
ALPS II Magnet String, HERA North, DESY

# A TES Detector for ALPS II

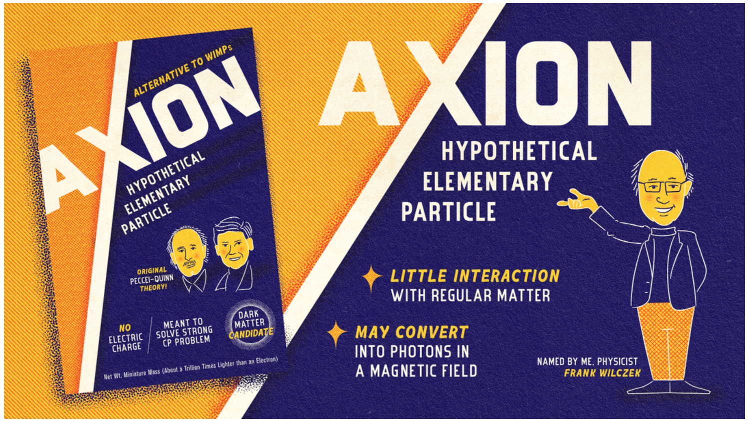
**EPS-HEP, July 2021**

*Rikhav Shah, for the ALPS Collaboration*

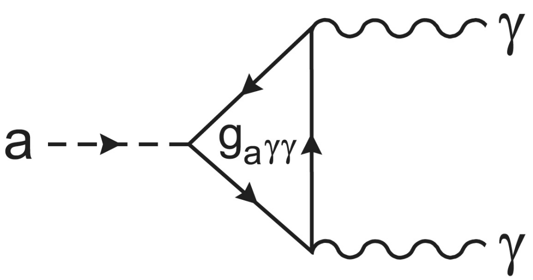
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES · NSF · HEISING-SIMONS FOUNDATION · Science & Technology Facilities Council · DESY. · UF UNIVERSITY of FLORIDA · Leibniz Universität Hannover · JG|U

# Origins: Axions

- QCD interaction includes CP-violating term
- "Strong CP" problem mitigated by a Peccei-Quinn symmetry
  R. D. Peccei, H. R. Quinn, "CP Conservation in the Presence of Pseudoparticles", Phys. Rev. Lett. **38**, 1440
- Leads to new pseudo Nambu-Goldstone boson (*very low mass and very low interaction*): ***axion***
  S. Weinberg, A New Light Boson?, Phys. Rev. Lett. 40 (1978) 223.
- Well motivated WISP candidate!
  M. Dine, W. Fischler, M. Srednicki, A Simple Solution to the Strong CP Problem with a Harmless Axion, Phys. Lett. B 104 (1981) 199.
- Couples to gauge bosons, importantly:
  $$\mathscr{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$
- Interaction used in most experiments




https://www.symmetrymagazine.org/article/the-other-dark-matter-candidate



# Origins: Alps

- Breaking of other such global symmetries
- Many pseudo Nambu-Goldstone bosons arise: ***axion-like particles*** (alps)
- Lighter cousins to axions, similar interaction
- Contributors to cold dark matter
  A. Chatzistavrakidis, E. Erfani, H. P. Nilles, I. Zavala, Axiology, JCAP 1209 (2012) 006 [arXiv:1207.1128 [hep-ph]].
- Hints for such WISPs from:
  - Transparency of the universe to TeV photons
    D. Horns, M. Meyer, Indications for a Pair-Production Anomaly from the Propagation of VHE Gamma-Rays, JCAP 1202 (2012) 033 [arXiv:1201.4711 [astro-ph.CO]]
  - Anomalous cooling of Horizontal Branch (HB) stars
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- Using modified axion-photon coupling via Primakoff-like Sikivie effect
  P. Sikivie, Experimental Tests of the Invisible Axion, Phys. Rev. Lett. 51 (1983) 1415 [Erratum-ibid. 52 (1984) 695].


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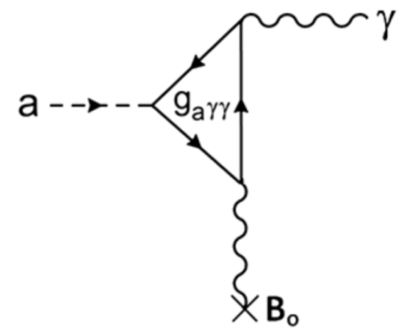

# ALPS II, DESY

- ***A***ny ***L***ight ***P***article ***S***earch II: LSW Experiment,  successor to ALPS I

# ALPS II, DESY

***Schematic of the ALPS II experiment***

*Laser*
*1064 nm*

# ALPS II, DESY

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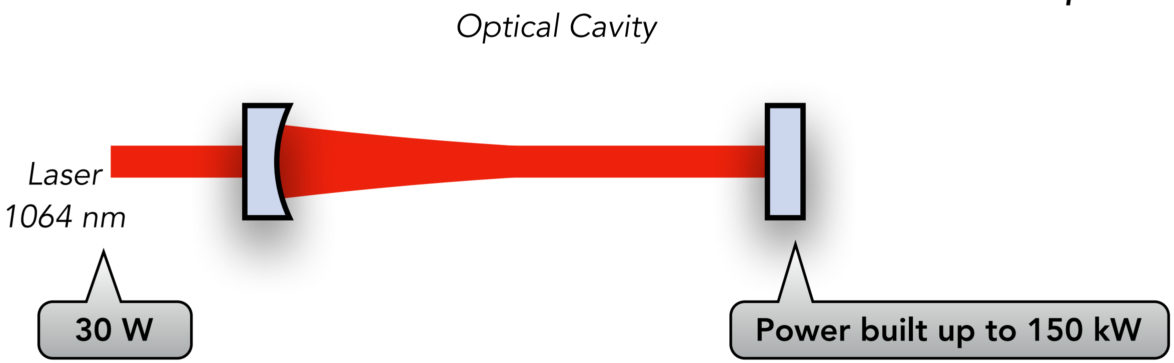

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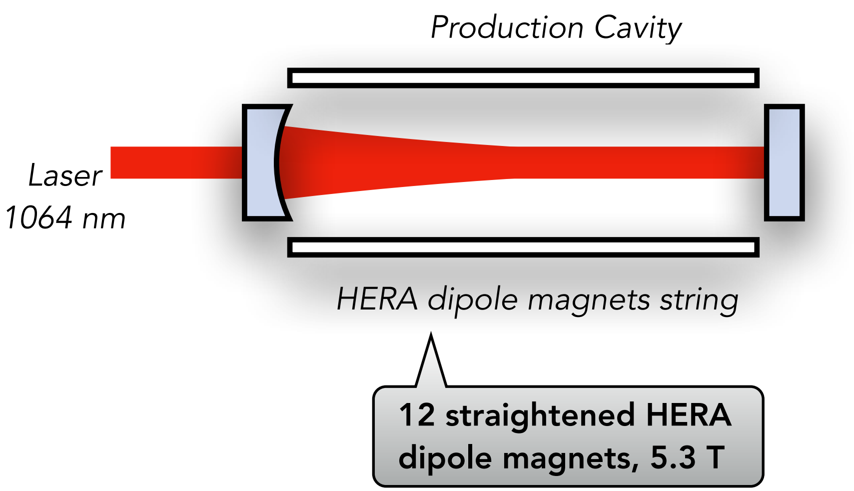

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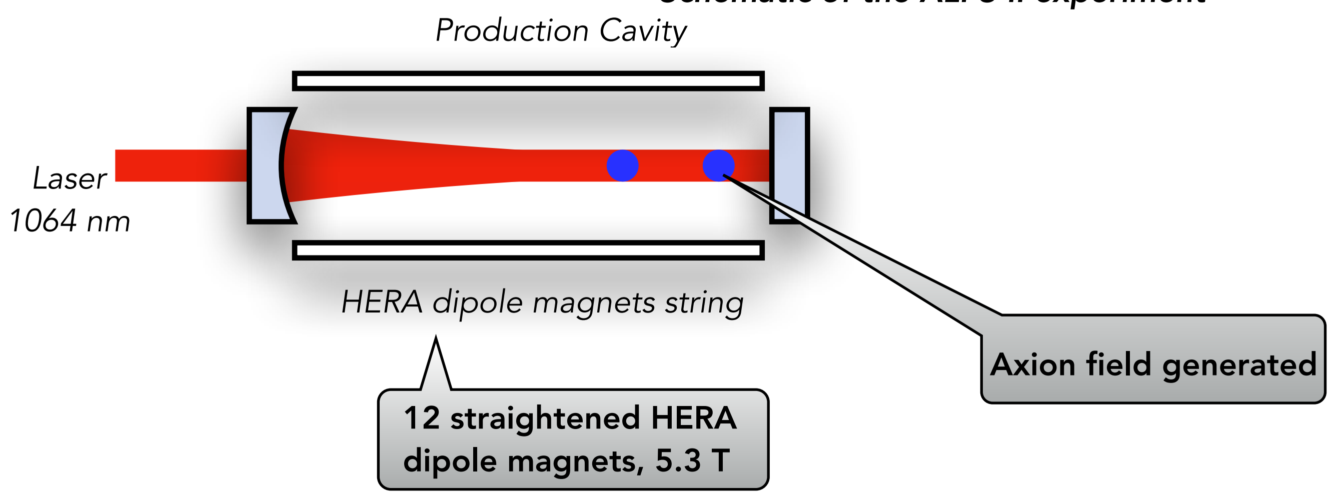
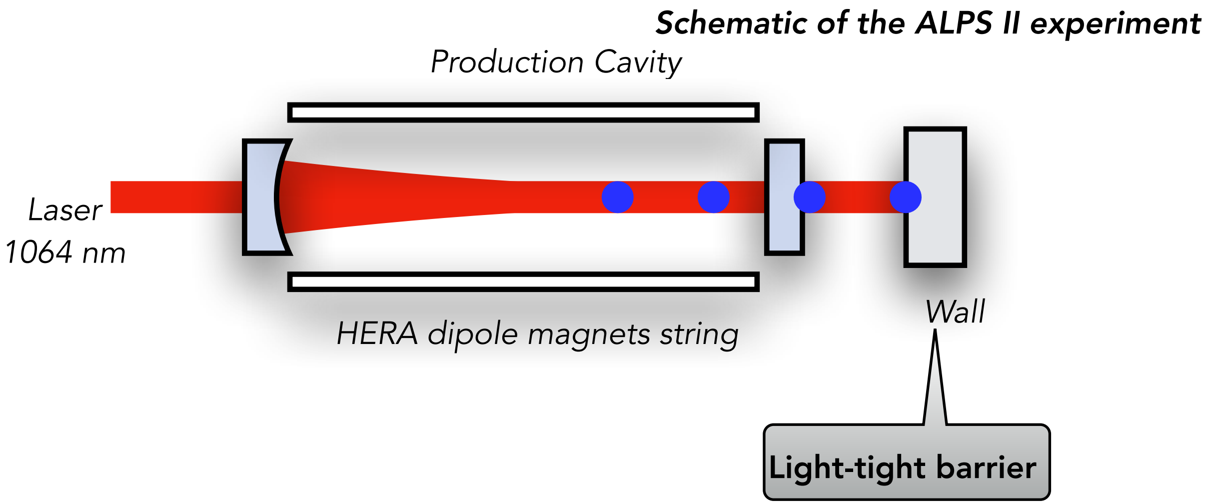



$$P_{\gamma \to a} \sim \mathscr{F}_{PC} \left( g_{a\gamma\gamma} B l \right)^2$$

# ALPS II, DESY

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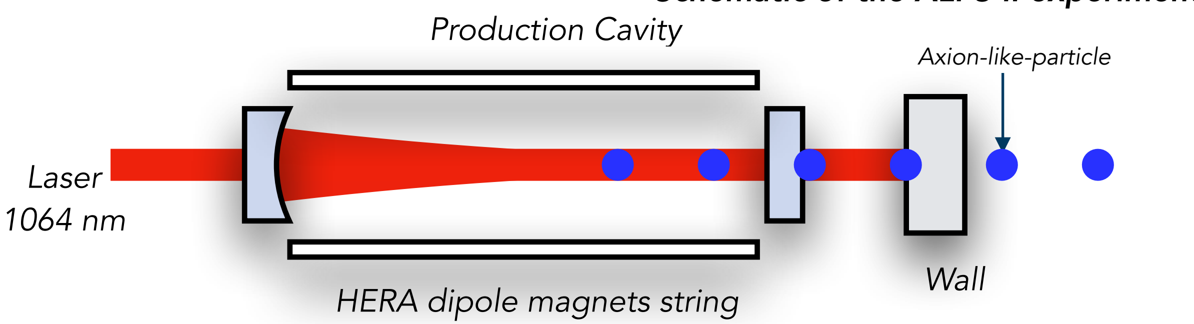
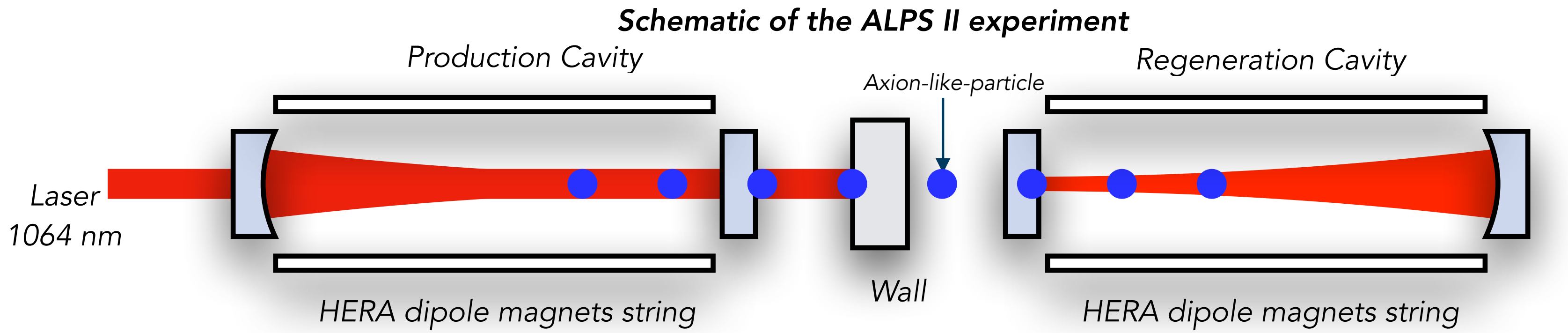



$$P_{\gamma \to a \to \gamma} \sim \mathscr{F}_{PC} \left( g_{a\gamma\gamma} B l \right)^2$$

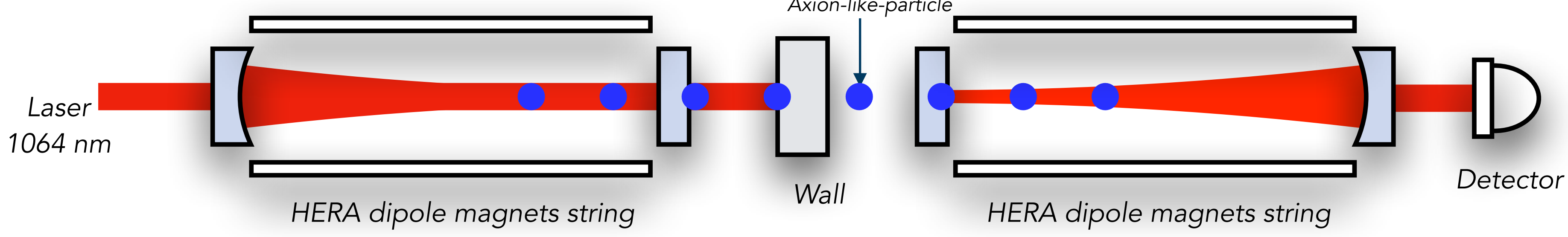
# ALPS II, DESY




**Symmetric optical cavity, power build up by 40,000**

$$P_{\gamma \to a \to \gamma} \sim \mathscr{F}_{PC} \left( g_{a\gamma\gamma} B l \right)^2 \cdot \mathscr{F}_{RC} \left( g_{a\gamma\gamma} B l \right)^2$$

# ALPS II, DESY




- Photon-to-alp conversion and reconversion in cavities

| |
|---|
| Further details in "**Towards new particle discoveries: ALPS II experiment shines soon**" by Ayman Hallal, 29 July 2021, 11:10, Parallel Session T03: Dark Matter |

| |
|---|
| **ALPS II in DESY & UHH Labs tour** 29 July 2021, 18:15 |

*Schematic adapted from Katharina-Sophie Isleif*

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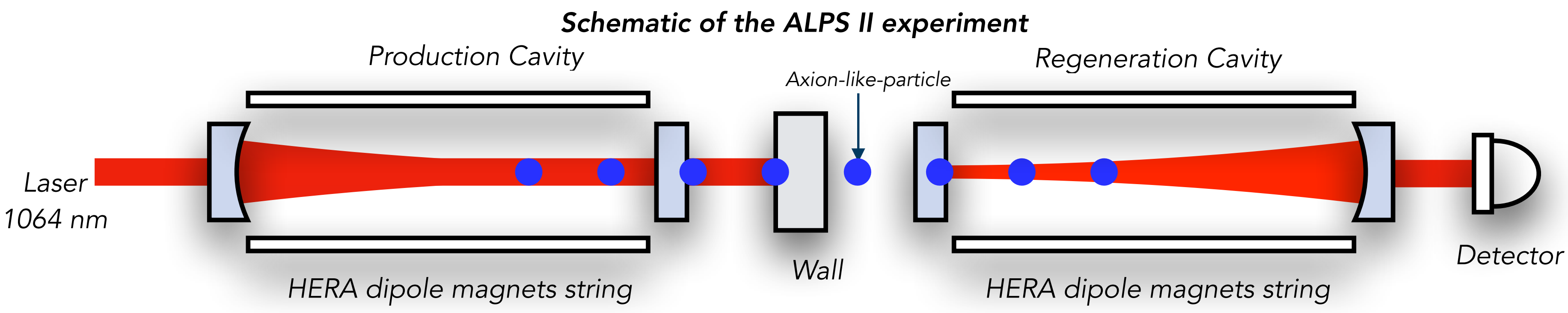


- Photon-to-alp conversion and reconversion in cavities

$$P_{\gamma\to a\to\gamma} = \frac{1}{16}\mathcal{F}_{PC}\mathcal{F}_{RC}\left(g_{a\gamma\gamma}Bl\right)^4 = 6\cdot 10^{-38}\mathcal{F}_{PC}\mathcal{F}_{RC}\left(\frac{g_{a\gamma\gamma}}{10^{-10}\ GeV^{-1}}\frac{B}{1\ T}\frac{l}{10\ m}\right)$$

*Schematic adapted from Katharina-Sophie Isleif*

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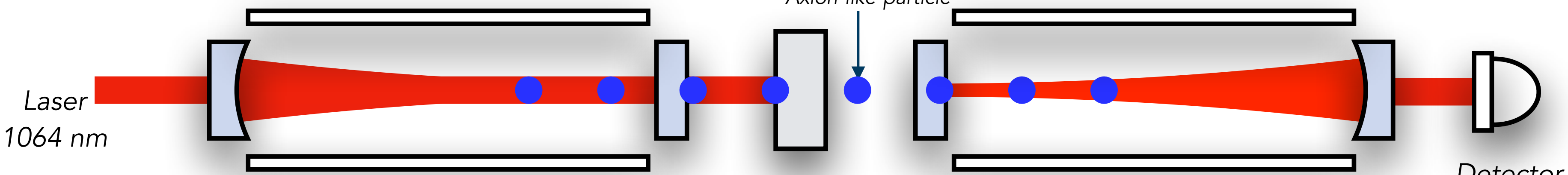


$g_{a\gamma\gamma} \approx 0.2$

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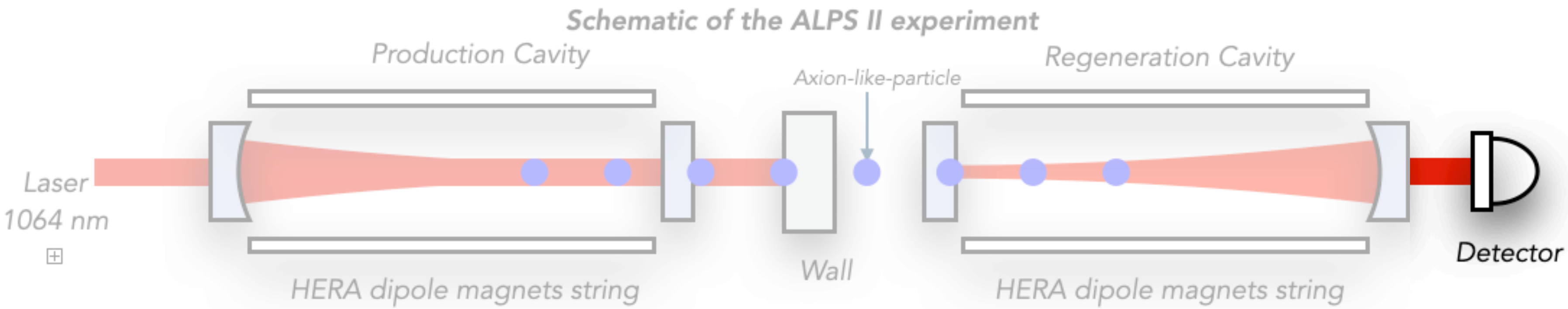
Results in regenerated photon rate $\sim 2\cdot 10^{-5}$ /s
i.e. $\sim 2$ photons per day!

.....pre-detection

# Detector Needs



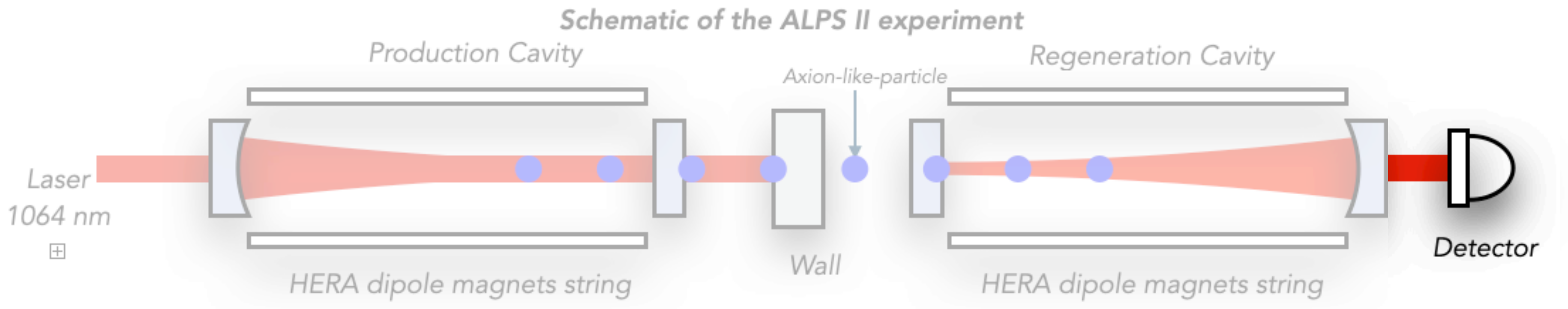

Very low 1064 nm photon regeneration rate: $\sim$ 2 **photons a day**

- **Very low rates**
  (1-2 photons a day)
- **Low energy photon detection**
  (~1.16 eV)
- **Low background rate**
  (< 1 photon a day)[1]
- **High quantum efficiency**
- **High detection efficiency**

*Takes a lot to see light at the end of the tunnel*

[1]Dark rate $\leq 7.7 \cdot 10^{-6}$ Hz for TES to be viable, value from Transition Edge Sensor, *ALPS II - Design requirement document, Document number v3, Jan Hendrik Põld and Hartmut Grote*

# Detector Needs

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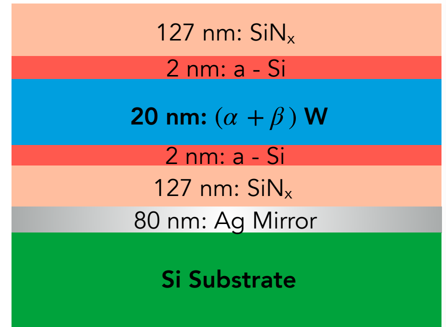
**Achievable with a Transition Edge Sensor![1]**

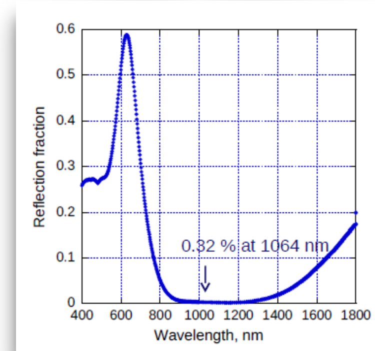
[1]Lita, Adriana E., Aaron J. Miller, and Sae Woo Nam. "Counting near-infrared single-photons with 95% efficiency." *Optics express* 16.5 (2008): 3032-3040.

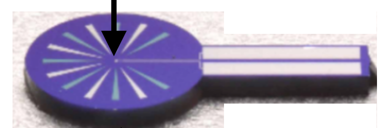
# TES

- Transition Edge Sensor: Superconducting microcalorimeter operated at its critical temperature $\sim 140$ mK, exploiting resistance dependence
- Tungsten micro-wafer: $25\mu$m x $25\mu$m x $20$nm designed for 1064 nm photon detection
- Anti-reflective coatings, etc. maximise photon incidence
- Manufactured by NIST[1], USA
- Read out by sensitive magnetometers on module, integrated on module by PTB[2]

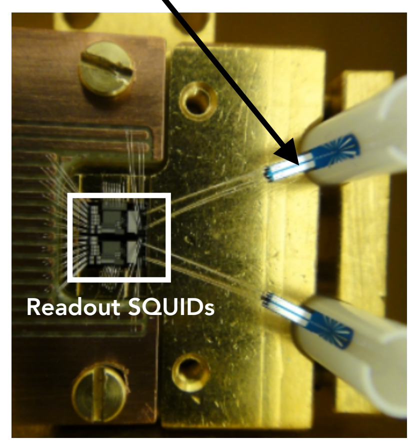
*TES Stack, Cross-section*

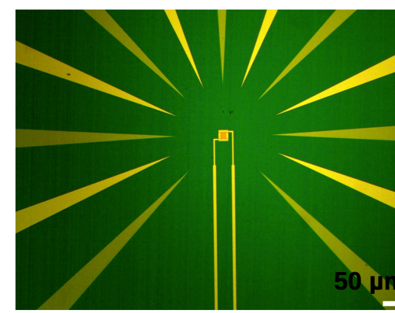


**NIST TES Chip**




TESs integrated on module

[1]National Institute of Standards and Technology
[2]Physikalisch-Technische Bundesanstalt, Germany

# Detector Setup

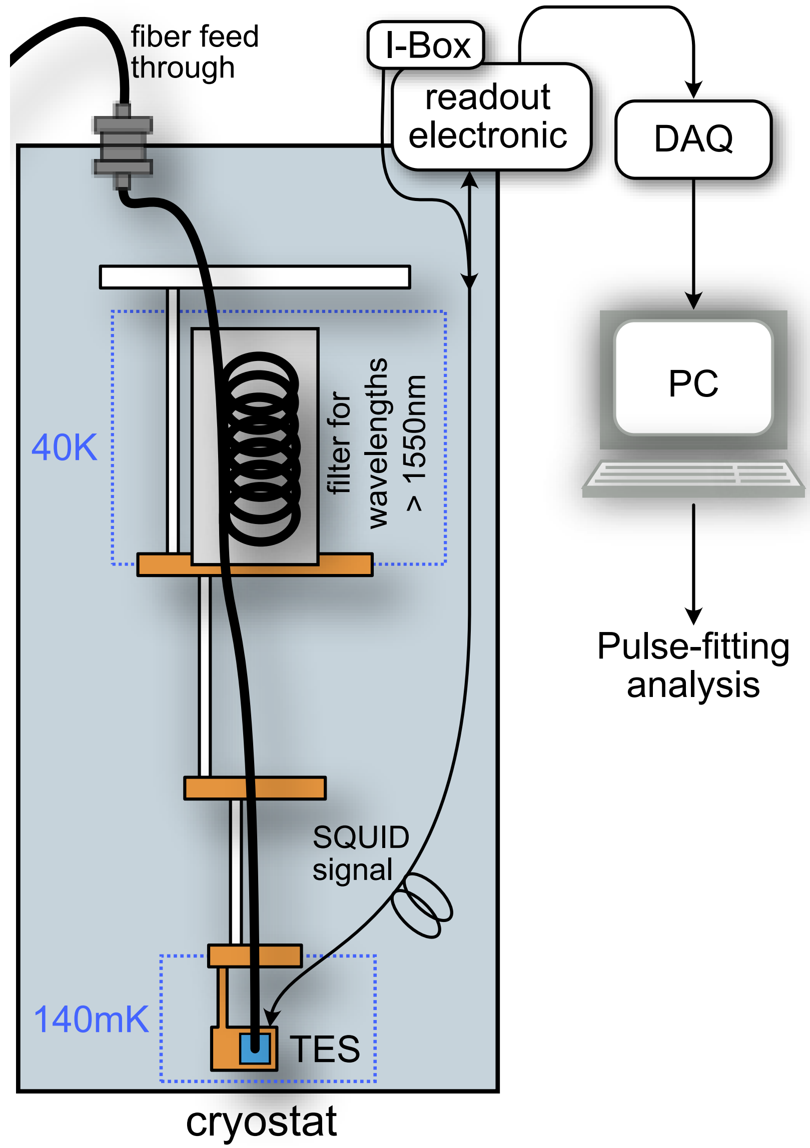
Setup housed in BlueFors dilution refrigerator: ($^3He/^4He$) mixture

Operated at 25 mK

Fiber input to TES from feedthrough

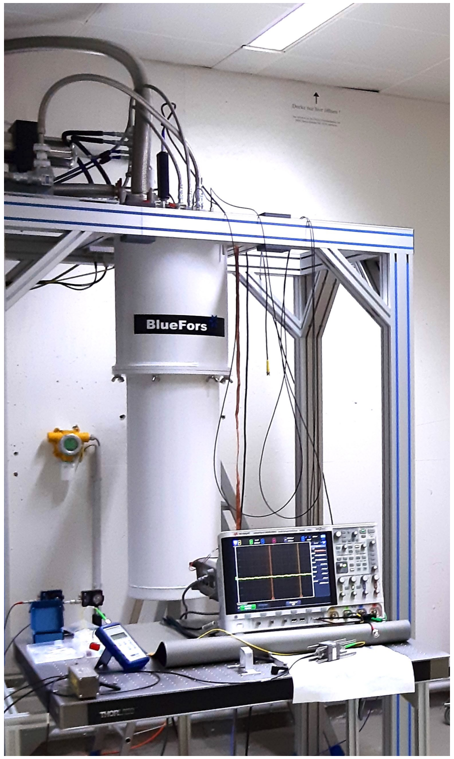
SQUID signal readout/ output via cryocable to electronics

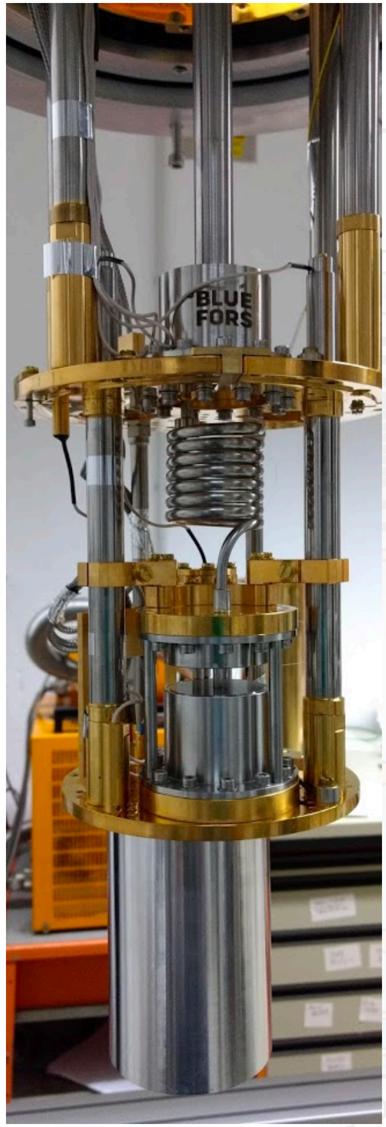
TES Module on Cu cold finger, in Al can housing

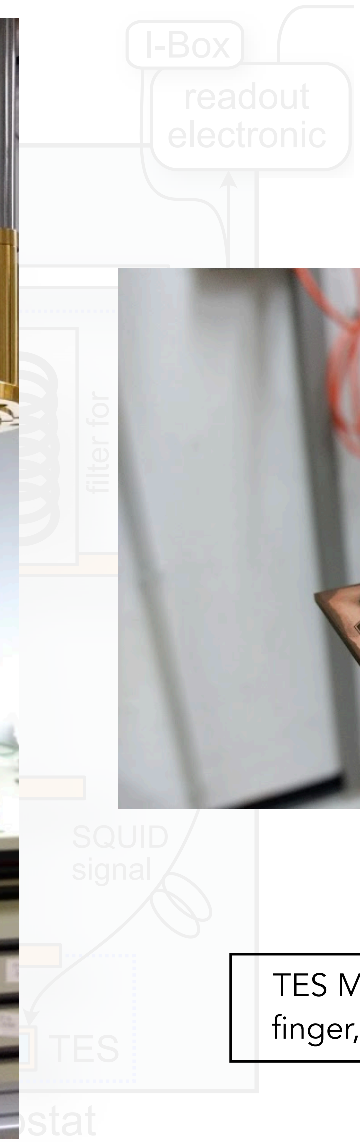


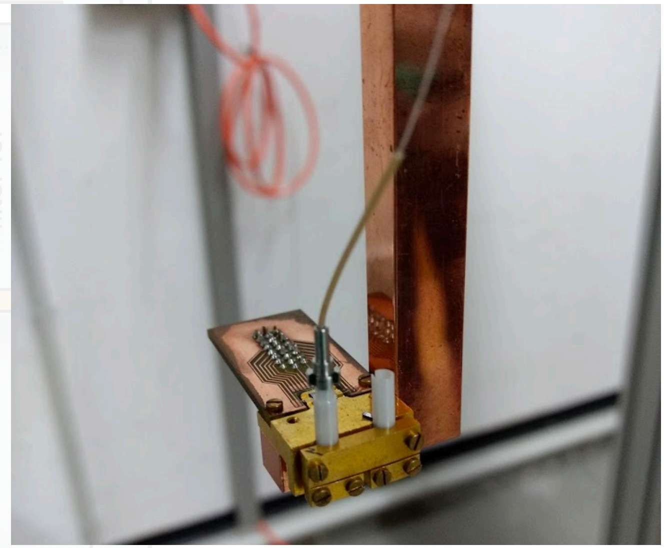

DAQ via Alazar ATS9626 250Ms/s on Linux system with in-house GUI

# Detector Setup



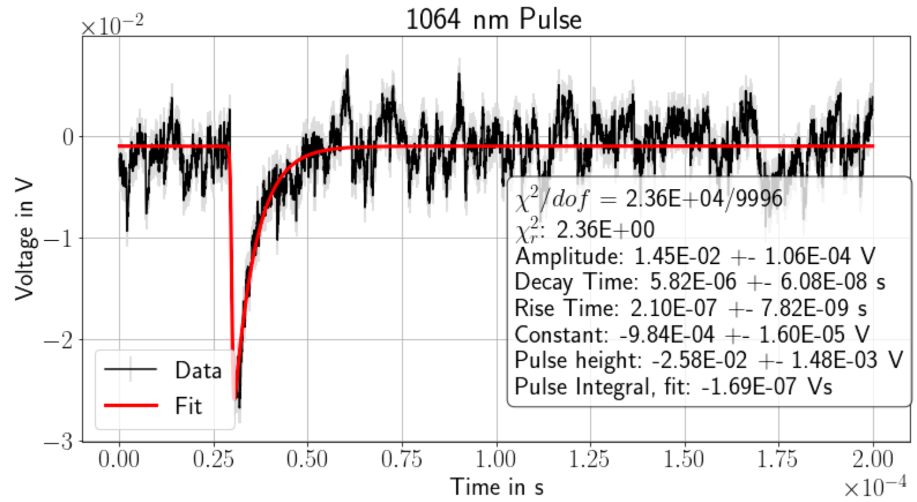



TES Module on Cu cold finger, in Al can housing

# TES: Signals

- Fiber coupled TES, 1064 nm cw laser input
- Chosen working point, e.g. $30\,\%\,R_N$
- Able to detect 1064 nm photons!
- Comparison to TES response
- Modification for fitting




Fitting allows freedom/restrictions on parameter values for constant $c$, amplitude $a$, trigger time $t_0$, time constants $\tau_1, \tau_2$.

Build other fit parameters like Pulse Integral (deposited energy)

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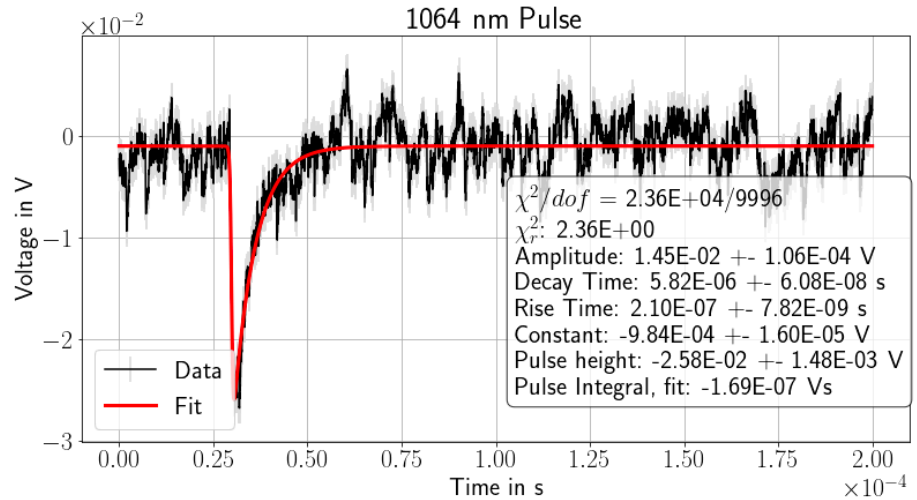


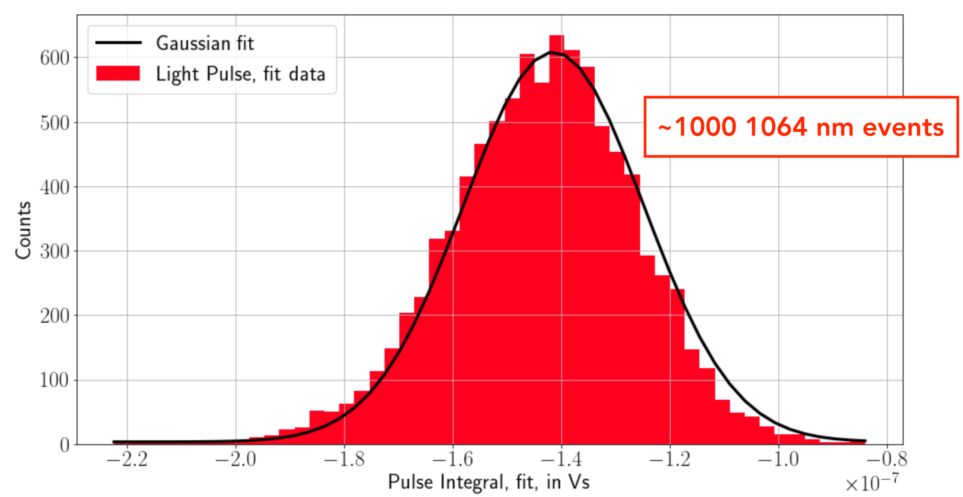

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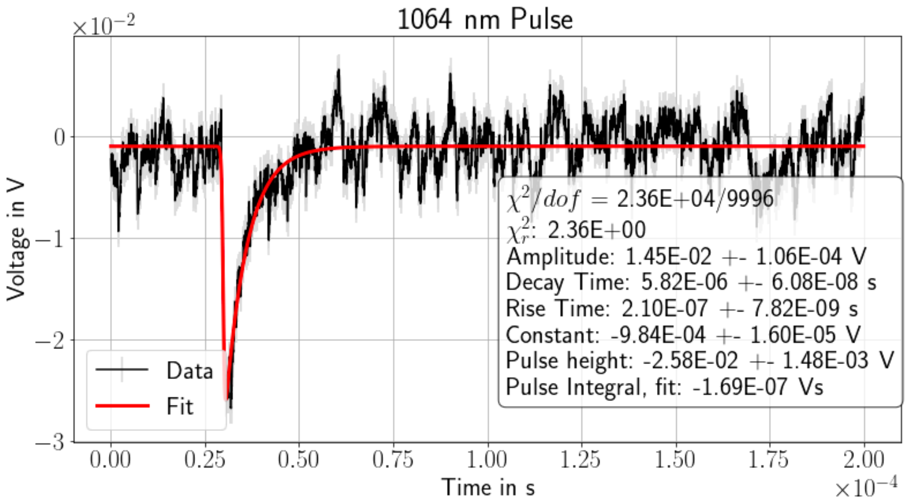


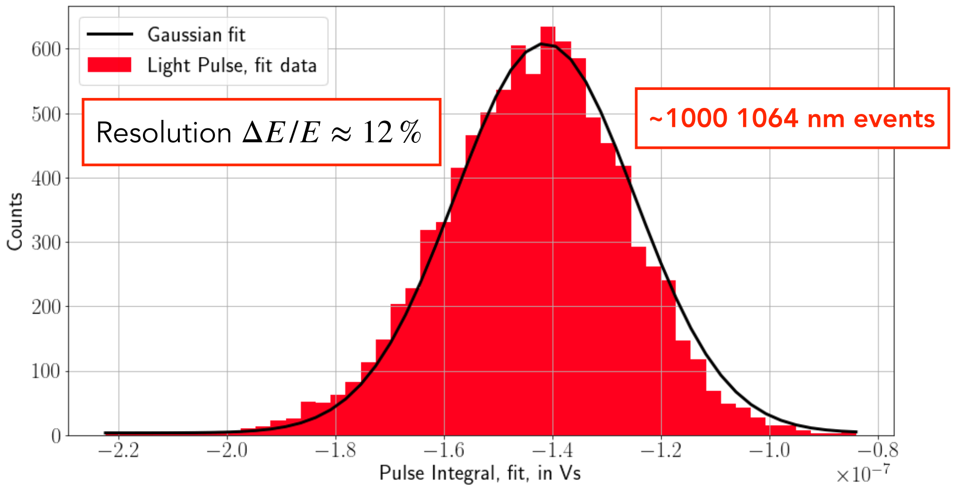

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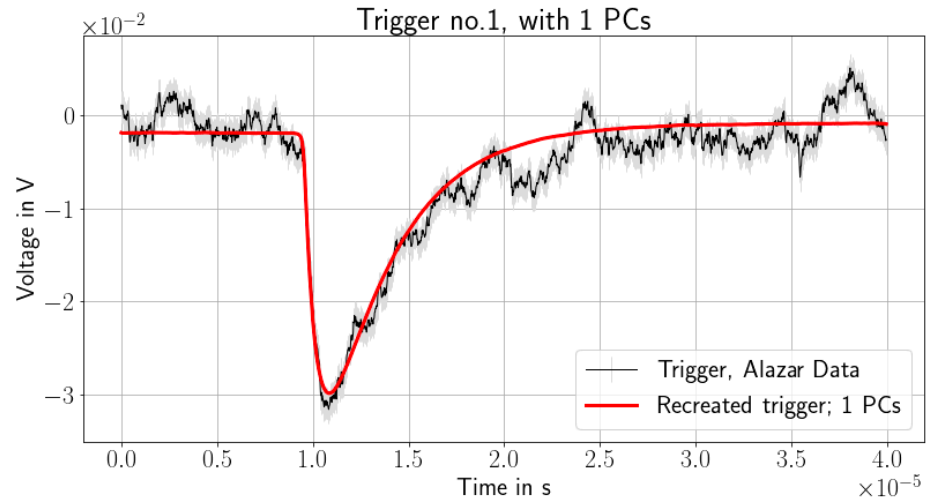
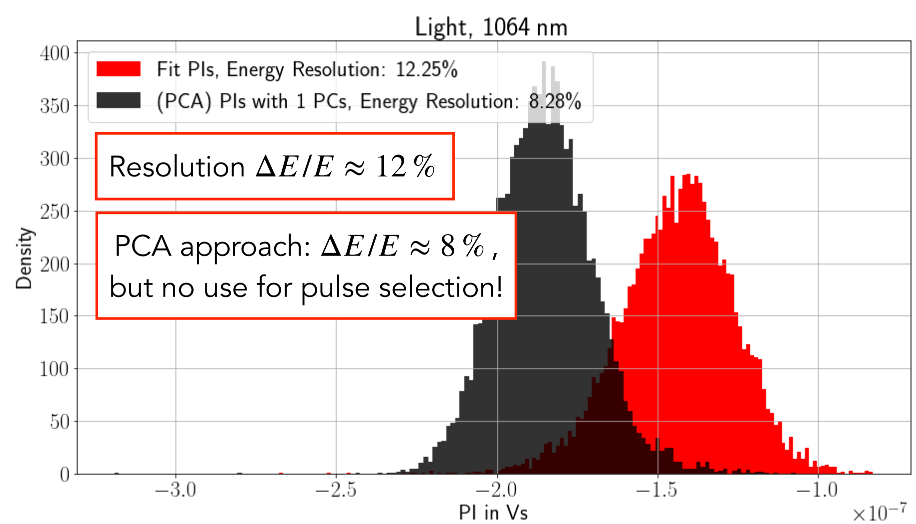
Pulse recreation with PCA: Principal Component Analysis



# TES: Backgrounds

**All backgrounds**

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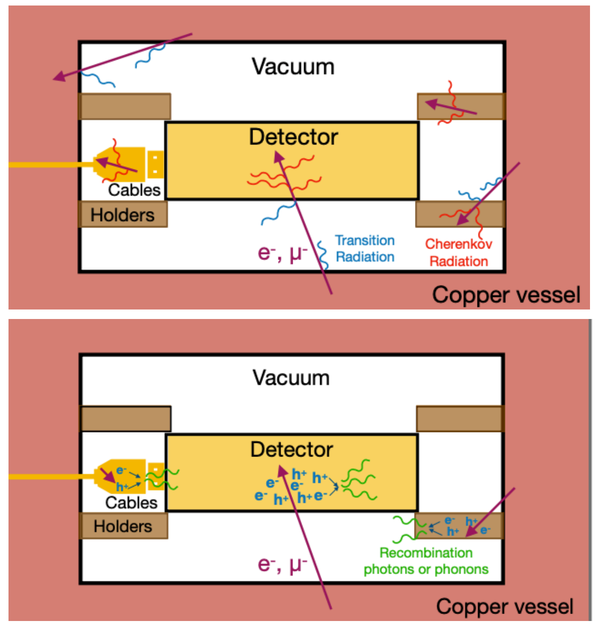
**Intrinsics**

Populations without the optical fiber attached to the TES

Cosmic muons causing Cherenkov radiation, etc.;
radiogenic $\gamma$ or $e^-$,
stray or trapped magnetic fields

**Track-related** events dominate




**Extrinsics**

Populations with the optical fiber attached to the TES, no laser input

Black body radiation (direct and/or indirect), radiogenic $\gamma$ or $e^-$

**Non track-related** events dominate

Schematic from Du, Peizhi, et al. "Sources of low-energy events in low-threshold dark matter detectors." *arXiv preprint arXiv:2011.13939* (2020).

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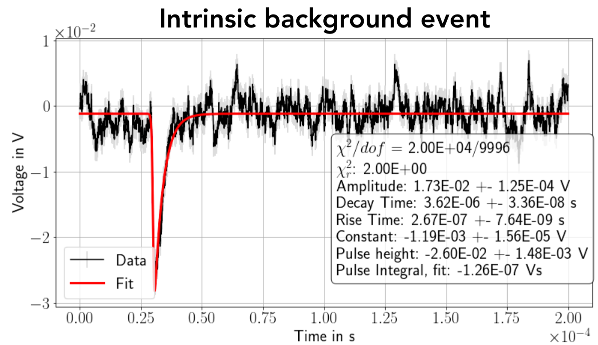


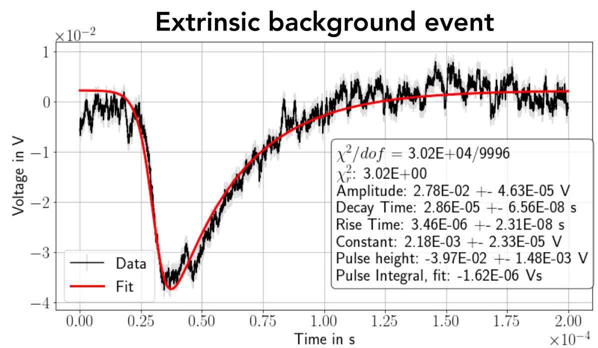


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**Dark rate required $\leq 7.7 \cdot 10^{-6}$ Hz over 20 day DAQ period**[1]

[1]Dark rate $\leq 7.7 \cdot 10^{-6}$ Hz for photon detection at $5\sigma$ with 50% DE, value from Transition Edge Sensor, *ALPS II - Design requirement document, Document number v3, Jan Hendrik Põld and Hartmut Grote*

# TES: Backgrounds


Populations **without** the optical fiber attached to the TES

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## Intrinsics

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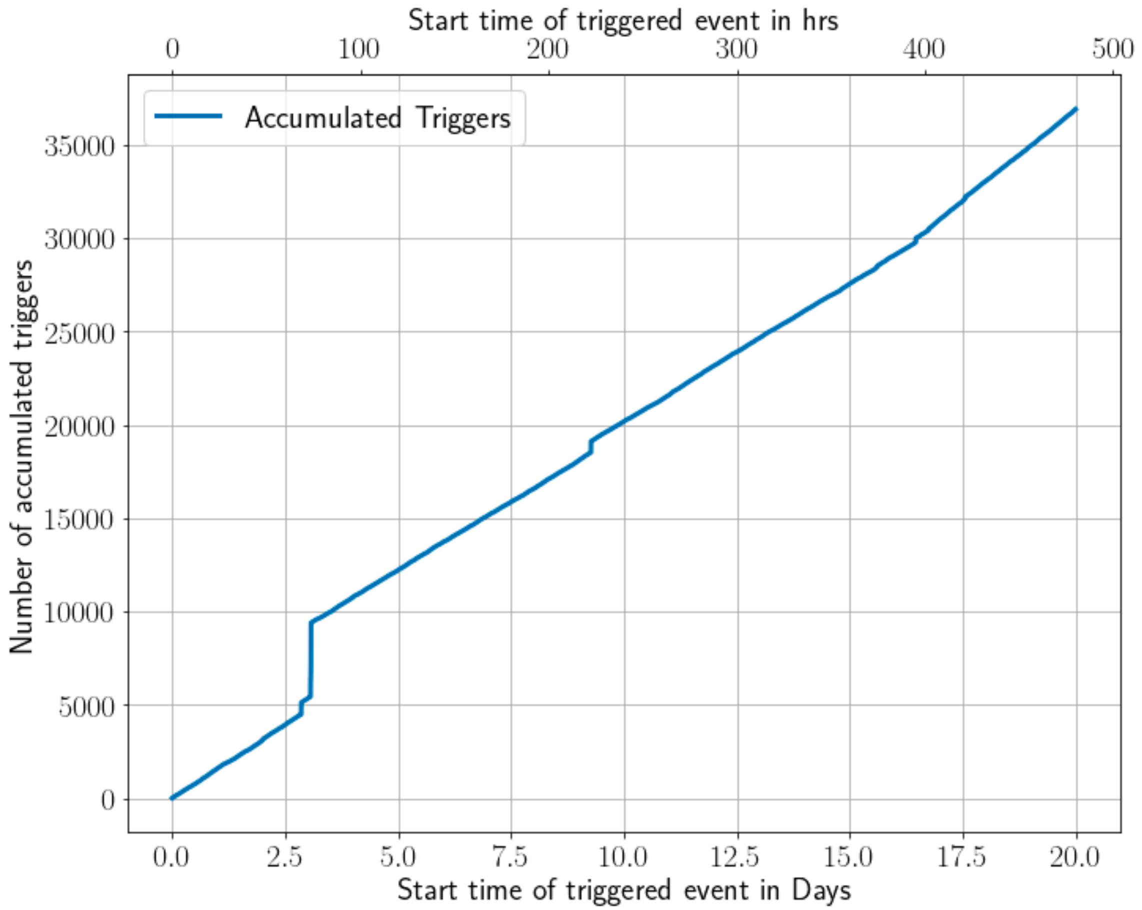
Populations **without** the optical fiber attached to the TES

20 day long DAQ to check viability!



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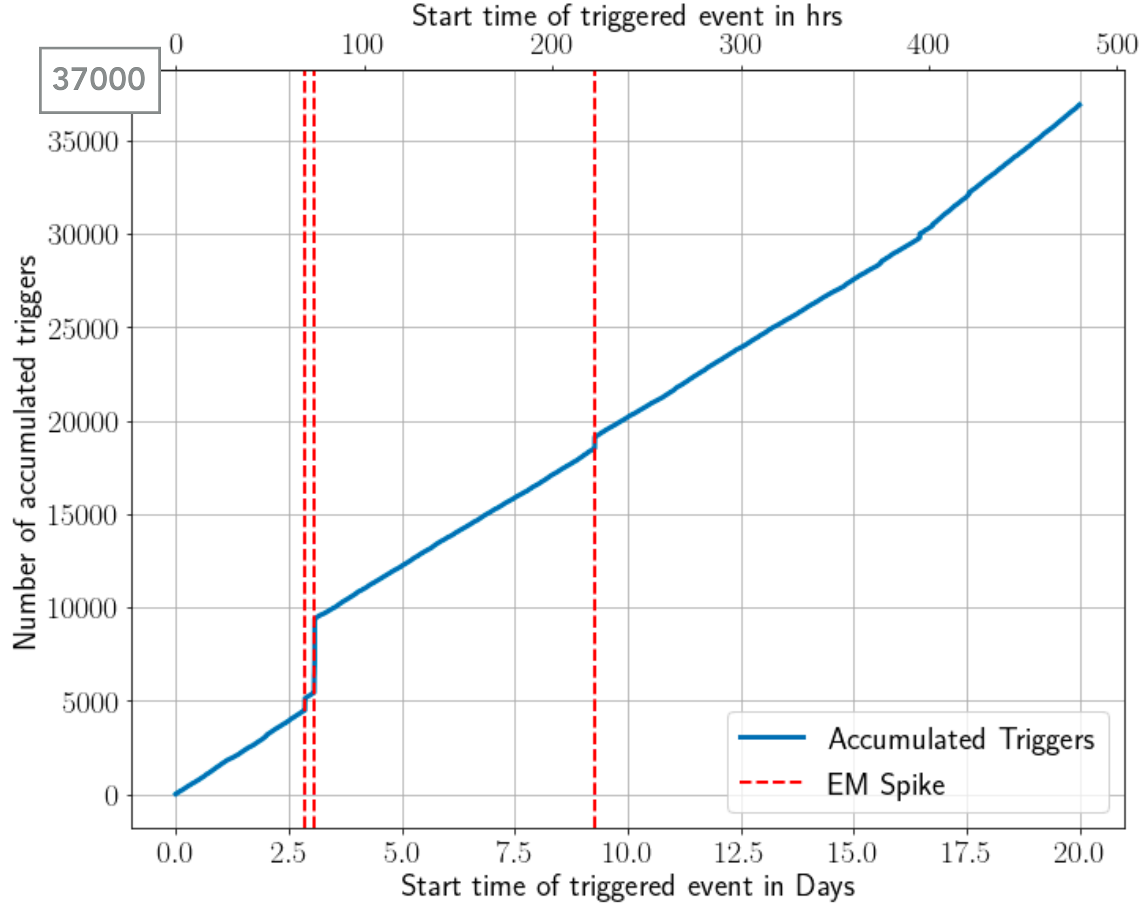
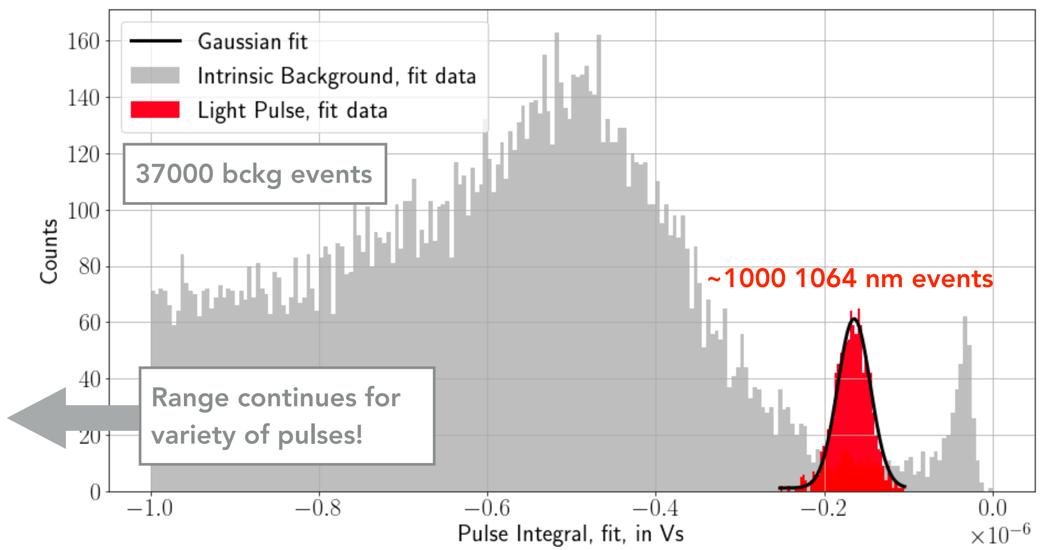


# TES: Backgrounds

## Intrinsics

Pulse selection/background rejection using fit parameters like pulse integral, time constants, etc.

Comparison to 1064 nm "light" data

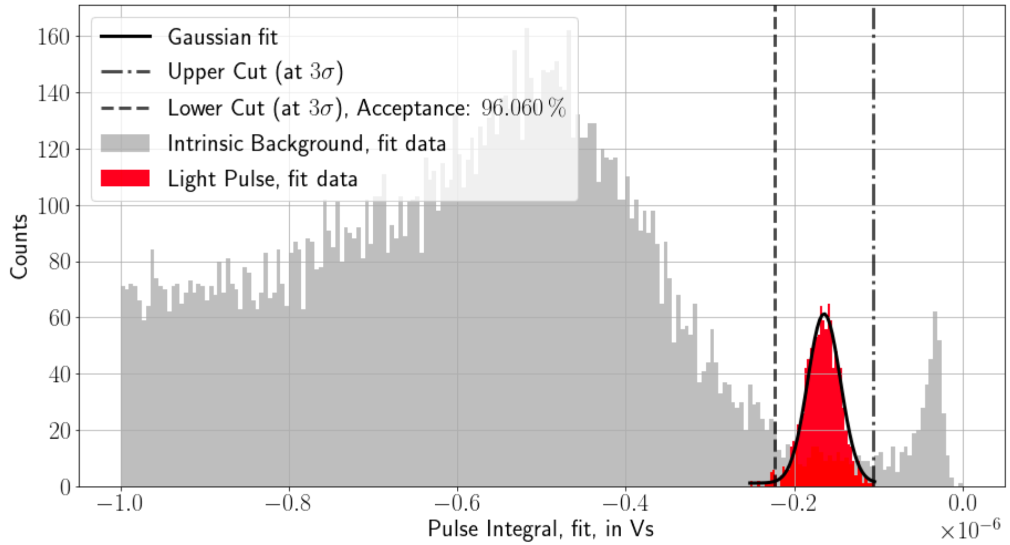


# TES: Backgrounds

## Intrinsics

Pulse selection/background rejection using fit parameters like pulse integral, time constants, etc.

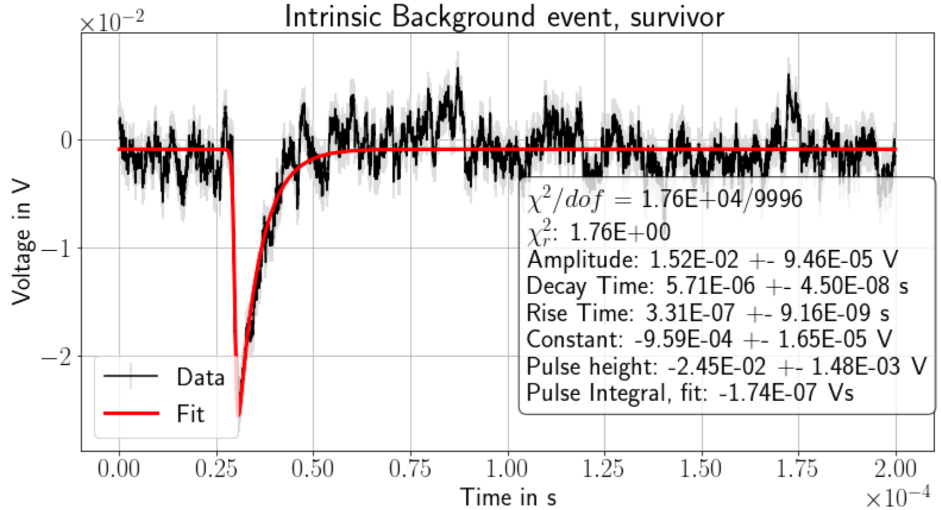
Comparison to 1064 nm "light" data leads to a **selection region**

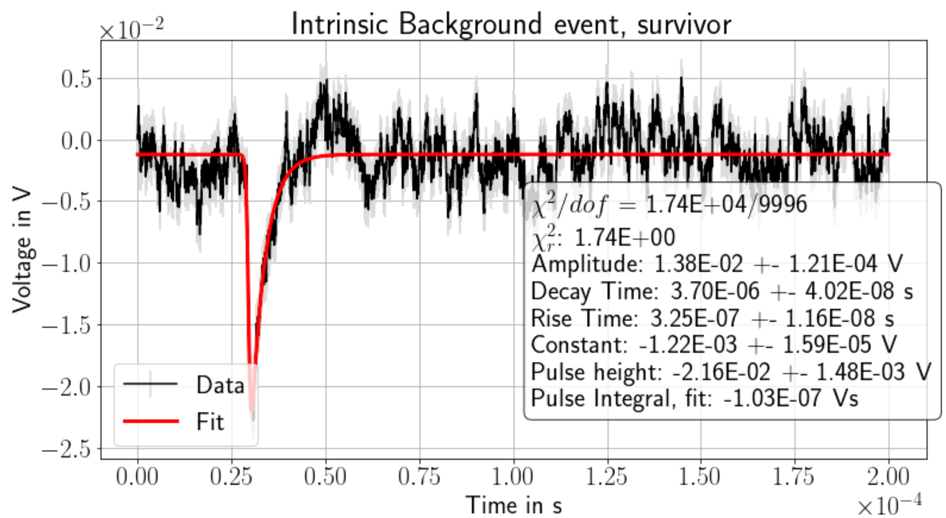


# TES: Backgrounds

## Intrinsics

Apply cuts to fit parameters on 20 day dataset



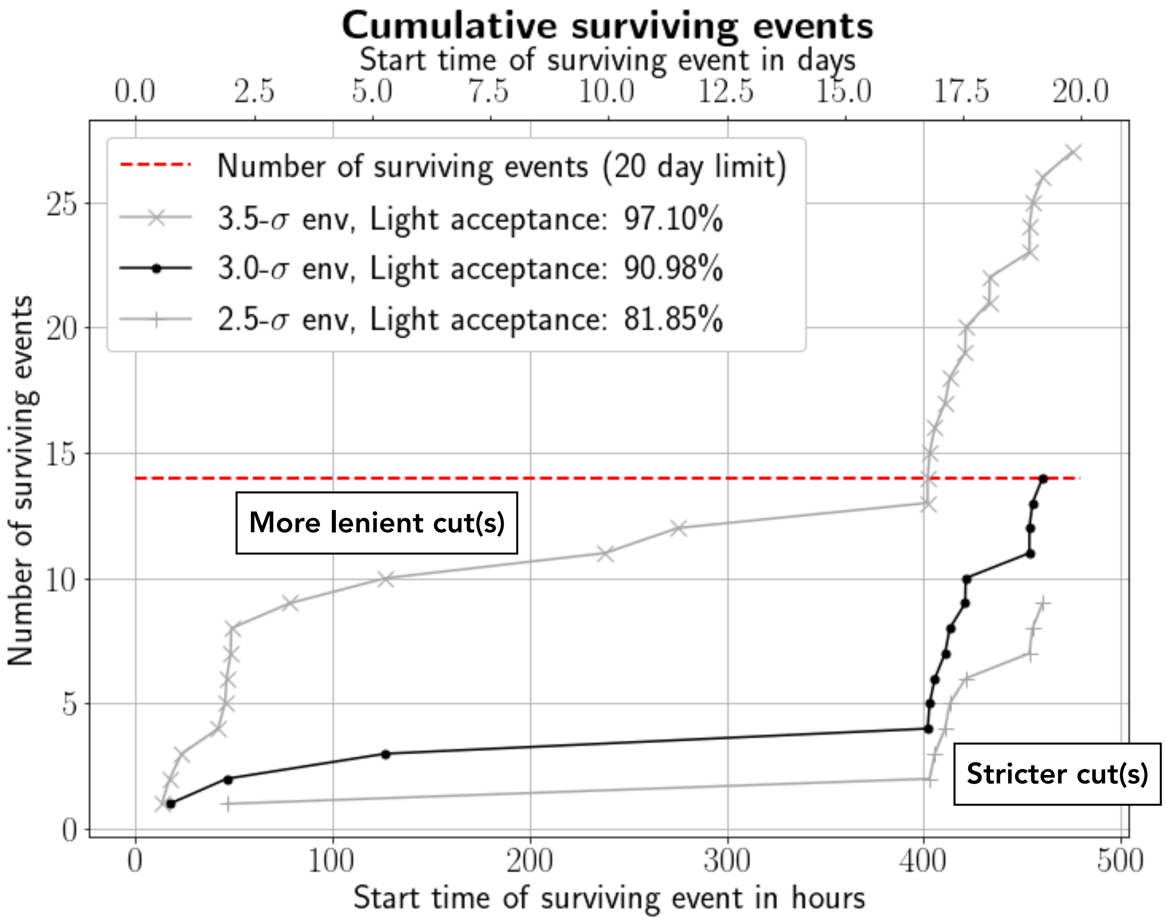



# TES: Backgrounds

## Intrinsics

Apply cuts to fit parameters on 20 day dataset

Map out surviving events for choice of cut(s)



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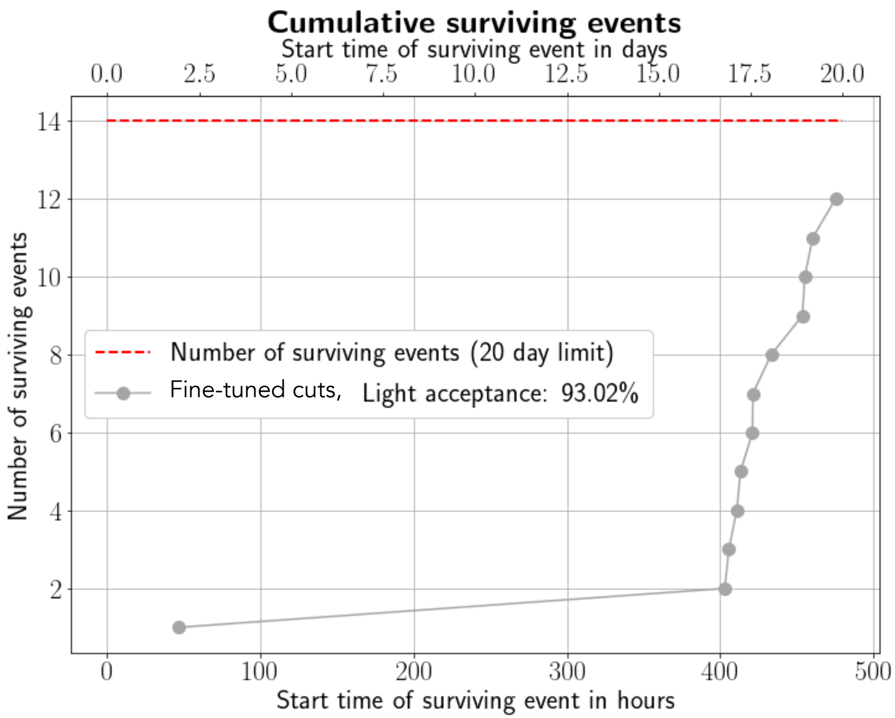
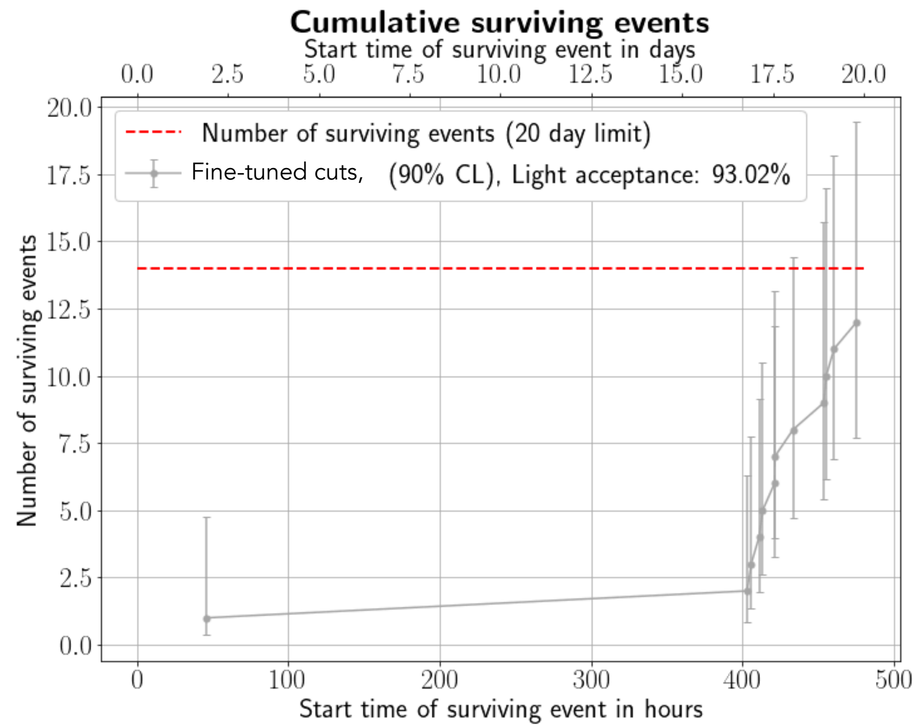



**Achieve dark rate $6.9^{+5.18}_{-2.93} \cdot 10^{-6}$ Hz (95% CL)**

***TES viable for use in ALPS III!***

# Summary and Outlook

- Stable and robust detector and readout system
- Successful, reproducible operation and DAQ of the TES
- Very good understanding of the TES response
- Successful **single photon detection at 1.16 eV** (1064 nm) with **8% energy resolution**
- Reliable and uniform pulse analysis pipeline with independent approaches
- **Long term 20 day DAQ for (intrinsic) background events**
- Effective pulse selection to obtain **dark rate < 7 $\mu$Hz**
- **TES viable for use in ALPS II**

# Summary and Outlook

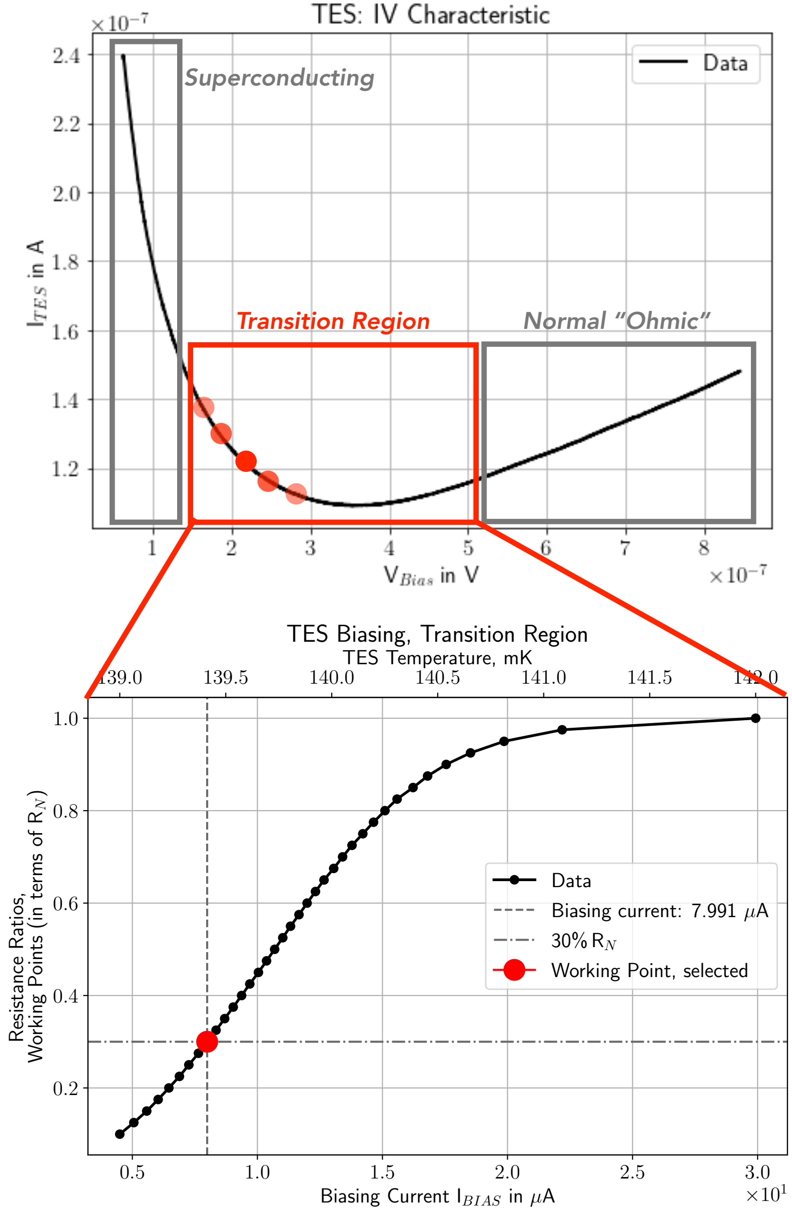
- Stable and robust detector and readout system
- Successful, reproducible operation and DAQ of the TES
- Very good understanding of the TES response
- Successful **single photon detection at 1.16 eV** (1064 nm) with **8% energy resolution**
- Reliable and uniform pulse analysis pipeline with independent approaches
- **Long term 20 day DAQ for (intrinsic) background events**
- Effective pulse selection to obtain **dark rate < 7 $\mu$Hz**
- **TES viable for use in ALPS II**
- Work on future measurements for TES: efficiency, background suppression, etc.
- Designing TES implementation in ALPS II and dedicated TES Lab
- Simulations of TES pulses and backgrounds also underway
- Completing background characterisation
- Moving and re-characterising system at ALPS II for DAQ in 2022

Thank you!

# Backup

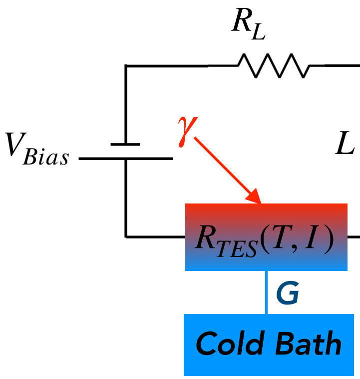
# TES: Photon Incidence

- Heat the TES to transition region
- Requires biasing, realised with constant voltage across the TES
- Working point(s) within transition region
- Chosen in fractions of normal "Ohmic" resistance $R_N$
- Ensure high dynamic range and energy resolution
- Photon incidence heats TES by $\sim 300\mu$K and resistance by $7\Omega$

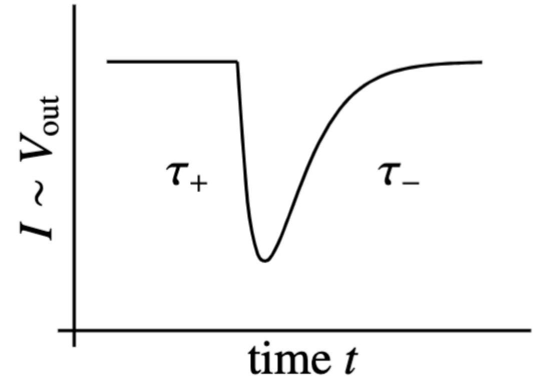


# TES Response

- TES in electrothermal circuit




With certain assumptions, the TES signal for photon absorption will rise and decay with time constants $\tau_+, \tau_-$



# TES Response

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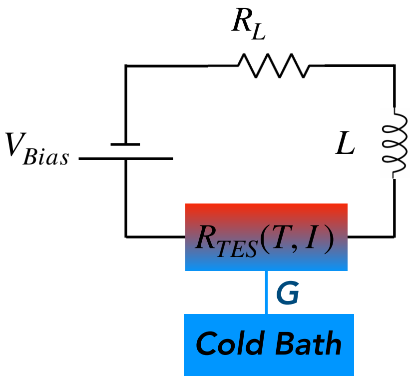



$$L\frac{\mathrm{d}I}{\mathrm{d}t} = V_{\mathrm{BIAS}} - IR_{\mathrm{L}} - IR(T,I)$$

*Induced voltage* — *TES Voltage*

$$C\frac{\mathrm{d}T}{\mathrm{d}t} = -P_{\mathrm{bath}} + P_{\mathrm{J}}(R(T,I)) + P$$

*TES Power* — *Joule dissipation* — *External Power*

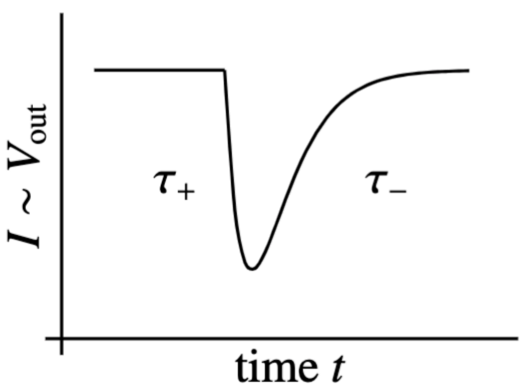
Solve after uncoupling, linearise $R_{TES}(I,T)$!

$$R(T,I) \approx R_0 + \alpha\frac{R_0}{T_0}\delta T + \beta\frac{R_0}{I_0}\delta I$$

*Working point Resistance* — *Sensitivities*

$$\alpha,\beta = \left(\frac{\partial \log R}{\partial \log T}\right)_{WP}, \left(\frac{\partial \log R}{\partial \log I}\right)_{WP}$$

$$\delta I(t) = \left(\frac{\tau_I}{\tau_+} - 1\right)\left(\frac{\tau_I}{\tau_-} - 1\right)\frac{1}{(2+\beta)}\frac{C\Delta T}{I_0 R_0 \tau_I^2}\frac{\left(e^{-t/\tau_+} - e^{-t/\tau_-}\right)}{(1/\tau_+ - 1/\tau_-)}$$




With certain assumptions, the TES signal for photon absorption will rise and decay with time constants $\tau_+, \tau_-$

$$\tau_+ = \frac{L}{R_L + R_0(1+\beta)} = 2.28 \pm 0.01 \text{ ns}$$

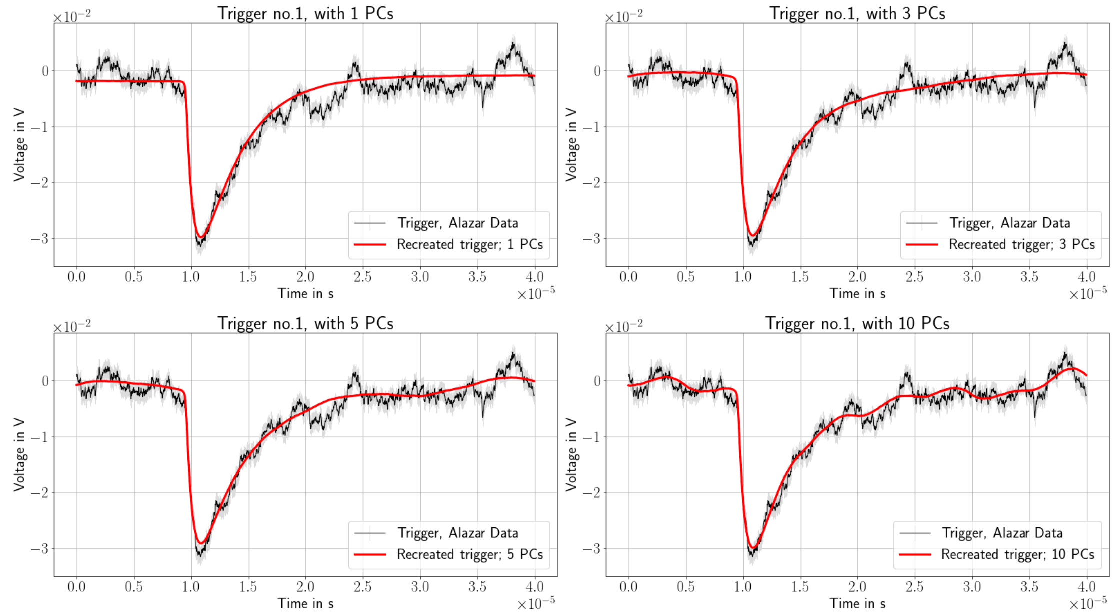
$$\tau_- = \frac{C/G}{1+\alpha/n} = 11.33 \pm 2.5\ \mu\text{s}$$

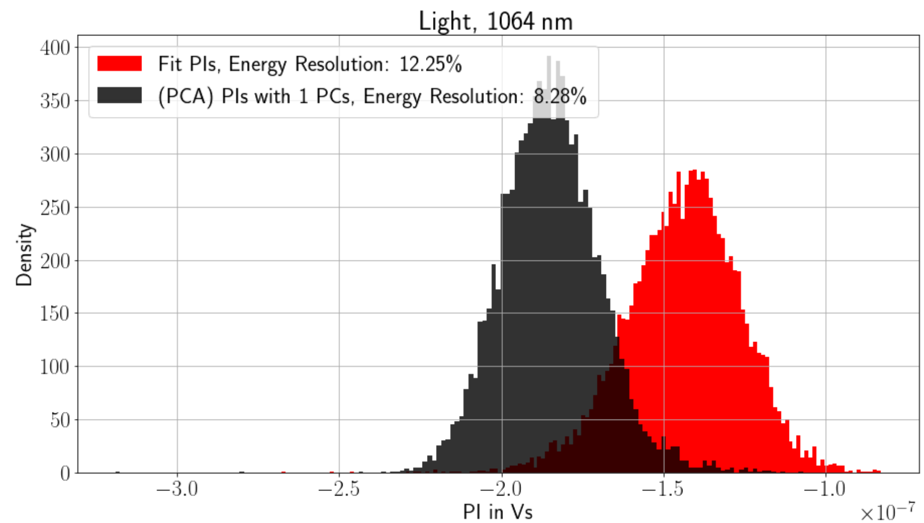
$$\Delta E_{RMS} \approx \sqrt{\frac{4k_B T_0^2 C}{\alpha}} \approx 2\,\%$$

Adapted from Irwin, Kent D., and Gene C. Hilton. "Transition-edge sensors." *Cryogenic particle detection* (2005): 63-150.

# TES: Signals

- Improving energy resolution, de-noising data
- Using Principal Component Analysis (PCA): Reduce dataset dimensionality, each "component" is orthogonal to each other Essentially, each datapoint $d = \sum_i w_i \cdot PC_i$
- Succeeding components capture much lower, 'noisy' information
- Achieve Energy resolution $\approx 8\,\%$
- Recreate and clean light pulses, but no pulse selection with backgrounds



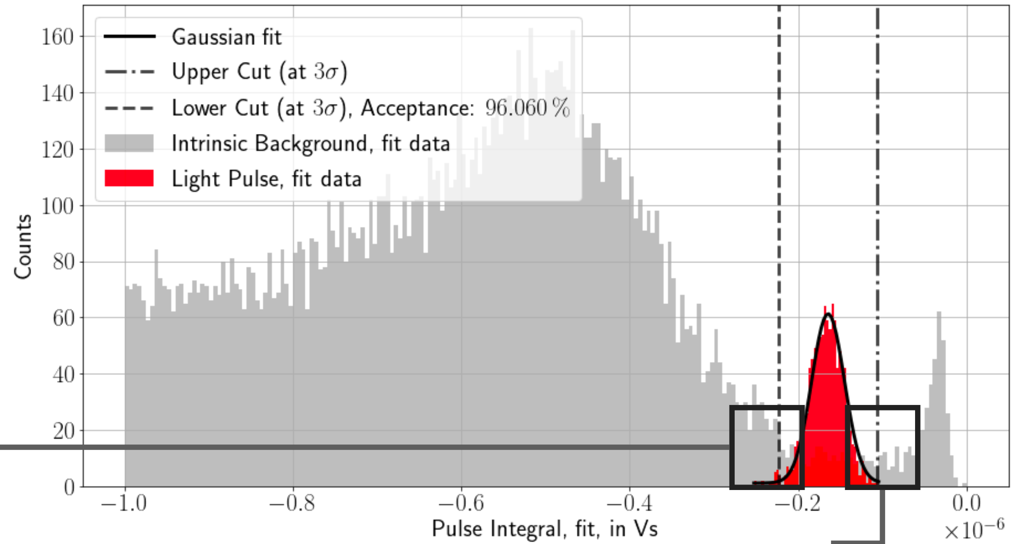
# TES: Backgrounds

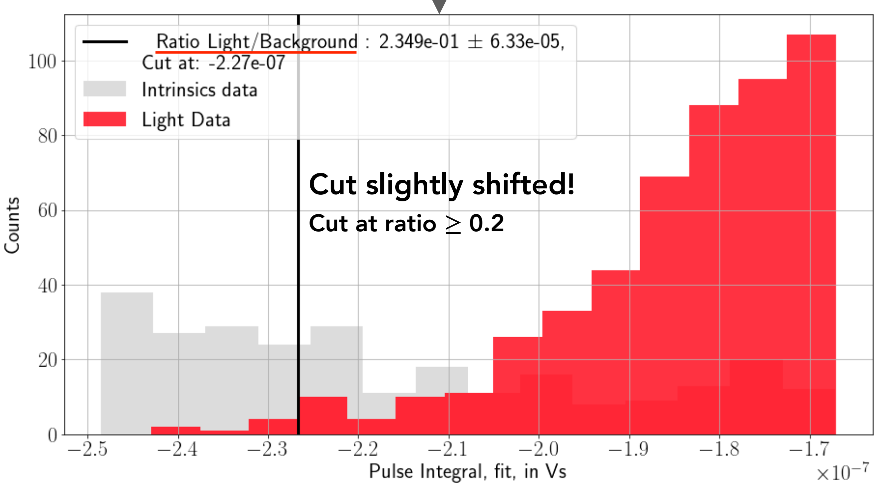
## Intrinsics

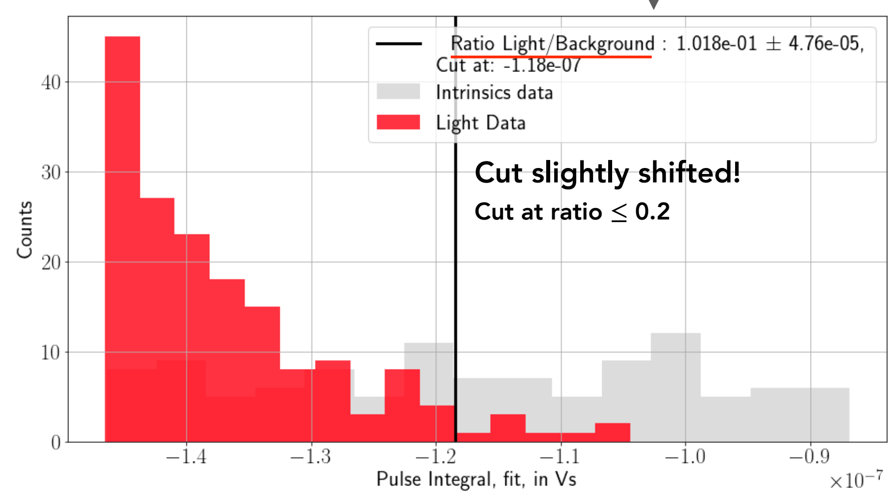
"**Symmetric**" cuts may fall short!

Can be fine-tuned depending on ratio of bin contents in regions of interest

Modulate the ratio to obtain looser/tighter "**asymmetric**" cuts



## How to: PCs calculation

- For a dataset, we can calculate $W =$ eigenvectors $(V^T V)$, where $V^T V$ is the covariance matrix for $V$
- The matrix $W$ (of the principal components) is the matrix corresponding to each trigger in the original dataset $V$.
- If N is number of chosen principal components for the analysis:

$$V = (\text{trigger } 1|\text{trigger } 2|\text{trigger } 3|\ldots|\text{trigger } T)_{M\times T}$$
$$\implies W = (\text{Column of N PCs for trigger 1}|\ldots|\text{Column of N PCs for trigger T}|)_{N\times T}$$

- To express the dataset $V$ in terms of $W$, we use $V = S \cdot W$, and calculate the coefficient matrix $S$ using $S = V \cdot W^T$:
- $$\begin{pmatrix} s_{11} & s_{12} & \cdots & s_{1N} \\ \cdots & & & \\ s_{M1} & & \cdots & s_{MN} \end{pmatrix}_{M\times N}$$
- For the **reduced dataset $V' = S \cdot W$, which has then the same dimensions as $V$,** but each measured $v_i$ has lesser noisy information

  ….we hope: **most (useful) information is captured in the PCs used**

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**Reduction in dimensions: Each trigger can be understood as a few PCs, like it was the few fit parameters.**

$$V = (\text{trigger 1}|\text{trigger 2}|\text{trigger 3}|\ldots|\text{trigger }T)_{M\times T}$$
$$\implies W = (\text{Column of N PCs for trigger 1}|\ldots|\text{Column of N PCs for trigger T})_{N\times T}$$

Each row is the array of PCs

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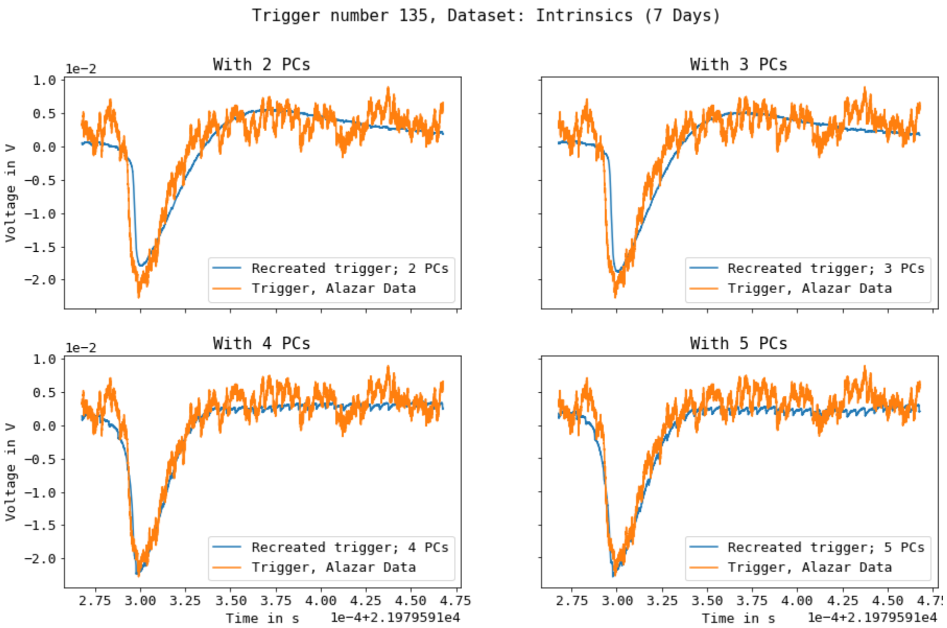
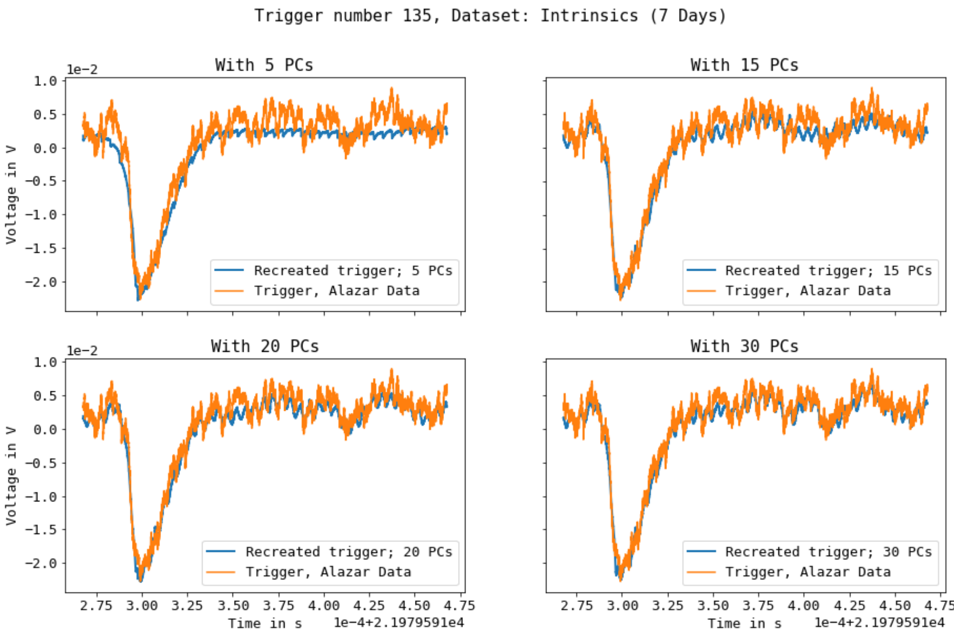
# Recreating Pulses

## Choice of PCs



What can trigger events?

Track related events

Cosmic muons causing Cherenkov radiation, transition radiation, recombination and luminescence

Radiogenics with same profile

Can be modelled via the detection system for possible response i.e energies and rates?

Non-track related events

Black body radiation (direct and/or indirect), radiogenic $\gamma$ or e-, stray or trapped magnetic fields

Possible to estimate numbers at the trigger location?

Which source(s) of background events dominate(s) and/or need(s) reduction?

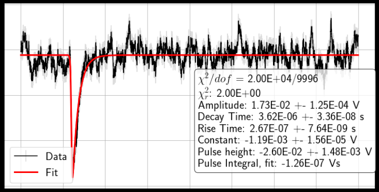
20-day limit on DR is < 7.7 $\mu$Hz, so a source is major contributor if expected rate at trigger location exceeds ~1 $\mu$Hz (post-analysis selection)

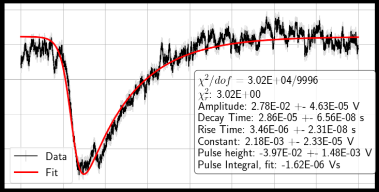
Where can background events be triggered?

TES, TES Stack

SQUIDs

Can these be separated in analysis due to possible changes/differences in pulse characteristics of fitted event?




Which location is more susceptible to which source of the (various) backgrounds?

Can tell us which source dominates if we reject based on pulse shape/ type

Possible elimination or reduction of background sources

Tracing the possible track, vetoing the time if known, or if the rate is known?

Making setup changes and improvements, like cold filtering and curling, etc.