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SEIT 1386

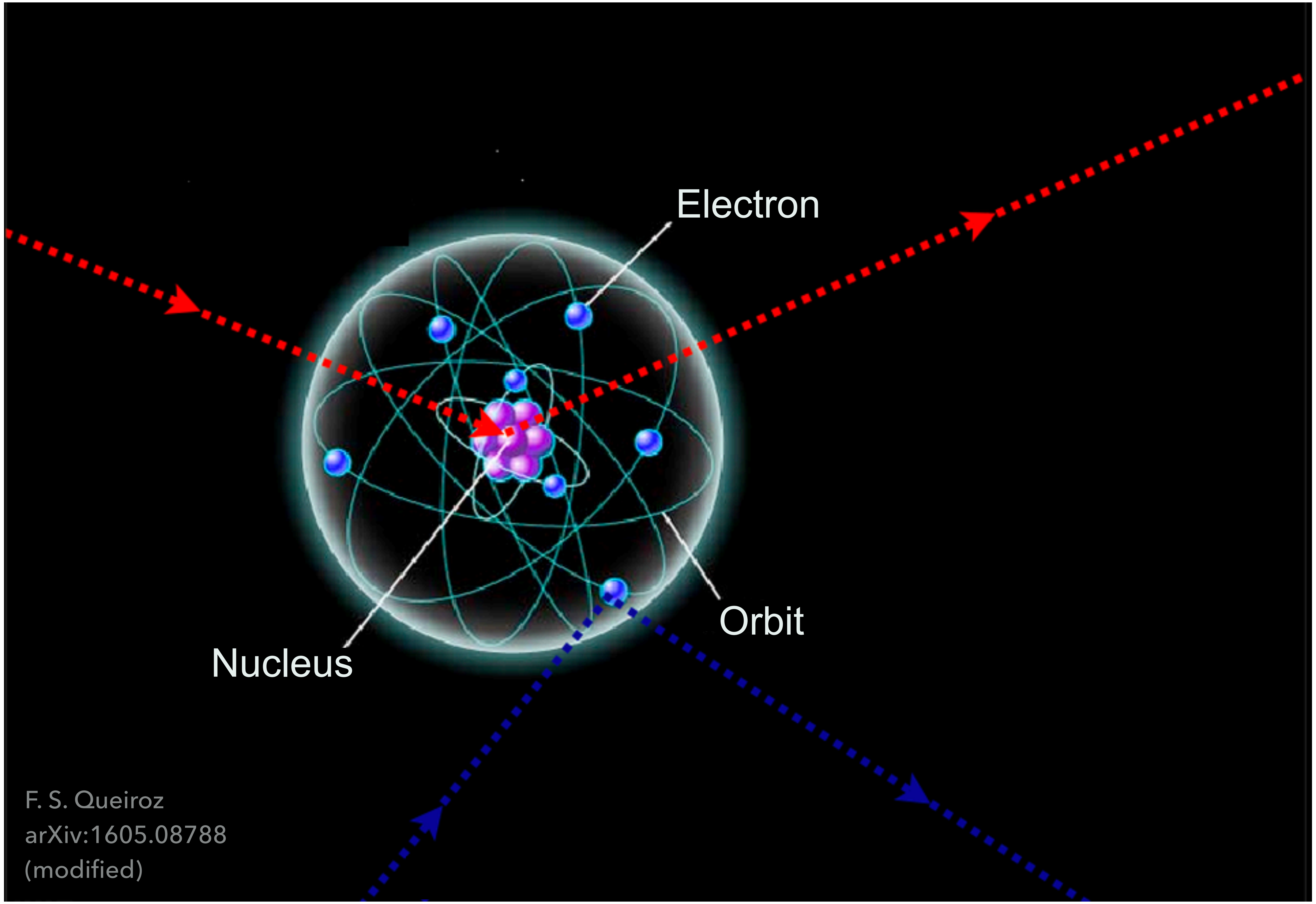
Direct detection of sub-GeV dark matter: Experimental status

Invisibles24 Workshop, 02. July 2024

Belina VON KROSIGK (bkrosigk@kip.uni-heidelberg.de)

Credit: Swinburne Astronomy Productions - J. Josephides

Direct dark matter detection in a nutshell



- Basic idea
  - Particles directly interact with the atoms of the detector material and cause a (potentially) observable recoil
- Signatures in detector
  - Nuclear Recoil **NR**
  - Electron Recoil **ER**

Direct dark matter detection in a nutshell

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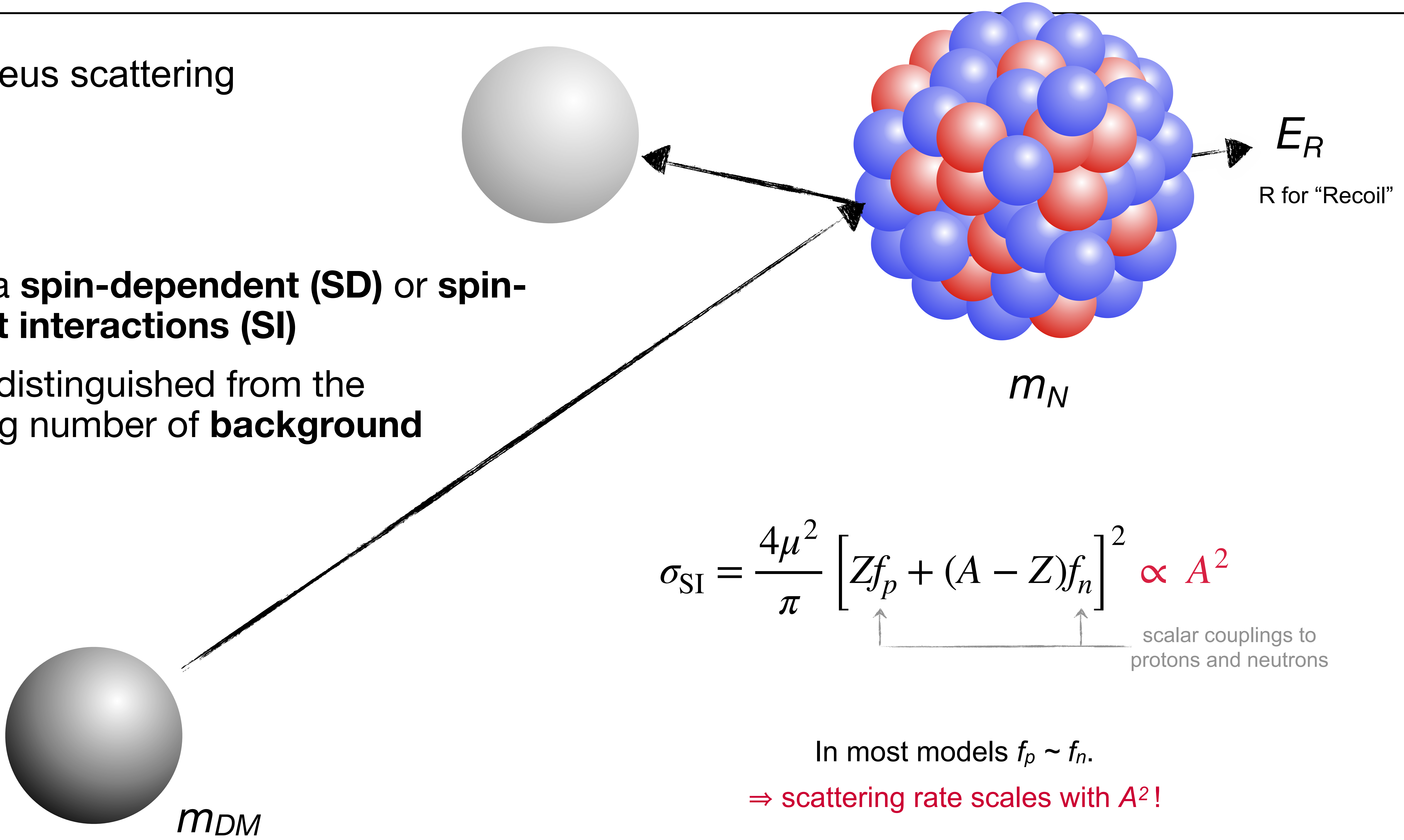
Elastic DM-nucleus scattering

- can occur via **spin-dependent (SD)** or **spin-independent interactions (SI)**
- needs to be distinguished from the overwhelming number of **background events**



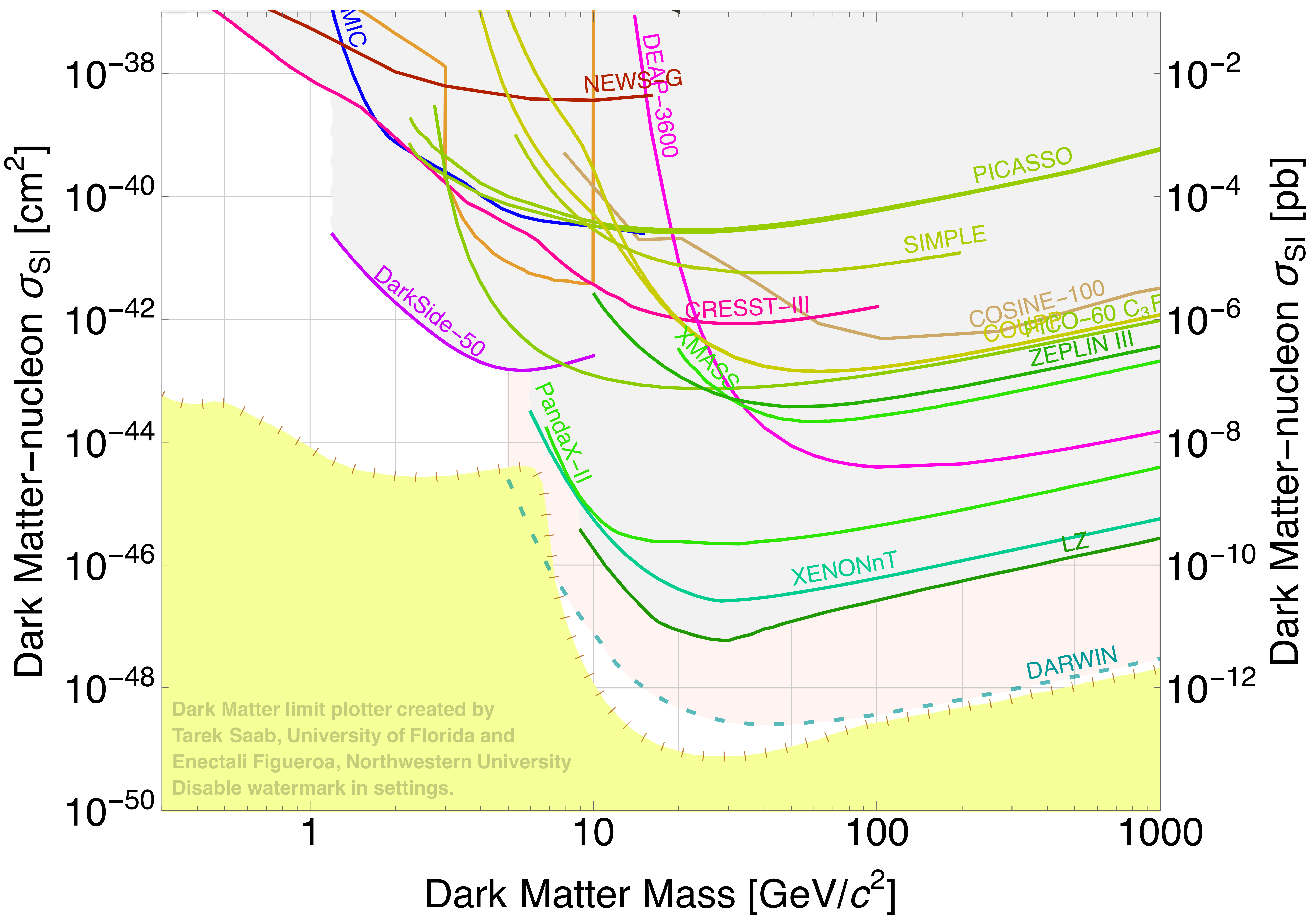
$$\sigma_{\mathrm{SI}} = \frac{4\mu^2}{\pi}\left[Z f_p + (A-Z) f_n\right]^2 \propto A^2$$

scalar couplings to protons and neutrons

In most models $f_p \sim f_n$.

⇒ scattering rate scales with A^2!

The “traditional” parameter space



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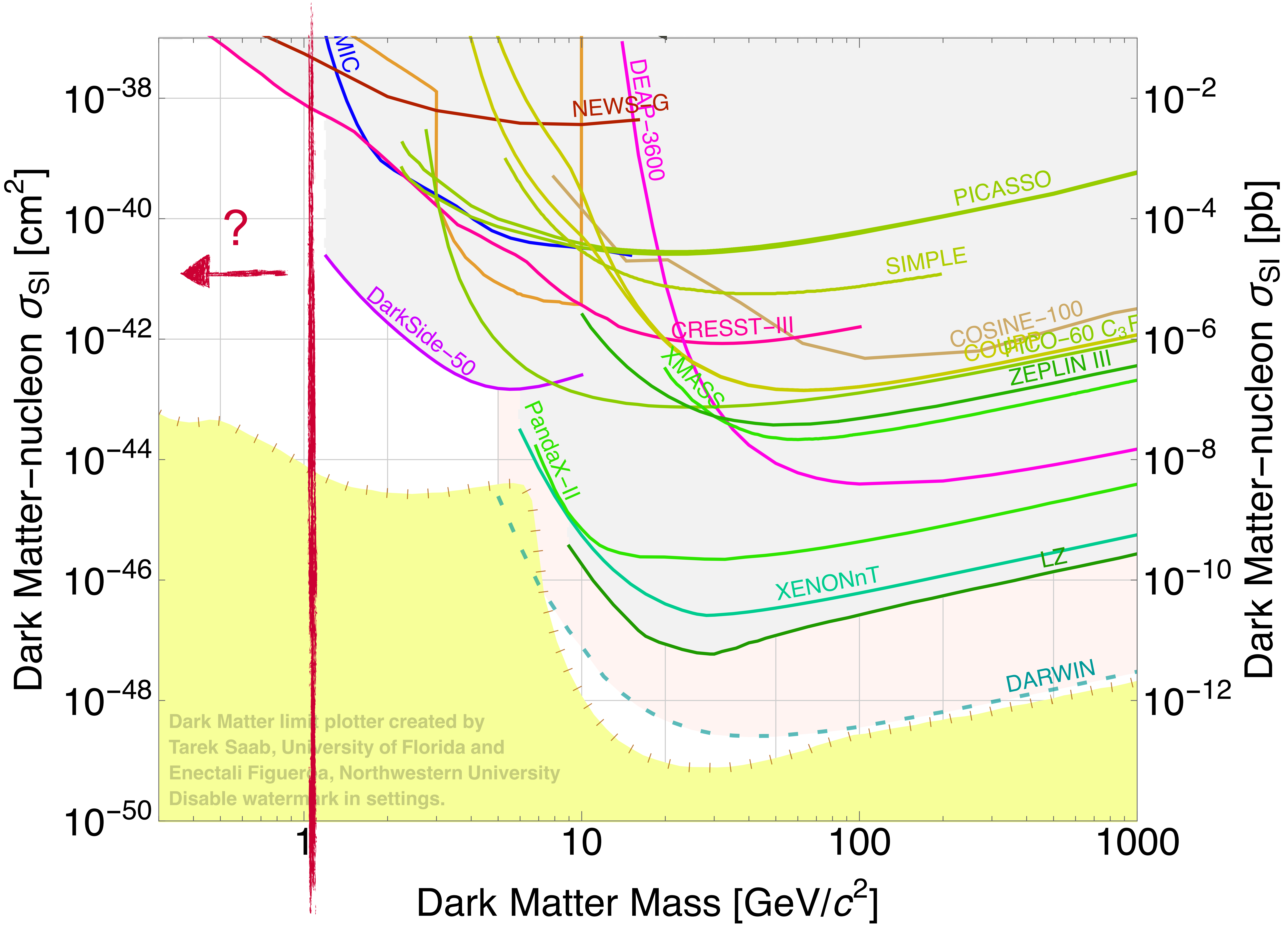
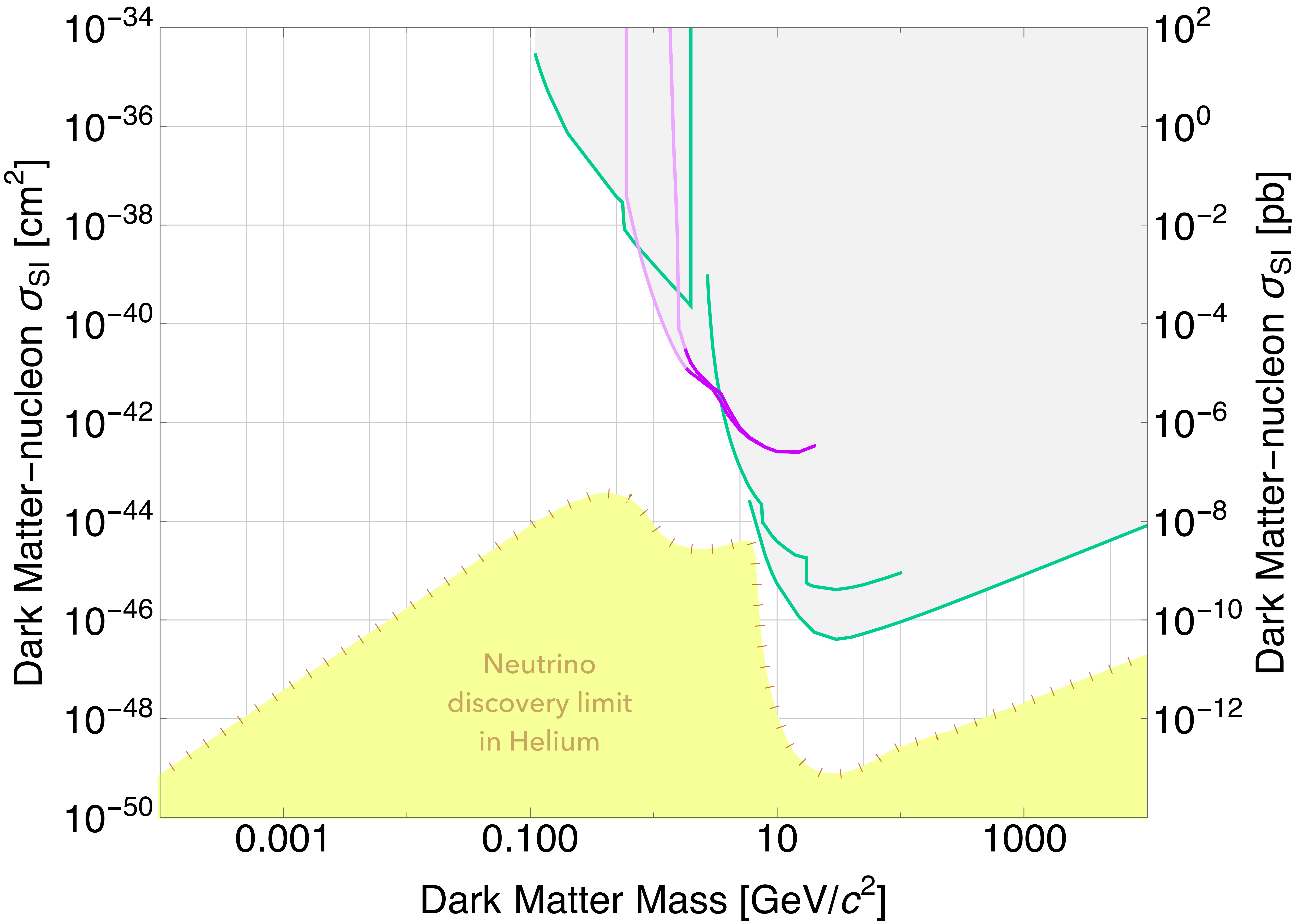
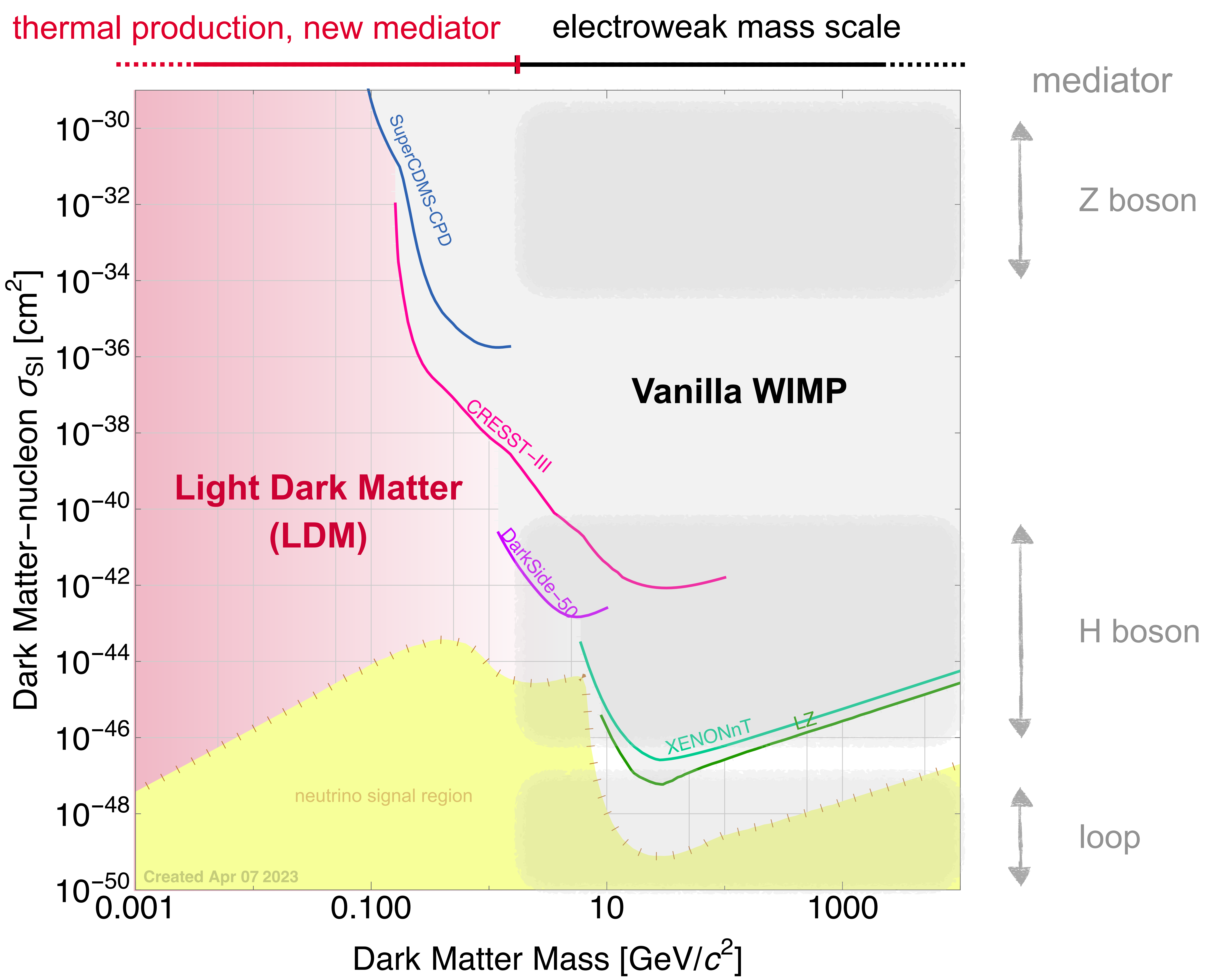


Towards light dark matter



Towards light dark matter



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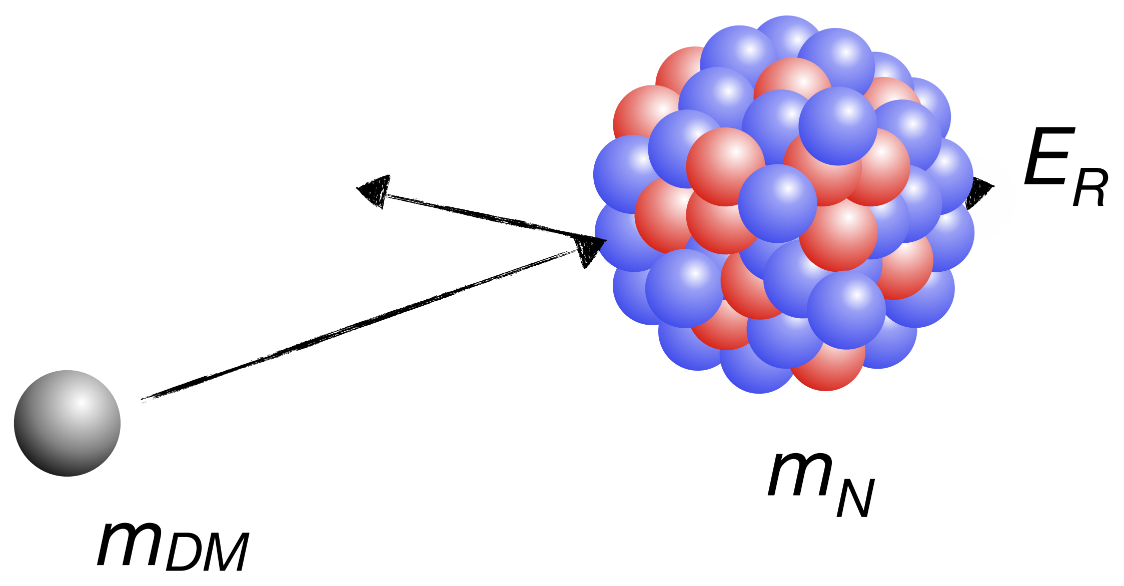
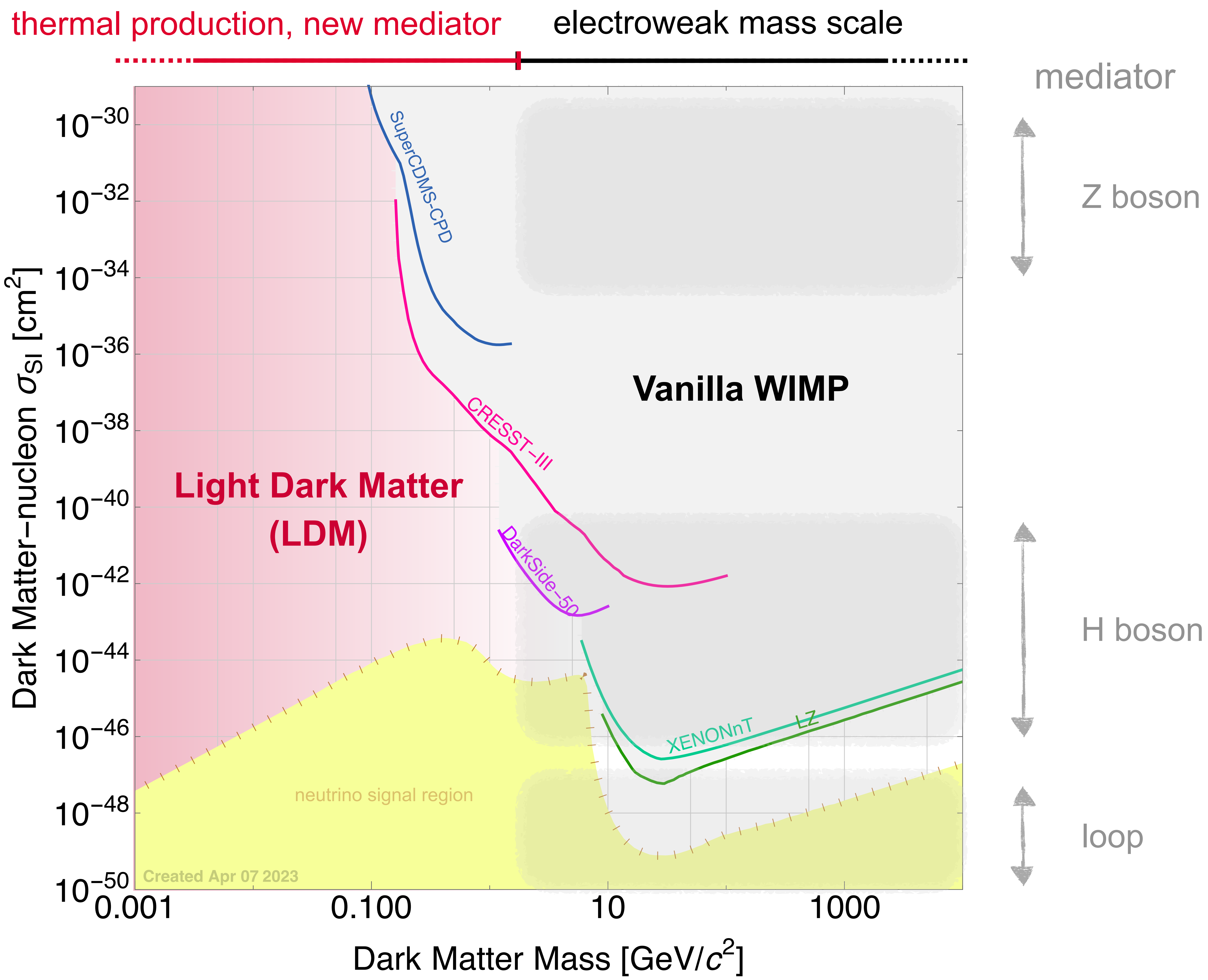
Towards light dark matter

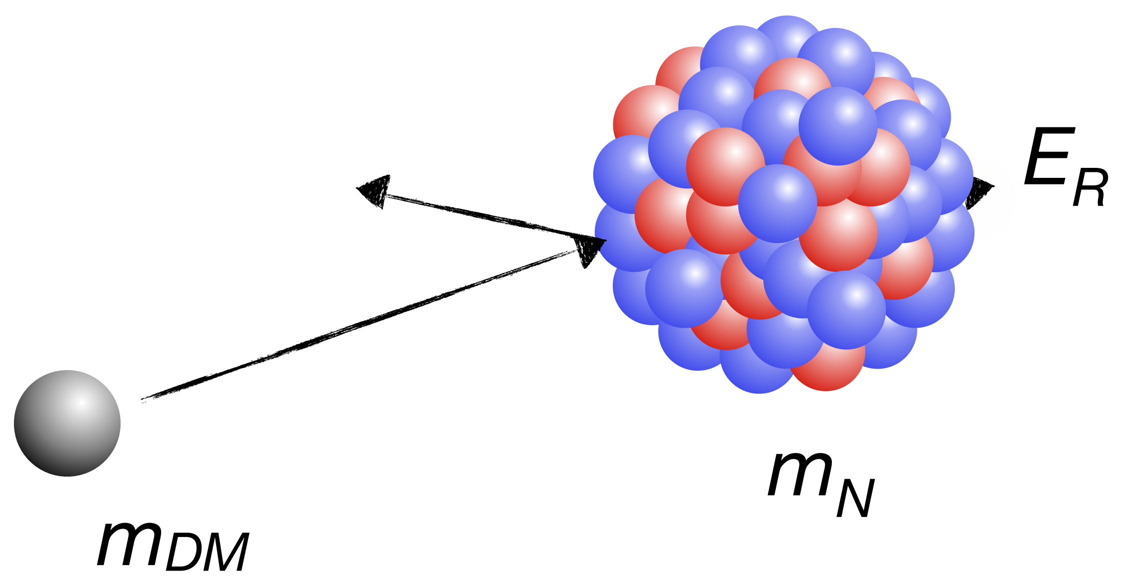


Observable recoil energy:

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



Towards light dark matter



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- Sub-GeV searches require…
  - … ultra-low energy thresholds and/or
  - … light scattering partners and/or
  - … interaction channels beyond scattering

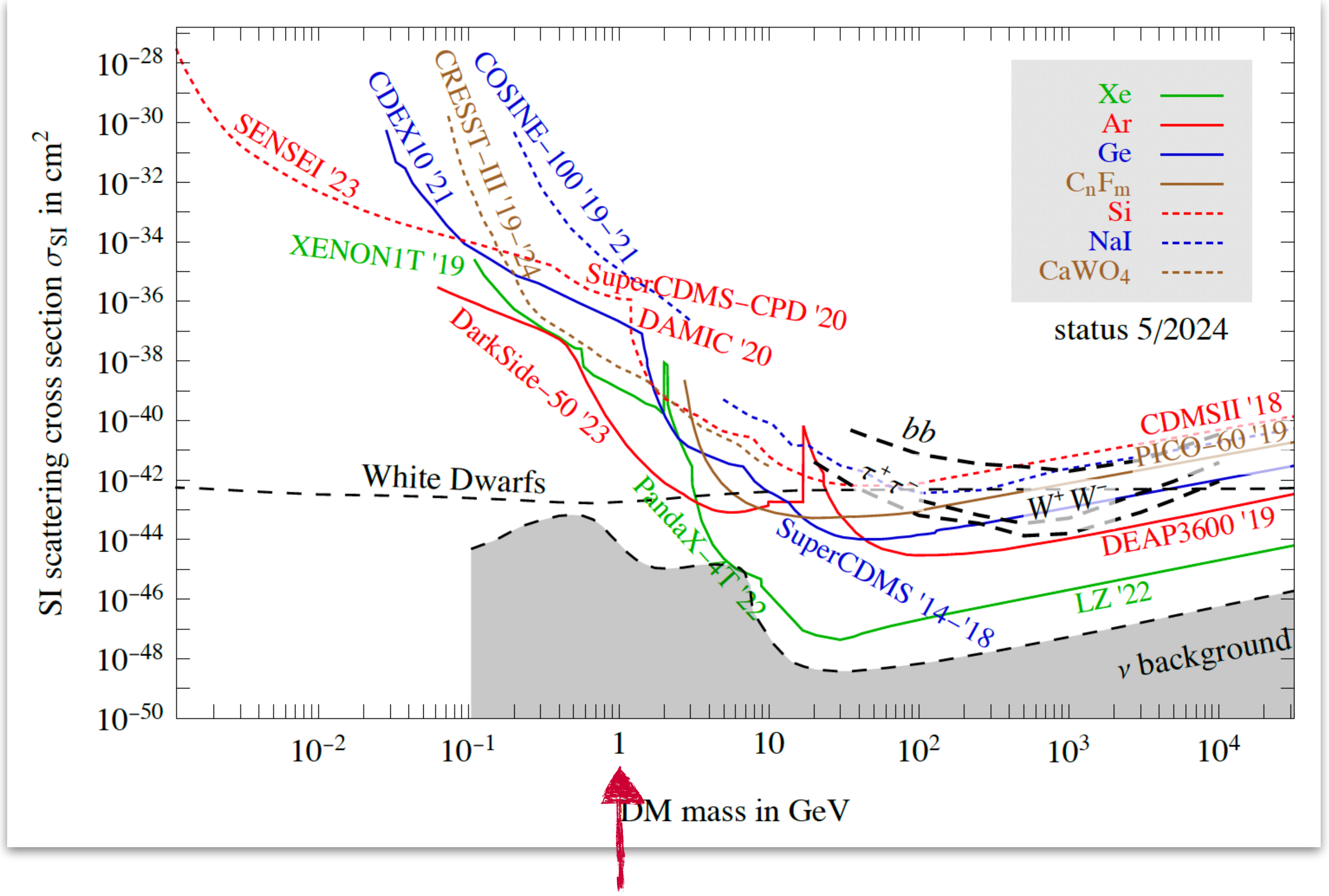
Experimental status:
DM-n scattering

DM-nucleon scattering

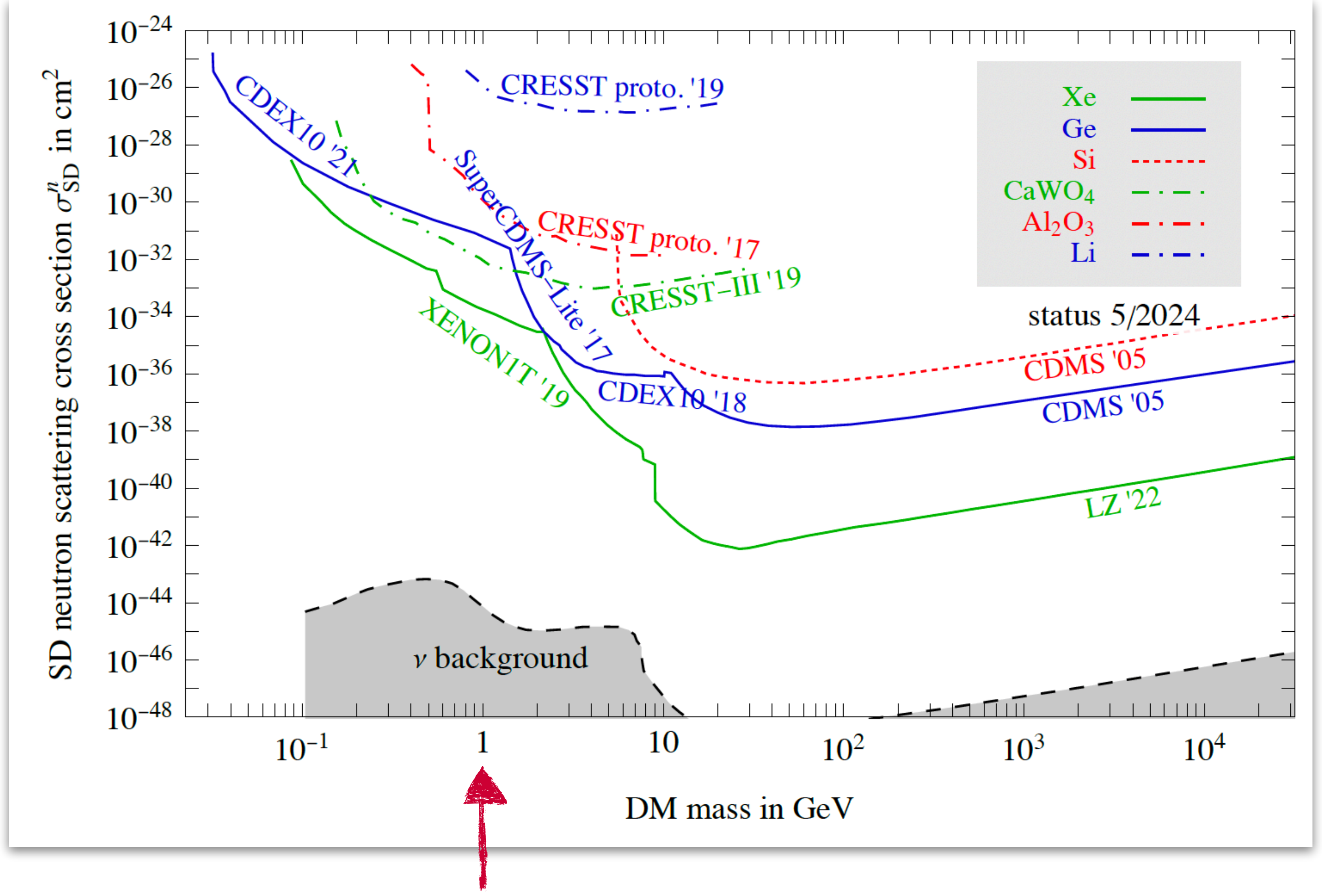
Many thanks to Marco Cirelli, Alessandro Strumia, Jure Zupan for a great, latest DM compilation!

arXiv:2406.01705

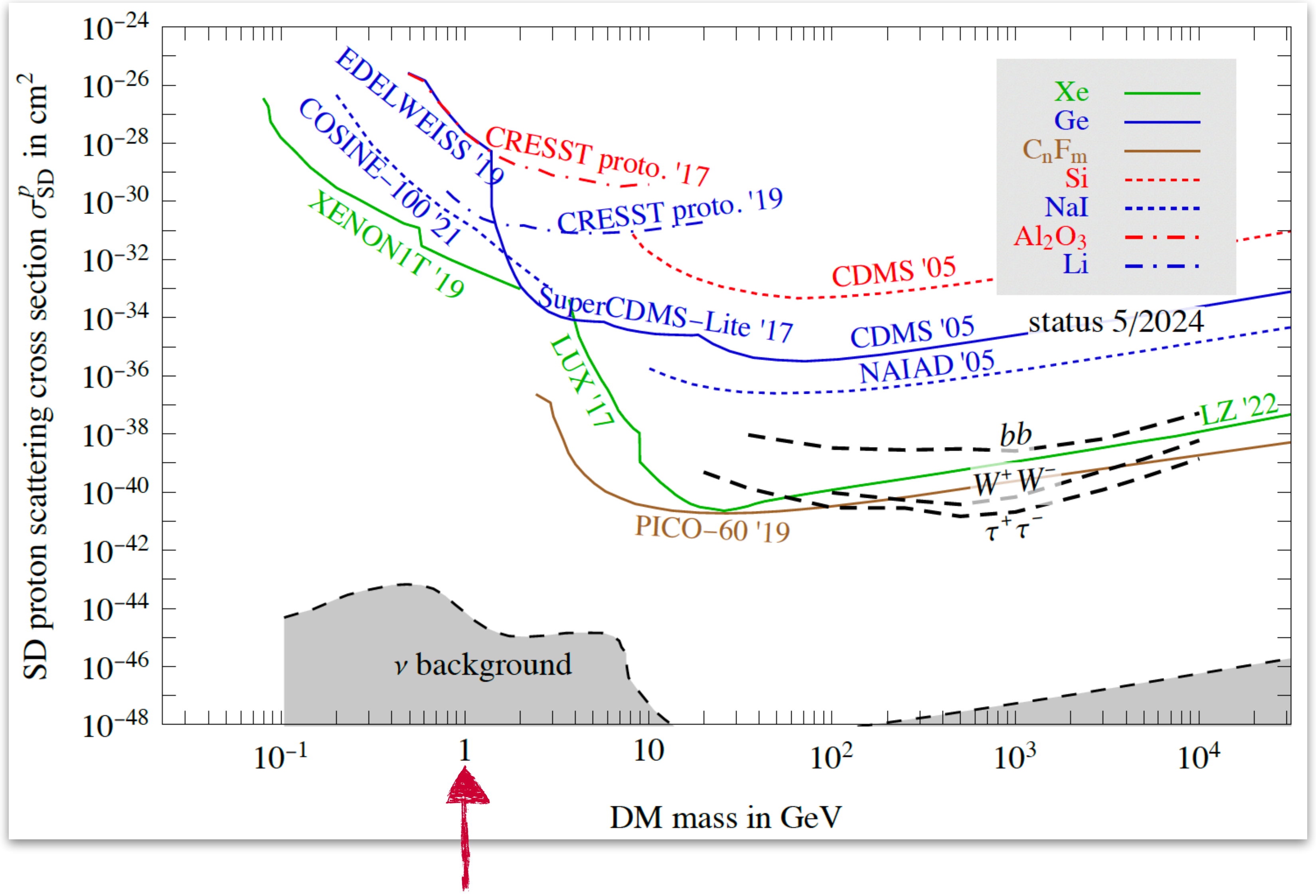
Spin-independent



Spin-dependent, neutron



Spin-dependent, proton



Quite some activity below 1 GeV!

DM-nucleon scattering

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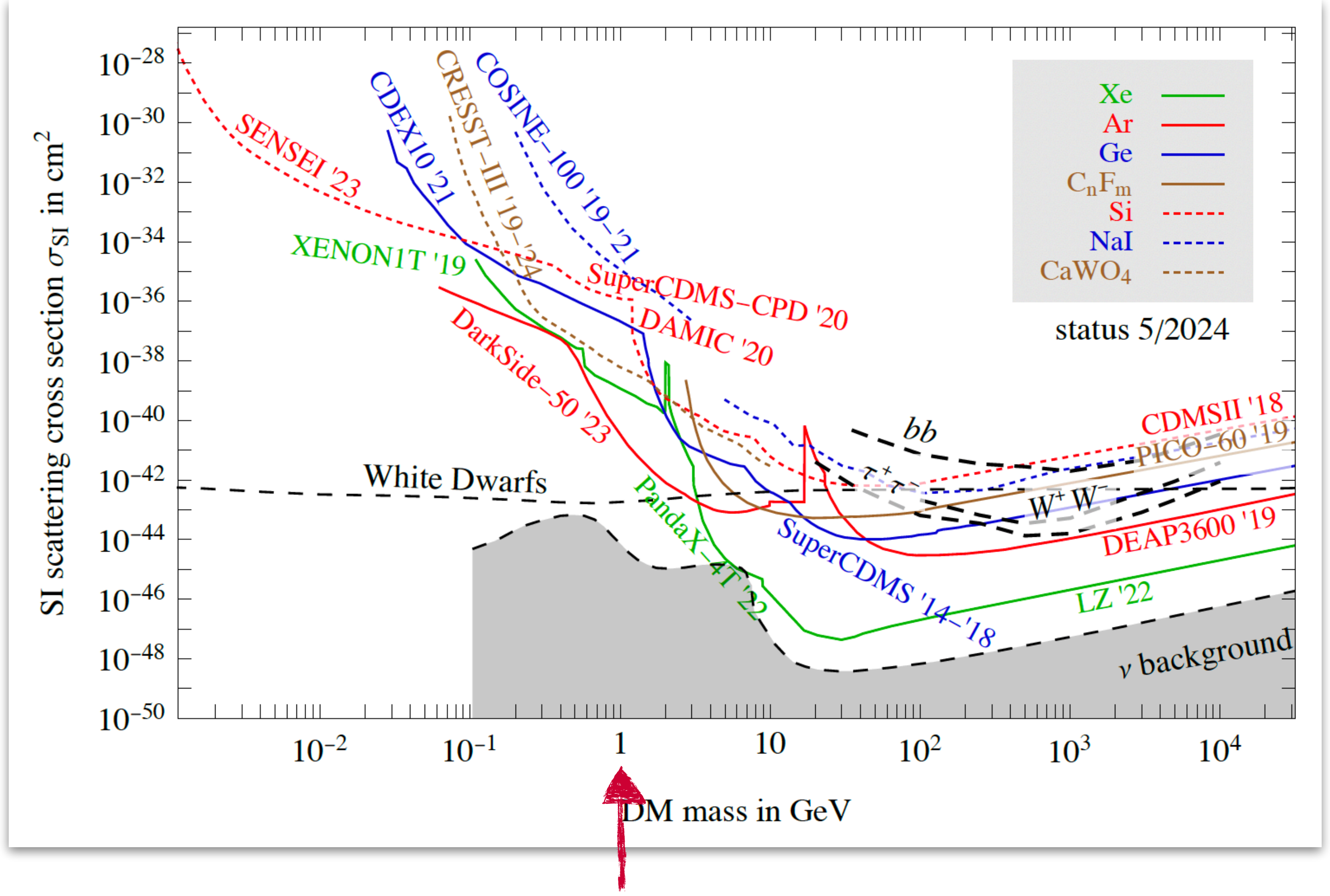
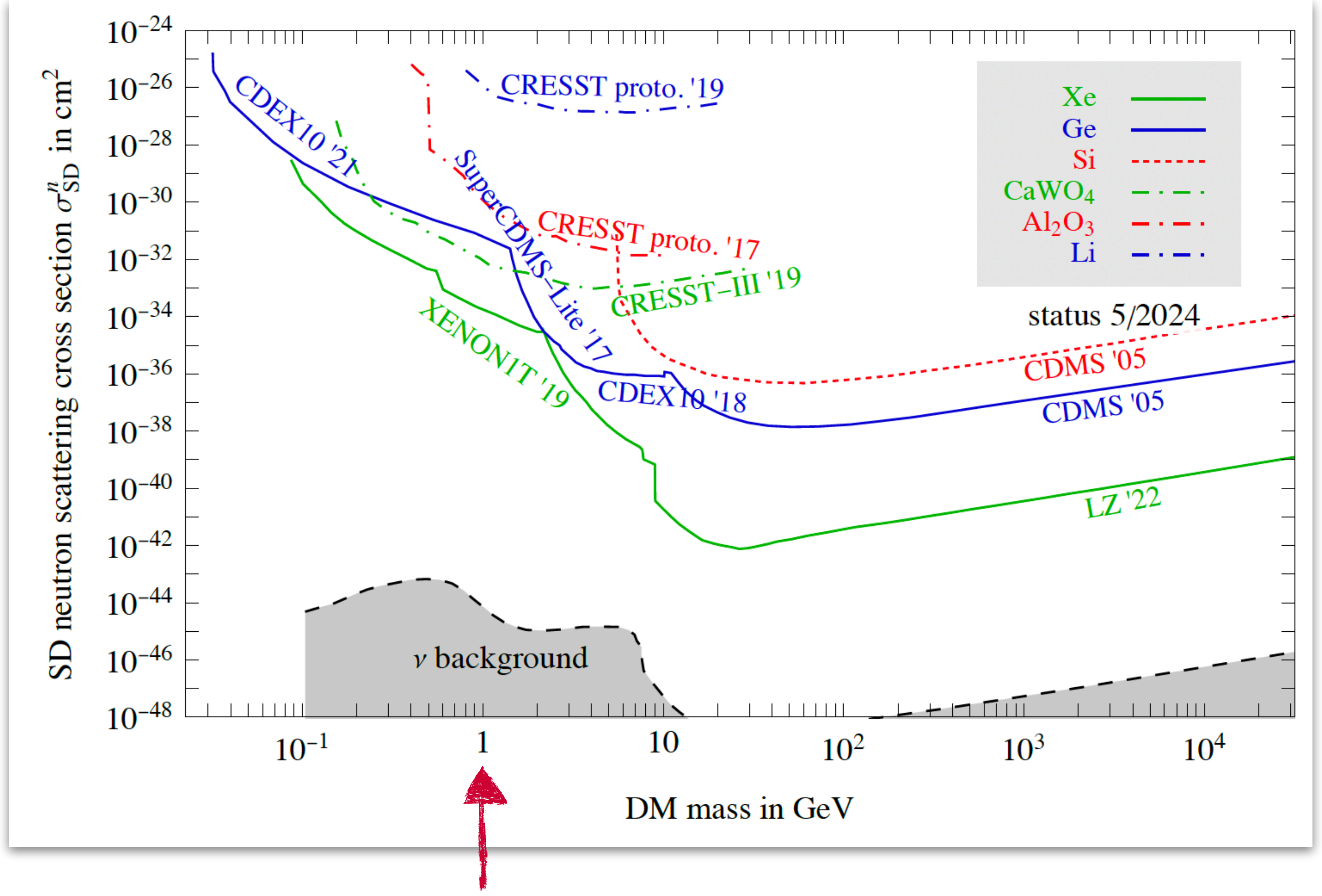
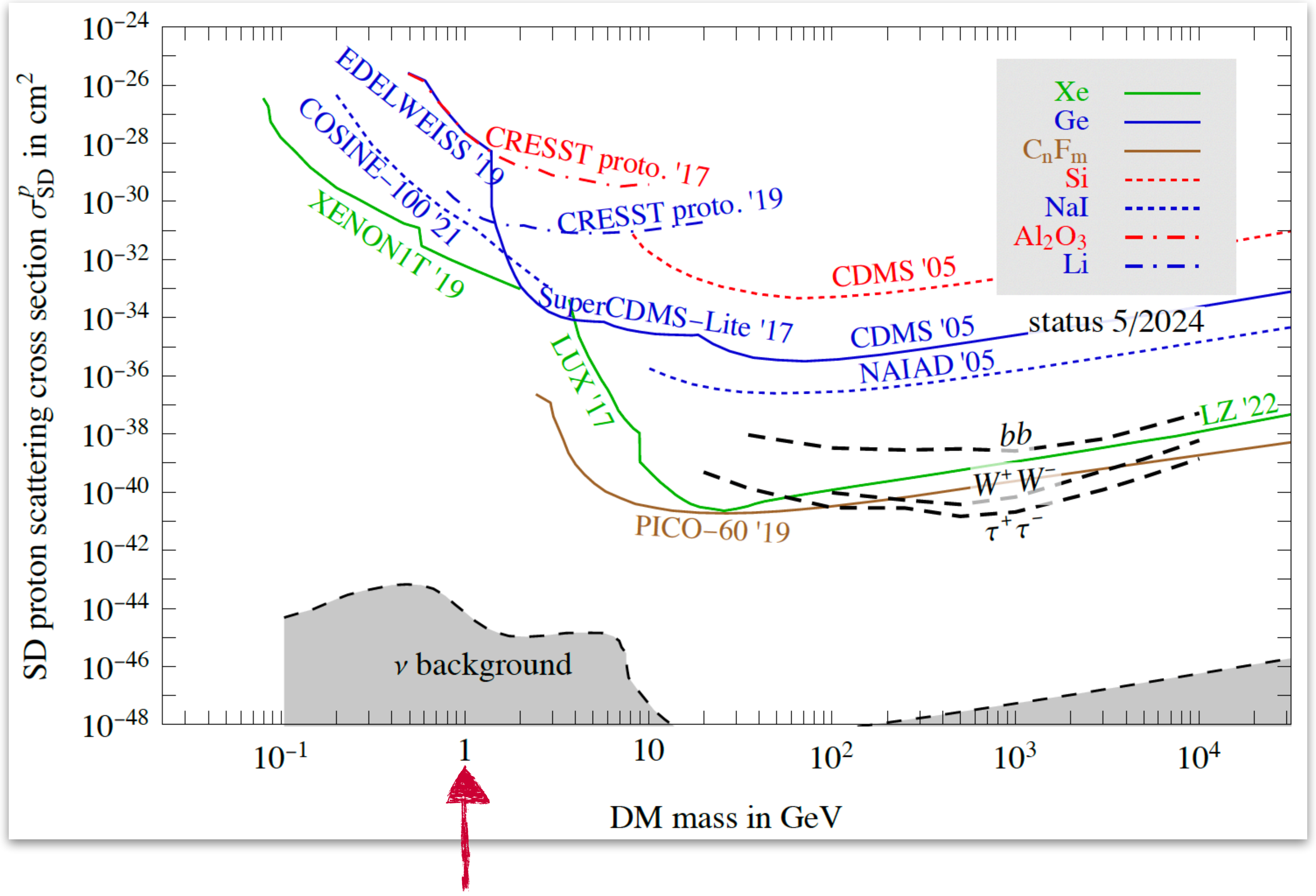
Spin-independent	Spin-dependent, neutron	Spin-dependent, proton





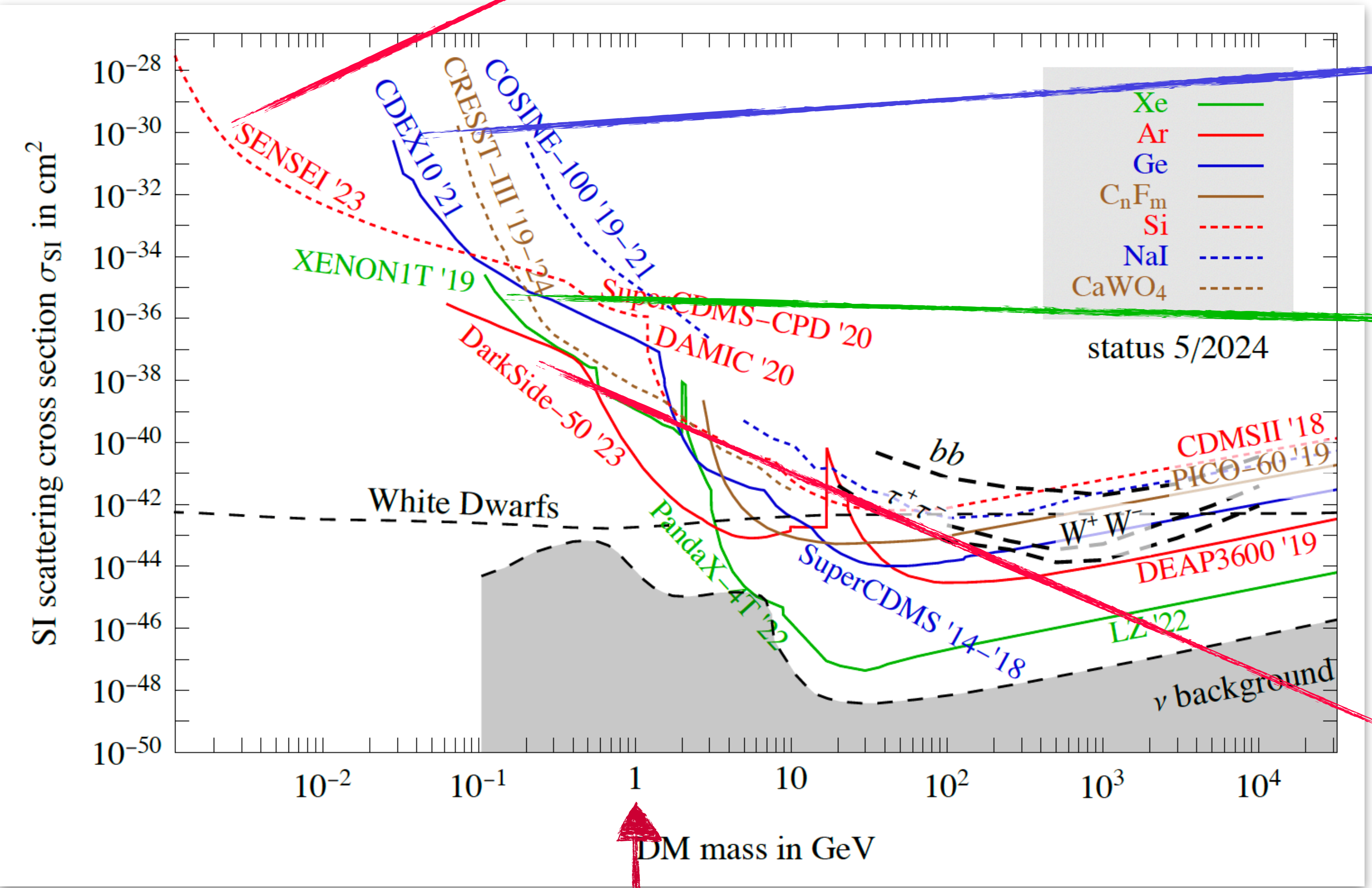


Quite some activity below 1 GeV!

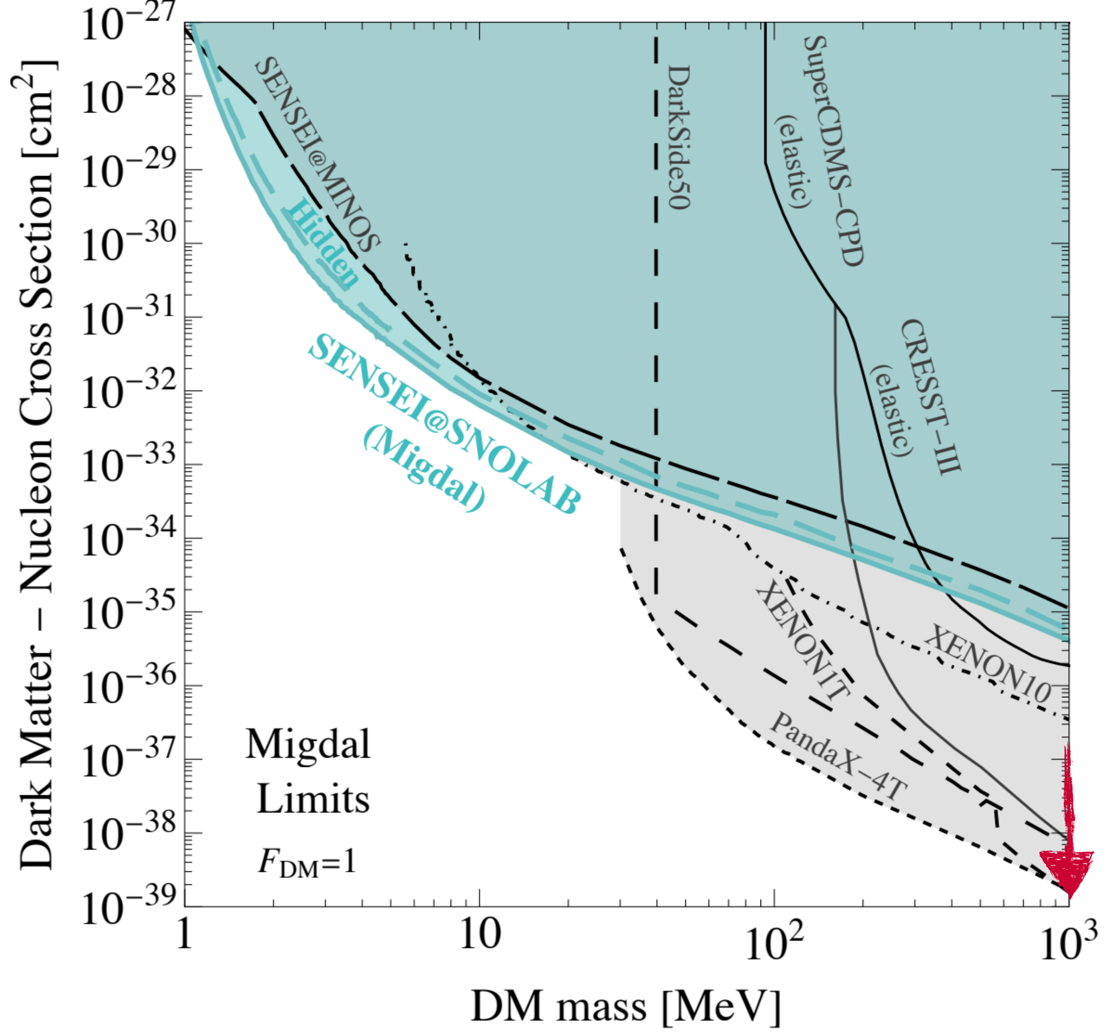
However, not all of it is **elastic** DM-nucleon scattering.

Direct detection of sub-GeV dark matter: Experimental status

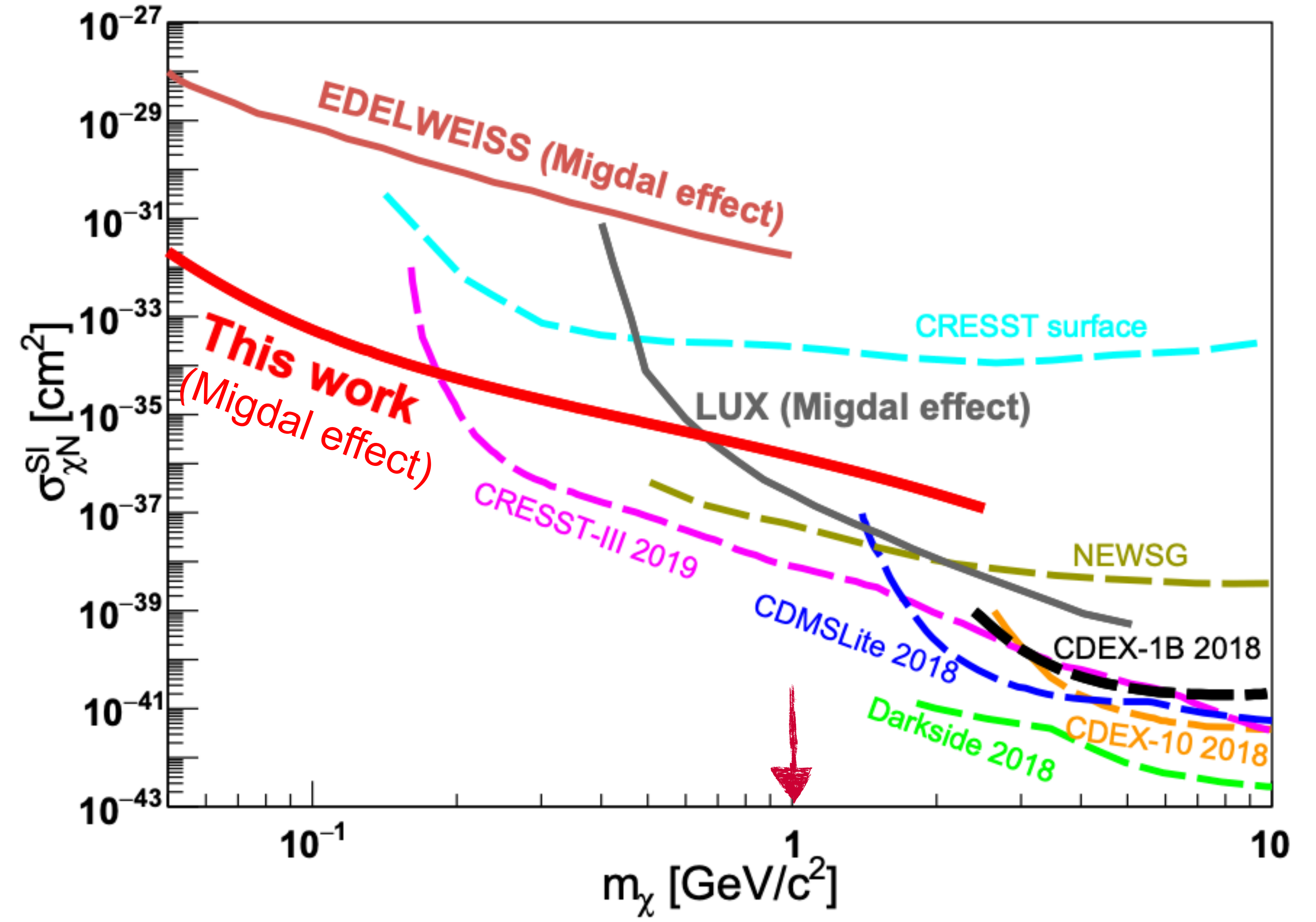
DM-nucleon scattering



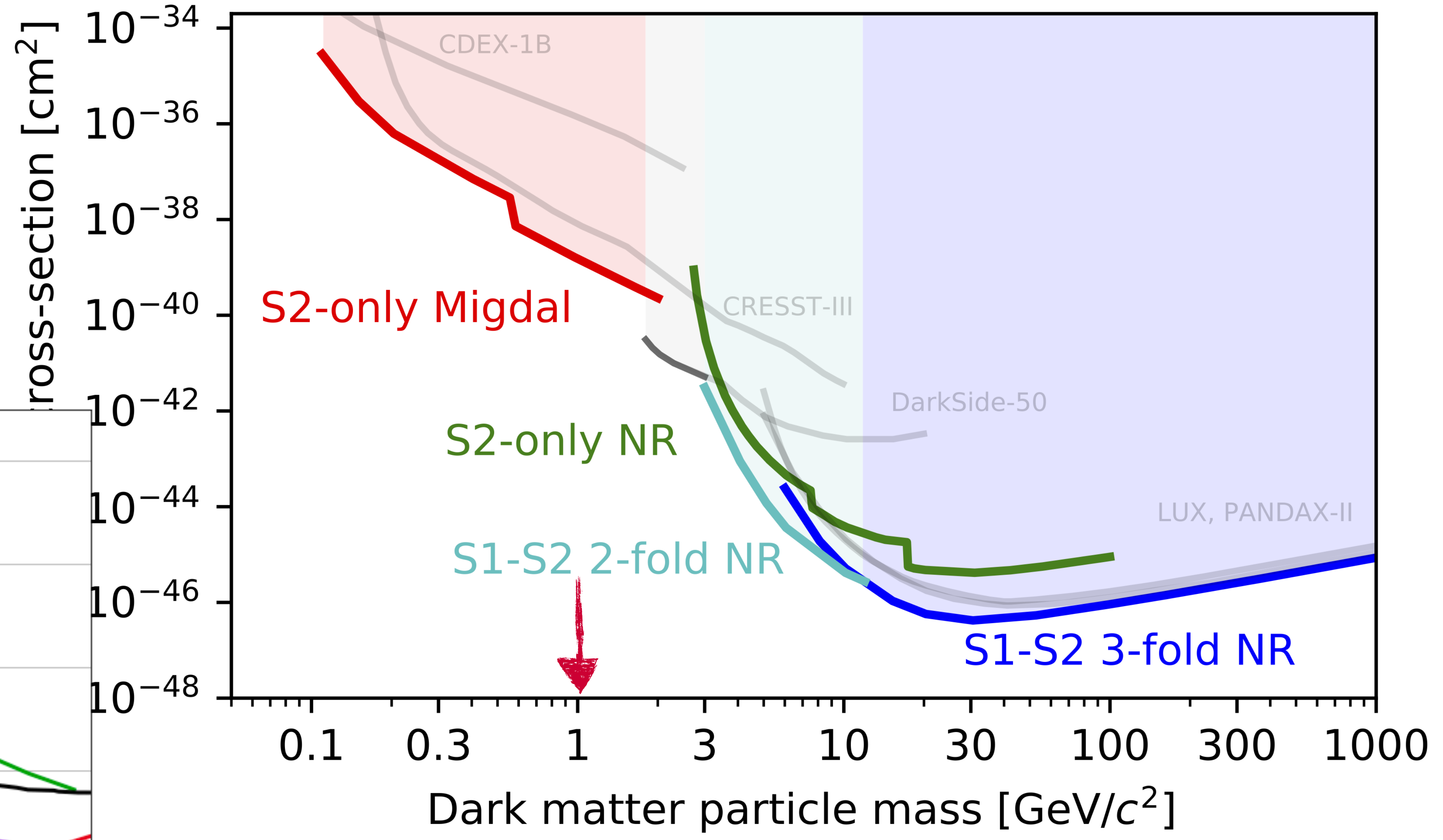
SENSEI, arXiv:2312.13342



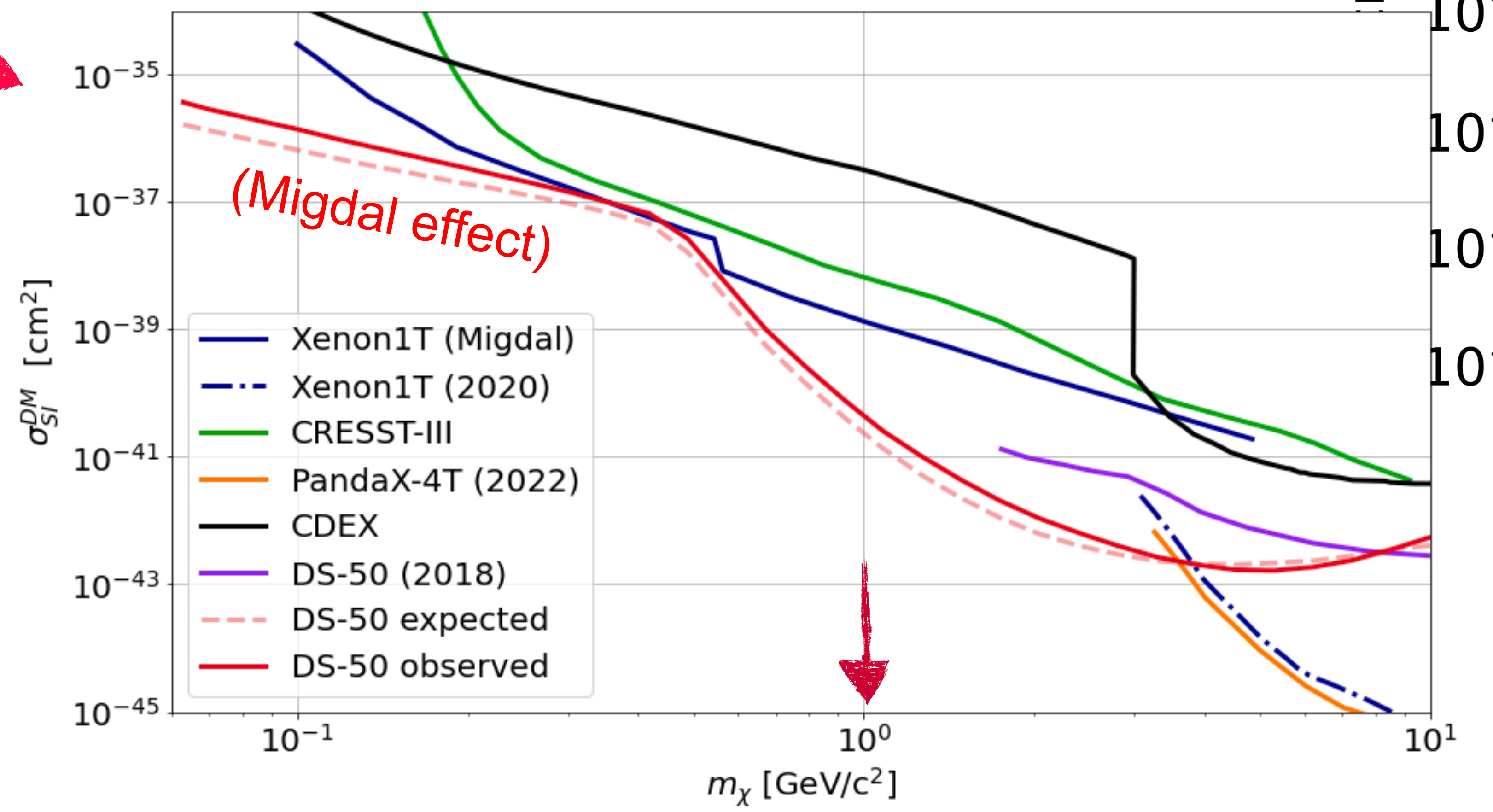
CDEX, Phys. Rev. Lett. 123, 161301



XENON1T, Phys. Rev. D 102, 072004

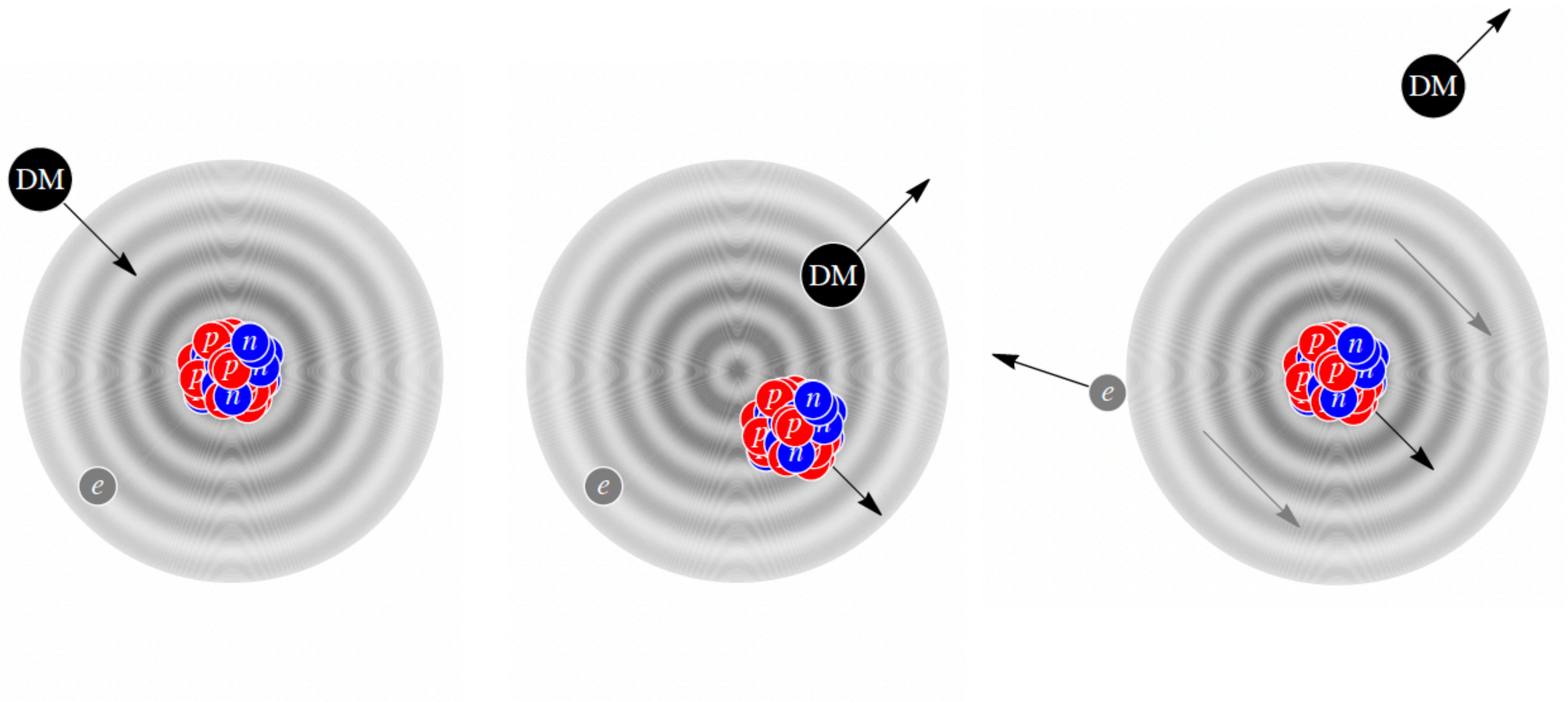


DarkSide-50, Eur. Phys. J. C 83, 322

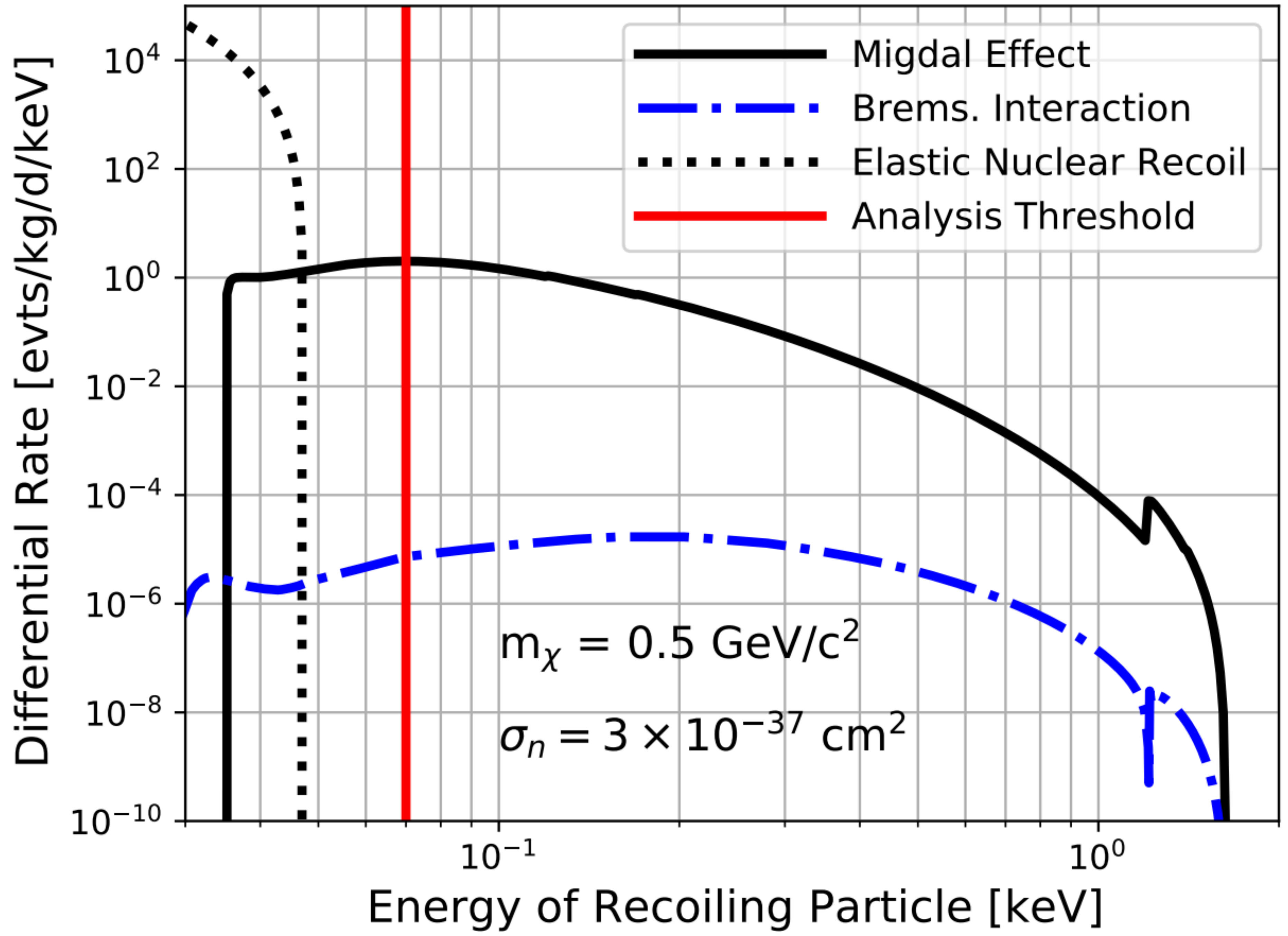


The Migdal effect

M. Cirelli, A. Strumia, J. Zupan, arXiv:2406.01705



SuperCDMS, Phys. Rev. D 107

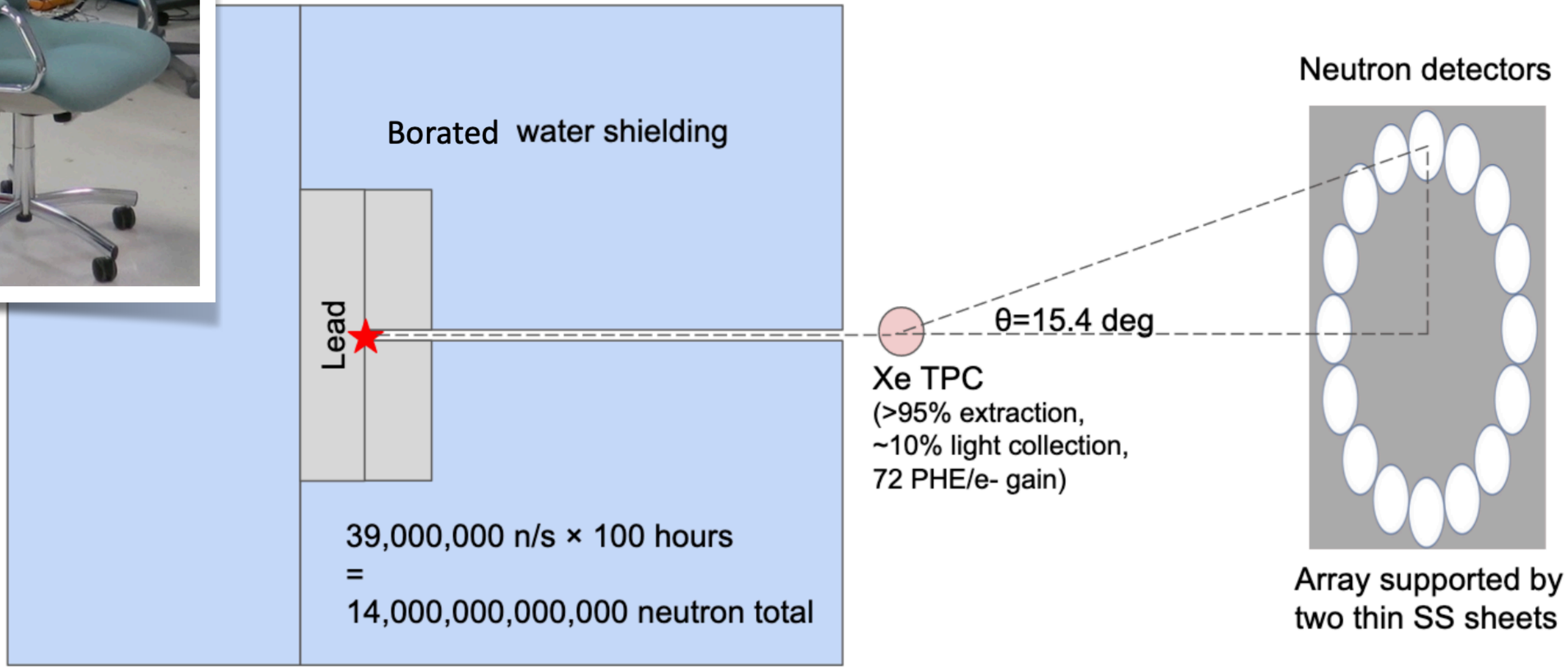


- Migdal atomic relaxation can lead to keV electron recoil energy for sub-keV nuclear recoils
- But… the Migdal effect has not yet been observed in nuclear scattering events!

Search for the Migdal effect in liquid xenon

J. Xu et al., Phys.Rev.D 109 (2024) 5, L051101

- Experimental set-up at LLNL
- High energy neutrons (14.1 MeV): enhance Migdal cross section, reduce neutron multiple scatter background



Search for the Migdal effect in liquid xenon

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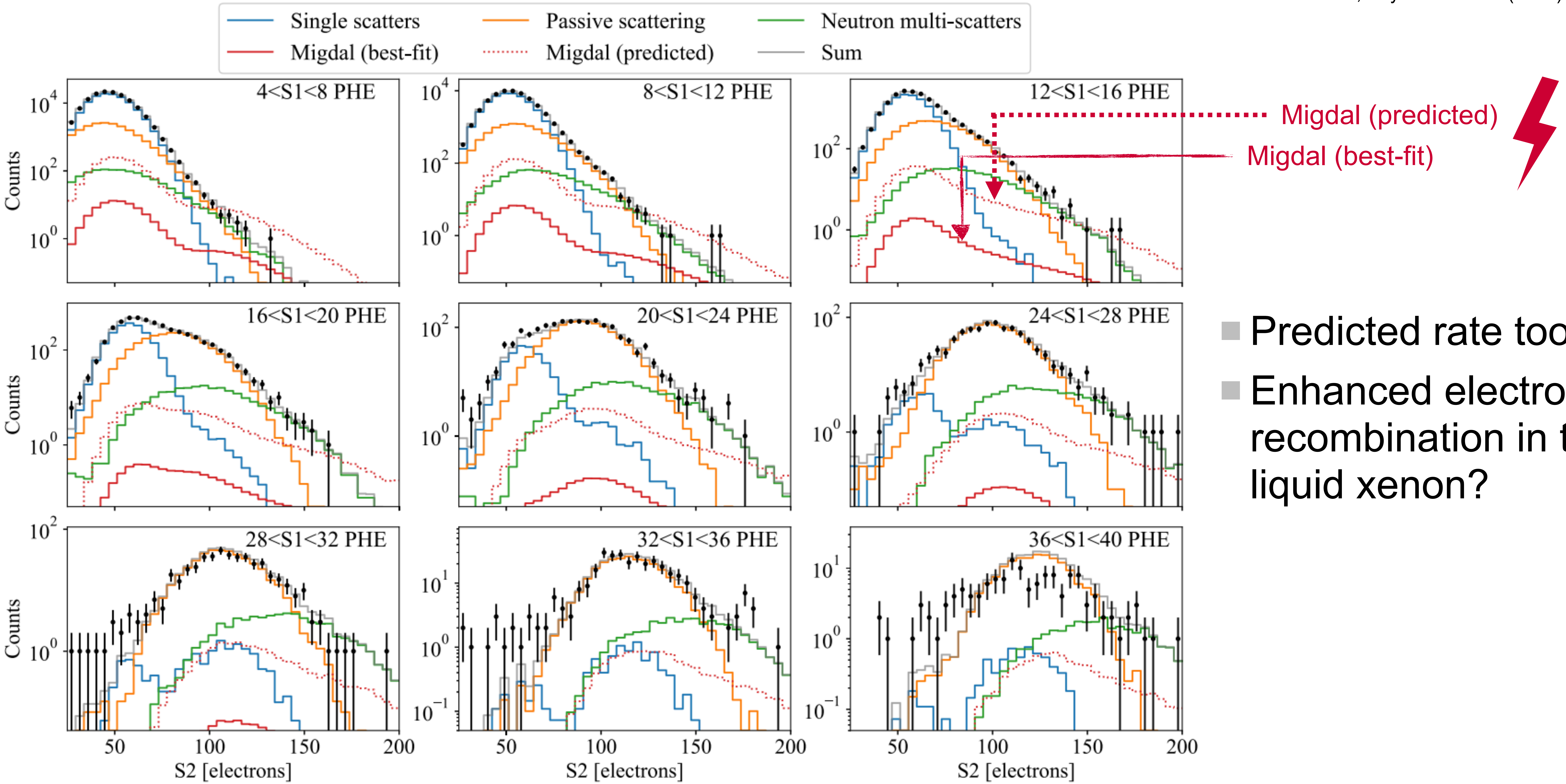

- Predicted rate too high?
- Enhanced electron-ion recombination in the liquid xenon?

DM-nucleon scattering

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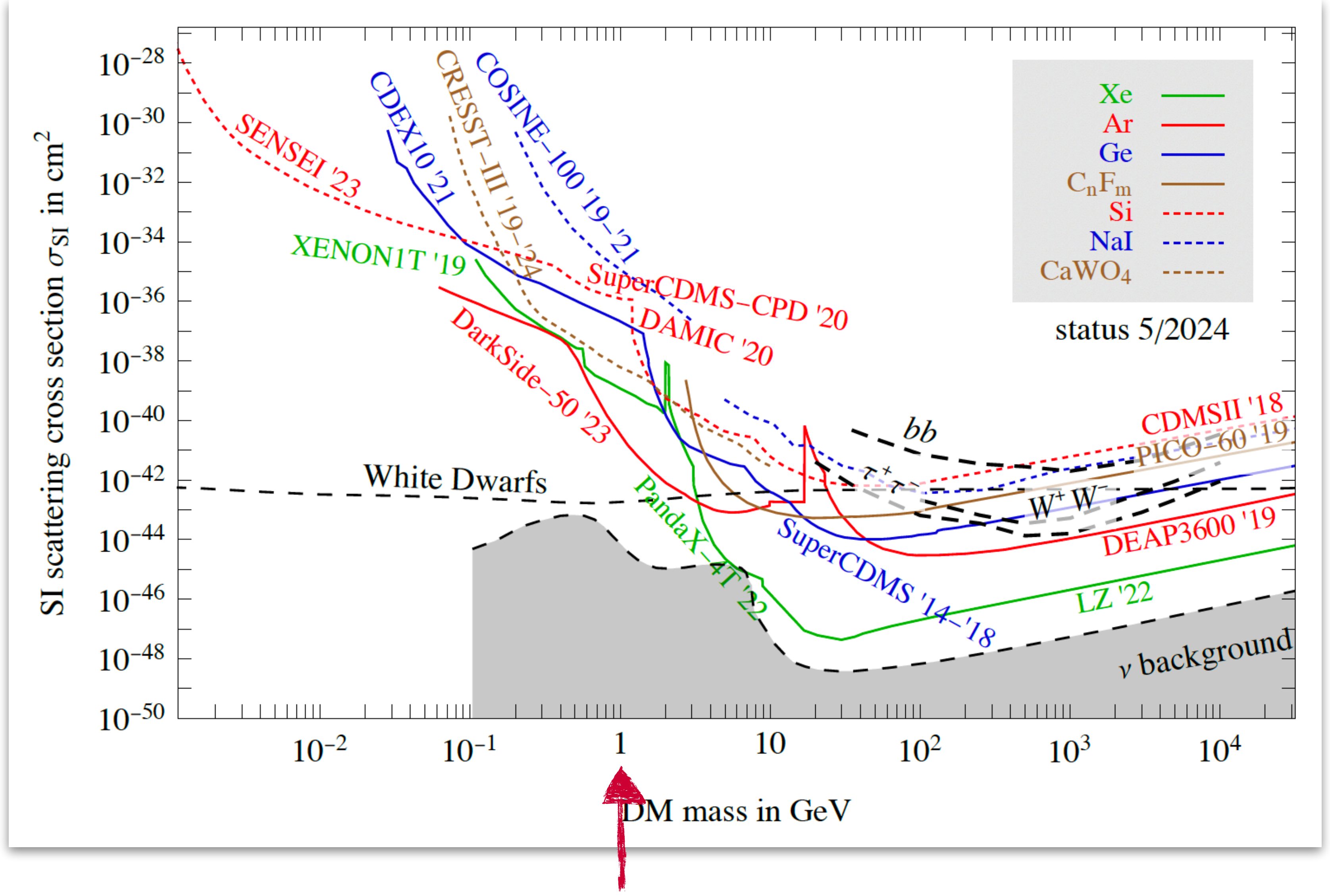
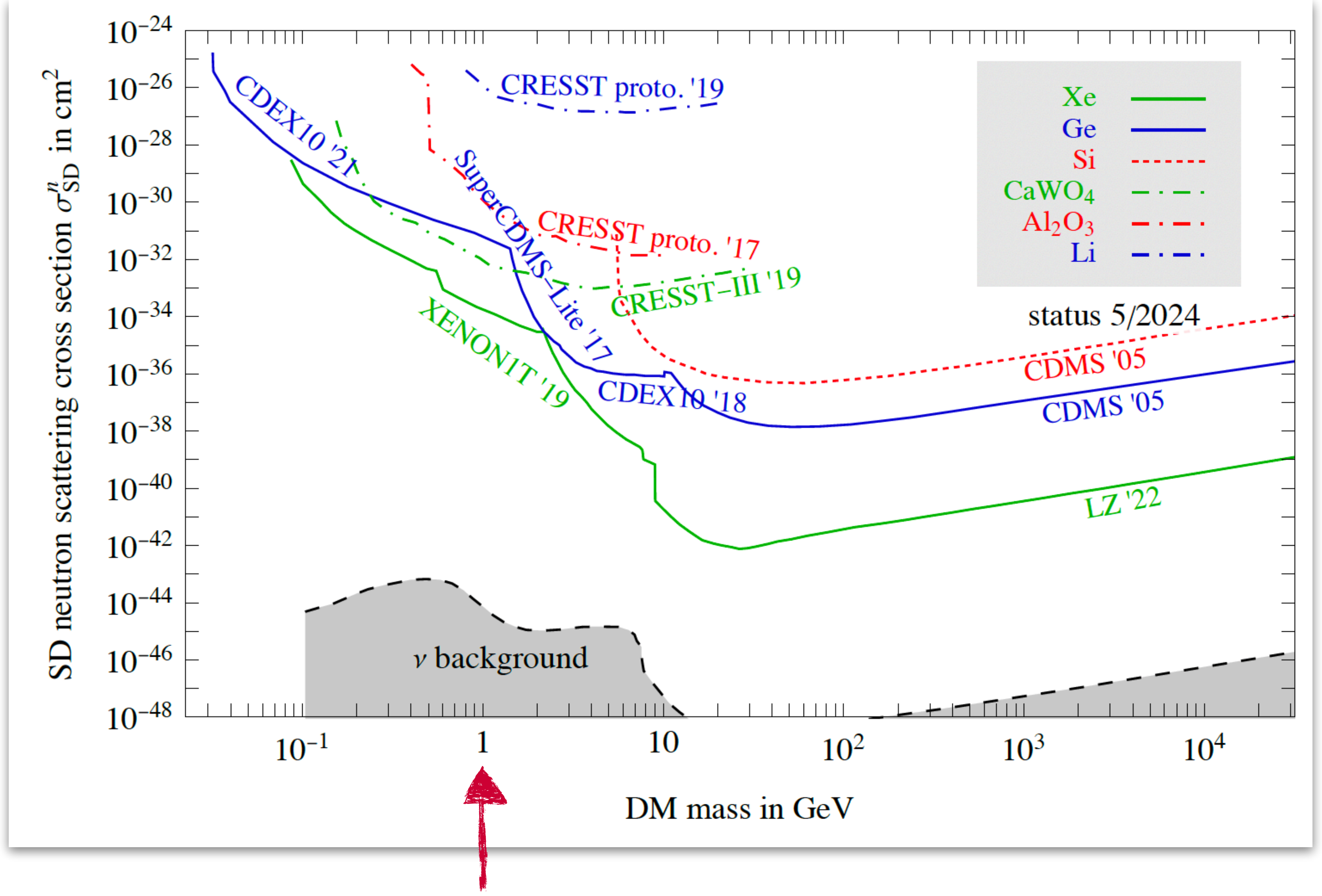
arXiv:2406.01705

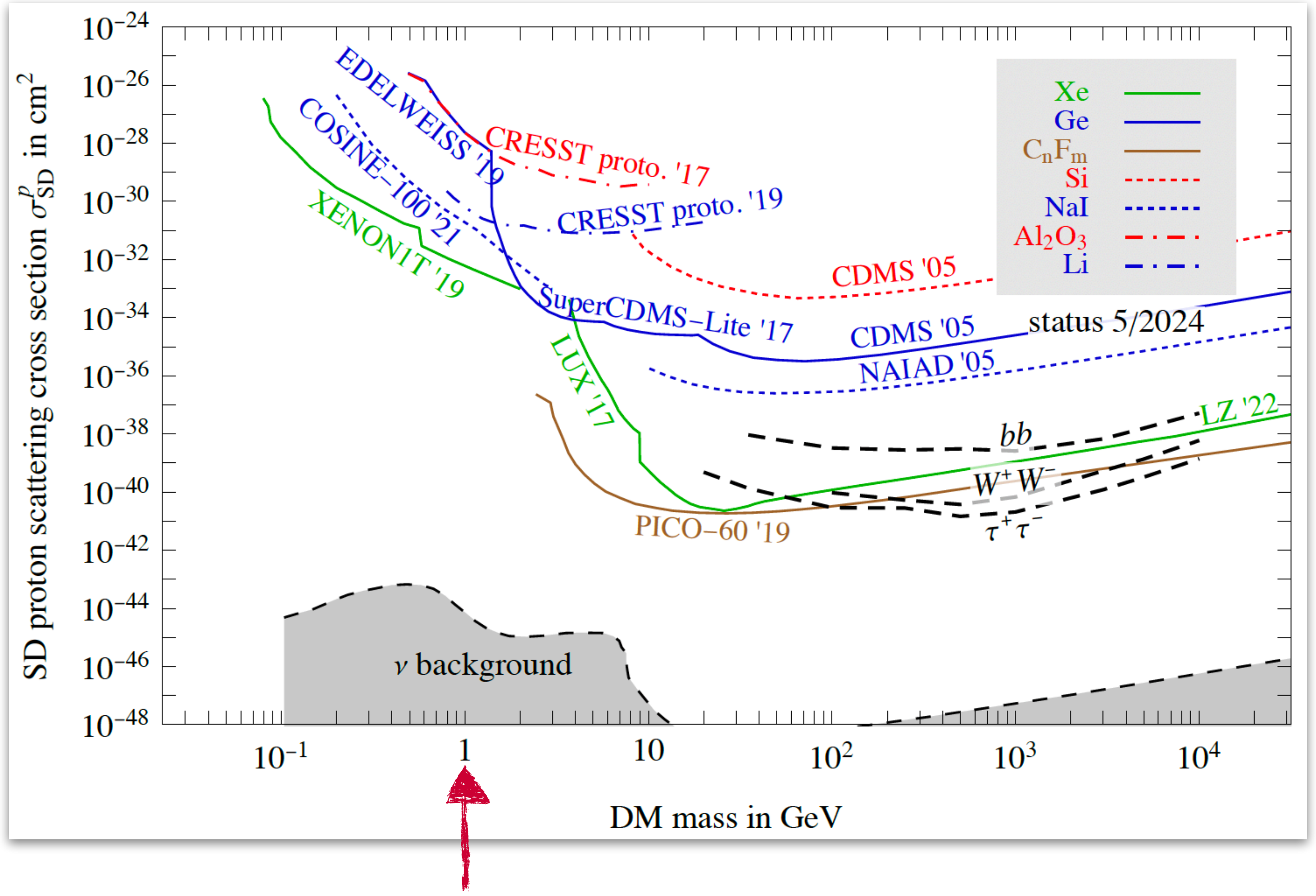
Spin-independent



Spin-dependent, neutron



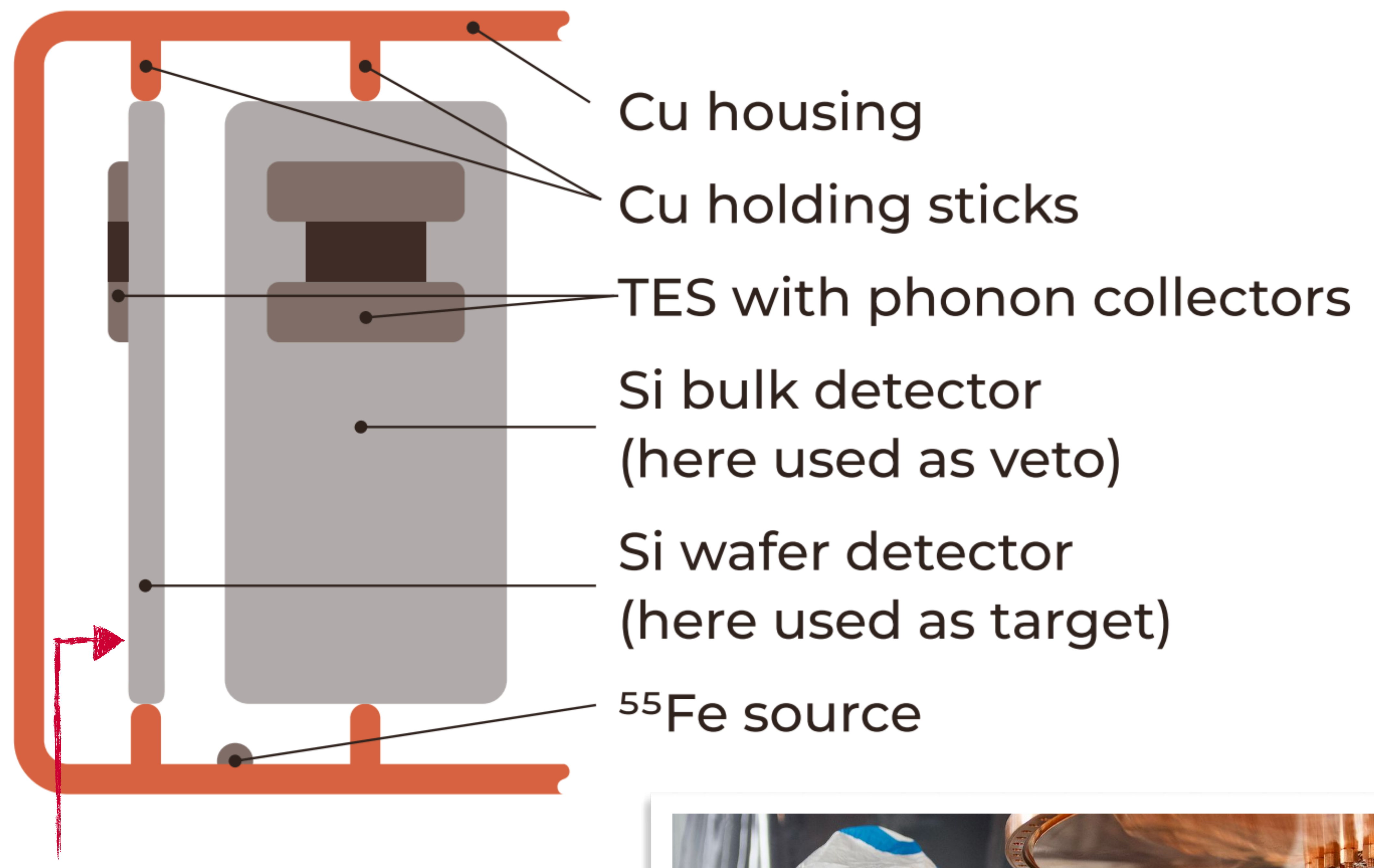
Spin-dependent, proton



However, not all of it is **elastic** DM-nucleon scattering!

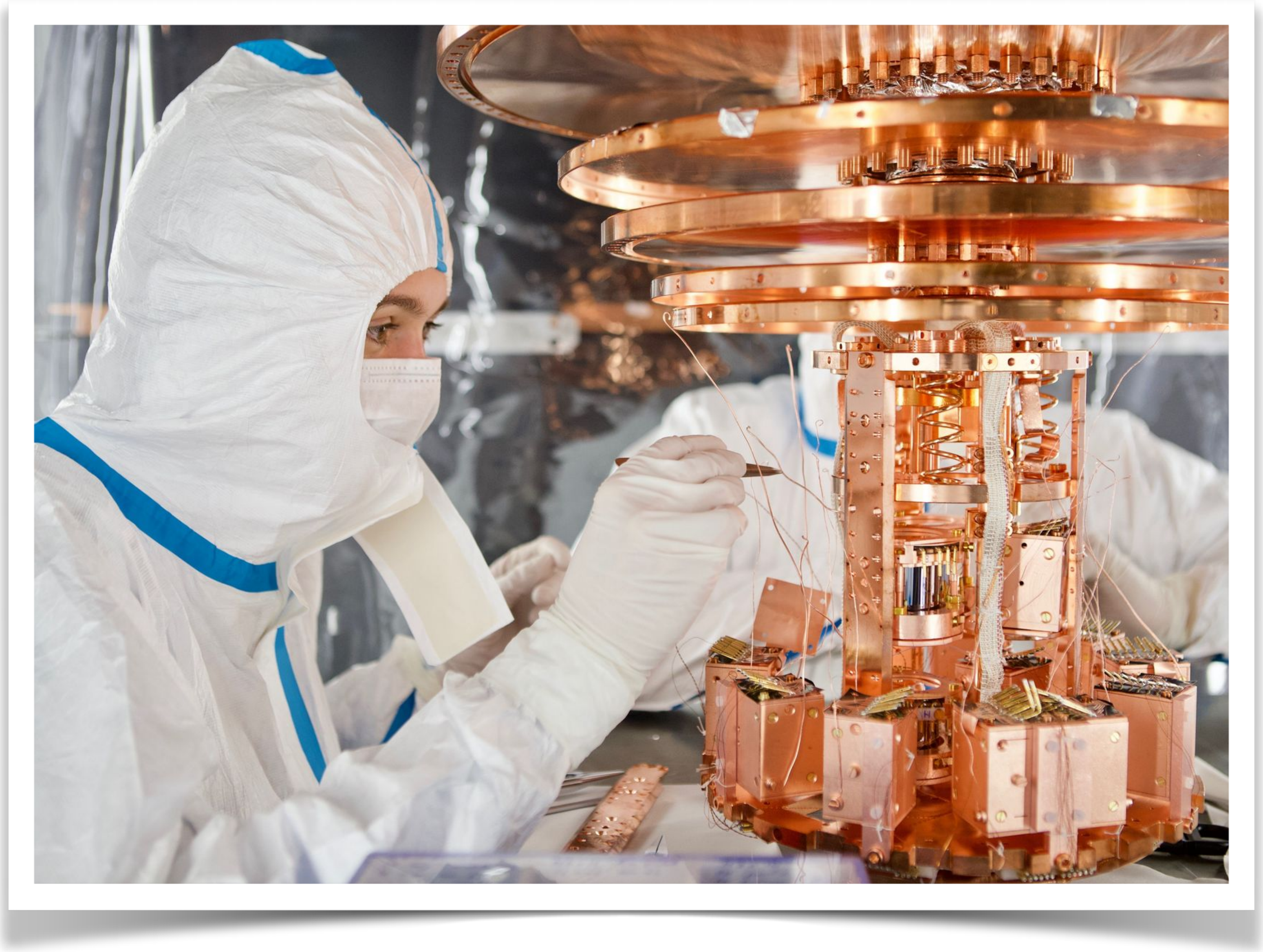
Not so many left with sub-GeV results…

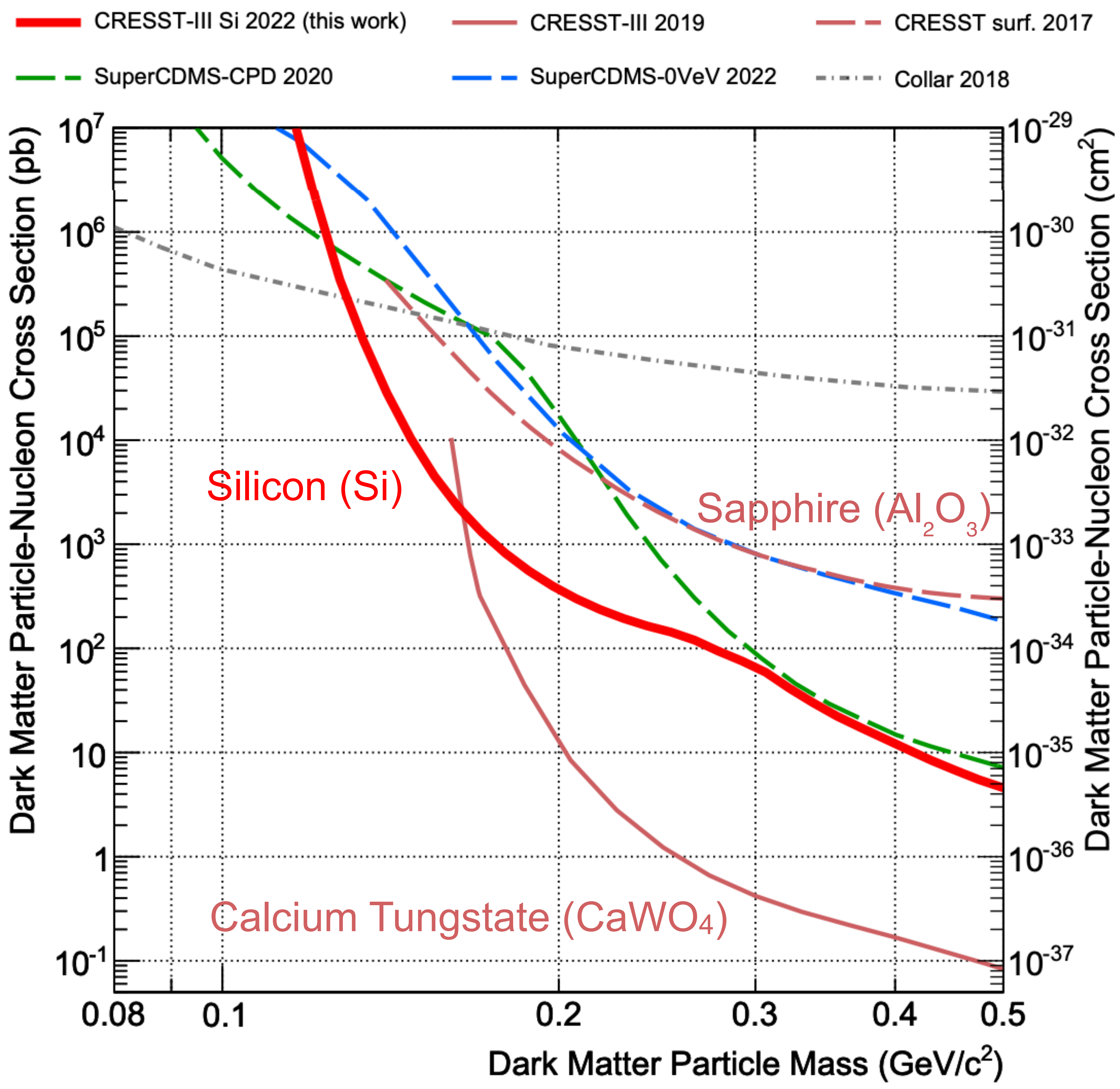
CRESST-III



thin 0.35 g Si detector $(20 \times 20 \times 0.4)$ mm^3

with 10 eV_{nr} threshold

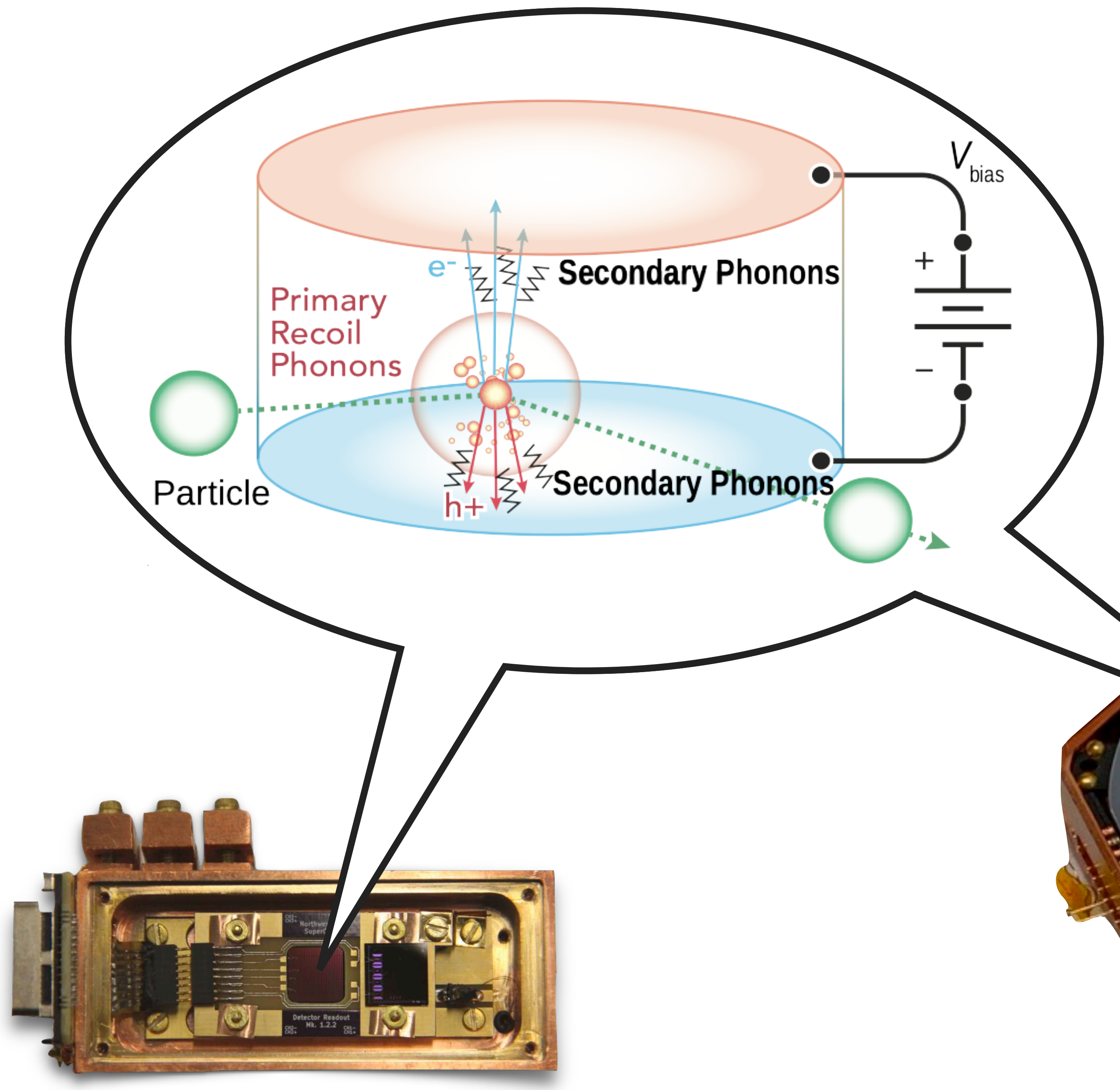




CRESST, Phys. Rev. D 107, 122003 (2023)

SuperCDMS (CPD, 0VeV)

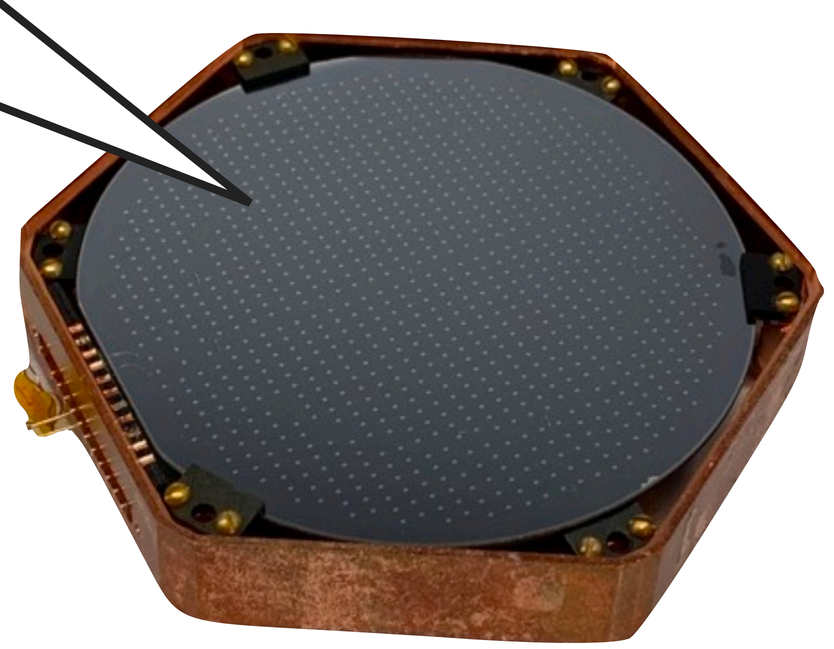
SuperCDMS, Phys. Rev. D 105, 112006 (2022)



CPD:

10.6 g Si with phonon sensors

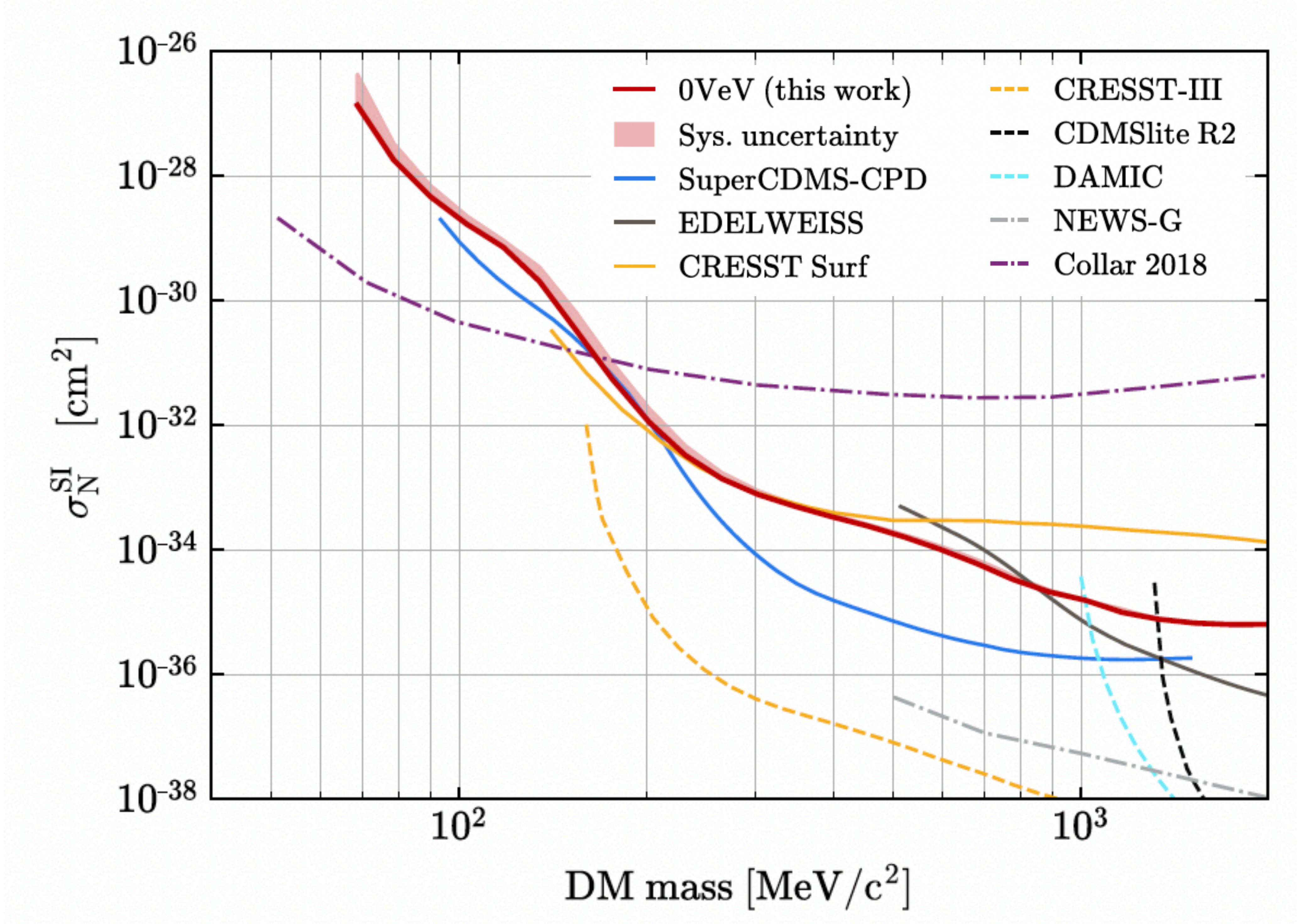
0V bias



HVeV / 0VeV:

0.93 g Si with phonon sensors

HV or 0V bias



- 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)

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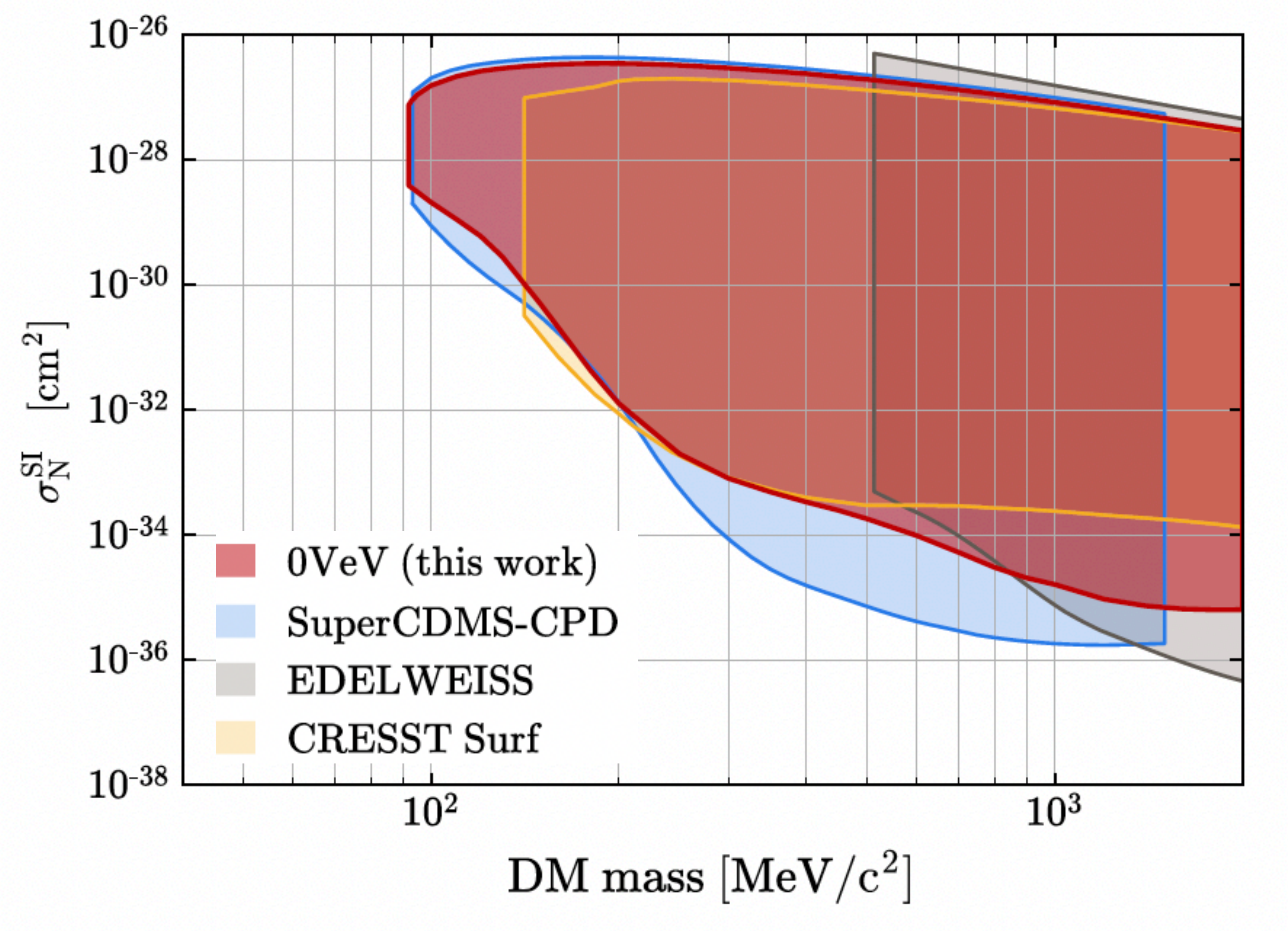
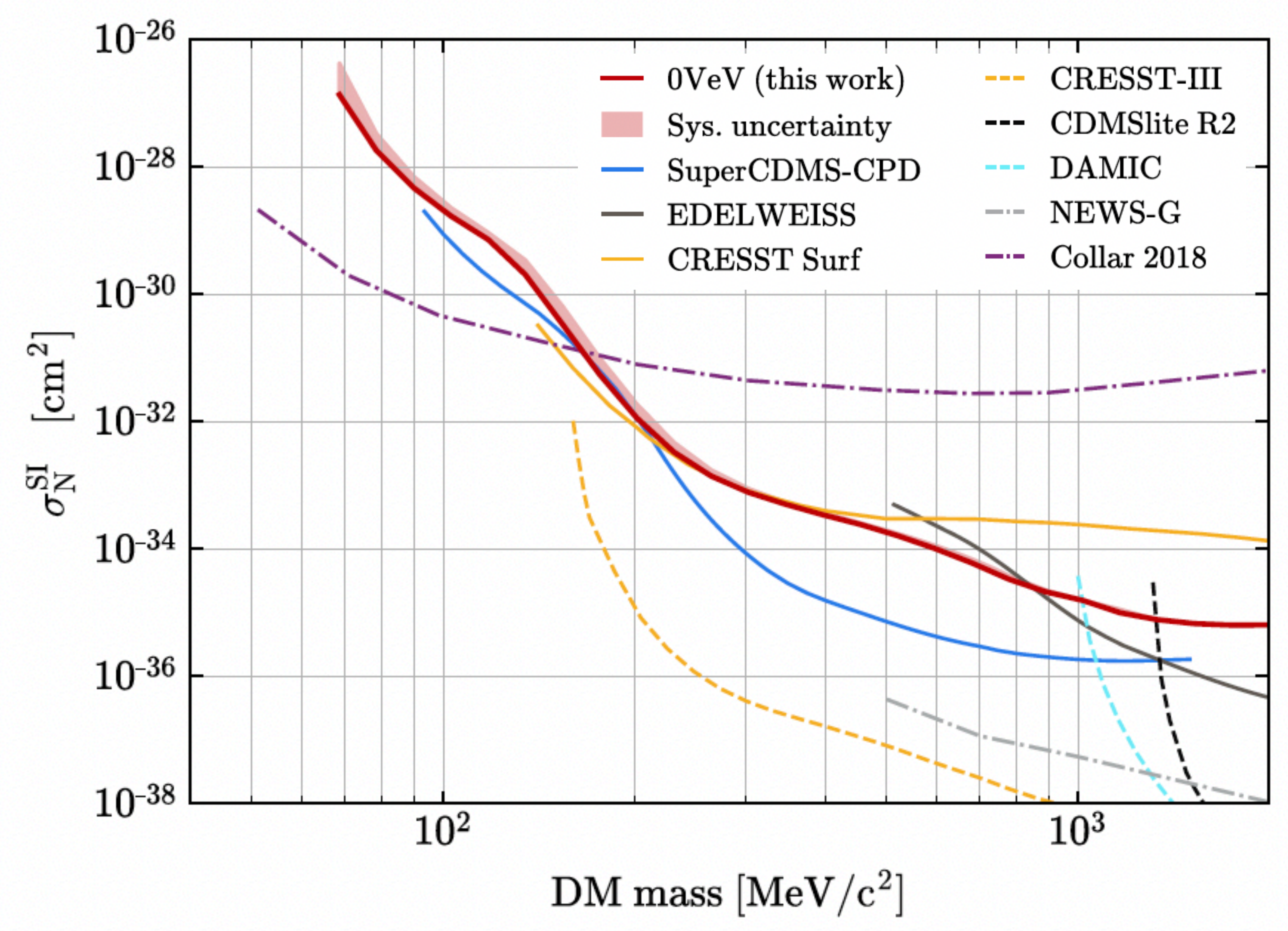
SuperCDMS (CPD, 0VeV)

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





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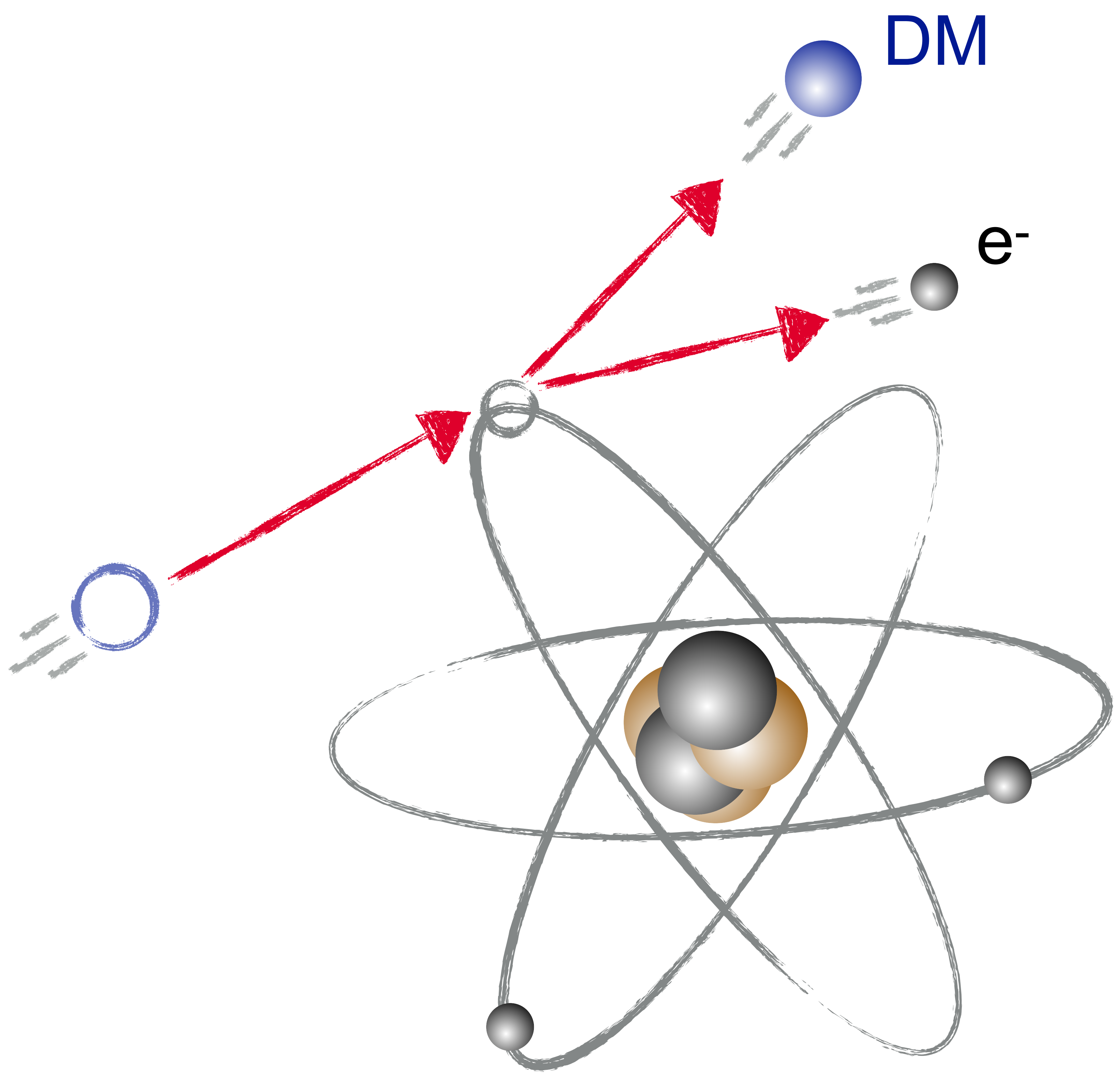
Experimental status: DM-e scattering

Inelastic DM-electron scattering



Need to overcome binding energy:

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

$$\Rightarrow m_{\mathrm{DM}} \gtrsim 300\,\mathrm{keV/c^2} \left(\frac{E_{\mathrm{bind.}}}{1\,\mathrm{eV}}\right)$$

for $v_{\mathrm{DM}} \lesssim 800\,\mathrm{km/s}$

$$m_{\mathrm{DM}} \ll \mathrm{GeV/c^2} \quad \text{accessible!}$$

with $E_{\mathrm{bind.}} \mathcal{O}(1 - 100\,\mathrm{eV})$

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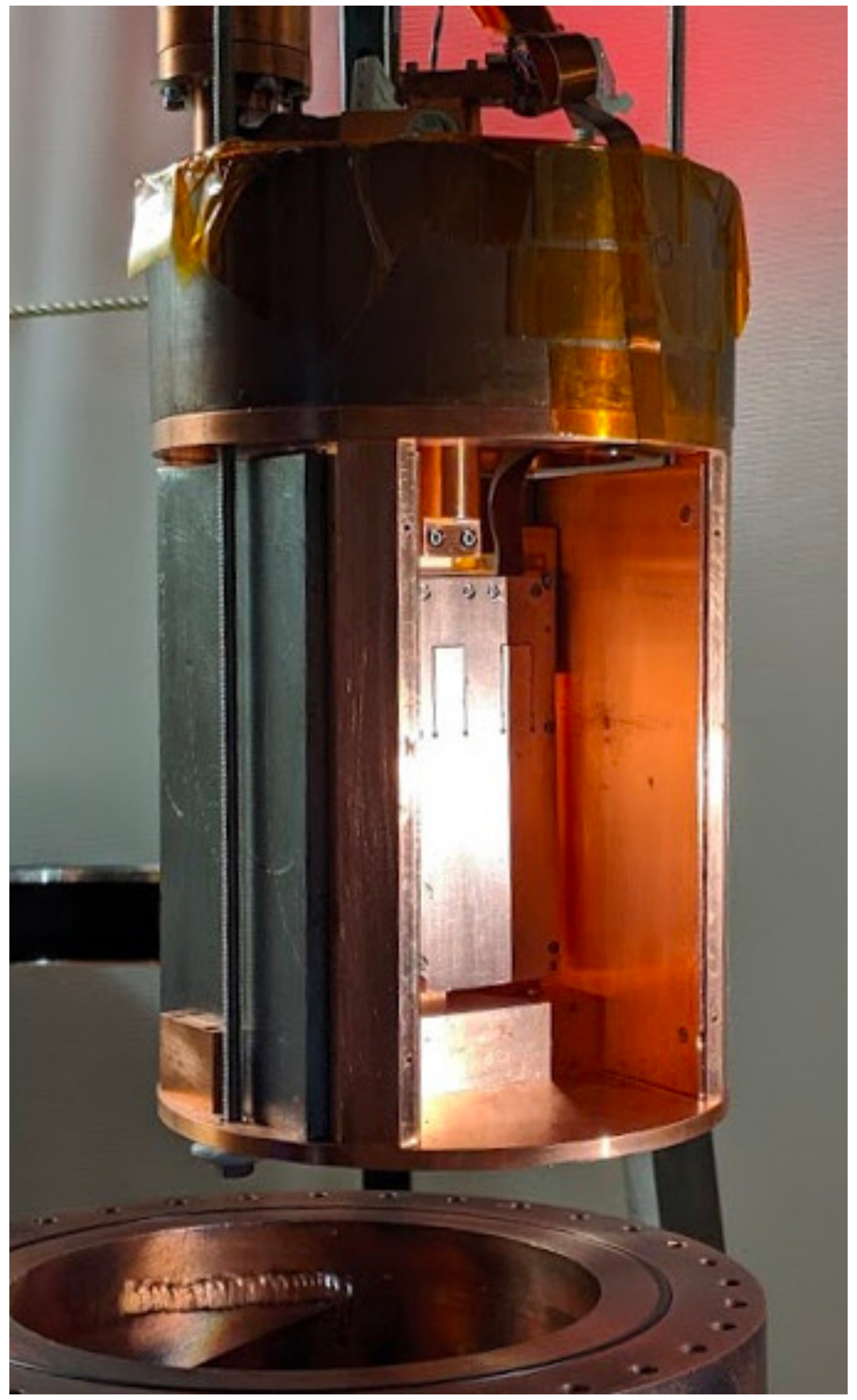
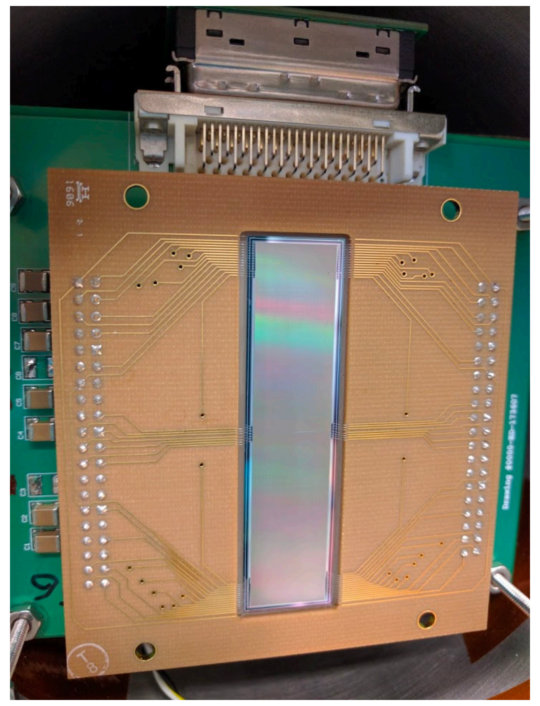
CCD-based: SENSEI & DAMIC

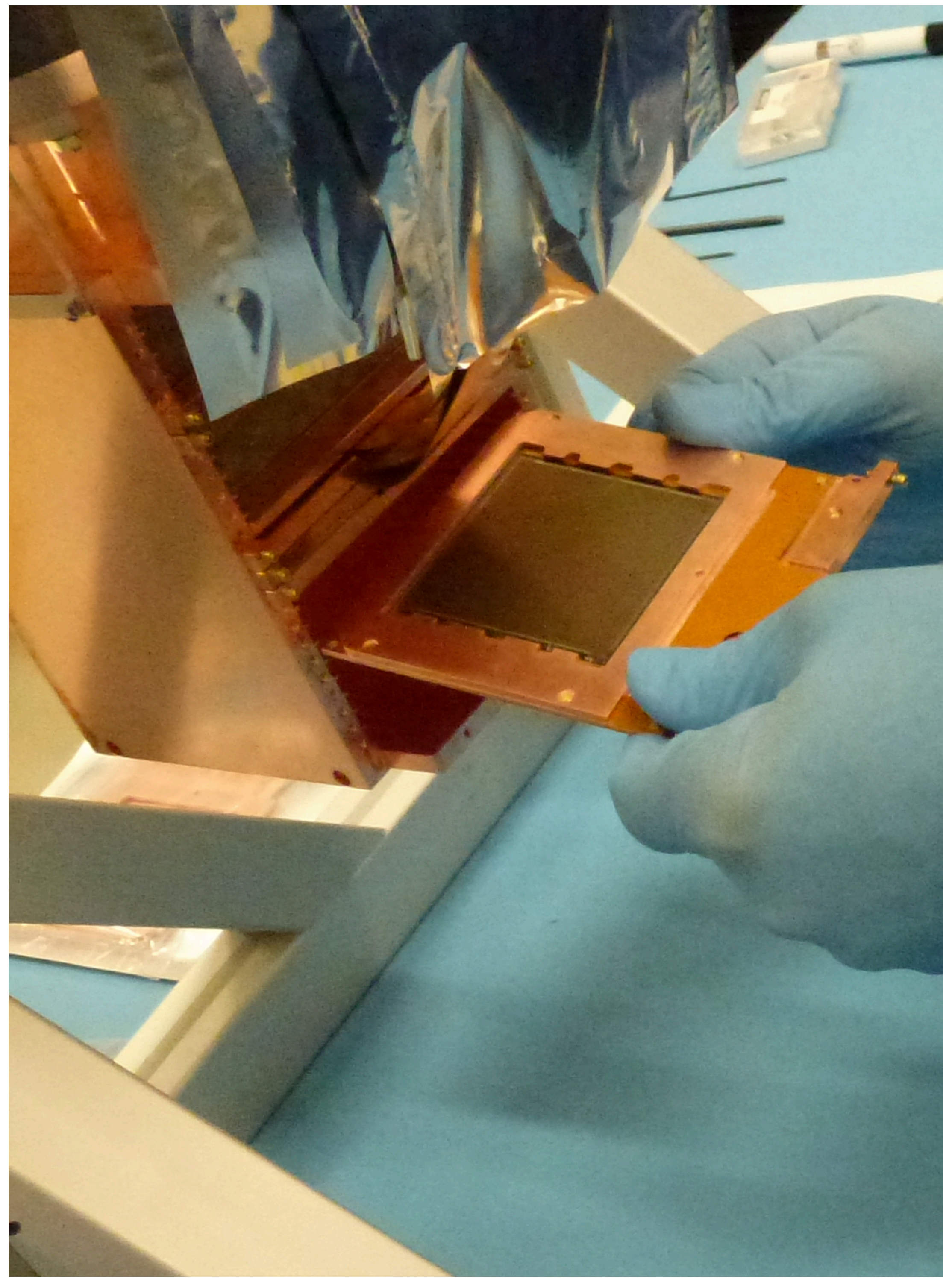
SENSEI

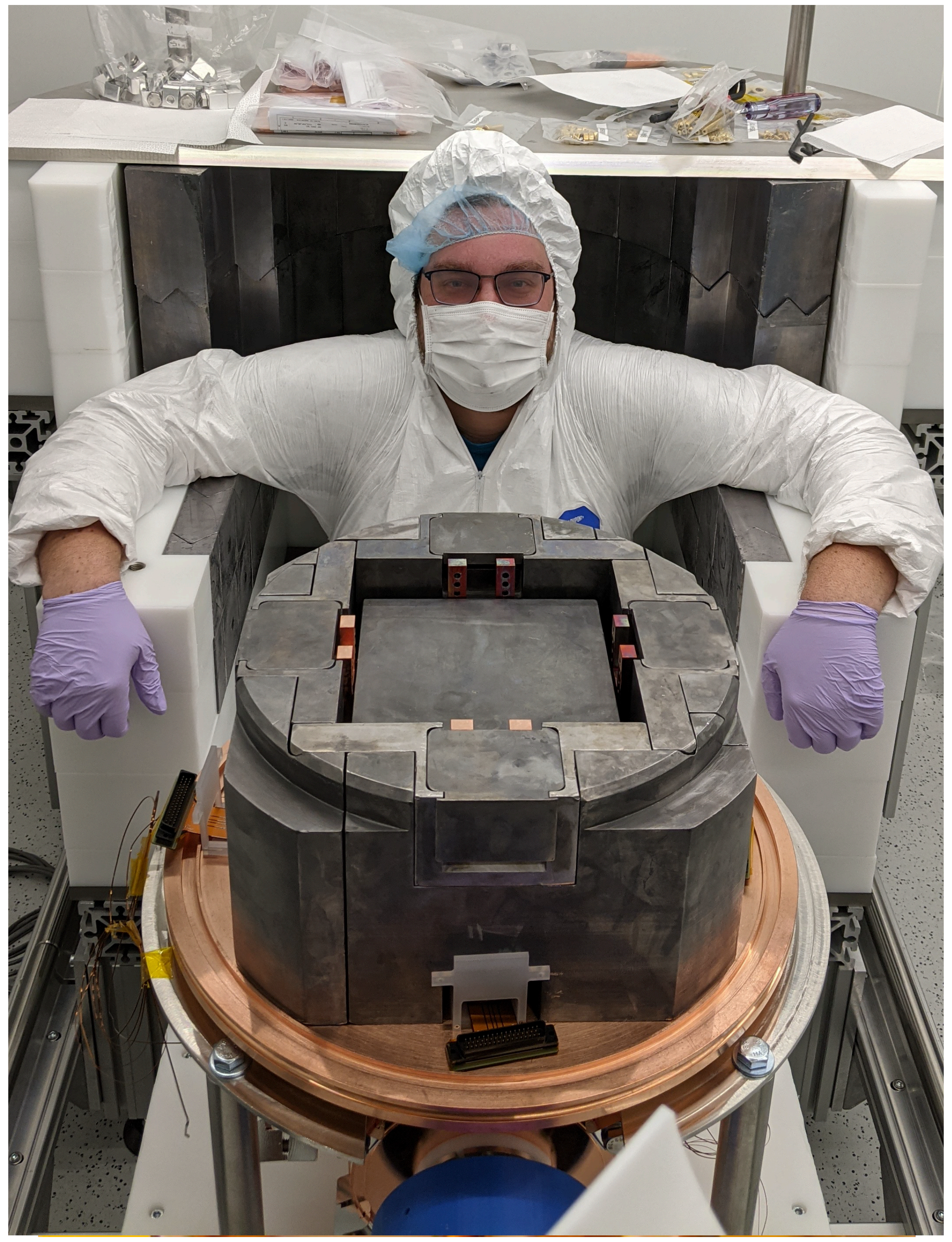
Pictures courtesy: SENSEI collaboration

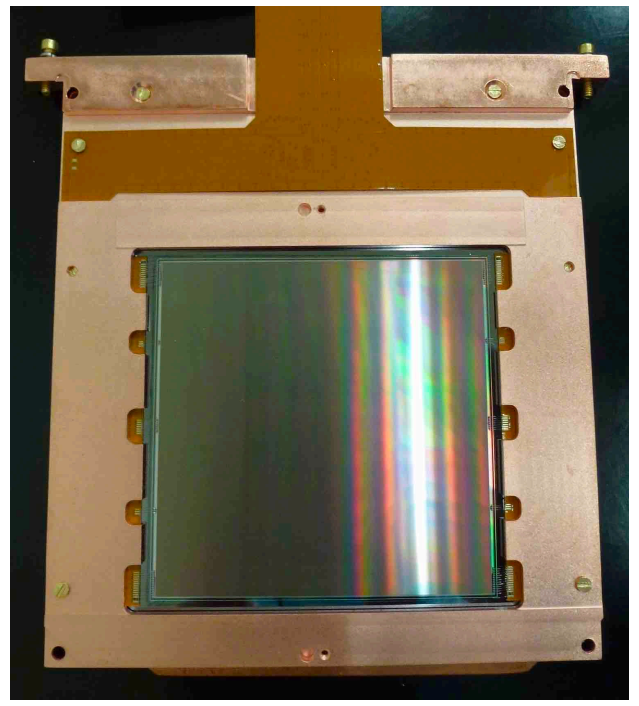




DAMIC / DAMIC-M





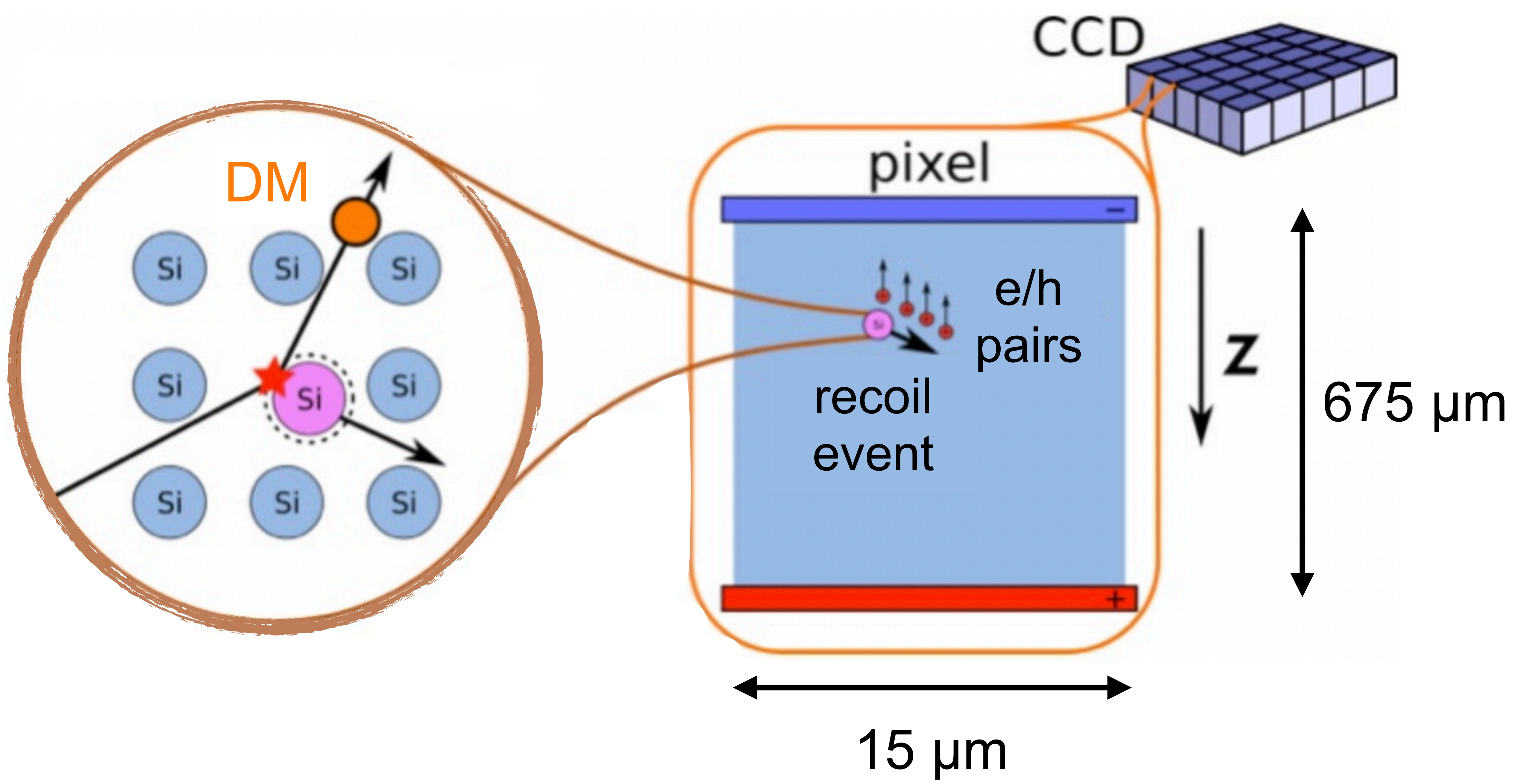


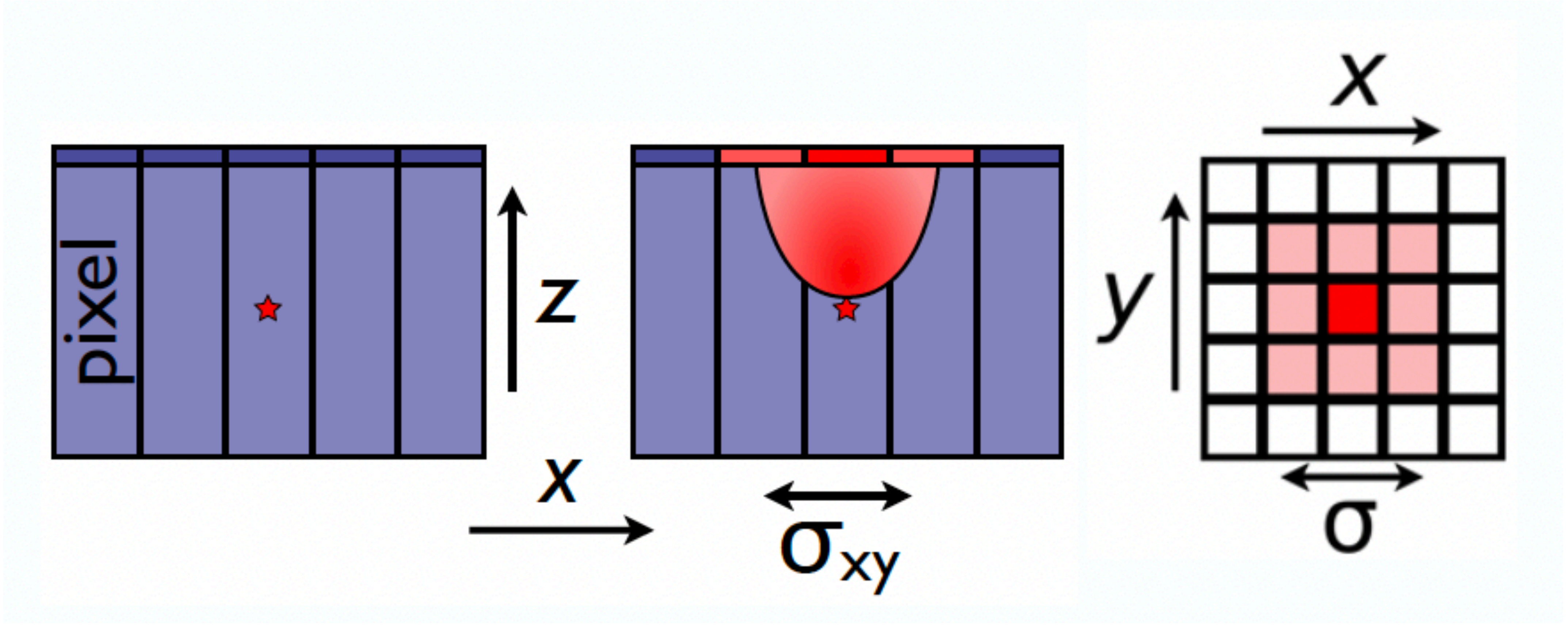
Pictures courtesy: DAMIC collaboration

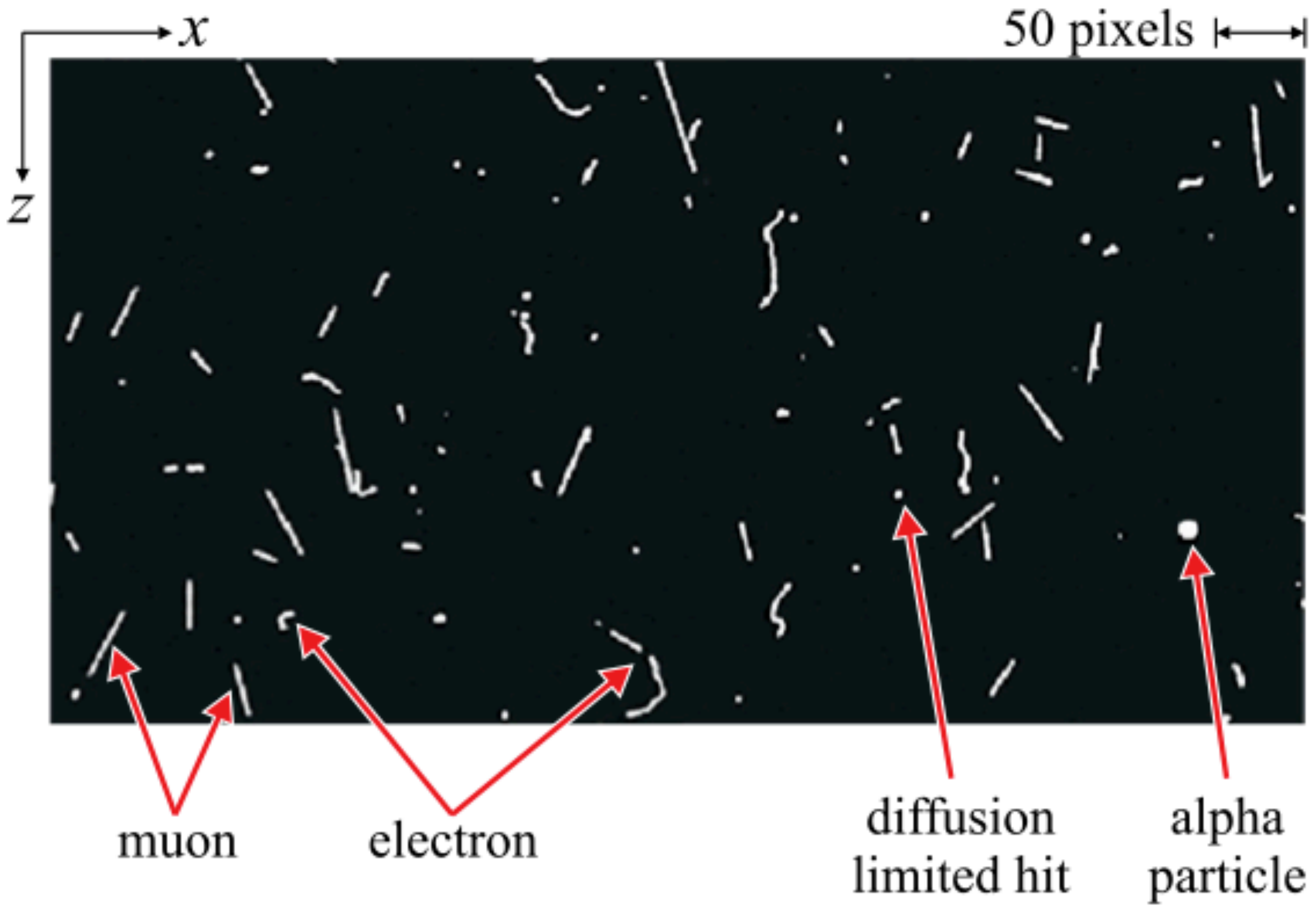
- High spatial and energy resolution but poor time resolution

CCD-based: SENSEI & DAMIC

DAMIC







Pictures courtesy: DAMIC collaboration

CCD-based: SENSEI & DAMIC

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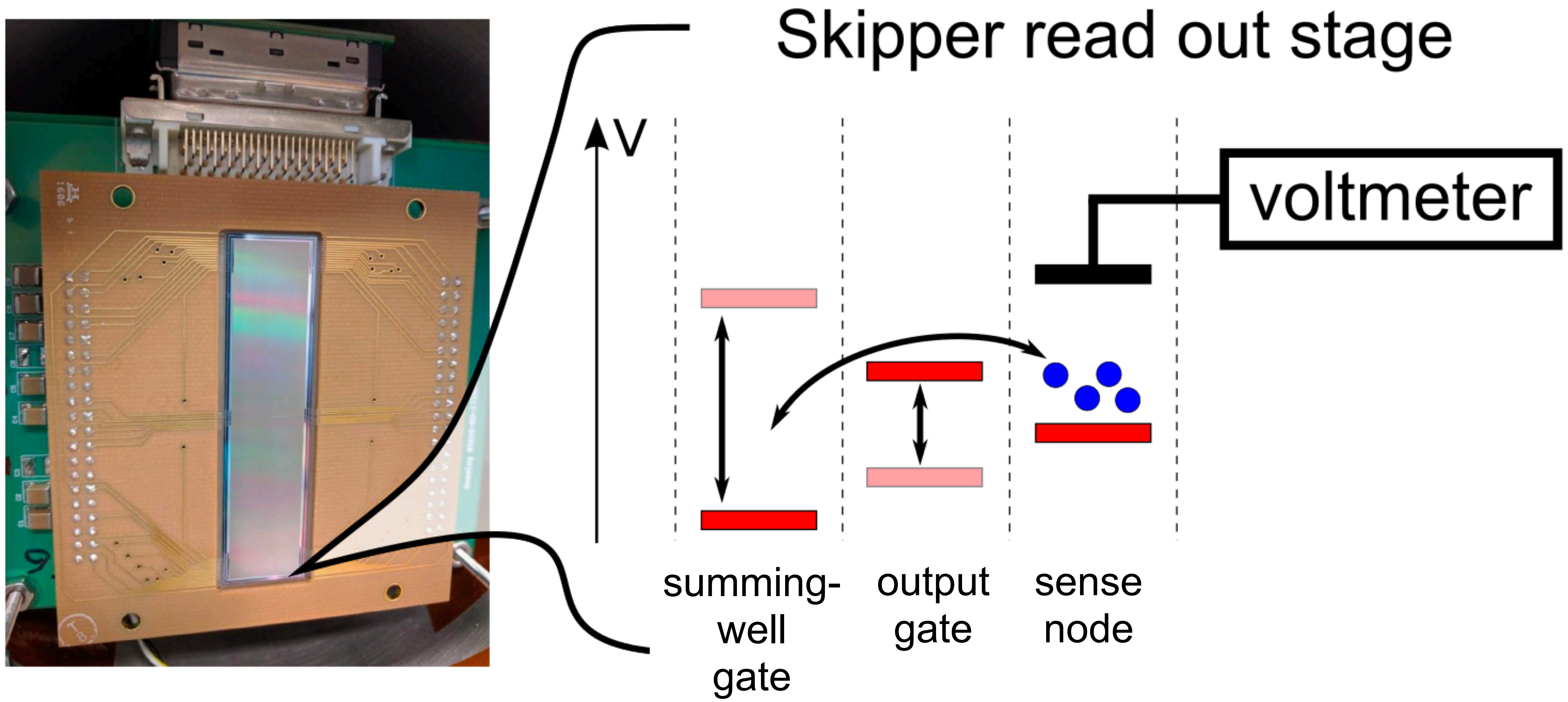
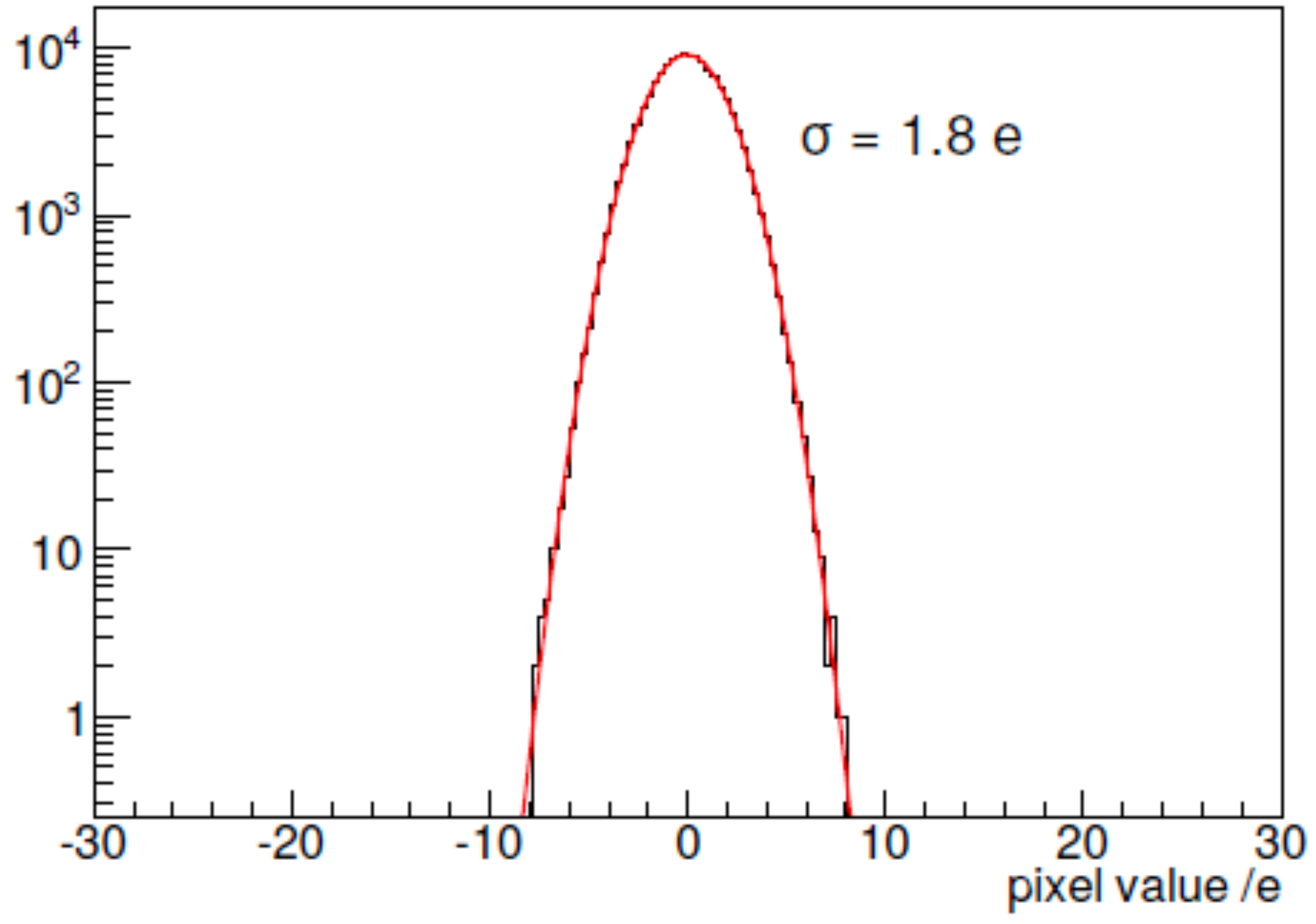
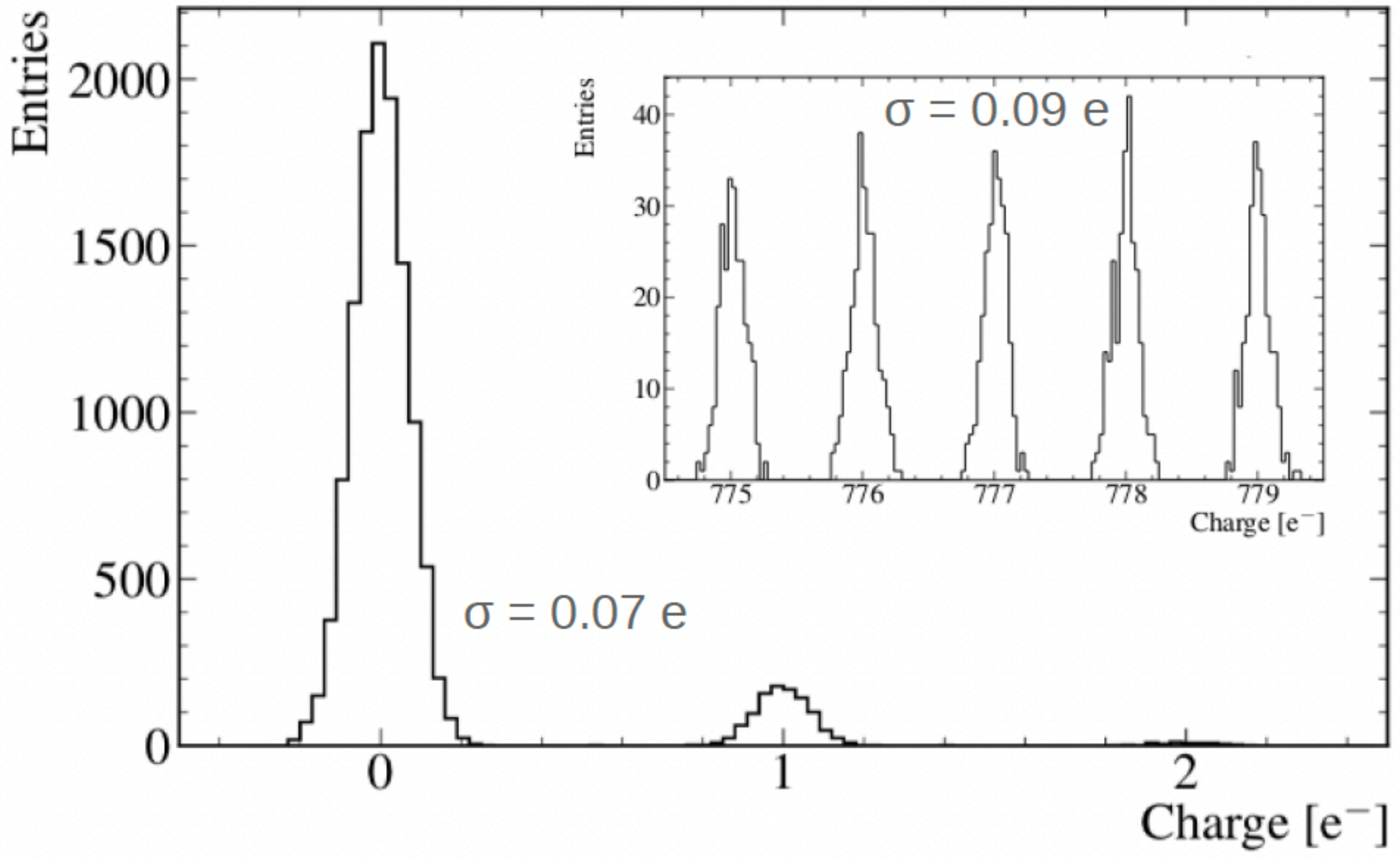


SENSEI

regular scientific CCD



skipper CCD

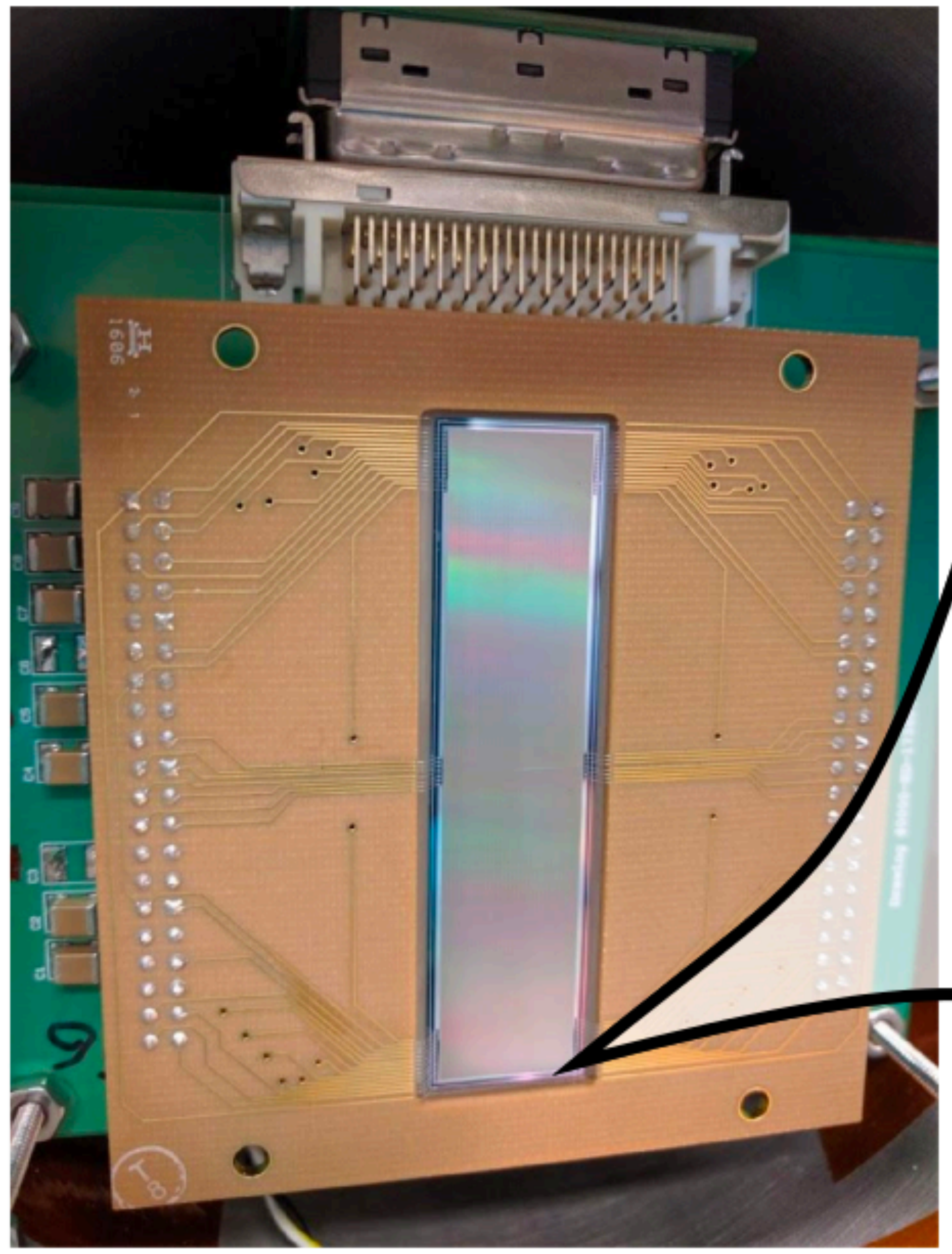


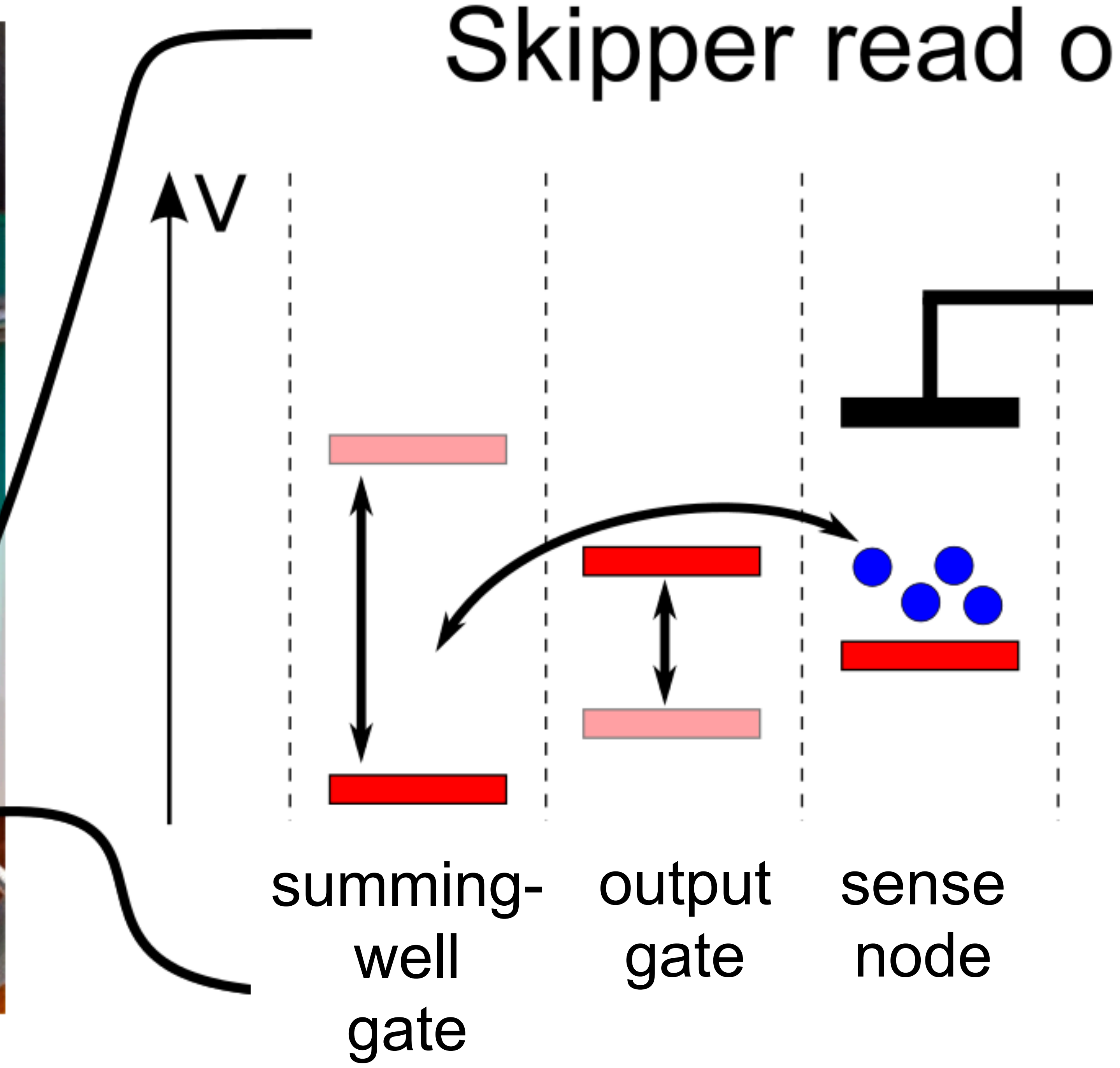
- Sampling the same charge packet multiple times strongly reduces the observed readout noise

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

CCD-based: SENSEI & DAMIC

Pictures courtesy: SENSEI collaboration





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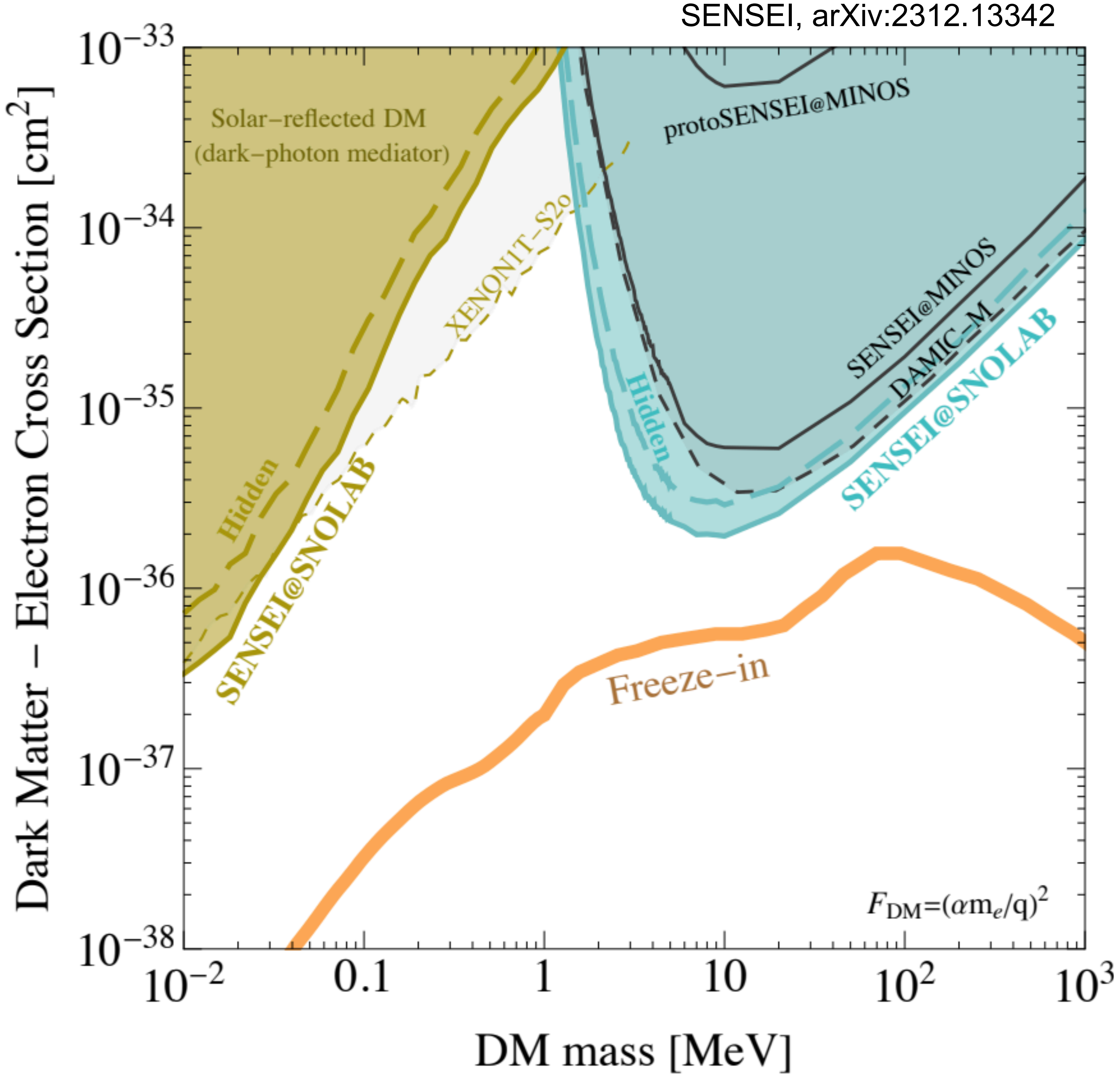
SENSEI

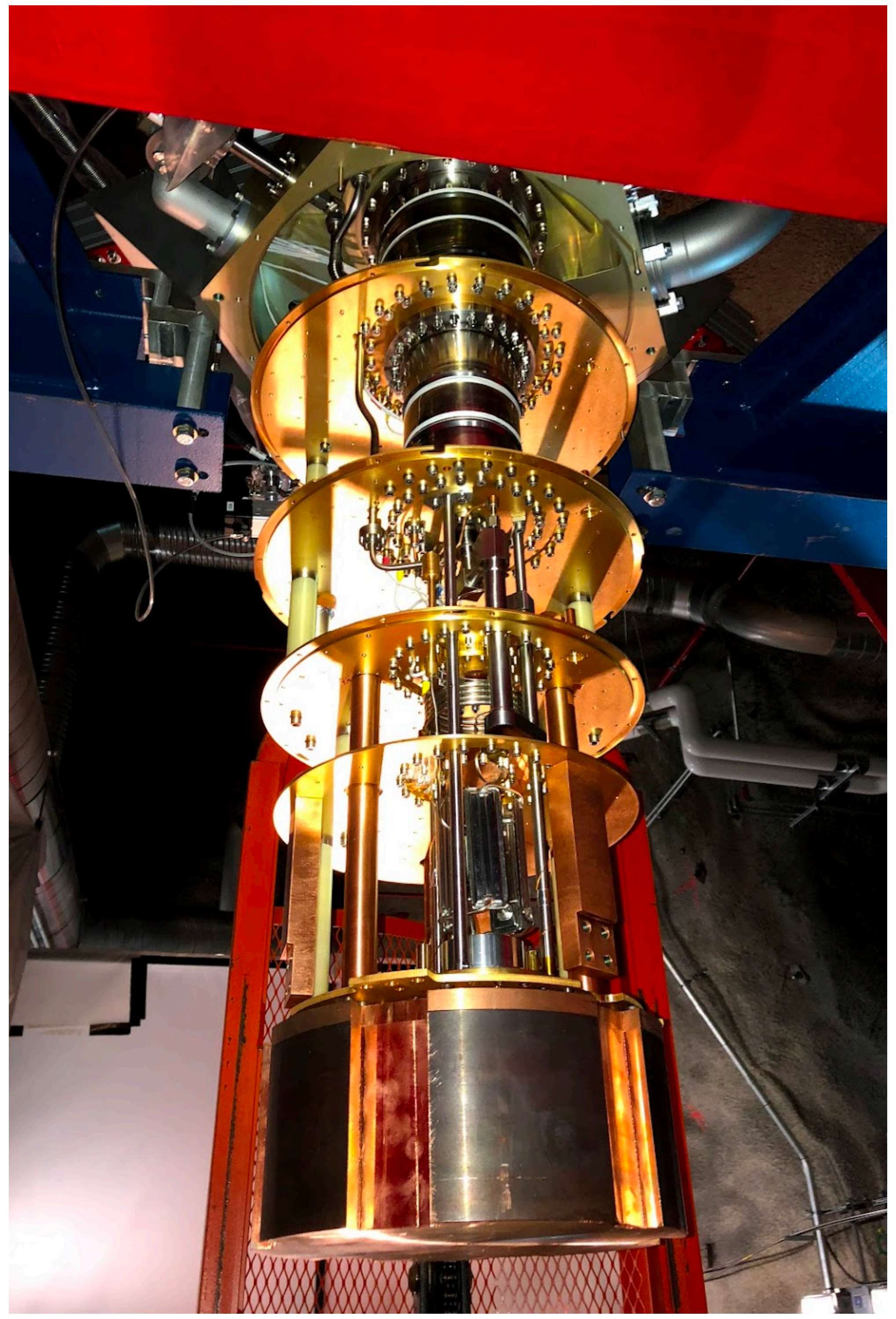
SENSEI, arXiv:2312.13342

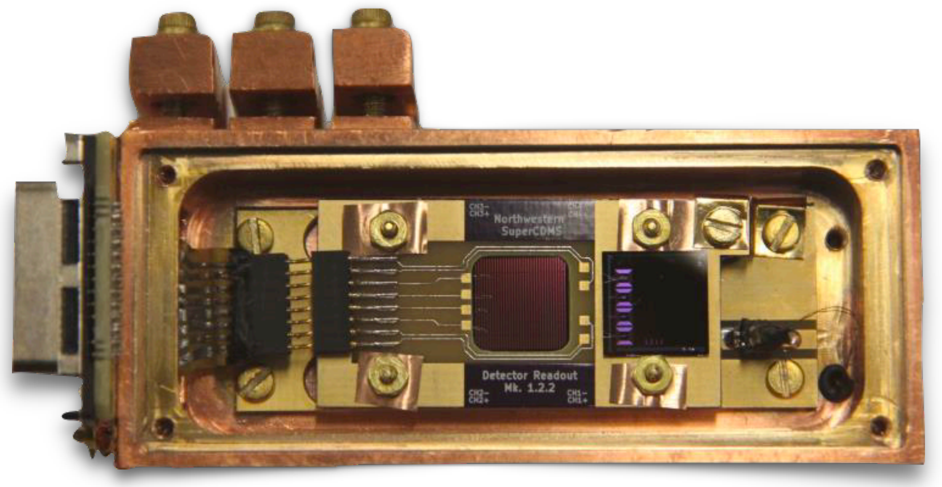


Phonon-based: SuperCDMS-HVeV & EDELWEISS

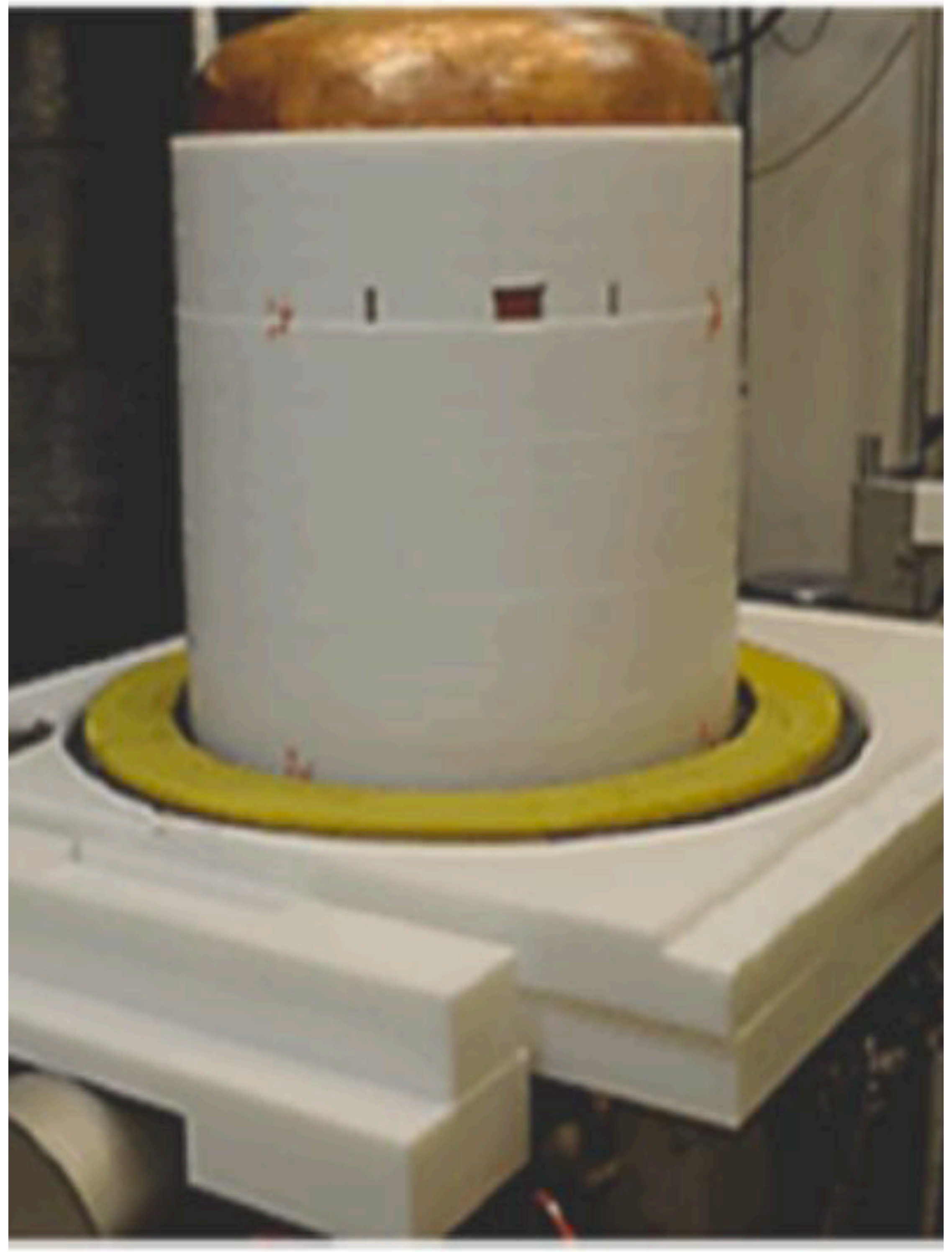
SuperCDMS-HVeV

Pictures courtesy: SuperCDMS collaboration

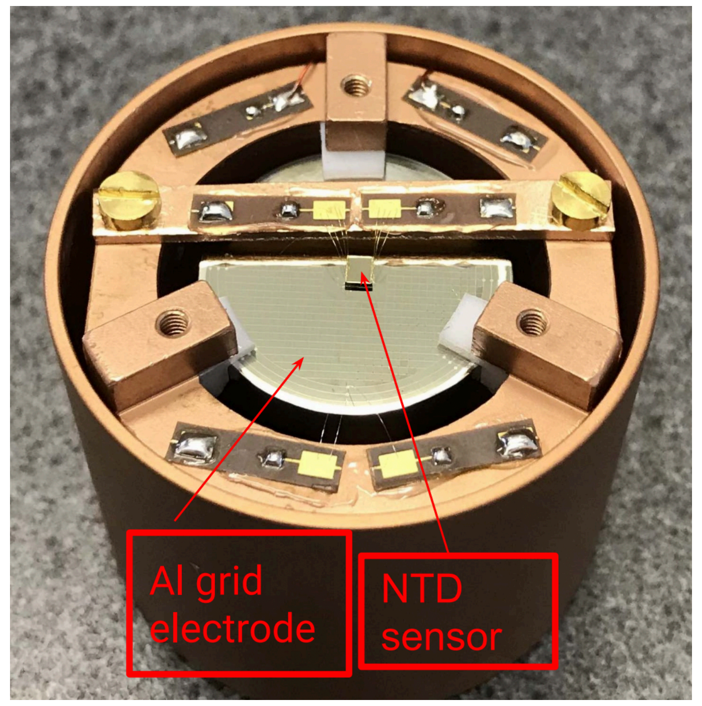




EDELWEISS



Pictures courtesy: EDELWEISS collaboration



- High time and energy resolution but poor spatial resolution

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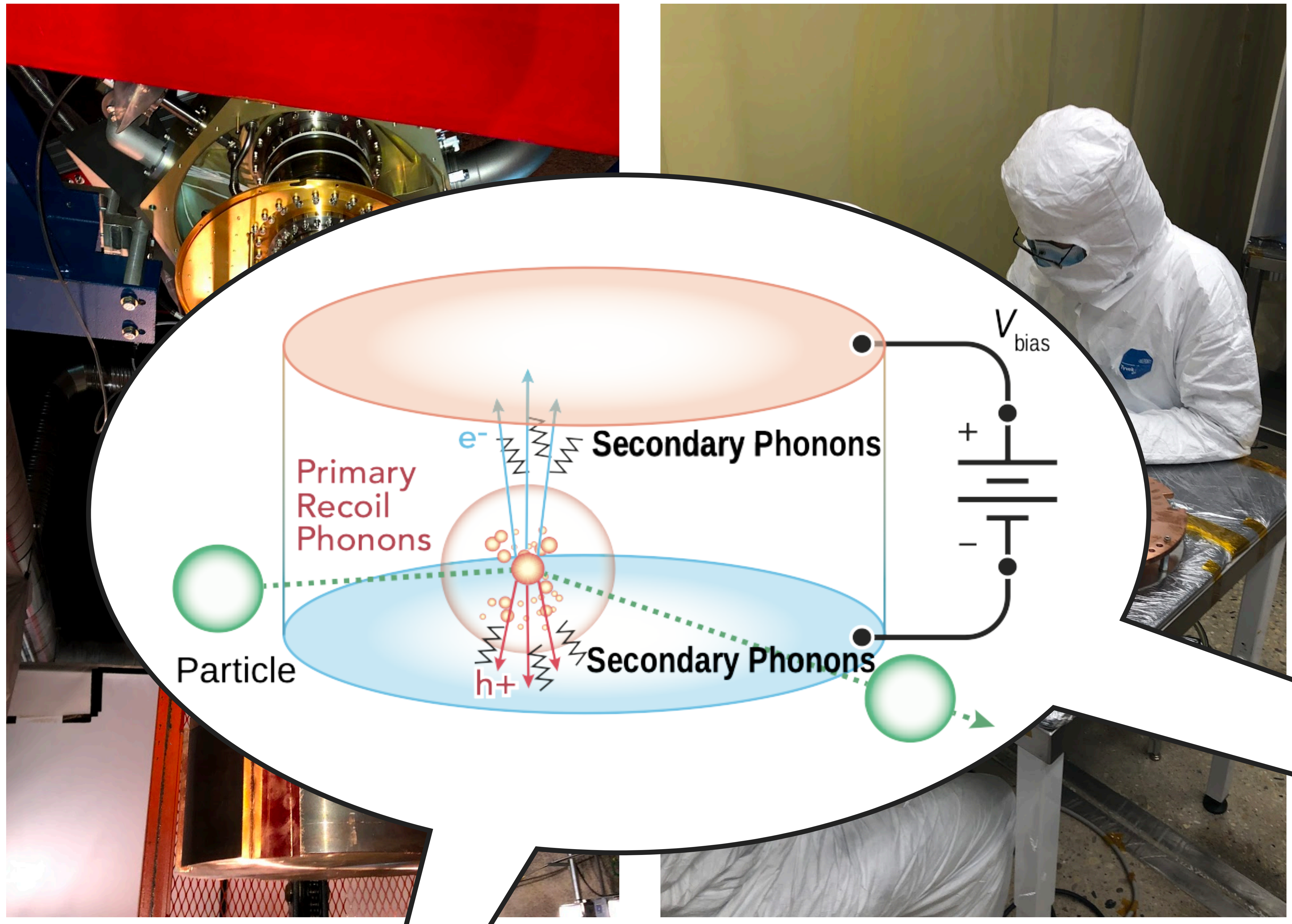
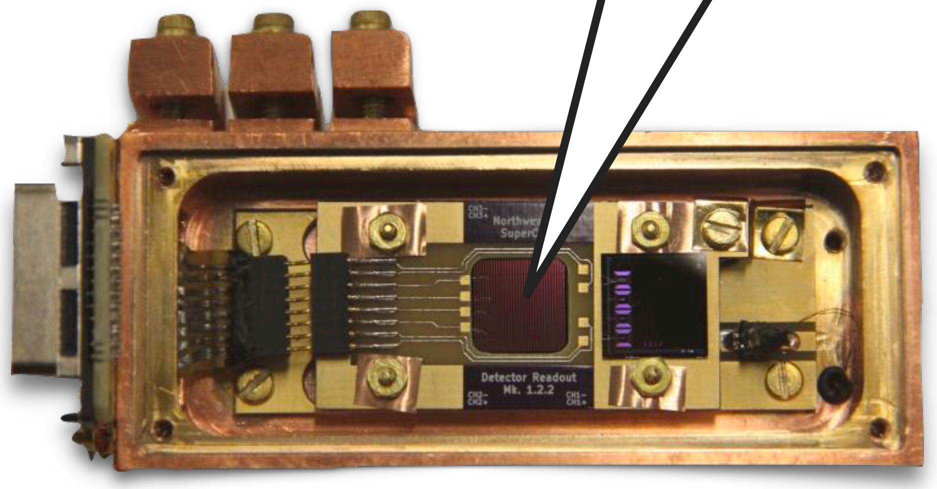
Phonon-based: SuperCDMS-HVeV & EDELWEISS

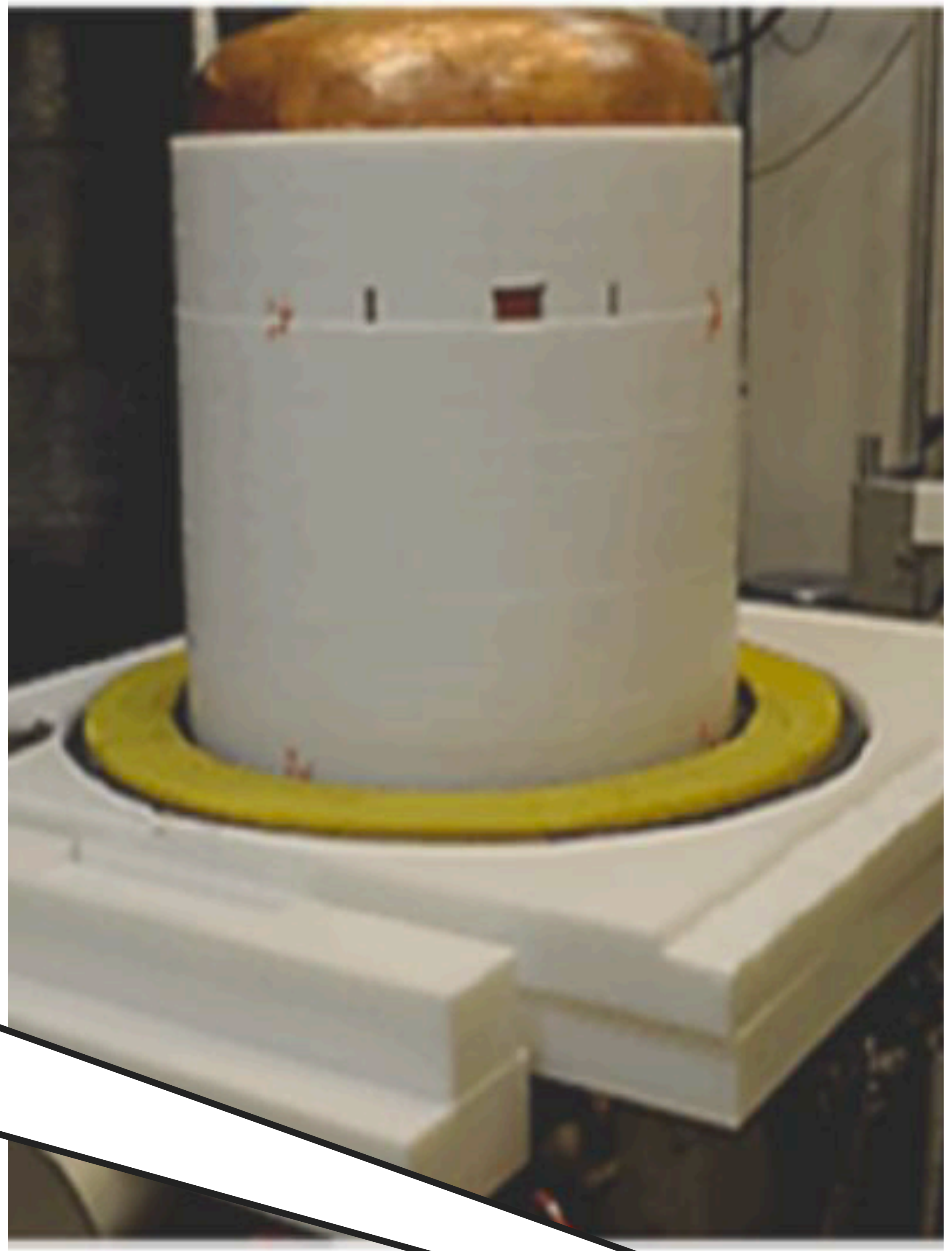
SuperCDMS-HVeV

Pictures courtesy: SuperCDMS collaboration





EDELWEISS



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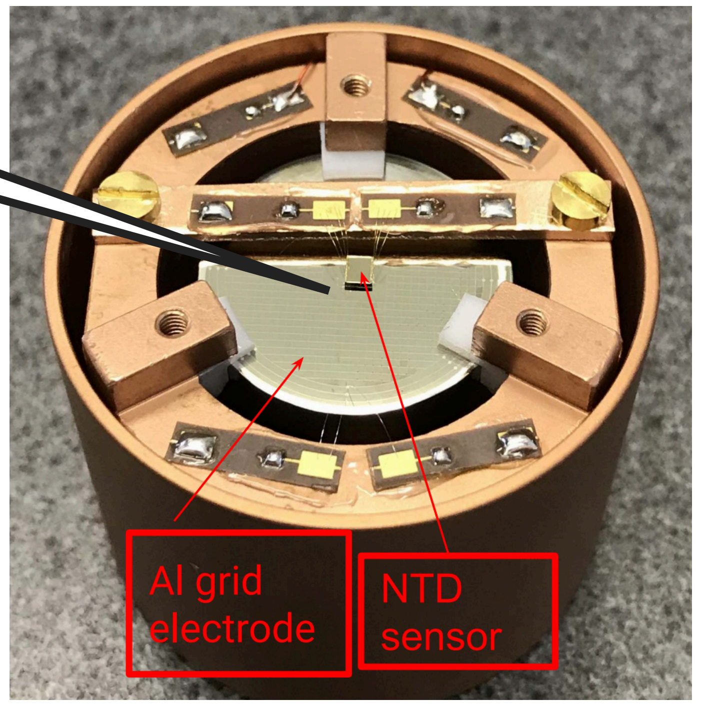

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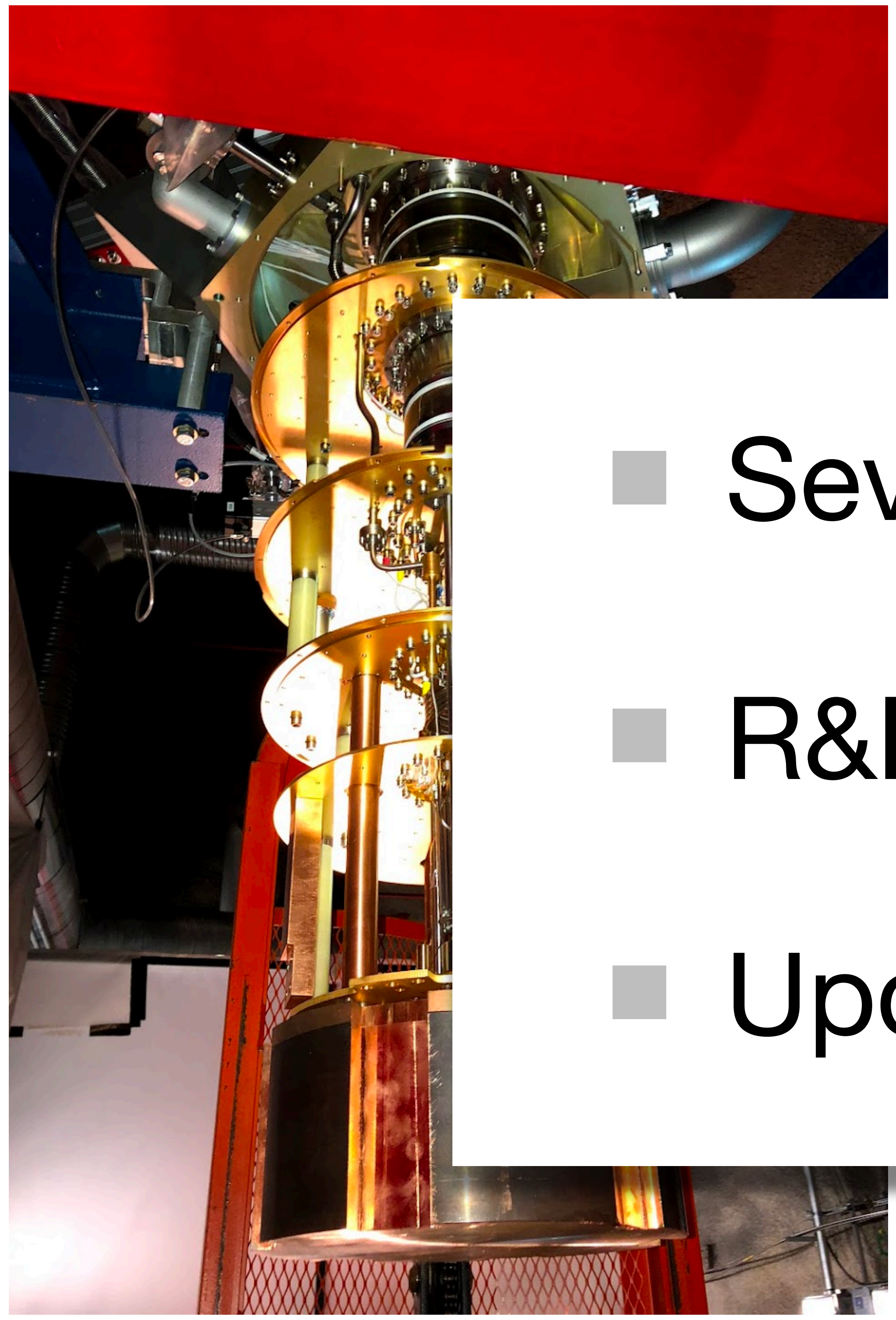
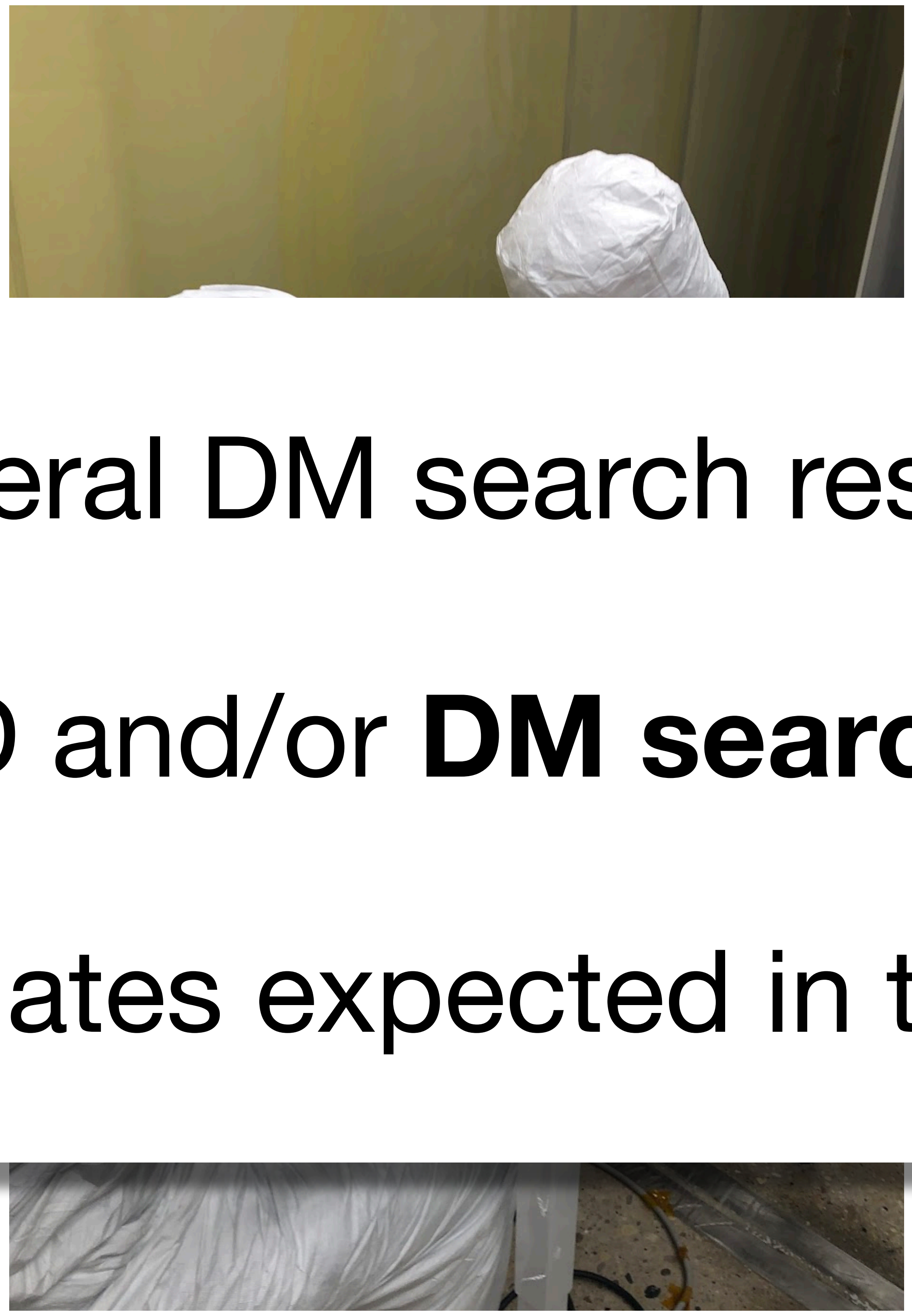
Phonon-based: SuperCDMS-HVeV & EDELWEISS

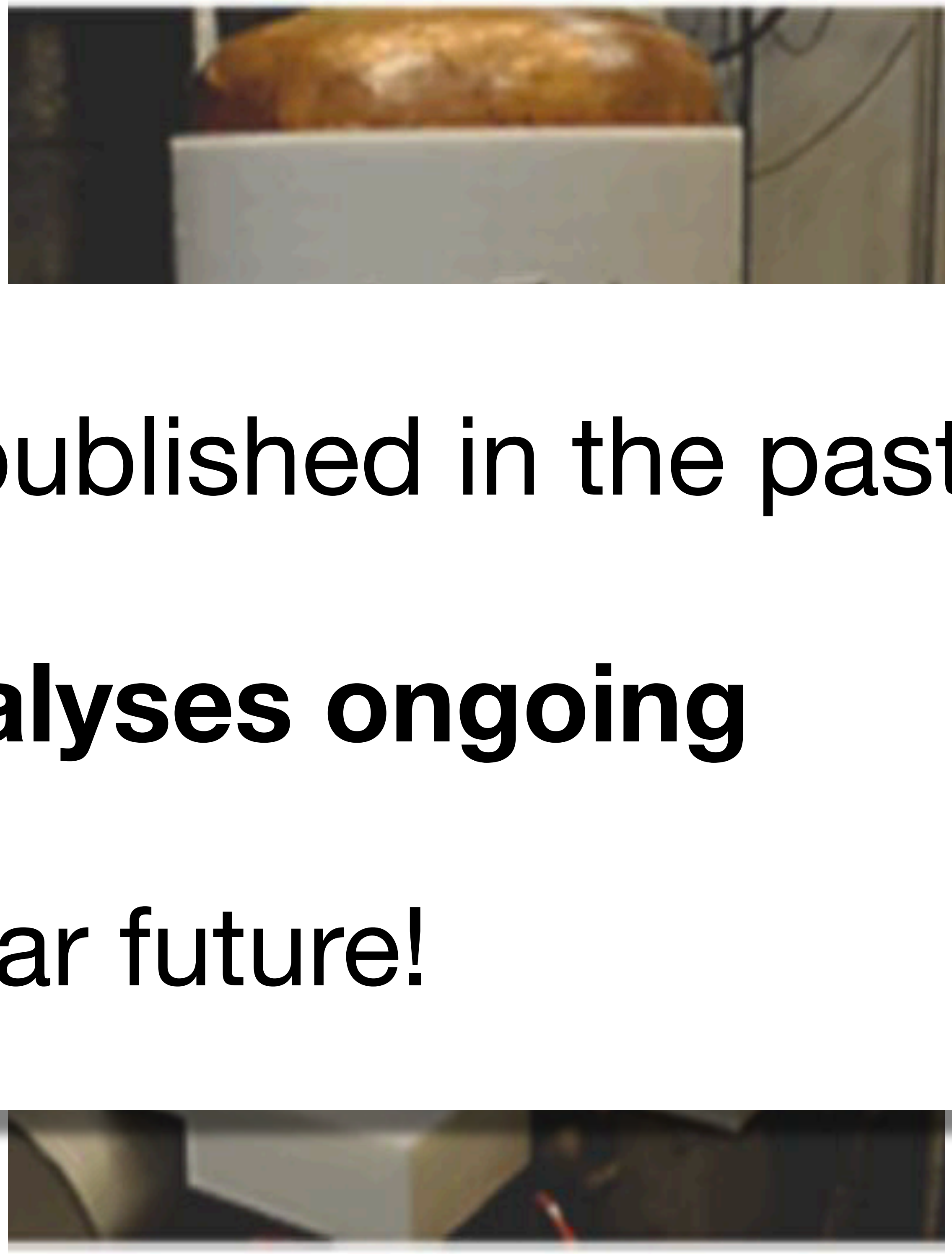
SuperCDMS-HVeV

EDELWEISS

Pictures courtesy: SuperCDMS collaboration

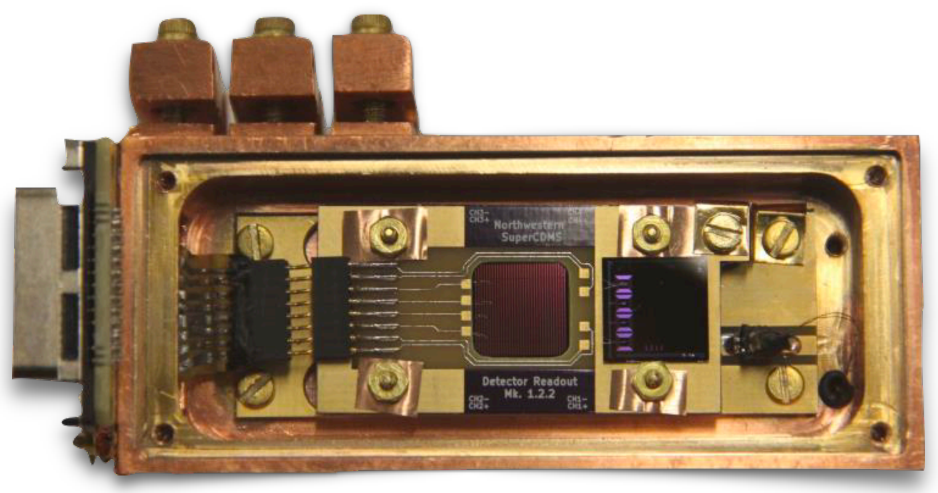




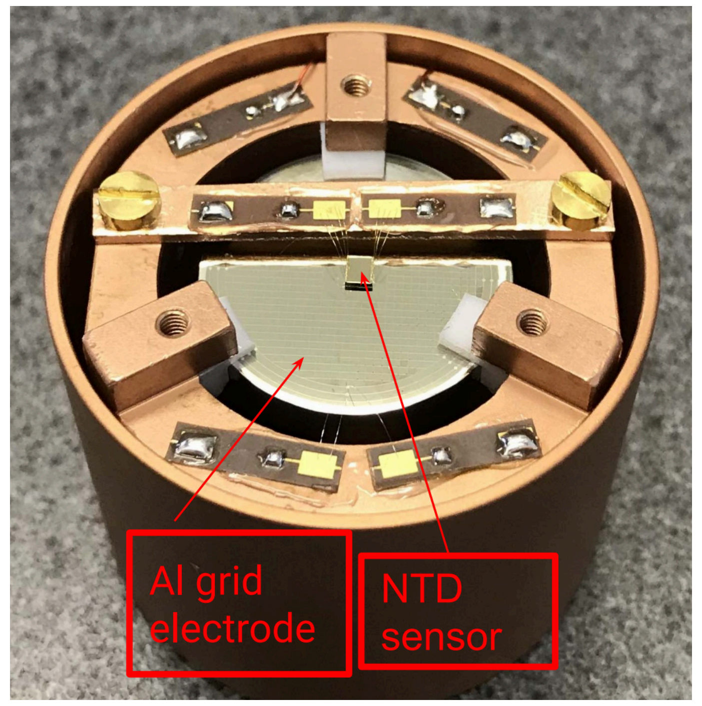


Pictures courtesy: EDELWEISS collaboration

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



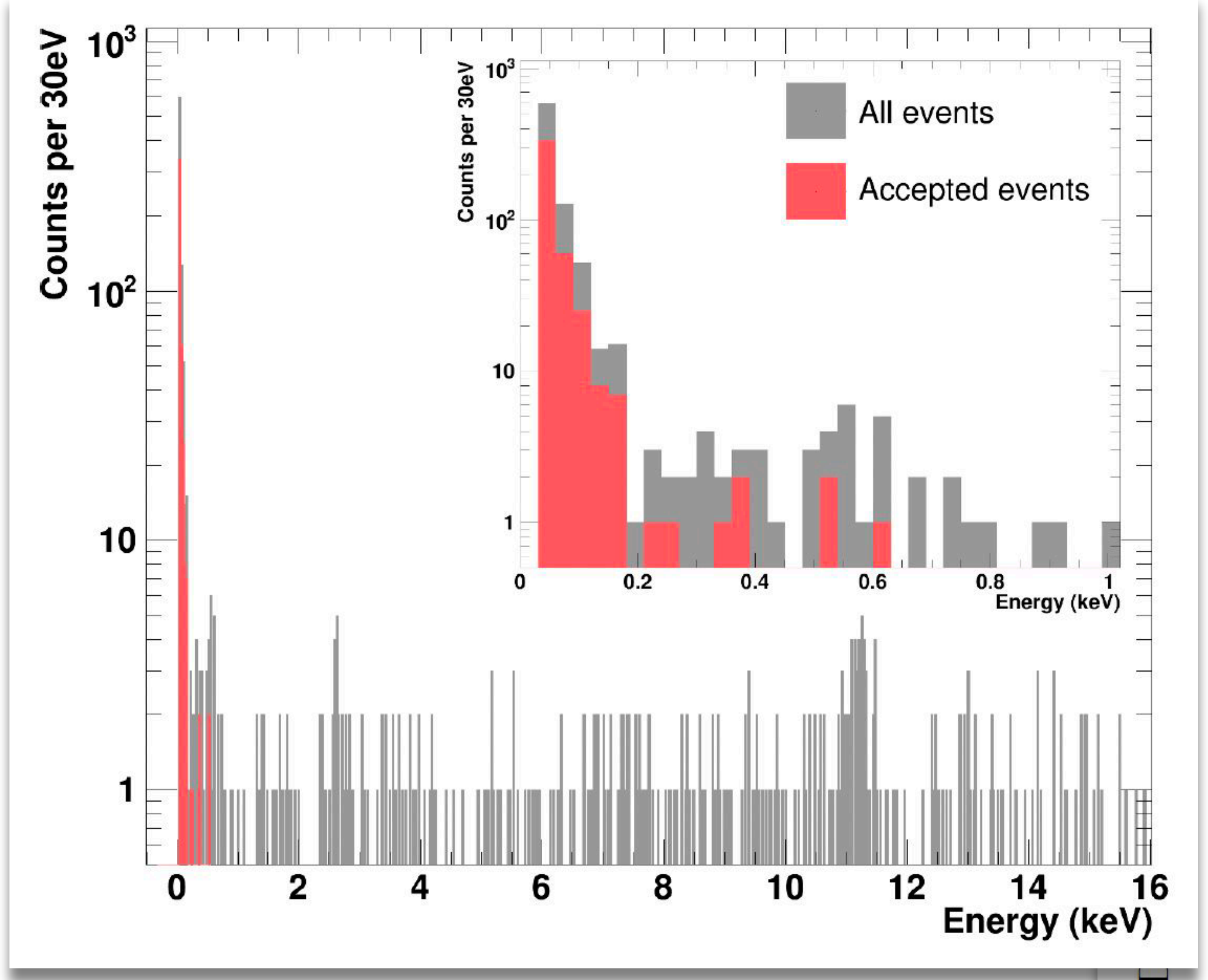
- High time and energy resolution but poor spatial resolution



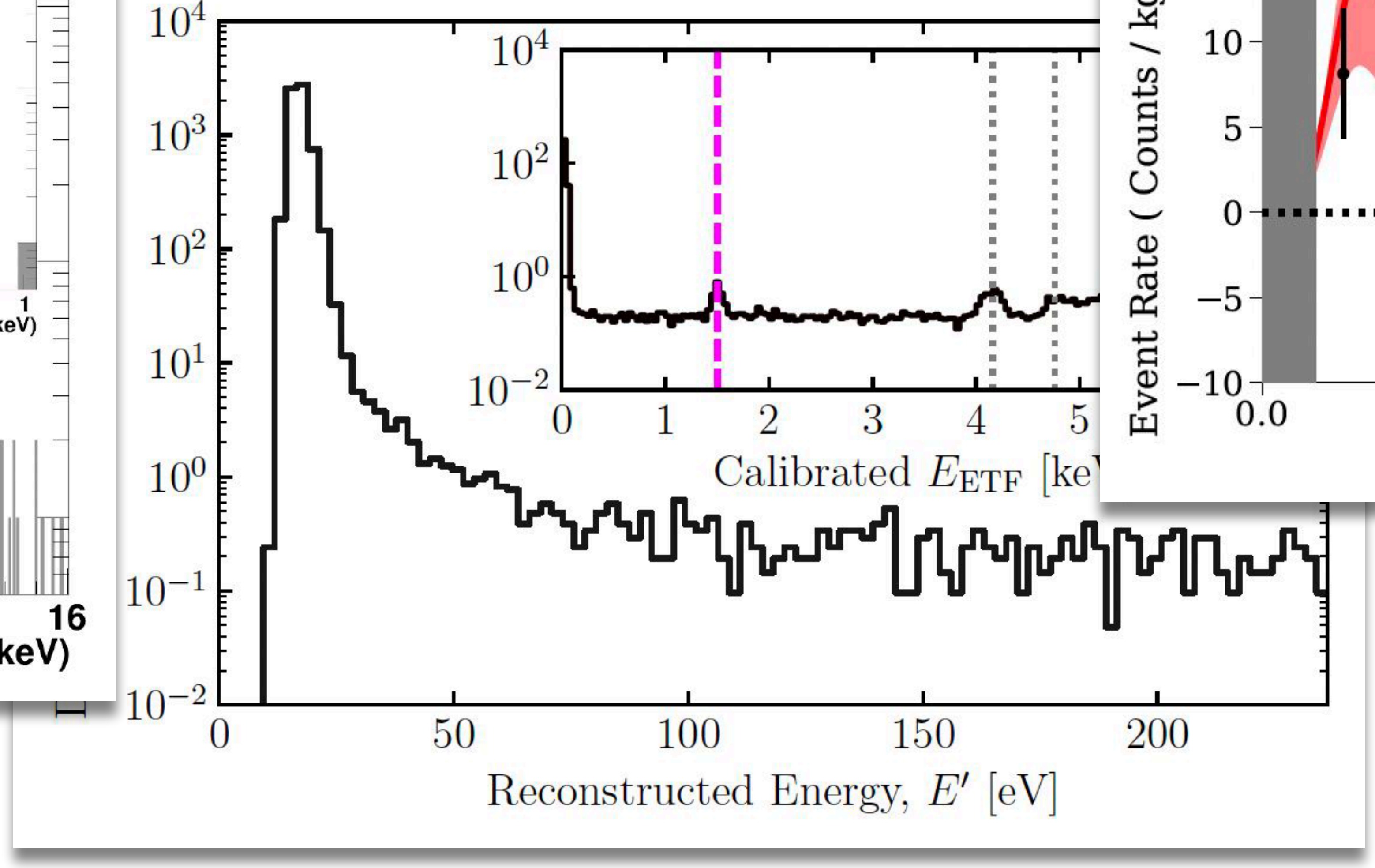
Experimental status: The infamous low-energy excess

Low energy excesses

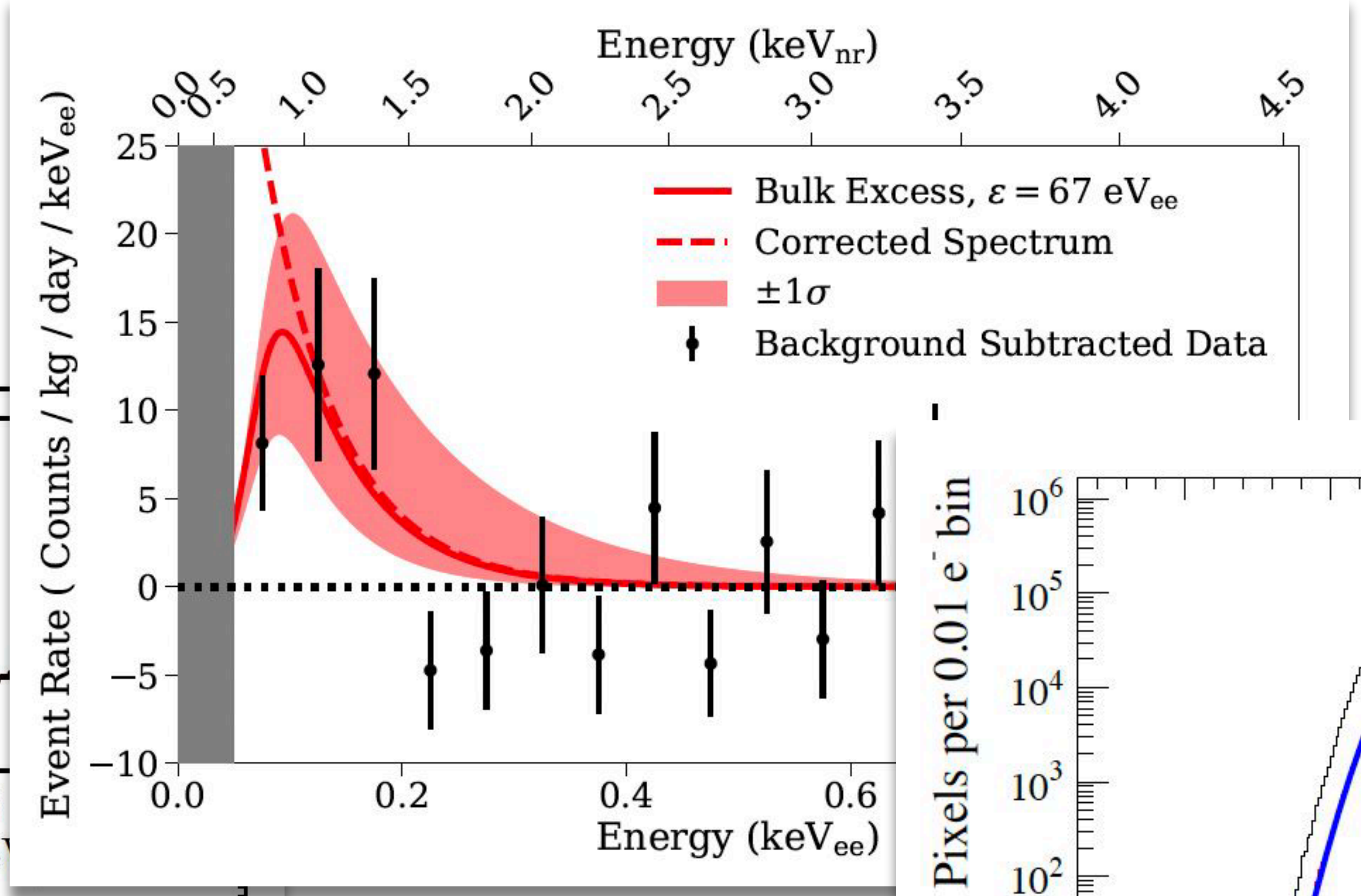
CRESST, Phys. Rev. D 100, 102002



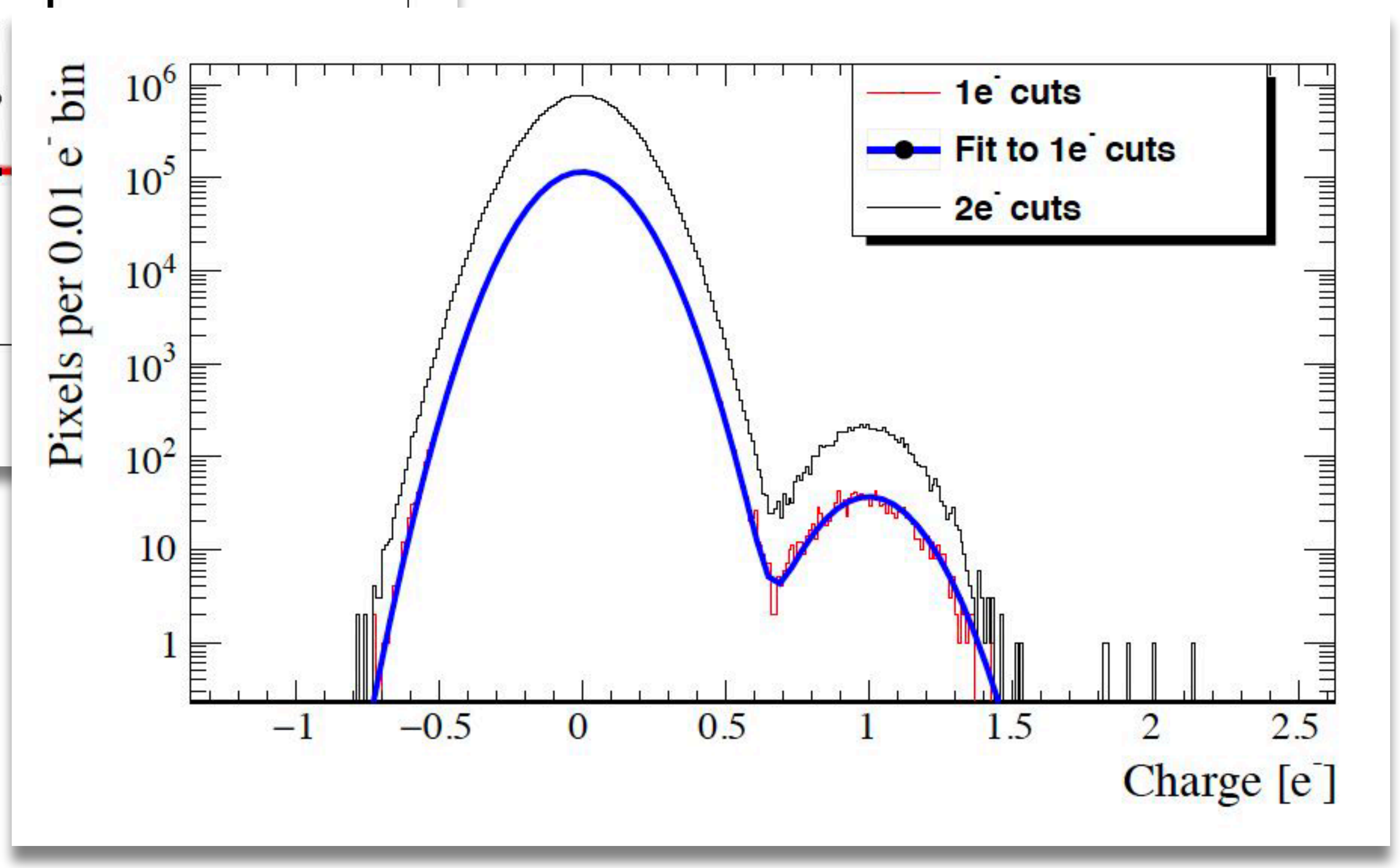
SuperCDMS, Phys. Rev. Lett. 127, 061801



DAMIC, Phys. Rev. Lett. 125, 241803

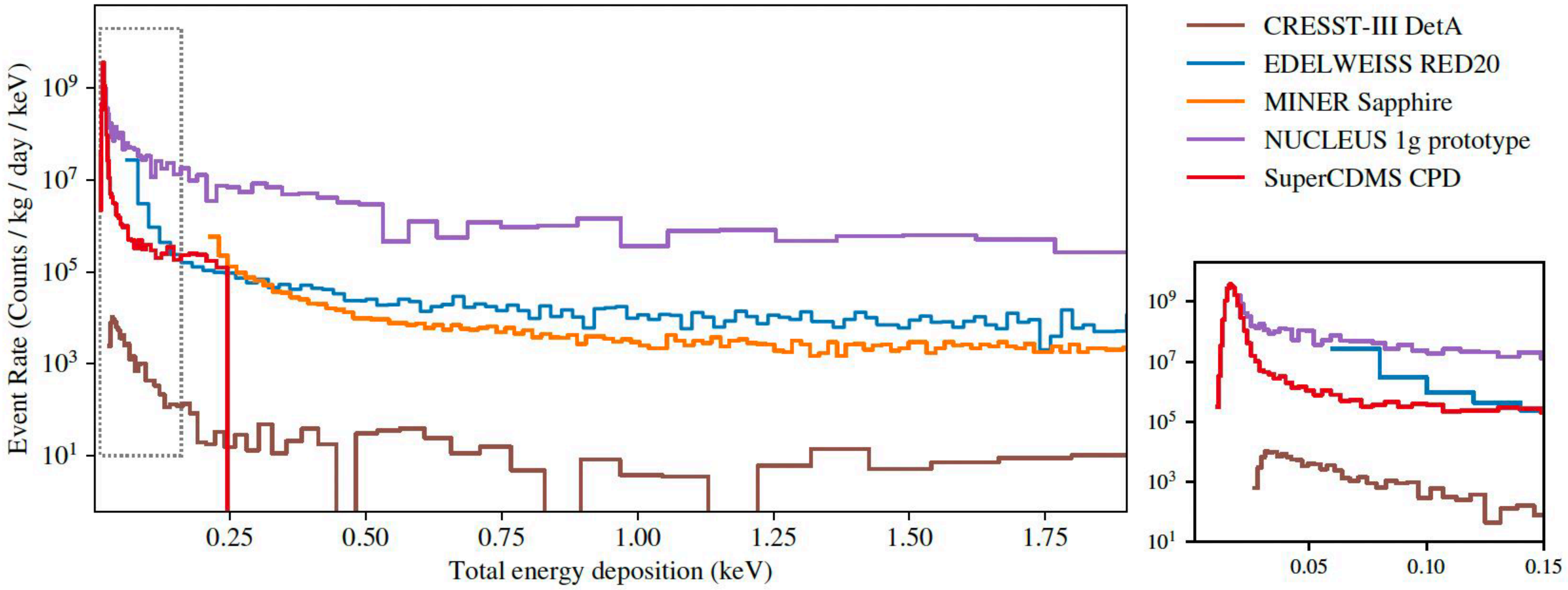


SENSEI, Phys. Rev. Lett. 125, 171802



- Status 2020:
  - cryogenic, CCD-like and gaseous ionization detectors have successfully lowered their recoil energy thresholds, down to ~10 eV
  - on these energy scales, they observe steeply rising excesses above known backgrounds

The EXCESS workshop series

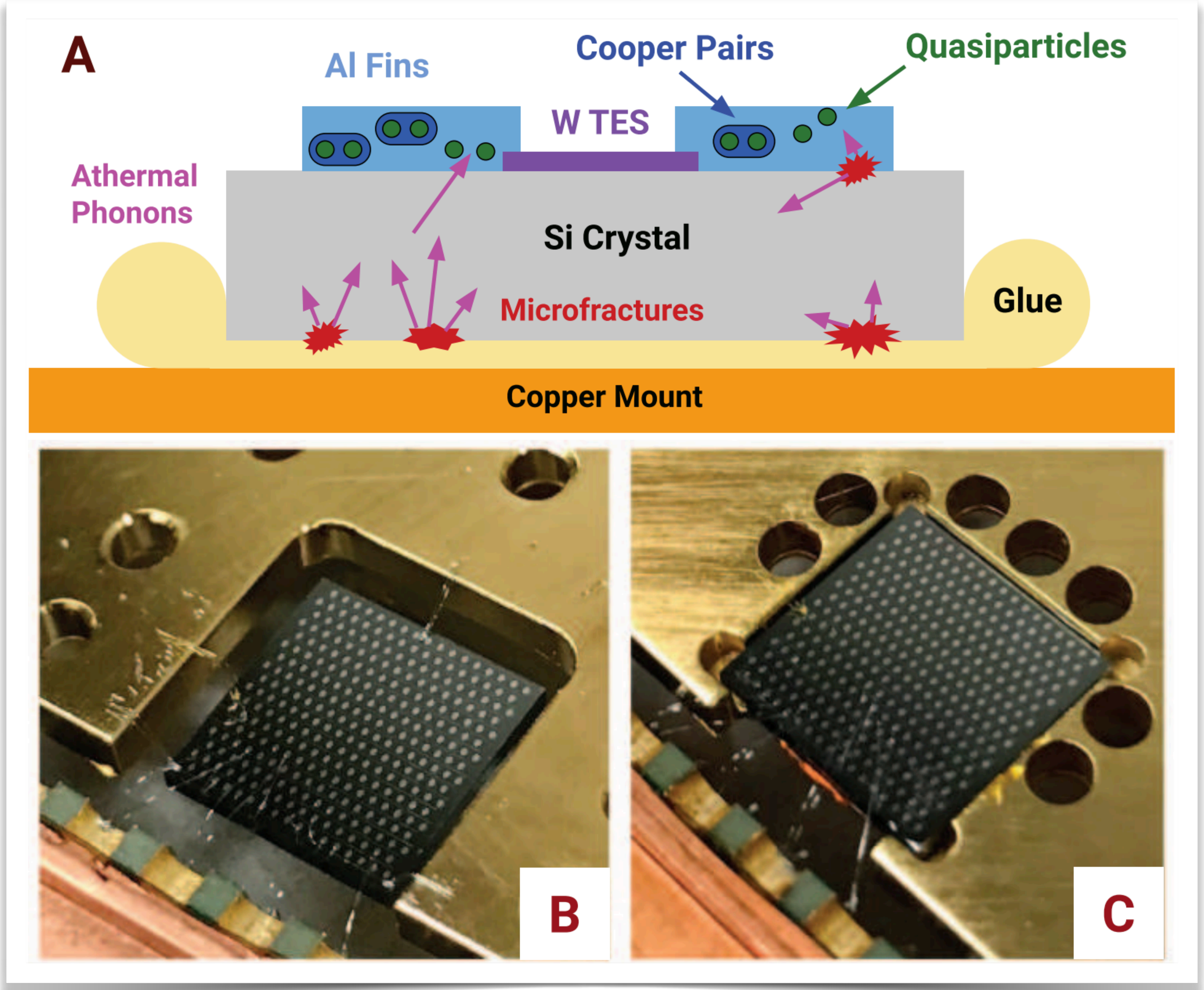


SciPost Phys. Proc. 9, 001 (2022)

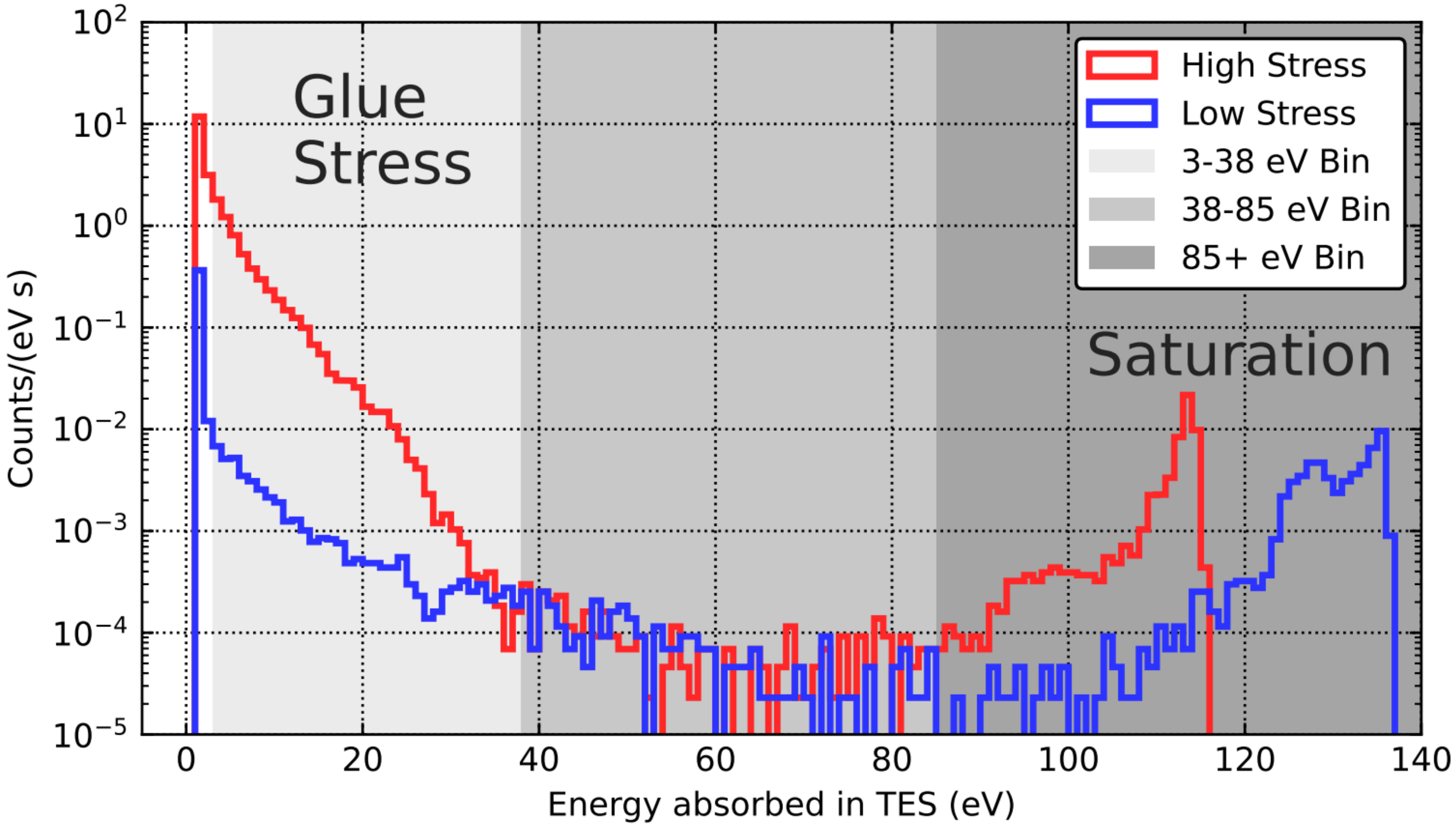
Contents

- We started a **community effort** 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
- Status 2024: 5th workshop iteration preceding IDM24 (this Saturday!)

Some of the key findings



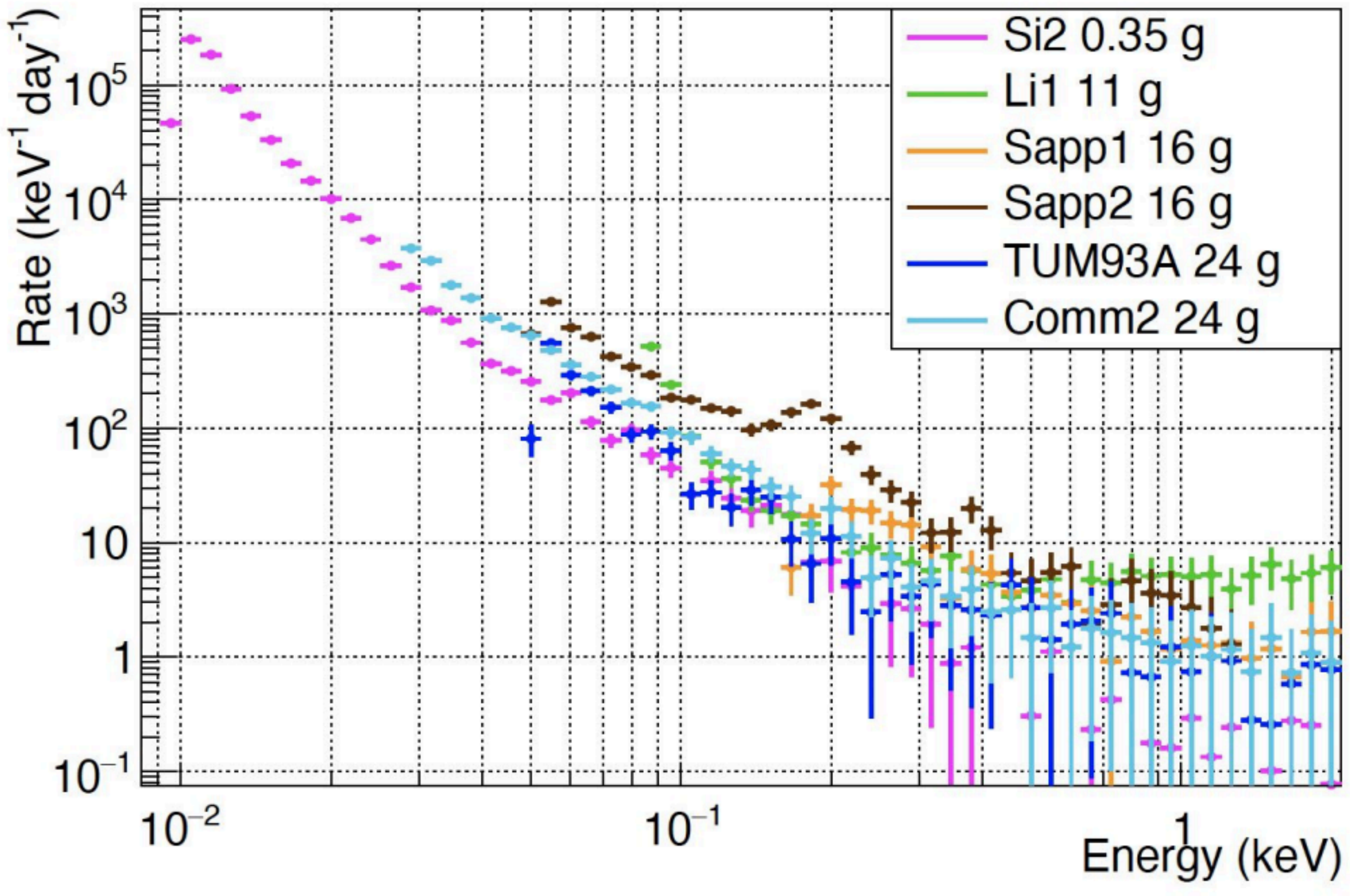
TESSERACT, arXiv:2208.02790

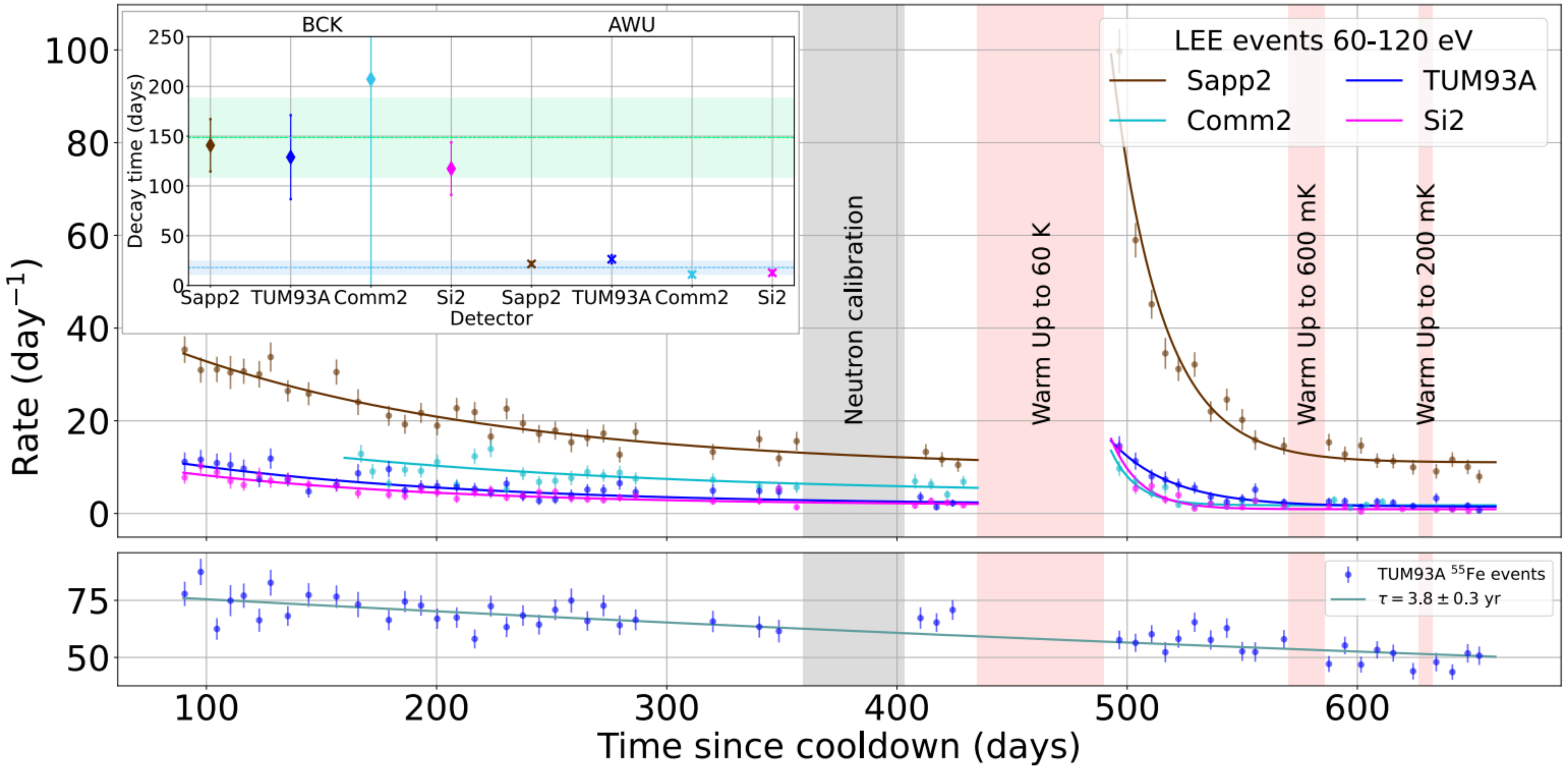


- Don’t stress your detectors!

Some of the key findings

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

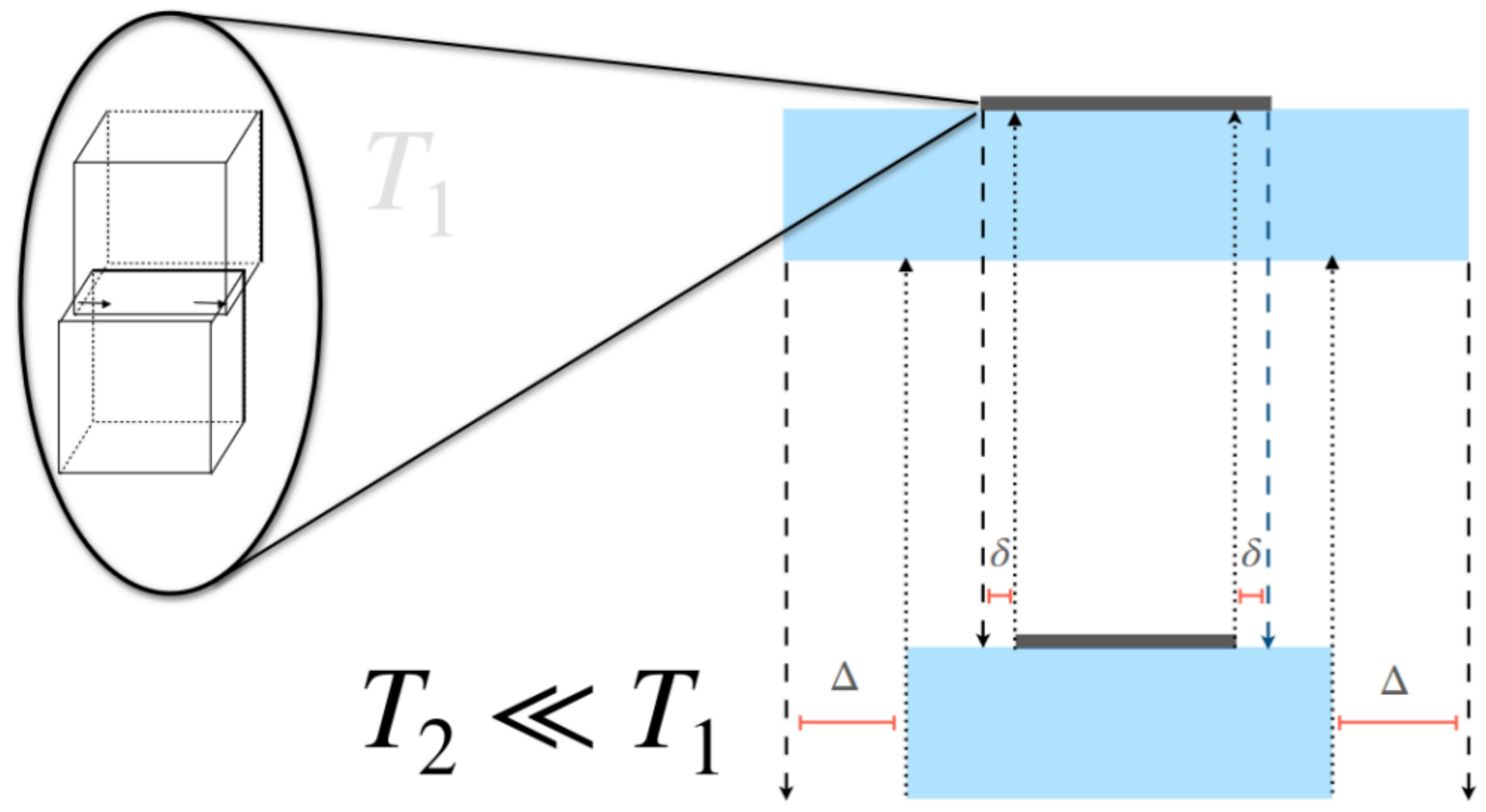


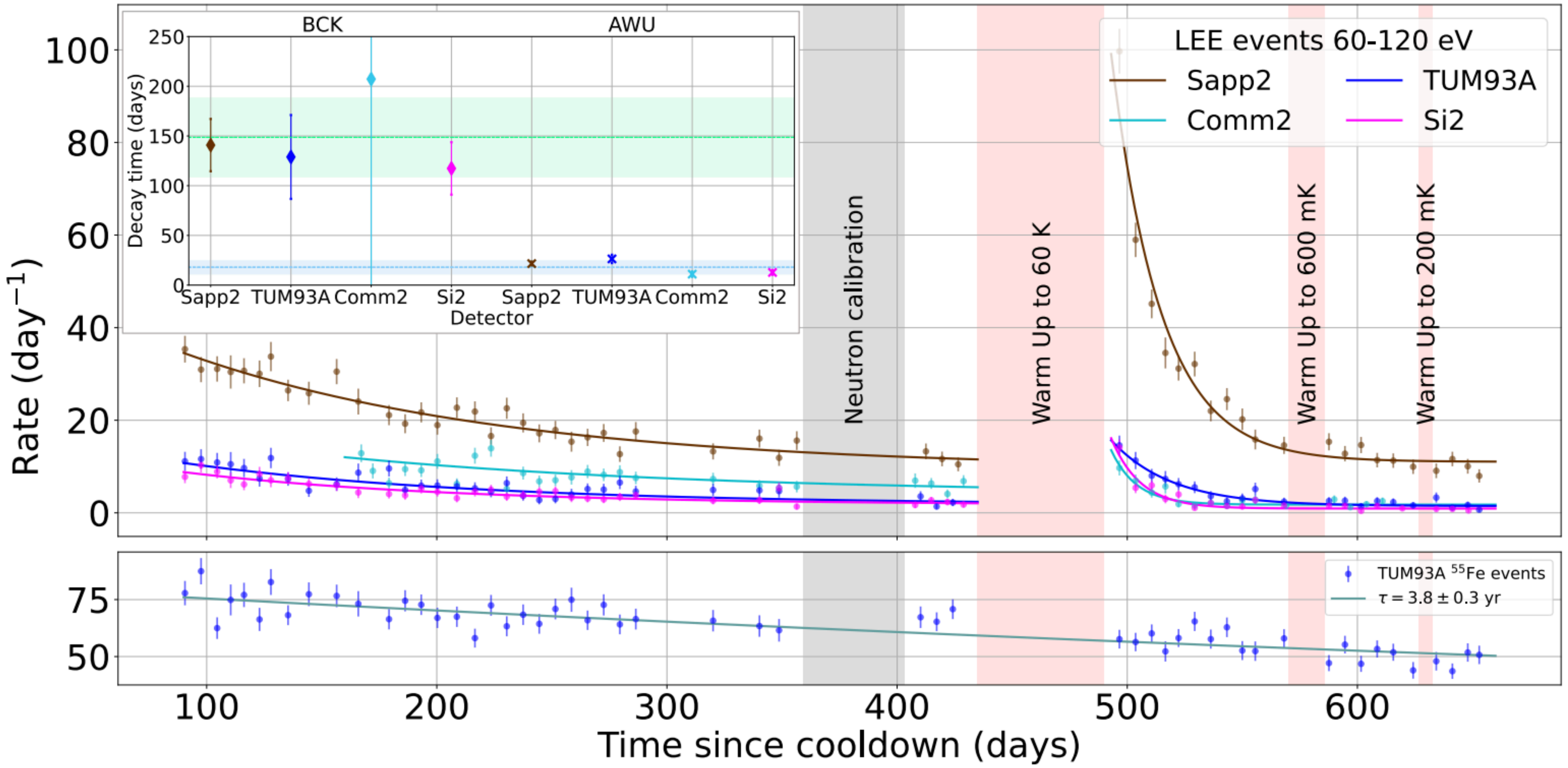


- CRESST observes vastly different excess rates in detector modules, with no obvious dependence on material and target size.
- The event rate decays after the cooldown of the experiment

Some of the key findings

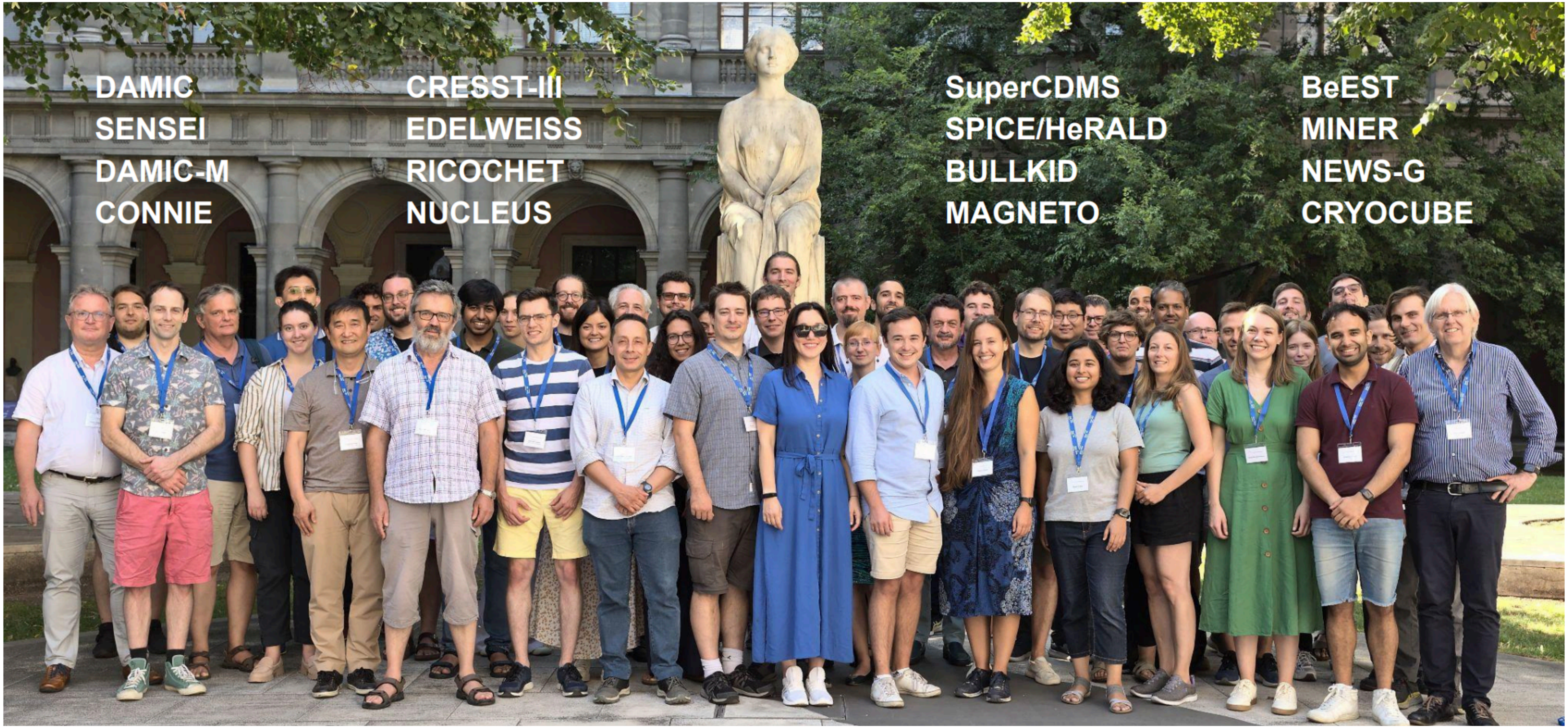
CRESST, SciPost Phys. Proc. 12, 013 (2023)





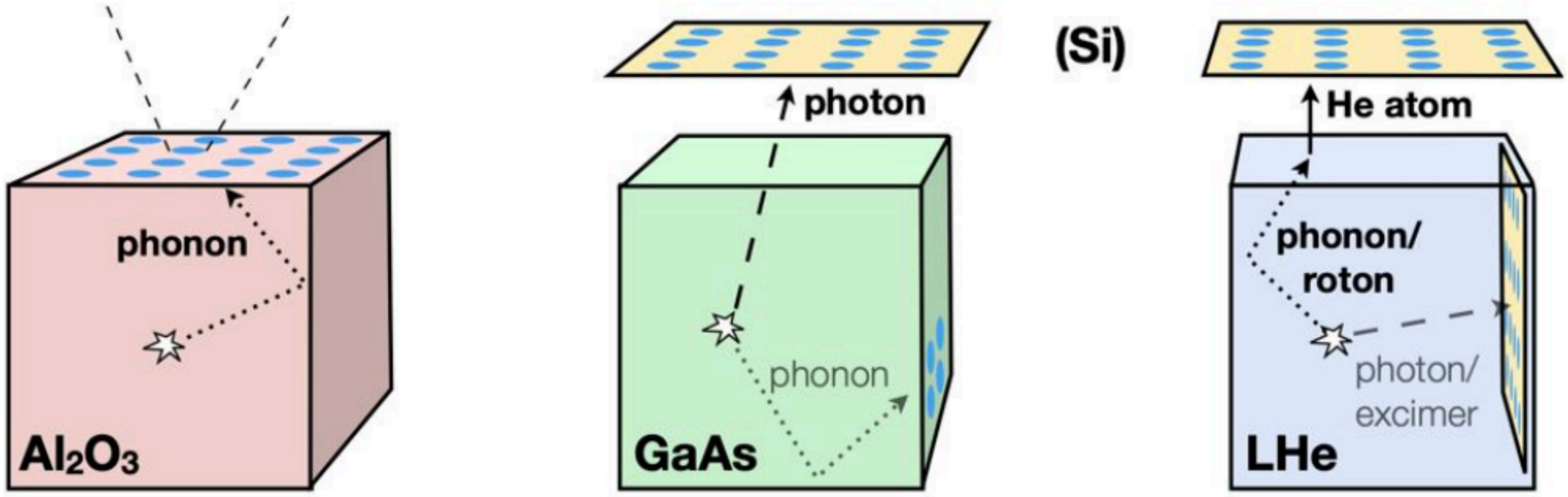
- CRESST observes vastly different excess rates in detector modules, with no obvious dependence on material and target size.
- The event rate decays after the cooldown of the experiment
- Thermal expansion coefficient mismatch is being investigated as a critical contributor to the excess

It's a low-threshold community effort!



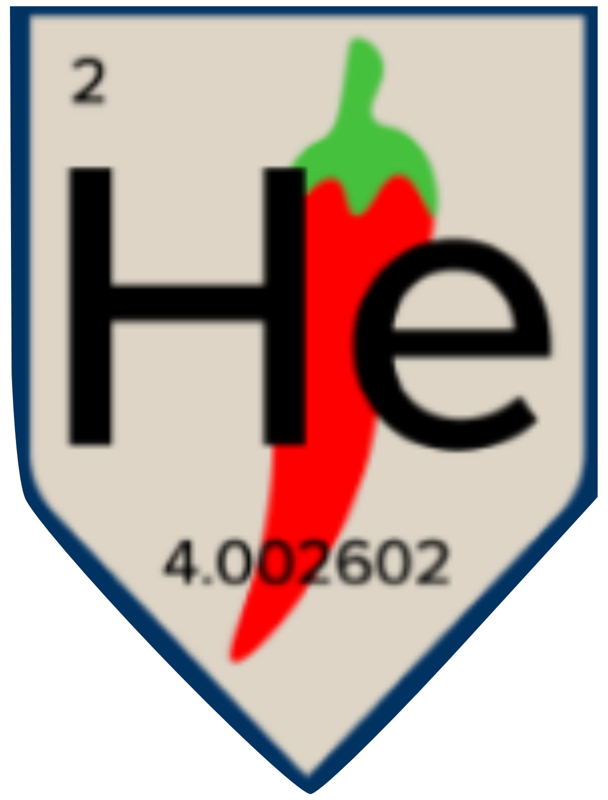
What's next?

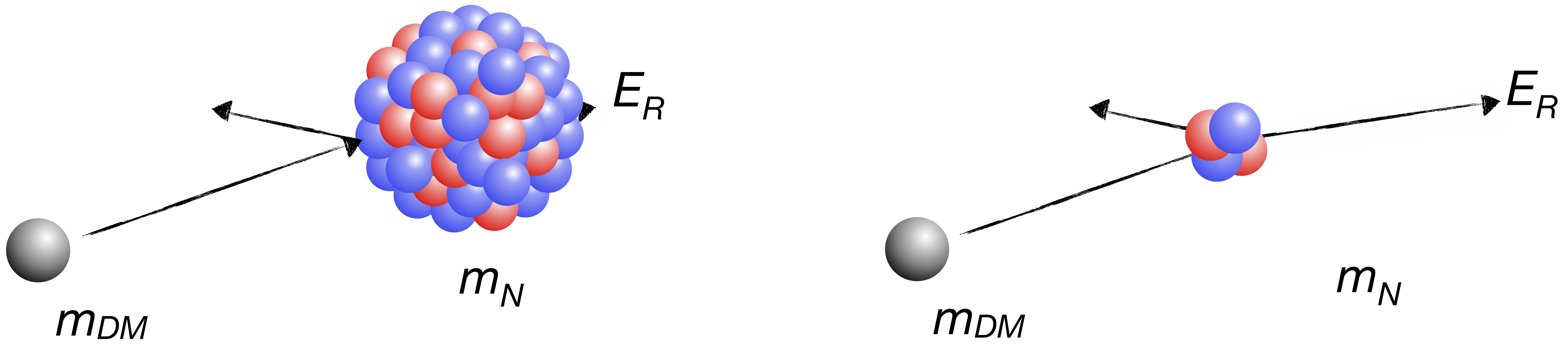
TESSERACT: The SPICE / HeRALD collaboration



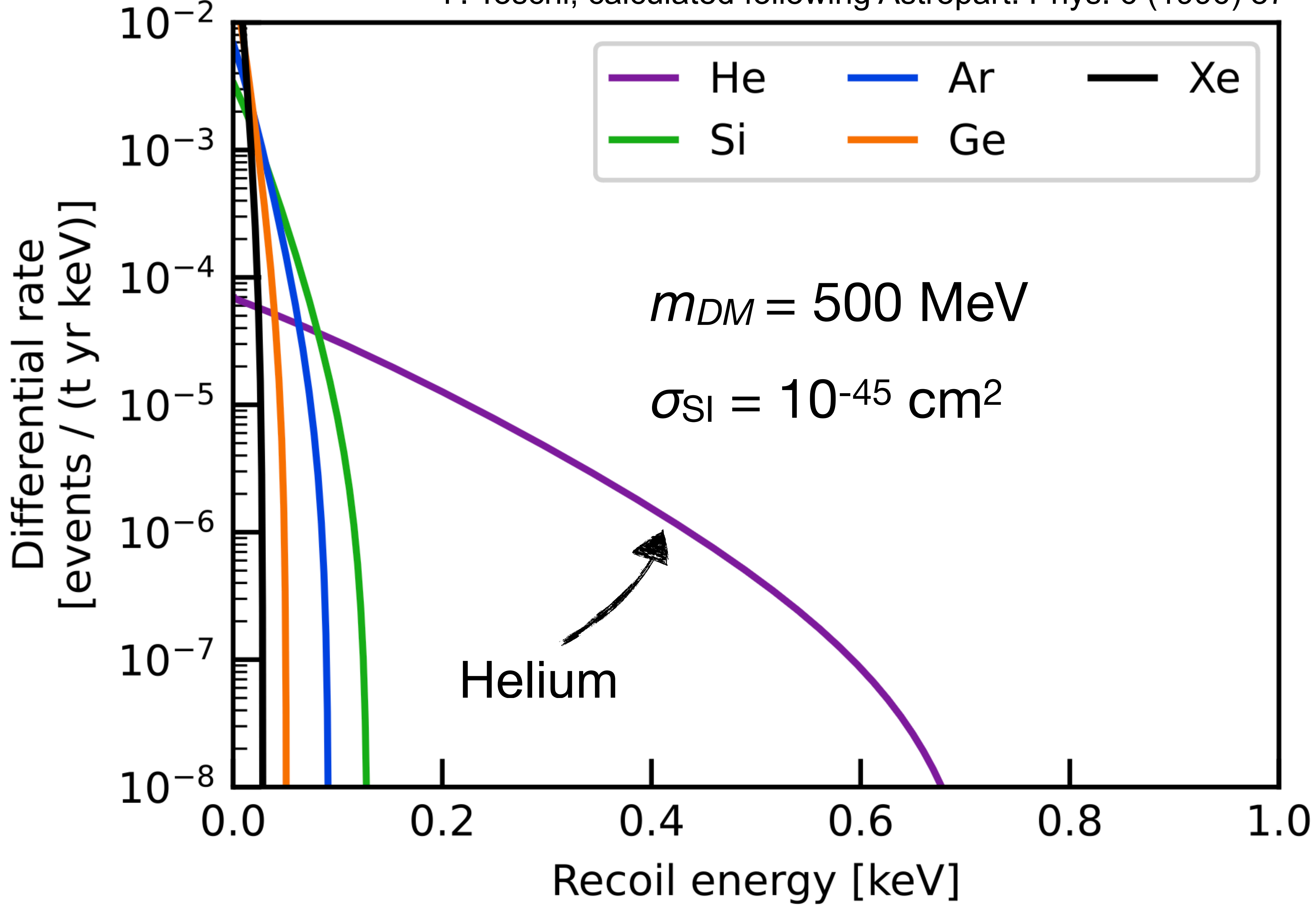
- Different targets with complementary DM sensitivity
- All using TES readout
- Includes SPICE (polar crystals) and HeRALD (superfluid He)

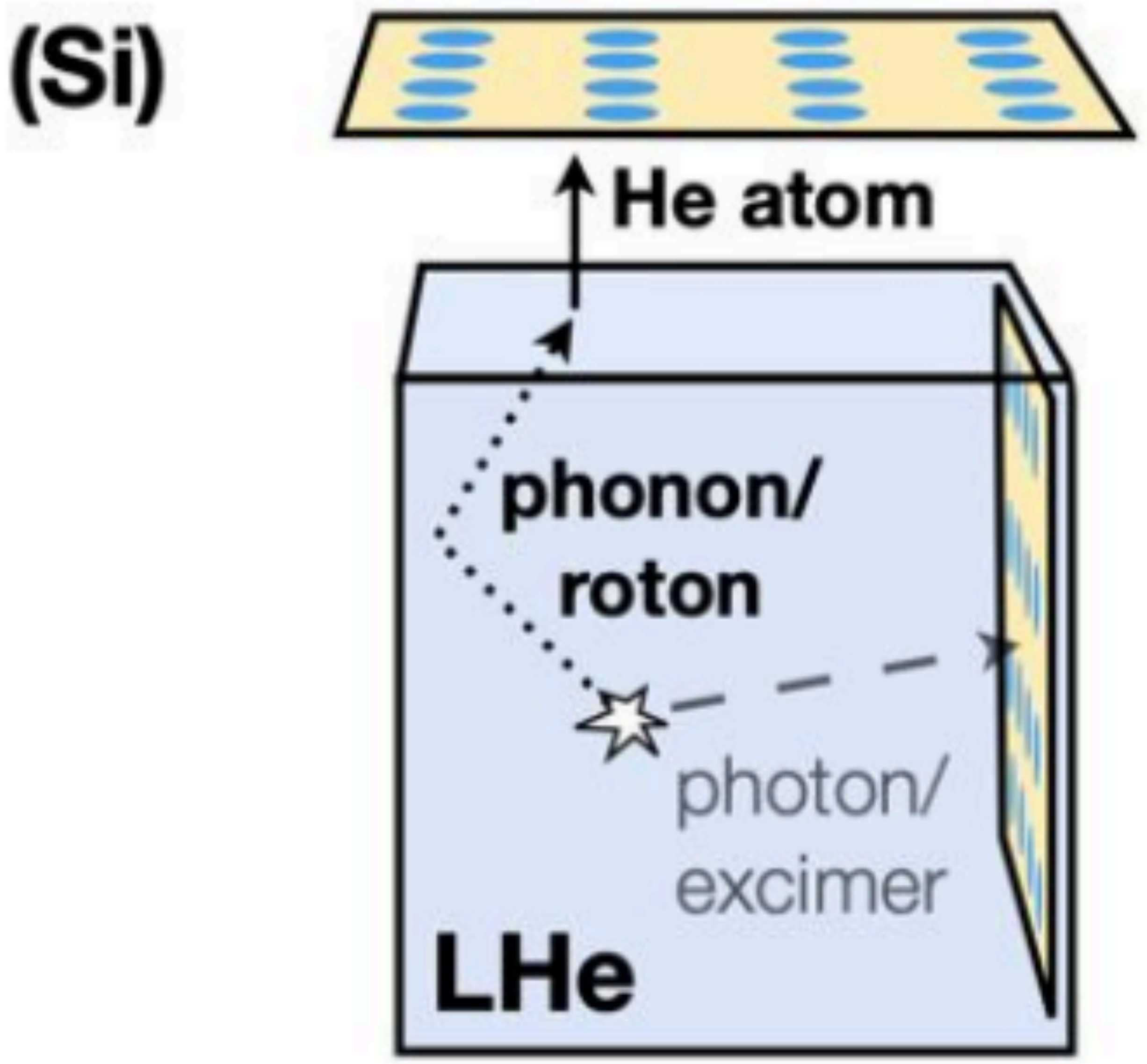
TESSERACT: The SPICE / HeRALD collaboration



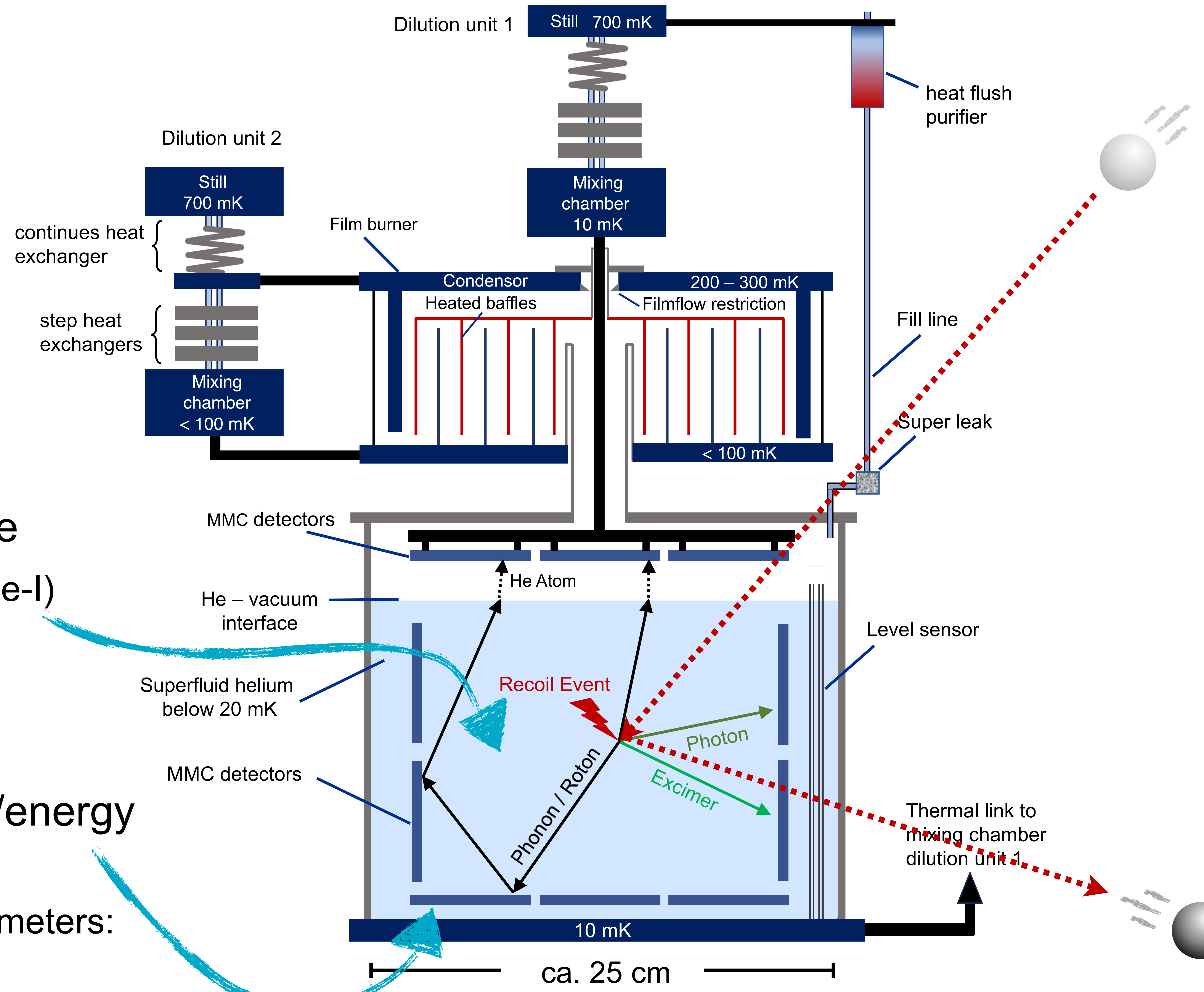


F. Toschi, calculated following Astropart. Phys. 6 (1996) 87





DELight



Superfluid ^4He

(~ 10 liters in phase-I)

Ultra-sensitive heat/energy sensors

(Magnetic MicroCalorimeters: MMCs)

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

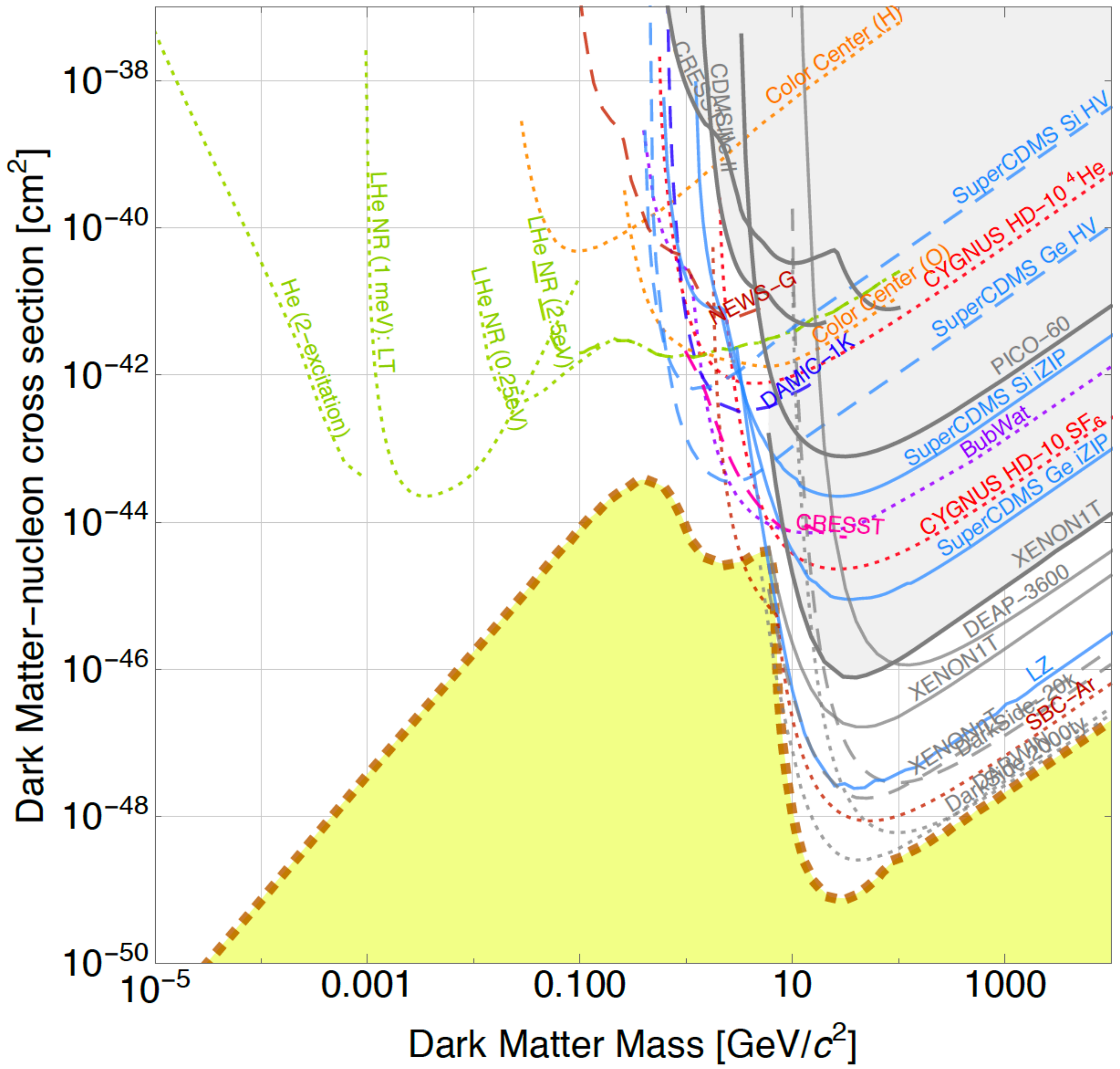
Karlsruhe Institute of Technology

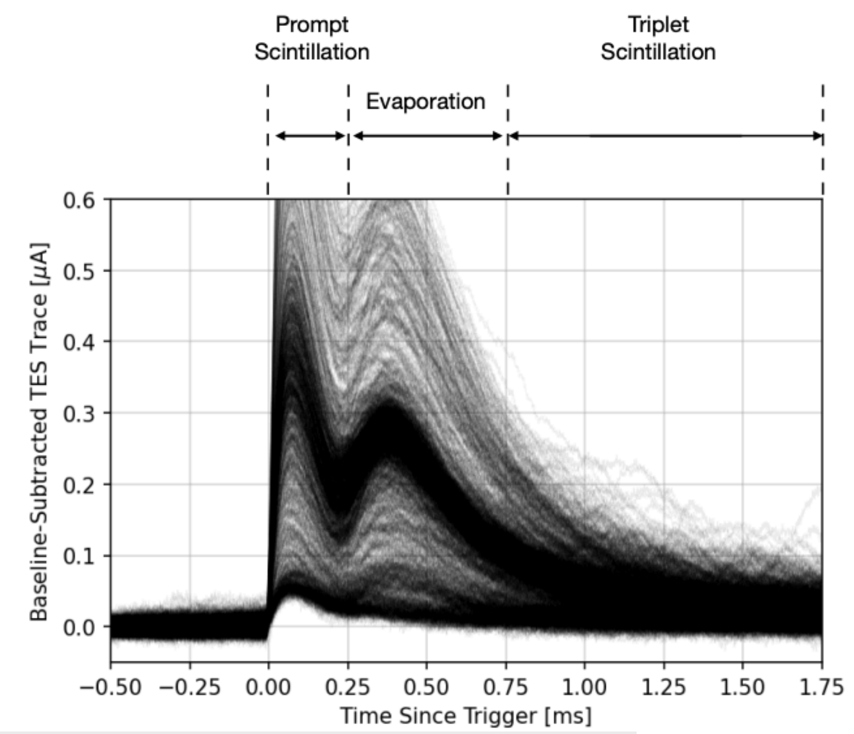
universität freiburg

Credit: Freepik Company

Lighter nuclei for lighter dark matter masses

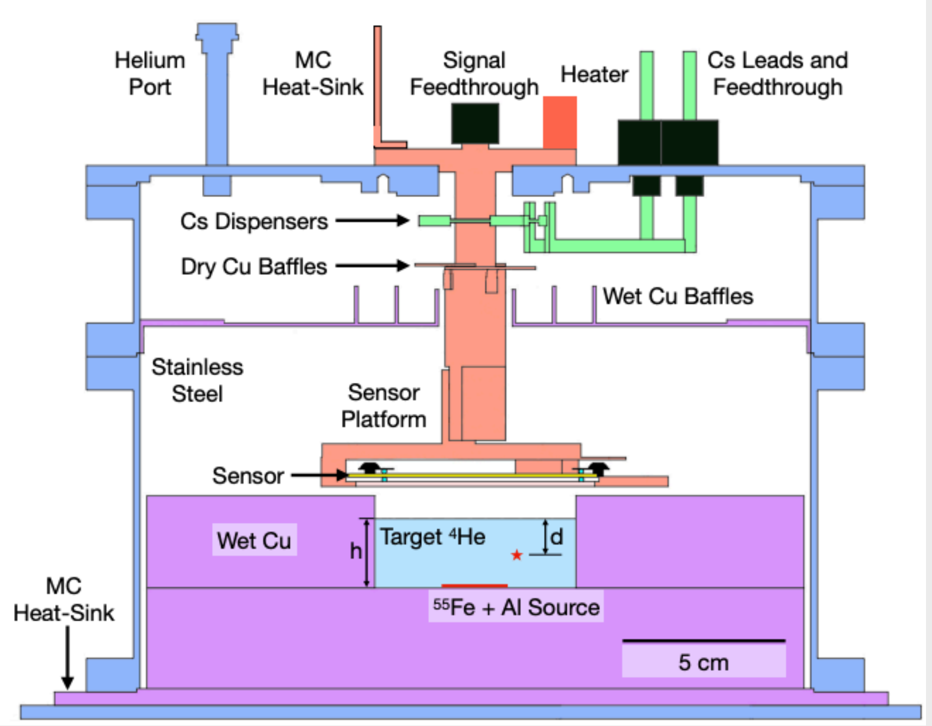
Community Report, arXiv:1707.04591 (2017)



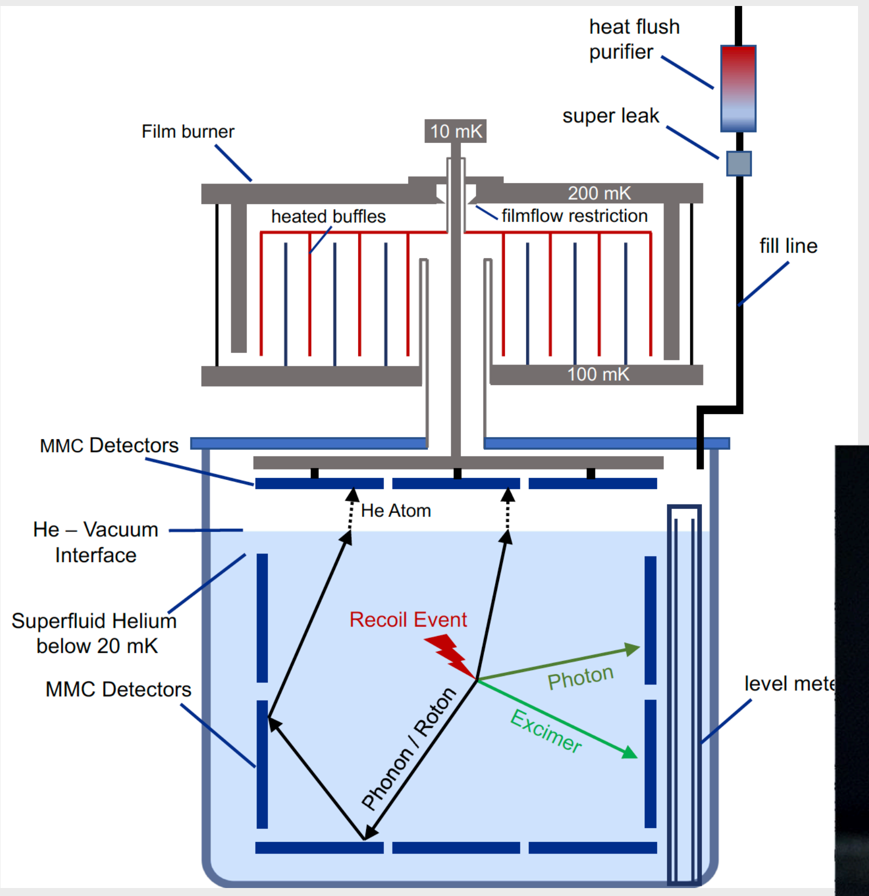


SPICE/HeRALD, arXiv:2307.11877 (2023)

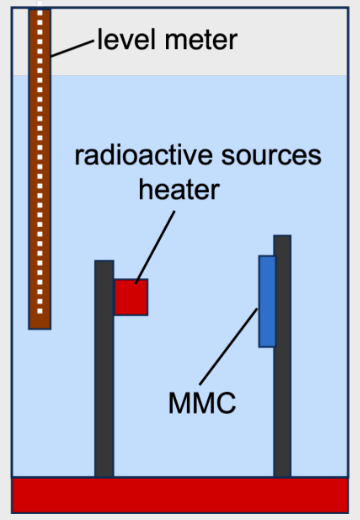
data of prototype detector with ~10g ^{4}He

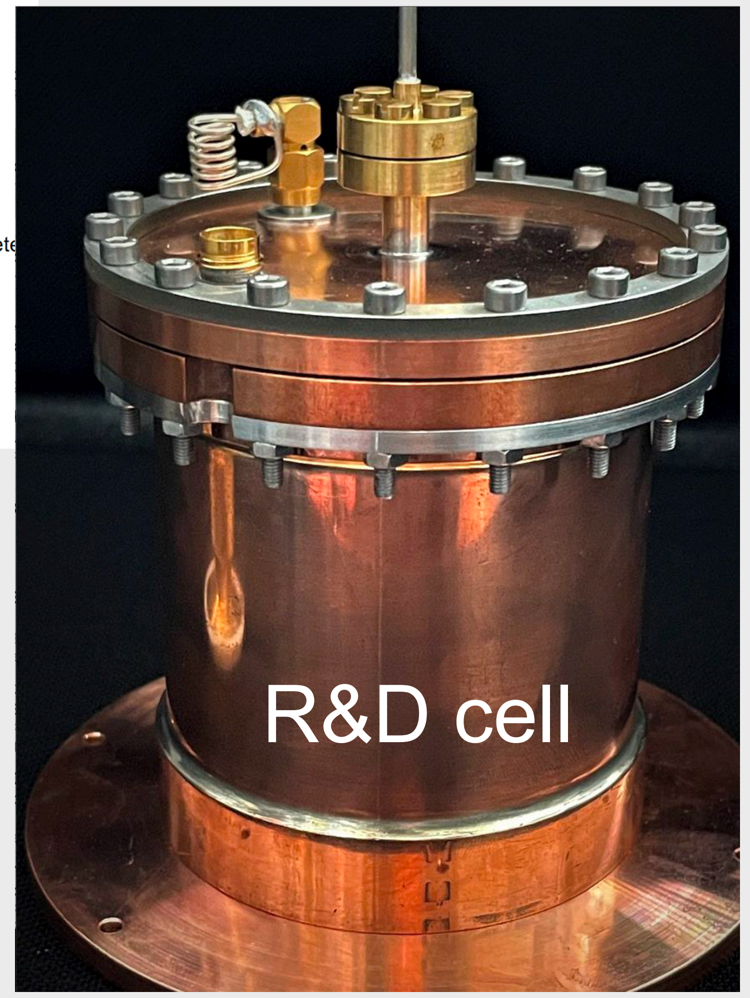


DELight, SciPost Phys. Proc. 12, 016 (2023)

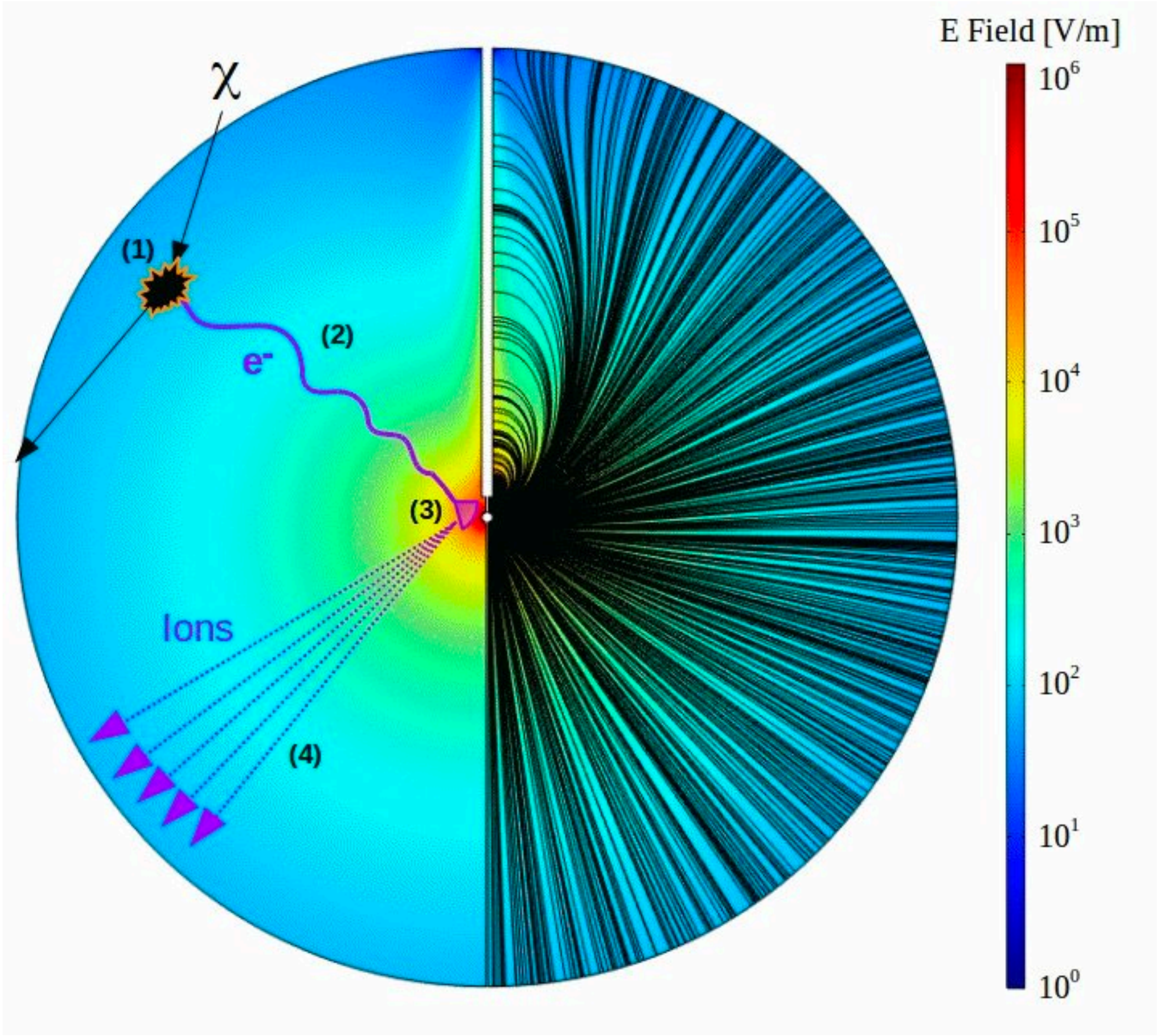


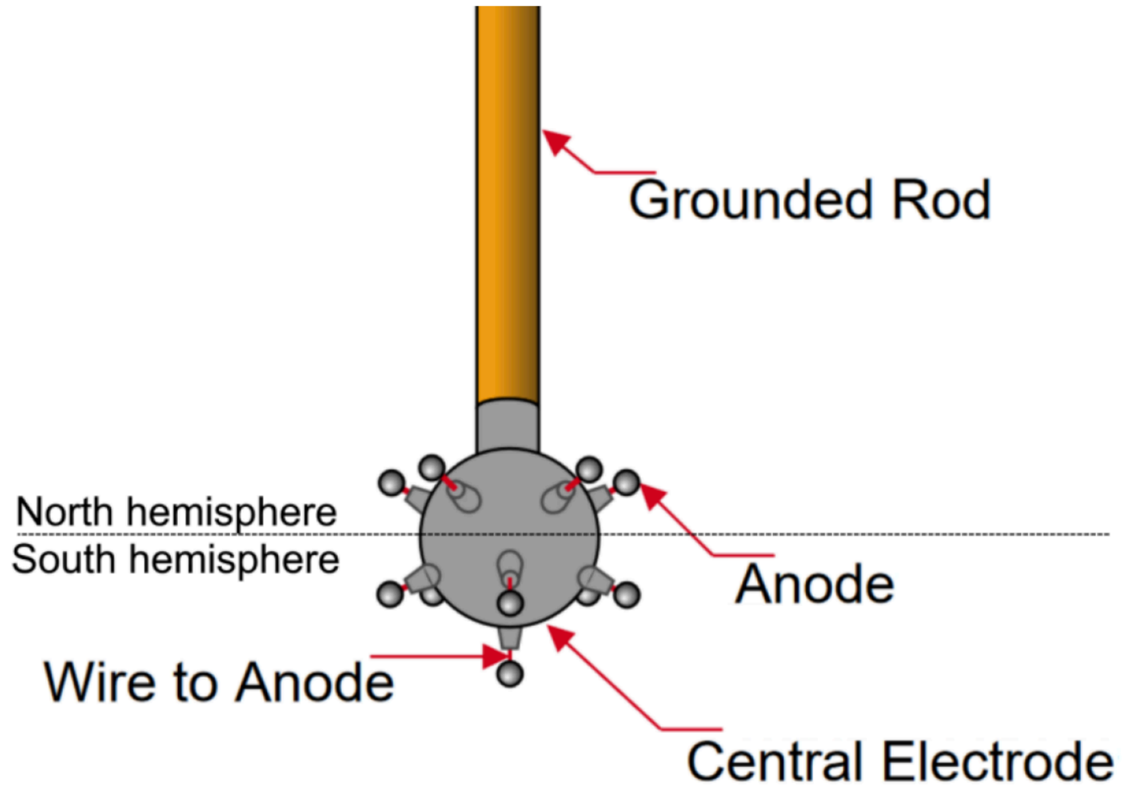
phase-I size: ~1.2kg ^{4}He





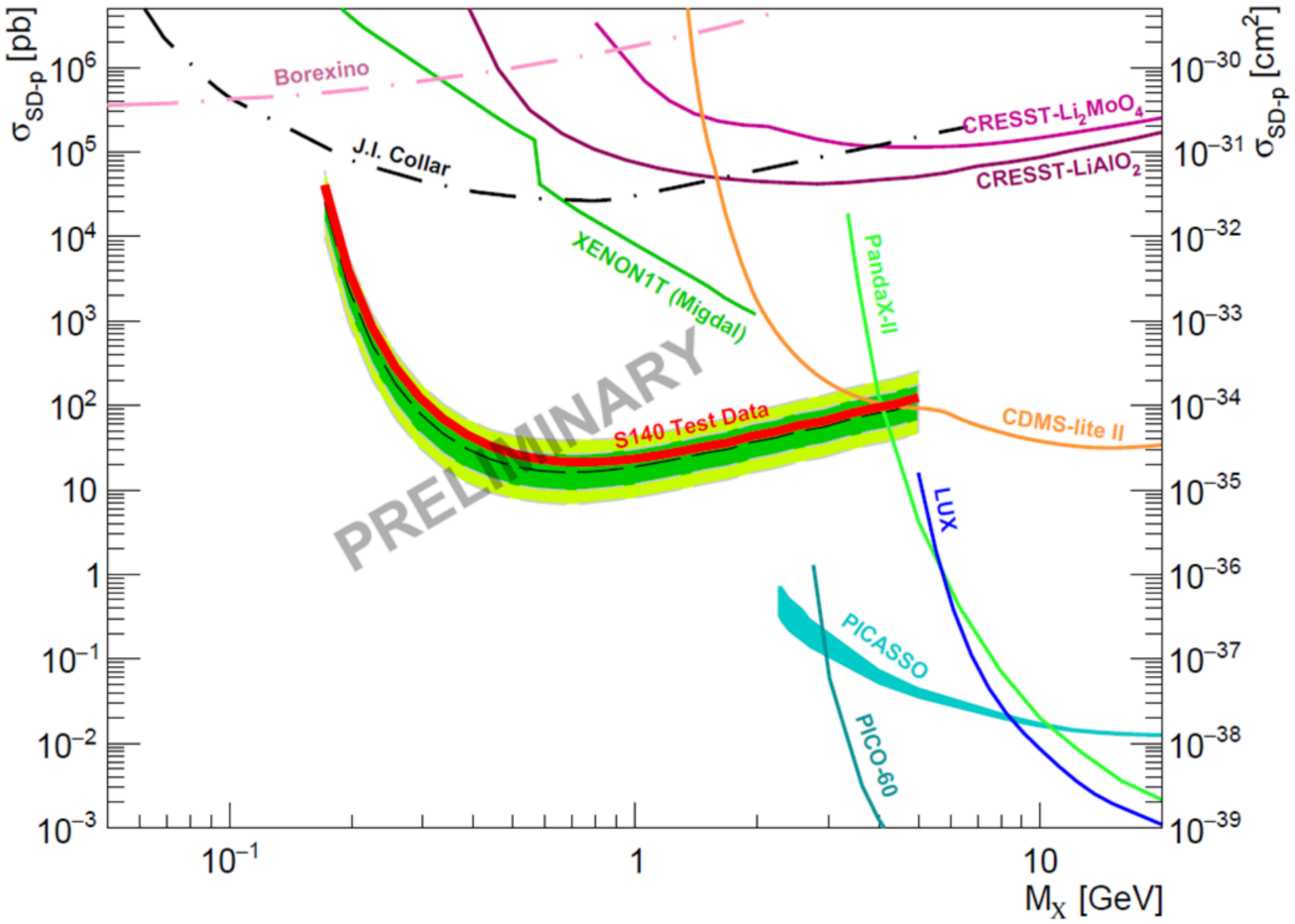
NEWS-G





First preliminary results from SD DM-proton scattering searches in methane (CH_4) !

NEWS-G, PoS TAUP2023 (2024) 042



- Lowest surface-area to volume ratio
- Light gas components for light DM sensitivity
- Variable target

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

And many more…

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. ($\sim 100\,\mu$K)	1 cm^3 ^{3}He	paper	[380]
DELight		202x	phon.+roton (~ 20 mK)	10 l ^{4}He	web	[381]
HeRALD		202x	phon.+roton (~ 50 mK)	~ 1 kg ^{4}He	web	[382]
SuperCDMS SNOLAB	SNOLAB, Canada	2023	ath. phon.[+ioniz.] (15 mK)	11[+14] kg Ge	web	[383]
			ath. phon.[+ioniz.] (15 mK)	2.4[+1.2] kg Si		
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	2024	scint. (~ 300 K)	50 kg NaI(Tl)	web	[336]
	SUPL, Australia	2023	scint. (~ 300 K)	50 kg NaI(Tl)	web	
PICOLON	Kamioka, Japan	202x	scint. (~ 300 K)	54 $\to$ 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 $\to$ 25 l 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]

M. Cirelli, A. Strumia, J. Zupan, arXiv:2406.01705

… to bring light into the darkness, one after the other.