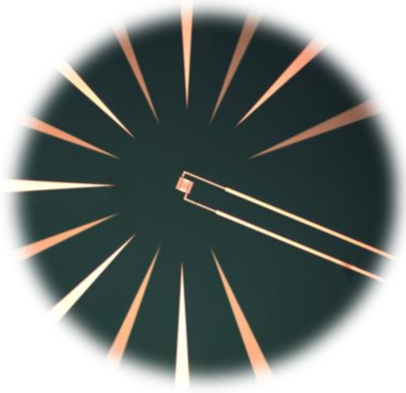
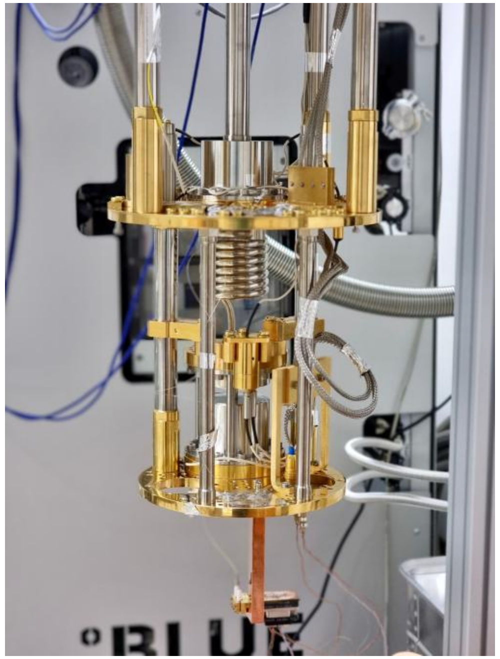
Expanding the search for light dark matter with cryogenic sensors

A direct measurement with a TES arXiv:2506.18982

José Alejandro Rubiera Gimeno for the ALPS TES team



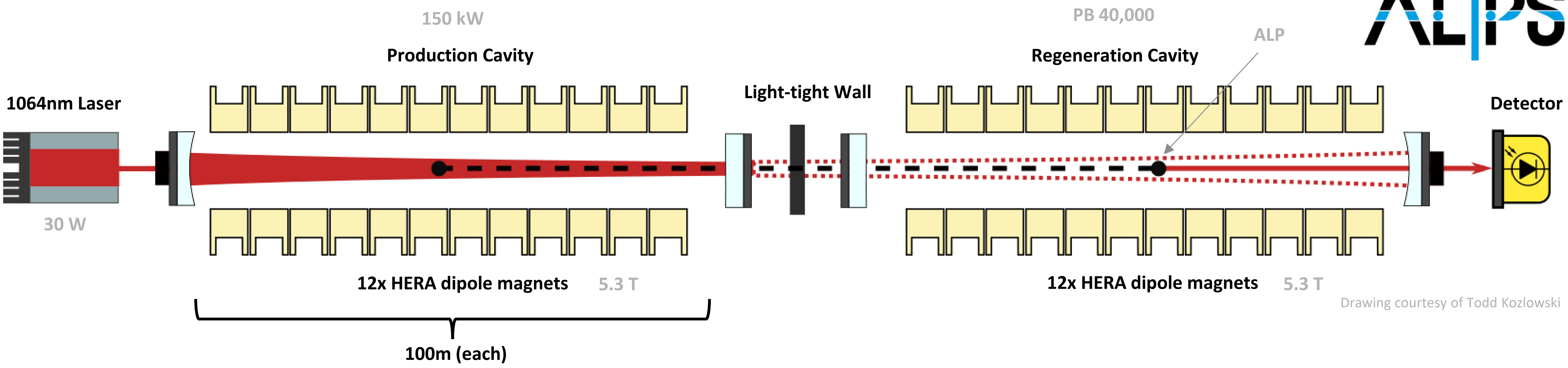


QS4Physics kickoff,
20.11.2025

HELMHOLTZ

Original challenge: The ALPS II experiment

A light-shining-through-walls experiment



Drawing courtesy of Todd Kozlowski

Detection probability: $P_{\gamma\to a\to\gamma} \propto PC \cdot RC \cdot g^4_{a\gamma\gamma} B^4 L^4$

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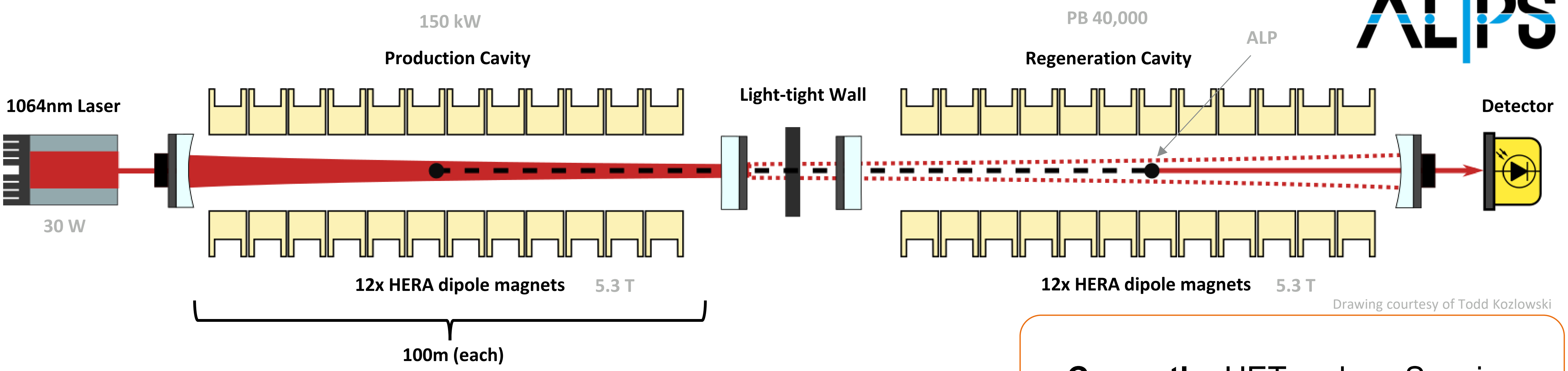

Currently: HETerodyne Sensing

Detection probability: $P_{\gamma\to a\to\gamma} \propto PC \cdot RC \cdot g^4_{a\gamma\gamma} B^4 L^4$

Expected rate of low energy ($\sim 1.16\,\mathrm{eV}$) photons:
$\dot{N}_\gamma \approx 2.8 \cdot 10^{-5} \frac{\gamma}{\mathrm{s}} \approx 1 \frac{\gamma}{\mathrm{day}}$ (for $g_{a\gamma\gamma} = 2 \cdot 10^{-11}\,\mathrm{GeV}^{-1}$)

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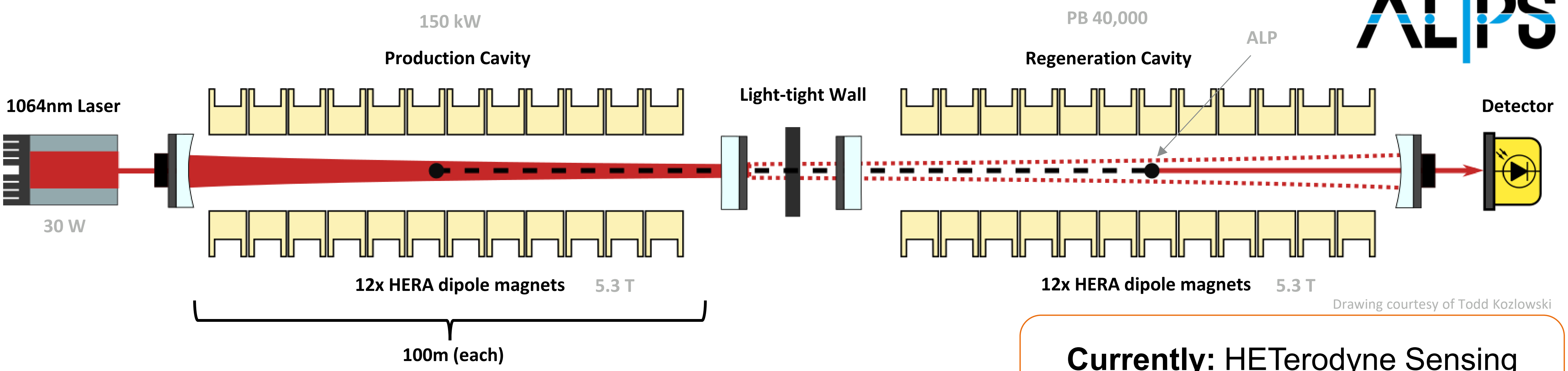

Currently: HETerodyne Sensing
Future Option: **TES**

Detection probability: $P_{\gamma\to a\to\gamma} \propto PC \cdot RC \cdot g^4_{a\gamma\gamma} B^4 L^4$

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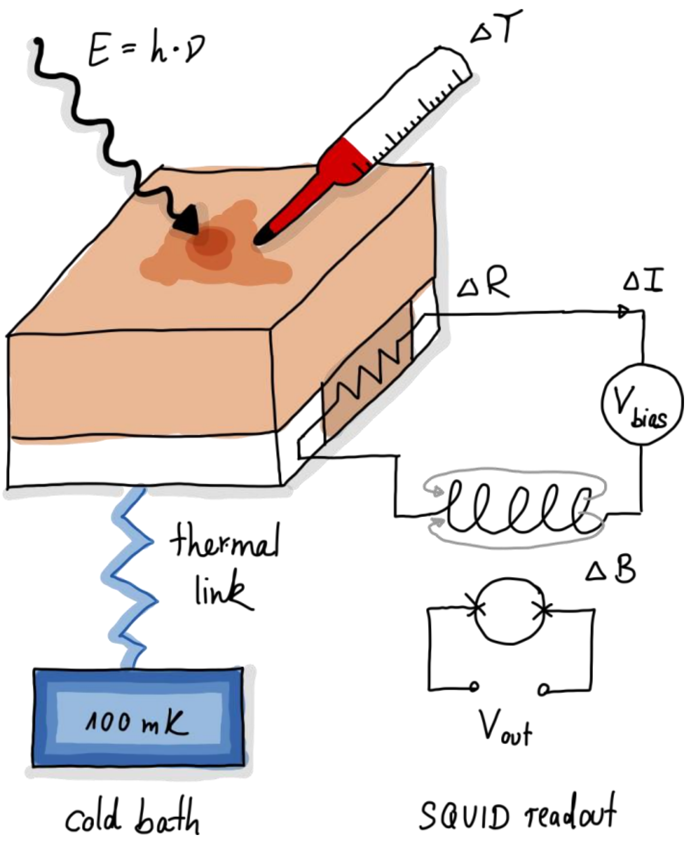
Single-photon detection requirements for ALPS II:

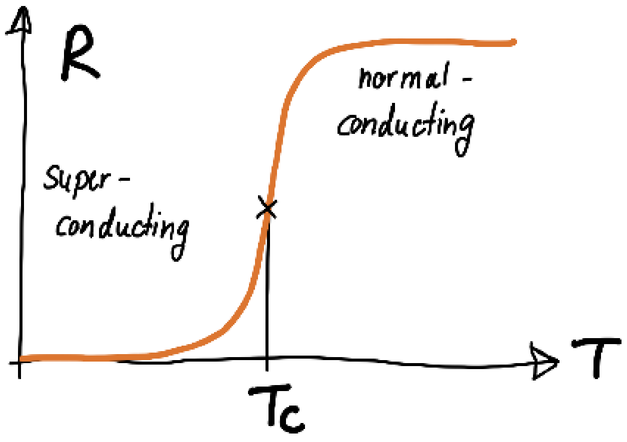
- Low energy photon detection
- **Low background (< 1 photon/day)**
- High detection efficiency

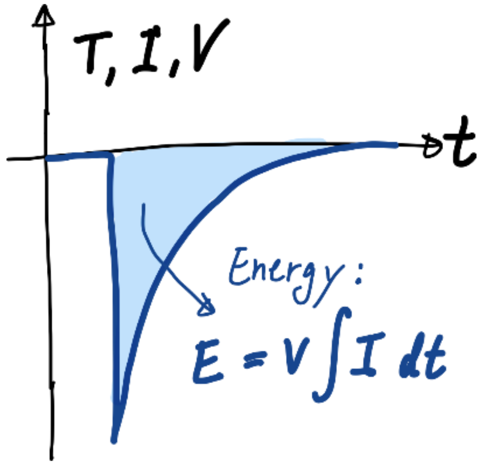
Reminder: Transition Edge Sensor

Working Principle



*Courtesy of Katharina-Sophie Isleif



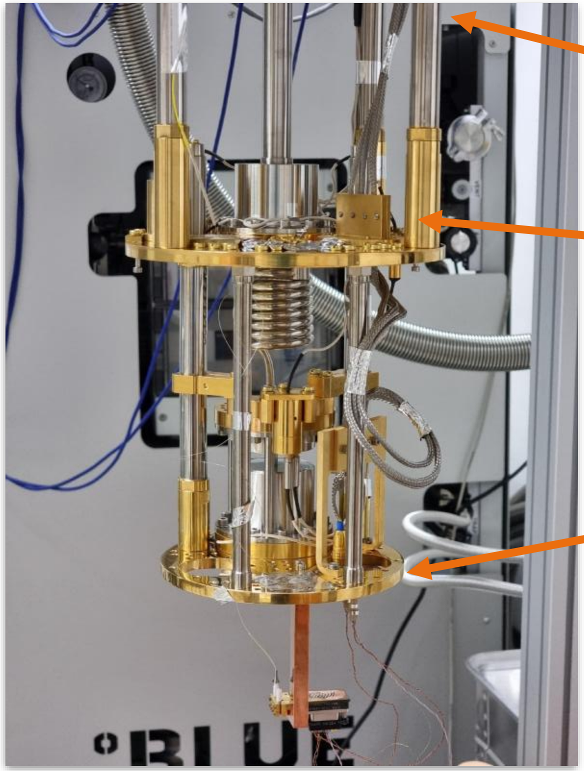


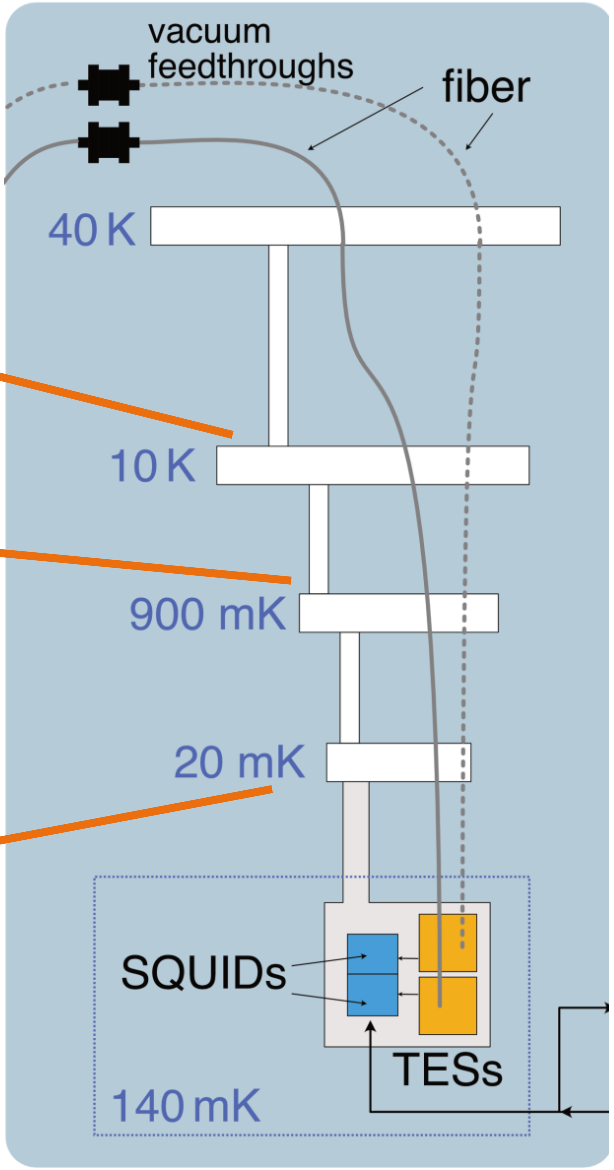
- Cryogenic microcalorimeter operated in superconducting transition region
- Connected to a colder thermal bath
- Working point controlled by a voltage bias circuit
- Change in resistance produced by energy deposition

ALPS II TES system @ DESY

Optimised for low-rate 1064 nm photon detection

Inside of Bluefors dilution refrigerator





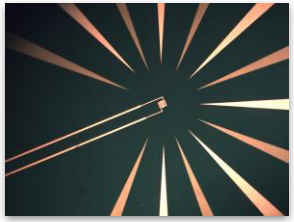
Shah, R., Isleif, KS., Januschek, F. *et al.* Characterising a Single-Photon Detector for ALPS II. *J Low Temp Phys* (2022). https://doi.org/10.1007/s10909-022-02720-0

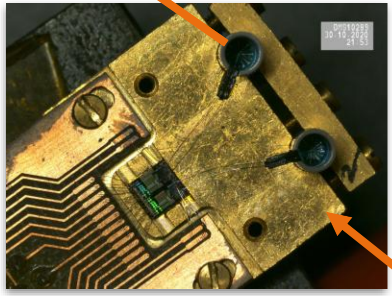
ALPS II TES system @ DESY

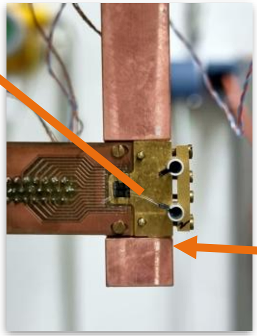
Optimised for low-rate 1064 nm photon detection

Area = 25 µm x 25 µm
Thickness = 20 nm
0.2 ng of Tungsten

127 nm SiNx
2 nm a-Si
20 nm W
2 nm a-Si
132 nm SiNx
80 nm Ag
Si substrate







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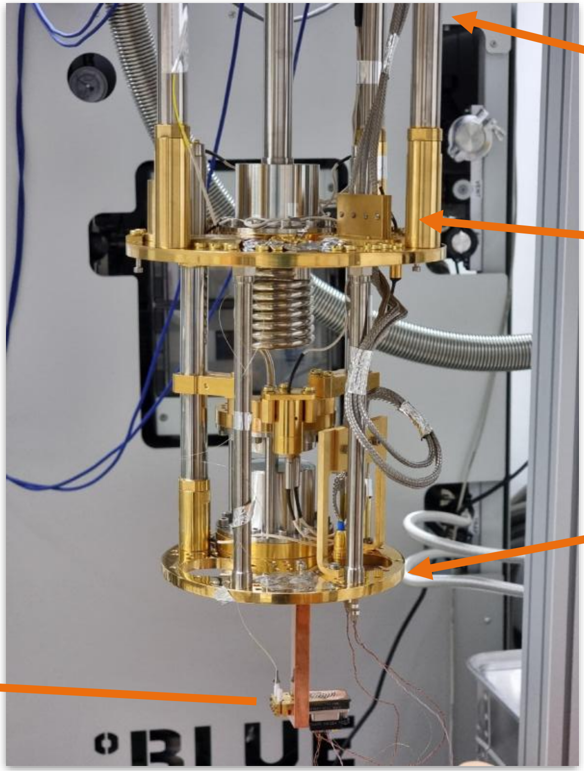

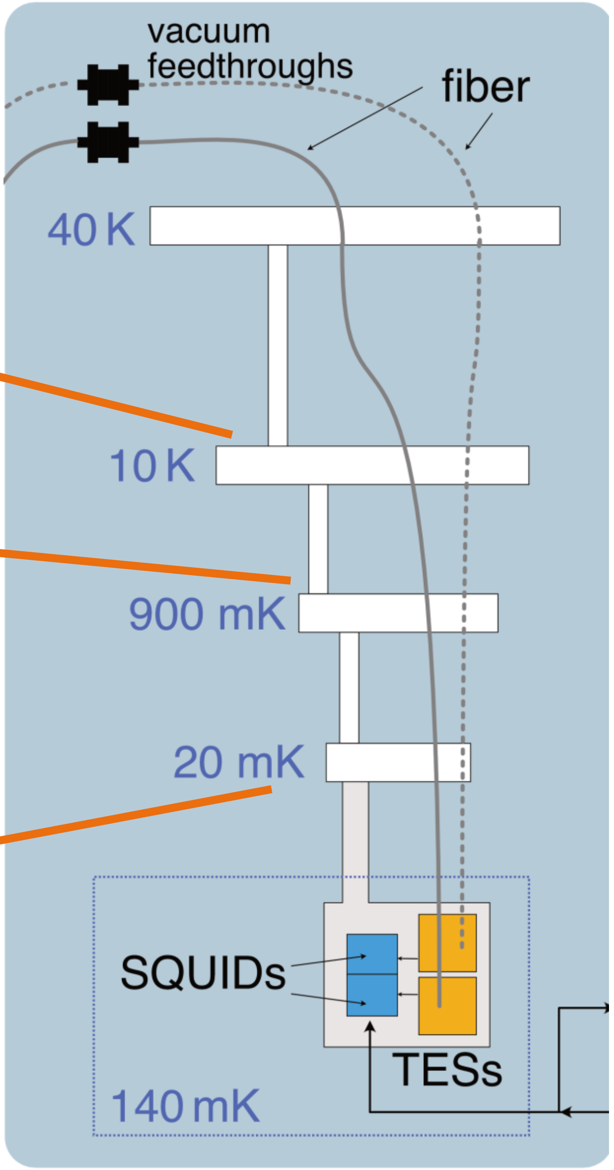

Sensors provided by: NIST

Packaging and SQUIDs provided by: PTB

ALPS II TES system @ DESY

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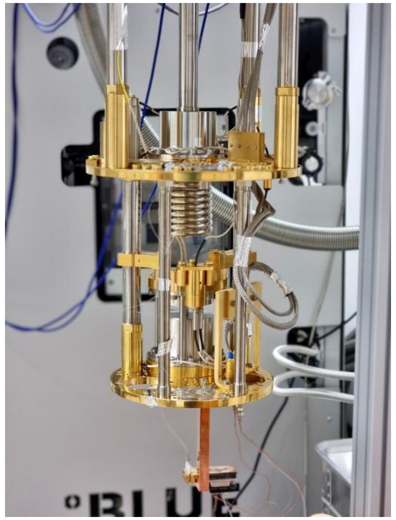
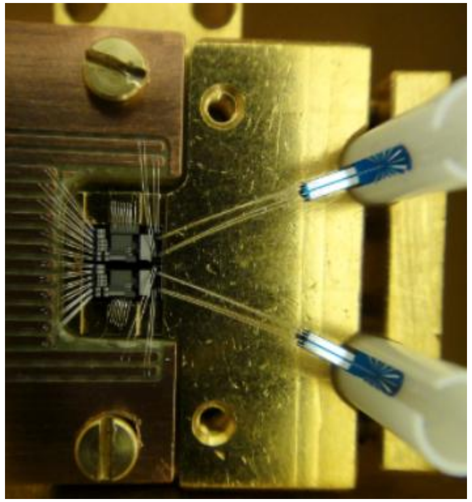




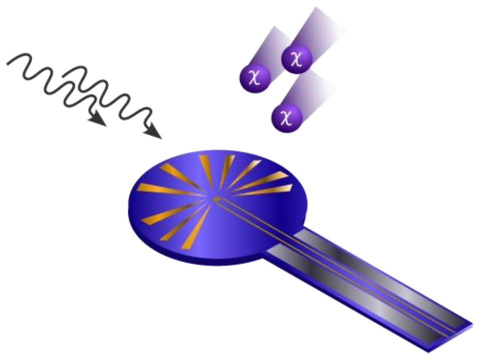
Highly sensitive Transition Edge Sensor

- Low noise
- High efficiency: $\epsilon > 80\ \%$
- Good energy resolution: $\mathrm{FWHM} = 0.14\ \mathrm{eV}$
- Ultra-low background rate at 1064nm: $\mathrm{b} = 6.9 \cdot 10^{-6}\mathrm{cps}$

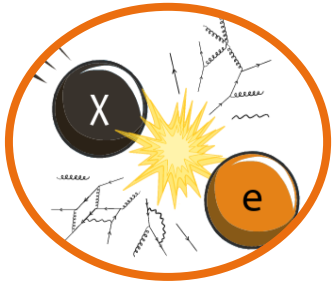
NIST

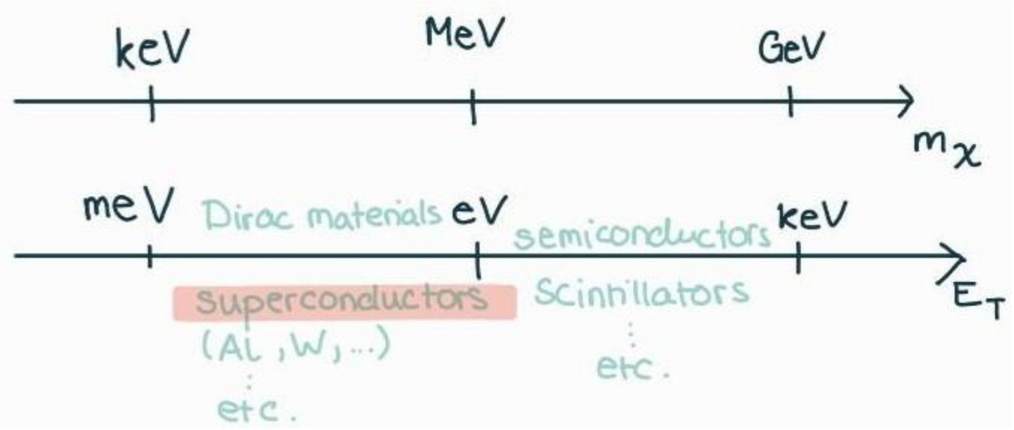
Shah, R., Isleif, KS., Januschek, F. *et al.* Characterising a Single-Photon Detector for ALPS II. *J Low Temp Phys* (2022). https://doi.org/10.1007/s10909-022-02720-0
J. A. Rubiera Gimeno et al., “A TES system for ALPS II - Status and Prospects”, PoS EPS-HEP2023 (2023) 567, doi:10.22323/1.449.0567

Can we use this for a dark matter search?



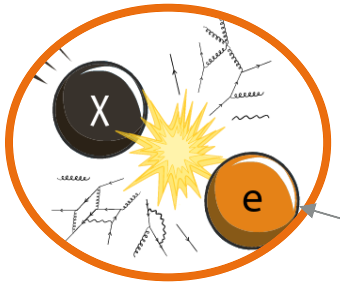
$$E_{\mathrm{T}_{\max}} = E_{\mathrm{kin}} \sim m_\chi v^2 \sim 10^{-6} m_\chi$$

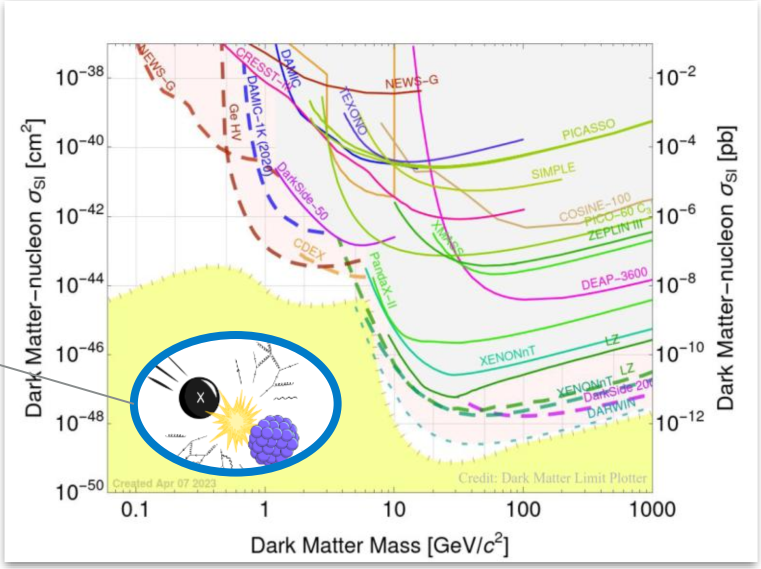




TES can enable low-threshold energy-resolved light DM searches

TES for DM searches





Why TES for Dark Matter?

- Direct DM detection via electron scattering opens access to sub-MeV DM
- TESs offer sub-eV thresholds
- Prior work with Superconducting Nanowire Single Photon Detector (SNSPD) able to set new limits with 4 dark counts in 180 h with 0.73 eV energy threshold Hochberg, Y. et al. arXiv:2110.01586 (2021)
- lacked energy resolution → TES can provide spectral information

PRL **116,** 011301 (2016) PHYSICAL REVIEW LETTERS week ending 8 JANUARY 2016

Superconducting Detectors for Superlight Dark Matter

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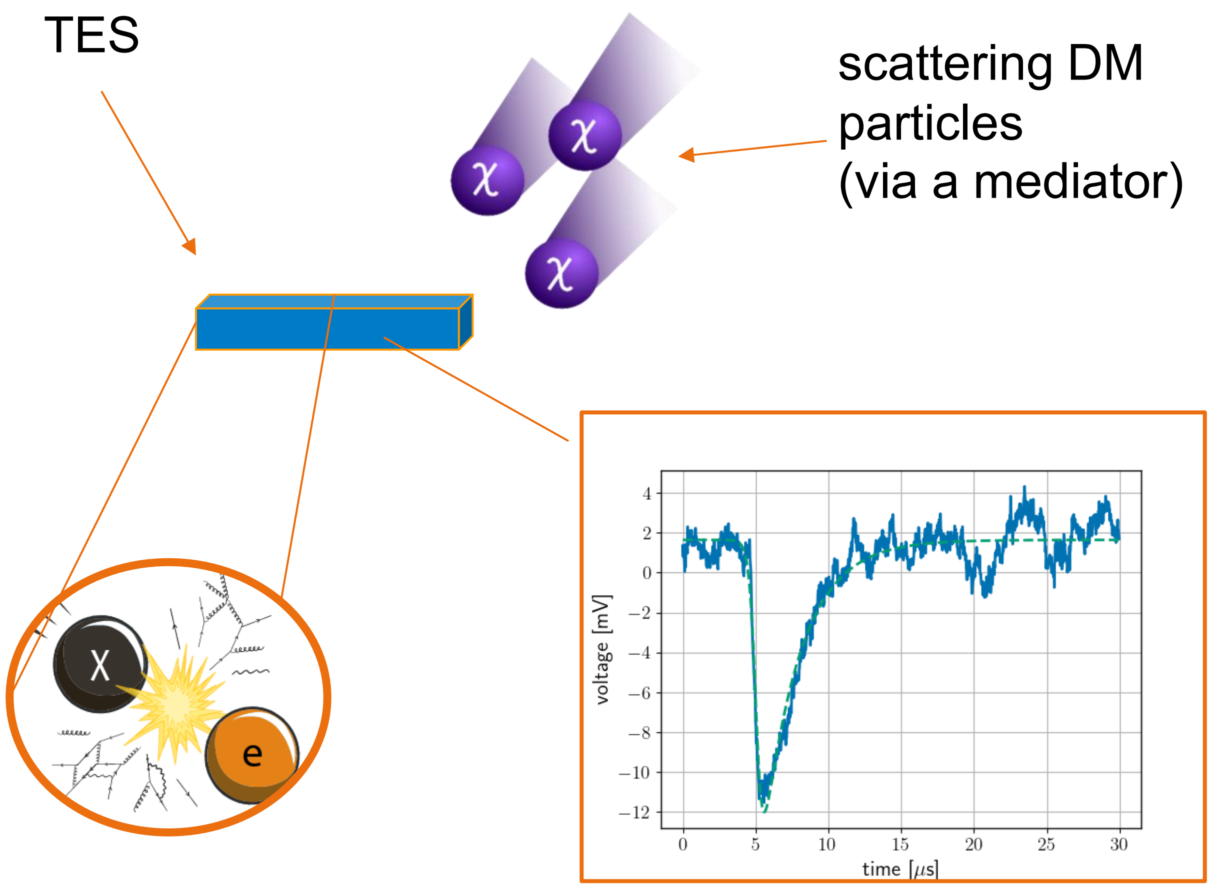
(Received 8 June 2015; revised manuscript received 21 October 2015; published 7 January 2016)

We propose and study a new class of superconducting detectors that are sensitive to $\mathcal{O}$(meV) electron recoils from dark matter–electron scattering. Such devices could detect dark matter as light as the warm dark-matter limit, $m_X \gtrsim 1$ keV. We compute the rate of dark-matter scattering off of free electrons in a (superconducting) metal, including the relevant Pauli blocking factors. We demonstrate that classes of dark matter consistent with terrestrial and cosmological or astrophysical constraints could be detected by such detectors with a moderate size exposure.

DOI: 10.1103/PhysRevLett.116.011301

Proof-of-principle: TES for Direct Dark Matter Searches

TES as simultaneous target & sensor



DM-nucleon scattering sketch adapted from Benjamin V. Lehmann

- First attempt to use TES as **target & sensor** for DM
- Direct DM detection via electron-scattering
- Should yield similar energy-dependent response as photon-interactions
- Enables small-scale high-sensitivity DM search
- Recently proposed as well in

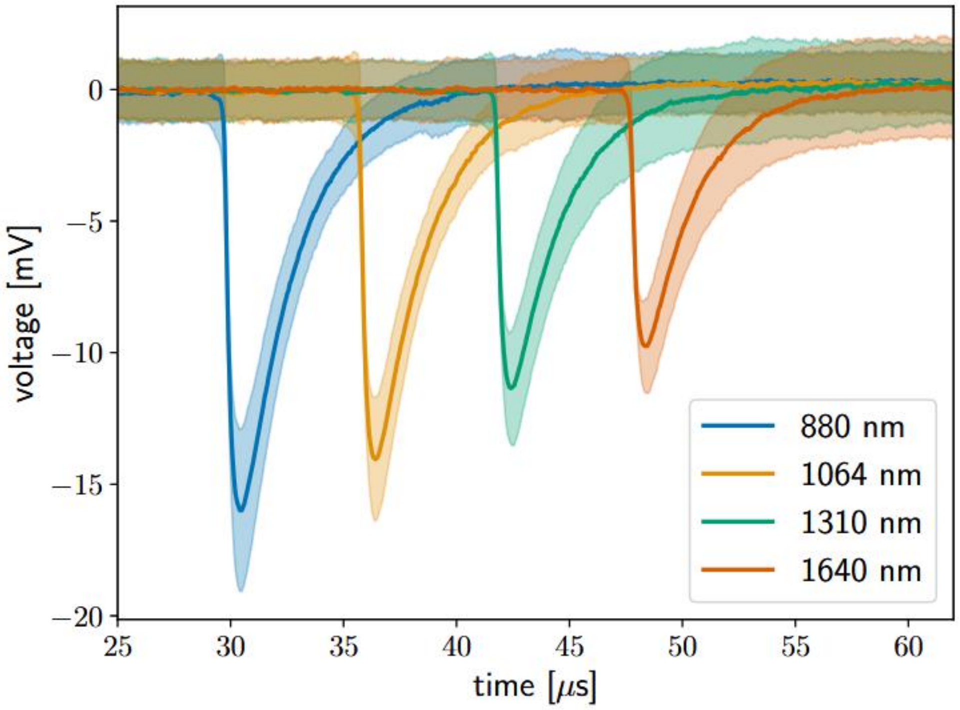
Muping Chen et al.: "Light Dark Matter Detection with Sub-eV Transition-Edge Sensors", arXiv:2506.10070

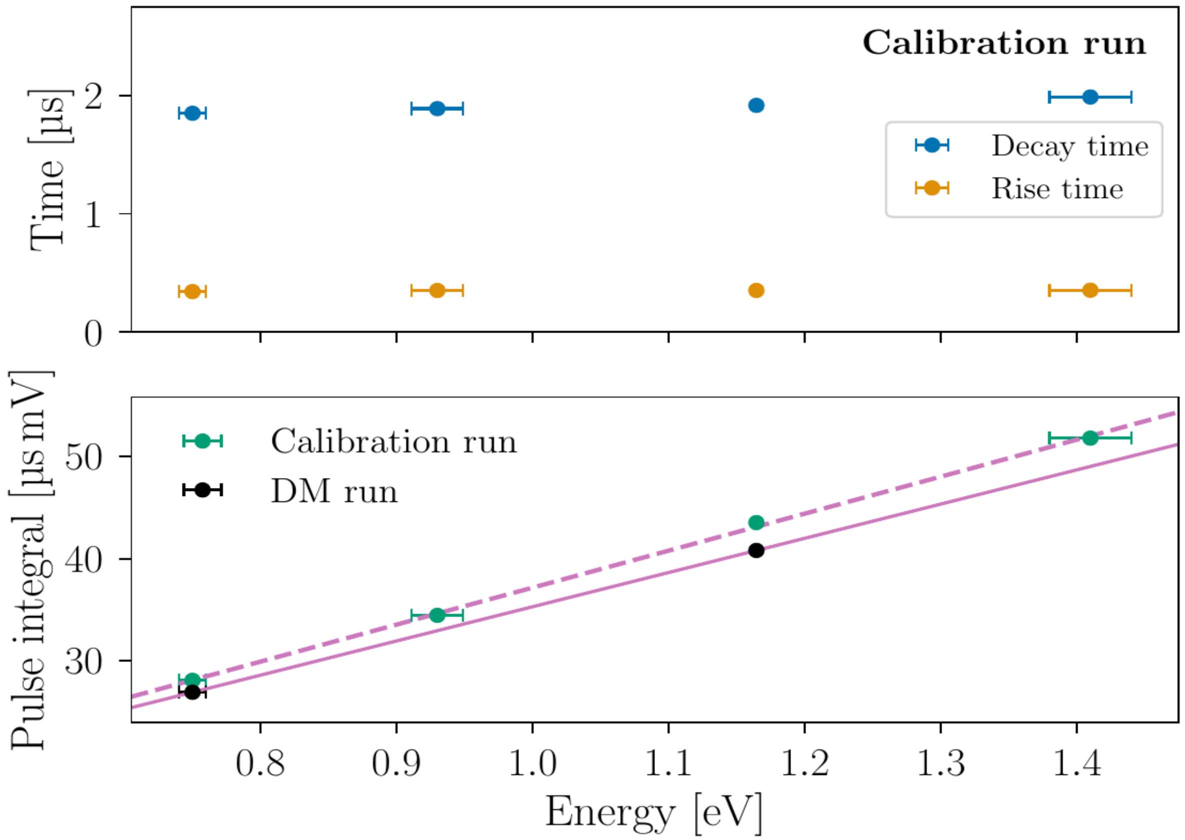
Challenges:

- low mass (0.2 ng)
- small area (25 x 25 μm)
- **limited knowledge about broadband response**

Can we use our TES for other energies?

Going to lower energies





Confirmed assumptions:

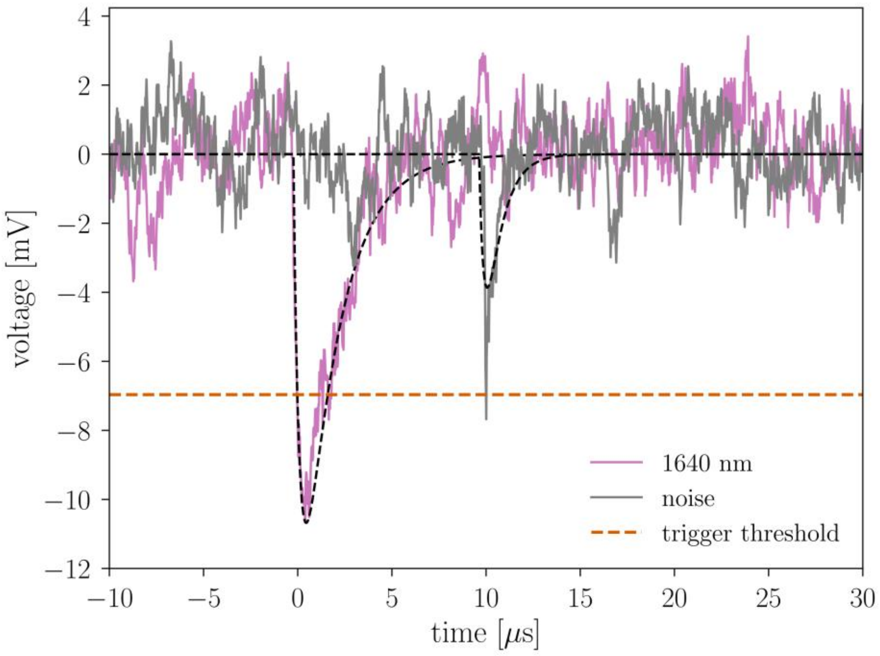
- constant rise and decay time response
- linear pulse integral/height response for different energies.

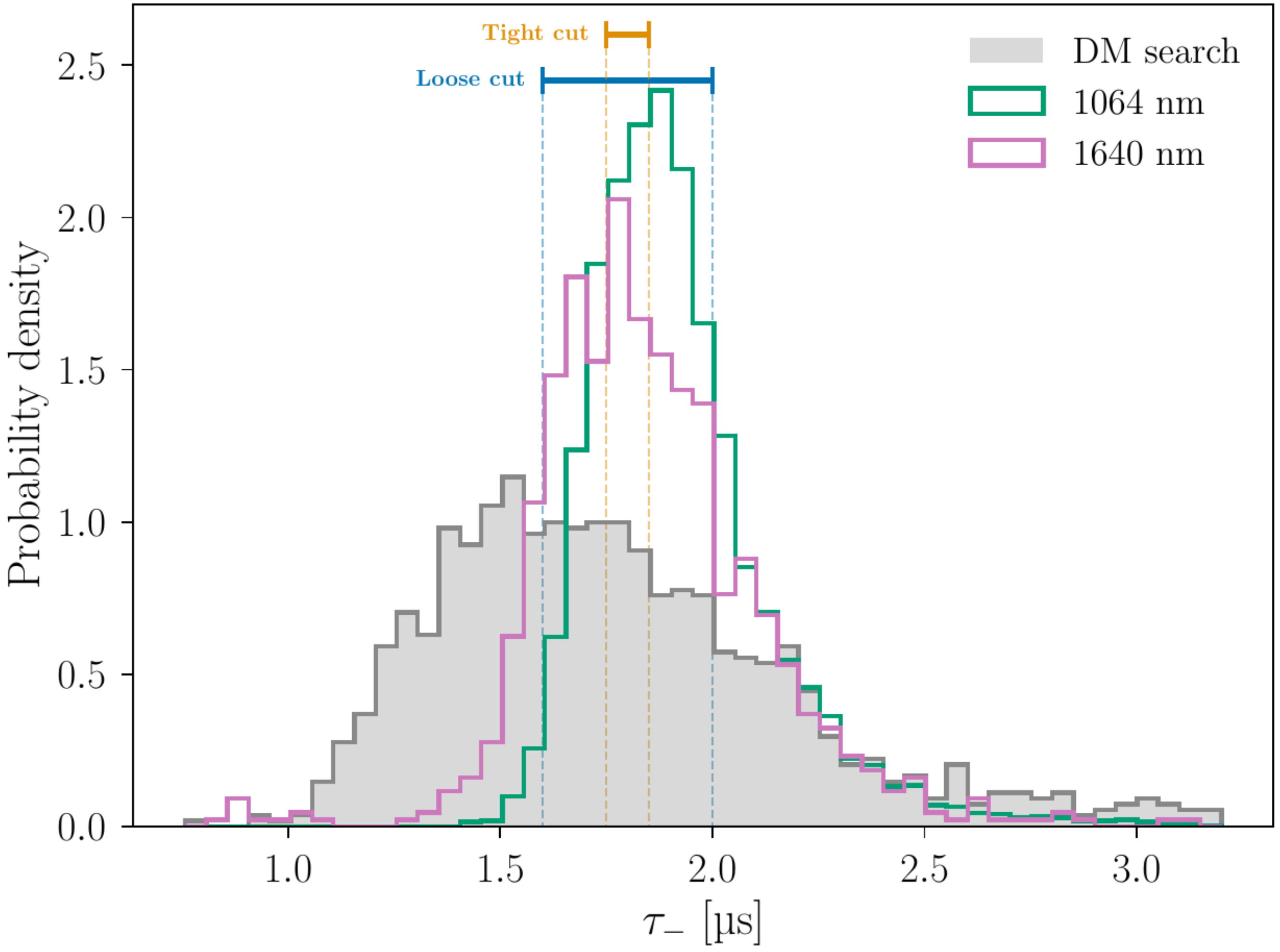
→ isolating photon-like signals based on calibration and simulation results of broad-band TES response is possible

Event selection

Evaluating a 489 h dedicated DM search run

- 489 h DM search measurement
- Cuts based on calibration samples
- Looking for photon-like shapes (in particular also rise, decay times)

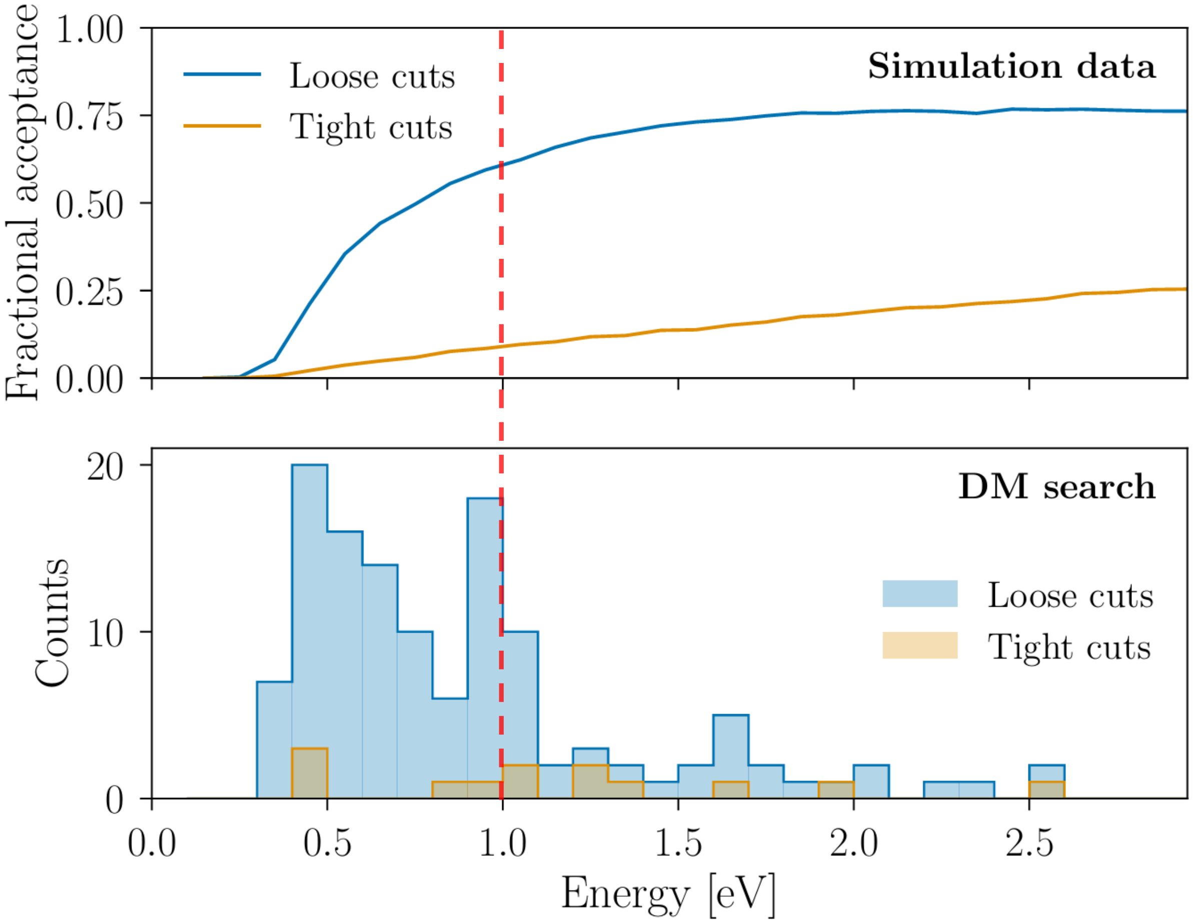




Observed event spectrum

Remaining events after two different cut schemes

- Two different cut schemes with different acceptance (based on calibration & simulations) for different energies
- Sensitivity also below 1 eV
- 126 events (loose) and 13 events (tight) remaining after selection
- Resulting spectrum compared with expected DM model
- Used to set exclusion limits on DM-electron scattering cross section with 95% C.L. for ~MeV light DM



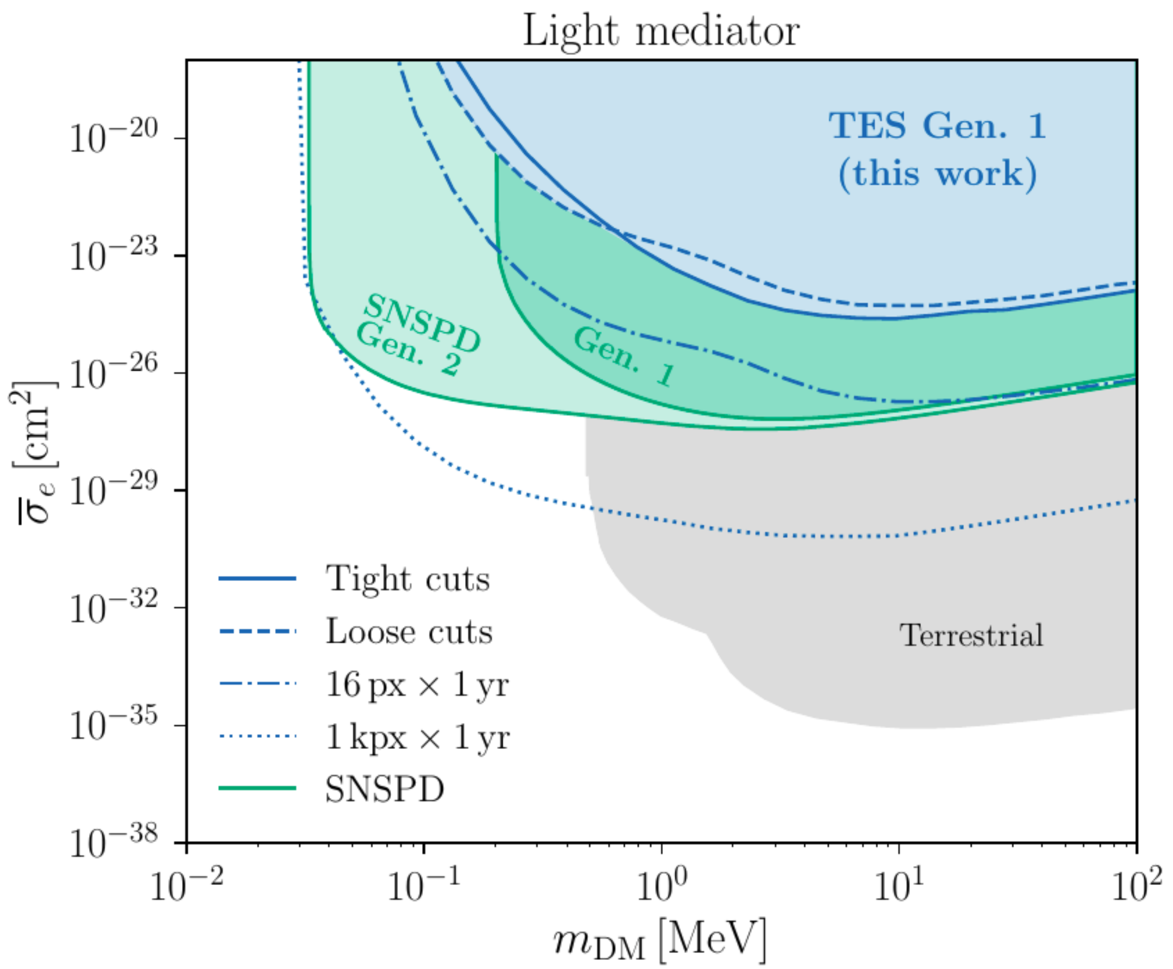
TES sensitivity for DM-electron scattering

Compared to similar searches

C. Schwemmbauer et al., “First direct search for light dark matter interactions in a transition-edge sensor”, arXiv:2506.18982 → journal submission to follow

- **Results** of the 0.2 ng dark matter search: exclusion limits on DM-electron scattering cross section with 95% C.L. for ~MeV light DM
- Interesting in particular for the low energy region
- **Here**: Compared to 1st and 2nd generation SNSPD DM search

Important note: Overburden effects need to be considered above approximately the order of 10^{-24} cm^2 depending on the model and might relax the constraints.
➔ Proof-of-concept



SNSPD Gen. 2 results based on: L. Baudis et al., “A New Bite Into Dark Matter with the SNSPD-Based QROCODILE Experiment”, arXiv:2412.16279

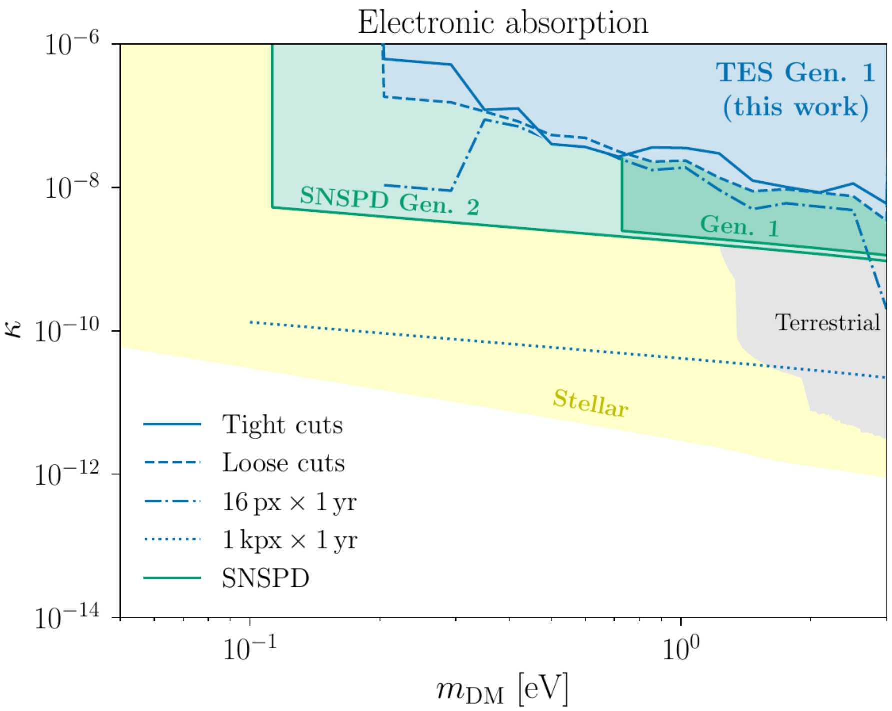
Additional Dark Matter interactions

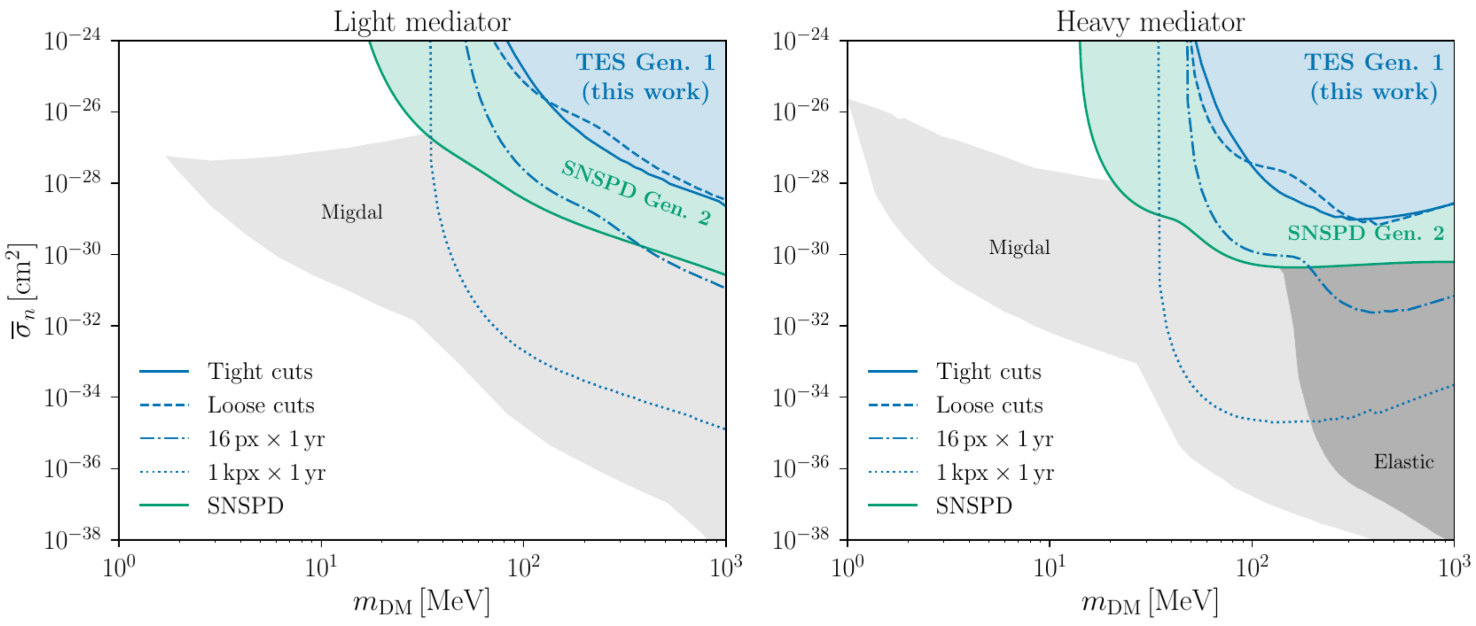
Electronic absorption and DM-nucleon scattering

C. Schwemmbauer et al., “First direct search for light dark matter interactions in a transition-edge sensor”, arXiv:2506.18982 → journal submission to follow

- Results can be used to set constraints on dark photon absorption
- and DM-nucleon scattering as well

S.M.Griffin et al., “Dark Matter-Electron Detectors for Dark Matter-Nucleon Interactions“, arXiv:2412.16283v1





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Improving the limits

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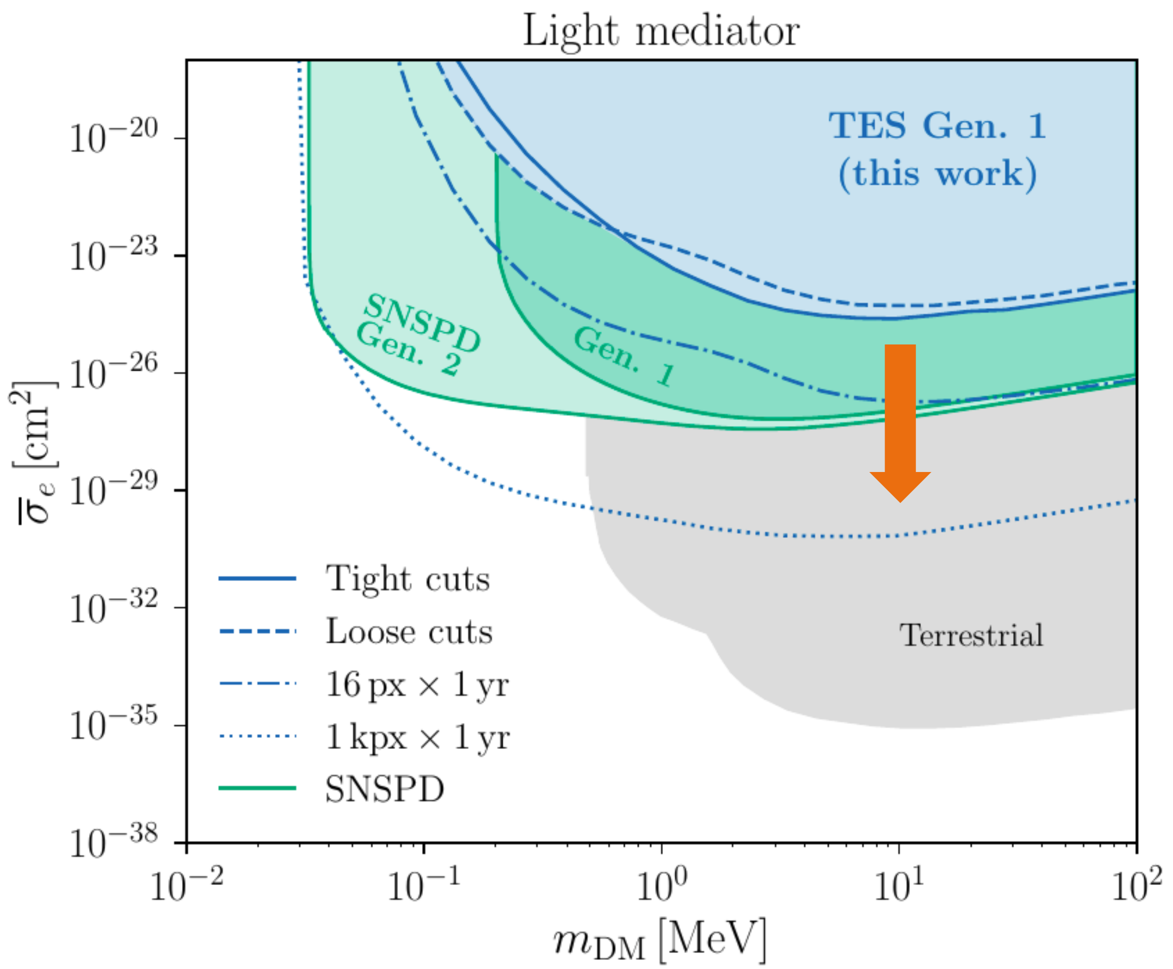
  - Complex TES readout for larger systems
  - New possibilities with Kinetic Inductance Current Sensors



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  - Improves energy resolution
  - Allows lower energy threshold
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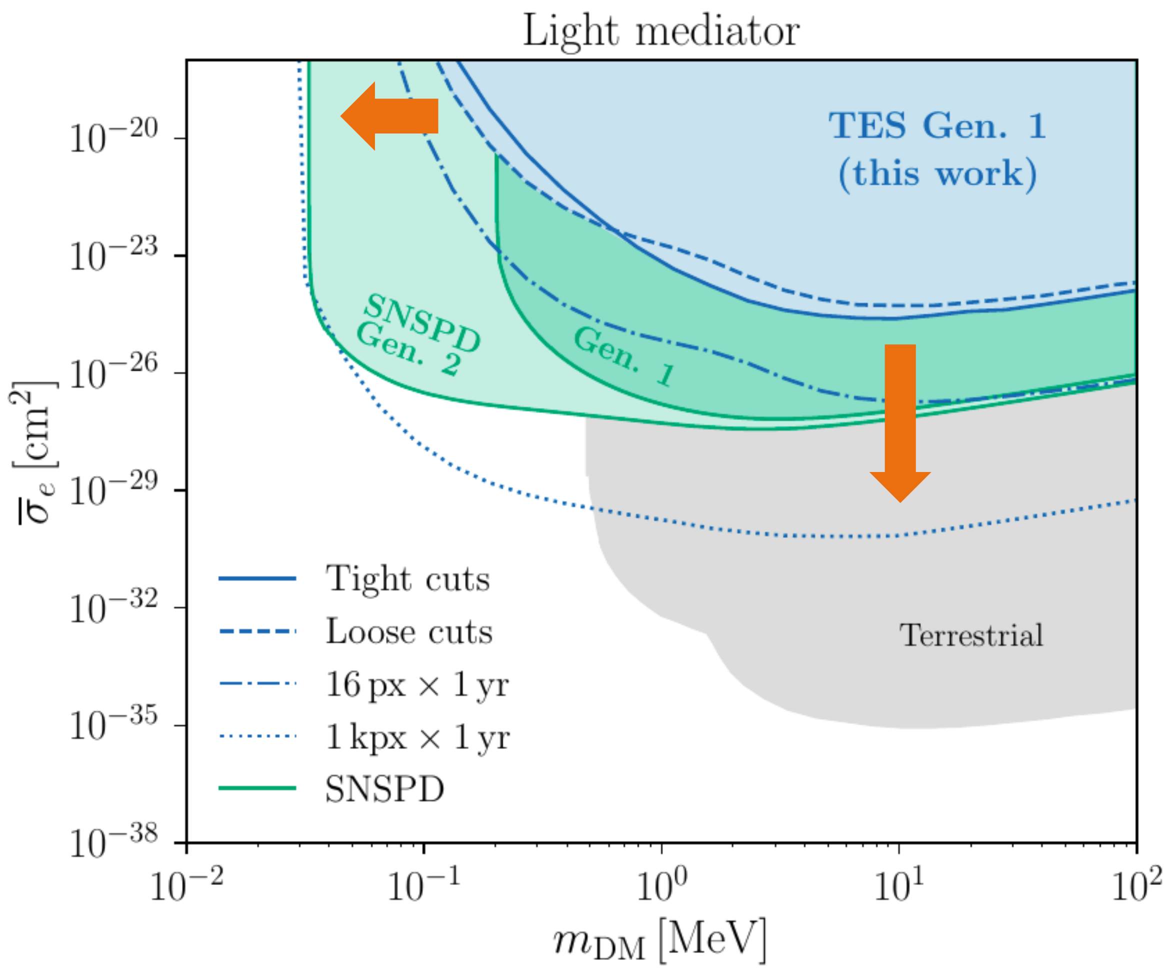

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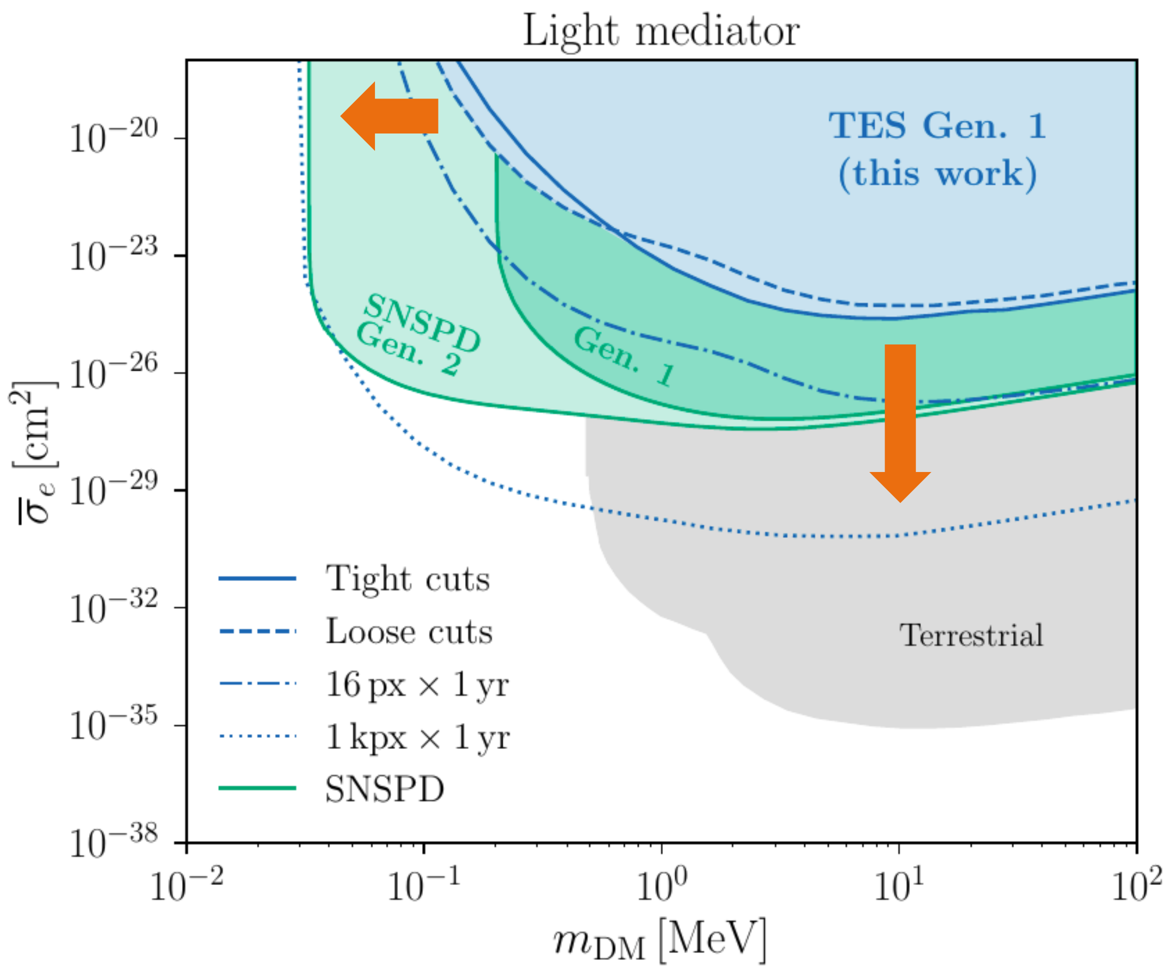

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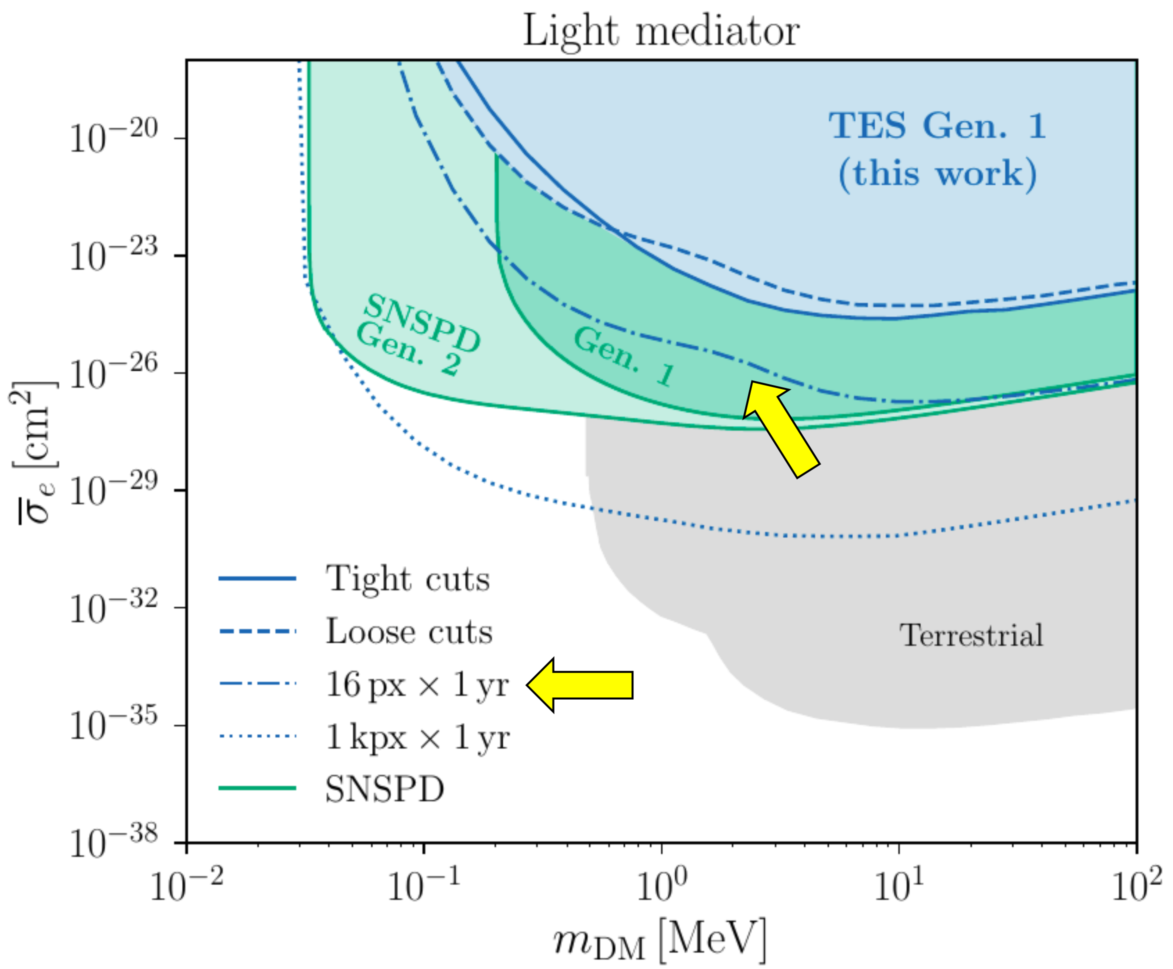

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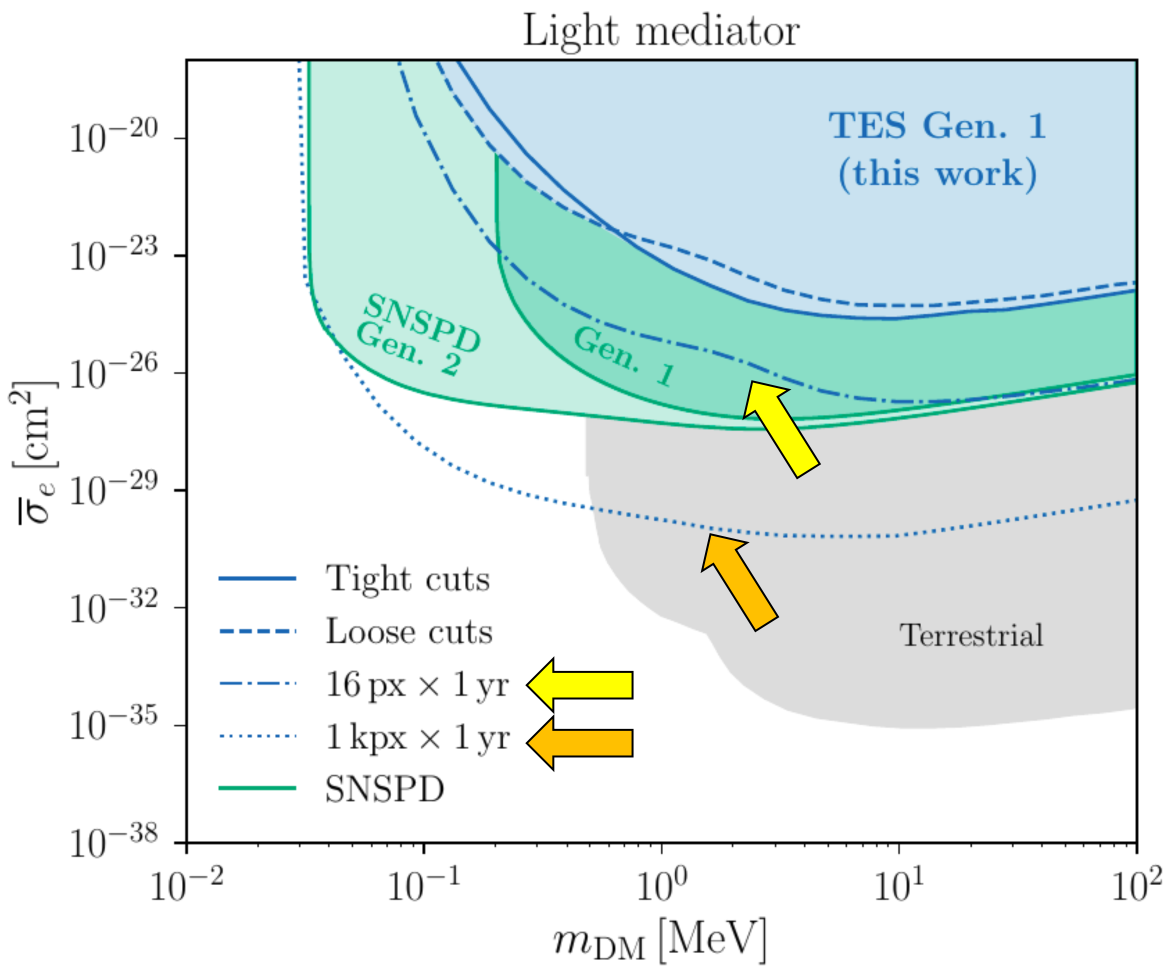

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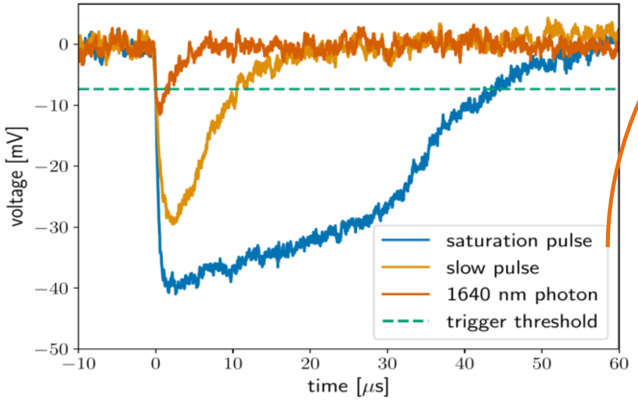
Optimised Sensors

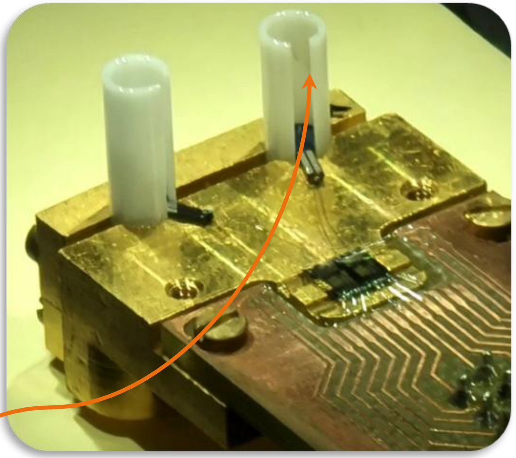
Reducing background further

- The sensor of this study was optimised for 1064 nm photon detection
  ➔ other sensors?

- Background reduction?
  - Most (non baseline) triggers from interactions in Si substrate



ALPS TES module



Background simulations with GEANT4+COMSOL confirmed dominant contribution of radioactive decays from Zirconia fiber sleeves

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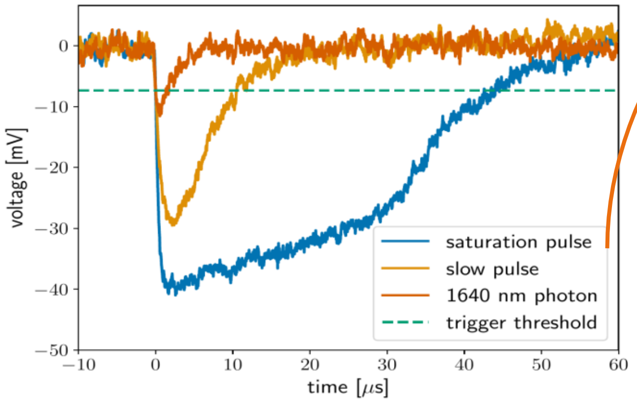

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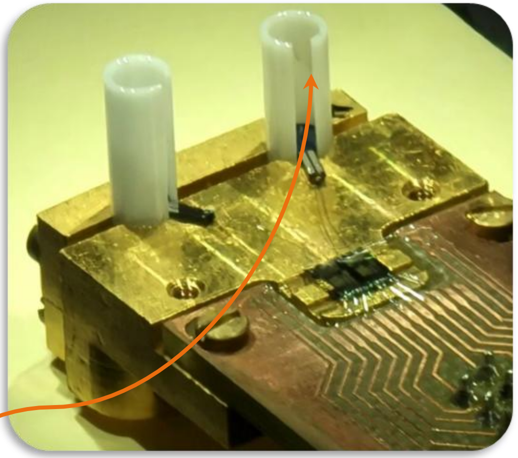
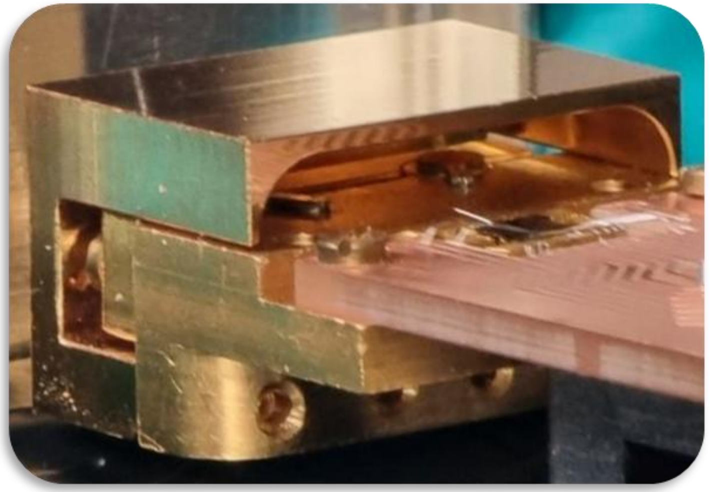


no fiber sleeves
(not needed for DM)



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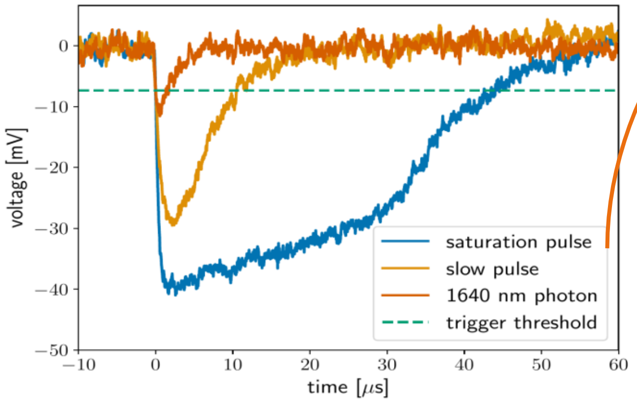

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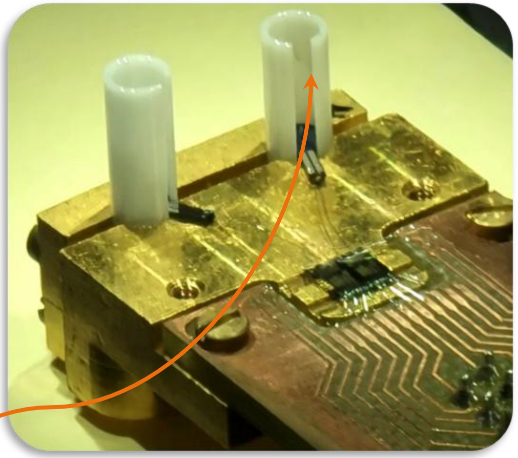

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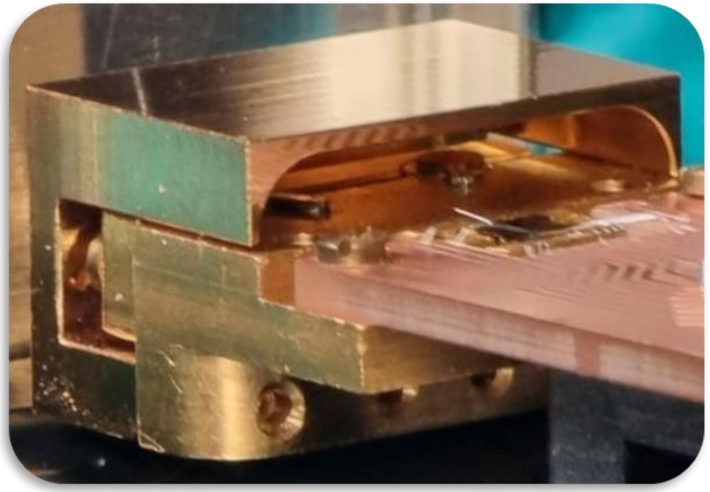
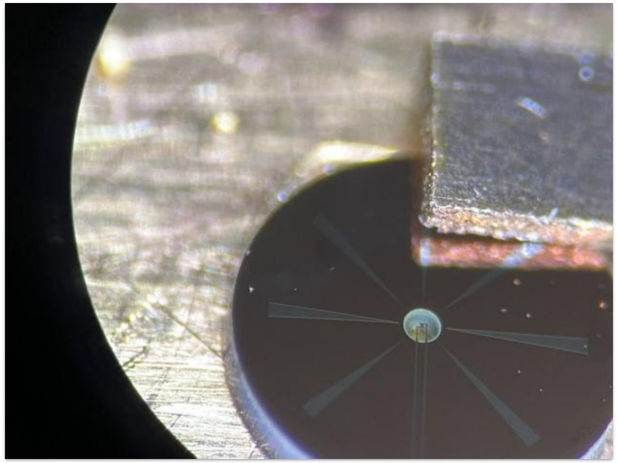


TES chip placed on SiNx membrane



Background simulations with GEANT4+COMSOL confirmed dominant contribution of radioactive decays from Zirconia fiber sleeves

Status of the project

- Currently testing new membrane TES optimized for low background
- Preliminary results look promising:
  - Better energy resolution

Previous sensor: $\mathrm{FWHM} = 0.14\ \mathrm{eV}$

Membrane sensor: $\mathrm{FWHM} = 0.11\ \mathrm{eV}$

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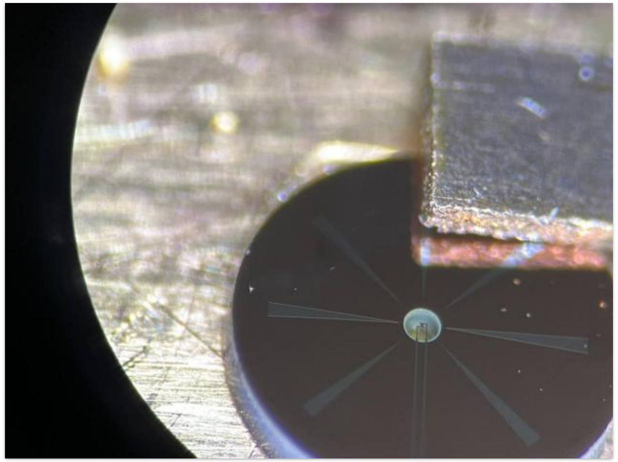

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  - Lower raw background rate

    Rate at a pulse equivalent to 1064nm photons

    Previous sensor: $\mathrm{b} = 1.04 \cdot 10^{-2}\mathrm{cps}$

    Membrane sensor: $\mathrm{b} = 1.30 \cdot 10^{-4}\mathrm{cps}$

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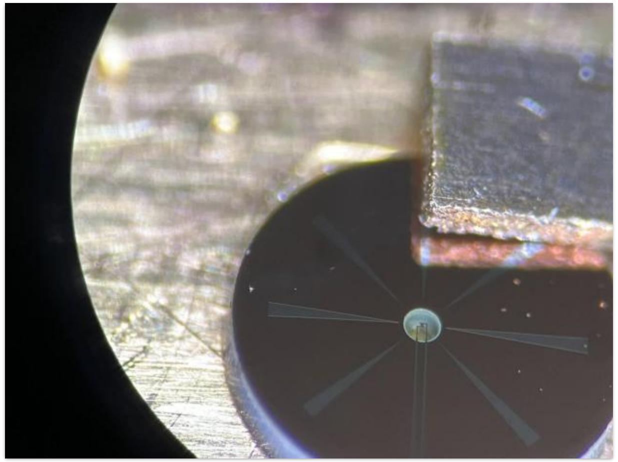

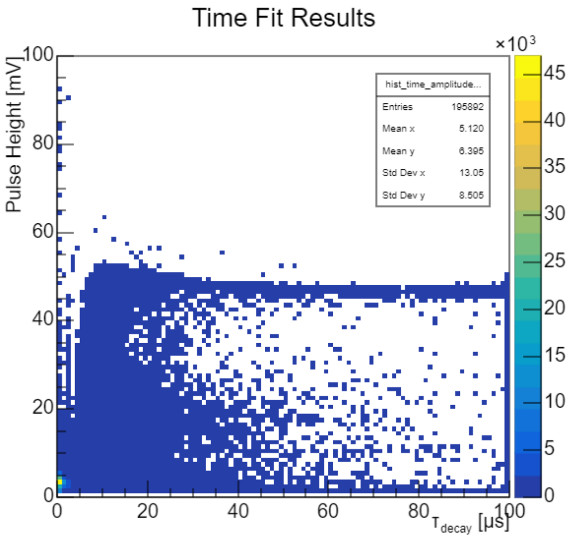

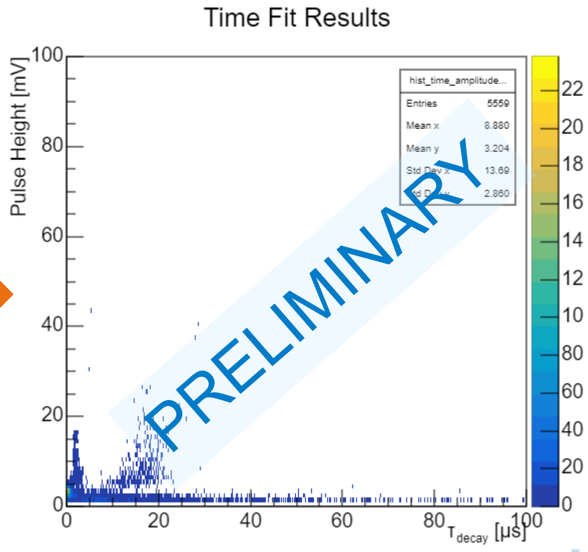

Next steps

- Dedicated DM run with new membrane TES optimized for low background
- Continue development on more robust and precise background simulations
- Feasibility study of larger system together with other QS4Physics partners, in particular KIT

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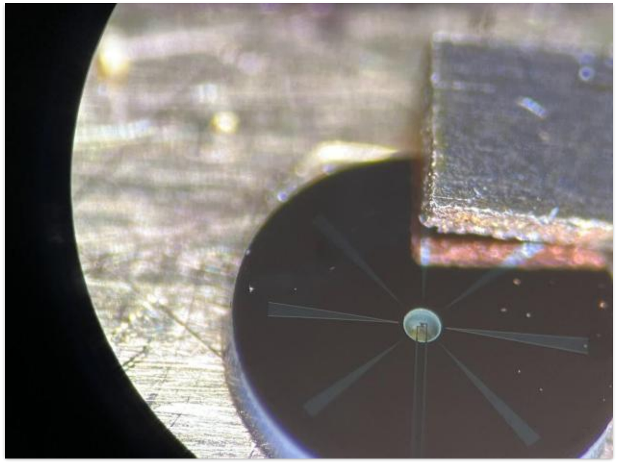
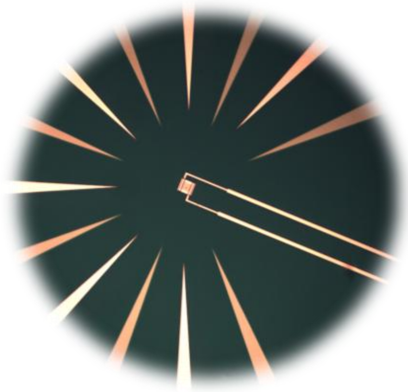


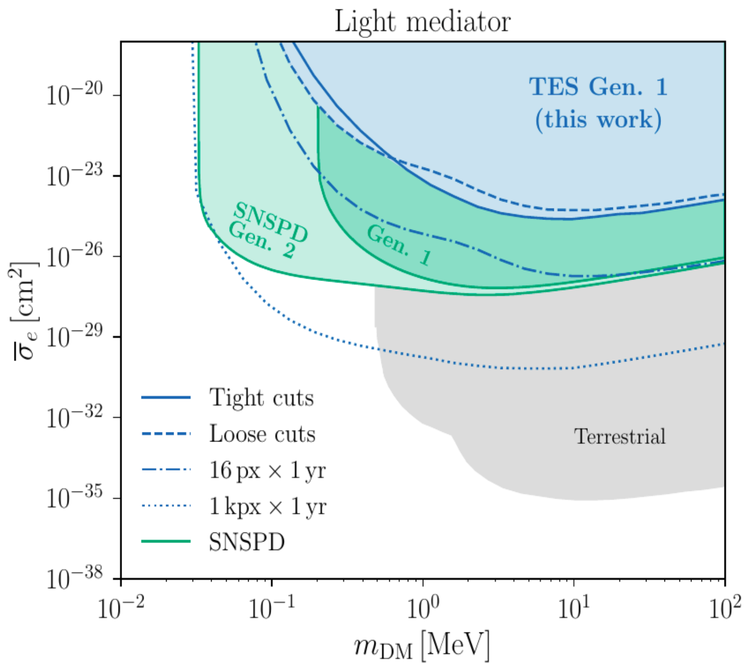
Summary



- First direct search for light dark matter interactions in a TES (use of the TES as target and sensor simultaneously)
  ➔ Successful proof-of-concept study
  - Here: 0.2 ng detector in a system originally for the ALPS II experiment was used ➔ Small setup, not optimized for a DDM search

- Improving the limits:
  - Even better understanding/reduction of background could increase the sensitivity considerably
  - DM run with membrane TES sensor
  - Larger systems with optimized sensors

- Within the QS4Physics project we aim to evaluate the feasibility and efficacy of a larger system

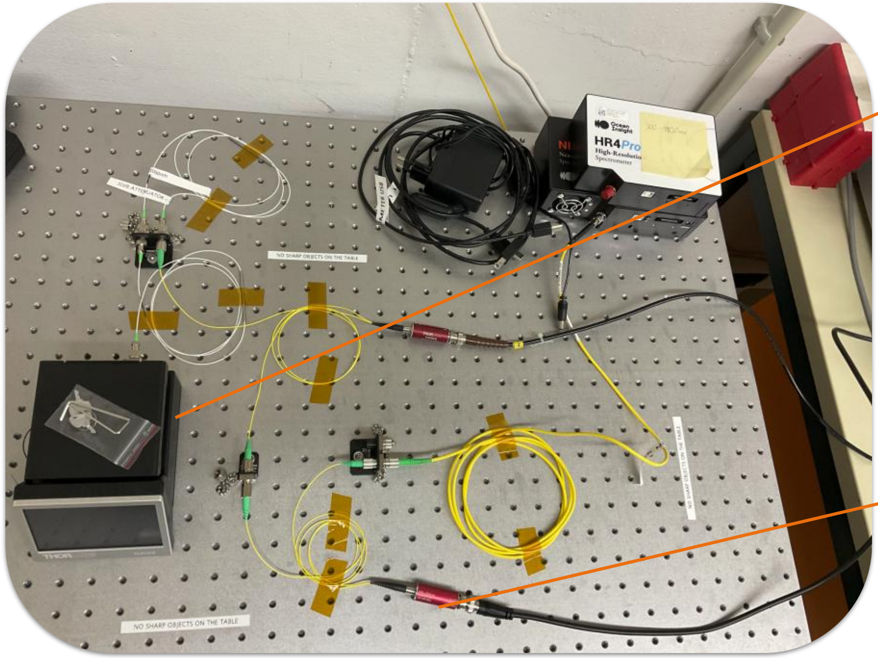


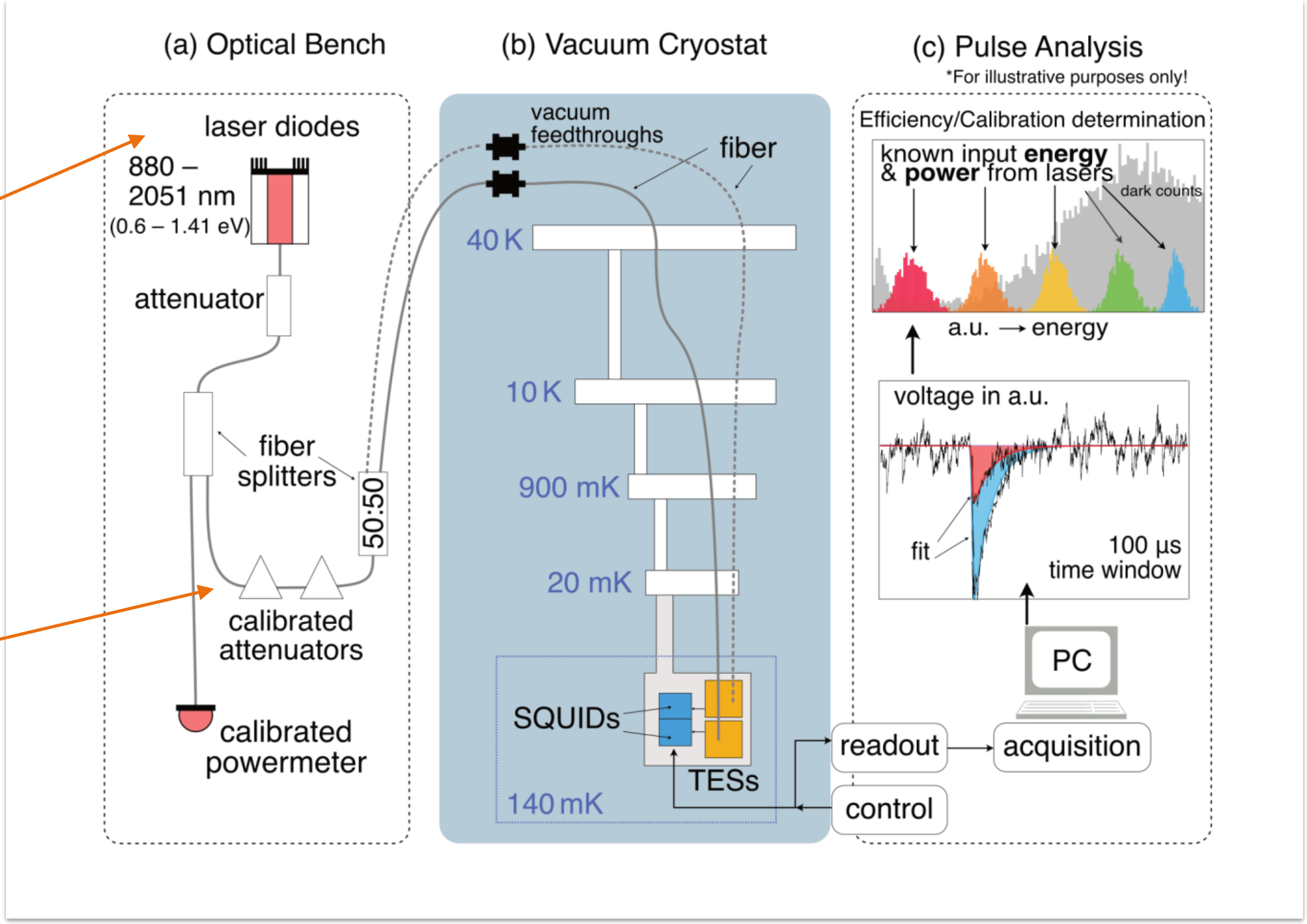
arXiv:2506.18982

Backup

Can we use our TES for other energies?

Calibration Setup

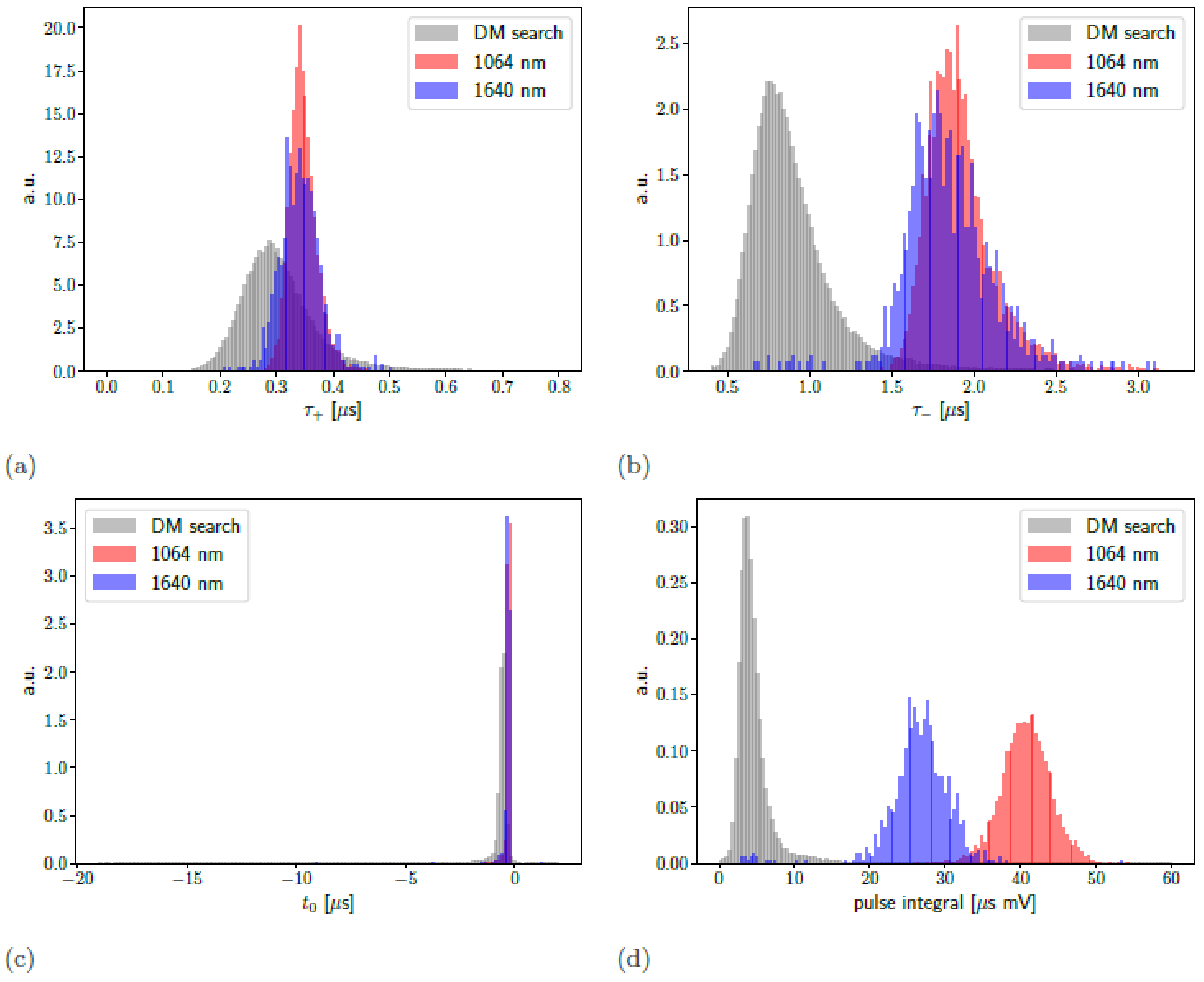




Event selection: Cuts

Loose and tight cuts

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



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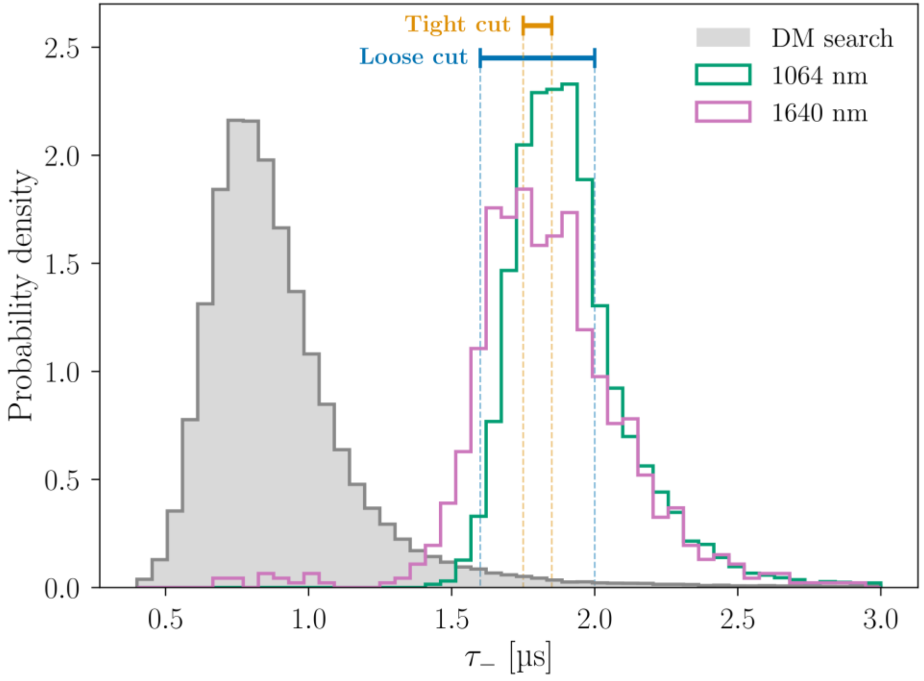
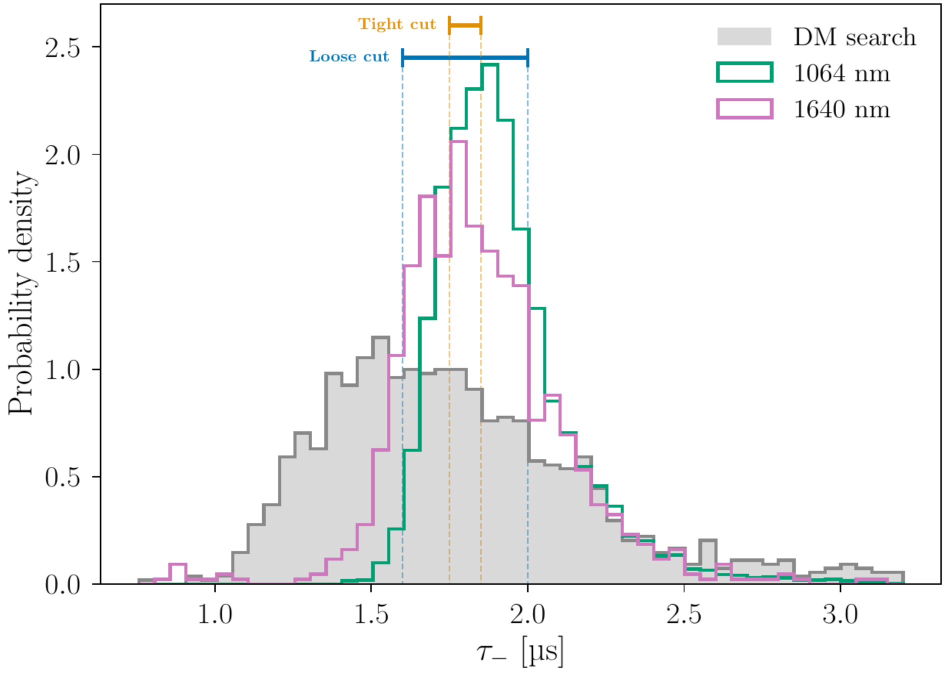
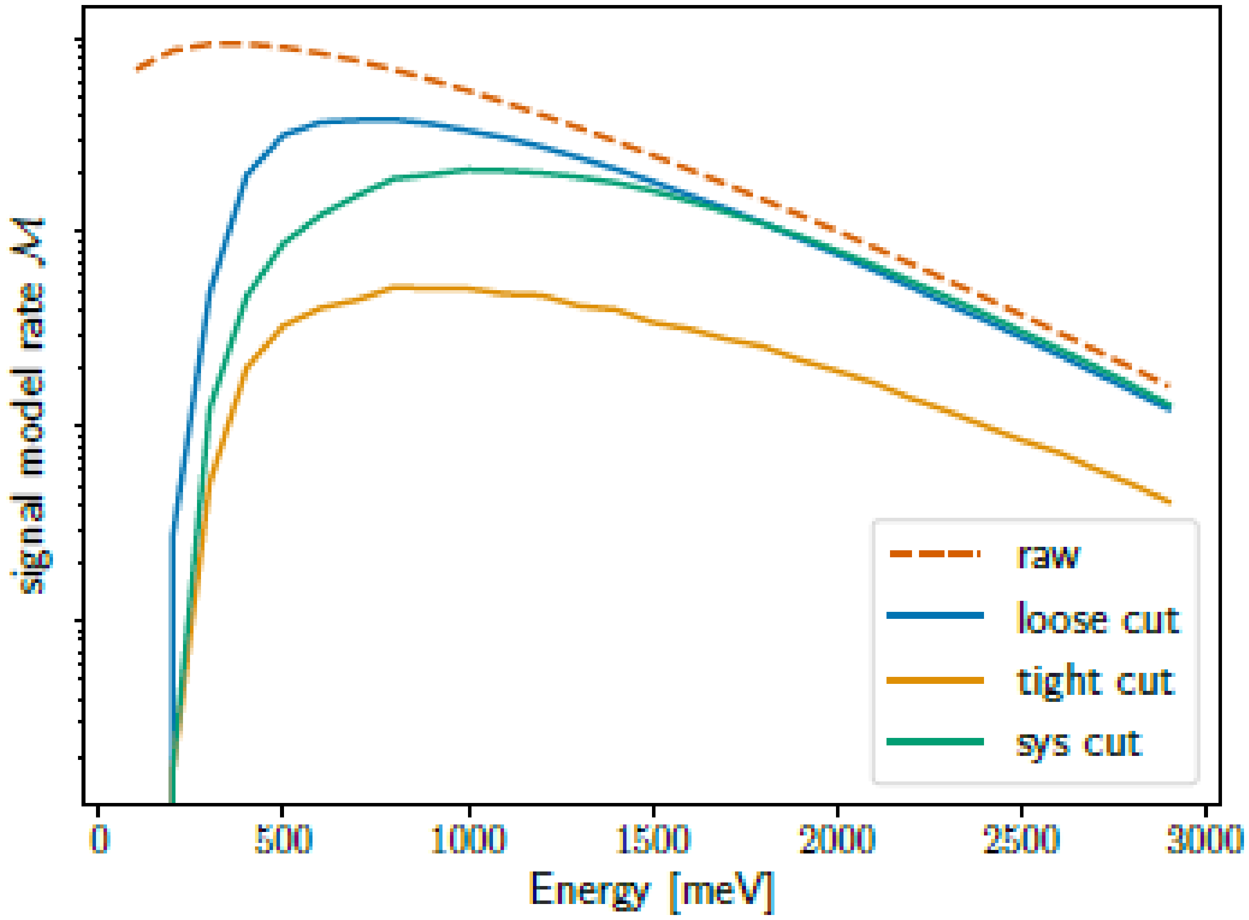




Predictions

Dark matter model dependent



Energy resolution

PhD Thesis José Alejandro Rubiera Gimeno (DESY, now @ HSU)

- Energy resolution of the TES can be understood and reproduced from the noise

J. A. Rubiera Gimeno et al., “The TES detector of the ALPS II experiment”, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 1046 (January 2023) 167588, doi:10.1016/j.nima.2022.167588

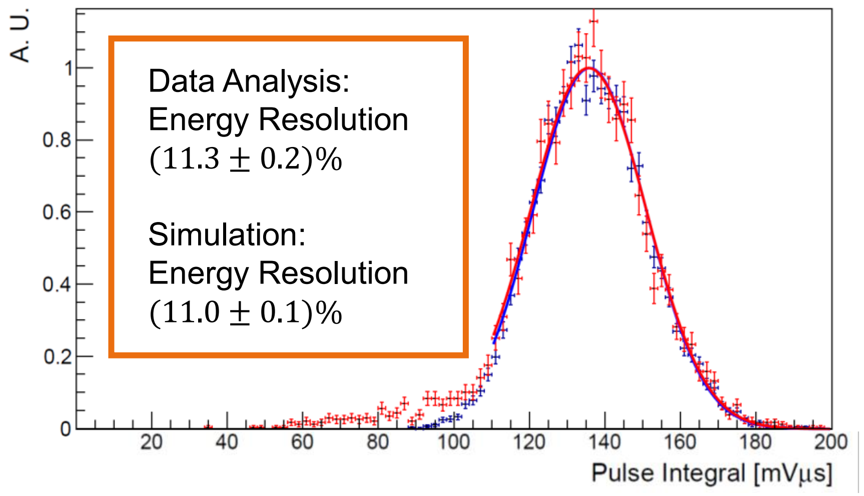
- With improved analysis, we can reach an energy resolution of **about 5%**
  - Faster fitting in the frequency domain
  - Access to physical properties of the sensor
  - Improvement in energy resolution by a factor of 2

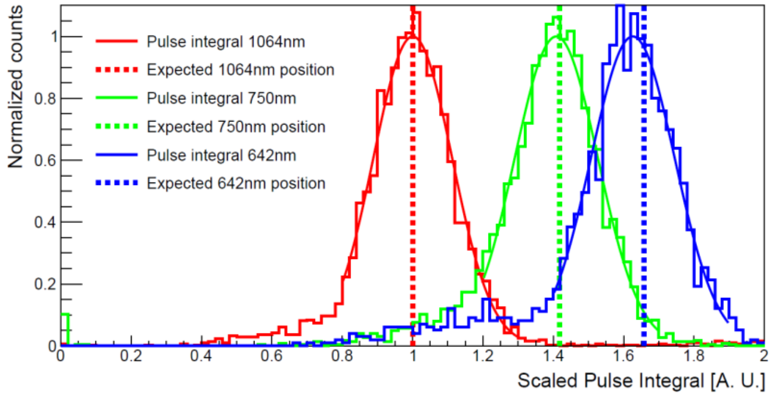
    (0.31 eV ➔ 0.14 eV FWHM)

J. A. Rubiera Gimeno et al., “A TES system for ALPS II - Status and Prospects”, PoS EPS-HEP2023 (2023) 567, doi:10.22323/1.449.0567

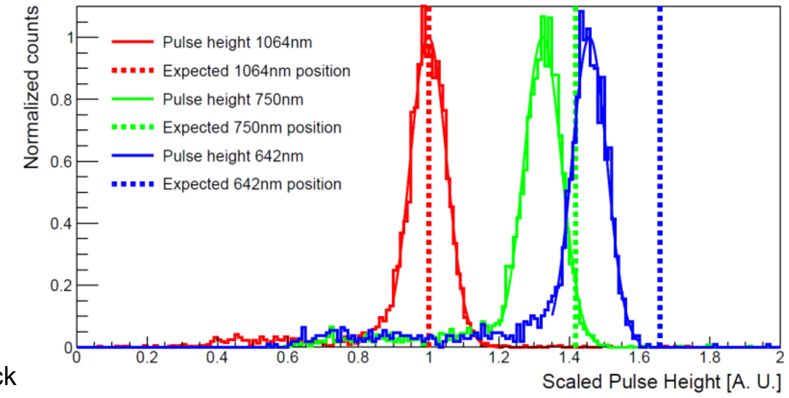
Pulse height, FFT (1064 nm)

$$\frac{\sigma}{\mu}100\% = (5.31 \pm 0.06)\%$$





(a)



Intrinsic dark counts

PhD Thesis Rikhav Shah (Mainz, now UHH)

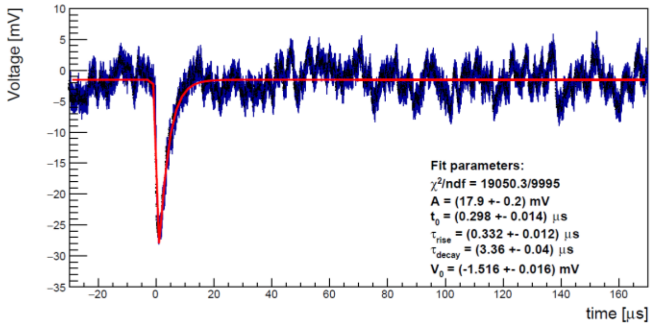
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

- With data analysis rate of events in the order of 10^{-2} Hz could be reduced to a dark count rate of $\mathbf{6.9 \cdot 10^{-6}}$ **Hz** over 20 days for 1064 nm photons with an acceptance greater than 90%

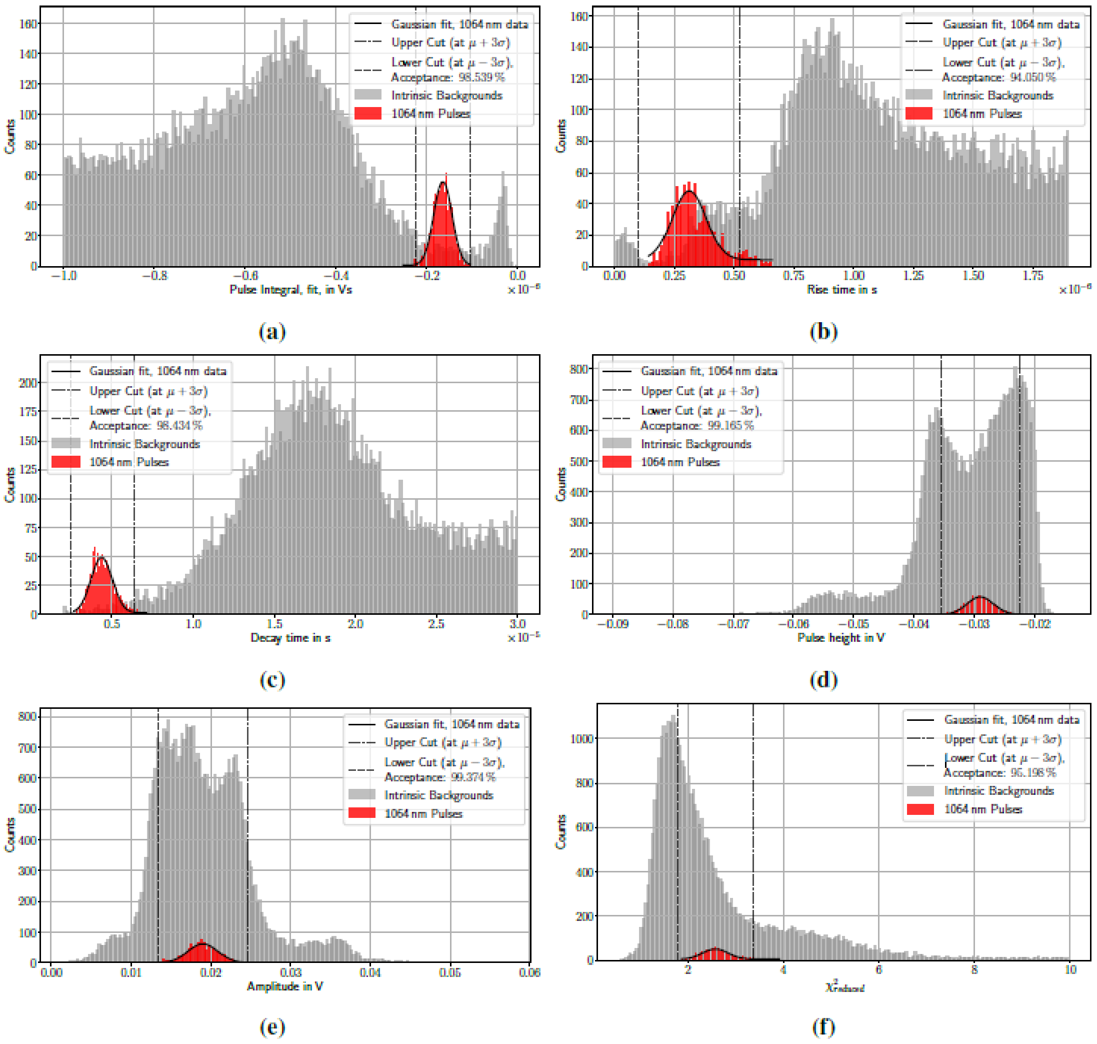
Shah, R., Isleif, KS., Januschek, F. *et al.* Characterising a Single-Photon Detector for ALPS II. *J Low Temp Phys* (2022). https://doi.org/10.1007/s10909-022-02720-0

- Currently investigating improvements with Machine Learning Algorithms

Meyer, M., Isleif, KS, Januschek, F et al. A First Application of Machine and Deep Learning for Background Rejection in the ALPS II TES Detector https://doi.org/10.1002/andp.202200545



Cut-based-analysis

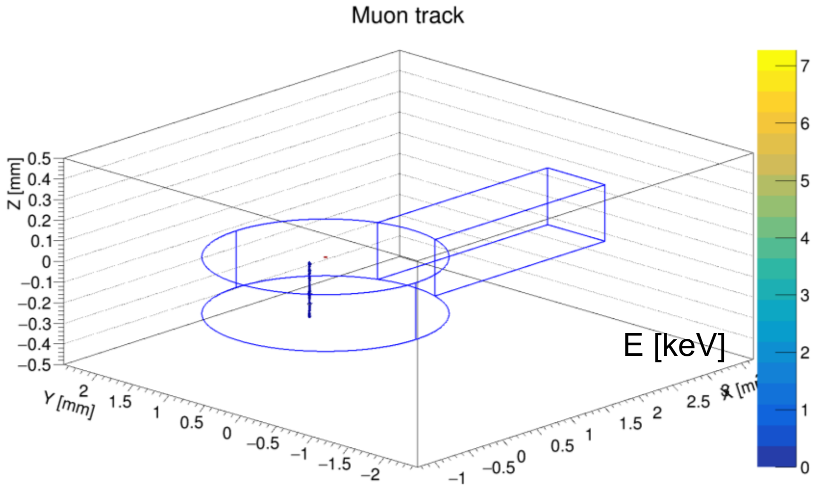


Simulations of noise, background and signals

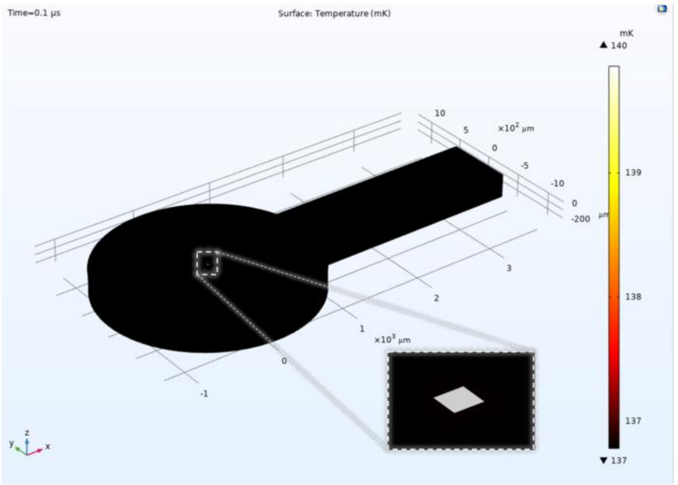
PhD Thesis José Alejandro Rubiera Gimeno (DESY, now HSU)

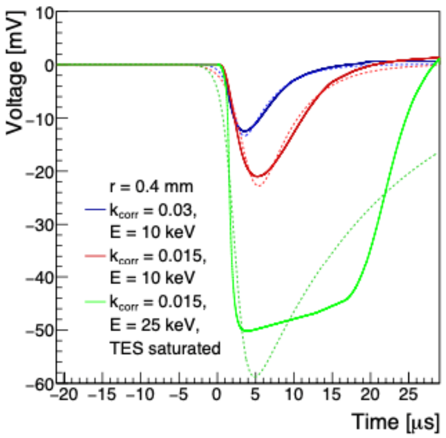
- Simulation of noise for understanding and improving energy resolution as well as reduction of noise counts
- Simulation of TES signal➔ understanding of the system, improving selection criteria
- Simulation of background ➔ background reduction

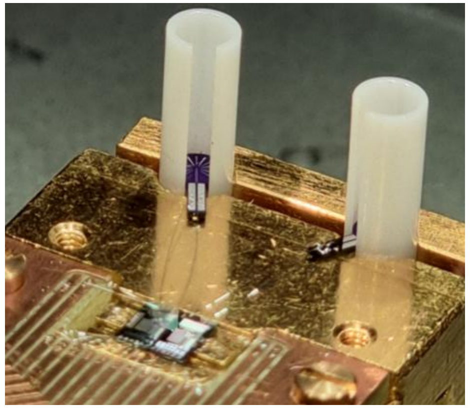
Simulation of energy deposition of radiation (muon, gamma) in Geant4



Simulation of TES physics and transport of heat in silicon substrate using COMSOL Multiphysics



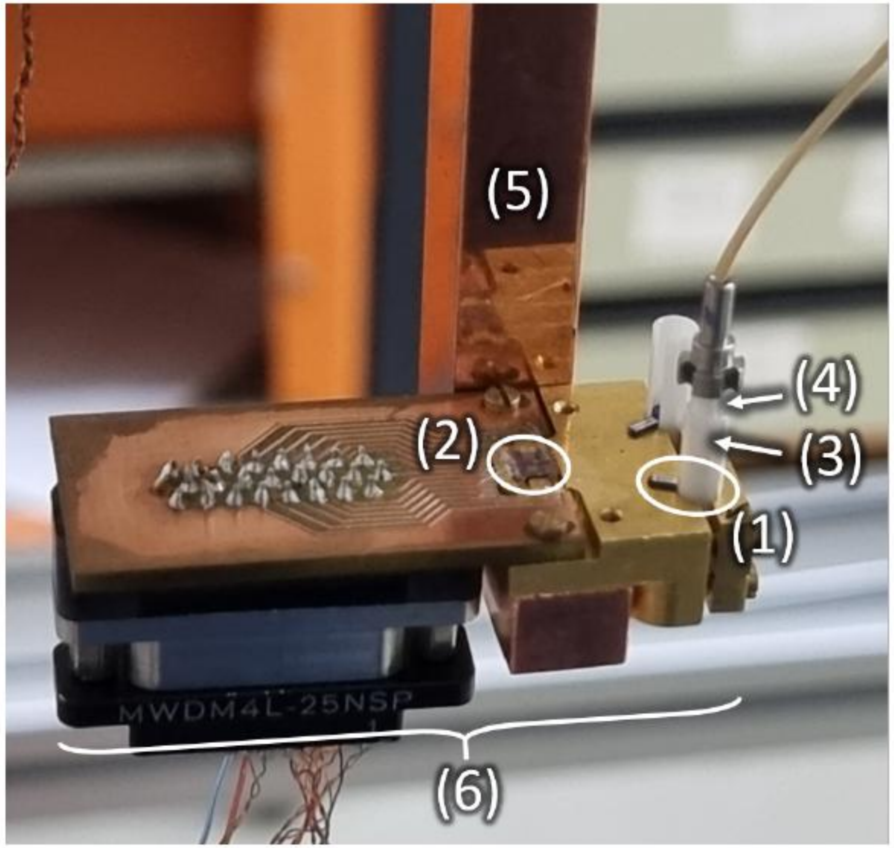




Radioactivity of the Zirconia from the fiber sleeve can explain the majority of the remaining „intrinsic“ background!

Black Body Radiation simulation framework for simulating spectrum detected by the TES with different suppression methods

Geant4 simulation geometry



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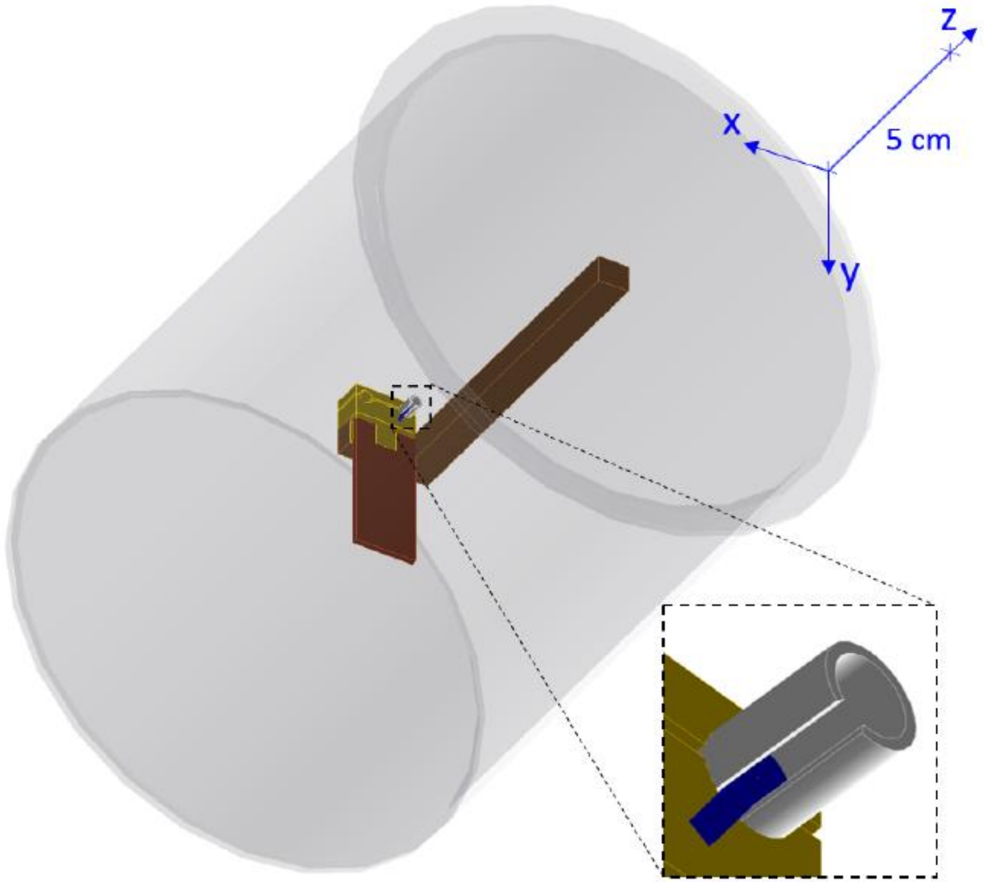

(b)

Simulation of intrinsic background

Zirconia as main background contributor

- Shape describe different types of events
- Rate of events passing the threshold are compatible with data

Rates from Geant4 + COMSOL simulation

Zirconia: rate $\in [0.33\ ;\ 2.1] \cdot 10^{-2}$ cps
Muon: rate = $8 \cdot 10^{-5}$ cps

Rate from data: $2.1 \cdot 10^{-2}$ cps