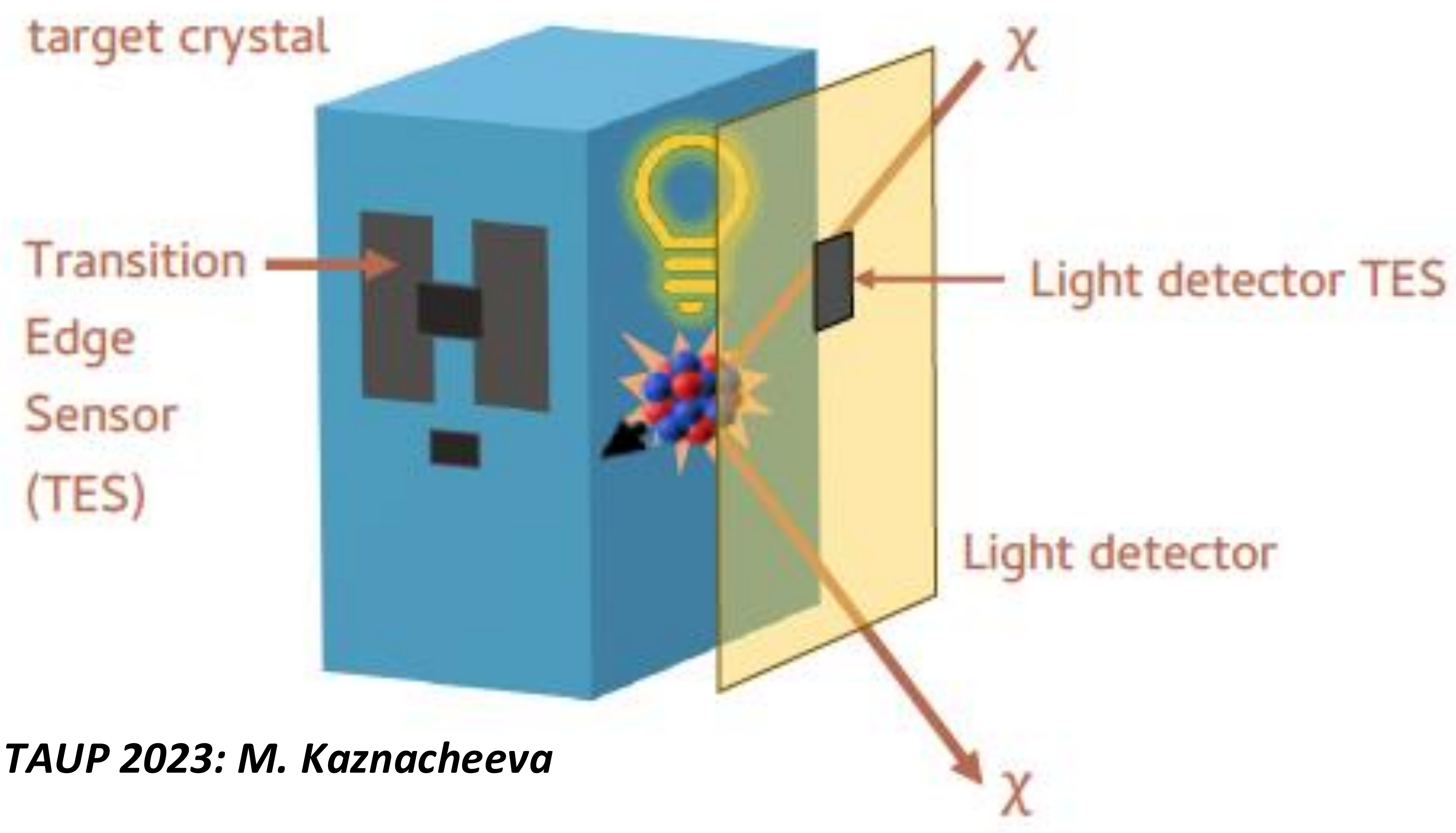
Sensor: W-TES @ 15 mK

Energy Threshold : $\mathcal{O}(10\ \mathrm{eV})$

CRESST-III



CRESST, Phys. Rev. D 107, 122003 (2023)



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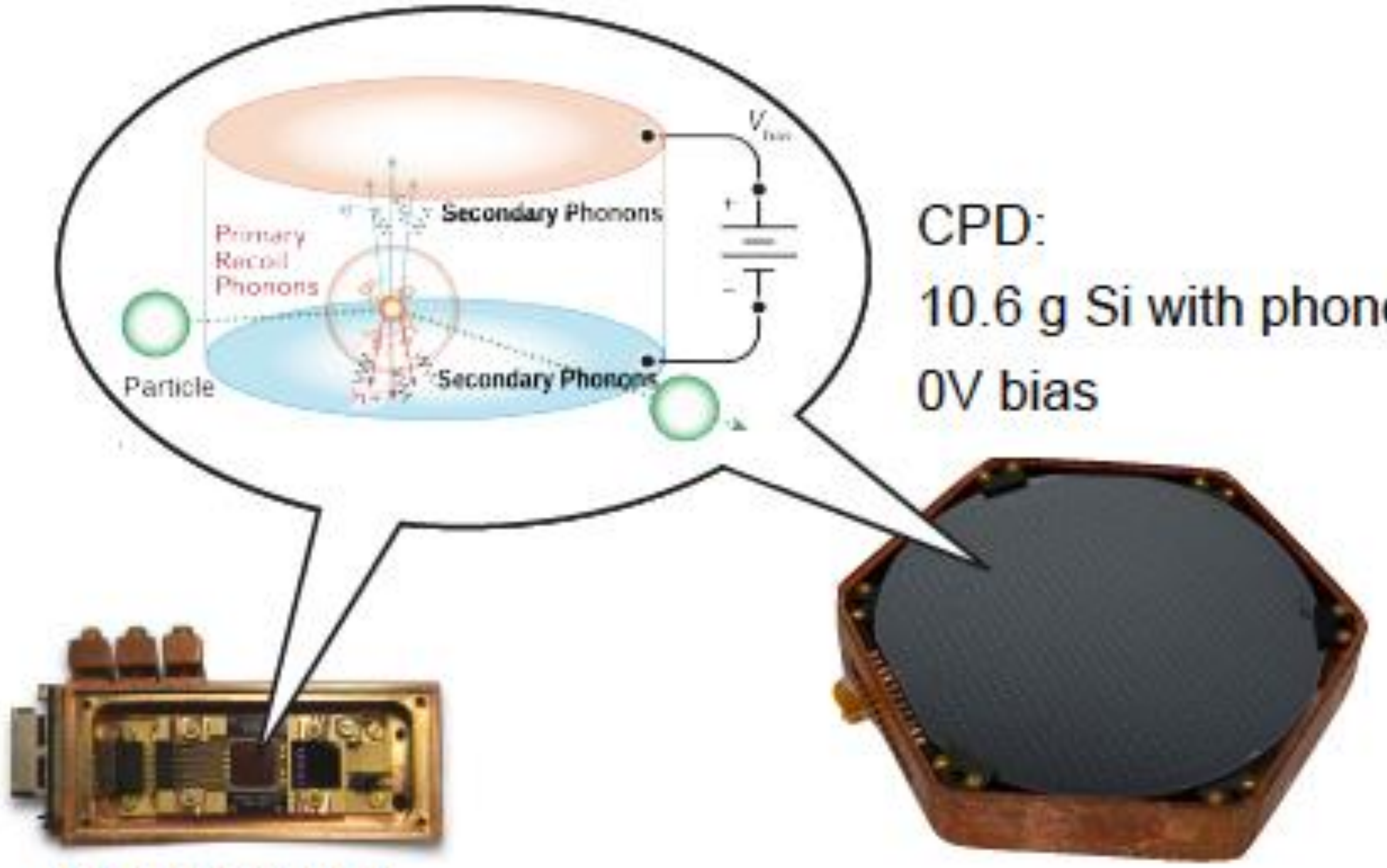
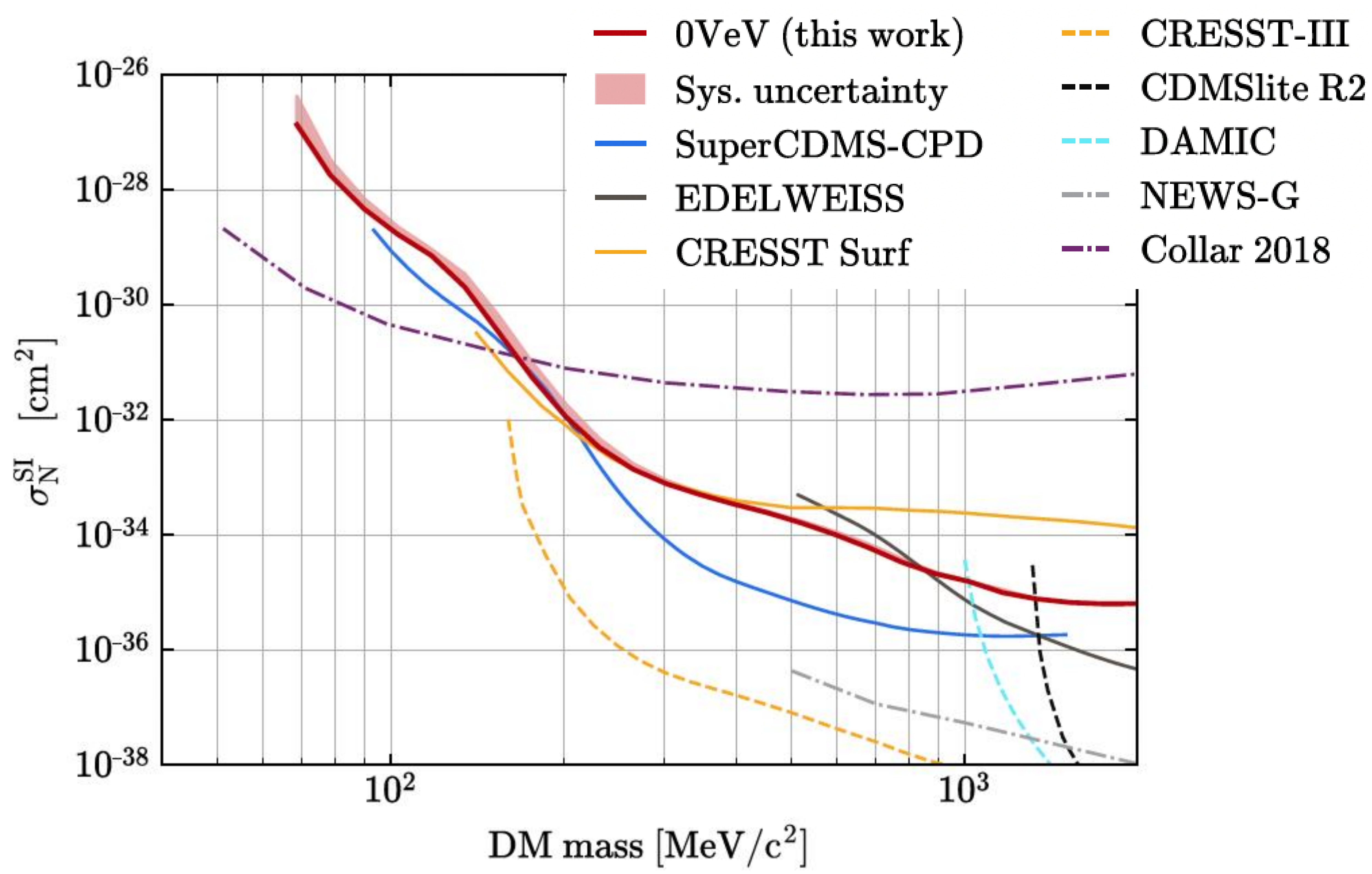
SuperCDMS (CPD, 0VeV)



SuperCDMS, Phys. Rev. D 105, 112006 (2022)

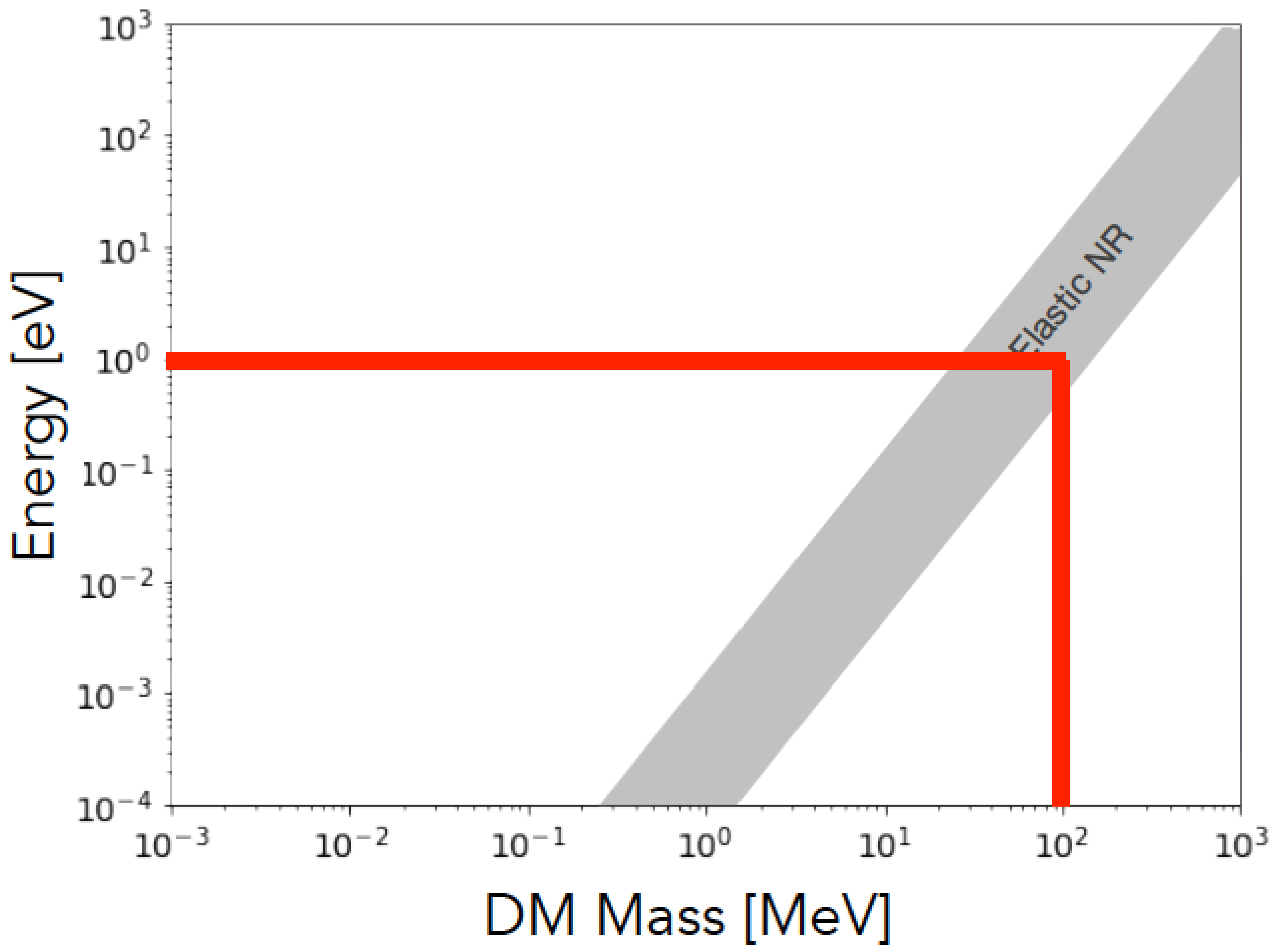


- **SuperCDMS** is currently in transition between 2 generations (Soudan → SNOLAB)
- Both **SuperCDMS-0VeV** and **SuperCDMS-CPD** are 1-10g **R&D phonon detectors**
- Exposure: 0.4 g*days (0VeV) and 9.9 g*days (CPD)

DM – electron scattering

Kinematics of DM Scattering

arXiv:2203.08297

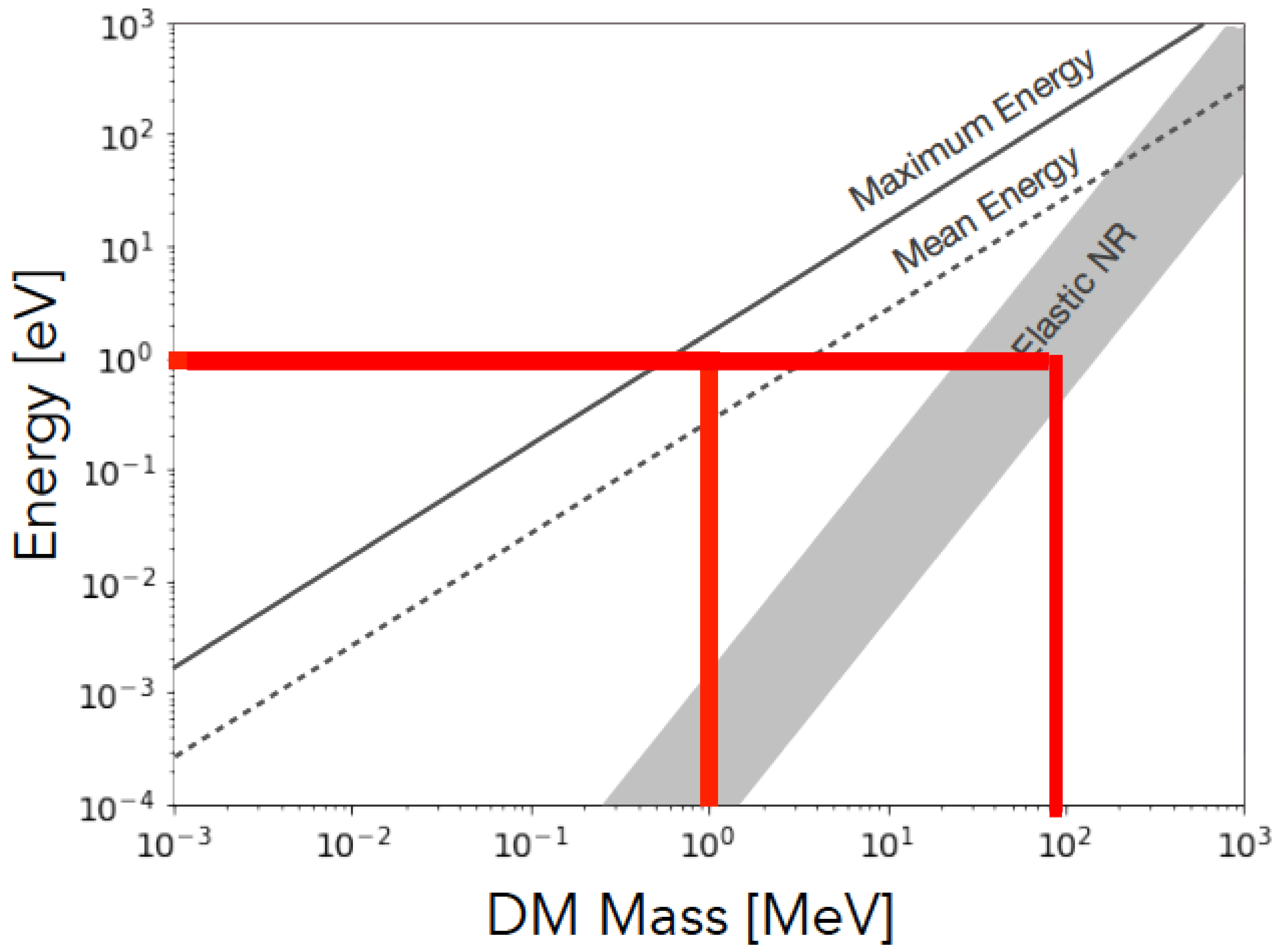


Very low momentum transfer to nucleus from low mass dark matter.

$$E_{NR}^{max} = \frac{q2}{2m_N} \sim 1\,\mathrm{eV}\left(\frac{m_{DM}}{100\,\mathrm{MeV}}\right)\left(\frac{10\,\mathrm{GeV}}{m_N}\right)$$

Kinematics of DM Scattering

arXiv:2203.08297



Very low momentum transfer to nucleus from low mass dark matter.

$$E_{NR}^{max} = \frac{q2}{2m_N} \sim 1\,\mathrm{eV}\left(\frac{m_{DM}}{100\,\mathrm{MeV}}\right)\left(\frac{10\,\mathrm{GeV}}{m_N}\right)$$

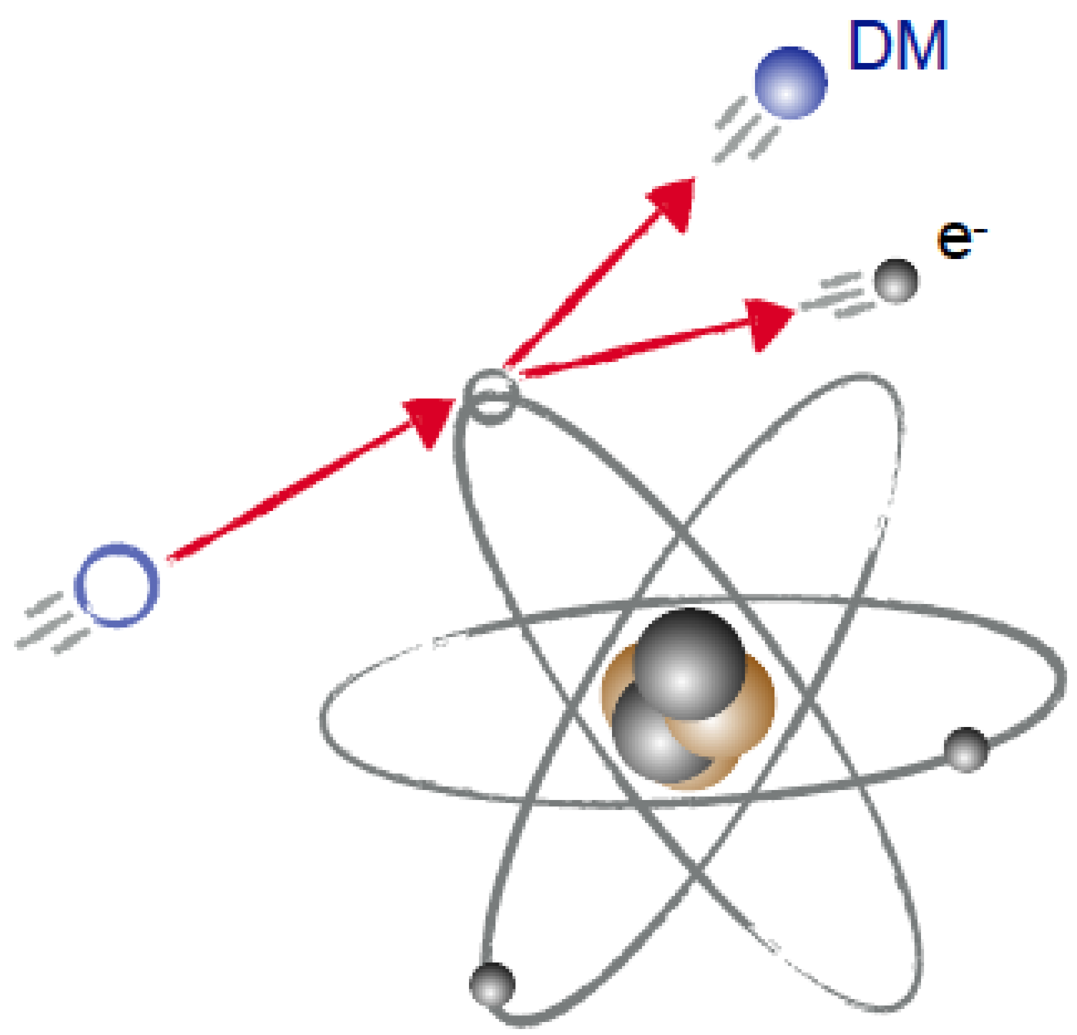
Available **dark matter kinetic energy** is **much larger**!

$$E_{kin} = \frac{1}{2} m_{DM} v_{DM}^2 \sim 1\,\mathrm{eV}\left(\frac{m_{DM}}{1\,\mathrm{MeV}}\right)$$

Inelastic DM - Electron Scattering

Only need to overcome binding energy:

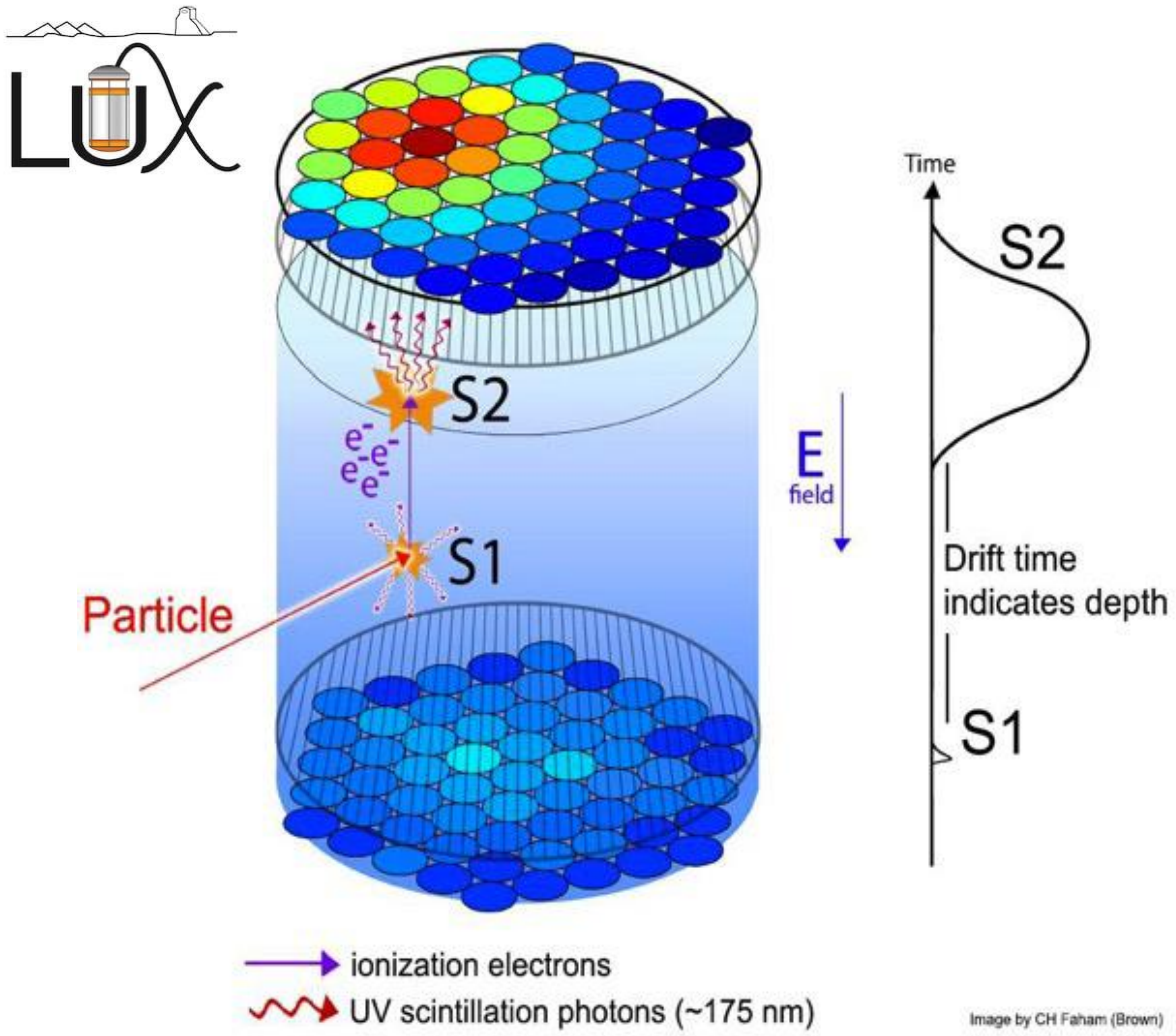
$$E_{\rm DM} \sim \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 > E_{\rm bind.}$$



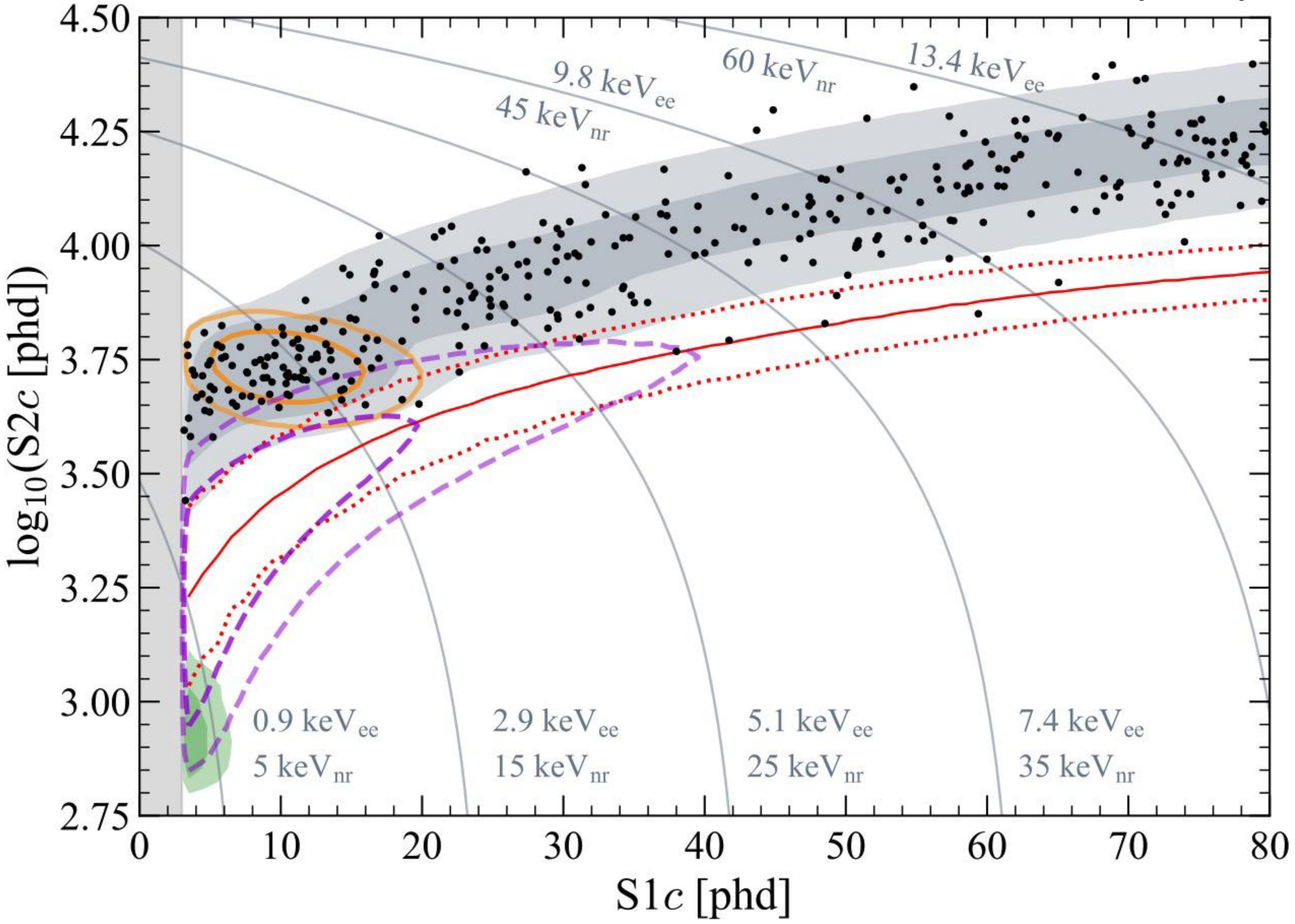
To make DM << GeV/c^2 accessible!

Material	Binding Energy (least bound electron)
Atoms (e.g. Xe,…)	$\mathcal{O}(10\ \mathrm{eV})$
Insulators (e.g. diamond, NaI)	$\mathcal{O}(5\ \mathrm{eV})$
Semiconductors (e.g. Si, Ge, GaAs)	$\mathcal{O}(1\ \mathrm{eV})$
Low-gap materials (e.g. Dirac Materials, doped semiconductors, and superconductors)	$\mathcal{O}(\mathrm{few\ meV})$

Liquid Nobel 2-Phase Detection Principles



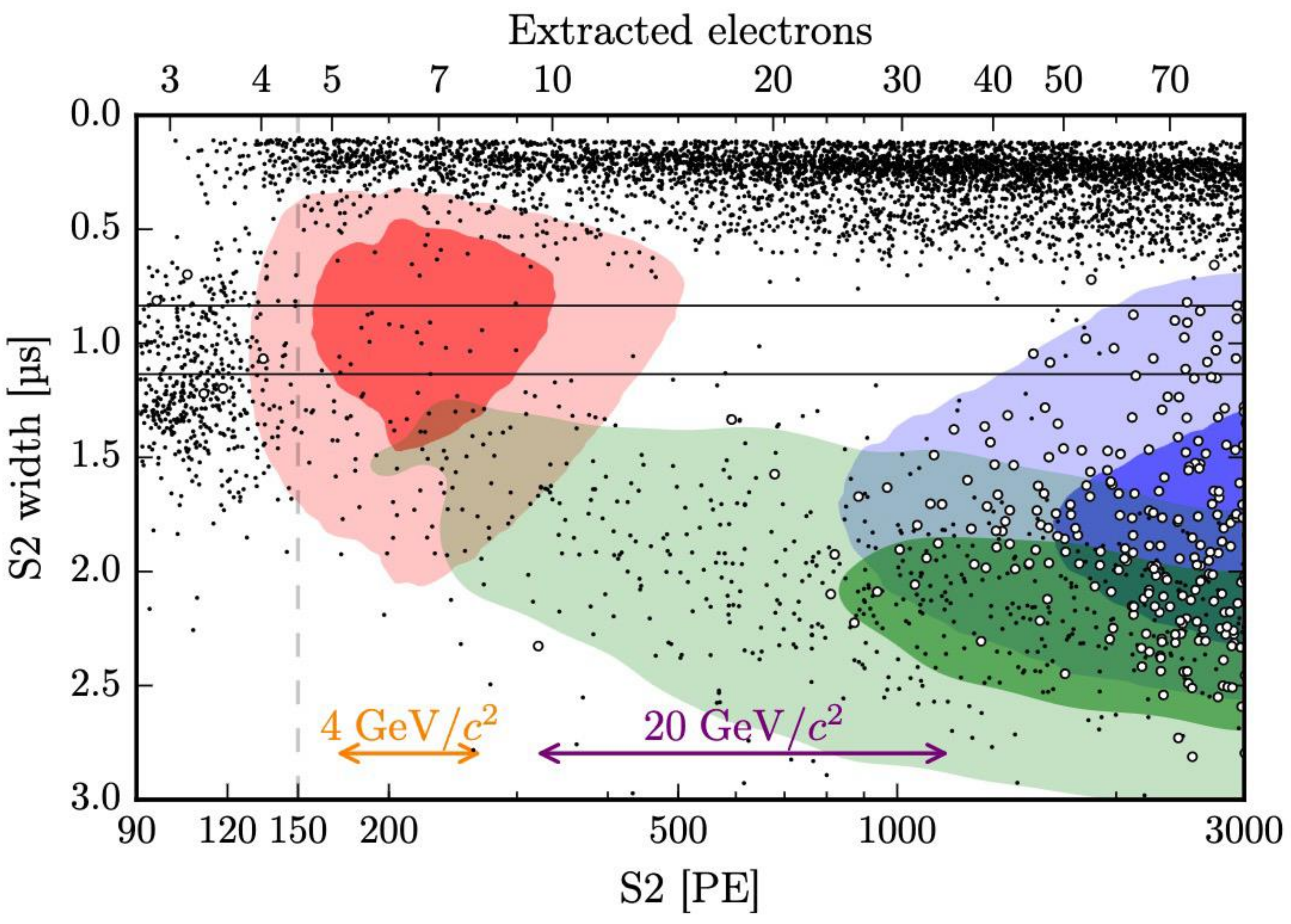
Aalbers et al, PRL 131, 041002 (2023)

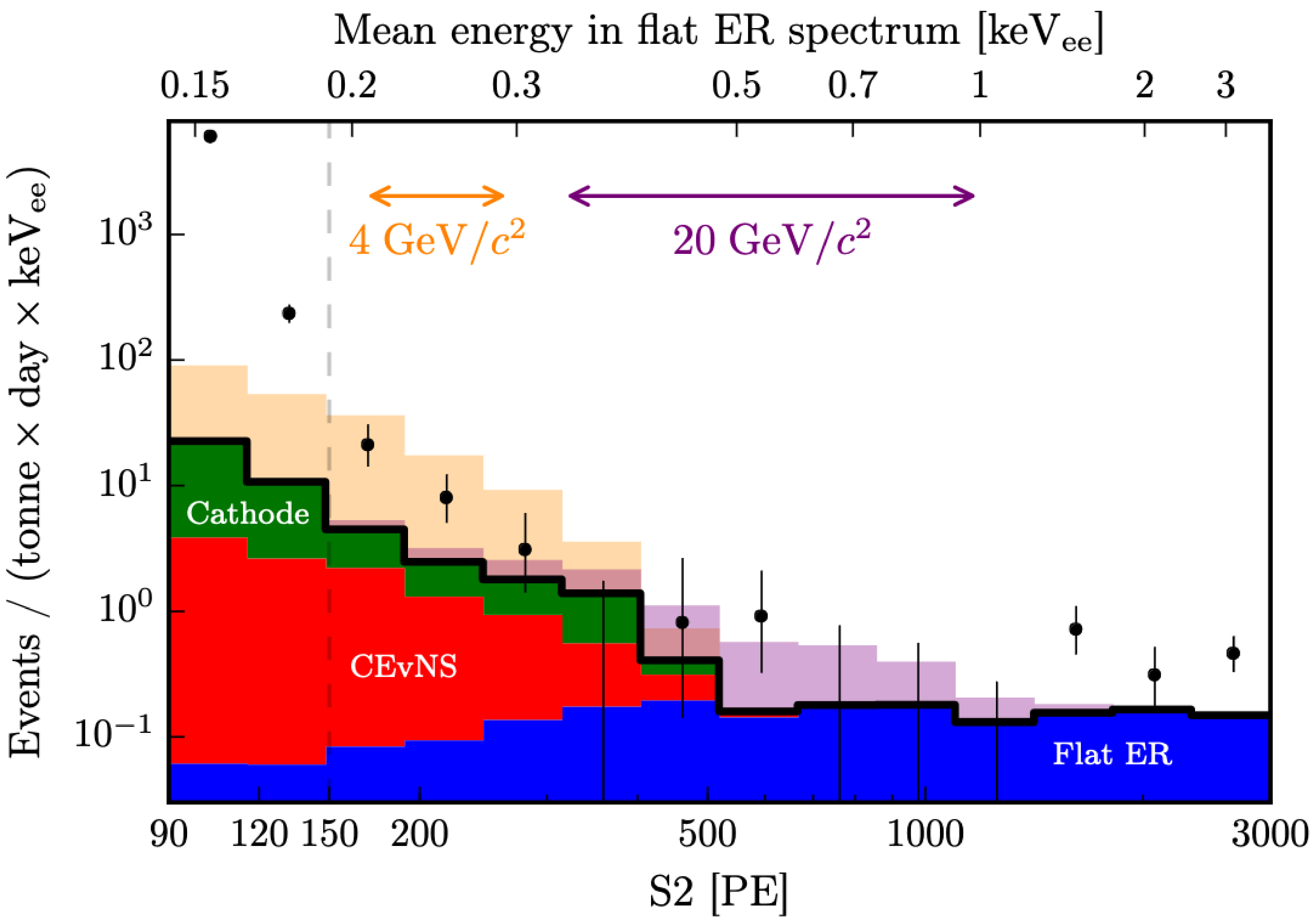


Sacrifice discrimination for lower threshold by not requiring S1 photons.

S2 Only Seaches – XENON1T

Aprile et al, PRL 123, 251801 (2019)





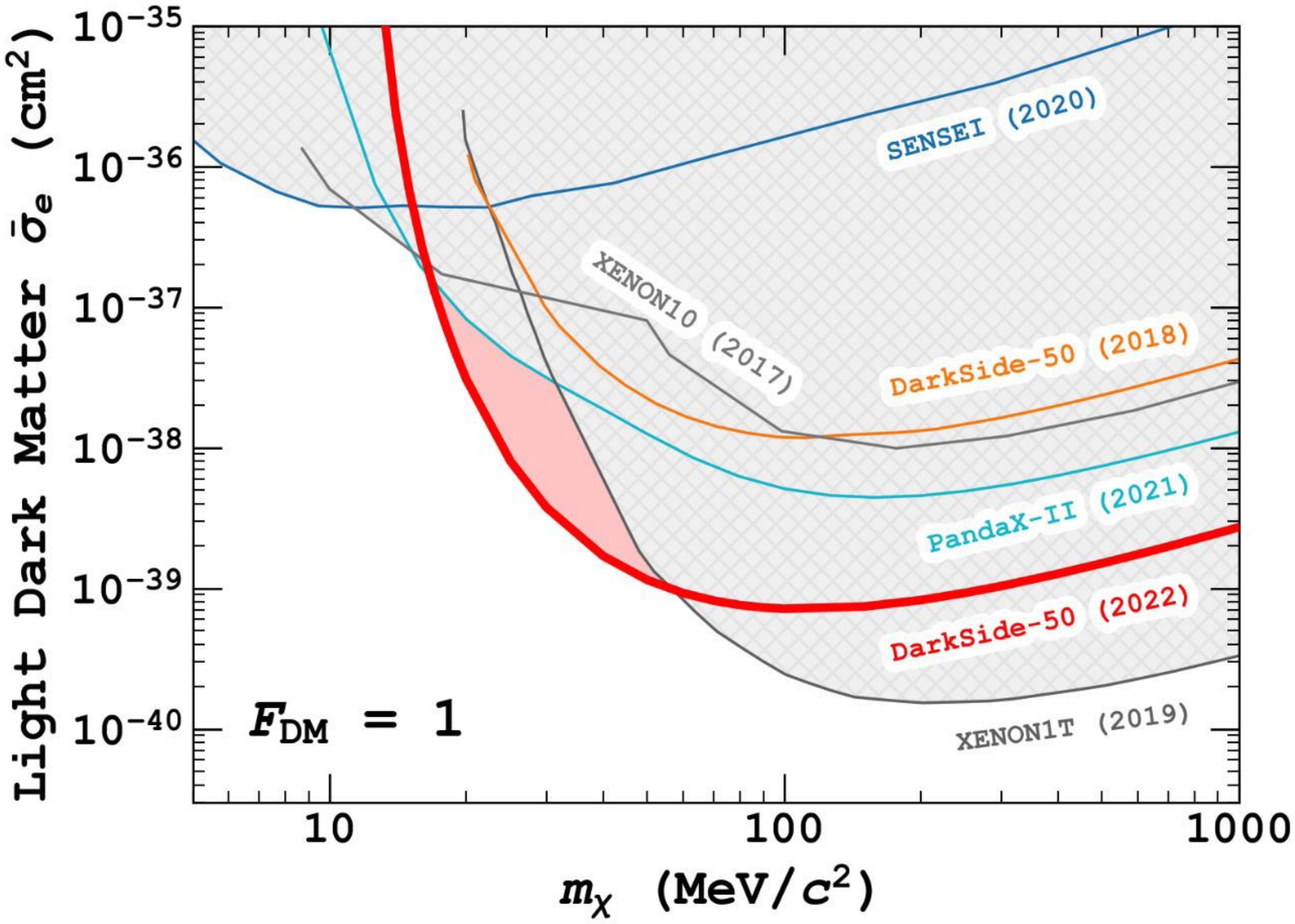
Pros: large exposures, 1-10 mdru modeled background, XY position resolution, and timing.

Cons: a large unmodeled dark rate, leading to a high analysis threshold (100+ eV), no event discrimination.

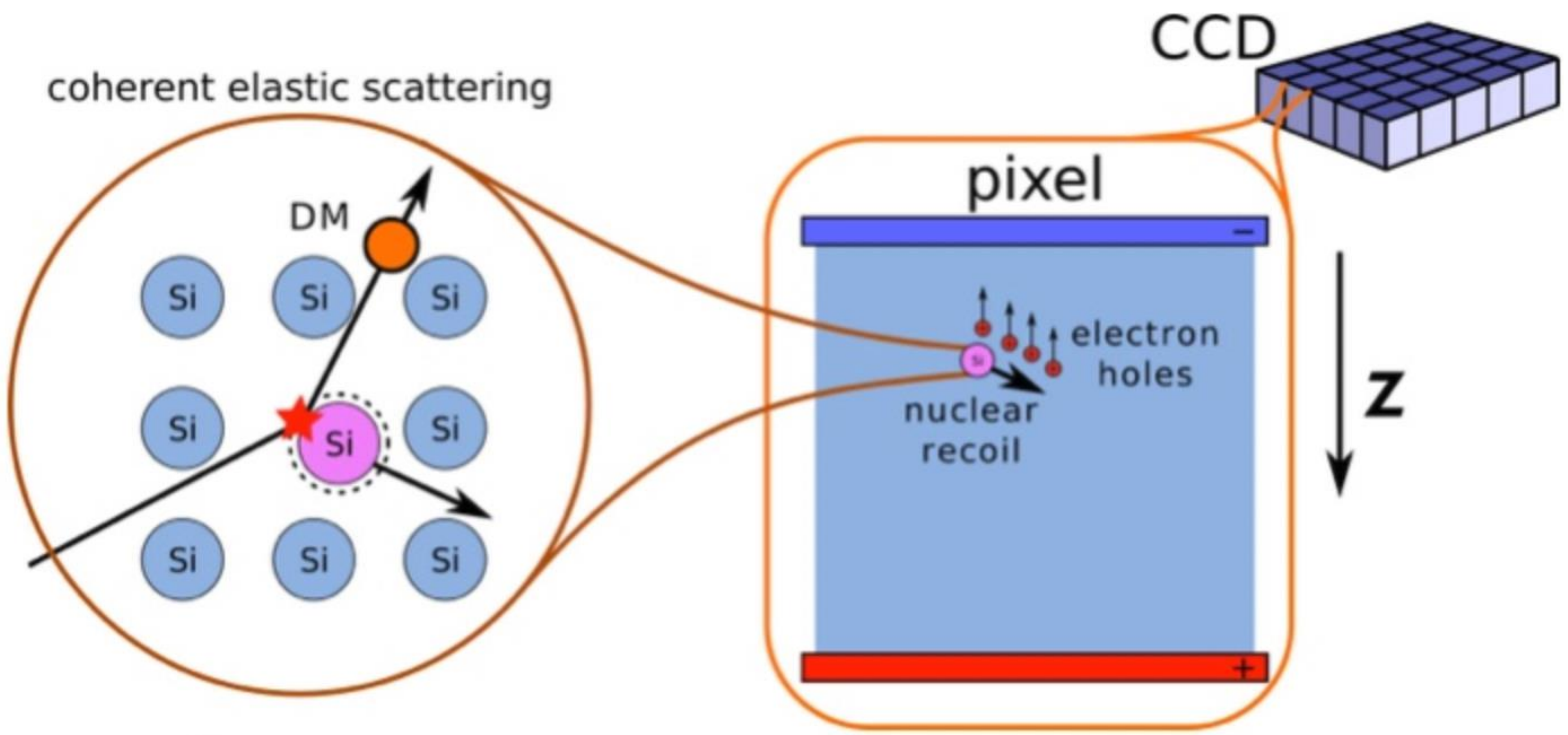
Notation: dru = differential rate unit = count/kg/day/keV

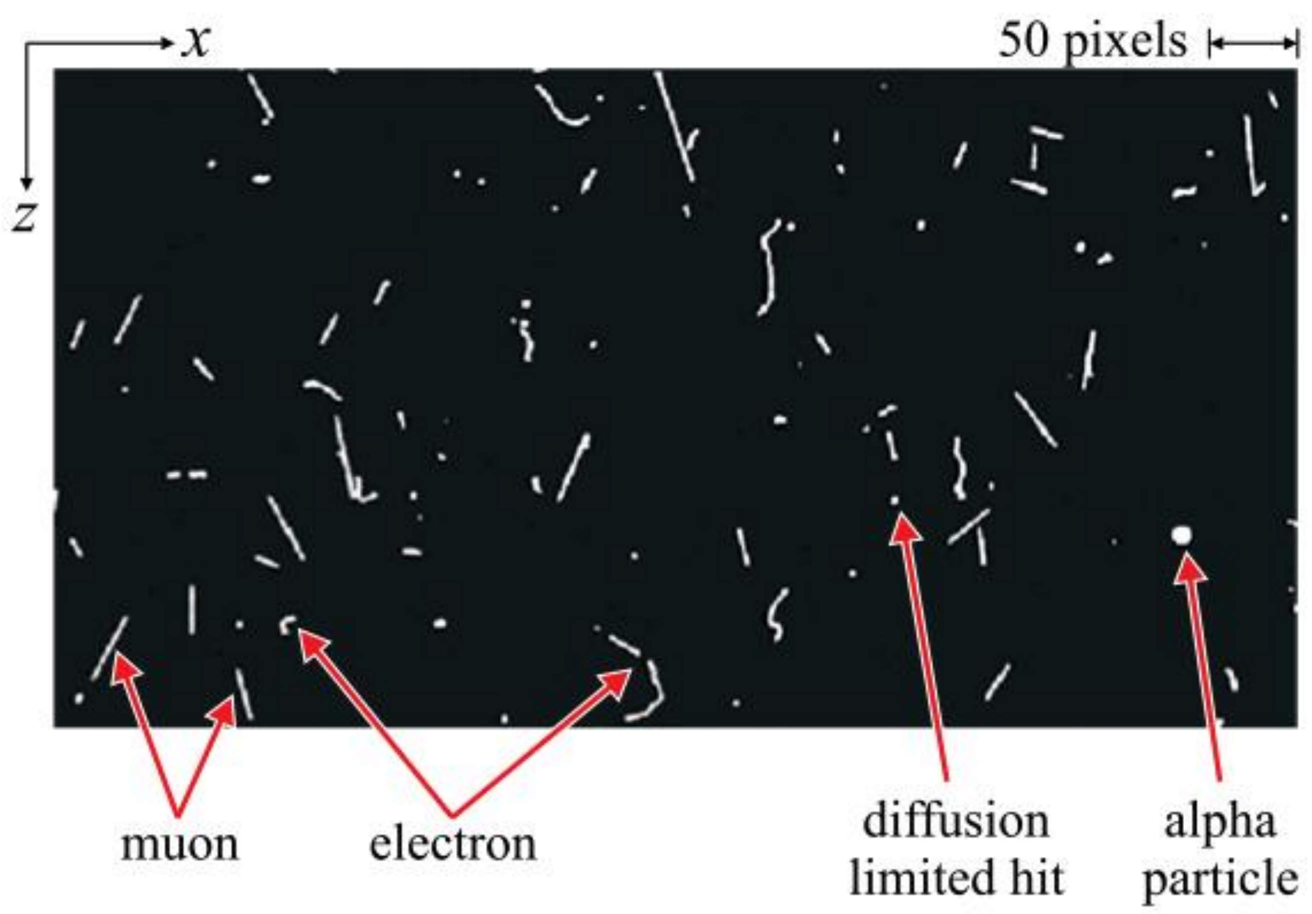
S2 Only Searches

Agnes et al, PRL 130, 101002 (2023)



CCD Detectors – DAMIC/DAMIC-M and SENSEI





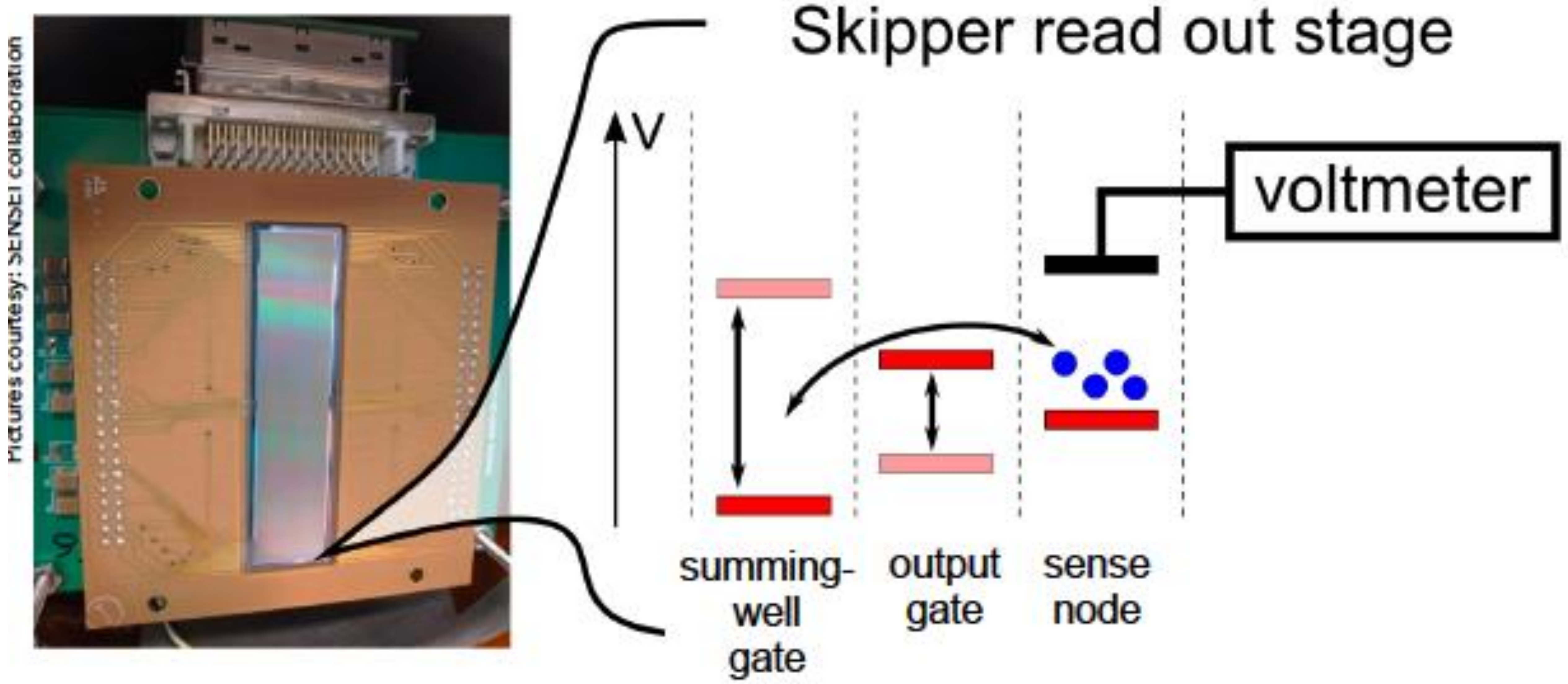
Interactions with silicon produce free charge carriers….

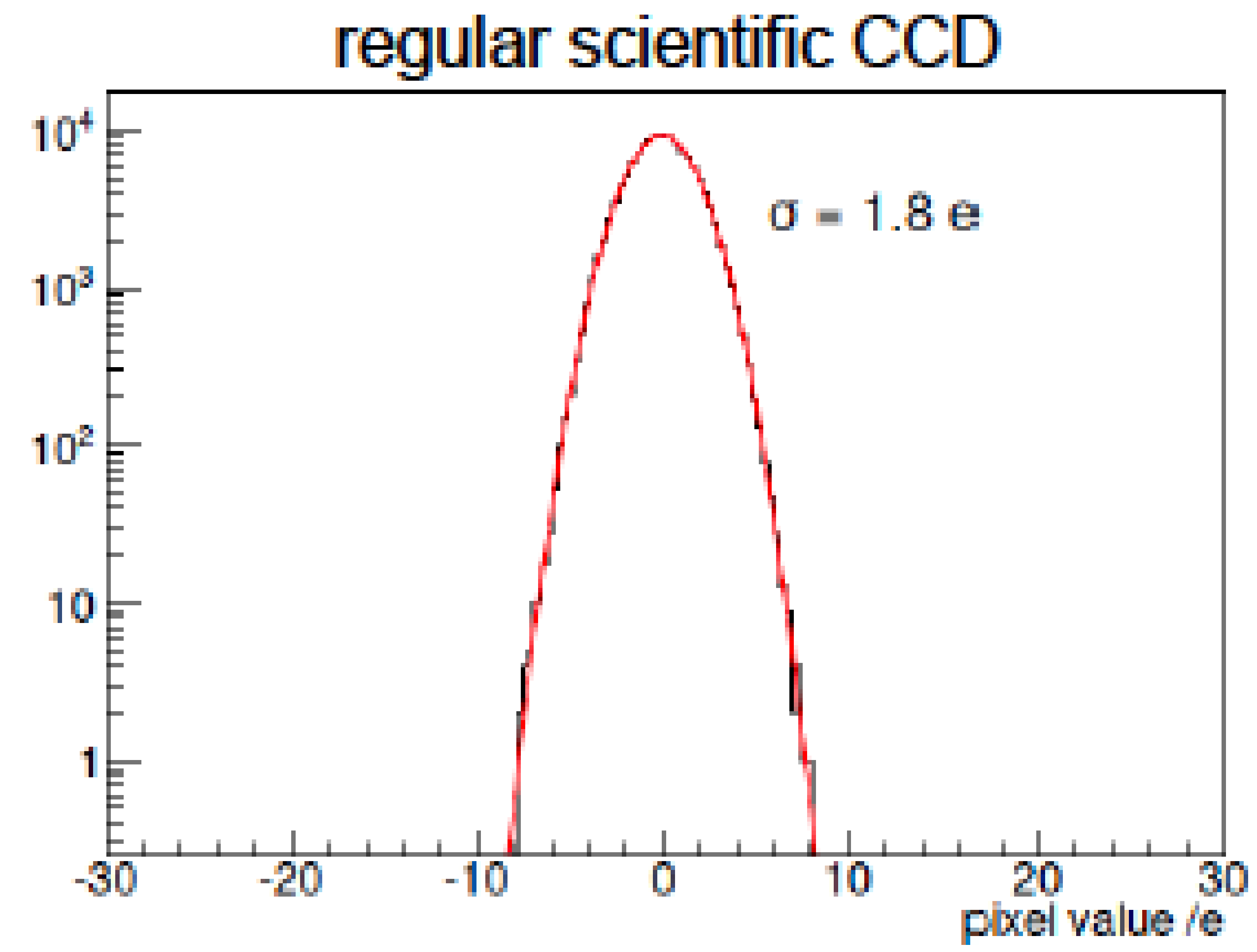
- are drifted across a fully depleted region *(no loss of charge)*
- collected in 15 micron pixels *(excellent position resolution)*
- and stored until a user-defined readout time *(after many hours)*

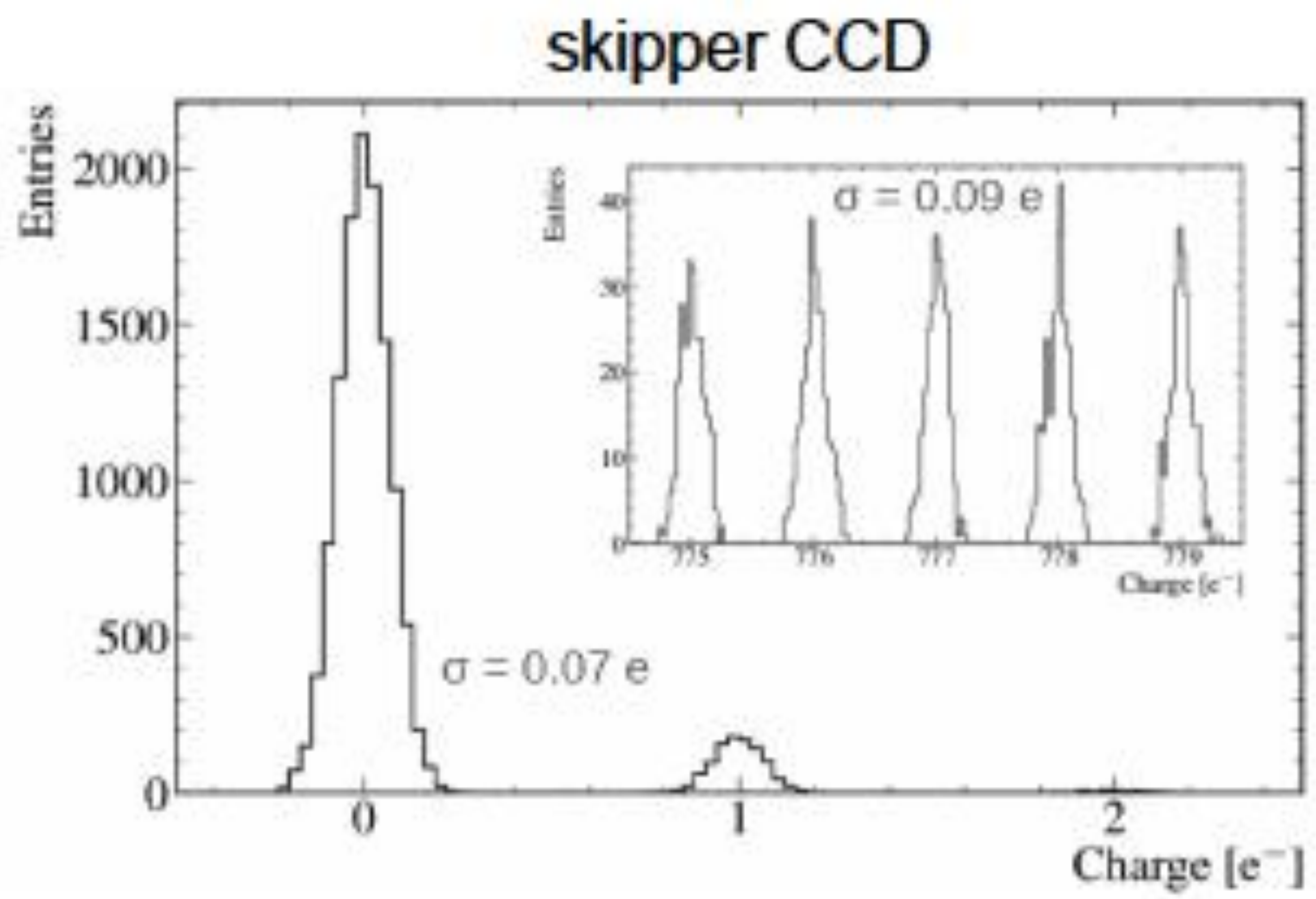
High spatial and energy resolution
but poor time resolution

CCD Detectors: Readout

Skipper Amplifiers: allow repeated, non-destructive measurement of the same charge packet
→ significantly reduces observed readout noise.





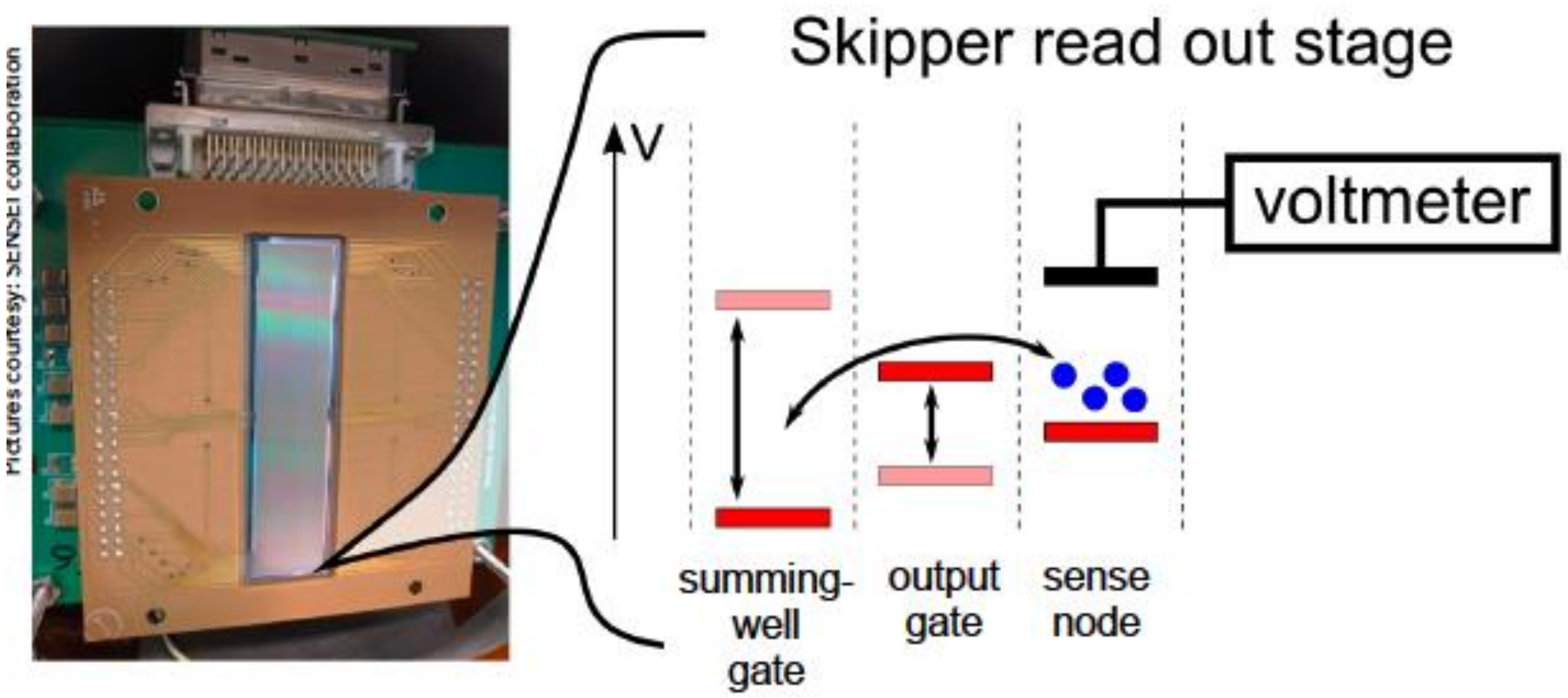


SENSEI Collaboration
Phys. Rev. Lett. 119, 131802 (2017)

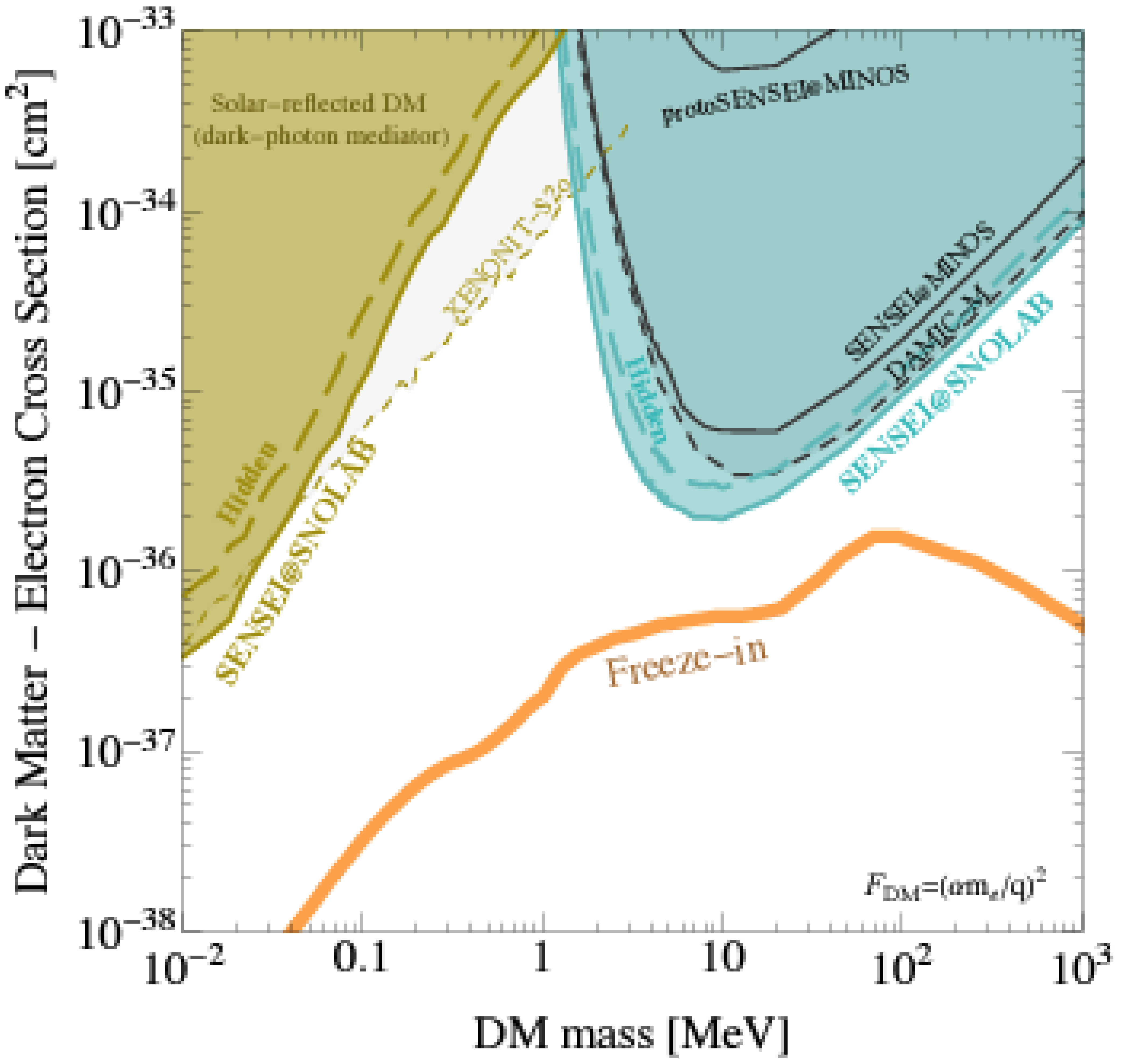
CCD Detectors: Readout

SENSEI Recent Results:

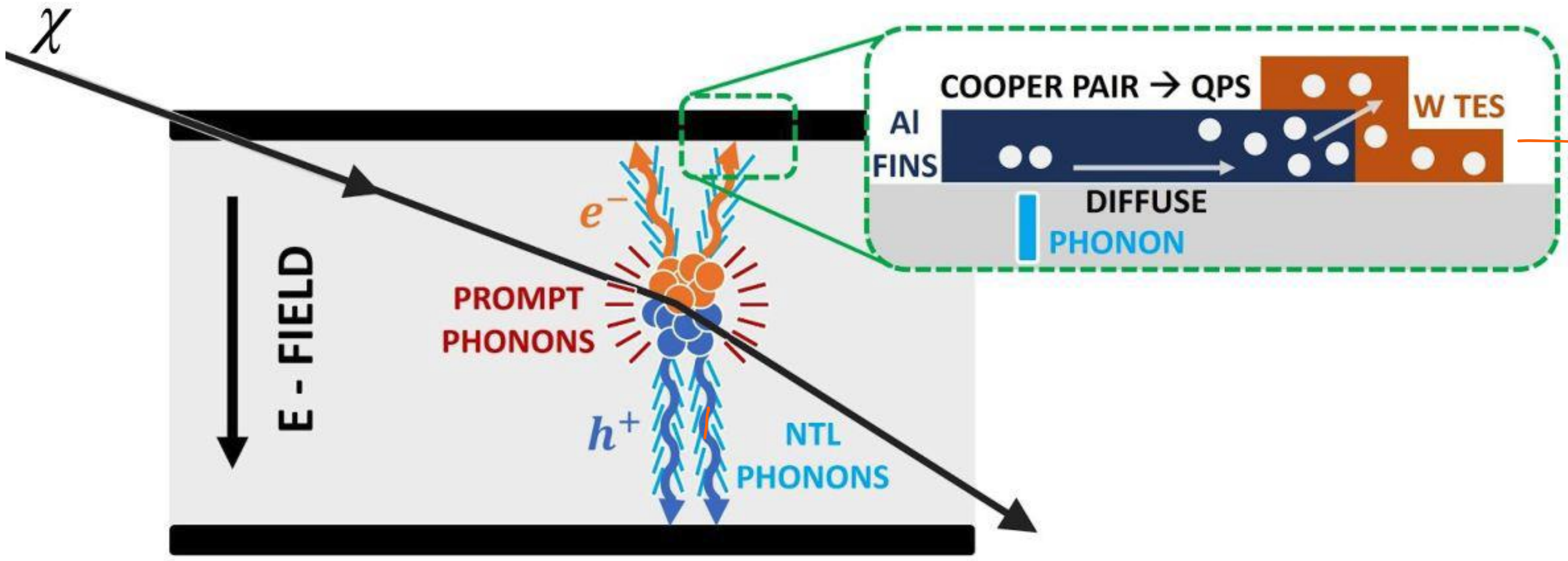
6 sensors operating at SNOLAB with an exposure of 534.9 gram-days.

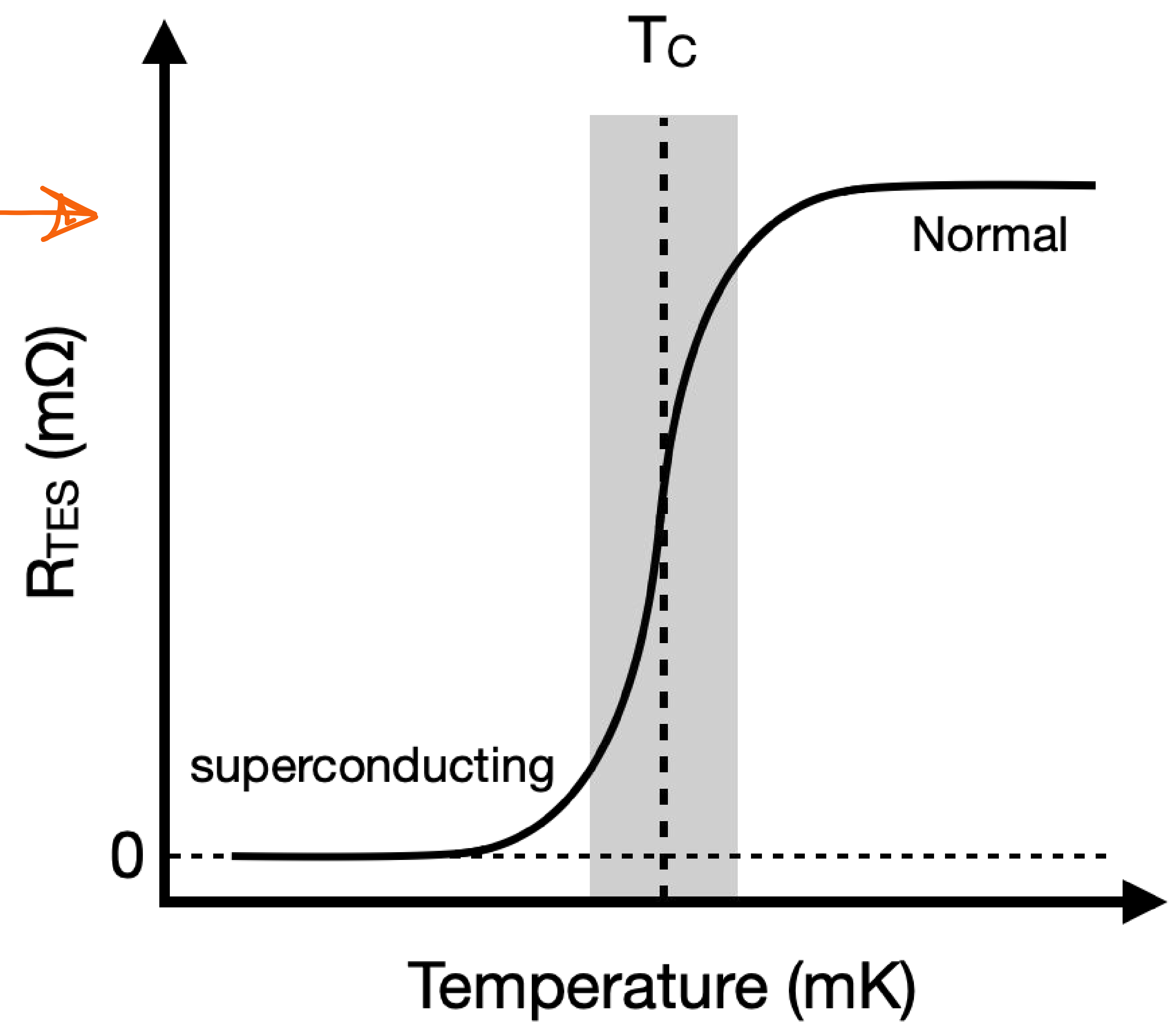


SENSEI arXiv:2312.13342



Phonon-Based Detectors: SuperCDMS



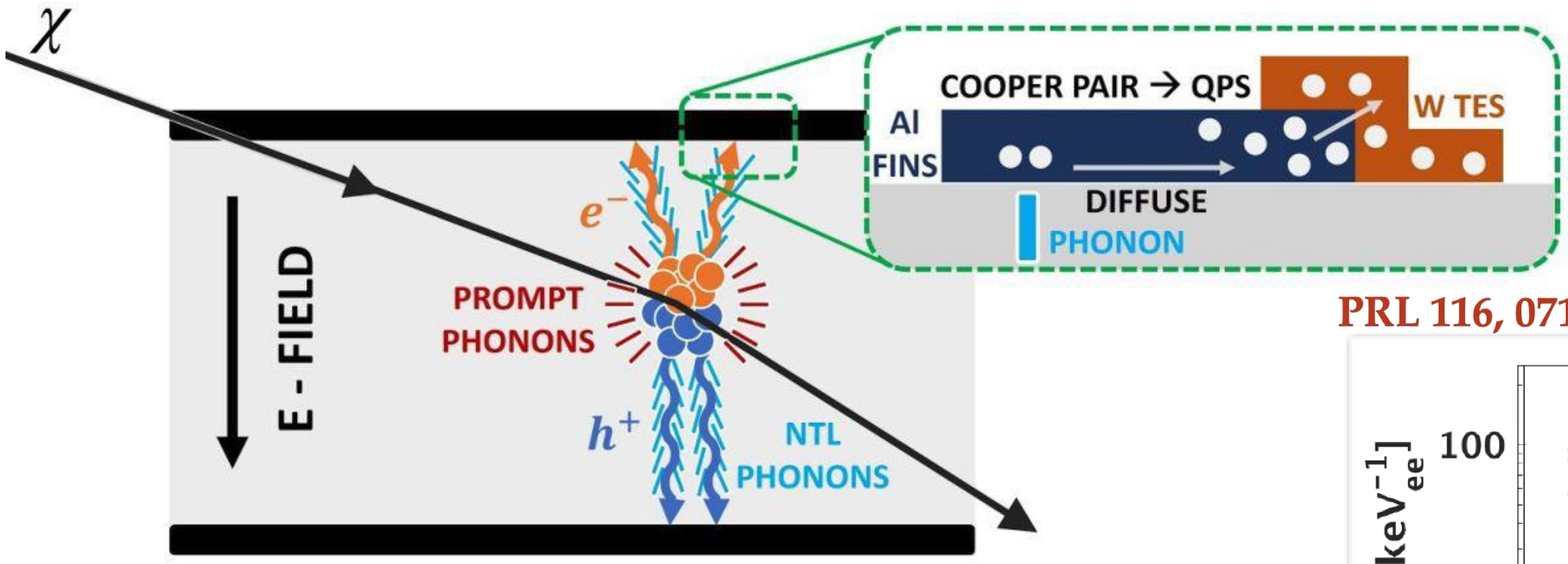


NTL-Amplification

$$E_{\text{phonon}} = E_{\text{recoil}} + n_{eh} \cdot e \cdot V_{\text{bias}}$$

Neganov-Trofimov-Luke gain

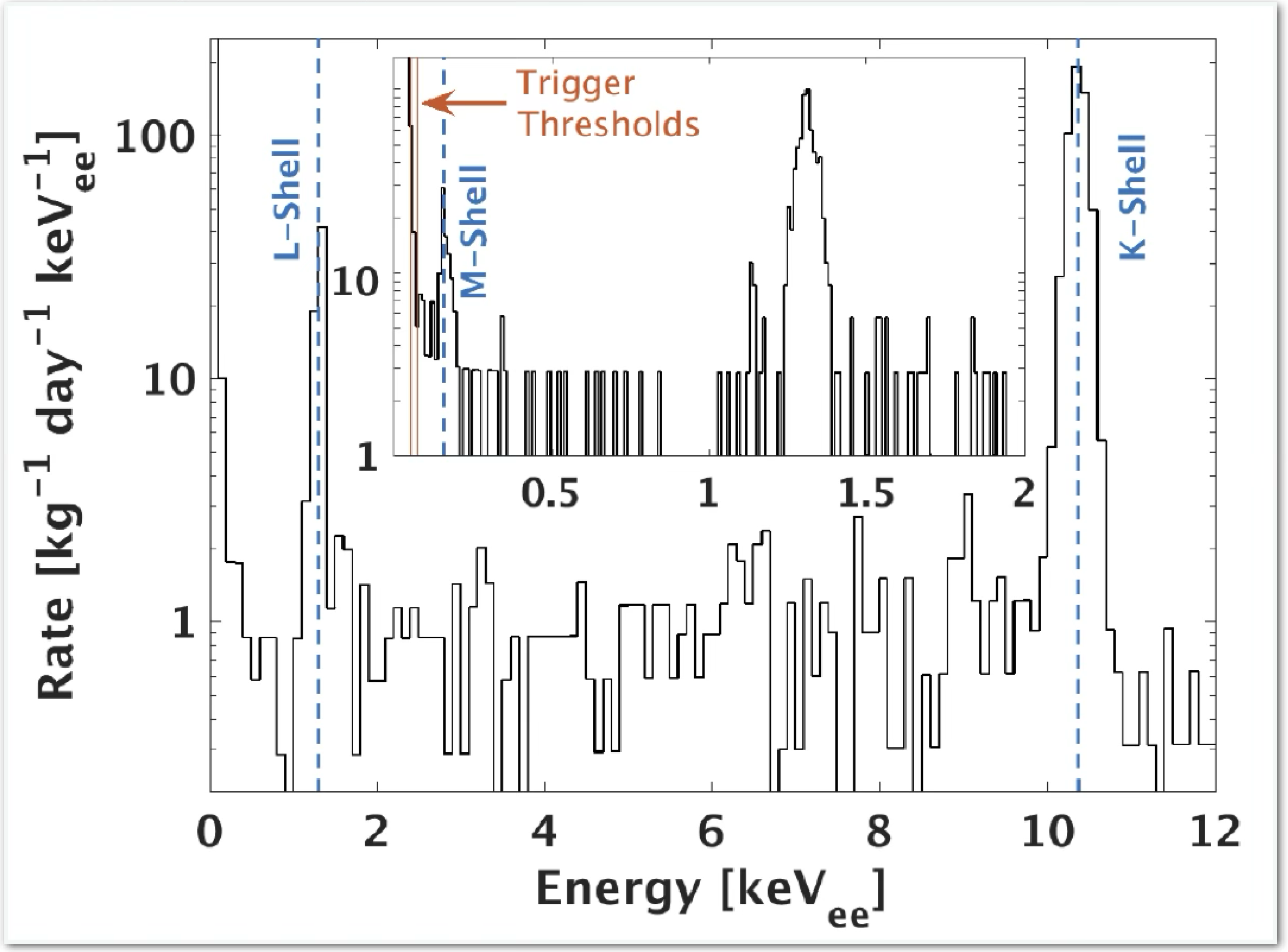
Phonon-Based Detectors: SuperCDMS



NTL-Amplification

$$E_{\text{phonon}} = E_{\text{recoil}} + n_{eh} \cdot e \cdot V_{\text{bias}}$$

PRL 116, 071301, 2016

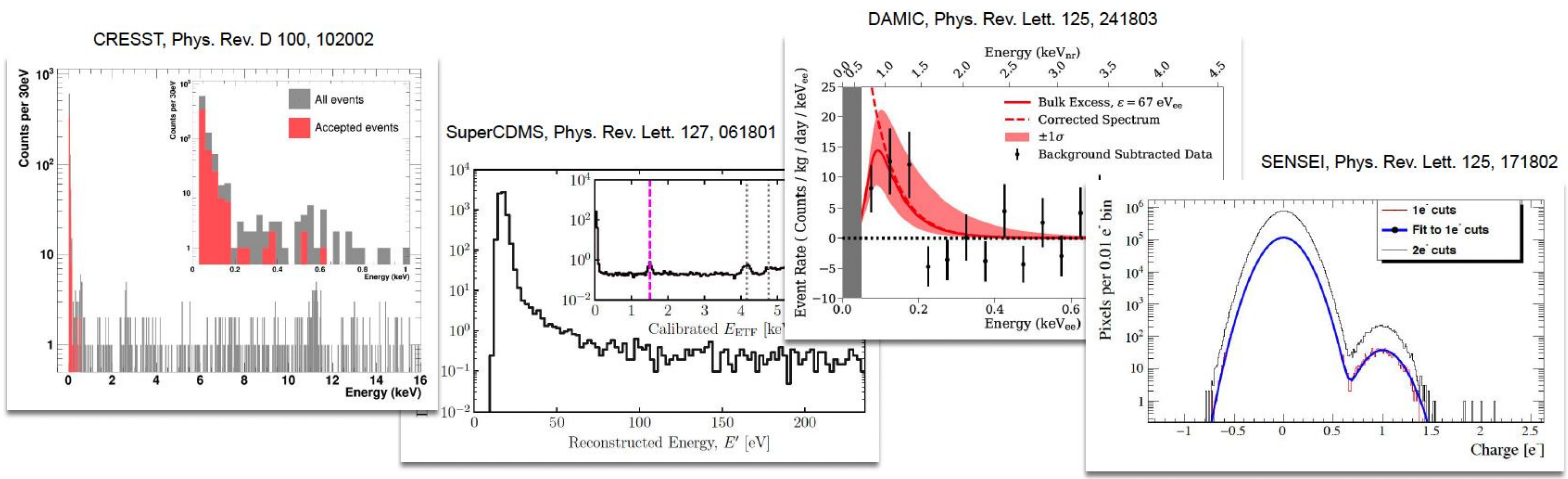


SuperCDMS Status

- **Installation at SNOLAB is ongoing!**
- Several DM search results published in the past years
- R&D and/or **DM search analyses ongoing**
- Updates expected in the near future!

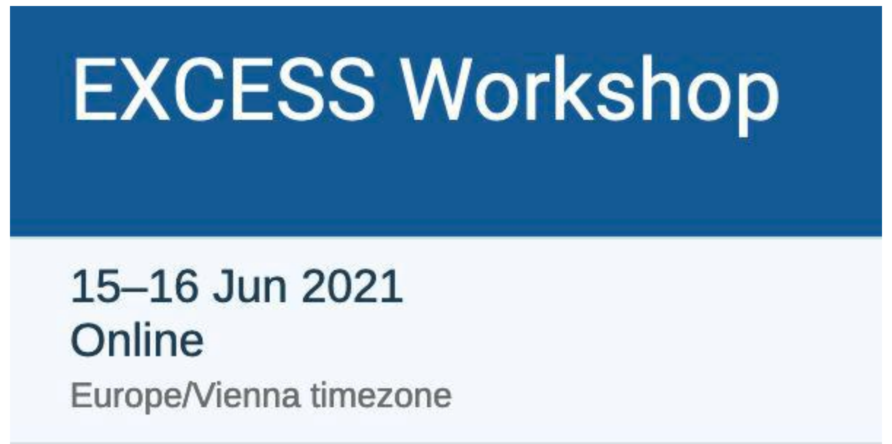
Low Energy Excess

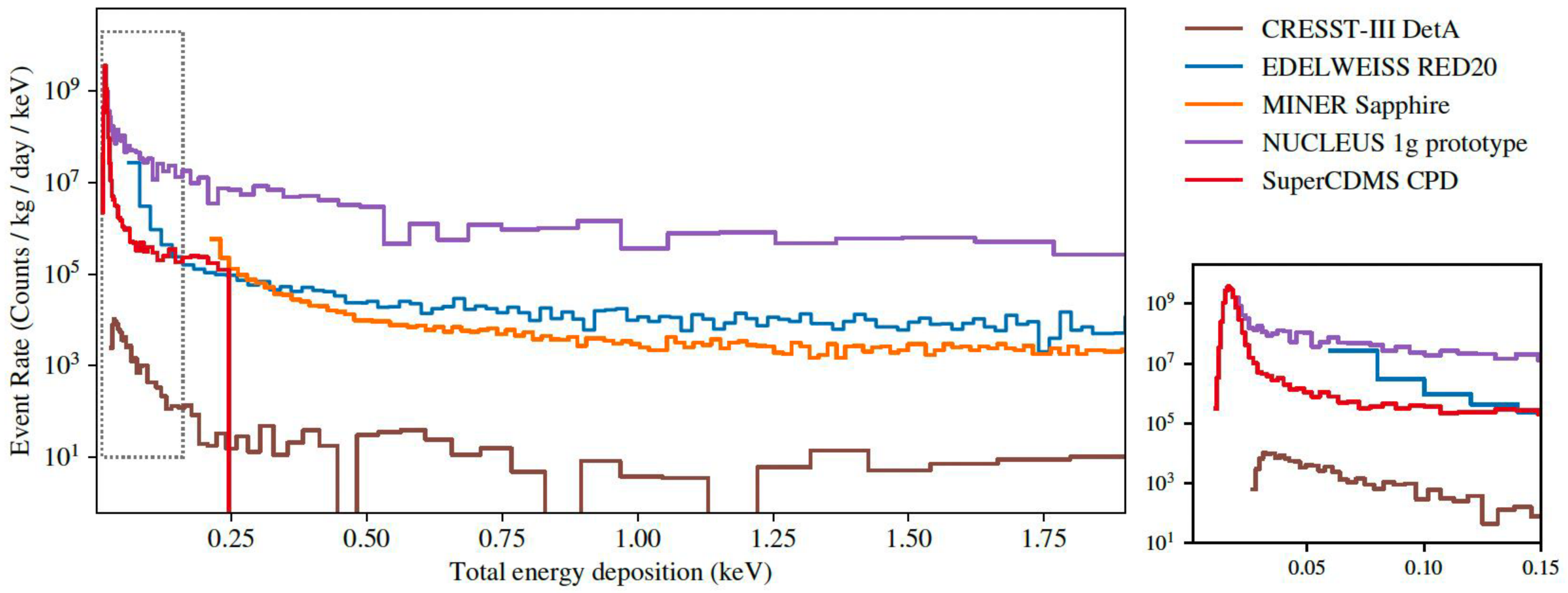
Circa 2020: Low Energy Excess

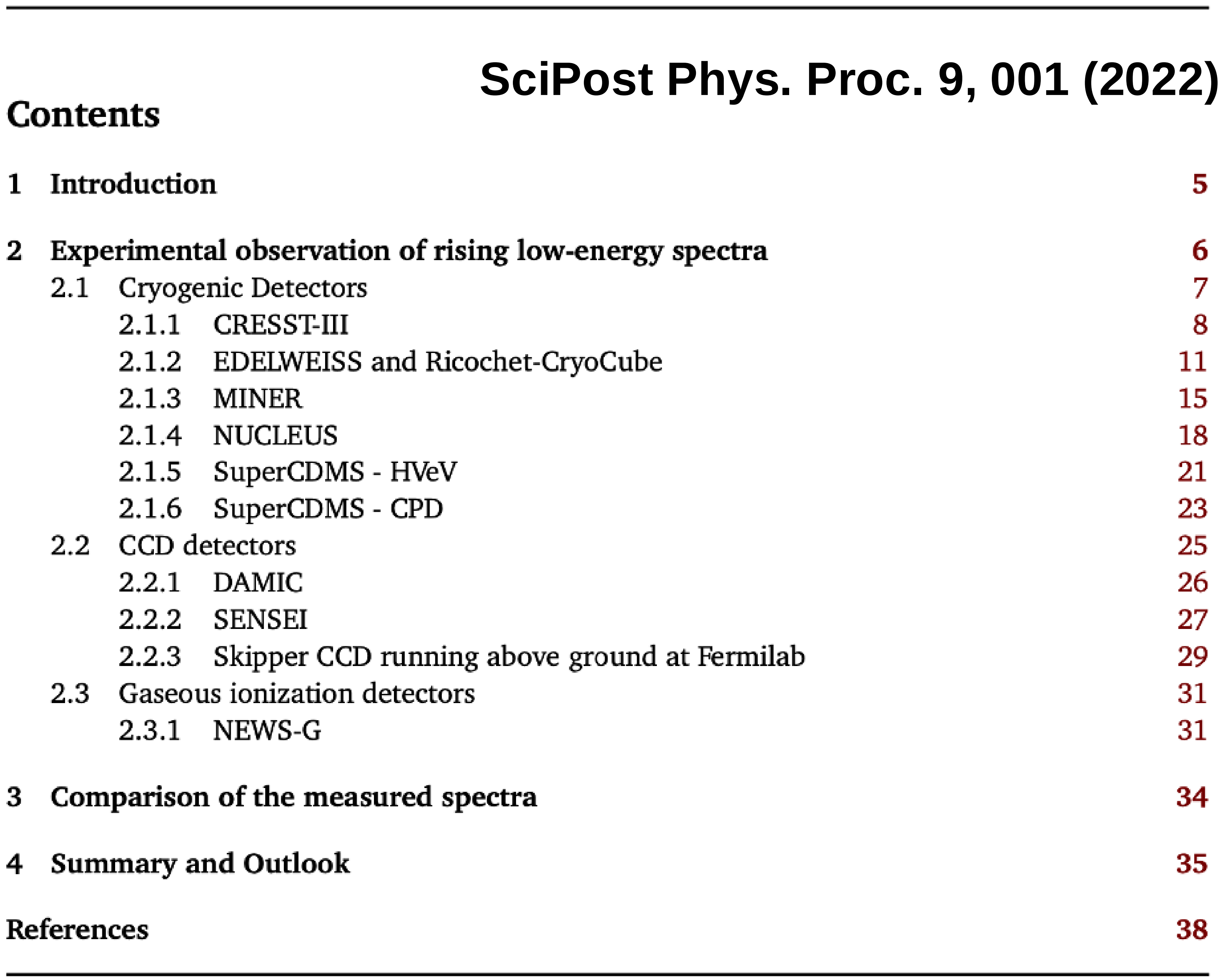


- **Cryogenic, CCD-like** and **gaseous ionization detectors** had successfully lowered their recoil energy **thresholds**, down to **~10 eV**
- ***Steeply rising excesses*** above known backgrounds were observed

EXCESS Workshop Series Began





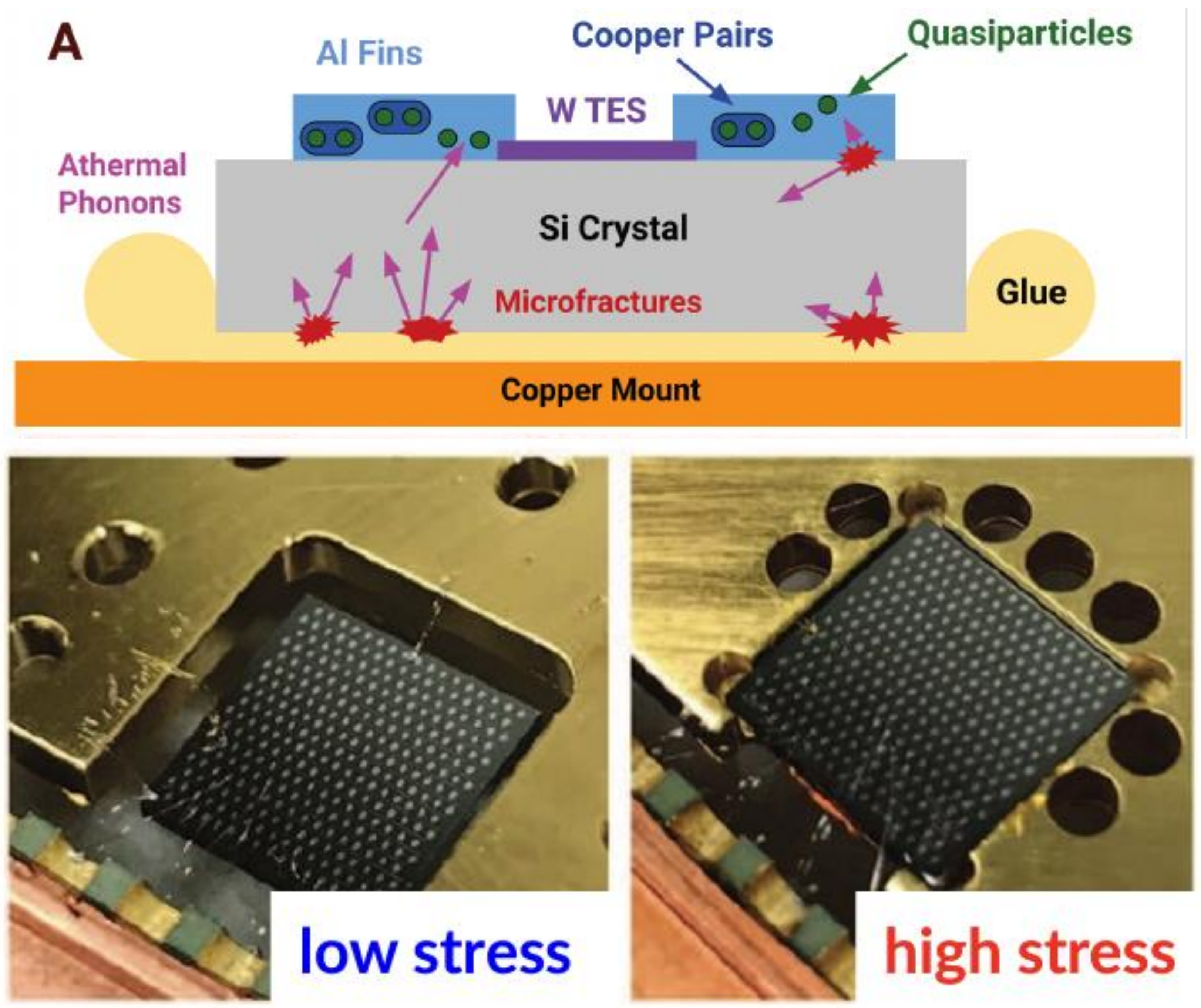


SciPost Phys. Proc. 9, 001 (2022)

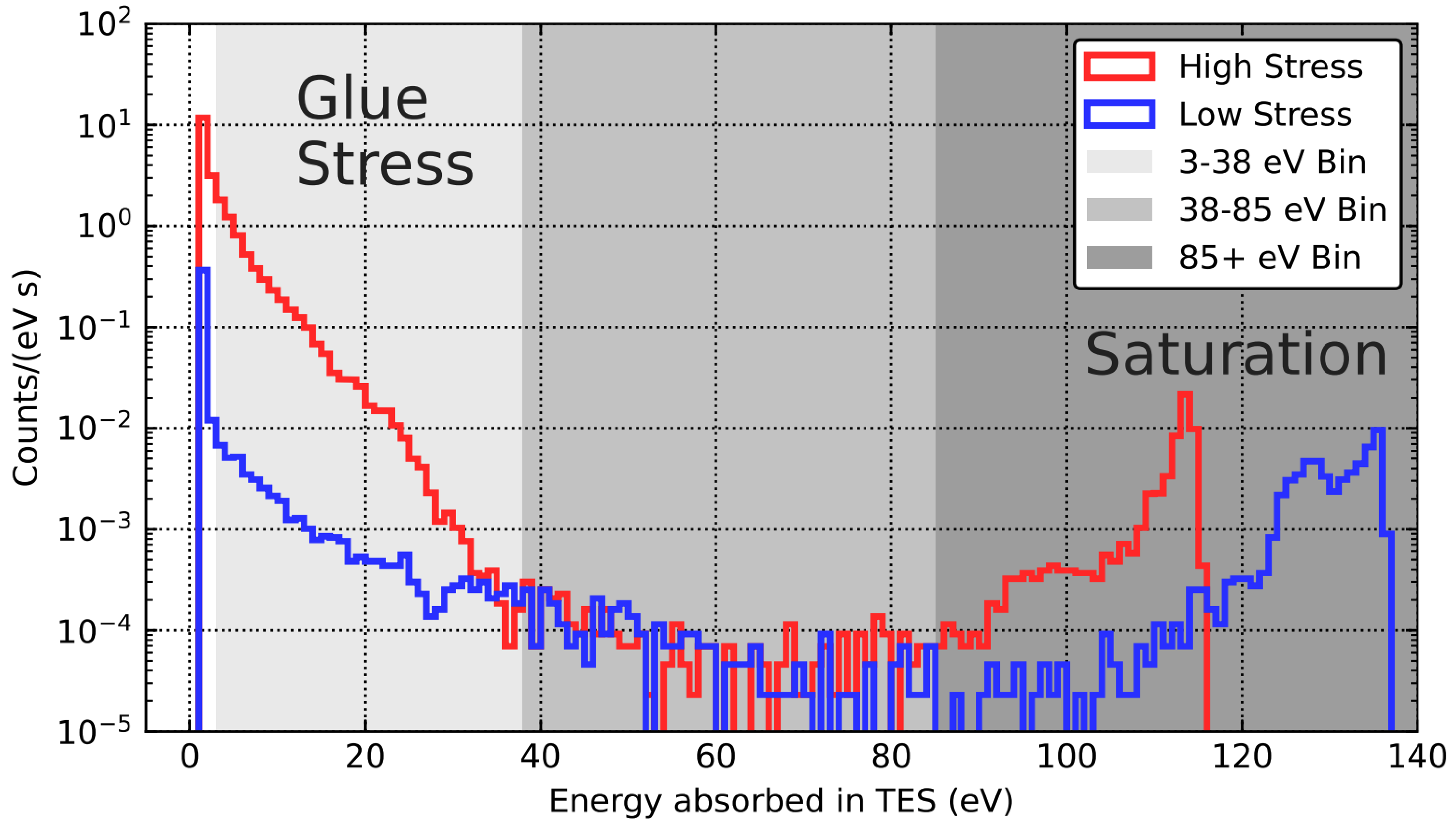
Contents

- In 2021, **community effort** was started to study the observations & learn more about the new backgrounds.
- **“New physics”** origin of excesses mostly excluded - but possibly “**previously not directly observed physics phenomena”** at (partially) low temperatures and energies.

Some Key Findings



TESSERACT, arXiv:2208.02790

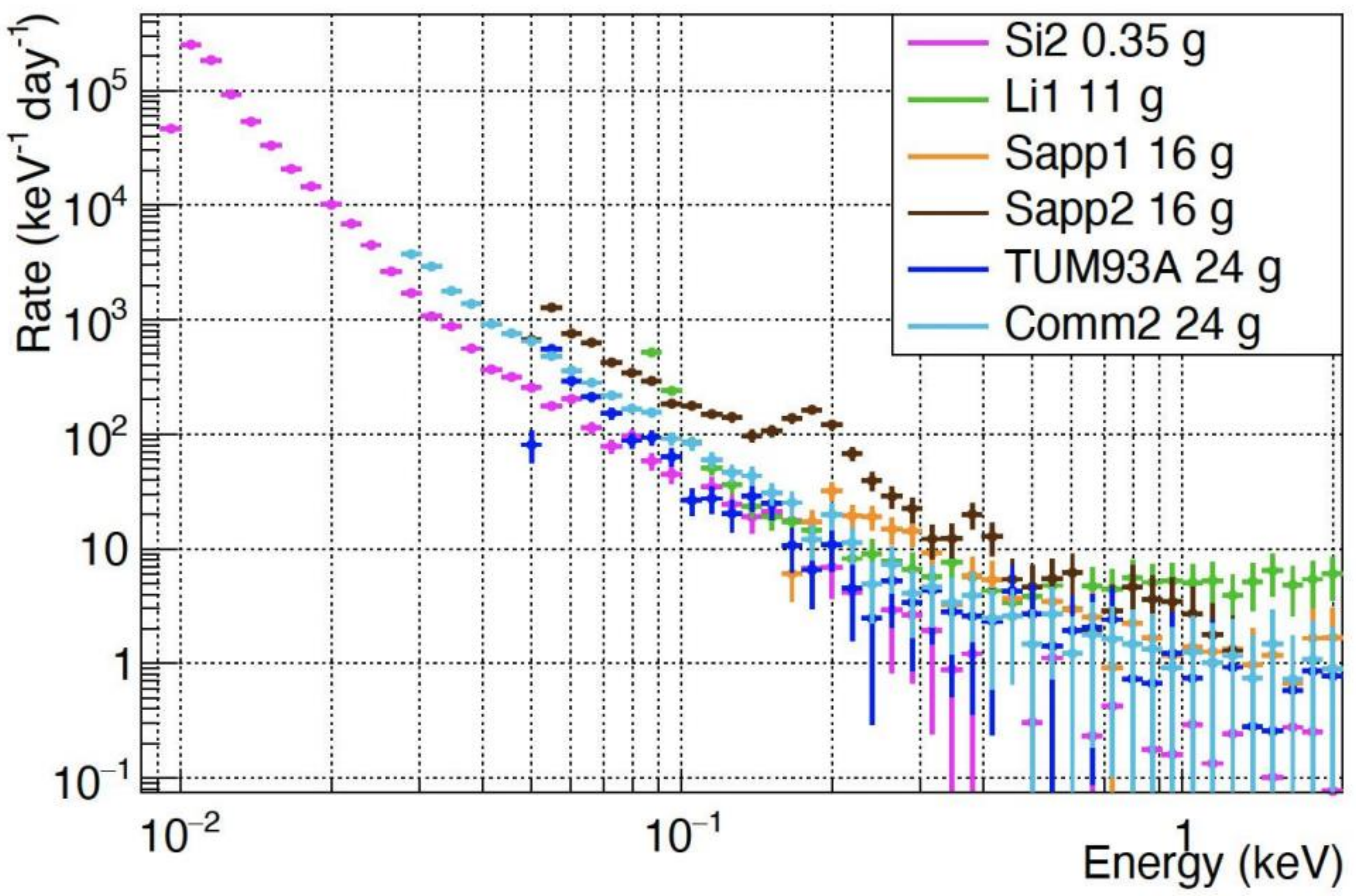


Excess events can be caused by external stress!

Some Key Findings

- CRESST observed vastly **different excess rates in detector modules**, with no obvious dependence on material and target size.
- The **event rate decays after the cooldown** of the experiment.
- **Hypothesis:** Differential thermal expansion in the various layers of a sensor could introduce stress during thermal cycles

CRESST, SciPost Phys. Proc. 12, 013 (2023)



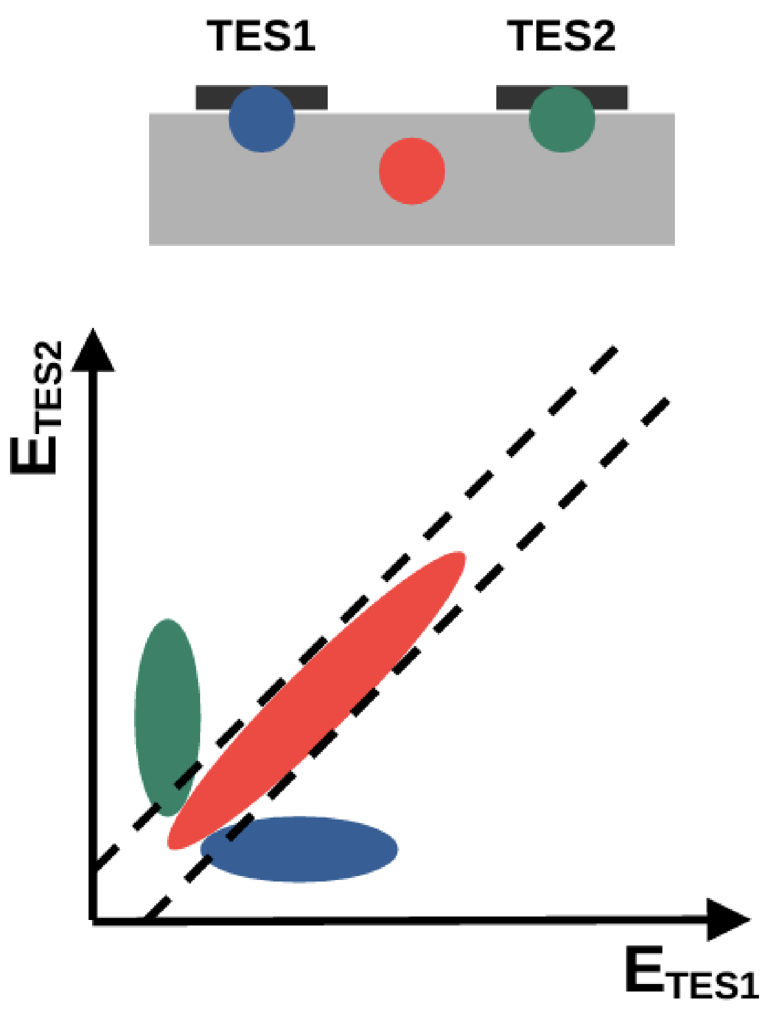
Some Key Findings

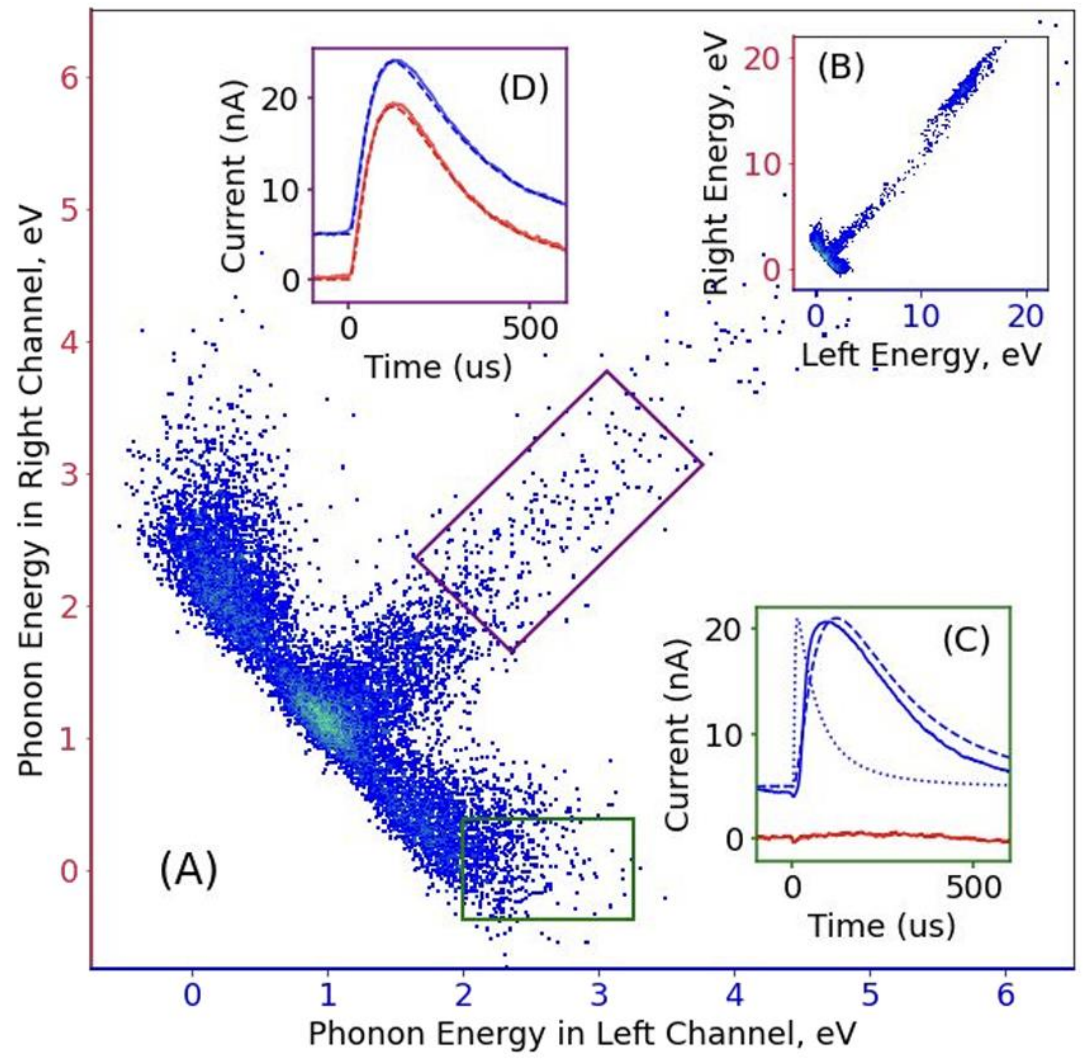
Use multiple sensors to identify sensor events

- Singles: *events from sensor itself should only show up in that sensor*
- Shared: *bulk events should be seen by all sensors*
- First prototypes tested by CRESST and SPICE

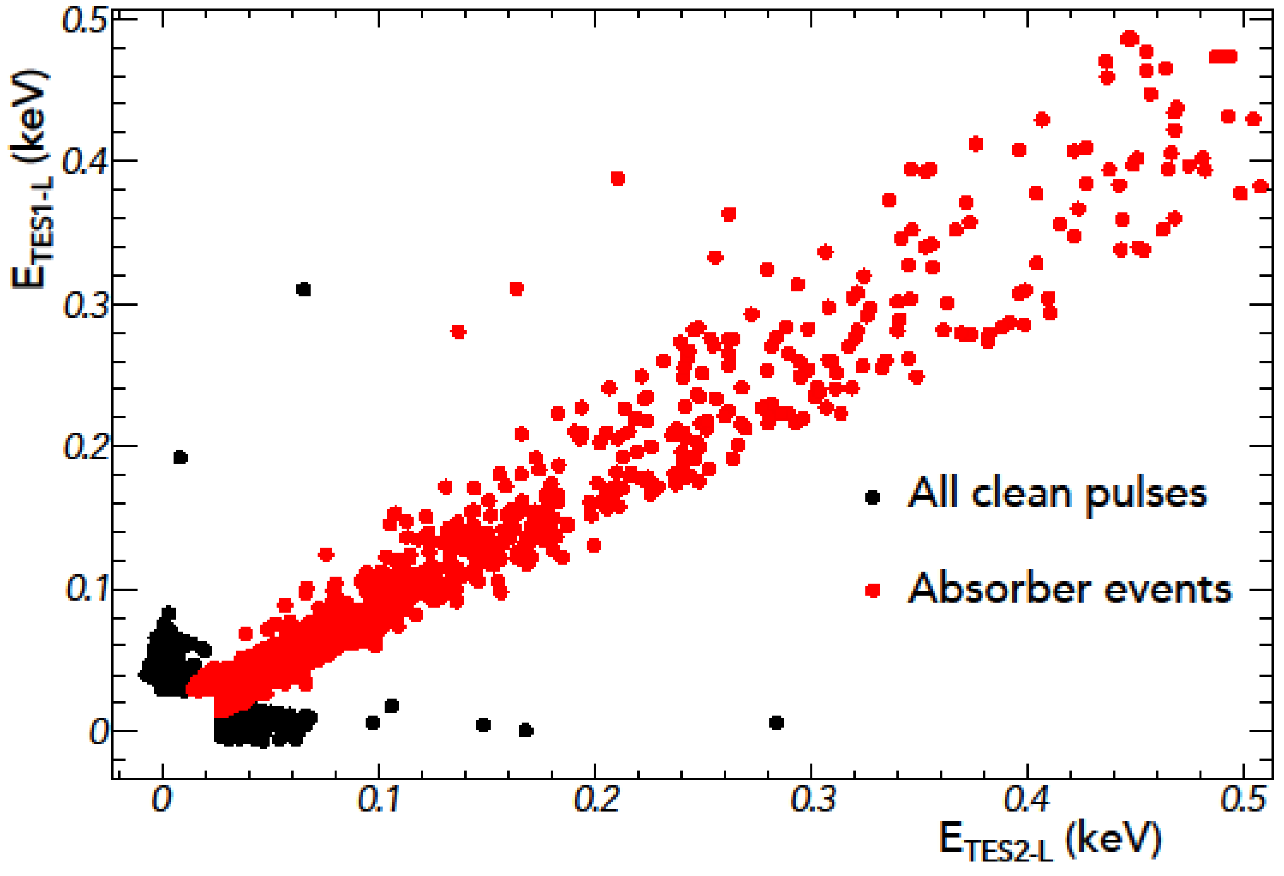
Recent **CRESST results** from observations for shared event low energy excess (LEE):

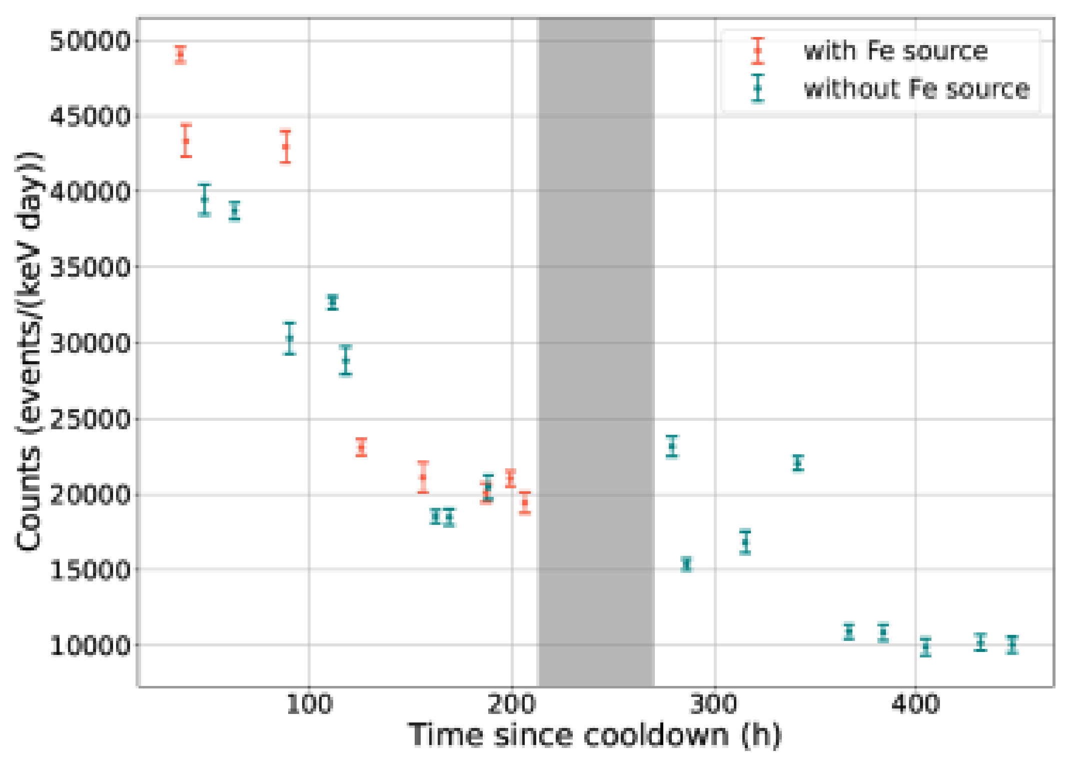
- decays with time
- is not compatible with noise
- External radiation does not impact the LEE





Romani, EXCESS 2023



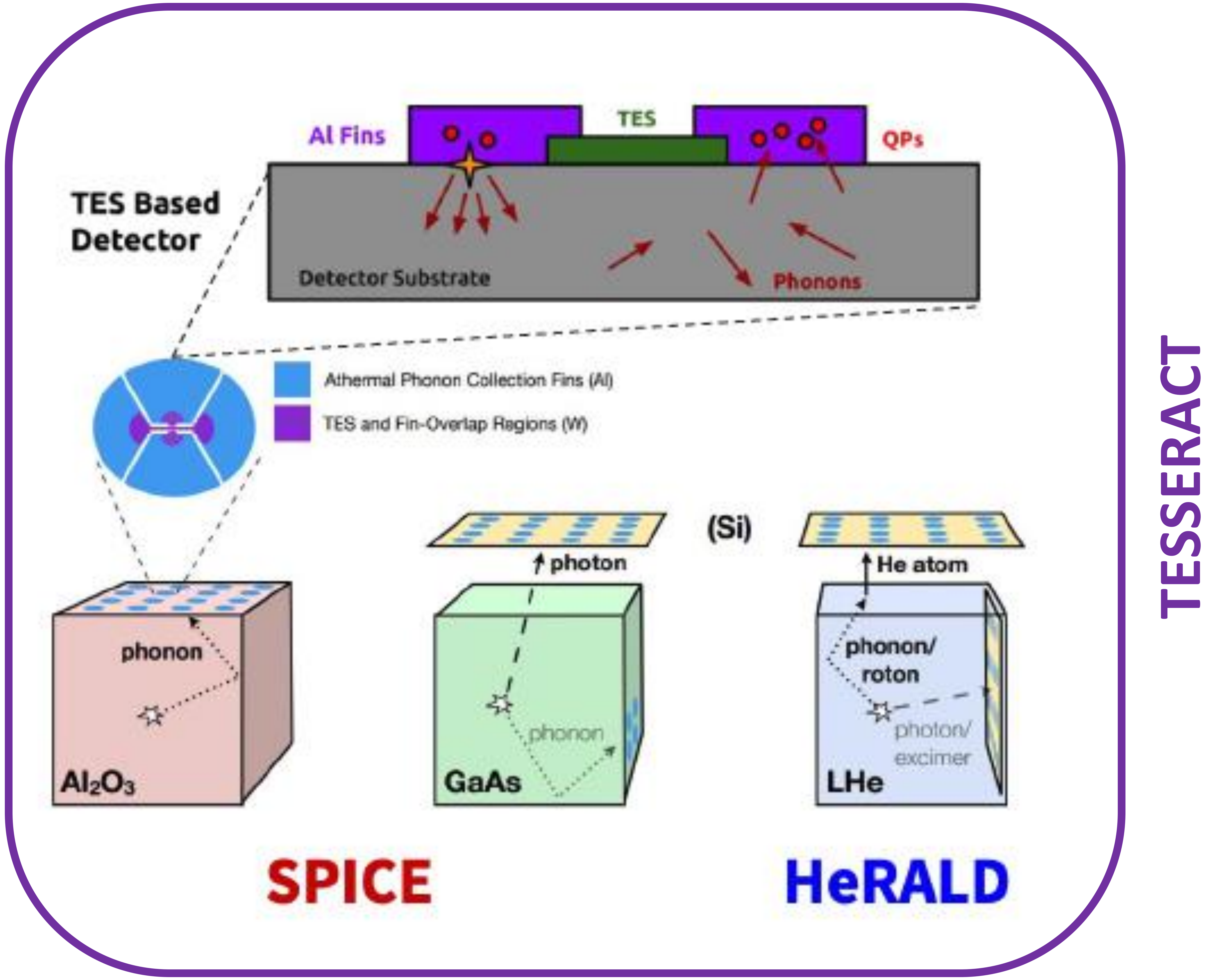


CRESST, arXIv:2404.02607v1

Future Detectors

TESSERACT: SPICE/HeRALD Collaboration

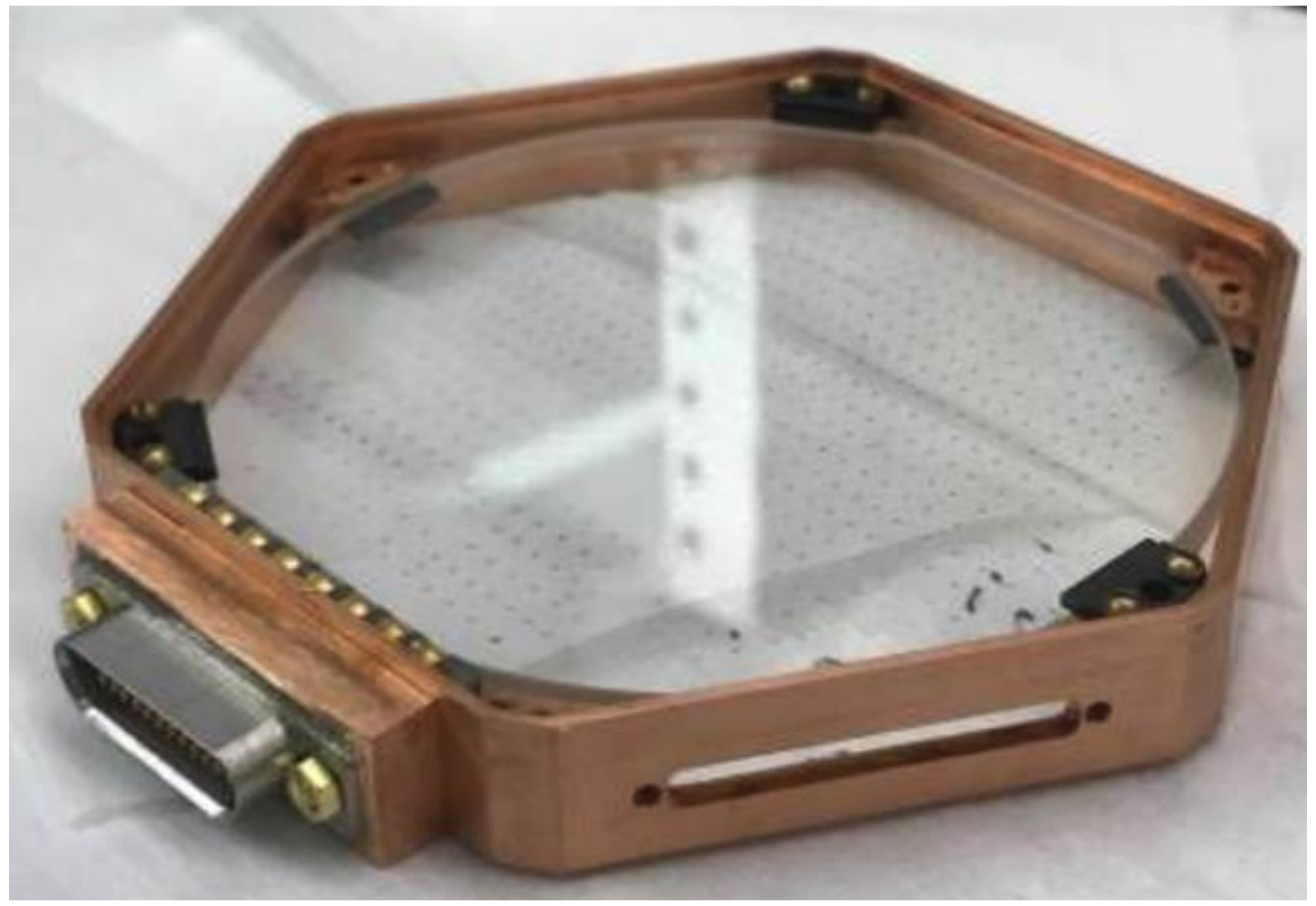
- **Sapphire (Al_2O_3)** – optical phonon modes kinematically-matched to sub-MeV DM (need 10 meV energy thresholds)
- **Gallium arsenide (GaAs)** – scintillation light can be collected in addition to phonon signals, potentially enables discrimination
- **Superfluid He (LHe)** – scintillation, triplet excimer signals, and phonon/rotons provide many signals for strong discriminatory power

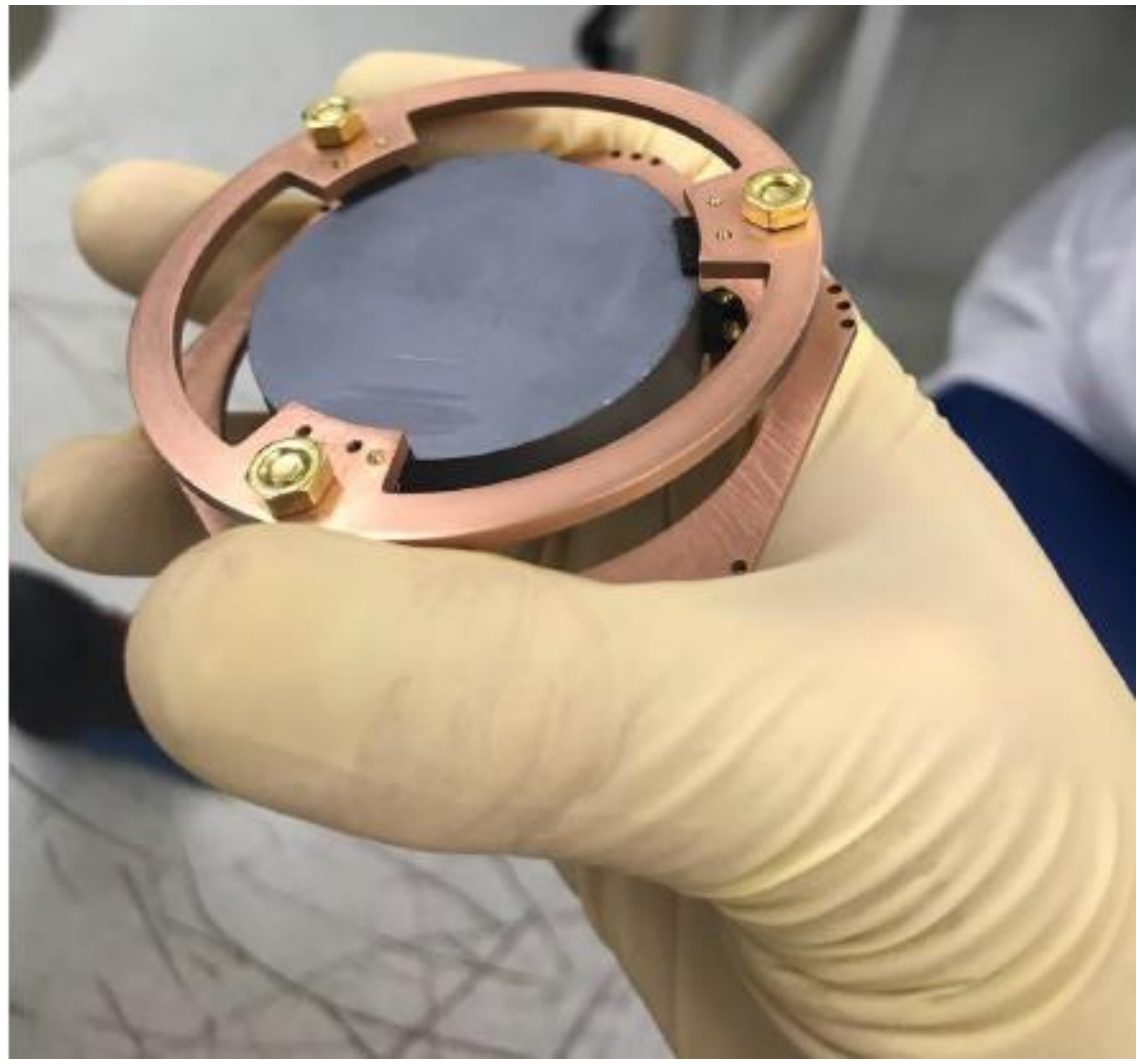


Romani – EXCESS 2024

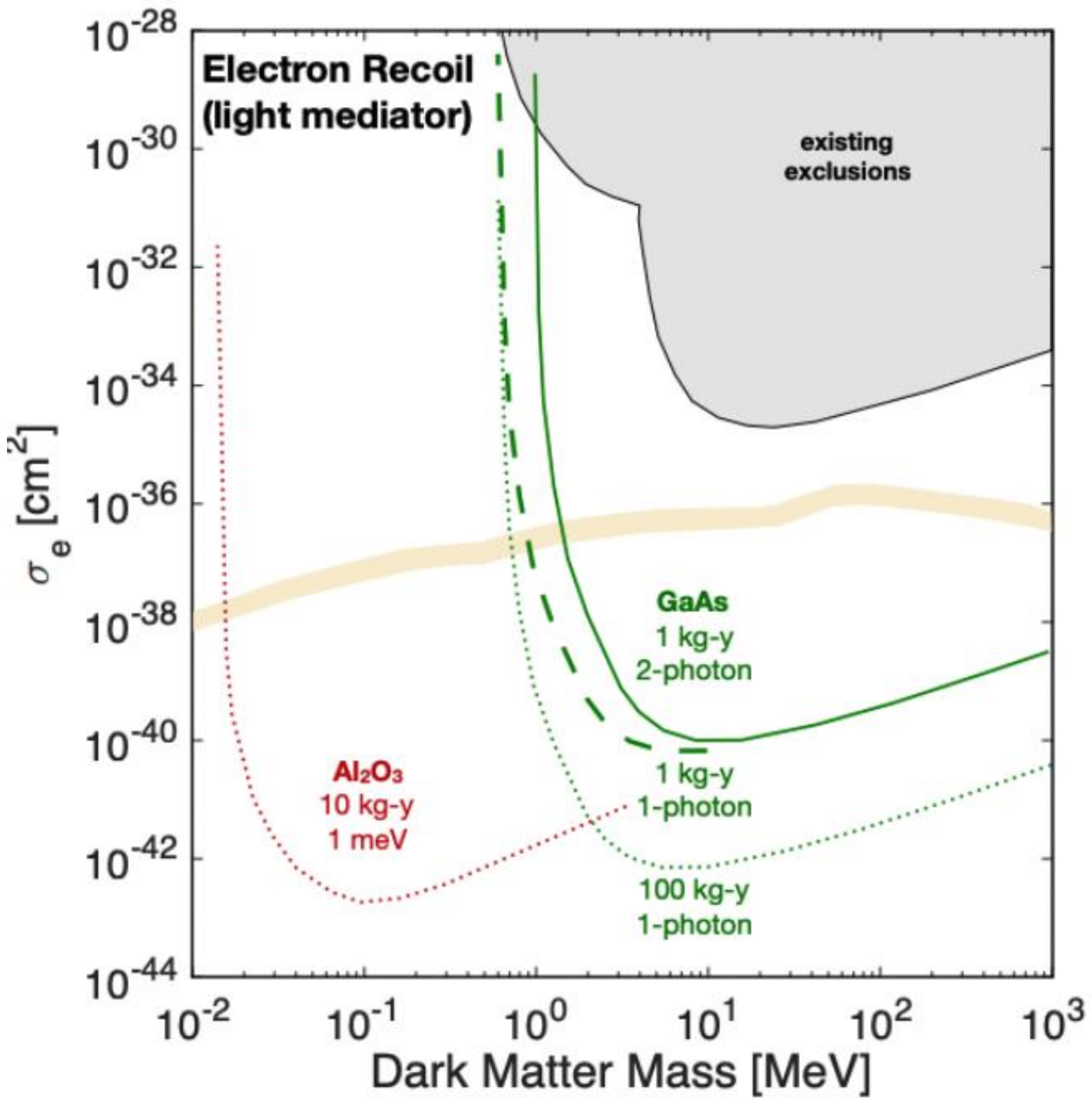
SPICE – Quasiparticle Detection

Low mass oxygen nuclei as nuclear recoil dark matter target. Can produce optical phonons down to 100s of meV.



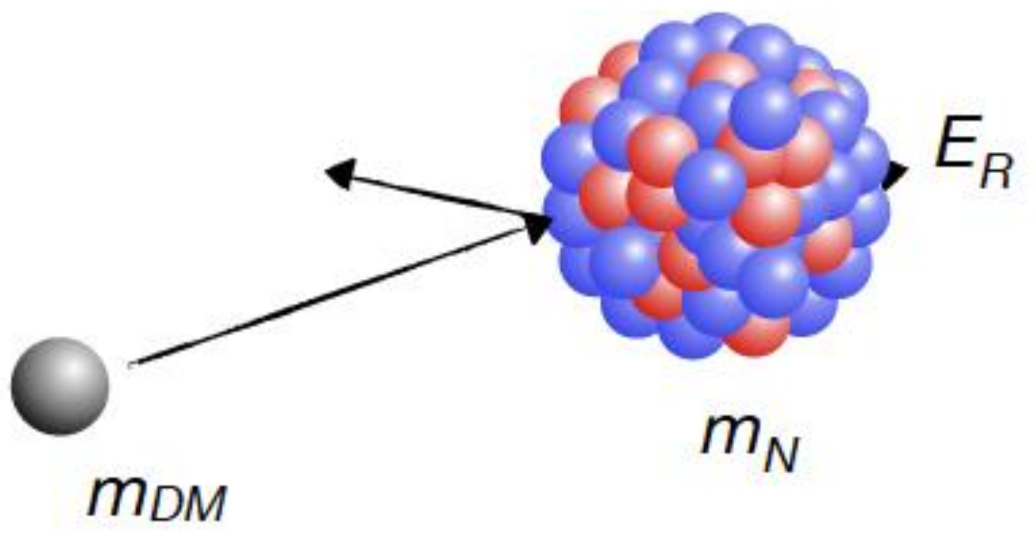


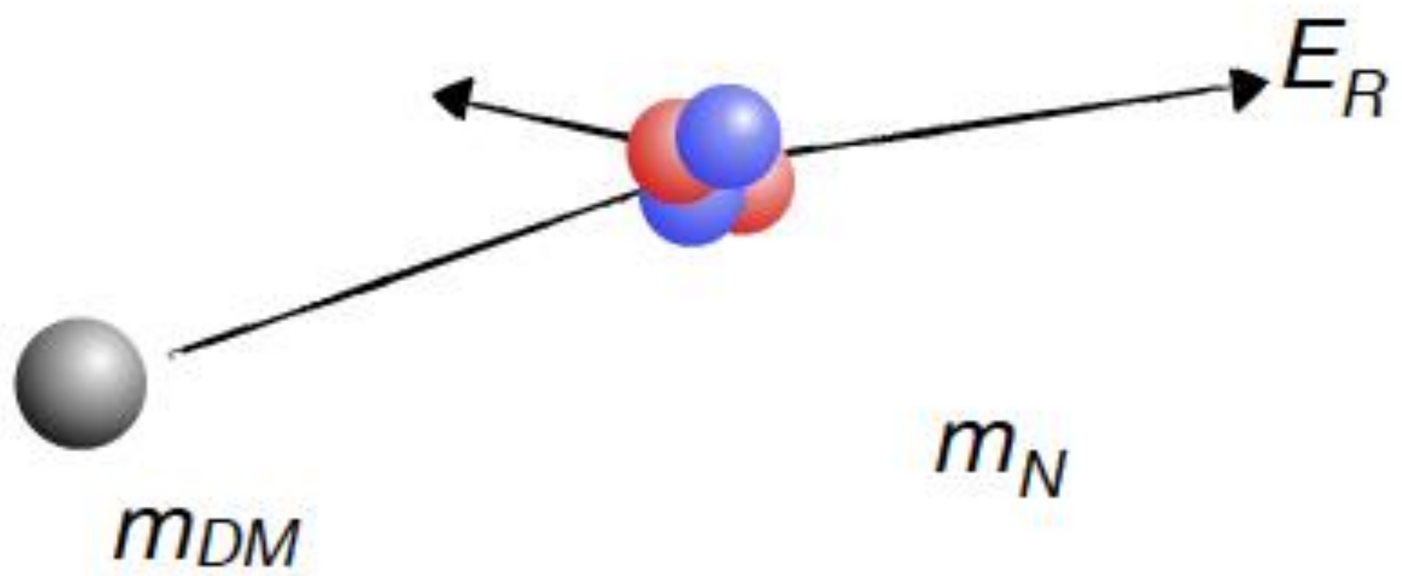
Scintillation + phonon signal allows for NR/ER discrimination down to **eV scale signals.**

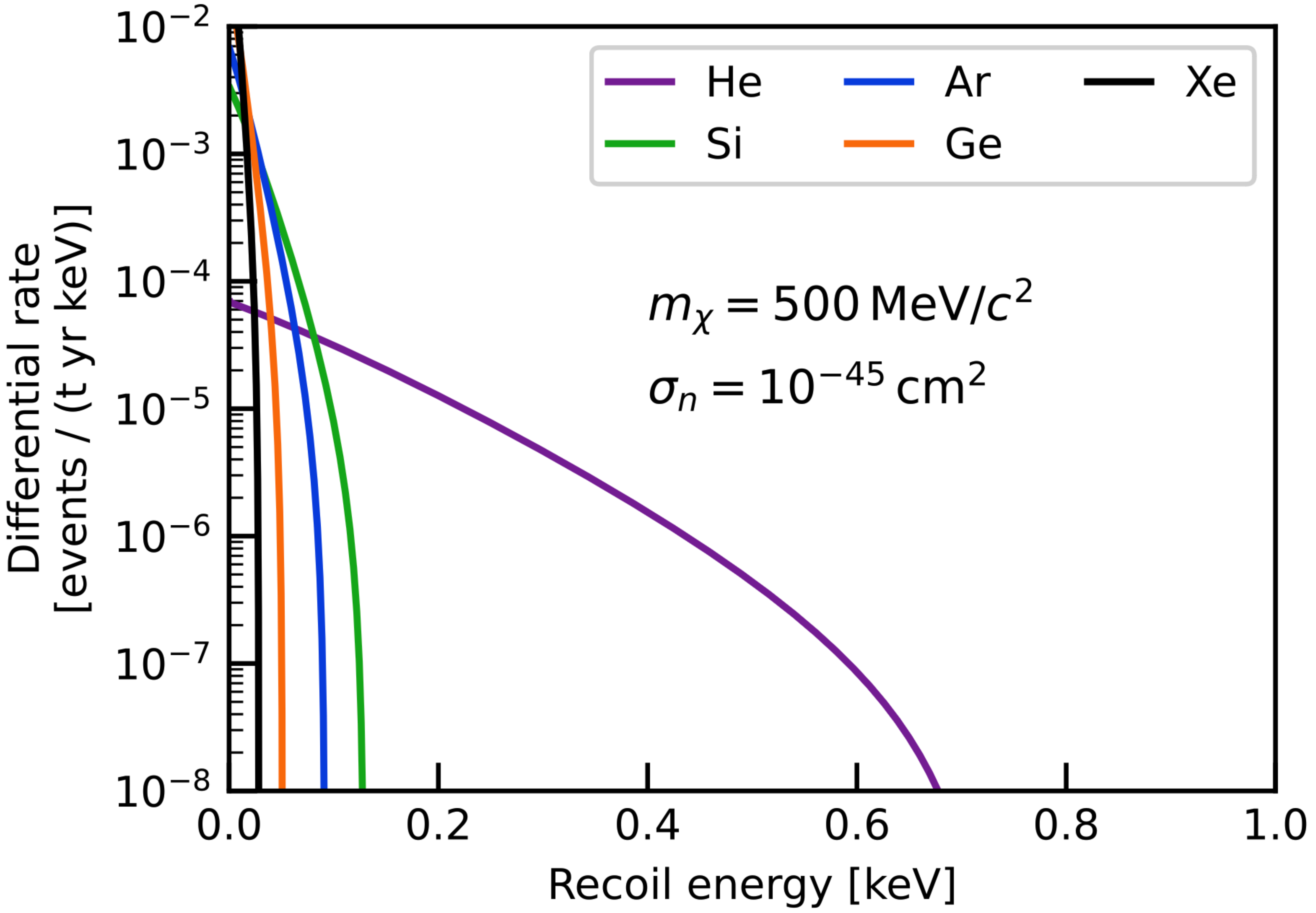


Romani – IDM 2024

Superfluid He - Quasiparticle Detection

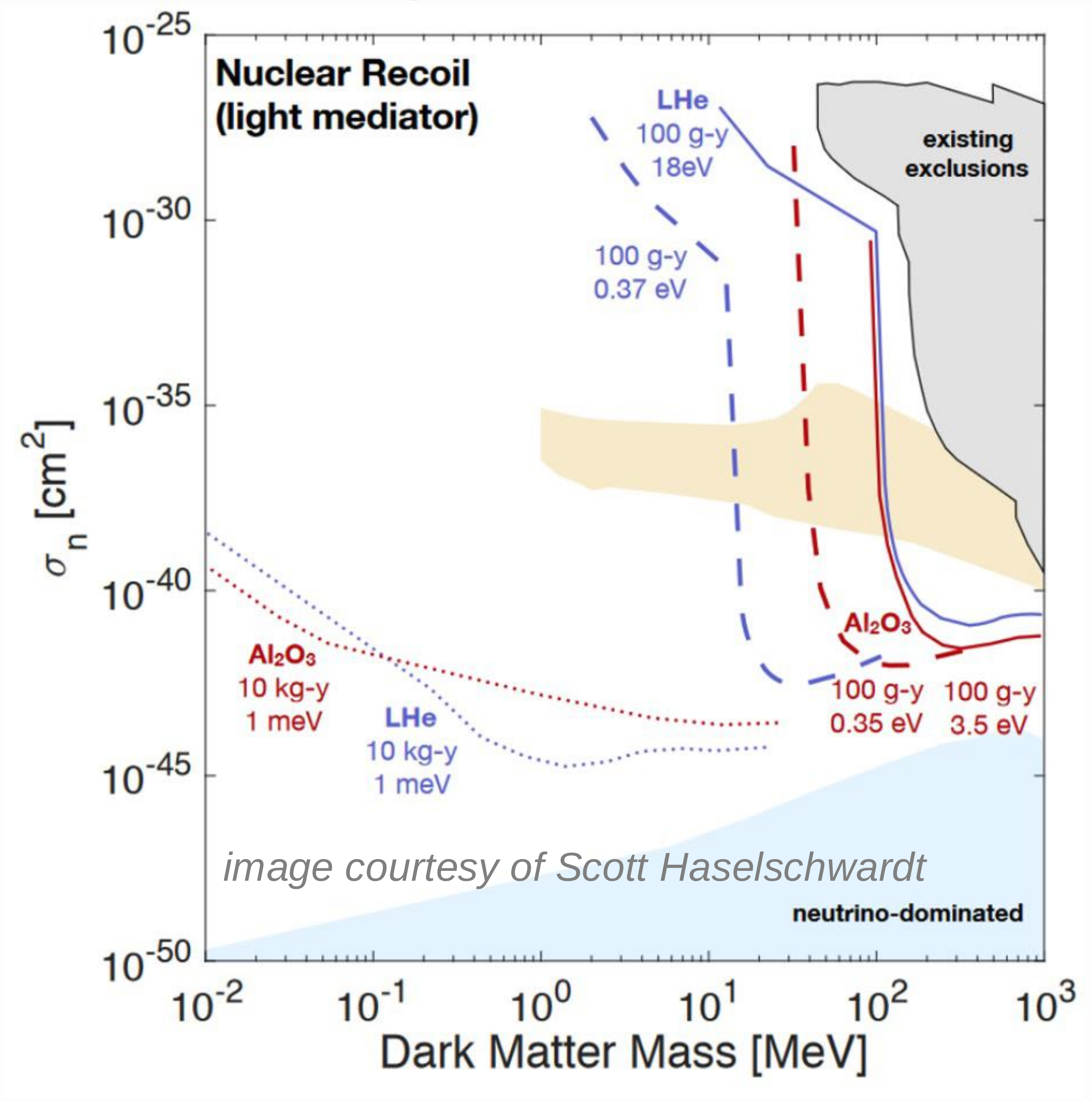


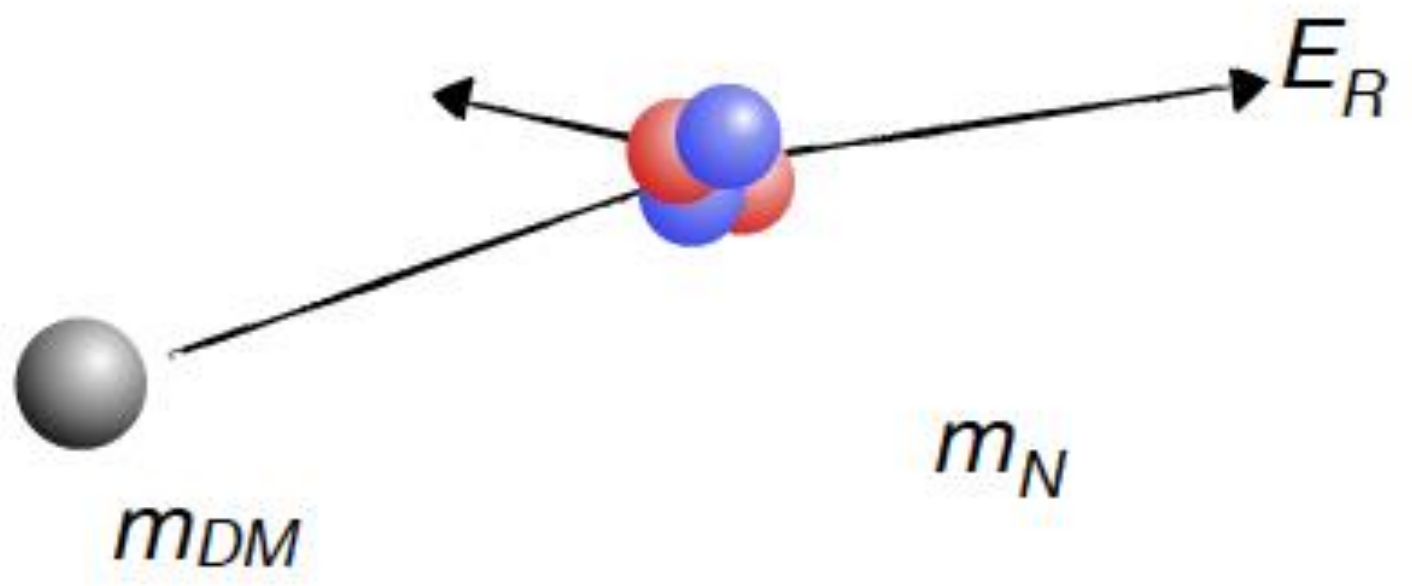




- Kinematics favourable to light DM candidates
- Three signal channels at different times!
  - **Prompt scintillation** *(dimer state)*
  - **Quantum evaporation** *(phonon/rotons)*
  - **Slow scintillation** *(trimer state)*
- Non-helium impurities freeze out → self-shielding!

Superfluid He - Quasiparticle Detection





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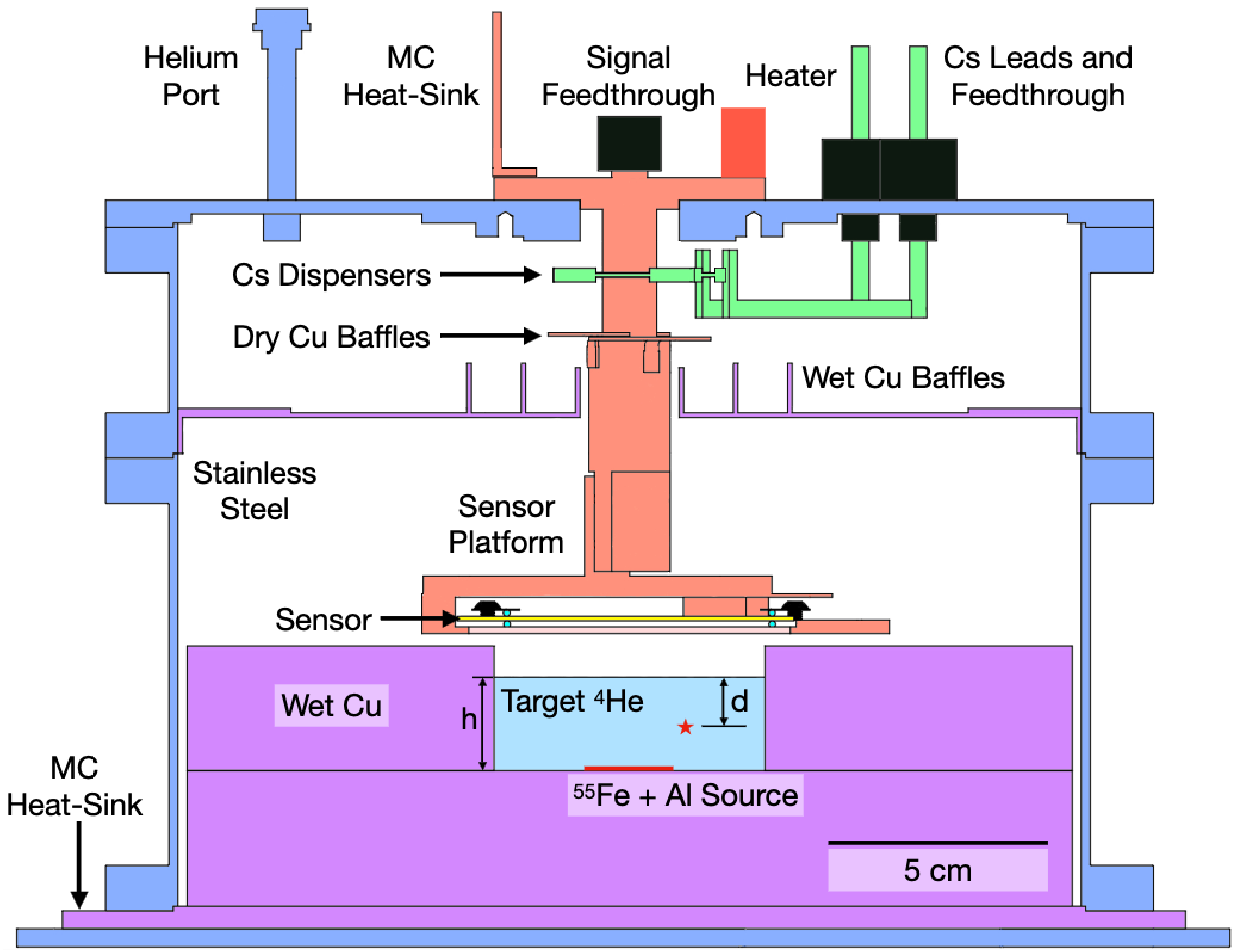
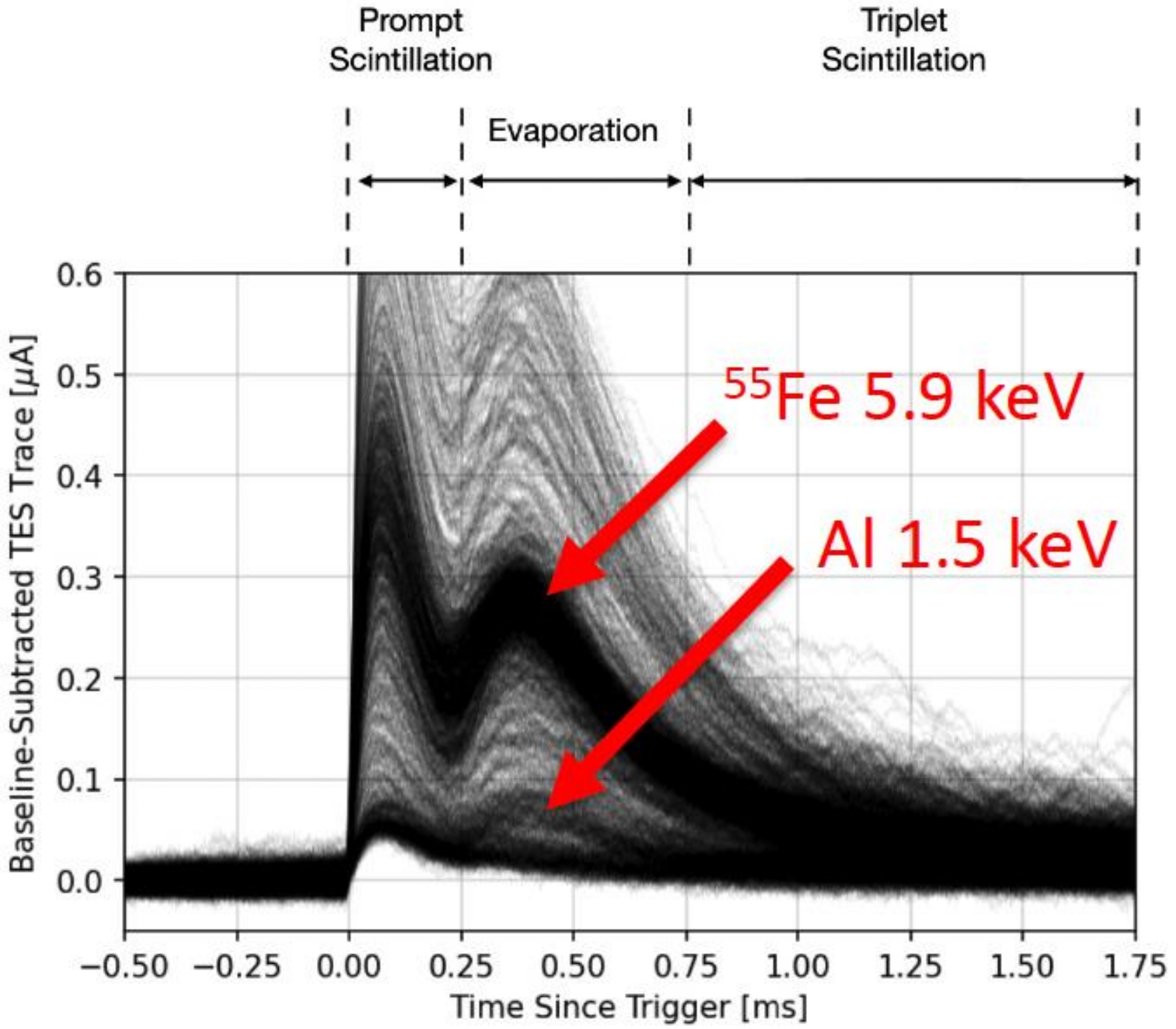
- Non-helium impurities freeze out → self-shielding!
- Sub-GeV dark matter phase space accessible with modest targets.

Superfluid He - HeRALD

Prototype under construction and testing at LBNL





SPICE/HeRALD- arXiv:2307.11877

Superfluid He - DElight

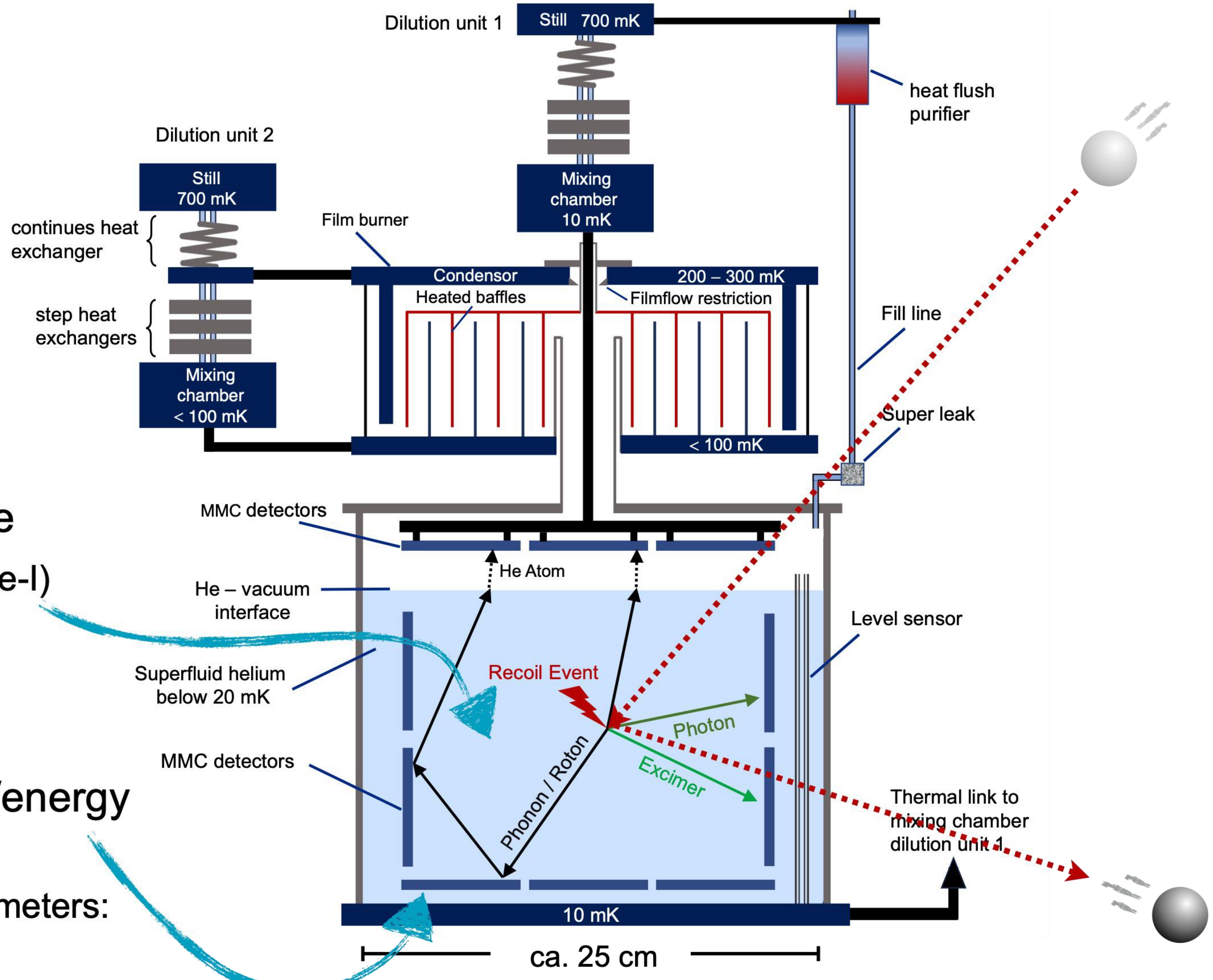
Uses MMCs (instead of TESs)

Superfluid ^{4}He

(~ 10 liters in phase-I)

Ultra-sensitive heat/energy sensors

(Magnetic MicroCalorimeters: MMCs)



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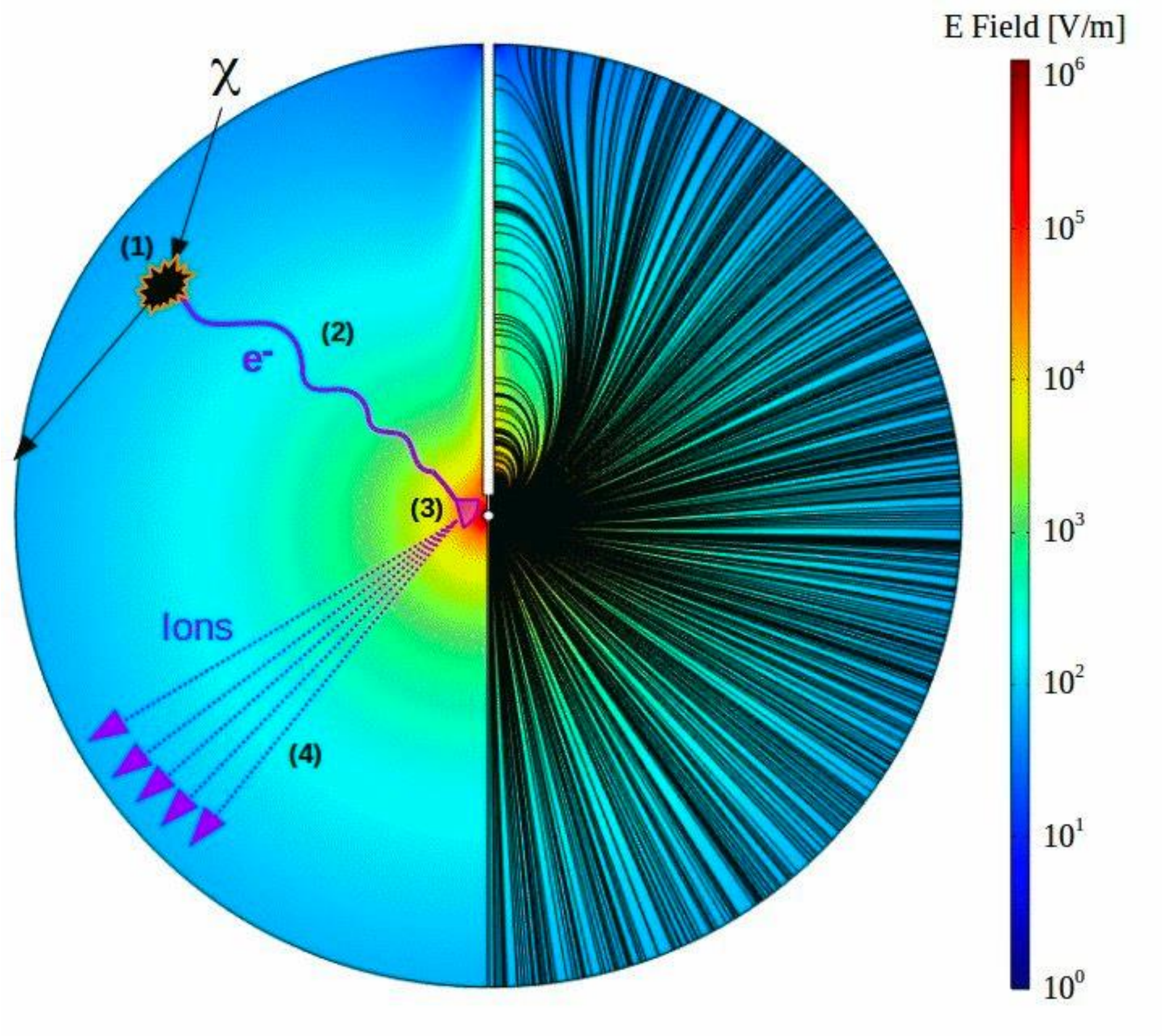
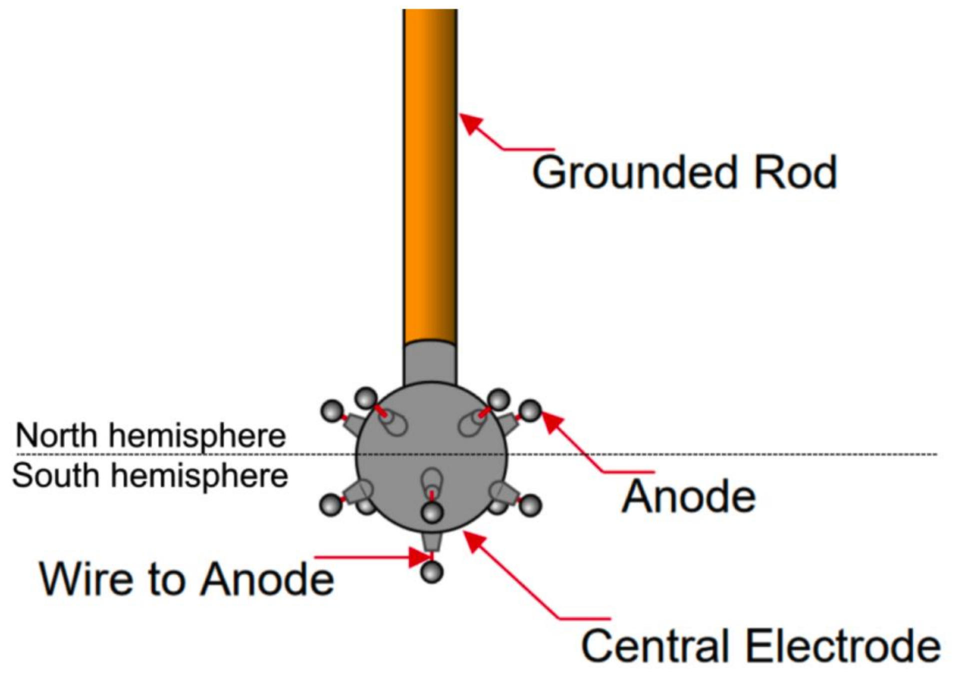
Karlsruhe Institute of Technology

universität freiburg

Delight, arXiv:2209.10950

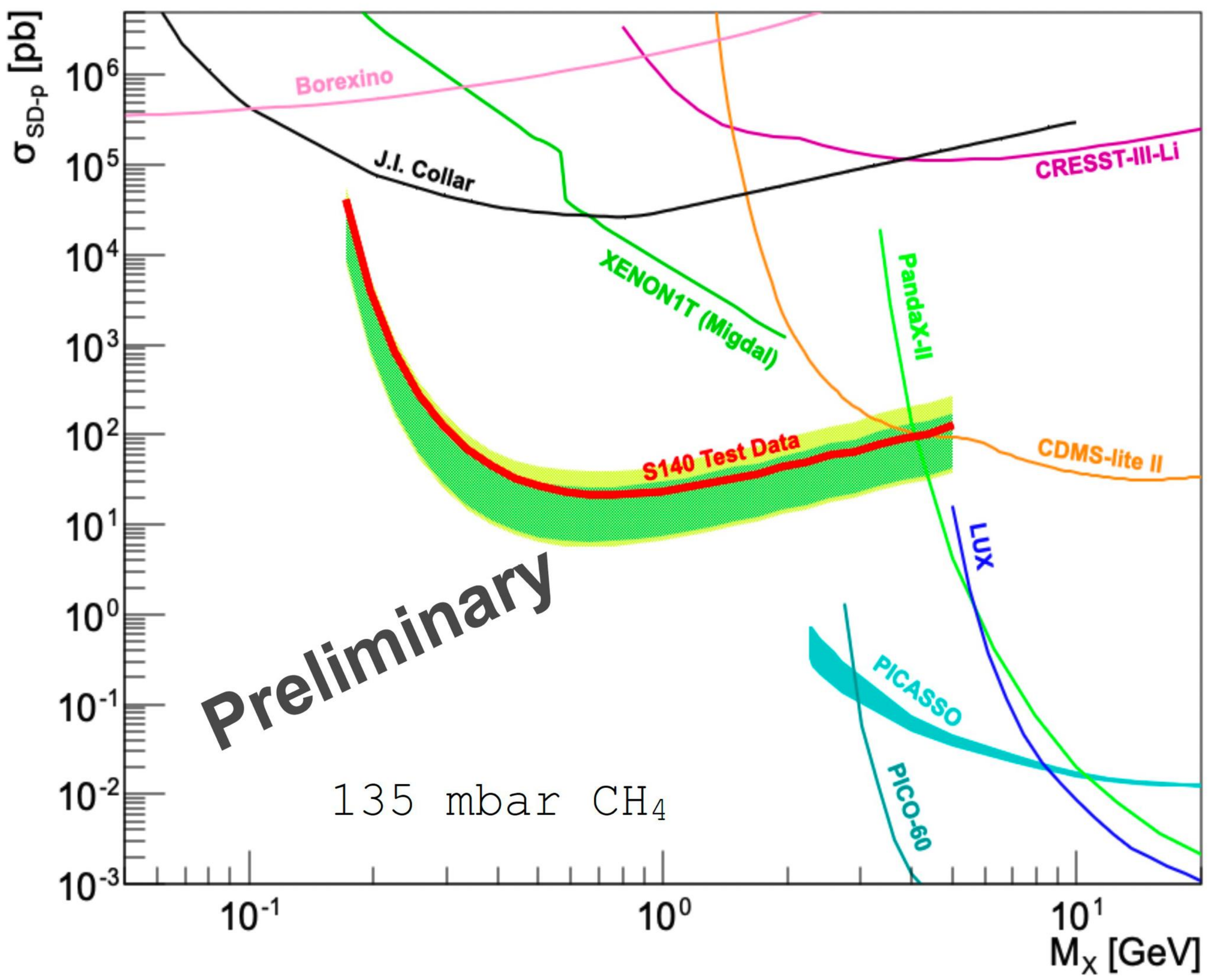
Spherical Proportional Counters - NEWS-G





First preliminary results from SD DM-proton scattering searches in methane (CH4) from 10 day run at LSM.

NEWS-G, PoS TAUP2023 (2024) 042



Advantages:

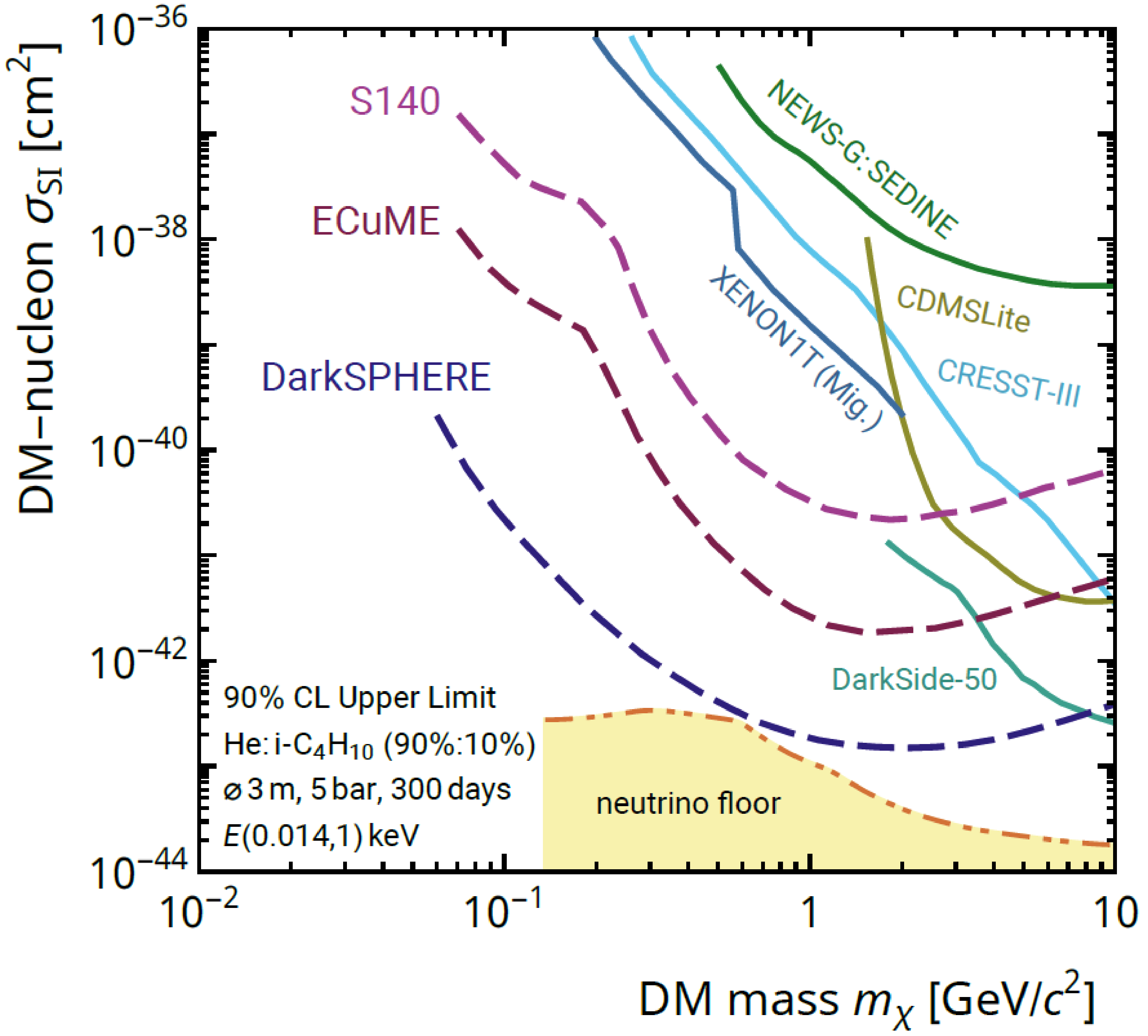
- Low capacitance → *single electron detection*
- Maximal surface to volume ratio
- Variable target

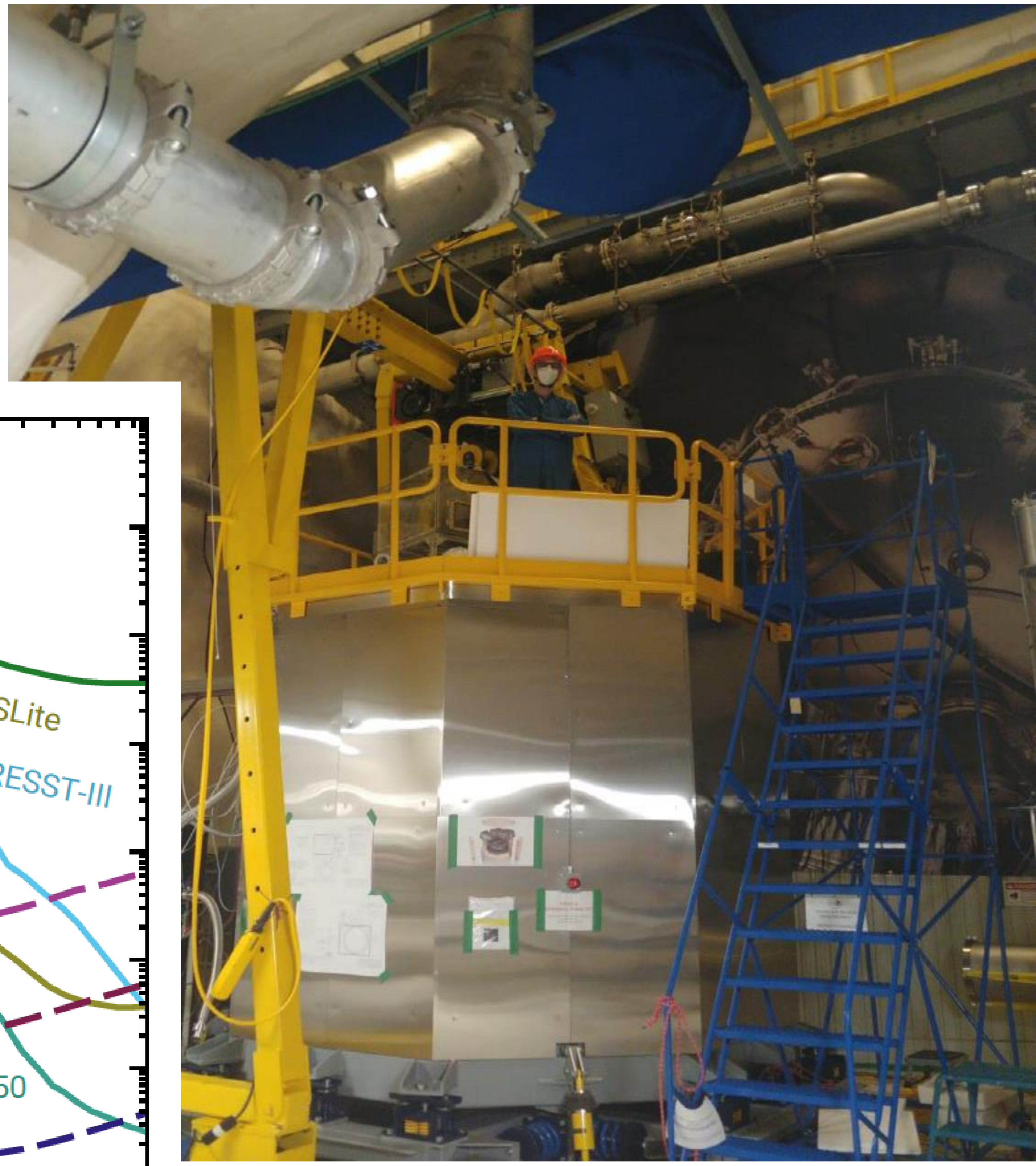
Spherical Proportional Counters - Status

- ***First physics run in SNOLAB*** in 2023 → ~20 kg days exposure with Ne:CH_4 mixture. Operations ongoing.

Spherical Proportional Counters - Status

- ***First physics run in SNOLAB*** in 2023 → ~20 kg days exposure with Ne:CH_4 mixture. Operations ongoing.
- **ECuME (& miniECuME):**
  - Electroformed 140 cm diameter copper sphere in SNOLAB + scale model at PNNL
  - STFC funding for ultra-pure EFCu facility in Boubly (under construction)
- **DarkSPHERE:**
  - Fully electroformed 3m of diameter sphere + water shield in Boulby.



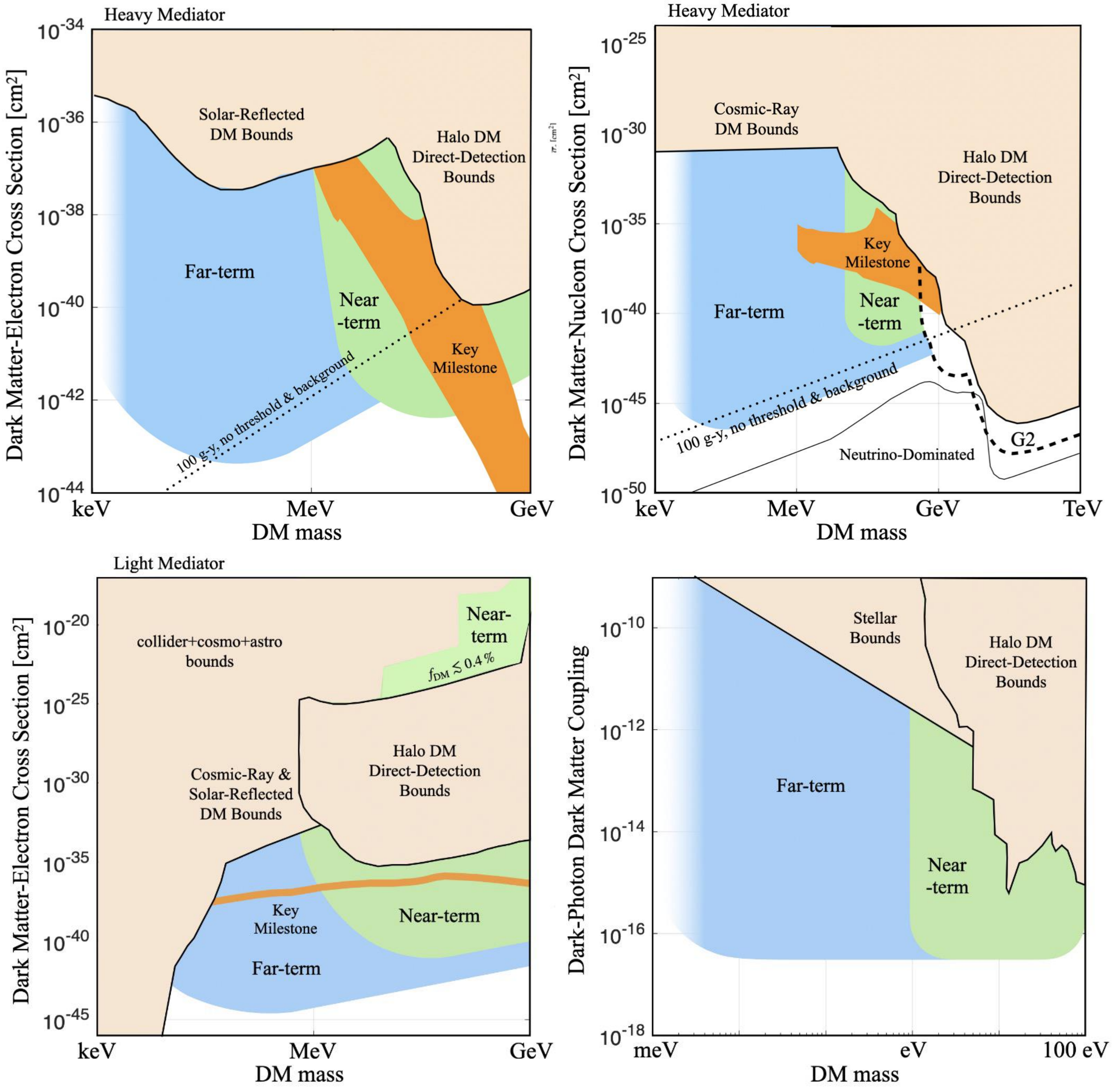


I. Manthos – IDM2024

There are many detectors …

And hopefully, a discovery in the near future!

Experiment	Location	Data Taking	Readout	Target	Home	Ref.
DarkSide-20k	Gran Sasso, Italy	2023	scint.+ioniz. (~ 85 K)	20 t Ar	web	[375]
SBC	SNOLAB, Canada	2028	scint. bubble chamb. (~ 100 K)	10 kg Ar	talk	[376]
ARGO	SNOLAB, Canada	2029	scint.+ioniz. (~ 85 K)	300 t Ar	web	web
DarkSide-LM			scint.+ioniz. (~ 85 K)	1.5 t Ar	web	[377]
LZ-HydroX	Sanford, SD	202x	ioniz.+scint. (174 K)	5.5 t Xe + 2 kg H_2	web	LOI
DARWIN/XLZD/G3	undetermined	2027/28	scint.+ioniz. (~ 170 K)	40 t Xe	web	[378]
PandaX-xT	Jinping, China	202x	scint.+ioniz. (~ 170 K)	43 t Xe	web	[379]
QUEST-DMC			quasipart. (~ 100 μK)	1 cm^3 ^3He	paper	[380]
DELight		202x	phon.+roton (~ 20 mK)	10 l ^4He	web	[381]
HeRALD		202x	phon.+roton (~ 50 mK)	~ 1 kg ^4He	web	[382]
SuperCDMS SNOLAB	SNOLAB, Canada	2023	{ ath. phon.[+ioniz.] (15 mK) ath. phon.[+ioniz.] (15 mK)	11[+14] kg Ge 2.4[+1.2] kg Si	web	[383]
DAMIC-M	Modane, France	2025	ioniz. (~ 120 K)	0.7 kg Si	web	[384]
OSCURA	SNOLAB, Canada	2029	ioniz. (~ 130 K)	10 kg Si	web	[385]
CDEX-50	Jinping, China	202x	ioniz. (~ 90 K)	~ 300 kg Ge	web	talk
EDELWEISS-CRYOSEL	Modane, France	202x	ath. phon. (~ 10 mK)	~ 30 g Ge	web	[386]
CDEX-300	Jinping, China	2027	ioniz. (~ 90 K)	~ 300 kg Ge	web	LOI
CDEX-1T	Jinping, China	2033	ioniz. (~ 90 K)	~ 1 t Ge	web	LOI
CDEX-10T	Jinping, China	2040	ioniz. (~ 90 K)	~ 10 t Ge	web	LOI
COSINE-200	Yemilab, South Korea	2024	scint. (~ 300 K)	~ 200 kg NaI(Tl)	web	talk
COSINUS	Gran Sasso, Italy	2024	scint. (~ 10 mK)	~ 1 kg NaI(Tl)	web	[387]
SABRE {	Gran Sasso, Italy SUPL, Australia	2024 2023	scint. (~ 300 K) scint. (~ 300 K)	50 kg NaI(Tl) 50 kg NaI(Tl)	web web	[336]
PICOLON	Kamioka, Japan	202x	scint. (~ 300 K)	54 → 250 kg NaI(Tl)	paper	[388]
KamLAND-PICO	Kamioka, Japan	203x	scint. (~ 300 K)	1000 kg NaI(Tl)	paper	[388]
DMICE-250	South Pole		scint. (~ 260 K)	~ 200 kg NaI(Tl)	talk	talk
PICO-40L	SNOLAB, Canada	2023	bubble chamber (~ 290 K)	~ 50 kg C_3F_8	web	[389]
PICO-500	SNOLAB, Canada	202x	bubble chamber (~ 290 K)	360 kg C_3F_8	web	[390]
MOSCAB	Gran Sasso, Italy	202x	bubble chamber (~ 290 K)	2 → 251 C_3F_8	paper	[345]
MIMAC	Grenoble, France		ioniz. (~ 300 K)	CF_4+CHF_3	paper	[349]
NEWS-G : ECUME	SNOLAB, Canada		ioniz. (~ 300 K)	~ 2 kg CH_4	web	[332]
NEWS-G : DarkSPHERE	Boulby, UK		ioniz. (~ 300 K)	27 kg He+C_4H_{10}	web	[332]
CYGNO	Gran Sasso, Italy	2024	ioniz. (~ 300 K)	1 m^3 He+CF_4	web	[351]
CYGNUS	multiple sites		ioniz. (~ 300 K)	10^3 m^3 He+SF_6/CF_4	web	[352]
SNOWBALL			supercooled liq. (~ 250 K)	1 kg H_2O	talk	[391]
ALETHEA			scint.+ioniz. (~ 4 K)	10 kg He	paper	[392]
TESSERACT			ath. phon.	Al_2O_3, GaAs, He	web	LOI
SPLENDOR			ioniz	$Eu_5In_2Sb_6$, $EuZn_2P_2$	poster	LOI
Windchime			accelerometers		paper	[263]



Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

Coming Dark Matter Day 2024!