A TES for ALPS II
Status and Prospects

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for the TES team in the ALPS II collaboration

EPS-HEP2023
August 21st

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

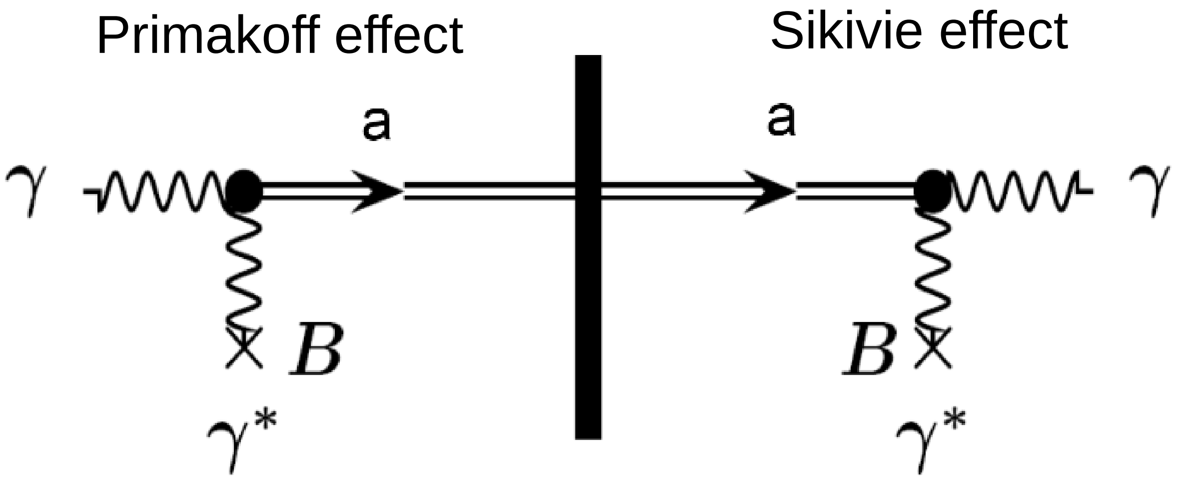
*With the support of NIST and PTB

Outline

- Axions, ALPs and Any Light Particle Search II (ALPS II)
- Transition Edge Sensor (TES)
  - Setup for characterization
  - Data analysis for background rejection
  - Efficiency measurement
- Summary and outlook

Axions and Axion-like particles (ALPs)

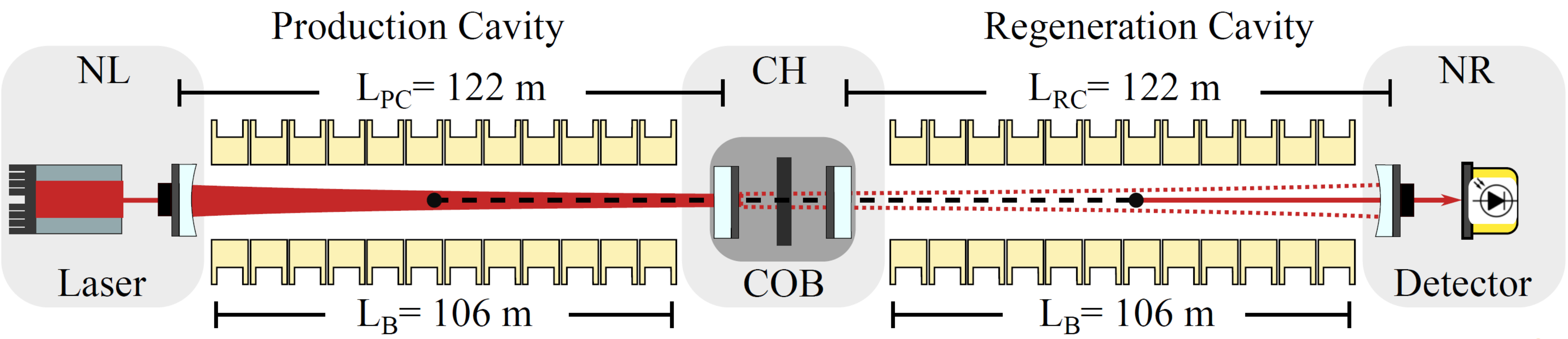
- Proposed as solution to strong CP problem
- Motivated by astrophysical observations:
  - Stellar evolution
  - TeV transparency
- Very weak interaction, good candidate for dark matter
- The main mechanism for detection of light weight axions is through its coupling to photons



Light Shining through a Wall (LSW)

Model independent approach, independent of dark matter paradigm

Any Light Particle Search II (ALPS II)



$\sim$40W
1064nm $\sim$ 1eV

$\sim 3 \cdot 10^{-24}$W
1064nm $\sim$ 1eV

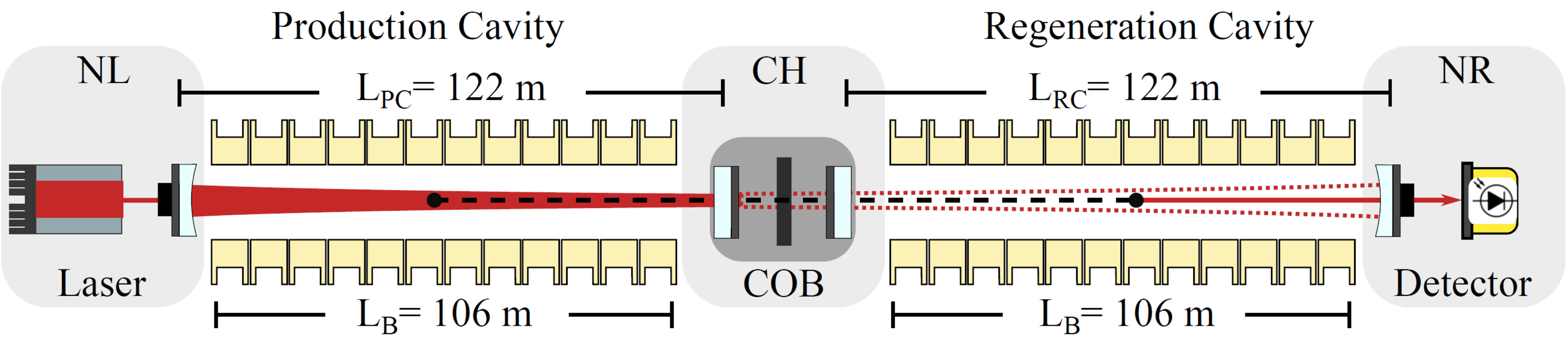
$$p_{\gamma \to a \to \gamma} = \frac{1}{16} \beta_{PC}\beta_{RC}\left(g_{a\gamma\gamma} B L_B\right)^4$$

$$p_{\gamma \to a \to \gamma} = 8 \cdot 10^{-26}$$

Enhancement by optical cavities

$2 \cdot 10^{-11}\mathrm{GeV}^{-1}$
From astrophysics

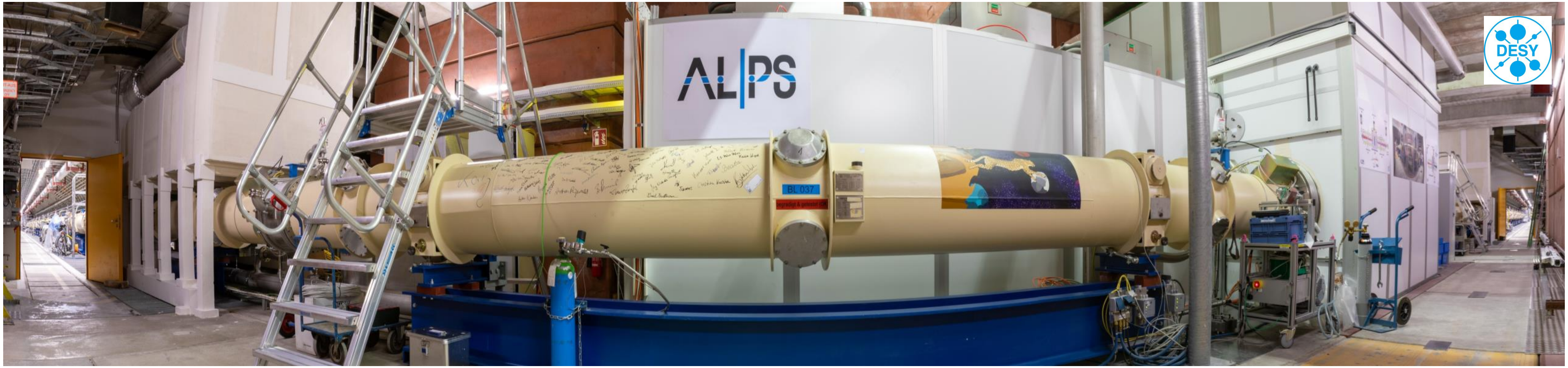
Any Light Particle Search II (ALPS II)



ALPS II might produce a rate in the order of 1 reconverted photon per day

Any Light Particle Search II (ALPS II)

Initial Science Run started on 23.05.2023



ALPS II might produce a rate in the order of 1 reconverted photon per day

Heterodyne scheme
Interferometry-based detection
Data taking ongoing!

Single Photon Detector
Alternative detection method
for confirmation

Thursday: T03 DM, Axion and ALP search with the ALPS II experiment at DESY • Isabella Oceano

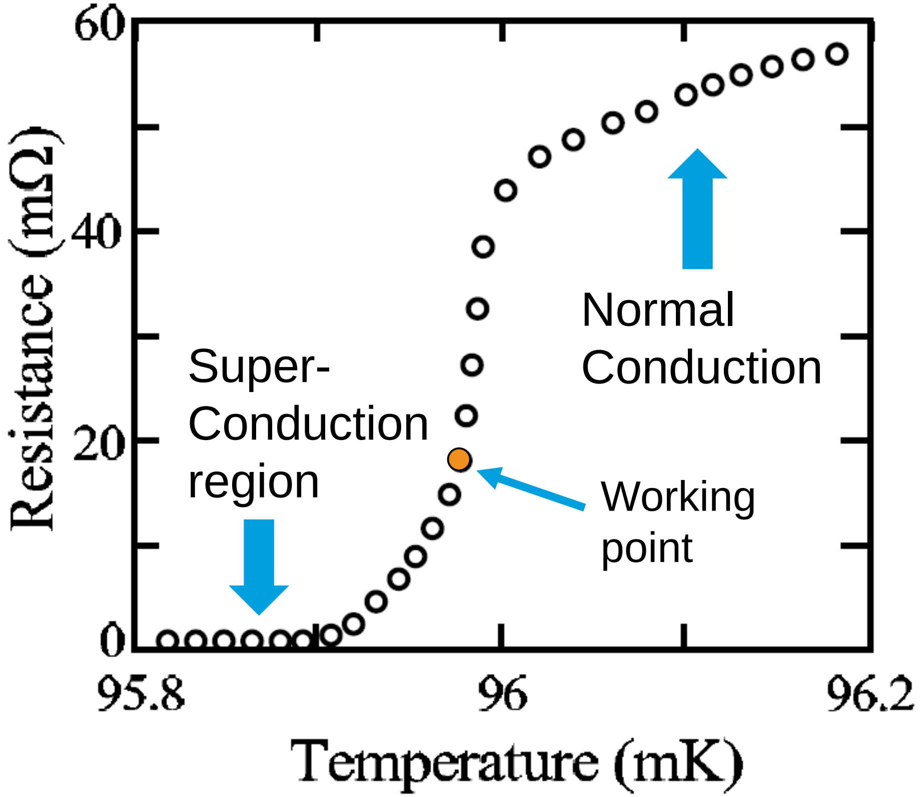
Single photon detector

Requirements for ALPS II:

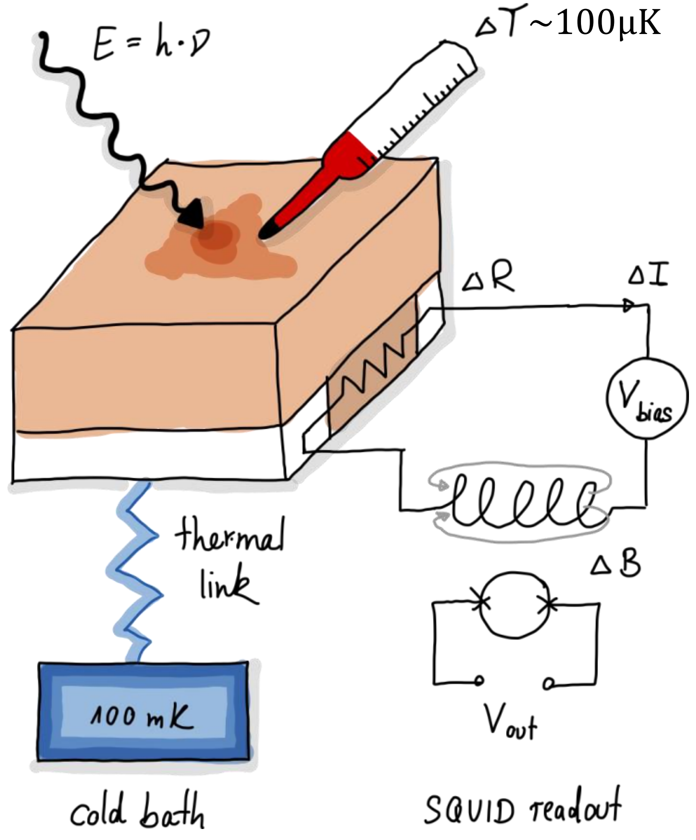
- Sensitivity to very low rates (1-2 photons a day)
- Low energy photon detection (1064nm equivalent to 1.16eV)
- Long term stability (~ 20 days)
- Low background rate: $< 7.7 \cdot 10^{-6}\mathrm{cps} \sim$ 1 photon (1064nm−like) every 2 days
  - Good energy resolution (for background rejection)
- High detection efficiency

A Transition Edge Sensor (TES) could meet them!

Transition Edge Sensors



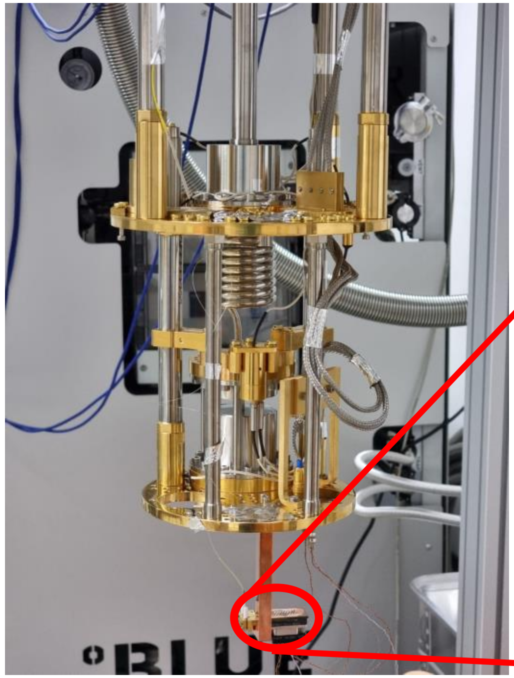
K. Irwin, G. Hilton, Transition-edge sensors, in: Cryogenic Particle Detection, Springer Berlin Heidelberg, Berlin, Heidelberg, 2005, pp. 63–150, http://dx.doi.org/10.1007/10933596_3.



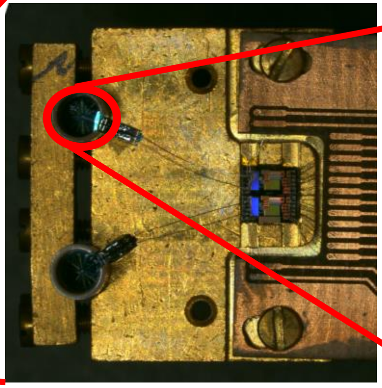
*Courtesy of Katharina-Sophie Isleif

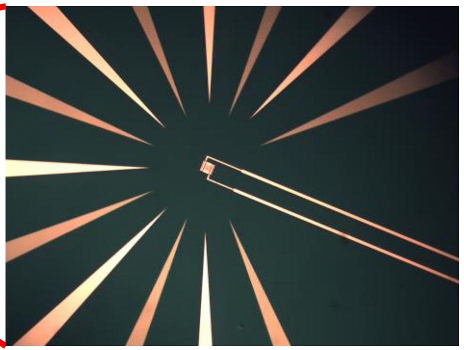
- Cryogenic microcalorimeter operated at transition region
- Connected to a colder thermal bath
- Working point controlled by a current bias circuit
- Change in resistance produced by energy deposition

TES at DESY



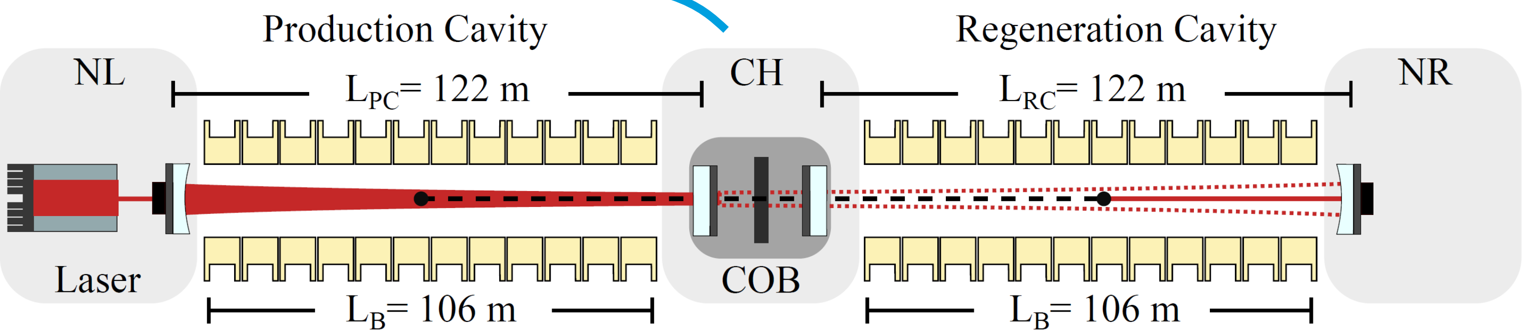
A tungsten microchip provided by NIST and PTB ($25\ \mu\text{m} \times 25\ \mu\text{m} \times 20\ \text{nm}$) operated in the transition region (~ 140 mK)

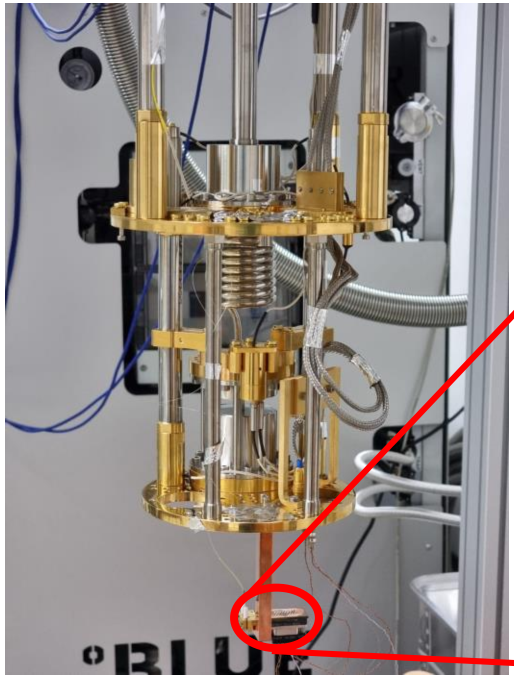




$1064\ \text{nm}$ photon
$\text{E} \approx 1.16\ \text{eV}$

TES at DESY





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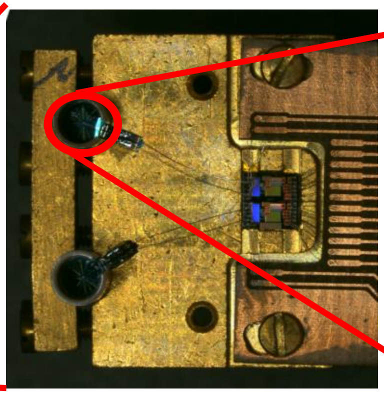
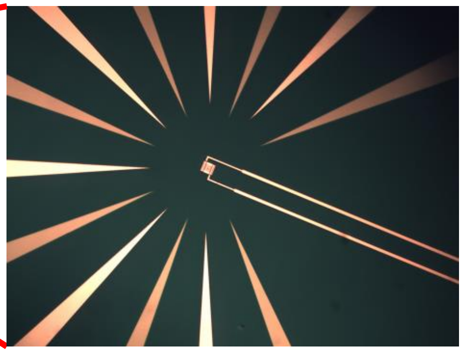
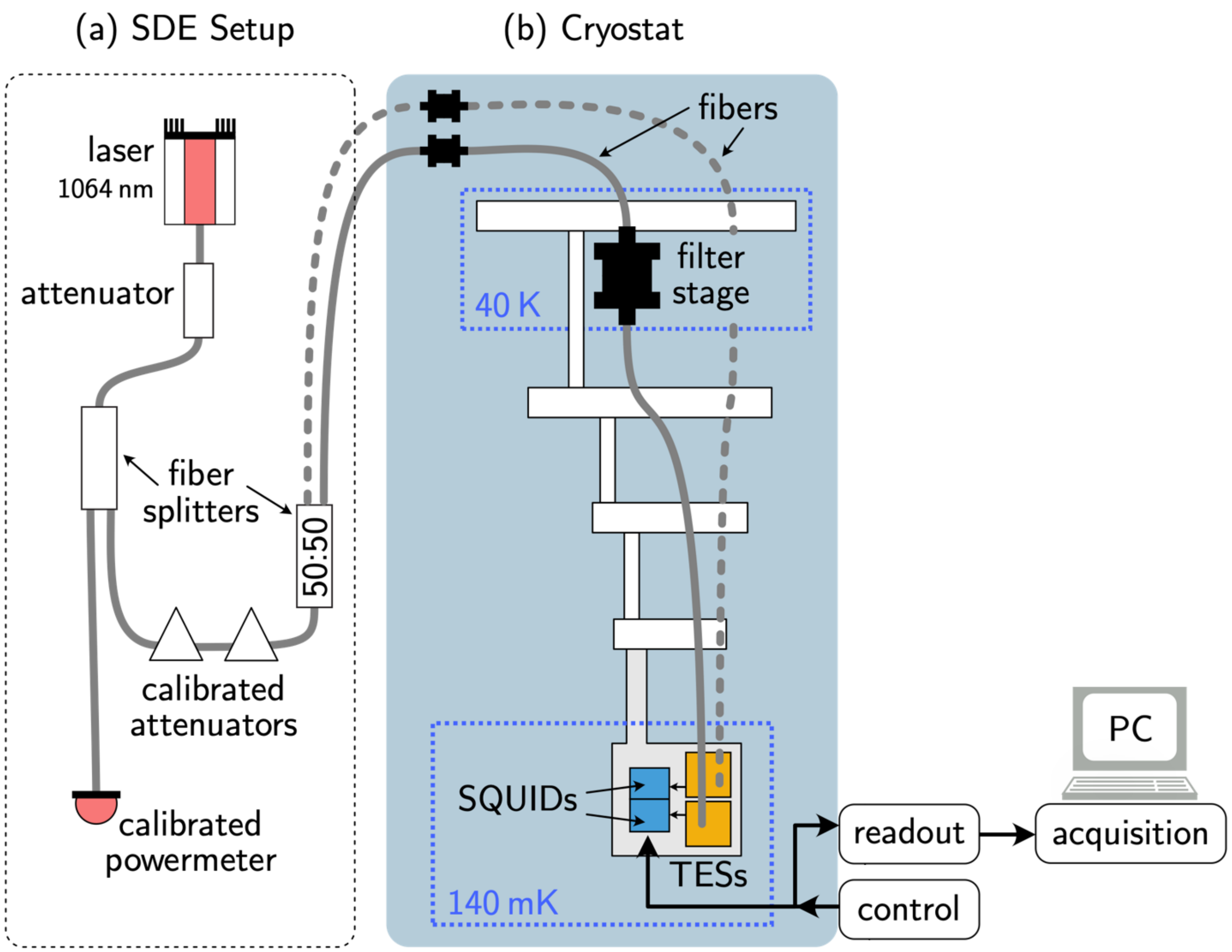




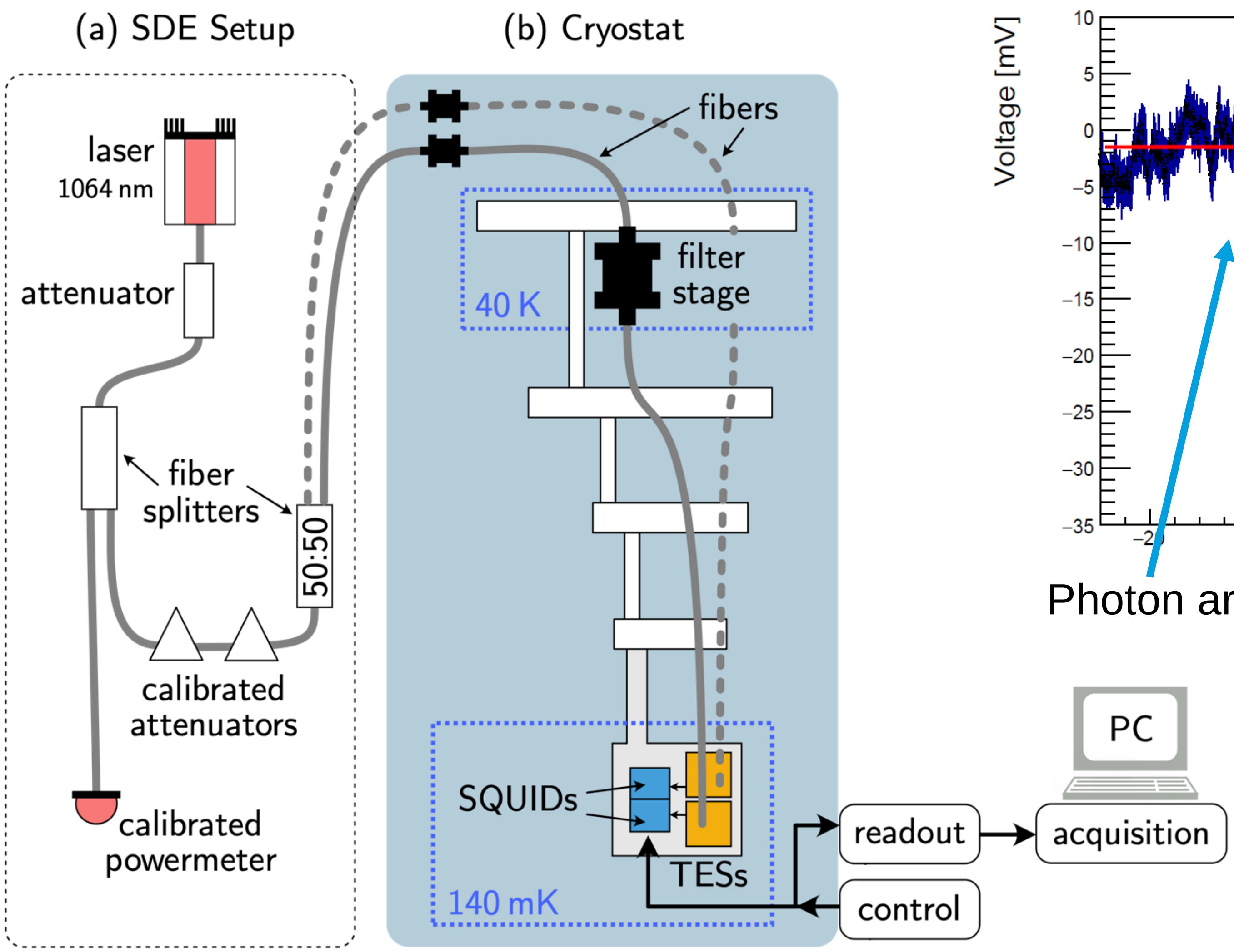
1064 nm photon
$E \approx 1.16$ eV

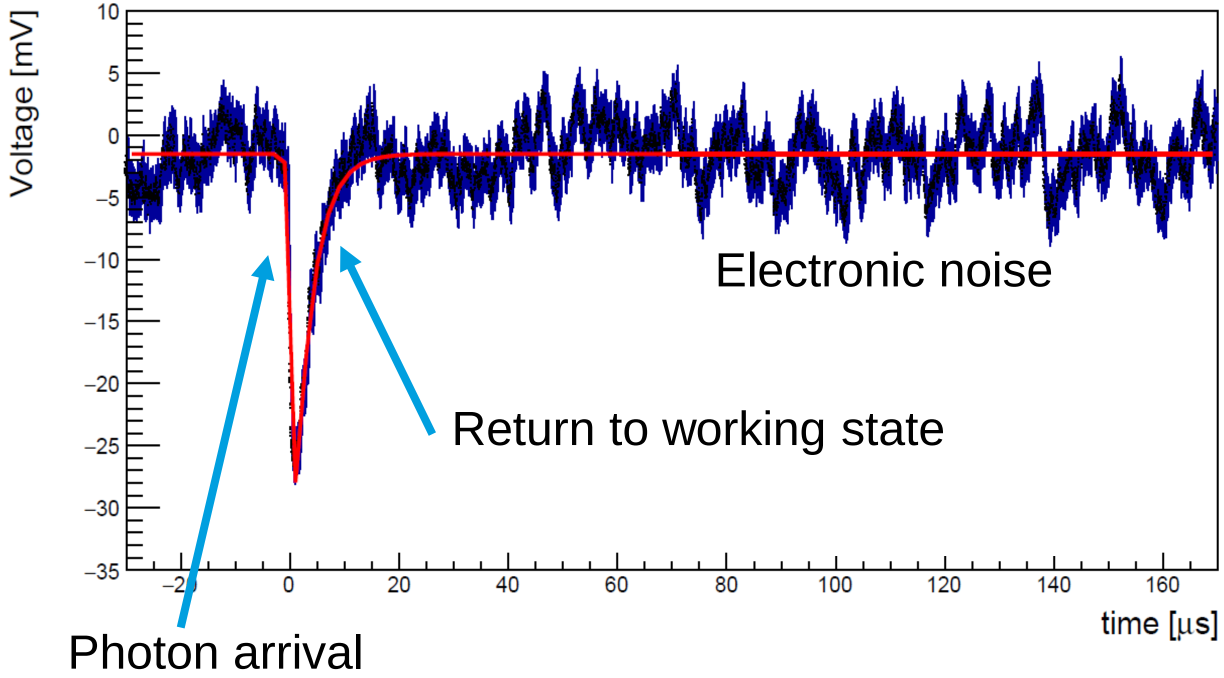
Characterizing the TES



Schematic adapted from Katharina-Sophie Isleif.

Characterizing the TES





$$E \propto \int_{t_1}^{t_2} U(t)dt$$

Schematic adapted from Katharina-Sophie Isleif.

Transition Edge Sensor

Requirements for ALPS II:

- Sensitivity to very low rates (1-2 photons a day) ✓
- Low energy photon detection (1064nm equivalent to 1.16eV) ✓
- Long term stability (~ 20 days)
- Low background rate: $< 7.7 \cdot 10^{-6}\mathrm{cps} \sim$ 1 photon (1064nm−like) every 2 days
  - Intrinsics
  - Extrinsics
  - Good energy resolution (for background rejection)
- High detection efficiency

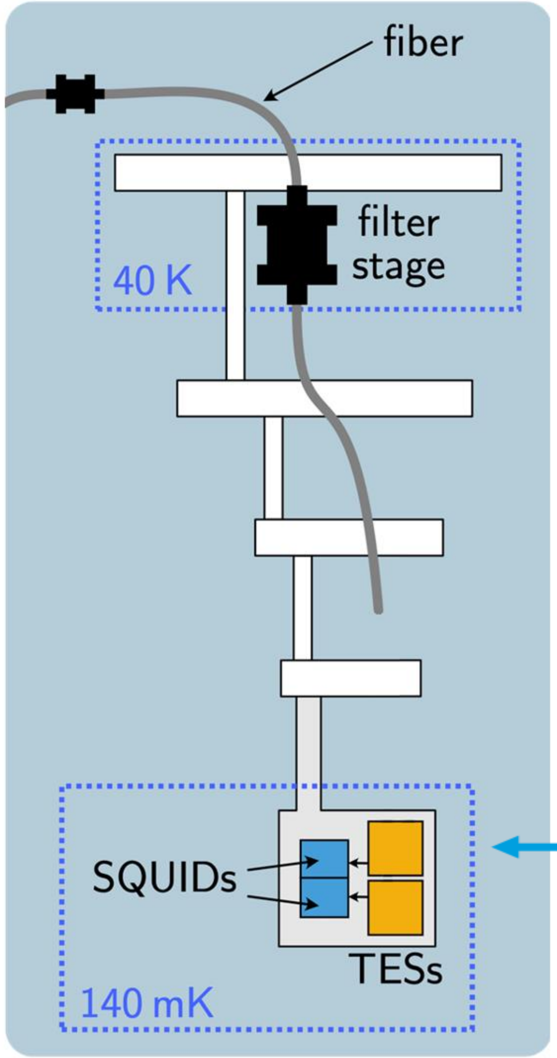
Intrinsics background (no fiber connected)

ALPS II requirements:
$< 7.7 * 10^{-6}\ cps$, 1064 nm like events

Recorded rate of events in the order of $10^{-2}\ cps$
(same trigger as 1064nm data taking) [1].

Possibly related to:

- Electronic noise
- Cosmic Rays (Muons)
- Radioactivity (Surrounding materials)



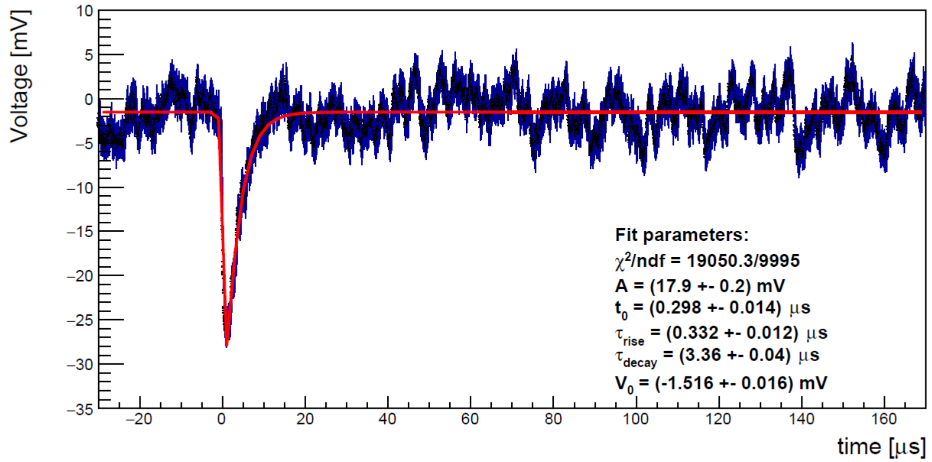
Schematic adapted from Katharina-Sophie Isleif.

[1] Rikhav Shah, Katharina-Sophie Isleif, Friederike Januschek, Axel Lindner and Matthias Schott, “TES Detector for ALPS II”, Proceedings of The European Physical Society Conference on High Energy Physics, Volume 398, Page 801, (2022); https://doi.org/10.22323/1.398.0801

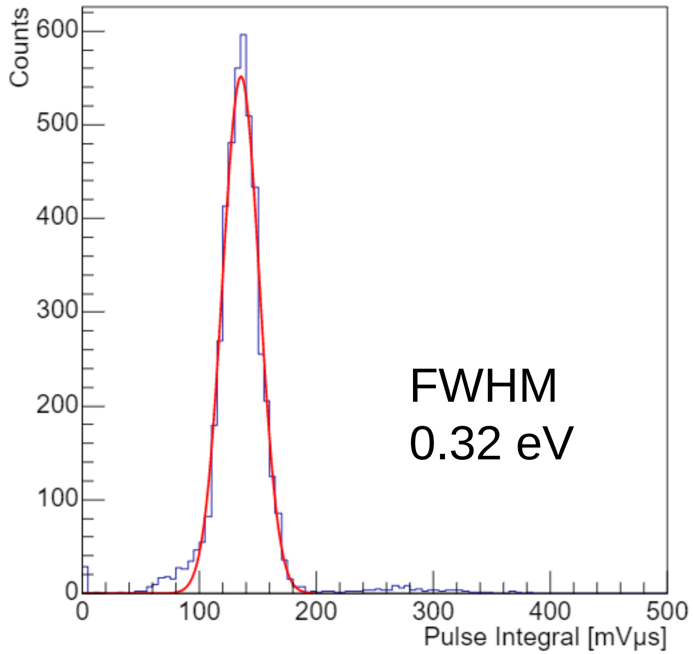
Intrinsics background results

Phenomenological approach:

$$f_1(t) = -\frac{2A}{\underbrace{\exp\left\{-\frac{1}{\tau_{rise}}(t-t_0)\right\}}_{\text{Rise component}} + \underbrace{\exp\left\{\frac{1}{\tau_{decay}}(t-t_0)\right\}}_{\text{Decay component}}} + V_0$$



$$E \propto \int_{t_1}^{t_2} U(t)dt$$



Time Integral, gaussian fit:

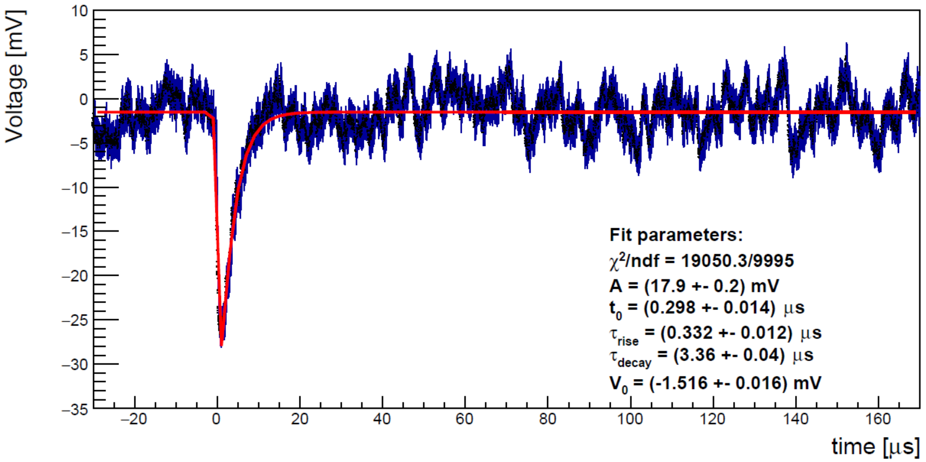
$$\frac{\sigma}{\mu}100\% = (11.6 \pm 0.2)\%$$

Cuts based on parameters from fitted $1064\ nm$ pulses, $A, \tau_{rise}, \tau_{decay}$, and Pulse integral

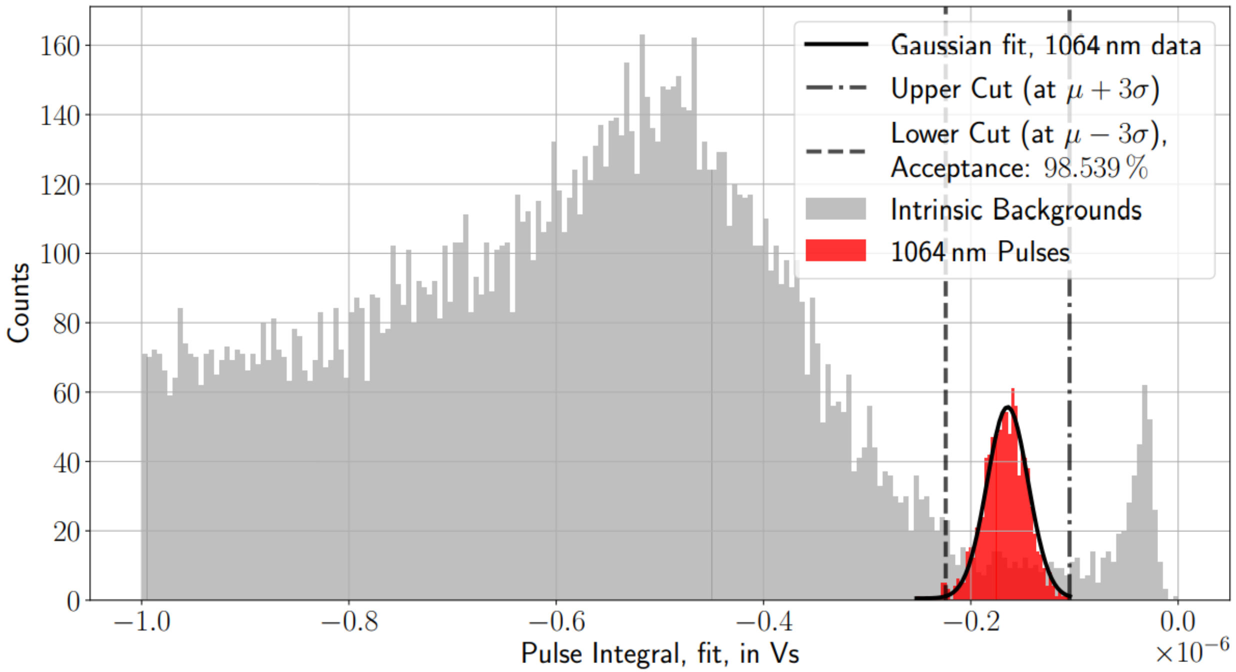
Intrinsics background results

Phenomenological approach:

$$f_1(t) = -\frac{2A}{\underbrace{\exp\left\{-\frac{1}{\tau_{rise}}(t-t_0)\right\}}_{\text{Rise component}} + \underbrace{\exp\left\{\frac{1}{\tau_{decay}}(t-t_0)\right\}}_{\text{Decay component}}} + V_0$$



Able to exclude intrinsics backgrounds and maintain the acceptance for 1064 nm pulses



[1] Rikhav Shah, Katharina-Sophie Isleif, Friederike Januschek, Axel Lindner and Matthias Schott, "TES Detector for ALPS II", Proceedings of The European Physical Society Conference on High Energy Physics, Volume 398, Page 801, (2022); https://doi.org/10.22323/1.398.0801

ALPS II requirements:
$< 7.7 \cdot 10^{-6}$ cps, 1064 nm like events

$6.9 \cdot 10^{-6}$ cps over 20 days was achieved with acceptance greater than 90% [1]

Extrinsics background (fiber connected)

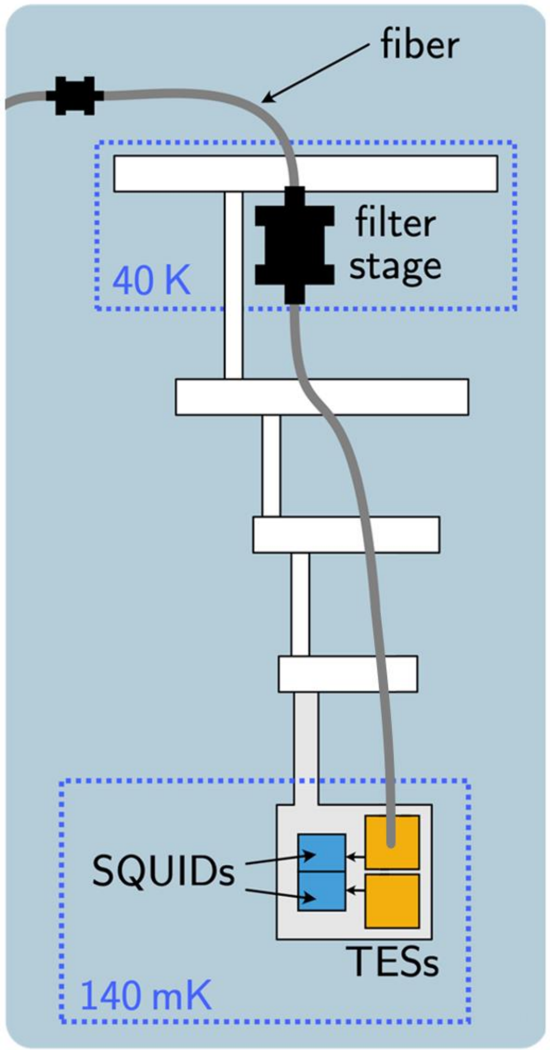
Expected additional contributions from:

- Black Body Radiation in the form of:
  - Direct photons ⟶ $\sim 1064\ \mathrm{nm}$
  - Pileup photons ⟶ looks like $\sim 1064\ \mathrm{nm}$

Photons with rate in the order of $10^{-2}\ cps$

Working on mitigating them by filtering non-1064 nm photons inside the cryostat

Improving energy resolution to mitigate background



Schematic adapted from Katharina-Sophie Isleif.

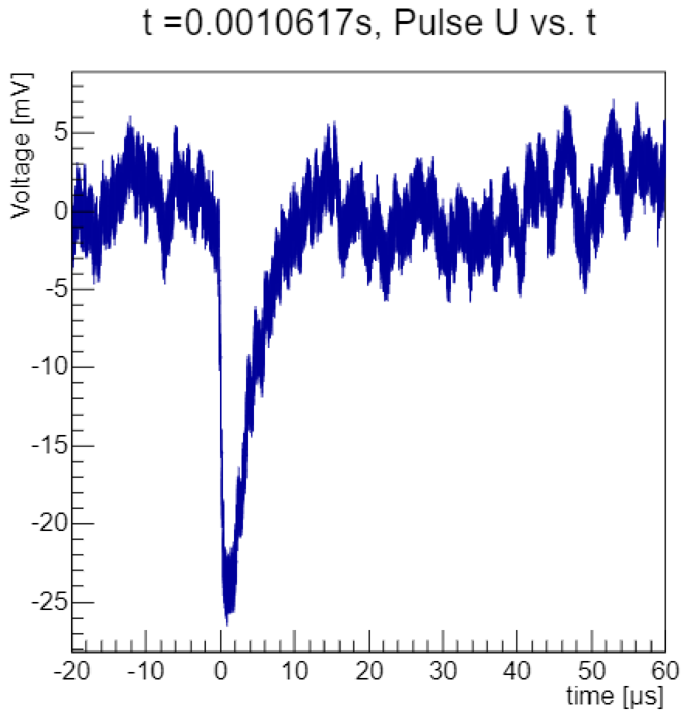
Tuesday, Poster session: A Cryogenic Single-Photon Detector for ALPS II • Gulden Othman

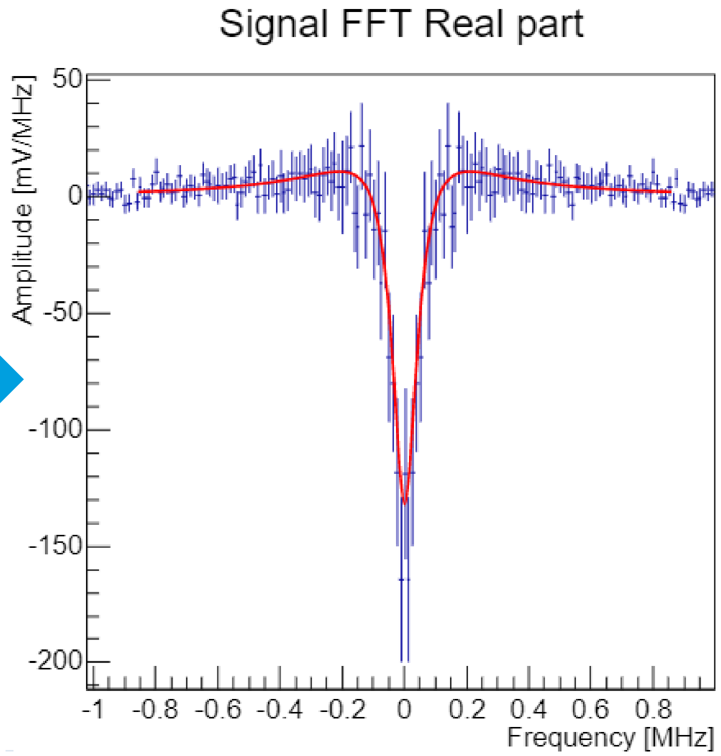
Frequency domain analysis

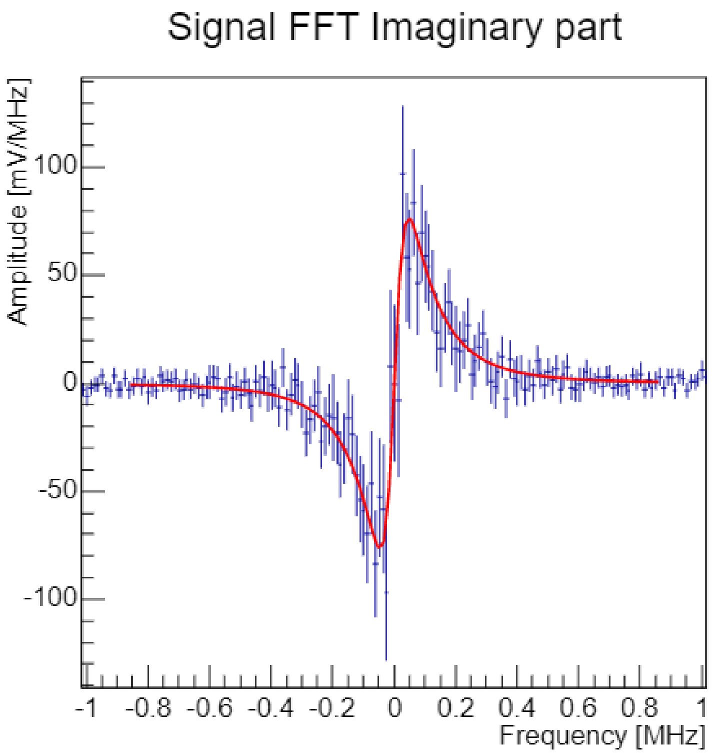
From TES theoretical description:

$$f_2(t) = \begin{cases} A\left(\exp\left\{-\frac{t-t_0}{\tau_+}\right\} - \exp\left\{-\frac{t-t_0}{\tau_-}\right\}\right) + V_0 & ,t \geq t_0 \\ V_0 & ,t < t_0 \end{cases}$$

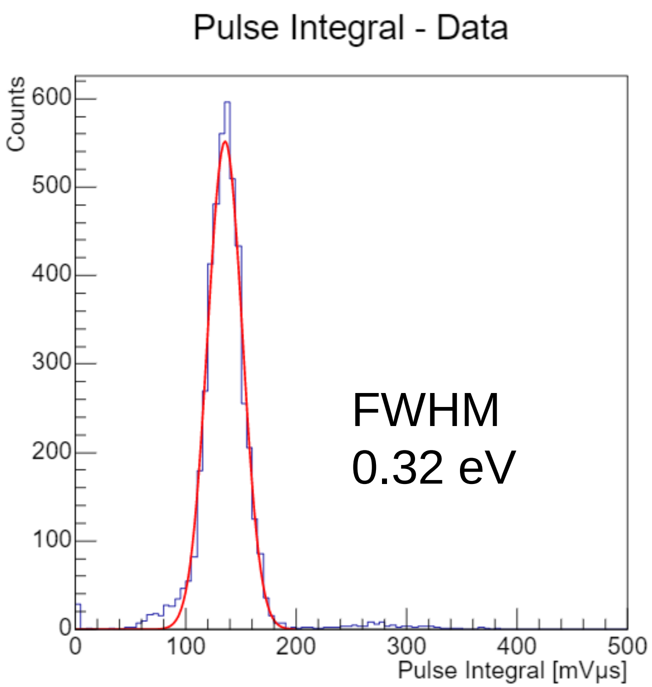
$$F(\nu) = A(\tau_+ - \tau_-)\frac{[1-(2\pi\nu)^2\tau_+\tau_-] - i\,2\pi\nu(\tau_+ + \tau_-)}{[1+\tau_+^2(2\pi\nu)^2][1+\tau_-^2(2\pi\nu)^2]}\exp\{-2\pi i\nu t_0\}$$







Frequency domain analysis

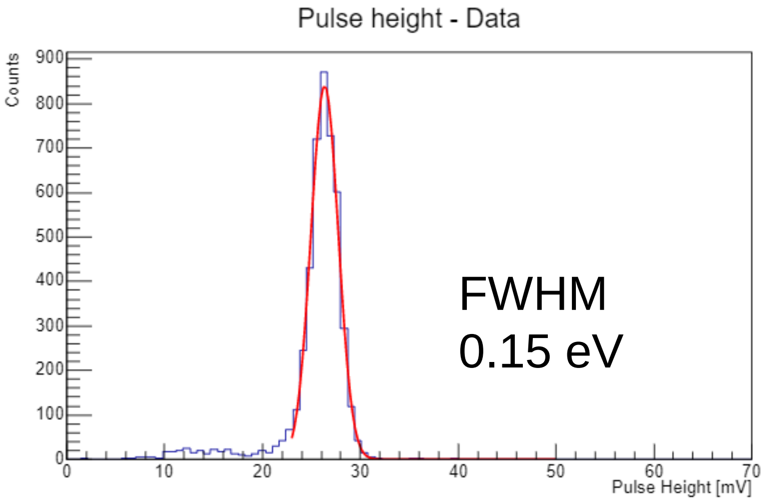


Phenomenological approach (time)

$$\frac{\sigma}{\mu}100\% = (11.6 \pm 0.2)\%$$

Pulse height as compromise between linear response and energy resolution

$$f_2'(t_{max}) = 0 \quad \Rightarrow \quad f_2(t_{max}) = \text{pulse height}$$



Pulse height, SST

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

- Faster fitting, one parameter less
- Access to physical properties of the sensor
- Improvement in energy resolution by a factor of 2

Transition Edge Sensor

Requirements for ALPS II:

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- Low energy photon detection (1064nm equivalent to 1.16eV) ✓
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- Low background rate: $< 7.7 \cdot 10^{-6}\mathrm{cps} \sim$ 1 photon (1064nm−like) every 2 days ✓
  - Intrinsics ✓
  - Extrinsics
  - Good energy resolution (for background rejection) ✓
- High detection efficiency

Efficiency measurement

Measuring efficiency of fiber coupling to detector. A high detection efficiency is required.

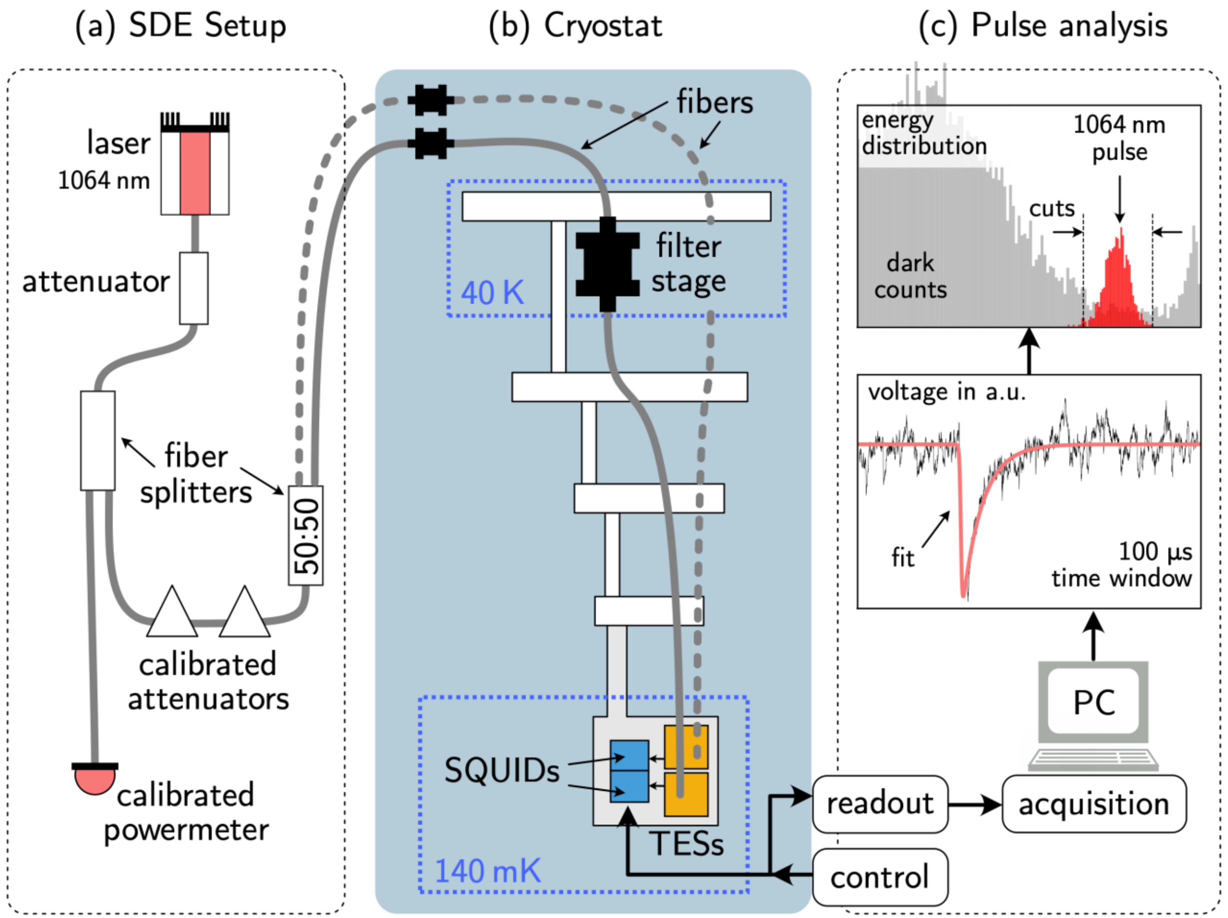
- Attenuated laser light (from 1mW to ~pW)
- Using reference photodiode
- Counting single photons reaching the TES

Counts converted to power and compared with reference

Main challenge:
- Minimum power in photodiode: $\sim 10^{-11}\mathrm{W}$
- Maximum power in TES: $\sim 10^{-15}\mathrm{W}$

ALPS II $\sim 3 \cdot 10^{-24}\mathrm{W}$

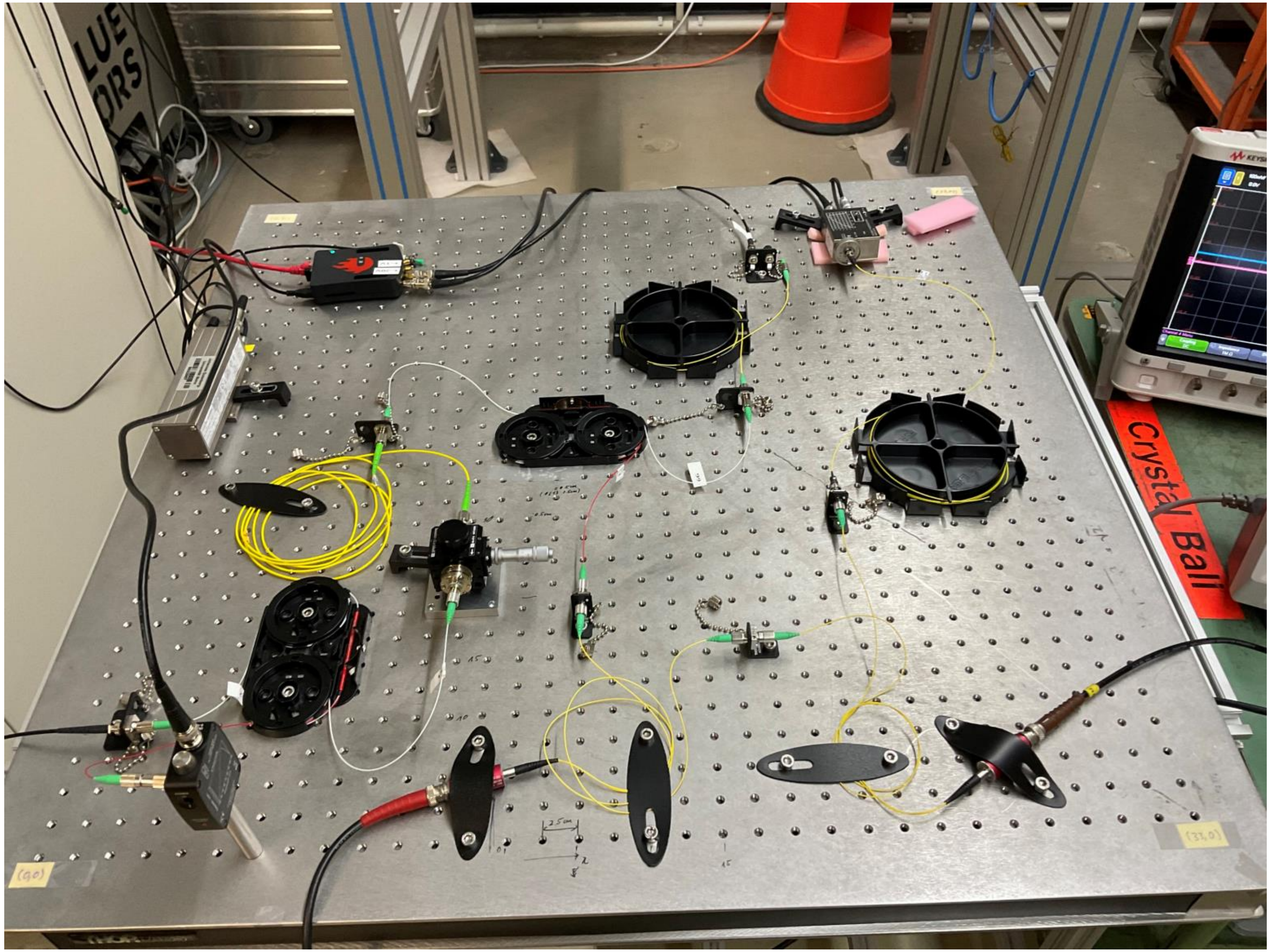
Measurement setup based on [2].



[2] Setup adapted from Marco Schmidt et al., "Photon-number-resolving transition-edge sensors for the metrology of photonic microstructures based on semiconductor quantum dots," Proc. SPIE 10933, Advances in Photonics of Quantum Computing, Memory, and Communication XII, 1093305 (4 March 2019); https://doi.org/10.1117/12.2514086

Schematic adapted from Katharina-Sophie Isleif.

Efficiency measurement



Photon rate in TES — Photon energy — Power split ratio

$$\mathrm{SDE} = \frac{d \cdot E_{1064nm} \cdot r \cdot a}{P}$$

Power in photodiode — Attenuation

Main challenge:

- Dynamic range of photodiode

Setup is done. Further checks, tests and assessment of uncertainties in progress.

Preliminary results:

Efficiency > 80%

Summary & Outlook

Requirements for ALPS II:

- Sensitivity to very low rates (1-2 photons a day) ✓
- Low energy photon detection (1064nm equivalent to 1.16eV) ✓
- Long term stability (~ 20 days) ✓
- Low background rate: $< 7.7 \cdot 10^{-6}$cps $\sim$ 1 photon (1064nm−like) every 2 days ✓

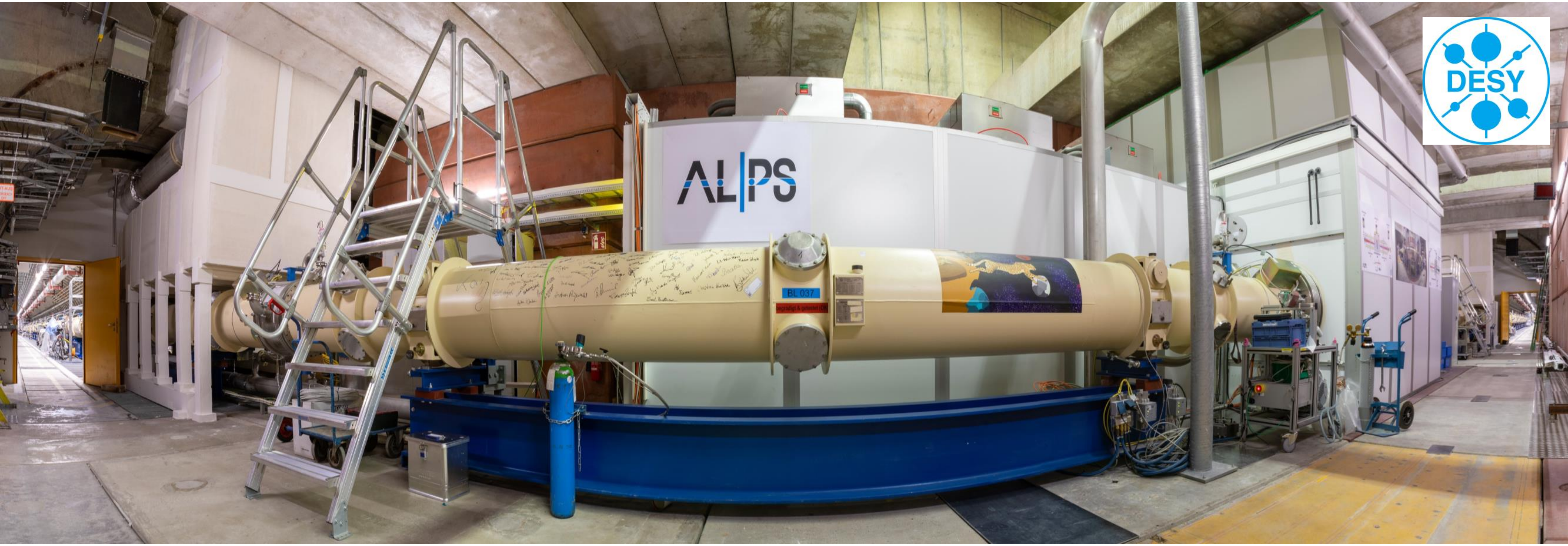
  Intrinsics ✓ extrinsics very good energy resolution ✓
- High detection efficiency ✓

And also …

ALPS II data taking started with HET

Studying feasibility of the TES for direct dark matter detection

Thursday: T03 DM, Direct dark matter searches using ALPS II's TES detector • Christina Schwemmbauer



Thank you.

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

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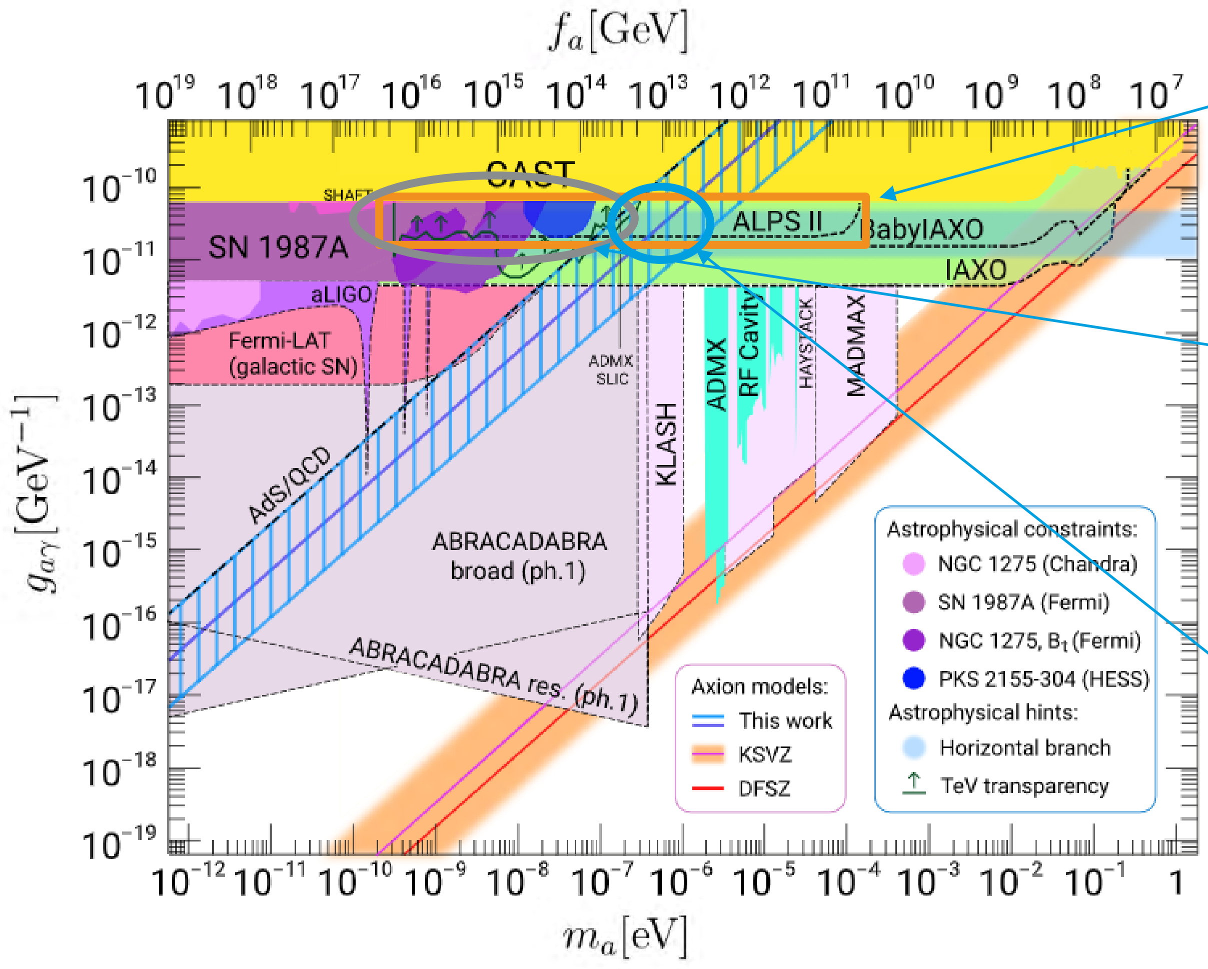
ALPS
jose.rubiera.gimeno@desy.de

Backup

Axion-photon coupling



ALPS II

Motivated by anomalies in the evolution of stars

$$10^{-11}GeV^{-1} \leq g_{a\gamma} \leq 10^{-10}GeV^{-1}$$

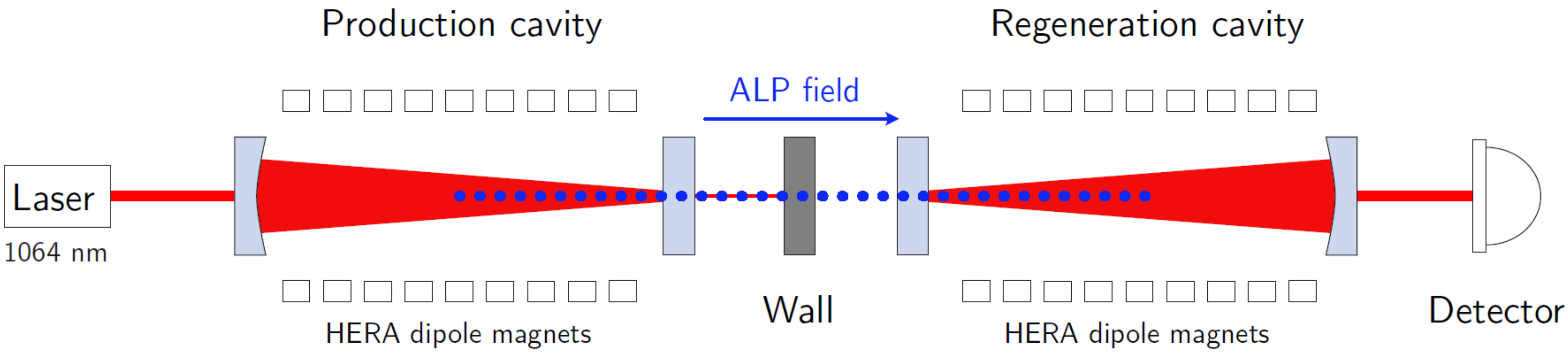
TeV Transparency

Best sensitivity among LSW experiments

New theory of QCD axion

[1] A. V. Sokolov and A. Ringwald, “Photophilic hadronic axion from heavy magneticmonopoles,” [arXiv:2104.02574 [hep-ph]].

Any Light Particle Search II (ALPS II)



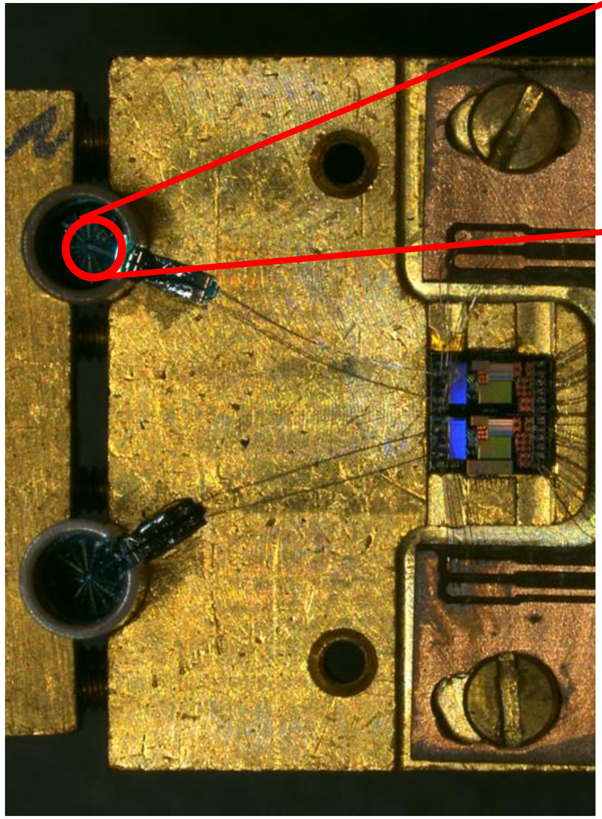
$$P_{\gamma \to a \to \gamma} = \frac{1}{16} \beta_{PC} \beta_{RC} (g_{a\gamma\gamma} B l)^4$$

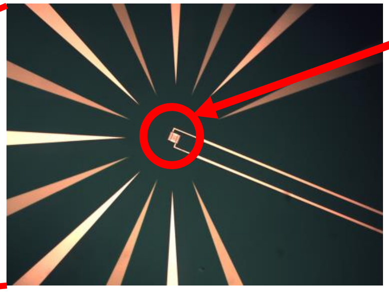
$$P_{\gamma \to a \to \gamma} = 8 \cdot 10^{-26}$$

$$P_{\gamma \to a \to \gamma} = 6 \cdot 10^{-38} \underbrace{\beta_{PC}}_{5000} \overbrace{\beta_{RC}}^{16000} \left(\underbrace{\frac{g_{a\gamma\gamma}}{10^{-10} GeV^{-1}}}_{0.2 \cdot 10^{-10} GeV^{-1}} \frac{\overbrace{B}^{5.3\,T}}{1T} \underbrace{\frac{l}{10m}}_{105.6\,m} \right)^4$$

Schematic adapted from Katharina-Sophie Isleif.

Simulation of intrinsic background

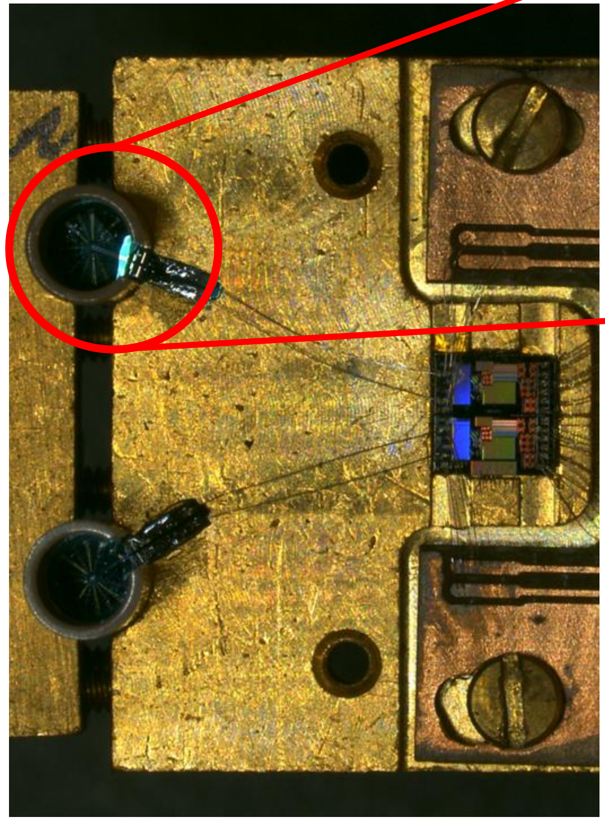


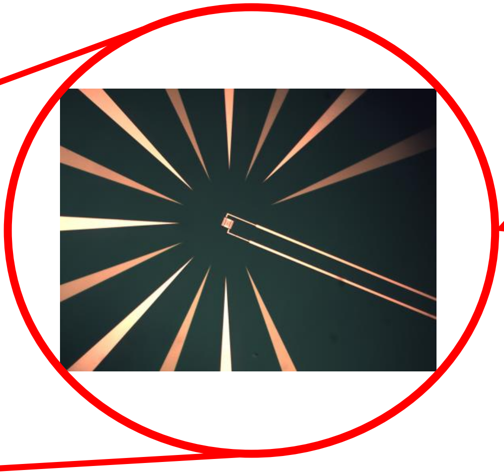


Sensitive area to 1064nm = 1.16eV photons

What happens if a much higher energy is deposited in the surroundings?

Simulation of intrinsic background

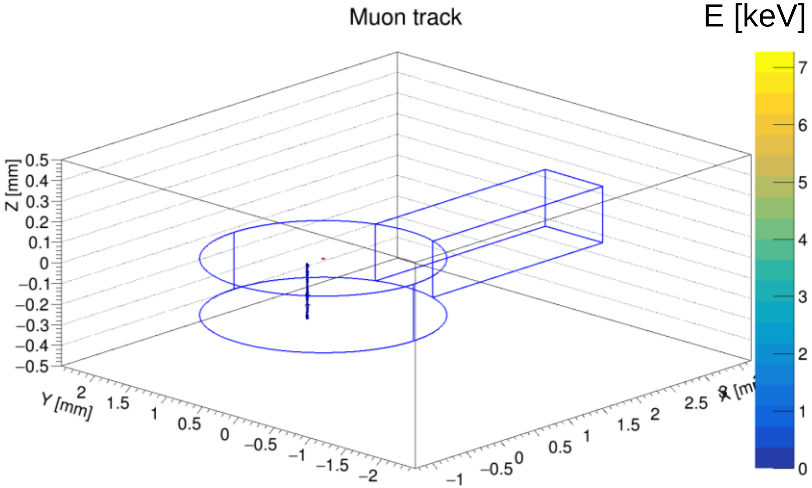




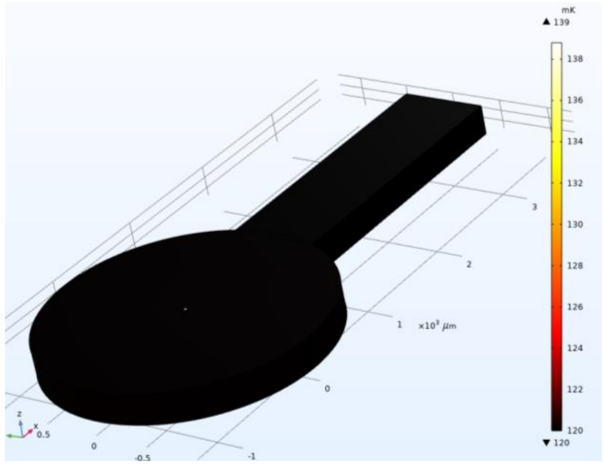
Sensitive area to 1064nm = 1.16eV photons

What happens if a much higher energy is deposited in the surroundings?

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

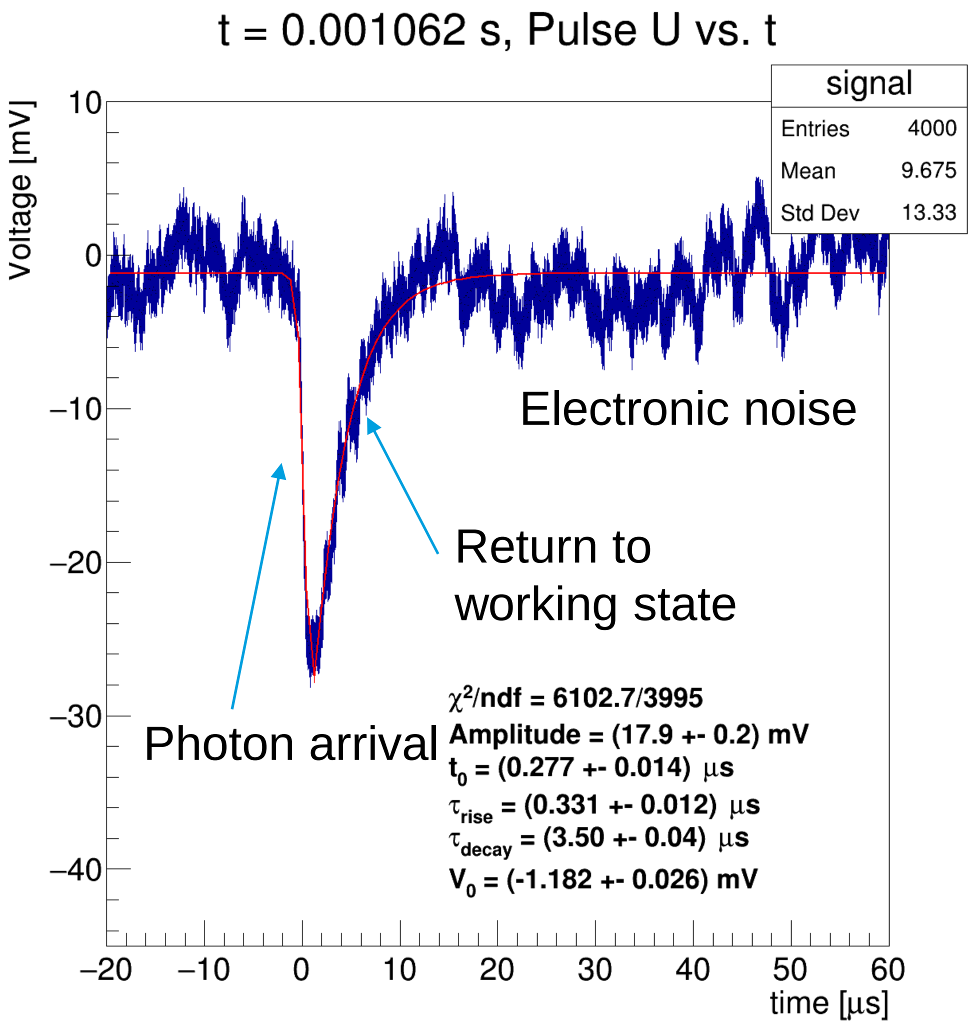


Simulation of TES physics and transport of heat in silicon substrate using COMSOL Multiphysics



Work in progress

Fitting procedure



From Small-Signal Theory:

$$f_2(t) = \begin{cases} A\left(\exp\left\{-\frac{(t-t_0)}{\tau_+}\right\} - \exp\left\{-\frac{(t-t_0)}{\tau_-}\right\}\right) + V_0, & t \geq t_0 \\ V_0, & else \end{cases}$$

Rise component — Decay component

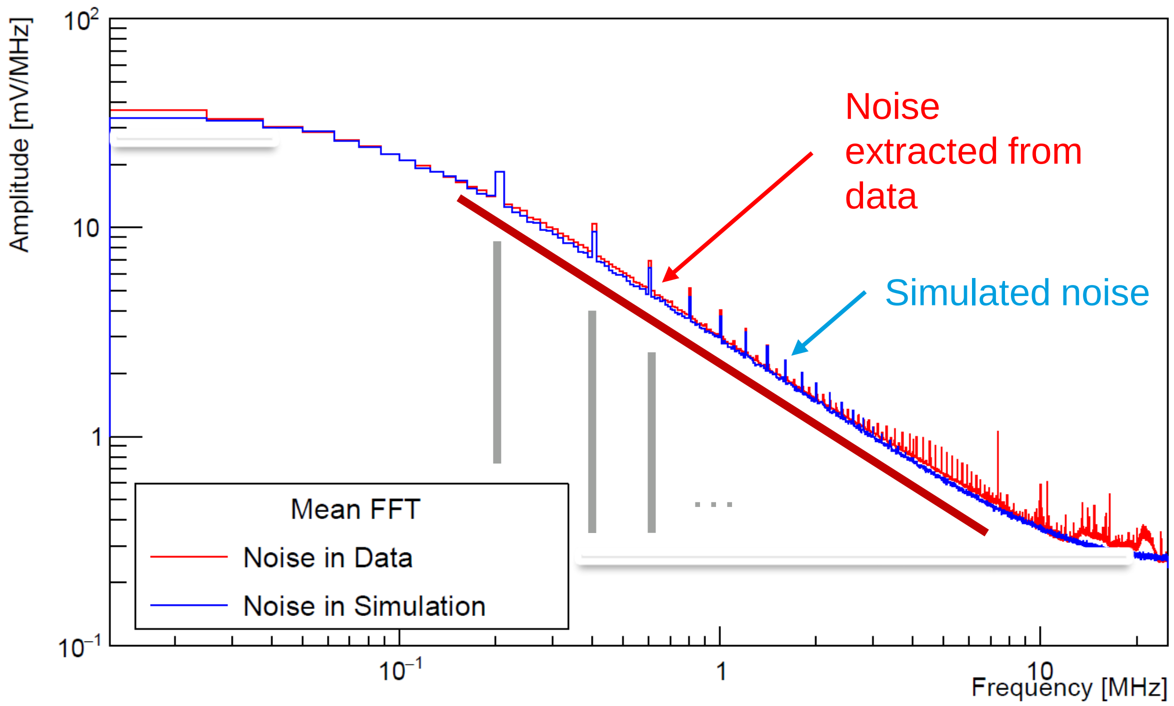
Piecewise function

Phenomenological approach:

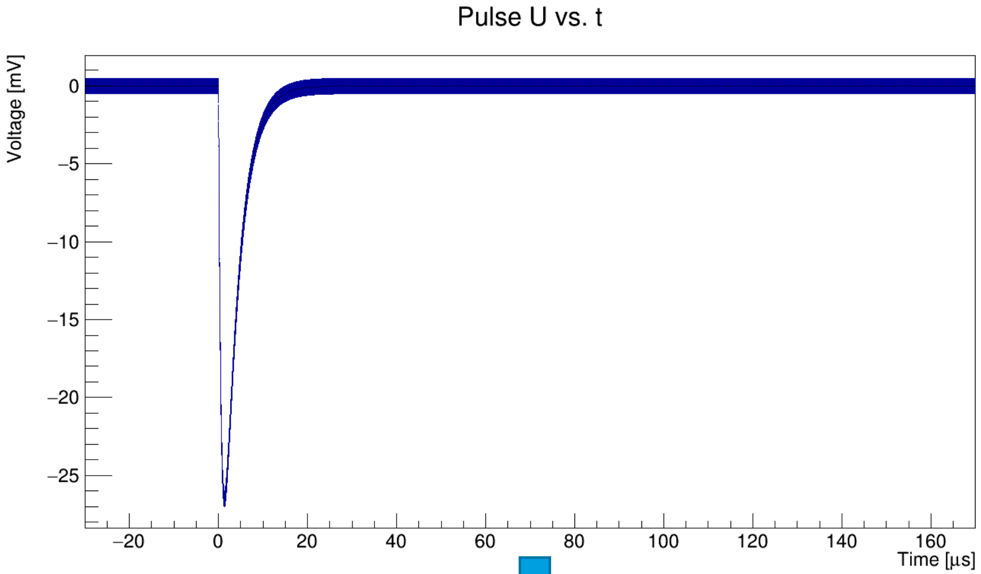
$$f_1(t) = -\frac{2A}{\exp\left\{-\frac{1}{\tau_{rise}}(t-t_0)\right\} + \exp\left\{\frac{1}{\tau_{decay}}(t-t_0)\right\}} + V_0$$

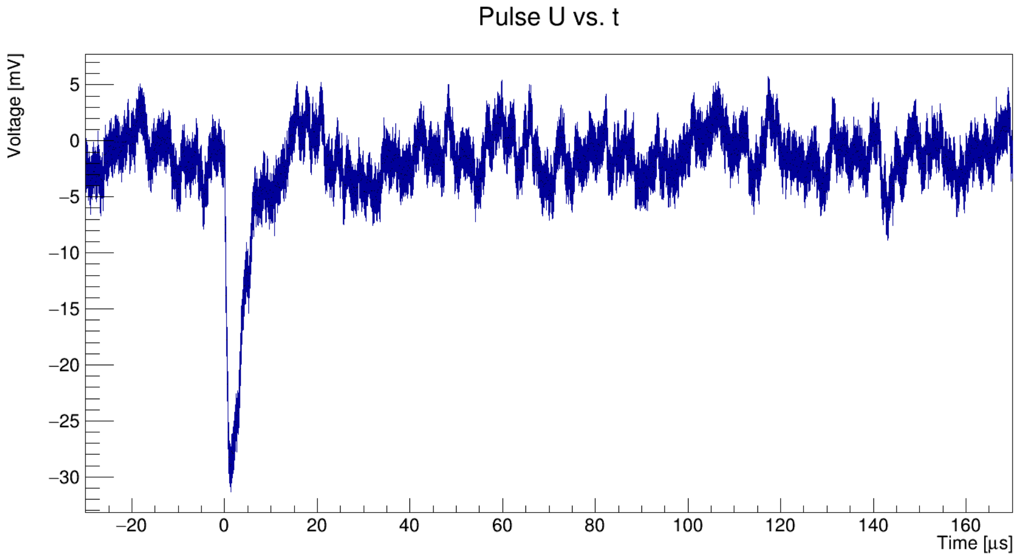
Rise component — Decay component

Simulation of baseline noise



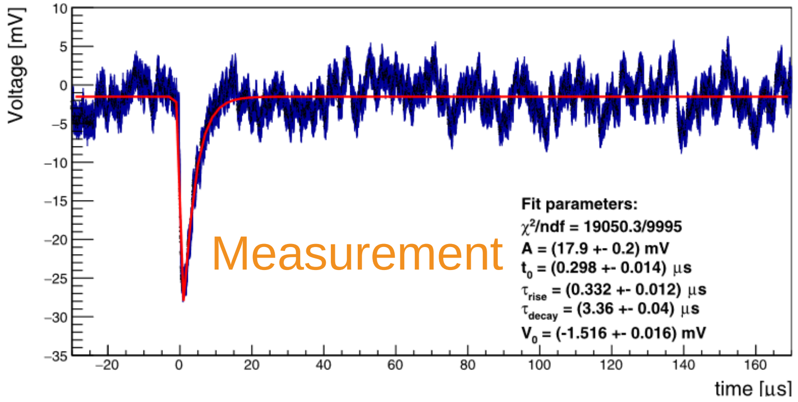
+

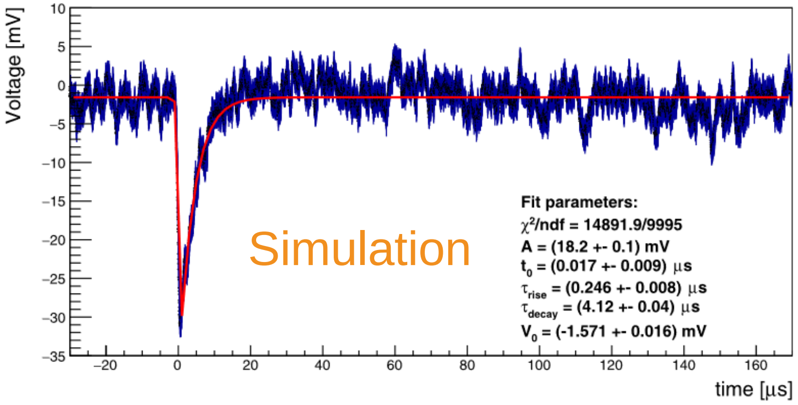


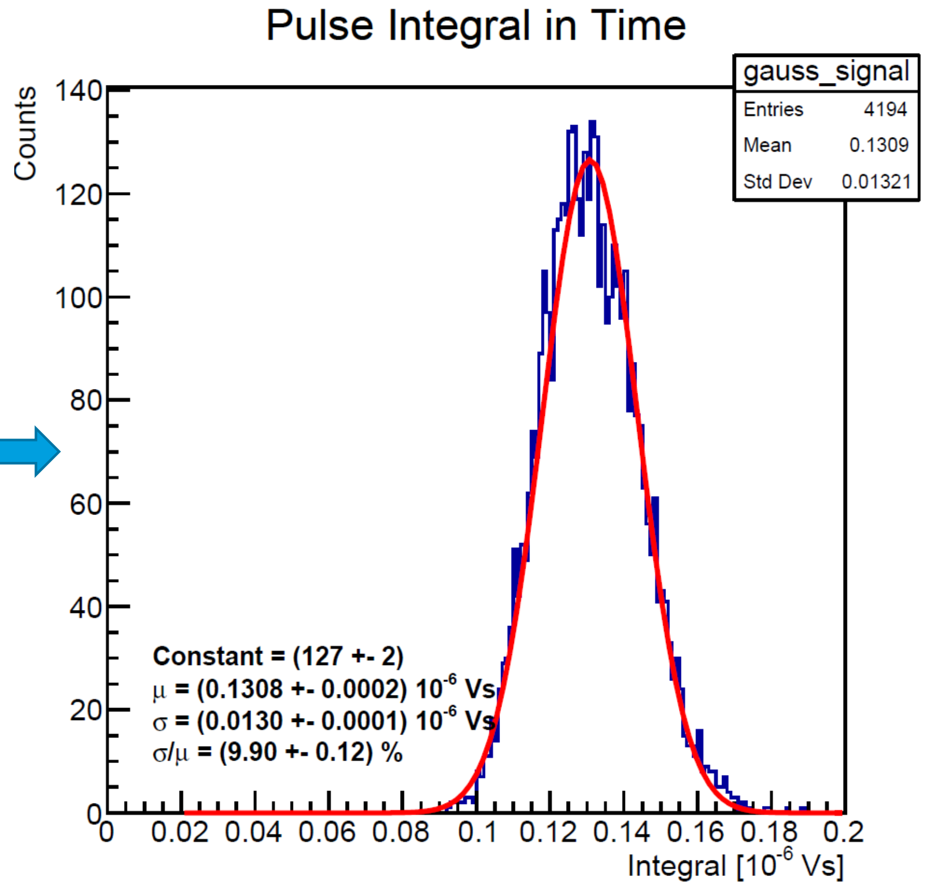


- 200 kHz harmonics
- White noise
- Brownian noise

Towards the understanding of our system







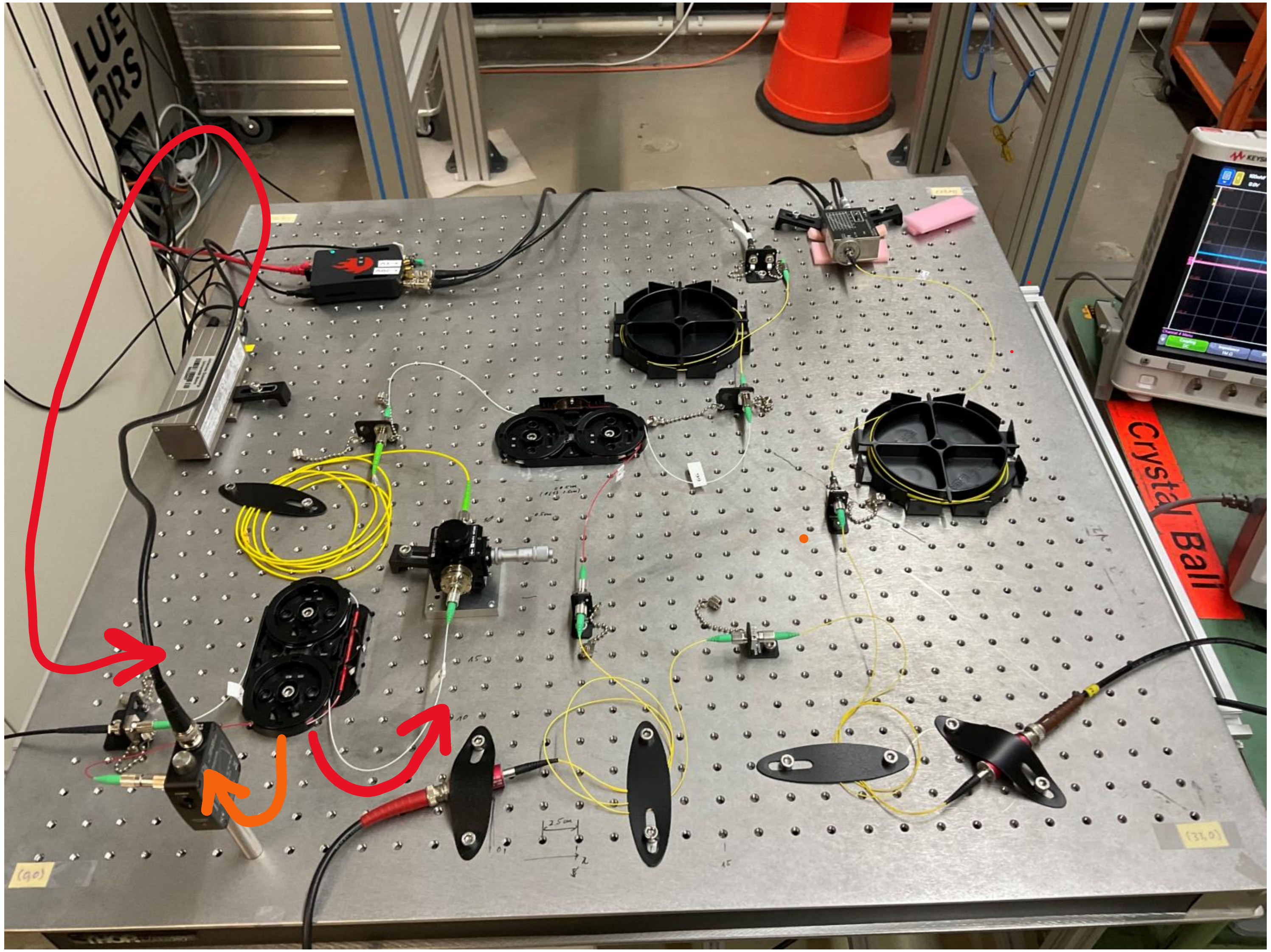
Data Analysis:
Energy Resolution
$(9.96 \pm 0.12)\%$

Simulation:
Energy Resolution
$(9.90 \pm 0.12)\%$

Studying other phenomena
- Rejection of pileup
- DAQ trigger efficiency.

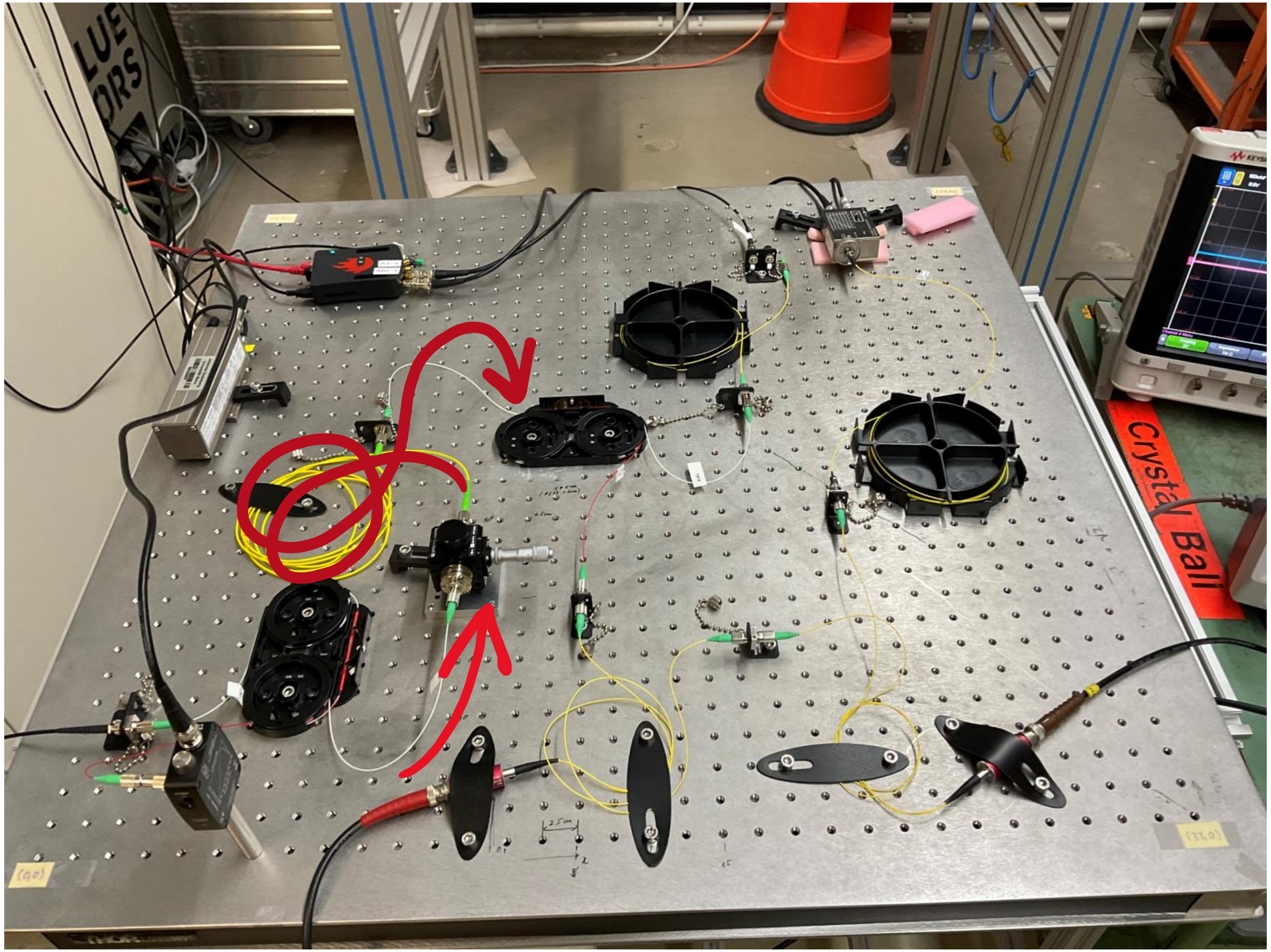
Simulation confirms energy resolution biggest component is the baseline noise.

Efficiency measurement



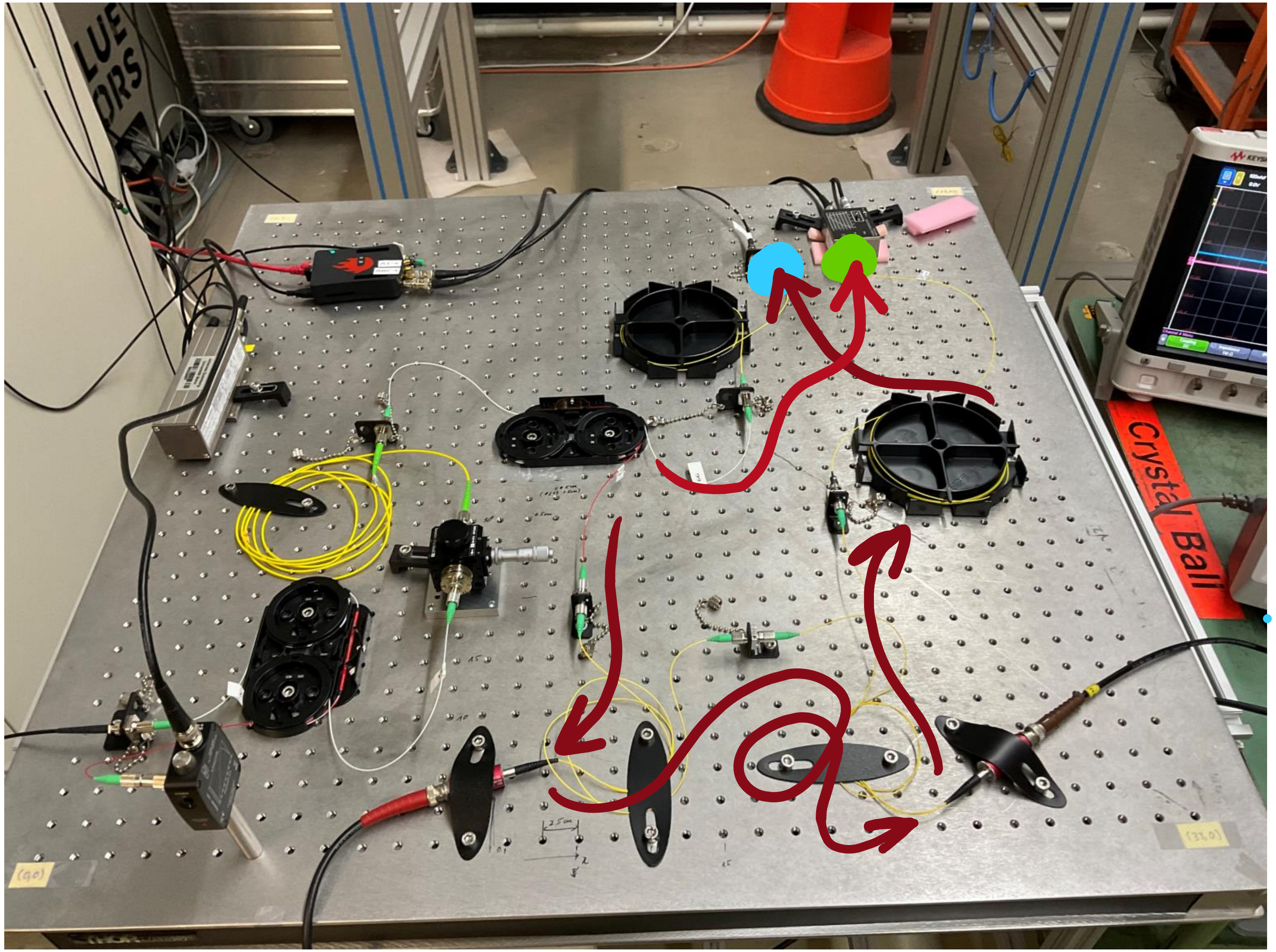
- **1064nm** laser light of 1mW.

Efficiency measurement



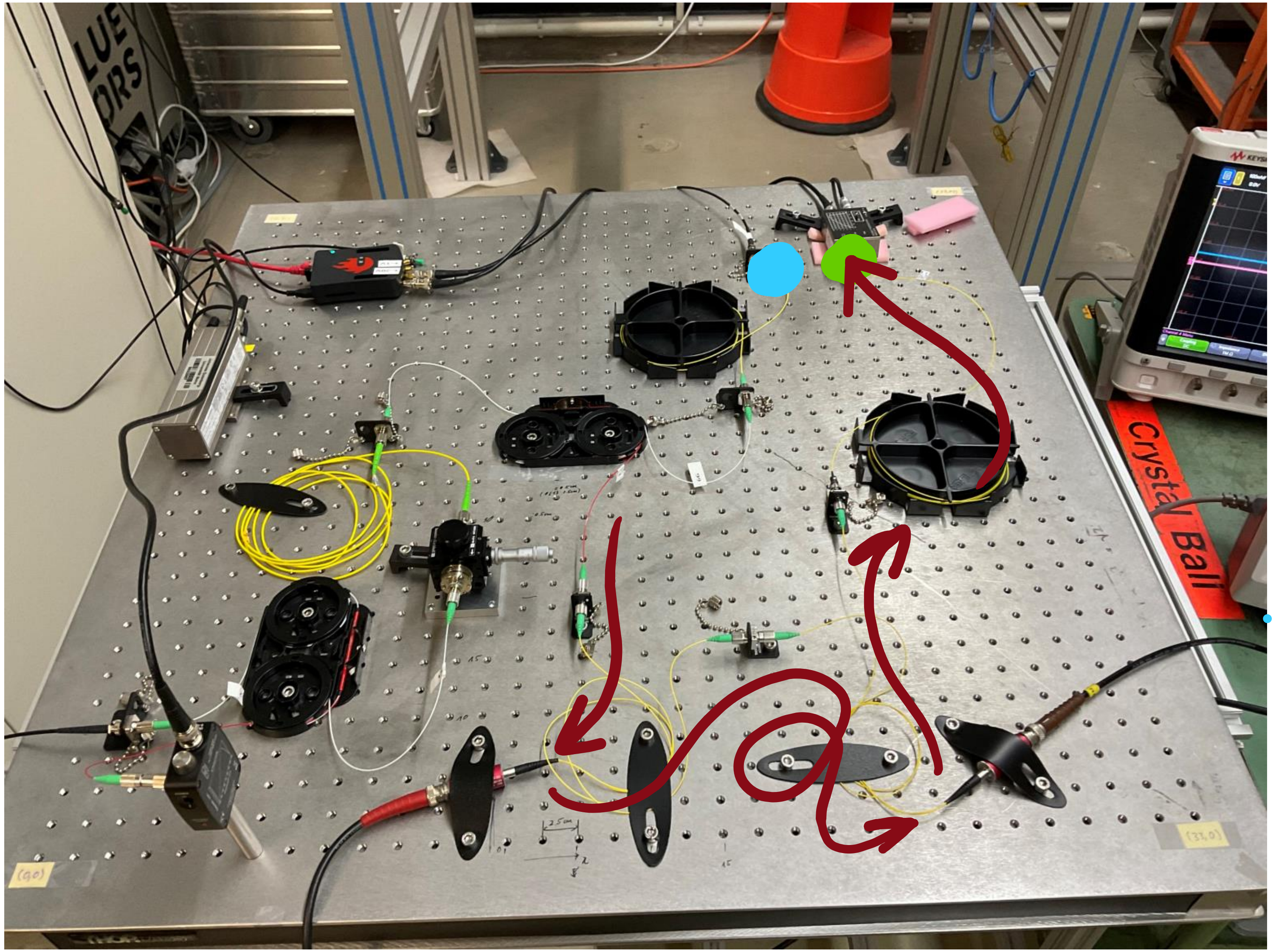
- **1064nm** laser light of 1mW.
- Attenuation to ~100pW.

Efficiency measurement



- 1064nm laser light of 1mW.
- Attenuation to ~100pW.
- 99% line to calibrated photodiode.
- 1% line to 2 VOAs and then to TES.

Efficiency measurement



- **1064nm** laser light of 1mW.
- Attenuation to ~100pW.
- 99% line to **calibrated photodiode**.
- 1% line to 2 VOAs and then to **TES**.

- Photodiode connected to 1% line to measure attenuation of components in the line.

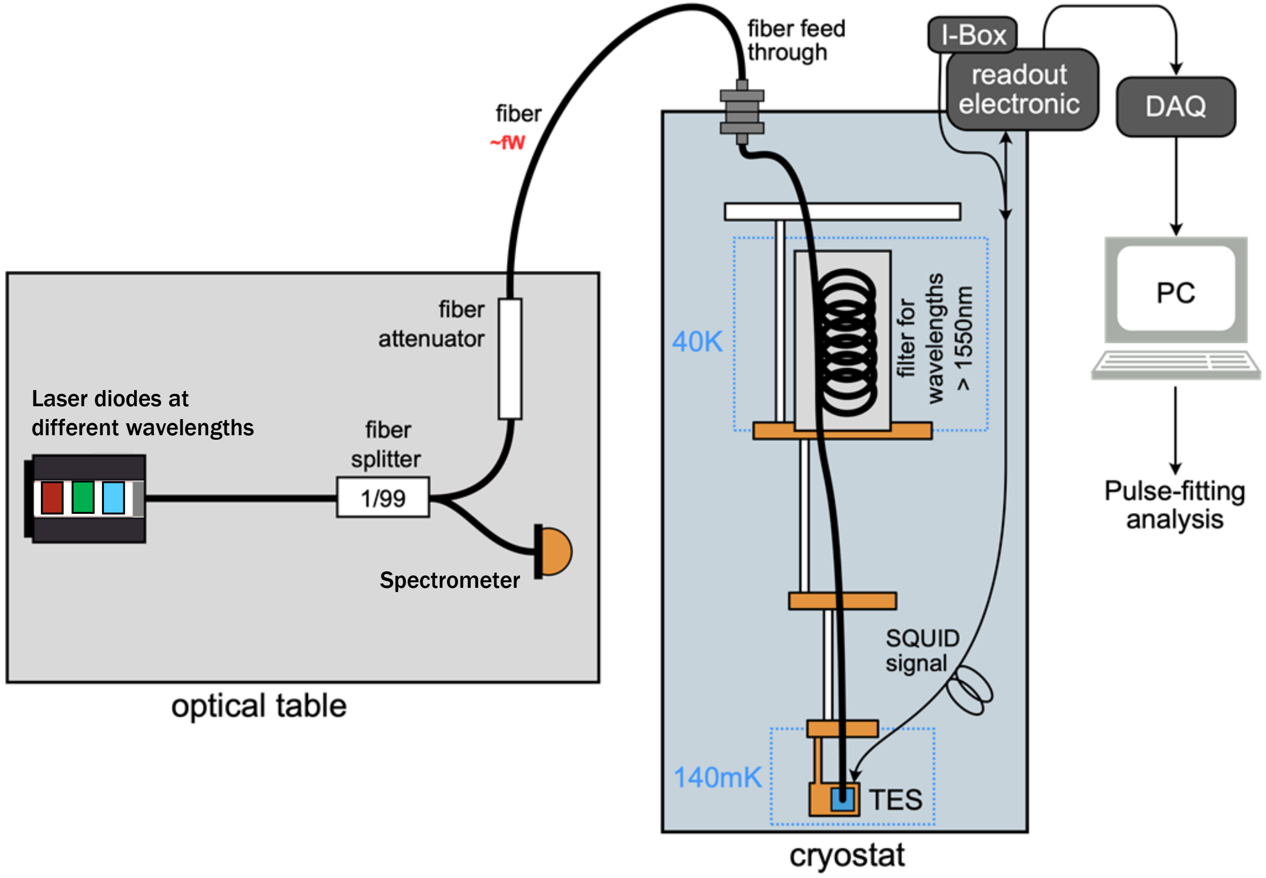
Calibration measurement

Characterization of response of the TES to photons at different wavelengths.

- The ratios between different wavelengths are determined for the TES and the spectrometer.
- The comparison of the TES results with the spectrometer allows to evaluate its linear behavior.

ALPS II: 532nm ≠ 1064nm
Blackbody spectrum: vicinity of 1064nm
Possible DM search: λ > 1064nm

Good energy resolution is required.



All equipment delivered. Measurements will start very soon.

Schematic adapted from Katharina-Sophie Isleif.