Direct dark matter searches using ALPS II's TES detector system

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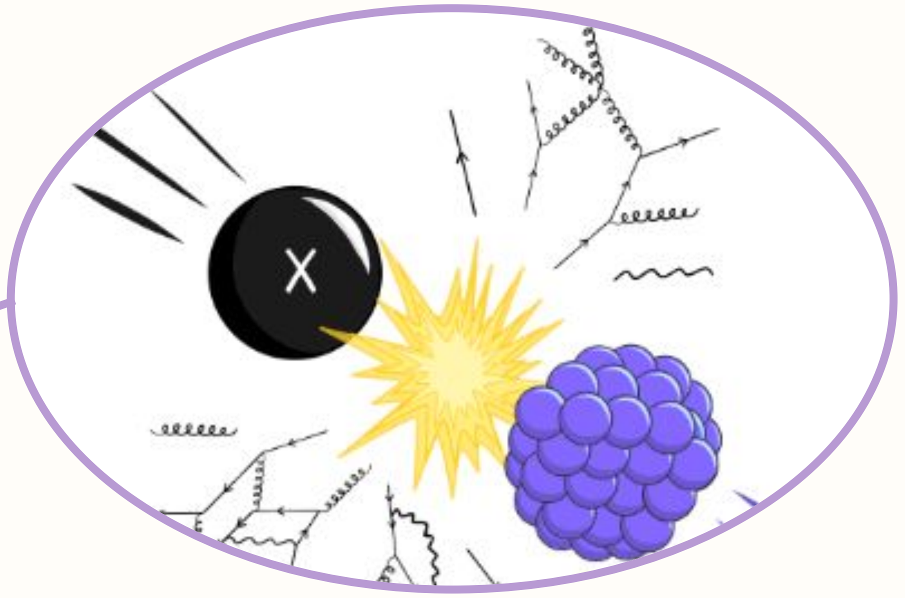
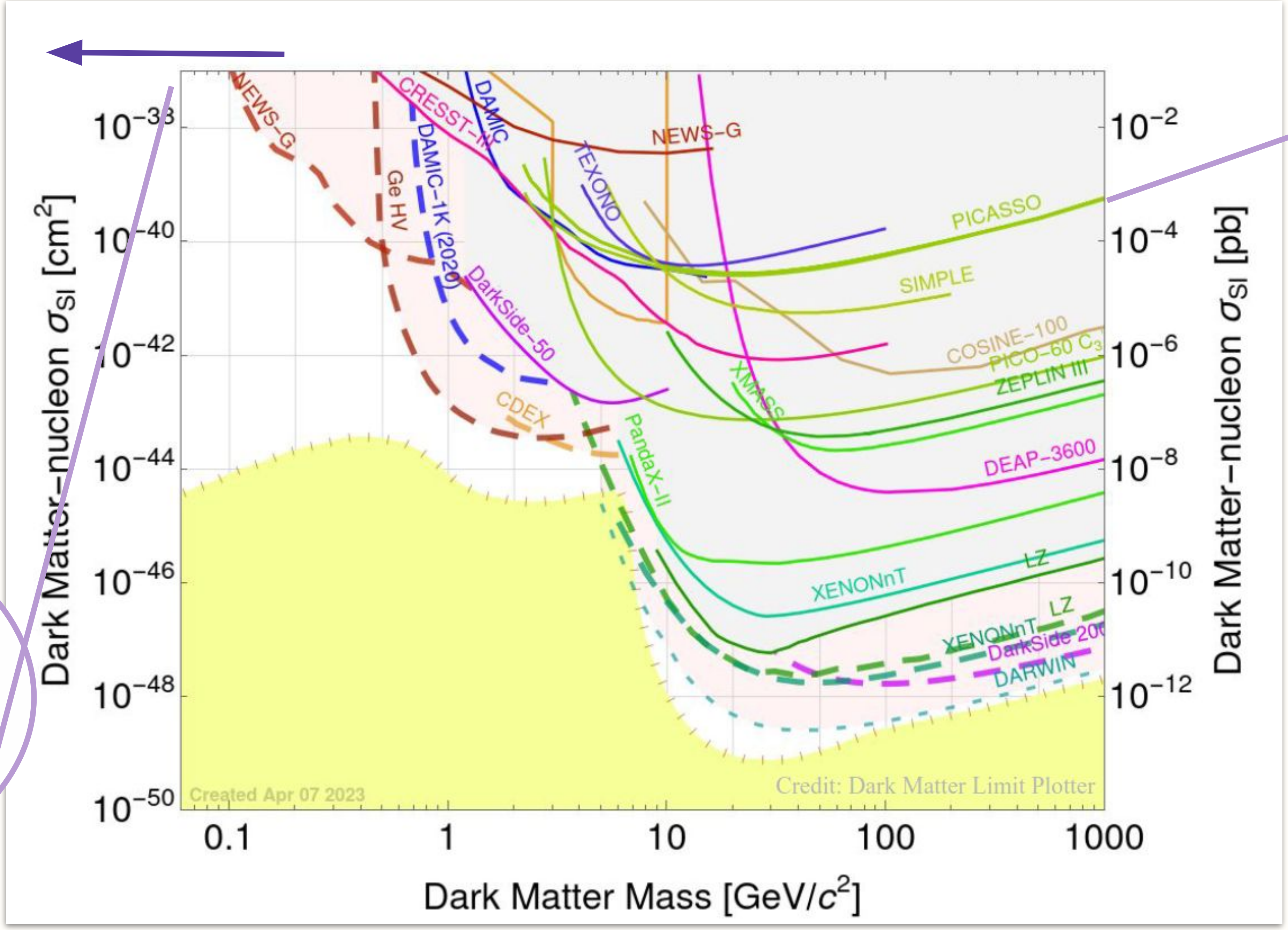
15th International Workshop on the Identification of Dark Matter

Direct Detection of sub-GeV DM?

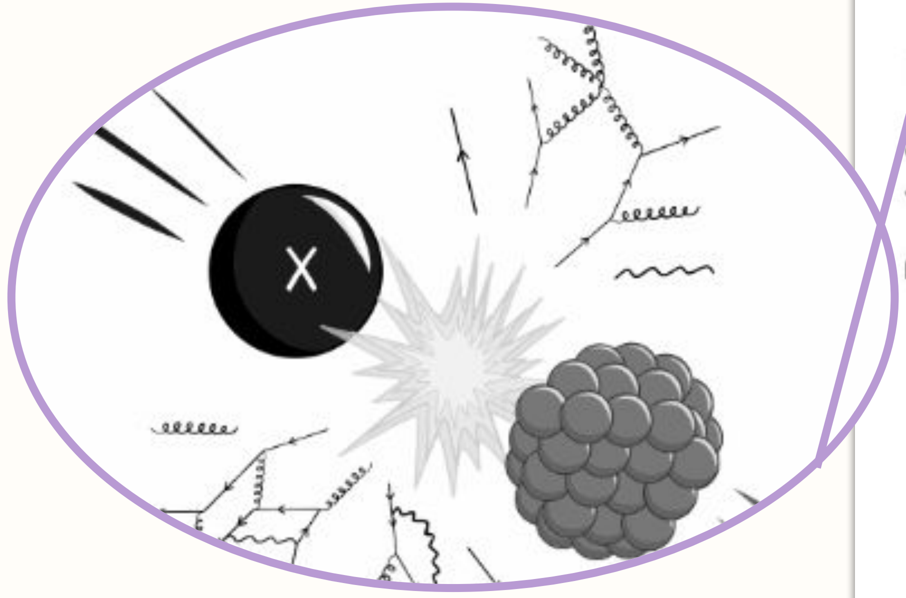
Sketch adapted from Benjamin V. Lehmann



DM-nucleon scattering



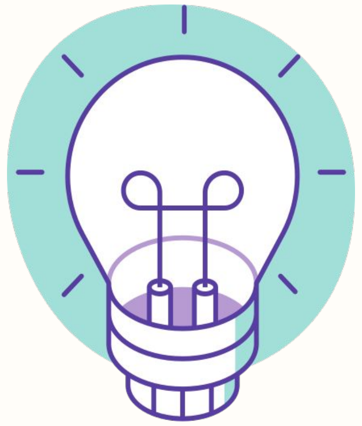
from S. Lindemann, “WIMP direct detection experiments”, 18th PATRAS Workshop on Axions, WIMPs and WISPs, Rijeka 2023

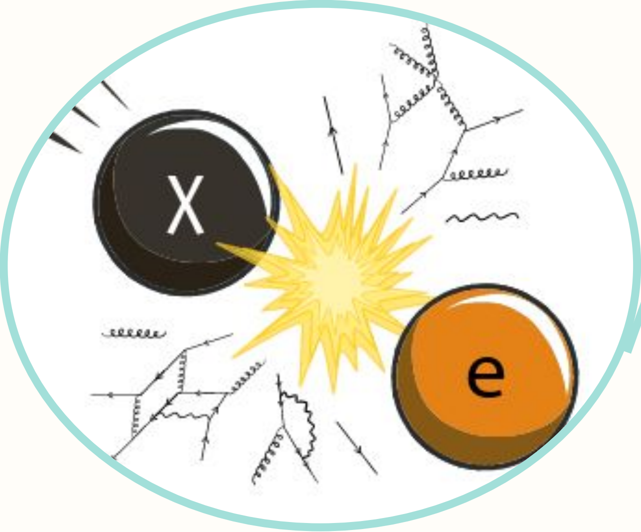


very low recoil energy
→ experiments lose sensitivity

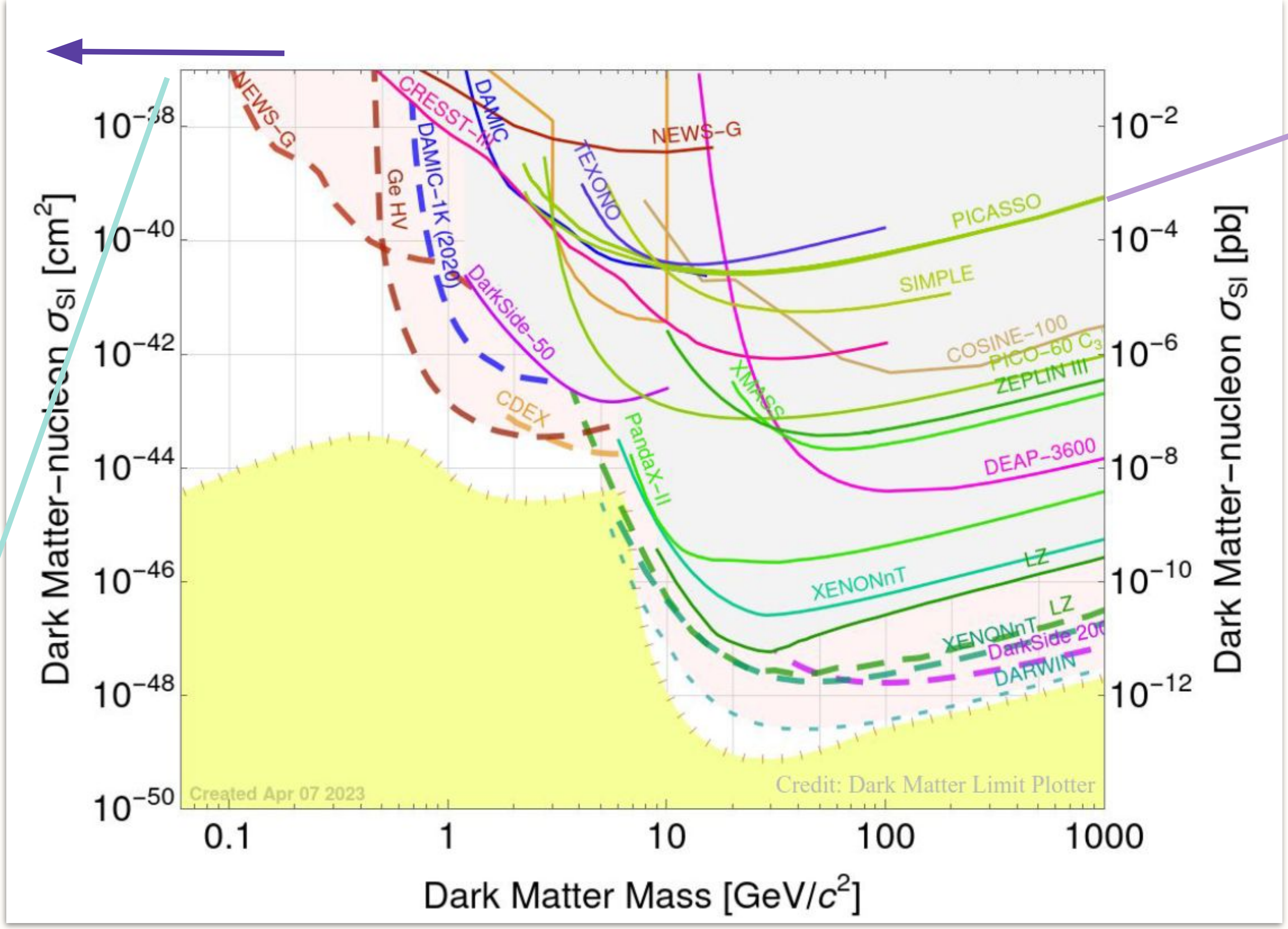
Direct Detection of sub-GeV DM?

Sketch adapted from Benjamin V. Lehmann

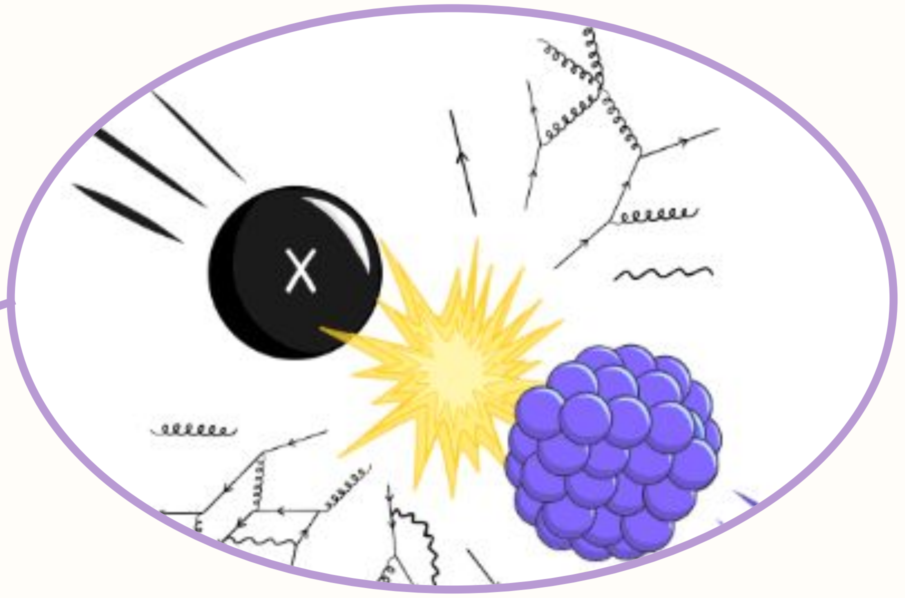




DM-electron scattering



from S. Lindemann, "WIMP direct detection experiments", 18th PATRAS Workshop on Axions, WIMPs and WISPs, Rijeka 2023



DM-nucleon scattering

Superconducting Detectors

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

Superconducting Detectors for Superlight Dark Matter

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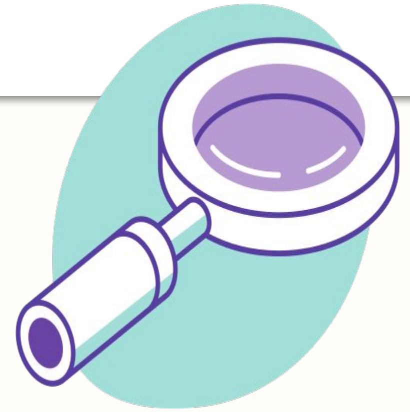
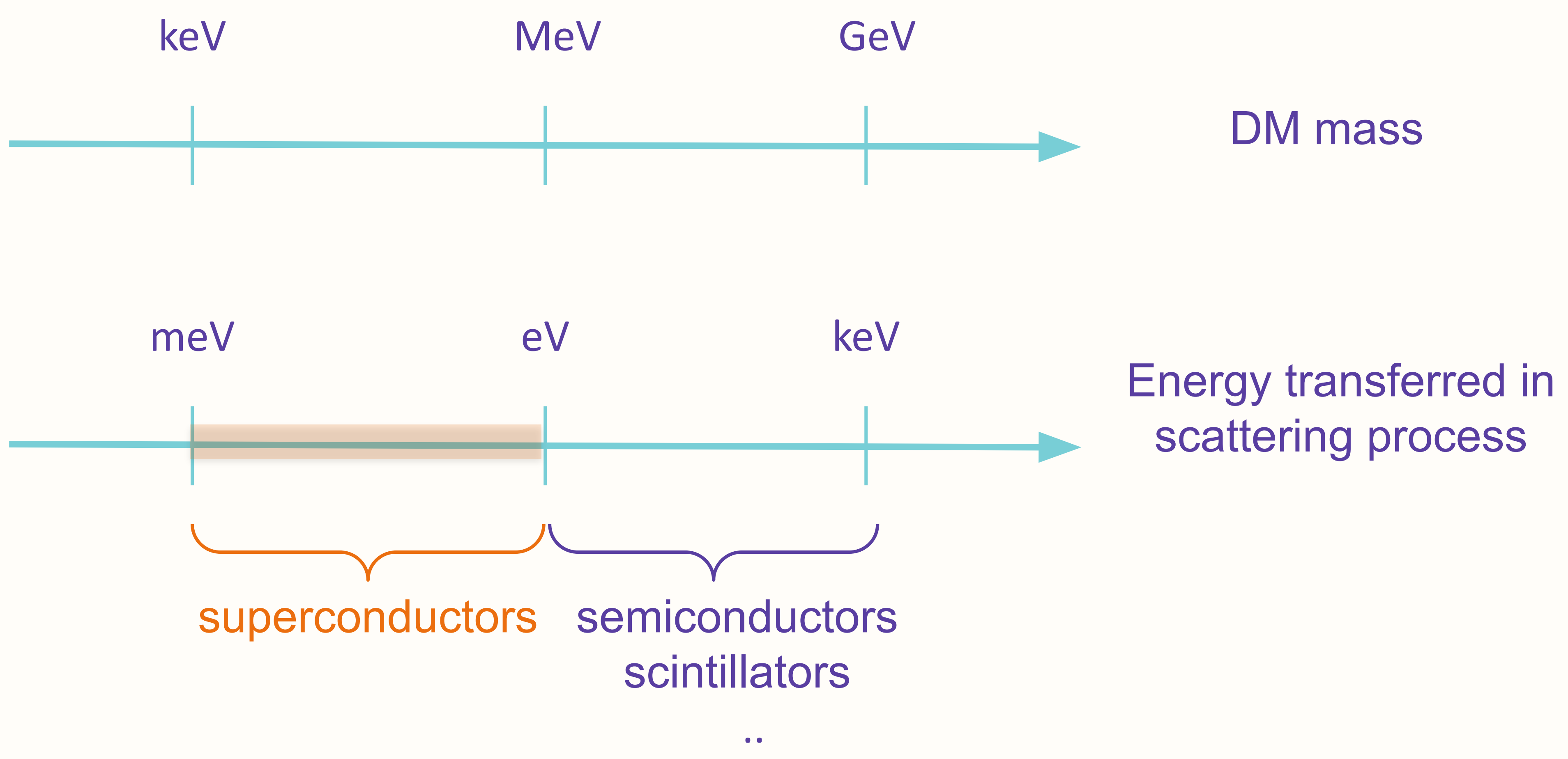
(Received 8 June 2015; revised manuscript received 21 October 2015; published 7 January 2016)

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



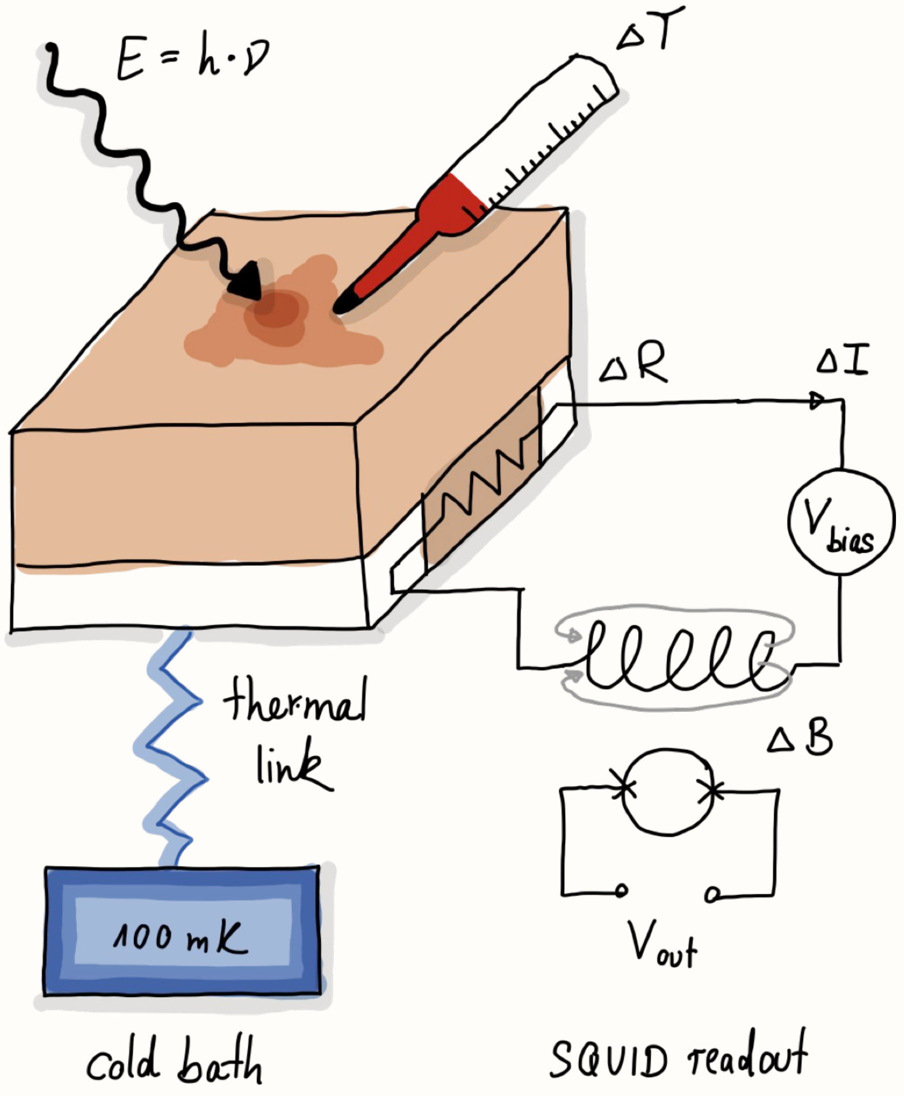
$$E_{\mathrm{T_{max}}} = E_{\mathrm{kin}} \sim m_\chi v^2 \sim 10^{-6} m_\chi$$



Transition Edge Sensors (TES)

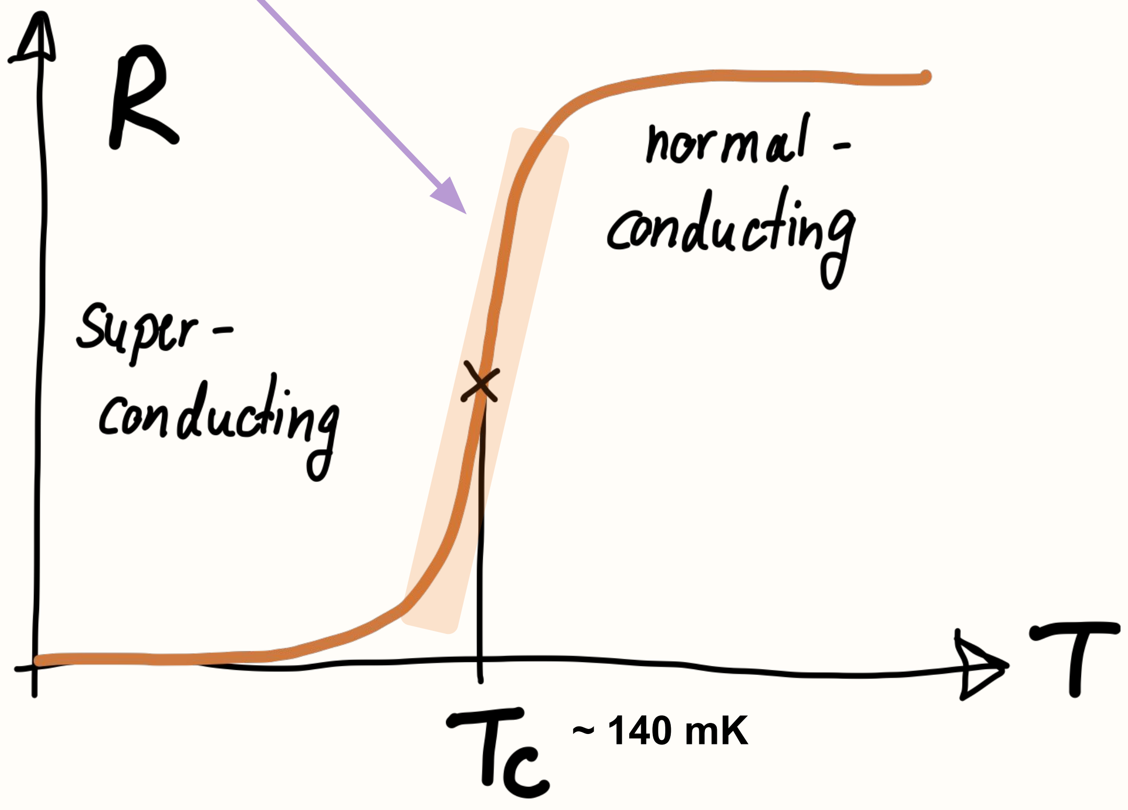
Incident photon on superconducting material leads to temperature increase

Drawings courtesy of Katharina-Sophie Isleif

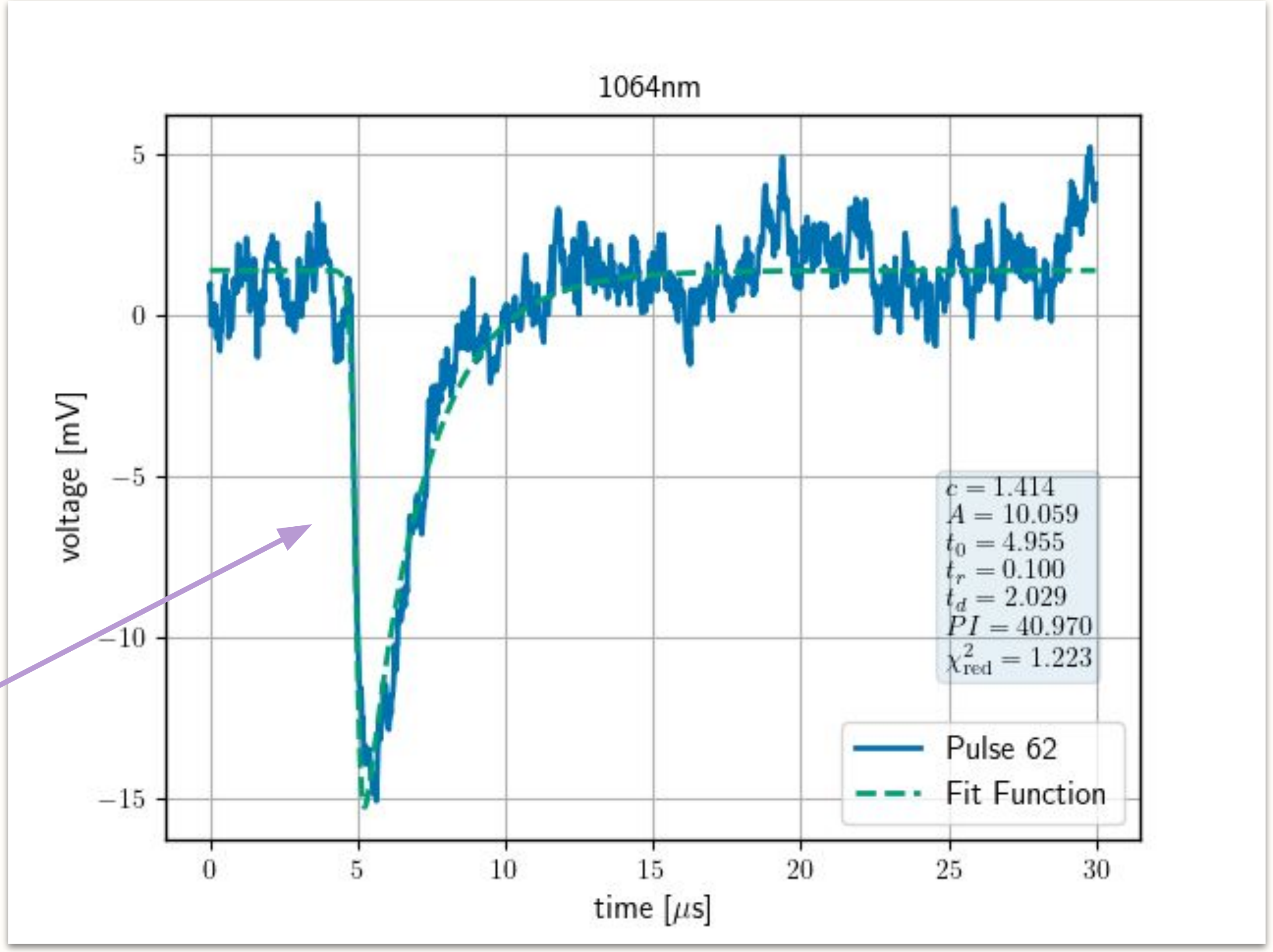


SQUID ≙ Superconducting Quantum Interference Device

Leading to a large increase in resistance on transition curve

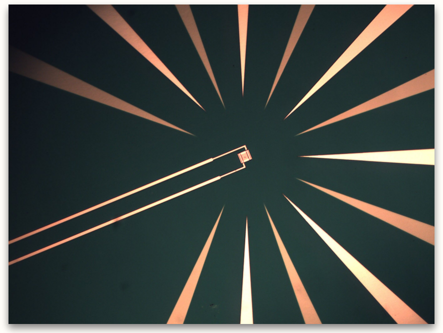


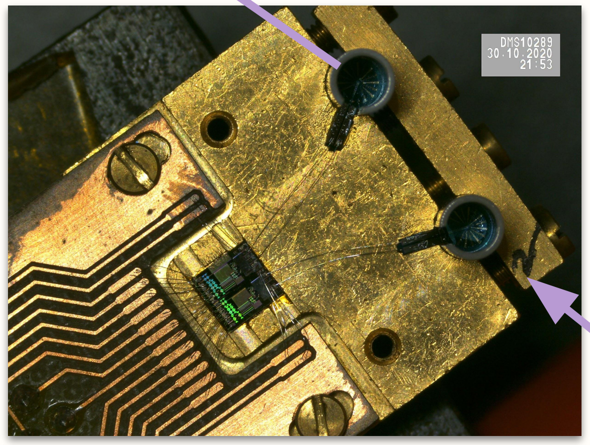
Single-photon pulse integral **proportional** to photon energy (1064 nm ≙ 1.165 eV)

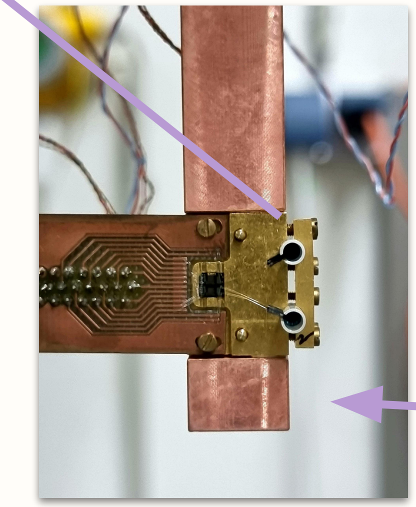


TES Setup @ DESY.

Area = 25 µm x 25 µm
Thickness = 20 nm



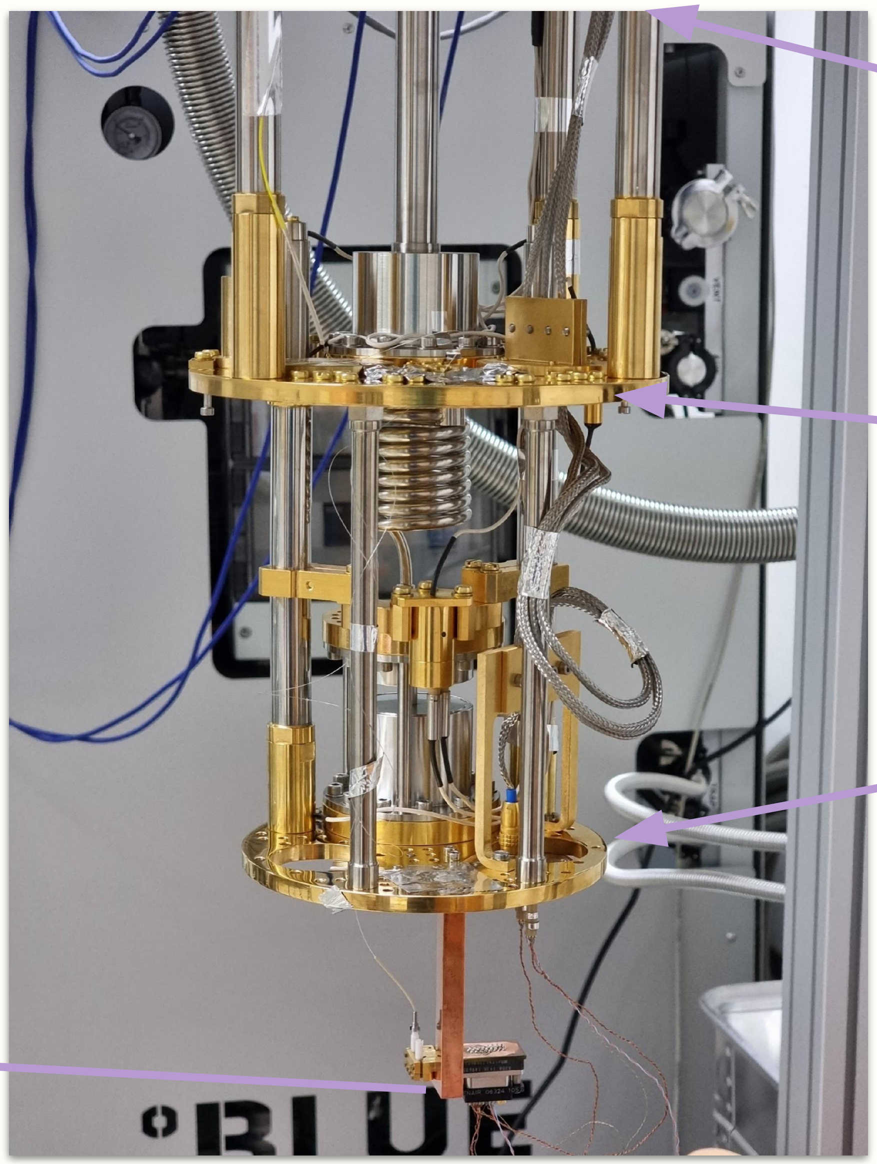


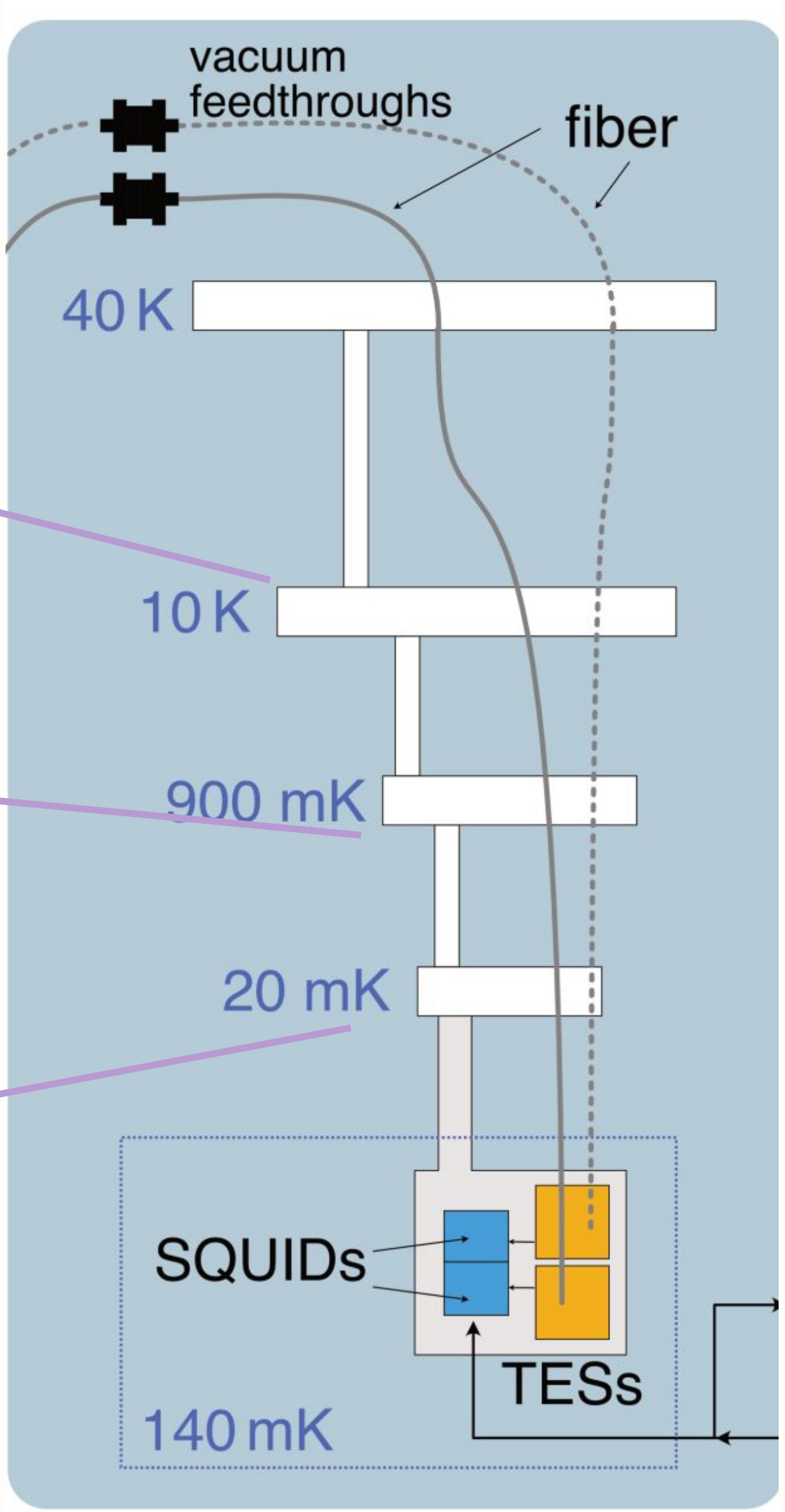


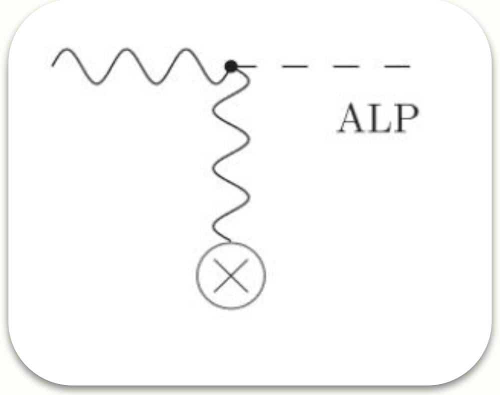
Sensors provided by: NIST

Packaging and
SQUIDs provided by: PTB

Inside of dilution refrigerator

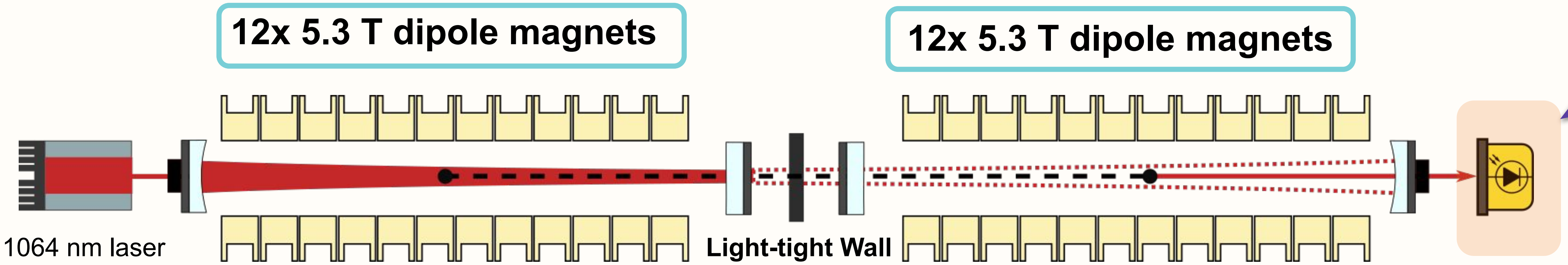






TES at ALPS II

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



Light Shining through a Wall experiment
Challenge: Detect single photon from axion-photon conversion
Currently: HETerodyne Sensing
Future Option: TES

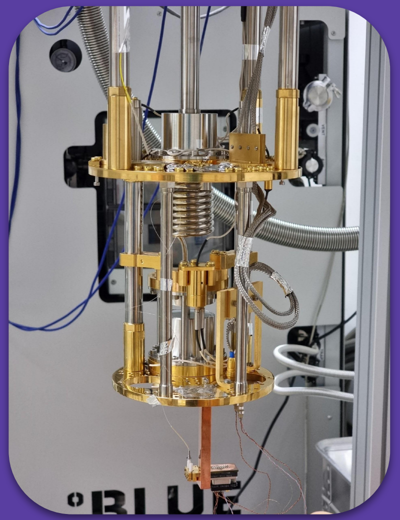
250m long experiment in "old" HERA accelerator tunnel

ALPS @ DESY.

See backup slides for details on ALPS II

ALPS II TES Requirements

Optimized setup, detector and analysis for 1064 nm (1.165 eV) photons

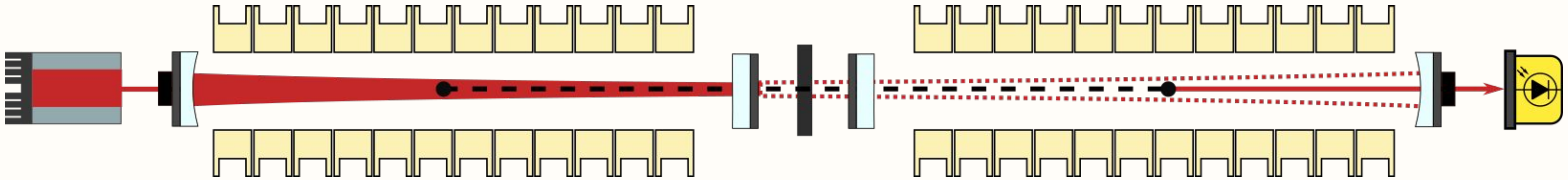


Extremely low background needed to detect ~ 1 photon/day

Currently 6.9×10^{-6} cps [1] intrinsic background

Very good system detection efficiency >50%

>90% measured in the lab (TES)! [2]

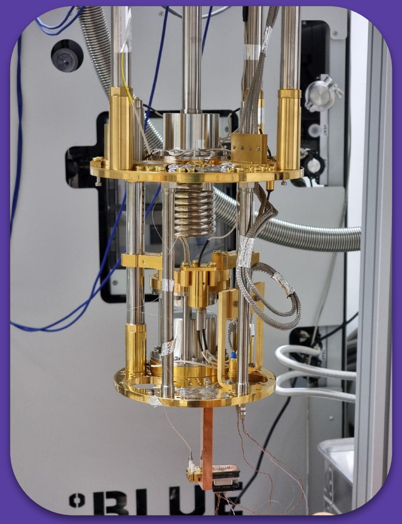


[1] R. Shah et al., PoS, EPS-HEP2021, 801 (2022)

[2] J.A. Rubiera Gimeno et al., PoS EPS-HEP2023, 567 (2024)

DDM ALPS II TES Requirements

Calibrated setup for a larger **energy range** especially **sub-eV**

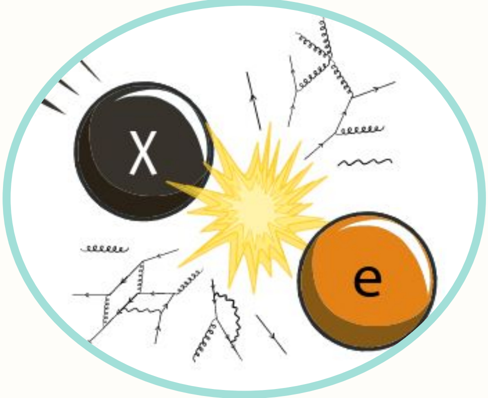


Extremely low background needed over a **range of energies**

Currently 6.9x10^{-6} cps [1] intrinsic background @ 1064 nm

Good energy resolution over broad energy spectrum

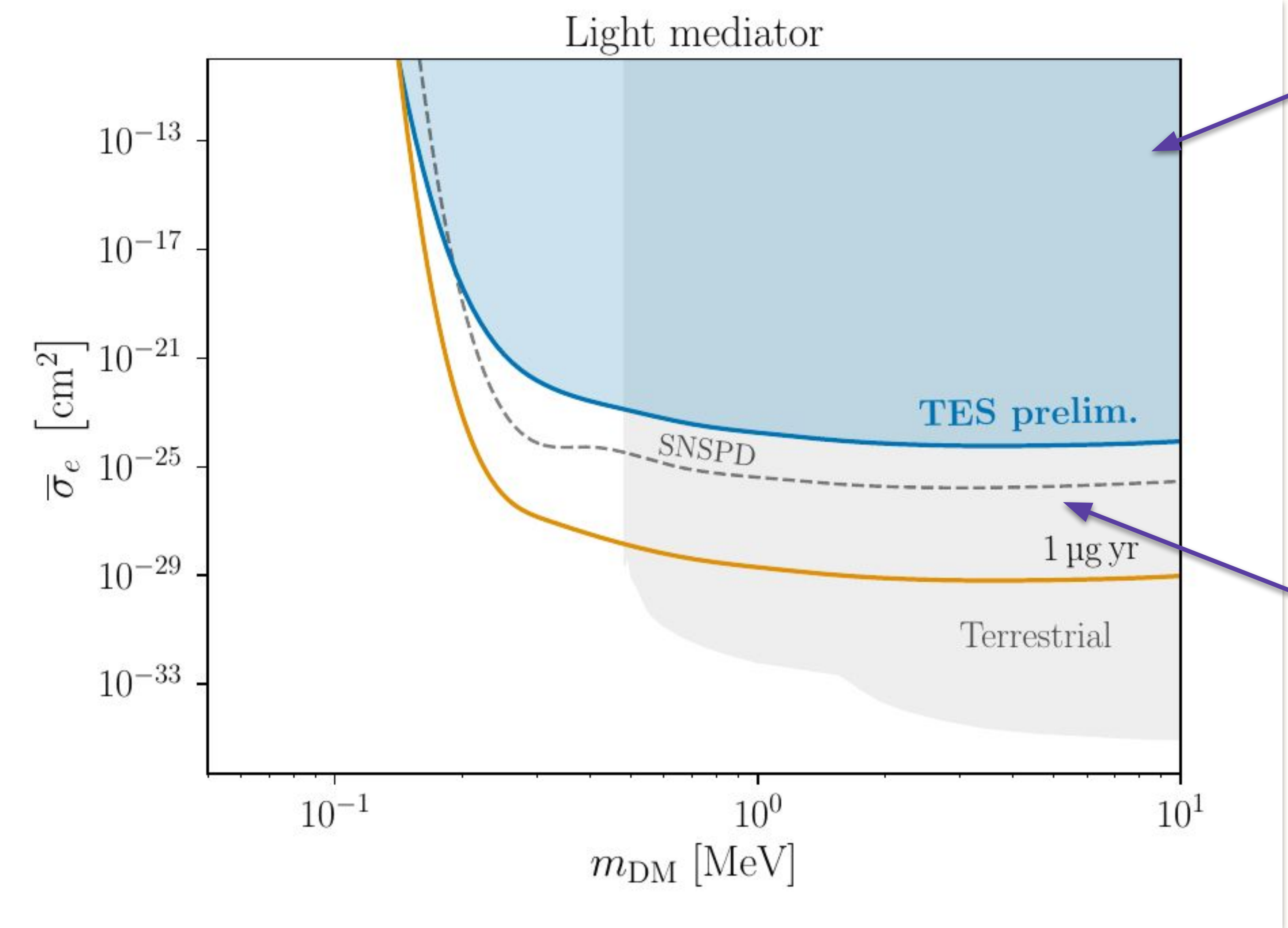
~5% @ 1.165 eV [2]



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

[2] J.A. Rubiera Gimeno et al., PoS EPS-HEP2023, 567 (2024)

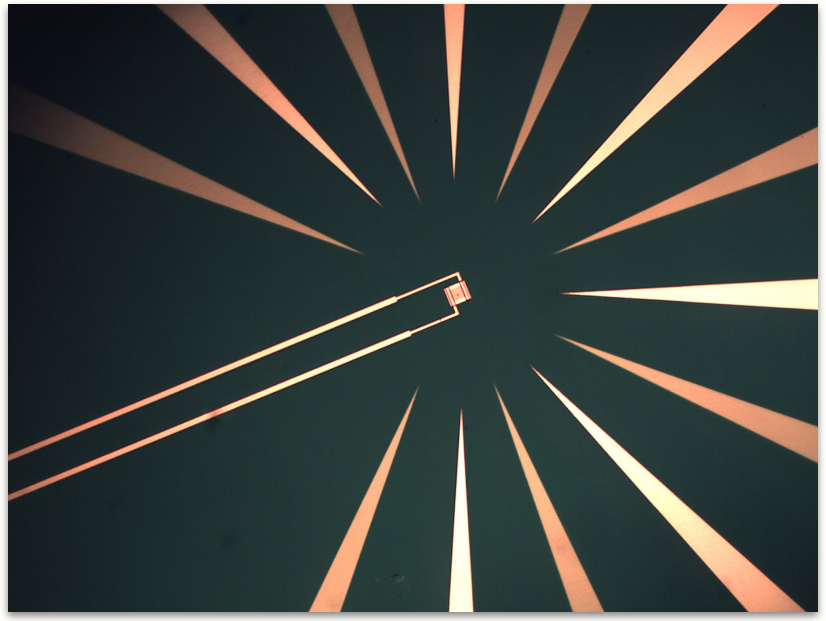
TES for DDM



Projections and plot by Benjamin V. Lehmann

Possible sensitivity based on our TES setup (based on previous intrinsic measurements)
→ **DDM hits expected to look like photon signature**

Superconducting Nanowire Single Photon Detector (SNSPD) with 4 dark counts in 180 h with 0.73 eV energy threshold [3]

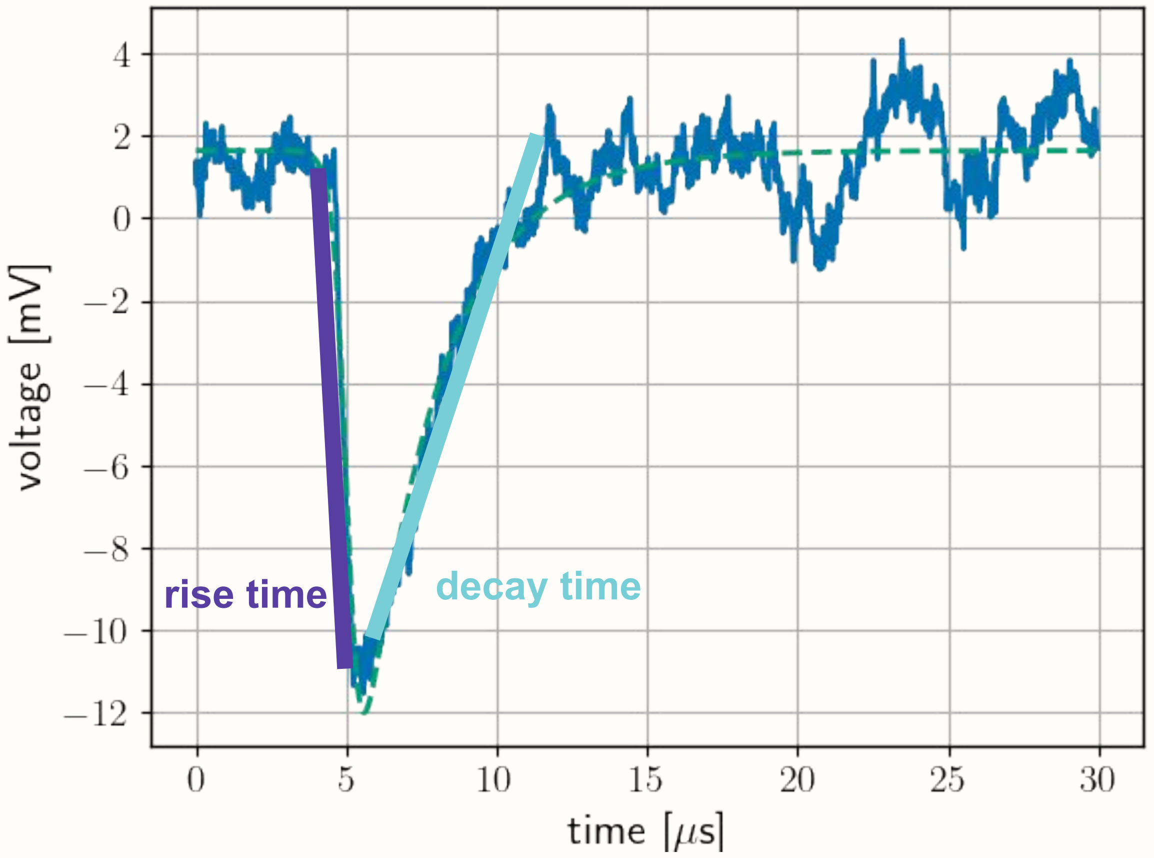


Challenges:

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

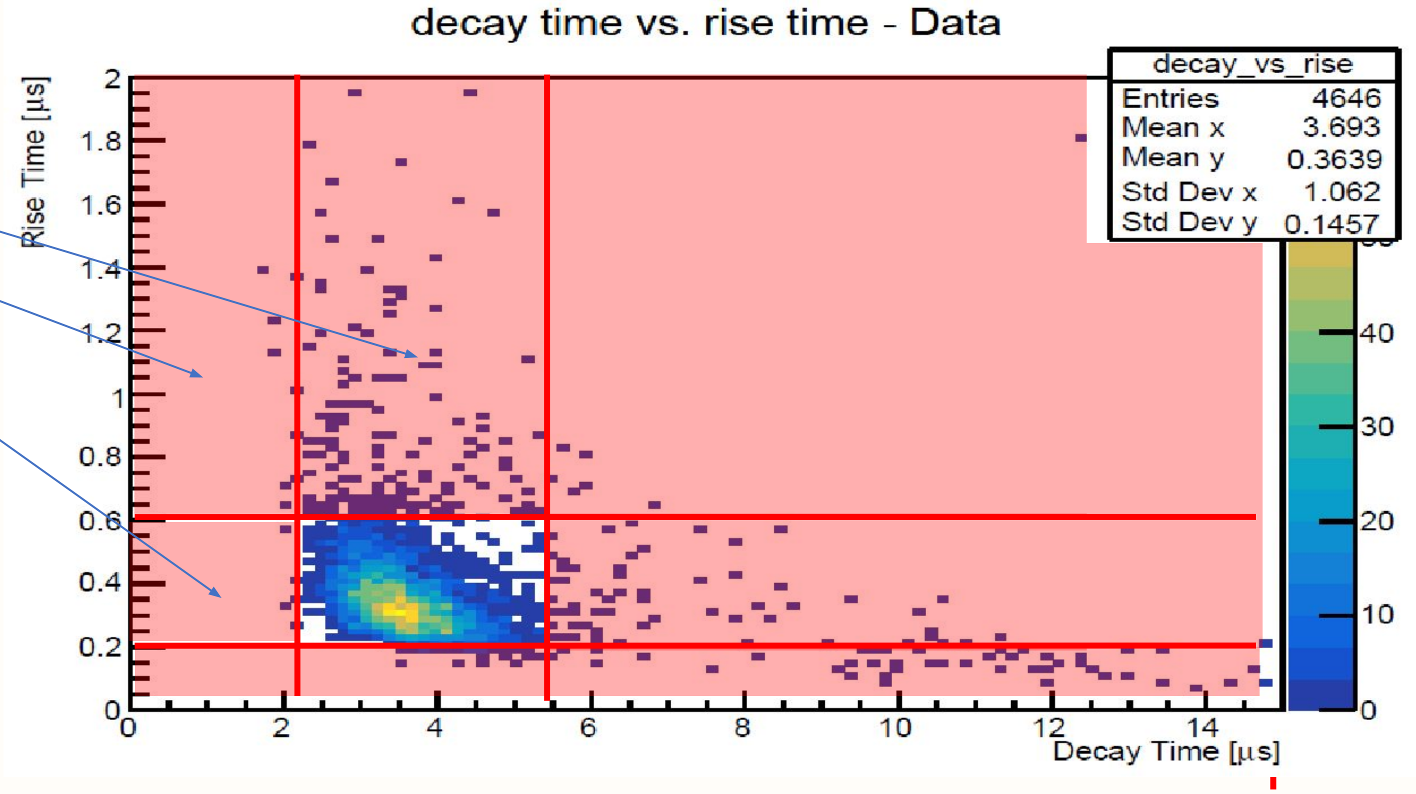
[3]Hochberg, Y. et al. arXiv:2110.01586 (2021)

Pulse Shape Analysis



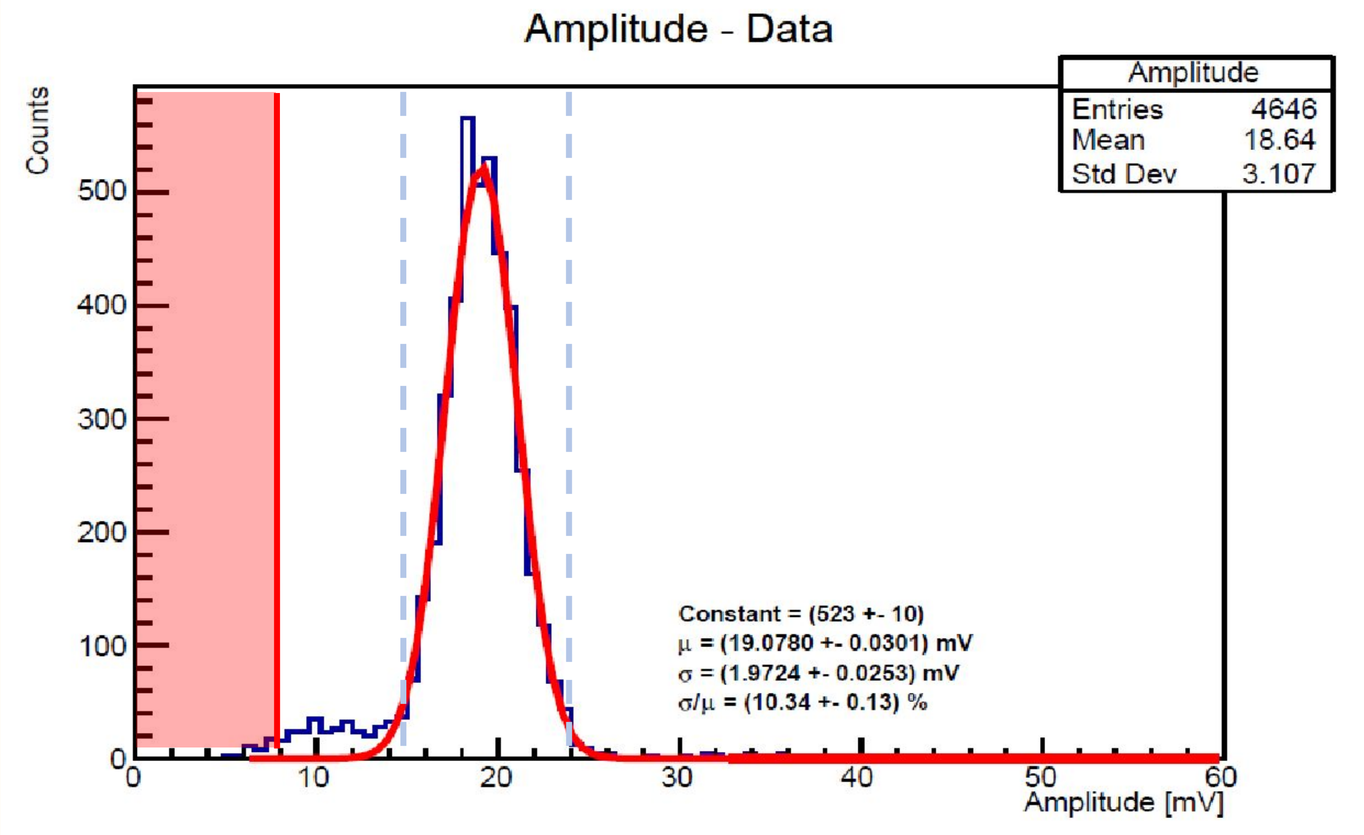
$$U(t) = -\frac{2A}{e^{-\frac{1}{\tau_{\text{rise}}}(t-t_0)} + e^{\frac{1}{\tau_{\text{decay}}}(t-t_0)}} + V_0$$

cutting away signals outside of central region



- 1064 nm calibration laser
- pulse shape fitted to all triggered pulses
- apply cuts on parameters like rise and decay time, pulse height or amplitude

→ apply for multiple wavelengths/ energies?

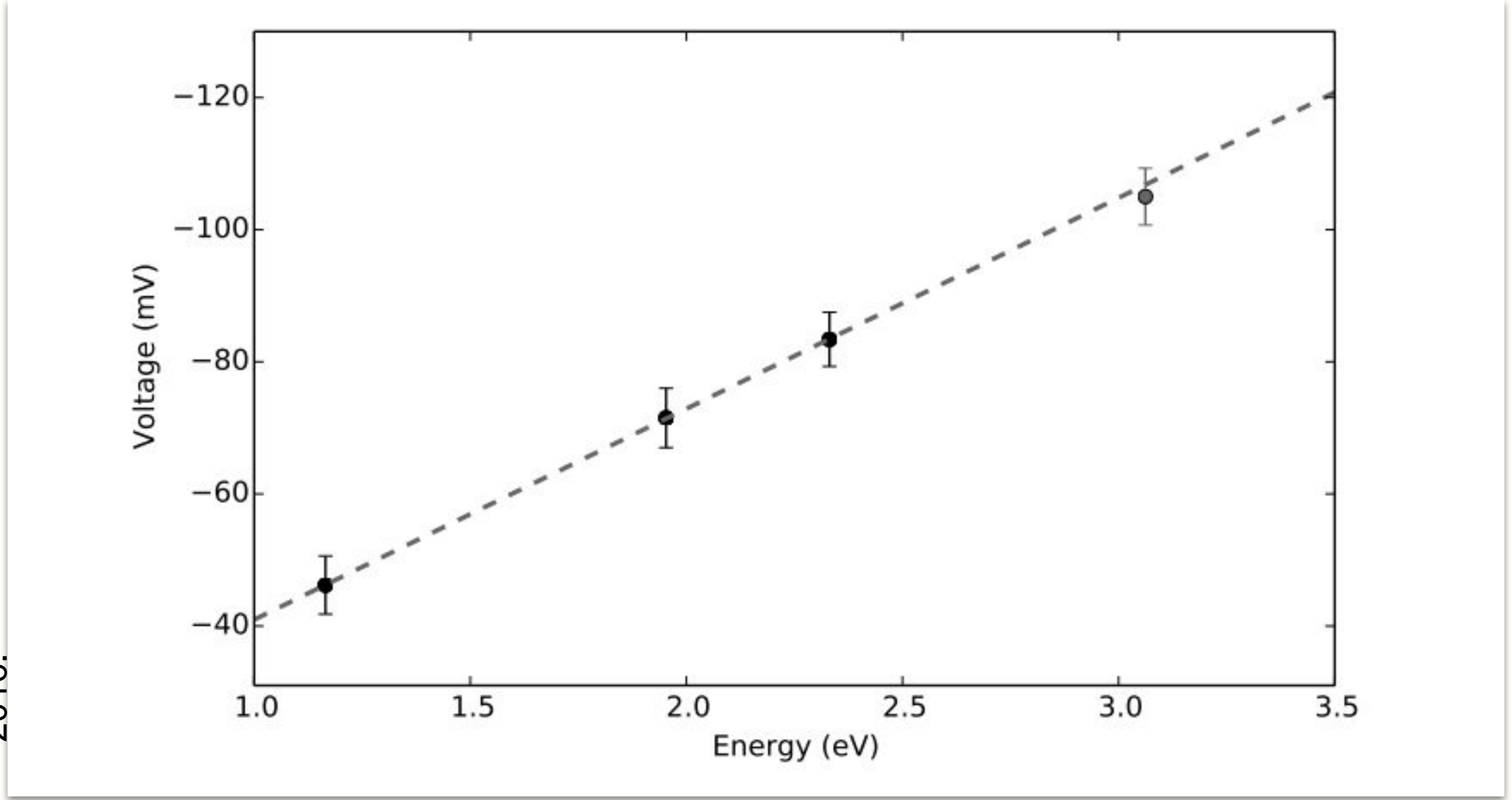


Energy Calibration

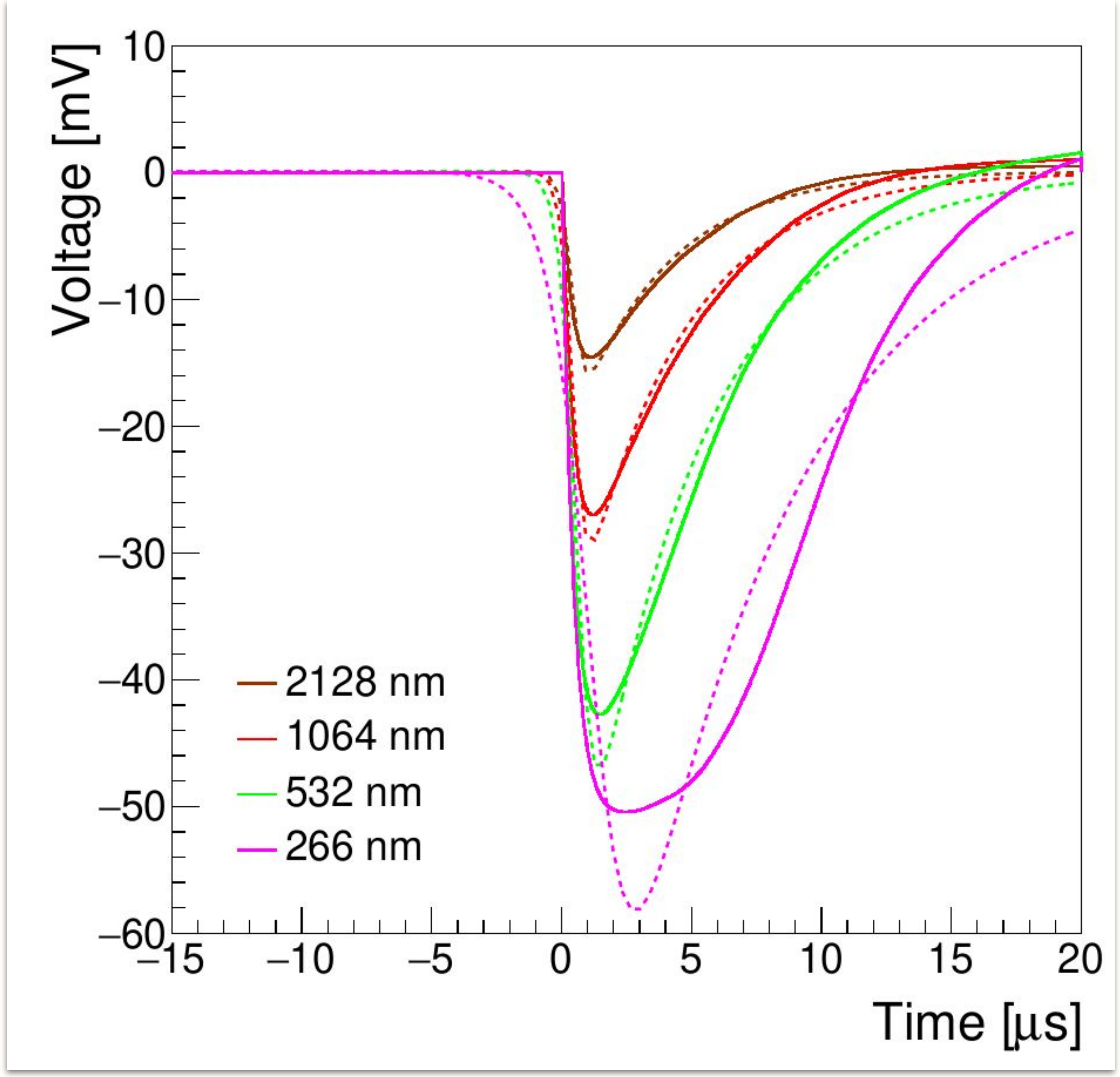
Expectations/Assumptions:
- **linear relationship** between pulse integral/amplitude and **energy**
- approximately **constant behavior** of **rise and decay time** (mainly governed by TES circuit)
- more challenging at lower energies (noise, etc.)

→previous simulations (DOI:10.22323/1.454.0055) showed promising results for a sub-MeV DM search based on these assumptions

Calibration measurement of a previous setup (2016)

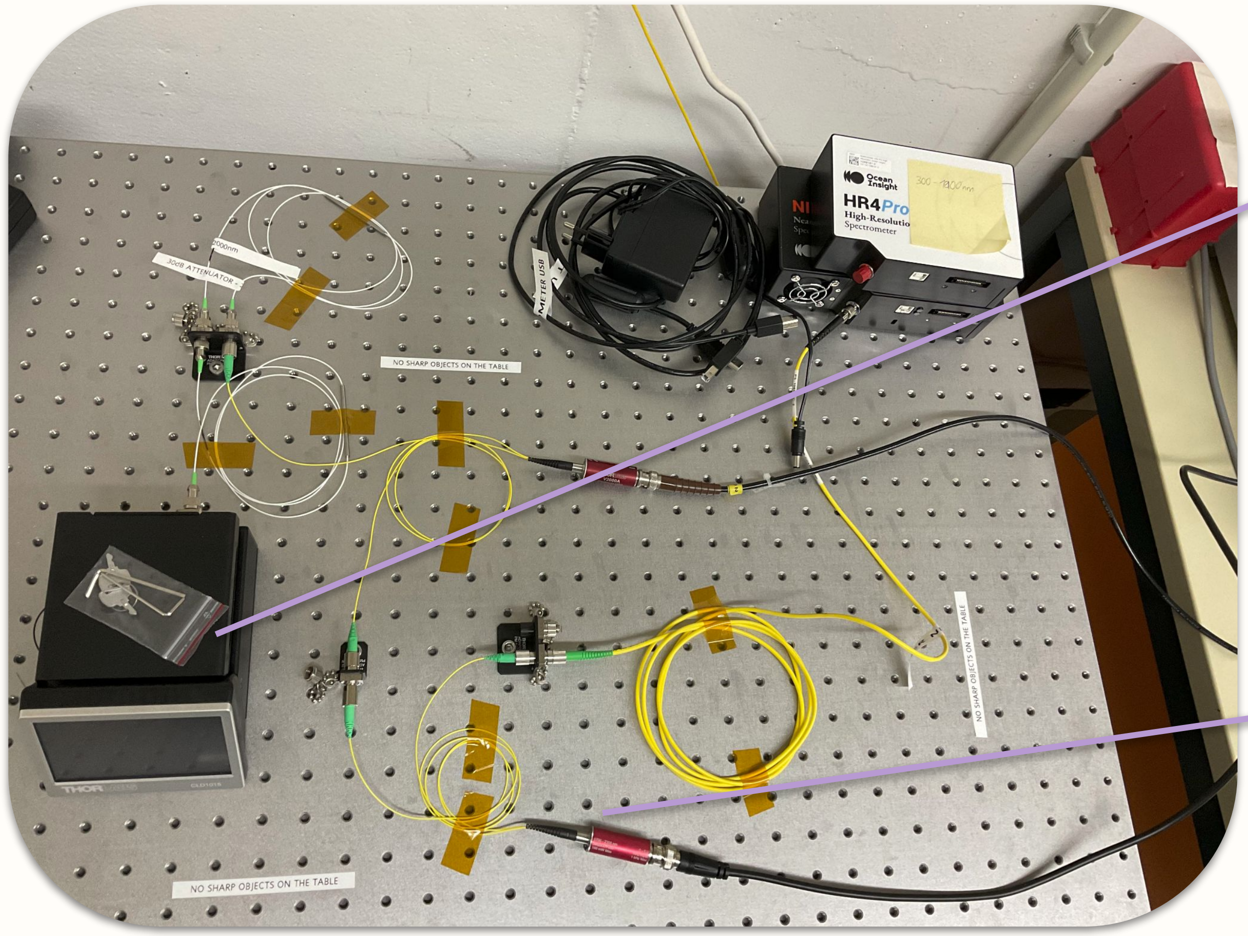


N. Bastidon, The cryogenic photon detection system for the ALPS II experiment: characterization, optimization and background reduction, PhD Thesis, Universität Hamburg, 2016.

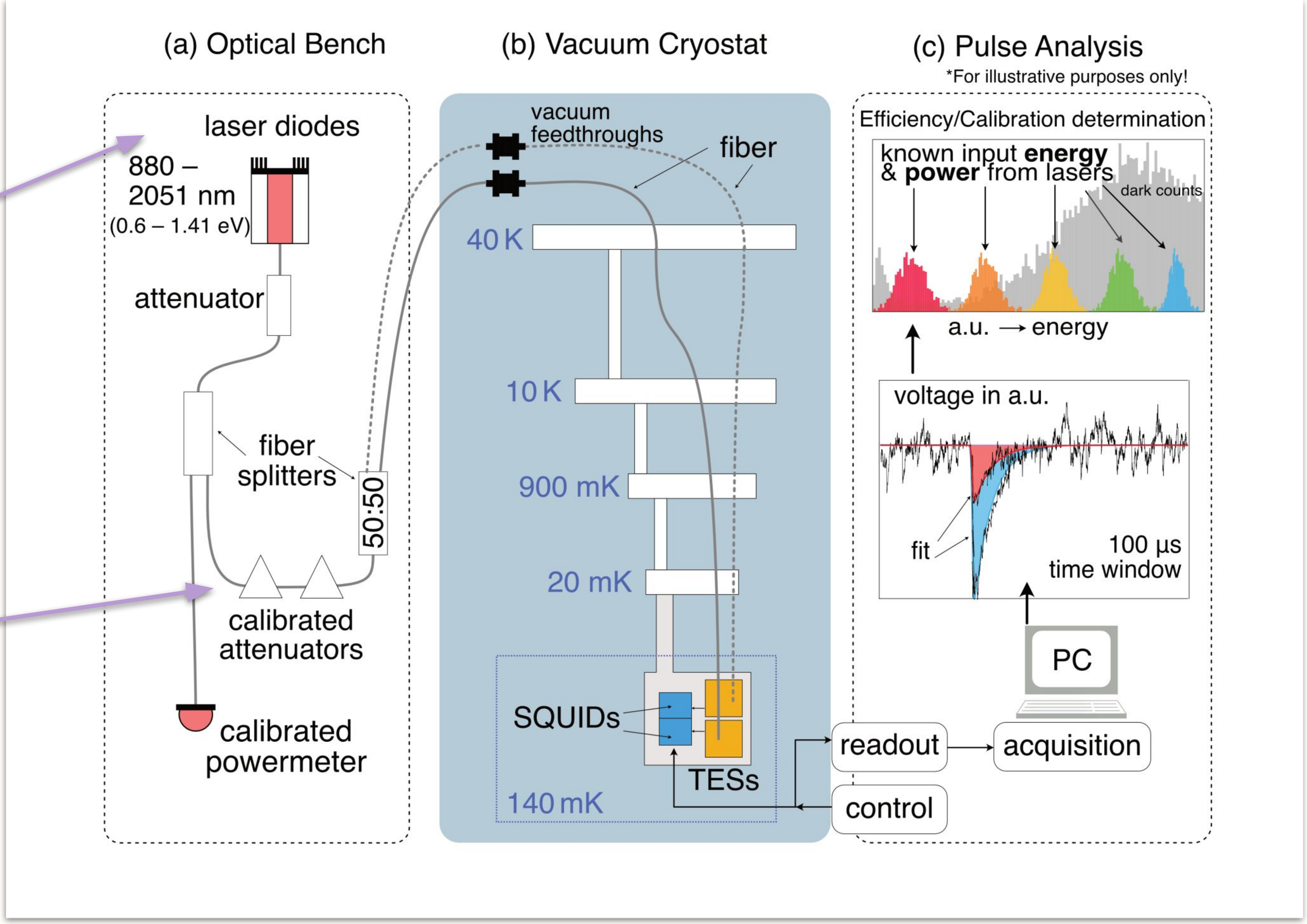


Simulated pulses of different wavelengths with fits (by Jose A. Rubiera Gimeno)

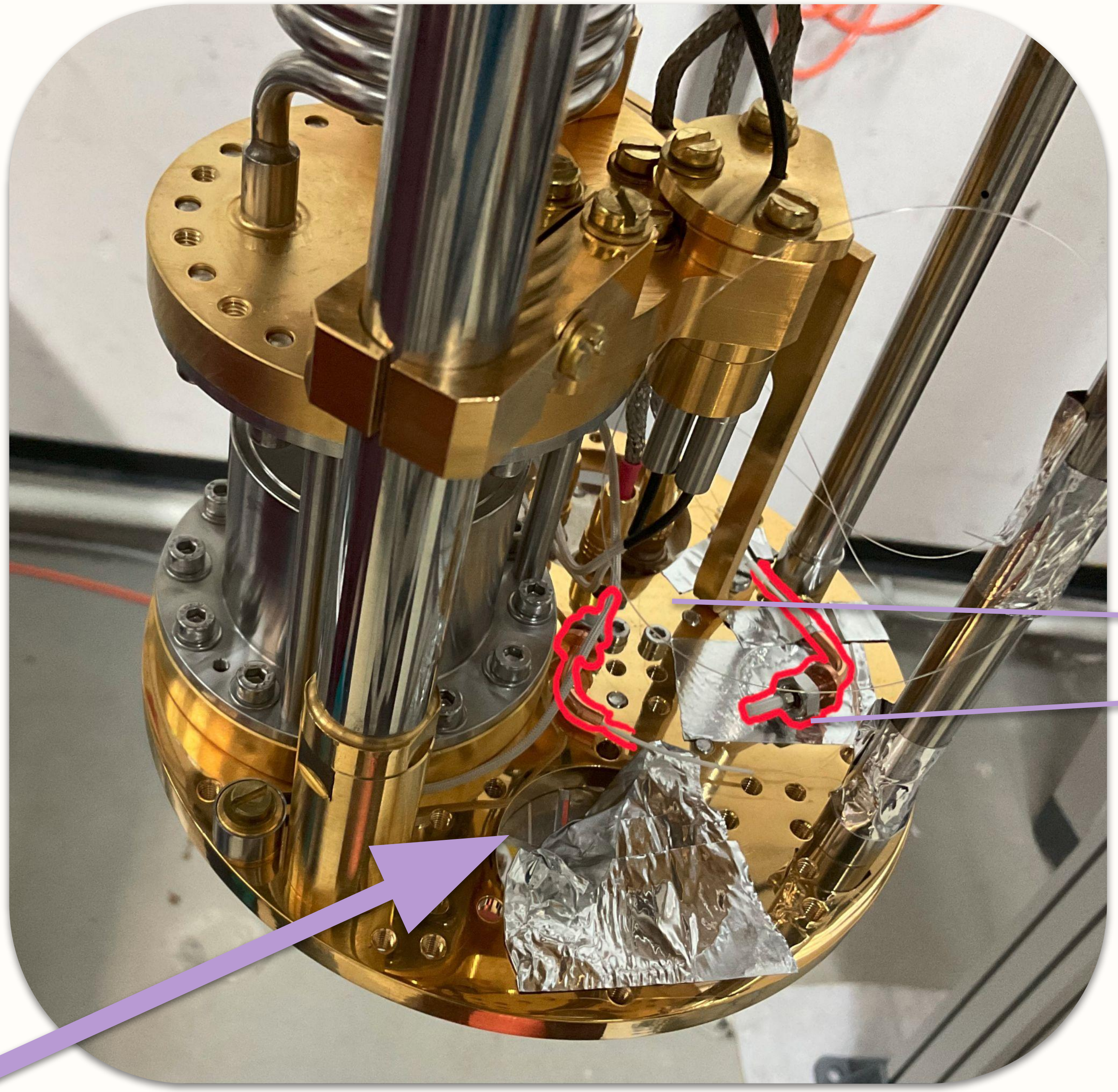
Calibration Setup



Experimental Setup including laser diodes

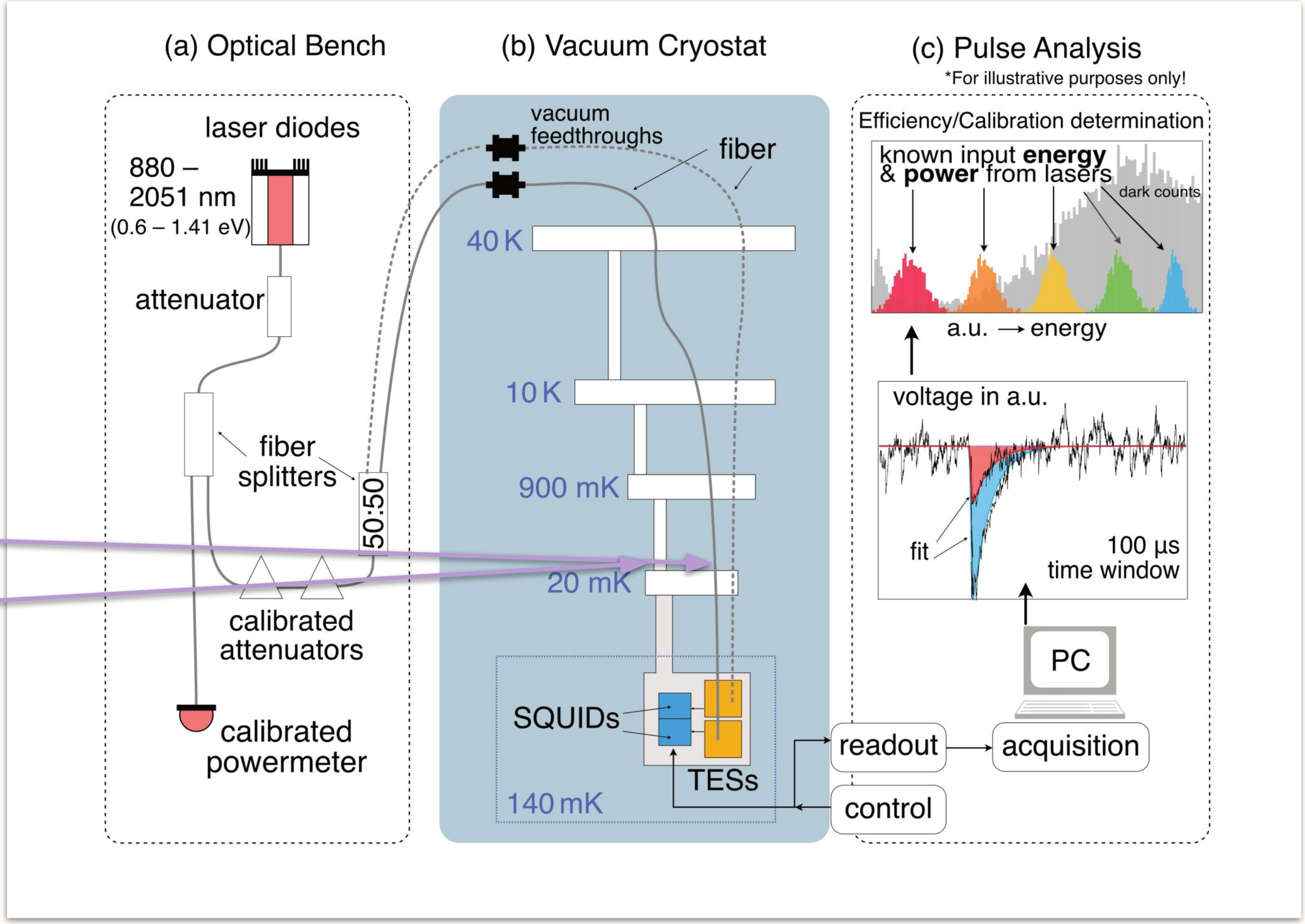


Calibration Setup



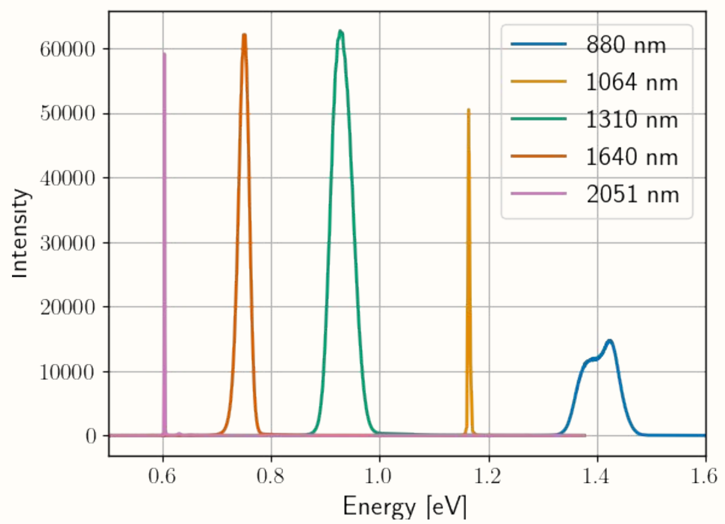
fiber tips

slit

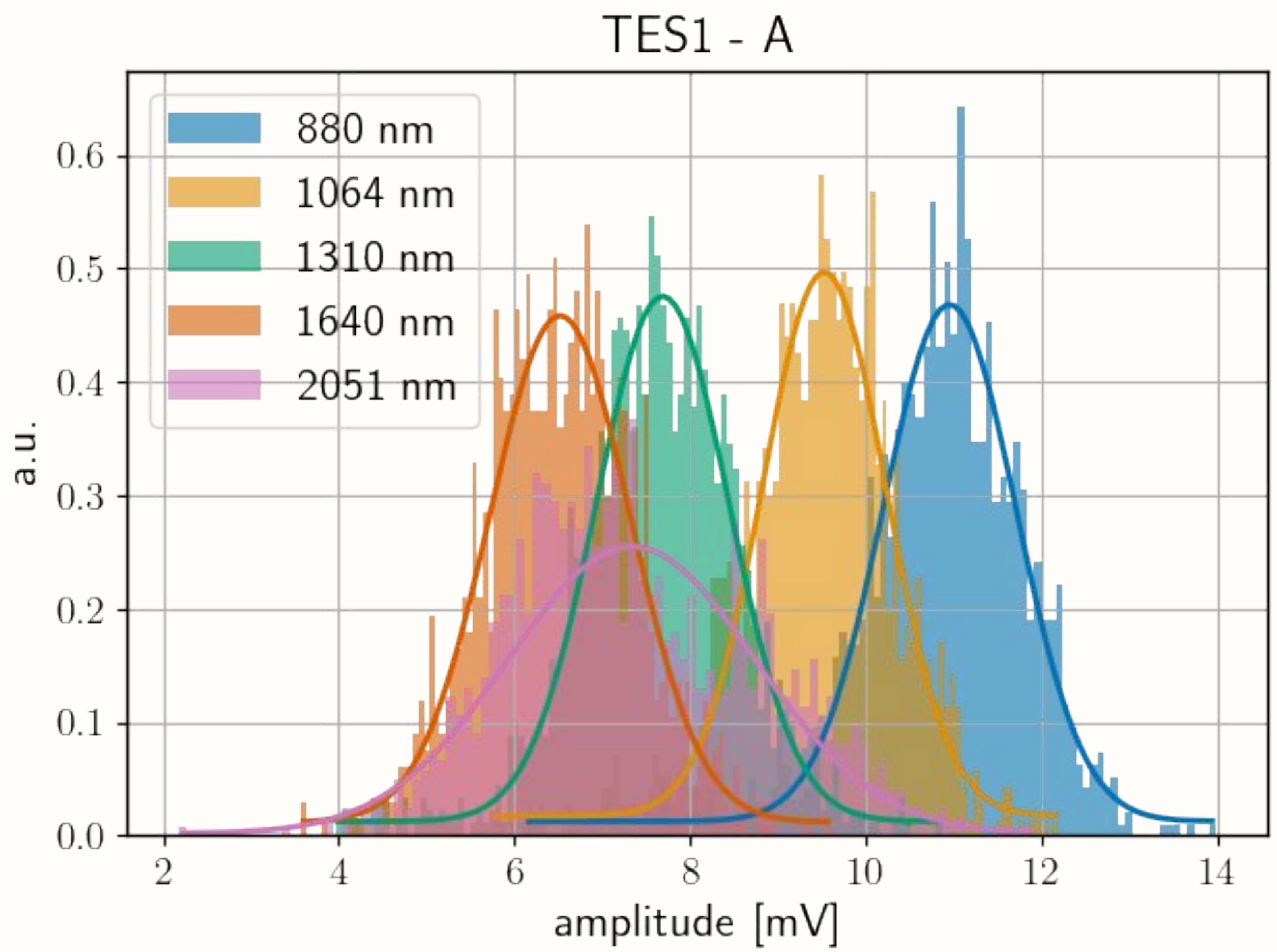


To mimic an intrinsic measurement, the fibers are placed on top of the 20 mK stage above the TES module to reduce black body radiation from the warmer parts of the cryostat. The light can enter the TES space through a small slit.

Calibration Results

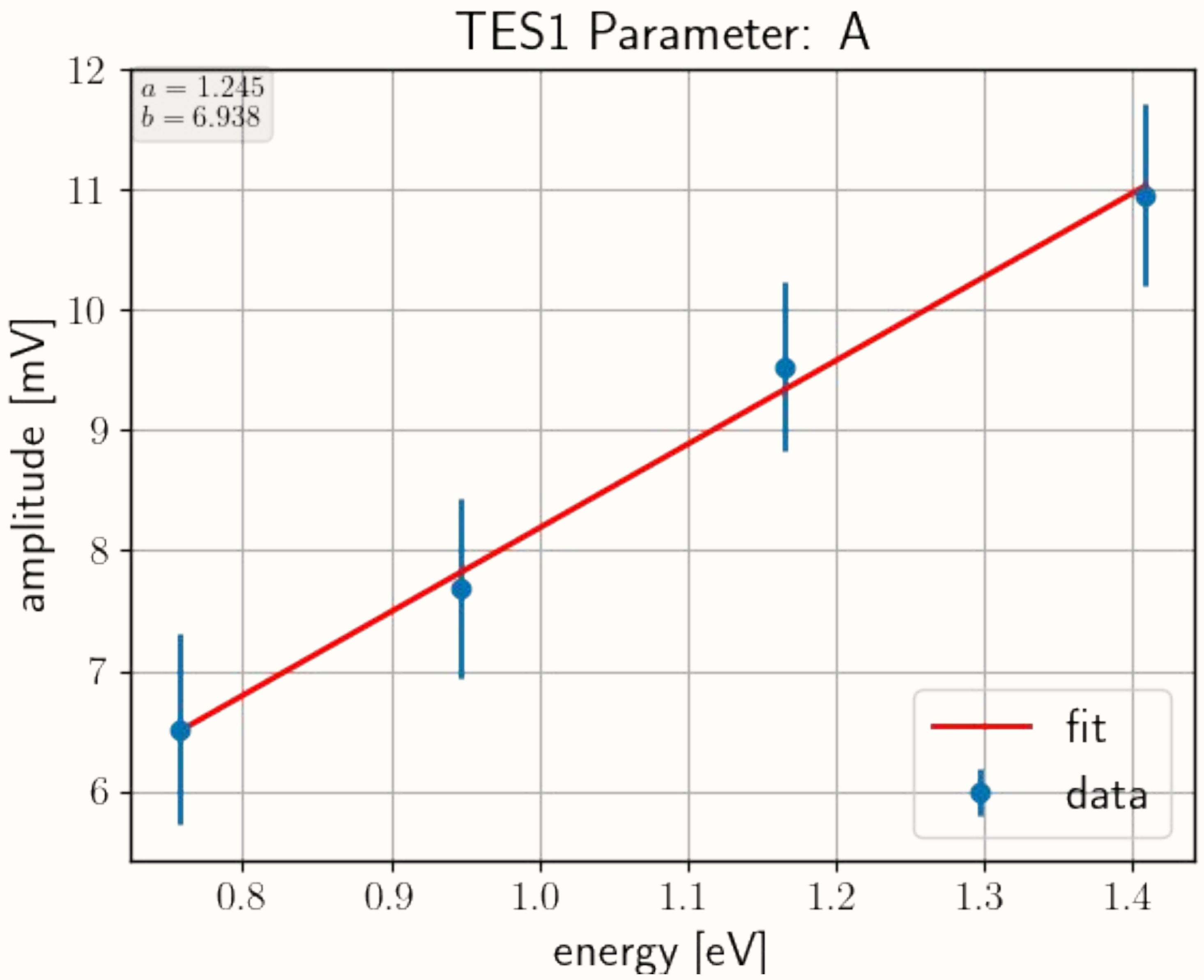


Energy spectrum of used laser diodes



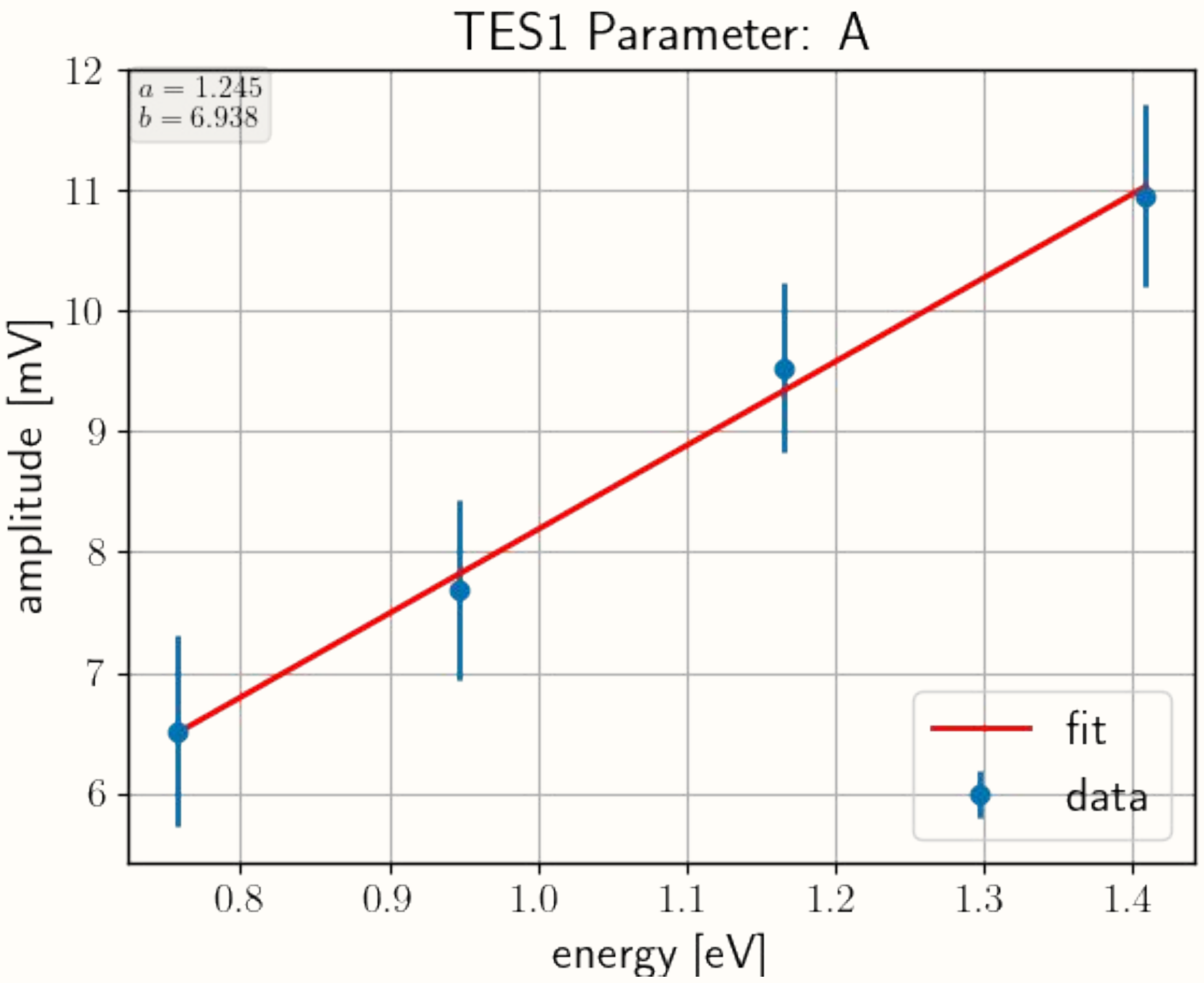
Fit parameters for different wavelengths

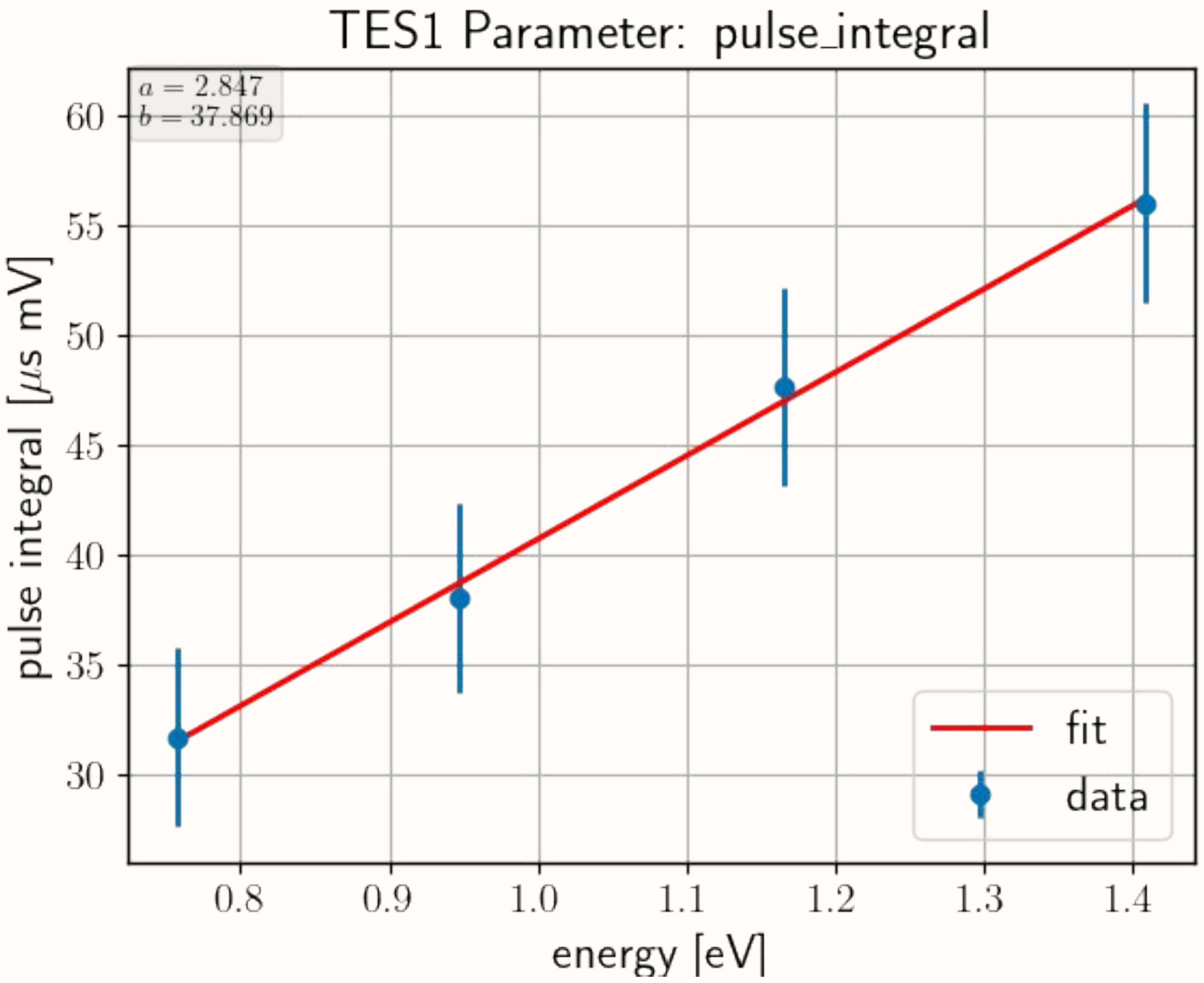
Calibration curve for pulse amplitude



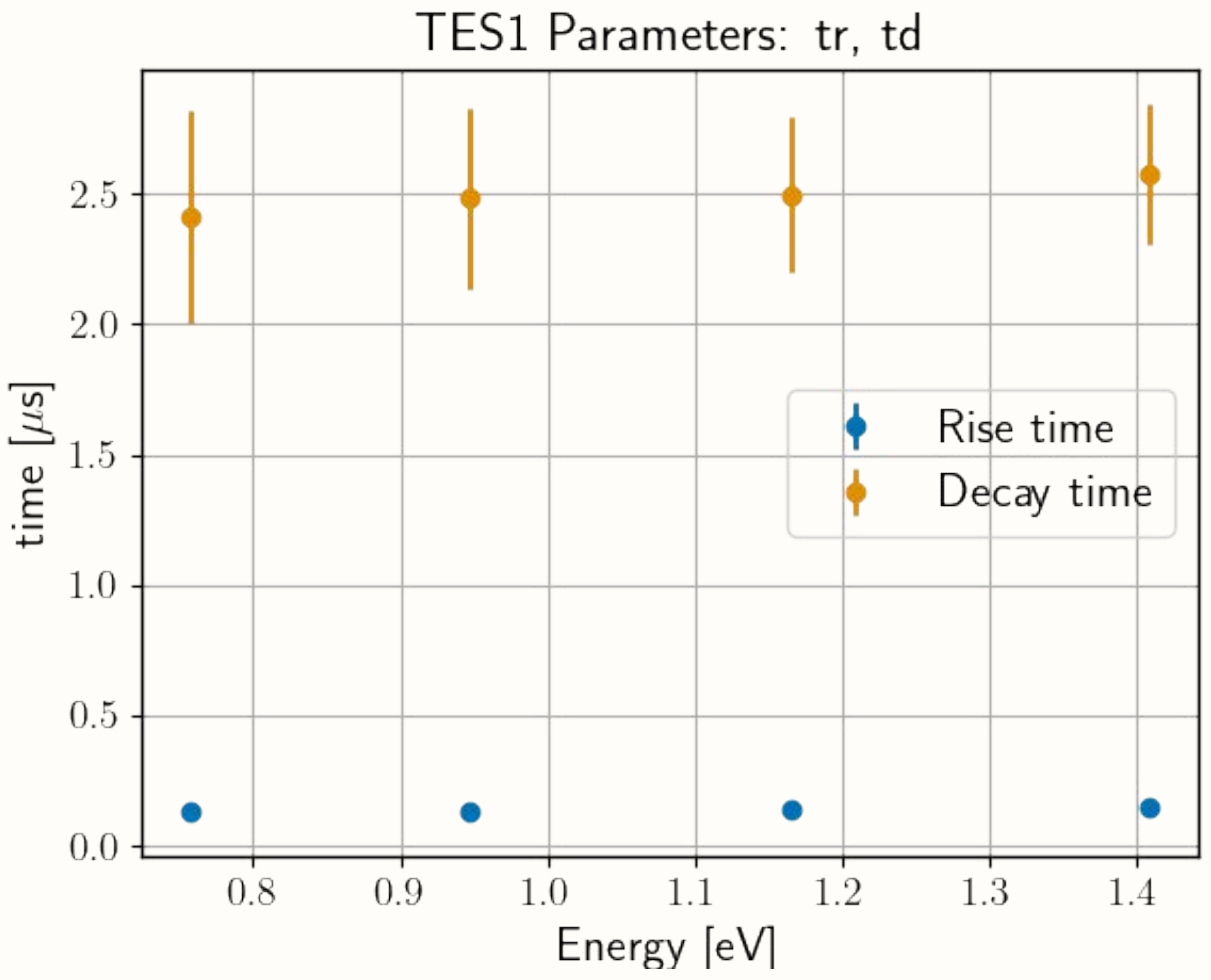
Calibration Results

Amplitude and pulse integral show linearity for the same setup and cooldown



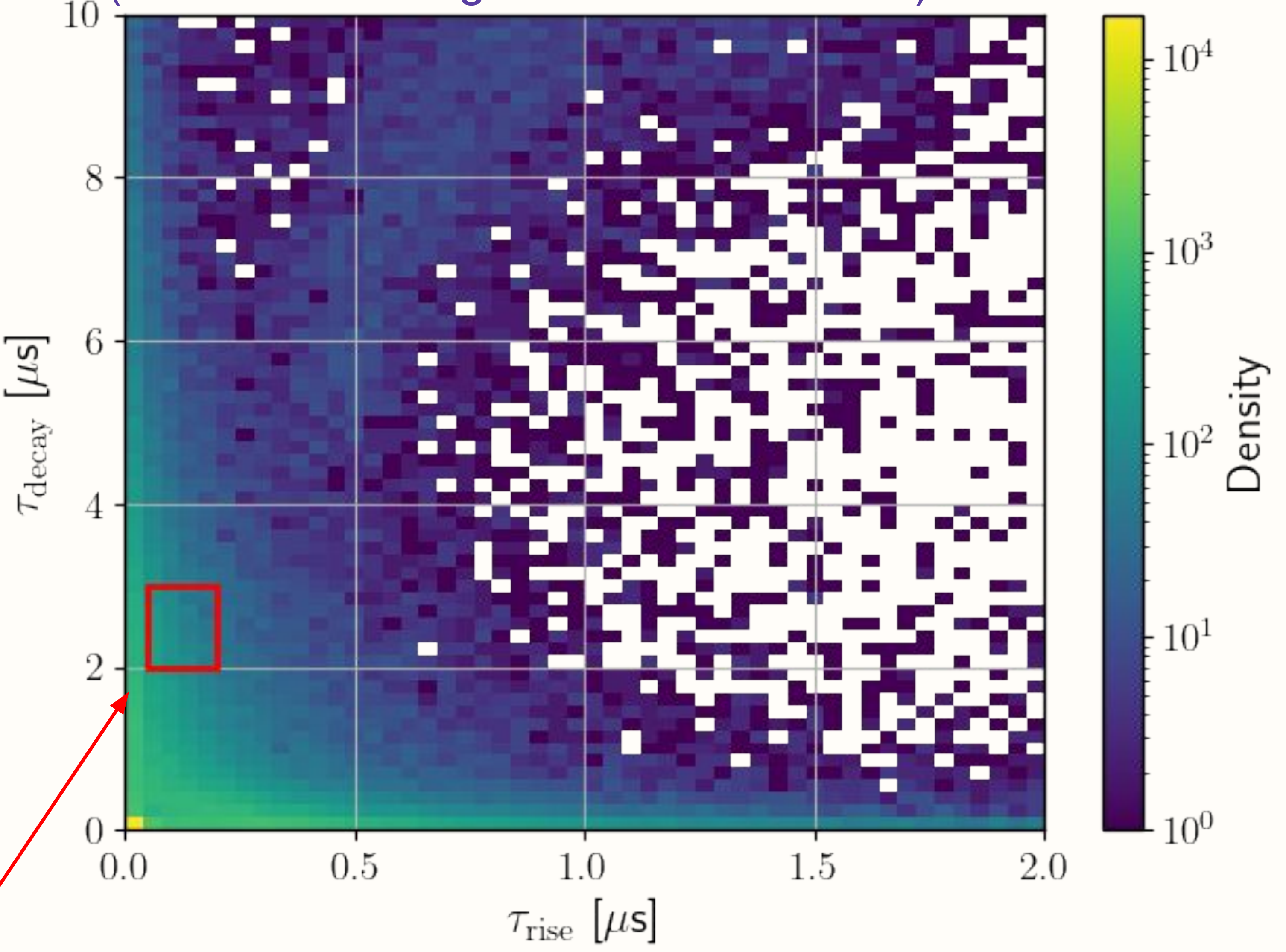


Calibration Results



Rise and decay time stay approximately constant over the energy range.

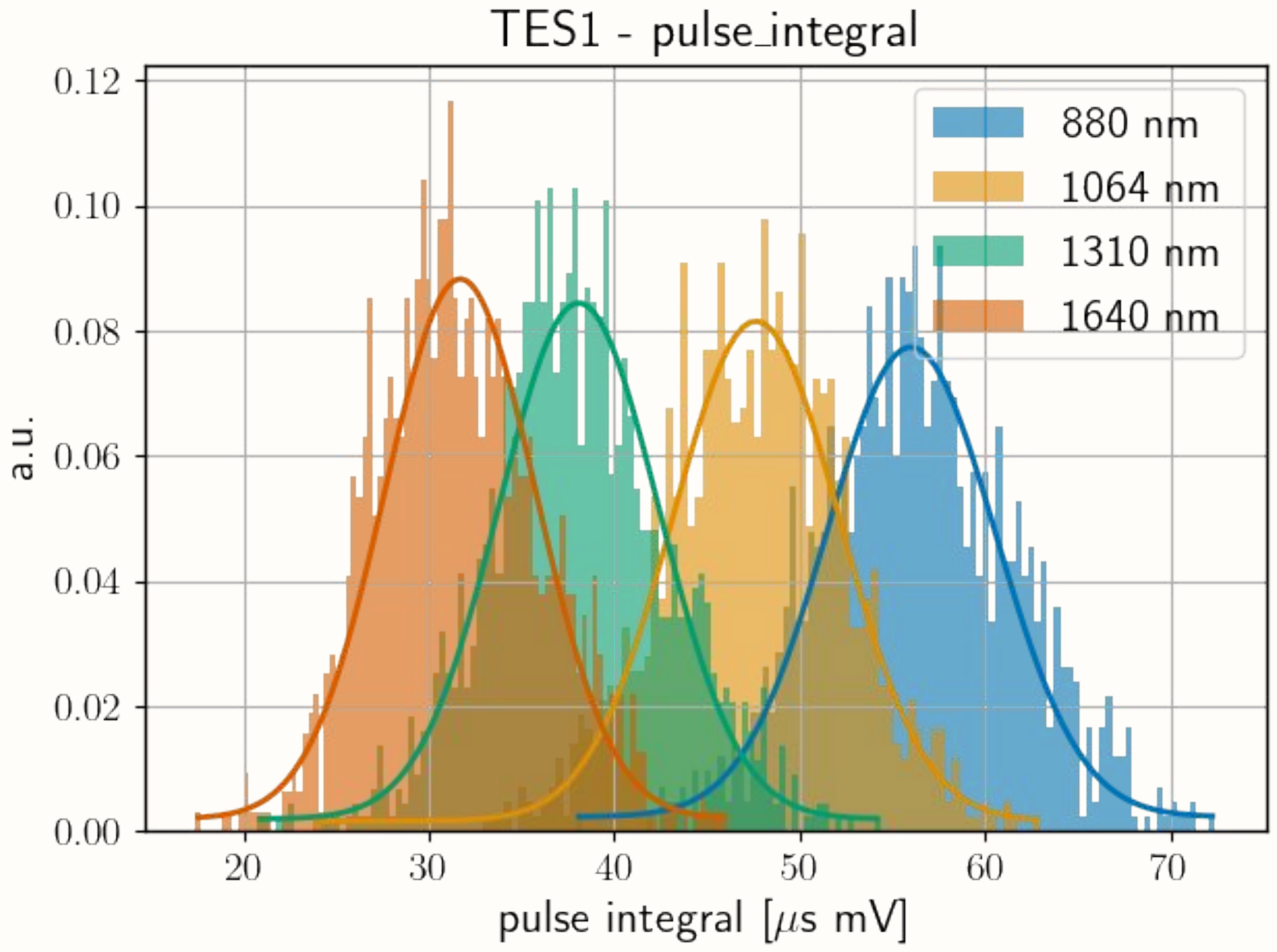
Important to eliminate backgrounds for low trigger thresholds
(Here: 91 h background measurement)



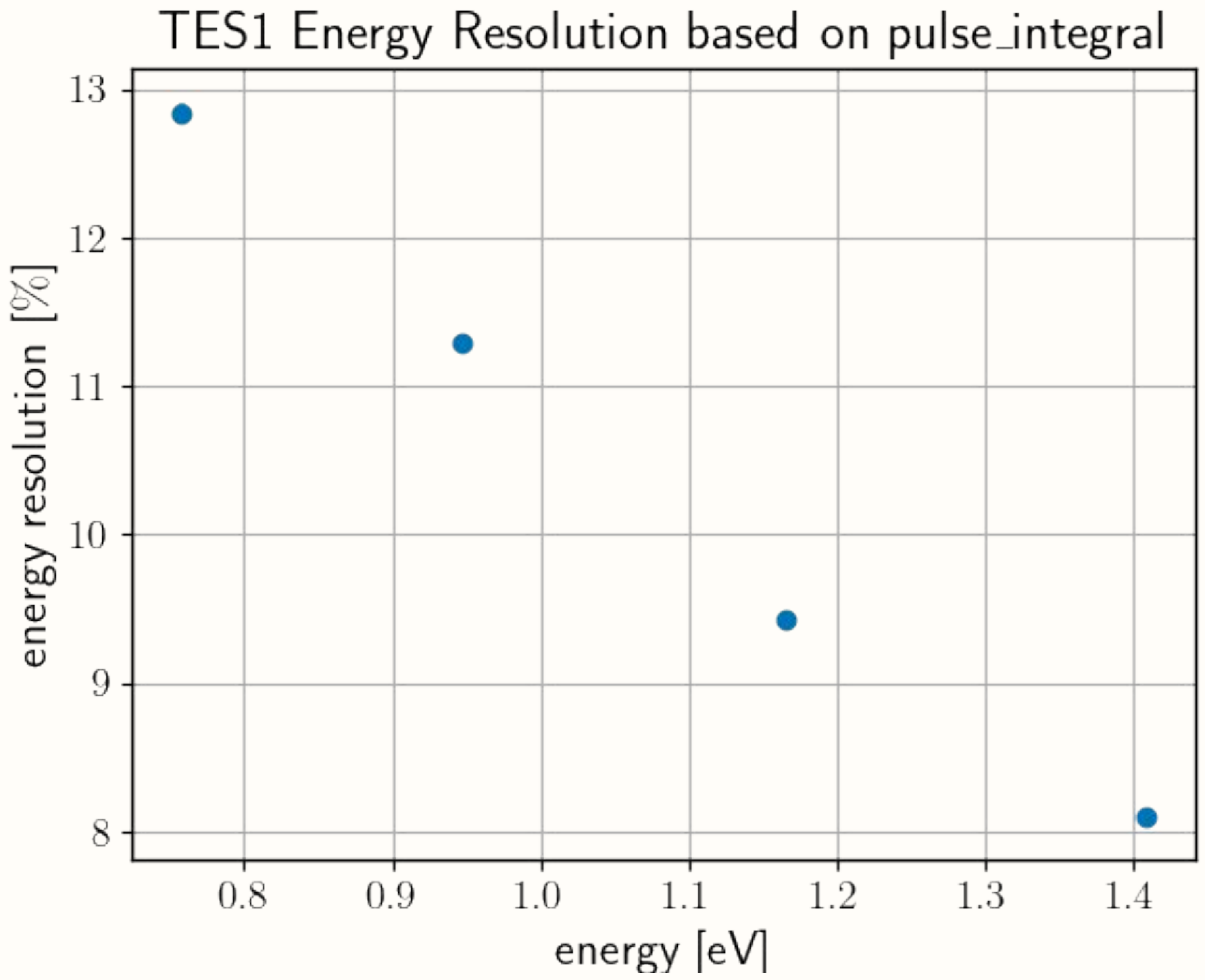
approximate region of interest

Energy Resolution

Energy resolution improves for higher energies (expected due to lower relative noise contribution)

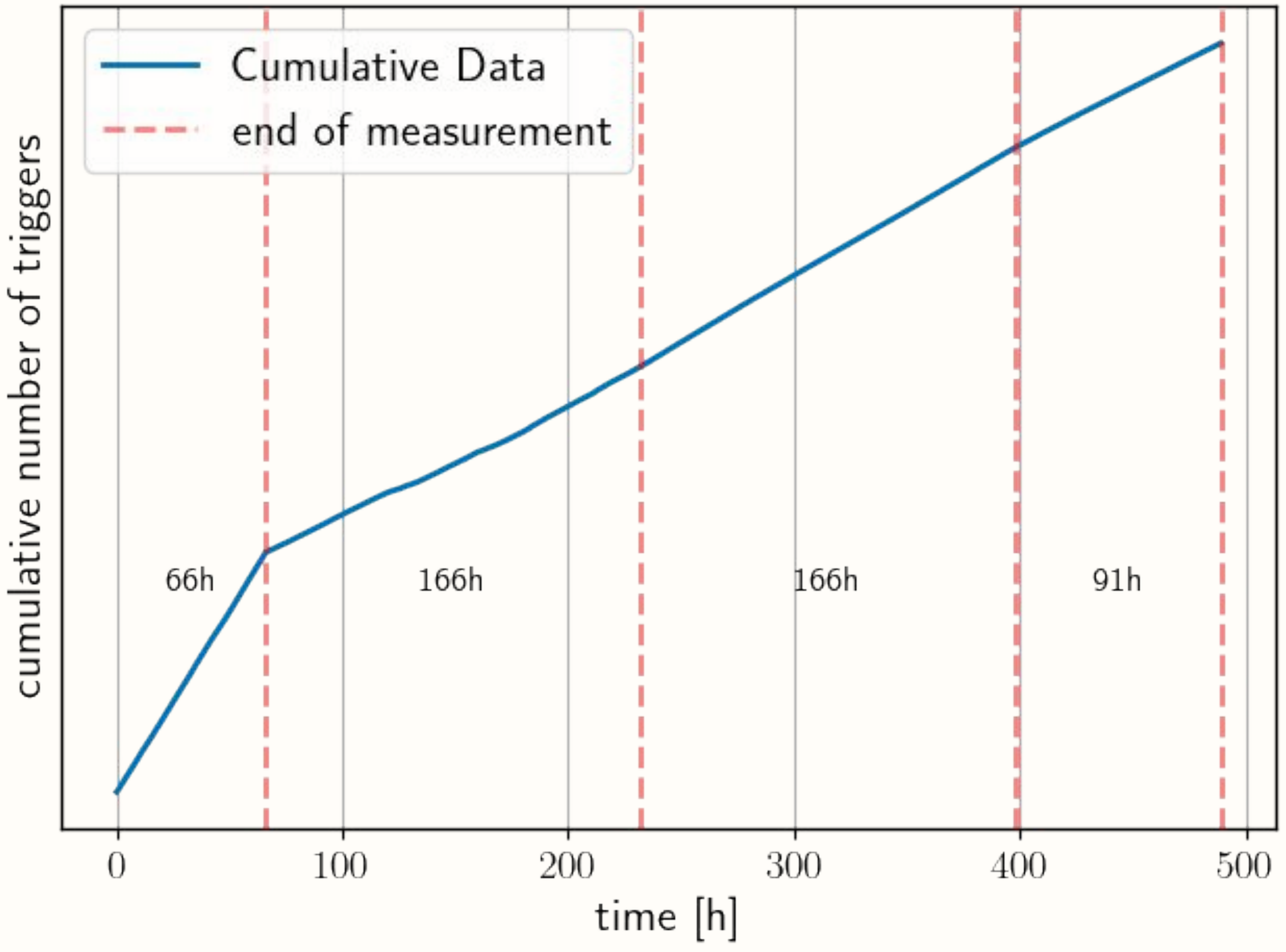


$$ER = \frac{\sigma}{\mu}$$

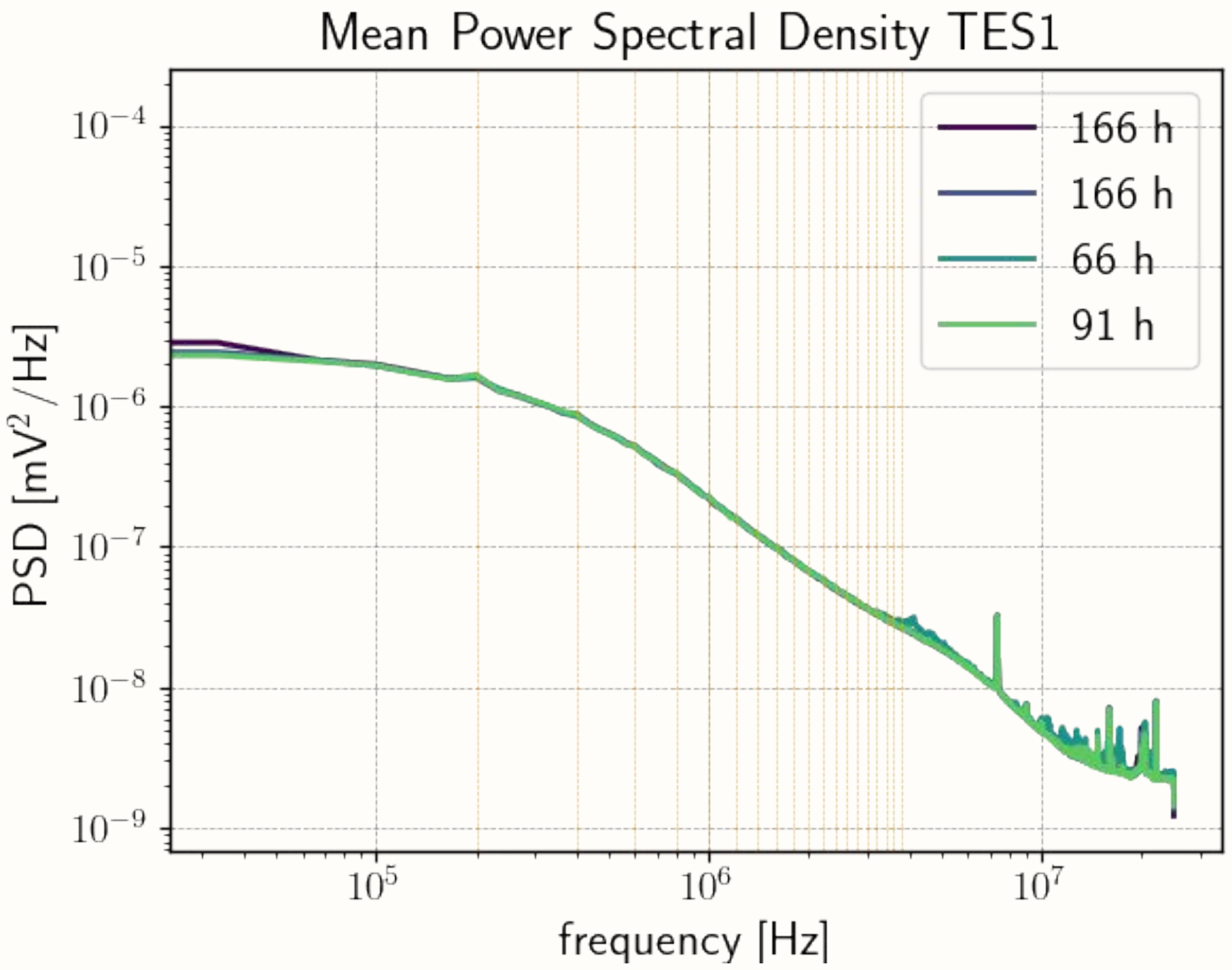


First dedicated DDM run

Total measurement time: 489 h

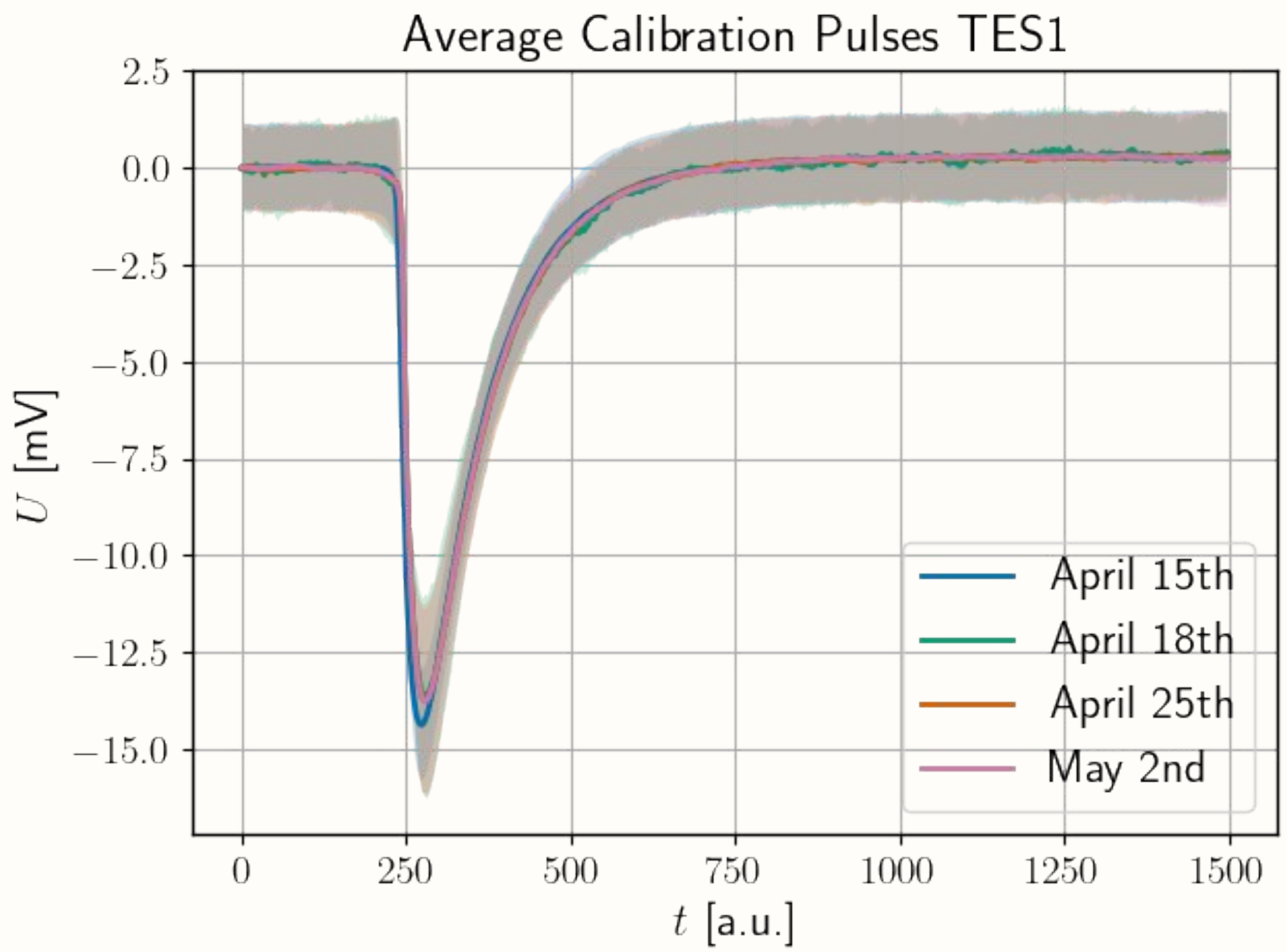


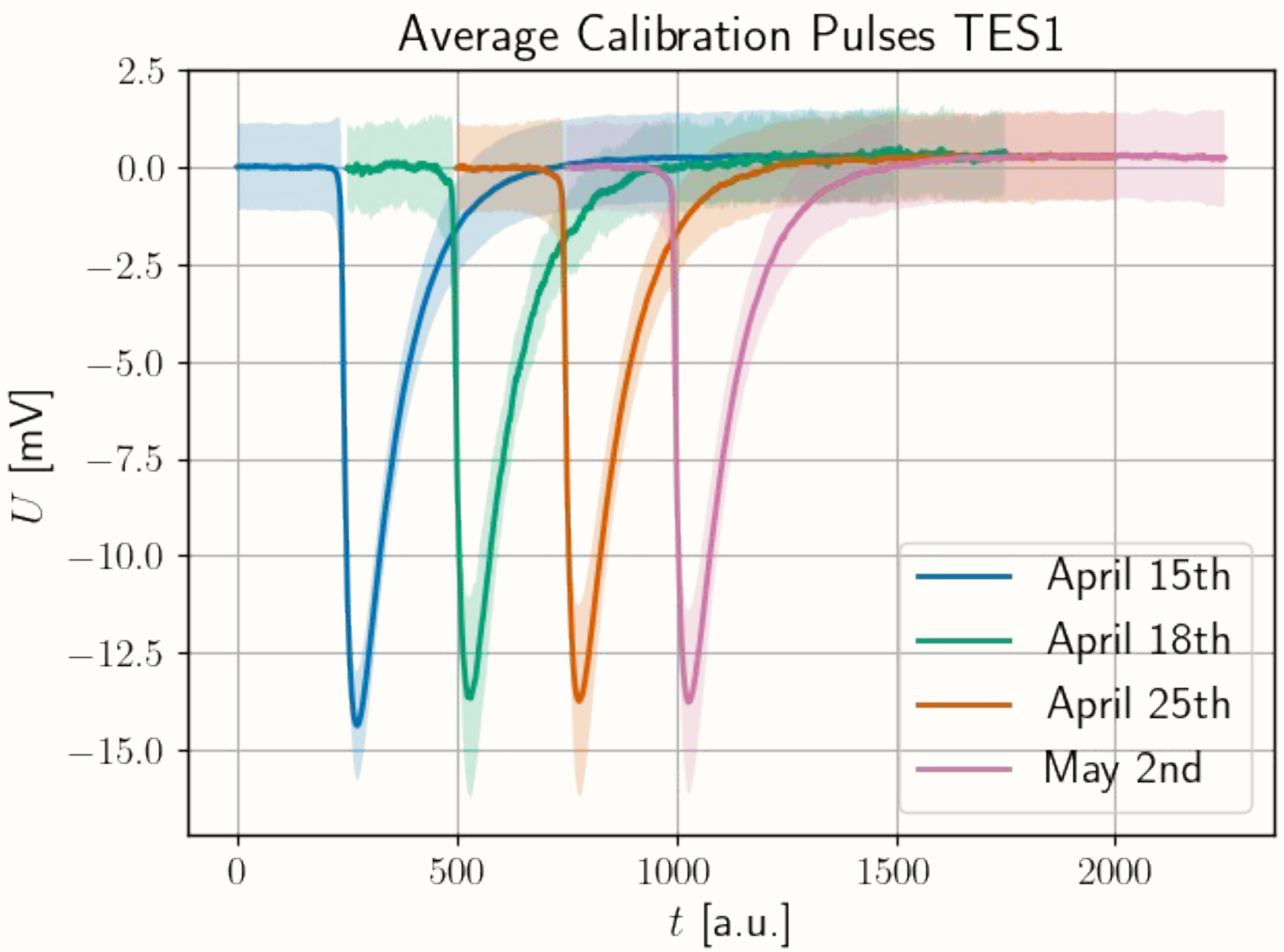
Overall stable baseline noise



First dedicated DDM run - Calibration

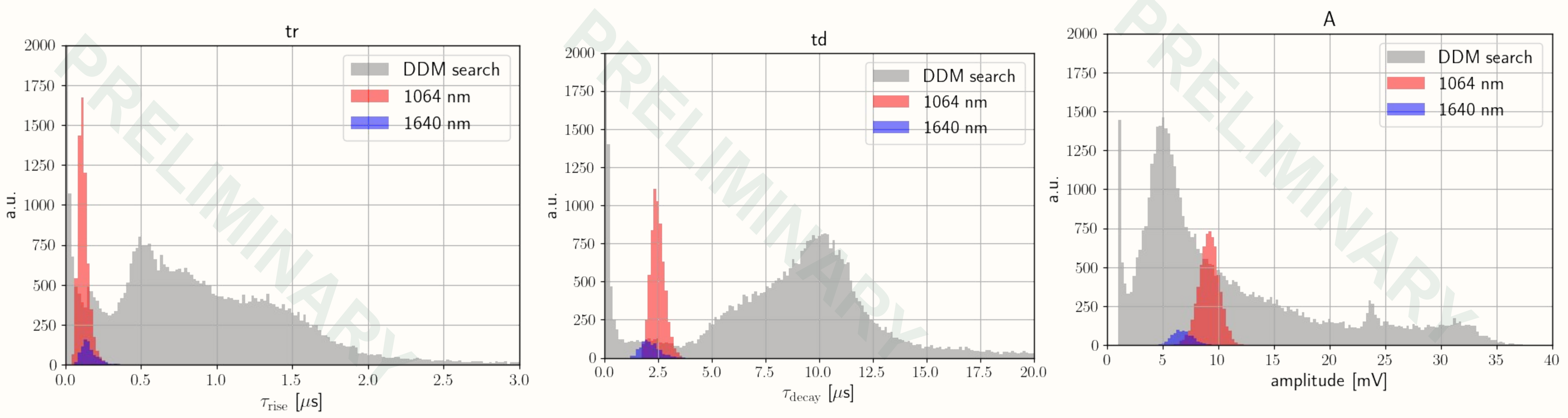
Average calibration pulses (1064nm) in between measurements: Stable over ~500 h





First dedicated DDM run - first results

Calibration samples (1064 nm [1.165 eV] & 1640 nm [0.756 eV] before data run) vs. background - fitting parameters

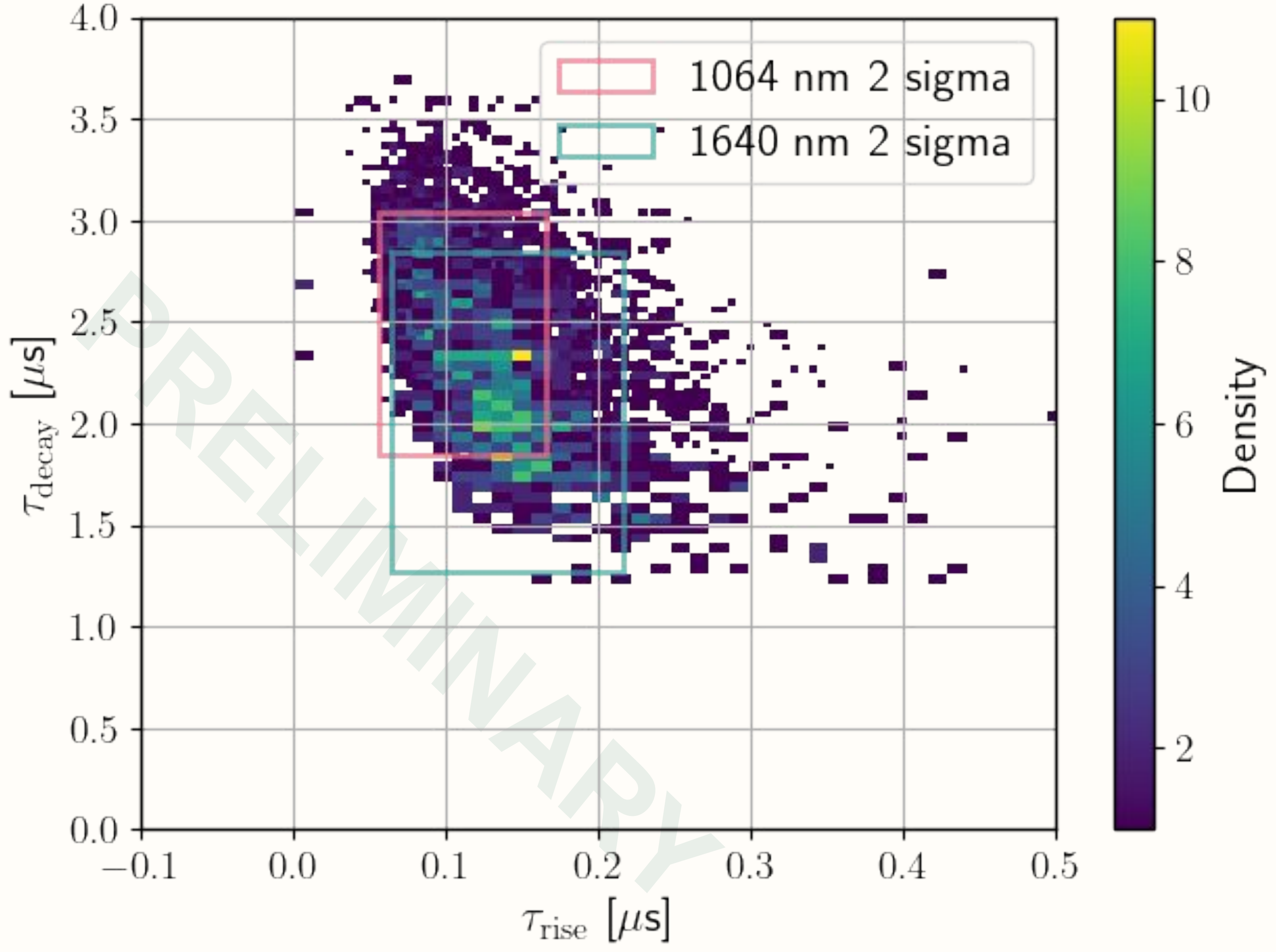


First dedicated DDM run - selection

Acceptance based on cutting on the **2 sigma** regions of *rise & decay time* and χ^2_{dof} using Gaussian statistics from calibration measurements → fitting to be optimized further

wavelength cuts	cut parameters	acceptance
1064 nm	tr, td, χ^2_{dof}	~ 72 %
1640 nm	tr, td, χ^2_{dof}	~ 83 %

Combined calibration (1064 nm & 1640 nm) fit parameter distribution with sigma regions



First dedicated DDM run - example

Example:

Acceptance from **1640 nm [0.756 eV]** calibration measurements using multiple cut parameters:

wavelength cuts	**cut parameters**	**sigma region**	**acceptance**
1064 nm	td, tr, A, t0, pulse integral, χ^2_{dof}	2σ	> 66 %

First dedicated DDM run - example

Example:

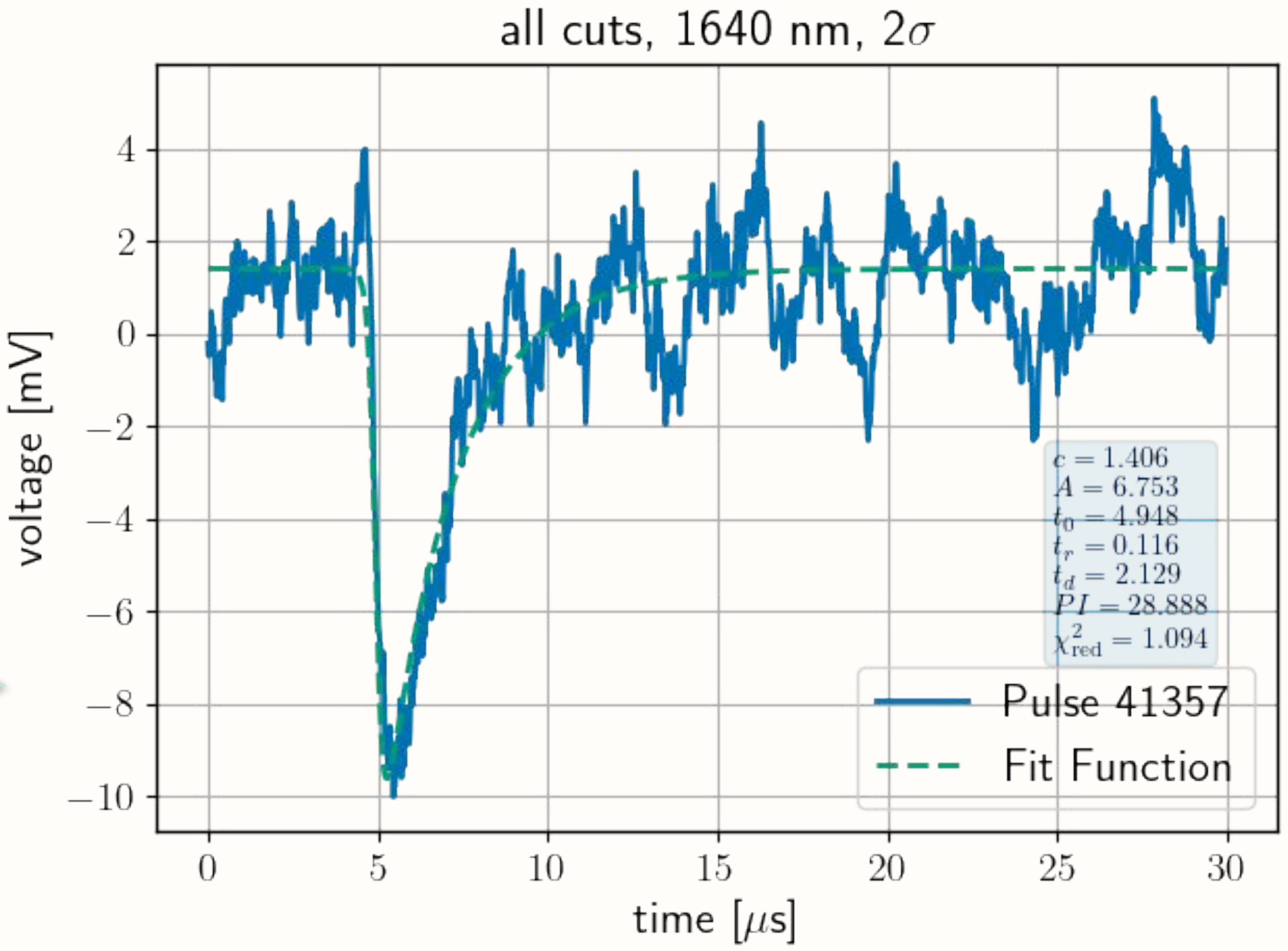
Acceptance from **1640 nm [0.756 eV]** calibration measurements using multiple cut parameters:

wavelength cuts	**cut parameters**	**sigma region**	**acceptance**
1064 nm	td, tr, A, t0, pulse integral, χ^2_{dof}	2**σ**	> 66 %

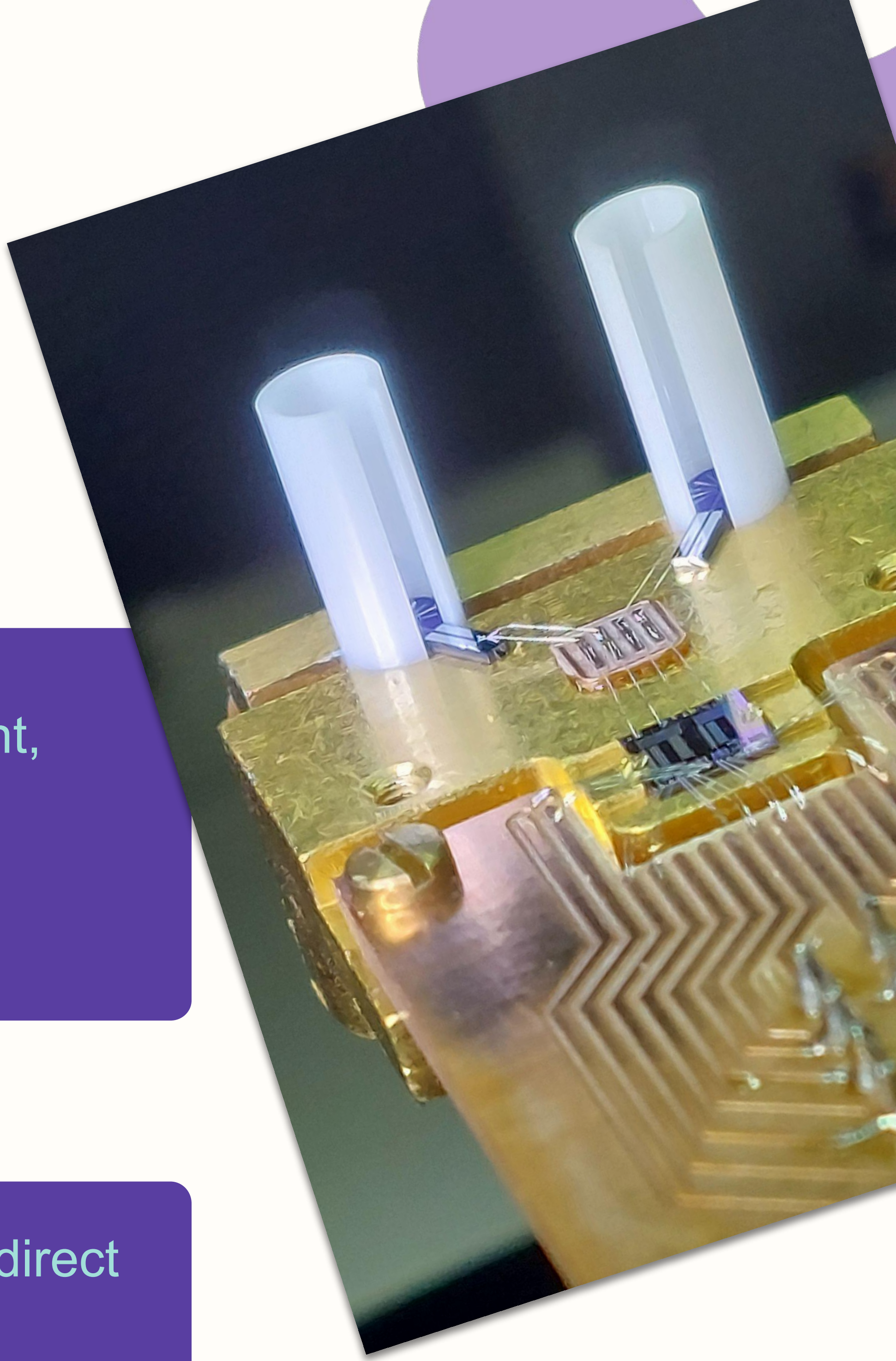
→ used on DDM search data leads to **~10^{-5} Hz** rate of surviving photon-like events

Soon:
- improvement of fitting algorithm
- energy binned spectrum of surviving events

Background or "dark matter"?
To be continued..

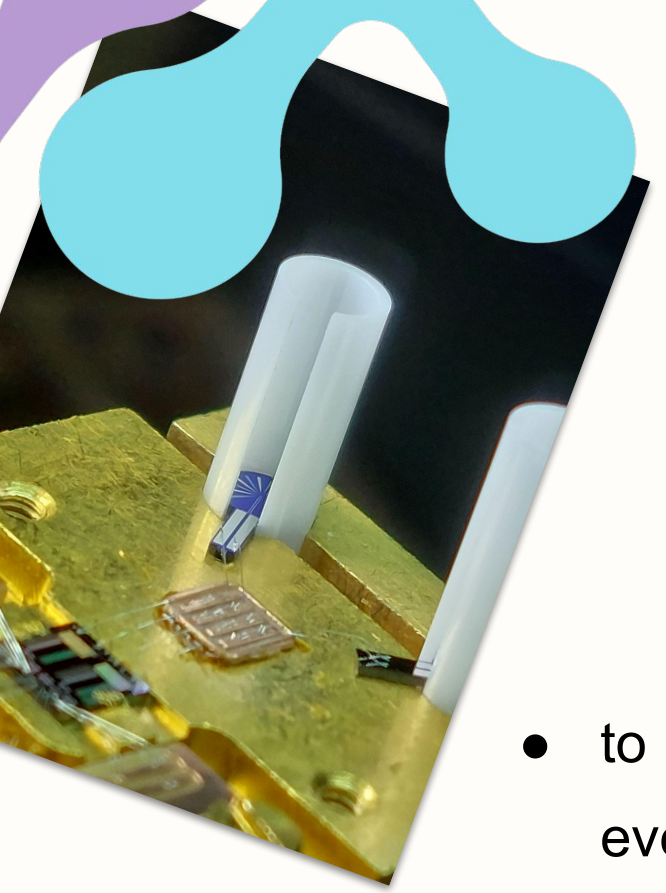


Summary

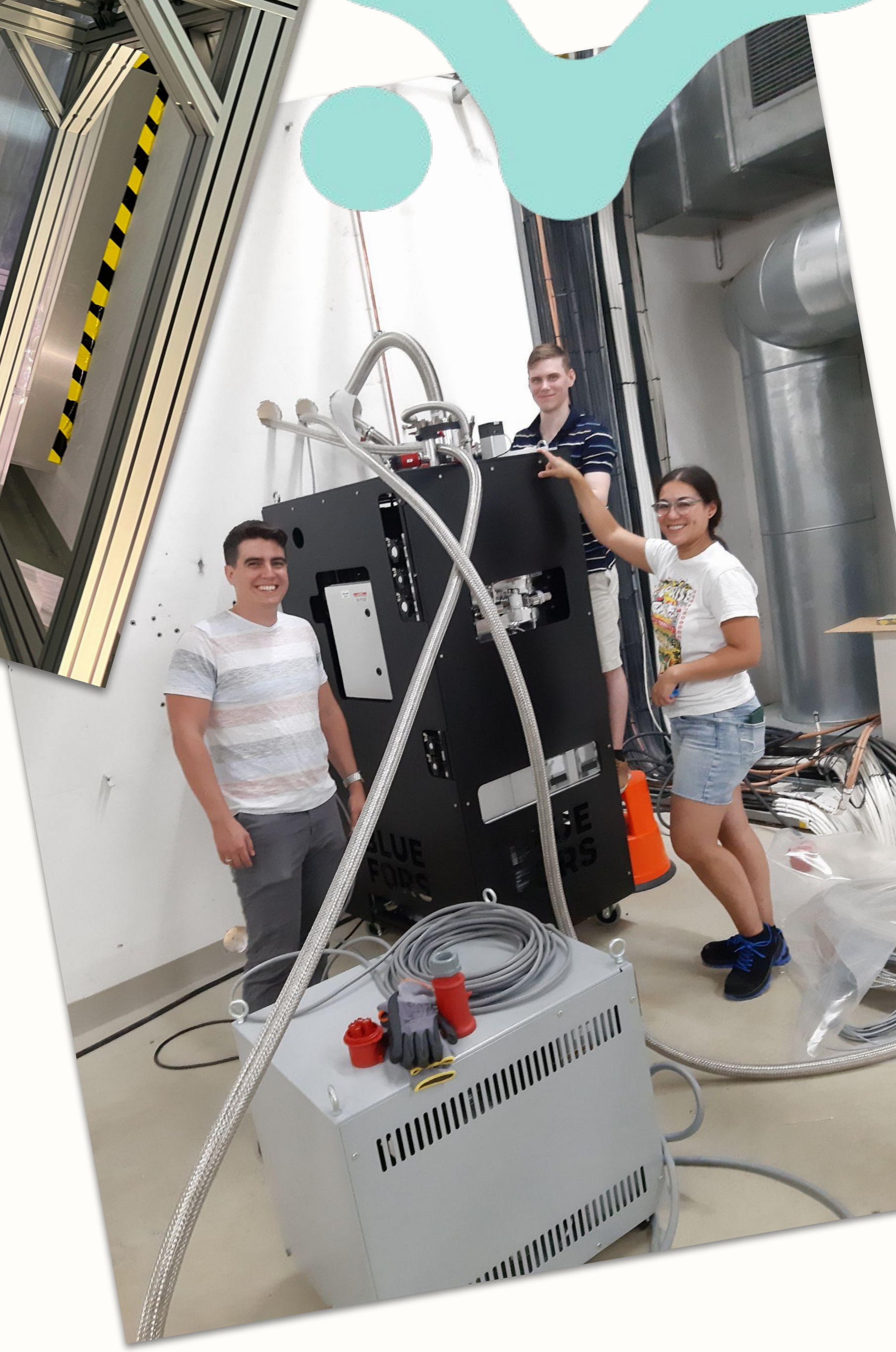


- Our TES can search for sub-MeV DM, prior to being employed in the ALPS II experiment, exploiting DM-electron scattering possibly reaching new sensitivities
- This could be a proof of principle for similar technologies being used as DM detectors

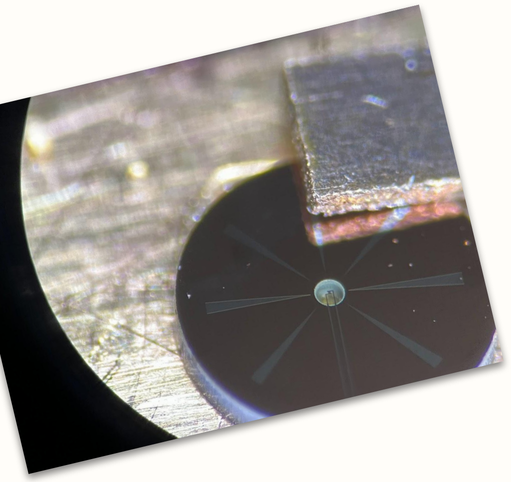
- calibration results enable a better understanding and support the analysis of dedicated direct DM searches
- 20 day dedicated DDM run performed in April/May, analysis ongoing
- first look at the data shows promising suppression of background rates



Outlook..



- to improve the analysis enables us to create an energy-binned spectrum of surviving events
- to further investigate intrinsic background (paper soon: *Simulating the response of a transition edge sensor to cosmic-ray and radioactivity induced backgrounds* by J.A. Rubiera Gimeno et al.)



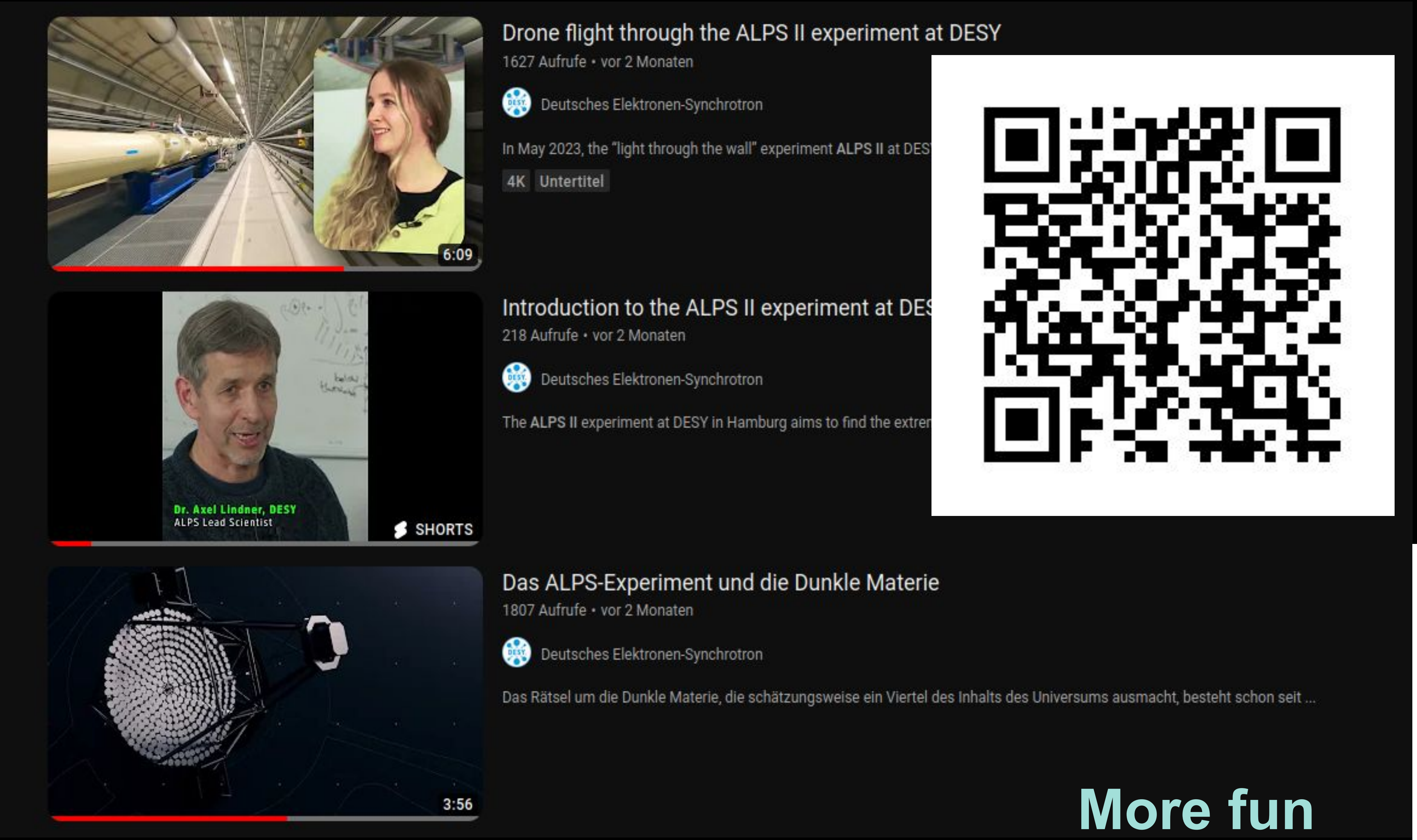
- to receive new TES and modules from NIST and PTB:
  - without zirconia fiber sleeves that could reduce intrinsic backgrounds (see paper!)
  - with TES chip placed on a membrane
- to further investigate behavior < 0.8 eV and repeat measurements with additional sensors

THANK YOU

Animation by SciComLab

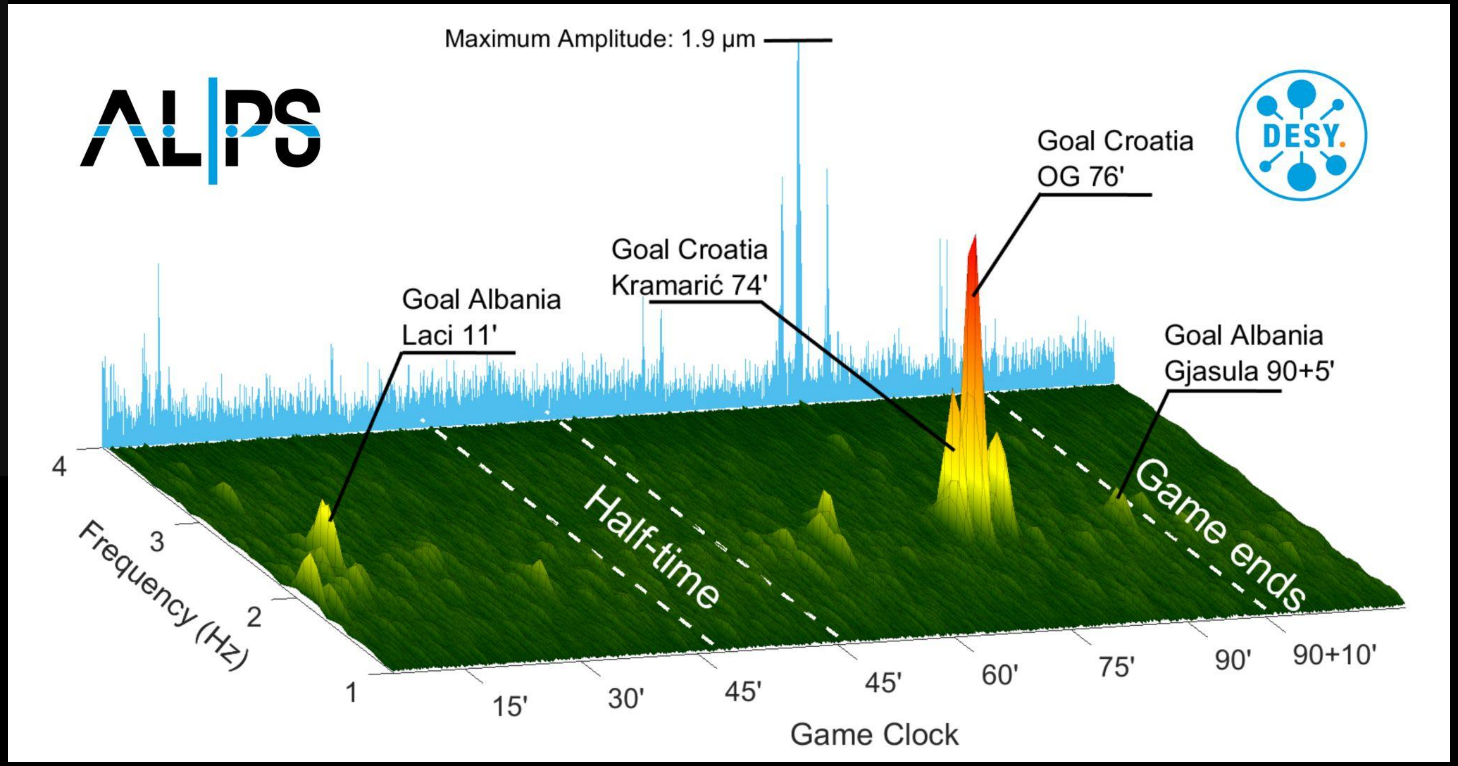
More ALPS II

Video material on YOUTUBE:

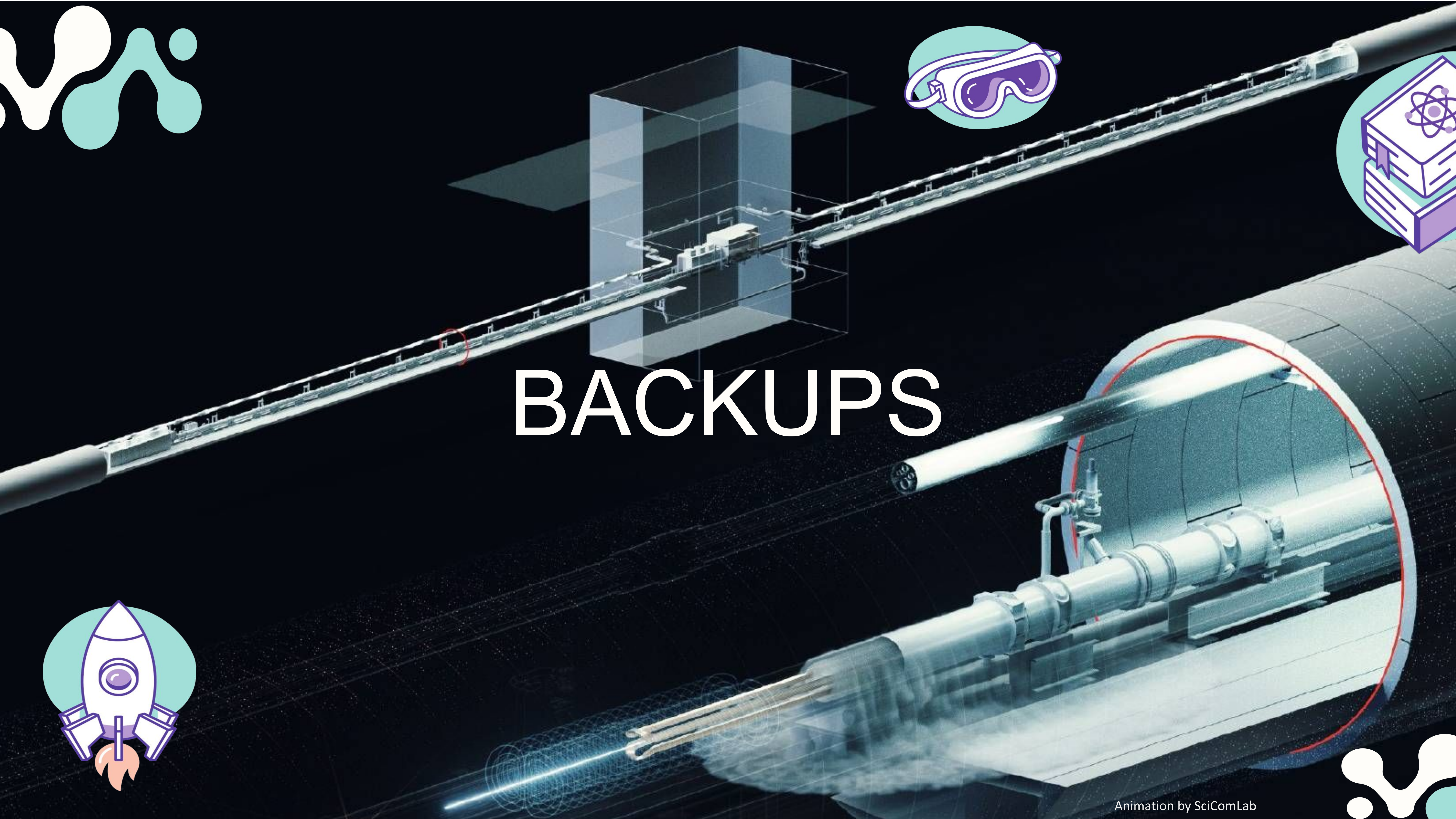


Podcasts (Spotify Links, but also available on other platforms)

More fun science:

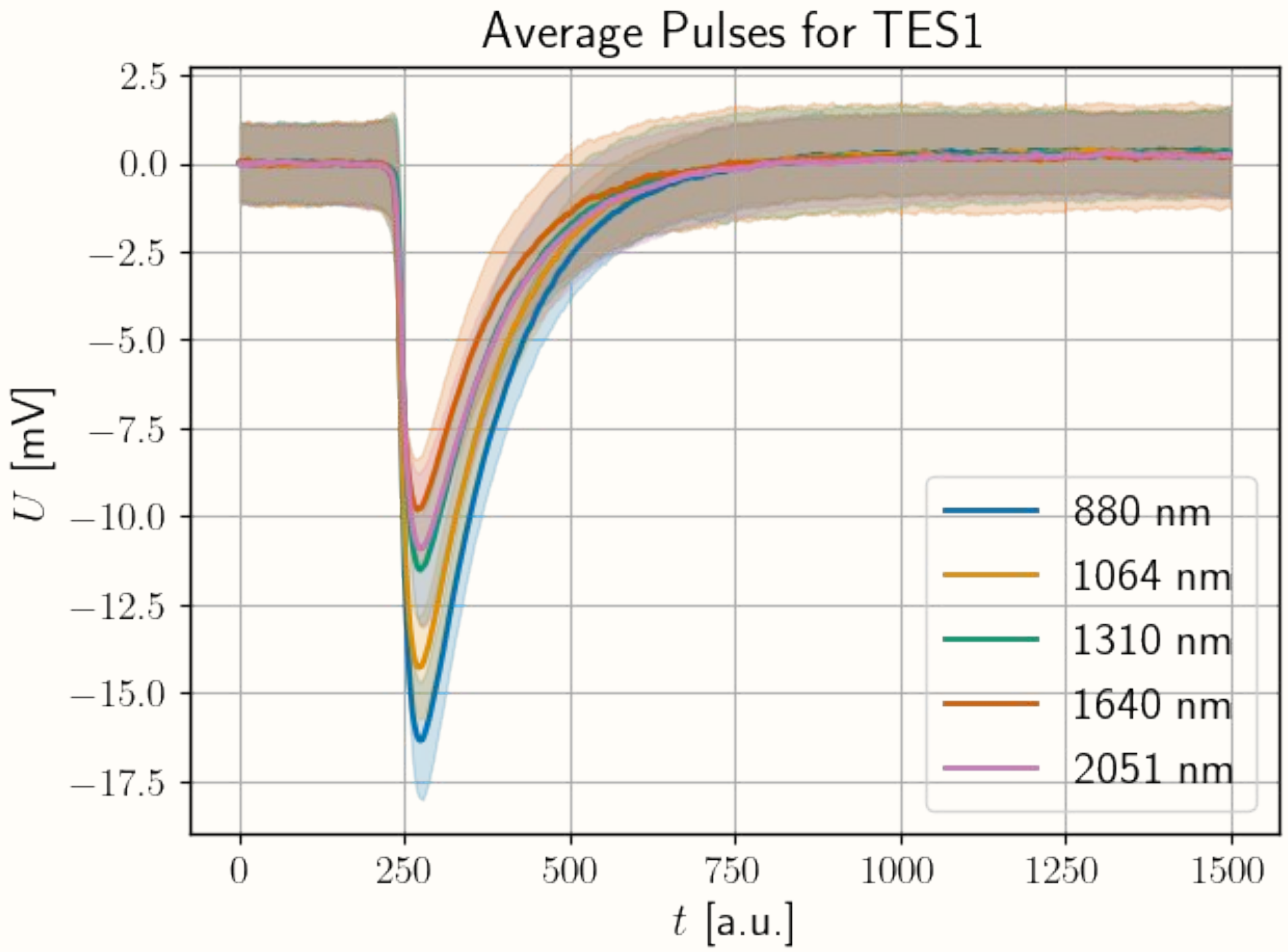


BACKUPS

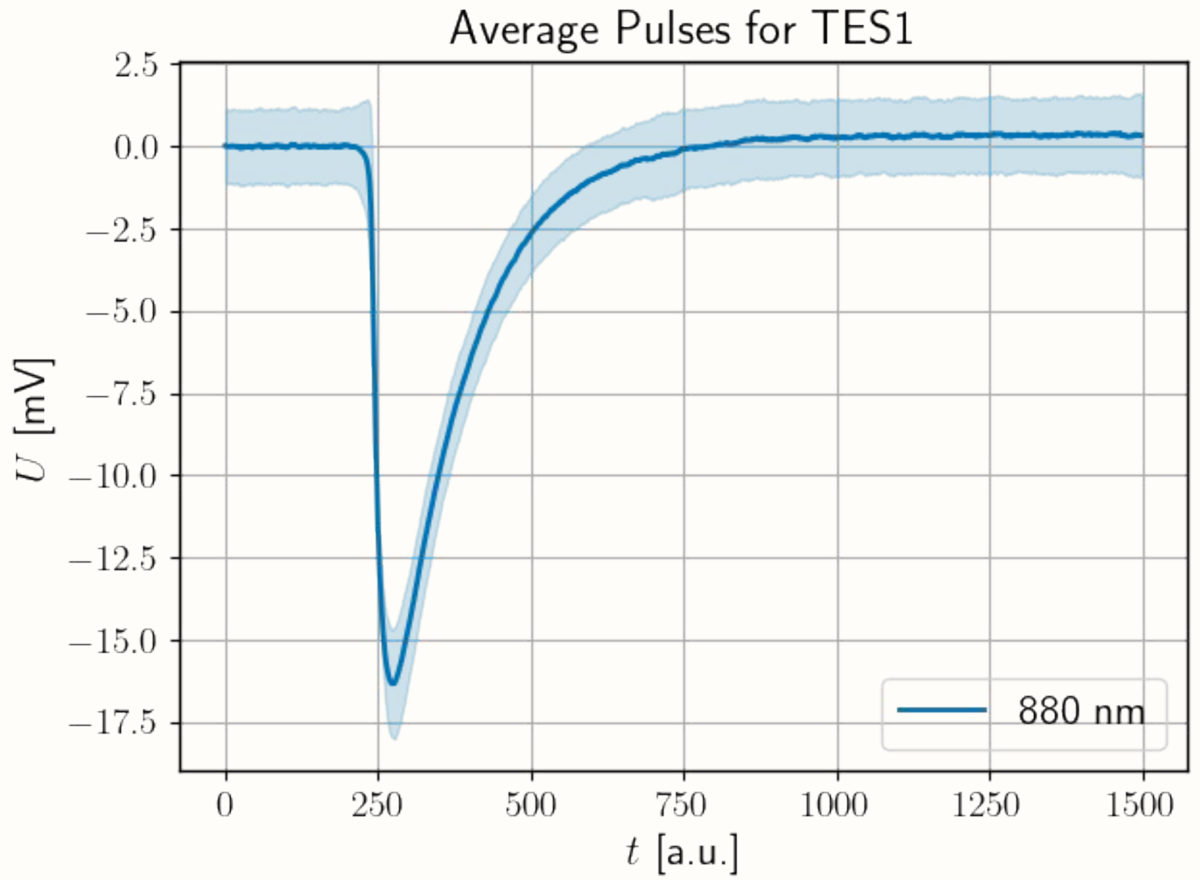


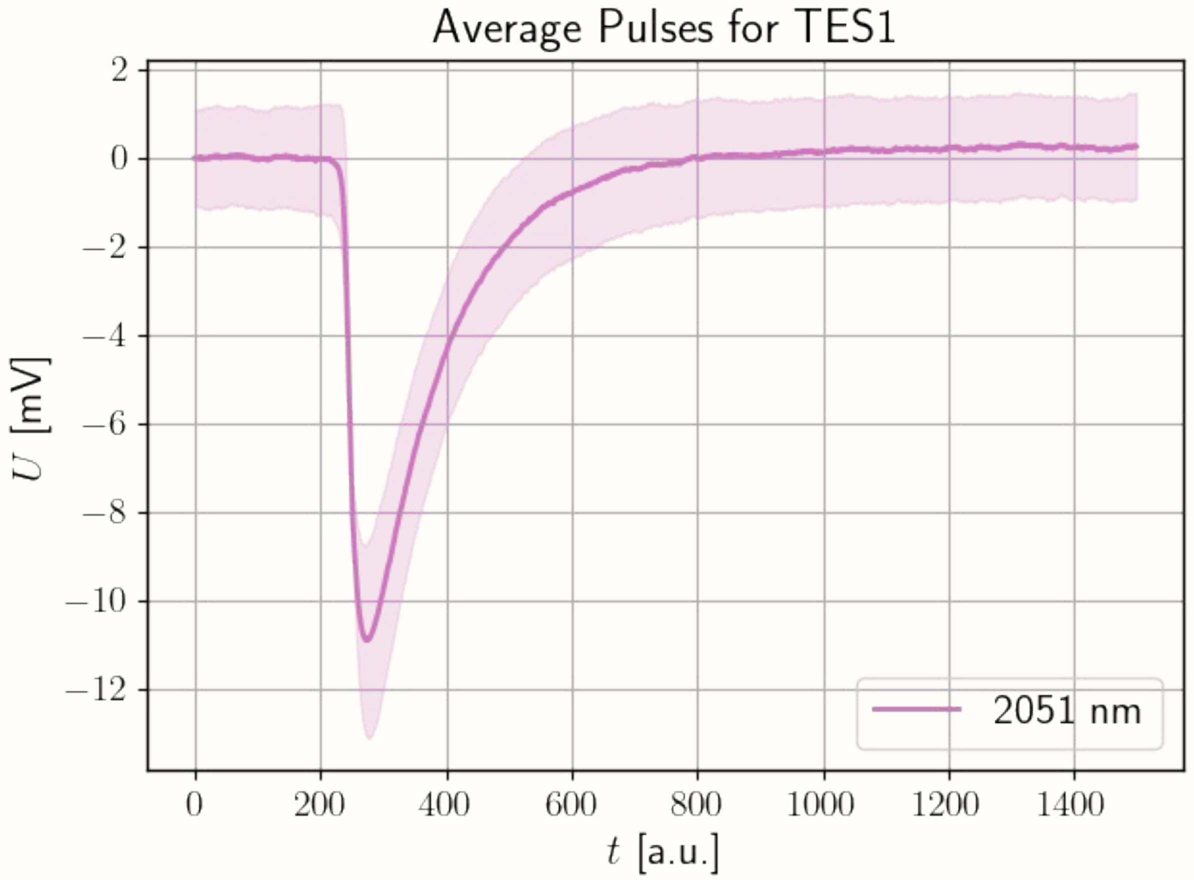
Animation by SciComLab

Measured calibration pulses



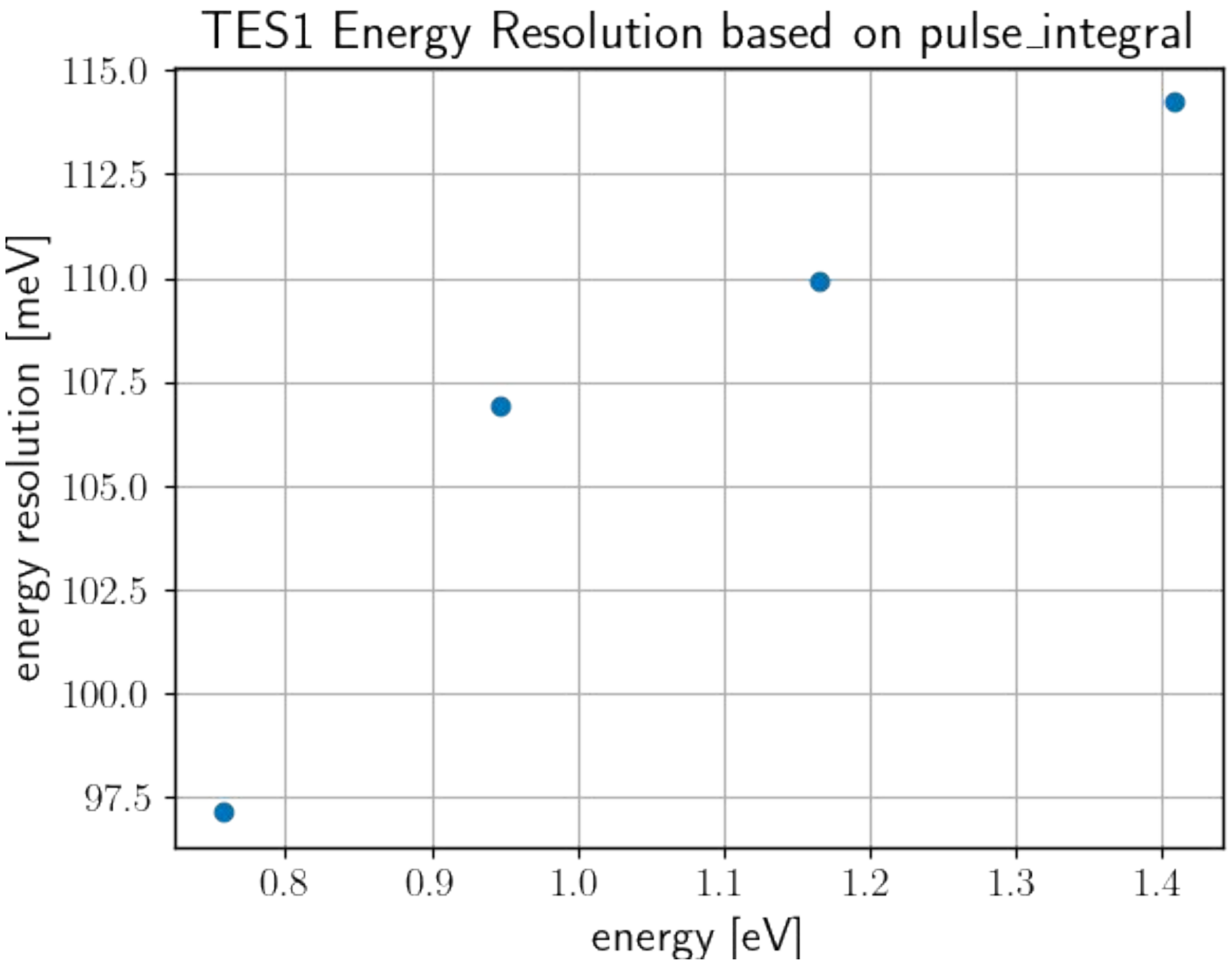
Average pulses of different wavelengths
(calibration measurement)

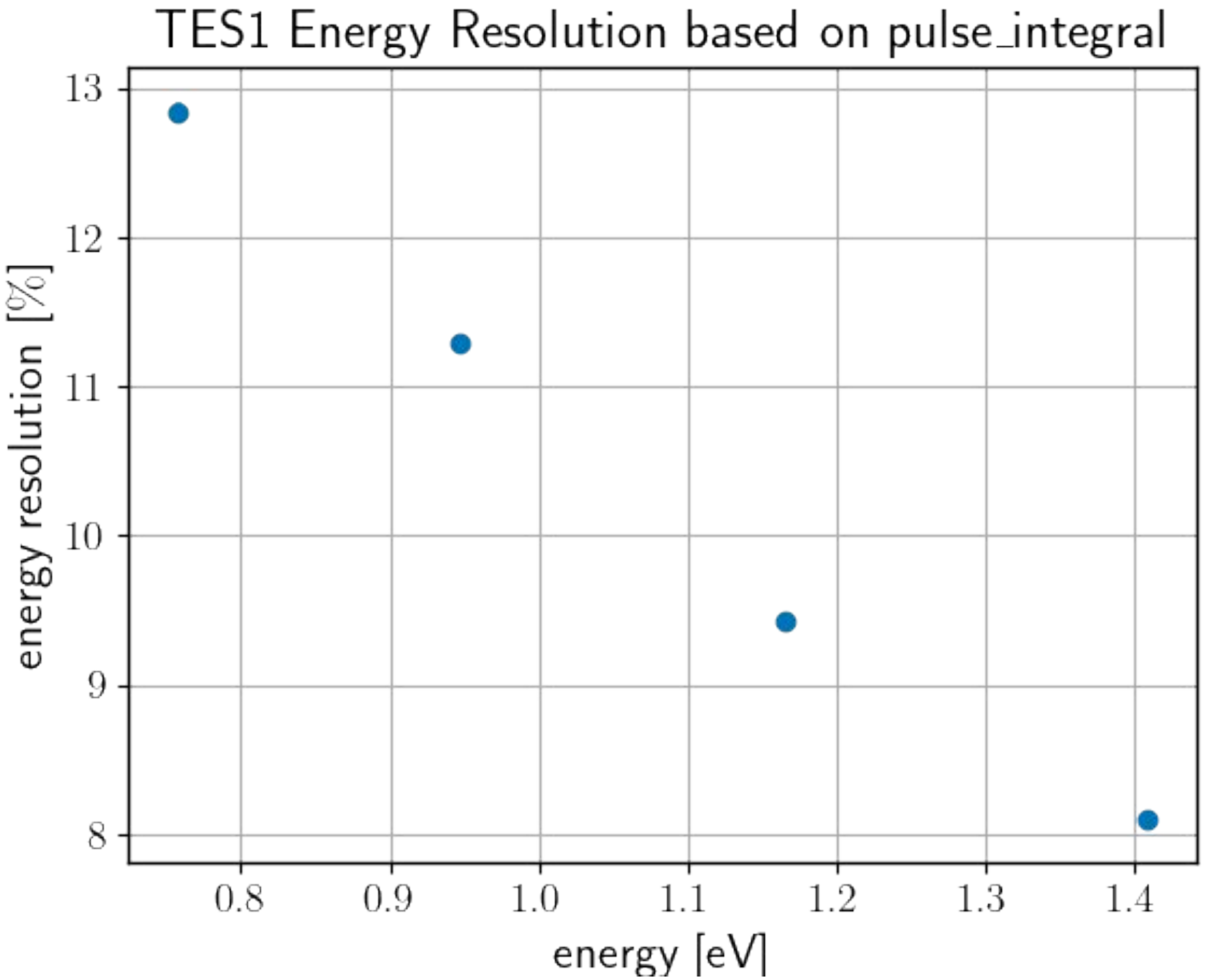




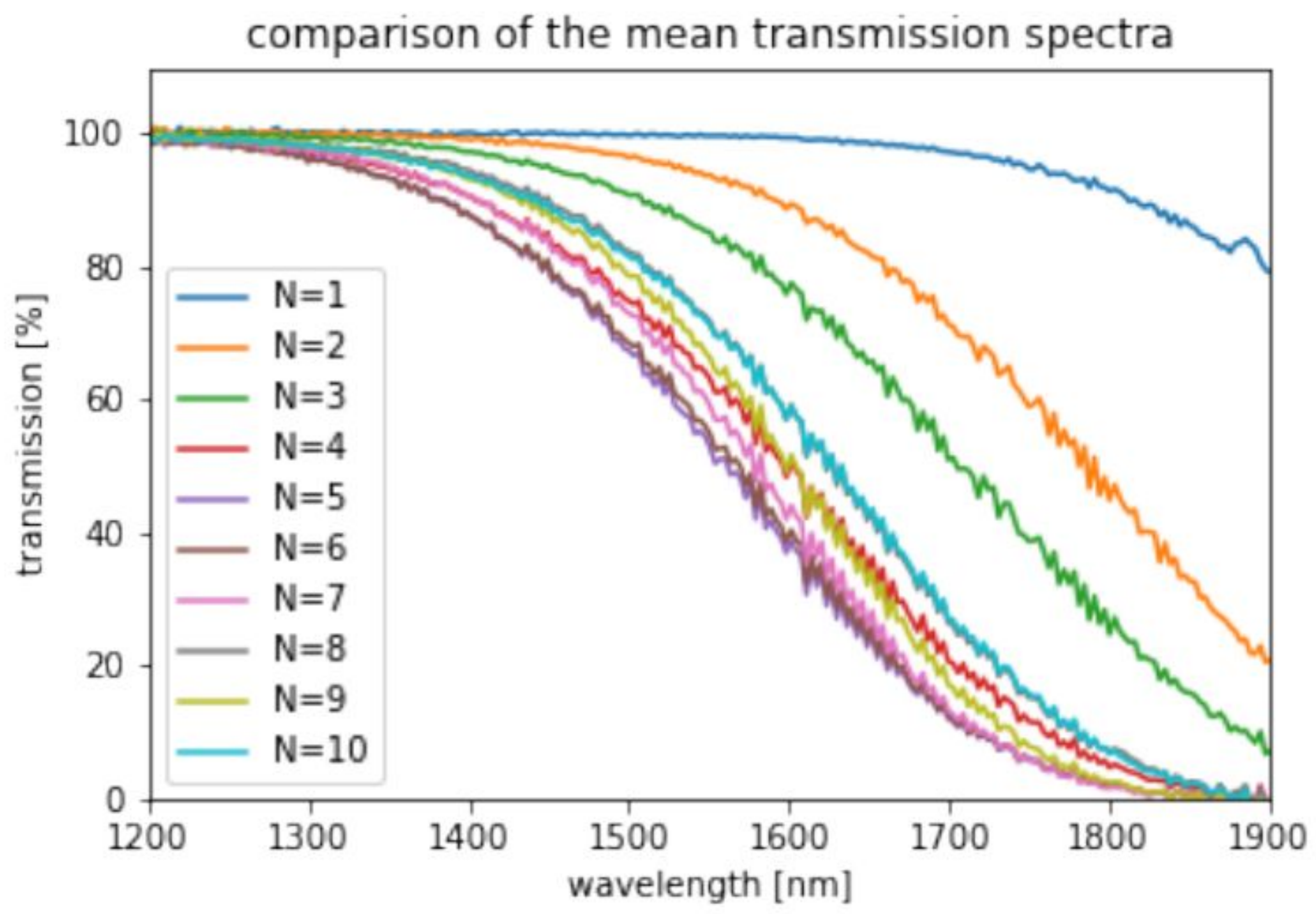
More noisy at lower trigger thresholds

Energy resolution - Calibration



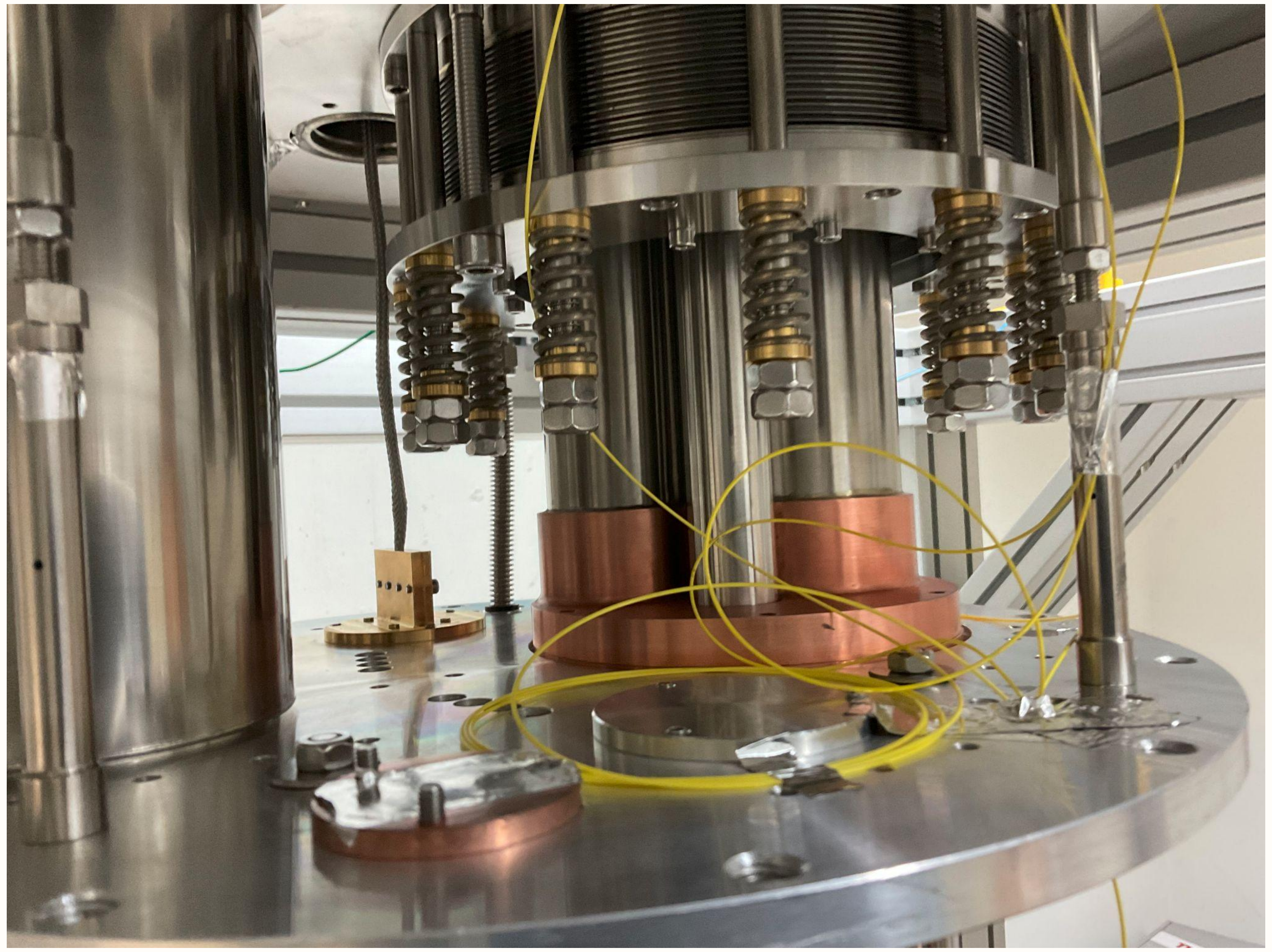


Effects due to fiber curling

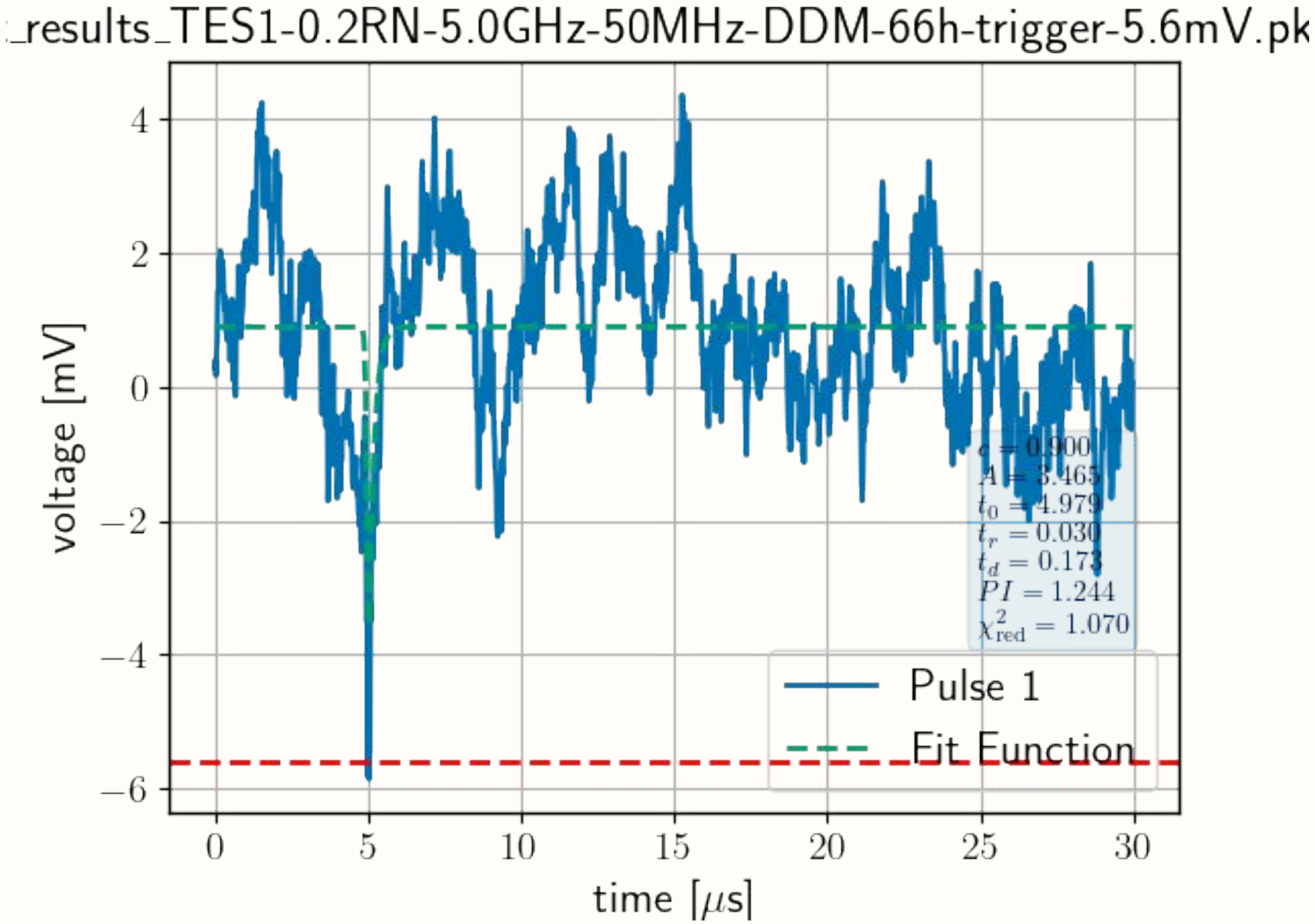


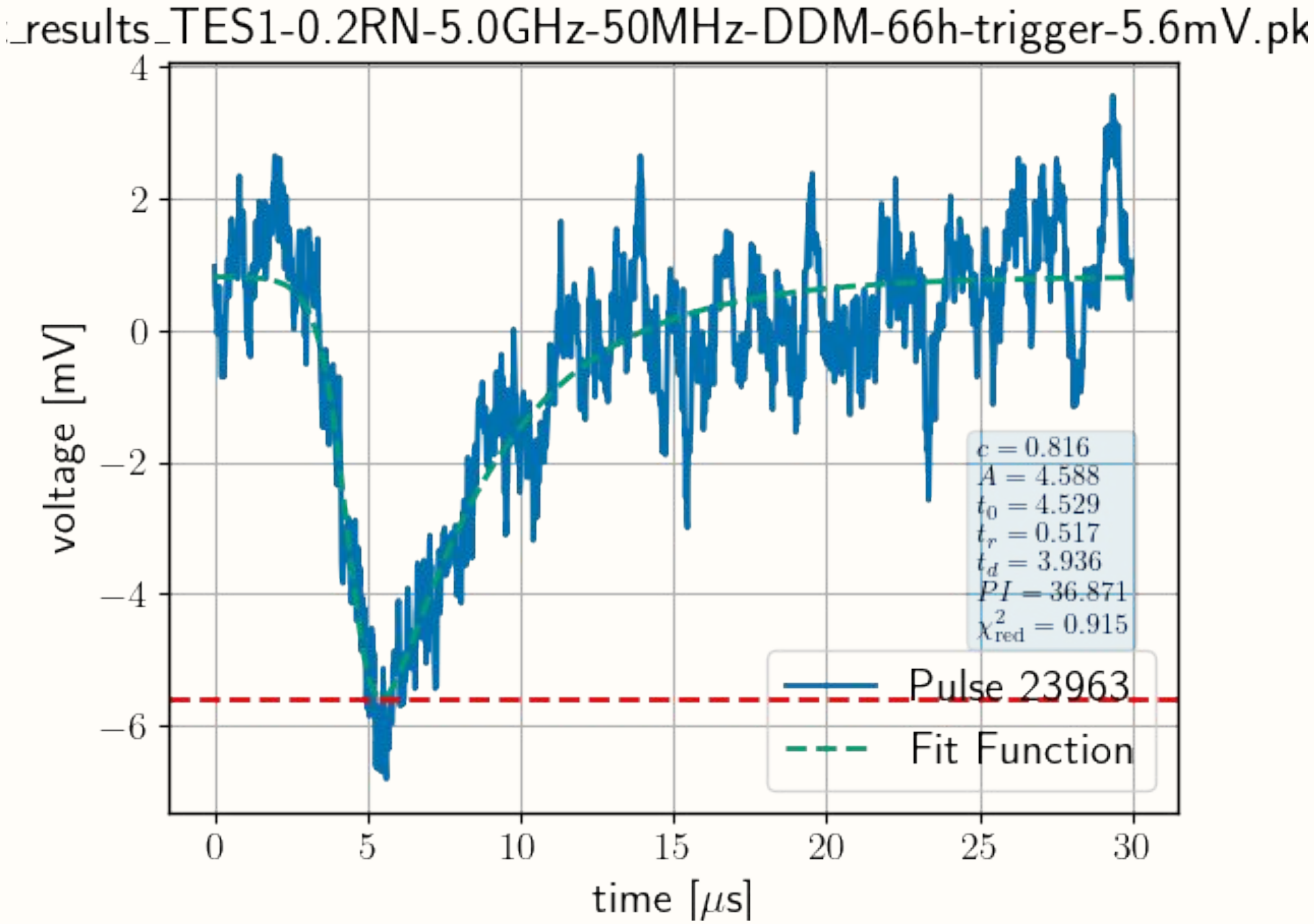
Transmission spectrum of a white light source for different windings of curled fiber - measured by intern Maria T. Pabst

Curled optical fiber on upper part of the cryostat.



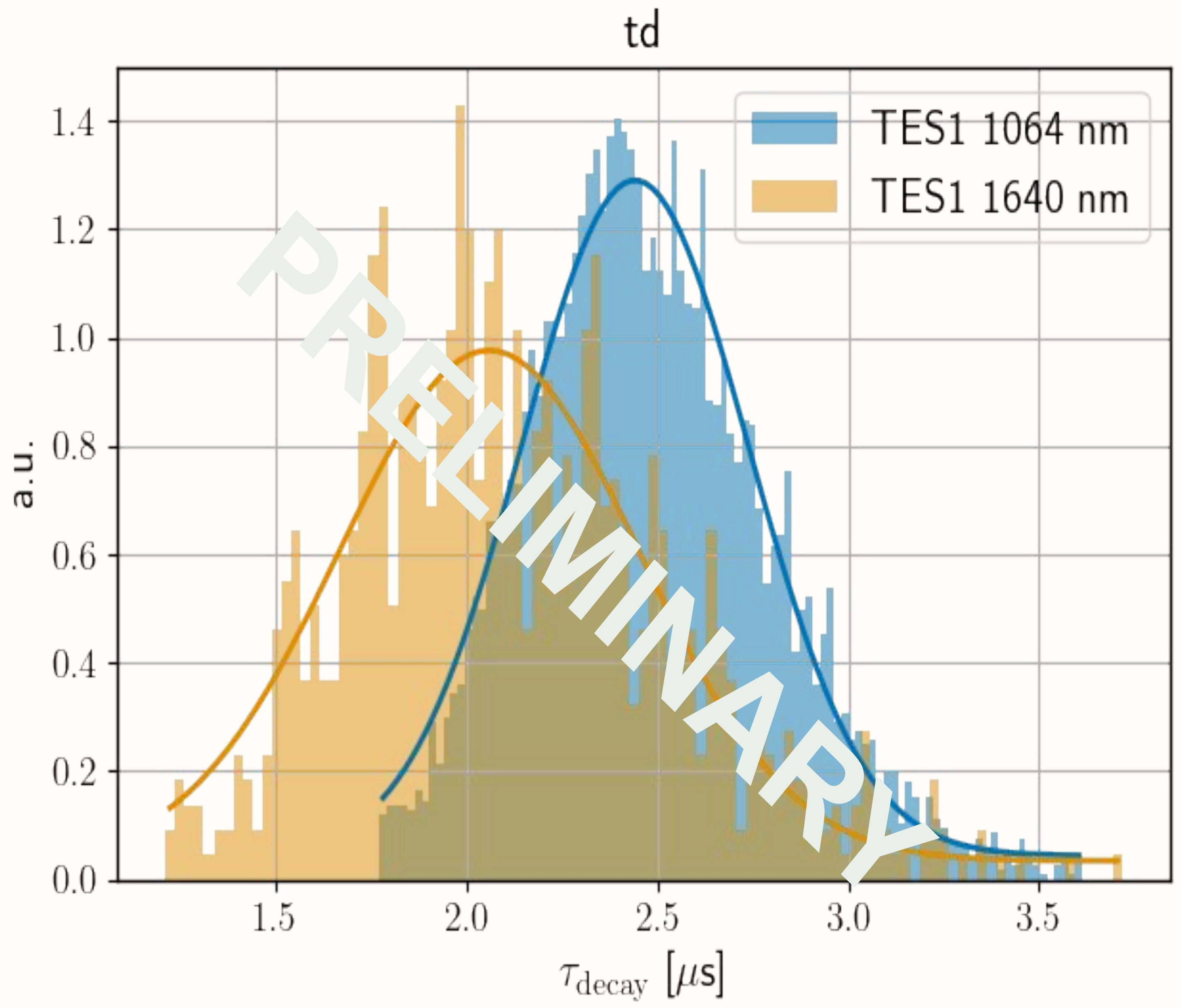
DDM backgrounds - electronic noise?

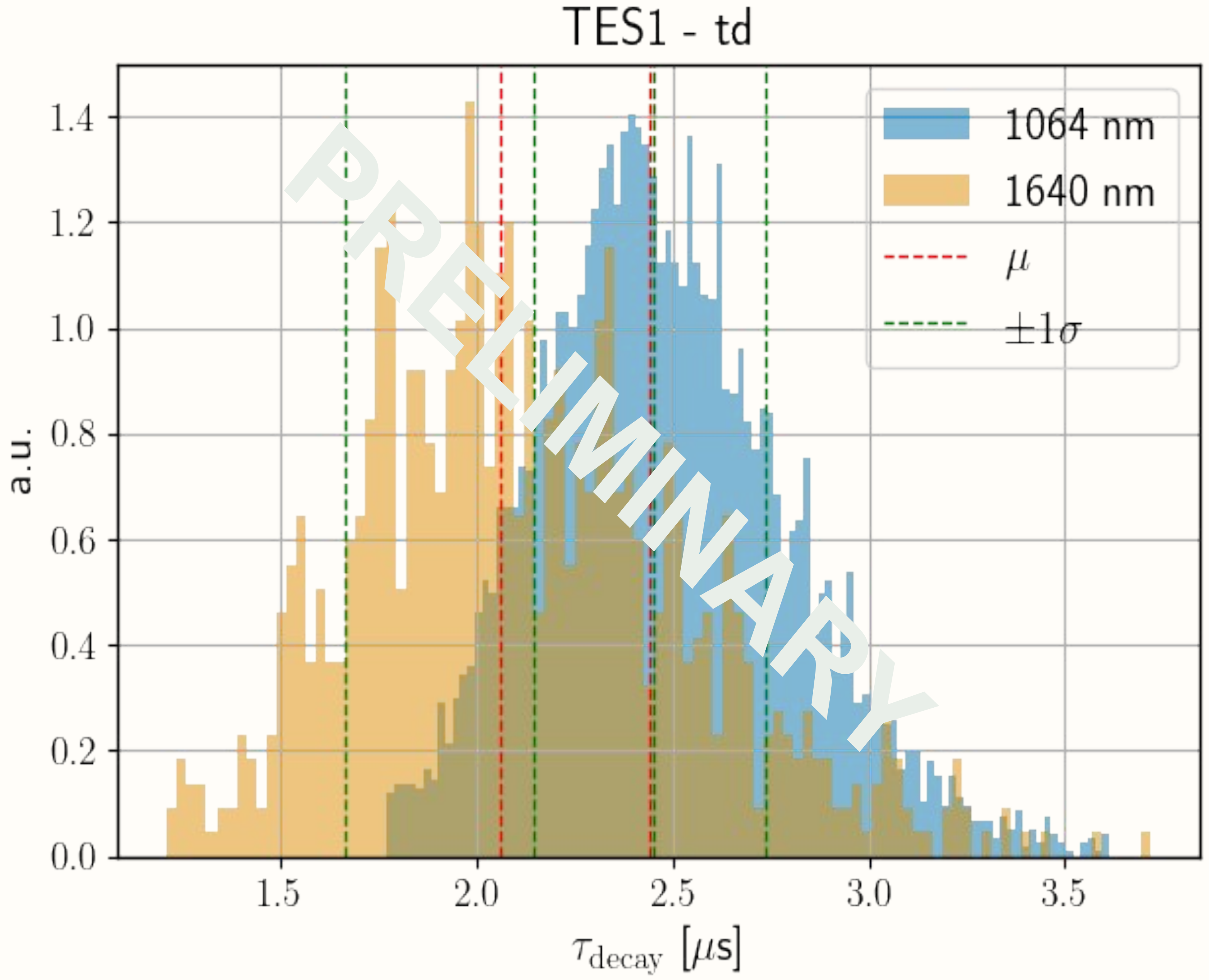




First dedicated DDM run - Cuts

Cutting on rise & decay time using Gaussian statistics - Example: 1064 nm & 1640 nm distributions

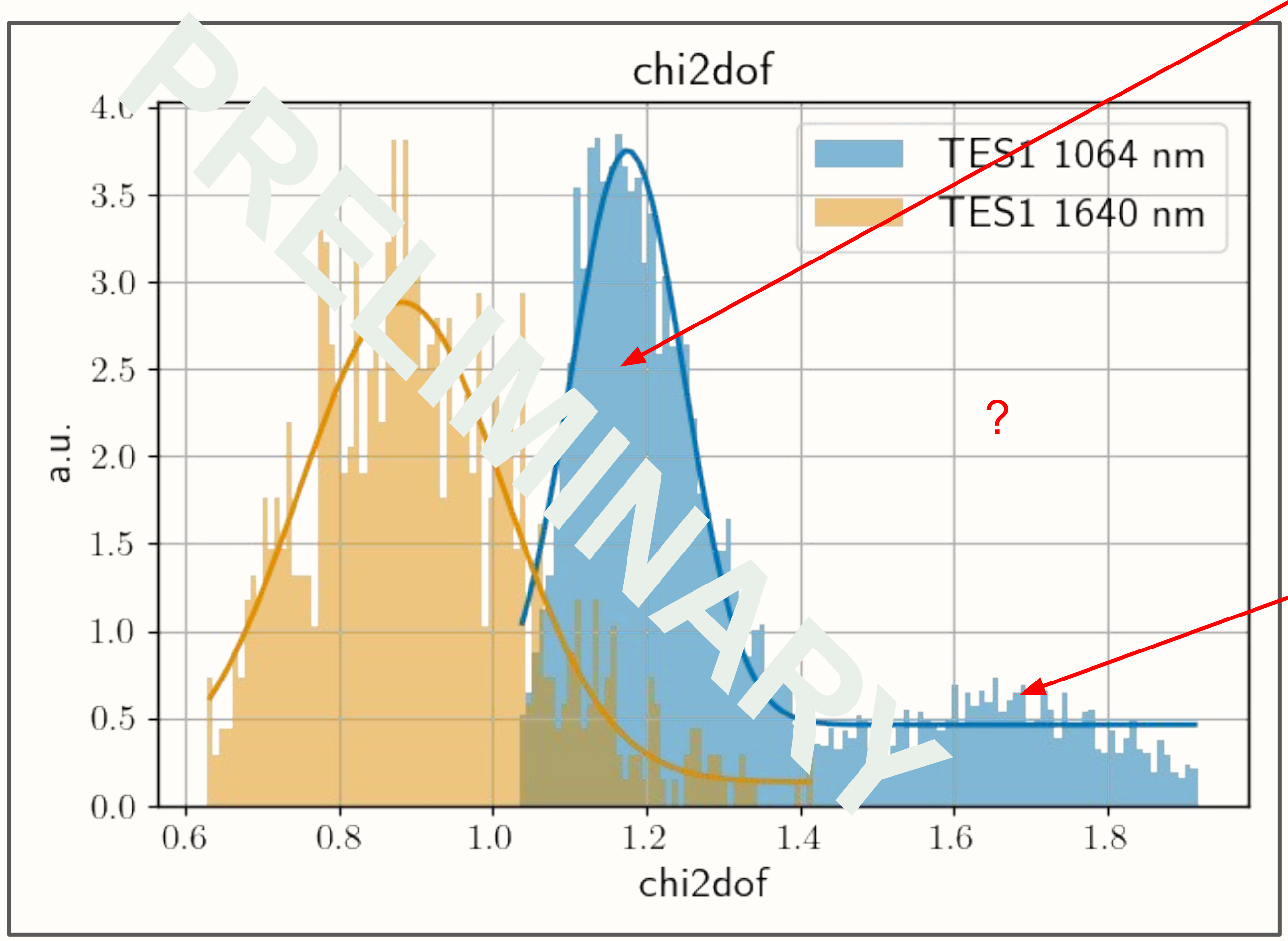


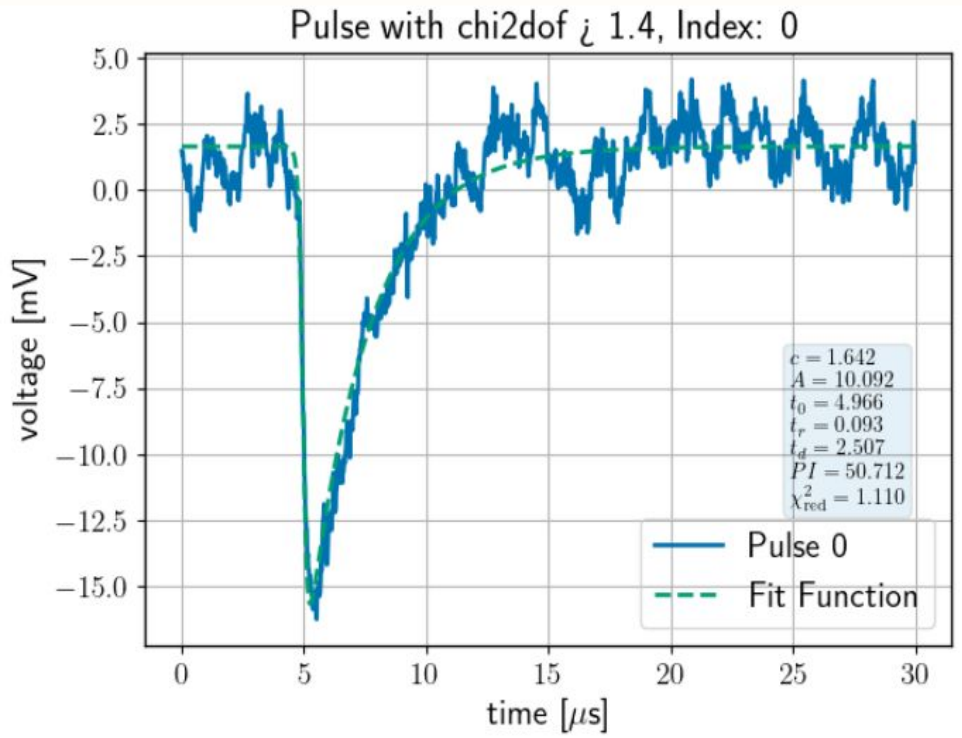


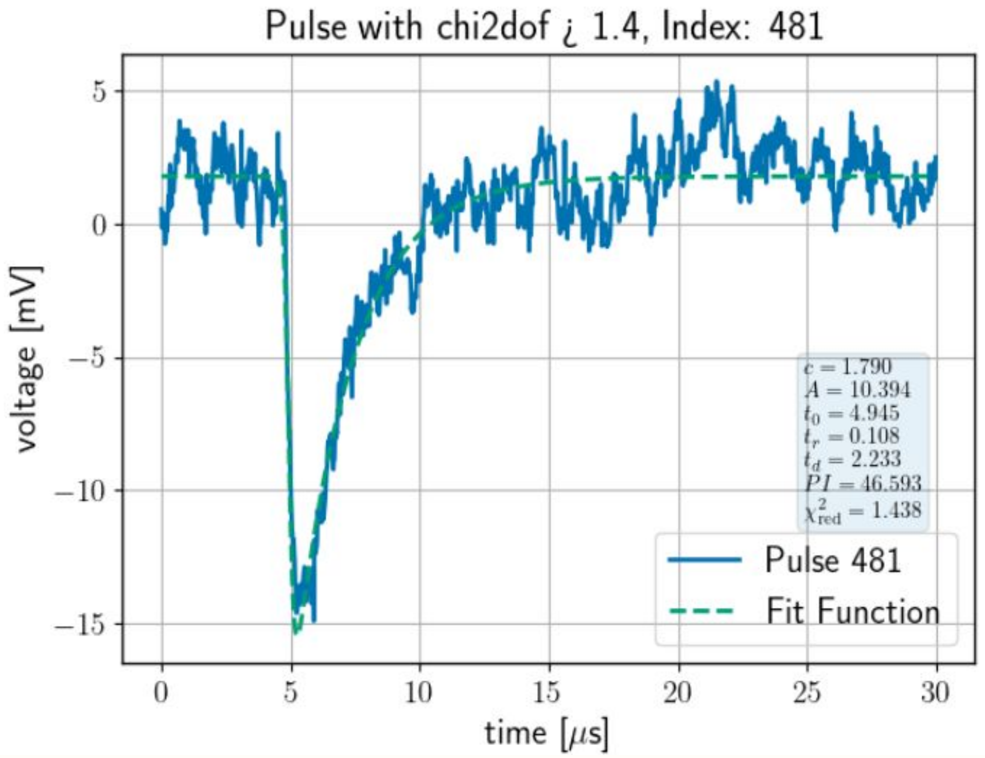
Fitting procedure

- Results should be taken with a grain of salt
- Fitting not optimized for this module - needs improvement

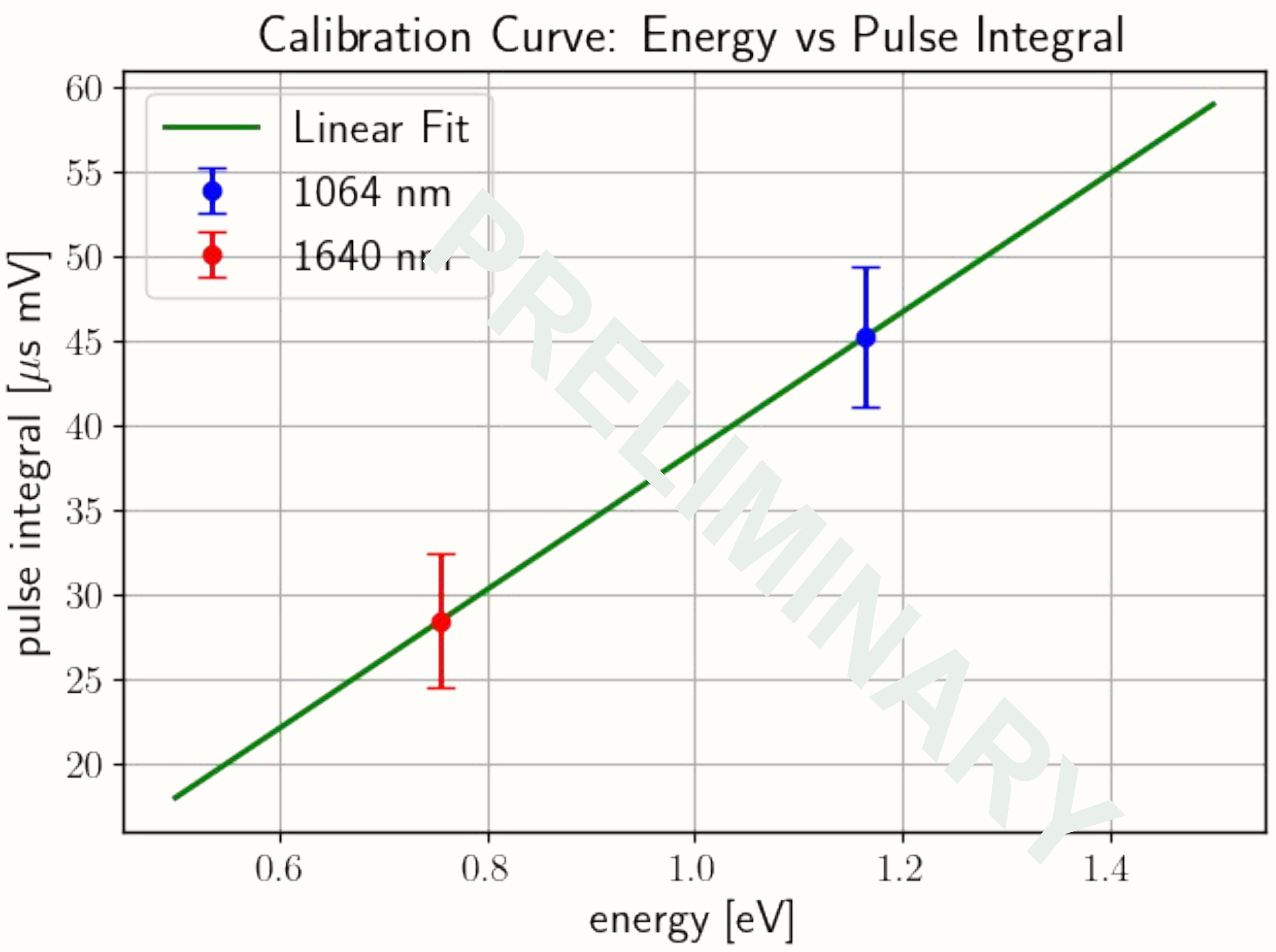
→ will improve cutting acceptance and enable tighter cuts

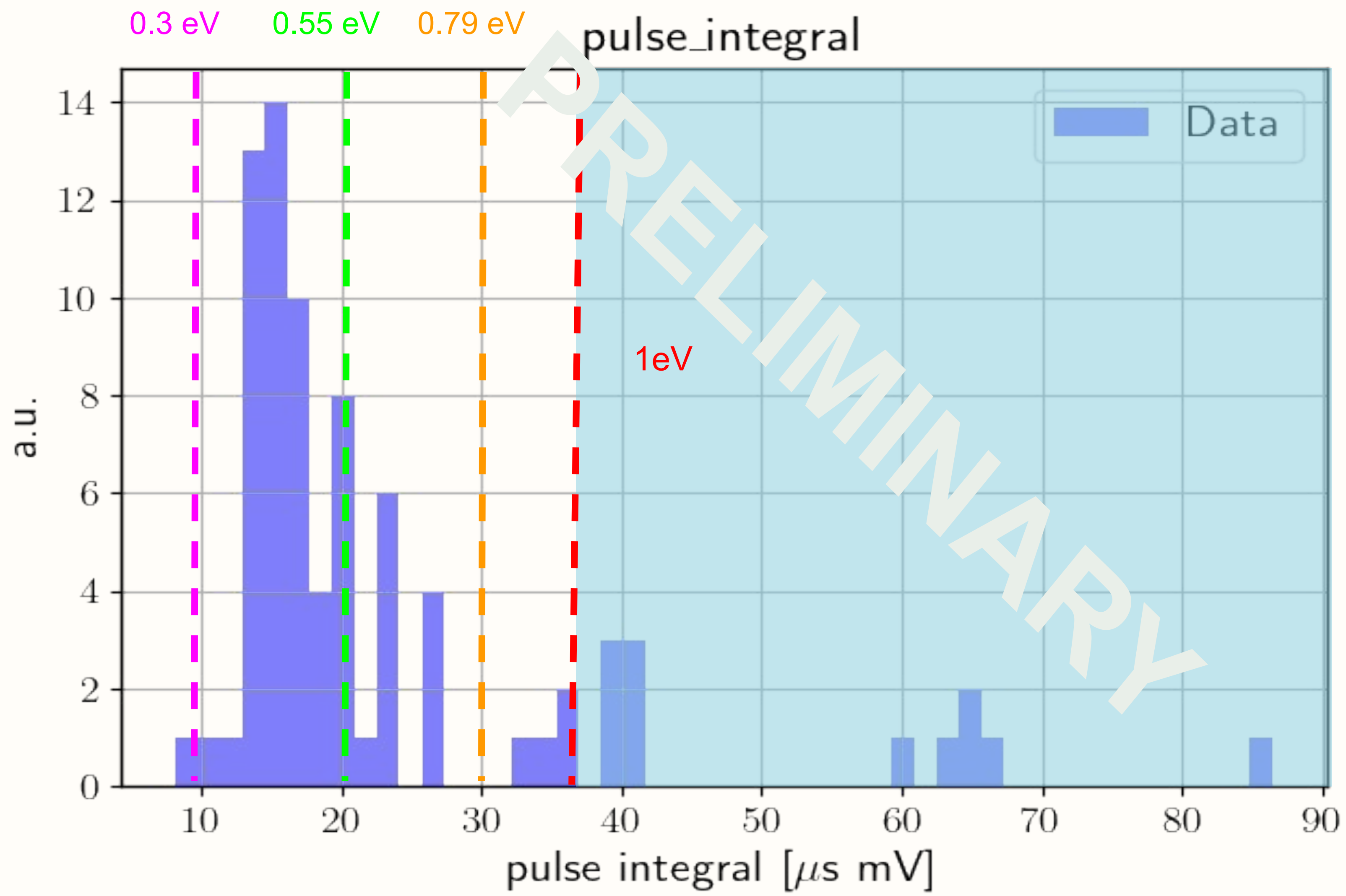




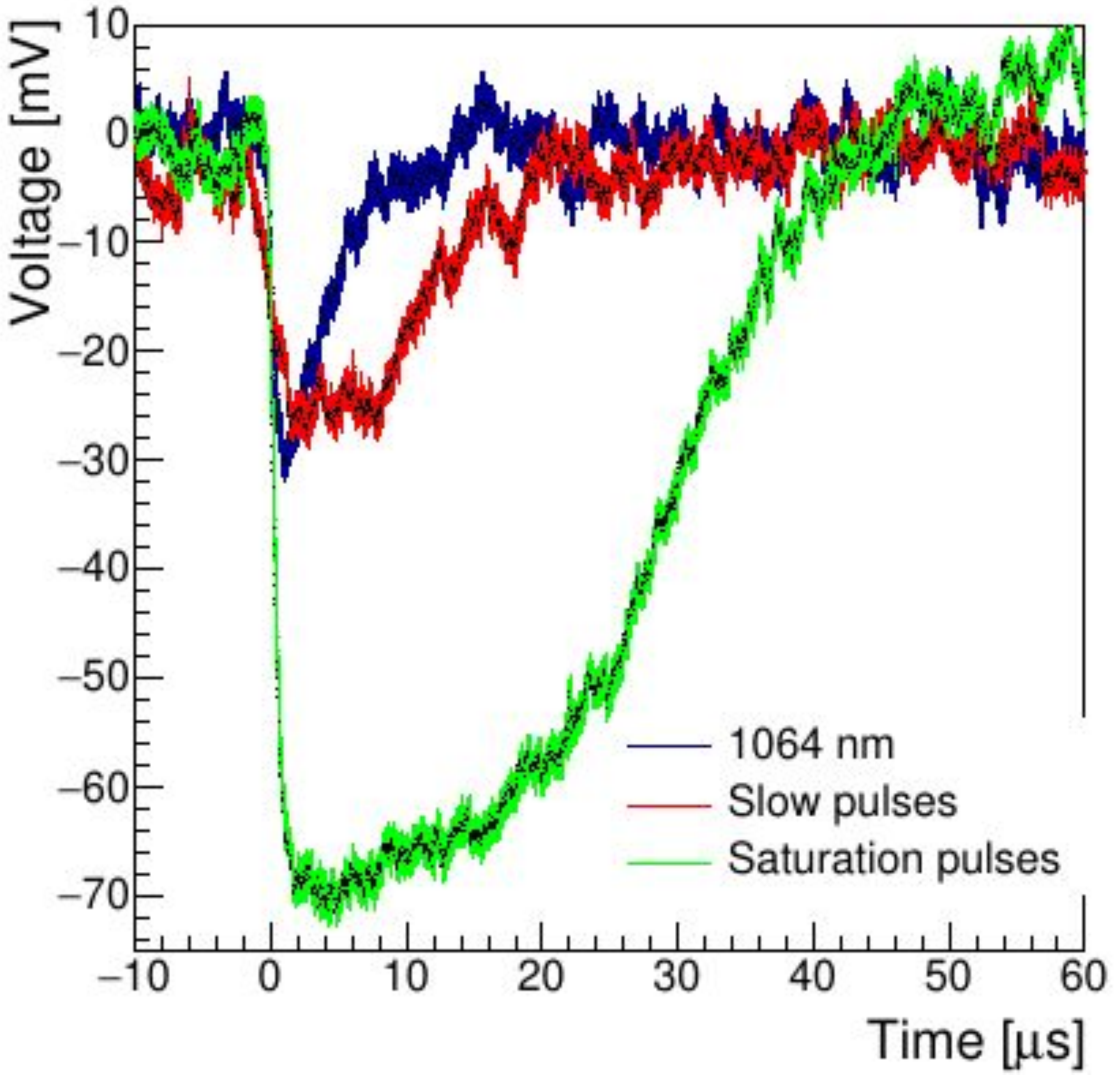


Energy calibration → surviving pulses

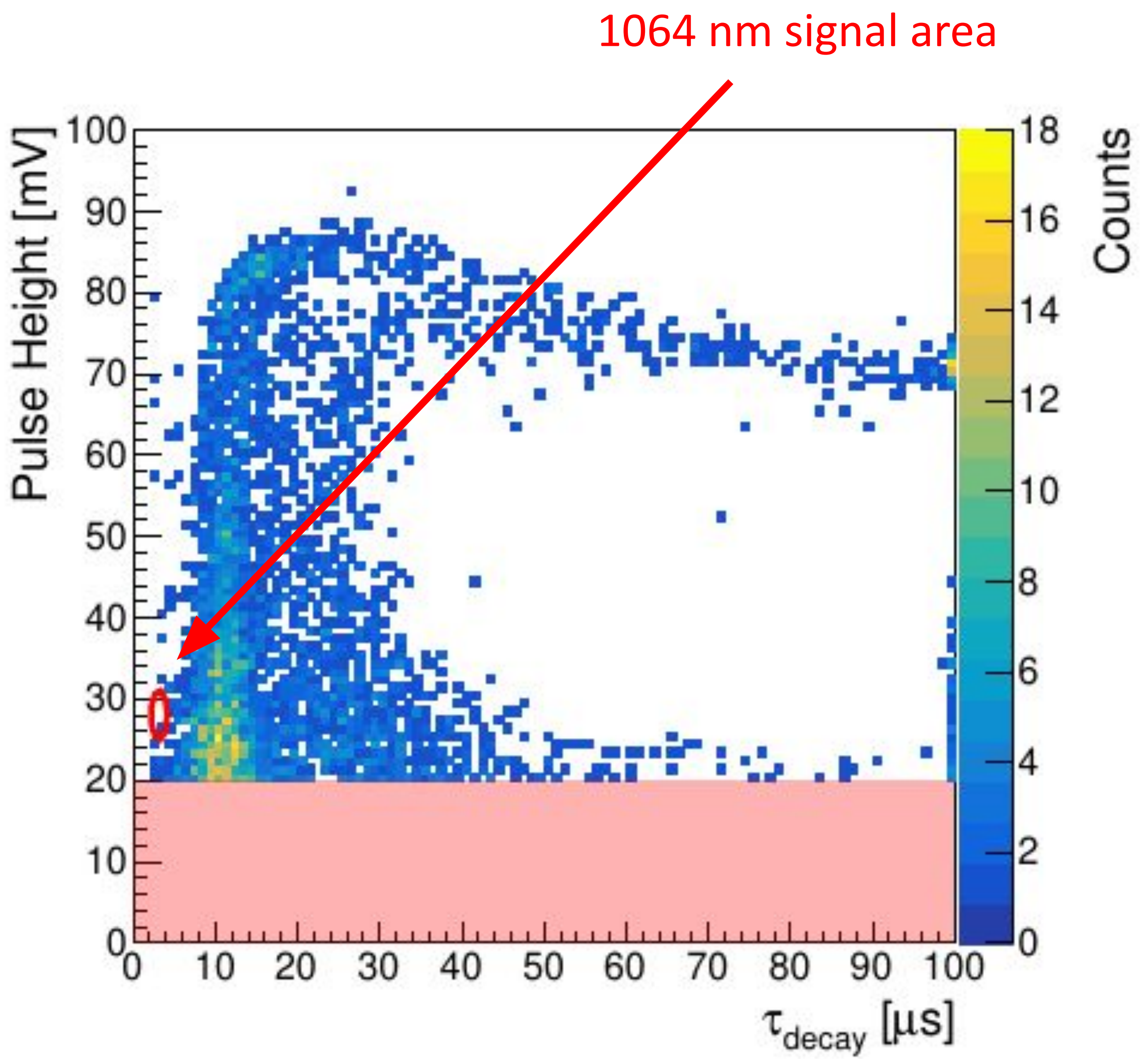




Intrinsic TES Backgrounds



Example pulses for intrinsic background

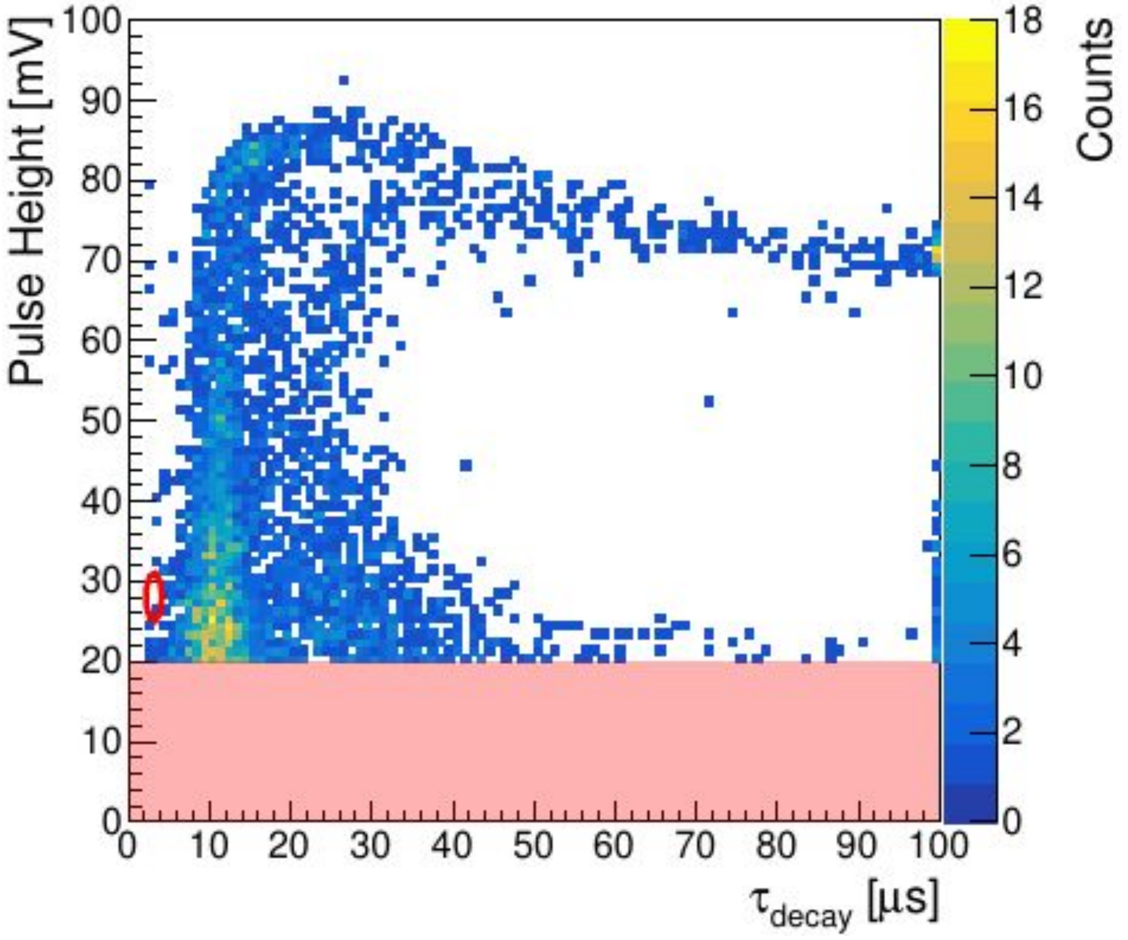


pulse-height distribution of intrinsic background pulses

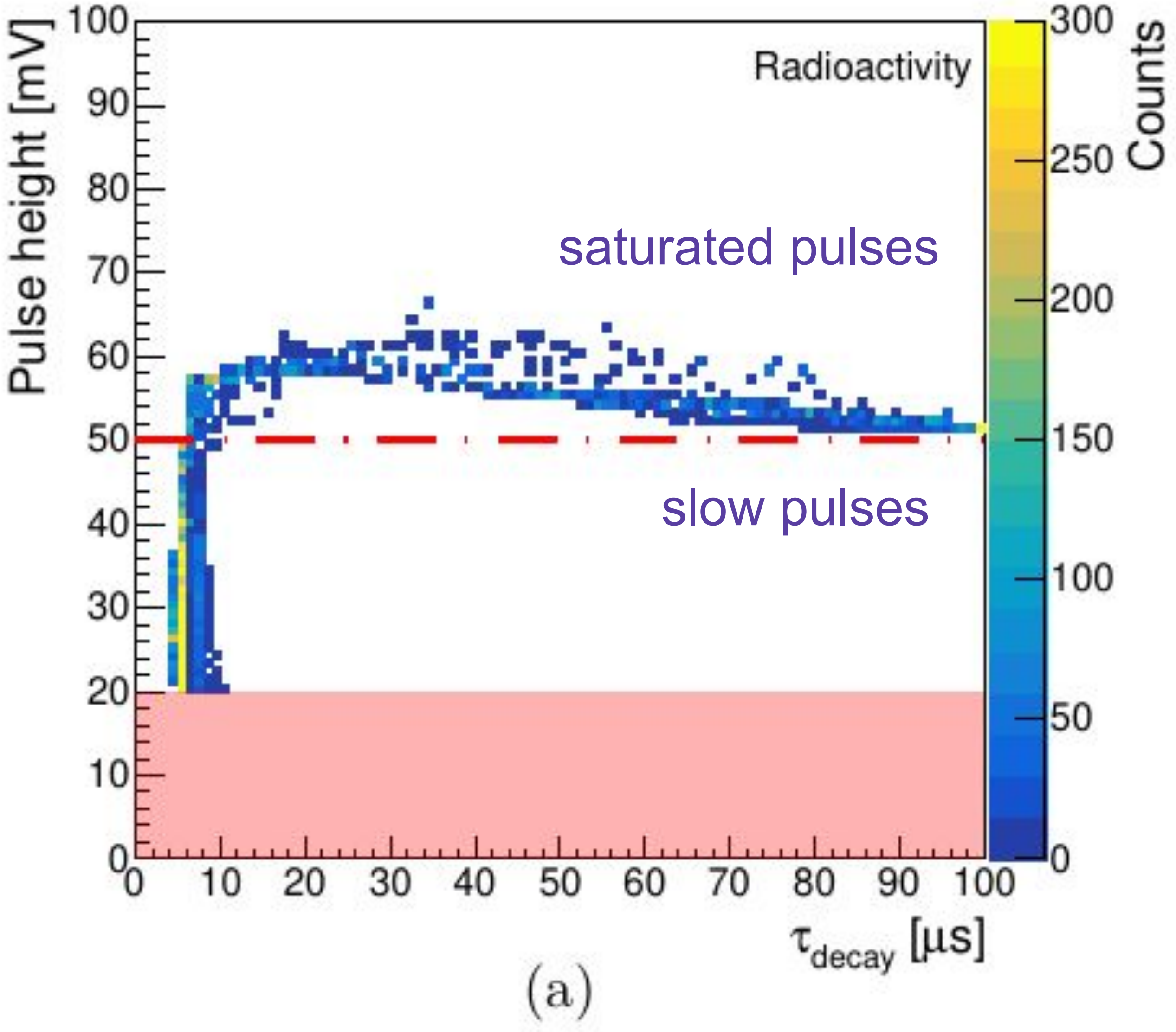
Studies by Jose A. Ruberia Gimeno

Studies by Jose A. Ruberia Gimeno

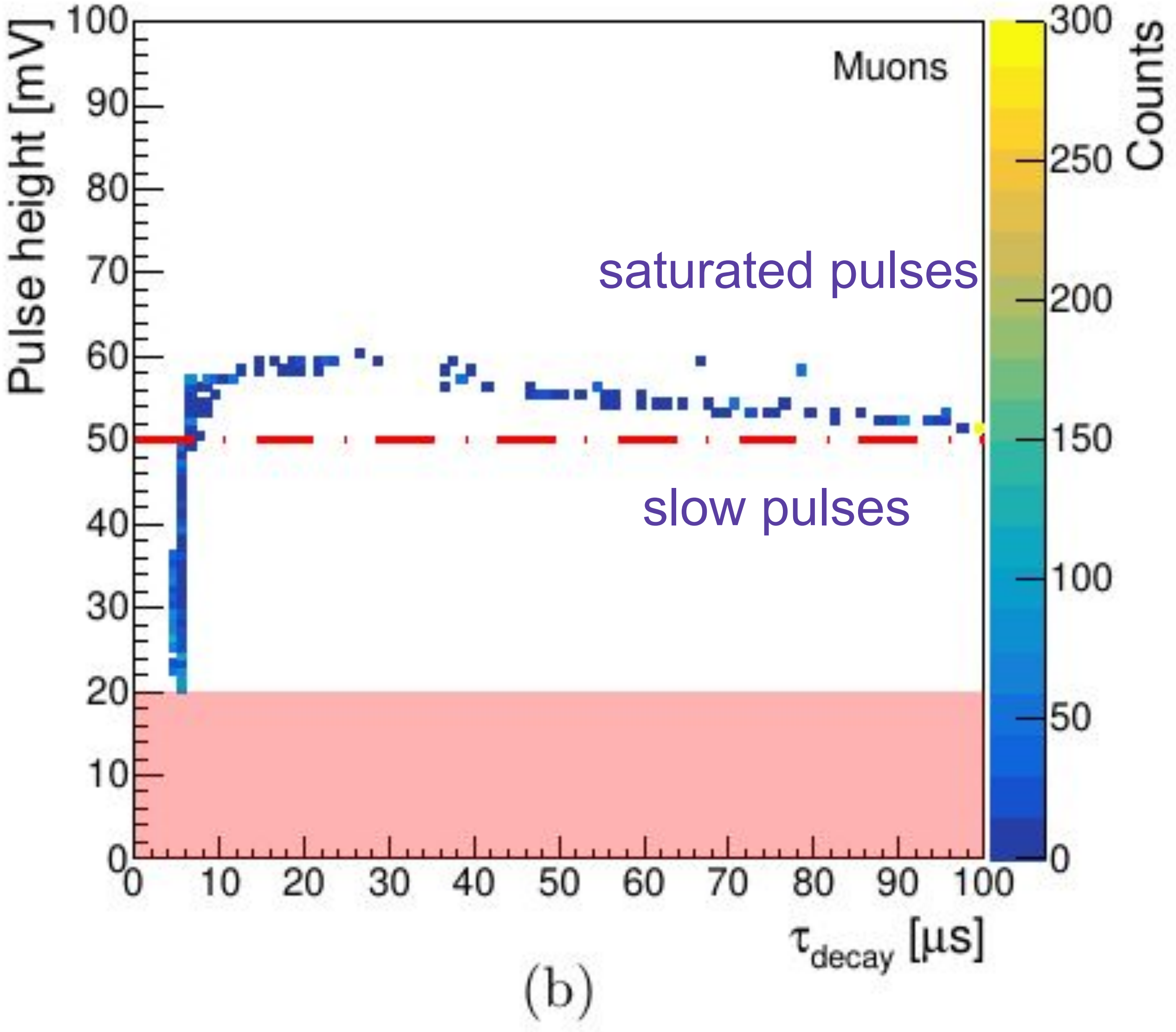
Intrinsic TES Backgrounds



intrinsic background measurement



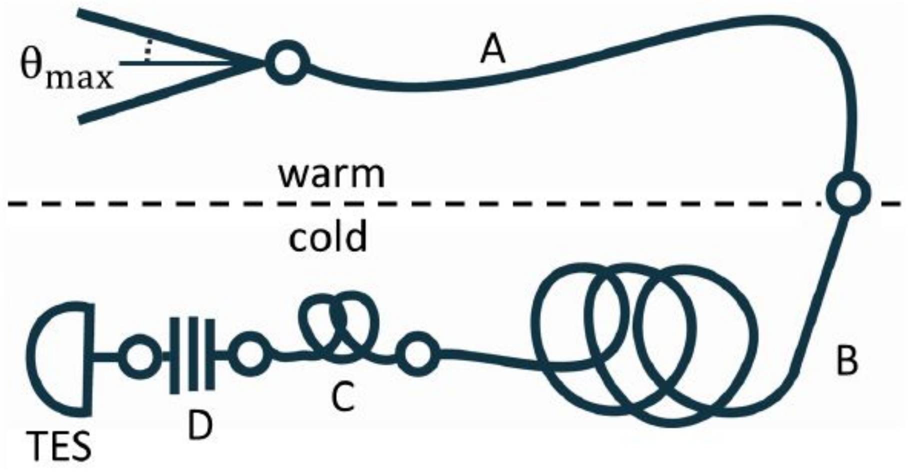
simulation of radioactivity (Zr in fiber sleeve)



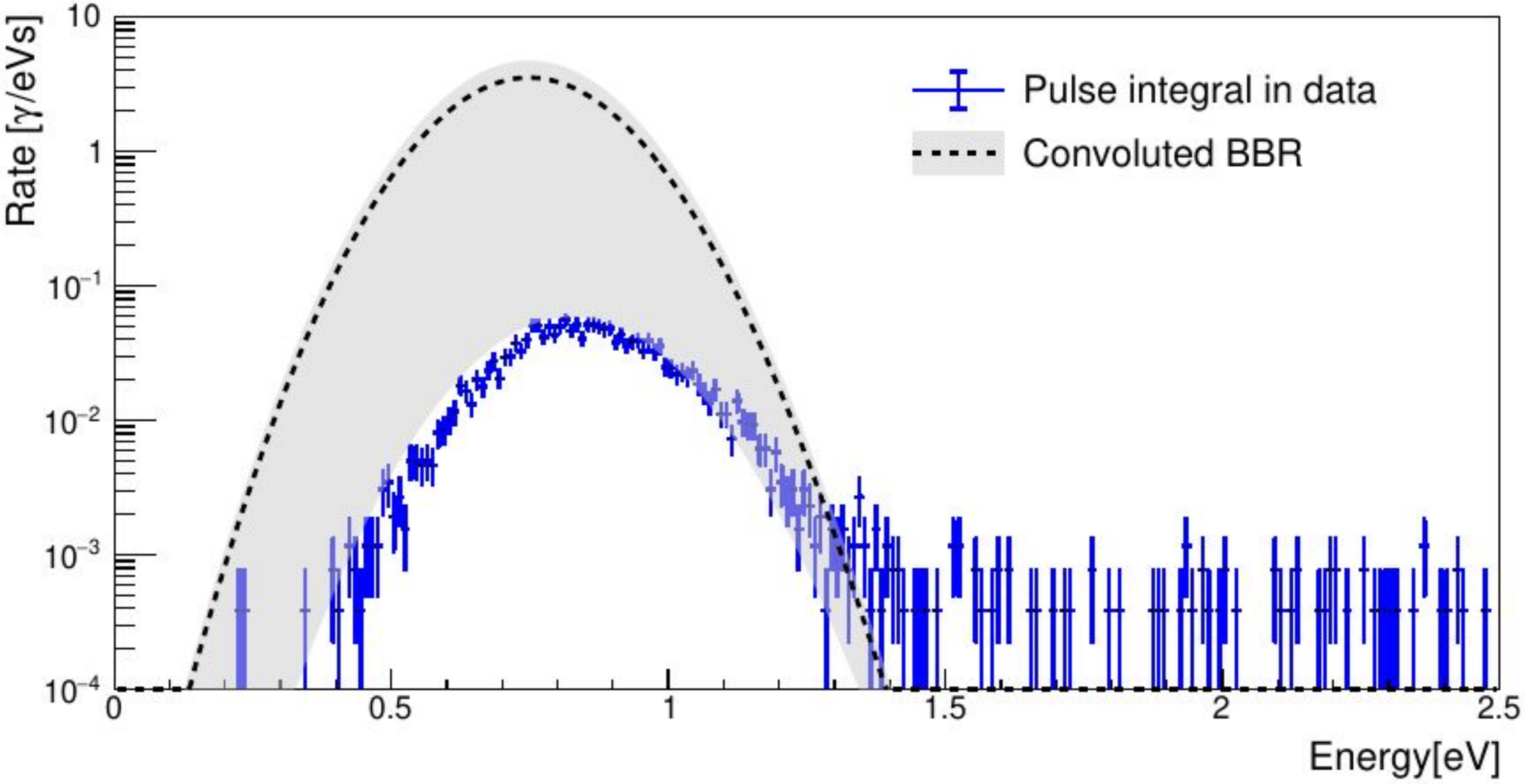
simulation of cosmic muon contribution

Studies by Jose A. Ruberia Gimeno

Extrinsic TES Backgrounds

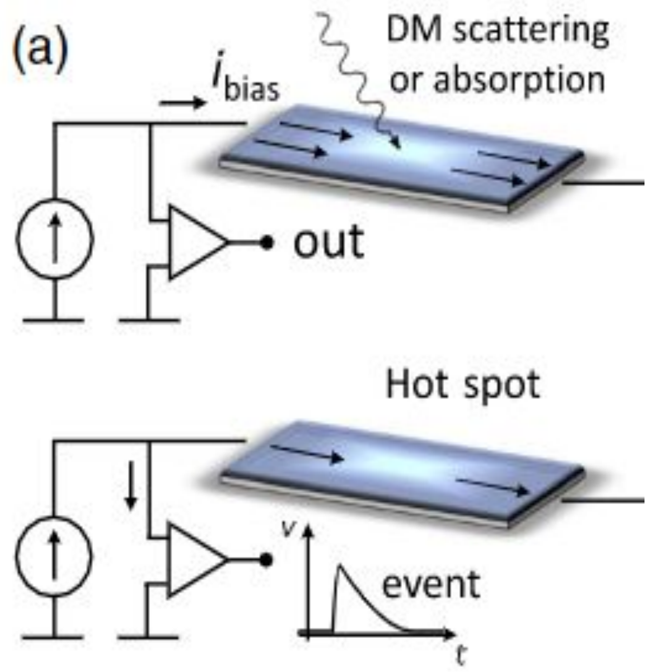


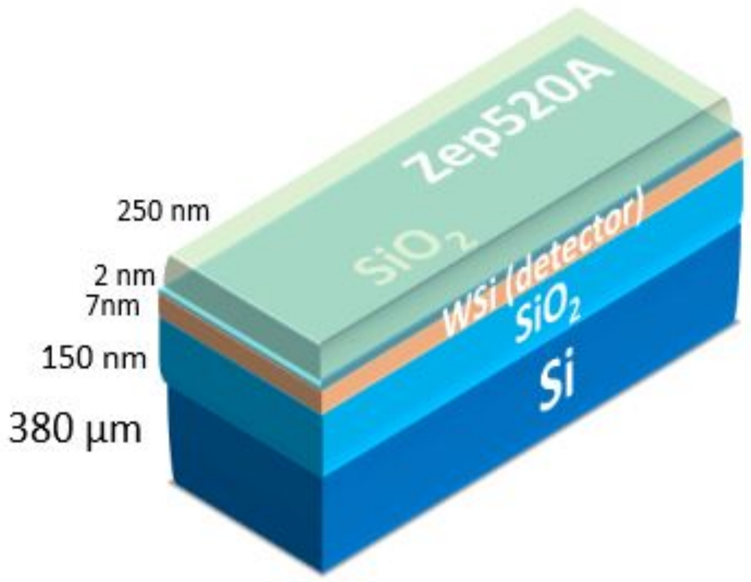
Simulation of black body background contribution considering fiber curling and other components influencing transmission

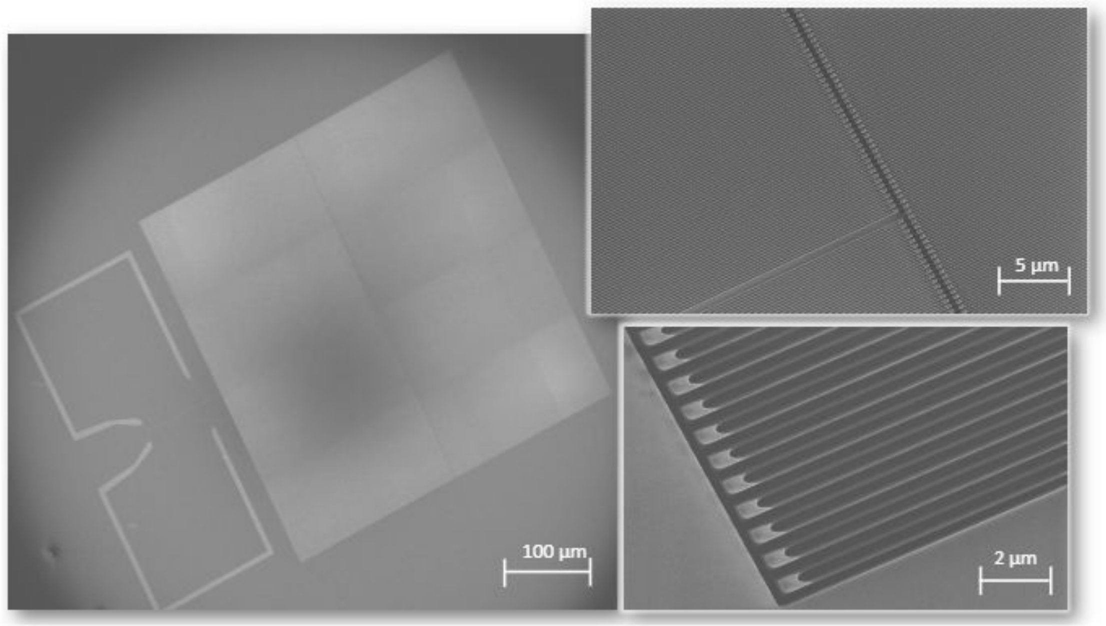


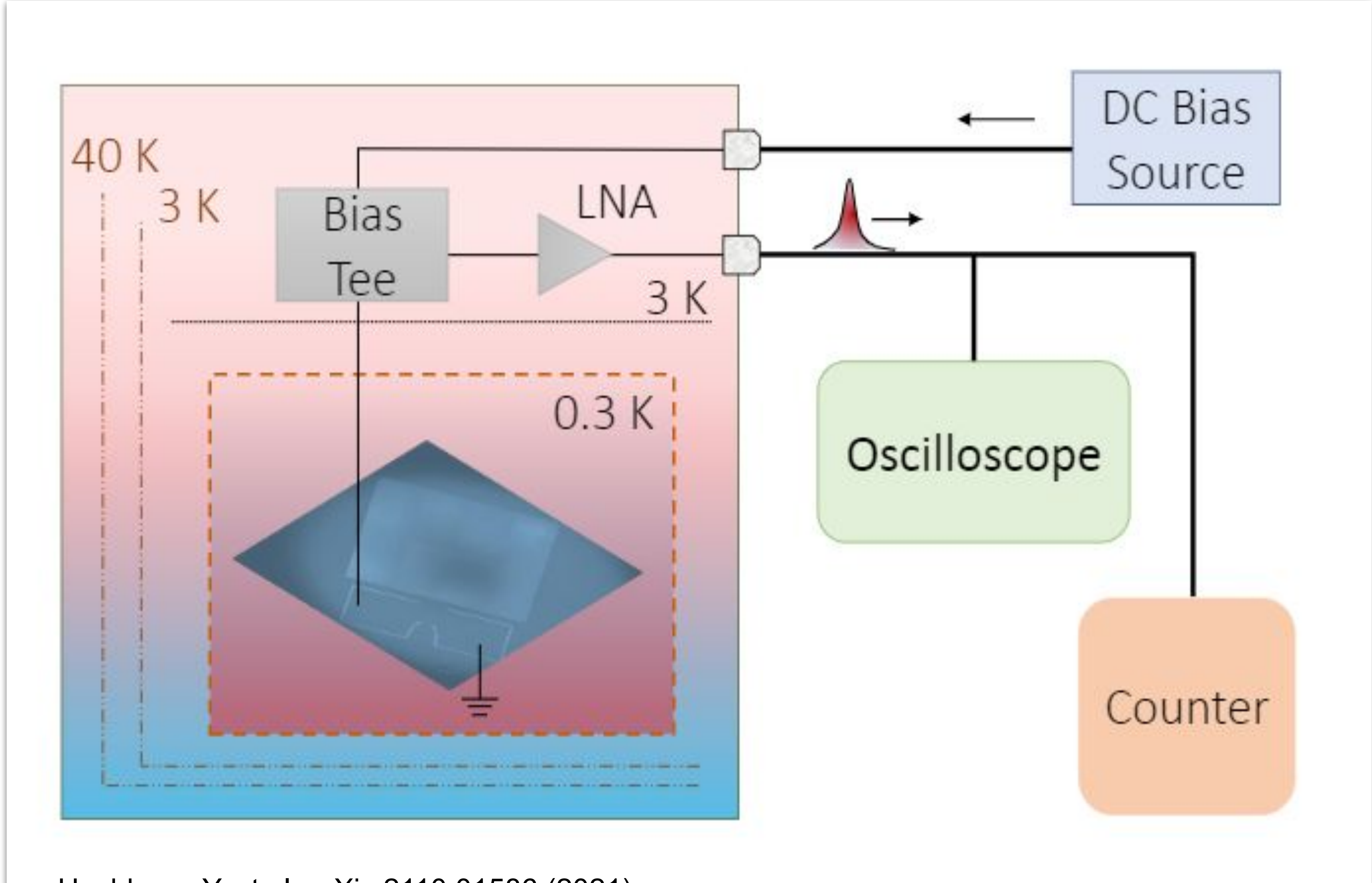
Studies by Jose A. Ruberia Gimeno

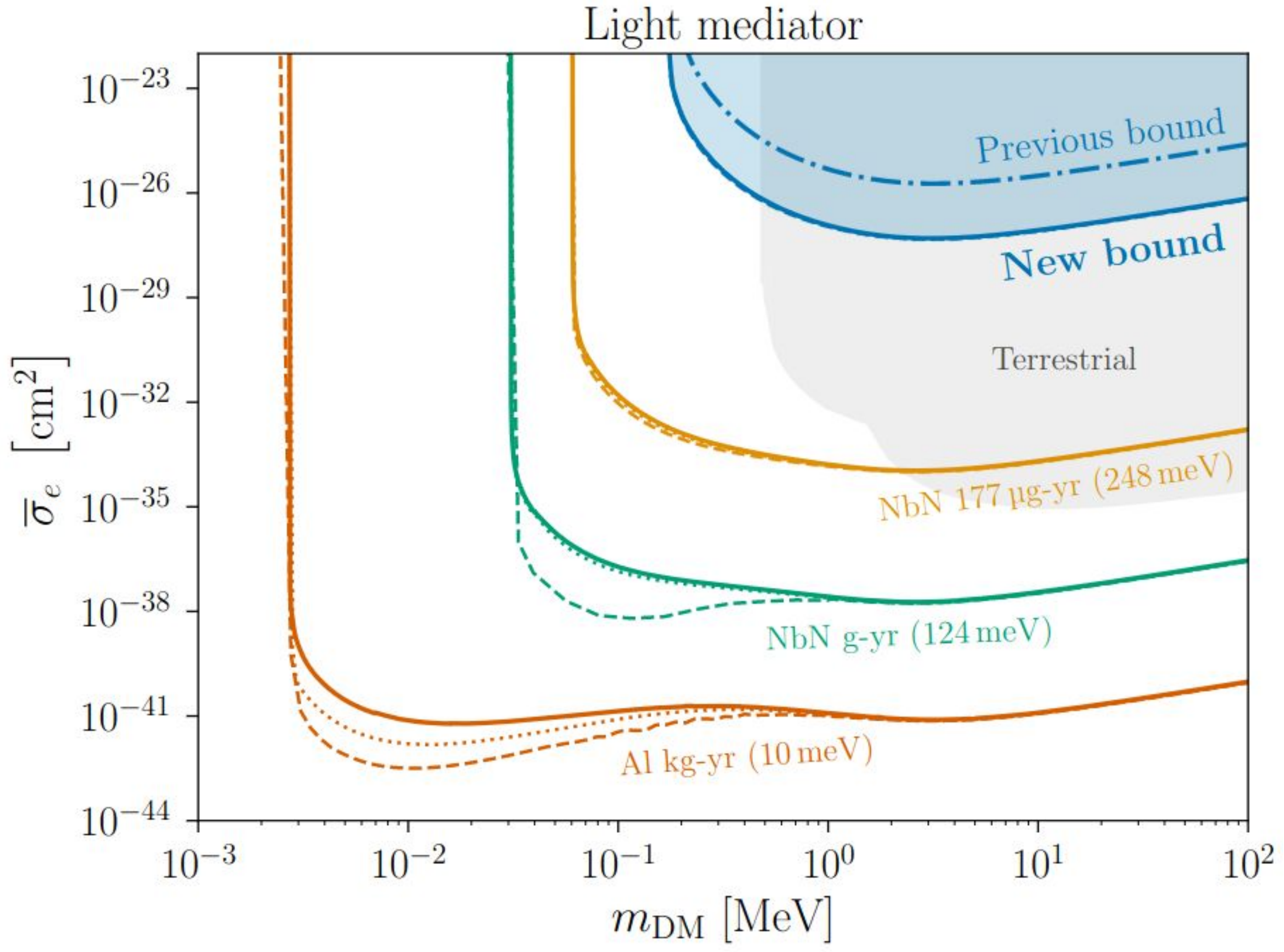
SNSPDs







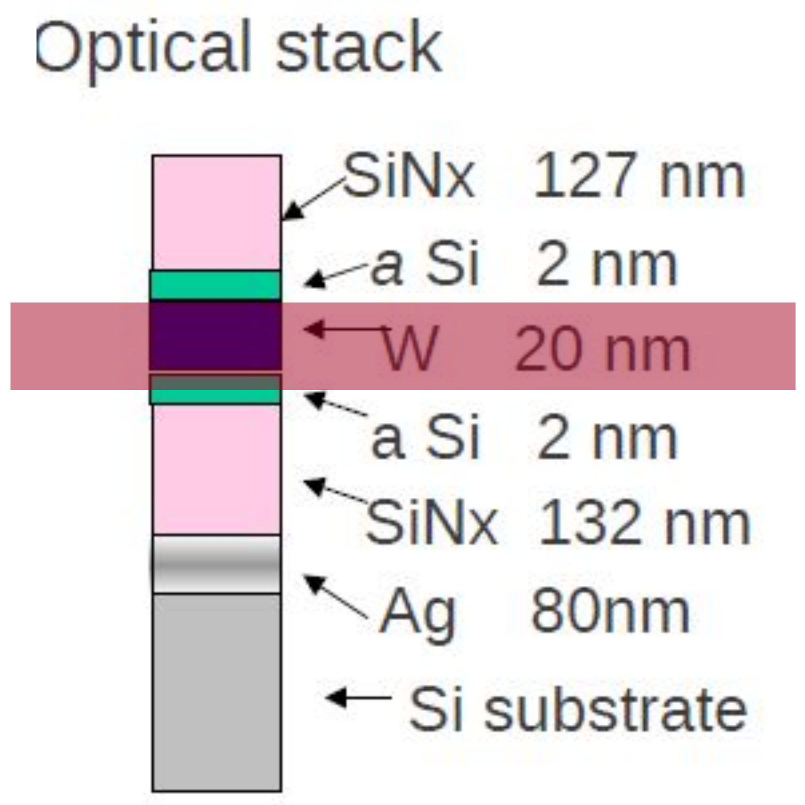




Hochberg, Y. et al. arXiv:2110.01586 (2021)

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

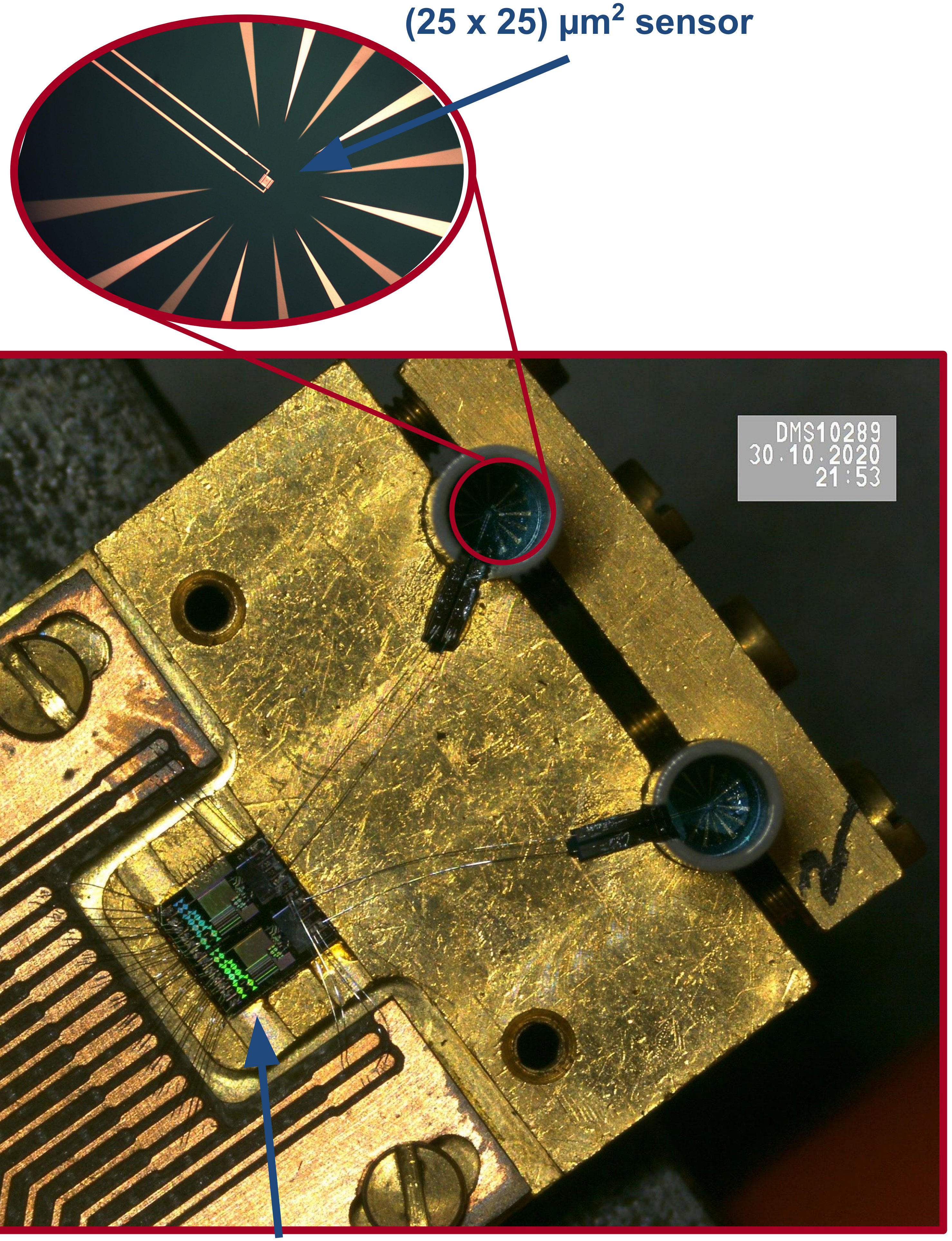
TES Details



A. Lita, NIST

Sensitive tungsten mass

(25 x 25) µm^2 sensor



SQUID chips

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

DDM viability simulations

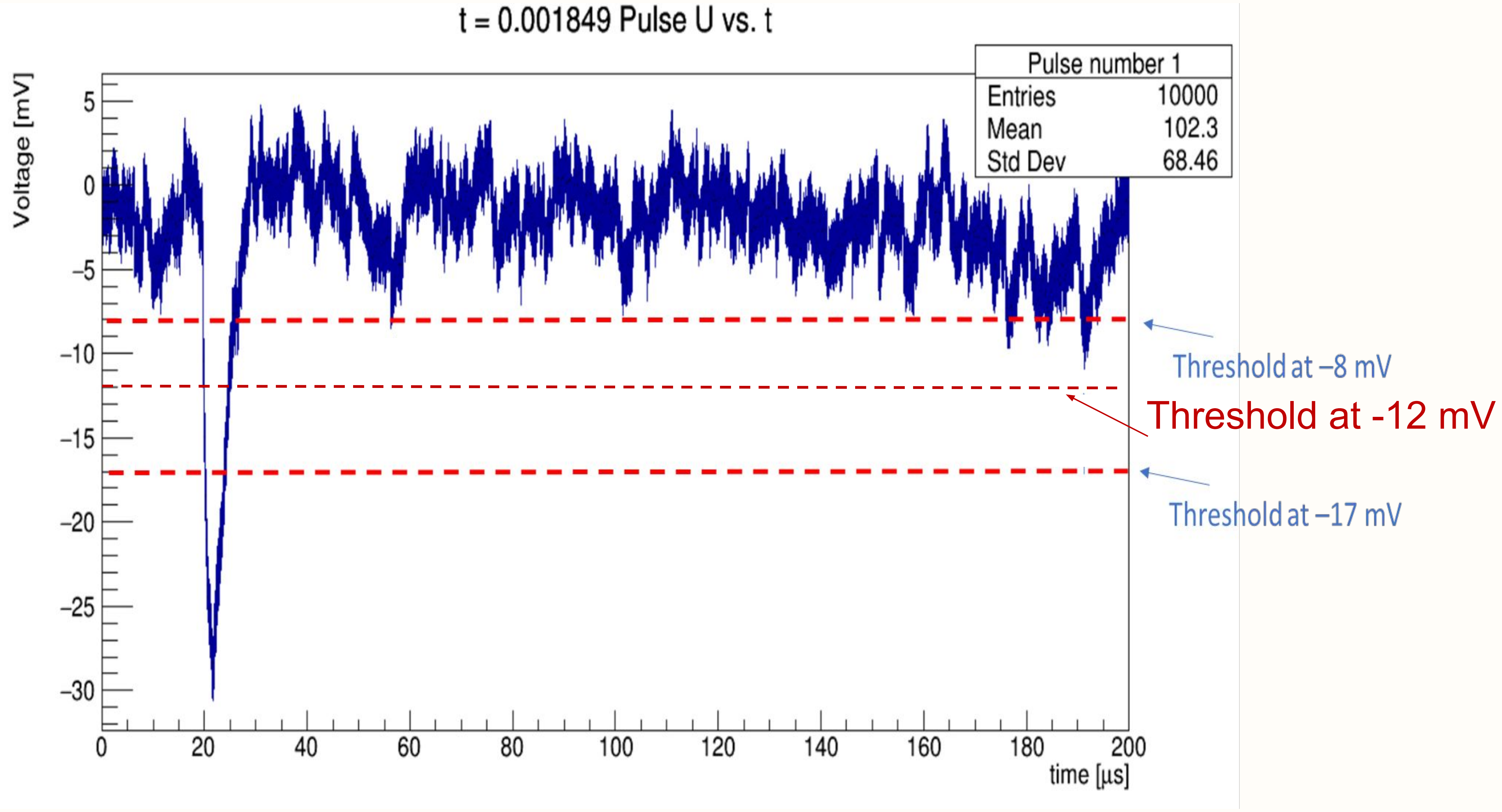
test background rate for lower triggers after analysis:
- ~ 70 min noise-only simulation
- Applying cuts optimized for 1.165eV and **0.583eV**

Noise-only simulations

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

after analysis & cuts

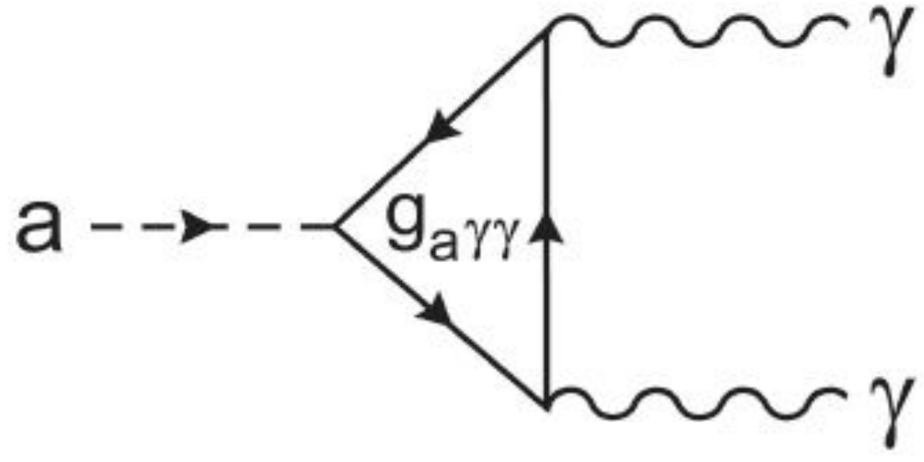
Cuts based on	Trigger Rate for -12 mV threshold
1.165 eV	< 0.0007 Hz
0.583 eV	< 0.0007 Hz



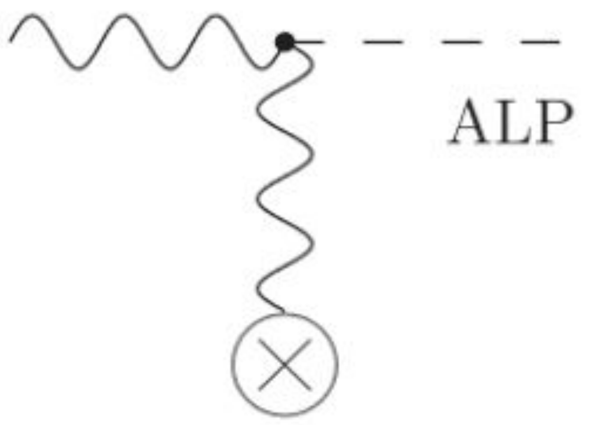
No noise passing analysis & cuts with ~56% acceptance of 0.583eV pulses
Promising for sub-MeV direct DM searches!

ALPS II - Any Light Particle Search

- SM-coupling to two photons

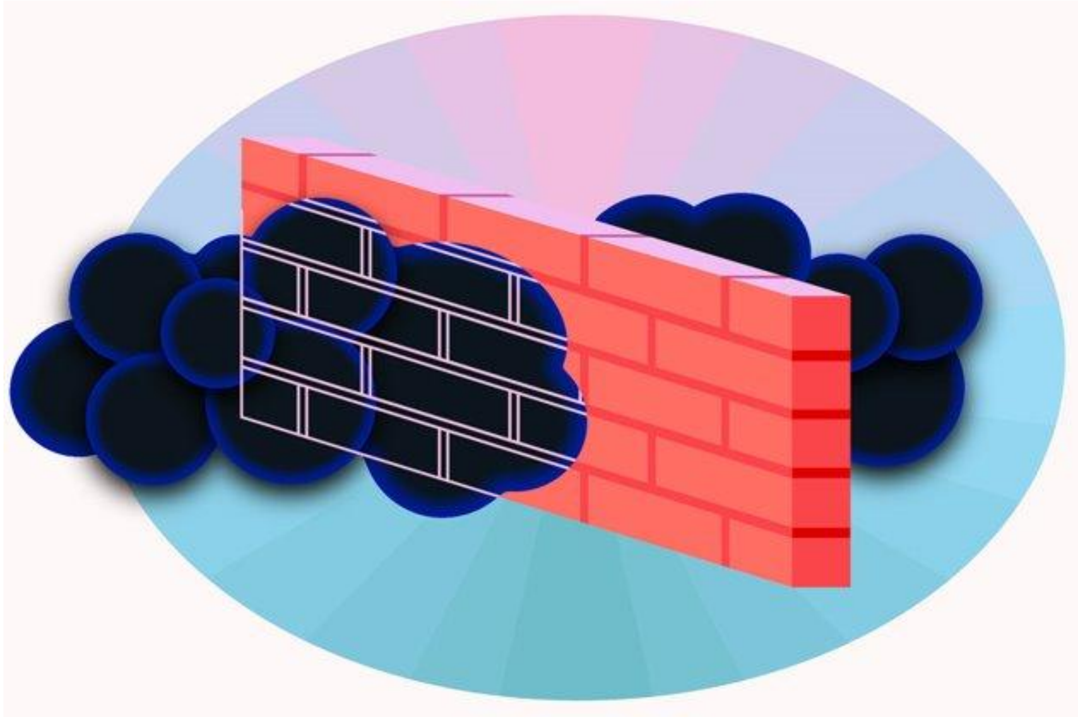


- Detection via Primakoff-like Sikivie effect
- Possible ALP **production** by photon-ALP – oscillation in the presence of strong magnetic fields



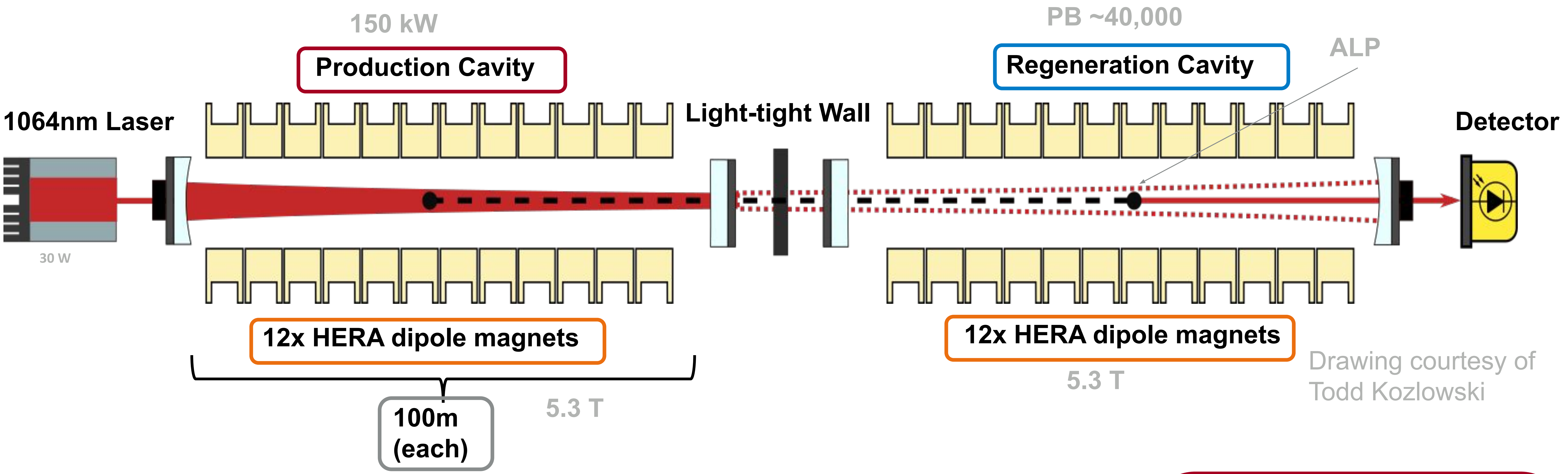
K. Ehret et.al., NIMA 612(1)83-960 (2009)

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



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

ALPS II - 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:
(for $g_{a\gamma\gamma} = 2\cdot 10^{-11}\,\mathrm{GeV}^{-1}$)

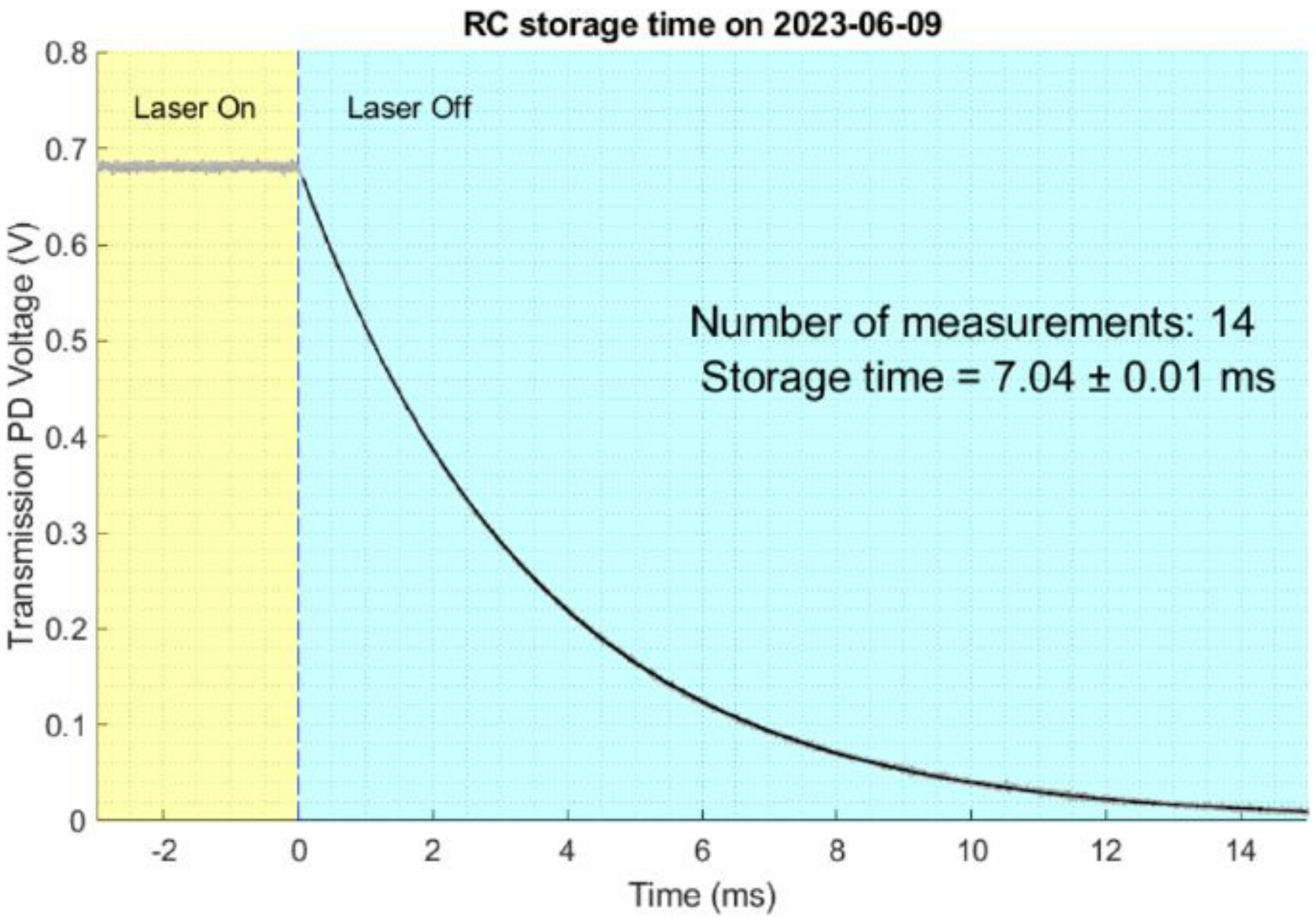
$$\dot{N}_\gamma \approx 2.8\cdot 10^{-5}\frac{\gamma}{\mathrm{s}} \approx 1\frac{\gamma}{\mathrm{day}}$$

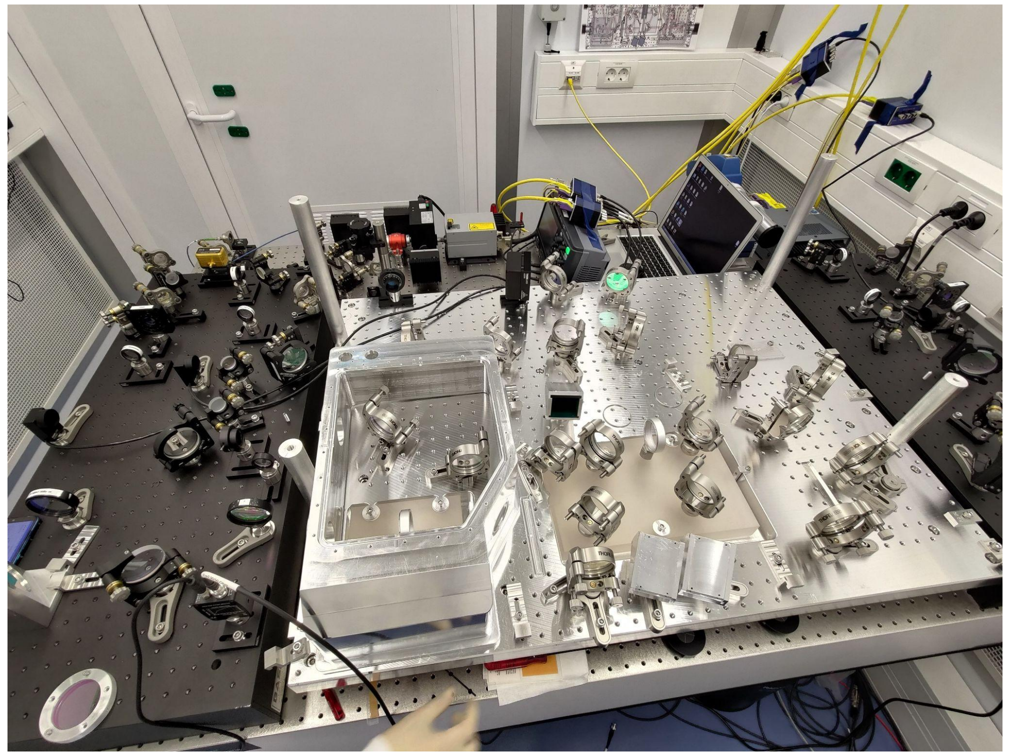
Single-photon detection requirements for ALPS II:

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

ALPS II - World leading precision interferometry

- Longest storage time Fabry Perot cavity ever!
- Length: 124.6m, FSR: 1.22 MHz
- Storage time: **7.04 ms**

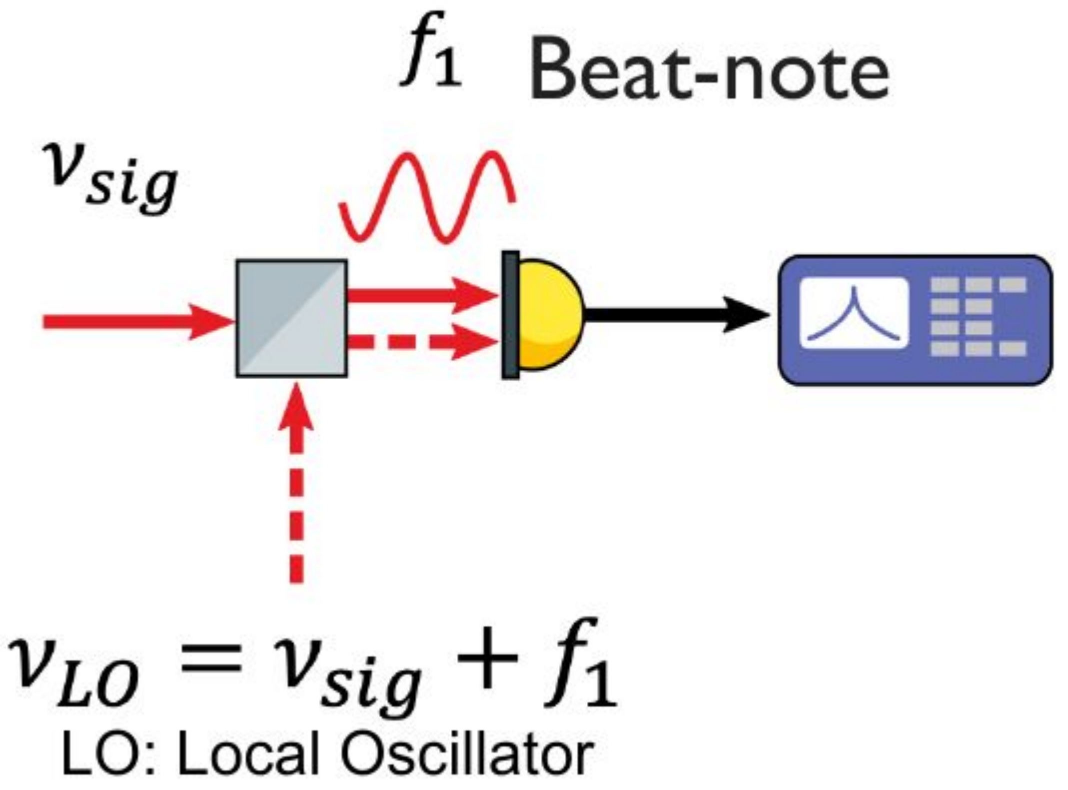


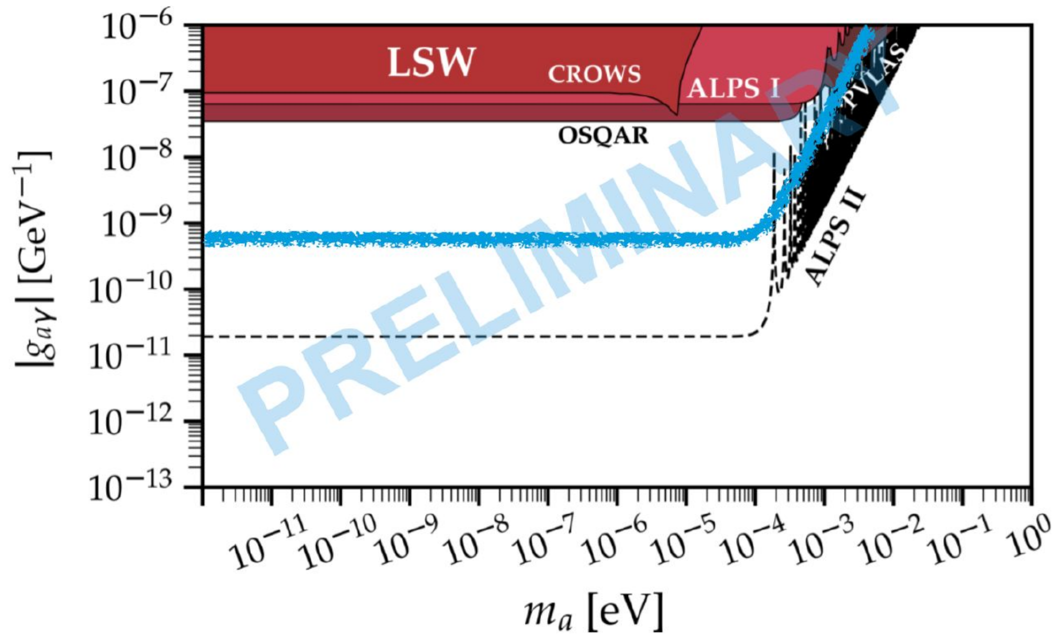


Leading precision interferometry!

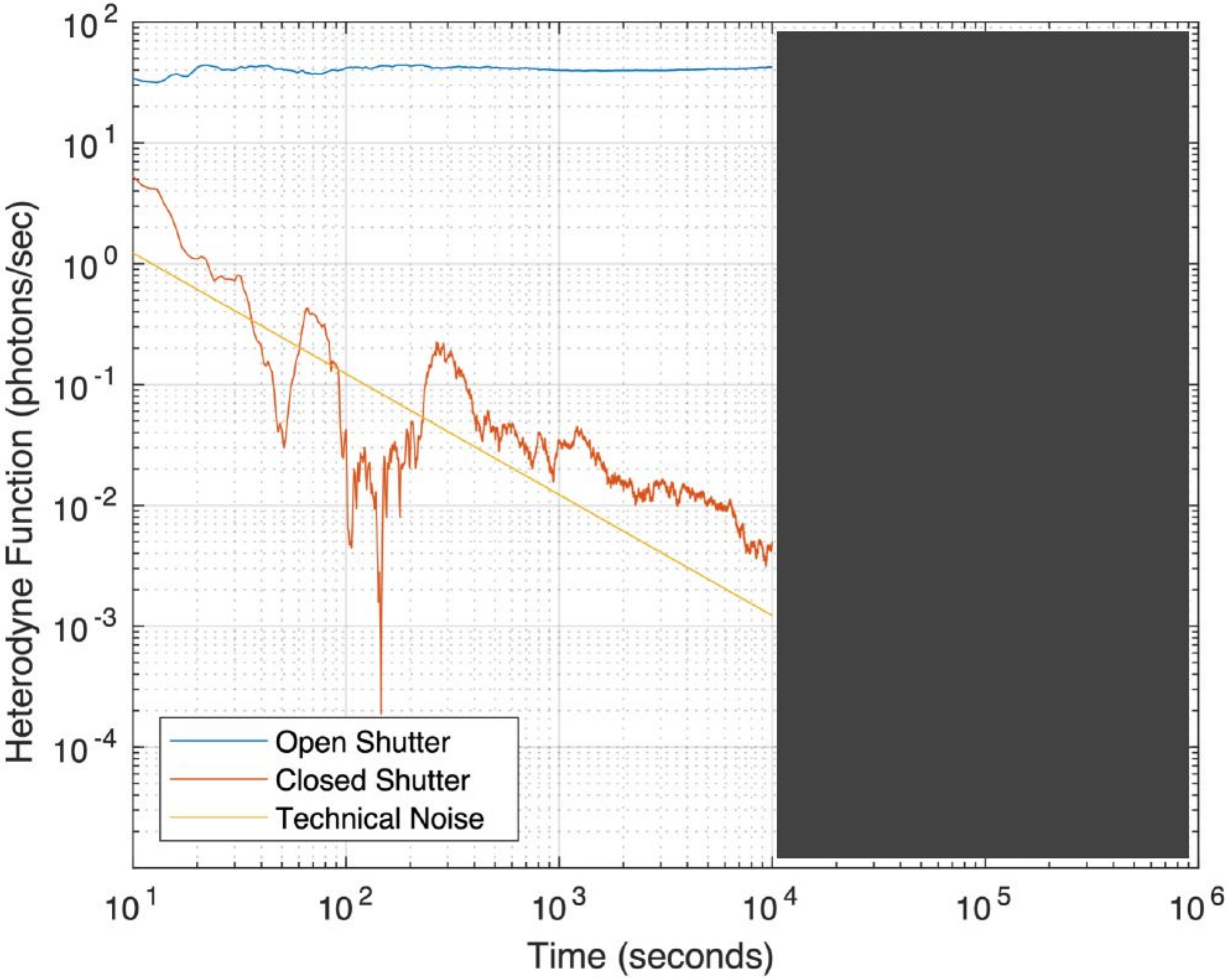
Slides adapted from Isabella Oceano

ALPS II - Heterodyne detection - first Results (Production Cavity only)



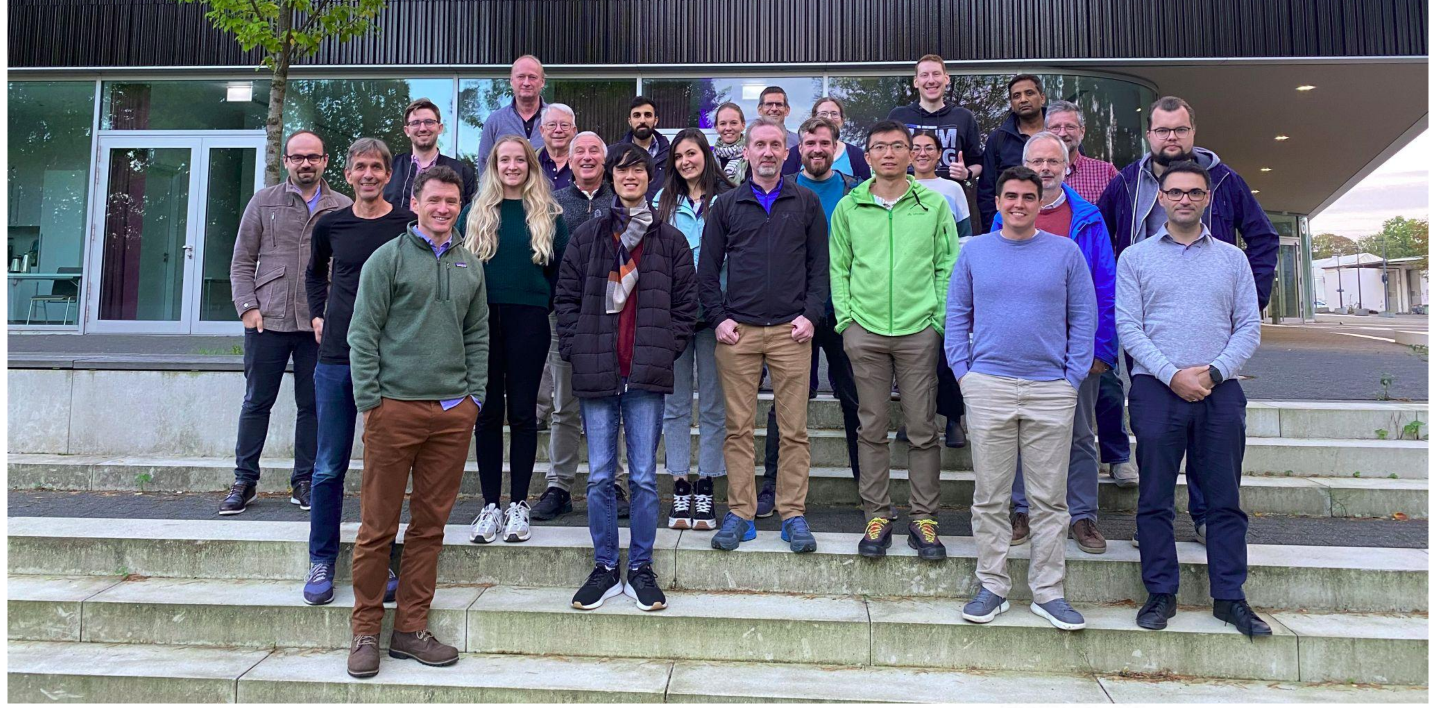


Scalar search



Slides adapted from Isabella Oceano

ALPS II - Timeline



2023 May
- Engineering run
  - ~150k s integration time
- Fix phase problems
- Improving the SNR
  - ~2.5 factor
- Automatise the locking procedure

2024 January
- Scalar search
  - ~800k s integration time

April
- Pseudoscalar search
  - 1M s integration time

July …
- Installation of the production cavity

2025
- Pseudoscalar search

2026 …
- Design sensitivity

Slides adapted from Isabella Oceano