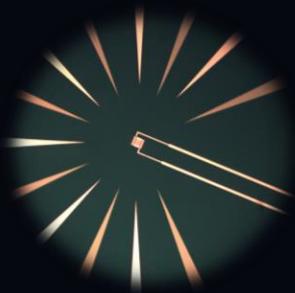


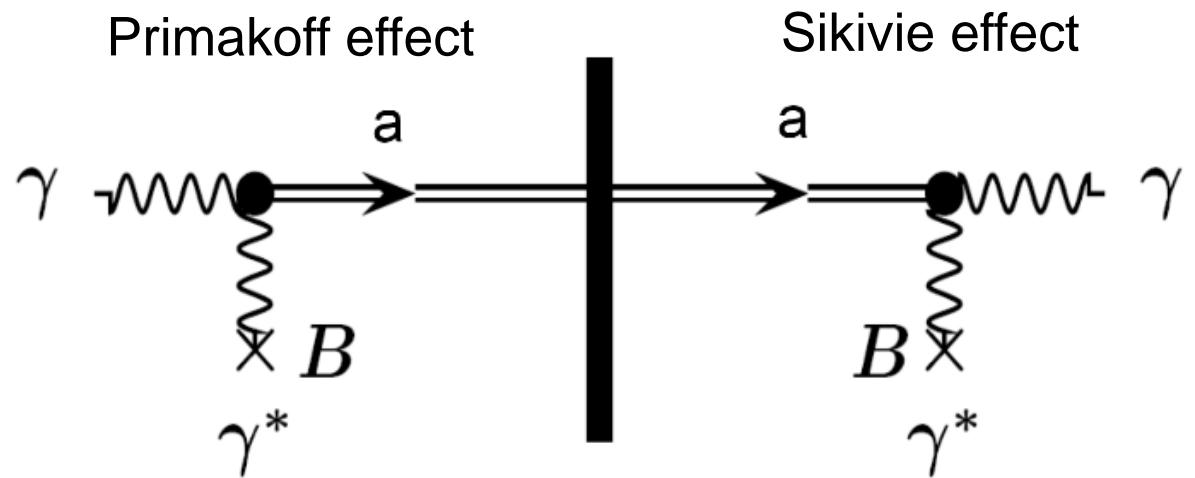
# Analysis of TES data for ALPS II



**José Alejandro Rubiera Gimeno (DESY)**  
for the TES team in the ALPS II collaboration  
**1st Training School COST Action COSMIC WISPerS**  
**September 13<sup>th</sup>**

# Axions and Axion-like particles (ALPs)

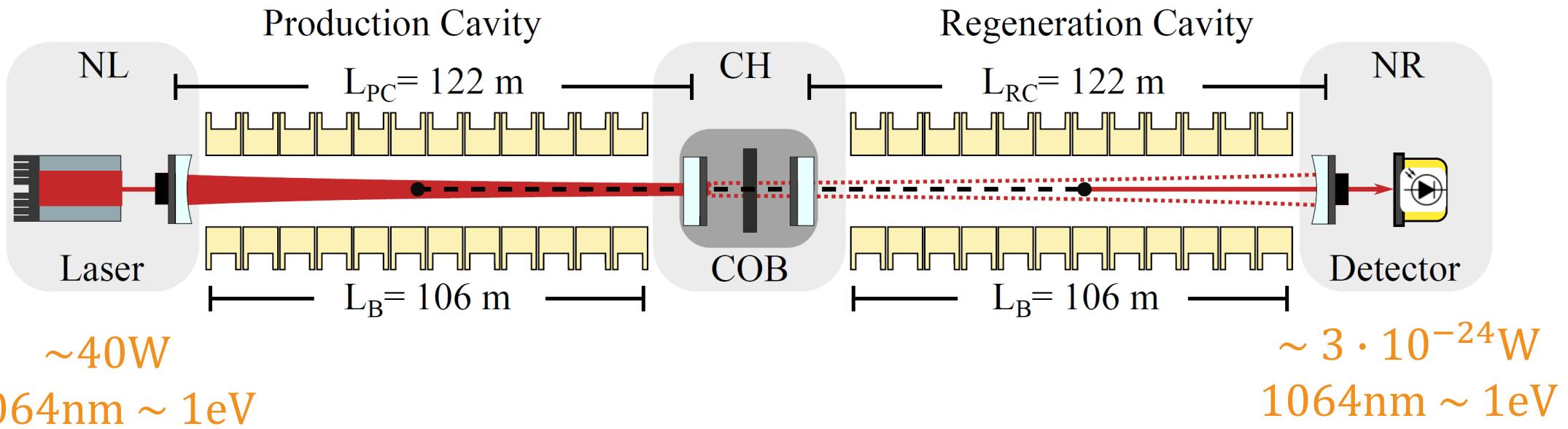
- Proposed as solution to strong CP problem
- Motivated by astrophysical observations:
  - Stellar evolution
  - TeV transparency
- Very weak interaction, good candidate for dark matter
- The main mechanism for detection of light weight axions is through its coupling to photons



Light Shining through a Wall (LSW)

Model independent approach,  
independent of dark matter paradigm

# Any Light Particle Search II (ALPS II)



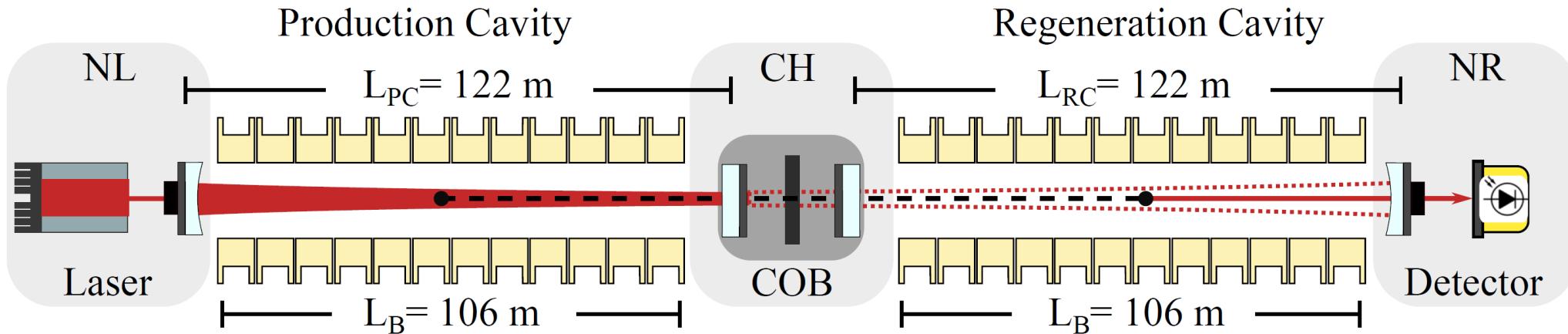
$$p_{\gamma \rightarrow a \rightarrow \gamma} = \frac{1}{16} \beta_{PC} \beta_{RC} (g_{a\gamma\gamma} B L_B)^4$$

Enhancement by  
optical cavities

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

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

# 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

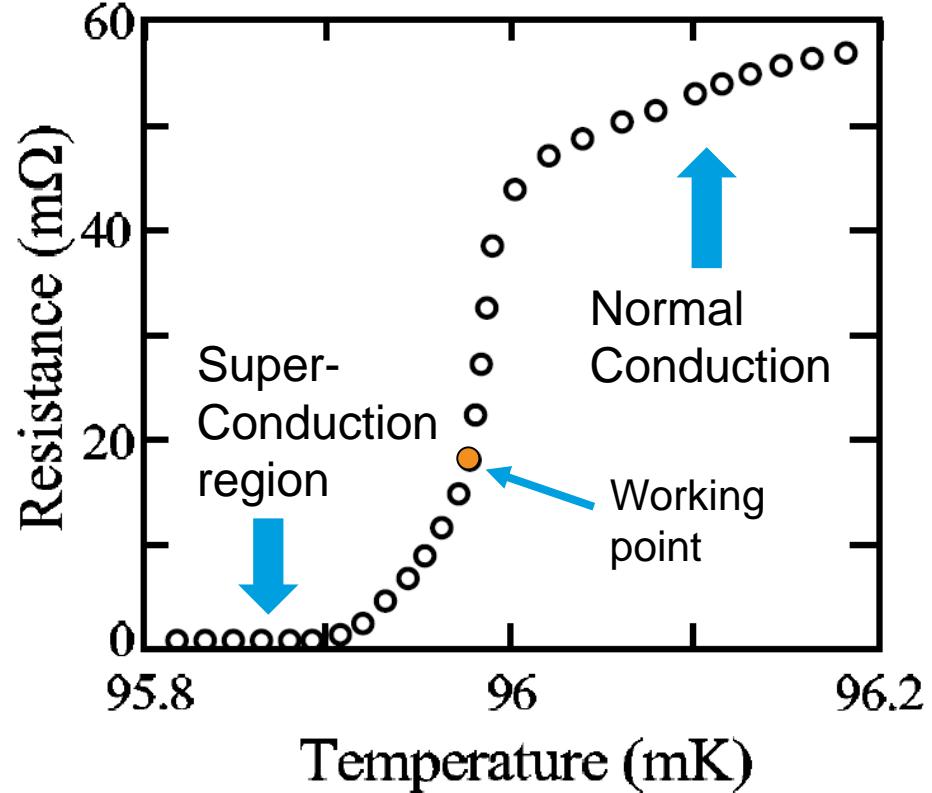
# Single photon detector

## Requirements for ALPS II:

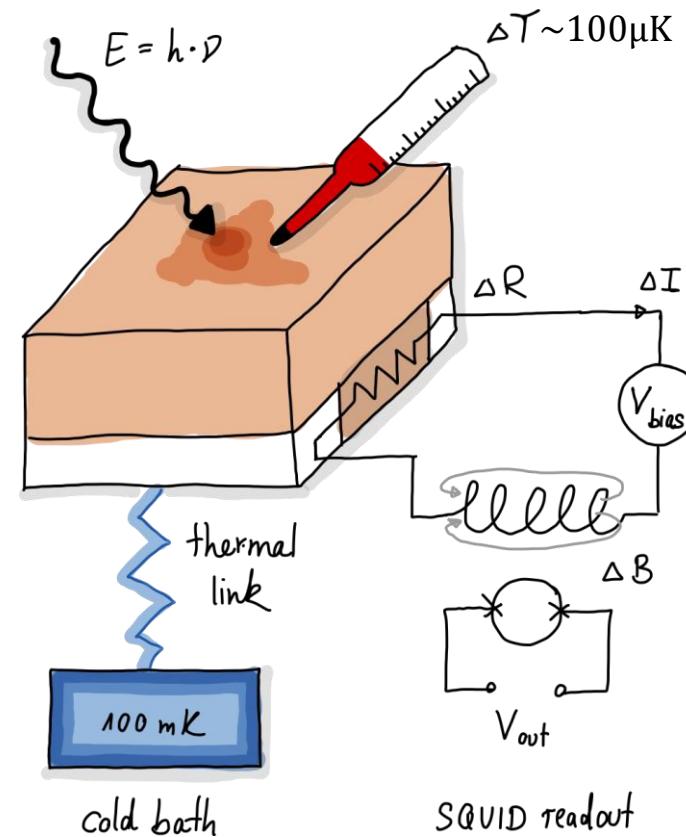
- Sensitivity to very low rates (1-2 photons a day)
- Low energy photon detection (1064nm equivalent to 1.16eV)
- Long term stability (~20 days)
- Low background rate:  $< 7.7 \cdot 10^{-6}$  cps  $\sim$  1 photon (1064nm-like) every 2 days
  - Good energy resolution (for background rejection)
- High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

A Transition Edge Sensor (TES) could meet them!

# Transition Edge Sensors



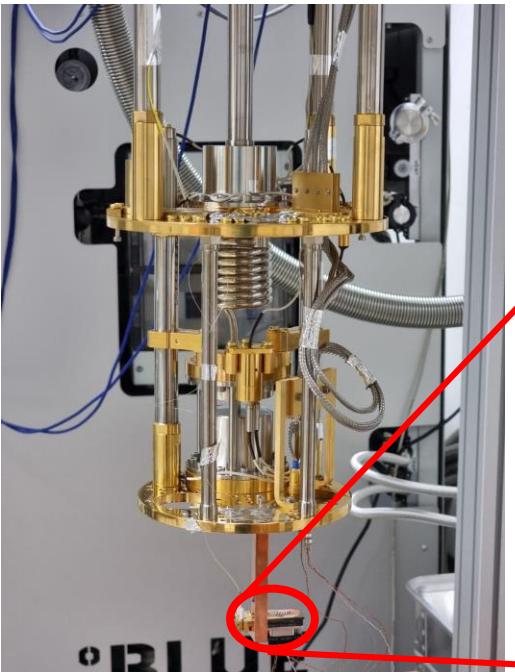
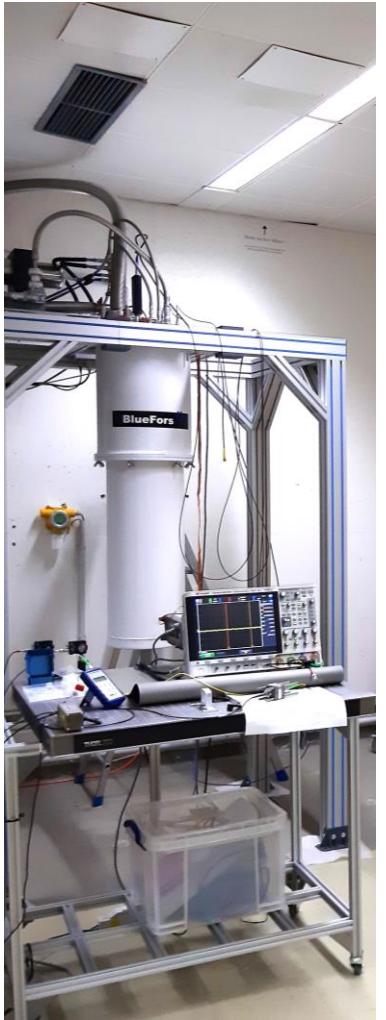
K. Irwin, G. Hilton, Transition-edge sensors, in: Cryogenic Particle Detection, Springer Berlin Heidelberg, Berlin, Heidelberg, 2005, pp. 63–150, [http://dx.doi.org/10.1007/10933596\\_3](http://dx.doi.org/10.1007/10933596_3).



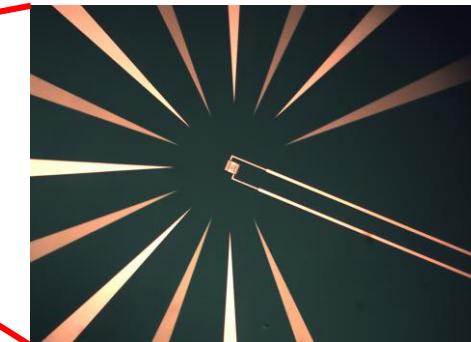
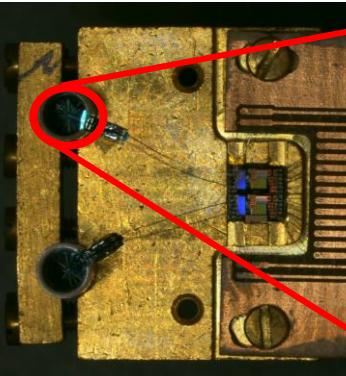
\*Courtesy of Katharina-Sophie Isleif

- 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

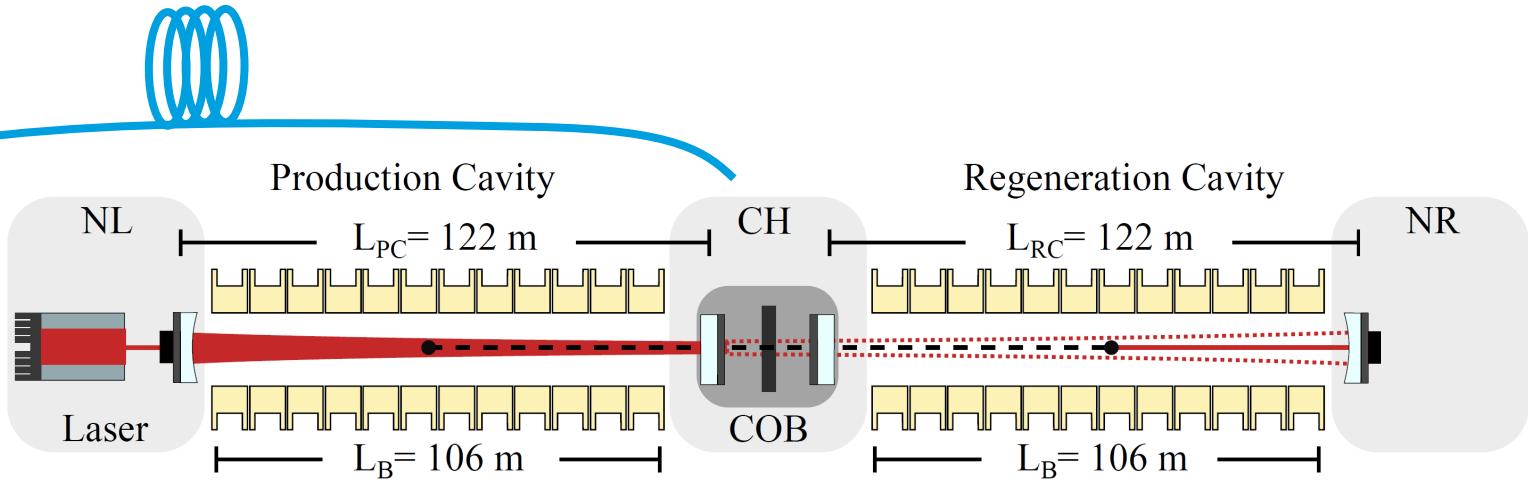
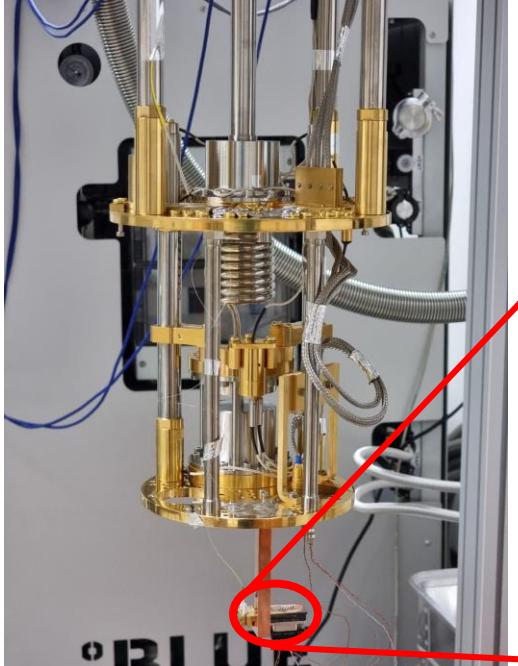


A tungsten microchip provided by NIST and PTB ( $25 \mu\text{m} \times 25 \mu\text{m} \times 20 \text{ nm}$ ) operated in the transition region ( $\sim 140 \text{ mK}$ )

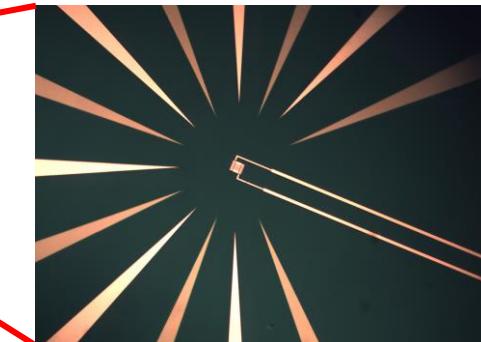
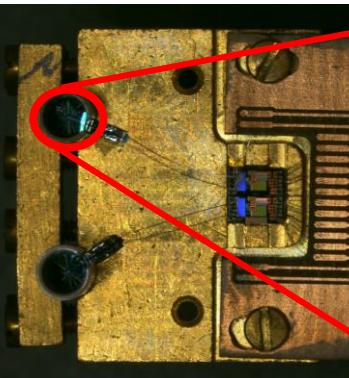


1064 nm photon  
 $E \approx 1.16 \text{ eV}$

# TES at DESY

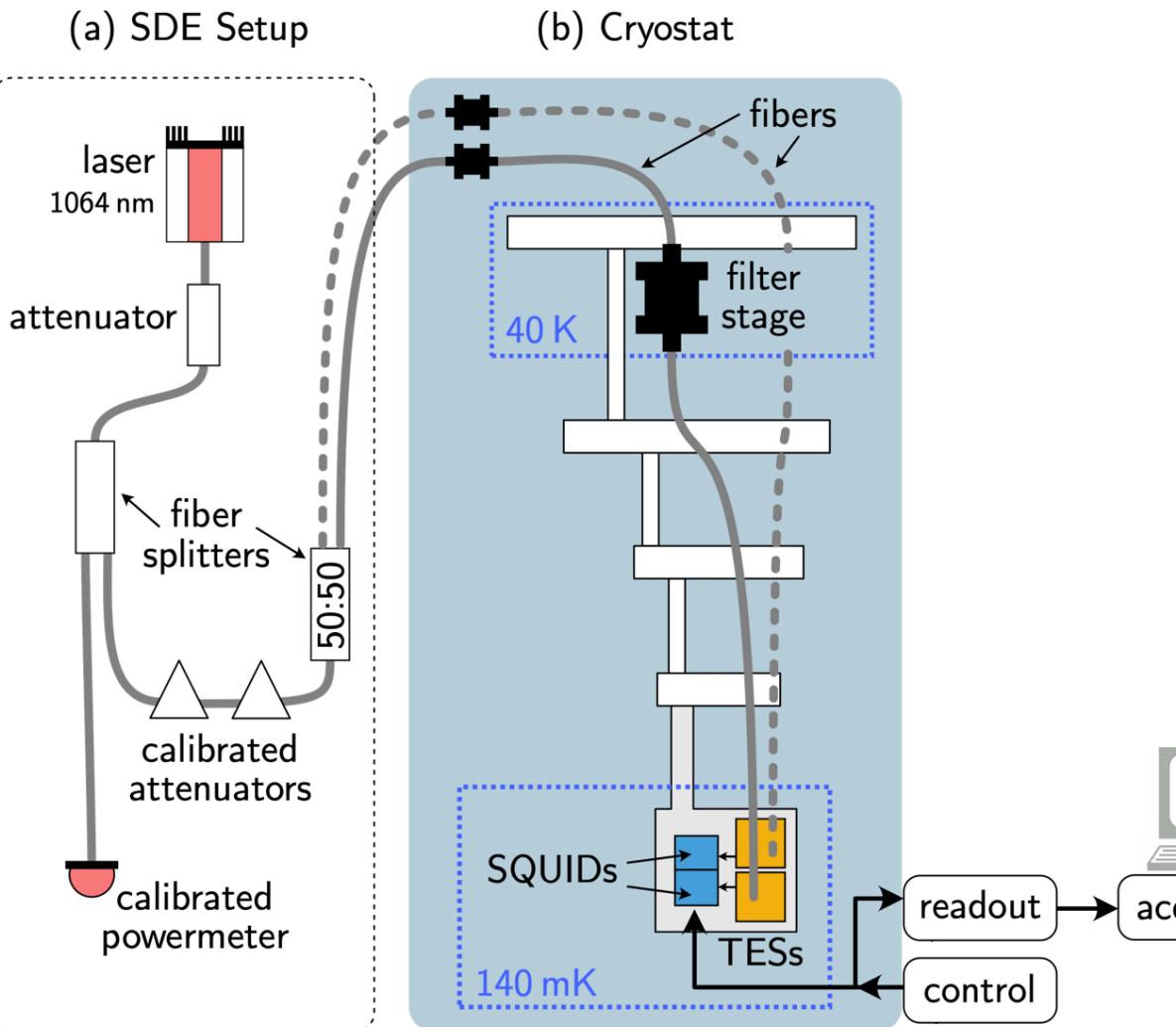


A tungsten microchip provided by NIST and PTB  
( $25 \mu\text{m} \times 25 \mu\text{m} \times 20 \text{ nm}$ ) operated in the transition region ( $\sim 140 \text{ mK}$ )



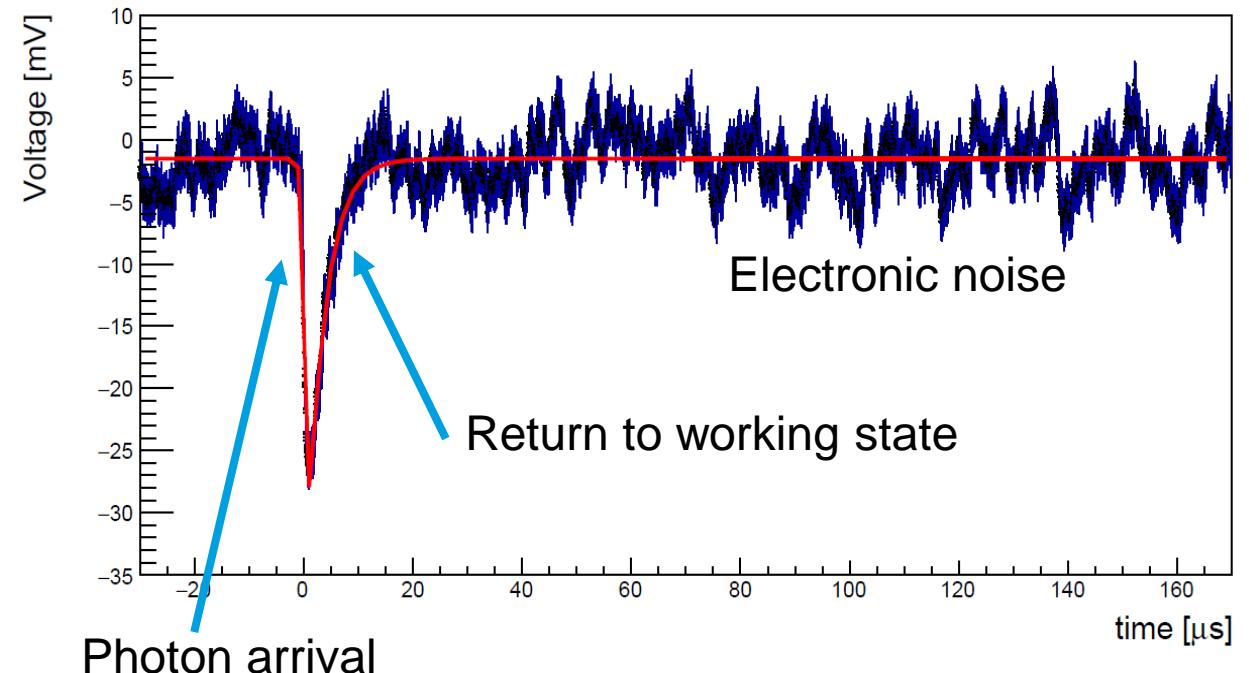
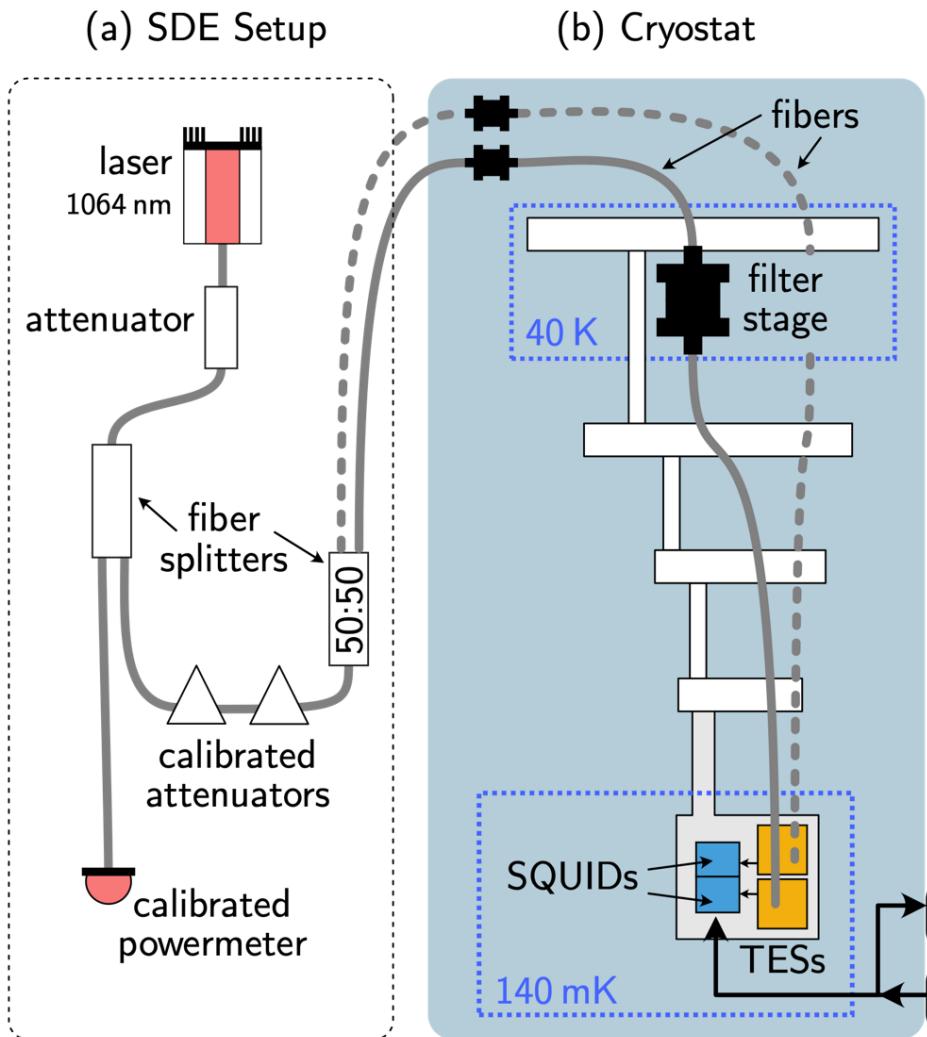
1064 nm photon  
 $E \approx 1.16 \text{ eV}$

# Characterizing the TES



Schematic adapted from Katharina-Sophie Isleif.

# Characterizing the TES



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

Schematic adapted from Katharina-Sophie Isleif.

# Intrinsics background (no fiber connected)

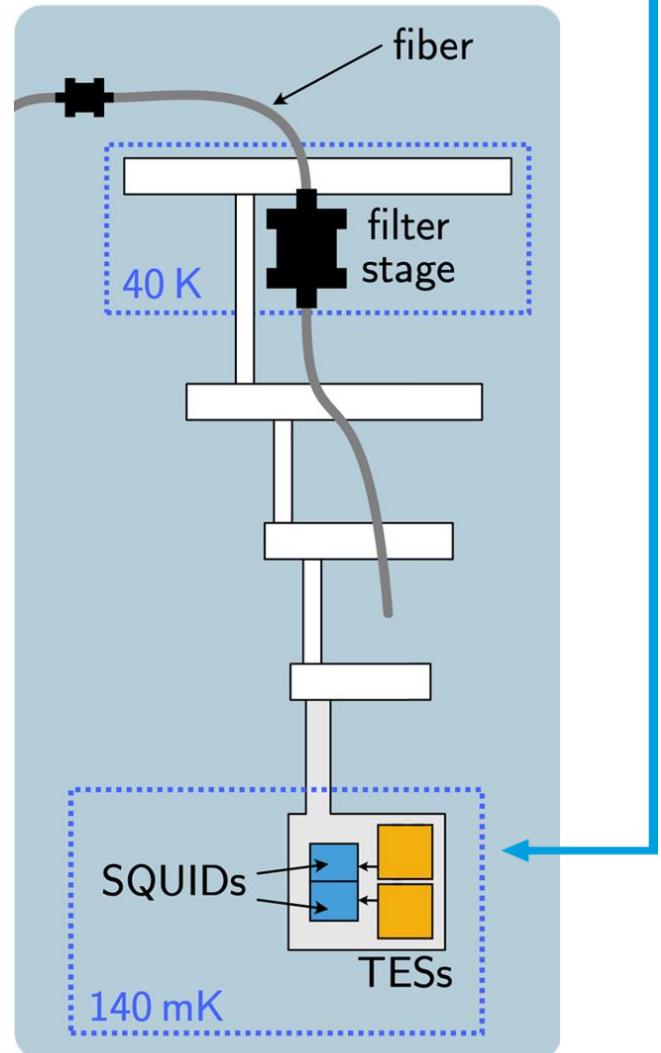
ALPS II requirements:

$< 7.7 * 10^{-6} \text{ cps}$ , 1064 nm like events

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

Possibly related to:

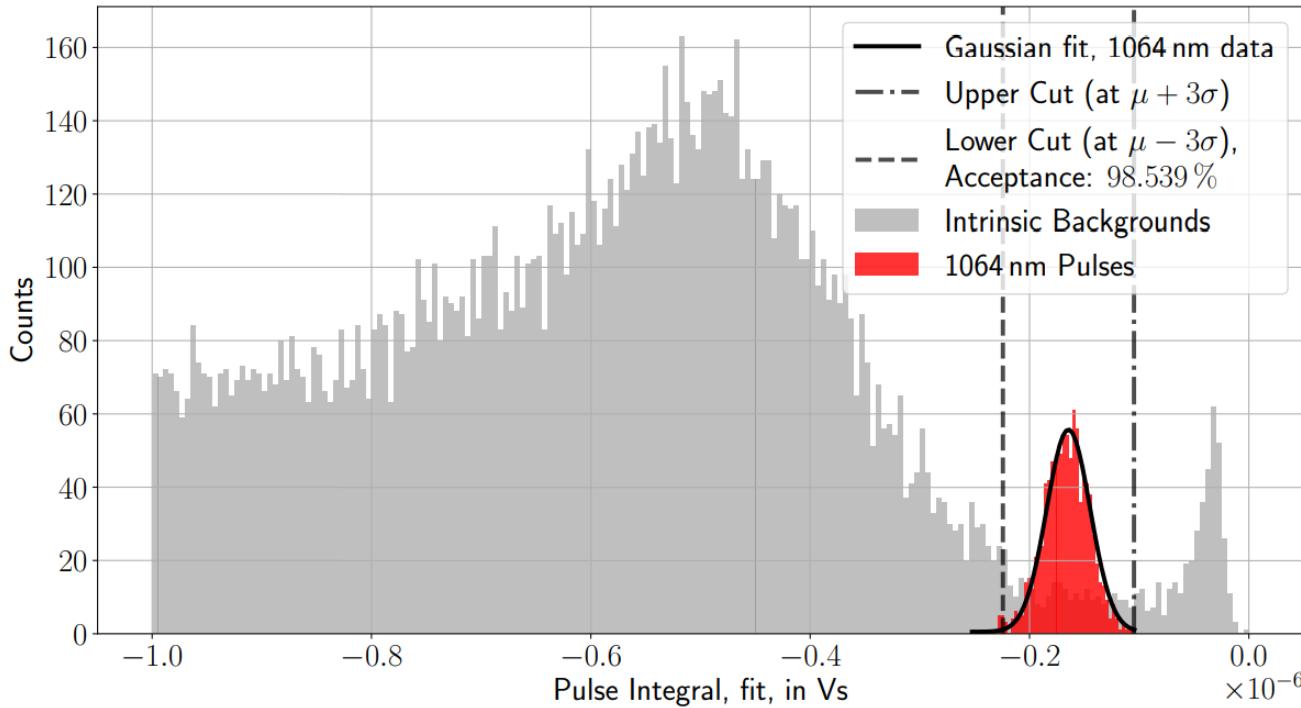
- Electronic noise
- Cosmic Rays (Muons)
- Radioactivity (Surrounding materials)



Schematic adapted from Katharina-Sophie Isleif.

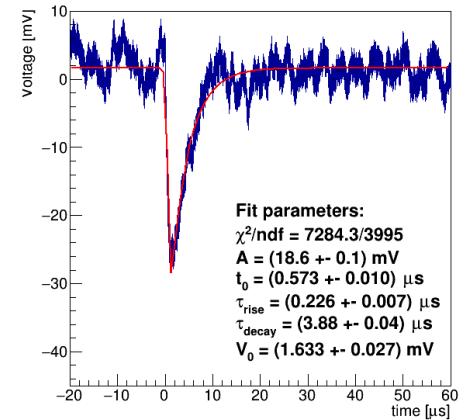
[1] Rikhav Shah, Katharina-Sophie Isleif, Friederike Januschek, Axel Lindner and Matthias Schott, "TES Detector for ALPS II", Proceedings of The European Physical Society Conference on High Energy Physics, Volume 398, Page 801, (2022); <https://doi.org/10.22323/1.398.0801>

# 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,  $A$ ,  $\tau_{\text{rise}}$ ,  $\tau_{\text{decay}}$ , and Pulse integral

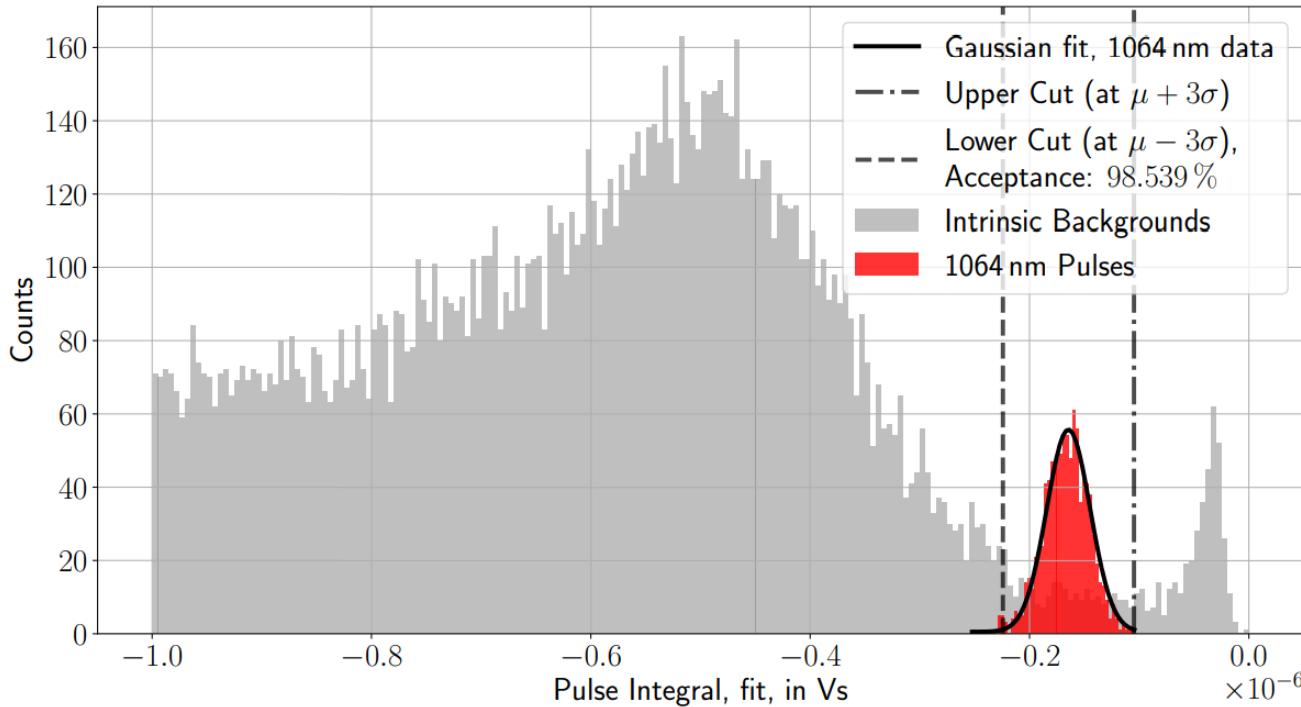


Able to exclude intrinsics backgrounds and maintain the acceptance for 1064 nm pulses

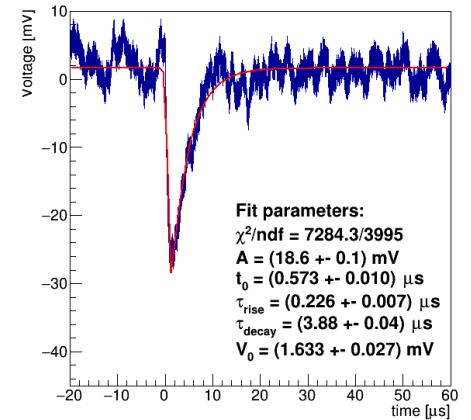
ALPS II requirements:  
 $< 7.7 \cdot 10^{-6} \text{ cps}$ , 1064 nm like events

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

# Intrinsics background results



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



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

Low background rates



Direct Dark Matter Searches with ALPS II's TES detector  
• Christina Schwemmbauer

# Extrinsics background (fiber connected)

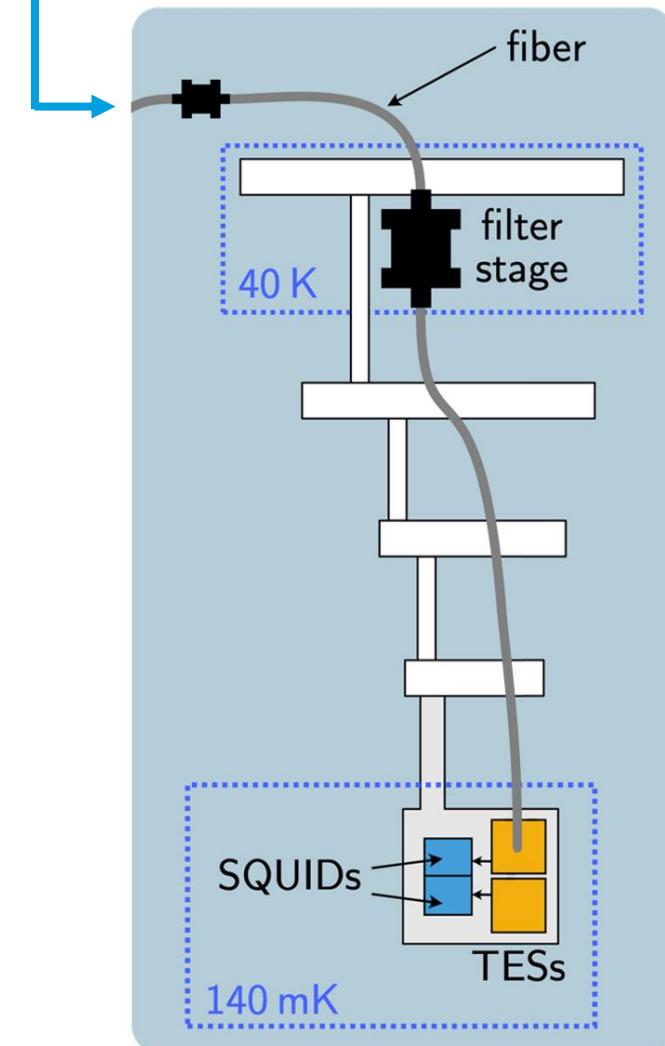
Expected additional contributions from:

- Black Body Radiation in the form of:
  - Direct photons  $\longrightarrow \sim 1064$  nm
  - Pile-up photons  $\longrightarrow$  looks like  $\sim 1064$  nm

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

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

Reject pile-up photon-like to mitigate background

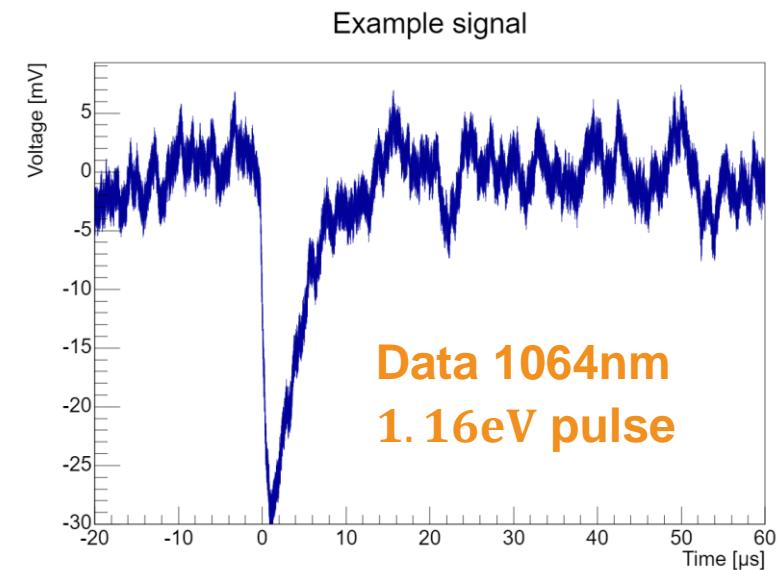
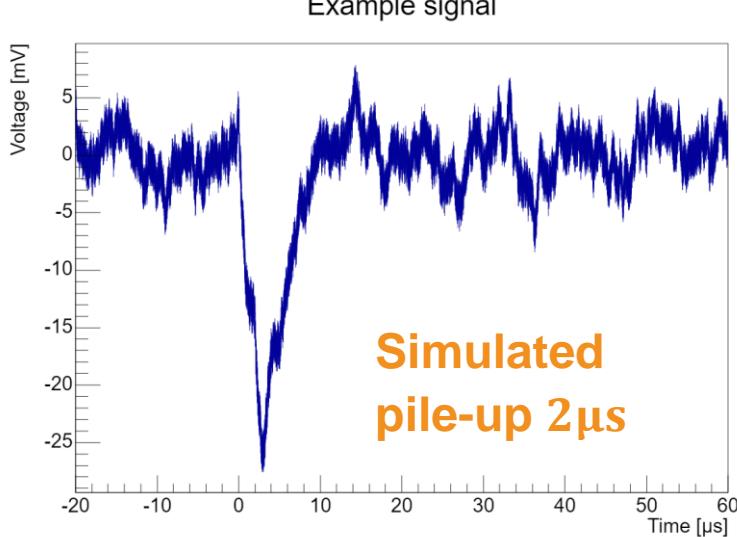


Schematic adapted from Katharina-Sophie Isleif.

# Pulse finder algorithm

Motivation:

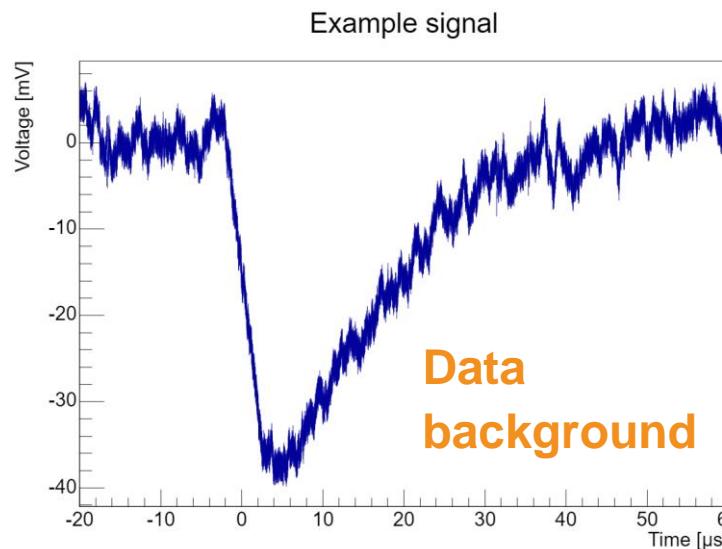
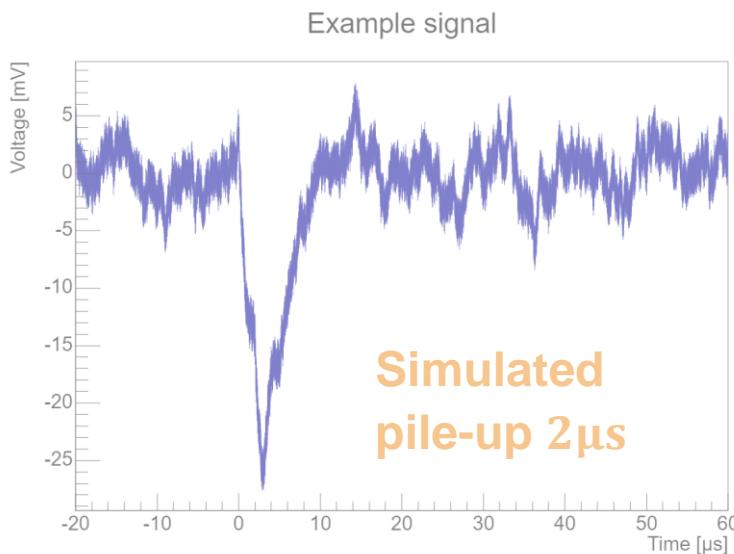
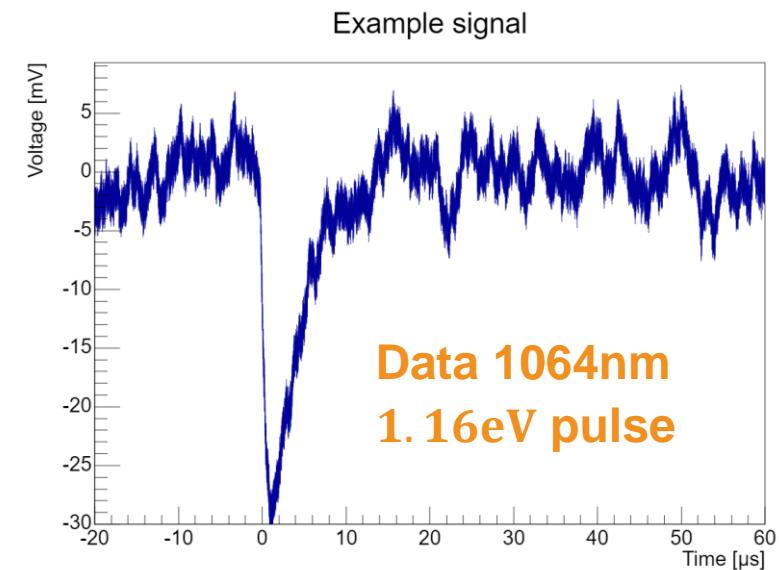
- Optimization of algorithm for pile-up rejection. (ALPS II)



# Pulse finder algorithm

Motivation:

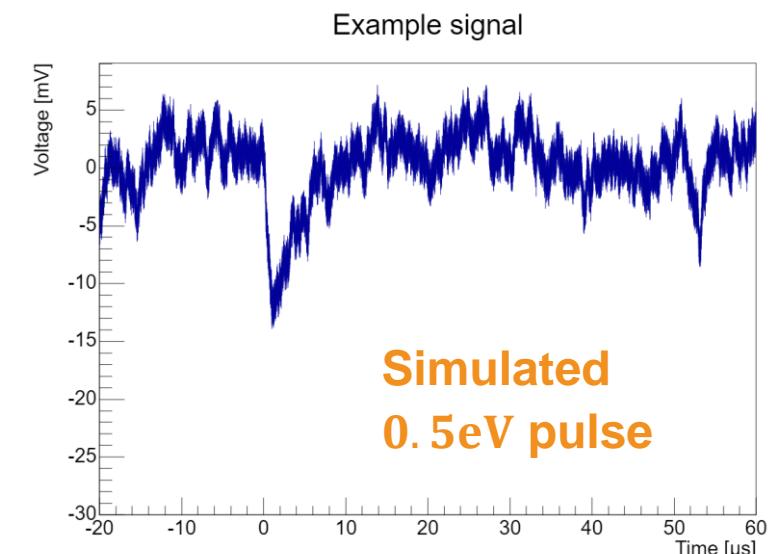
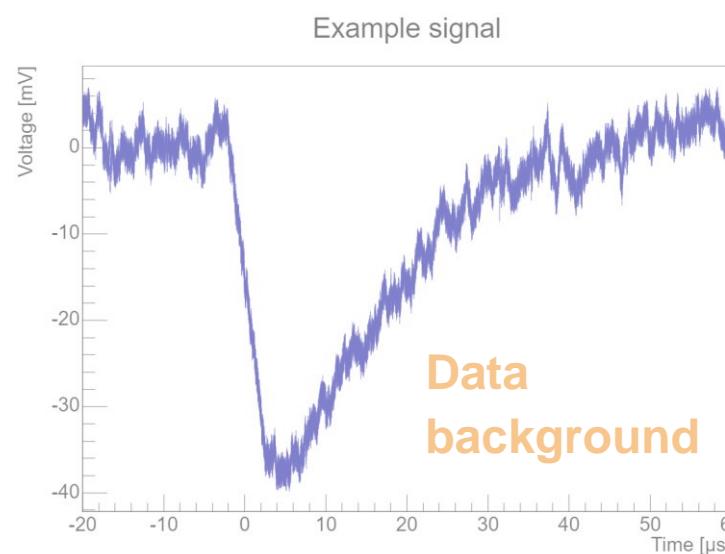
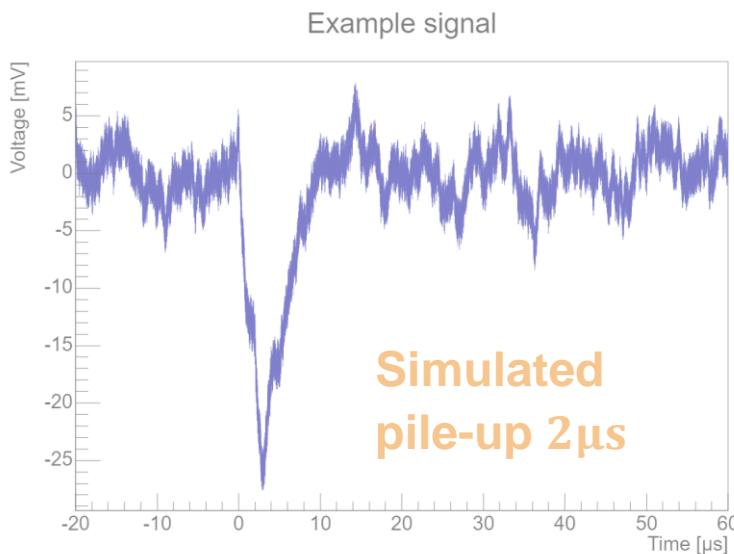
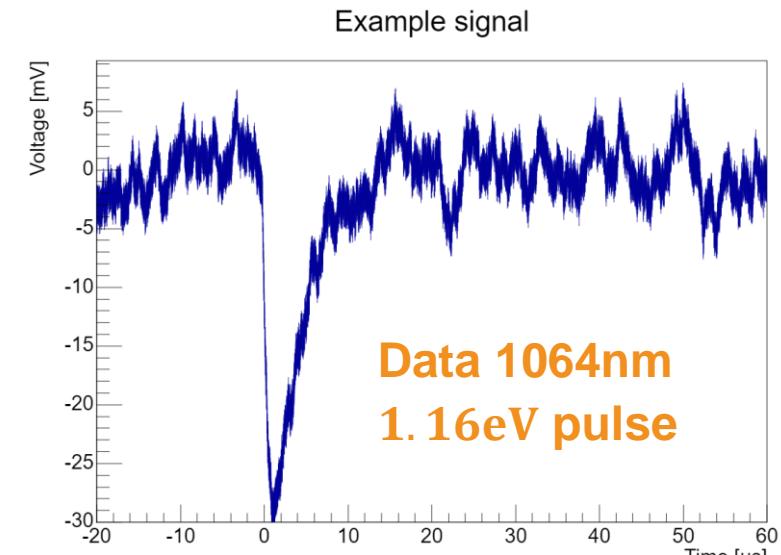
- Optimization of algorithm for pile-up rejection. (ALPS II)
- Slow fitting procedure. Strategy for rejection of clear background events. (ALPS II, dark matter)



# Pulse finder algorithm

## Motivation:

- Optimization of algorithm for pile-up rejection. (ALPS II)
- Slow fitting procedure. Strategy for rejection of clear background events. (ALPS II, dark matter)
- Optimization of algorithm to find low energy pulses. (Dark Matter)

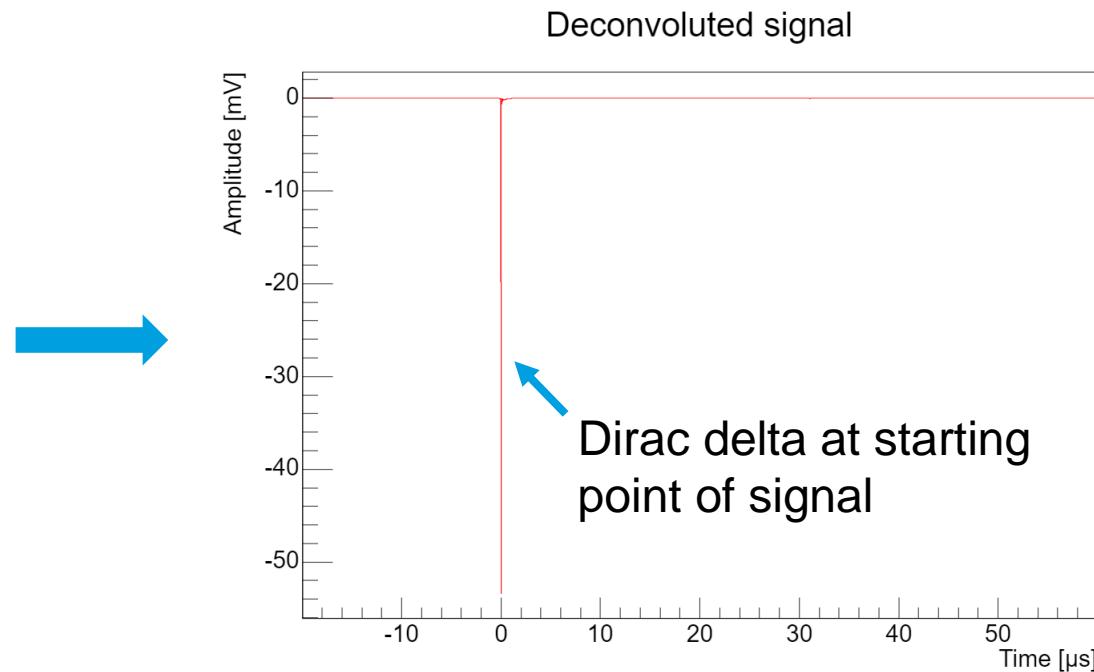
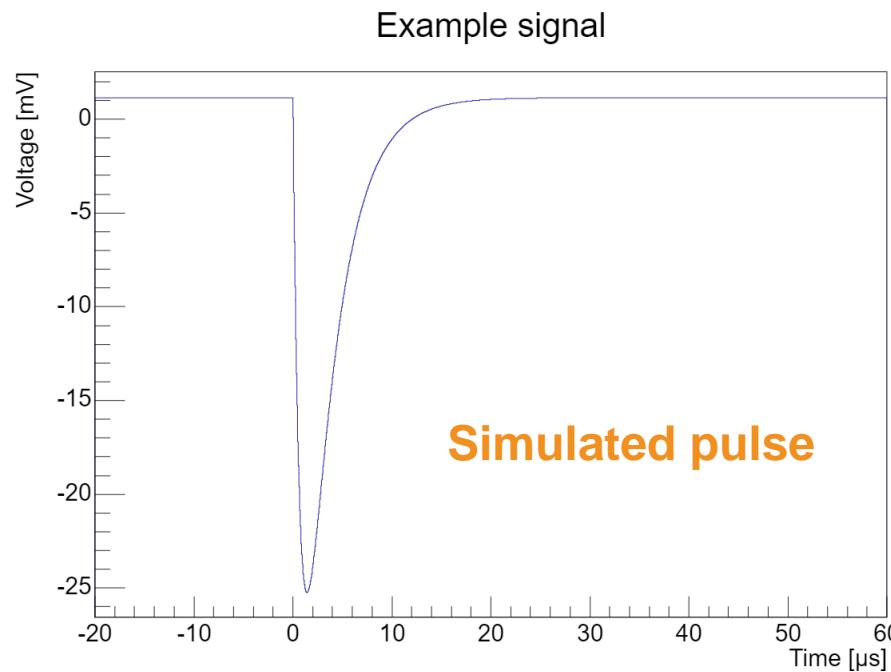


# Pulse finder algorithm

From TES theoretical description:

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

$$F(v) = A(\tau_+ - \tau_-) \frac{[1 - (2\pi v)^2 \tau_+ \tau_-] - i 2\pi v (\tau_+ + \tau_-)}{[1 + \tau_+^2 (2\pi v)^2][1 + \tau_-^2 (2\pi v)^2]} \exp\{-2\pi i v t_0\}$$
$$\mathcal{F}[y(t)] = \frac{\mathcal{F}[x(t)]}{\mathcal{F}[s(t)]}$$



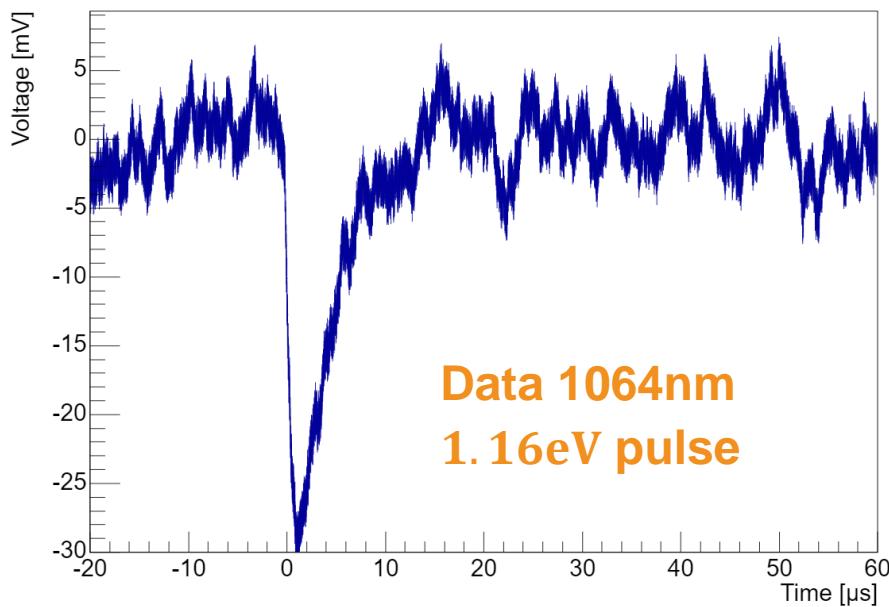
# Pulse finder algorithm

From TES theoretical description:

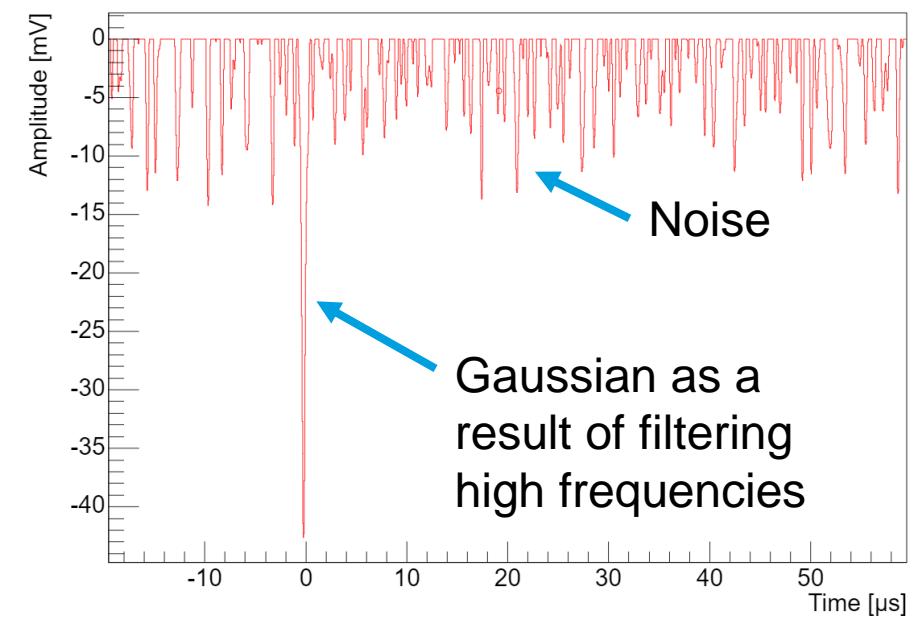
$$f_2(t) = \begin{cases} A \left( \exp\left\{-\frac{t-t_0}{\tau_+}\right\} - \exp\left\{-\frac{t-t_0}{\tau_-}\right\} \right) + V_0 & , t \geq t_0 \\ V_0 & , t < t_0 \end{cases}$$

$$F(v) = A(\tau_+ - \tau_-) \frac{[1 - (2\pi v)^2 \tau_+ \tau_-] - i 2\pi v (\tau_+ + \tau_-)}{[1 + \tau_+^2 (2\pi v)^2][1 + \tau_-^2 (2\pi v)^2]} \exp\{-2\pi i v t_0\}$$
$$\mathcal{F}[y(t)] = \frac{\mathcal{F}[x(t)]}{\mathcal{F}[s(t)]}$$

Example signal



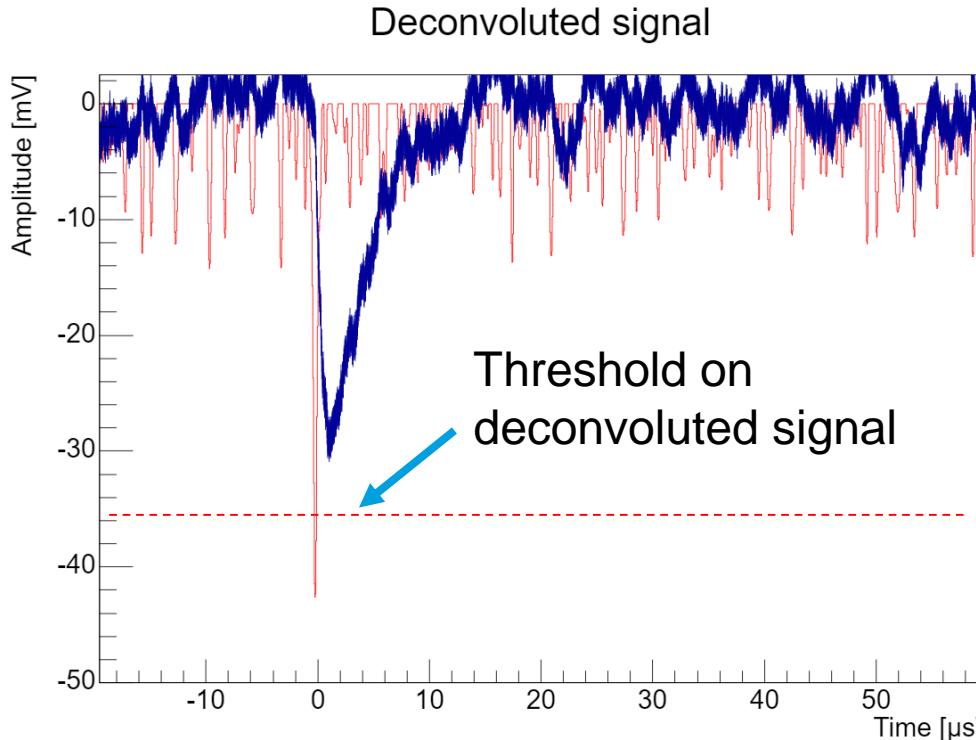
Deconvoluted signal



# Pulse finder algorithm

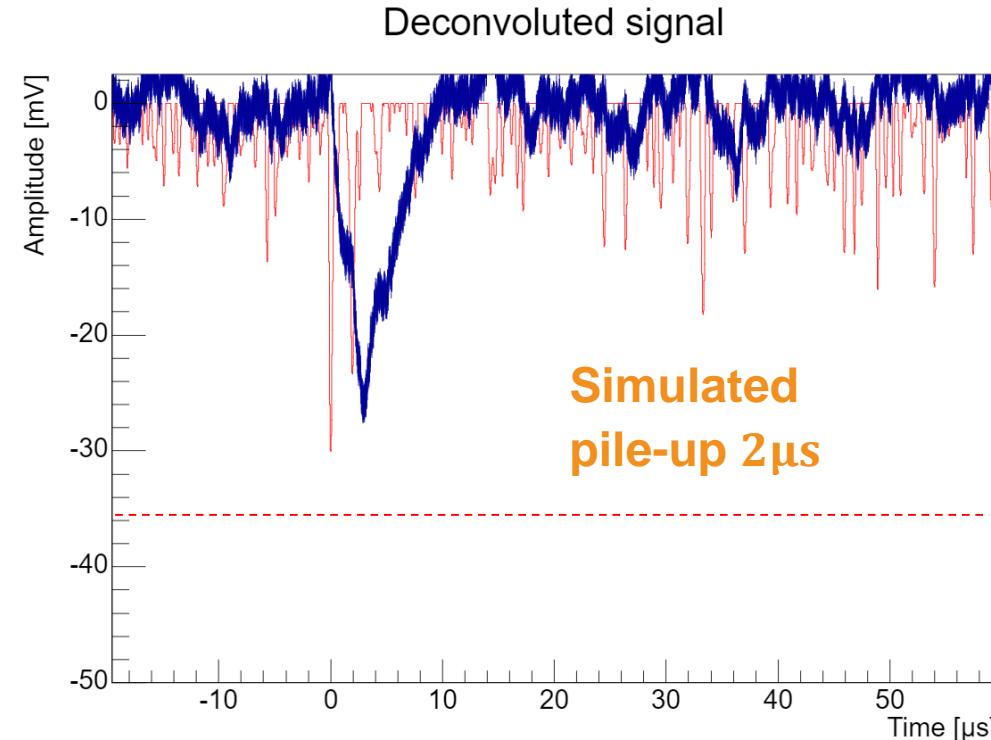
## Results and performance

- Amplitude of peak proportional to energy
- Time resolution depends on filter applied



Simulated pile-up with half the energy of 1064nm (1000 trials)

$\Delta t$	0μs	0.25μs	0.5μs	1μs	2μs
Efficiency	95.1%	33.0%	0.5%	0.3%	0%



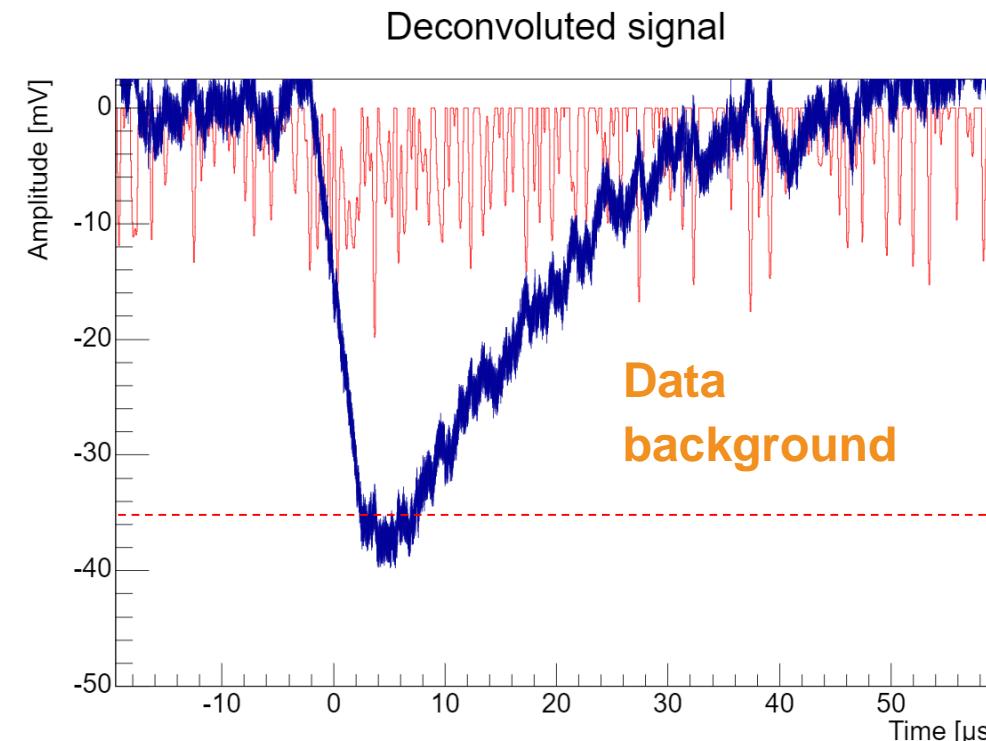
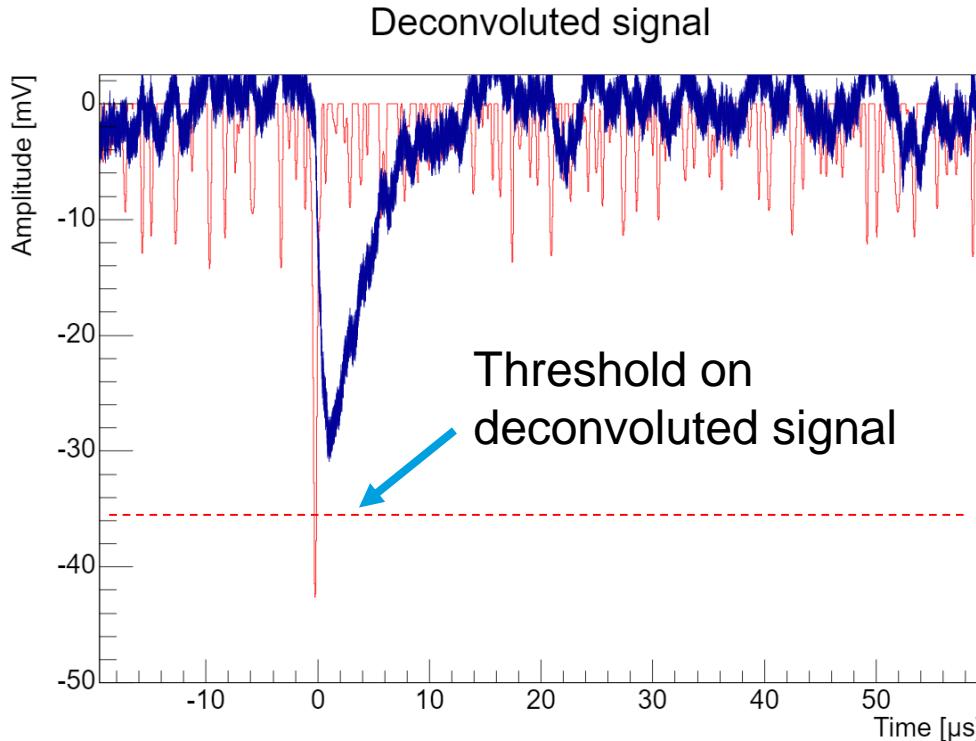
# Pulse finder algorithm

## Results and performance

- Sensitive to pulse shape
- Rejects background with shape different than 1064nm pulses

Faster than fitting procedure

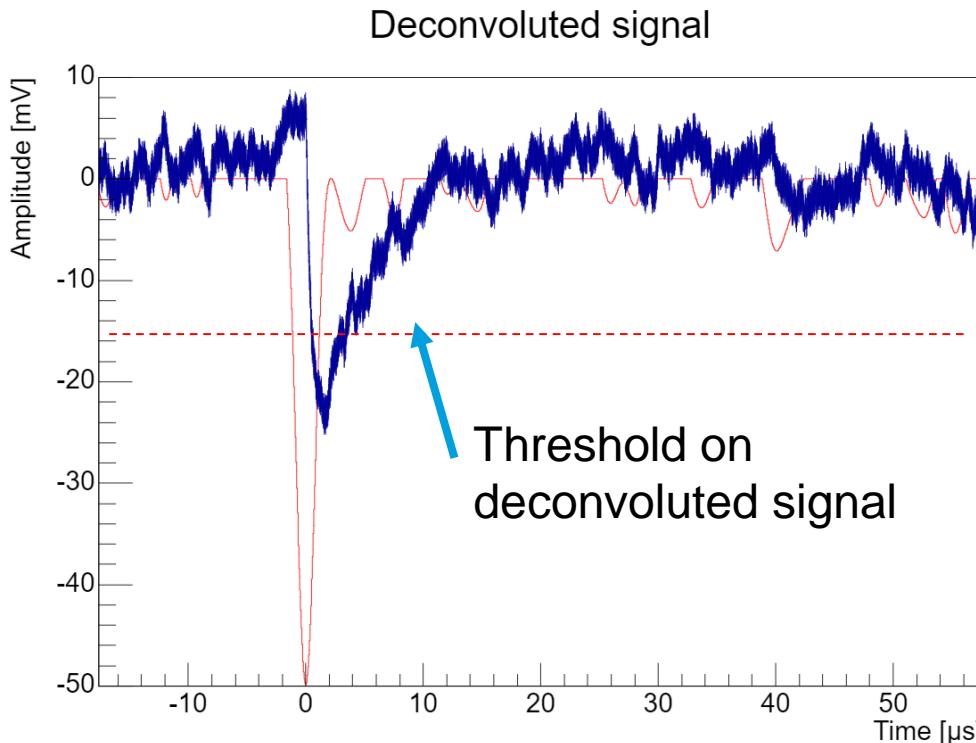
~4600 pulses: 8min  $\rightarrow$  15s



# Pulse finder algorithm

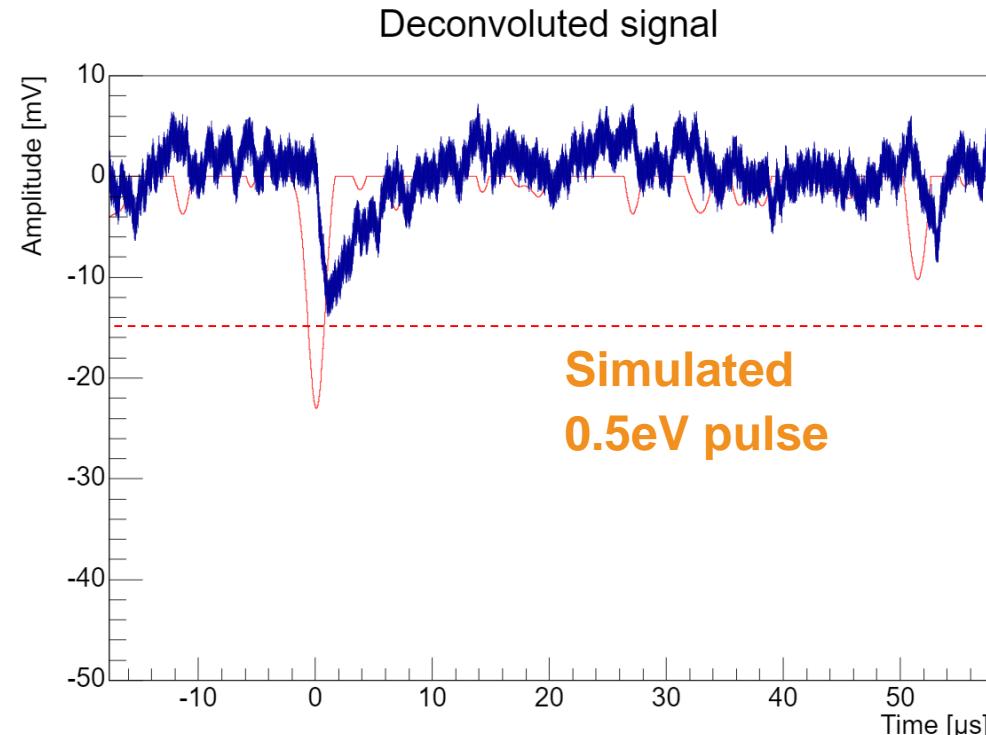
## Results and performance

- Amplitude of peak proportional to energy
- S/N ratio and time resolution depends on filter applied



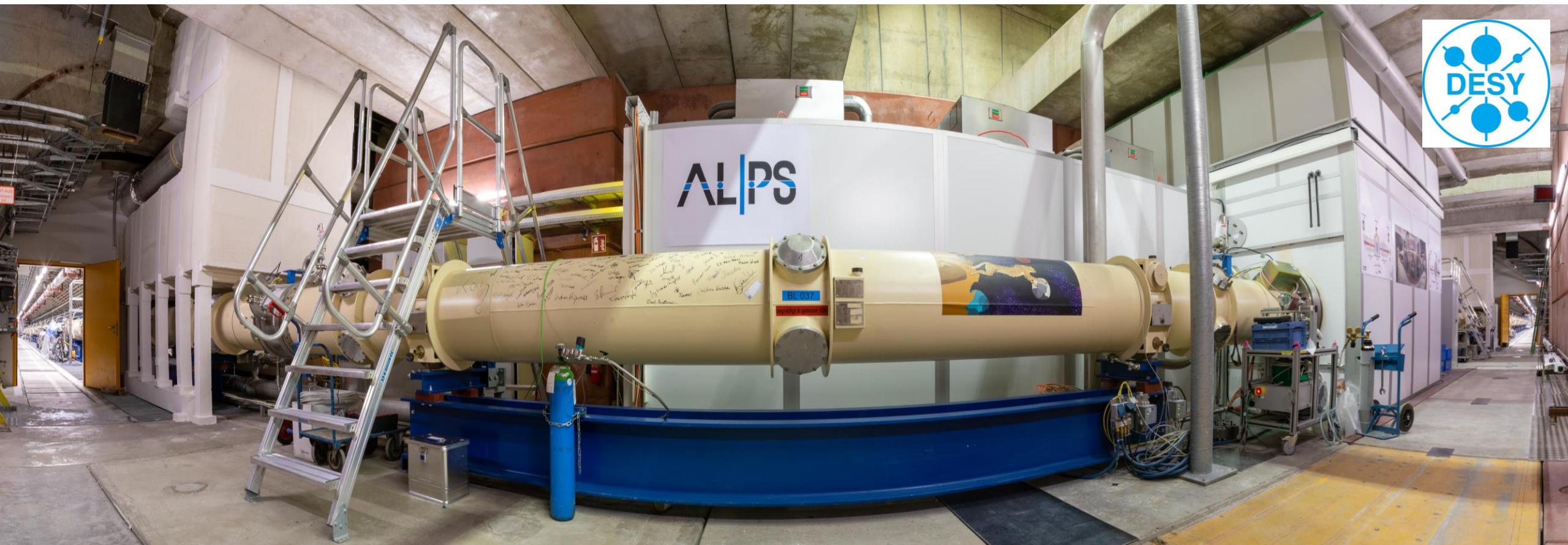
Simulated low energy pulses (1000 trials)

Energy	0.3eV	0.4eV	0.5eV	0.587eV	0.7eV
Efficiency	29.9%	80.0%	98.4%	99.9%	100%



# Summary

- ALPS II is taking data with a Heterodyne detection scheme.
- A TES scheme will be used as confirmation of signal.
- Low background rates in the TES motivates dark matter searches, more details in Christina's presentation.
- Pulse finder algorithm based on deconvolution was presented.
- This algorithm optimizes computing time, pile-up rejection and detection of low energy pulses.



Thank you.

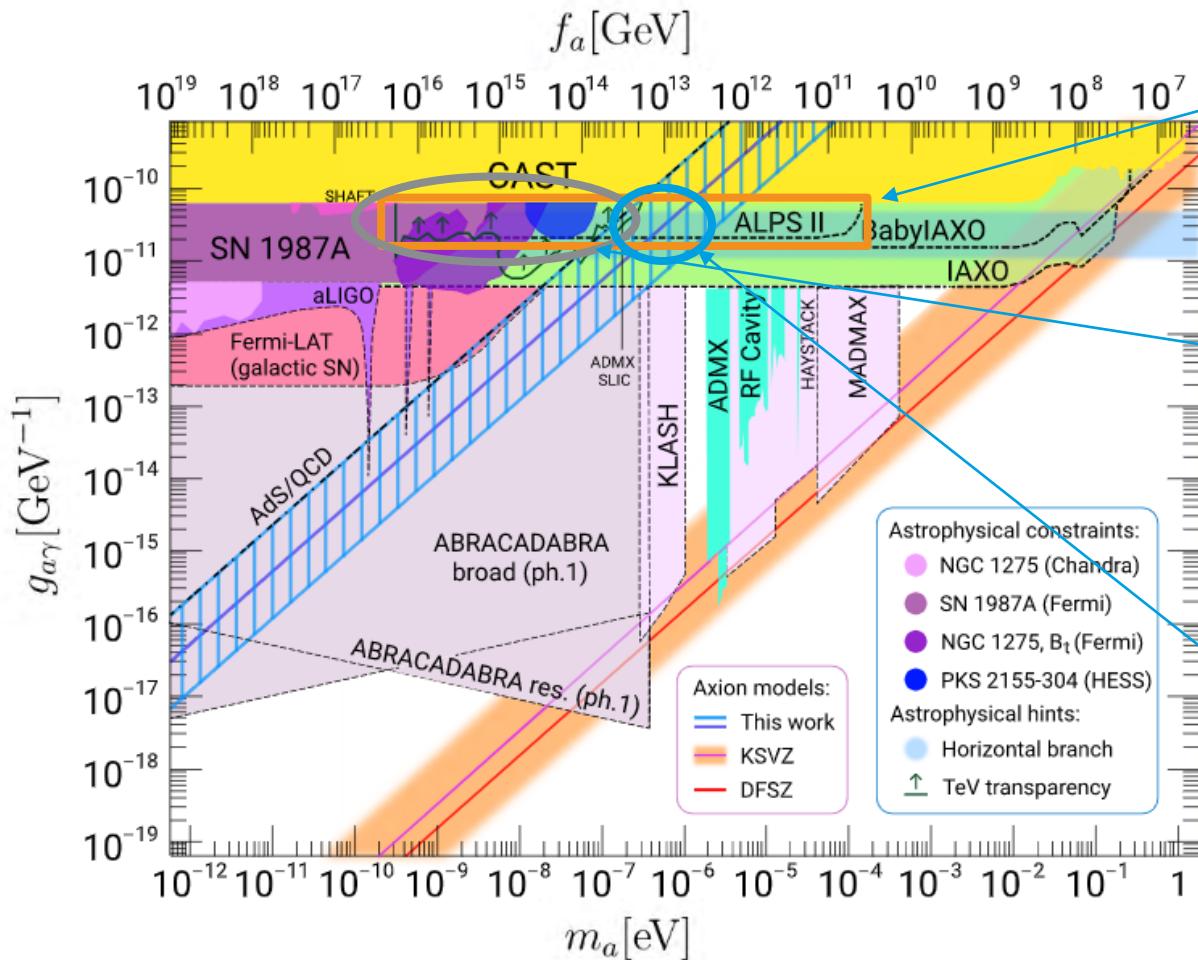
## Contact

**DESY.** Deutsches  
Elektronen-Synchrotron  
[www.desy.de](http://www.desy.de)

José Alejandro Rubiera Gimeno  
ALPS  
[jose.rubiera.gimeno@desy.de](mailto:jose.rubiera.gimeno@desy.de)

# Backup

# Axion-photon coupling



ALPS II

Motivated by anomalies in the evolution of stars

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

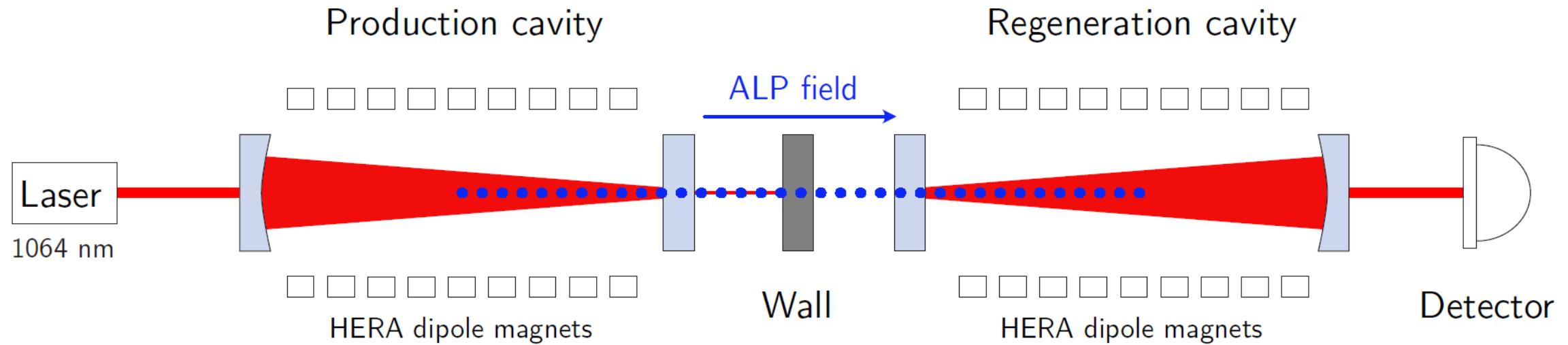
TeV Transparency

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)



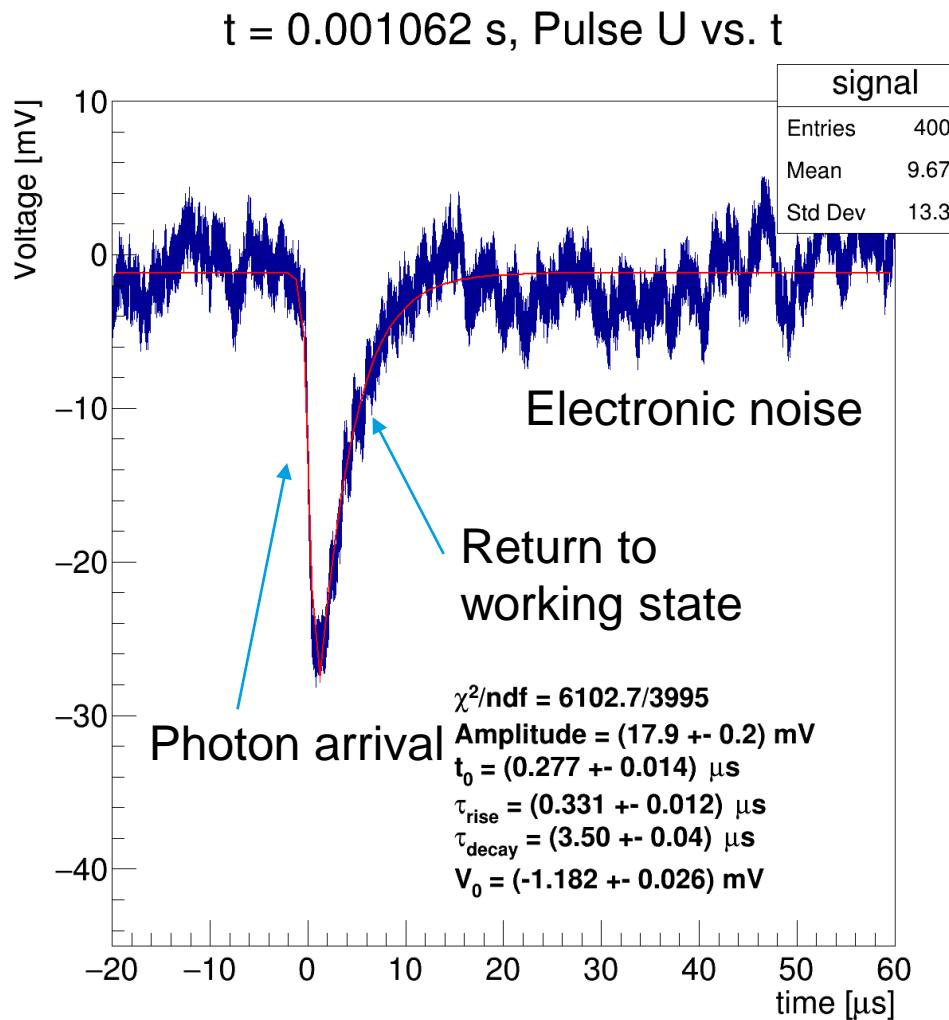
$$P_{\gamma \rightarrow a \rightarrow \gamma} = \frac{1}{16} \beta_{PC} \beta_{RC} (g_{a\gamma\gamma} B l)^4$$

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

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

Schematic adapted from Katharina-Sophie Isleif.

# Fitting procedure



From Small-Signal Theory:

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

Piecwise function

Phenomenological approach:

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

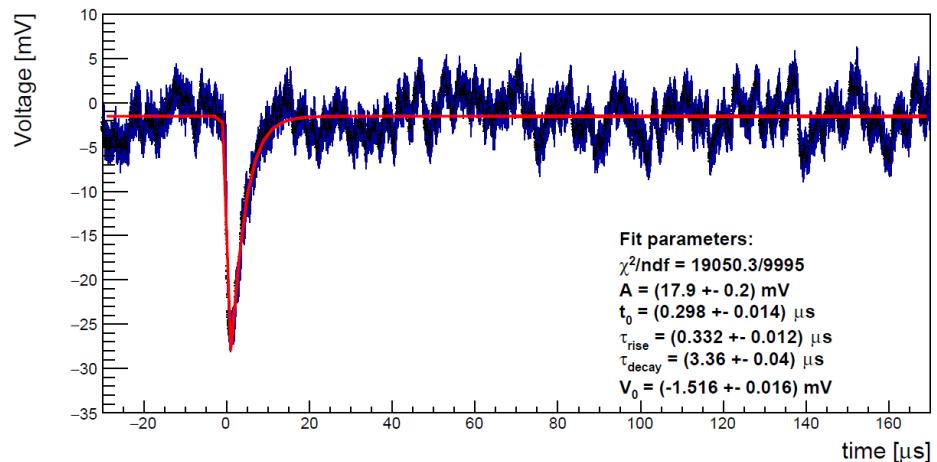
Rise component      Decay component

# Intrinsics background results

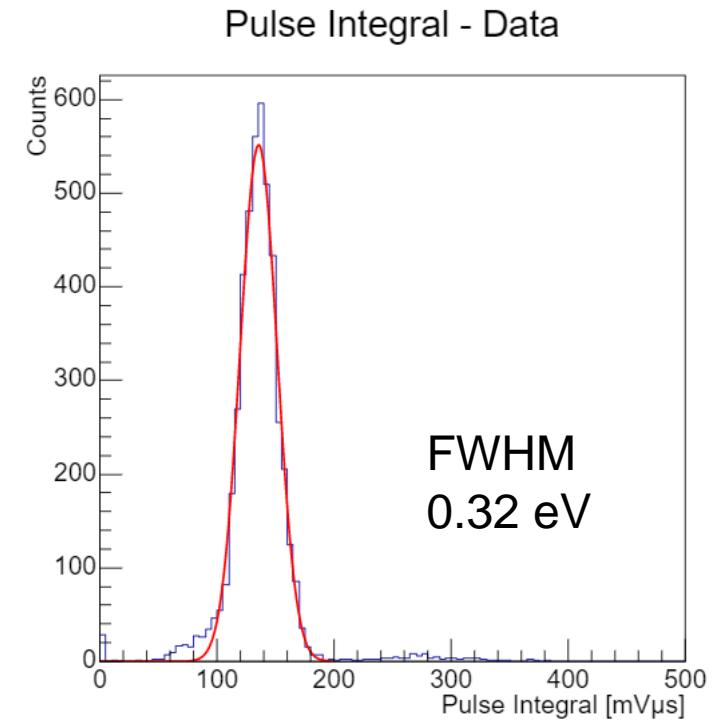
Phenomenological approach:

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

Rise component      Decay component



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



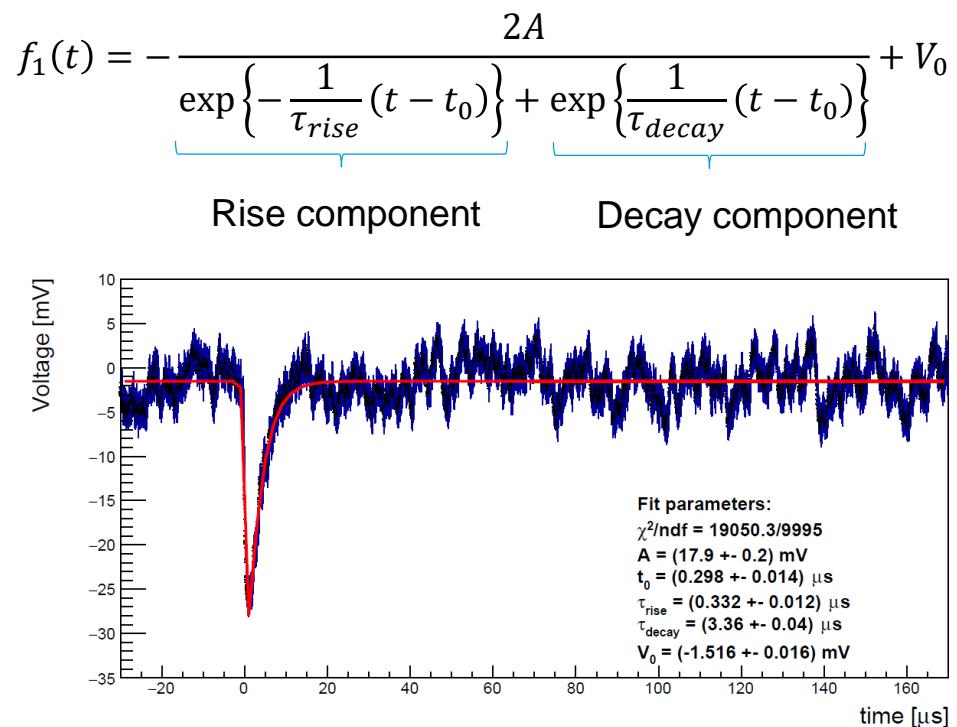
Time Integral, gaussian fit:

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

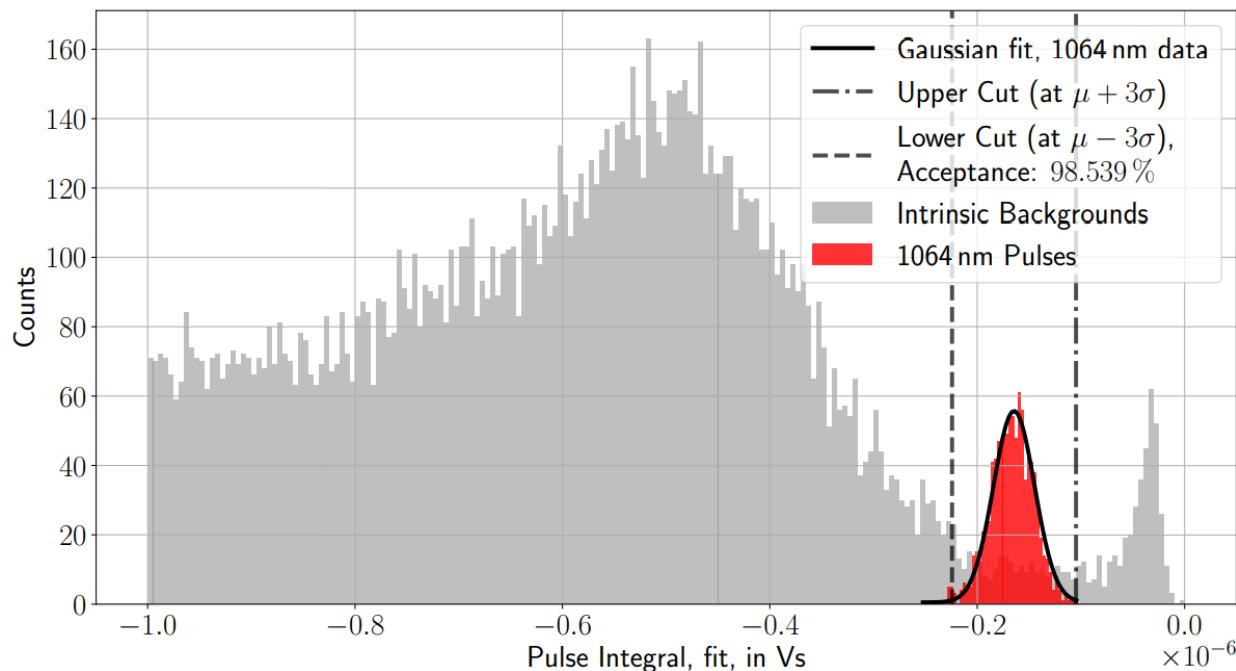
Cuts based on parameters from fitted 1064 nm pulses,  $A$ ,  $\tau_{\text{rise}}$ ,  $\tau_{\text{decay}}$ , and Pulse integral

# Intrinsics background results

Phenomenological approach:



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



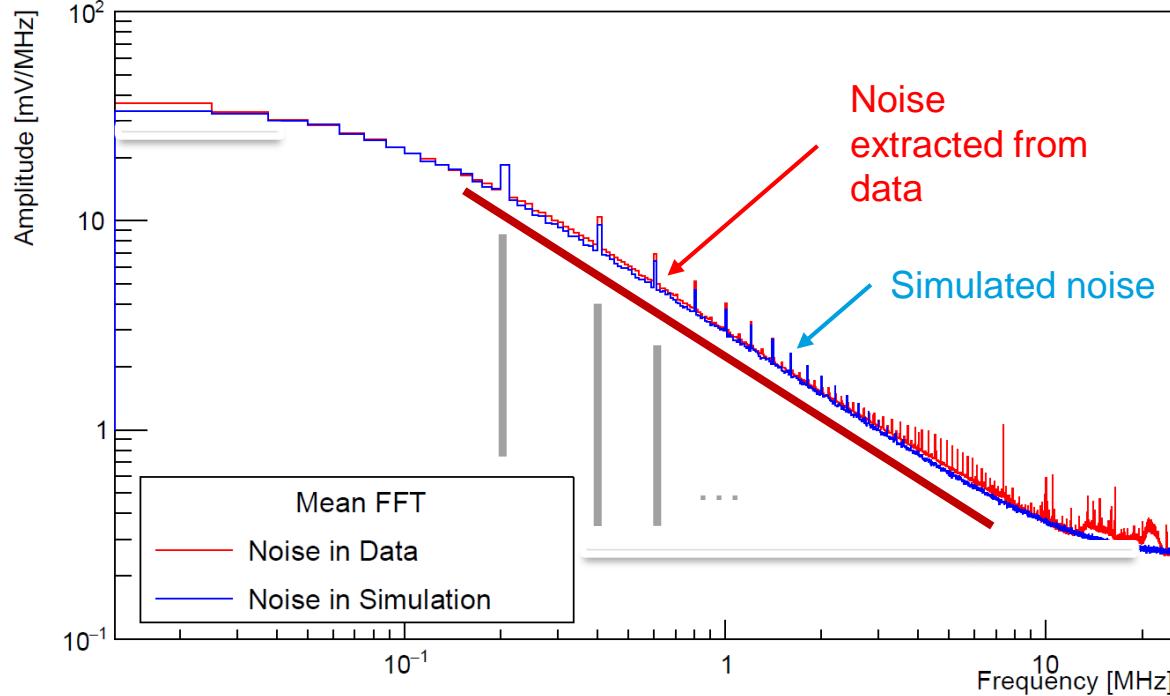
ALPS II requirements:  
 $< 7.7 \cdot 10^{-6}$  cps, 1064 nm like events



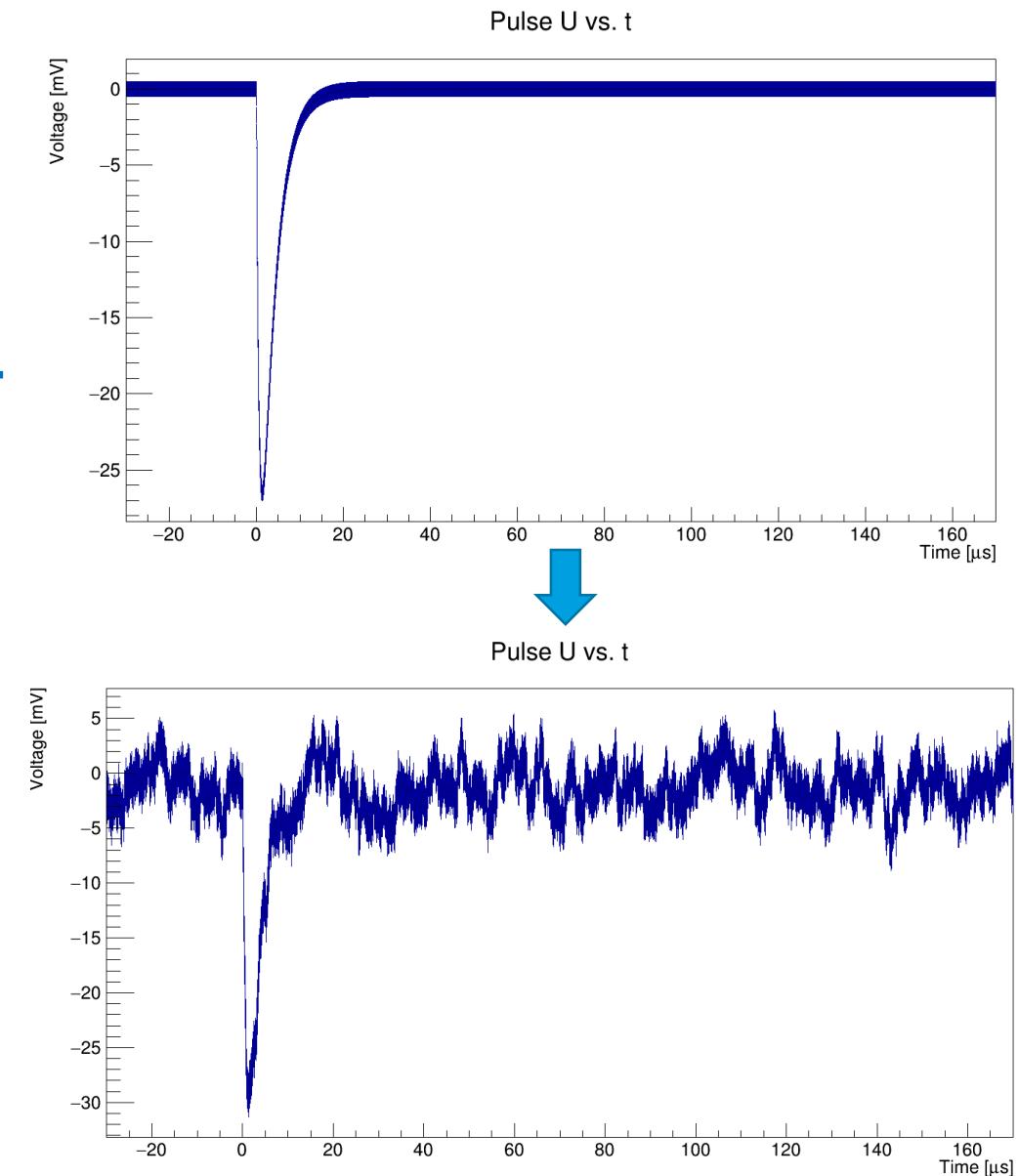
$6.9 \cdot 10^{-6}$  cps over 20 days was achieved with acceptance greater than 90% [1]

[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>

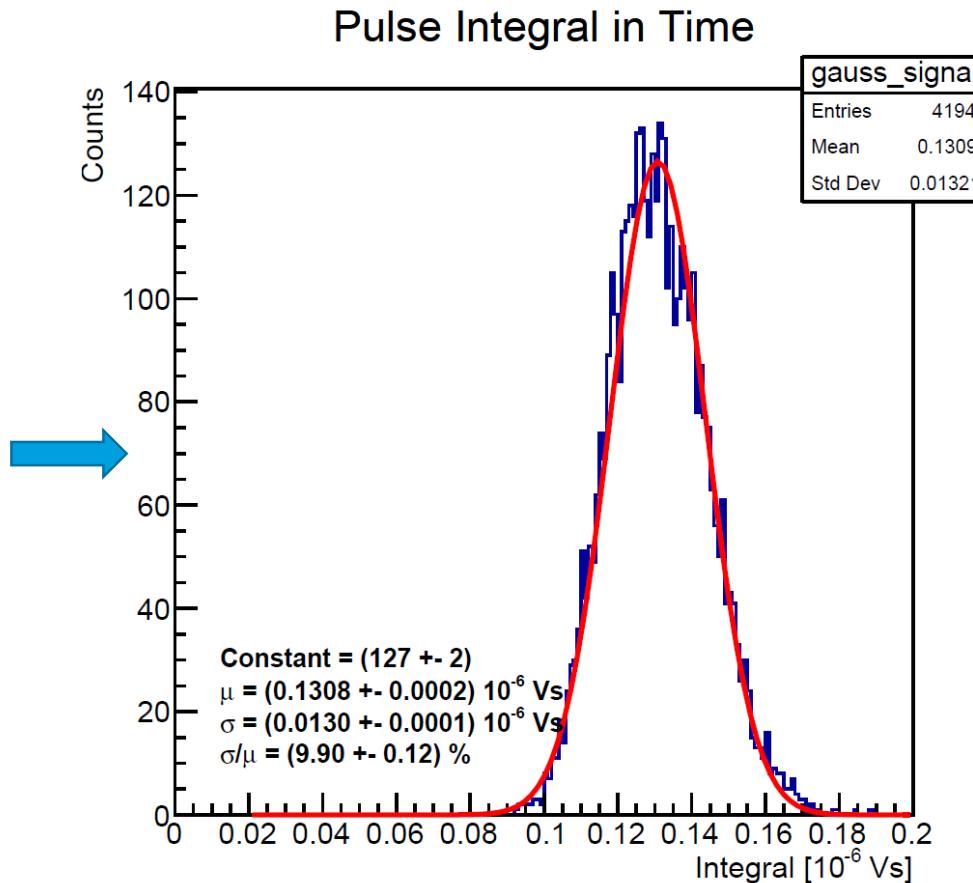
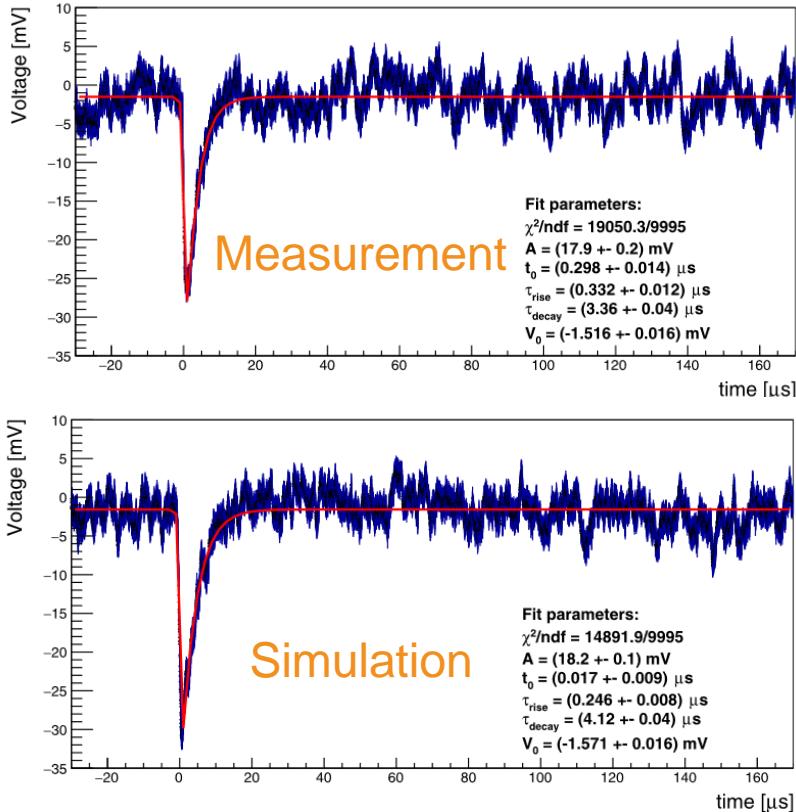
# Simulation of baseline noise



- 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  
 $(9.90 \pm 0.12)\%$

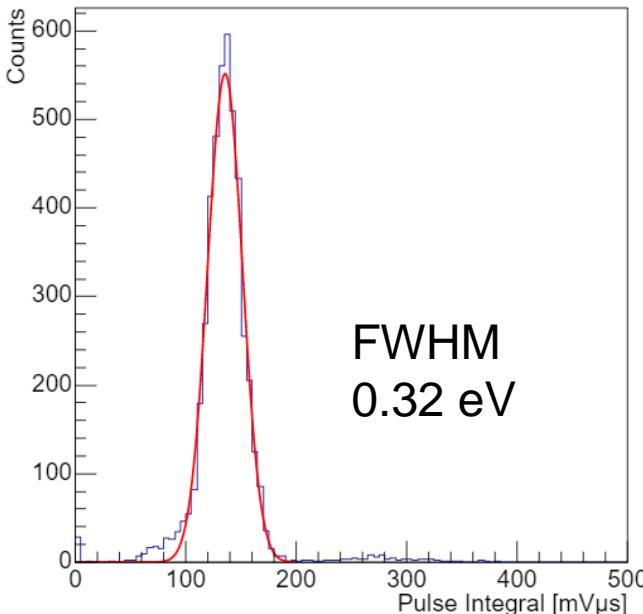
Studying other phenomena

- Rejection of pileup
- DAQ trigger efficiency.

Simulation confirms energy resolution biggest component is the baseline noise.

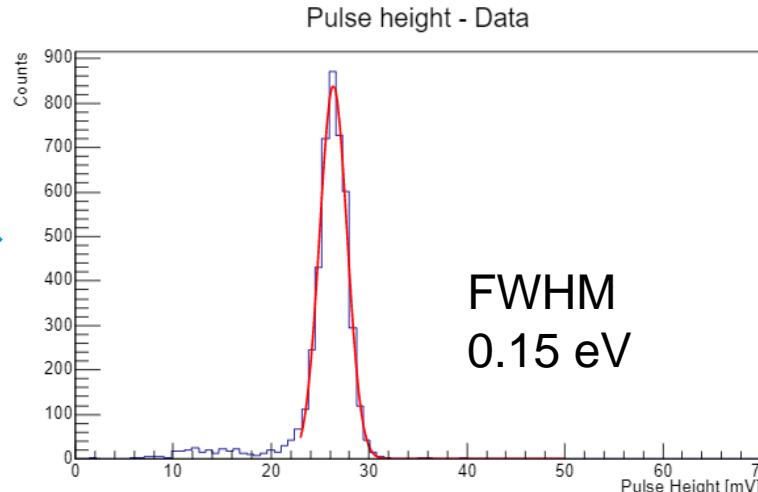
# Frequency domain analysis

Pulse Integral - Data



Pulse height as compromise between linear response and energy resolution

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



Phenomenological approach (time)

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

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