Further dark matter searches using ALPS II's TES detector

Image Credit: Scicom Lab

DPG Spring Meeting Dresden 2023

Christina Schwemmbauer on behalf of the ALPS II collaboration

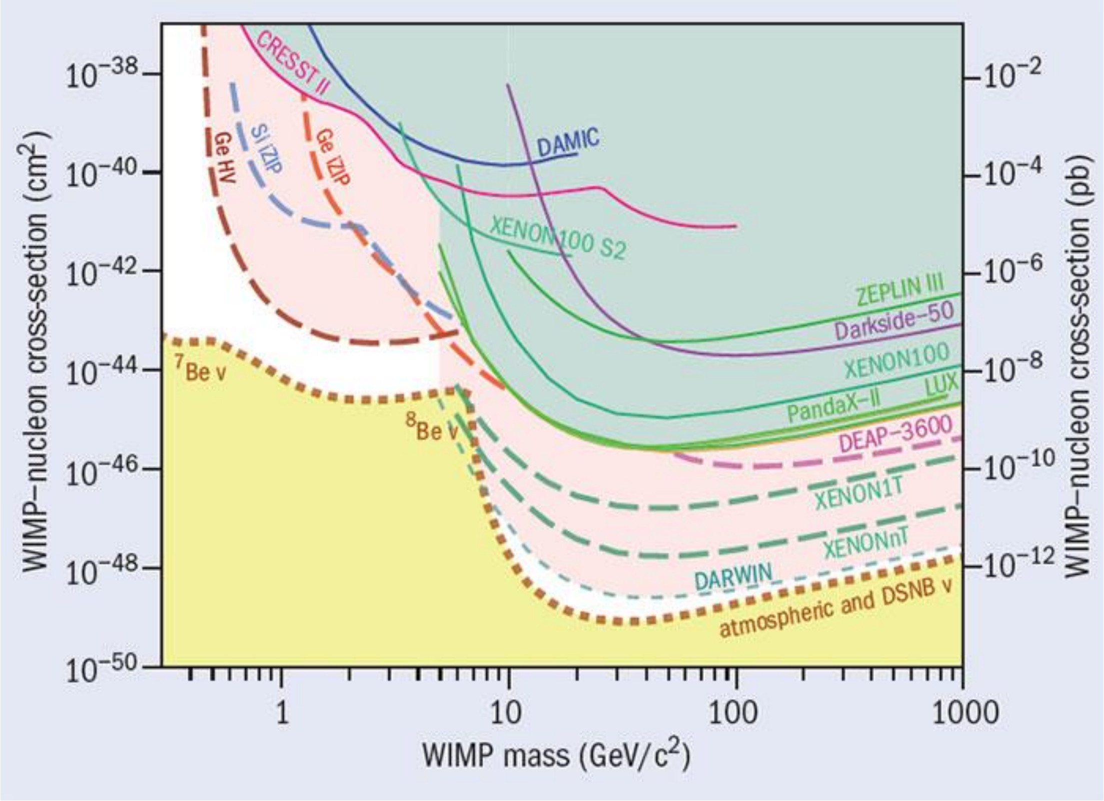
ALPS, DESY

Dresden, 23.03.2023

erc HELMHOLTZ · JG|U · Cardiff University Prifysgol Caerdydd · Leibniz Universität Hannover · UF University of Florida · SDU University of Southern Denmark · UHH Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG · ALPS · DESY.

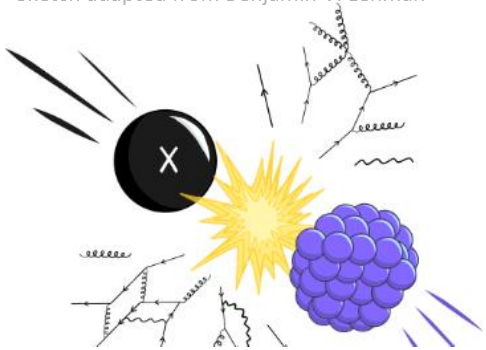
Detection of sub-GeV Dark Matter

Limits of nuclear recoil experiments



Cern Courier (2017)

Sketch adapted from Benjamin V. Lehman



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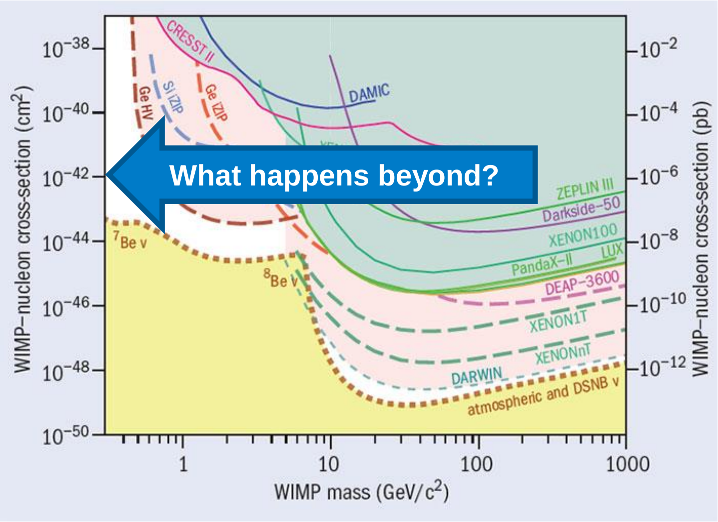

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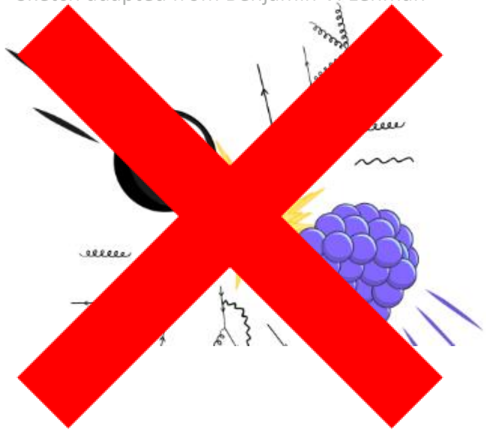
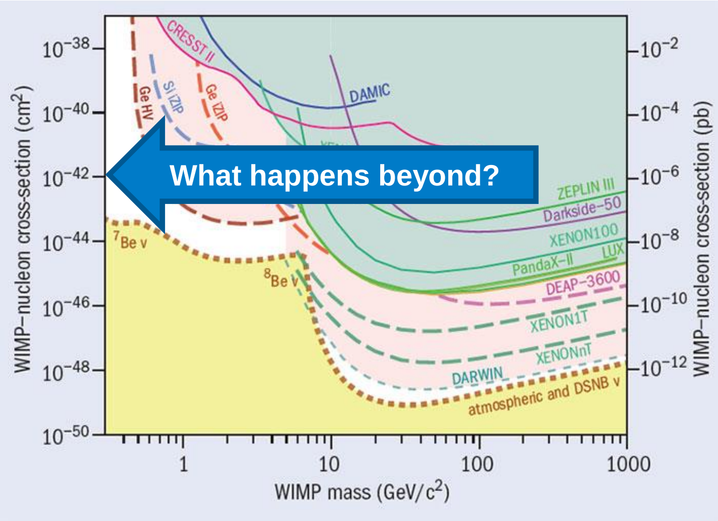


Detection of sub-GeV Dark Matter

Dark Matter – electron scattering



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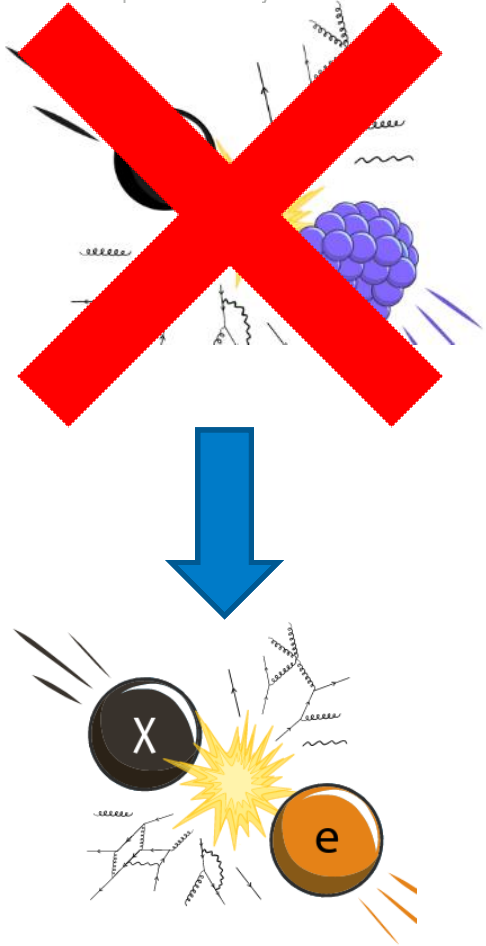

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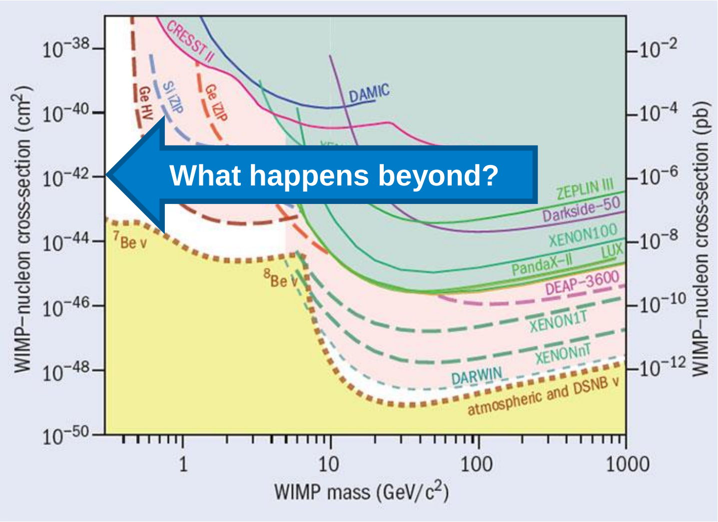

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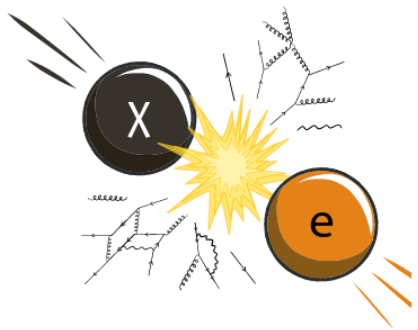

Assume:

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

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

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

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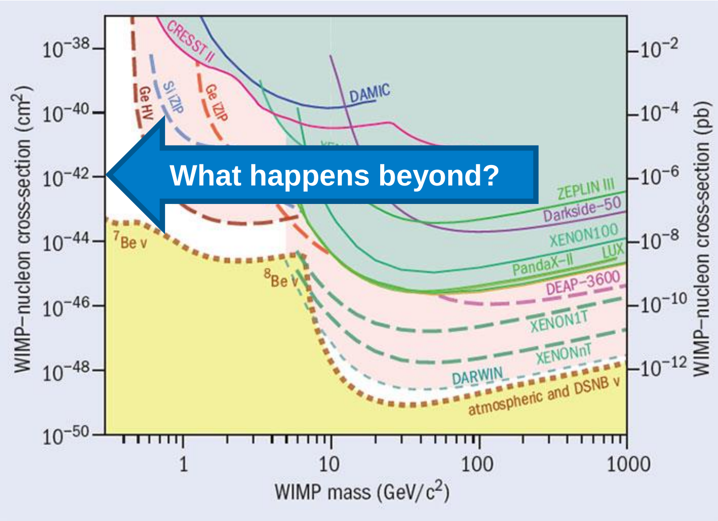

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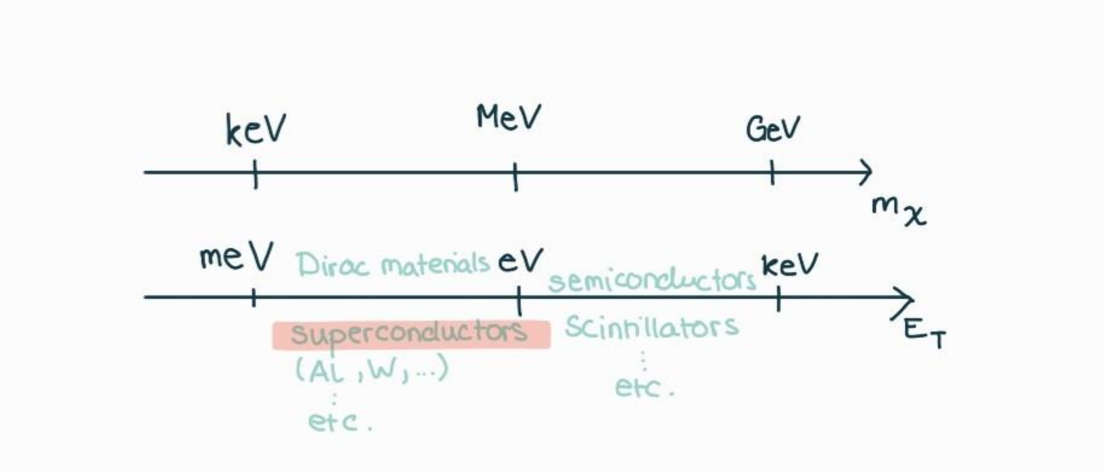

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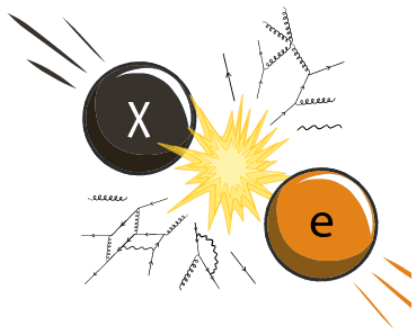

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DM Searches with Superconductors

Role model: SNSPDs

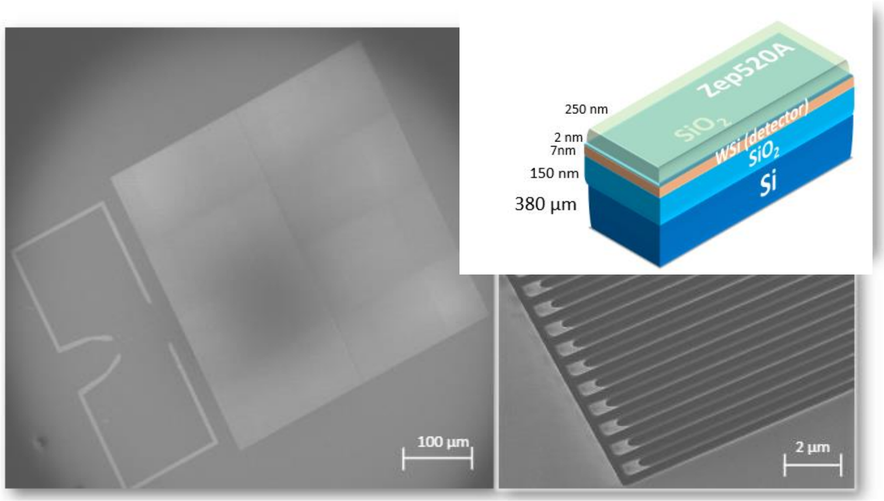
Hochberg, Y. et al. arXiv:2110.01586 (2021)

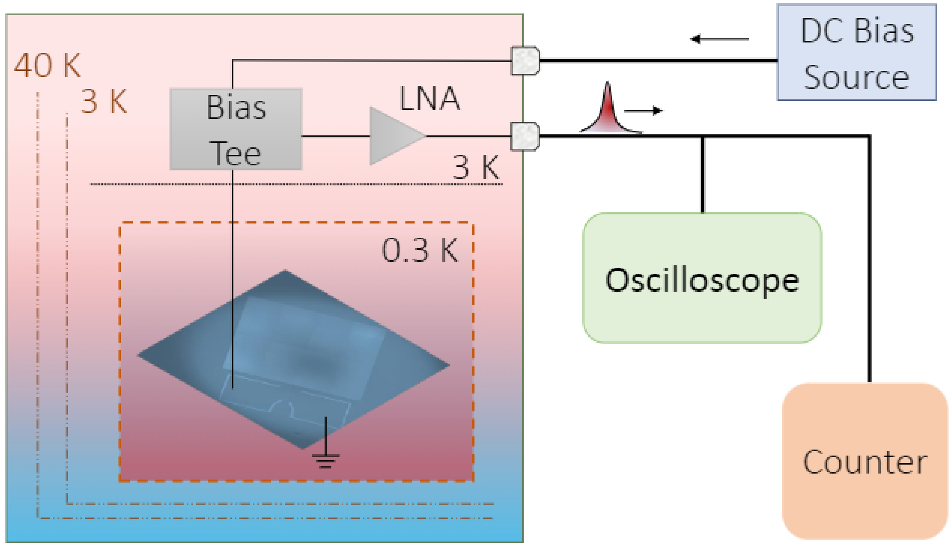
Example: principle proven for SNSPDs

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

(**S**uperconducting **N**anowire **S**ingle **P**hoton **D**etector)

- New bounds on parameter space with one measurement
- No background signals in 3 hrs
- **0.76 eV** energy threshold
- Allows to exclude DM-electron scattering parameter space





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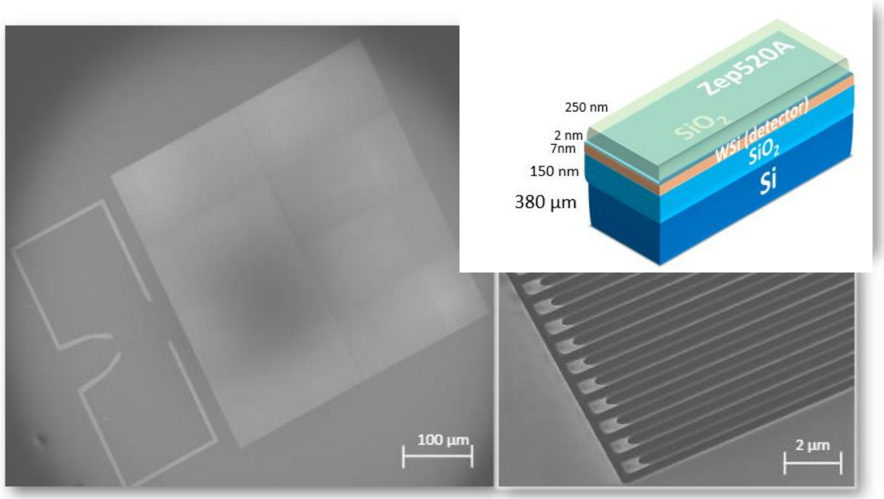
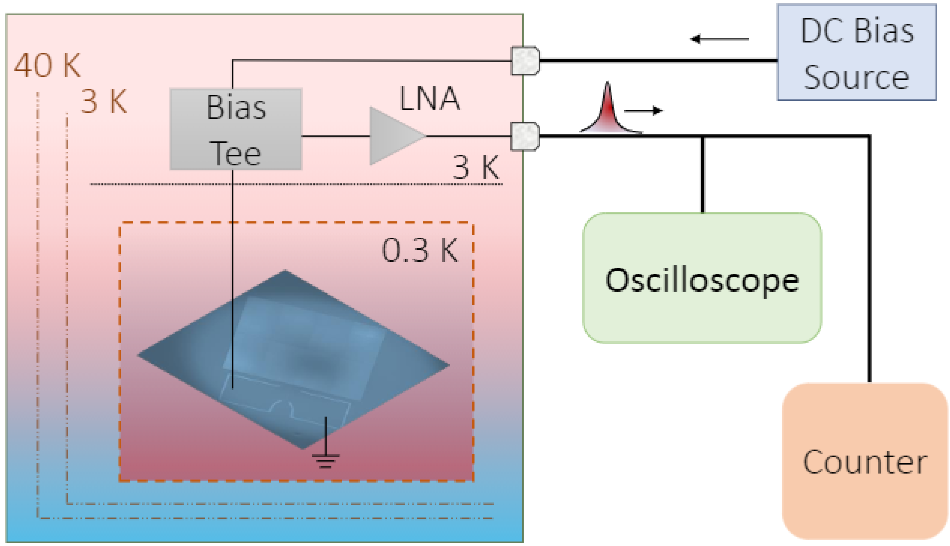
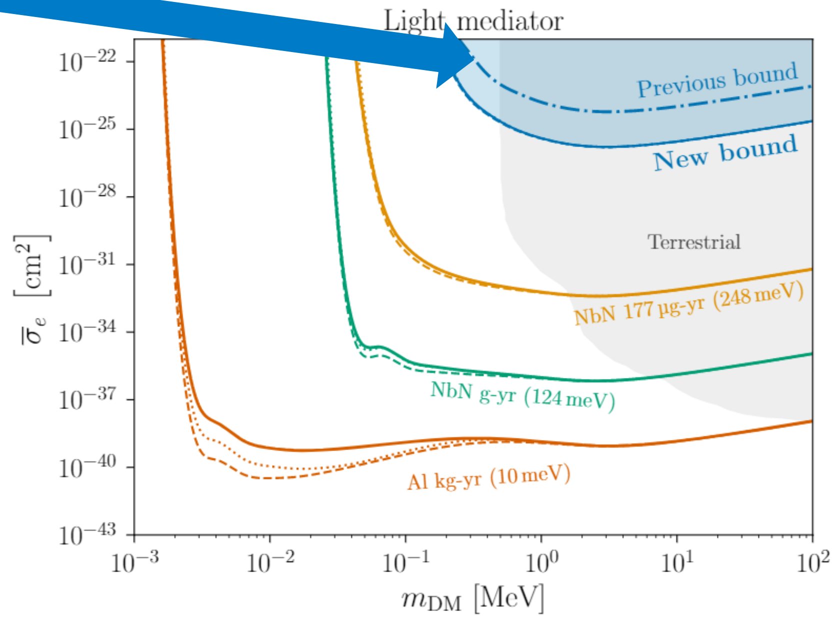






DM Searches with Superconductors

Role model: SNSPDs

Limits of SNSPDs:

Works like a counter

↓

No energy resolution

↓

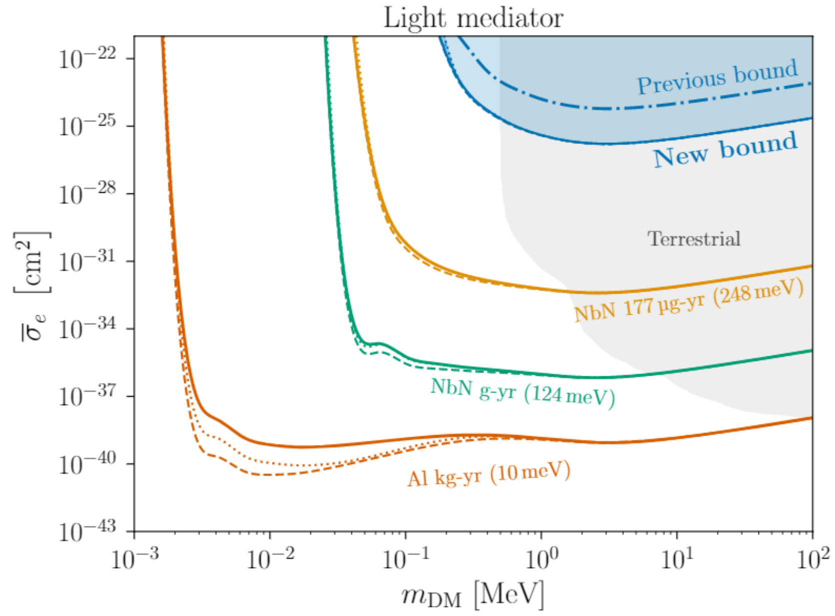
No further information about background signal such as rise and decay time, pulse integral, amplitude, etc.

Superconducting Detectors for Super Light Dark Matter

Yonit Hochberg,[1] Yue Zhao,[2] and Kathryn M. Zurek[1]

[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 of superconducting detectors which 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/astrophysical constraints could be detected by such detectors with a moderate size exposure.



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DM Searches with Superconductors

SNSPD vs TES

Limits of SNSPDs:

Works like a counter

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No energy resolution

↓

No further information about background signal such as rise and decay time, pulse integral, amplitude, etc.

Proposal: Use a **T**ransition **E**dge **S**ensor (TES)

- ✓ Superconductor
- ✓ Low noise
- ✓ Energy resolution
- ✓ Possibly lower energy threshold
- ✗ Lower mass (0.2 ng)
- ✗ Smaller target area

Superconducting Detectors for Super Light Dark Matter

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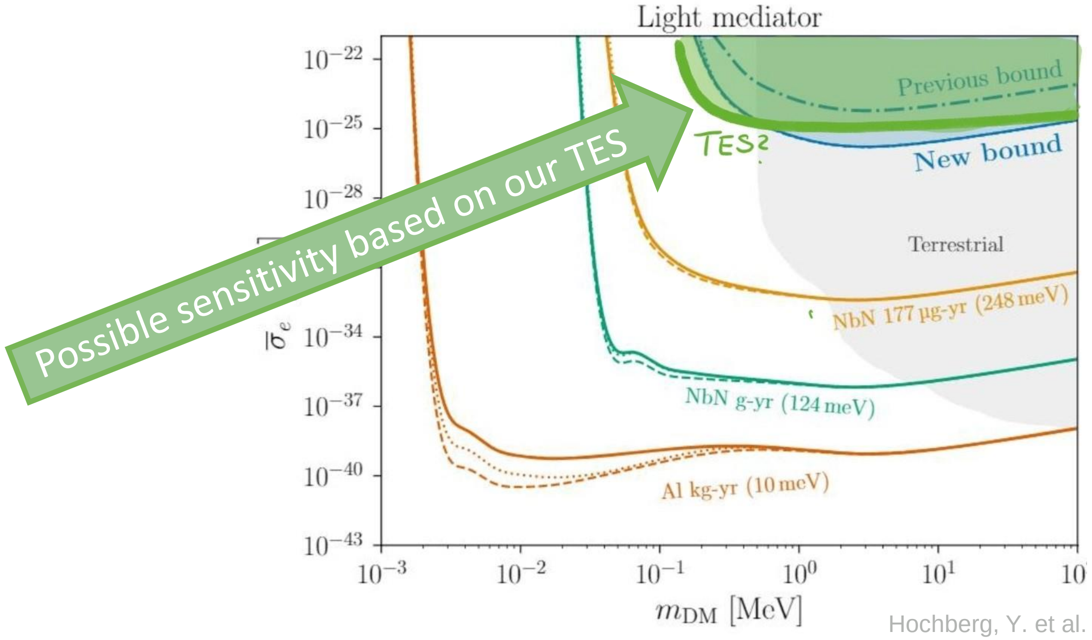

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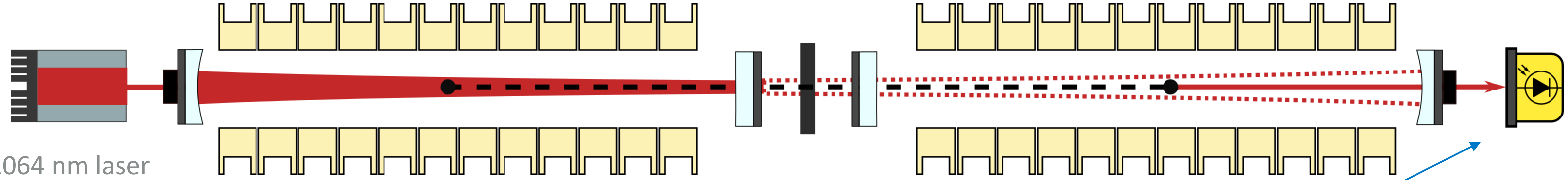
TES Single Photon Detection

Detection techniques in the ALPS II experiment



1064 nm laser

Light Shining through a Wall experiment
Challenge: Detect single photon from axion-photon conversion

Application of two photon-measurement schemes:

Heterodyne detection:
- Detects photon fields
- Mixing of regenerated fields with a local oscillator and measurement of resulting beat note

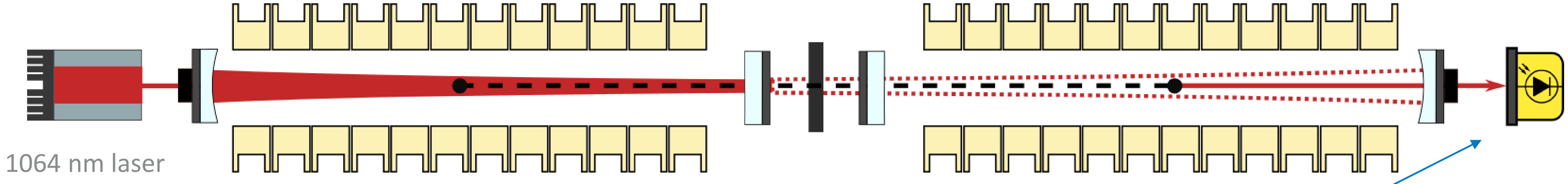
Transition **E**dge **S**ensor (TES):
- Single photon detection
- Using **superconducting** tungsten chip

Drawing courtesy of Todd Kozlowski

TES Single Photon Detection

Detection techniques in the ALPS II experiment

More details: "Recent Updates on the ALPS II experiment" – Gulden Othman, Mo 17:30, T5.5



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"Heterodyne detection of weak fields in ALPS II" – Isabella Oceano → Next talk!

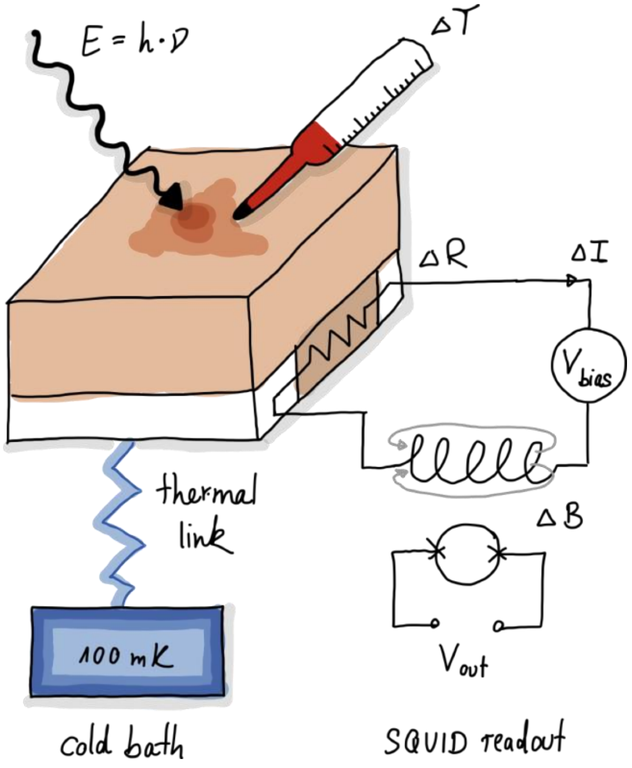
Transition Edge Sensor (TES):
- Single photon detection
- Using **superconducting** tungsten chip

More details: "A TES for ALPS II – Status and Prospects" – José Alejandro Rubiera Gimeno, Tue 18:00, T27.5

Drawing courtesy of Todd Kozlowski

TES Single Photon Detection

Transition Edge Sensors



- Cryogenic microcalorimeters
- Operated at superconducting transition temperature
- Read-out using **S**uperconducting **Q**uantum **I**nterference **D**evices (SQUIDs)

Drawings courtesy of Katharina-Sofie Isleif

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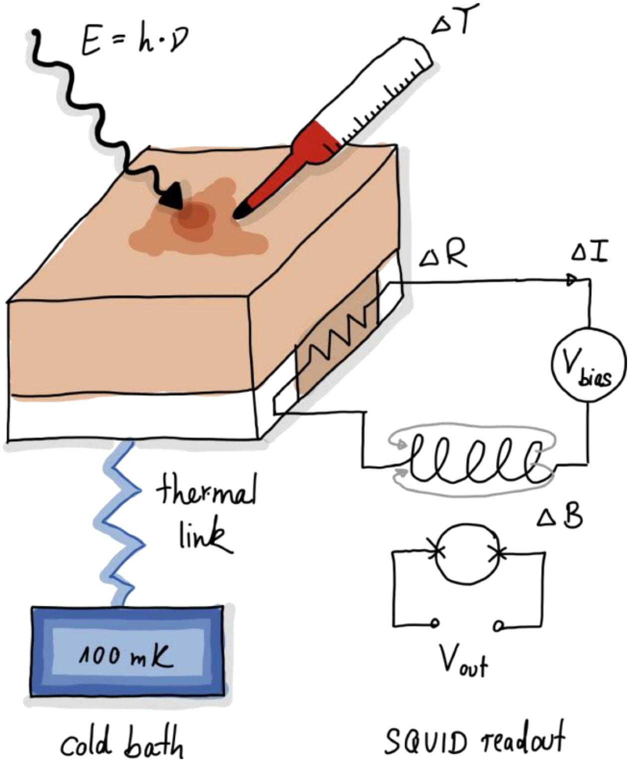

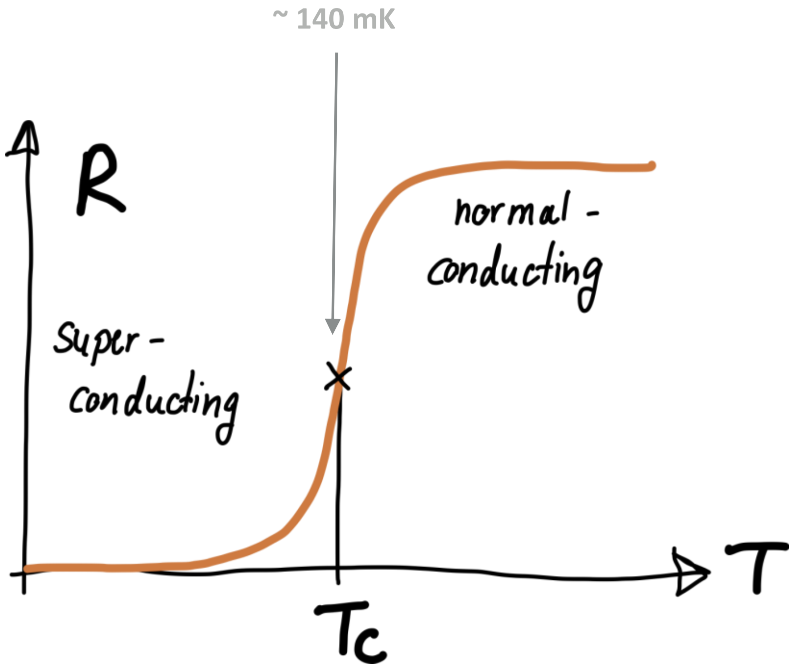

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- Small temperature increase leads to large variation in resistance

Drawings courtesy of Katharina-Sofie Isleif

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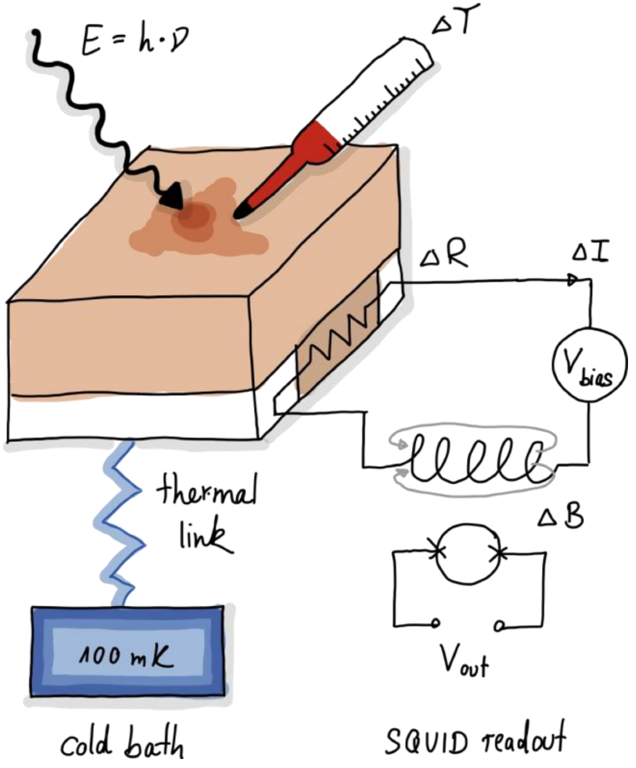

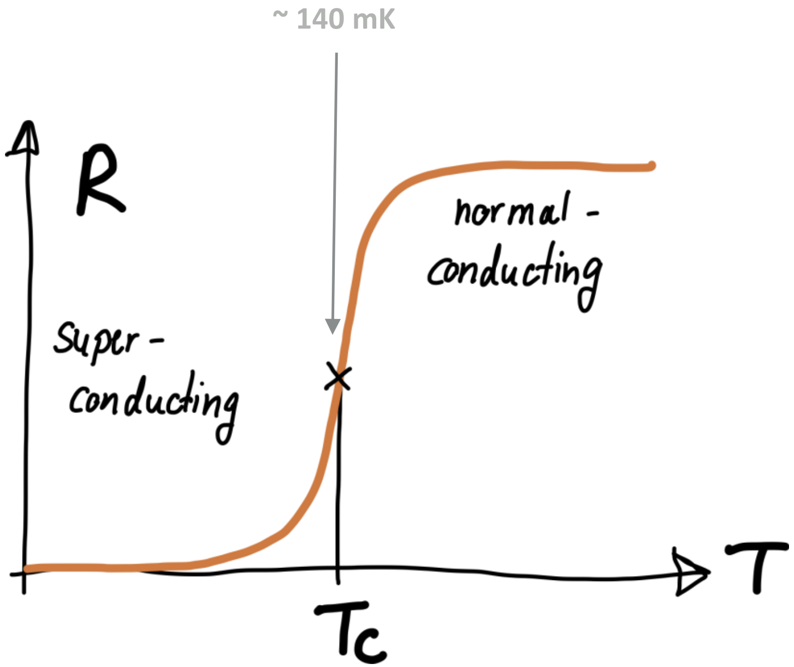

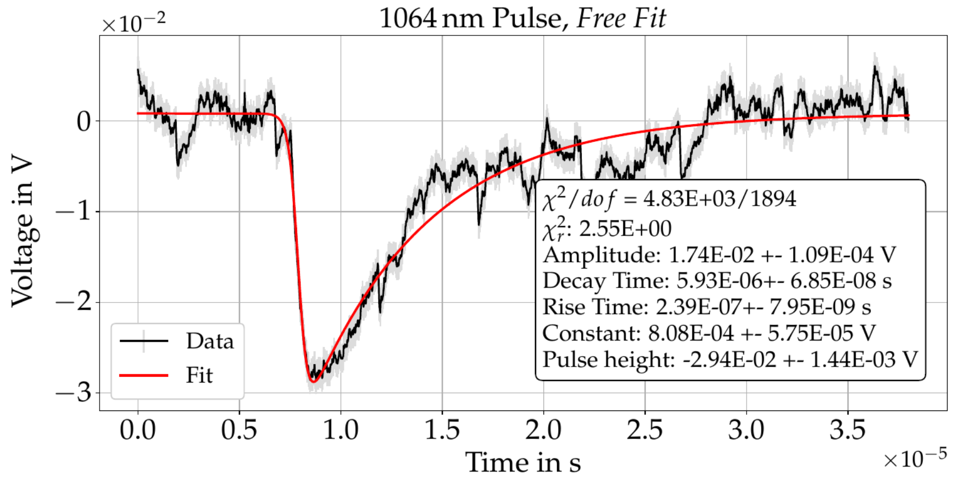

Courtesy of Rikhav Shah

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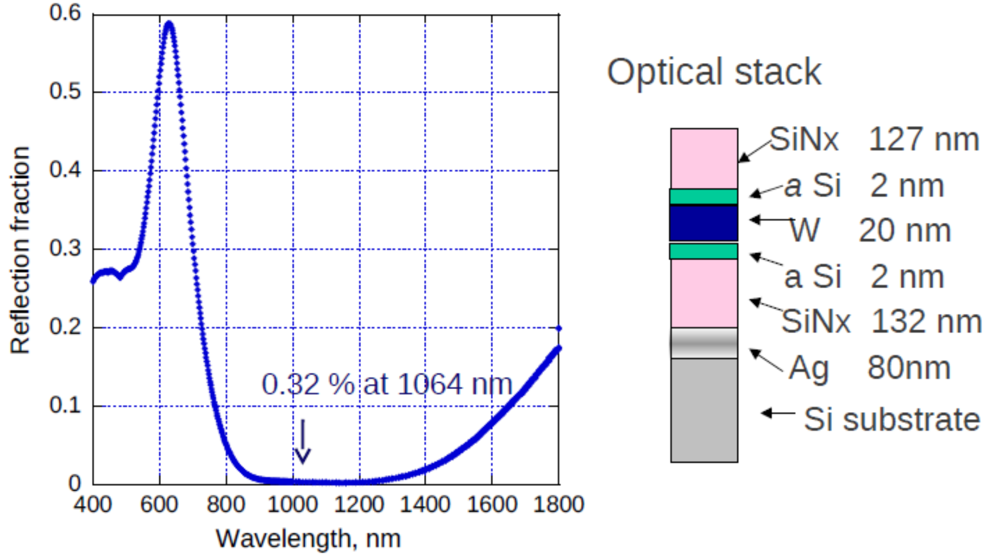
- Incident photon leads to temperature increase
- Small temperature increase leads to large variation in resistance

- Change in resistance is measured in changing current
- Signal is proportional to photon energy
- Energy resolution ~ 8%

Drawings courtesy of Katharina-Sofie Isleif

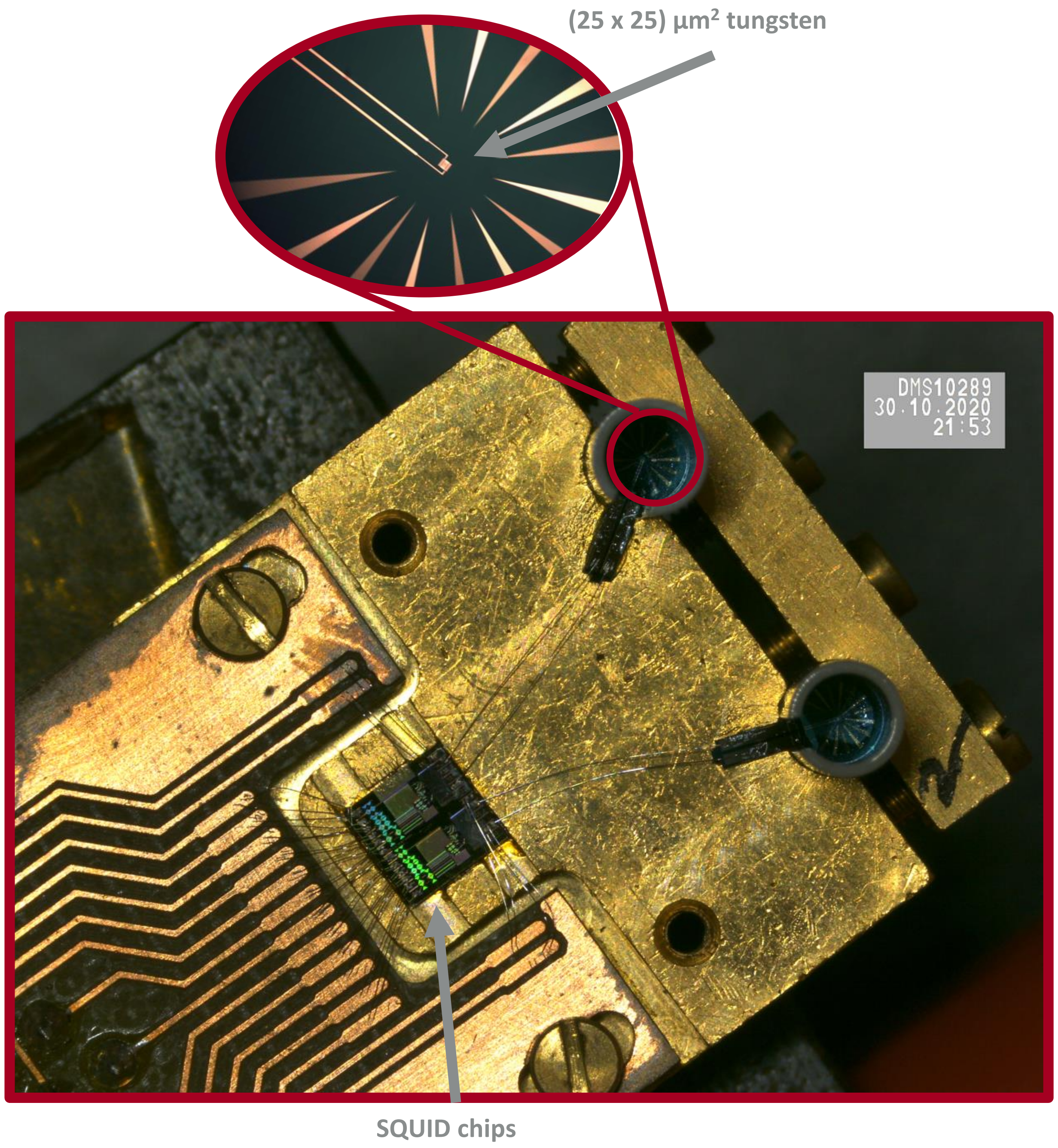
TES Single Photon Detection

Quantum Sensing Details



J. Dreyling-Eschweiler, Dissertation (2014)

- Very small active area
- Option for fiber coupling
- Optical stack & efficiency optimized for 1064nm photons
- Higher reflection for other photon-wavelengths



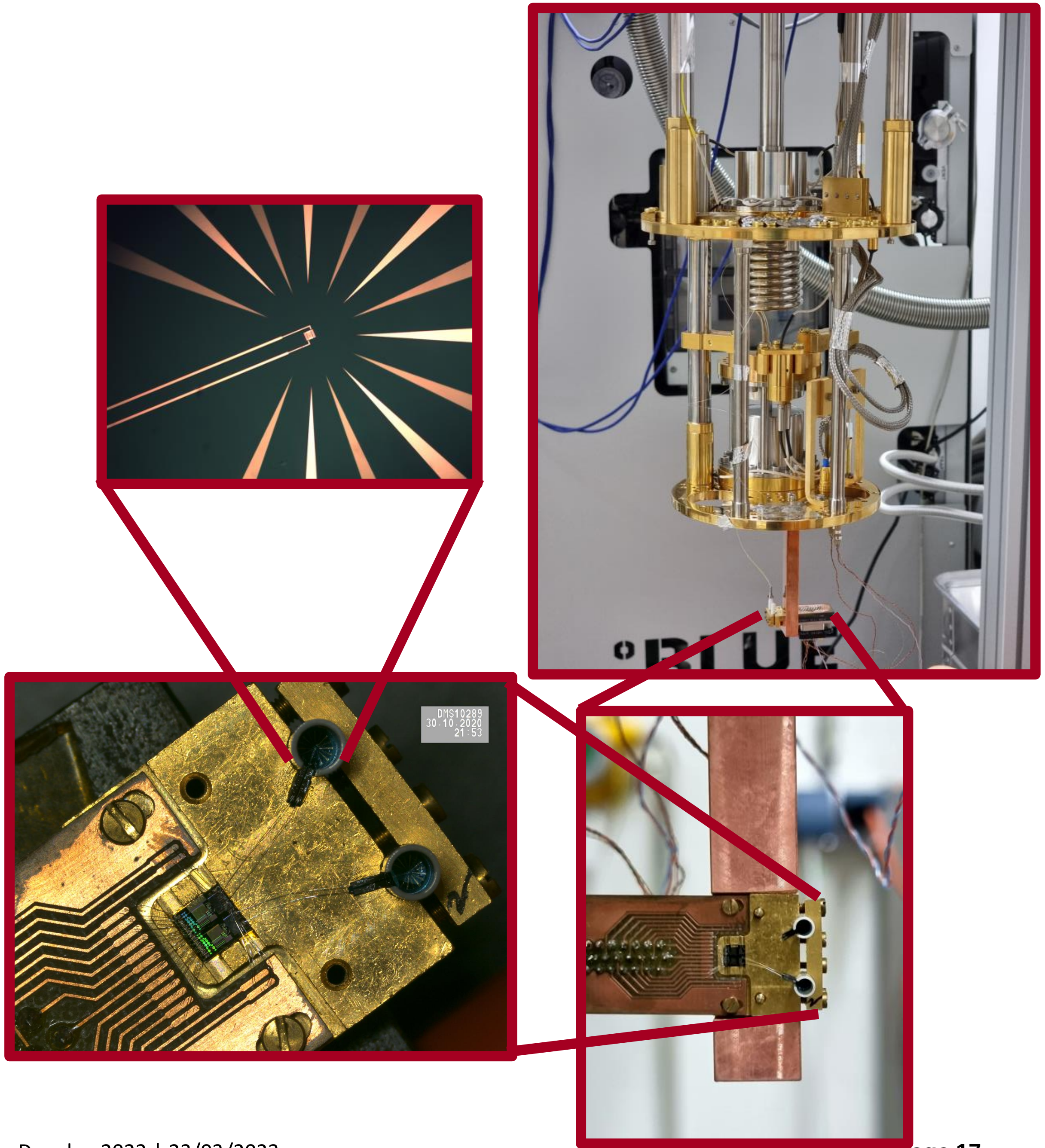
TES as Dark Matter Detector

Current Challenges

TES Status

- Optimized optical structure to increase absorption at 1064 nm→1.165 eV
- Limited knowledge about response to other wavelengths

Low background
(electronic noise, radioactivity, cosmic muons)
→ currently: 6.9×10^{-6} cps[1]
(intrinsic background for 1.165 eV signals)



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

TES as Dark Matter Detector

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• Optimized optical structure to increase absorption at 1064 nm→1.165 eV • Limited knowledge about response to other wavelengths	→	• Determine linearity of TES response, especially at lower (sub-eV) energies • Linearity measurements currently planned using diodes of different wavelengths (880 nm – 2000 nm)

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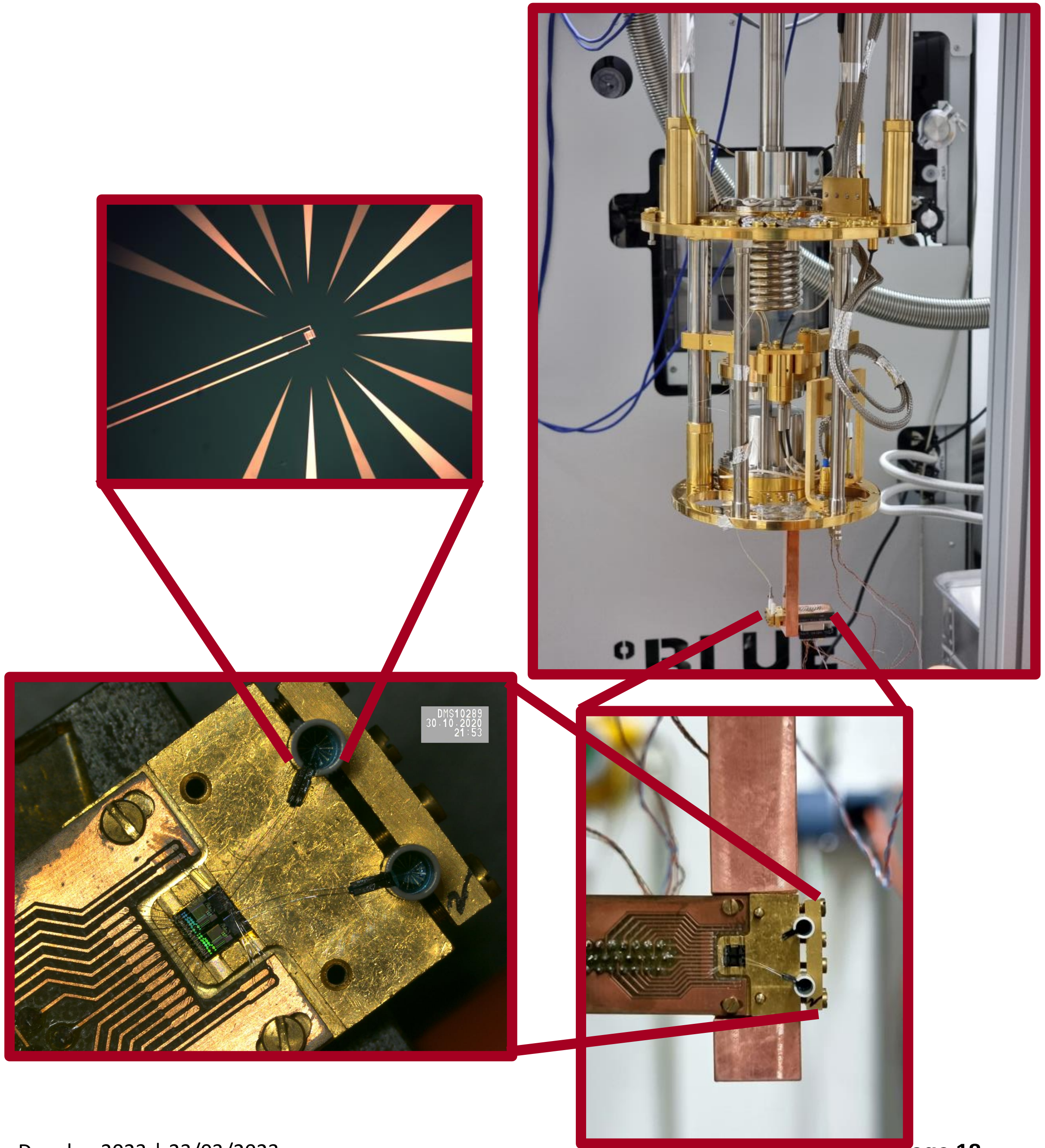

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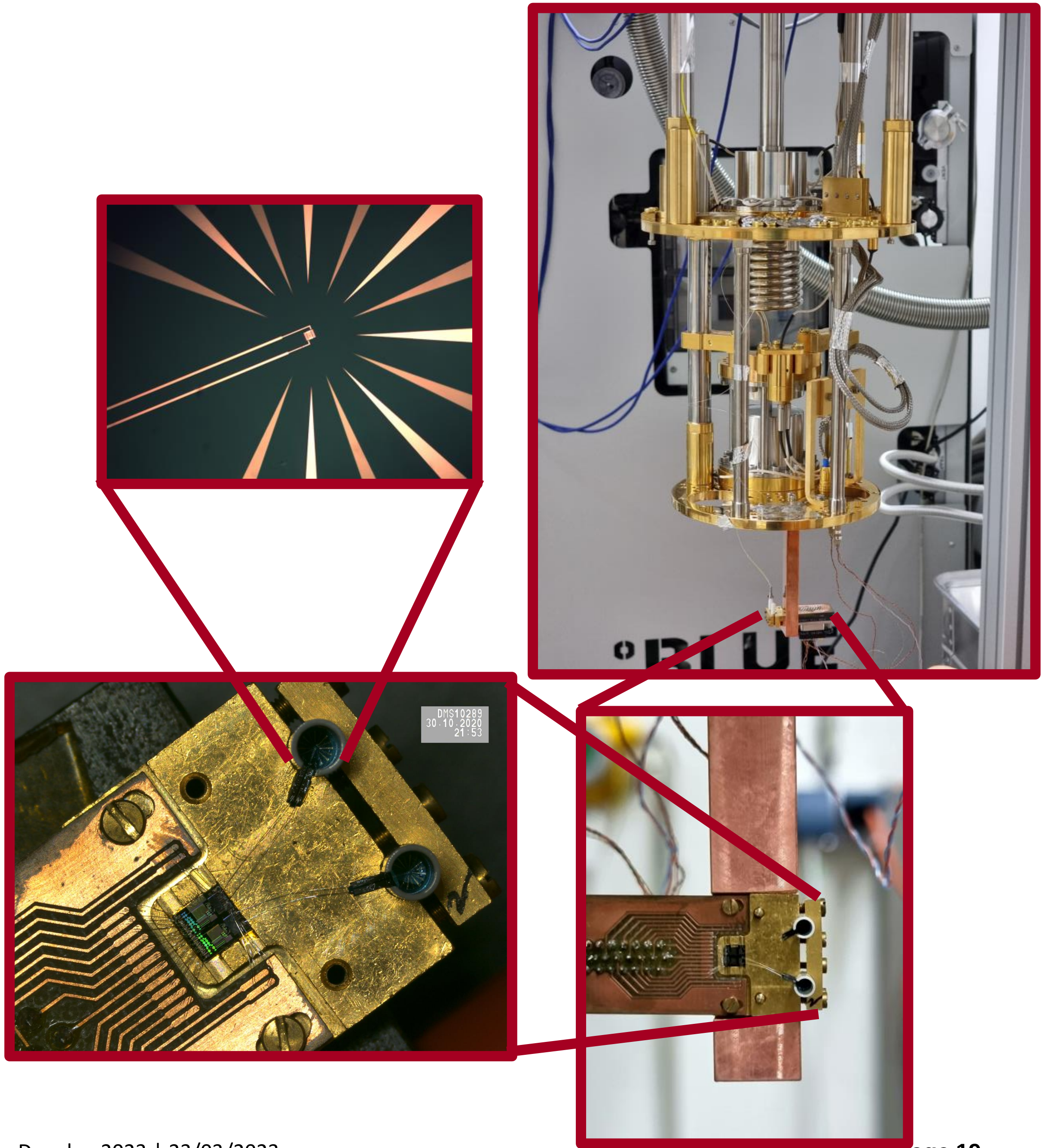
Low background (electronic noise, radioactivity, cosmic muons) → currently: 6.9×10^{-6} cps[1] (intrinsic background for 1.165 eV signals)	→	• Further investigate intrinsic backgrounds • Investigate alternative TES modules with lower noise background



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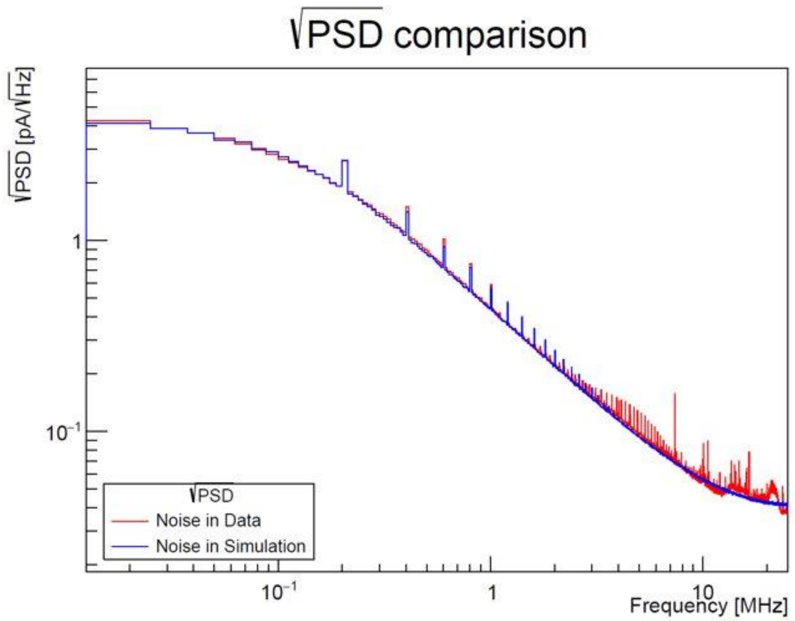
Direct Dark Matter Detection with TES

Background simulations

Simulate background

From fitting measured data set



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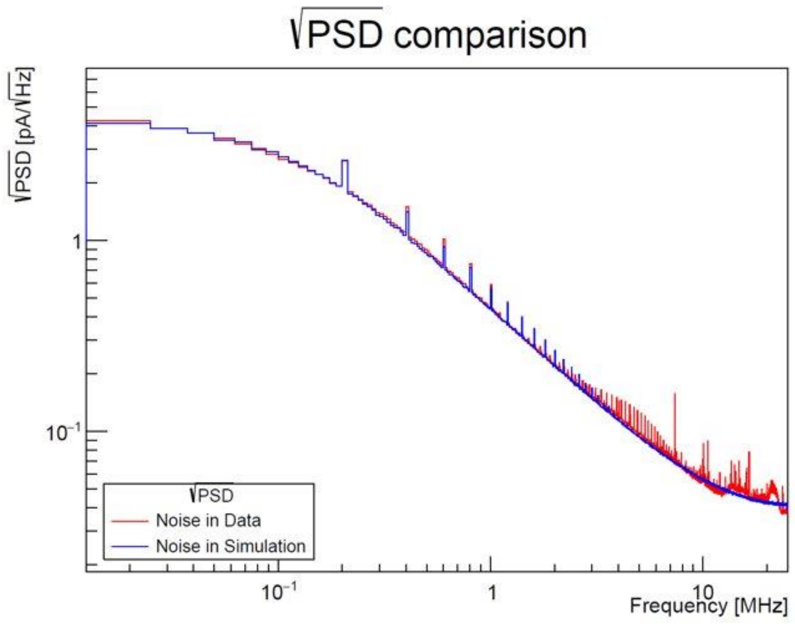
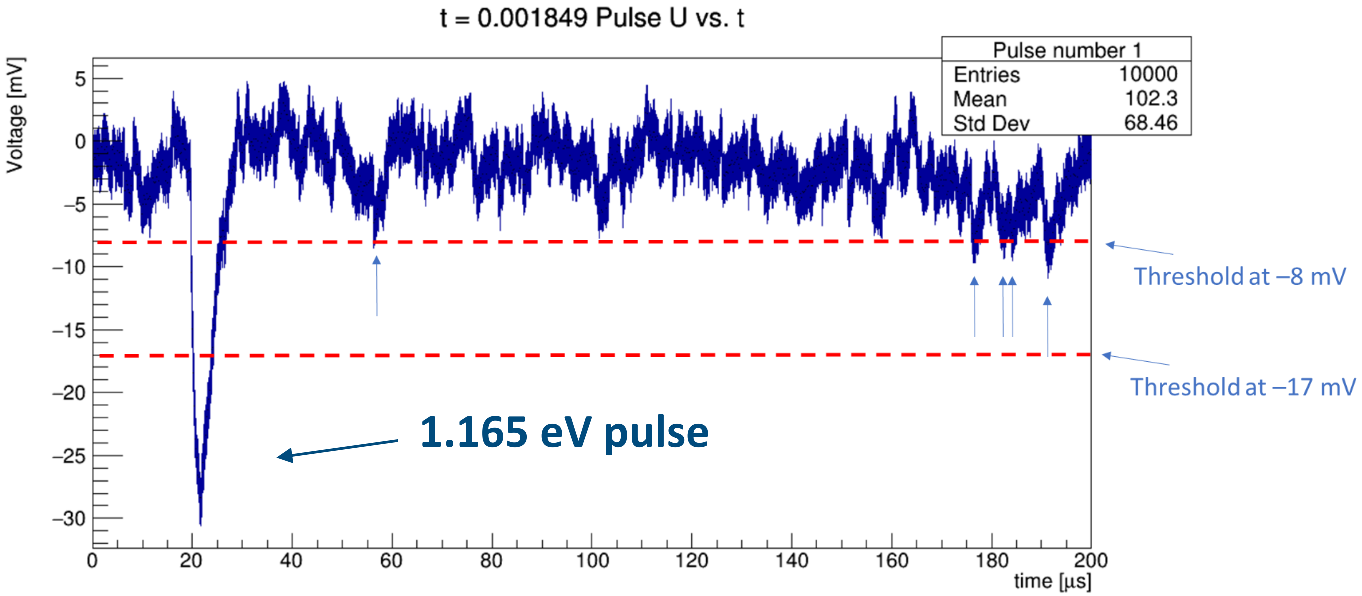


Simulate background and pulses

To optimize analysis for certain energies



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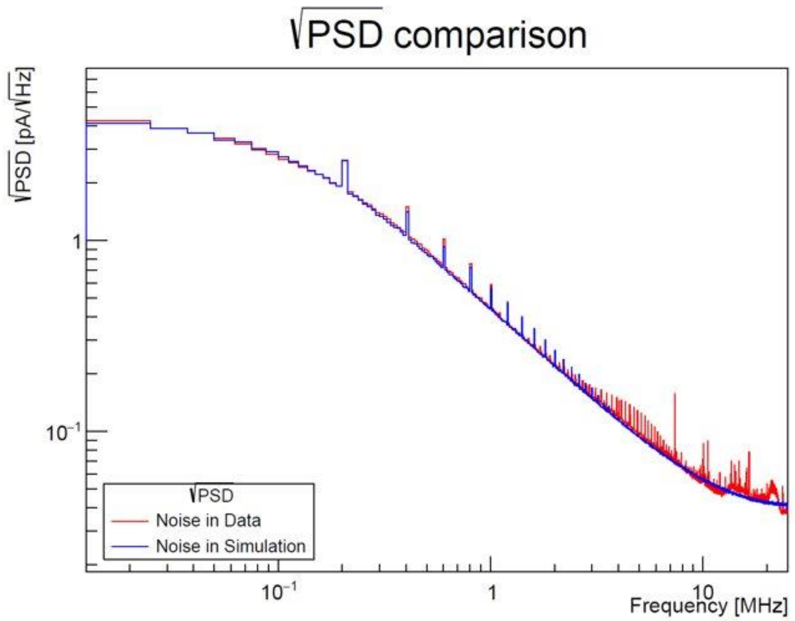

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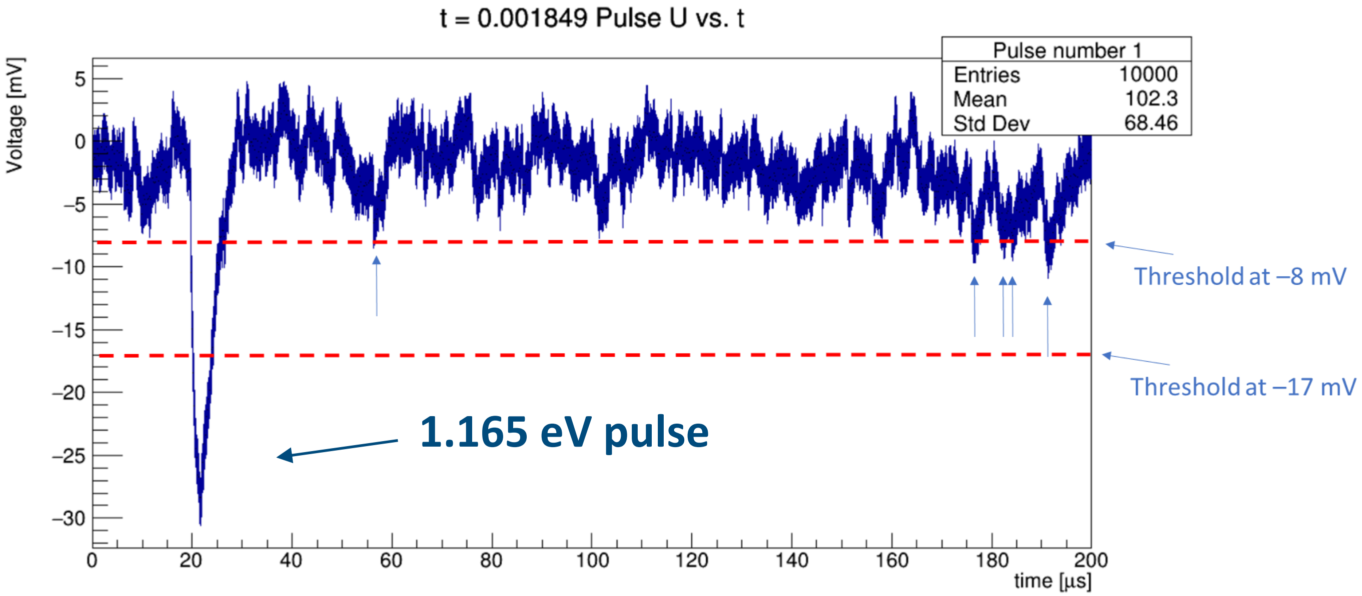


How to discern low energy pulses from noise?

Direct Dark Matter Detection with TES

ALPS II analysis optimized for lower energies

Using Simulations:

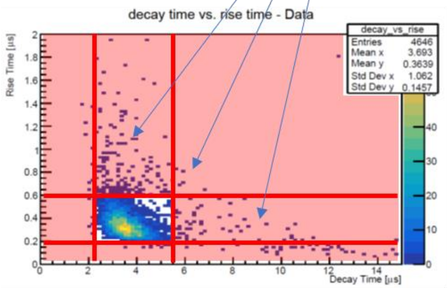
1. w/o pulses – only electronic noise: rate after trigger
2. With light pulses to optimize analysis and cuts for different energies
   - Assumption: Only pulse amplitude changes for different energies

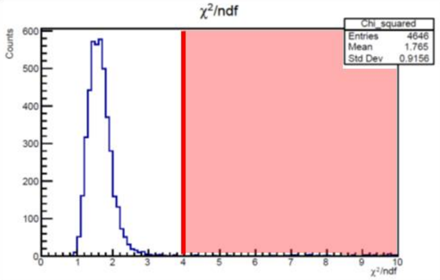
Noise-only simulations

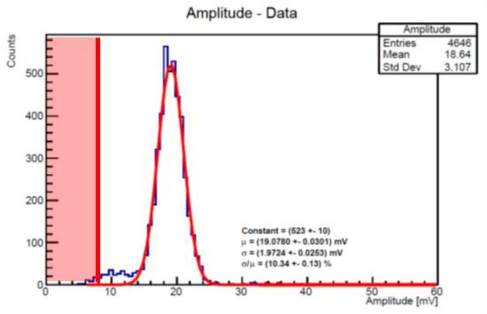
Rate for -11 mV threshold
4.21(0.09) Hz

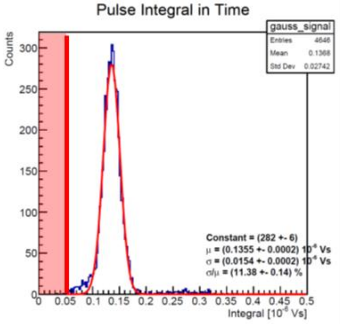
Pileup candidates

Method 1 – Time domain





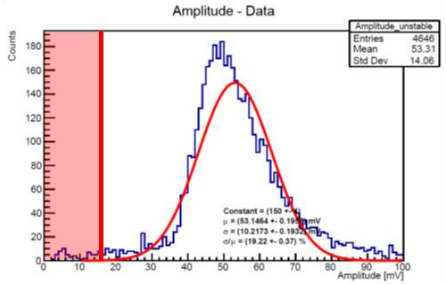




if 1064nm

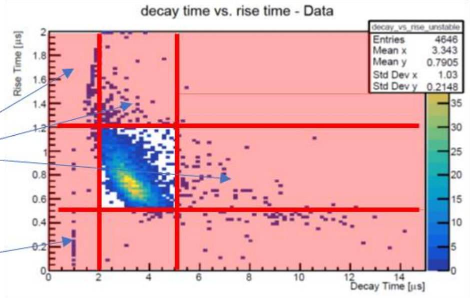
Mean pulse height: 28mV

Method 2 – Frequency domain



Pileup candidates

Noise triggers



Direct Dark Matter Detection with TES

ALPS II analysis optimized for lower energies

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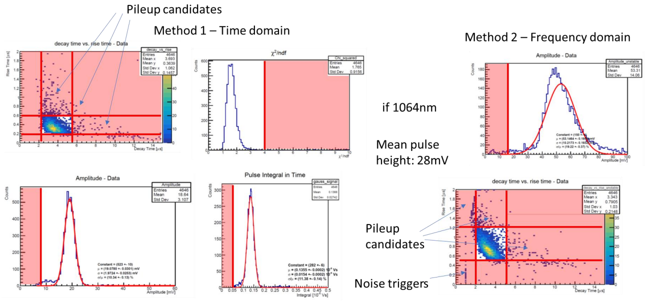

Test (electronic) background rate for low triggers after analysis:

- Simulation of noise-only data
- Applying cuts optimized for 1.165eV and 0.583eV

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Rate for -11 mV threshold
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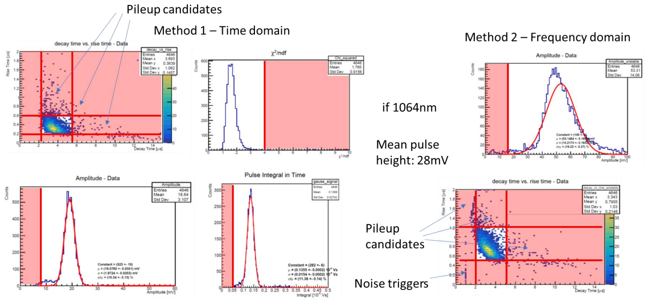


Test (electronic) background rate for low triggers after analysis:

- Simulation of noise-only data
- Applying cuts optimized for 1.165eV and 0.583eV
- No noise passing analysis & cuts in 88 min of simulated time with **54.9%** acceptance of **0.583eV** pulses

→ **Promising for direct DM searches!**

Noise-only simulations

Rate for -11 mV threshold
4.21(0.09) Hz

Noise-only simulations & analysis

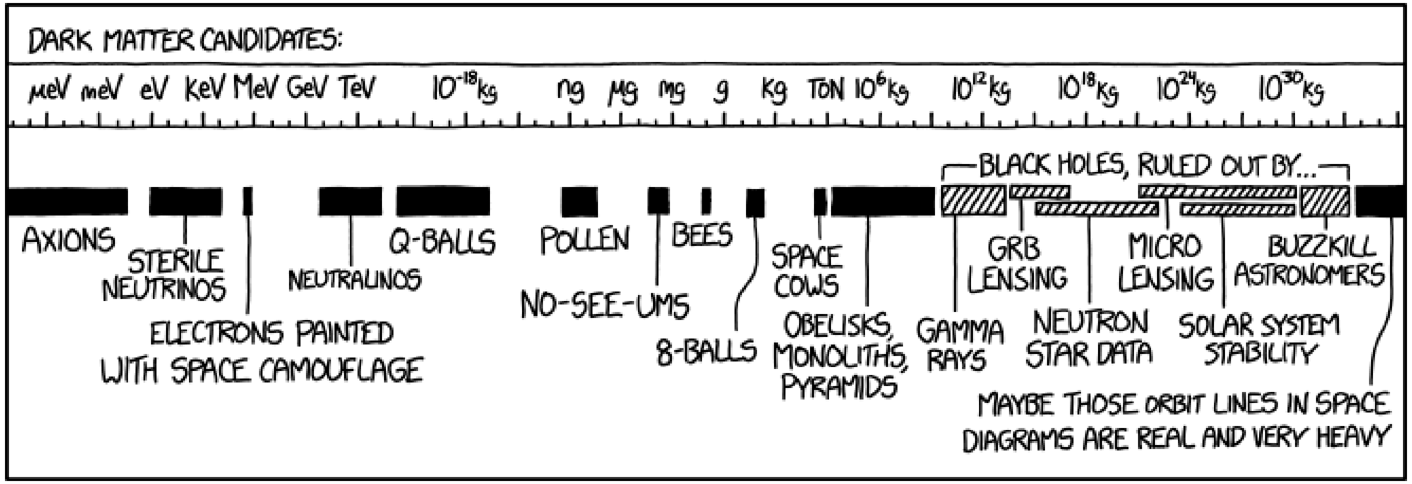
Cuts based on	Rate for -11 mV threshold
1.165 eV	0.0000(0.0004) Hz
0.583 eV	0.0000(0.0004) Hz

Summary and Outlook

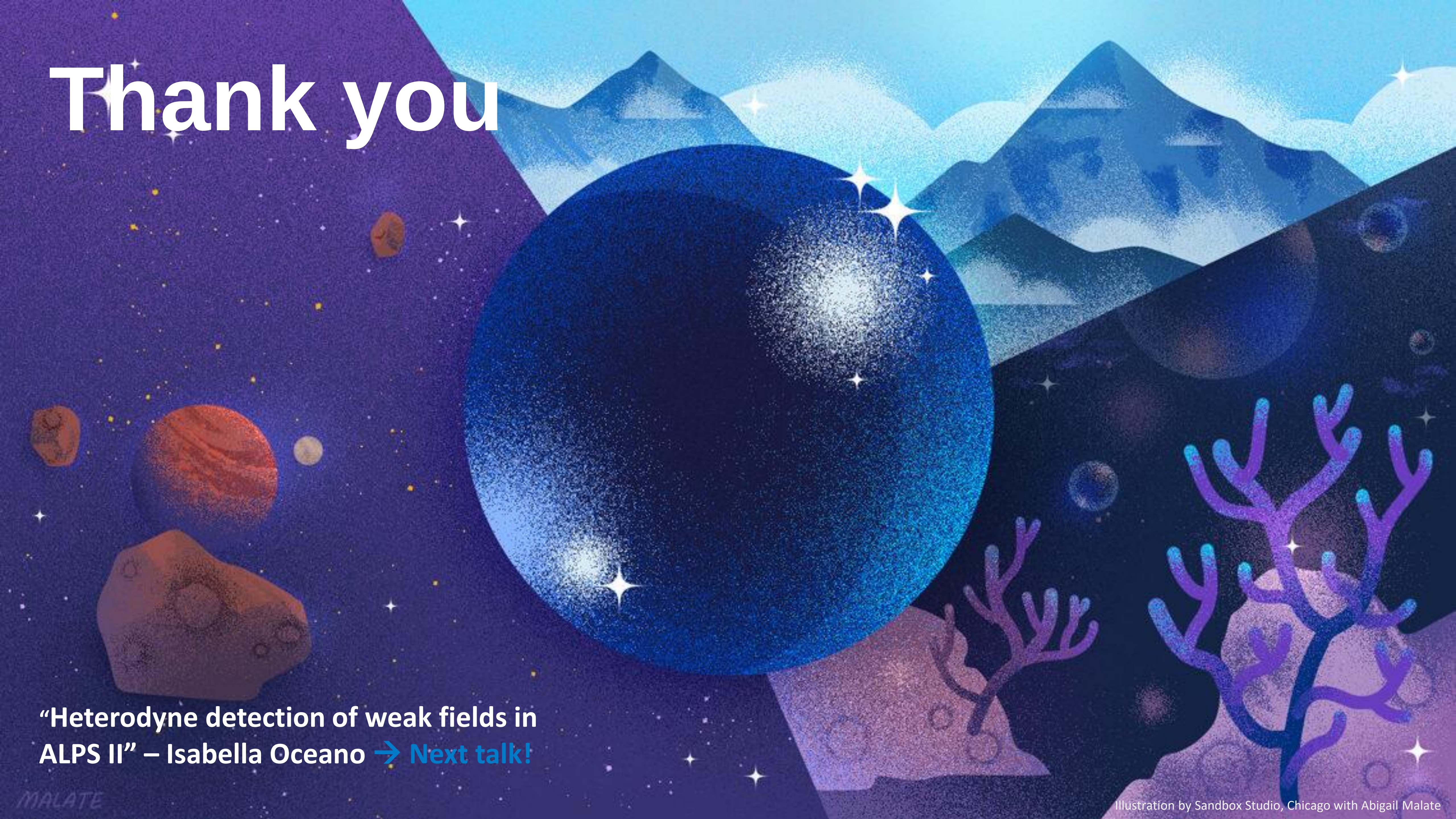
- TES technology used in **ALPS II** may be interesting for **direct dark matter searches** in the **sub-MeV DM** mass range exploiting DM-electron scattering
- Similar measurements have been conducted using **SNSPDs**
- Using TES for Direct DM Searches has been **proposed in literature** before
- **Would our TES be viable as well?**

- Perform **intrinsic background measurements** to compare with SNSPD results
- Investigate **linearity** of TES response for different energies (880 nm – 2000 nm or 1.4 eV – 0.6 eV)
- Further investigate **intrinsic background**
- Investigate **alternative/optimized TES modules**

Comic by xkcd



Thank you

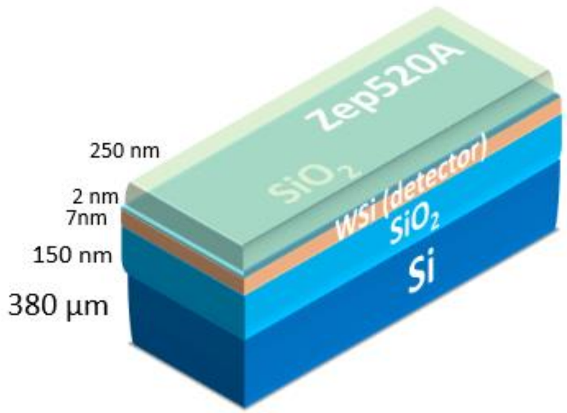


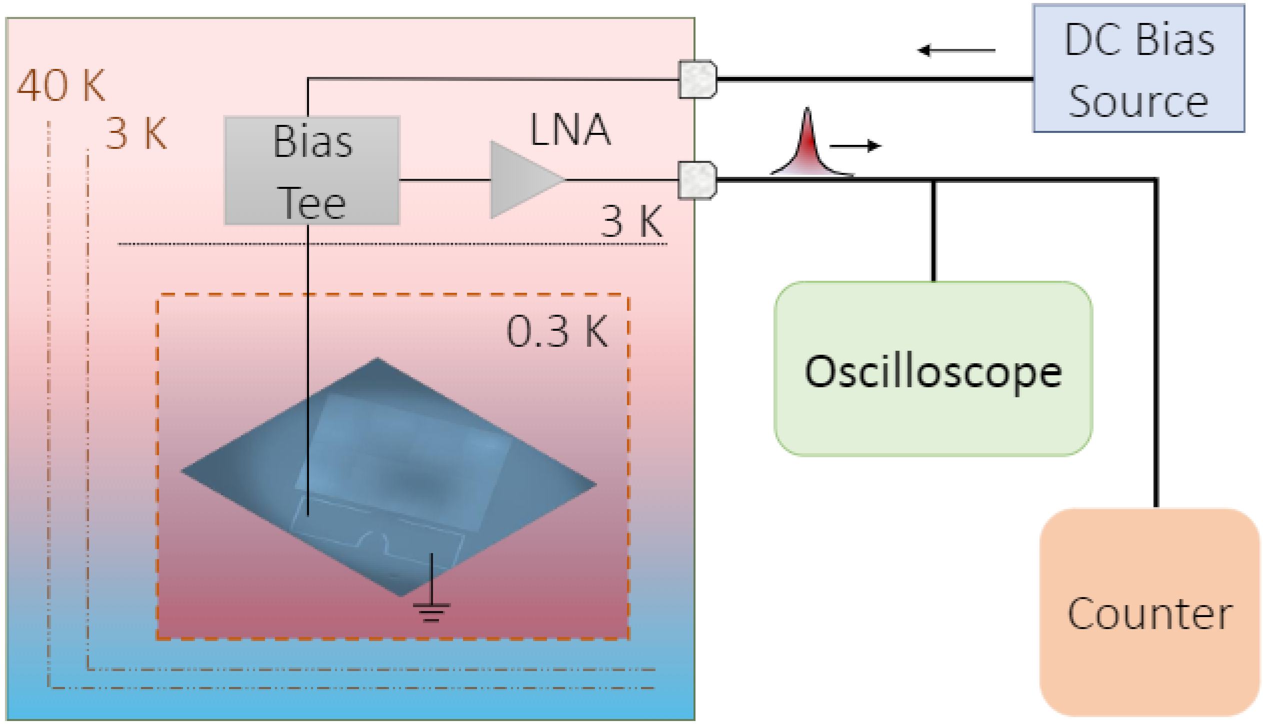
"Heterodyne detection of weak fields in ALPS II" – Isabella Oceano → Next talk!

Illustration by Sandbox Studio, Chicago with Abigail Malate

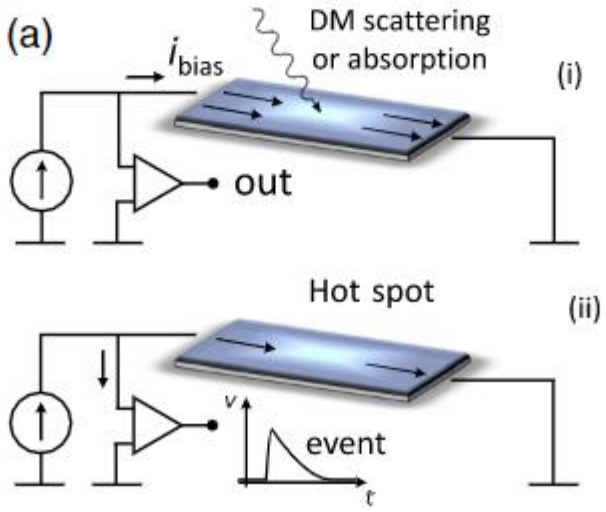
Backup

SNSPDs





Hochberg, Y. et al. arXiv:2110.01586 (2021)

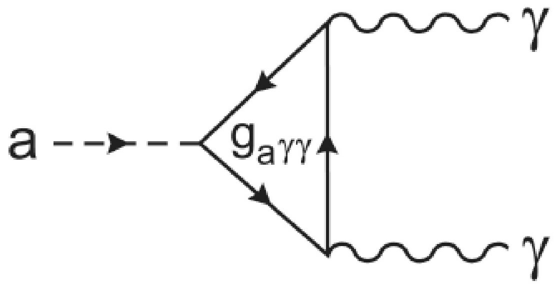


Hochberg, Y. et al., *Physical Review Letters, 123*(15). (2019)

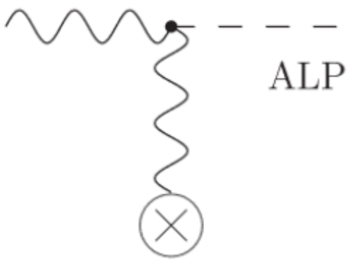
Backup

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 **S**hining Through **W**alls (LSW) experiments

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

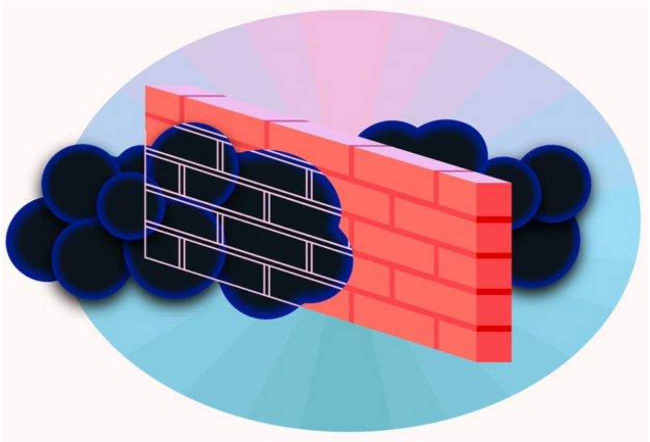
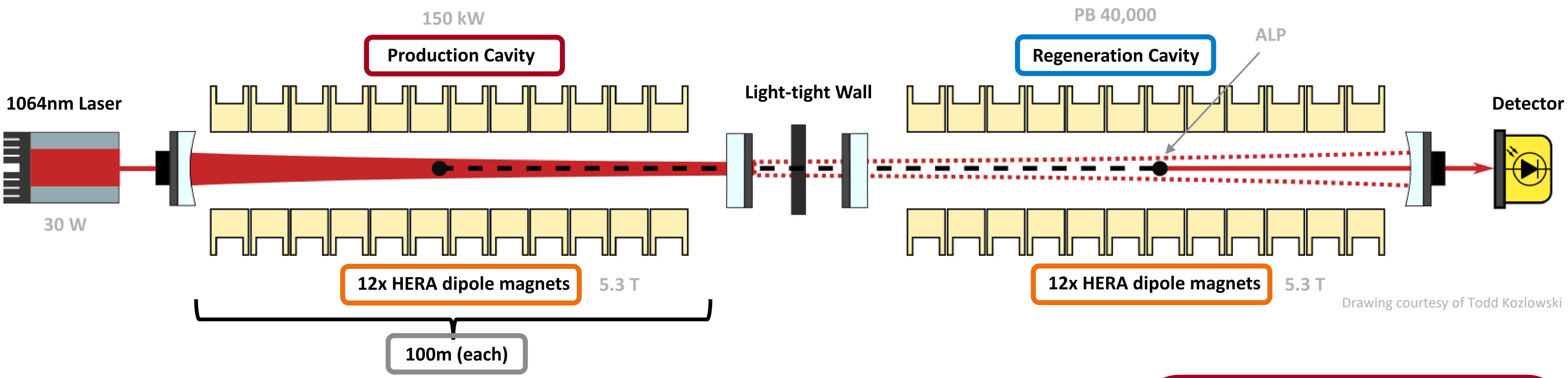


Illustration by Sandbox Studio, Chicago with Ana Kova

BACKUP

Any Light Particle Search with ALPS II - Experimental Setup



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

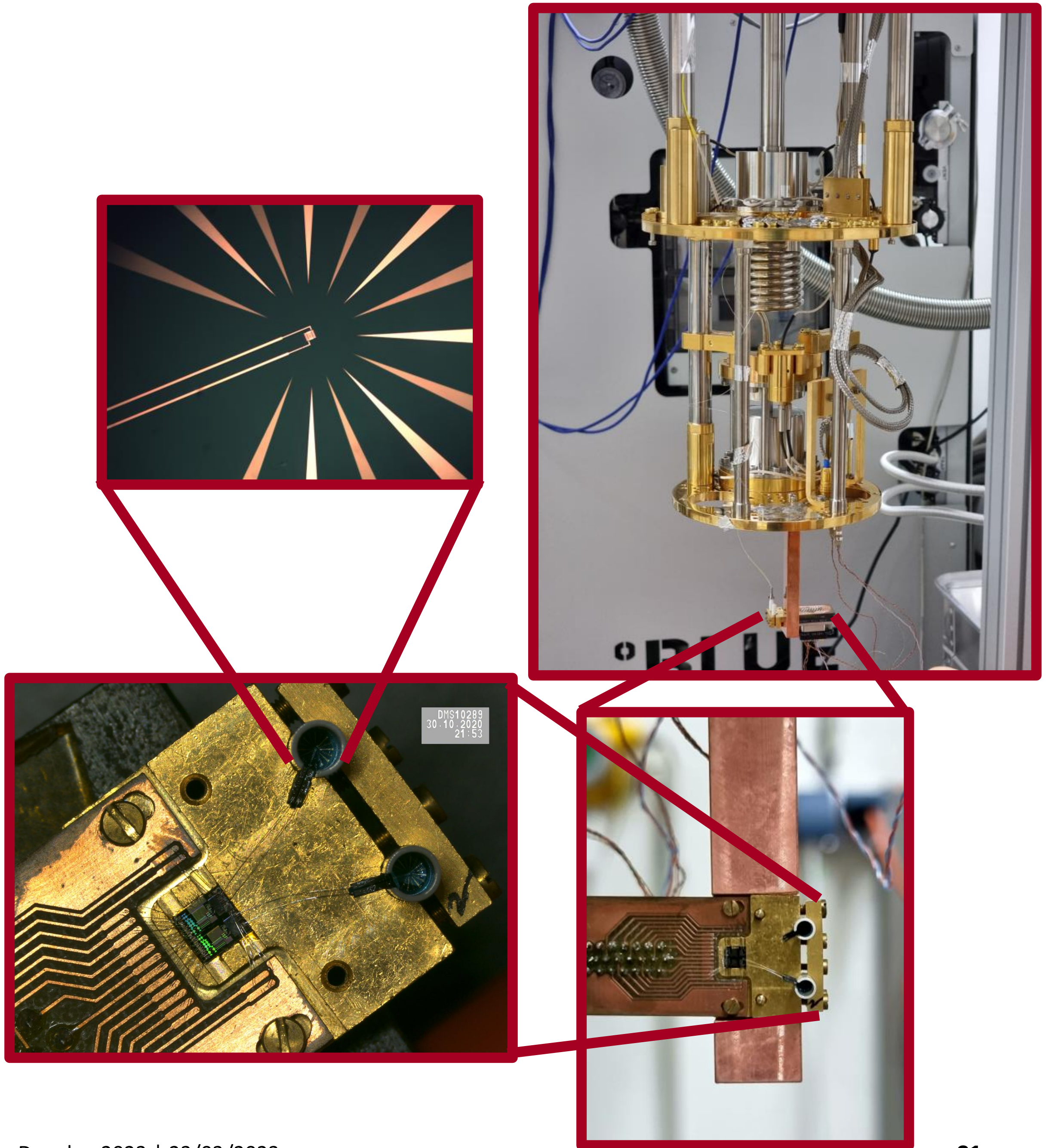
Expected rate of low energy ($\sim 1.16\,\mathrm{eV}$) photons: $\dot{N}_\gamma \approx 2.8 \cdot 10^{-5}\frac{\gamma}{\mathrm{s}} \approx 1\frac{\gamma}{\mathrm{day}}$
(for $g_{a\gamma\gamma} = 2 \cdot 10^{-11}\,\mathrm{GeV}^{-1}$)

Single-photon detection requirements for ALPS II:

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

Backup
ALPS II Setup

Detection requirements		TES solution
• Photon detection at low energies (1064 nm → 1.165 eV) • High quantum efficiency	→	optimized optical structure to increase absorption at 1064 nm
Low background (electronic noise, radioactive backgrounds, photons from black-body radiation) < 1 photon/day	→	shielding in cryostat and tests to reduce background: • fiber curling • filtering of black-body photons → currently: 6.9×10^{-6} cps[1] (intrinsic background)
High detection efficiency	→	determination ongoing, has been proven to be ~90% in other setups[2]



[1] R. Shah et al., PoS, EPS-HEP2021, 801 (2022)
[2] A. Lita et al., Advanced Photon Counting Techniques IV 7681 76810D (2010)

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

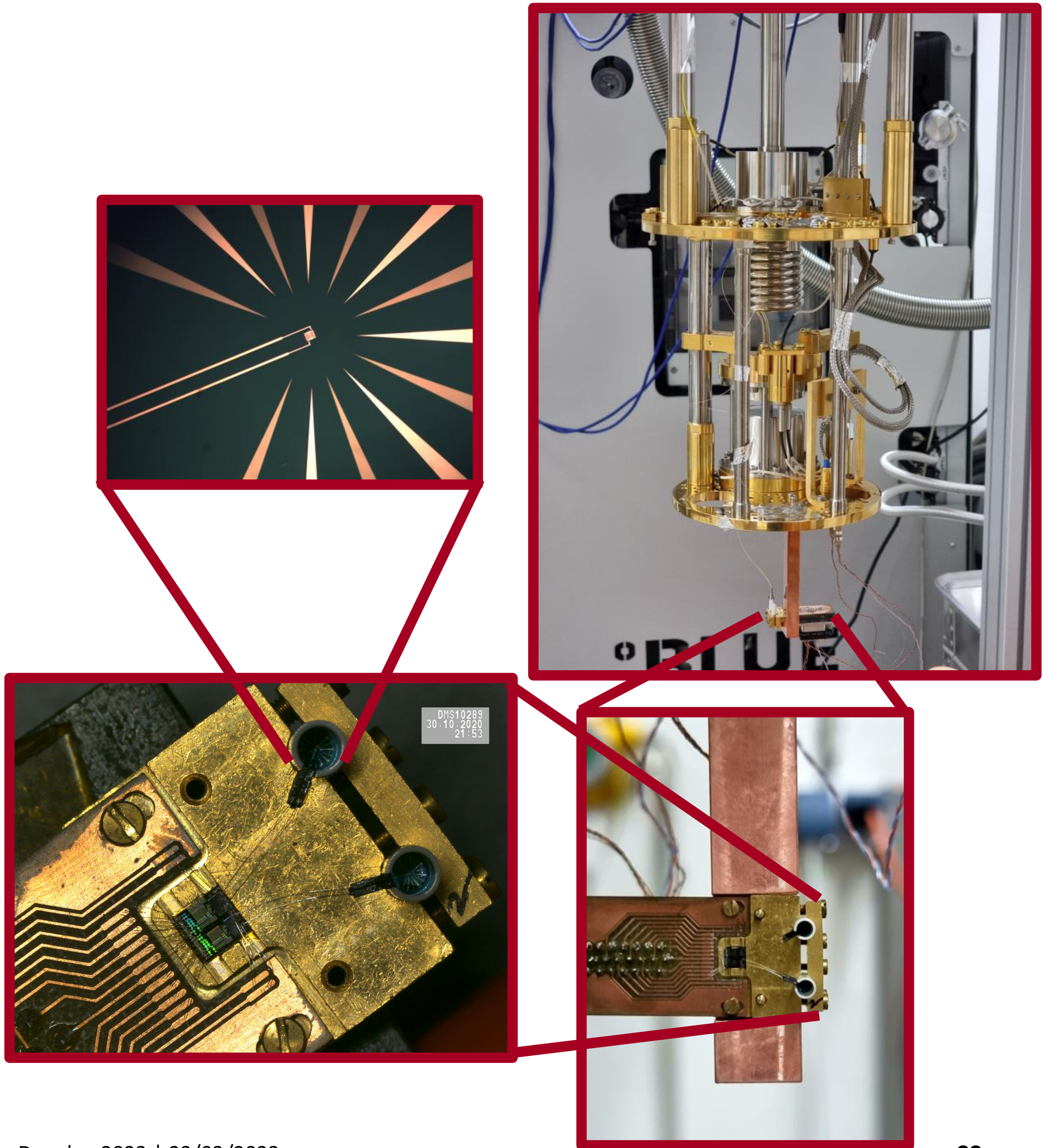
High detection efficiency

Still to do

Determine **linearity** of TES response

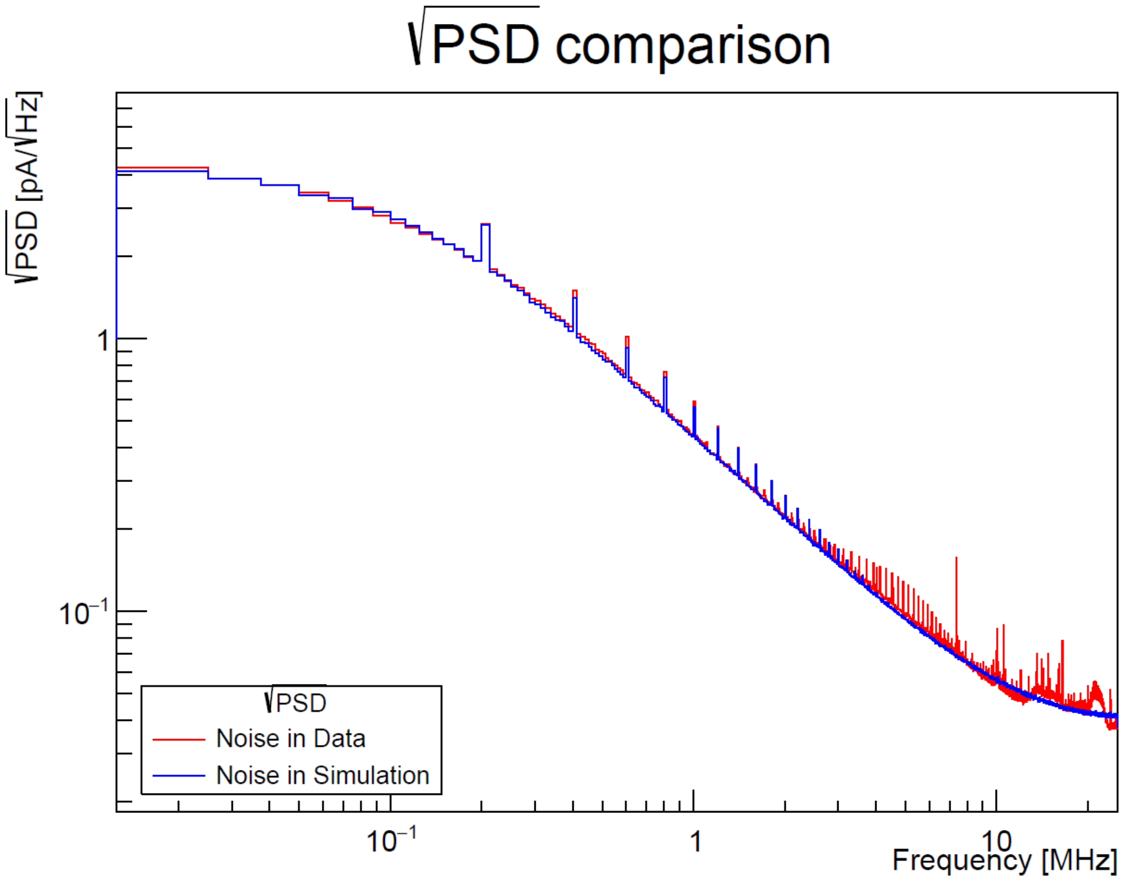
Good **intrinsic** background (no optical fiber attached)
Still need to reduce **extrinsic** background (introduced by optical fiber from the outside of the cryostat)

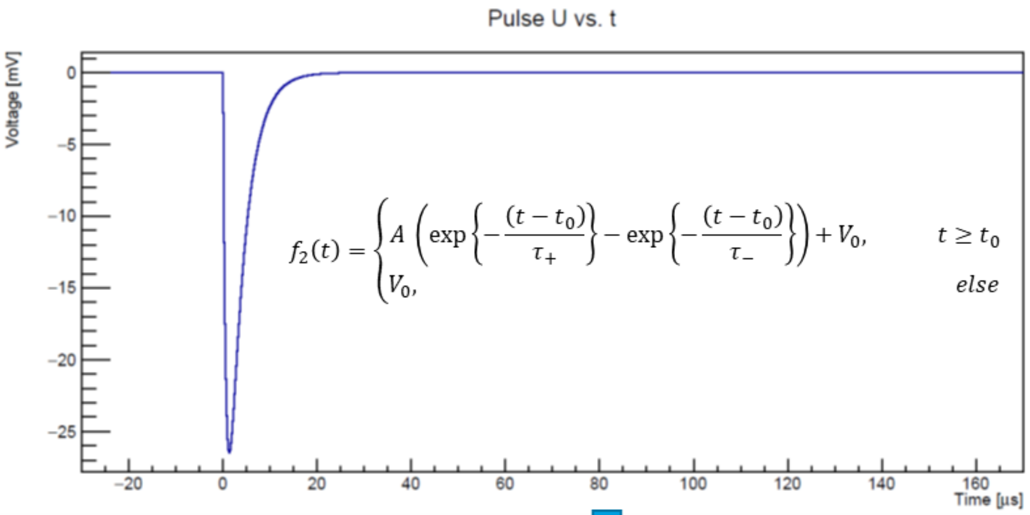
Optimize and **determine** system efficiency

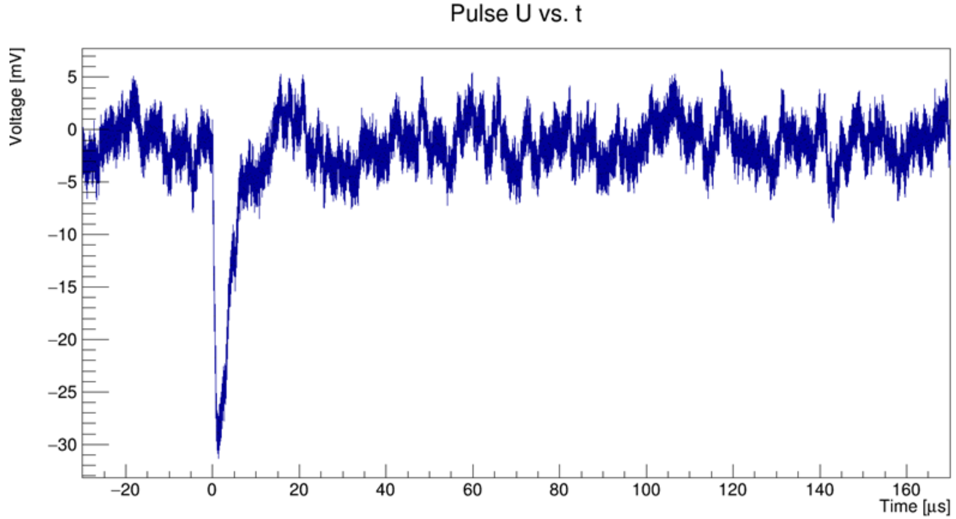


Backup

Simulation of pulses



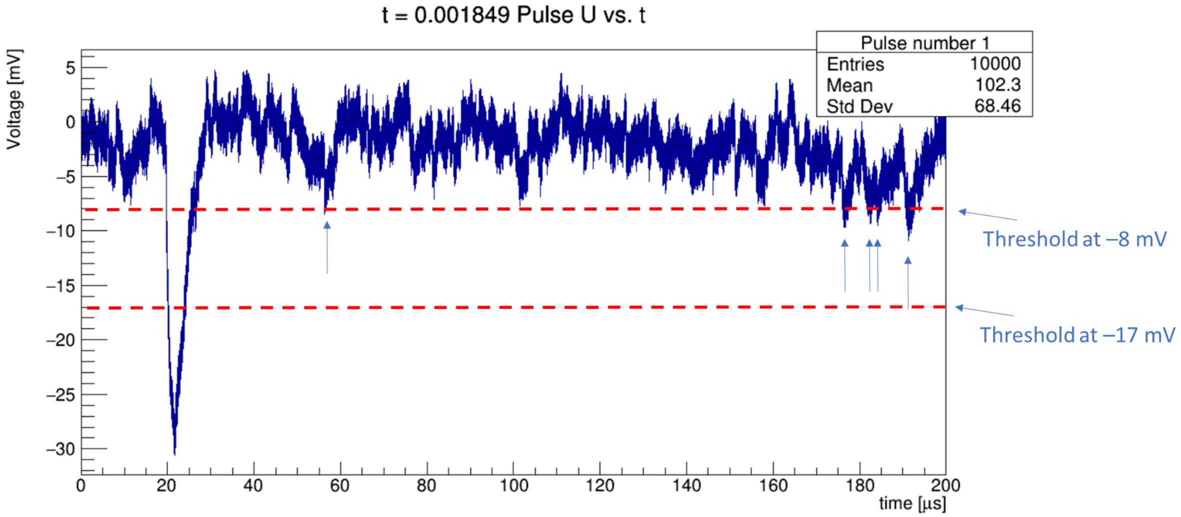




Backup

False trigger simulations

- Rate of triggered noise pulses for different thresholds and sample sizes
- Without simulated pulses – only noise contributions



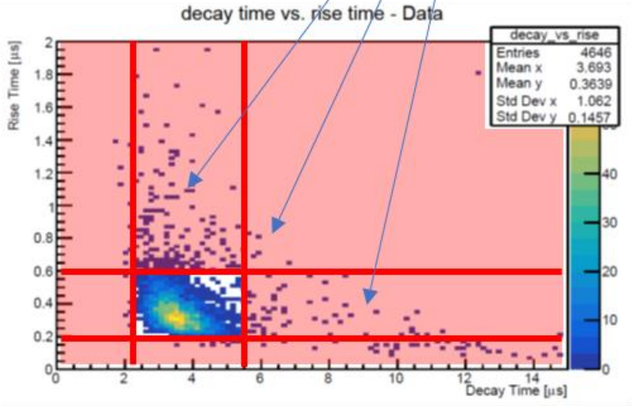
False Triggers - Rate of noise pulses passing different trigger thresholds											
		Usual trigger thresholds for 1064nm pulses					Threshold/mV				
		-17	**-16**	**-15**	**-14**	**-13**	**-12**	**-11**	**-10**	**-9**	-8
Simulated time	**# Samples**	**Rate 1/s (+/- statistical uncertainties)**									
9 sec	**45 000**	0	0	0	0	0	0.33 (0.19)	4.2 (0.7)	36 (2)	241 (5)	/
8 min 20 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)	974 (1)

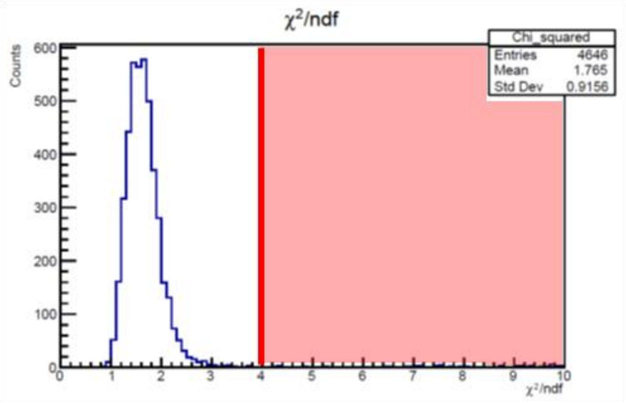
Backup

Cut-based analysis 1064nm signals

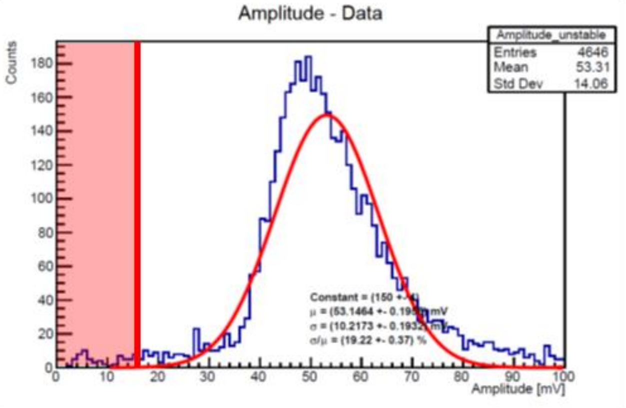
Pileup candidates

Method 1 – Time domain



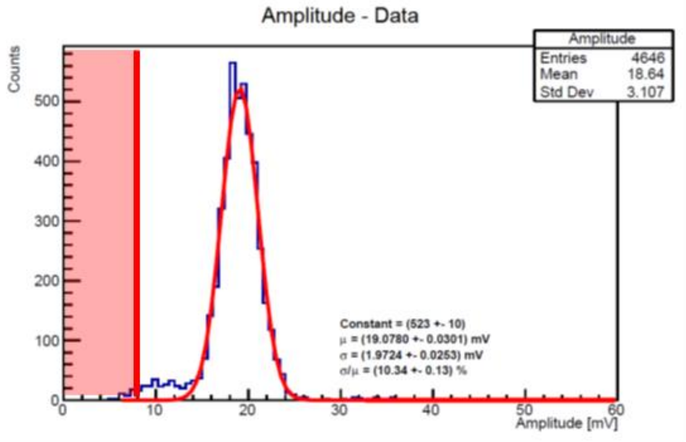


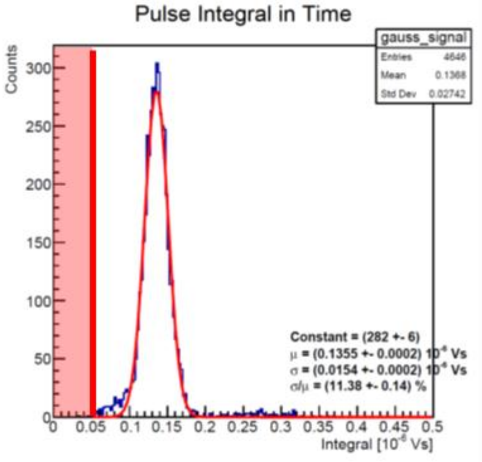
Method 2 – Frequency domain



if 1064nm

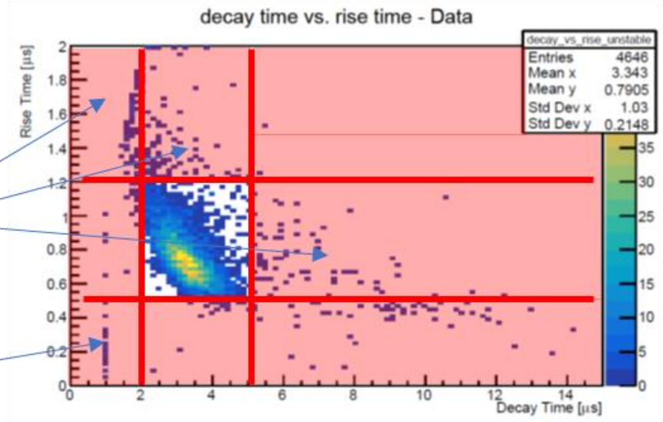
Mean pulse height: 28mV





Pileup candidates

Noise triggers



Backup

True trigger simulations and analysis - example

Example:
0.583 eV (2127 nm)

- **Before analysis:** Simulated trigger acceptance for different low energies and trigger threshold
- **Assumption:** Pulse-shape does not change for lower energies → only pulse height

True Triggers - Acceptance of triggered pulses - 5000 samples each									
trigger threshold / mV (+/- statistical uncertainties)									
Energy / eV	**-17**	**-16**	**-15**	**-14**	**-13**	**-12**	**-11**	**-10**	**-9**
0.583	16.8 (0.6)%	29.2 (0.8)%	44.9 (1.0) %	62.7 (1.1)%	77.1 (1.2)%	88.6 (1.3)%	95.3 (1.4)%	98.5 (1.4)%	100.0 (1.4)%

- Perform **cut based analysis** on pulses accepted by the trigger
- Analysis reduces acceptance based on pre-defined cuts (e.g. pulses with long decay times)
- Analysis initially optimized for 1.165 eV

→ Comparison with additional cuts on pulse-height for 0.583 eV

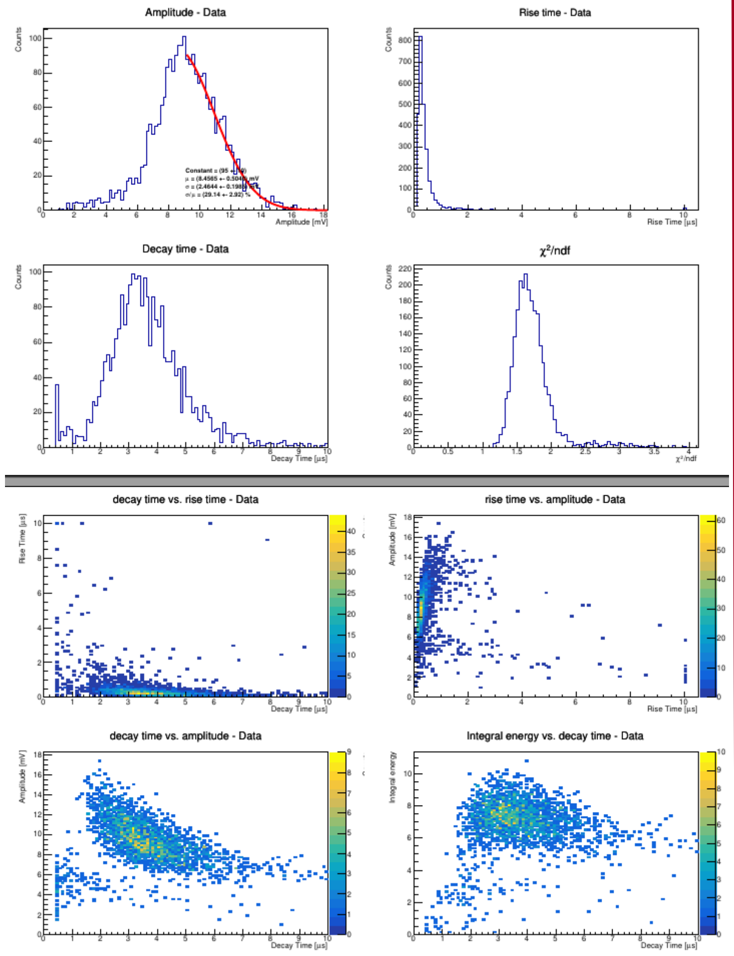
Trigger threshold	**-11 mV**
non optimized	37.6 (1.2)%
optimized	54.9 (1.5)%

Acceptance improvement

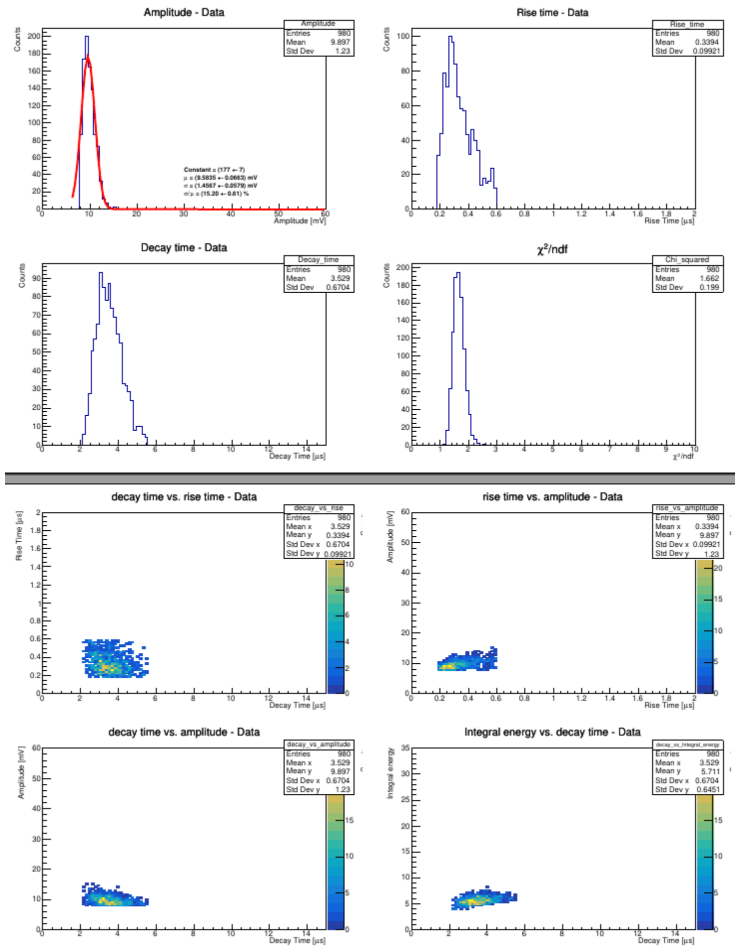
Backup

Simulation – Analysis and Cuts 0.583 eV

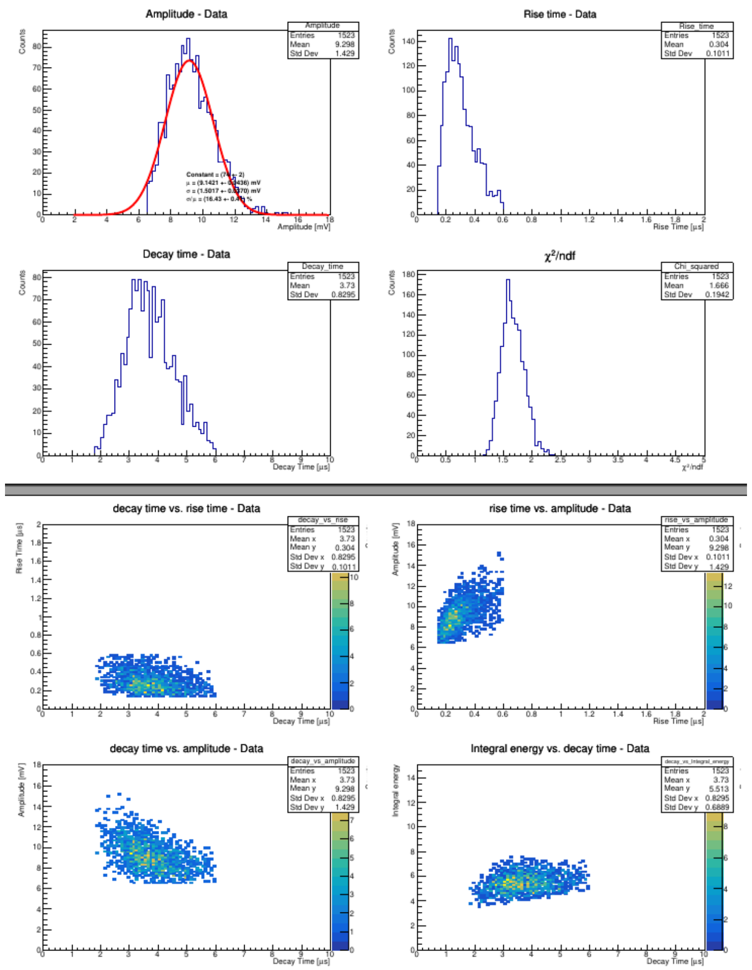
- Pre Cuts



- Post – 1.165eV optimized - Cuts



Post – 0.583eV optimized - Cuts



Examples in time domain

Backup
Dielectric function

Energy loss function of dielectric materials $\Im(-\epsilon_L^{-1}(\omega, k))$ depends on longitudinal dielectric permittivity
Longitudinal dielectric permittivity responds to
- Charge density perturbations with frequency ω
- Momentum transfer q

After Lasenby, R., & Prabhu, A. (2022)electromagnetic sum rules and Kramers-Kronig relation lead to rules that must be satisfied by materials in which DM – electron scattering happens:

$$\int_0^\infty \frac{d\omega}{\omega} \Im(-\epsilon^{-1}(\omega, q)) \leq \frac{\pi}{2}(1 - \epsilon^{-1}(0, q))$$

Which gives the maximum possible material response during scattering.
Leads to constraints on maximum average DM scattering rate in a material with DM-mediator coupling strength g_χ and mediator-EM coupling strength g_e leading to:

$$\bar{\Gamma} \lesssim g_\chi^2 g_e^2 m_\chi v_\chi$$

Materials saturating this rate will be good candidates for direct DM detection!

Backup

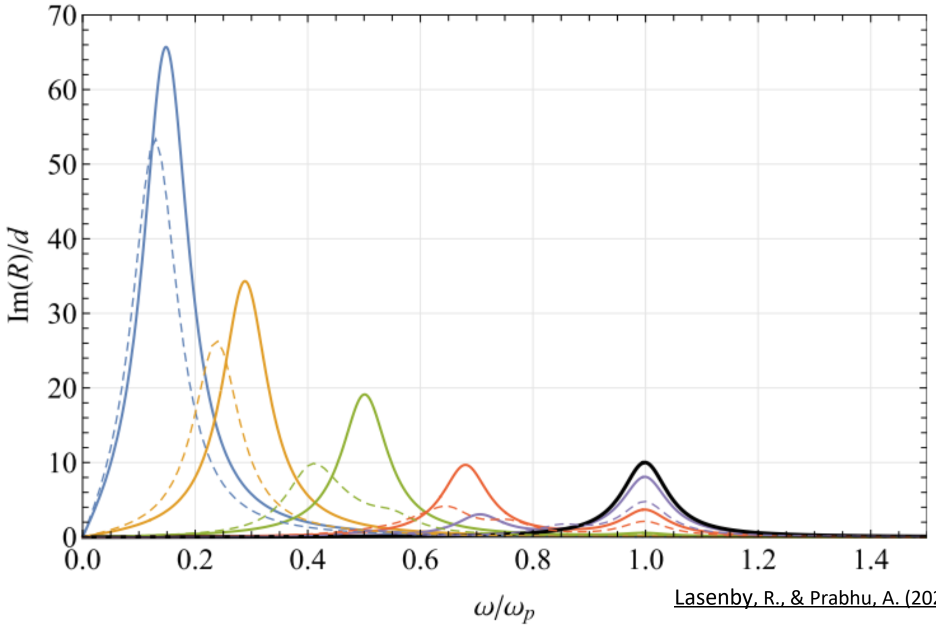
Thin films and plasma frequency

For thin layers per area scattering rate dependency on response function $\Im(R)$can be used instead of per volume scattering rate relying on$\Im(-\epsilon^{-1})$ moves material response to lower frequencies

Material response governed by **plasma frequency** ω_p, above which dielectric function of a conductor$(\epsilon \simeq -\omega_p^2/\omega^2)$ is positive (e\m waves can penetrate material). Waves with frequencies below plasma frequency are reflected.

Thin layer response function for $k_z d$ values between 0.05 and 10. Black line corresponds to bulk material $(\omega = \omega_p)$

→ Larger response for small thicknesses even below plasma frequency



Lasenby, R., & Prabhu, A. (2021)

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