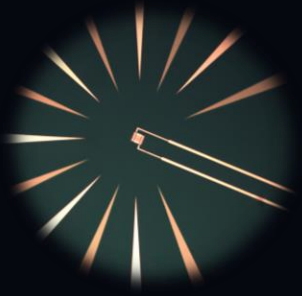


Characterization of a TES detector for ALPS II



José Alejandro Rubiera Gimeno (DESY)
for the TES team in the ALPS II collaboration
FH detector R&D platform retreat
January 19th, 2024

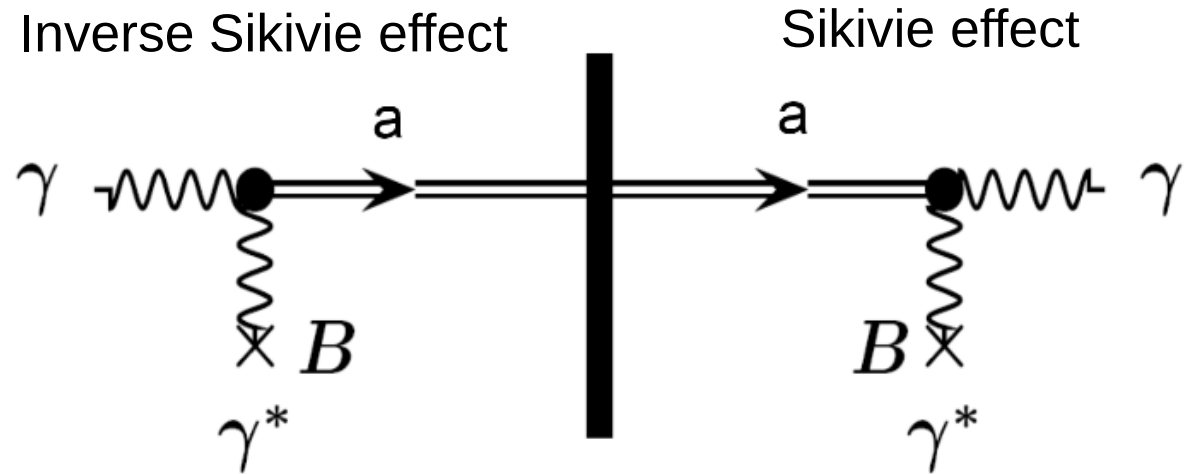
This morning, Direct Dark Matter
Searches with ALPS II's TES Detector
System • Christina Schwemmbauer

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)

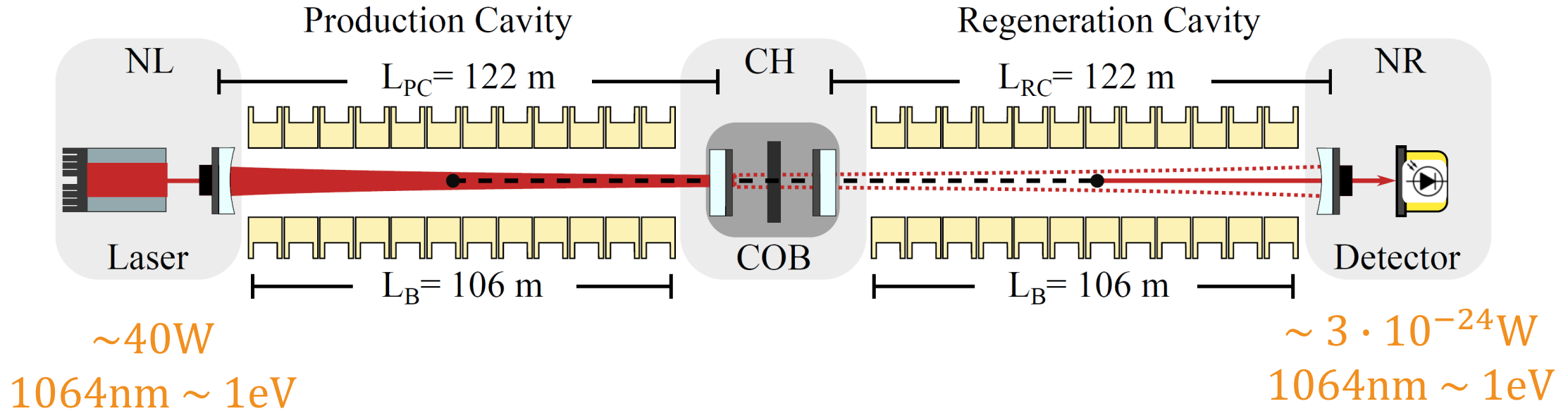
- Proposed as solution to strong CP problem
- Motivated by astrophysical observations:
 - Stellar evolution
 - TeV transparency
- Very weak interaction, good candidate for dark matter
- The main mechanism for detection of light weight axions is through its coupling to photons



Light Shining through a Wall (LSW)

Model independent approach,
independent of dark matter paradigm

Any Light Particle Search II (ALPS II)



Conversion-reconversion probability:

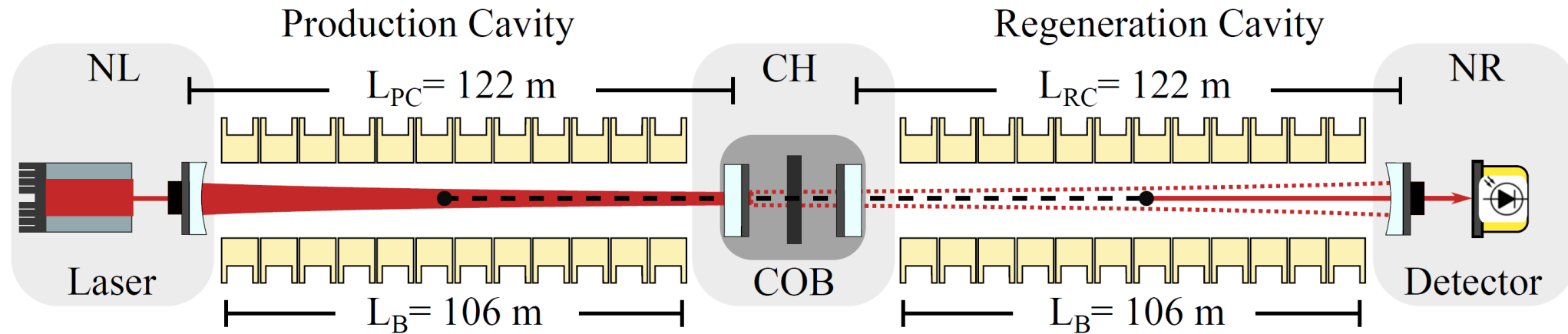
$$p_{\gamma \rightarrow a \rightarrow \gamma} = \frac{1}{16} \beta_{PC} \beta_{RC} (g_{a\gamma\gamma} B L_B)^4$$

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

Enhancement by
optical cavities

$2 \cdot 10^{-11} \text{ GeV}^{-1}$
Motivated by 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 with different systematics

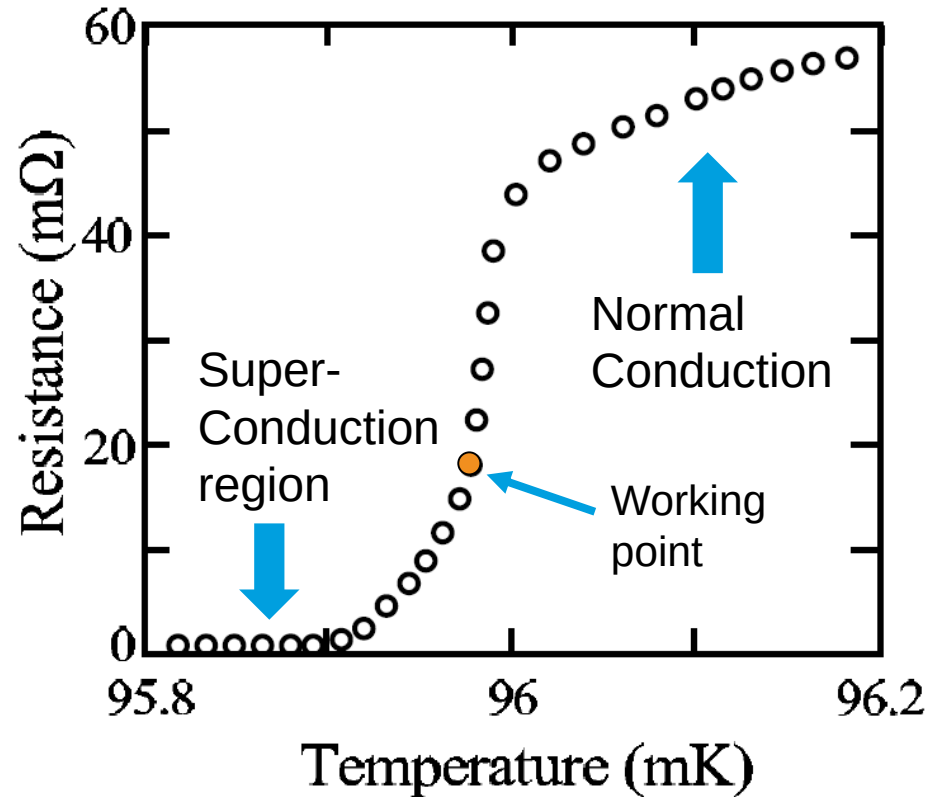
Single photon detector

Requirements for ALPS II:

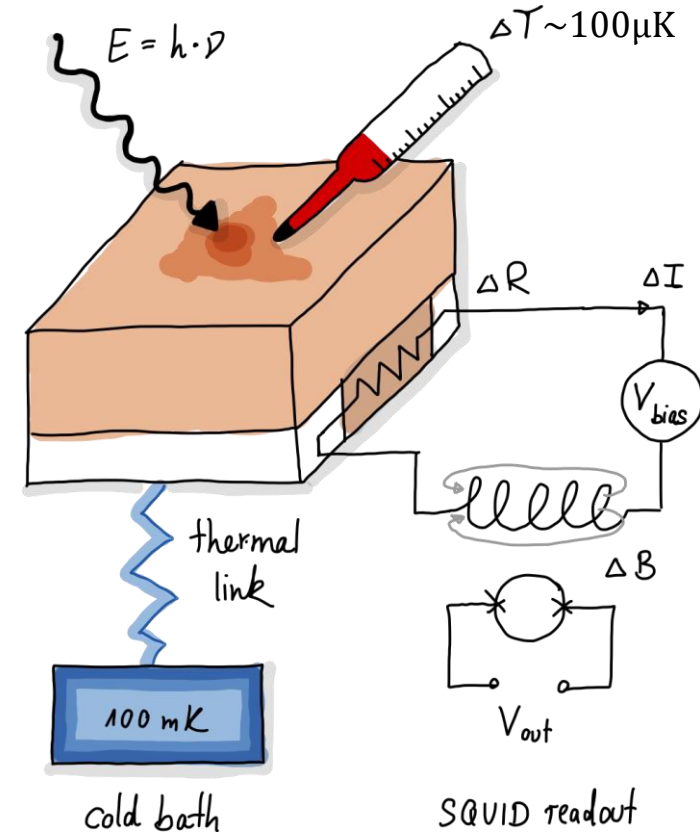
- Sensitivity to very low rates (1-2 photons a day)
- Low energy photon detection (1064nm equivalent to 1.16eV)
- Long term stability (~20 days)
- Low background rate: $< 7.7 \cdot 10^{-6} \text{cps} \sim 1 \text{ photon (1064nm-like) every 2 days}$
 - Good energy resolution (for background rejection)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

A Transition Edge Sensor (TES) could meet them!

Transition Edge Sensors



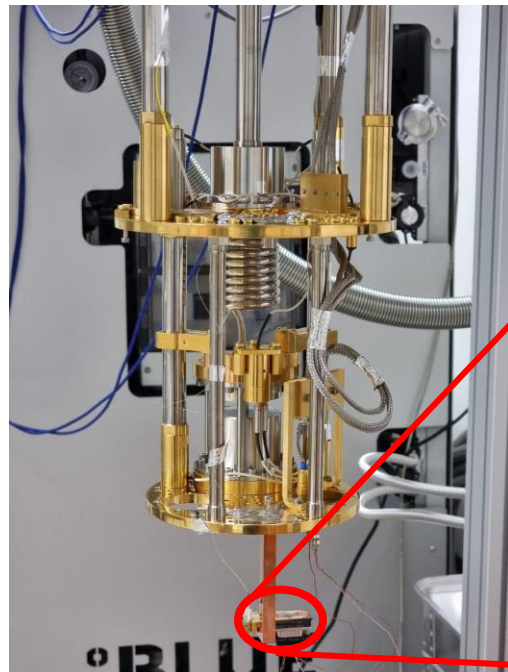
K. Irwin, G. Hilton, Transition-edge sensors, in: Cryogenic Particle Detection, Springer Berlin Heidelberg, Berlin, Heidelberg, 2005, pp. 63–150, http://dx.doi.org/10.1007/10933596_3.



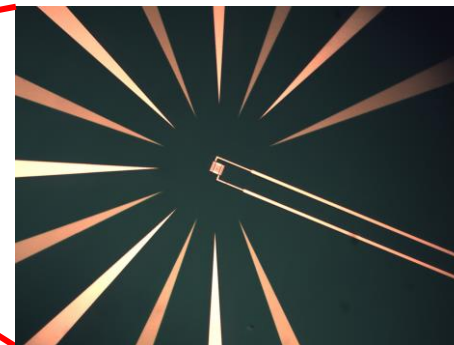
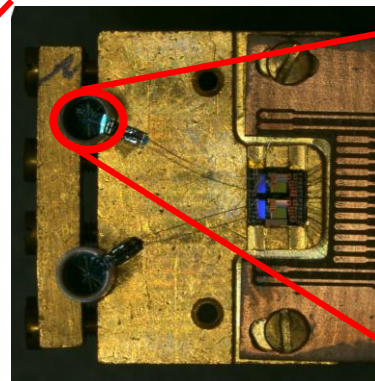
*Courtesy of Katharina-Sophie Isleif

- 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

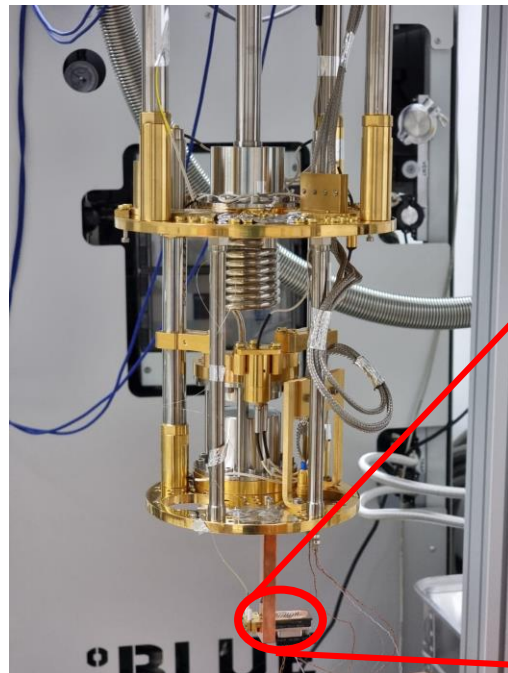
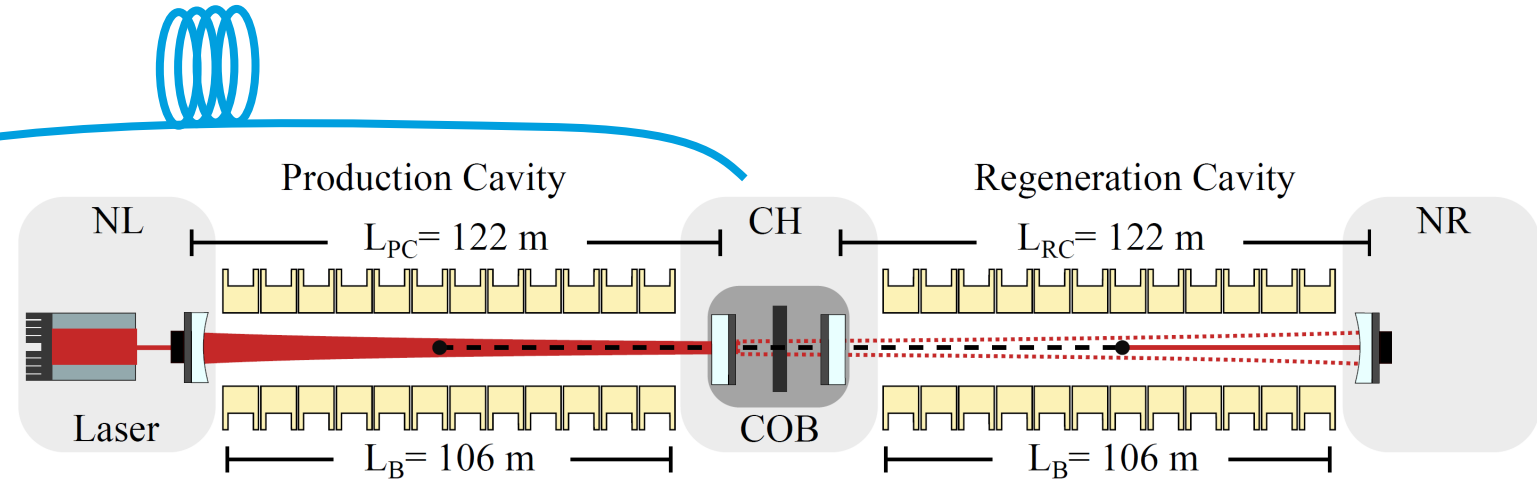


A tungsten microchip provided by NIST and PTB ($25\text{ }\mu\text{m} \times 25\text{ }\mu\text{m} \times 20\text{ nm}$) operated in the transition region ($\sim 140\text{ mK}$)

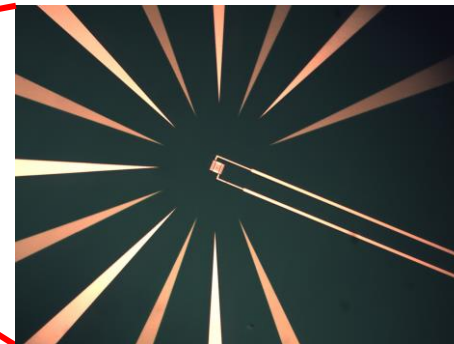
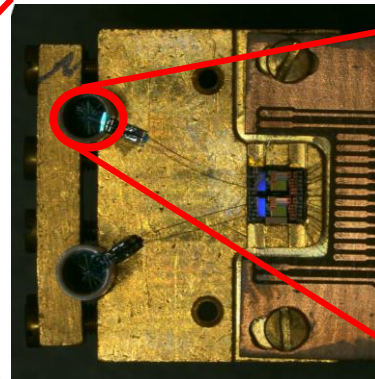


1064 nm photon
 $E \approx 1.16\text{ eV}$

TES at DESY

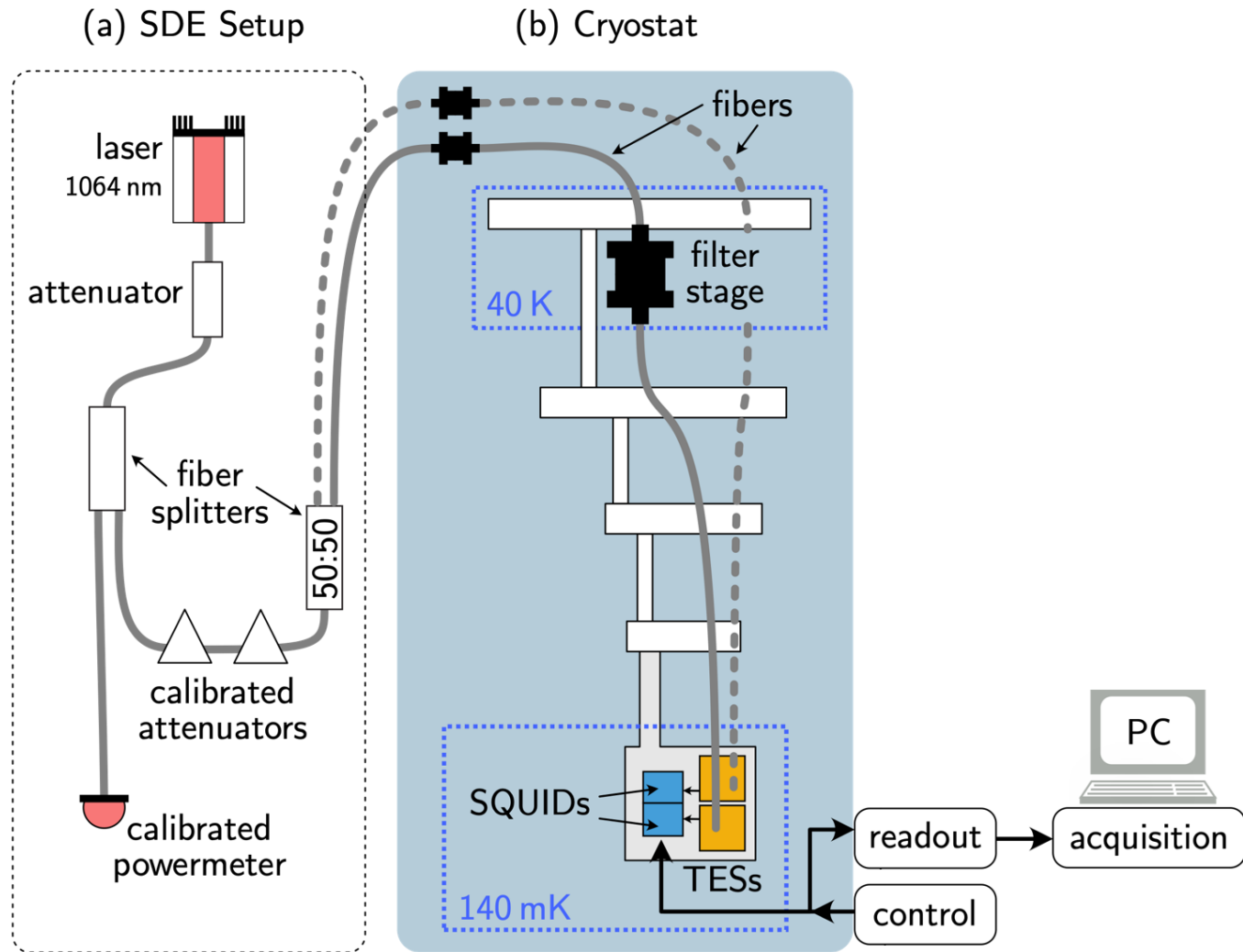


A tungsten microchip provided by NIST and PTB ($25\text{ }\mu\text{m} \times 25\text{ }\mu\text{m} \times 20\text{ nm}$) operated in the transition region ($\sim 140\text{ mK}$)



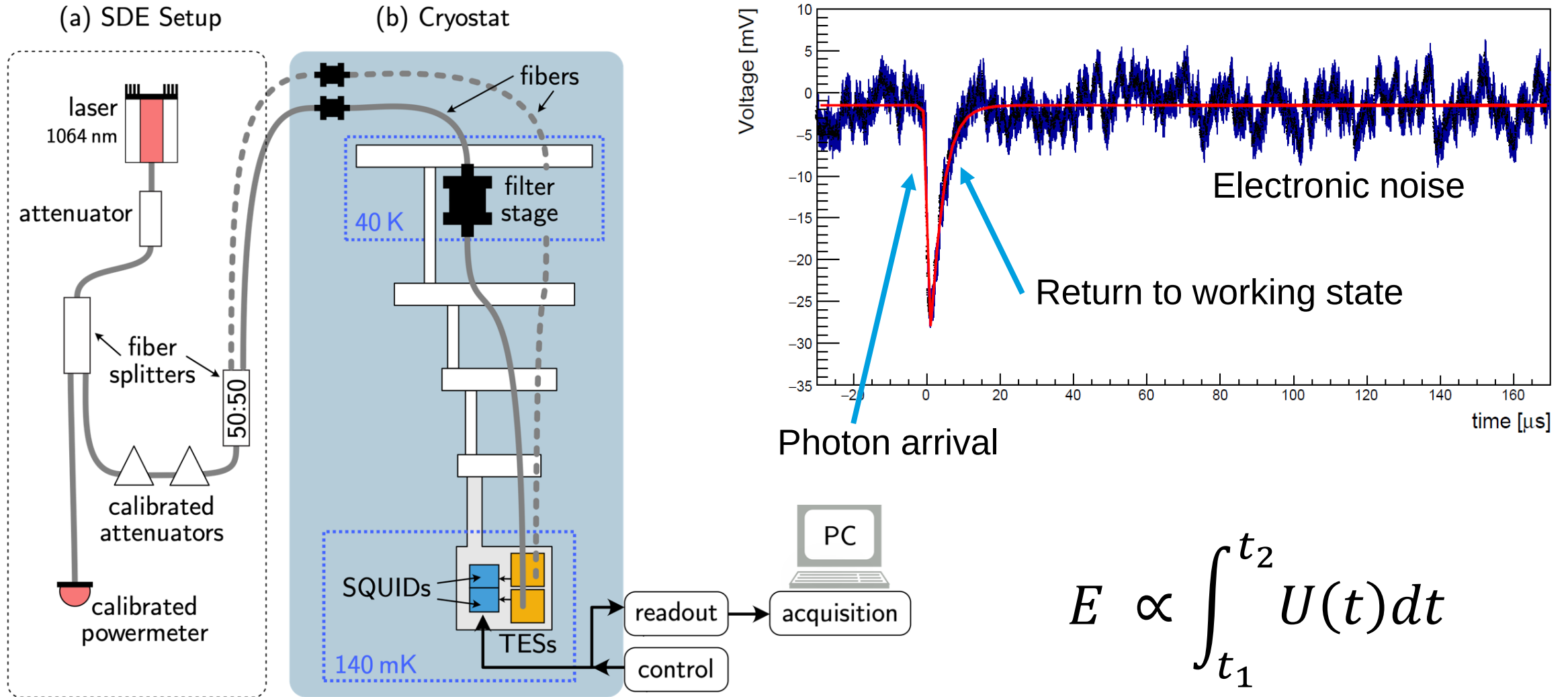
1064 nm photon
 $E \approx 1.16\text{ eV}$

Characterizing the TES



Schematic adapted from Katharina-Sophie Isleif.

Characterizing the TES



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: $< 7.7 \cdot 10^{-6} \text{cps} \sim 1 \text{ photon (1064nm-like) every 2 days}$
 - Intrinsic
 - Extrinsic
 - Good energy resolution (for background rejection)
- High detection efficiency

Intrinsics background (no fiber connected)

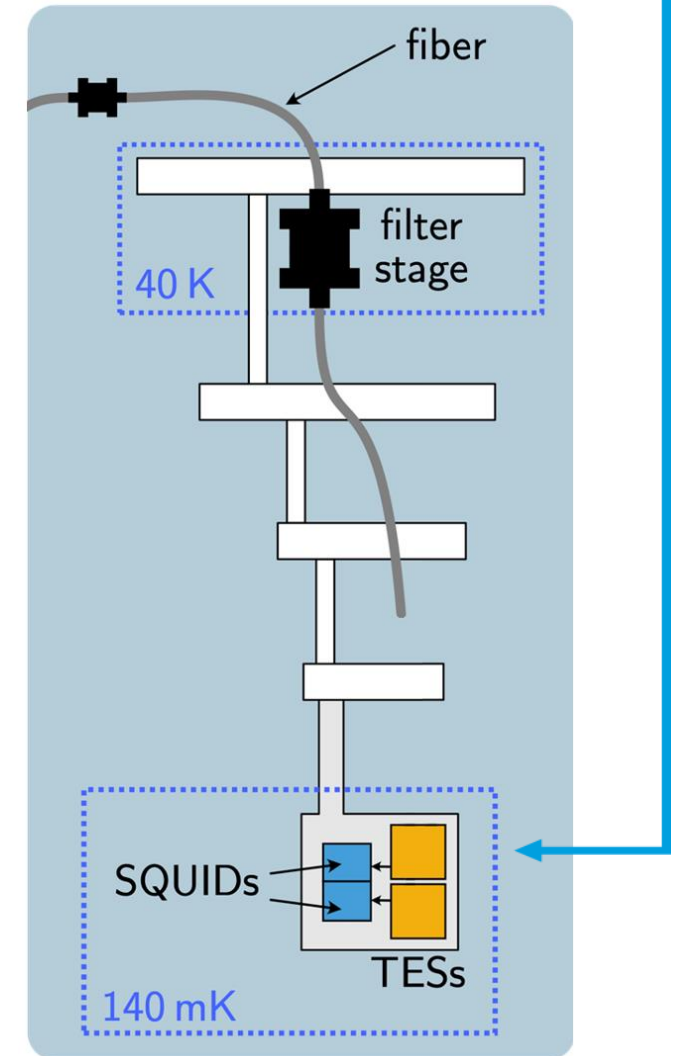
ALPS II requirements:

$< 7.7 * 10^{-6}$ 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:

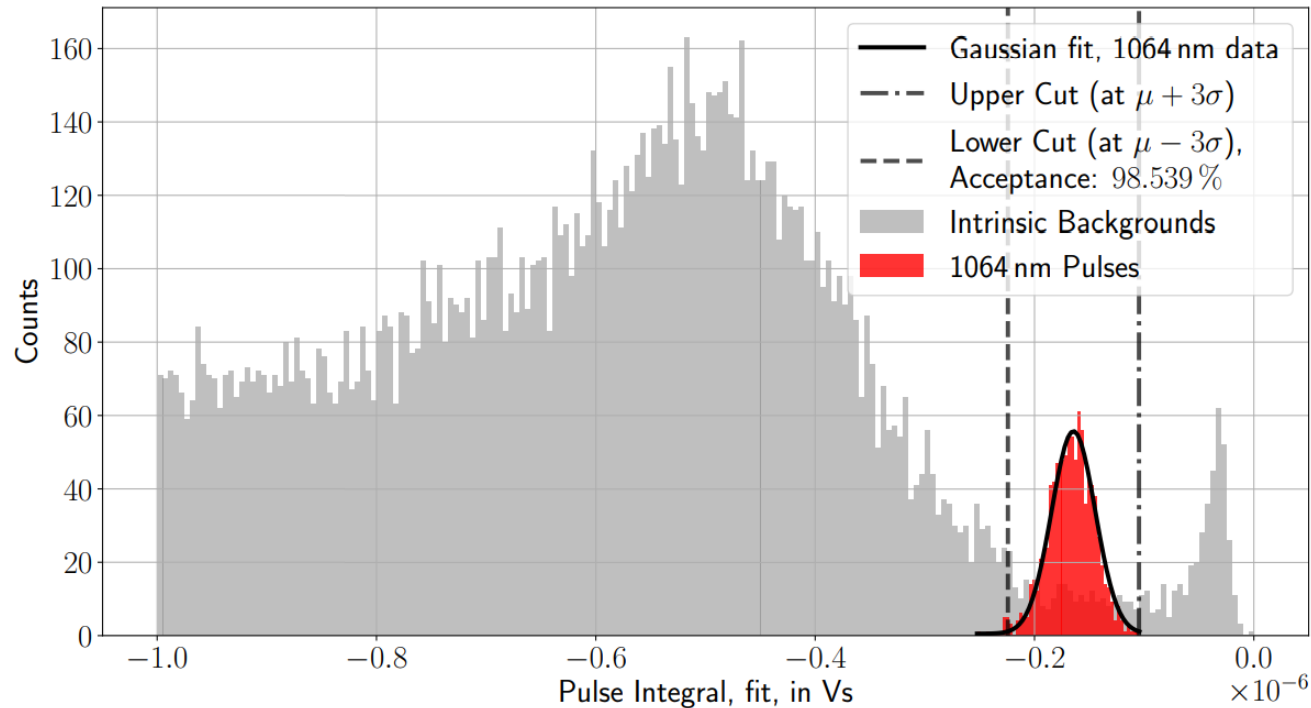
- Electronic noise
- Cosmic Rays (Muons)
- Radioactivity (Surrounding materials)



Schematic adapted from Katharina-Sophie Isleif.

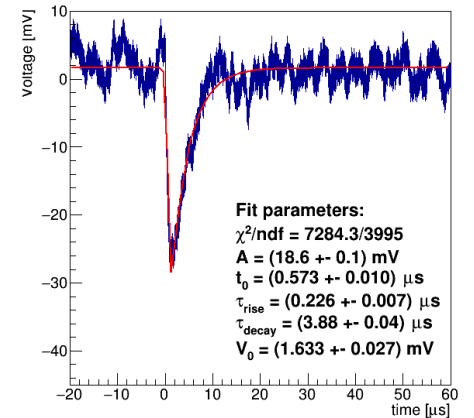
[1] Rikhav Shah, Katharina-Sophie Isleif, Friederike Januschek, Axel Lindner and Matthias Schott, "TES Detector for ALPS II", Proceedings of The European Physical Society Conference on High Energy Physics, Volume 398, Page 801, (2022); <https://doi.org/10.22323/1.398.0801>

Intrinsics background results



[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>

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



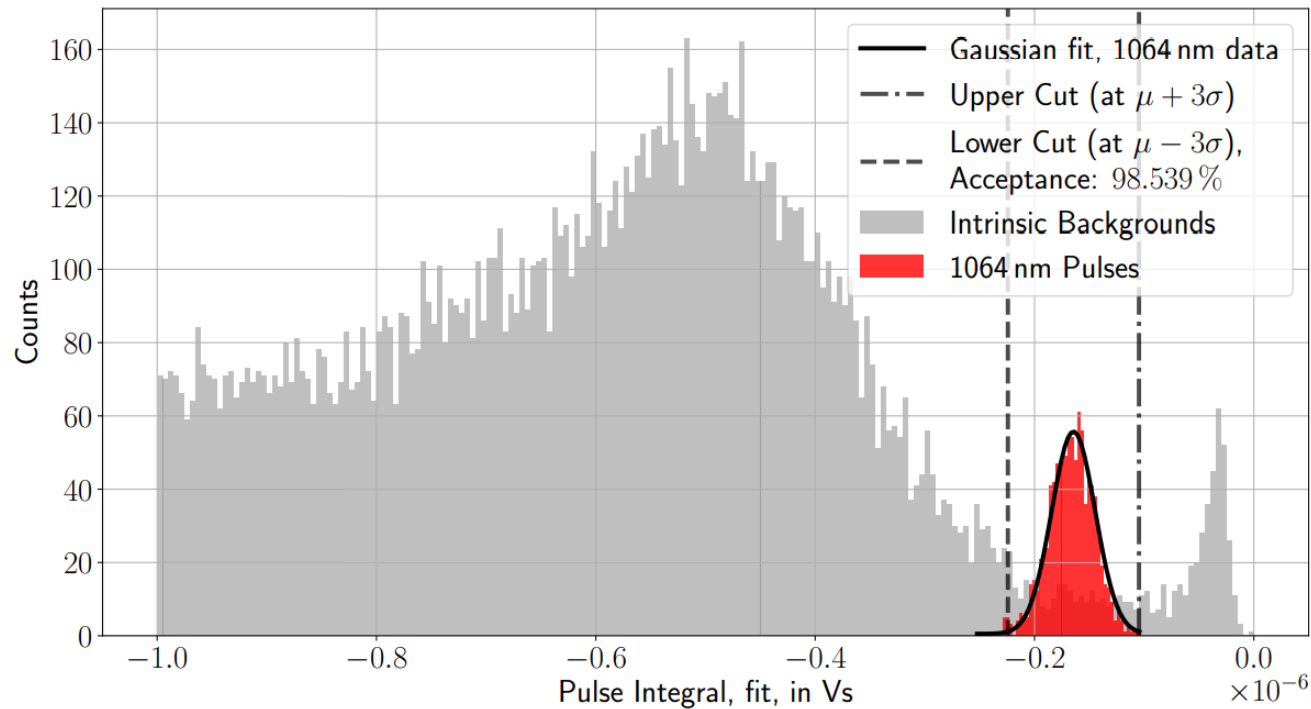
Able to exclude intrinsics backgrounds and maintain the acceptance for 1064 nm pulses

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]

Intrinsics background results

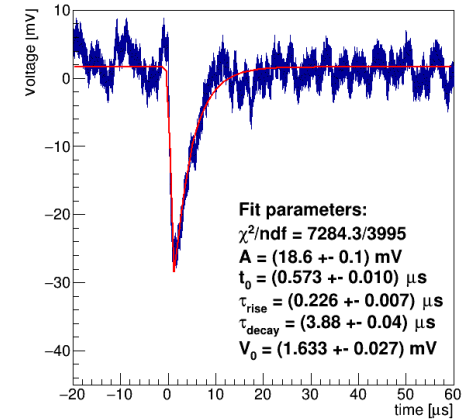


[1] Rikhav Shah, Katharina-Sophie Isleif, Friederike Januschek, Axel Lindner and Matthias Schott, "TES Detector for ALPS II", Proceedings of The European Physical Society Conference on High Energy Physics, Volume 398, Page 801, (2022); <https://doi.org/10.22323/1.398.0801>

The TES could be feasible for direct Dark Matter detection



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



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

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]

This morning, Direct Dark Matter Searches with ALPS II's TES Detector System • Christina Schwemmbauer

Extrinsics background (fiber connected)

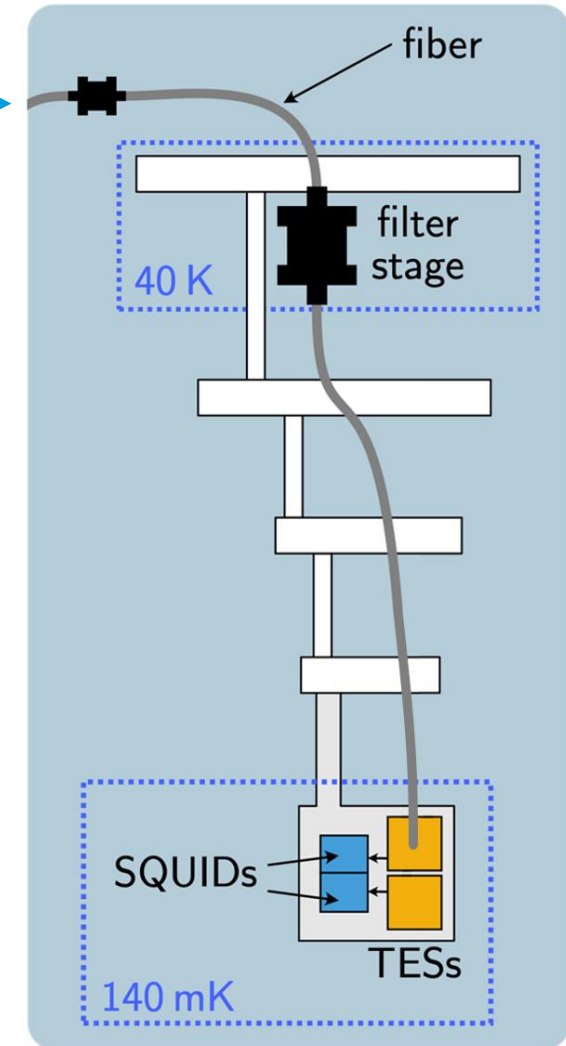
Expected additional contributions from:

- Black Body Radiation in the form of:
 - Direct photons $\longrightarrow$ ~ 1064 nm
 - Pileup photons $\longrightarrow$ looks like ~ 1064 nm

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

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

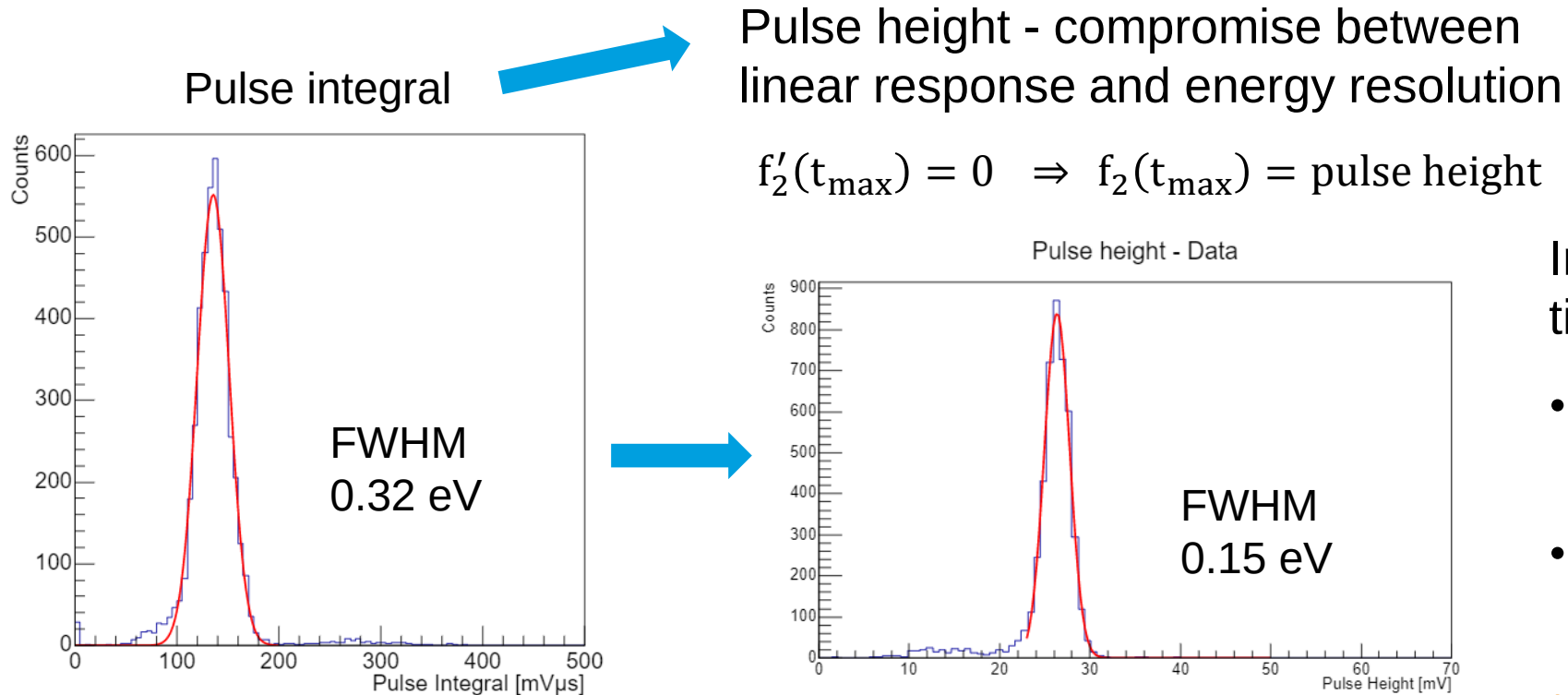
Improving **energy resolution** to mitigate background



Schematic adapted from Katharina-Sophie Isleif.

Frequency domain analysis

Fitting procedure in frequency domain, based on function from TES Small Signal theory [2].



Phenomenological approach (time)

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

Pulse height, SST

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

Improvements with respect to time domain analysis:

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

[2] K. Irwin, G. Hilton, Transition-Edge Sensors, Springer Berlin Heidelberg, Berlin, Heidelberg, 2005, pp. 63–150. doi:10.1007/10933596_3

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: $< 7.7 \cdot 10^{-6} \text{cps} \sim 1 \text{ photon (1064nm-like) every 2 days}$ ✓
 - Intrinsic ✓
 - Extrinsic ○
 - Good energy resolution (for background rejection) ✓
- High detection efficiency

System Detection Efficiency (SDE) 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

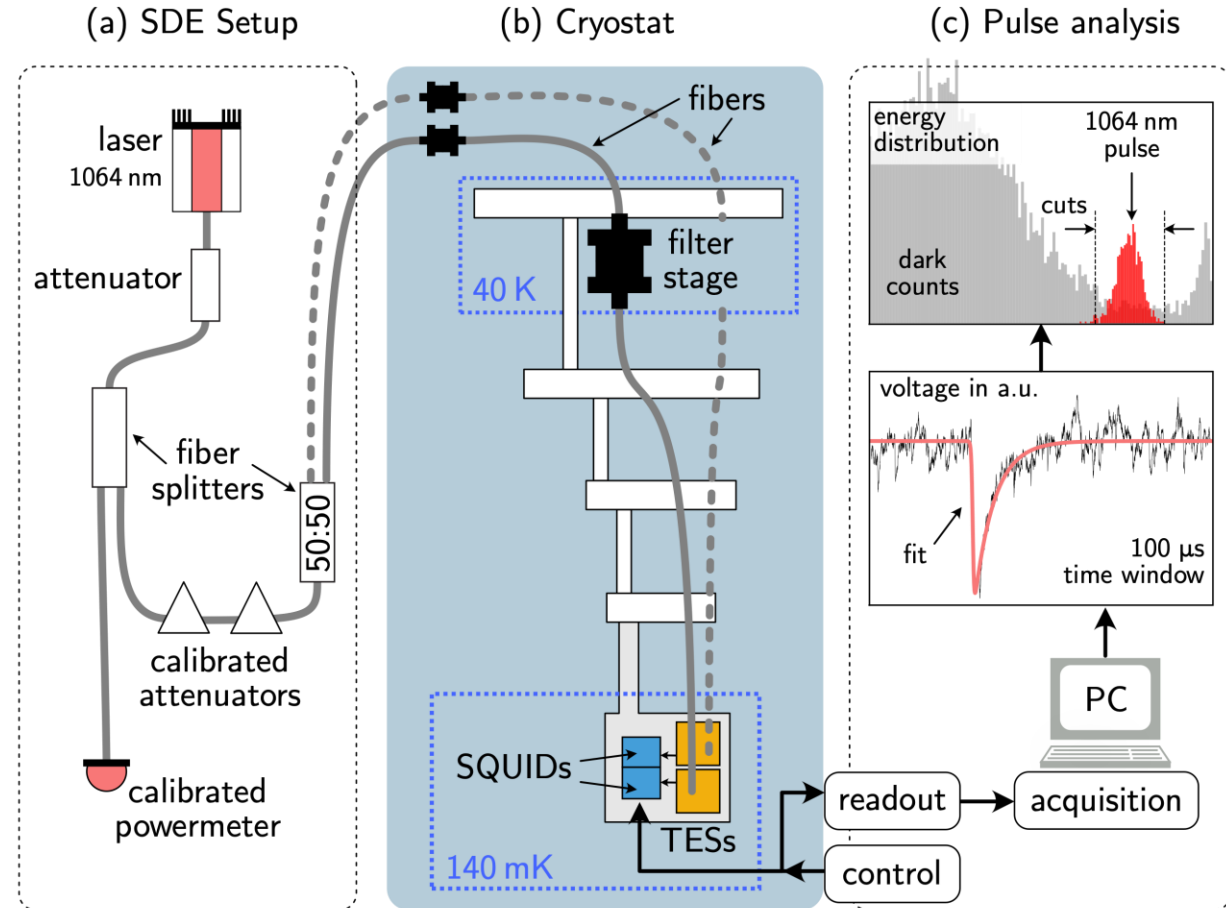
Counts converted to power and compared with reference

Main challenge:

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

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

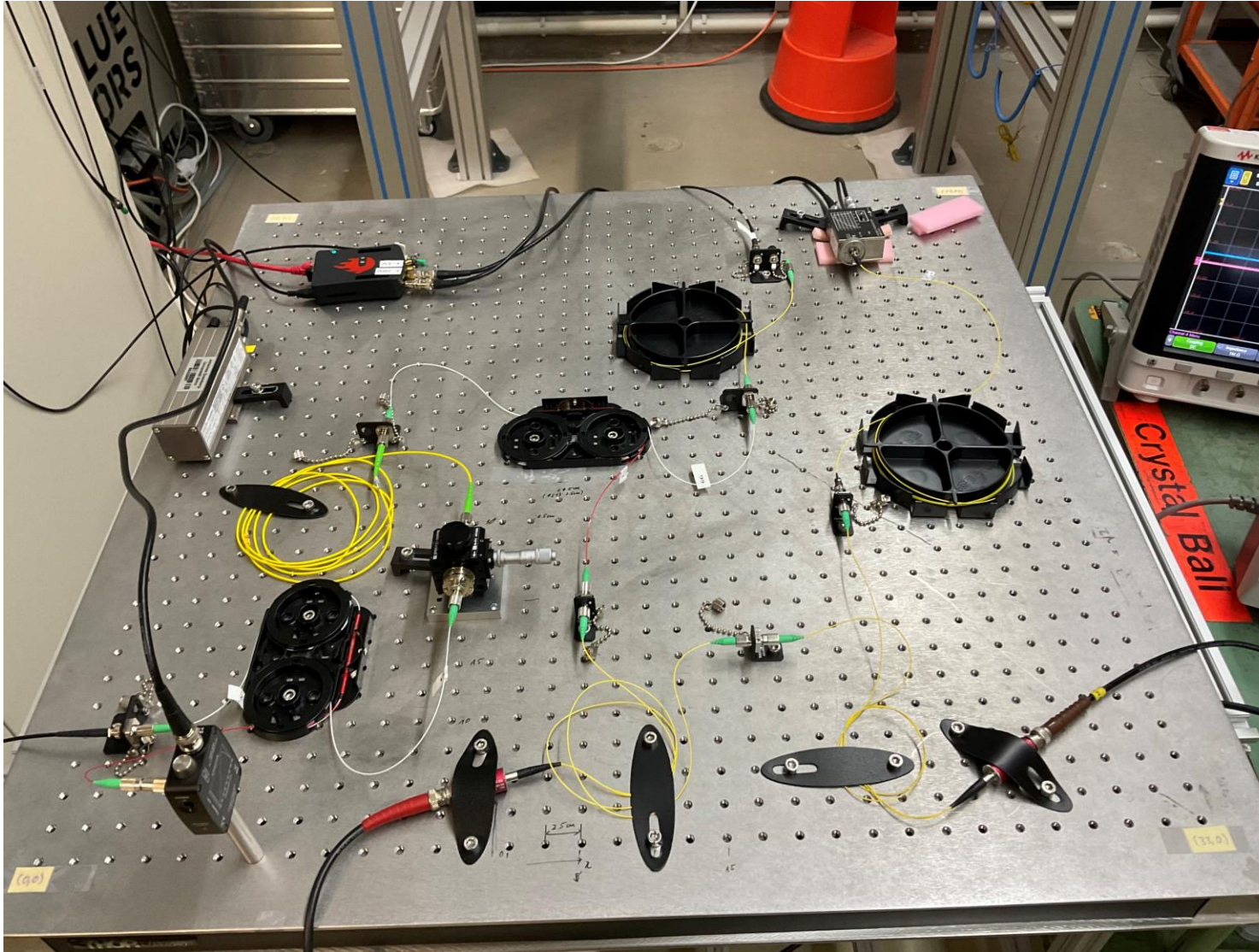
Measurement setup based on [3].



[3] 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.

System Detection Efficiency measurement



Photon rate in TES Photon energy Power split ratio

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

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 = $(93 \pm 1)\%$

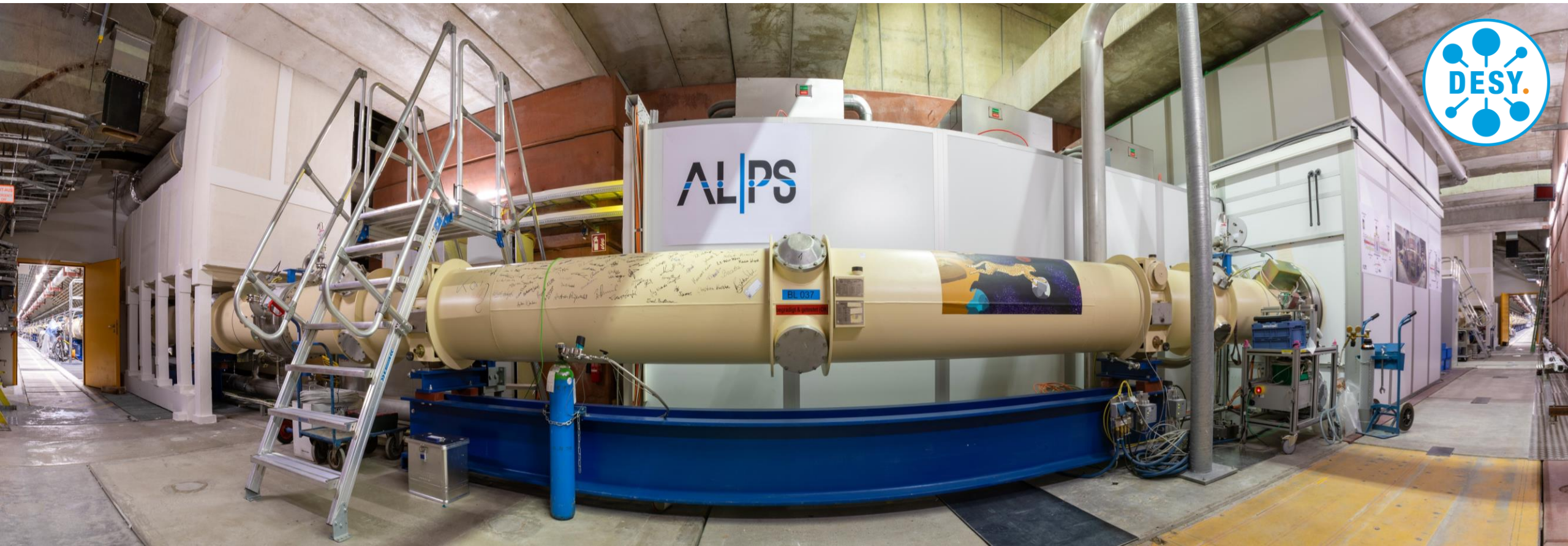
Summary & Outlook

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: $< 7.7 \cdot 10^{-6} \text{cps} \sim 1 \text{ photon (1064nm-like) every 2 days}$ ✓
- Intrinsic ✓ extrinsic ○ very good energy resolution ✓
- High detection efficiency ✓

And also ...

ALPS II data taking started with HET successfully
Studying feasibility of the TES for direct dark matter detection



Thank you.

Contact

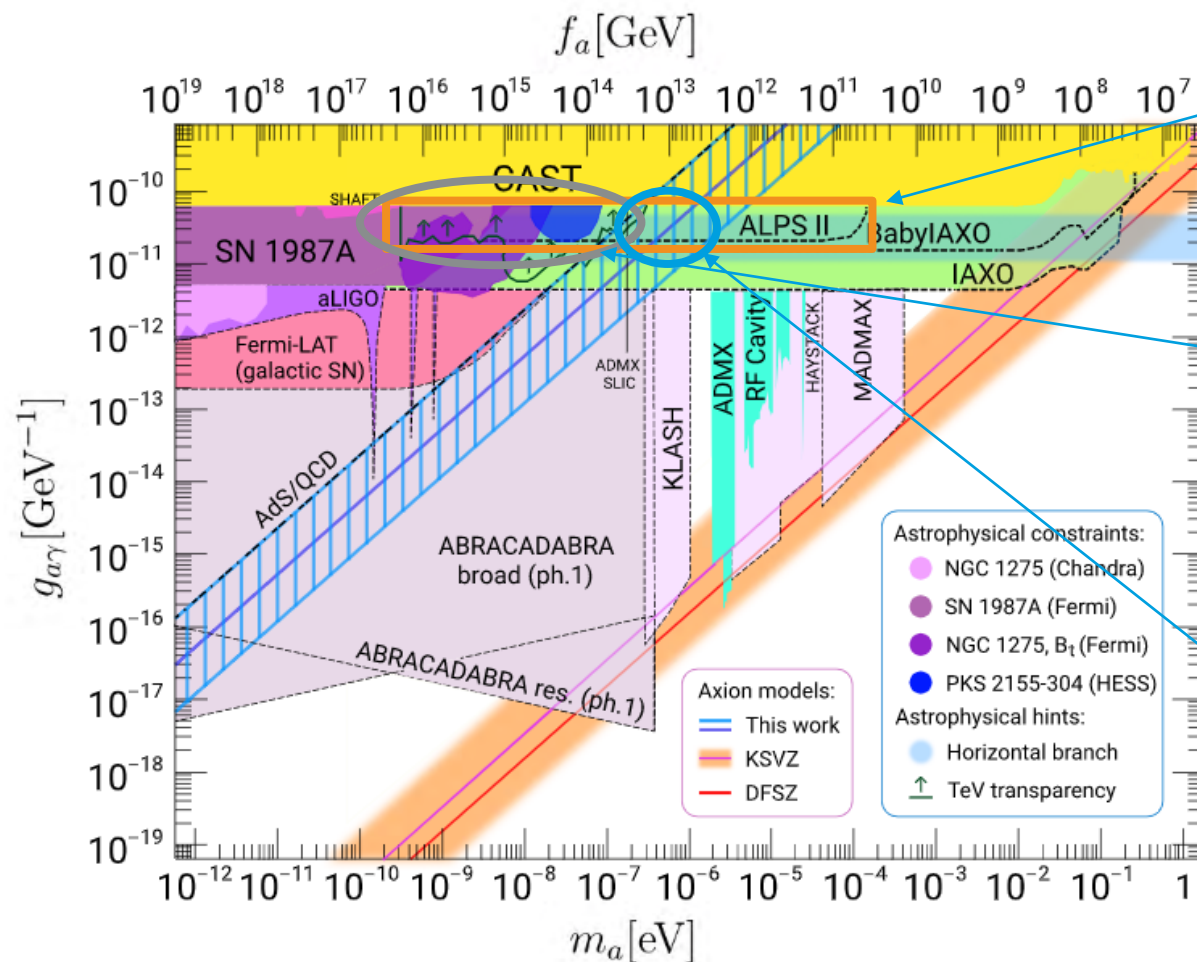
DESY. Deutsches
Elektronen-Synchrotron

www.desy.de

José Alejandro Rubiera Gimeno
ALPS
jose.rubiera.gimeno@desy.de

Backup

Axion-photon coupling



ALPS II

Motivated by anomalies in the evolution of stars

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

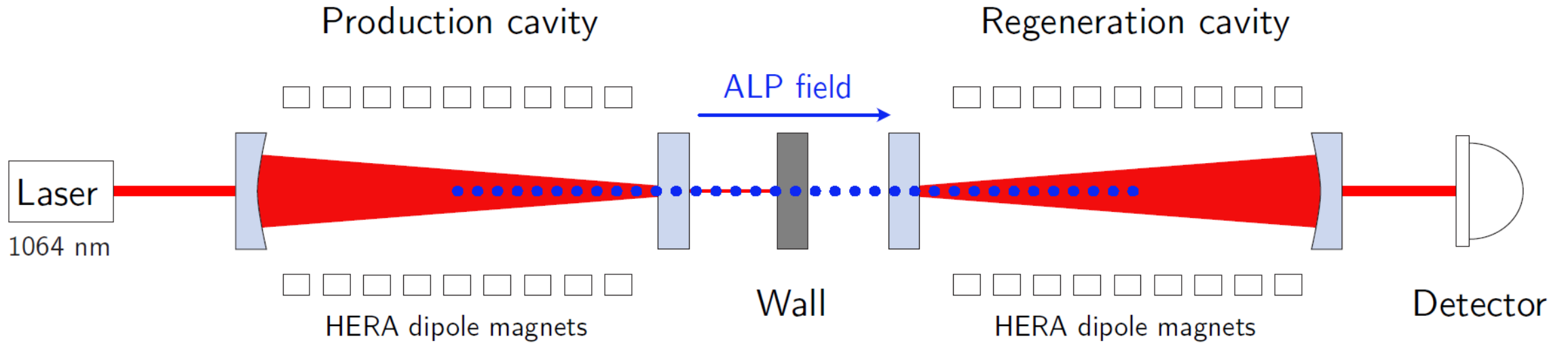
TeV Transparency

Best sensitivity among LSW experiments

New theory of QCD axion

[1] A. V. Sokolov and A. Ringwald, "Photophilic hadronic axion from heavy magnetic monopoles," [arXiv:2104.02574 [hep-ph]].

Any Light Particle Search II (ALPS II)



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

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

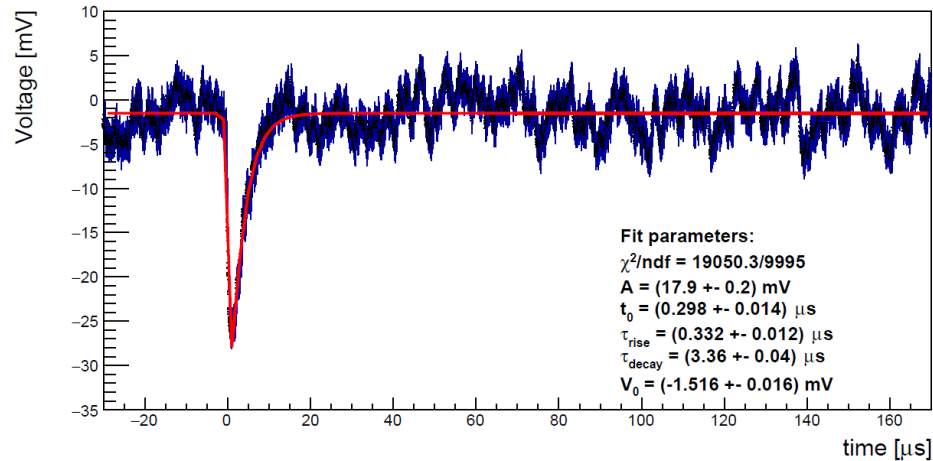
$$P_{\gamma \rightarrow a \rightarrow \gamma} = 6 \cdot 10^{-38} \underbrace{\beta_{PC}}_{5000} \underbrace{\beta_{RC}}_{16000} \left(\underbrace{\frac{g_{a\gamma\gamma}}{10^{-10} \text{ GeV}^{-1}}}_{0.2 \cdot 10^{-10} \text{ GeV}^{-1}} \underbrace{\frac{B}{1 \text{ T}}}_{5.3 \text{ T}} \underbrace{\frac{l}{10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

Schematic adapted from Katharina-Sophie Isleif.

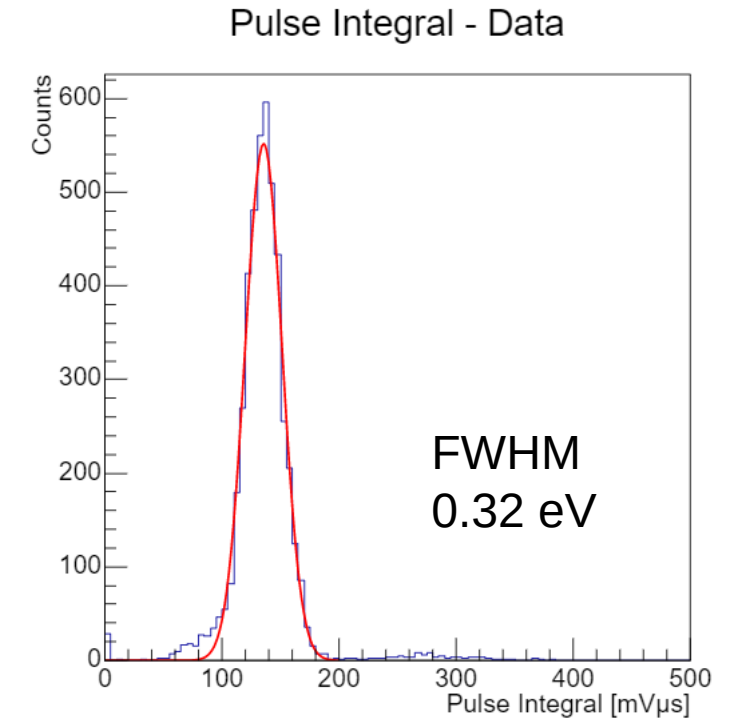
Intrinsics background results

Phenomenological approach:

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



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



Time Integral, gaussian fit:

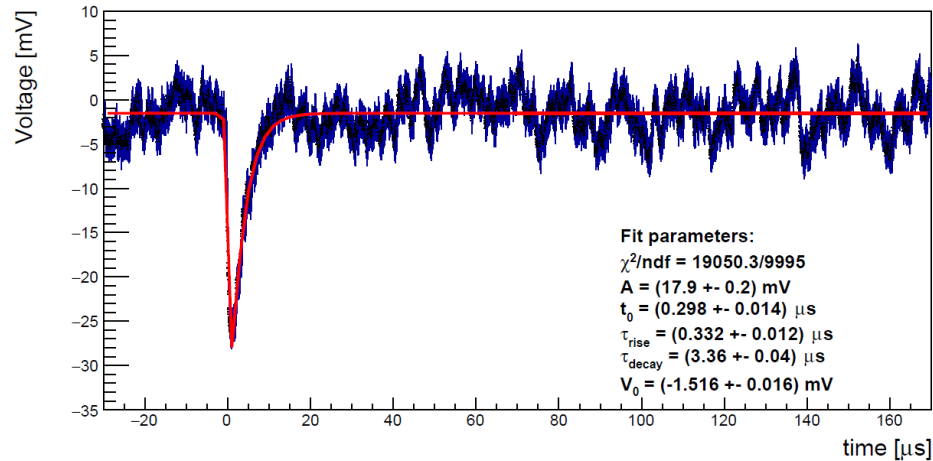
$$\frac{\sigma}{\mu} 100\% = (11.6 \pm 0.2)\%$$

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

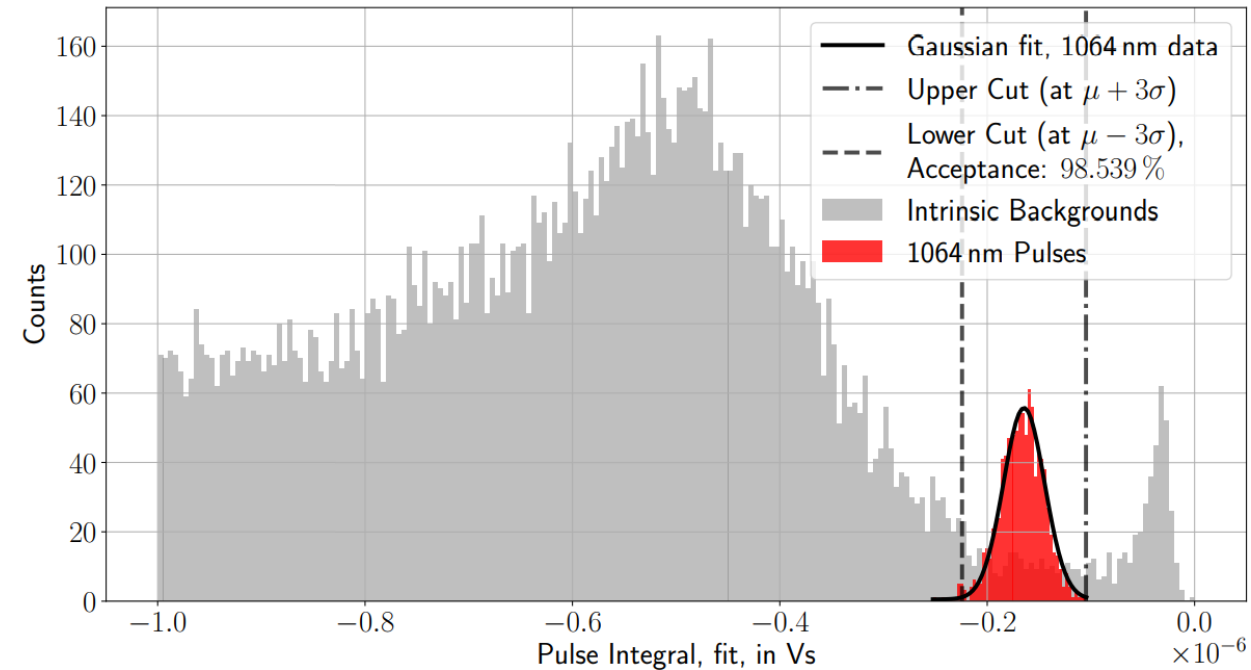
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Able to exclude intrinsics backgrounds and maintain the acceptance for 1064 nm pulses



[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



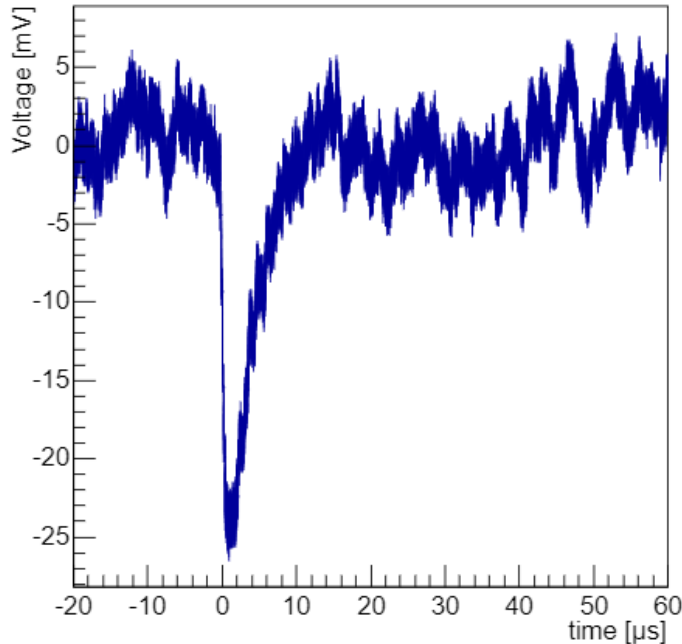
$6.9 \cdot 10^{-6}$ cps over 20 days was achieved
with acceptance greater than 90% [1]

Frequency domain analysis

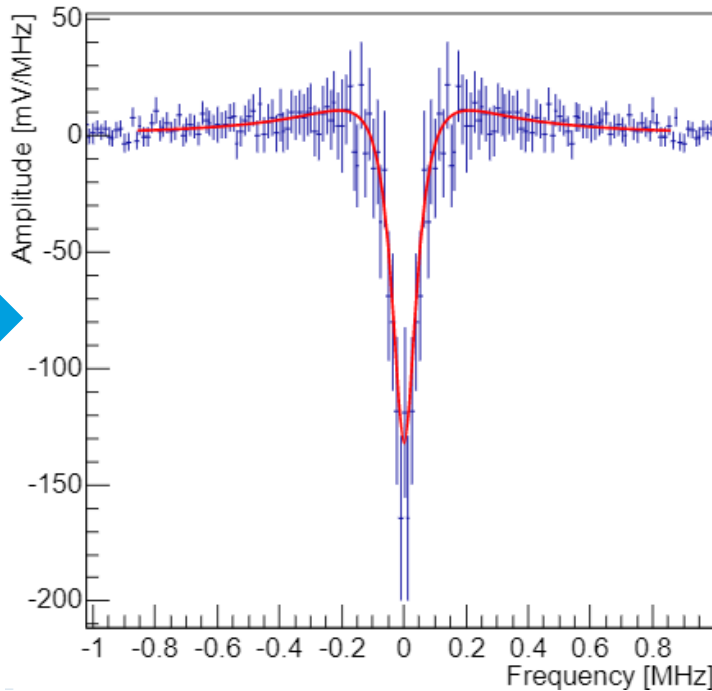
From TES theoretical description:

$$f_2(t) = \begin{cases} A \left(\exp \left\{ -\frac{t-t_0}{\tau_+} \right\} - \exp \left\{ -\frac{t-t_0}{\tau_-} \right\} \right) + V_0 & , t \geq t_0 \\ V_0 & , t < t_0 \end{cases} \quad \longrightarrow \quad F(v) = A(\tau_+ - \tau_-) \frac{[1 - (2\pi v)^2 \tau_+ \tau_-] - i 2\pi v(\tau_+ + \tau_-)}{[1 + \tau_+^2 (2\pi v)^2][1 + \tau_-^2 (2\pi v)^2]} \exp\{-2\pi i v t_0\}$$

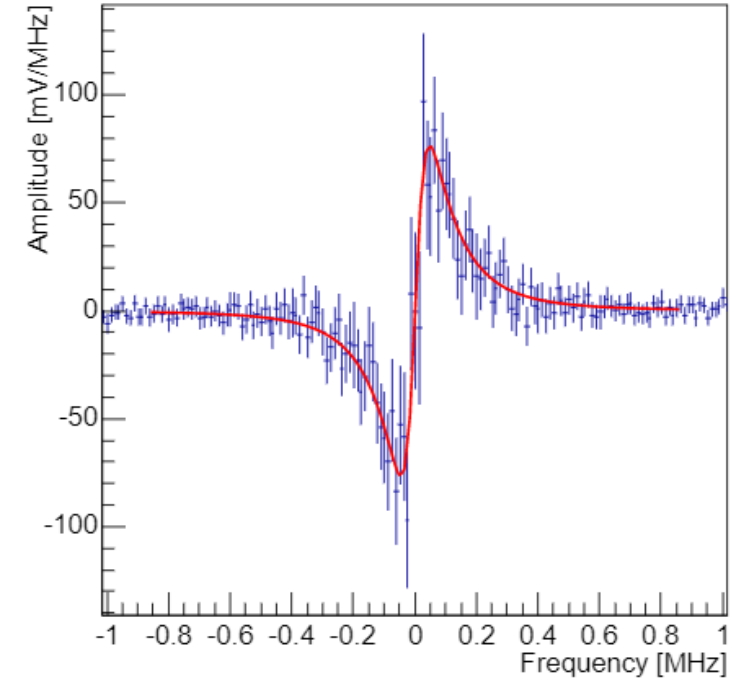
t = 0.0010617s, Pulse U vs. t



Signal FFT Real part



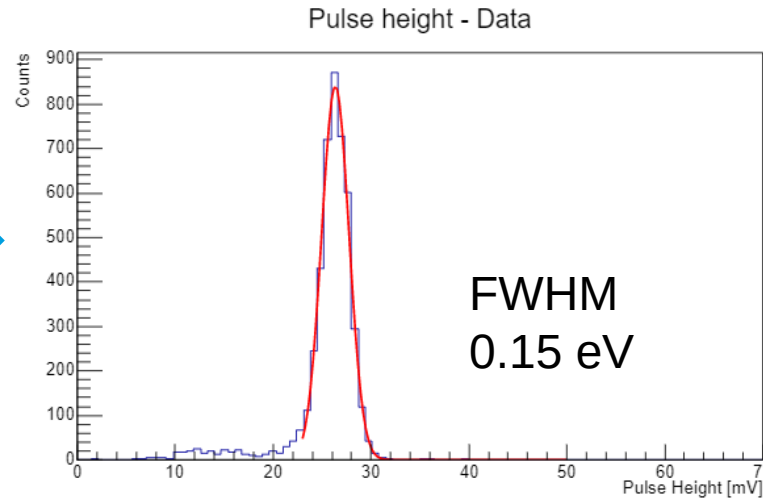
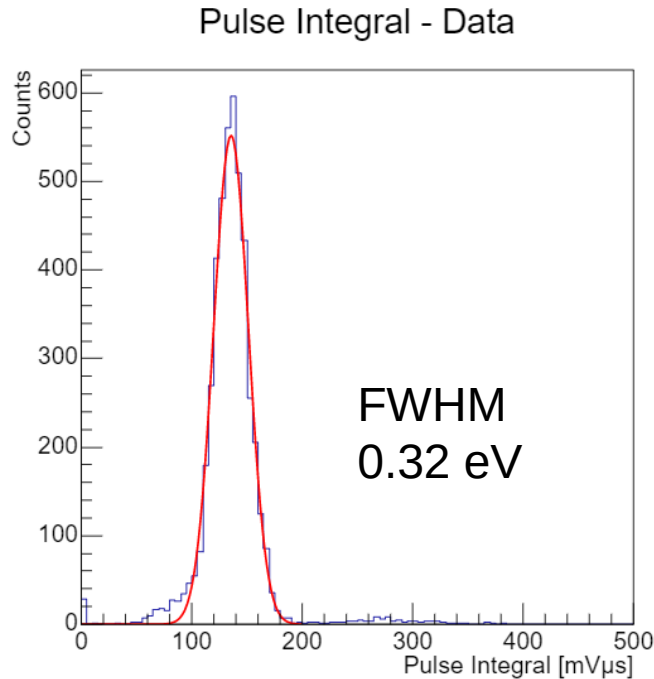
Signal FFT Imaginary part



Frequency domain analysis

Pulse height as compromise between linear response and energy resolution

$$f'_2(t_{\max}) = 0 \Rightarrow f_2(t_{\max}) = \text{pulse height}$$



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

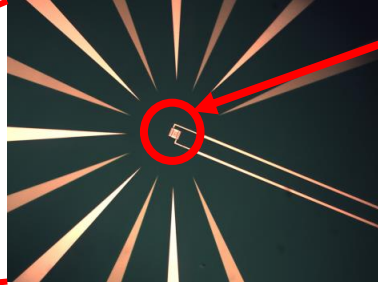
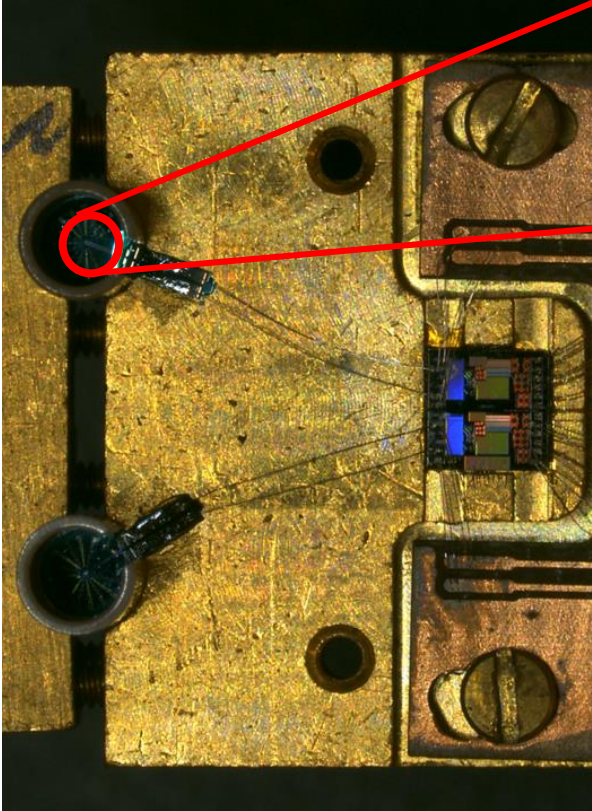
Phenomenological approach (time)

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

Pulse height, SST

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

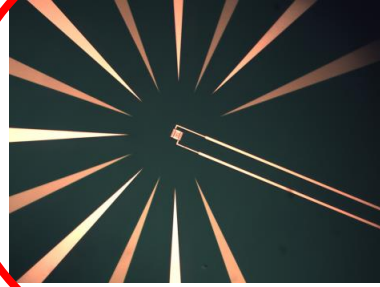
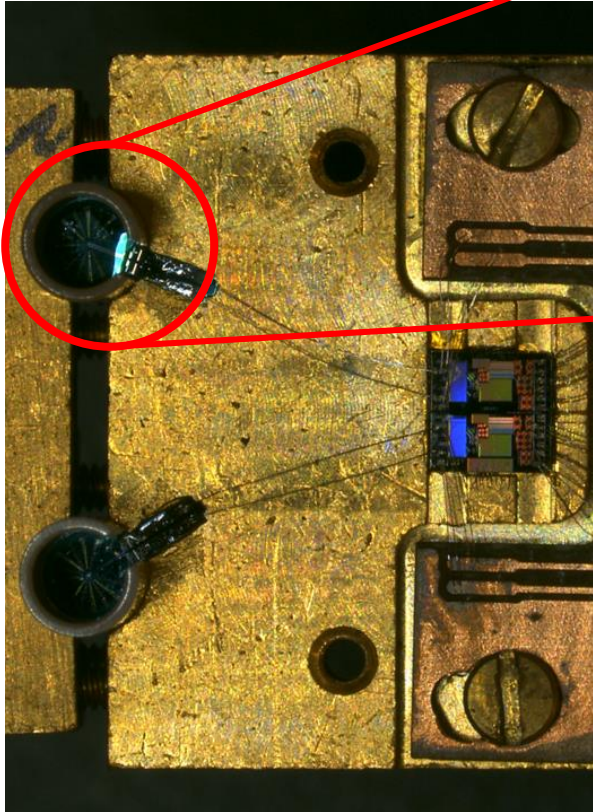
Simulation of intrinsic background



Sensitive area to 1064nm = 1.16eV photons

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

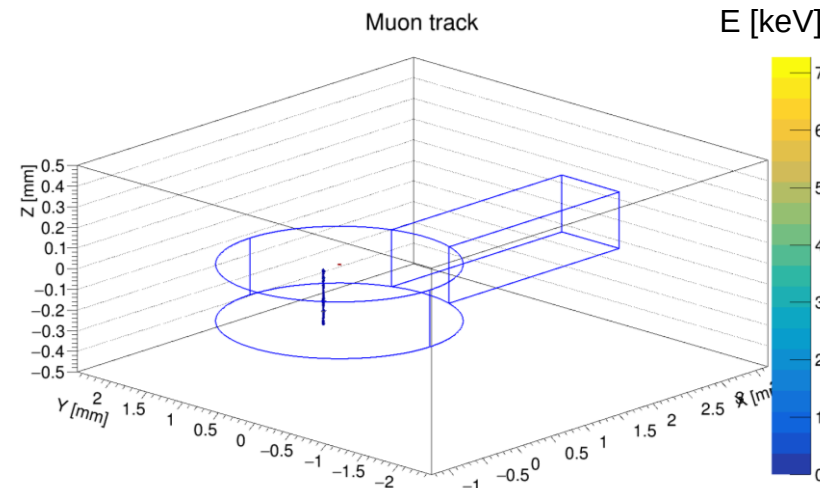
Simulation of intrinsic background



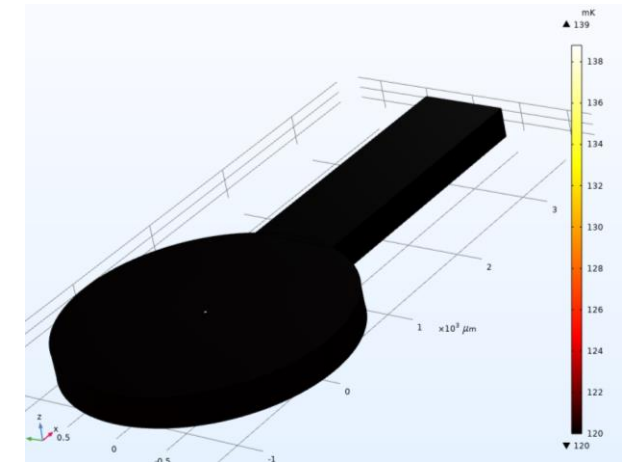
Sensitive area to $1064\text{nm} = 1.16\text{eV}$ photons

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

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

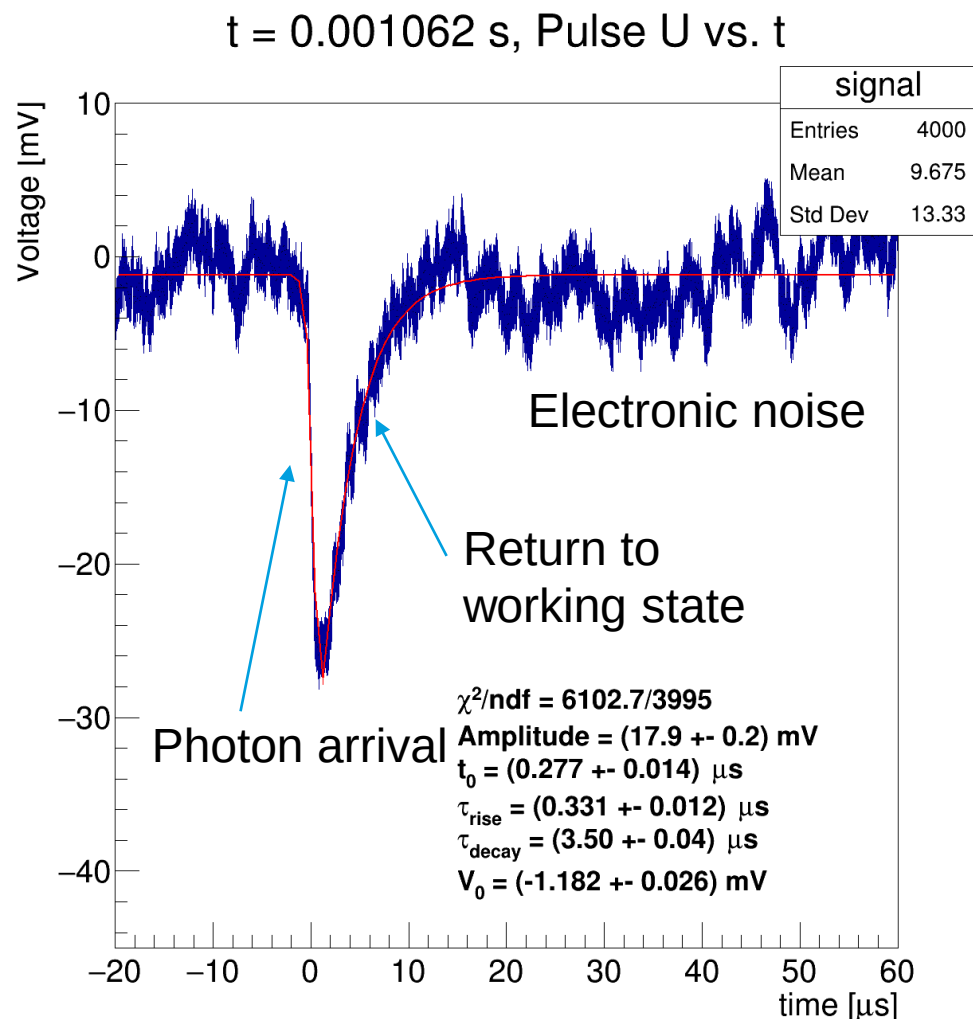


Simulation of TES physics and transport of heat in silicon substrate using COMSOL Multiphysics



Work in progress

Fitting procedure



From Small-Signal Theory:

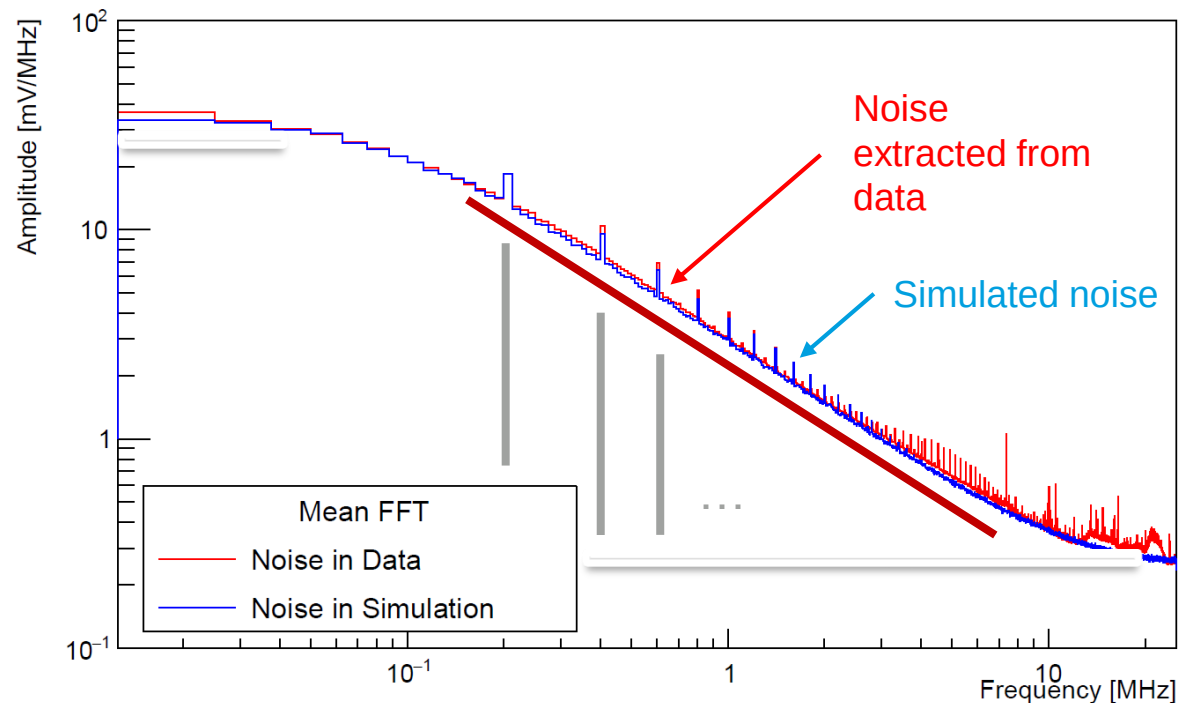
$$f_2(t) = \begin{cases} A \left(\underbrace{\exp\left\{-\frac{(t-t_0)}{\tau_+}\right\}}_{\text{Rise component}} - \underbrace{\exp\left\{-\frac{(t-t_0)}{\tau_-}\right\}}_{\text{Decay component}} \right) + V_0, & t \geq t_0 \\ V_0, & \text{else} \end{cases}$$

↓
Piecewise function

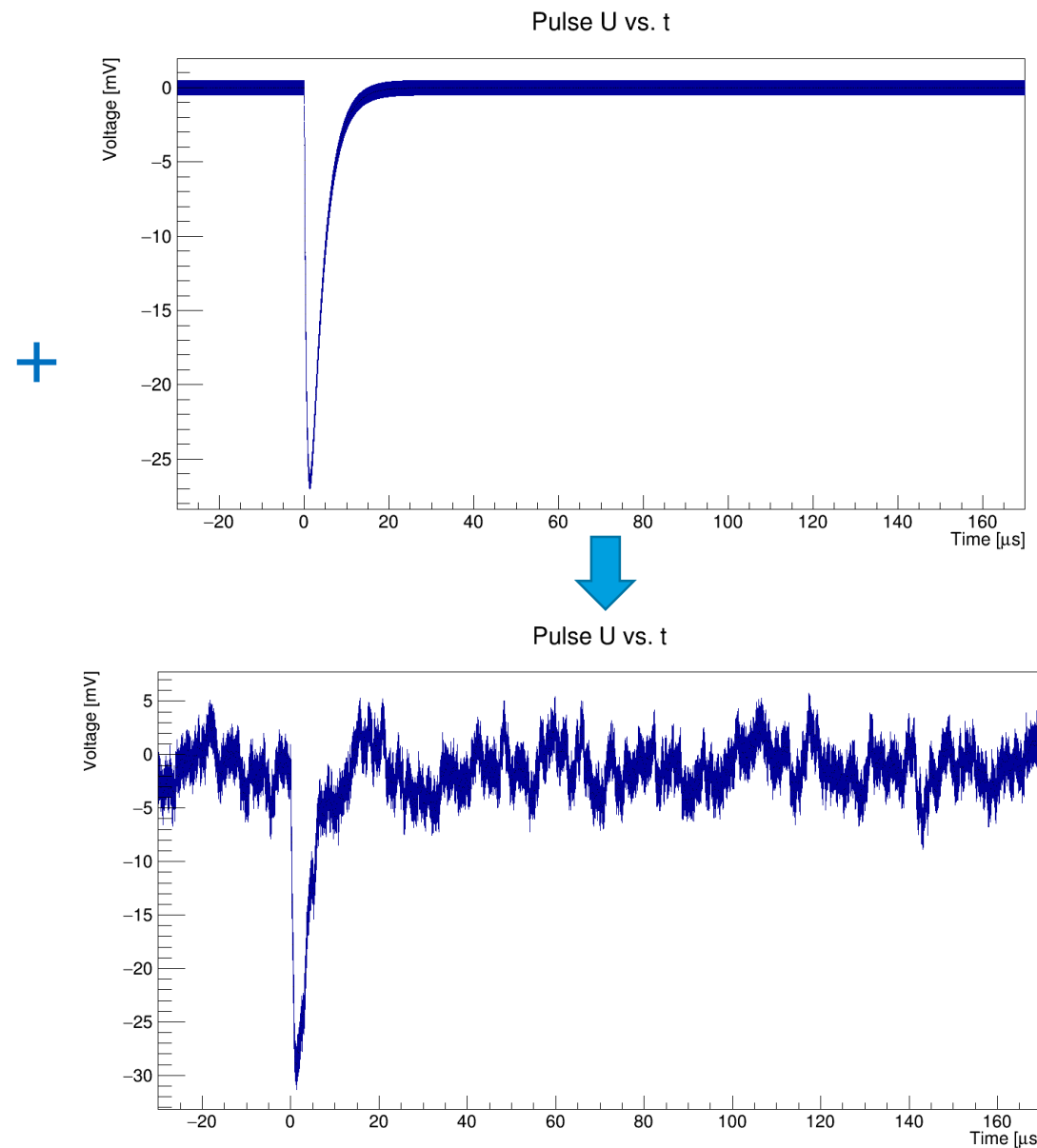
Phenomenological approach:

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

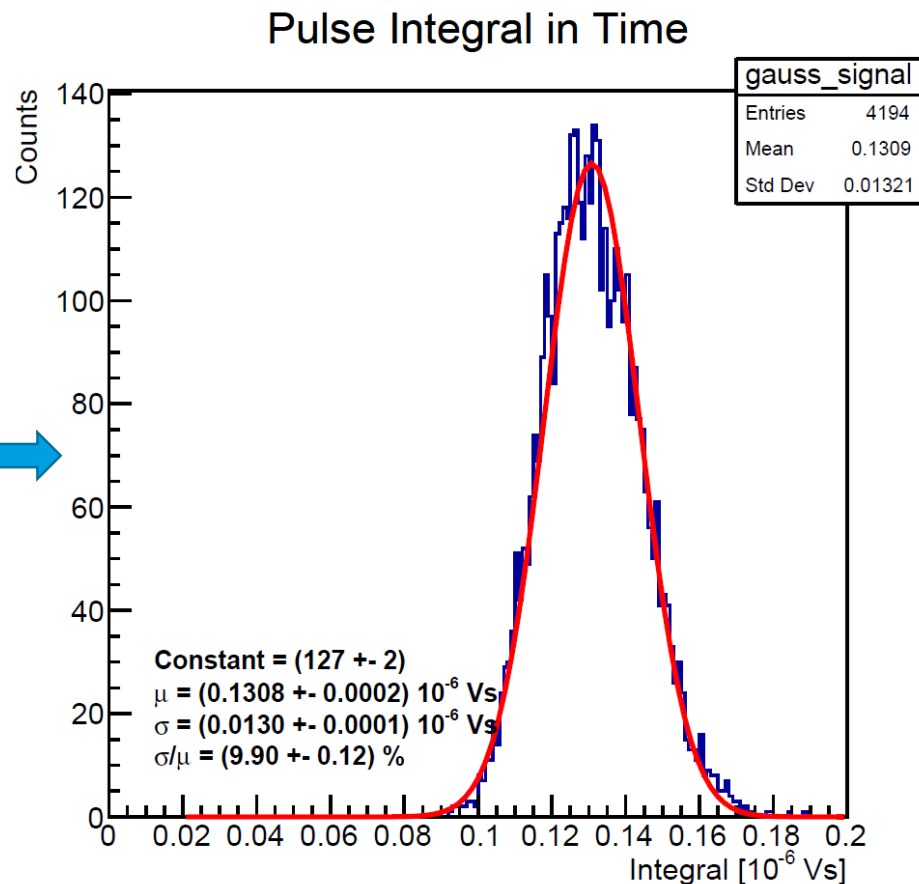
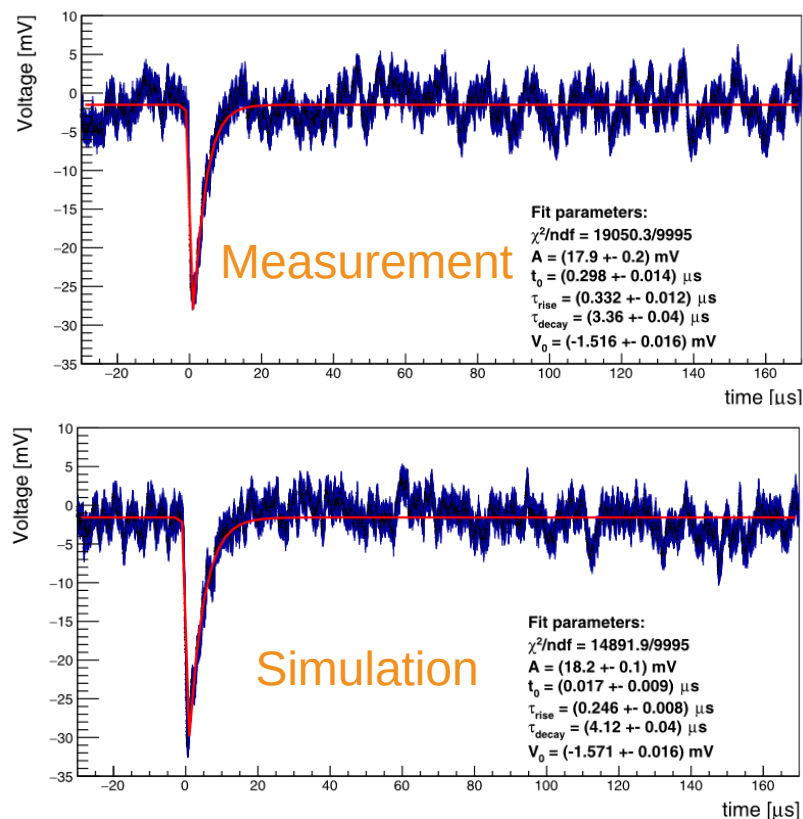
Simulation of baseline noise



- 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.

DM Searches with Superconductors

SNSPD vs TES

Limits of SNSPDs:

Works like a Geiger counter



No pulse-shape discrimination

Proposal: Use a **Transition Edge Sensor (TES)**

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

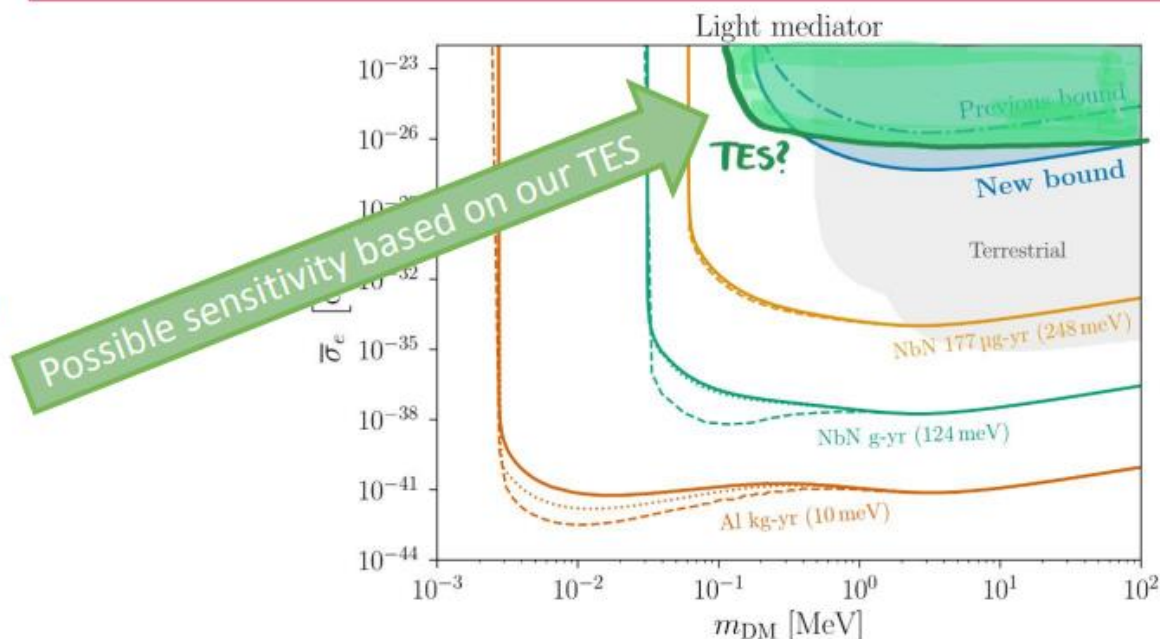
Superconducting Detectors for Super Light Dark Matter

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

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

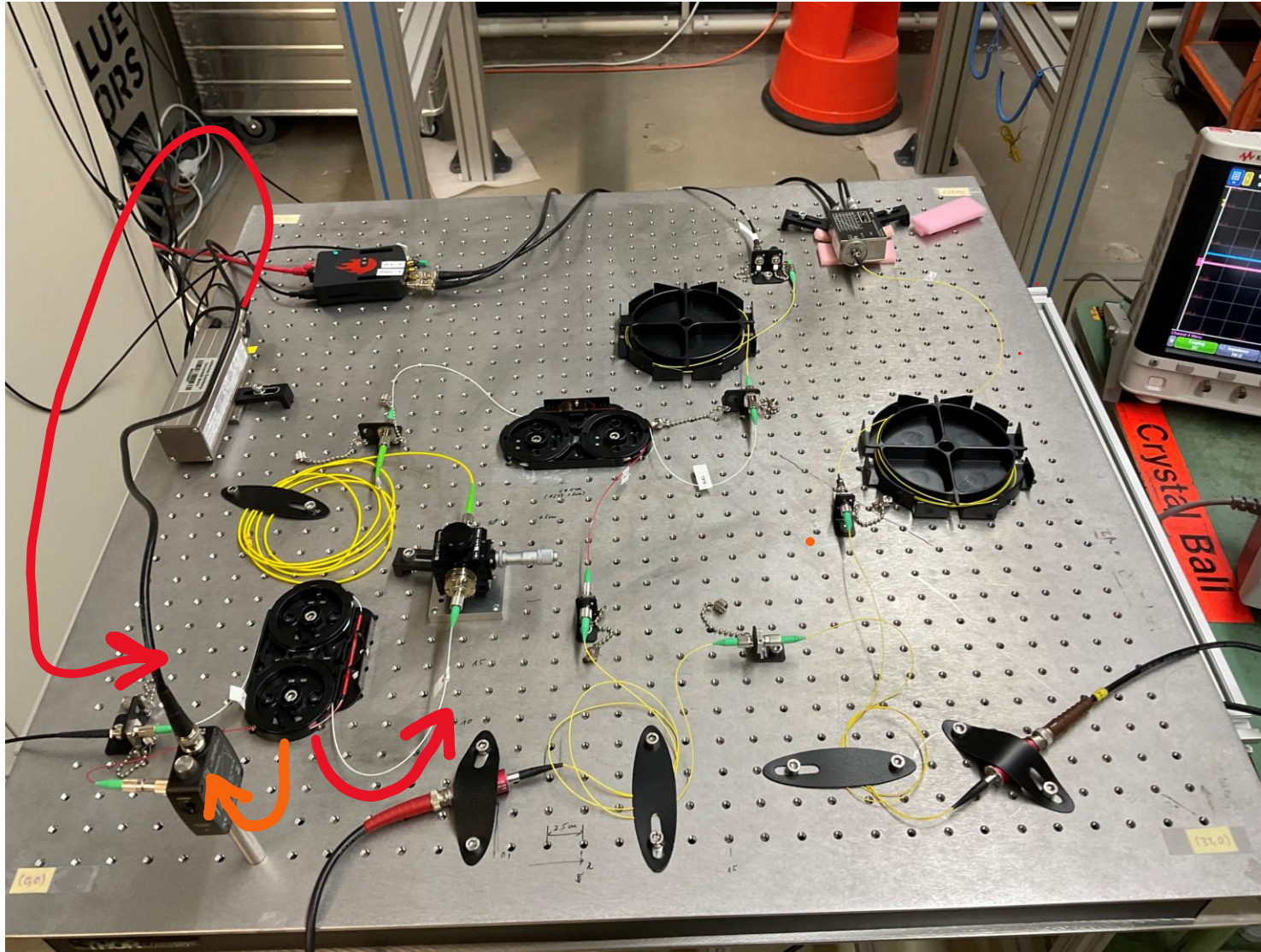
²Stanford Institute for Theoretical Physics, Department of Physics,
Stanford University, Stanford, CA 94305, U.S.A.

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.



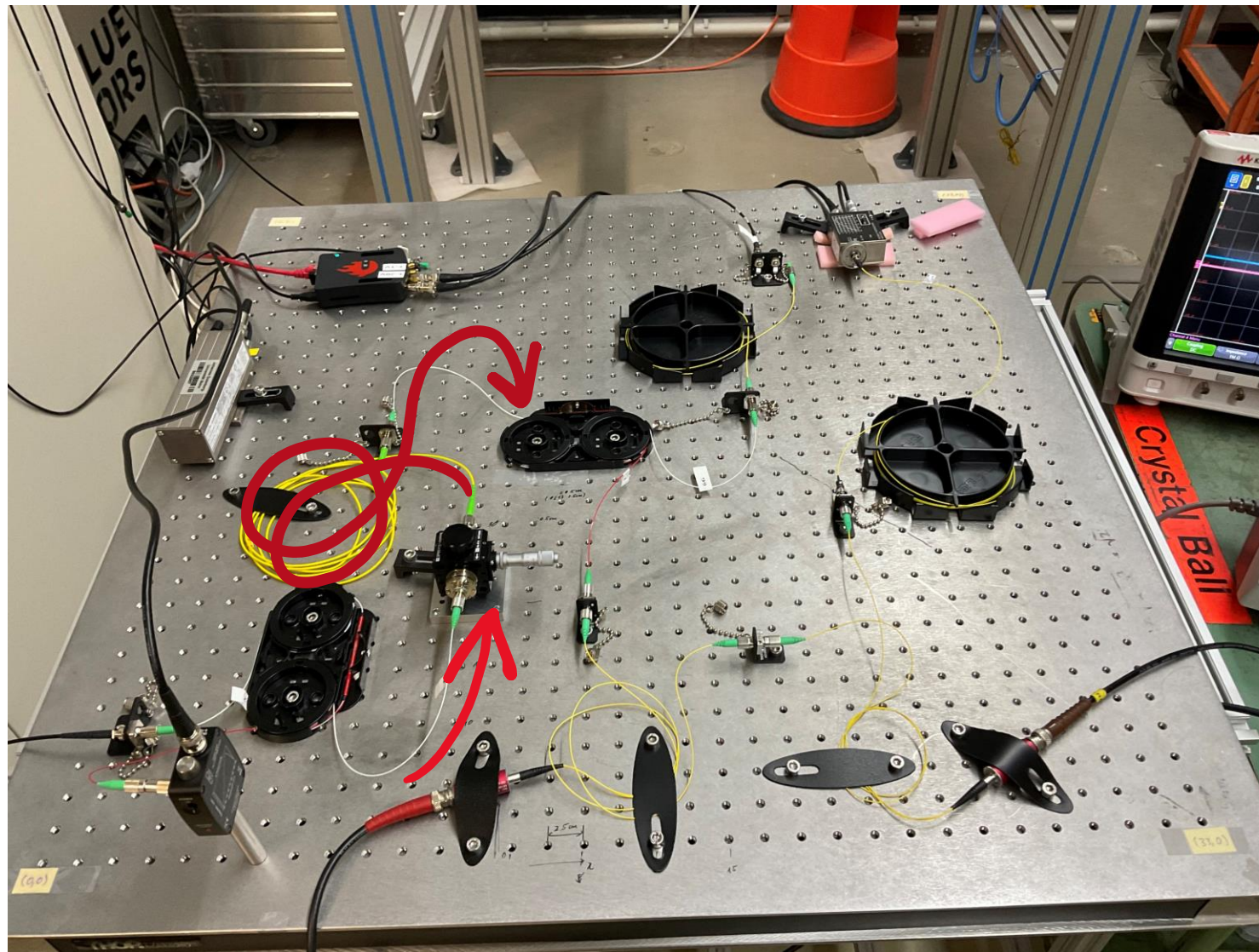
Hochberg, Y. et al. [arXiv:2110.01586](https://arxiv.org/abs/2110.01586) (2021)

Efficiency measurement



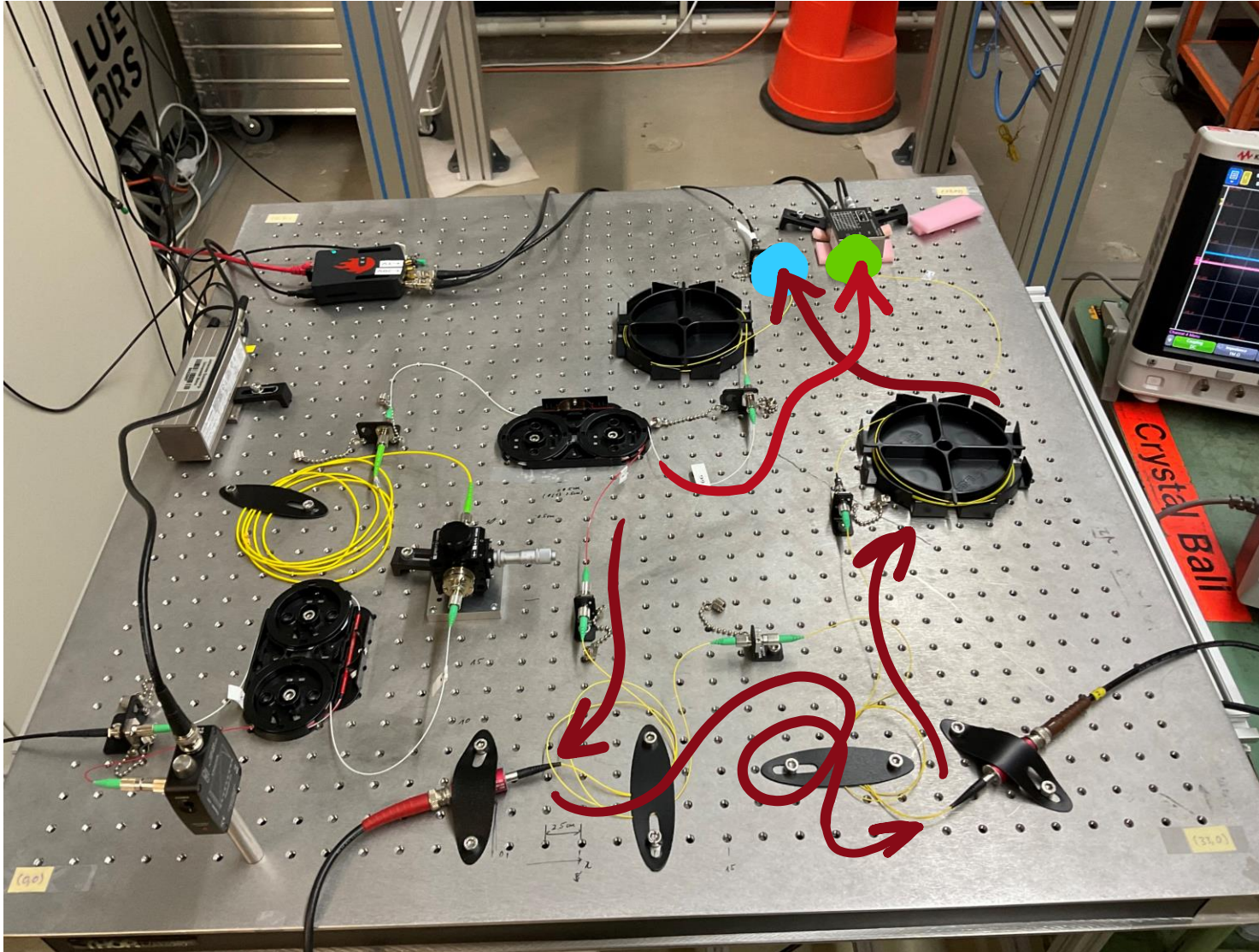
- **1064nm** laser light of 1mW.

Efficiency measurement



- **1064nm** laser light of 1mW.
- Attenuation to $\sim 100\text{pW}$.

Efficiency measurement



- **1064nm** laser light of 1mW.
- Attenuation to $\sim 100\text{pW}$.
- 99% line to **calibrated photodiode**.
- 1% line to 2 VOAs and then to **TES**.

A photograph of a laboratory setup on a perforated metal table. The setup includes various electronic components, cables, and a laptop. Red arrows and a green circle highlight specific connections or components. A yellow label '131.01' is visible in the bottom right corner.

- **1064nm** laser light of 1mW.
- Attenuation to $\sim 100\text{pW}$.
- 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 $\neq$ 1064nm

Blackbody spectrum: vicinity of 1064nm

Possible DM search: $\lambda > 1064\text{nm}$

Good energy resolution is required.

All equipment delivered. Measurements will start very soon.

