

Simulation of Direct Dark Matter Searches using ALPS II's TES detector

1st Training School COST Action COSMIC WISPerS

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Adriana E. Lita⁵, Jose Manuel López González⁶,
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⁶University of Santiago de Compostela, Spain

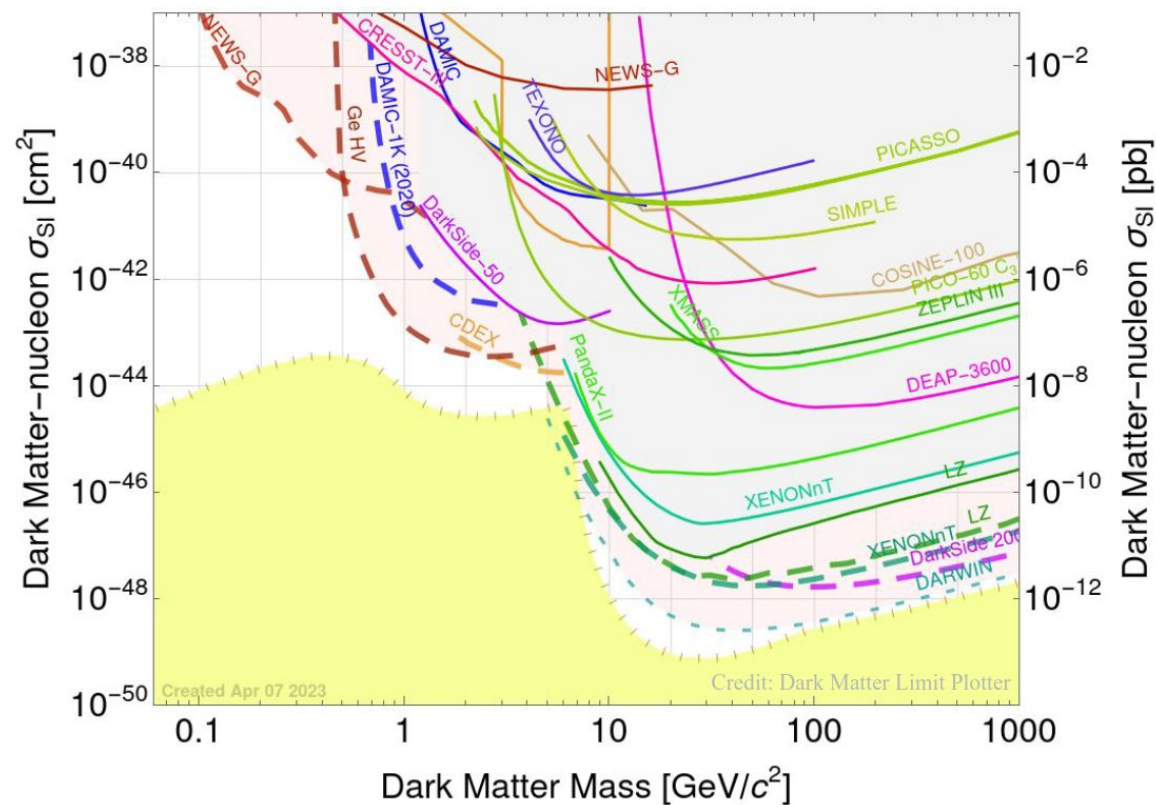
⁷Institut für Experimentalphysik, Universität Hamburg, Germany

⁸Johannes-Gutenberg Universität Mainz, Germany

Lecce, 13.09.2023

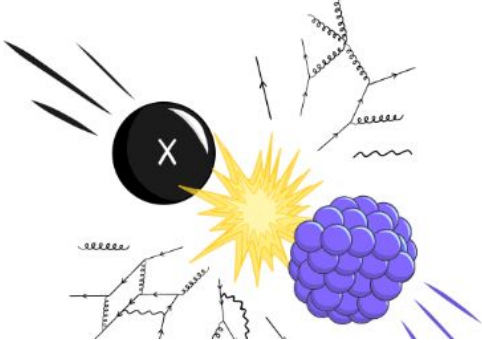
Detection of sub-GeV Dark Matter

Dark Matter – electron scattering



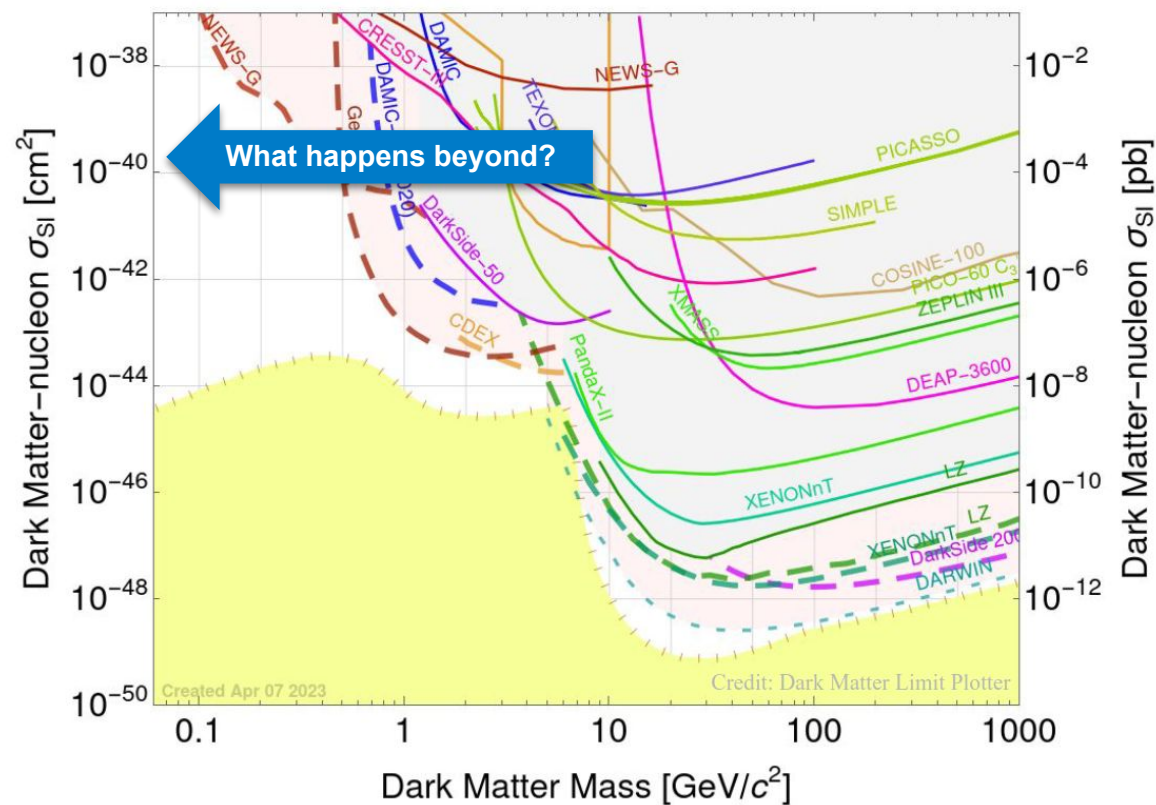
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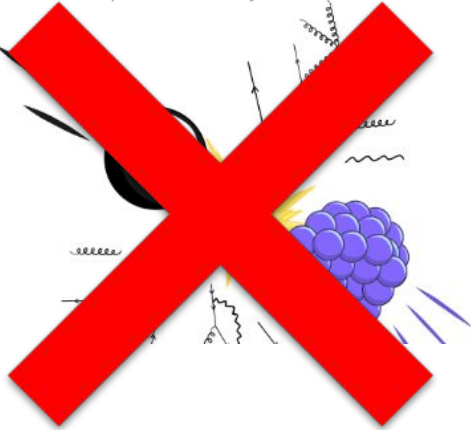
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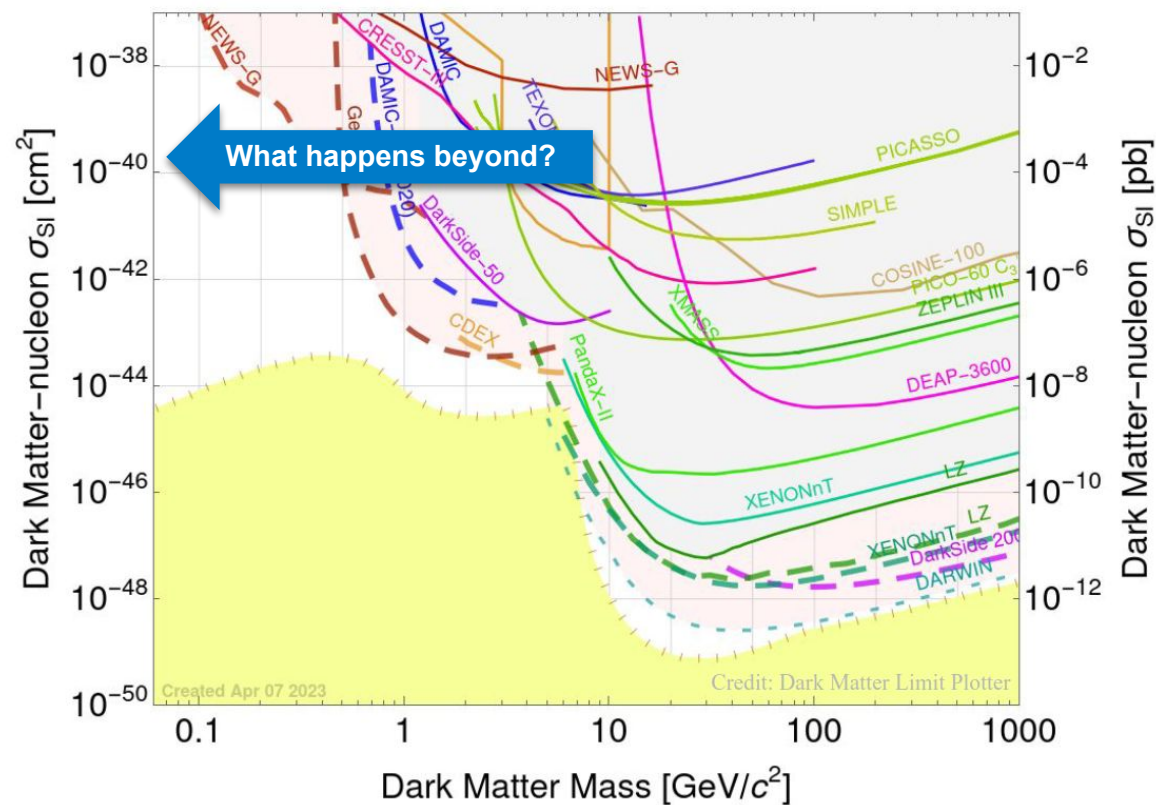
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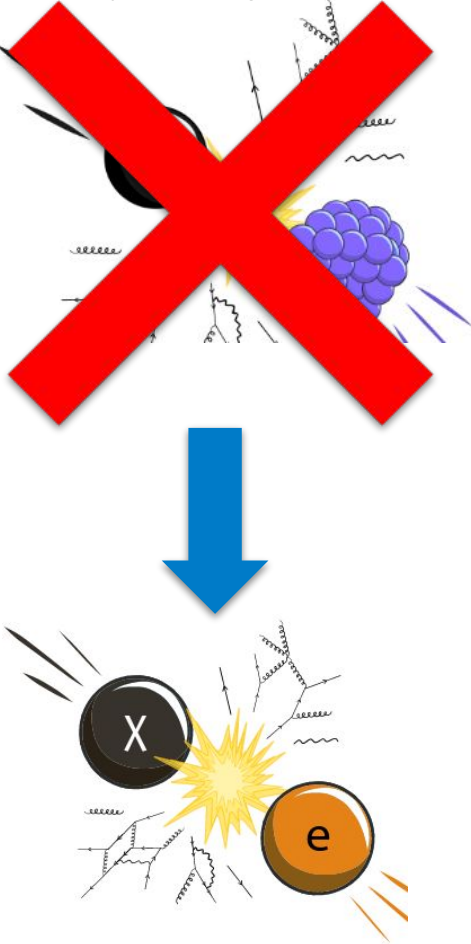
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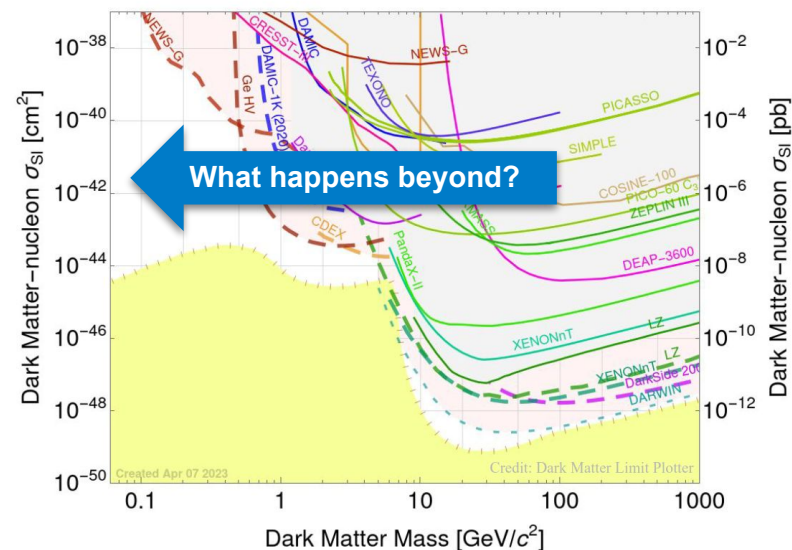
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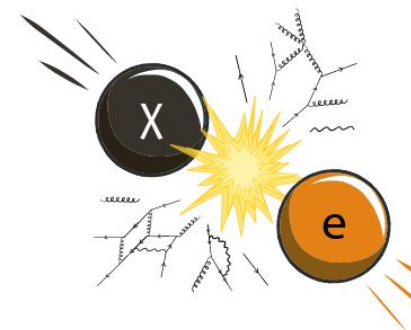
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Assume:

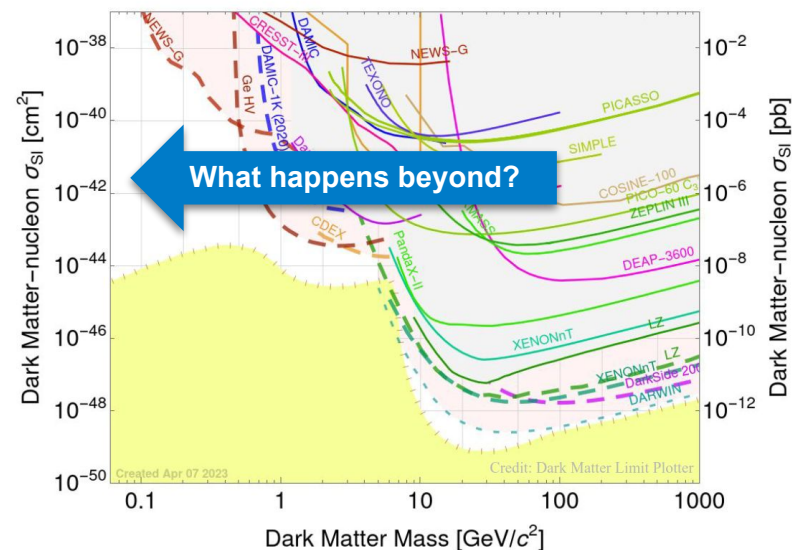
- Characteristic DM halo velocity $v_\chi \sim 10^{-3}c$
- Scattering via mediator (heavy or light) coupling to electrons (e.g. dark photon as massless mediator)

Maximum Energy transfer E_T in scattering event is entire kinetic energy of DM particle with mass m_χ :

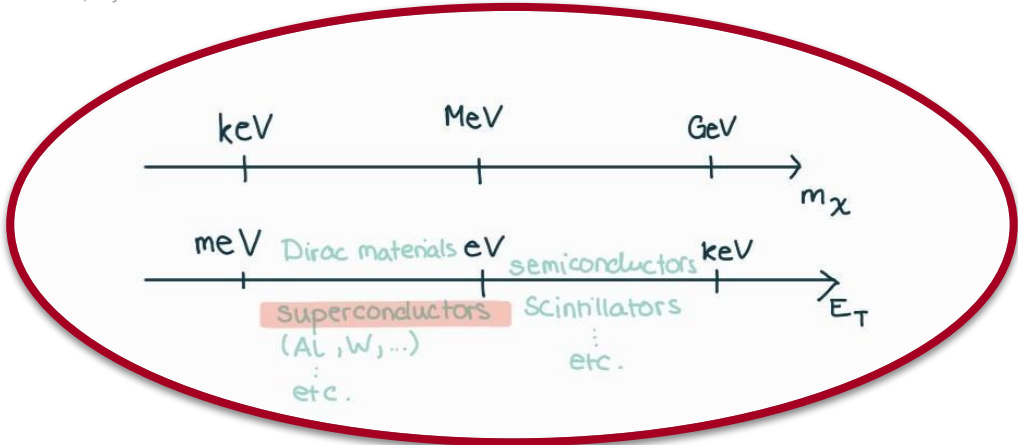
$$E_{T_{\max}} = E_{\text{kin}} \sim m_\chi v^2 \sim 10^{-6} m_\chi$$

Detection of sub-MeV Dark Matter

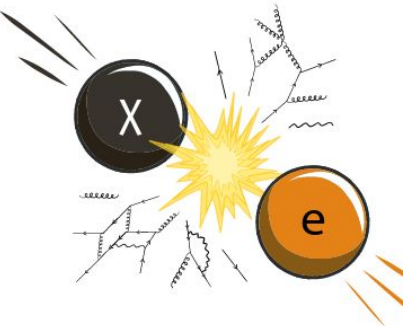
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DARK MATTER SEARCHES WITH SUPERCONDUCTORS

DM Searches with Superconductors

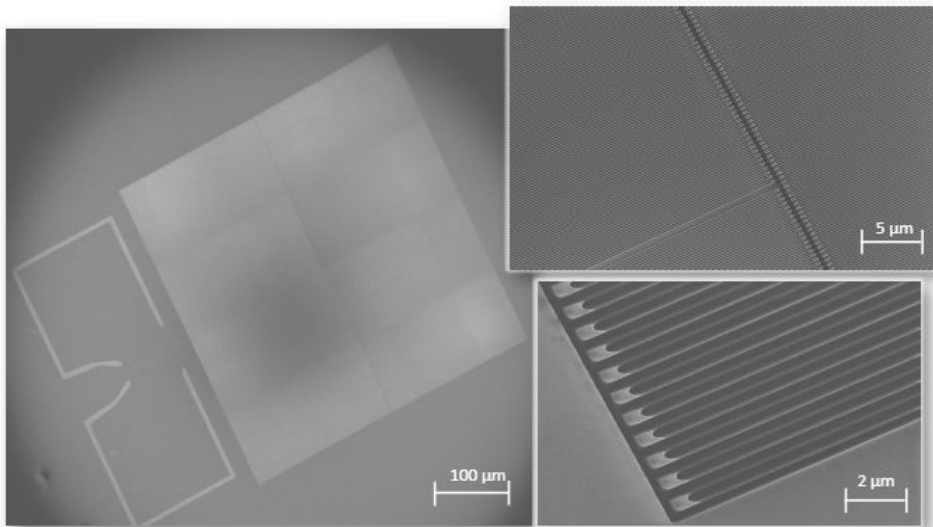
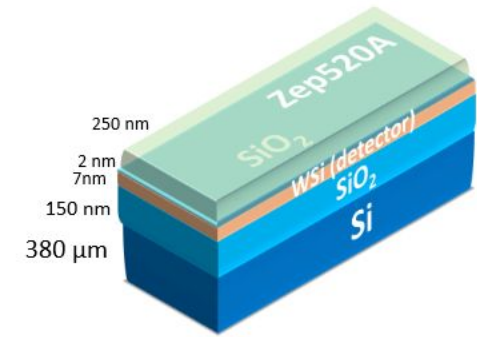
Role model: SNSPDs

Example: principle proven for SNSPDs

(Superconducting Nanowire Single Photon Detector)

- First measurements already set new bounds
- Only 4 dark counts in 180 hrs
- 0.73 eV energy threshold
- Allows to exclude DM-electron scattering parameter space

- Low noise
- 'Large' target mass (4.3 ng)
- Low energy threshold



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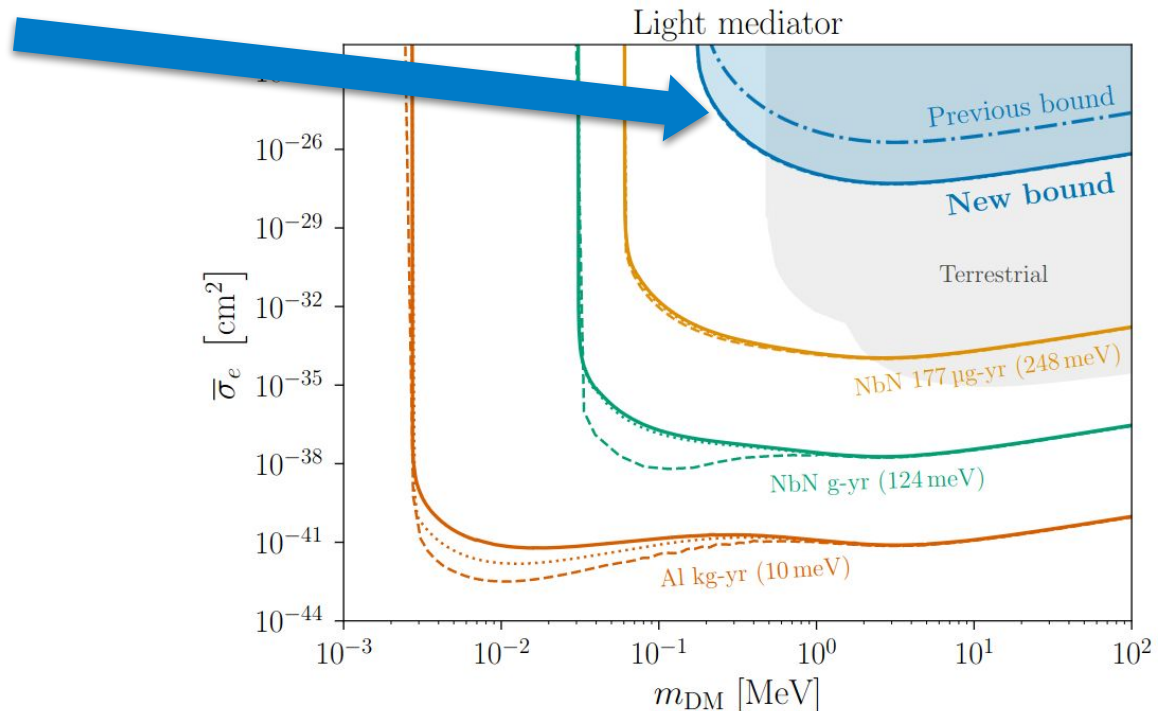
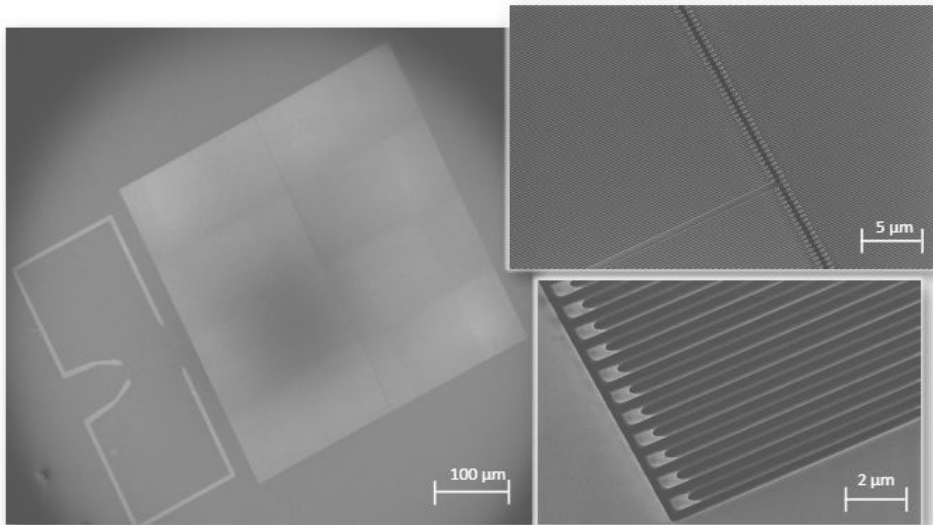
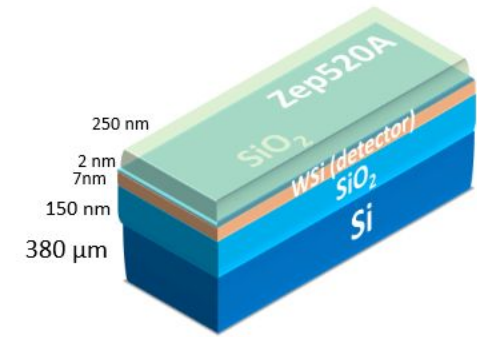
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DM Searches with Superconductors

SNSPD vs TES

Limits of SNSPDs:

Works like a Geiger counter



No pulse-shape discrimination

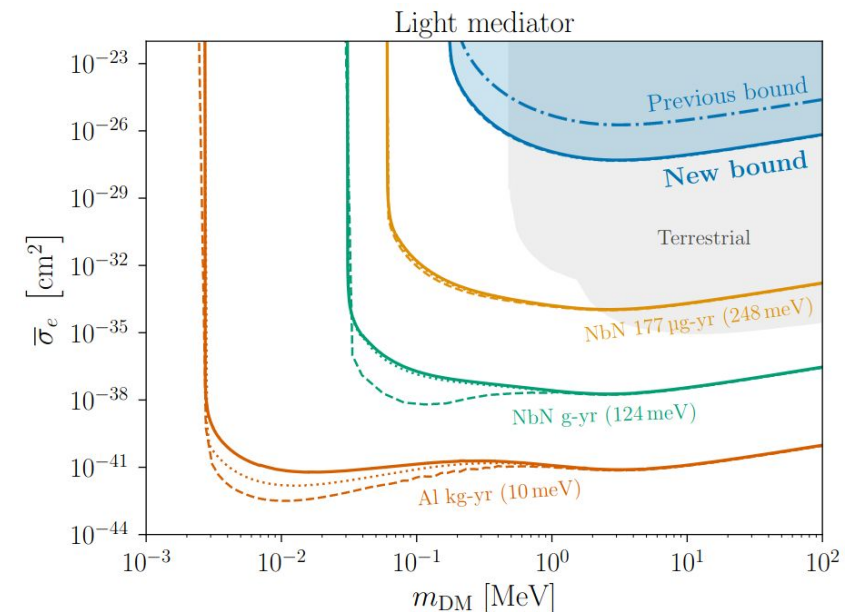
Superconducting Detectors for Super Light Dark Matter

Yonit Hochberg,¹ Yue Zhao,² and Kathryn M. Zurek¹

¹*Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720
Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720*

²*Stanford Institute for Theoretical Physics, Department of Physics,
Stanford University, Stanford, CA 94305, U.S.A.*

We propose and study a new class of superconducting detectors which are sensitive to $\mathcal{O}(\text{meV})$ electron recoils from dark matter-electron scattering. Such devices could detect dark matter as light as the warm dark matter limit, $m_X \gtrsim 1 \text{ keV}$. 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/astrophysical constraints could be detected by such detectors with a moderate size exposure.



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- ✓ Energy information (Pulse shape analysis possible)
- ✓ Possibly lower energy threshold
- ✗ Lower mass (0.2 ng)

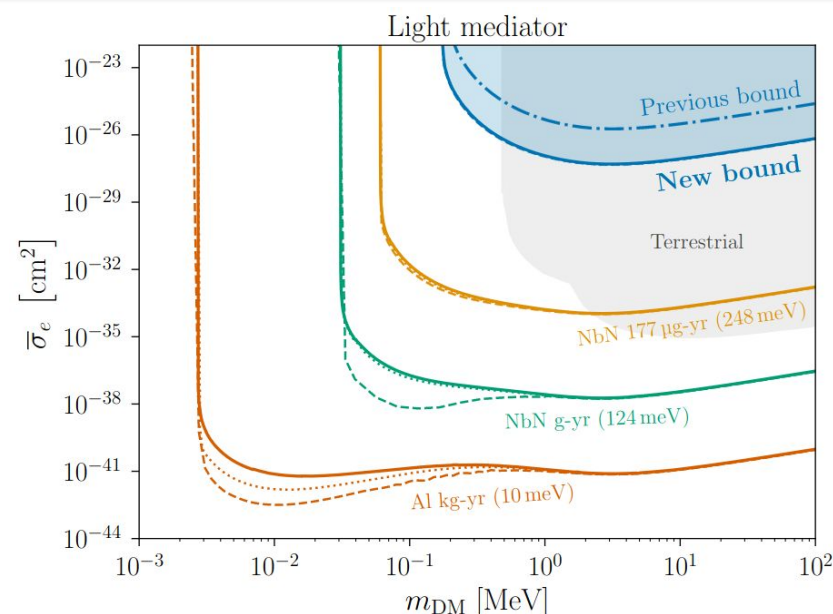
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Possible sensitivity based on our TES

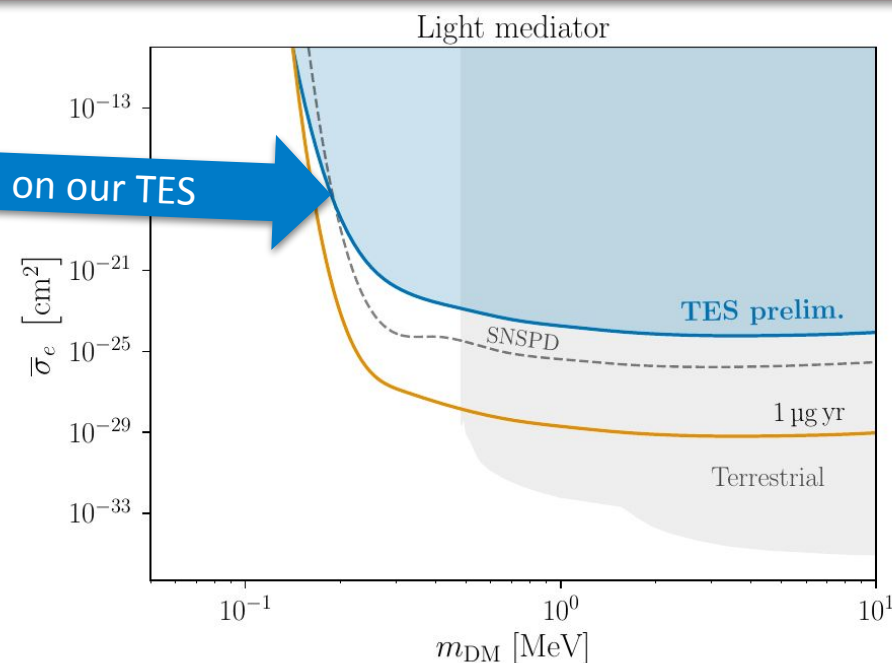
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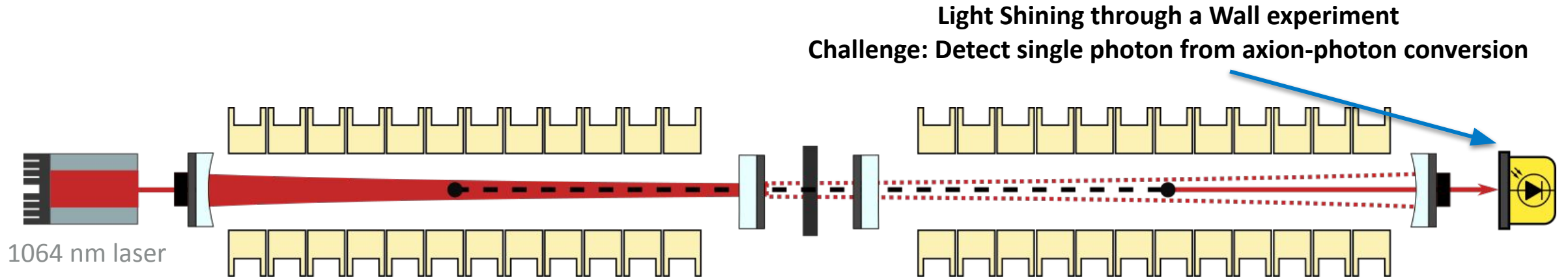
Projections and plot by Benjamin V. Lehmann

The background is a monochromatic blue-toned illustration. It features a central large, textured sphere resembling a planet or moon. Behind it are jagged mountain peaks. The sky is filled with numerous small stars and several larger, irregularly shaped celestial bodies or rocks. In the lower right, there are stylized, branching structures that look like coral or alien vegetation. The overall style is artistic and dreamlike.

TES @ ALPS II

TES Single Photon Detection

Detection techniques in the ALPS II experiment



Application of two photon-measurement schemes:

HETerodyne interferometry (HET)

- detects photon fields
- mixing of regenerated fields with local oscillator
- measurement of resulting beat note

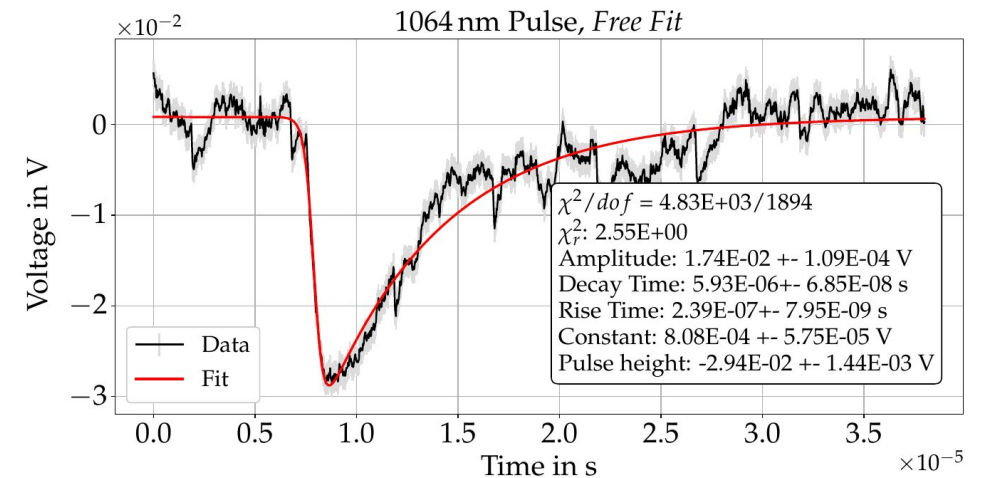
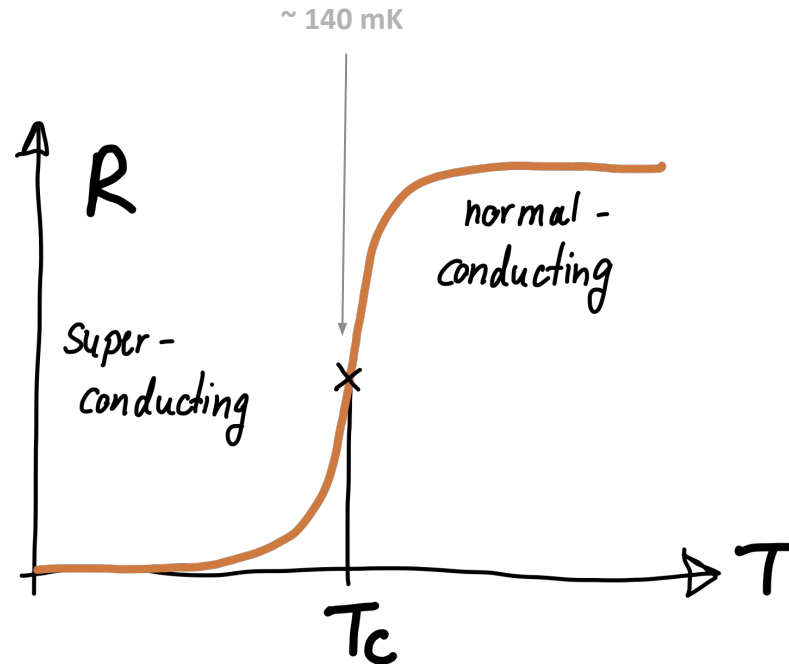
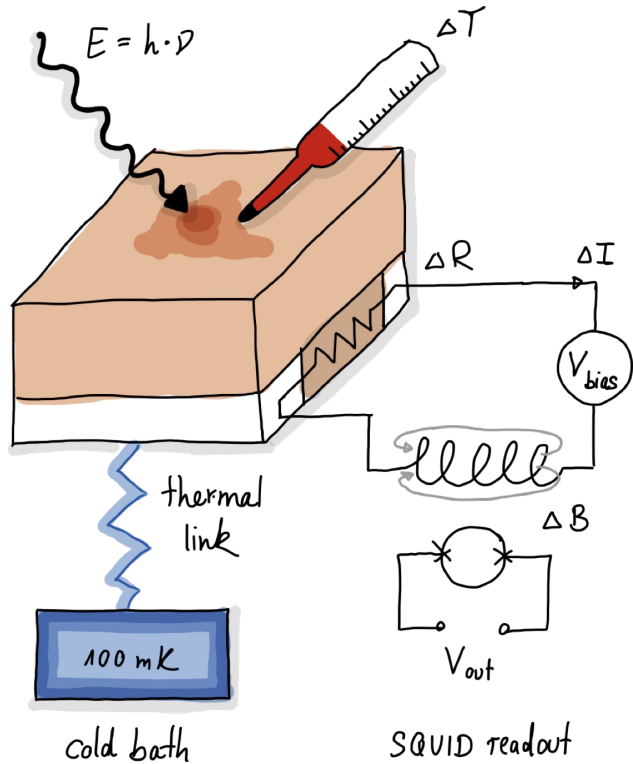
Transition Edge Sensor (TES):

- Single photon detection
- Using **superconducting** tungsten chip

More details: "Analysis of Transition Edge Sensor data for the ALPS II experiment." – José Alejandro Rubiera Gimeno

TES Single Photon Detection

Transition Edge Sensors



Courtesy of Rikhav Shah

- Cryogenic microcalorimeters
- Operated at superconducting transition temperature
- Read-out using Superconducting Quantum Interference Devices (SQUIDs)

- Incident photon leads to temperature increase
- Small temperature increase leads to large variation in resistance

- Change in resistance is measured in changing current
- Signal is proportional to photon energy
- Energy resolution $\leq 10\%$
- DM signal expected to look like photon

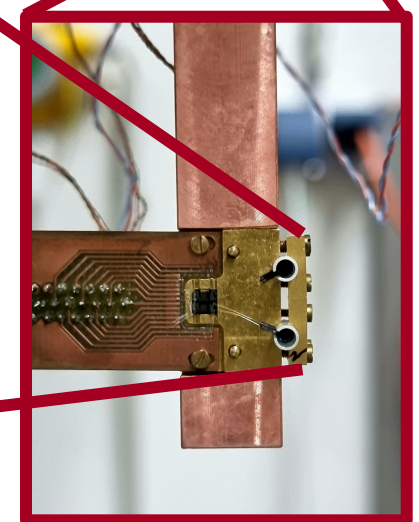
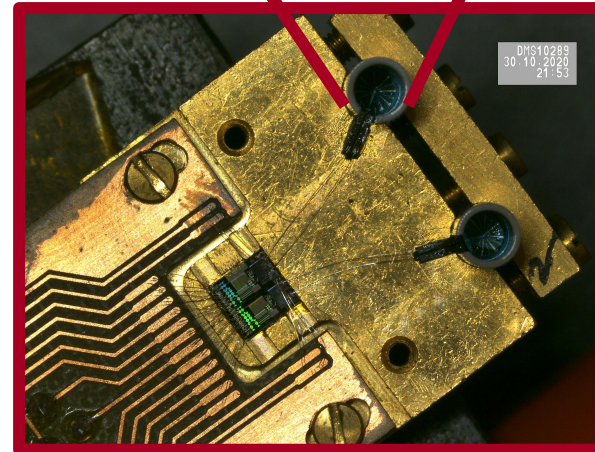
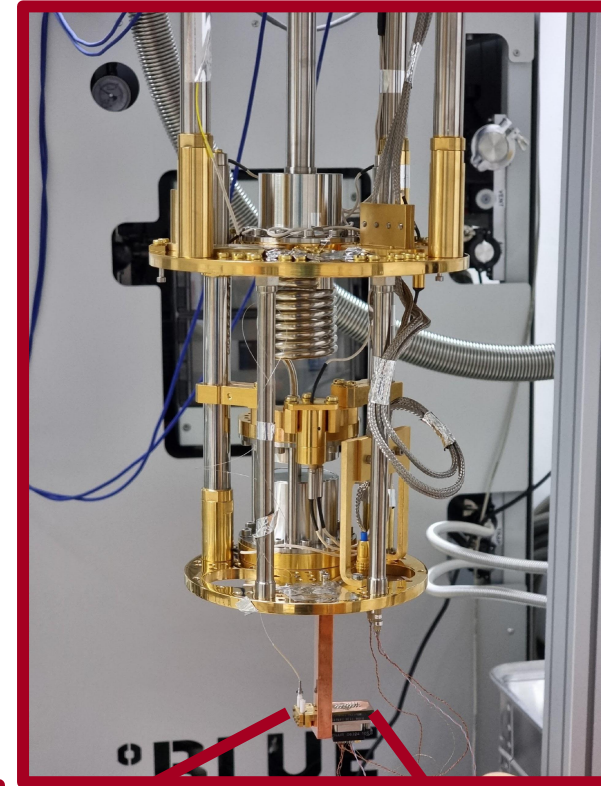
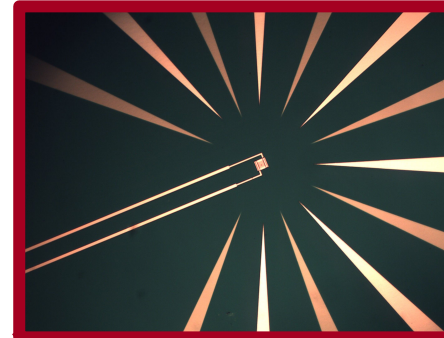
Drawings courtesy of Katharina-Sofie Isleif

TES as Dark Matter Detector

Current Challenges

TES @ ALPS II Status

TES chips and module
provided by NIST and PTB



¹ R. Shah et al., PoS, EPS-HEP2021, 801 (2022)

TES as Dark Matter Detector

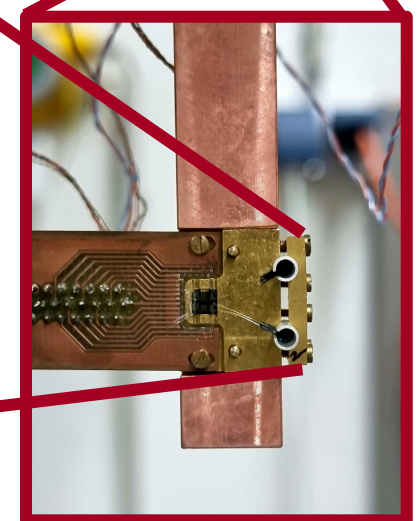
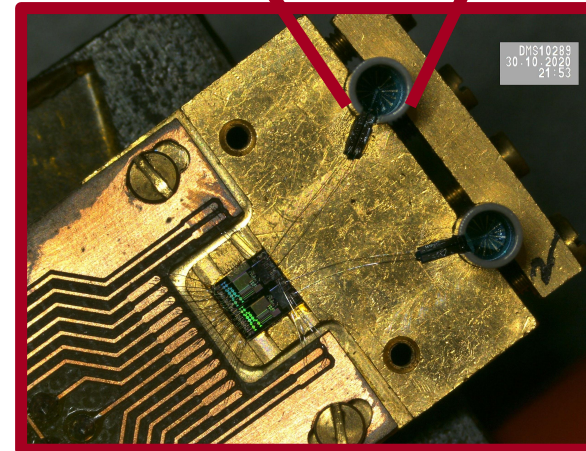
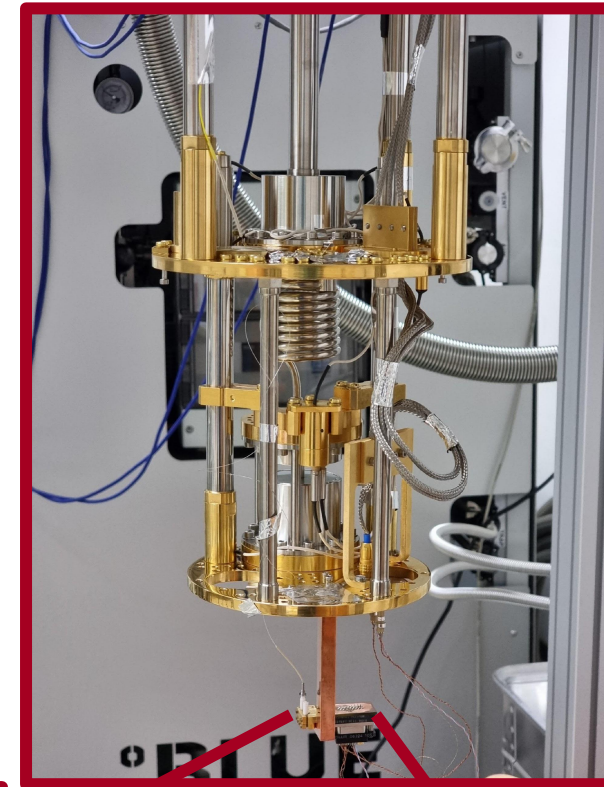
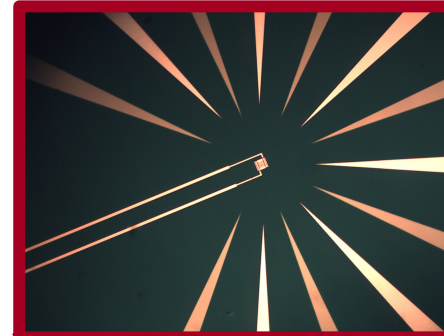
Current Challenges

TES @ ALPS II Status

- Optimized infrastructure (setup, analysis) for signals at 1064 nm → **1.165 eV**
- Limited knowledge about response to other wavelengths

Low background (electronic noise, radioactivity, cosmic backgrounds)
→ currently: $6.9 \times 10^{-6} \text{ cps}^1$
(intrinsic background for 1.165 eV signals)

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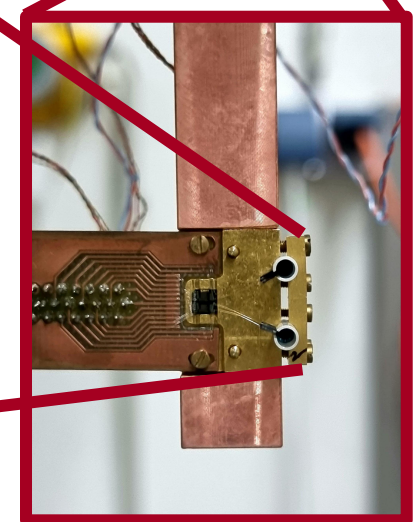
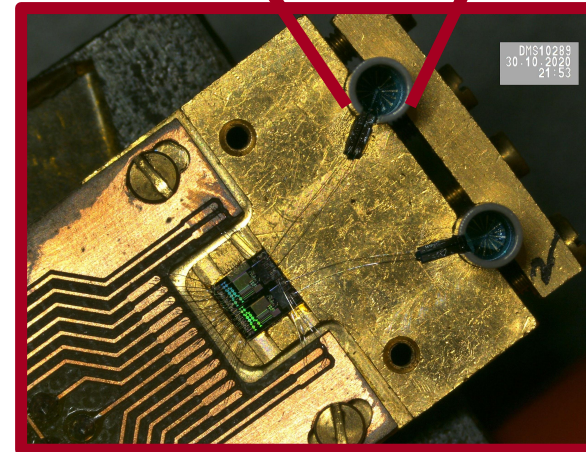
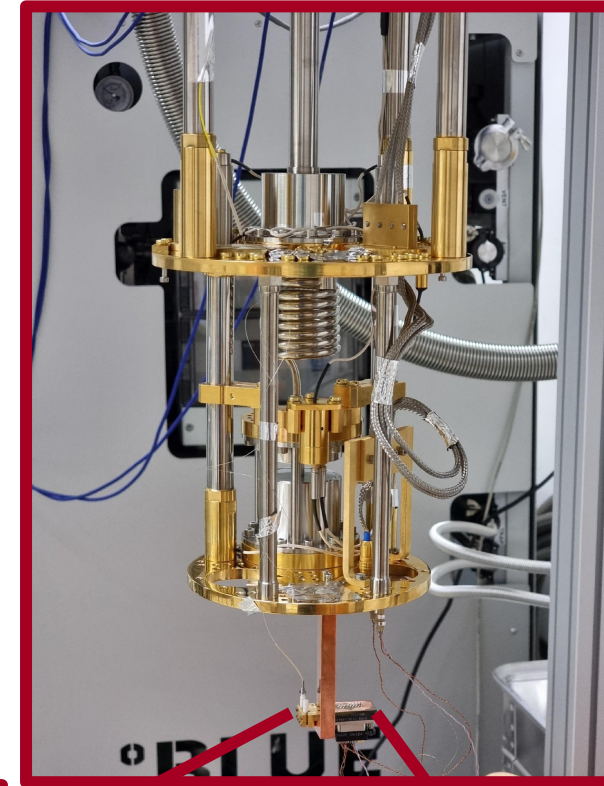
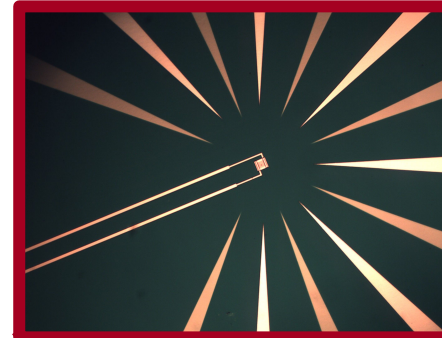
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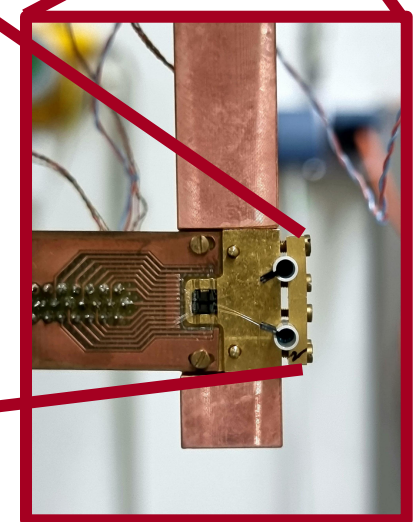
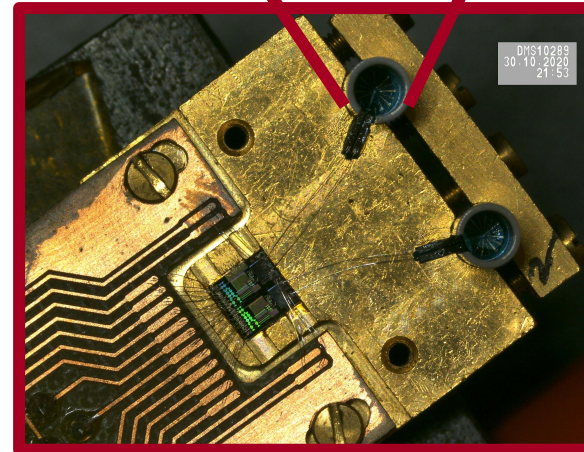
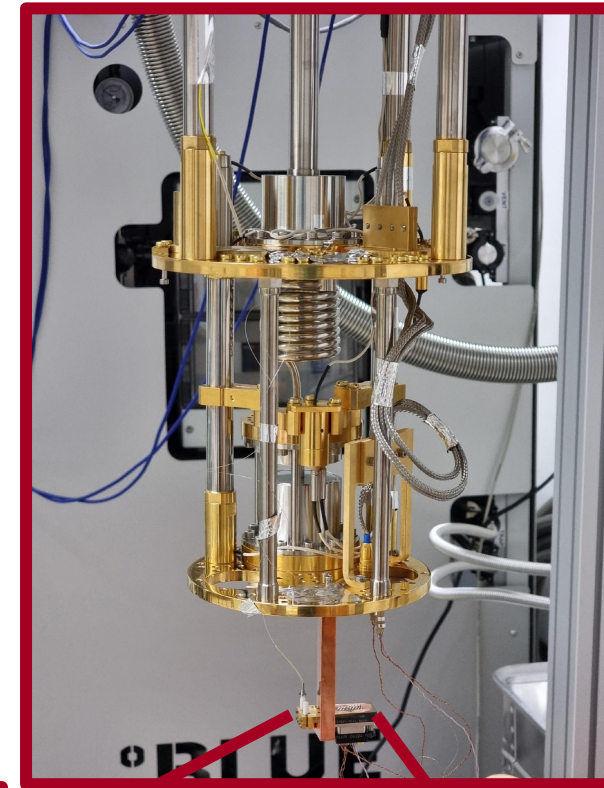
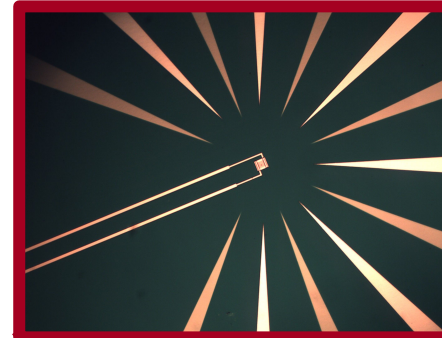
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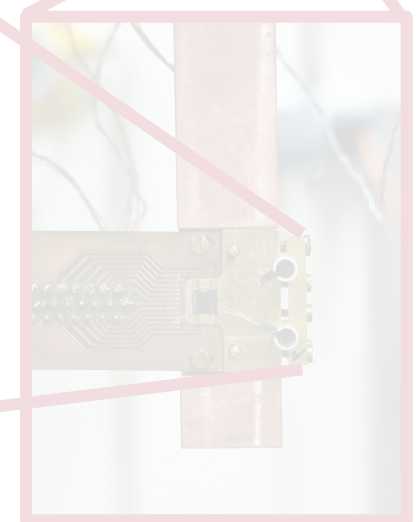
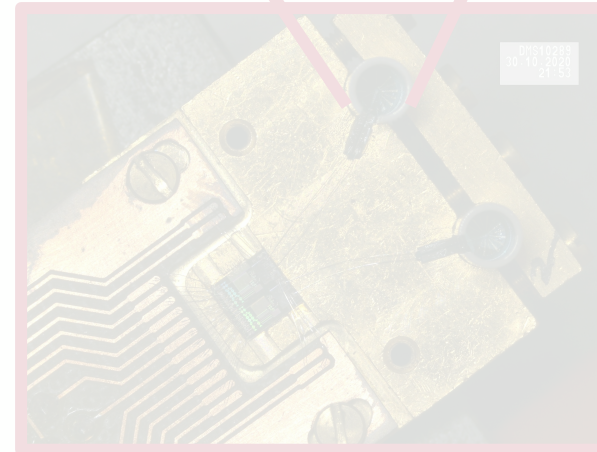
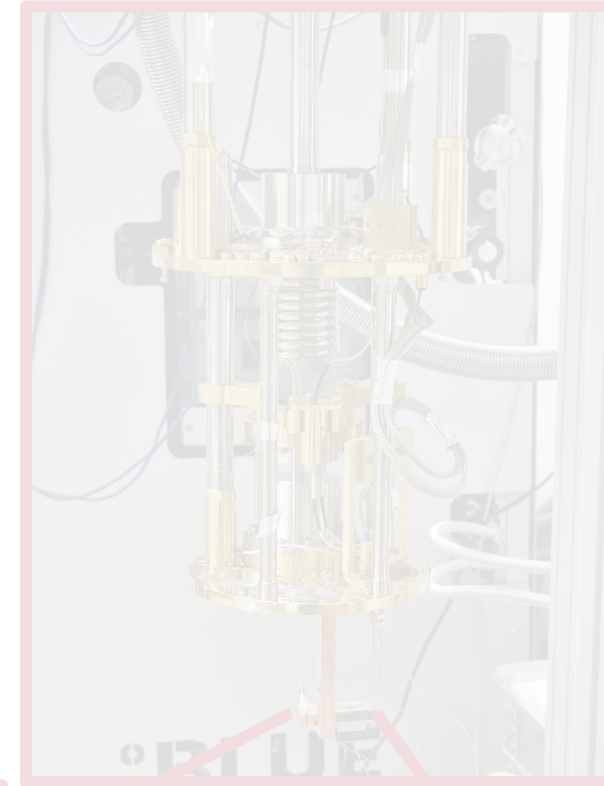
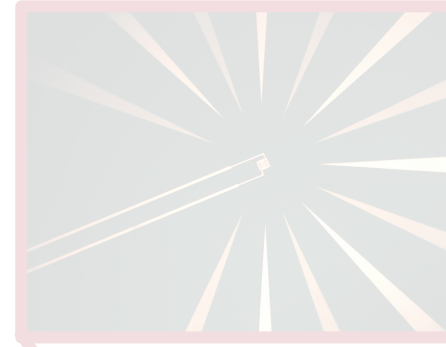
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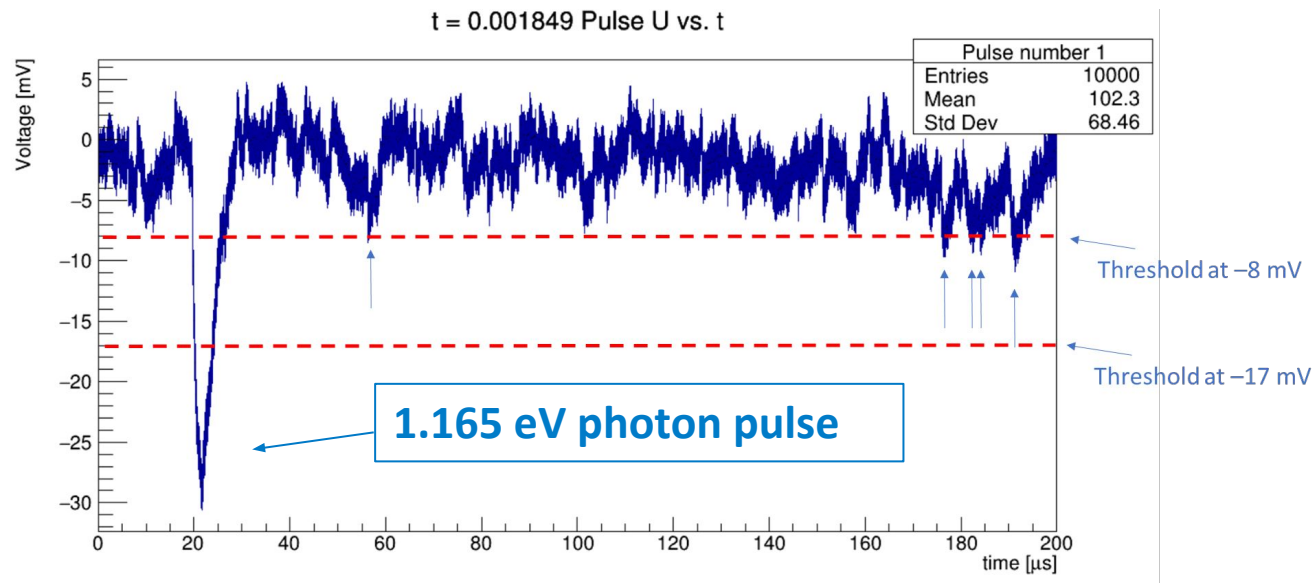
DIRECT DARK MATTER SEARCHES WITH TES - SIMULATIONS

TES pulses - simulation and analysis

How low can we go?

- Based on laser (1.165 eV) calibration
- and noise measurements

Simulation of electronic noise & pulses

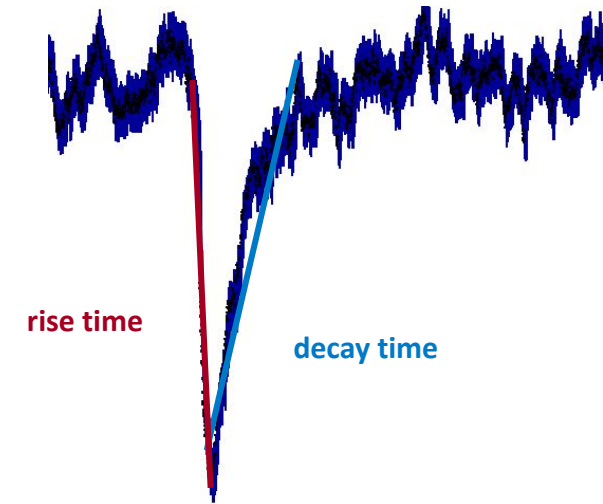
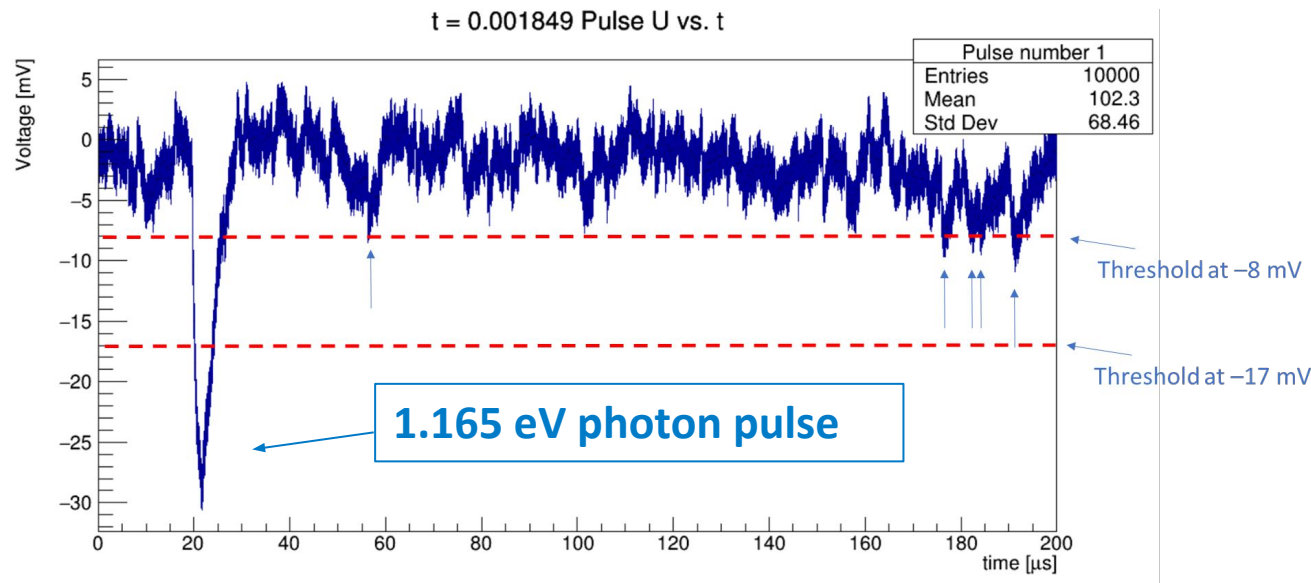


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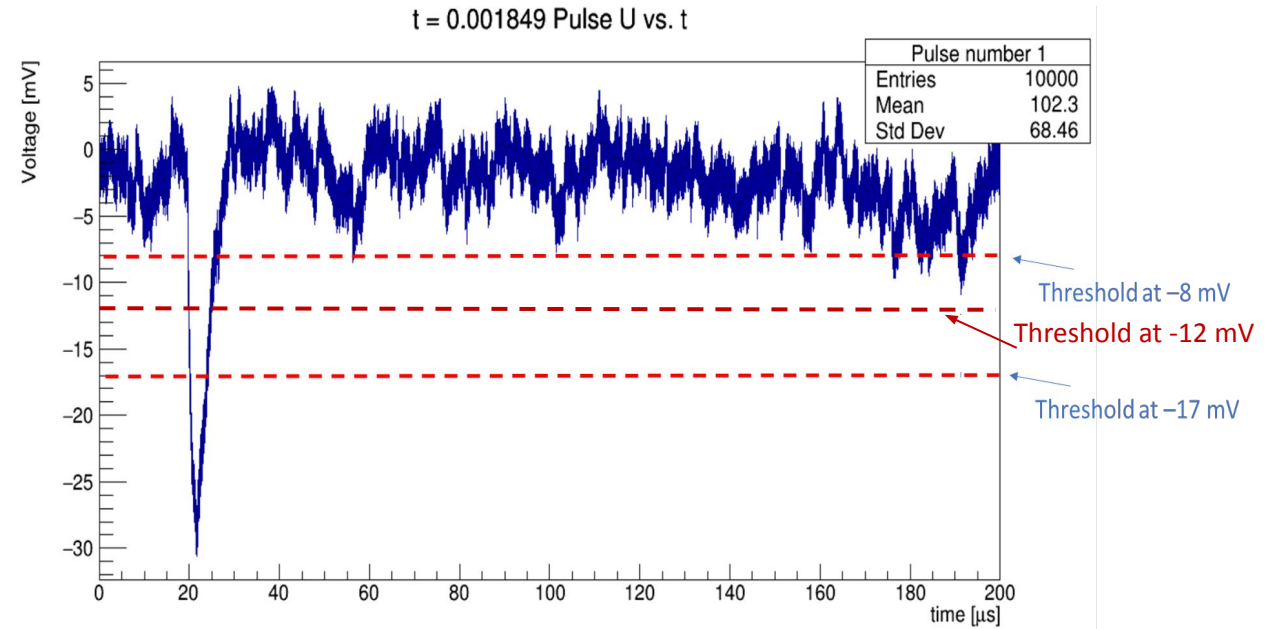
$$U(t) = -\frac{2A}{e^{-\frac{1}{\tau_{\text{rise}}}(t-t_0)} + e^{\frac{1}{\tau_{\text{decay}}}(t-t_0)}} + V_0$$

- known pulse shape fitted to all triggered pulses (recording single-photon pulses of an attenuated laser)
- can apply cuts on parameters e.g.
 - reduced χ^2
 - rise and decay time of the pulse
 - pulse height / amplitude

TES pulses - simulation

Triggered noise baseline simulations

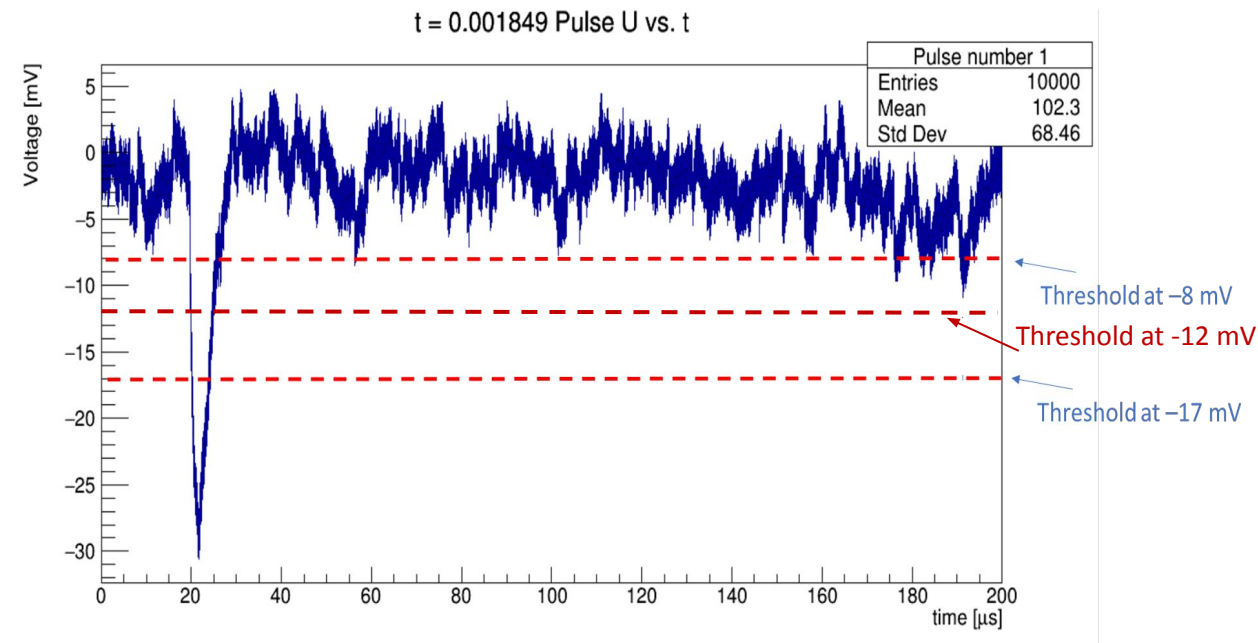
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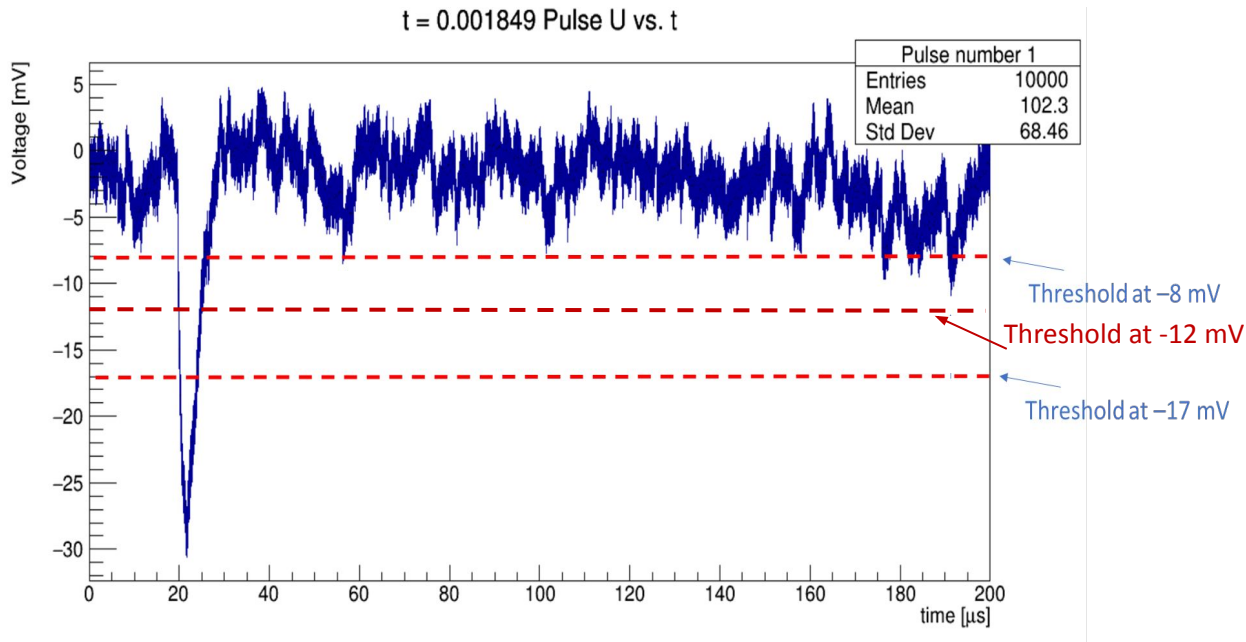
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Type	Time	-17 mV trigger	-12 mV trigger
		Rate [1/s]	
Simulation	500 sec	0	0.32 (0.03)

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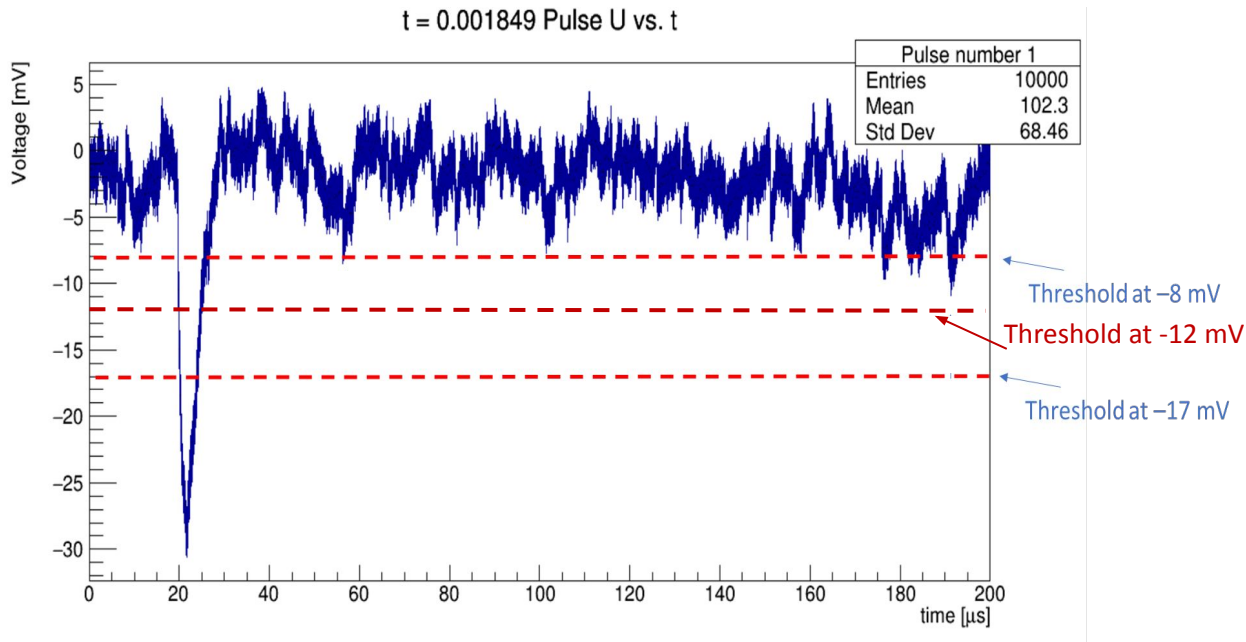
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For sub-eV: Can we discern low energy pulses from noise?

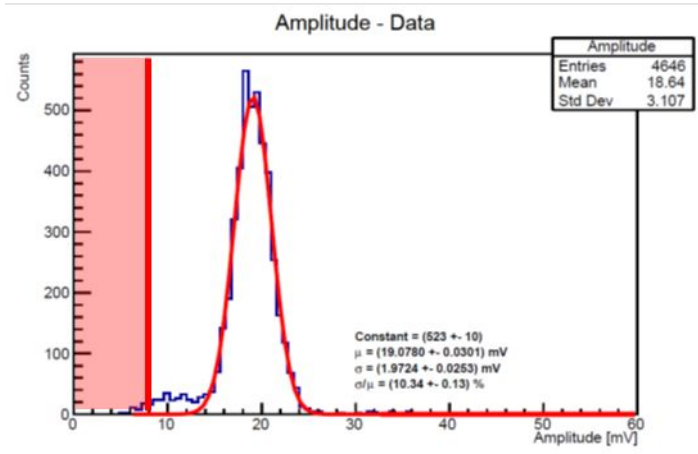
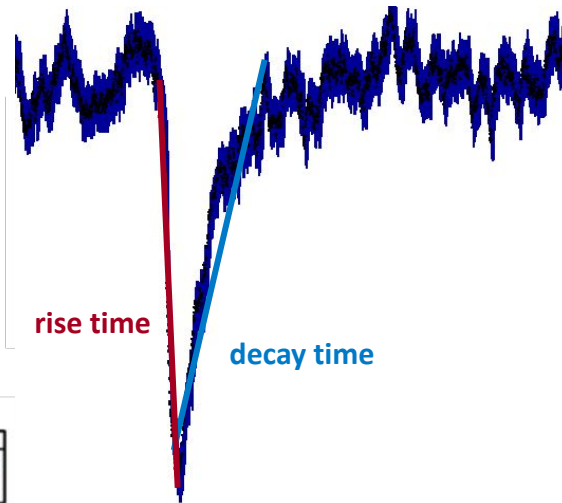
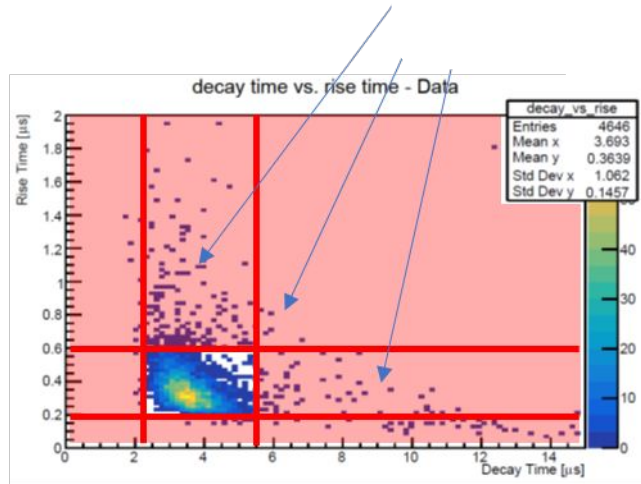


False Triggers			
Type	Time	-17 mV trigger	-12 mV trigger
		Rate [1/s]	
Simulation	500 sec	0	0.32 (0.03)
Measurement	72 hours	/	0.5070 (0.0014)

TES pulses - cut-based analysis

Example: 1.165 eV photon pulses

cutting away signals outside of central region



Assumptions for DM-electron scattering:

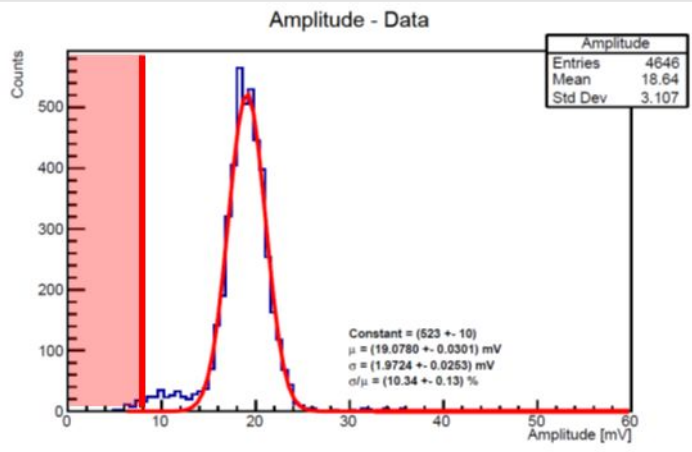
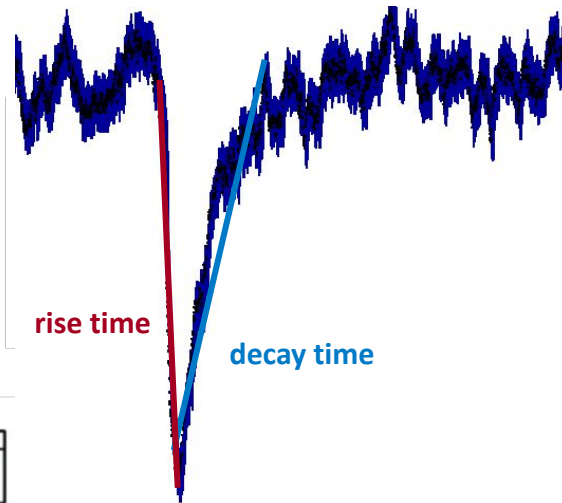
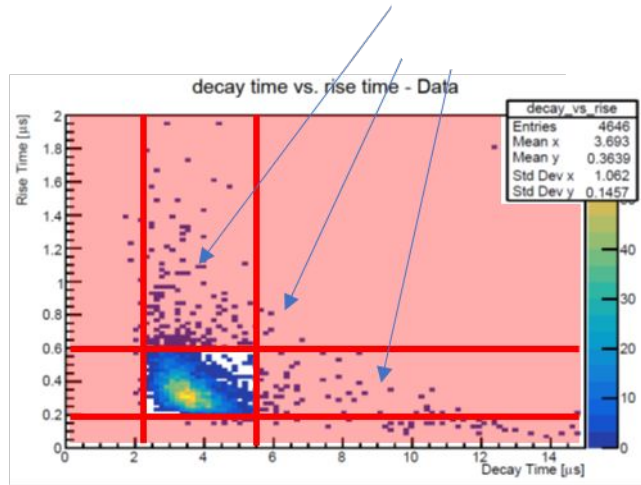
→ expect similar rise and decay time of pulses (governed by TES circuit)

→ expect varying pulse height (linearly) **proportional** to the deposited energy

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Assumptions for DM-electron scattering:

→ expect similar rise and decay time of pulses (governed by TES circuit)

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Simulating lower energy pulses:

→ simulate pulses based on 1.165 eV calibration and assumptions above

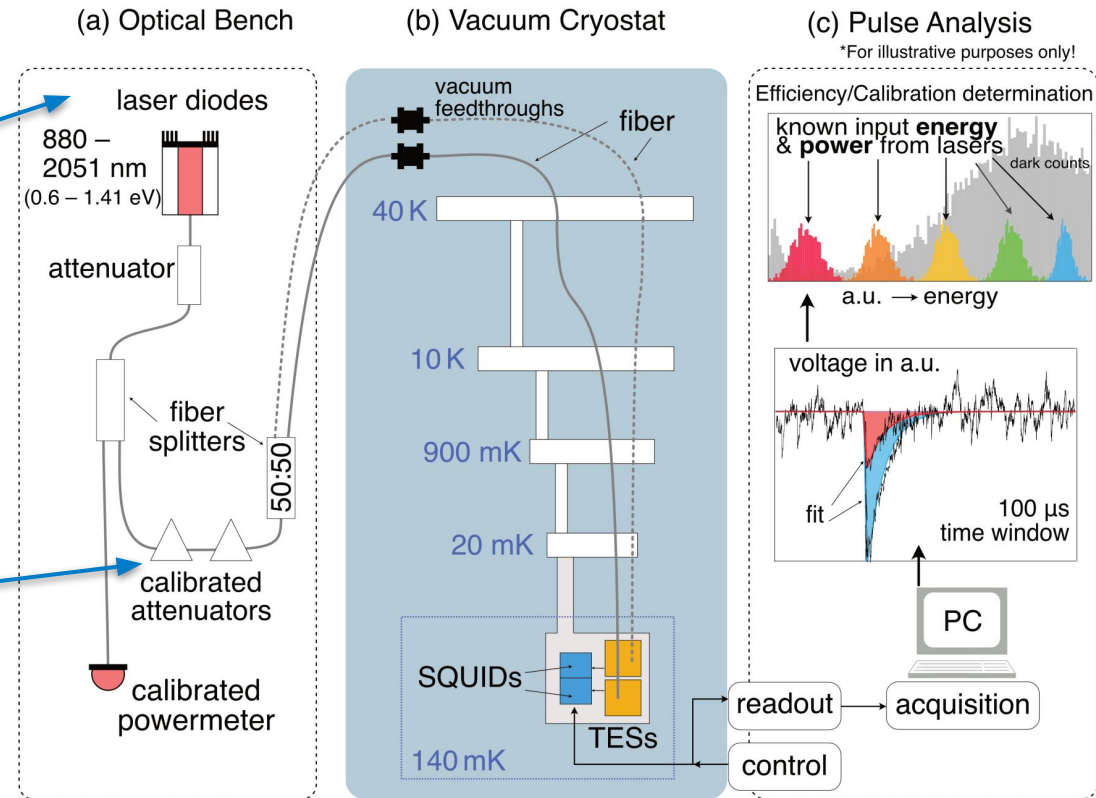
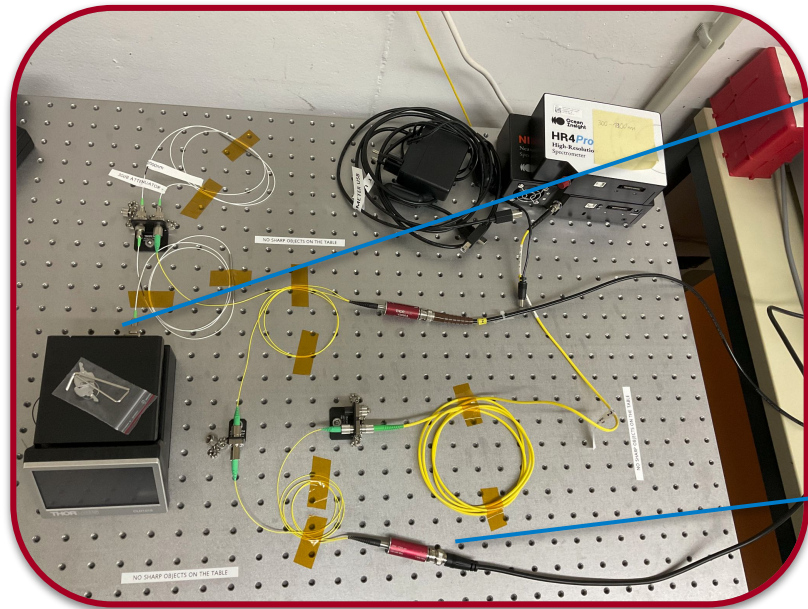
→ adjust cut-based analysis for different energies

What is the TES response to lower energies?
Are these assumptions correct?

TES Calibration

Experimental setup: Using laser diodes of different wavelengths

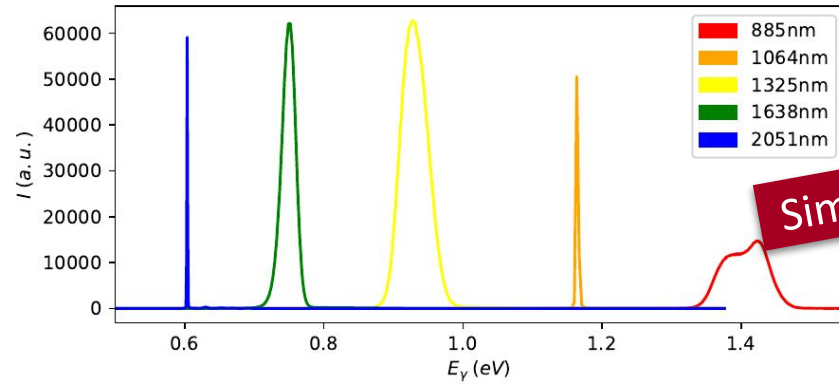
Goal: Determine calibration curve e.g. pulse height vs. energy



TES Calibration

Simulating response to laser diodes

measured energy spectrum from laser diodes

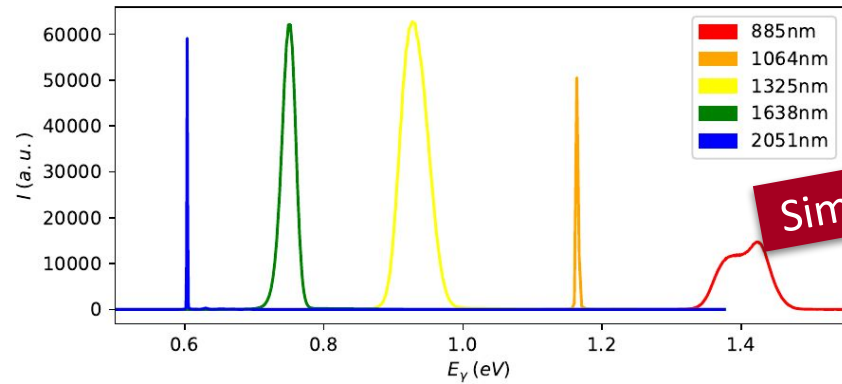


Simulate TES response

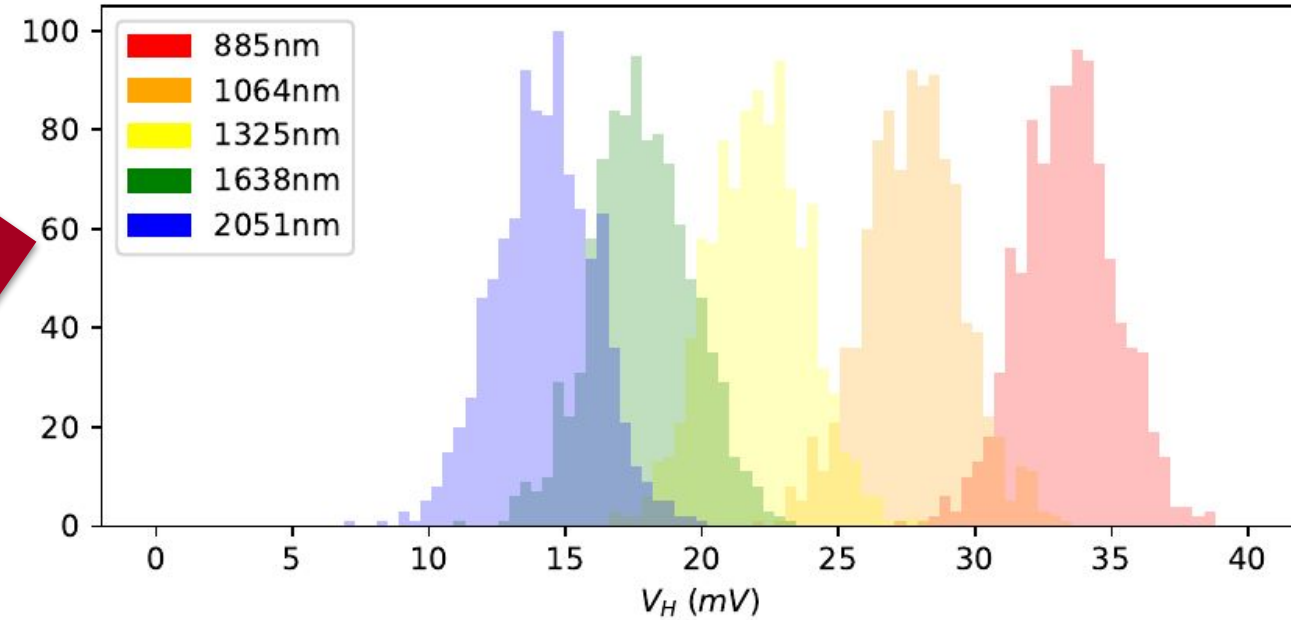
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Simulating response to laser diodes

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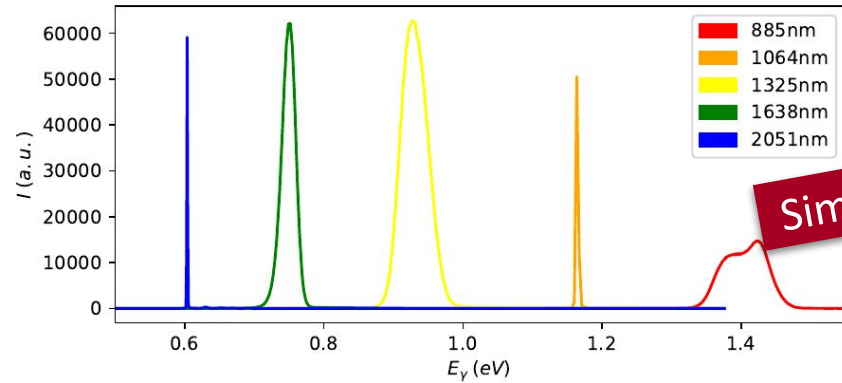
simulated pulse height for different diodes



TES Calibration

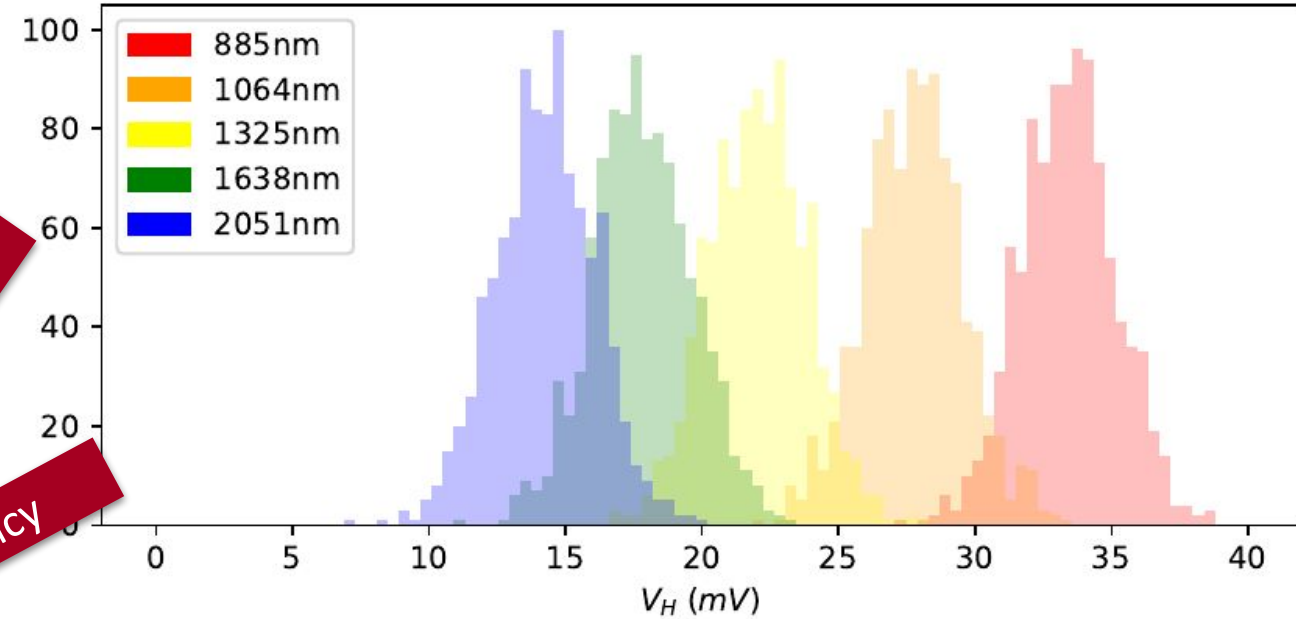
Simulating response to laser diodes

measured energy spectrum from laser diodes



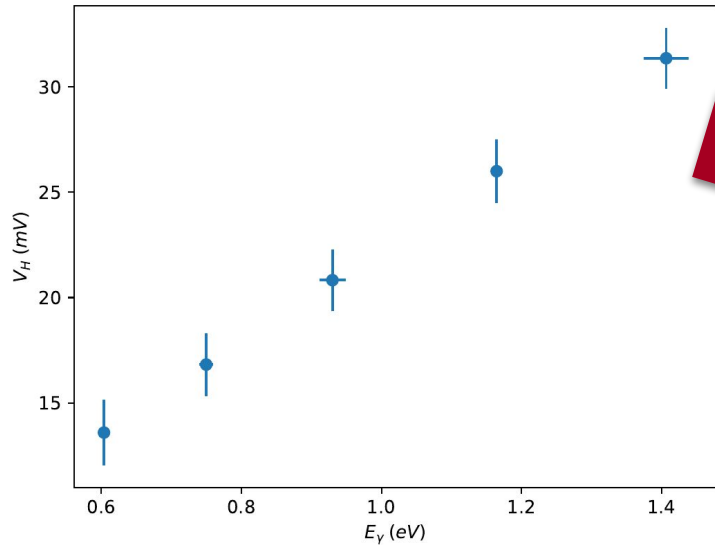
Simulate TES response

simulated pulse height for different diodes



Determine dependency

simulated energy vs. pulse height calibration curve



Can be immediately tested with new sensors and compared with simulation

Baseline simulations

Using cut-based analysis for lower energy pulses

Noise-only simulations

Trigger Rate for -12 mV threshold
0.422 (0.010) Hz



after analysis & cuts

Based on these assumptions, for now we can

test background rate for lower triggers after analysis:

- ~ 70 min noise-only simulation
- Applying cuts optimized for 1.165eV and **0.583eV**

Baseline simulations

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after analysis & cuts

Cuts based on	Trigger Rate for -12 mV threshold
1.165 eV	< 0.0007 Hz
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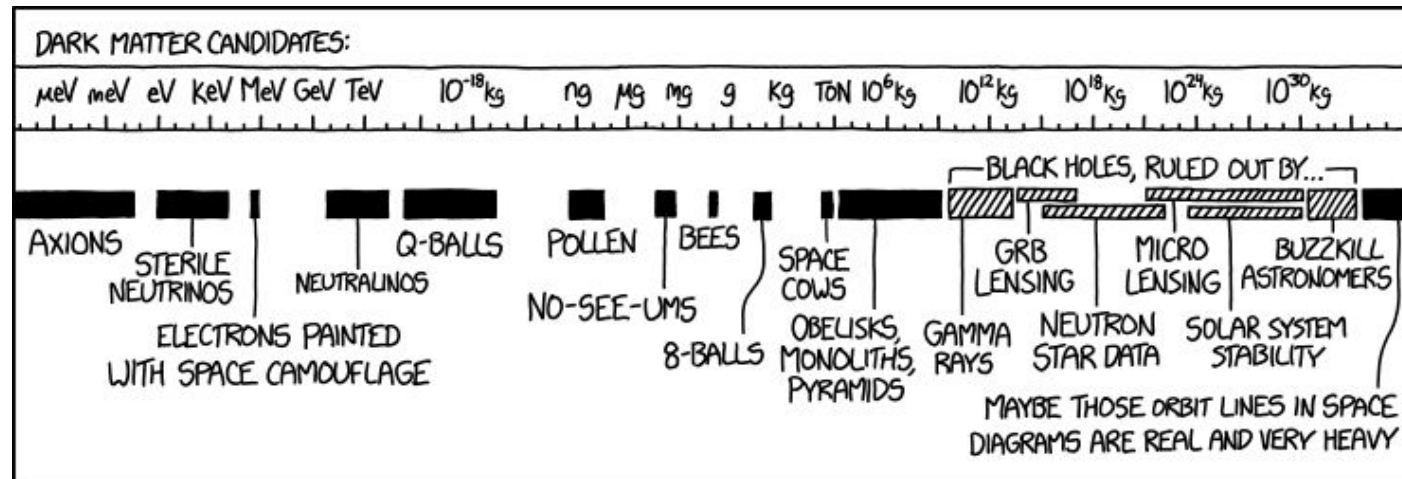
- ~ 70 min noise-only simulation
- Applying cuts optimized for 1.165eV and **0.583eV**

No noise passing analysis & cuts with
~56% acceptance of **0.583eV** pulses
Promising for sub-MeV direct DM searches!

Summary

- TES technology used in **ALPS II** may be viable for **direct dark matter searches** in the **sub-MeV DM** mass range exploiting DM-electron scattering
- Similar measurements have been conducted using **SNSPDs**
- Could reach new sensitivities **without dedicated hardware development**
- Could be a proof of principle for similar technologies as dark matter detectors

Comic adapted from xkcd



Summary

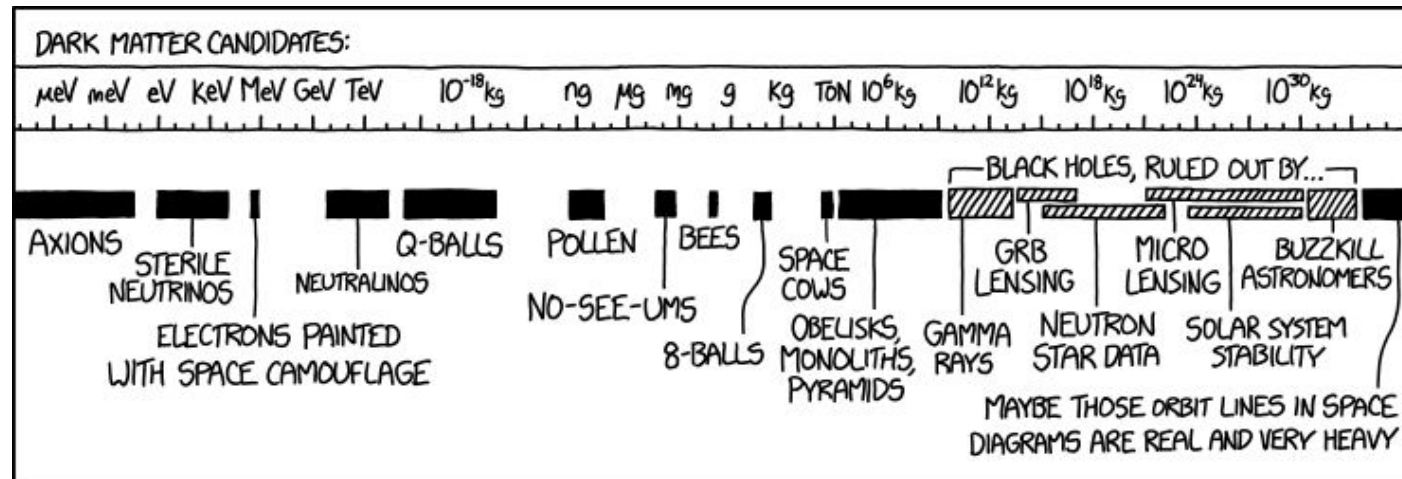
and

Outlook

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- Measure **TES response** for different energies (1.4 eV – 0.6 eV i.e. 880 nm – 2000 nm)
- Perform **calibrated intrinsic background measurements** to compare with SNSPD results
- Further investigate **intrinsic background**
- Investigate and test **new/optimized TES modules**

Comic adapted from xkcd



Summary

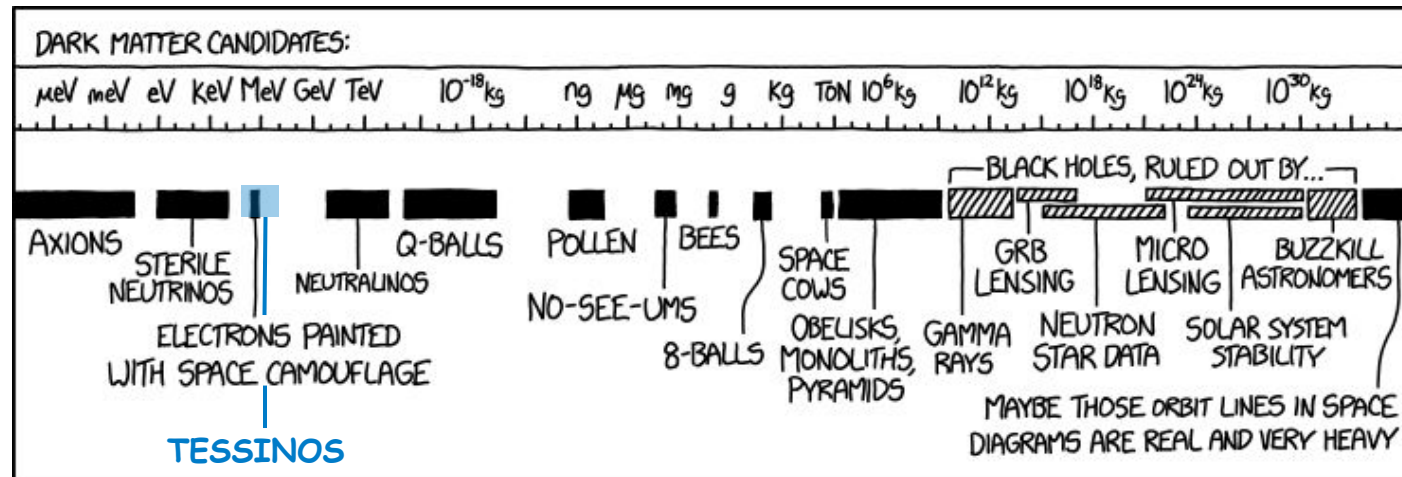
and

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Comic adapted from xkcd



Thank you

Fancy video material on Youtube:



Drone flight through the ALPS II experiment at DESY

1627 Aufrufe · vor 2 Monaten

Deutsches Elektronen-Synchrotron

In May 2023, the "light through the wall" experiment ALPS II at DESY will start taking data. Its objective: the detection of dark matter ...

4K Untertitel

6:09



Introduction to the ALPS II experiment at DESY

218 Aufrufe · vor 2 Monaten

Deutsches Elektronen-Synchrotron

The ALPS II experiment at DESY in Hamburg aims to find the extremely elusive dark matter. To do this, it needs to detect the light ...

SHORTS



Das ALPS-Experiment und die Dunkle Materie

1807 Aufrufe · vor 2 Monaten

Deutsches Elektronen-Synchrotron

Das Rätsel um die Dunkle Materie, die schätzungsweise ein Viertel des Inhalts des Universums ausmacht, besteht schon seit ...

3:56

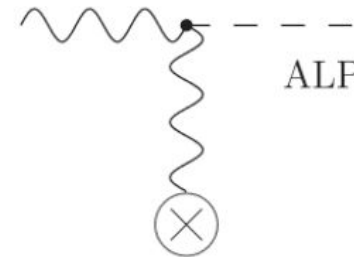
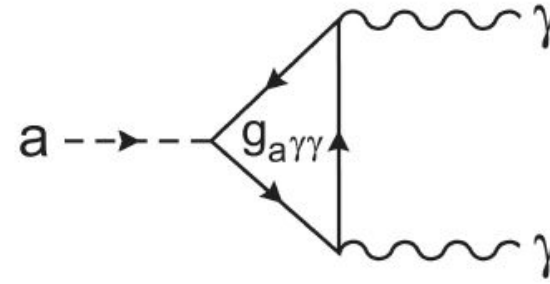
Other ALPS II related talks @ Cosmic WISPers:

“Analysis of Transition Edge Sensor data for the ALPS II experiment.” – José Alejandro Rubiera Gimeno

Backup

ALPS II - General Idea

- SM-coupling to two photons
- Detection via Primakoff-like Sikivie effect
- Possible ALP **production** by photon-ALP – oscillation in the presence of strong magnetic fields



K. Ehret et.al., [NIMA 612\(1\)83-960 \(2009\)](#)

Light Shining Through **W**alls (LSW) experiments

$$\rightarrow P_{\gamma \rightarrow a} \propto g_{a\gamma\gamma}^2 B^2 L^2$$

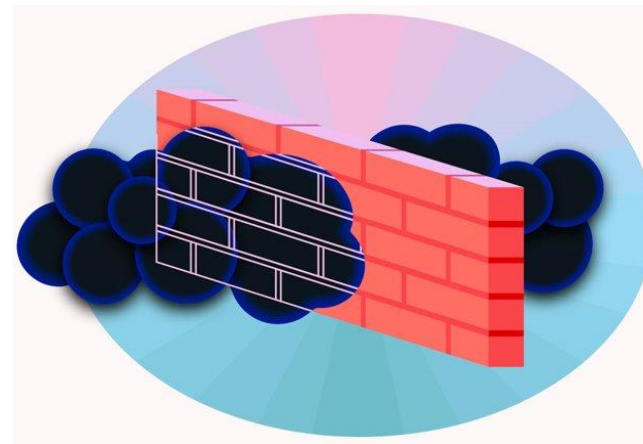
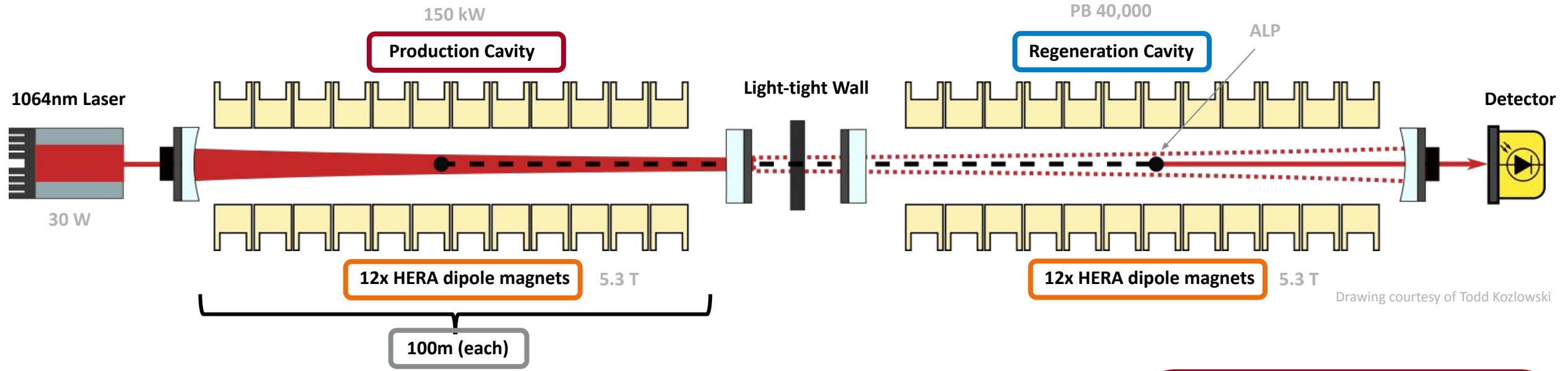


Illustration by Sandbox Studio, Chicago with Ana Kova

Backup

Any Light Particle Search with ALPS II - Experimental Setup



Detection probability:

$$P_{\gamma \rightarrow a \rightarrow \gamma} \propto PC \cdot RC \cdot g_{a\gamma\gamma}^4 B^4 L^4$$

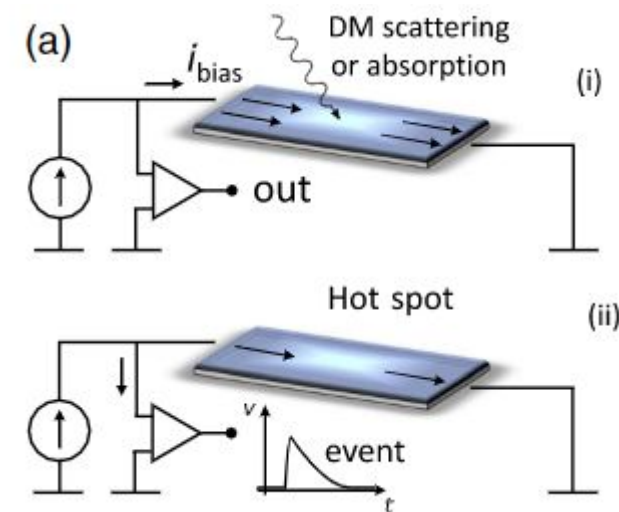
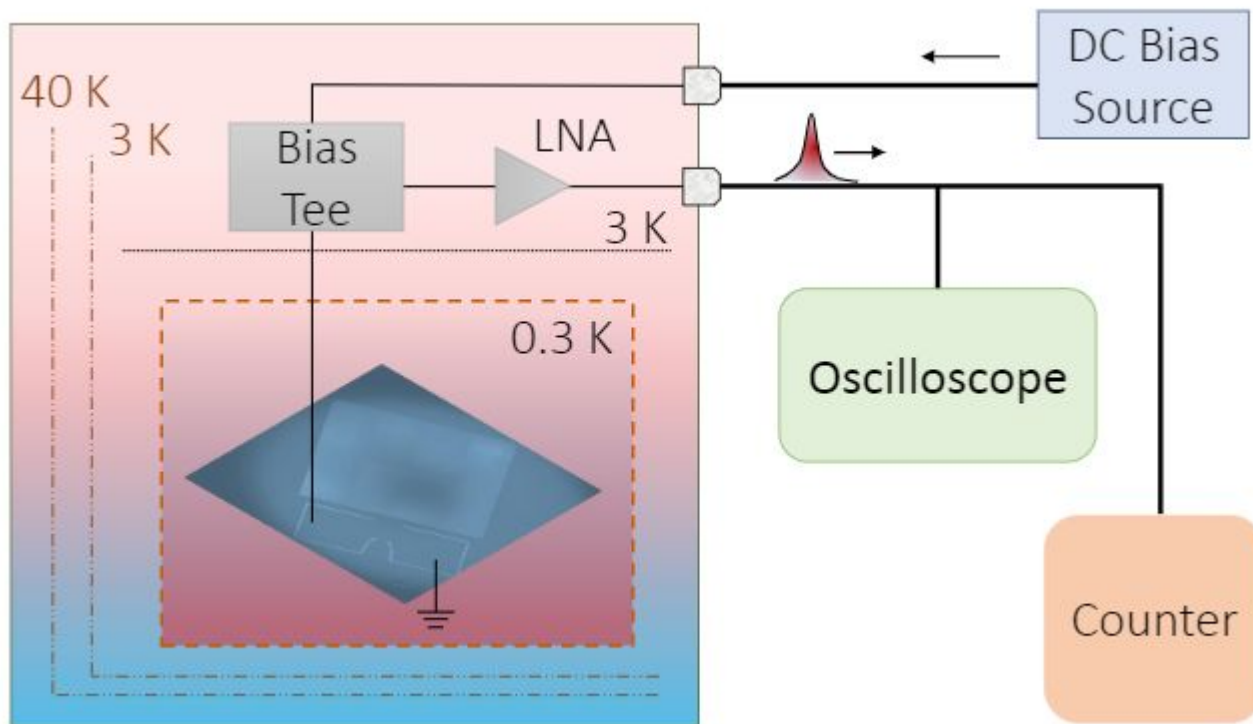
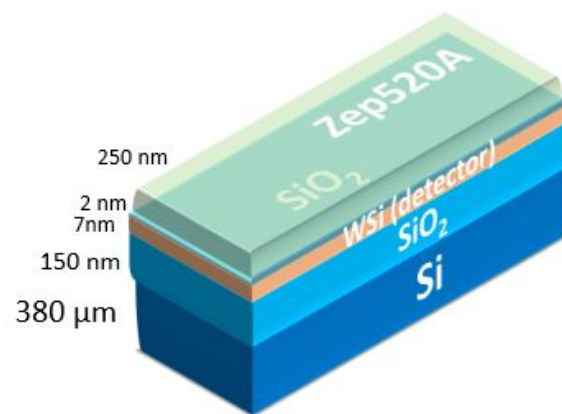
Expected rate of low energy (~ 1.16 eV) photons: $\dot{N}_\gamma \approx 2.8 \cdot 10^{-5} \frac{\gamma}{s} \approx 1 \frac{\gamma}{\text{day}}$
(for $g_{a\gamma\gamma} = 2 \cdot 10^{-11} \text{ GeV}^{-1}$)

Single-photon detection requirements for ALPS II:

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

Backup

SNSPDs

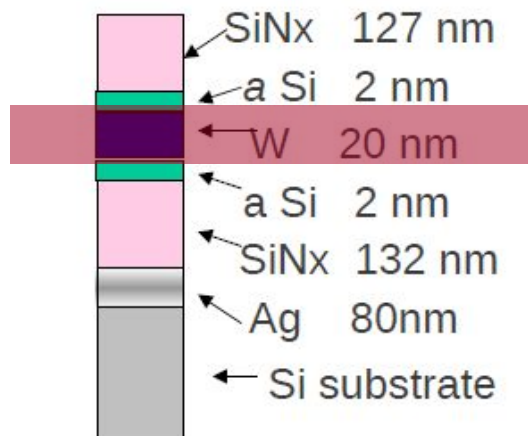


Hochberg, Y. et al., *Physical Review Letters*, 123(15), (2019)

Backup

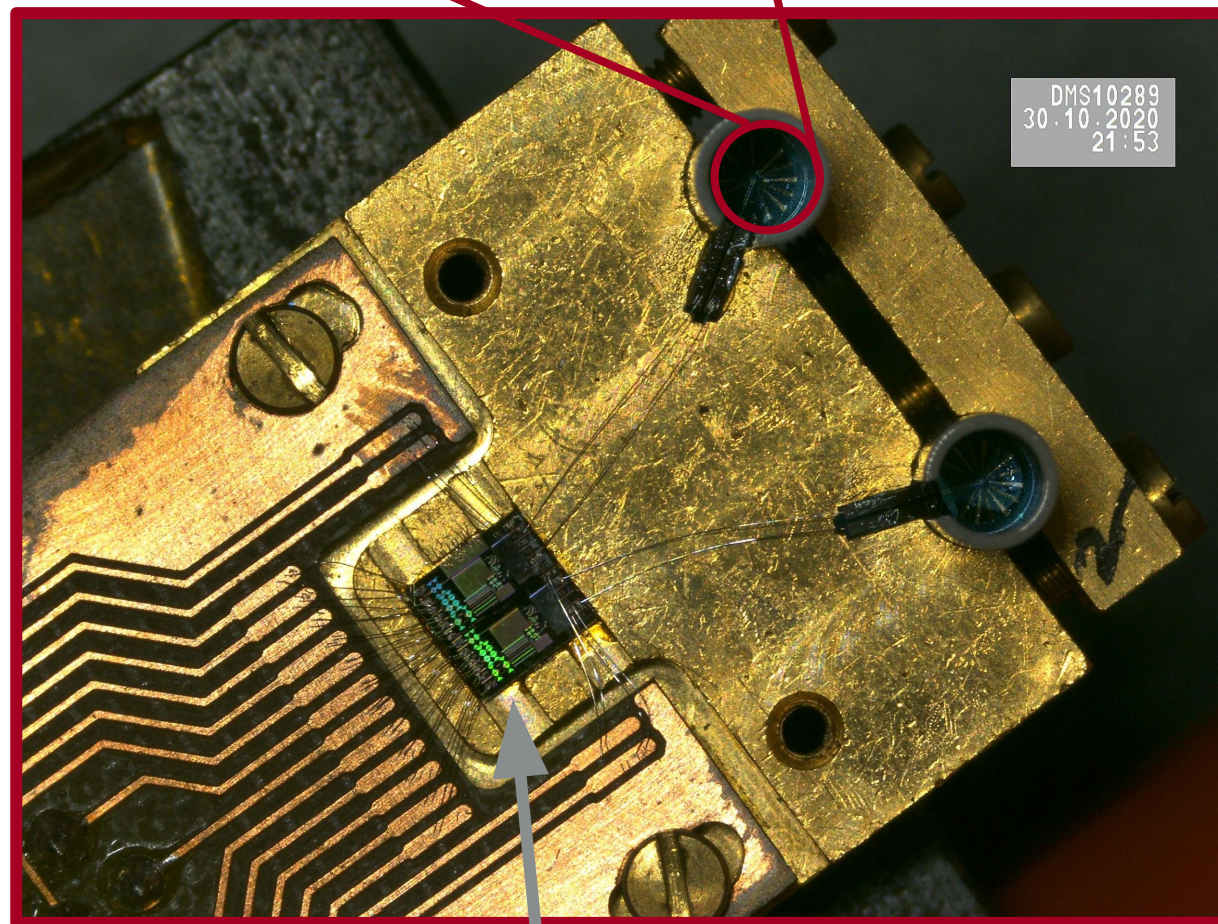
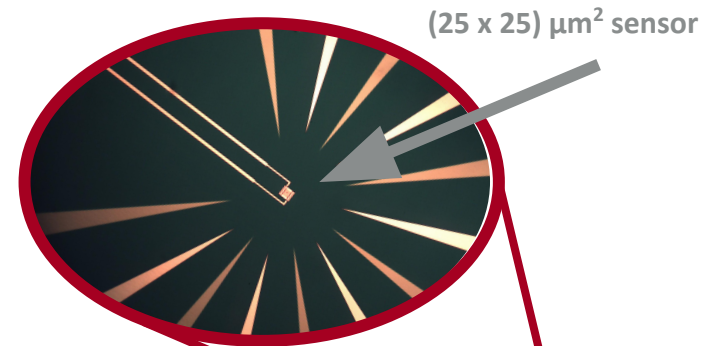
Quantum Sensing Details

Optical stack



A. Lita, NIST

- Very small active area – energy deposition in tungsten layer
- Option for fiber coupling
- Optical stack & efficiency optimized for 1064nm (1.165 eV) photons
- Wider range of energies interesting for direct DM searches



SQUID chips

Backup

ALPS II Setup

Detection requirements

- Photon detection at low energies (1064 nm → 1.165 eV)
- High quantum efficiency

Low background (electronic noise, radioactive backgrounds, photons from black-body radiation)
< 1 photon/day

High detection efficiency

TES solution

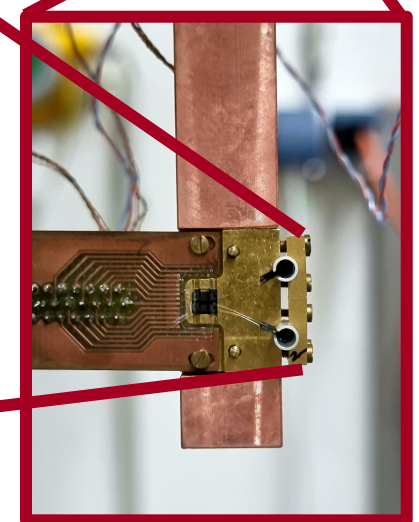
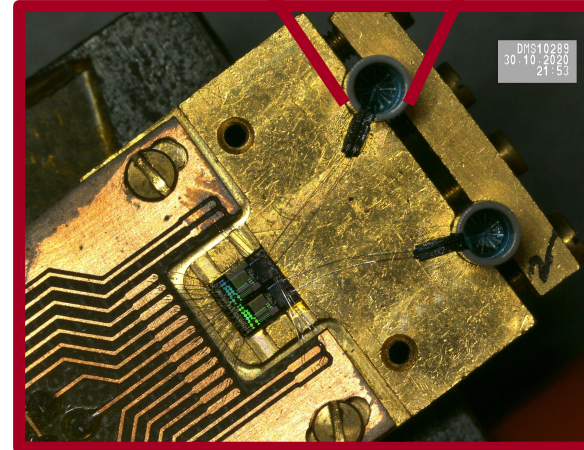
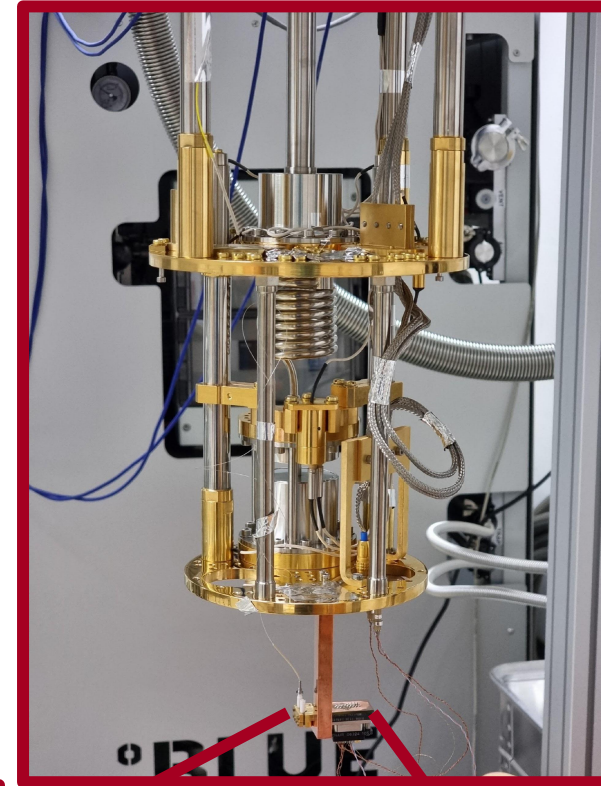
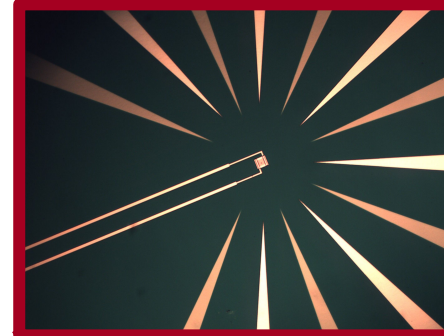
optimized optical structure to increase absorption at 1064 nm

shielding in cryostat and tests to reduce background:

- fiber curling
- filtering of black-body photons

→ currently: 6.9×10^{-6} cps¹ (intrinsic background)

preliminary results suggest at least 80% efficiency



¹ R. Shah et al., PoS, EPS-HEP2021, 801 (2022)

Backup

ALPS II Setup

Detection requirements

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- High quantum efficiency

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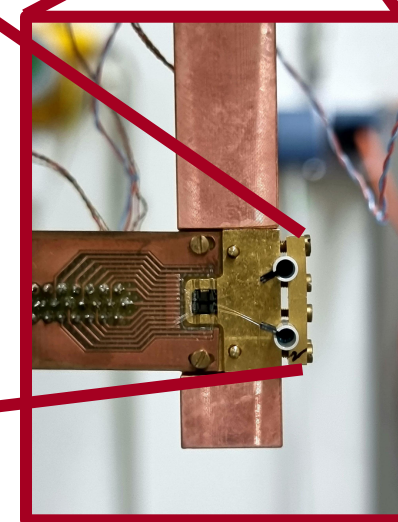
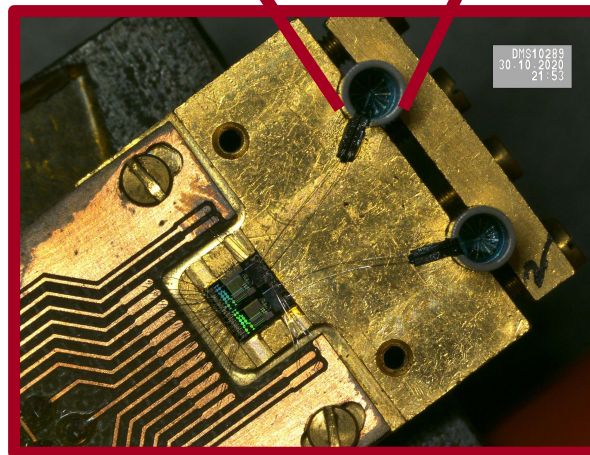
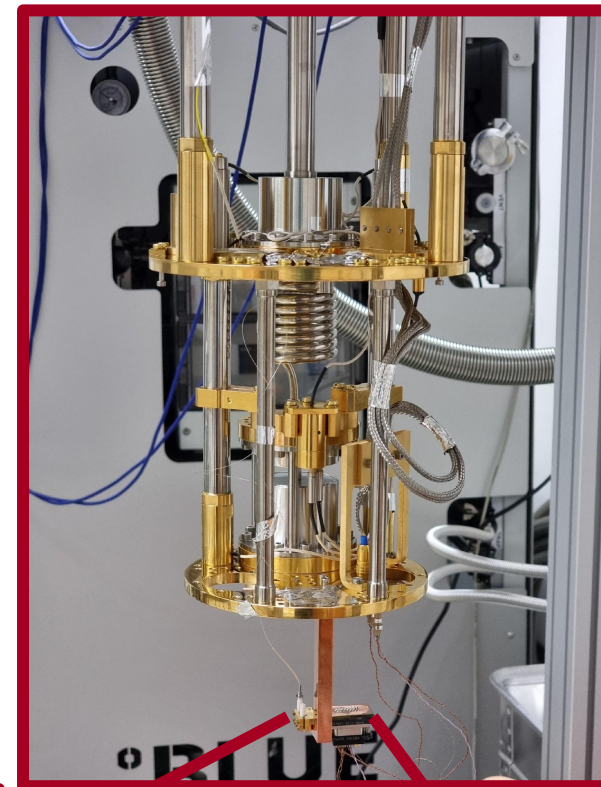
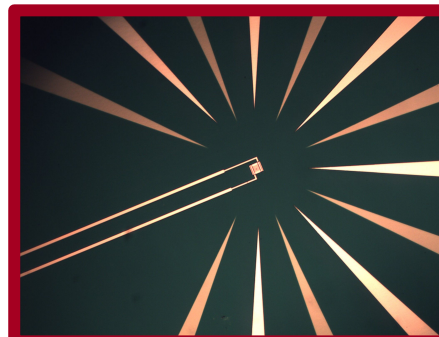
High detection efficiency

Still to do

Determine **linearity** of TES response (pulse height)

Good **intrinsic** background (no optical fiber attached)
Still need to reduce **extrinsic** background (introduced by optical fiber from the outside of the cryostat)

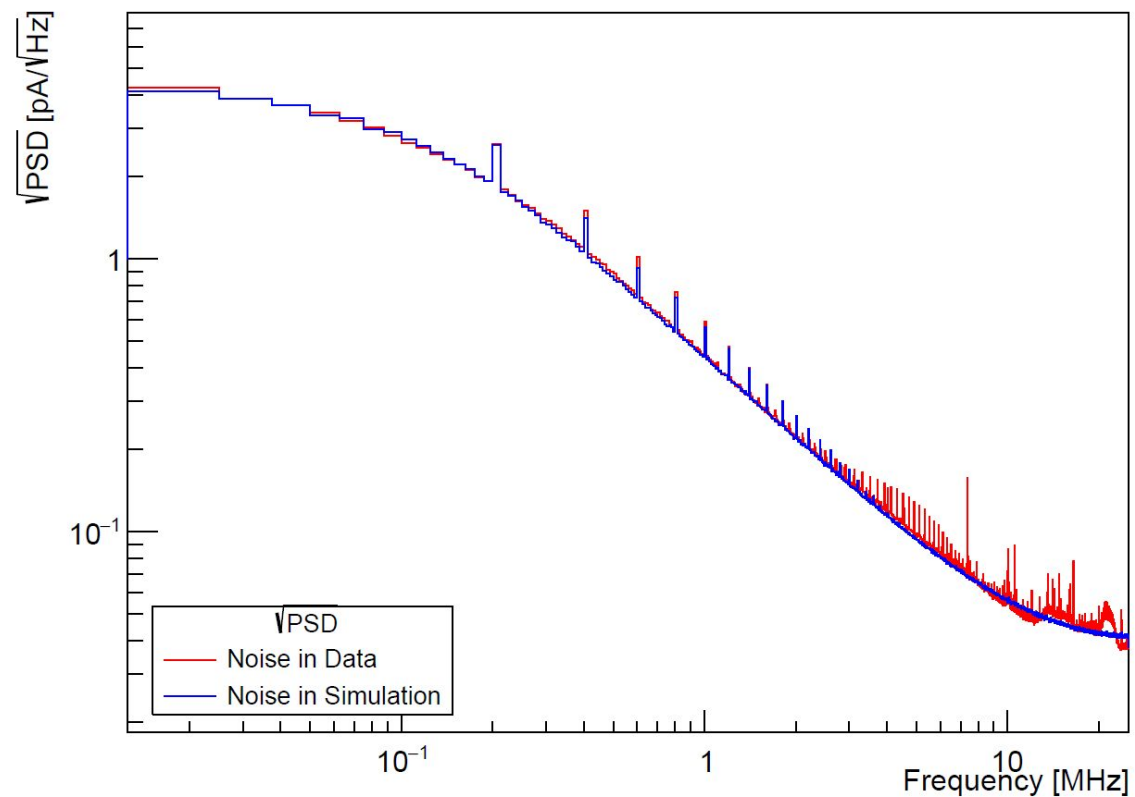
Investigate options to **optimize** system efficiency



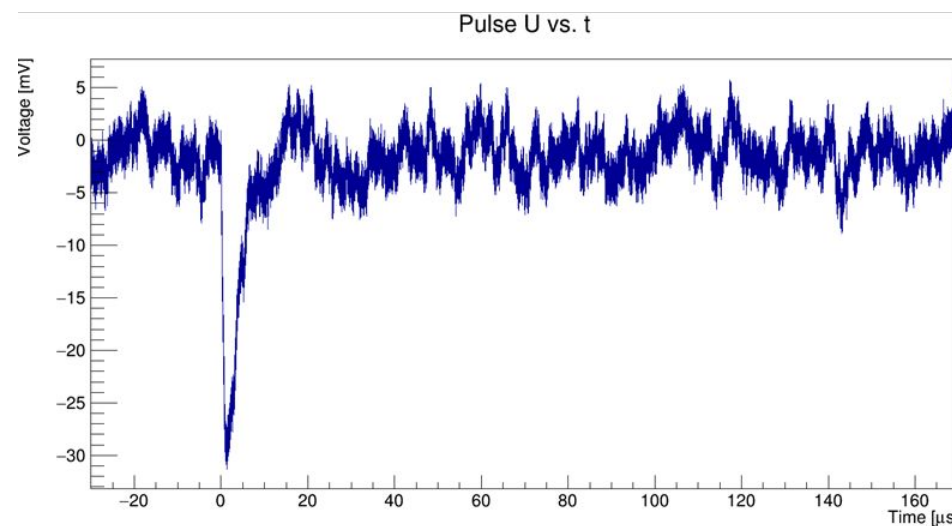
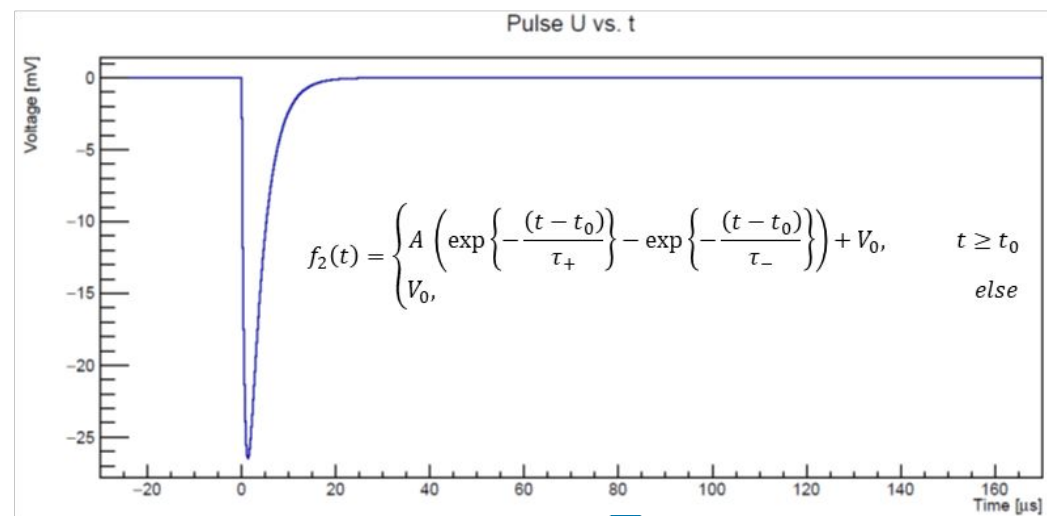
Backup

Simulation of pulses

$\sqrt{\text{PSD}}$ comparison



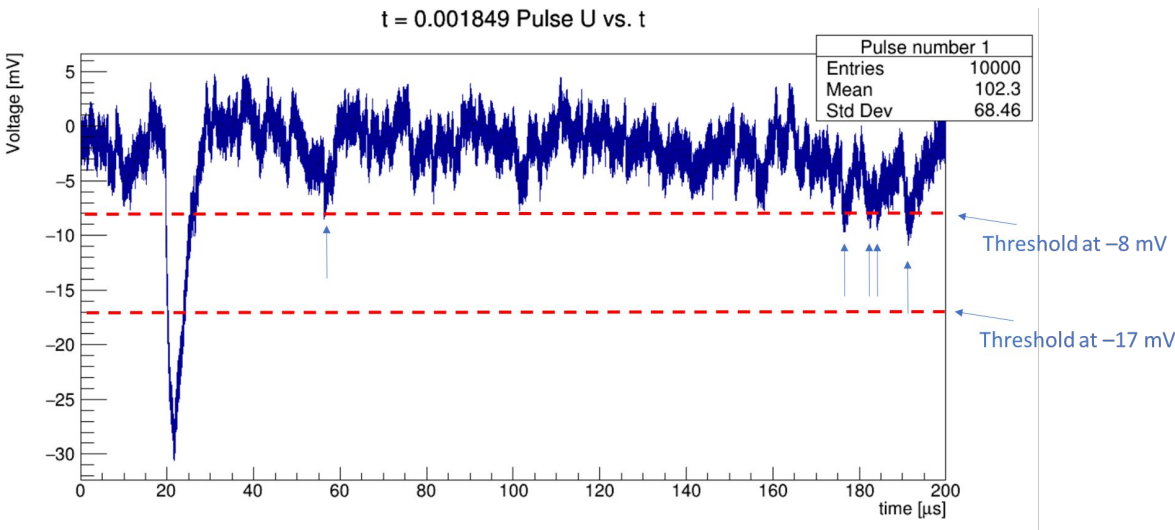
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Backup

False trigger simulations

- Simulated rate of triggered noise pulses for different thresholds
- Without simulated pulses → expect only noise contributions
- Simulation fits order of magnitude of 3 day intrinsic measurement with -12mV threshold

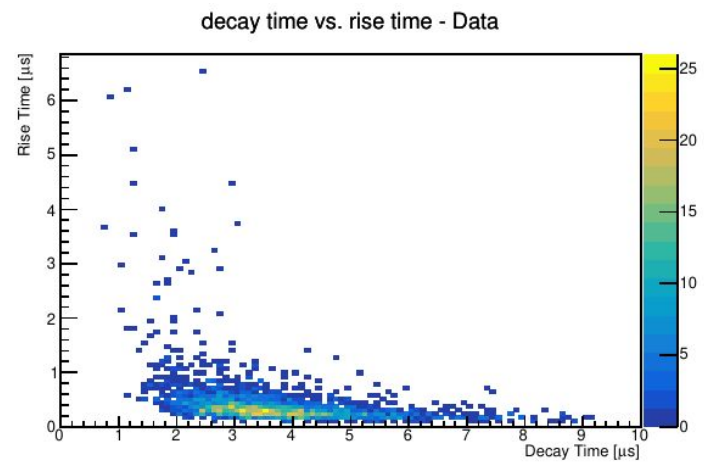


False Triggers - Rate of noise pulses passing different trigger thresholds										
		Usual trigger thresholds for 1064nm pulses								
		Threshold [mV]								
		-17	-16	-15	-14	-13	-12	-11	-10	-9
Simulated time	# Samples	Rate [1/s]								
500 sec	2.5e6	0	0	0	0	0.014 (0.005)	0.32 (0.03)	4.21 (0.09)	38.8 (0.3)	251.1 (0.7)
72 hours	no simulation						0.5070 (0.0014)			

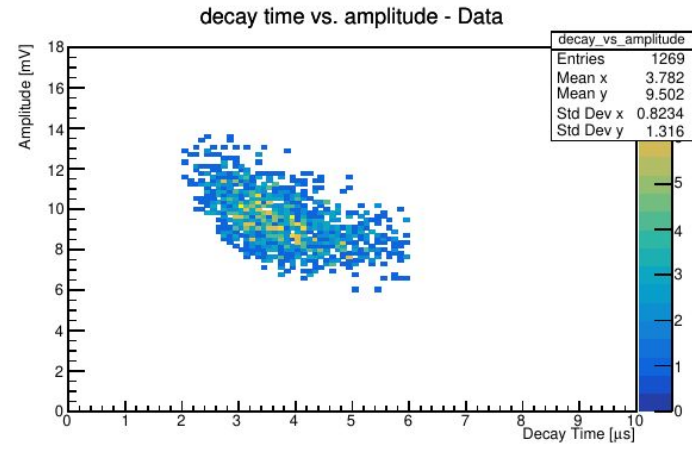
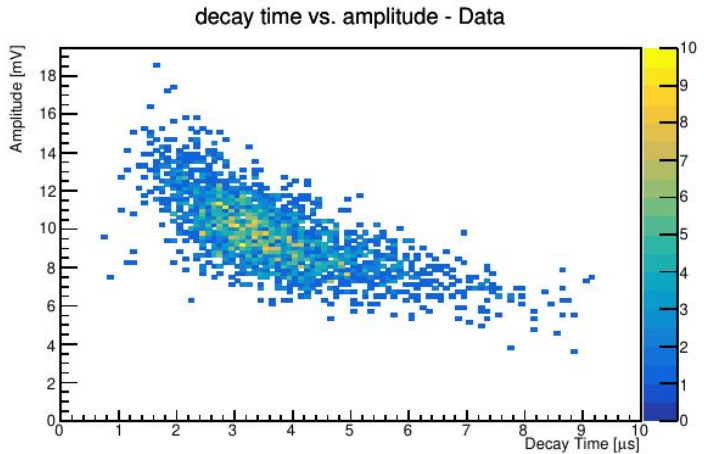
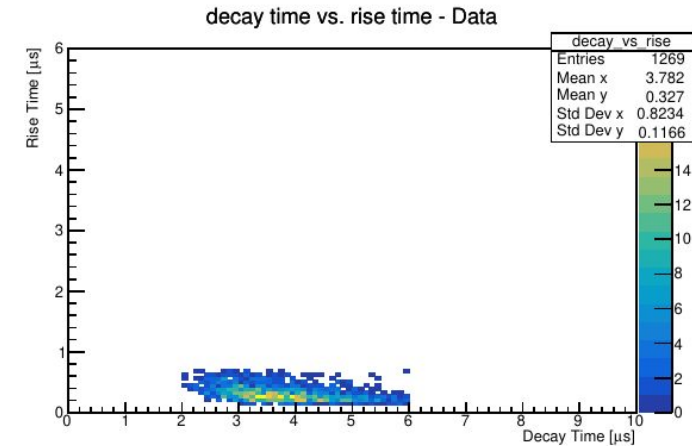
Backup

Simulation – Cut-based analysis for lower energy pulses

Pre Cuts



Post – 0.583eV optimized - Cuts



Contact

Deutsches Elektronen-
Synchrotron DESY

www.desy.de

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