

SEARCH FOR DARK MATTER WITH A 0.2 NG TES DETECTOR



C. Schwemmbauer¹, G. D. Hadas², Y. Hochberg^{2,3}, K.-S. Isleif⁴, F. Januschek¹, B. V. Lehmann⁵, A. Lindner¹, A. E. Lita⁶, M. Meyer⁷, G. Othman⁴, Elmeri O. Rivasto¹, J. A. Rubiera Gimeno⁴

¹ Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany

² Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem 91904, Israel

³ Laboratory for Elementary Particle Physics, Cornell University, Ithaca, New York 14853, USA

⁴ Helmut-Schmidt-Universität, Holstenhofweg 85, 22043 Hamburg, Germany

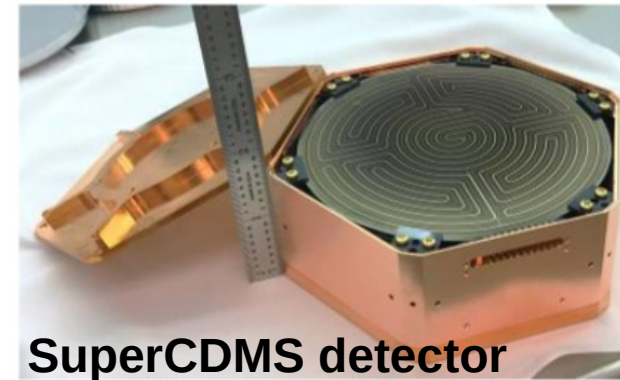
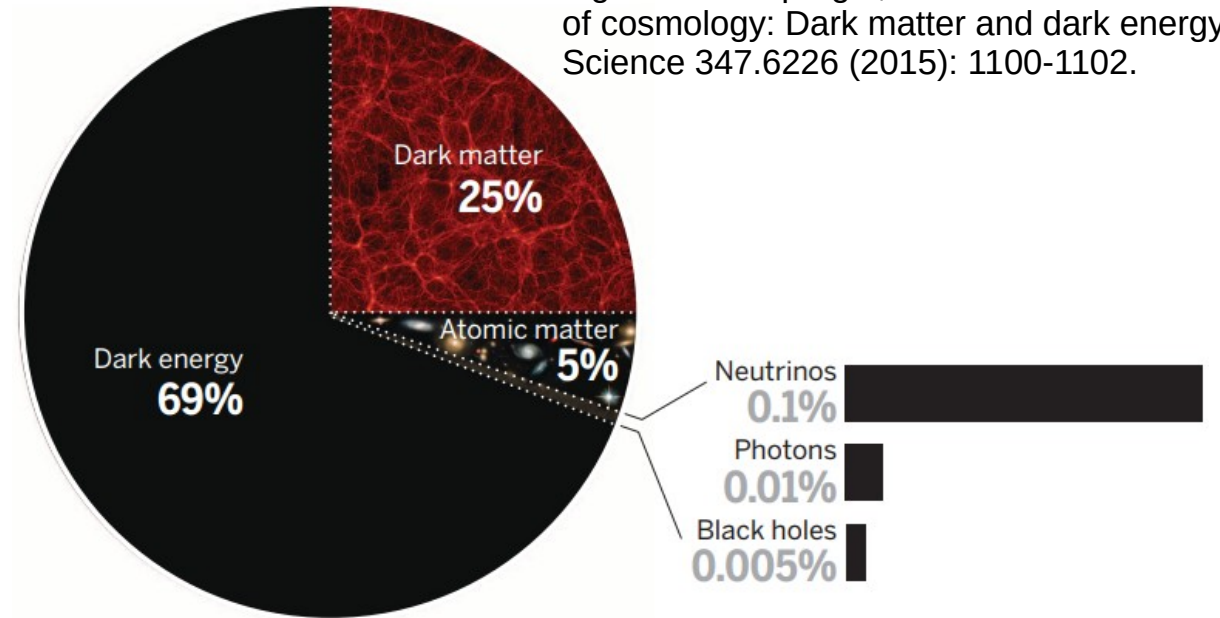
⁵ Center for Theoretical Physics—a Leinweber Institute, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

Phys. Rev. D **114,
012006 (2026)**

DOI: <https://doi.org/10.1103/zytz-n25v>

Motivation

- What is dark matter (DM)?
- WIMP searches:
 - DM-nucleon scattering
 - Large targets coupled to single-photon detectors
 - Typically aiming above keV energy depositions
- Example: SuperCDMS [1]
 - **Target:** Ge and Si crystals (10 cm diameter, 3.3 cm thick)
 - **Sensor:** SC Transition Edge Sensor (TES)
 - **Energy threshold:** ~ 10 eV



SuperCDMS detector

Figure from:
<https://supercdms.slac.stanford.edu/overview/experiment-overview>

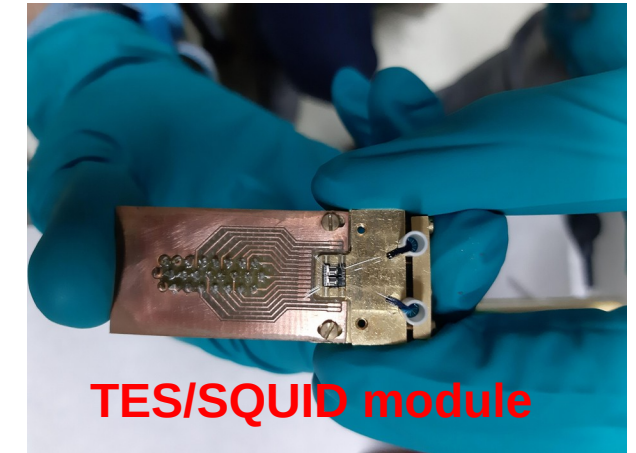
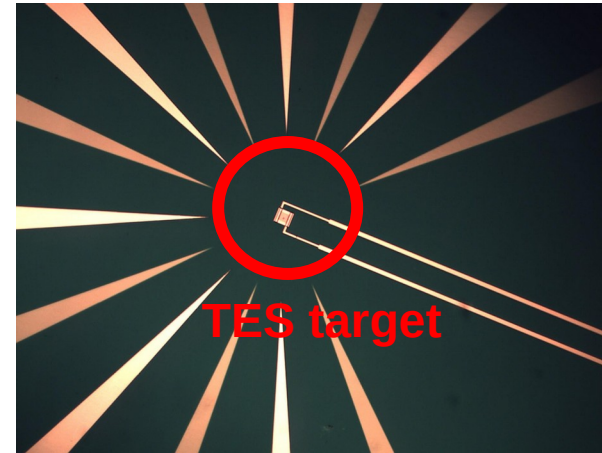
[1] Noah Kurinsky, Paul Brink, Richard Partridge, Blas Cabrera, and Matt Pyle. "SuperCDMS SNOLAB Low-Mass Detectors: Ultra-Sensitive Phonon Calorimeters for a Sub-GeV Dark Matter Search" (2016), <https://doi.org/10.48550/arXiv.1611.04083>

Motivation

- This work:
 - **Use TES as both target and sensor**
(proof-of-principle)
 - Sensitivity to sub-eV energy depositions
→ DM-electron scattering
(sub-MeV DM masses)
 - Energy resolving detection
 - Advantage: Ultra-low noise, high quantum efficiency
 - Disadvantage: Small target mass
- Previous proof-of-concept for *Superconducting Nanowire Single-Photon Detectors* (SNSPD)

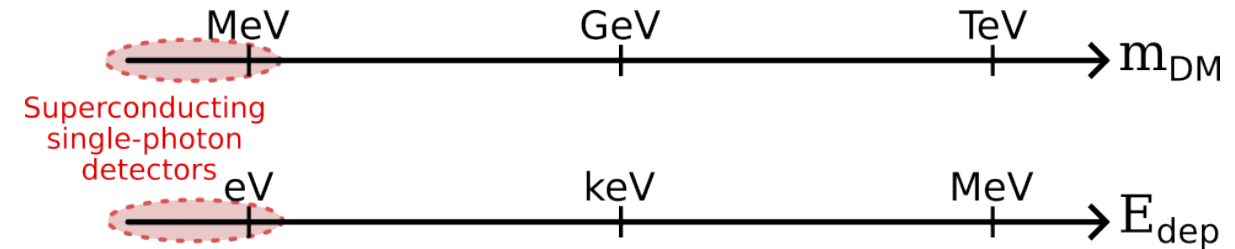
Y. Hochberg, Phys. Rev. D 106, 112005

<https://doi.org/10.1103/PhysRevD.106.112005>



“Rule of thumb”

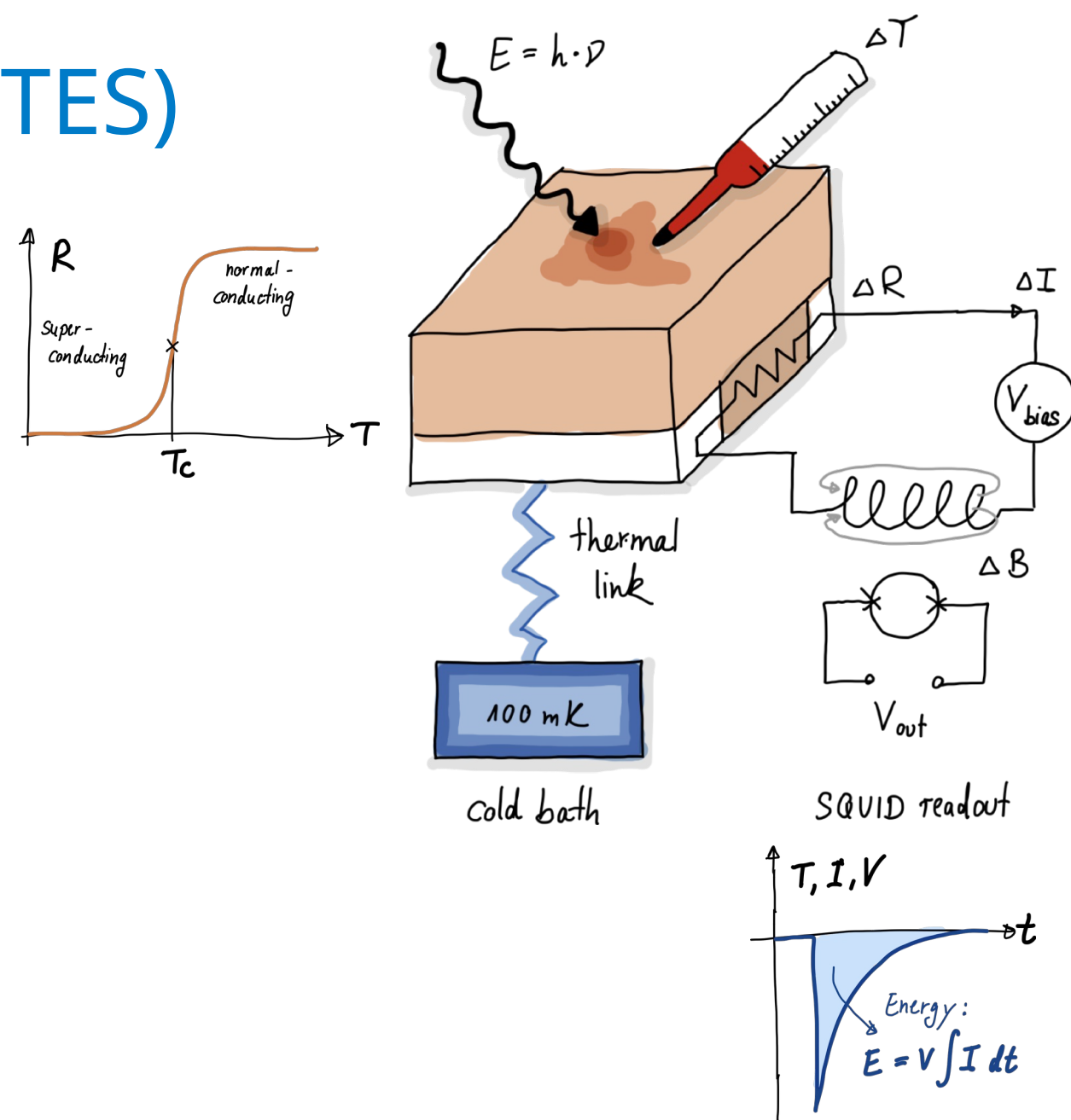
$$E_{\text{dep}} \sim 10^{-6} m_{\text{DM}}$$



Transition Edge Sensor (TES)

- Superconducting microcalorimeter
 - Absorbed heat changes resistance
- Measure change in current via inductively coupled SQUID
- Energy sensitive detection

Pulse integral $\propto$ Absorbed energy



Transition Edge Sensor (TES)

- Assume that DM interaction results in photon-like pulse
- Easily distinguishable from intrinsic backgrounds (e.g. radioactive decays) from pulse shape
- Effective background mitigation (more on this later)

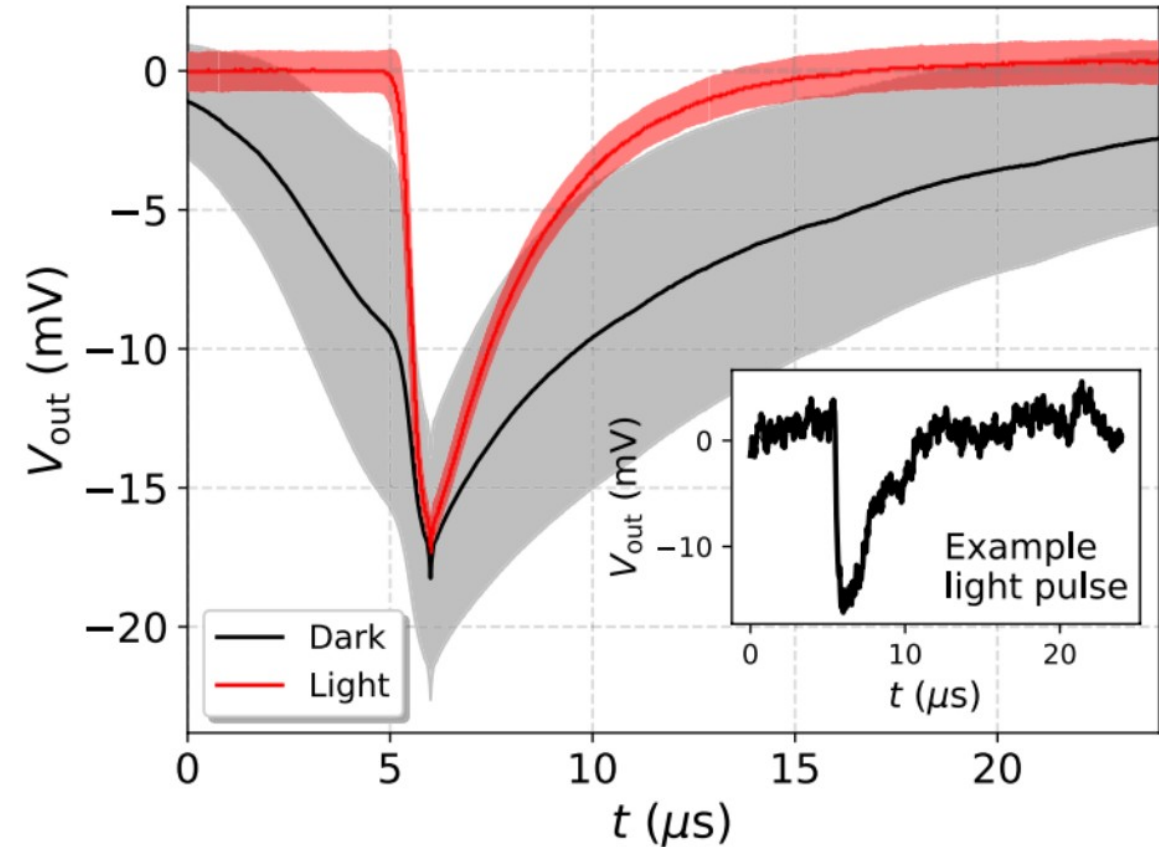
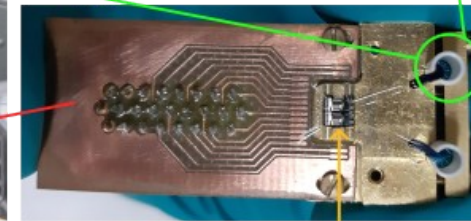
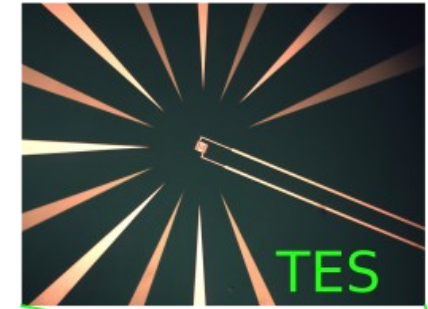


Figure from: E. Rivasto et al. "Binary classification of signal and background triggers of a transition edge sensor using convolutional neural networks." Scientific Reports 16.1 (2026): 3389

Transition Edge Sensor (TES)

- Tungsten thin film
 - **Area:** $25 \times 25 \text{ } \mu\text{m}^2$
 - **Thickness:** 20 nm
 - **Mass:** 0.2 ng
- **Energy resolution:** 8% @1.17 eV [1]
- **System detection efficiency:** 86% @1.17 eV [2]
- **Detection threshold:** 0.3 eV
- Operated in dilution refrigerator at 20 mK



SQUIDS

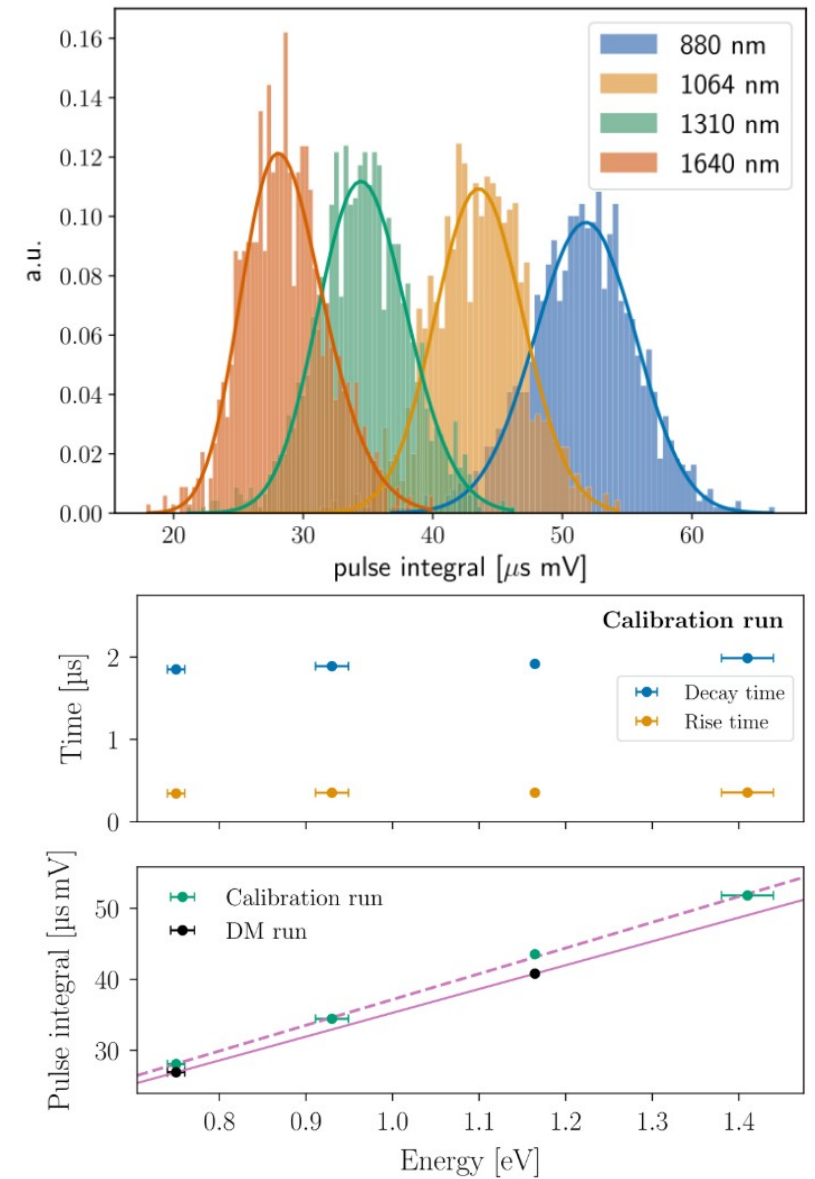
[1] Gimeno, José Alejandro Rubiera, et al. "A TES system for ALPS II-status and prospects." Proceedings of Science 449 (2024): 567. DOI: <https://doi.org/10.22323/1.449.0567>

[2] Meyer, Manuel, et al. "Characterization of a Two-Channel Optical and Near-infrared Transition Edge Sensor System for Rare-Event Searches." arXiv preprint: arXiv:2605.07423 (2026). DOI: <https://doi.org/10.48550/arXiv.2605.07423>

TES characterization

Energy calibration

- Calibrated using 4 laser sources (880-1640 nm)
 - Linear relationship
- Pulse shape independent of deposited energy
 - Mitigation of non-photon-like backgrounds



Figures from: Schwemmbauer, Christina, et al. "First direct search for light dark matter interactions in a transition-edge sensor." Physical Review D 114.1 (2026): 012006.

TES characterization

Mitigation of non-photonic backgrounds

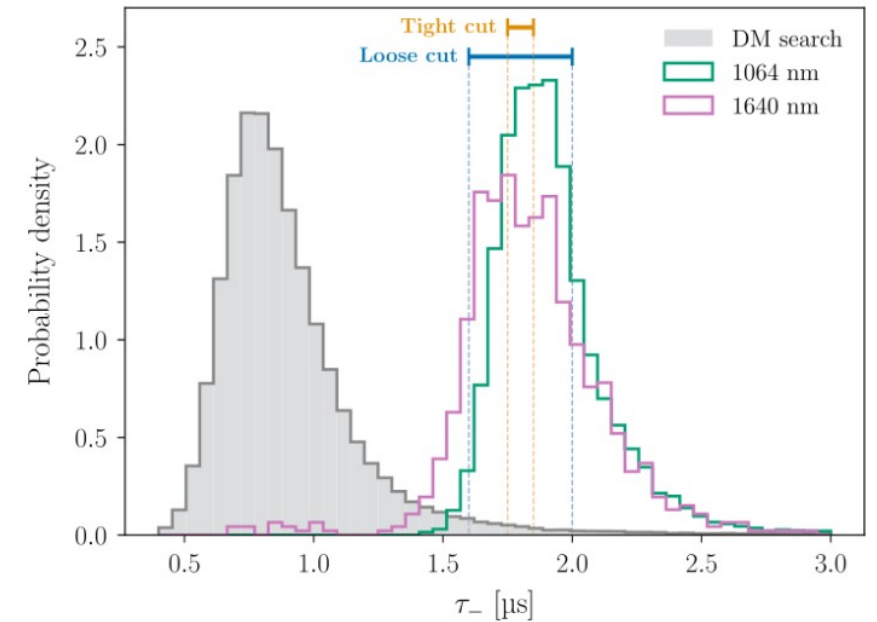
- Use pulse finding algorithm [1] to pick photon-like pulses for further analyses

- Filter signal
 - Deconvolution+low-pass filter
 - Fit in frequency domain

Small signal theory:

$$V(t) = V_0 + \begin{cases} A \cdot (e^{-(t-t_0)/\tau_+} - e^{-(t-t_0)/\tau_-}), & \text{if } t \geq t_0. \\ 0, & \text{else} \end{cases}$$

- Impose cuts



Parameter		Loose	Tight
Cuts	$\tau_+ (\mu\text{s})$	(0.3, 0.4)	(0.325, 0.375)
	$\tau_- (\mu\text{s})$	(1.6, 2.0)	(1.75, 1.85)
	χ^2_{red}	(0.9, 1.1)	(0.95, 1.05)
	$t_0 (\mu\text{s})$	(-0.5, 0.5)	(-0.5, 0.5)
	$\mathcal{R}_{\text{dev}}$	(0.73, 1.10)	(0.73, 1.10)
Results	Event rate (Hz)	7.2×10^{-5}	7.4×10^{-6}
	Survival (%)	0.107	0.011

[1] J. A. Rubiera Gimeno, Optimizing a transition edge sensor detector system for low flux infrared photon measurements at the ALPS II experiment, Ph.D. thesis, Hamburg U., Hamburg, 2024, <https://bib-pubdb1.desy.de/record/619057>

TES characterization

Acceptance as a function of energy

- Predicted DM interaction events at given energy (subscript i) must be multiplied by detector acceptance

$$N_i^{\text{signal}}(m_{\text{DM}}, m_\phi, \sigma) \equiv \mathcal{A}_i \cdot N_i^{\text{DM}}$$

- Three components:

$$\mathcal{A}_i = \alpha_i^{\text{trig}} \times \alpha_i^{\text{pulse}} \times \alpha_i^{\text{cut}}$$

- Determine each component separately using simulated pulses
- TESPASS framework [1]:
 - Simulate experimentally measured noise
 - Simulate photonic pulses of arbitrary energy using small signal theory

[1] J. A. Rubiera Gimeno, Optimizing a transition edge sensor detector system for low flux infrared photon measurements at the ALPS II experiment, Ph.D. thesis, Hamburg U., Hamburg, 2024, <https://bib-pubdb1.desy.de/record/619057>

TES characterization

Acceptance as a function of energy

- DM interaction rate model:
 - Standard DM Halo [1]
 - Spin-independent DM-e scattering [2](also DM-nucleon scattering and electronic absorption)

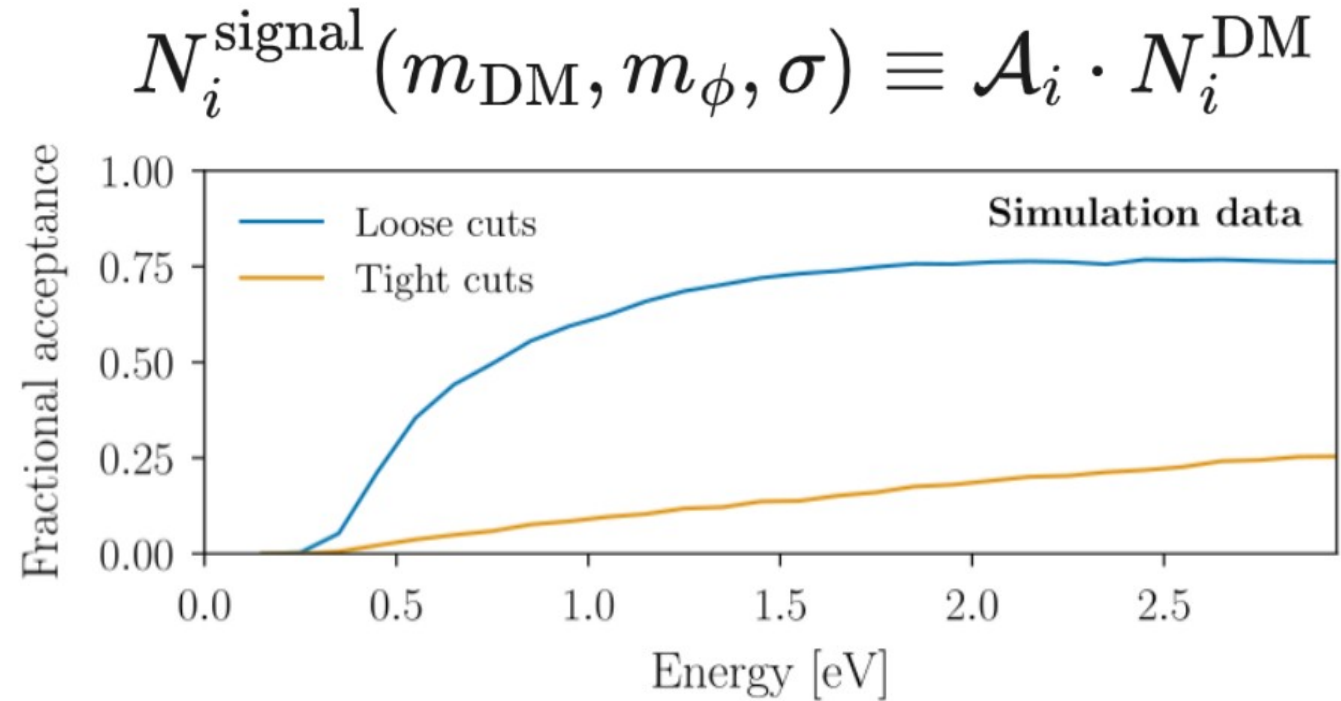


Figure from: C. Schwemmbauer et al, Phys. Rev. D 114, 012006 (2026)

[1] J. D. Lewin et al., Review of mathematics, numerical factors, and corrections for dark matter experiments based on elastic nuclear recoil, *Astropart. Phys.* 6, 87 (1996).
[https://doi.org/10.1016/S0927-6505\(96\)00047-3](https://doi.org/10.1016/S0927-6505(96)00047-3)

[2] Y. Hochberg et al., Determining dark-matter–electron scattering rates from the dielectric function, *Phys. Rev. Lett.* 127, 151802 (2021).
<https://doi.org/10.1103/PhysRevLett.127.151802>

Experimental results

Event spectrum

- Total of 489 hours of data (measured in April/May 2024)
 - **Loose cuts:** 126 events
 - **Tight cuts:** 13 events

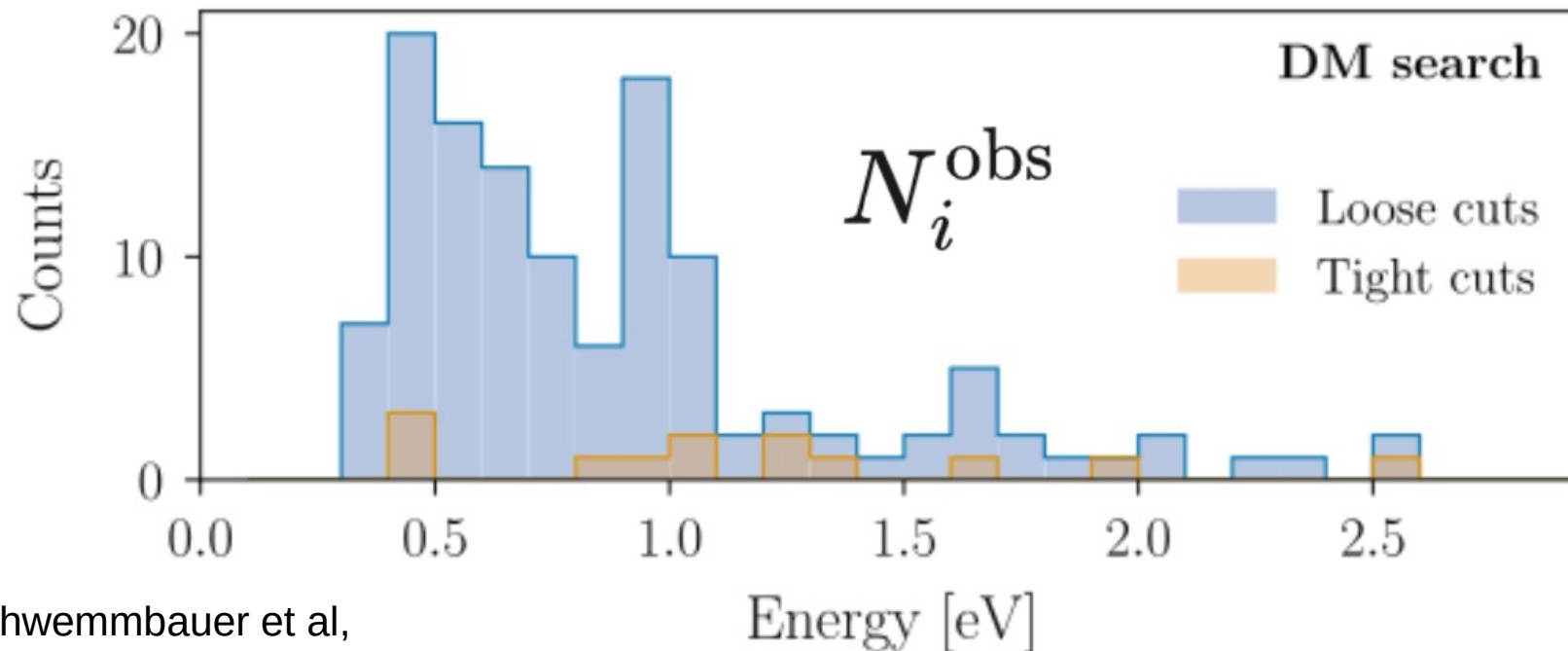


Figure from: C. Schwemmbauer et al,
Phys. Rev. D 114, 012006 (2026)

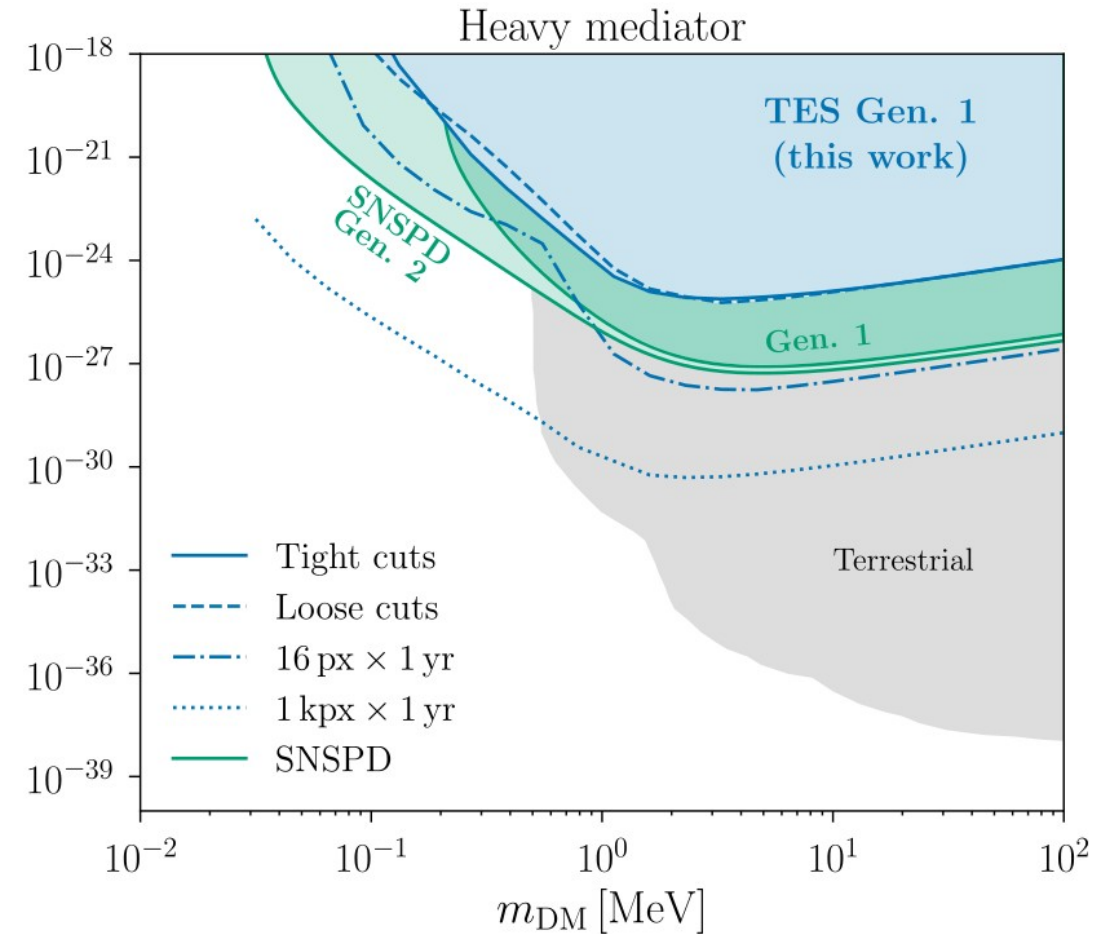
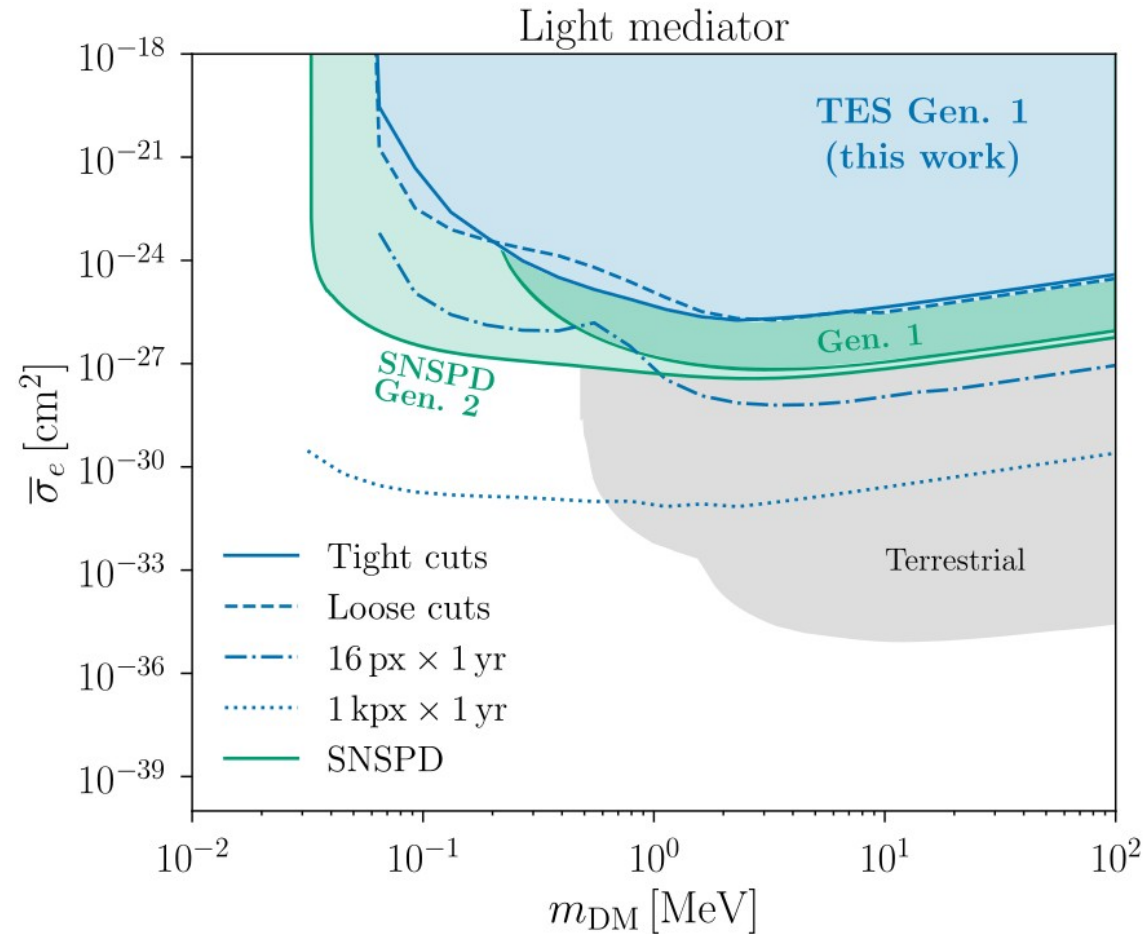
Setting the constraints

- Conservative limit
 - No assumptions about the observed counts
 - We cannot establish DM discovery, but only set limits
- Procedure:
 - Fix DM mass (m_{DM})
 - Fix mediator mass (m_ϕ , *only light and heavy limits*)
 - Find maximum cross-section (σ) compatible with N_i^{obs}

New constraints

DM-electron scattering

Figures from: C. Schwemmbauer et al, Phys. Rev. D 114, 012006 (2026)



Summary and outlook

- **First successful direct search for DM using TES both as target and sensor!**
 - DM-electron scattering
 - Sensitivity to sub-MeV DM masses
 - Energy resolving detection accounts for spectral information
- Future possibilities for expanding the constraints:
 - Decreasing energy threshold
 - Improving energy resolution
 - Increase target mass via multiplexing
 - Background mitigation

Summary and outlook

- **First successful direct search for DM using TES both as target and sensor!**
 - DM-electron scattering
 - Sensitivity to sub-MeV DM masses
 - Energy resolving detection accounts for spectral information
- Future possibilities for expanding the constraints:
 - Decreasing energy threshold
 - Improving energy
 - Increase target mass via multiplexing
 - Background mitigation

THANK YOU!

BACKUP SLIDES

Interaction model

$$\Gamma = \frac{\pi n_{\text{DM}} \hat{\sigma}_t}{\mu_{t,\text{DM}}^2} \int \frac{d^3 \mathbf{v}_{\text{DM}} d^3 \mathbf{q} d\omega}{(2\pi)^3} \cdot f_{\text{DM}}(\mathbf{v}_{\text{DM}}) \cdot \mathcal{F}(q)^2 \cdot S(\mathbf{q}, \omega) \cdot \delta(\omega - \omega_{\mathbf{q}})$$

Assumes the Standard Dark Matter Halo model [1]

	halo model parameters
DM density	0.4 GeV/cm ³
DM velocity dispersion	220 km/s
local galactic escape velocity	550 km/s
Earth velocity	232 km/s

Dielectric permittivity calculated based on Lindhard model: Martin Dressel and George Grüner. Electrodynamics of solids: optical properties of electrons in matter. Cambridge university press, 2002 (cit. on p. 20).

Form factor

$$\mathcal{F}(q) = \frac{m_\phi^2 + q_{0,t}^2}{m_\phi^2 + q^2}$$

Dynamic structure factors:

Spin-independent
DM-e scattering [2]:

$$S(\mathbf{q}, \omega) = \frac{2\mathbf{q}^2}{e^2} \text{Im} \left(-\frac{1}{\epsilon(\mathbf{q}, \omega)} \right)$$

DM-nucleon
scattering [3]:

$$S(\mathbf{q}, \omega) = \frac{2\pi\rho_T}{\Sigma_N A_N} \sum_N \frac{A_N^3}{m_N} F_N(\mathbf{q})^2 \delta \left(\omega - \frac{\mathbf{q}^2}{2m_N} \right)$$

For more details see:

Schwemmbauer, C., Exploring Potential: ALPS II's TES Detection System for Direct Dark Matter Searches, PhD thesis, 2025, link: <https://bib-pubdb1.desy.de/record/639249>

Interaction model (DM absorption)

- Kinetically mixed dark photon DM
- Rate given by [1]

$$\Gamma_A = \kappa^2 m_{\text{DM}} \text{Im} \left(-\frac{1}{\epsilon(m_{\text{DM}} \mathbf{v}_{\text{DM}}, m_{\text{DM}})} \right)$$

[1] Y. Hochberg, Phys. Rev. D 106, 112005, <https://doi.org/10.1103/PhysRevD.106.112005>

Setting the constraints

- Assume Poissonian backgrounds
- Calculate Poisson likelihoods:

$$l_{\text{DM}} \equiv \log \mathcal{L}_{\text{P}} \left[N_i^{\text{obs}} | N_i^{\text{bg}} + N_i^{\text{signal}}(\sigma) \right]$$

$$l_{\text{bg}} \equiv \log \mathcal{L}_{\text{P}} \left[N_i^{\text{obs}} | N_i^{\text{bg}} \right]$$

- Evaluate profile likelihood ratio test statistics:

$$\lambda \equiv 2 \left[\max_{\{\sigma, N_i^{\text{bg}}\}} l_{\text{DM}} - \max_{\{N_i^{\text{bg}}\}} l_{\text{bg}} \right]$$

- λ is χ^2 -distributed random variable
 - Exclude λ s above 95% quantile (95% Confidence level)

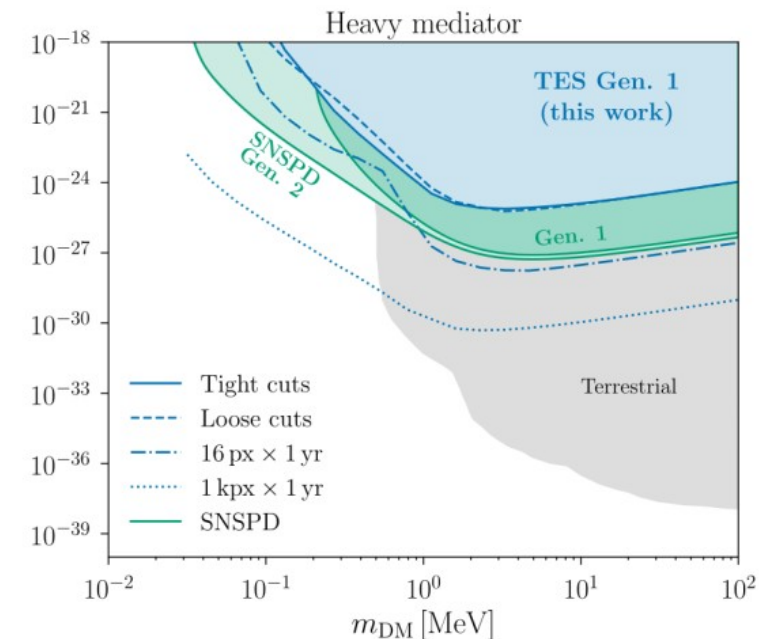
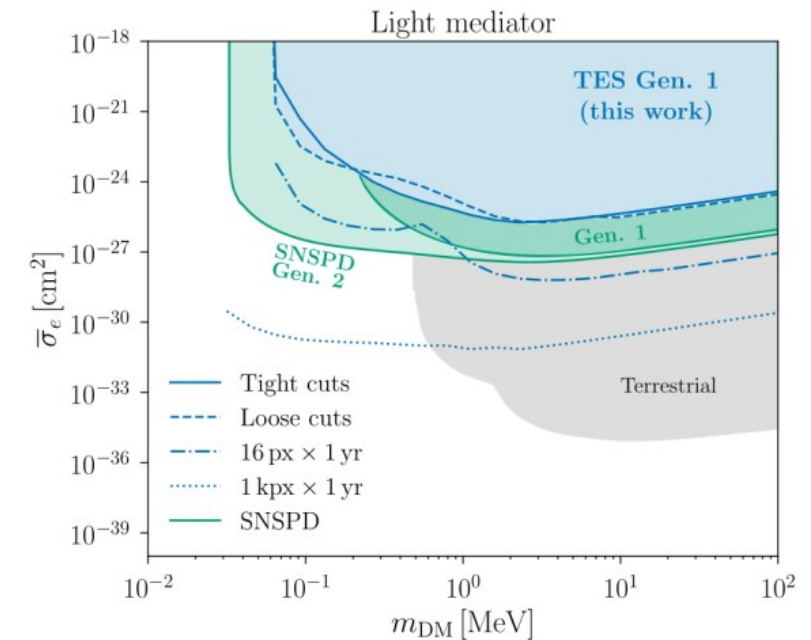
New constraints

DM-electron scattering

- Constraints obtained in this work
 - Tight cuts
 - Loose cuts
- Projections for future
 - **16 px array operated for 1 year**
 - Assume parameters of our TES
 - Assume that observed counts increase with exposure
 - **1 kpx array operated for 1 year**
 - Assume 70 meV energy threshold (Ref. [1])
 - Assume zero observed counts

[1] K. Hattori, An optical transition-edge sensor with high energy resolution, Superconductor Science and Technology. 35, 095002 (2022)

Figures from: C. Schwemmbauer et al, Phys. Rev. D 114, 012006 (2026)



New constraints

DM-electron scattering

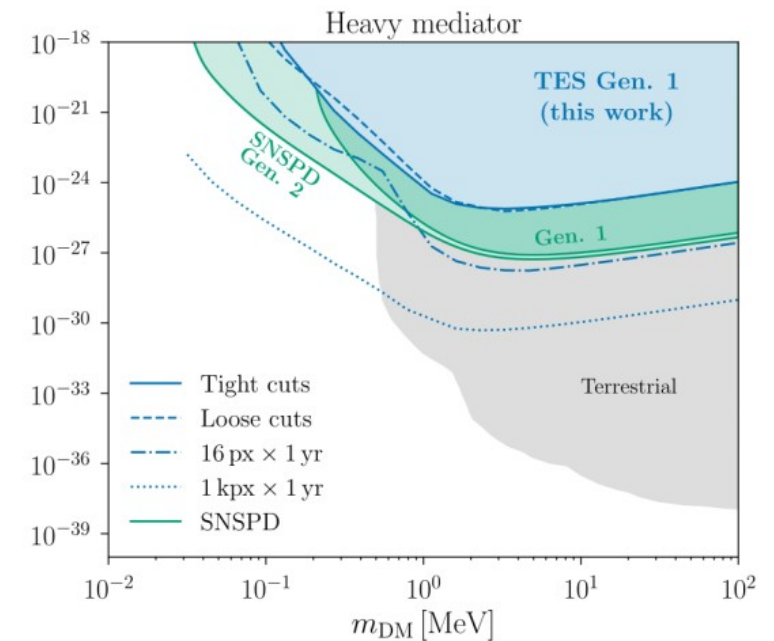
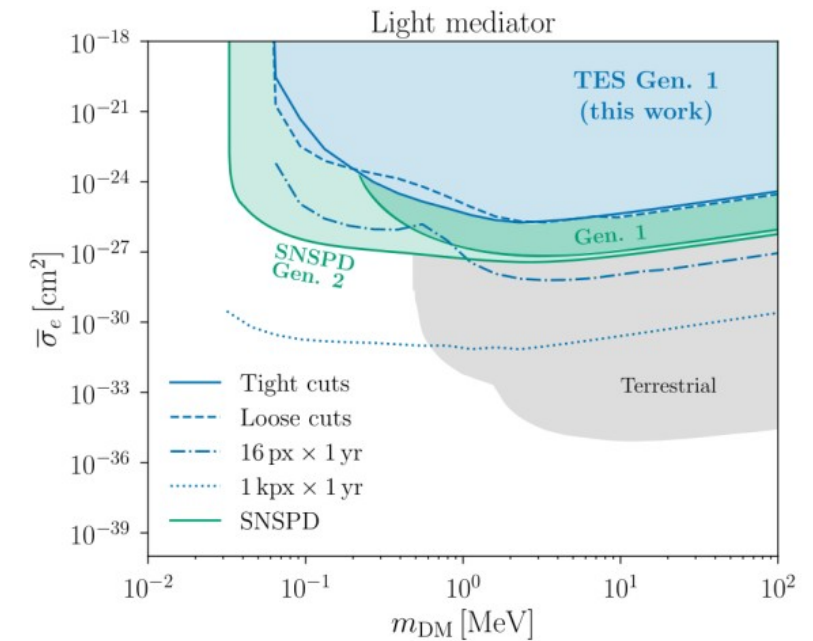
- Comparison to **Gen. 1 SNSPDs** (Refs. [1,2])
 - 0.73 eV threshold
 - 4.3 ng
 - 180 h exposure
- Comparison to **Gen. 2 SNSPDs** (Ref. [3])
 - 0.11 eV threshold
 - 1.67 ng
 - 415.15 h exposure

[1] Y. Hochberg et al., Phys. Rev. Lett. 123, 151802, 2019

[2] Y. Hochberg et al., Phys. Rev. D 106, 112005, 2022

[3] L. Baudis et al., Phys. Rev. Lett. 135, 081002, 2025

Figures from: C. Schwemmbauer et al, Phys. Rev. D 114, 012006 (2026)



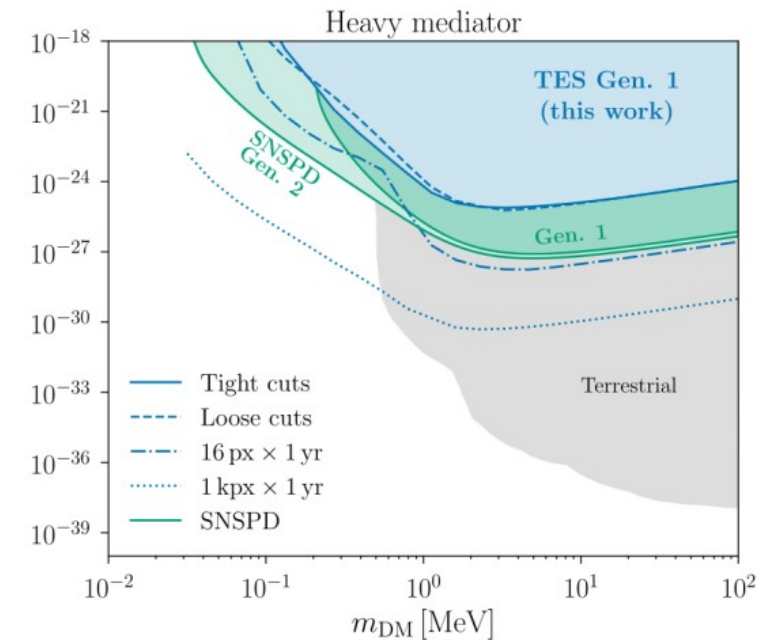
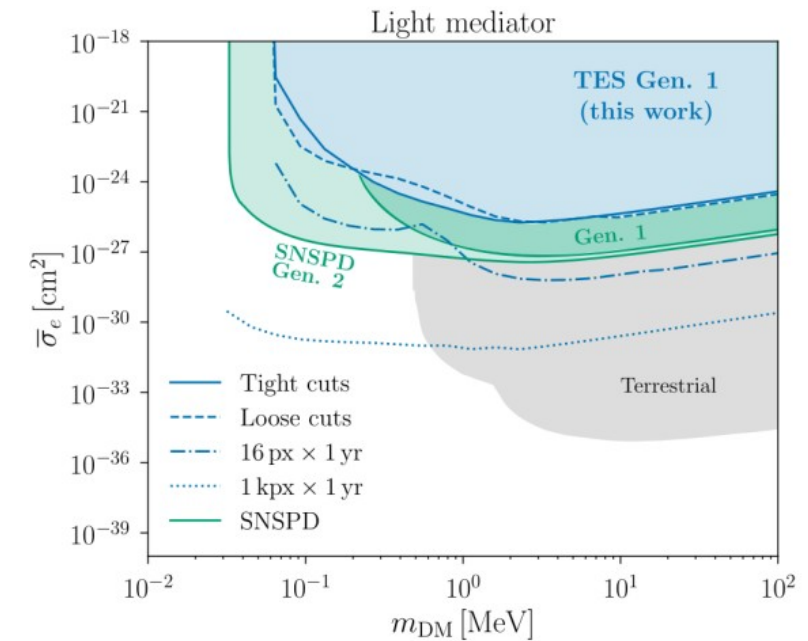
New constraints

DM-electron scattering

- Terrestrial constraints:

- Barak, Liron, et al. "SENSEI: Direct-detection results on sub-GeV dark matter from a new skipper CCD." Physical Review Letters 125.17 (2020): 171802.
- Amaral, D. W., et al. "Constraints on low-mass, relic dark matter candidates from a surface-operated SuperCDMS single-charge sensitive detector." Physical Review D 102.9 (2020): 091101.
- Aguilar-Arevalo, Alexis, et al. "Constraints on light dark matter particles interacting with electrons from DAMIC at SNOLAB." Physical review letters 123.18 (2019): 181802.
- Essig, Rouven, Tomer Volansky, and Tien-Tien Yu. "New constraints and prospects for sub-GeV dark matter scattering off electrons in xenon." Physical Review D 96.4 (2017): 043017.
- Agnes, Paolo, et al. "Constraints on sub-GeV dark-matter–electron scattering from the DarkSide-50 experiment." Physical review letters 121.11 (2018): 111303.
- Aprile, Elena, et al. "Light dark matter search with ionization signals in XENON1T." Physical Review Letters 123.25 (2019): 251801.

Figures from: C. Schwemmbauer et al, Phys. Rev. D 114, 012006 (2026)



New constraints

Figures from: C. Schwemmbauer et al, Phys. Rev. D 114, 012006 (2026)

DM-nucleon scattering / dark photon absorption

