Superconducting Quantum Sensors for Fundamental Physics Searches

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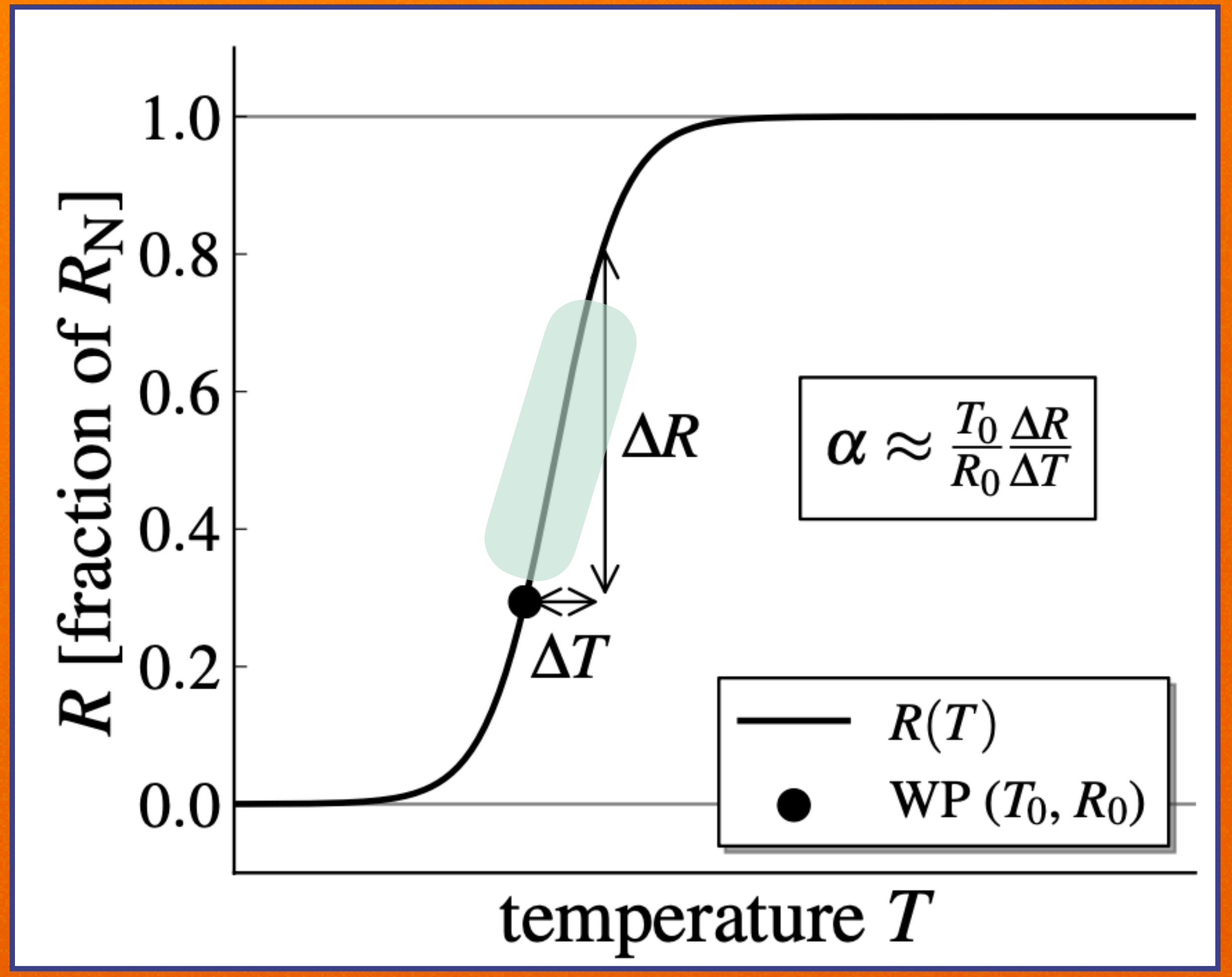
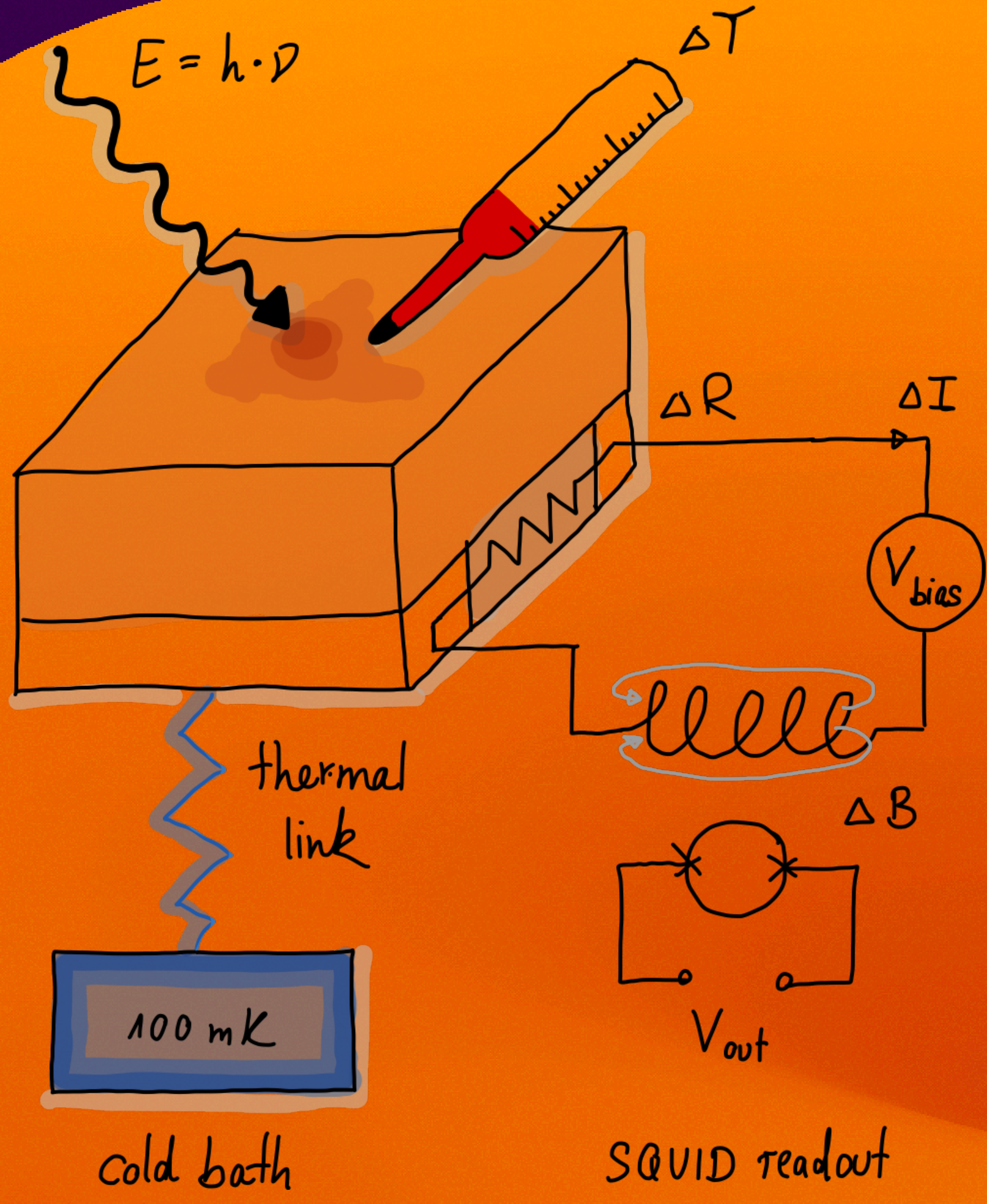
Universität der Bundeswehr Hamburg

Transition Edge Sensors (TESs)

Working Principle

- **Superconducting material held near transition (Tungsten: 140 mK)**
- **Incoming photon or other particle deposits energy, heats the material**
- **Temperature change causes a change in resistance**
- **Resistance change results in a current change**
- **SQUIDs (Superconducting Quantum Interference Devices) detect small current changes**





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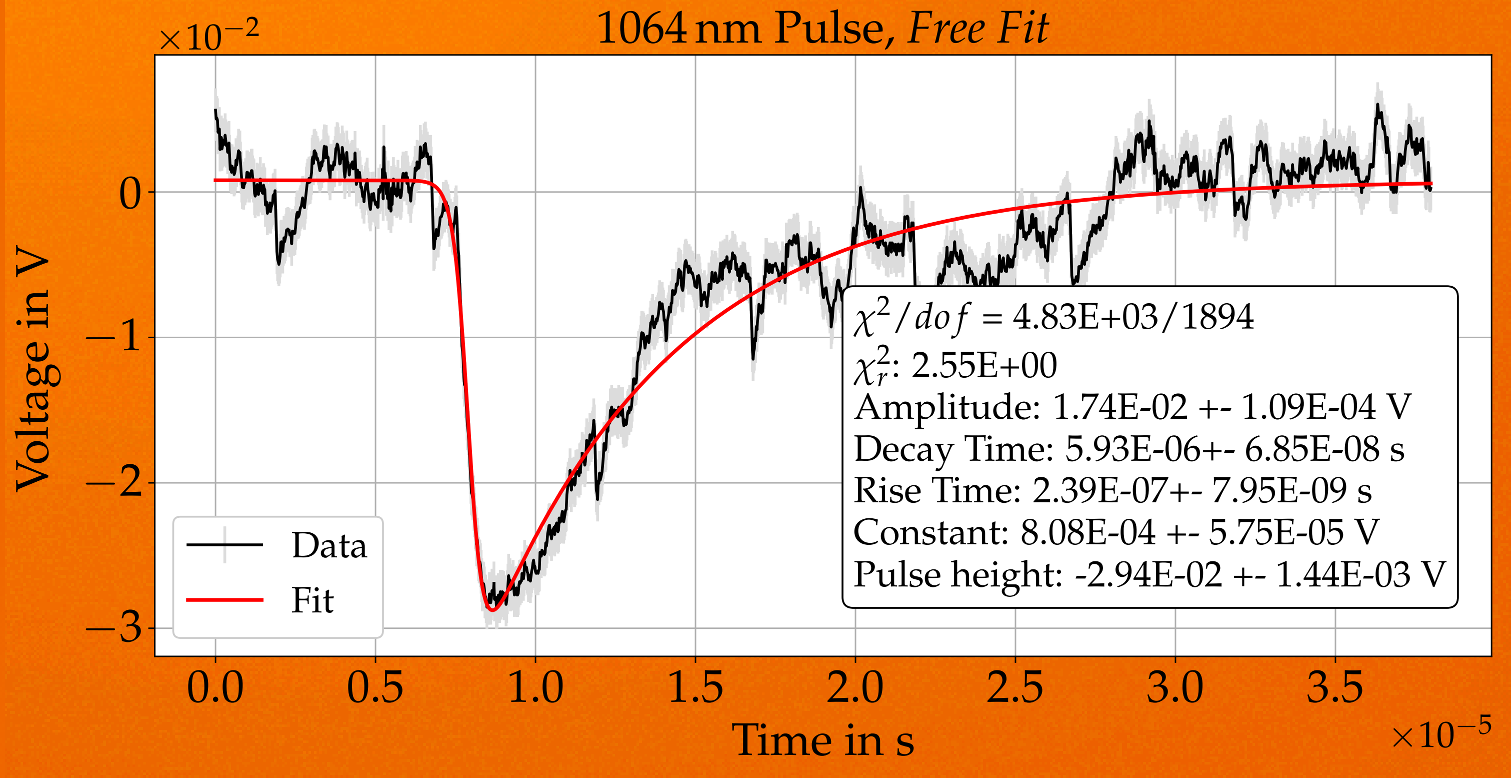
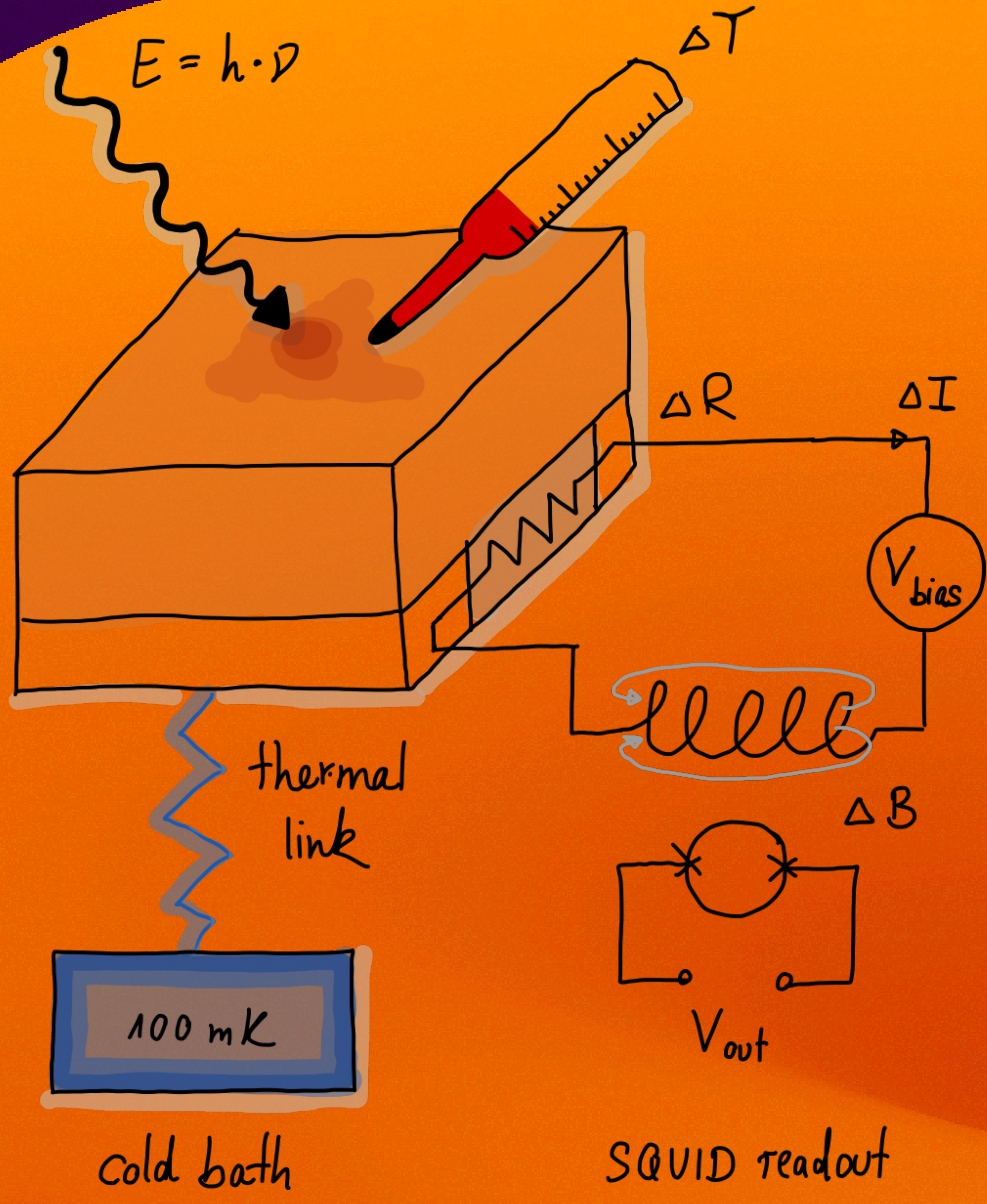
Example Light Pulse





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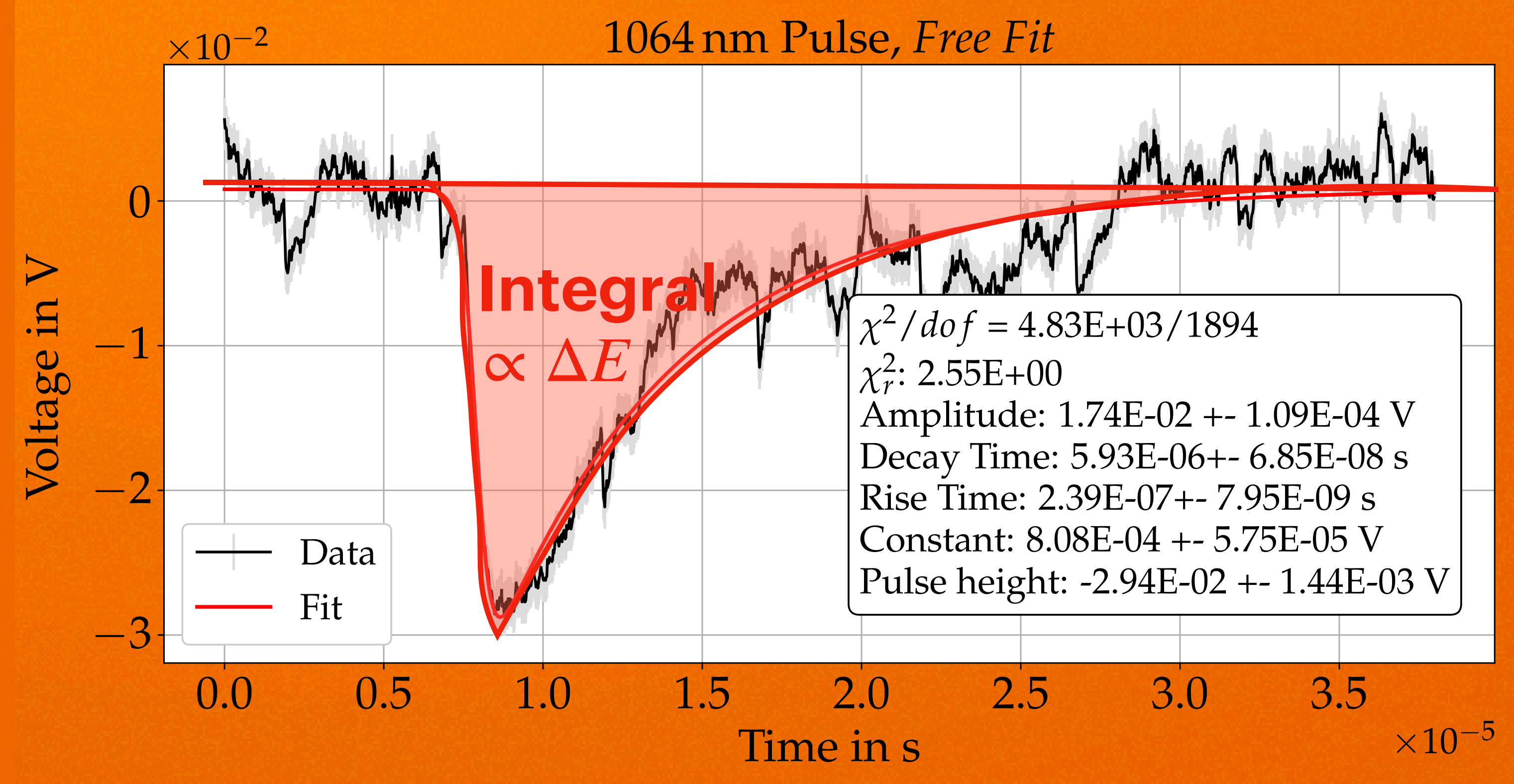
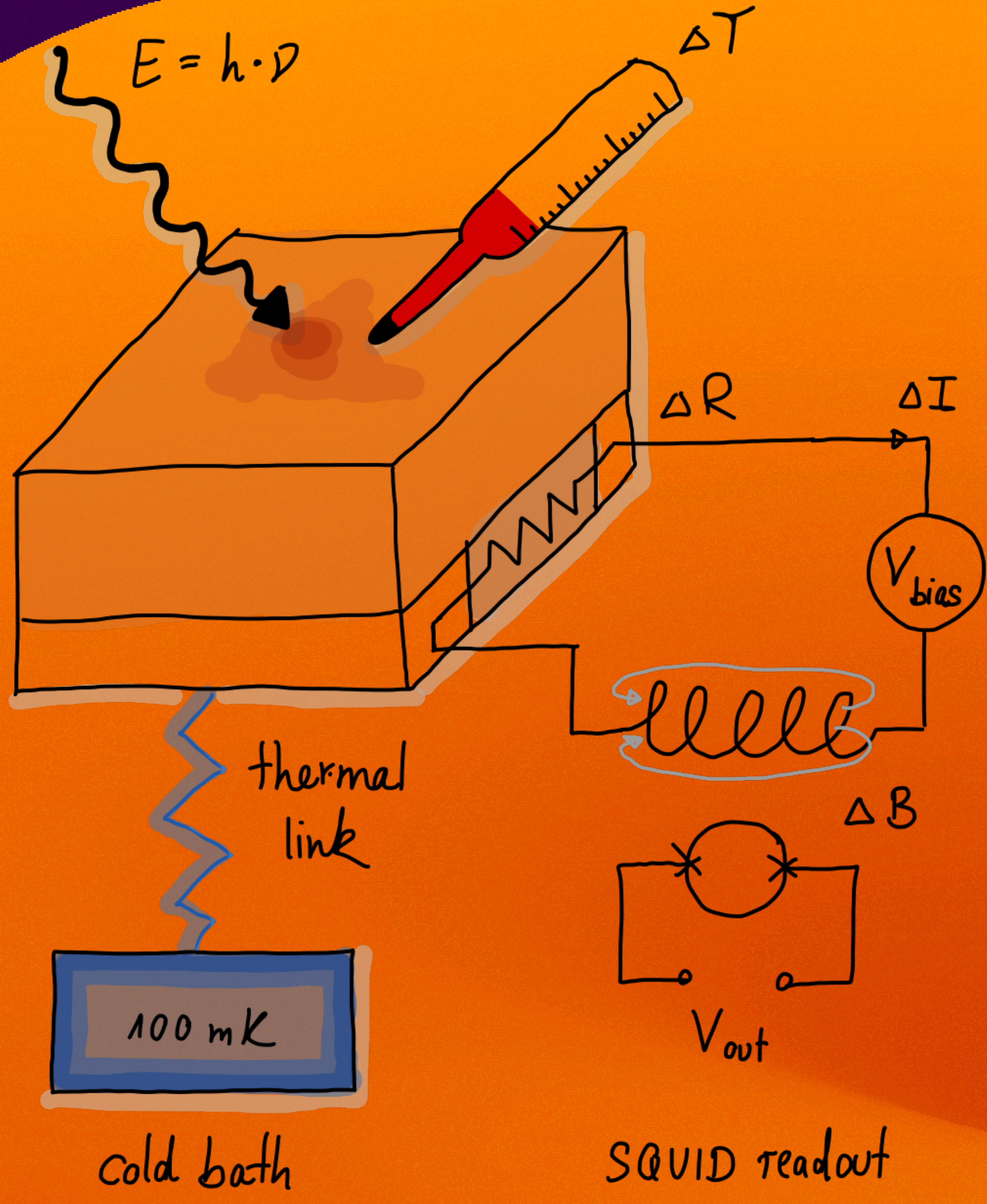


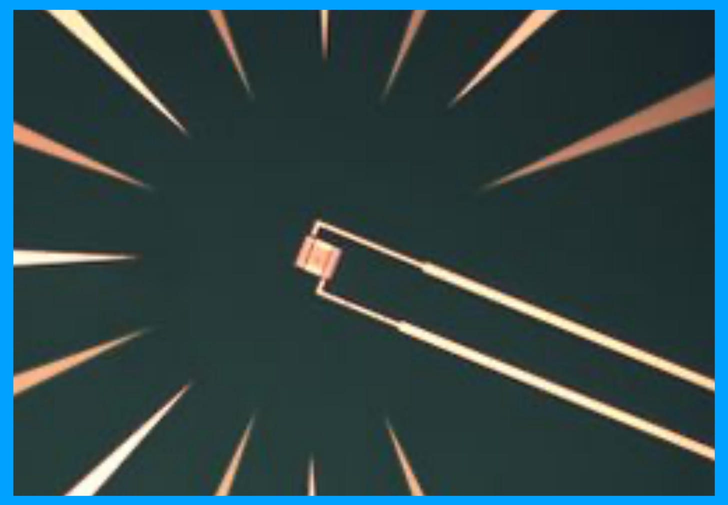


Benefits of TESs

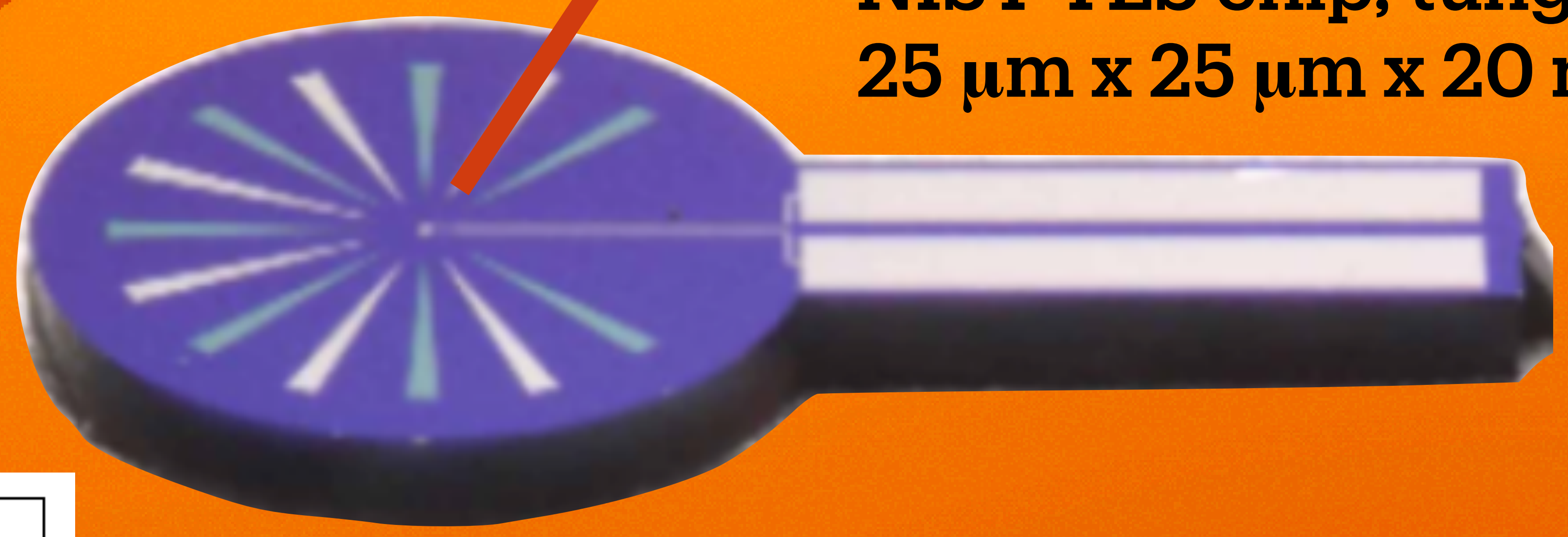
- **Single photon detectors with energy resolution, photon number resolution**

- **Demonstrated high quantum efficiency: $\geq$ 95% (near infrared)**
  [Lita et al. 2008]

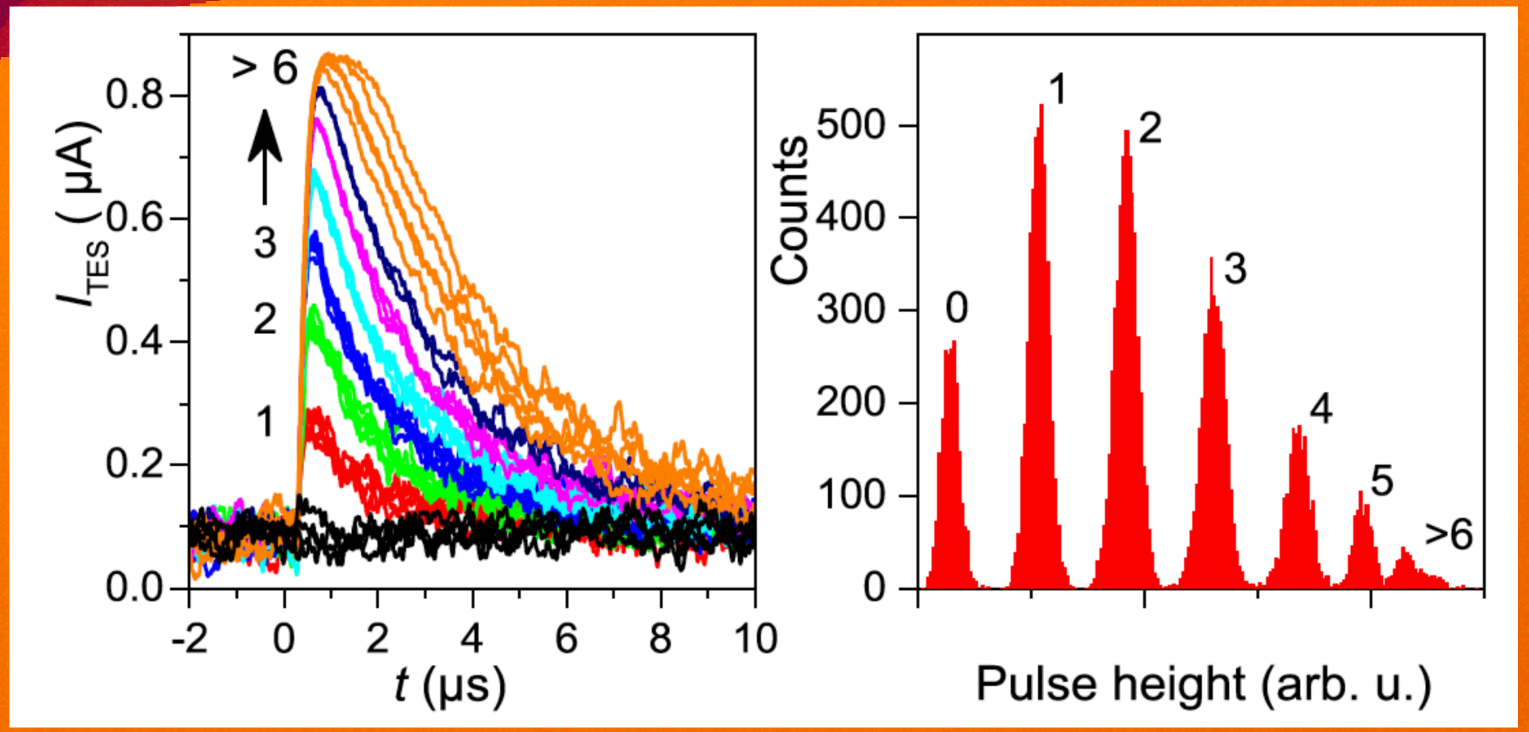
- **Low dark-count rates: $\leq 10^{-5}$ Hz**
  [Shah et al. 2022]



Tungsten microchip operating at $T_C \sim 140$ mK.
from NIST
(25 µm x 25 µm x 20nm)



NIST TES chip, tungsten 25 µm x 25 µm x 20 nm



Schmidt et al. (2018)

TESs at DESY

What the remainder of this talk will cover

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Universität der Bundeswehr Hamburg

SDU

Characterization and background reduction efforts:

- Energy calibration of our TESs
- System Detection Efficiency
- Simulating the TES response
- Measuring and reducing background rate

Fundamental physics searches:

- Direct Dark Matter Searches
- Measurement of Quantum Squeezed Light
- TES for ALPS II

DESY

UHH

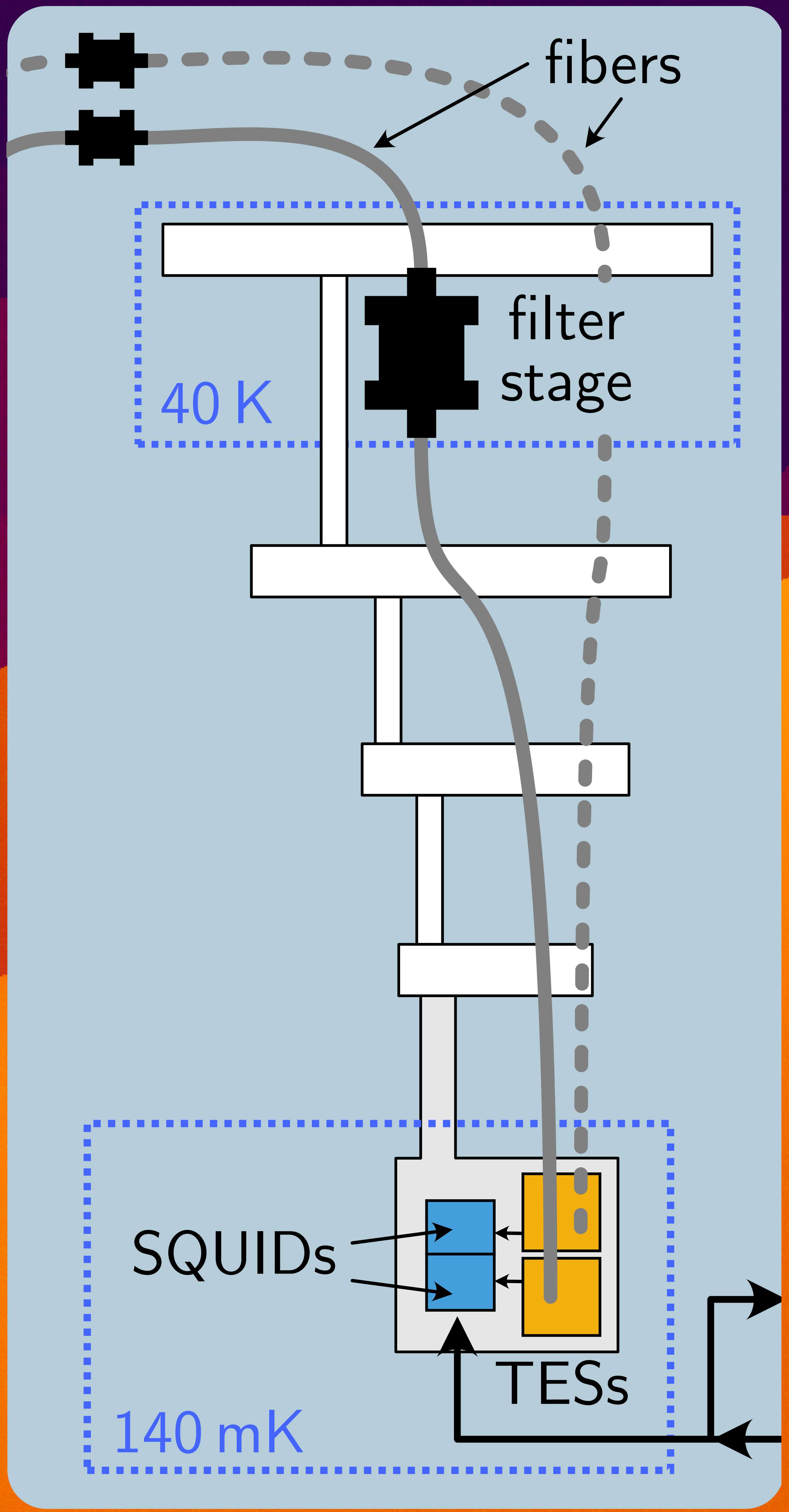
erc

TESs at DESY

Operate TES with SQUIDs in a Dilution Refrigerator

- Currently have **2 fridges**:
  One fully functioning, one being equipped with necessary cabling and hardware
- Light-tight, surrounded by muMetal and aluminum shielding against stray electric and magnetic fields

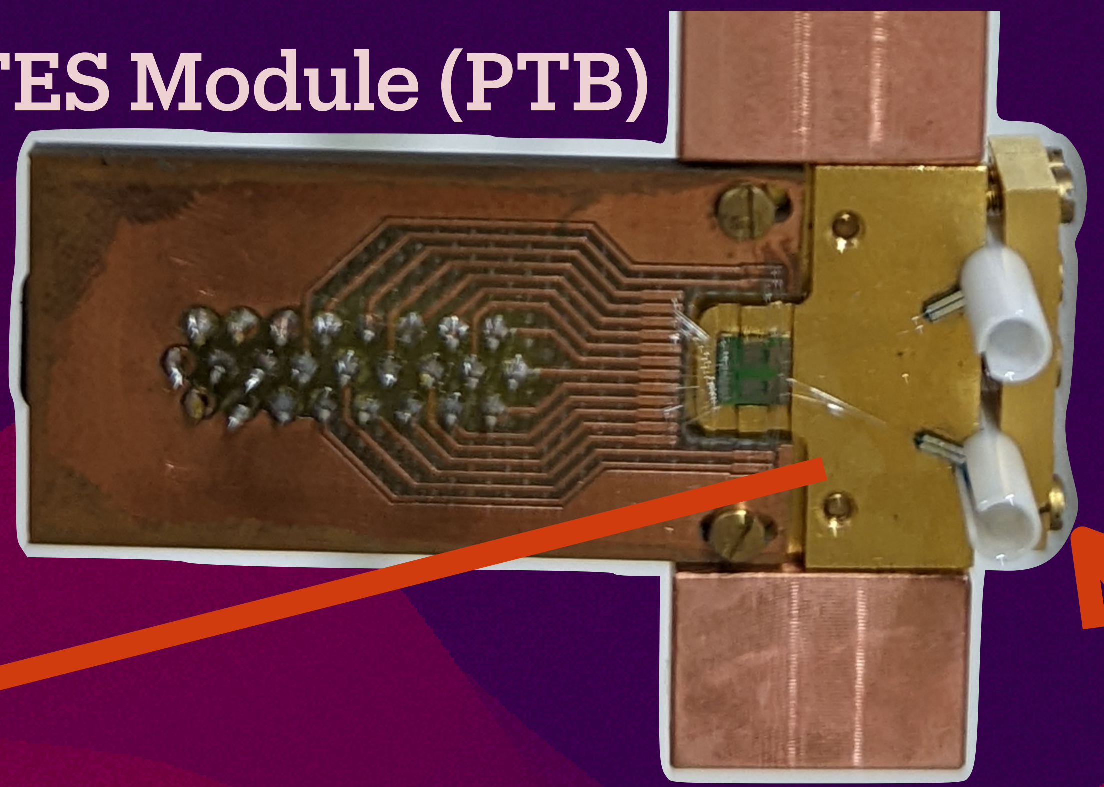
- **Direct Dark Matter searches:** No optical fibers connected to the TES
- **Other experiments:** Optical fibers from the light source of interest are connected to the TES via vacuum feedthroughs



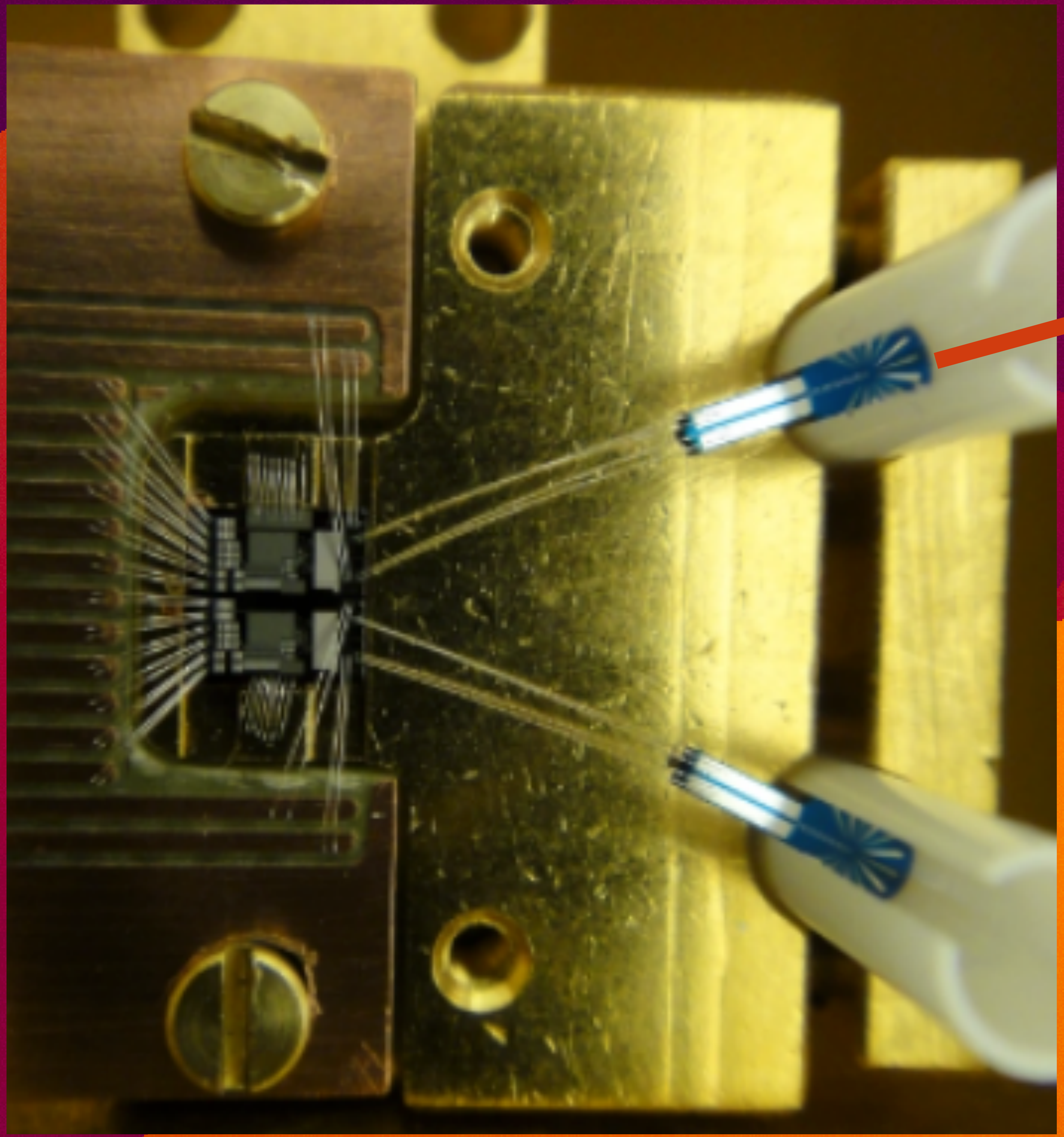
TES Module

Optimized for 1064 nm

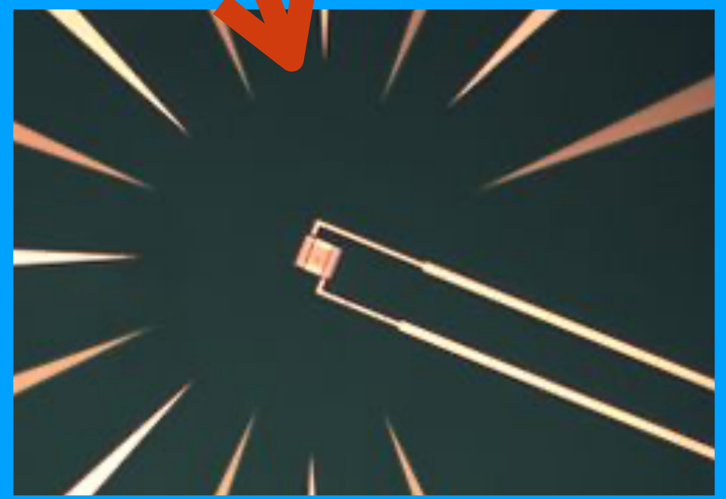
TES Module (PTB)



2 chips (NIST) + SQUID readout



NIST chip, tungsten
25 µm x 25 µm x 20 nm



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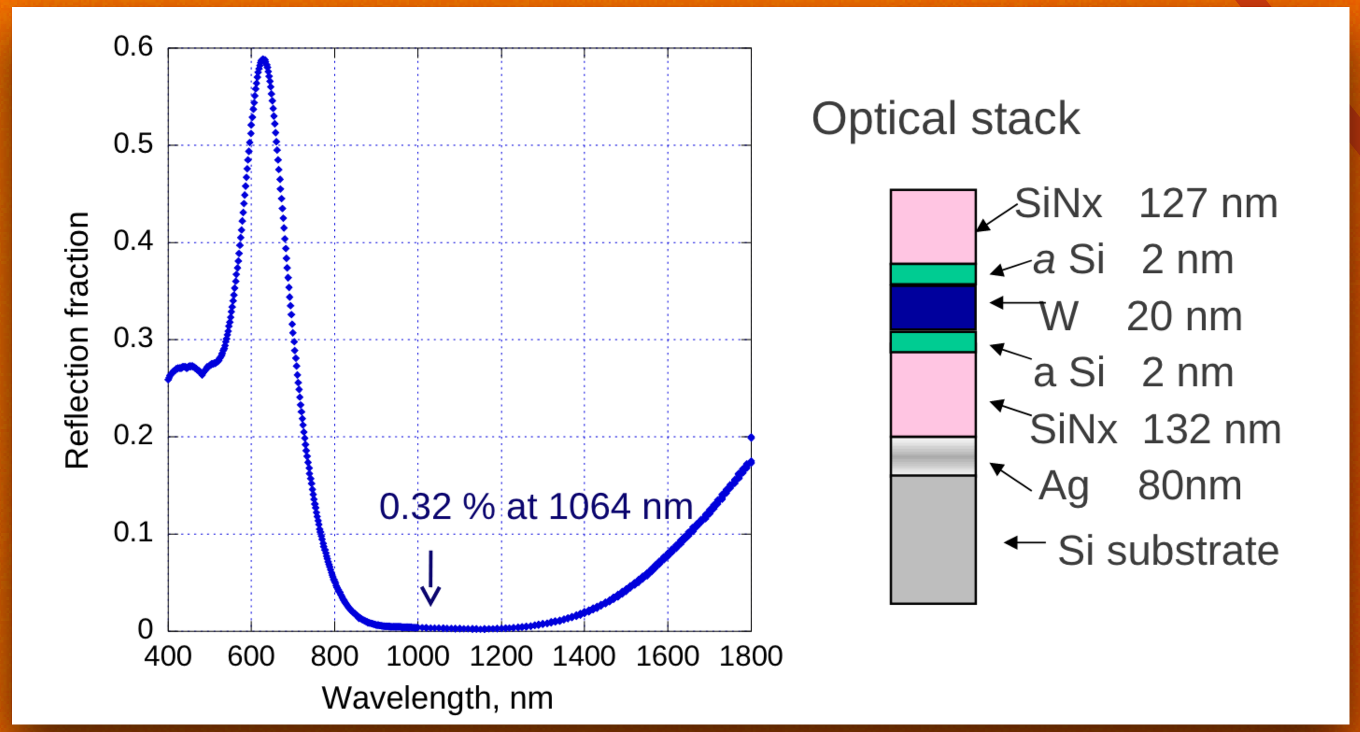
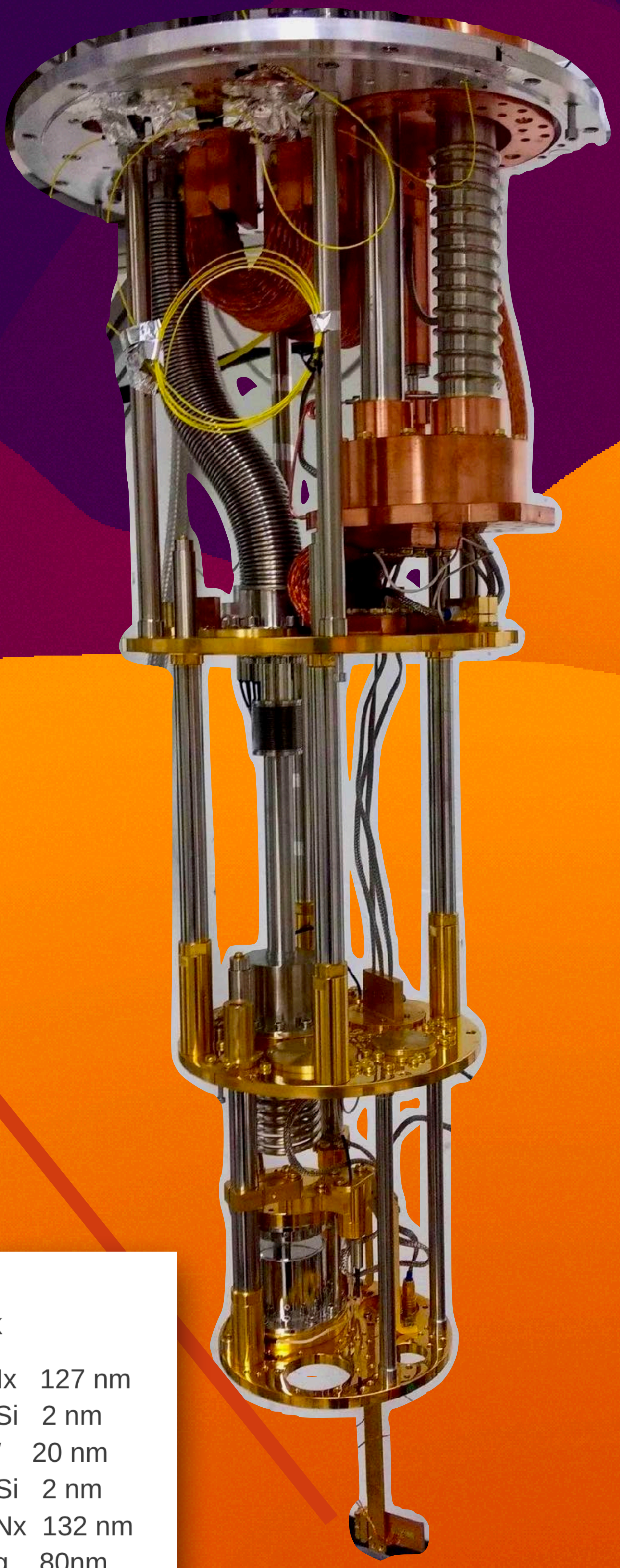


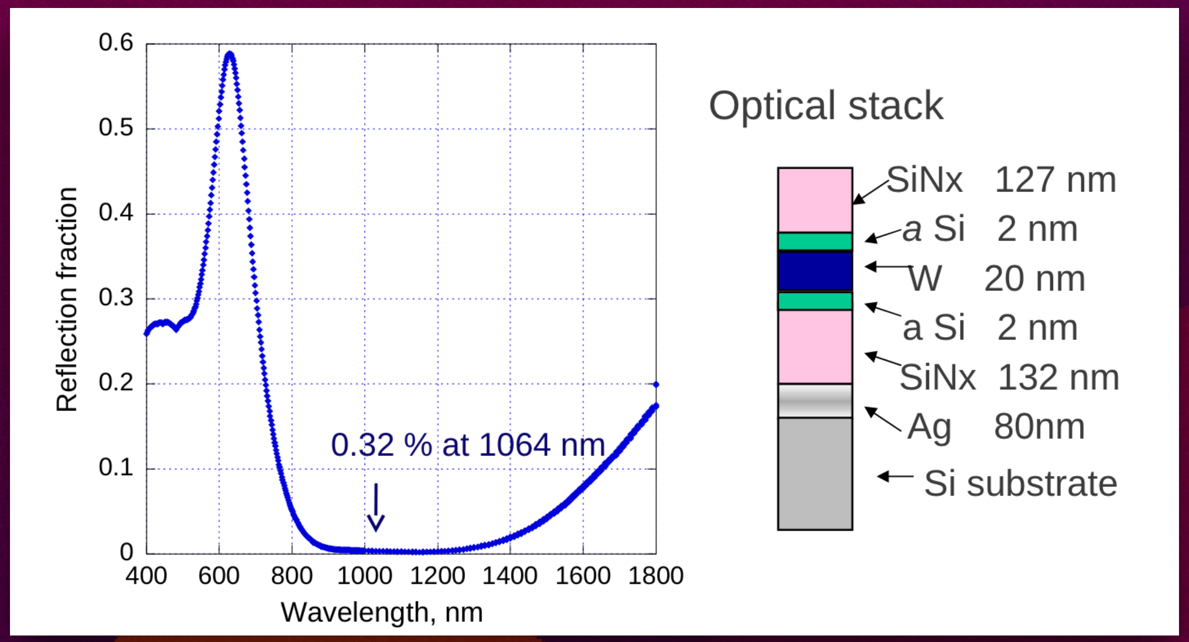


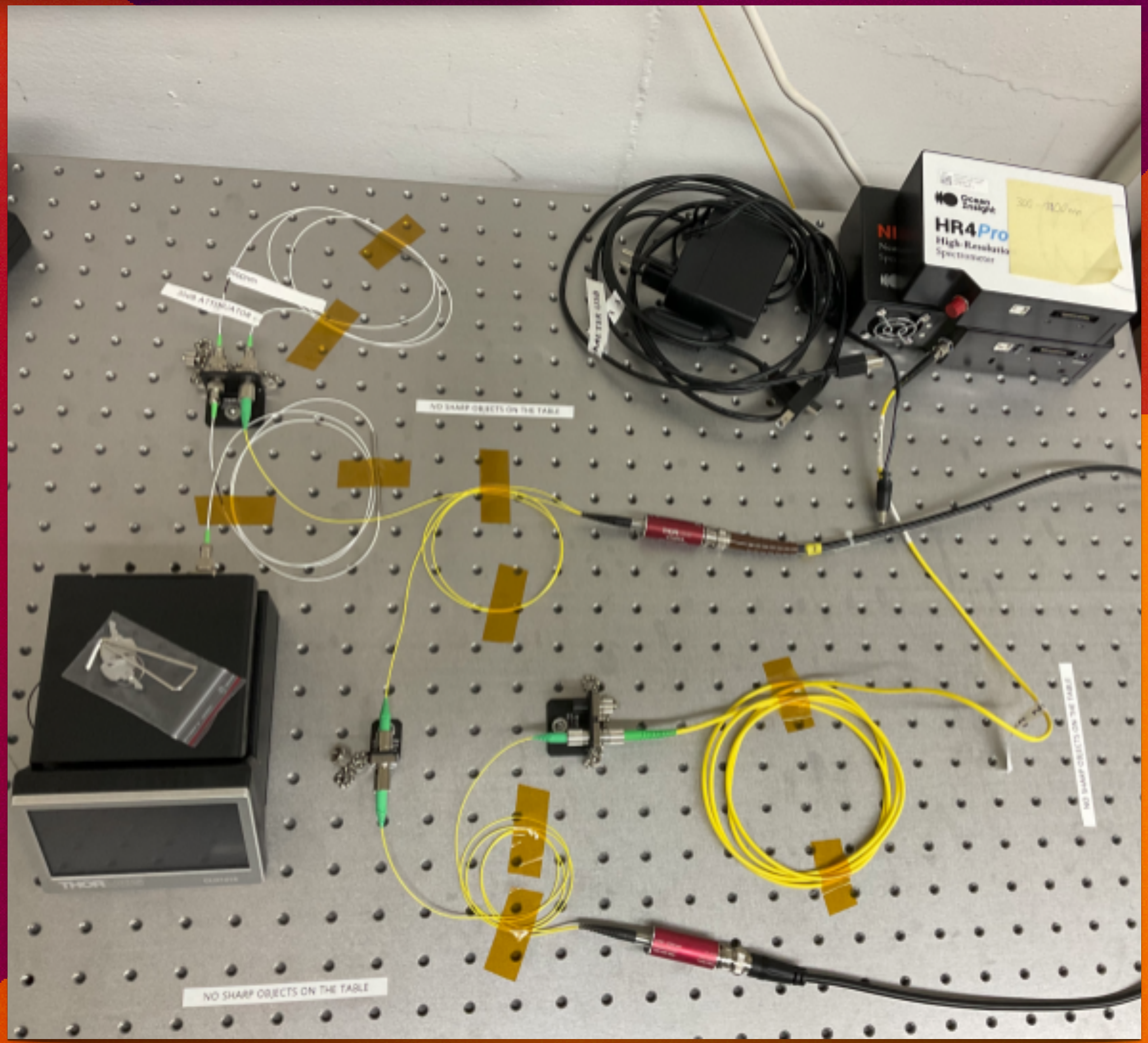
Characterization

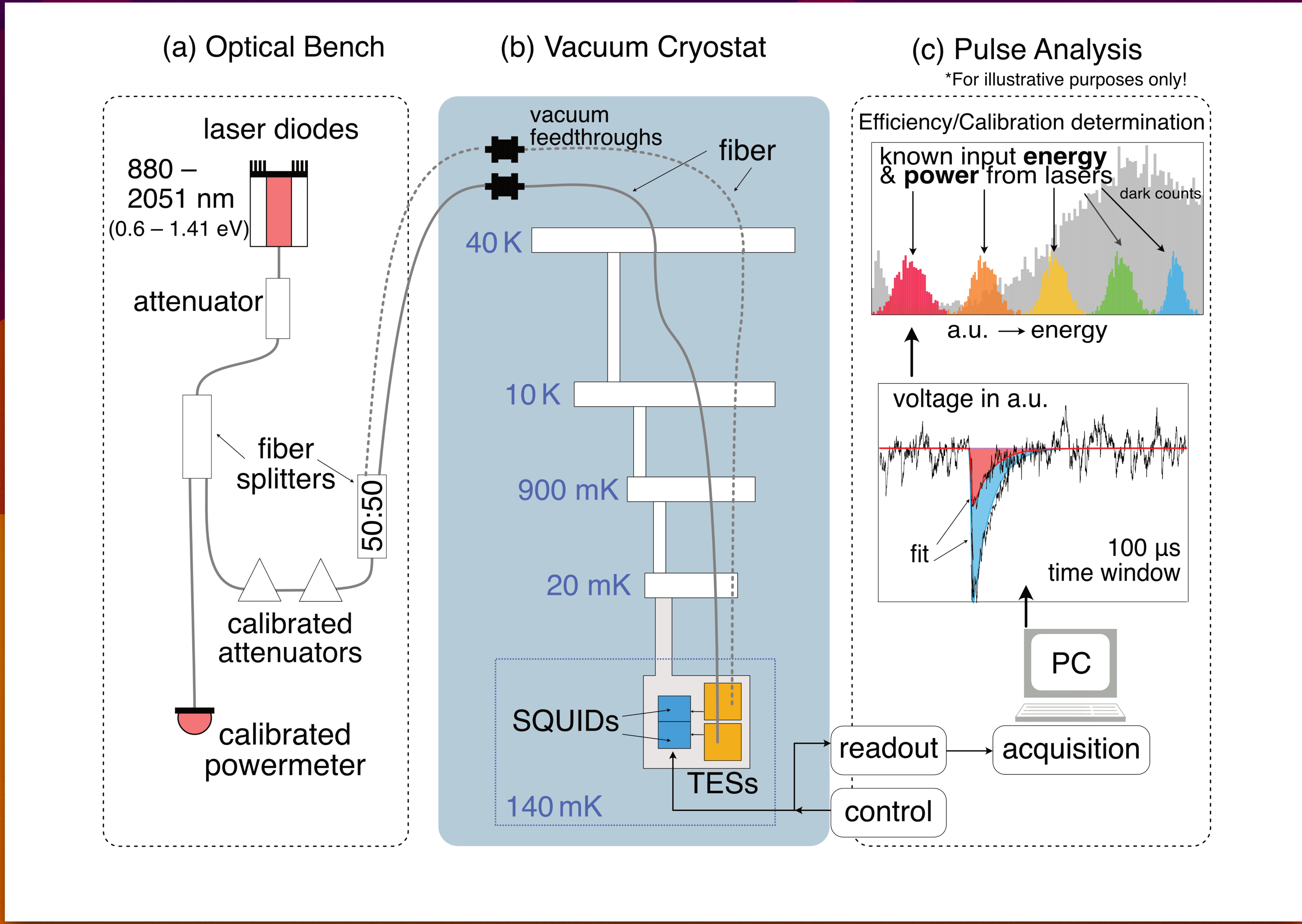
Energy Calibration

See C. Schwemmbauer's talk at IDM2024

PhD student
Christina Schwemmbauer
Gulden Othman







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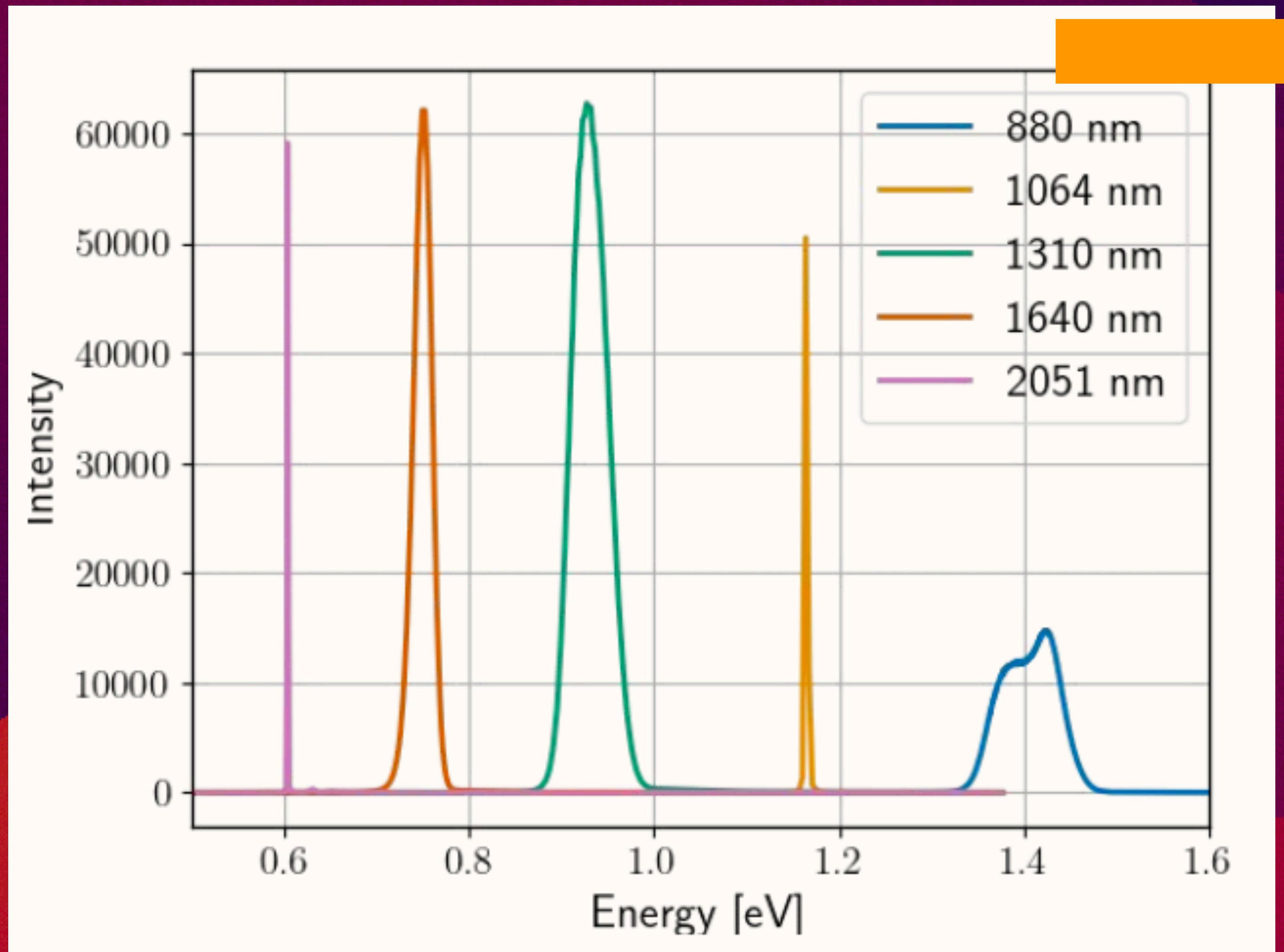
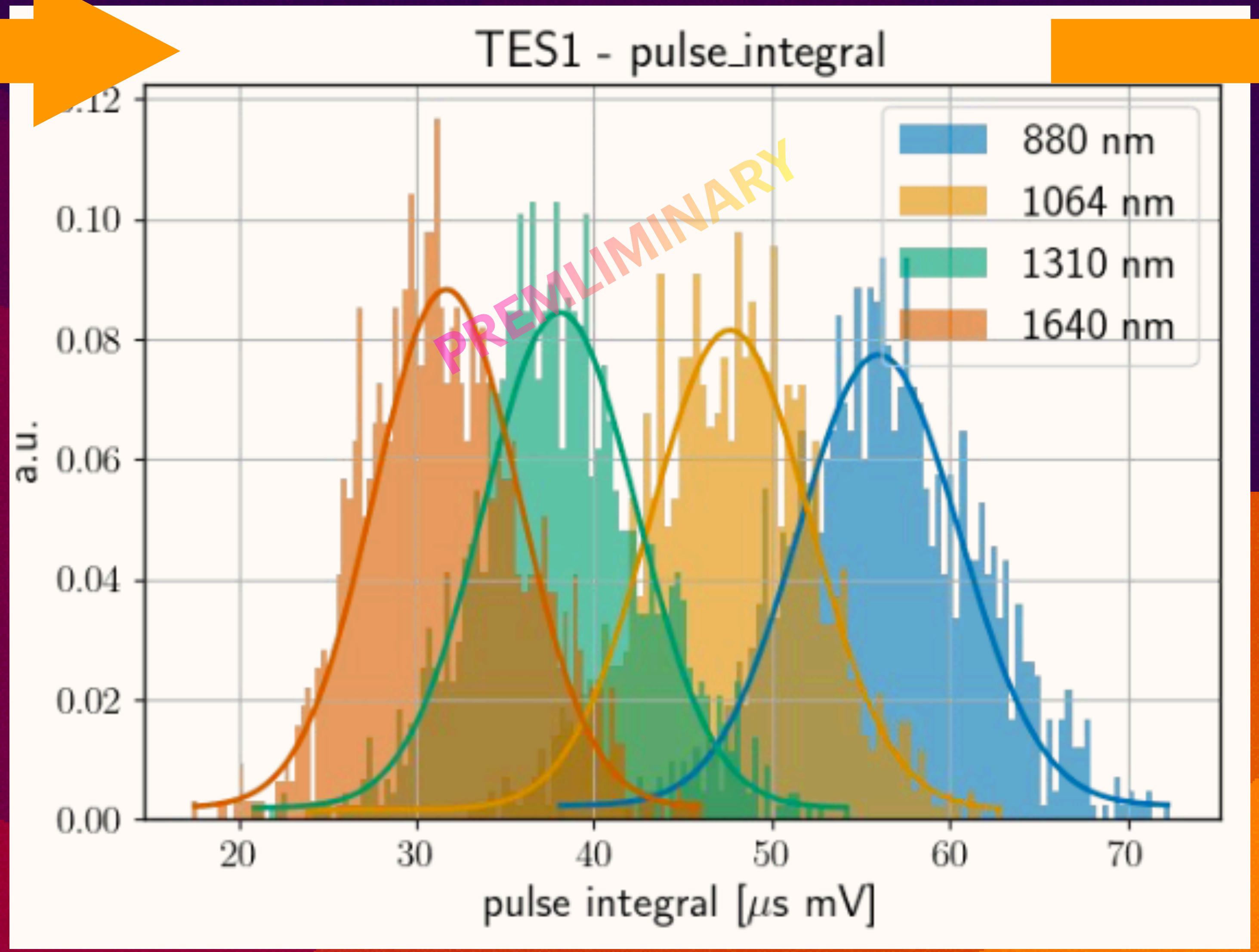
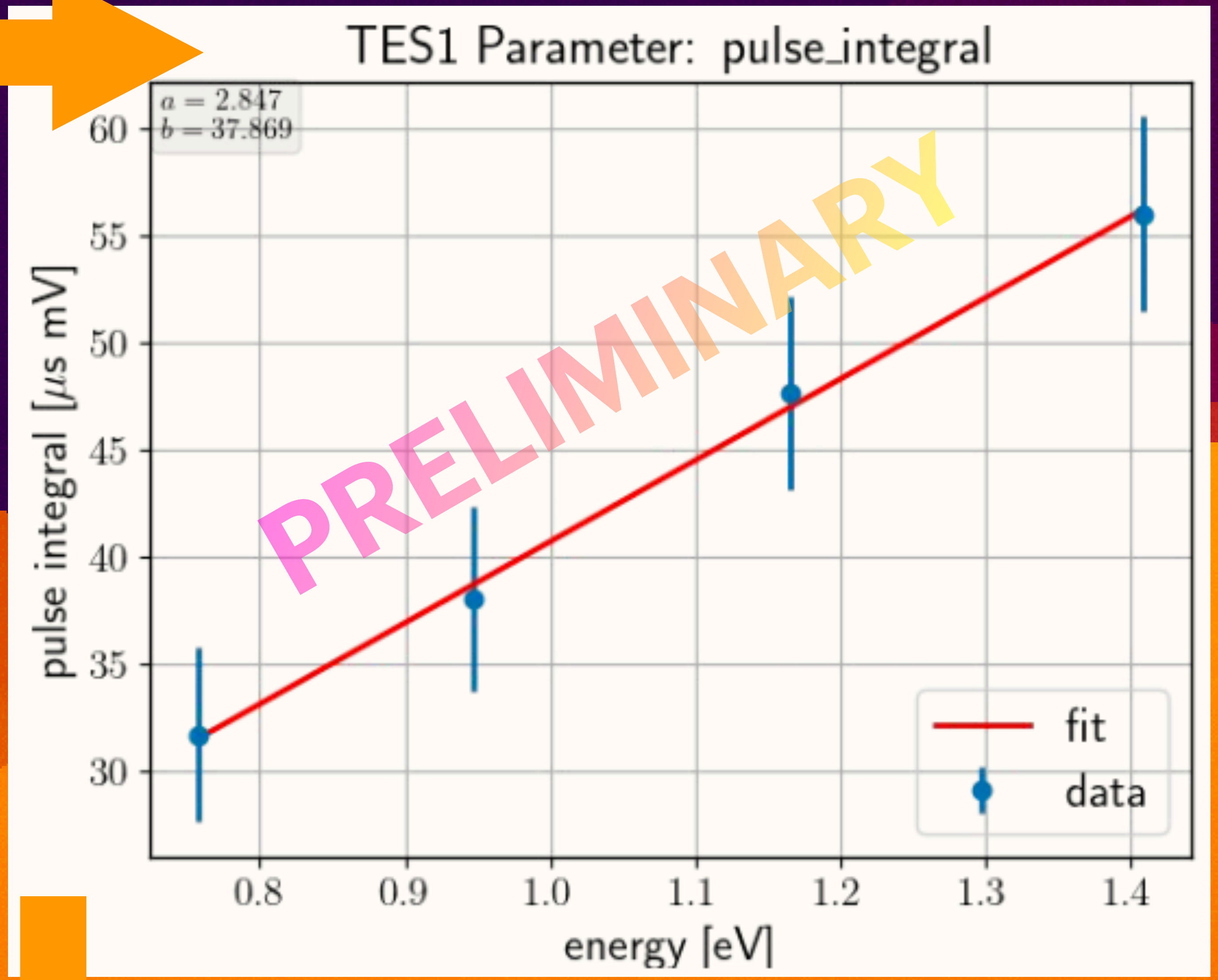
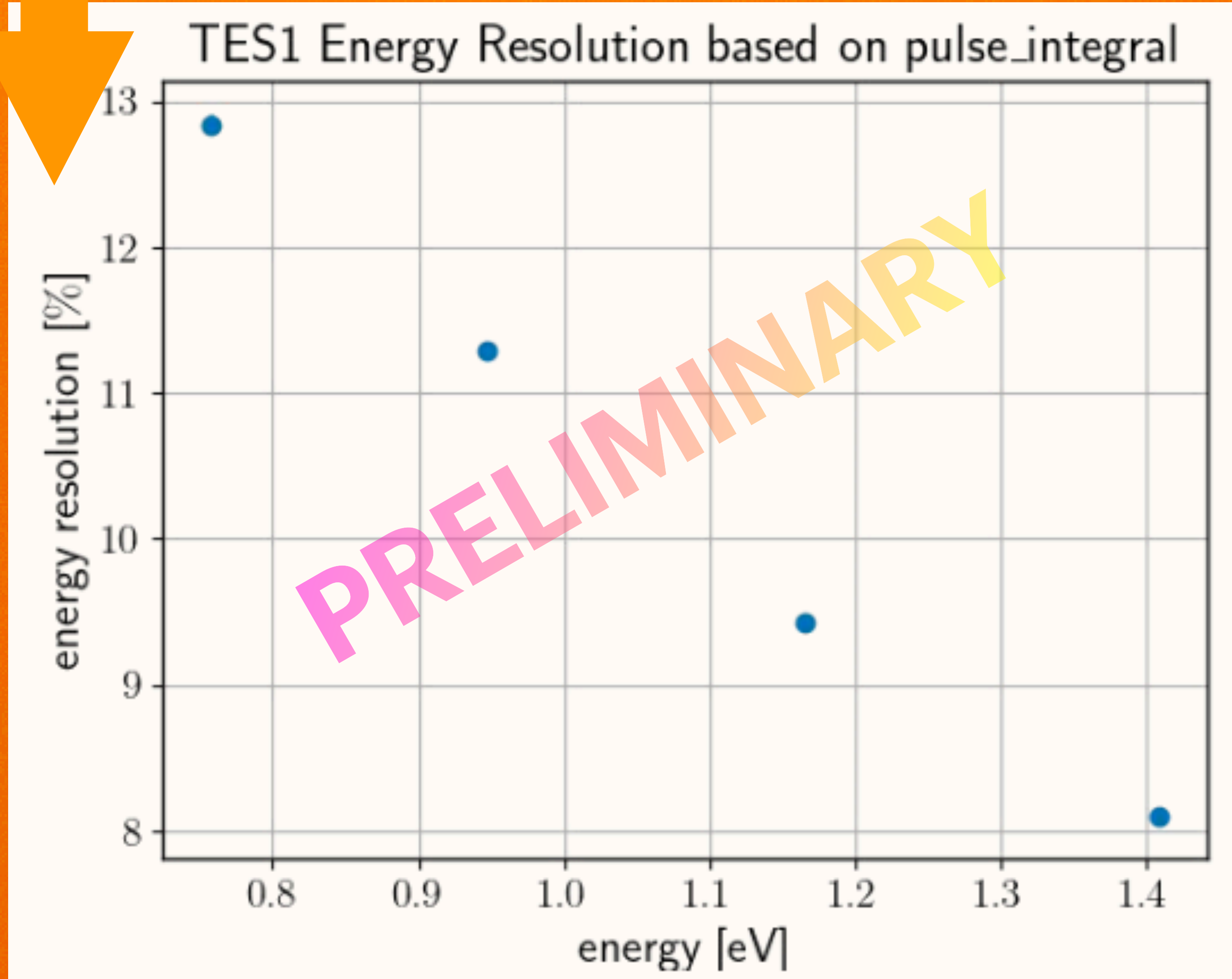








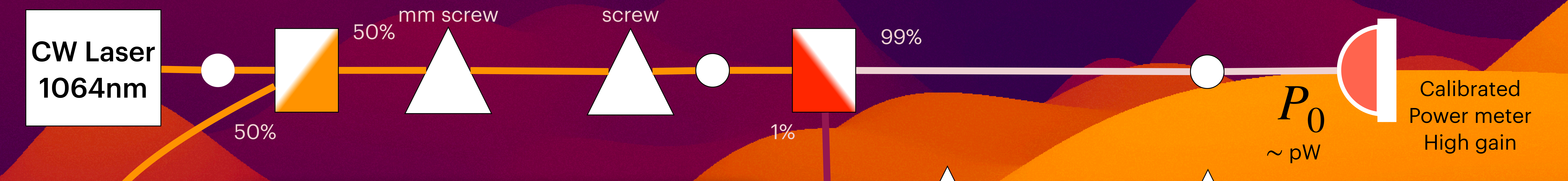
- Laser diodes of varying wavelengths used for calibration
  - Optical fiber not directly attached to TES in this run
- Determine energy resolution as $\Delta E/E = \sigma/\mu$
- σ, μ determined from histogram of pulse integral

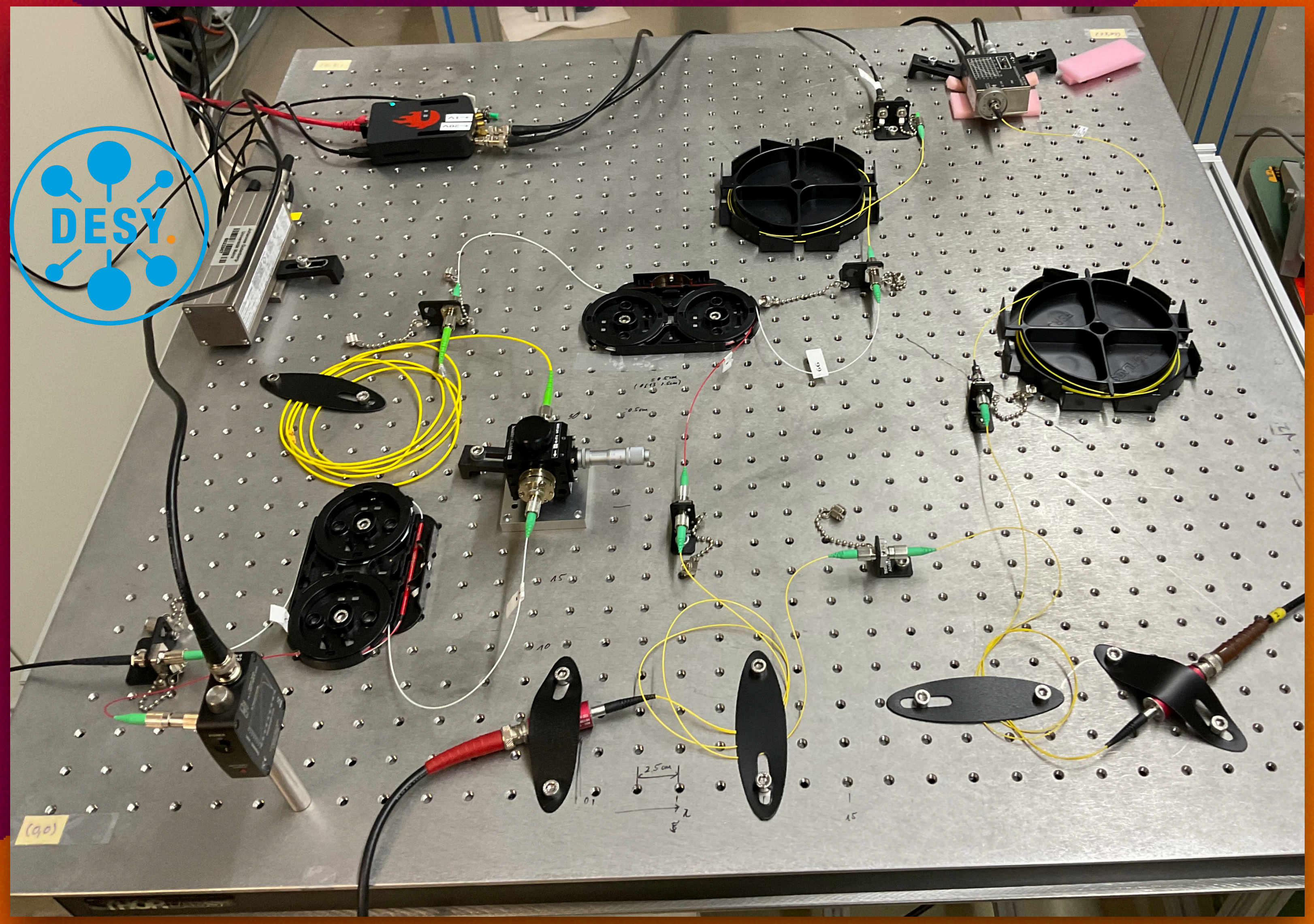
System Detection Efficiency

For fiber-coupled experiments

Prof. Manuel Meyer

Post docs
Gulden Othman
Elmeri Rivasto





$$\eta = \frac{P_{TES}}{P_{in}}$$

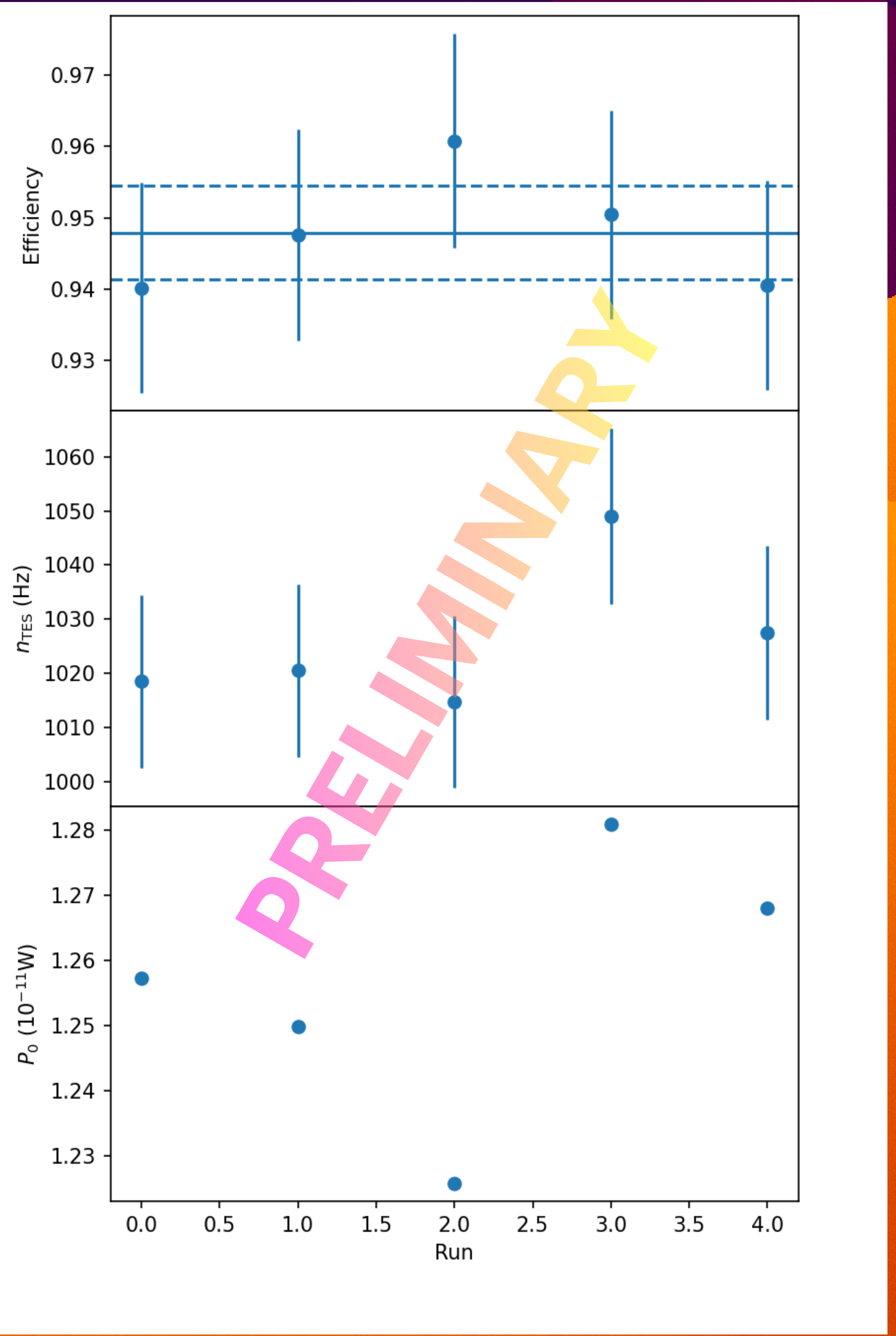
$$P_{TES} = n_{TES}\frac{hc}{\lambda}$$

$$P_{in} = P_0 10^{L_{tot}/10}$$

System Detection Efficiency

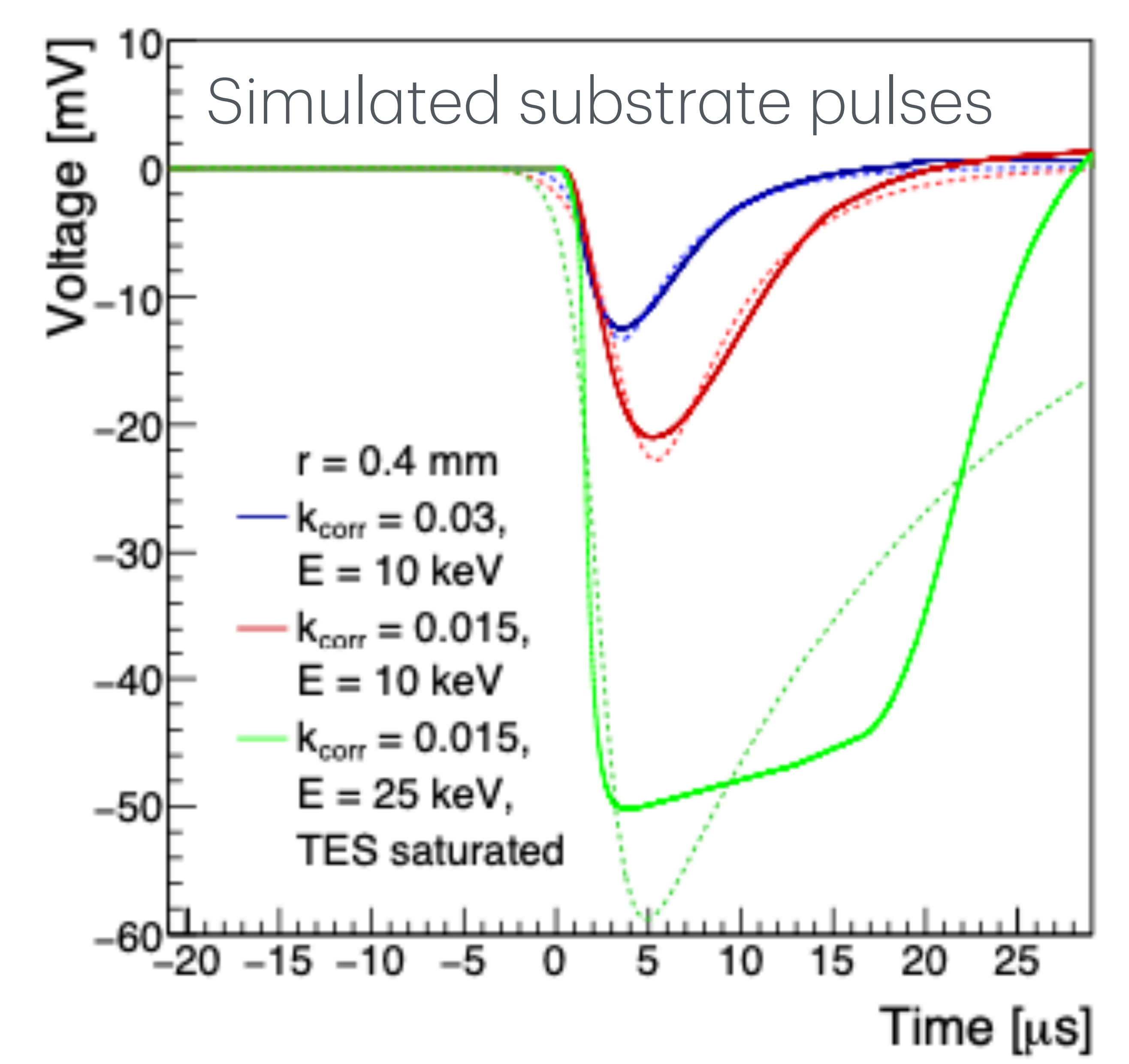
Preliminary Results

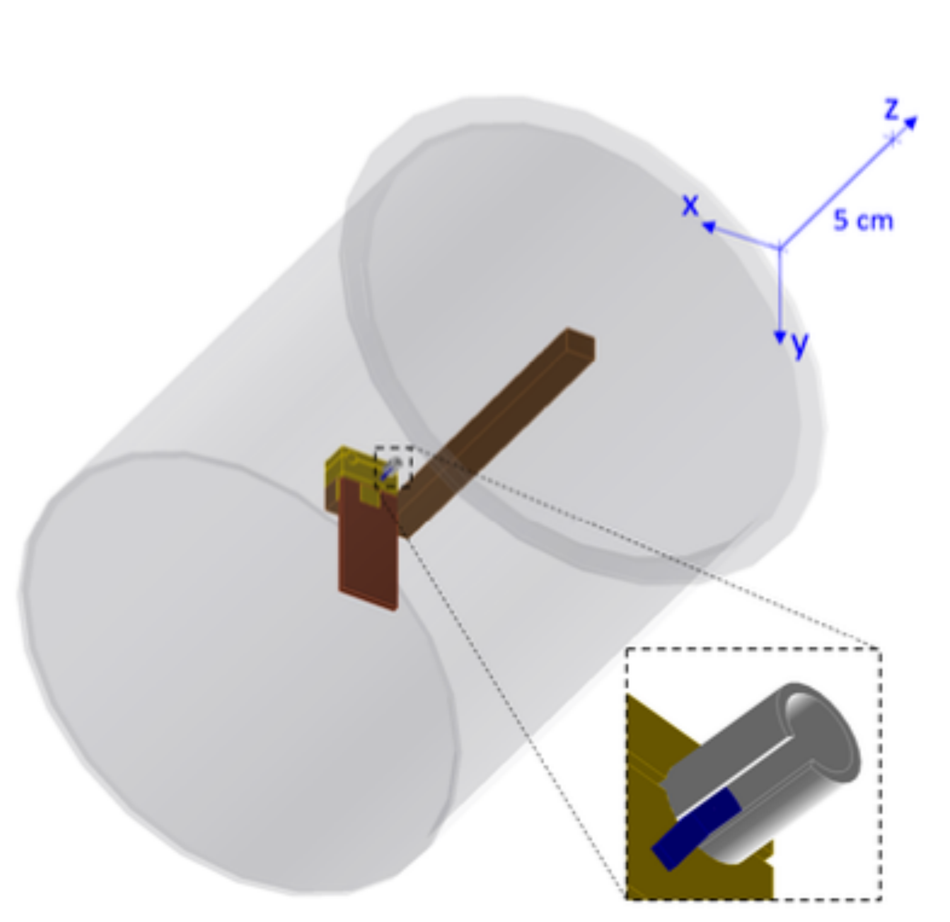
- **Use trapezoidal filter to find peaks in continuous time lines**
- **Five 4s time lines taken**
- P_0 **appears to correlate with** n_{TES} **as expected**
- **Large fluctuations in** P_0**, under investigation**
- $\eta \gtrsim 0.9$



Simulations

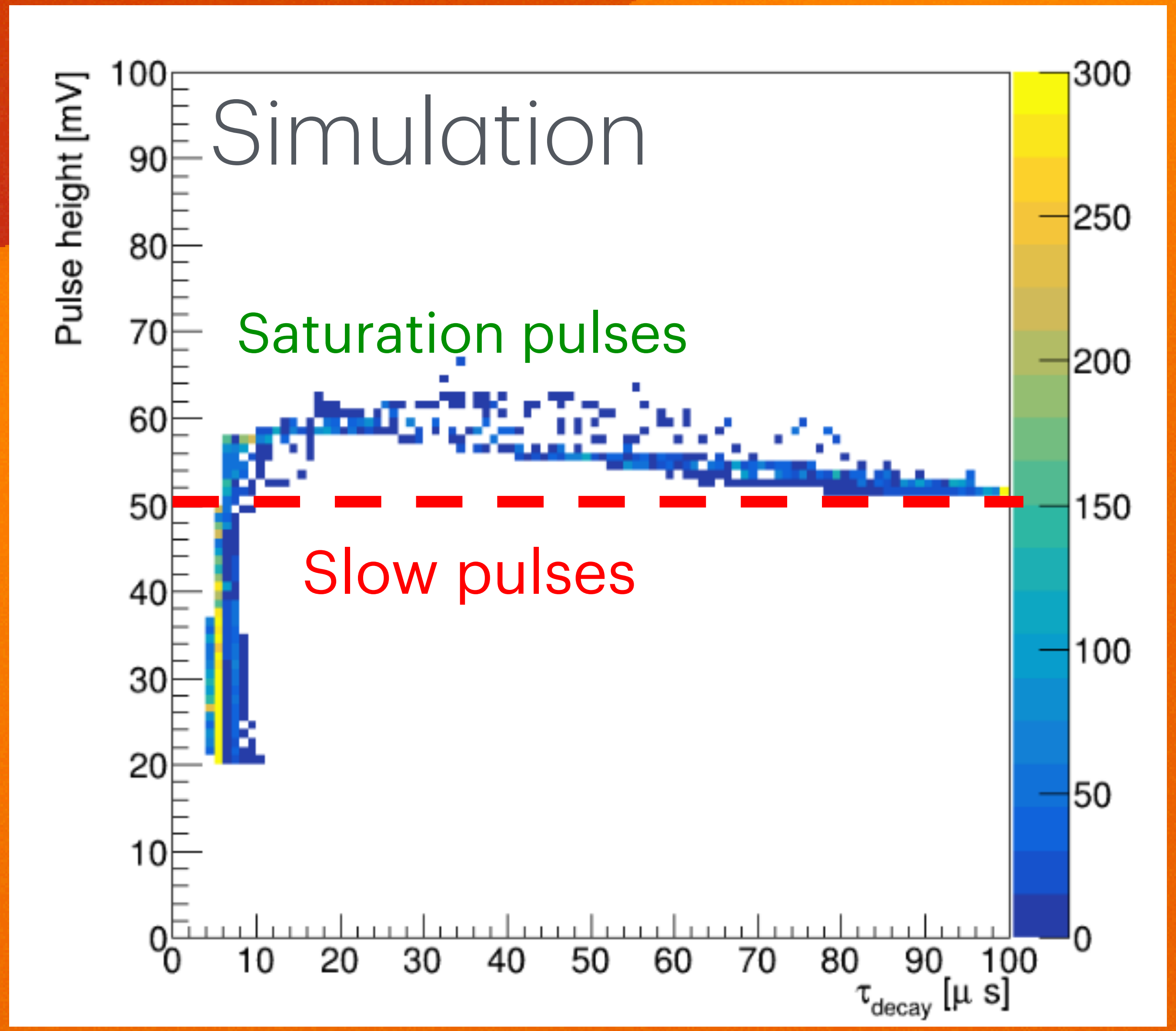
- **2-fold simulations:**
  - **GEANT4: simulate radioactive backgrounds, such as cosmic muons, intrinsic radioactivity**
  - **COMSOL: simulate heat transfer from energy depositions in the substrate around the TES**
    - **Simulate pulses based on the heat transfer**
- **Simulations predict a dominant background is Zirconia in the fiber sleeve**

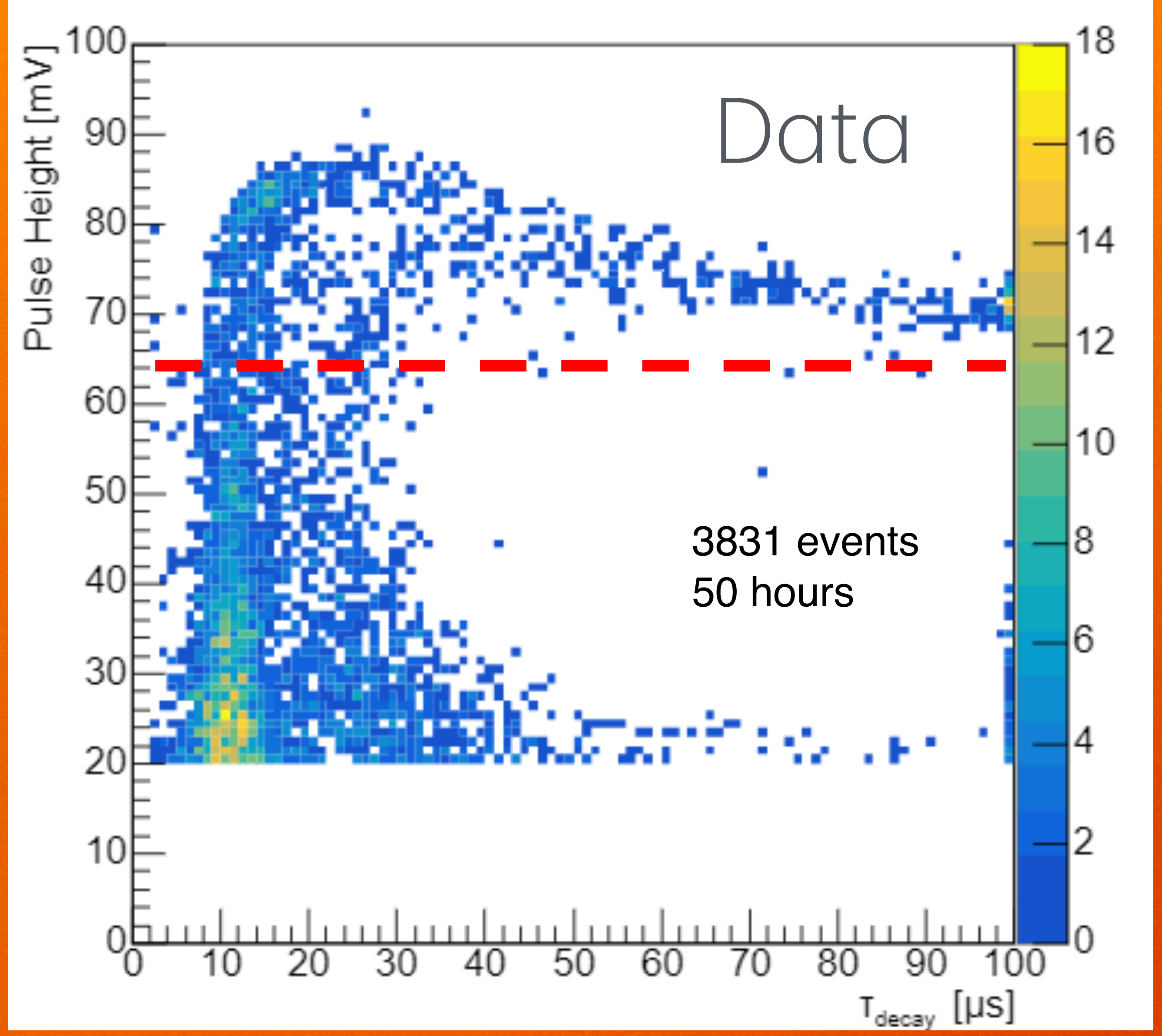




PhD thesis of José Alejandro Rubiera Gimeno, finished 2024 at DESY

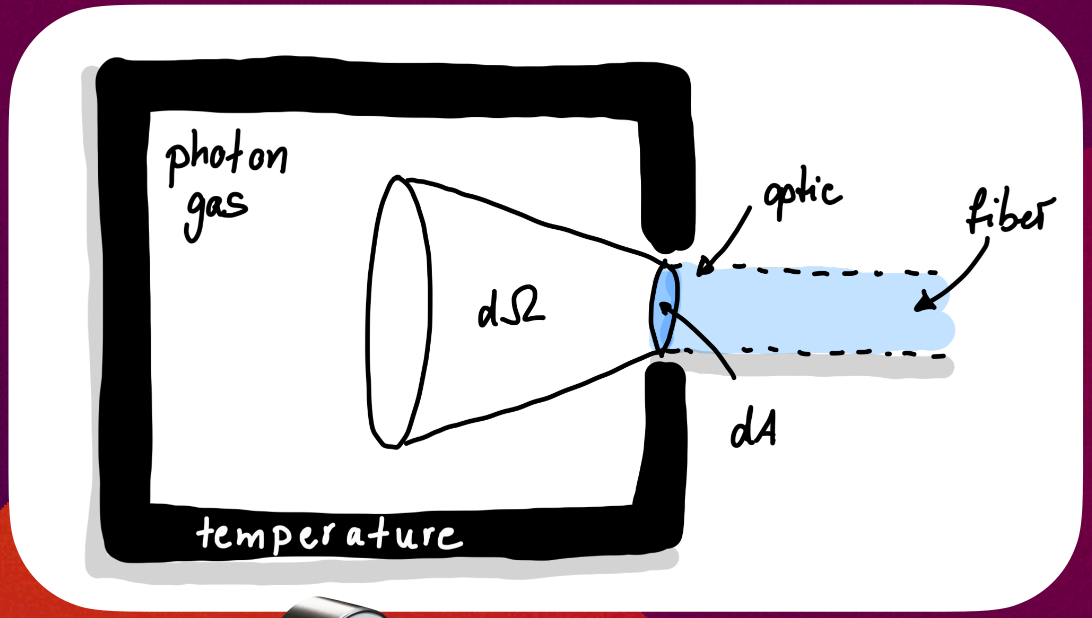
Rates from Geant4 + COMSOL simulation
Zirconia: rate $\in [0.33\ ;\ 2.1] \cdot 10^{-2}$ cps
Muon: rate = $8 \cdot 10^{-5}$ cps
Rate from data: $2.1 \cdot 10^{-2}$ cps

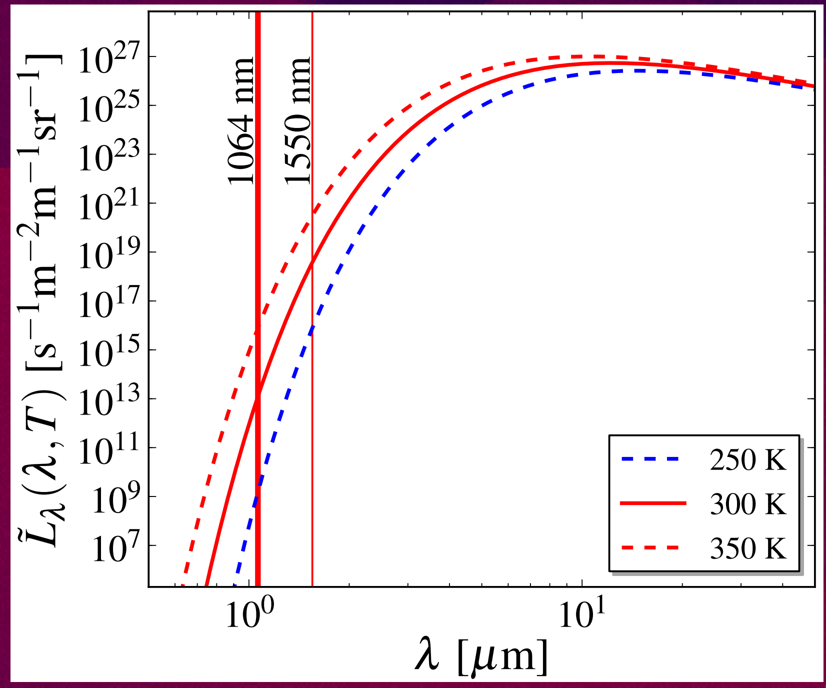


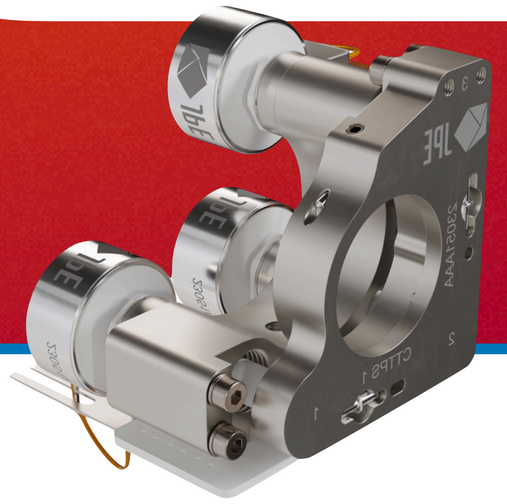


Backgrounds and Background Reduction

Black body radiation from laboratory, components @300K

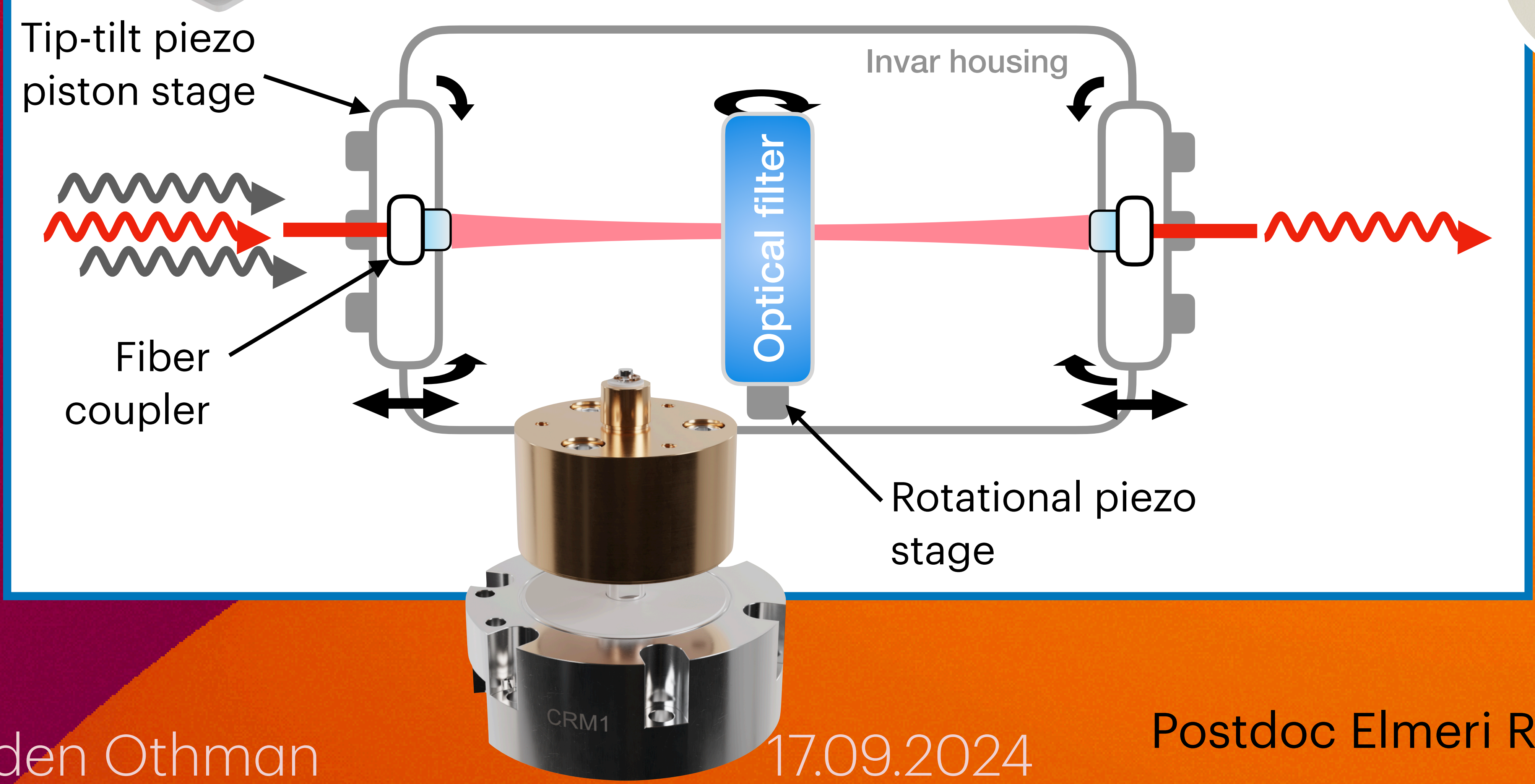






Prof. Manuel Meyer

Cold optical filter bench



Fiber-coupled backgrounds:

- Blackbody photons from warm side of fiber
  - Developing a cold optical filter bench

Backgrounds with no fiber:

- Intrinsic radioactivity and cosmic rays
  - Simulations show cosmic ray muons and secondaries did not have a large effect
  - Zirconium from fiber sleeves is a source of backgrounds
    - New modules without fiber sleeves for applications without fiber

Machine learning on TES pulses may help reduce both

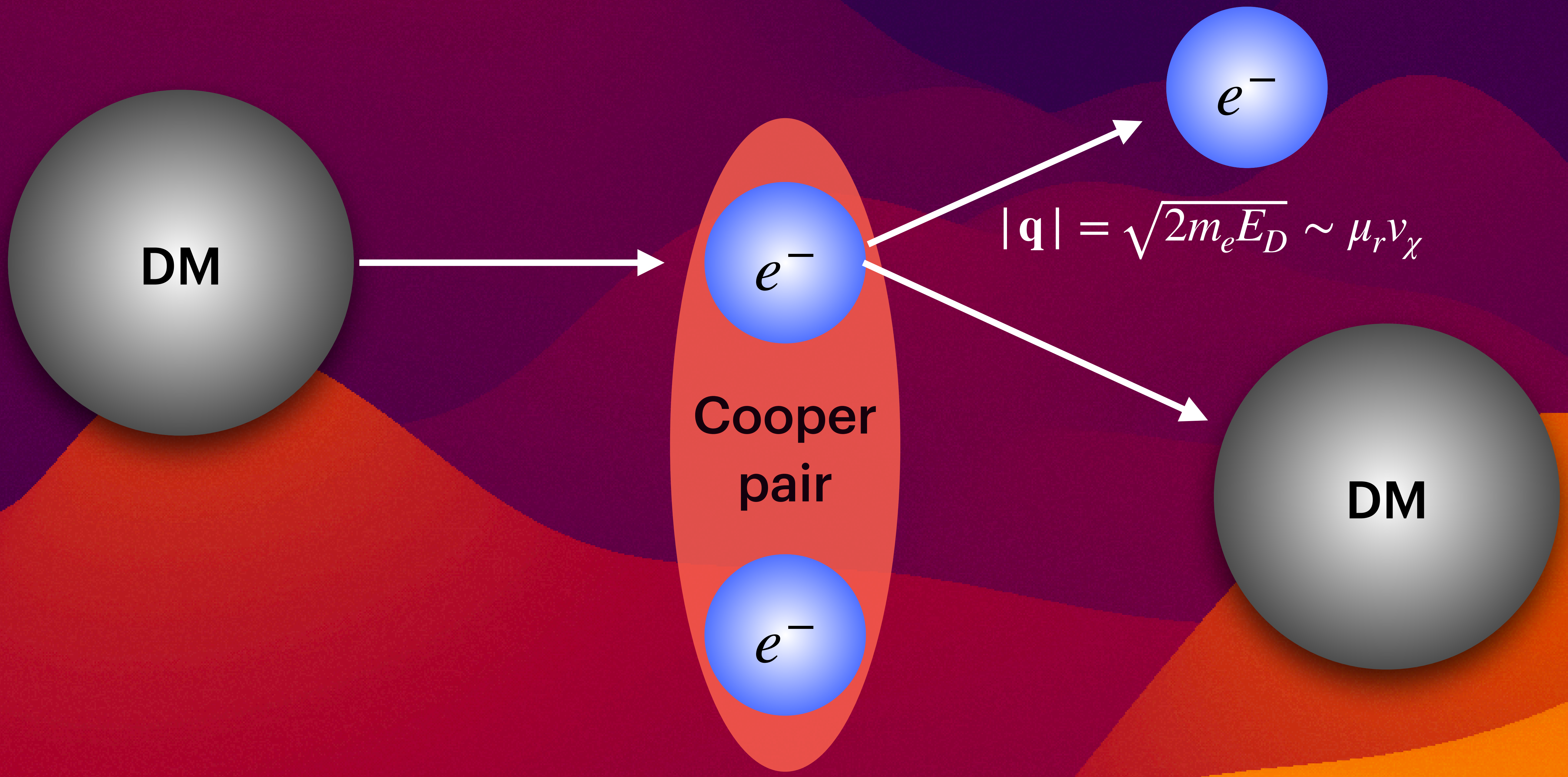
- Poster by Elmeri Rivasto

Postdoc Elmeri Rivasto

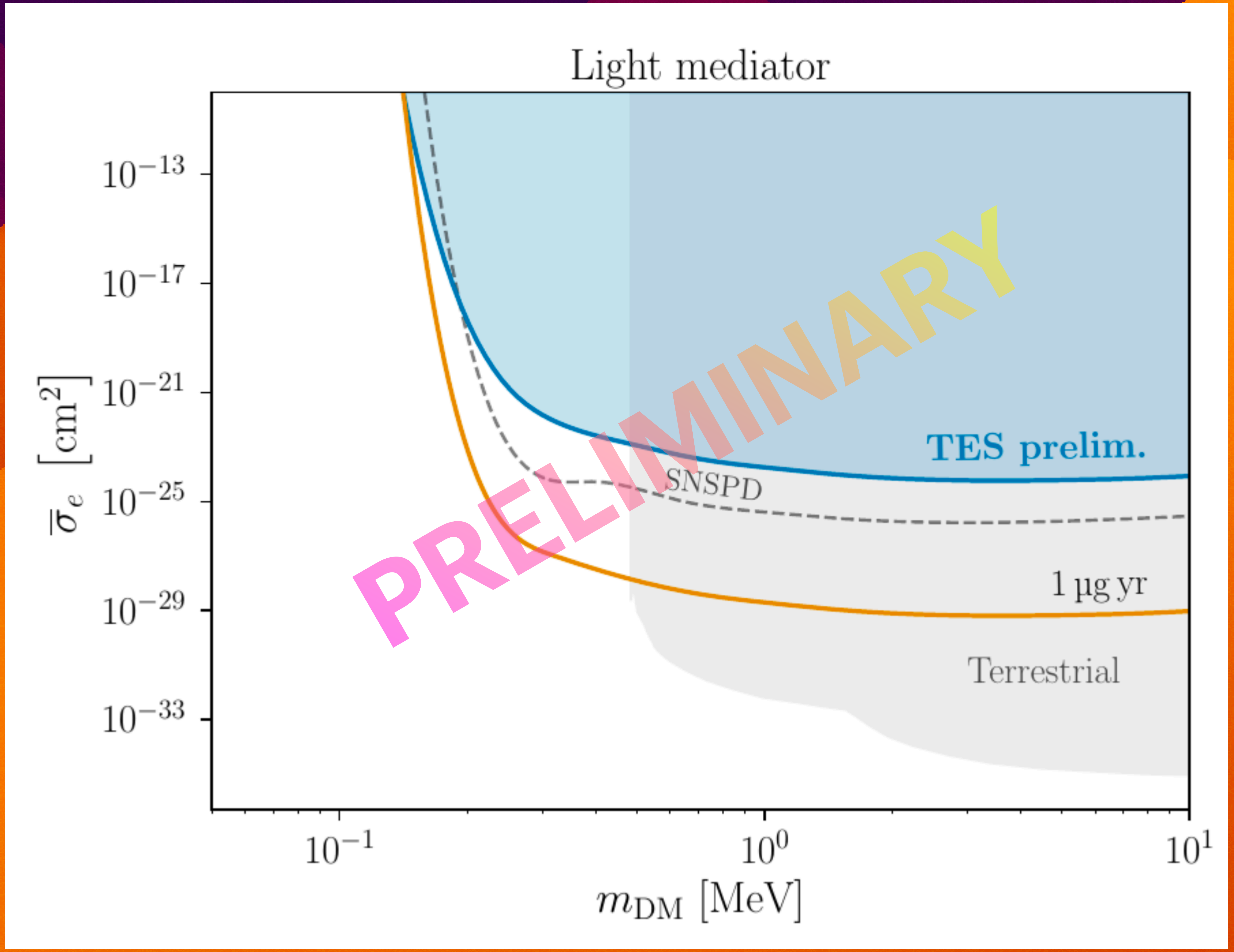
Physics Applications

See C. Schwemmbauer's talk at IDM2024

Direct Dark Matter Search



[Schwemmbauer et al. (2024), Hochberg et al. (2016)]



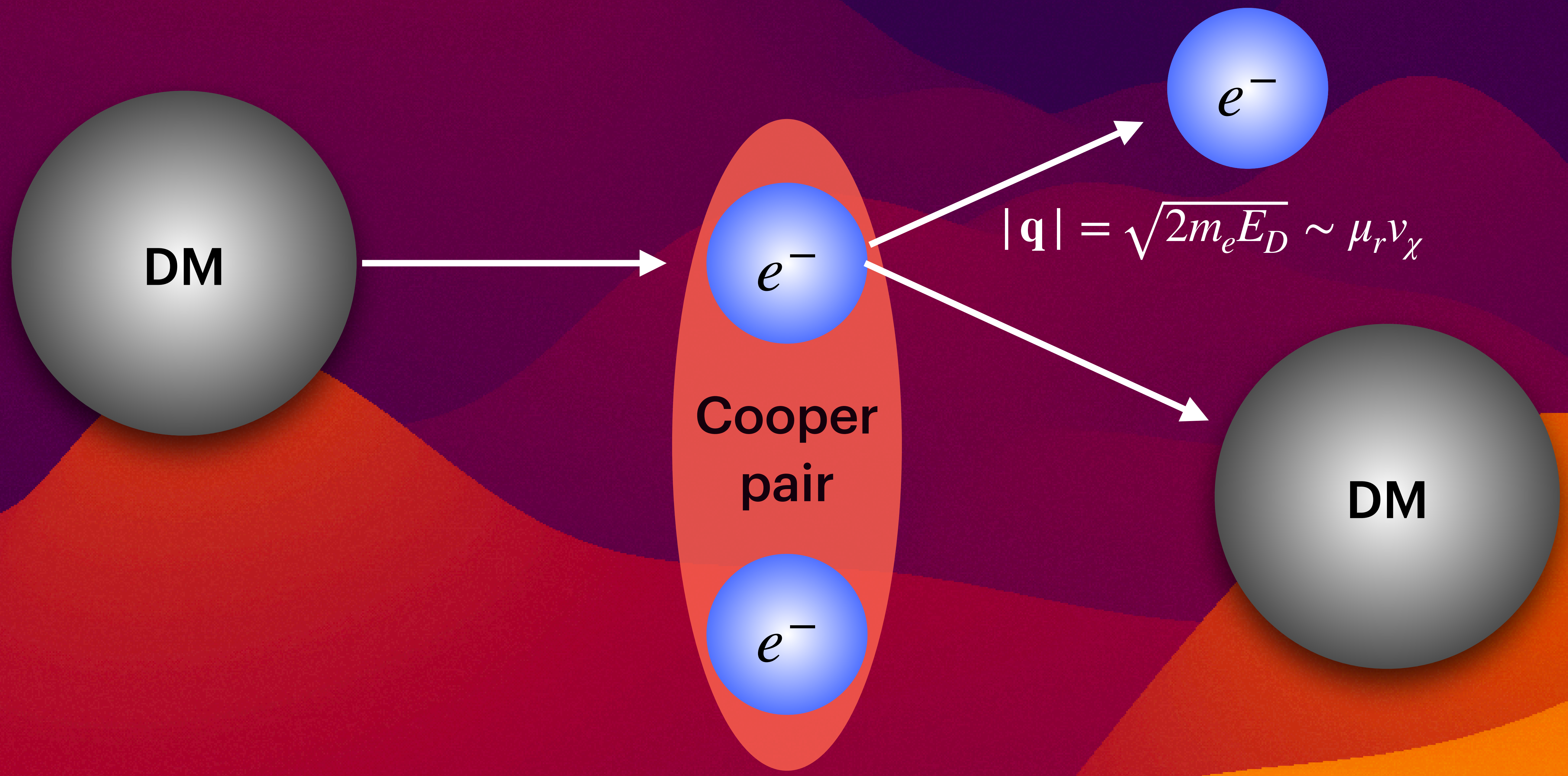
- DM-electron scattering could break Cooper pairs
  - meV threshold for this process, sensitive to light dark matter
- Our TES has sub-eV thresholds → MeV scale dark matter
- TES dark current measurements can be used to set limits
- TES never been used as the target materiel in direct dark matter searches before
- Finished ~1 month of data taking at DESY, analysis on-going

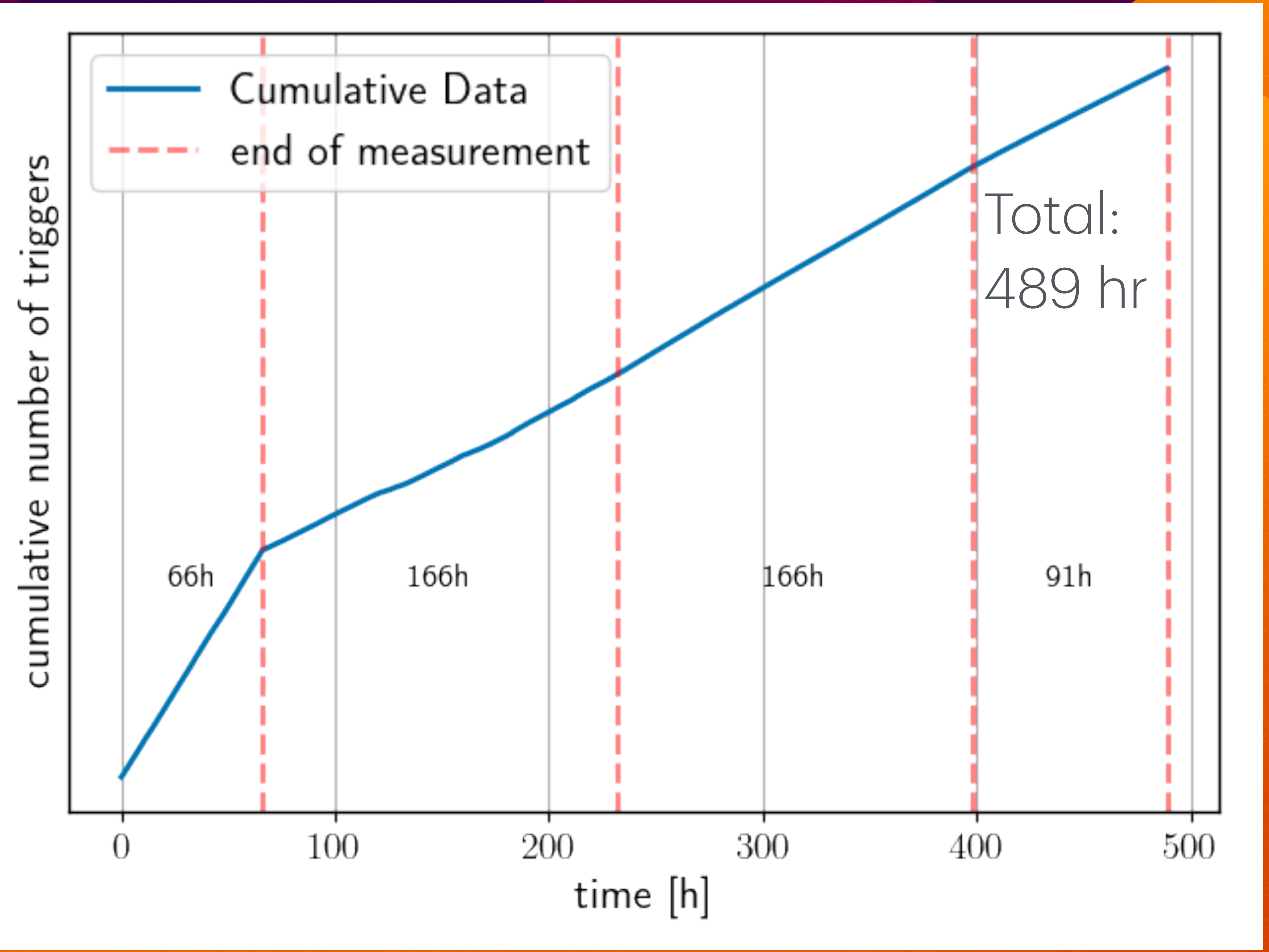
See C. Schwemmbauer's talk at IDM2024

Direct Dark Matter Search

PhD student Christina Schwemmbauer

[Schwemmbauer et al. (2024), Hochberg et al. (2016)]





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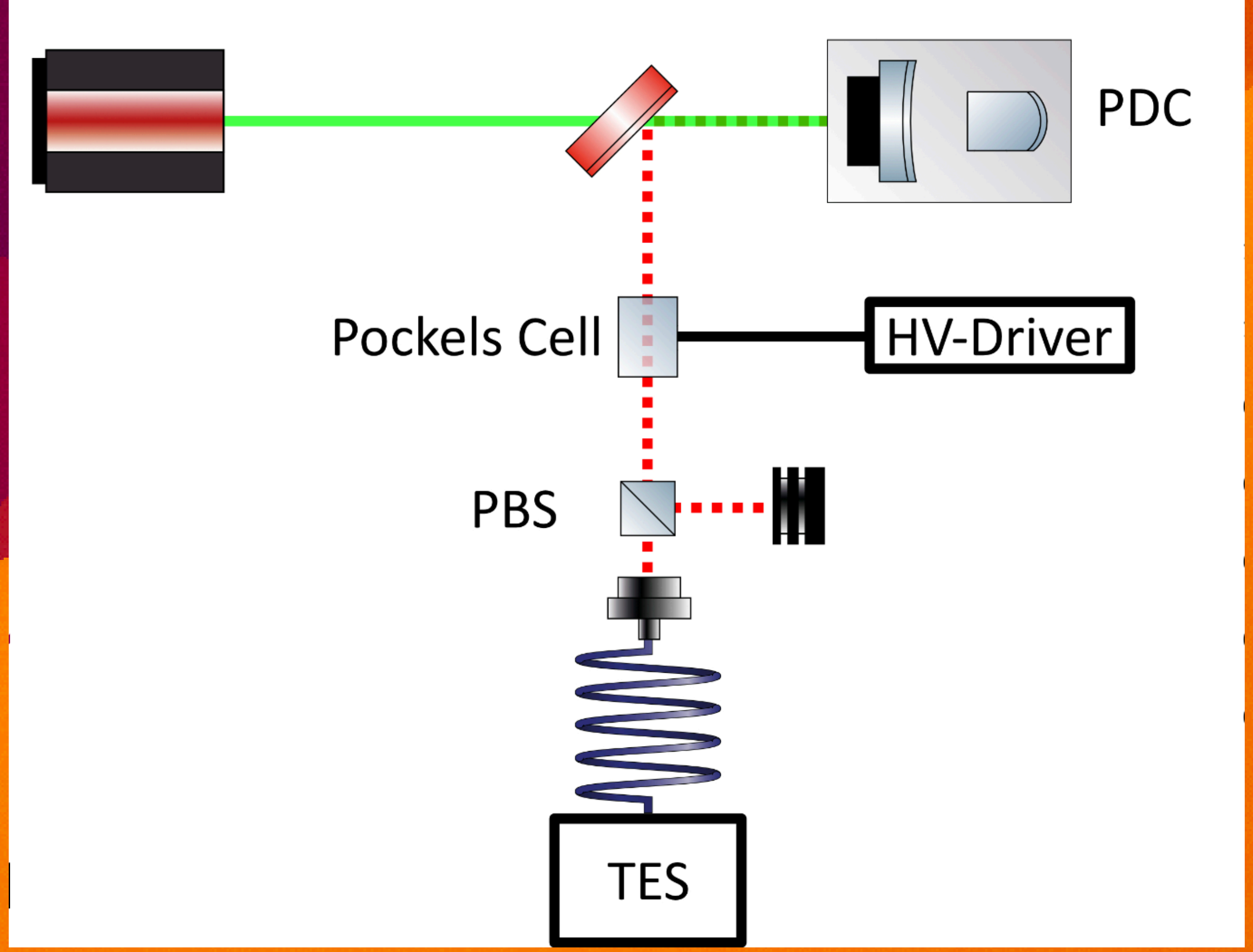
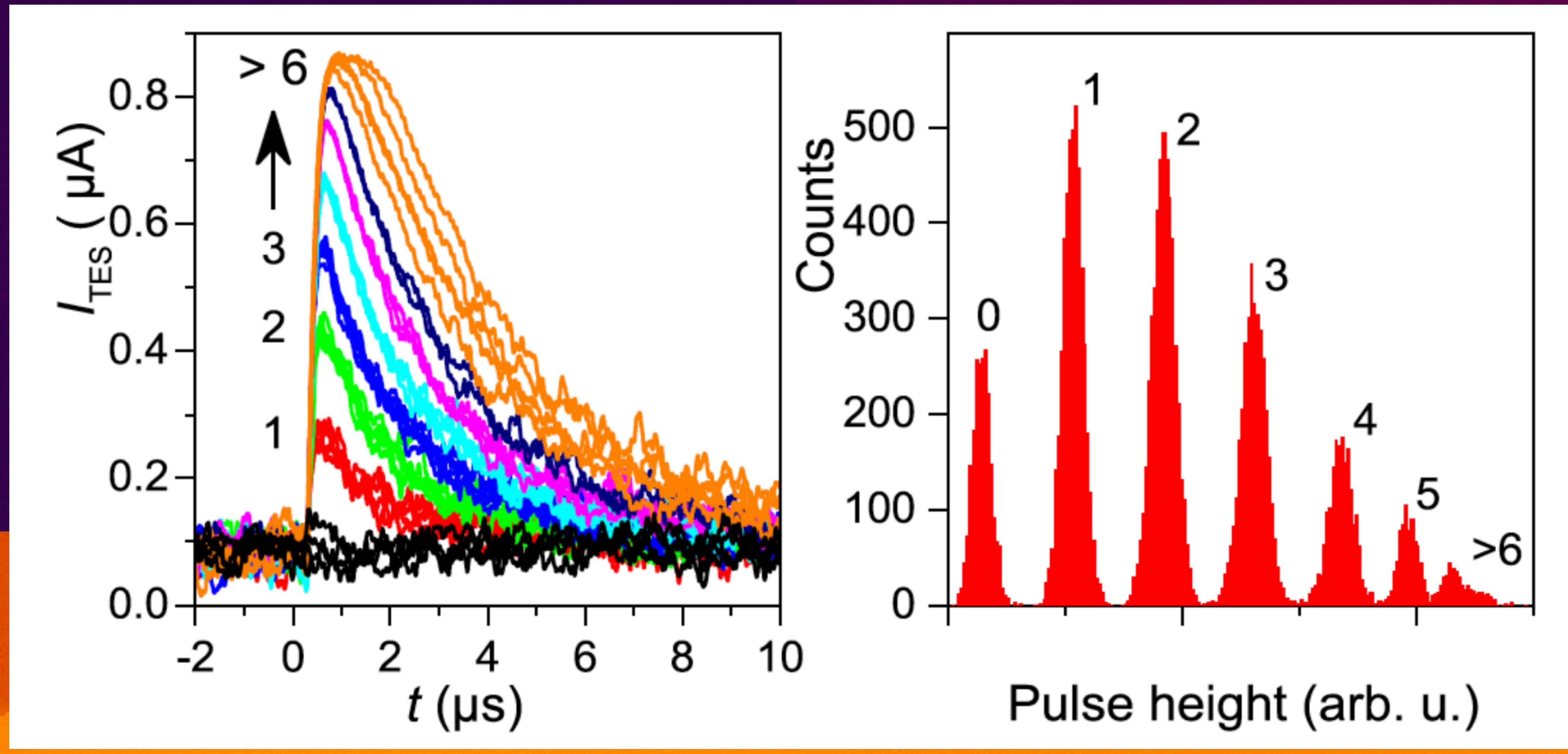
Measuring the Even Number Photon Distribution

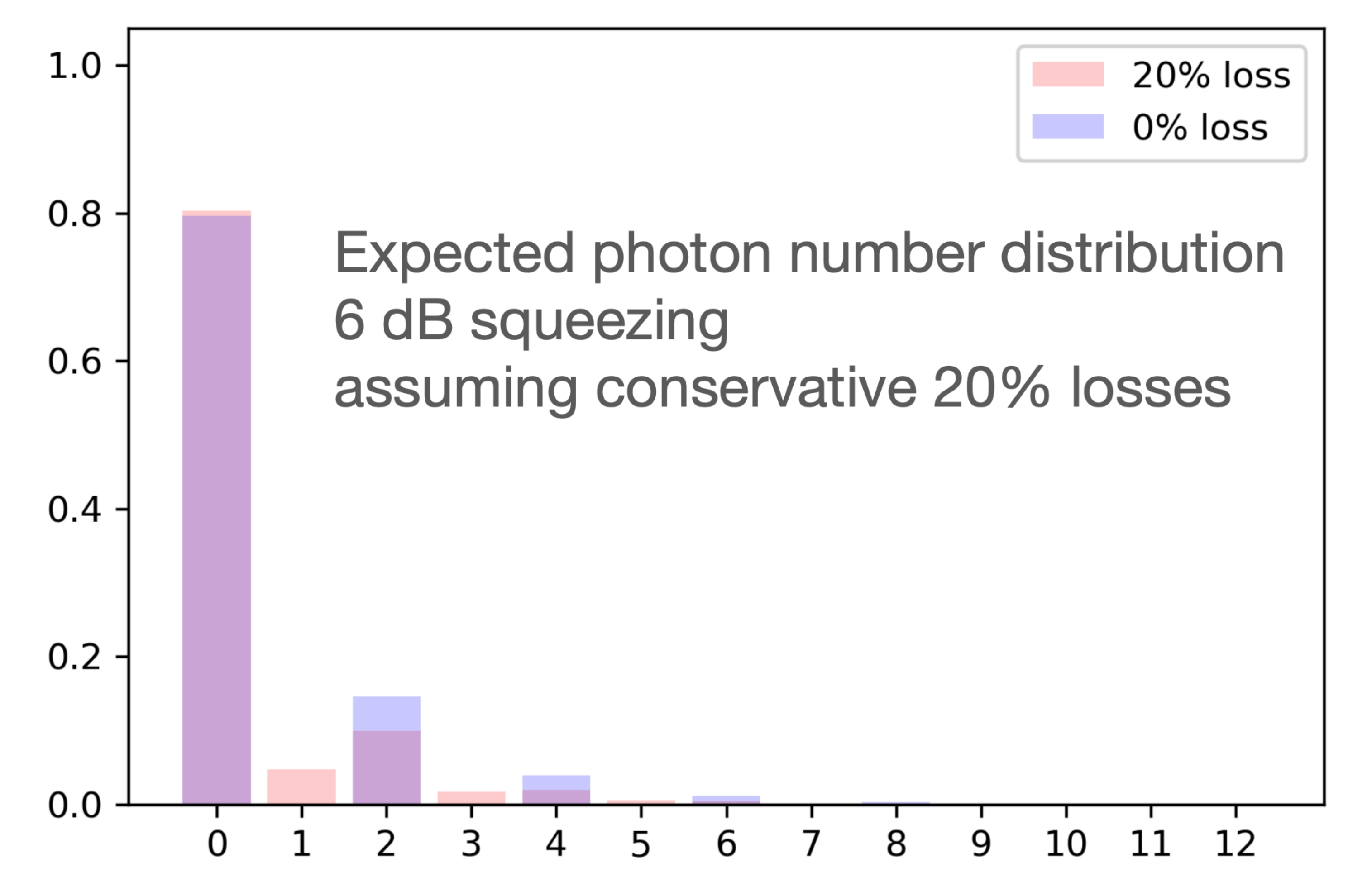
of a Squeezed Light Source at 1064 nm

- Squeezer provided by the Schnabel group at UHH
- Necessary step to realizing Gottesman– Kitaev–Preskill (GKP) States for Quantum Computation (QC)
- GKP qubits satisfy Universality, Scalability, and Fault Tolerance, which are necessary for practical quantum computation
- GKP qubits have not yet been realized in photonic QC



Schmidt et al. (2018)





Plot and simulations by PhD student Stephan Grebien

PIER
Partnership of Universität Hamburg and DESY

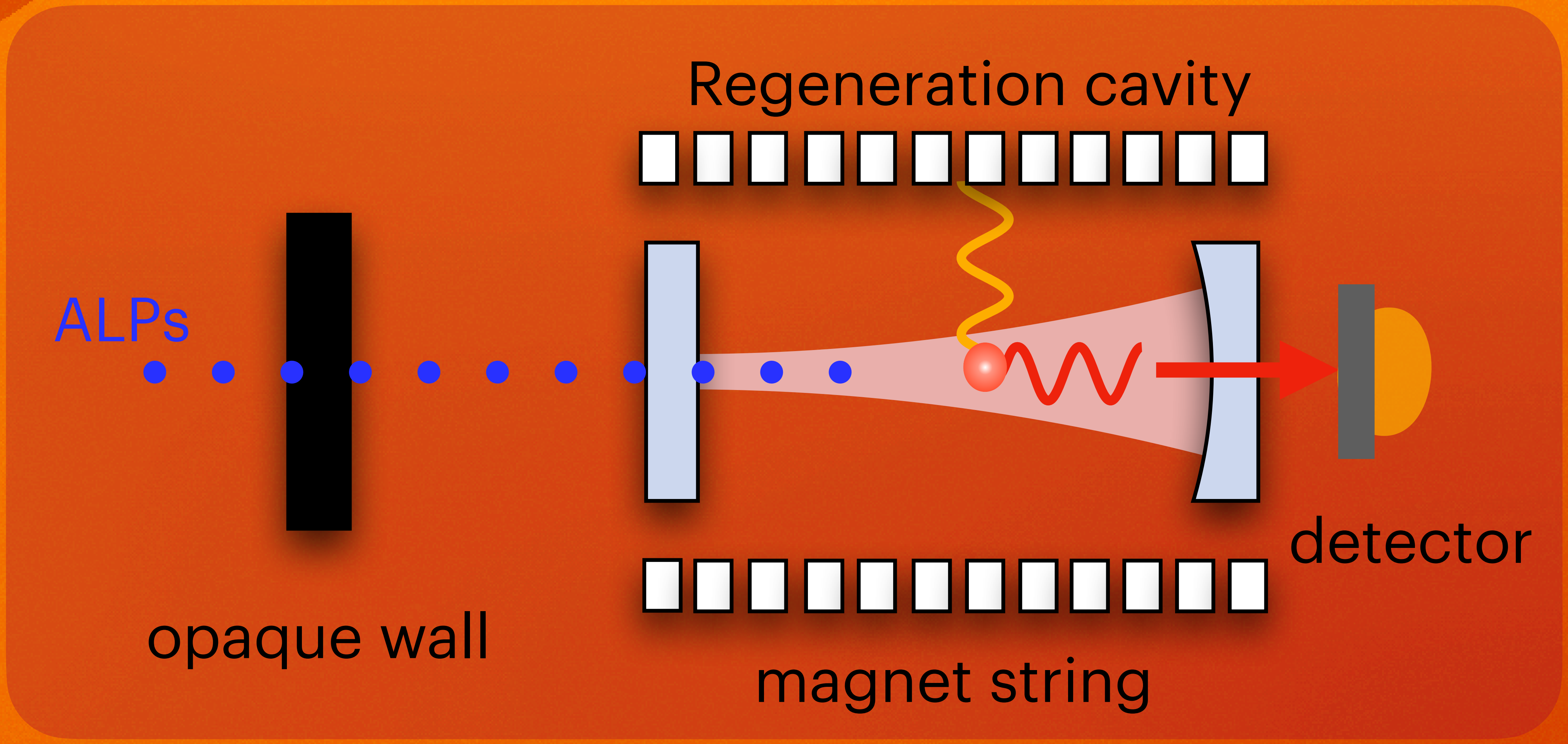
Secondary Detector for ALPS II

Talk by Aaron Spector later today

Goal: Single infrared photon detection, single photon per day
Second option: Photon counting

Requirements:

- High Quantum Efficiency
  - ~ **>99%** at wavelength of interest (1064 nm ~ 1.165 eV)
- Good energy resolution
  - Aids in separation of signal from background
- Low Dark-Count Rate
  - 7.7 μHz to claim 5σ detection after 20 days (no more than 14 events / 20 days)
- To-do:
  - Verify high System Detection Efficiency (fiber-coupled)
  - Achieve low dark count rate when fiber-coupled

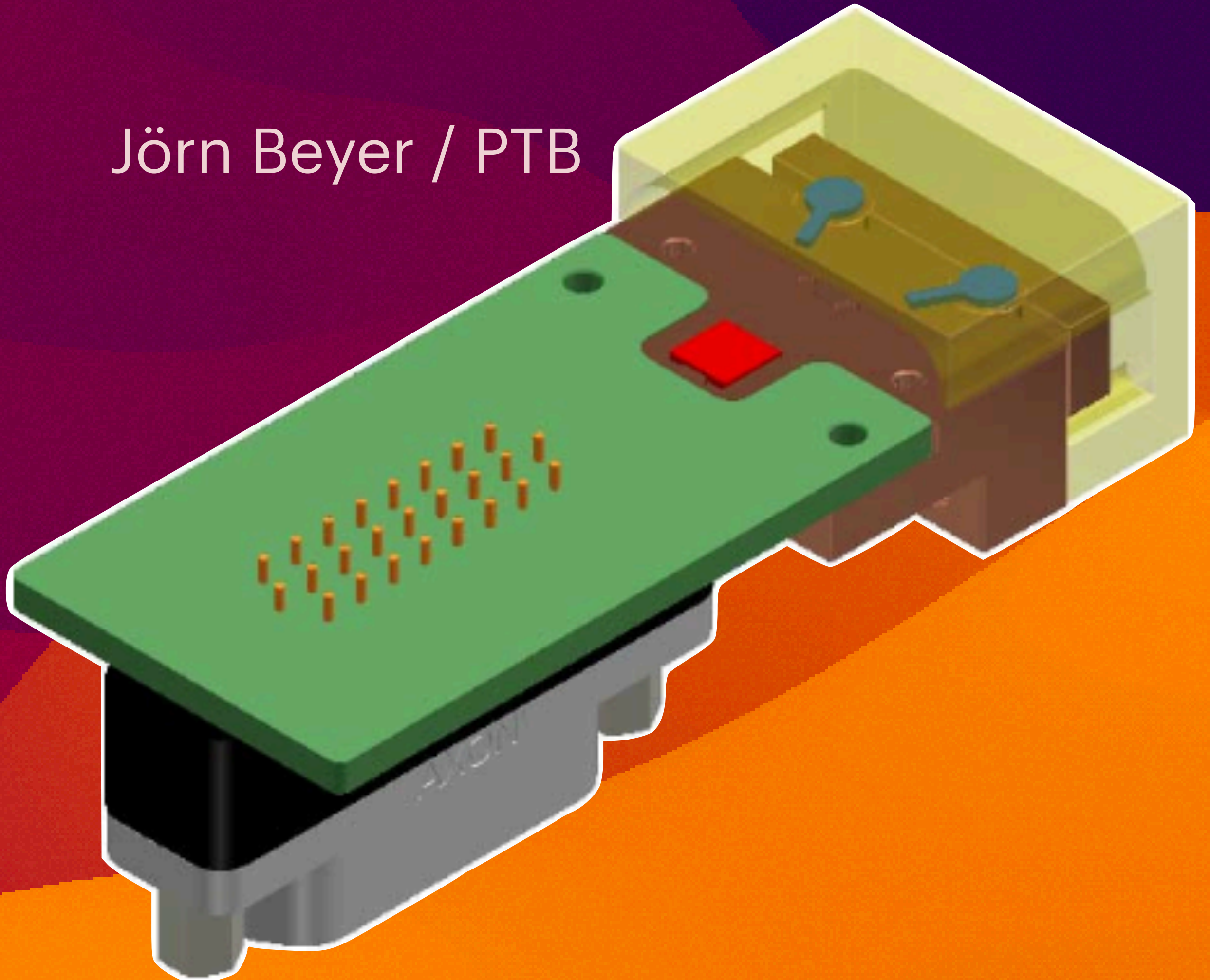


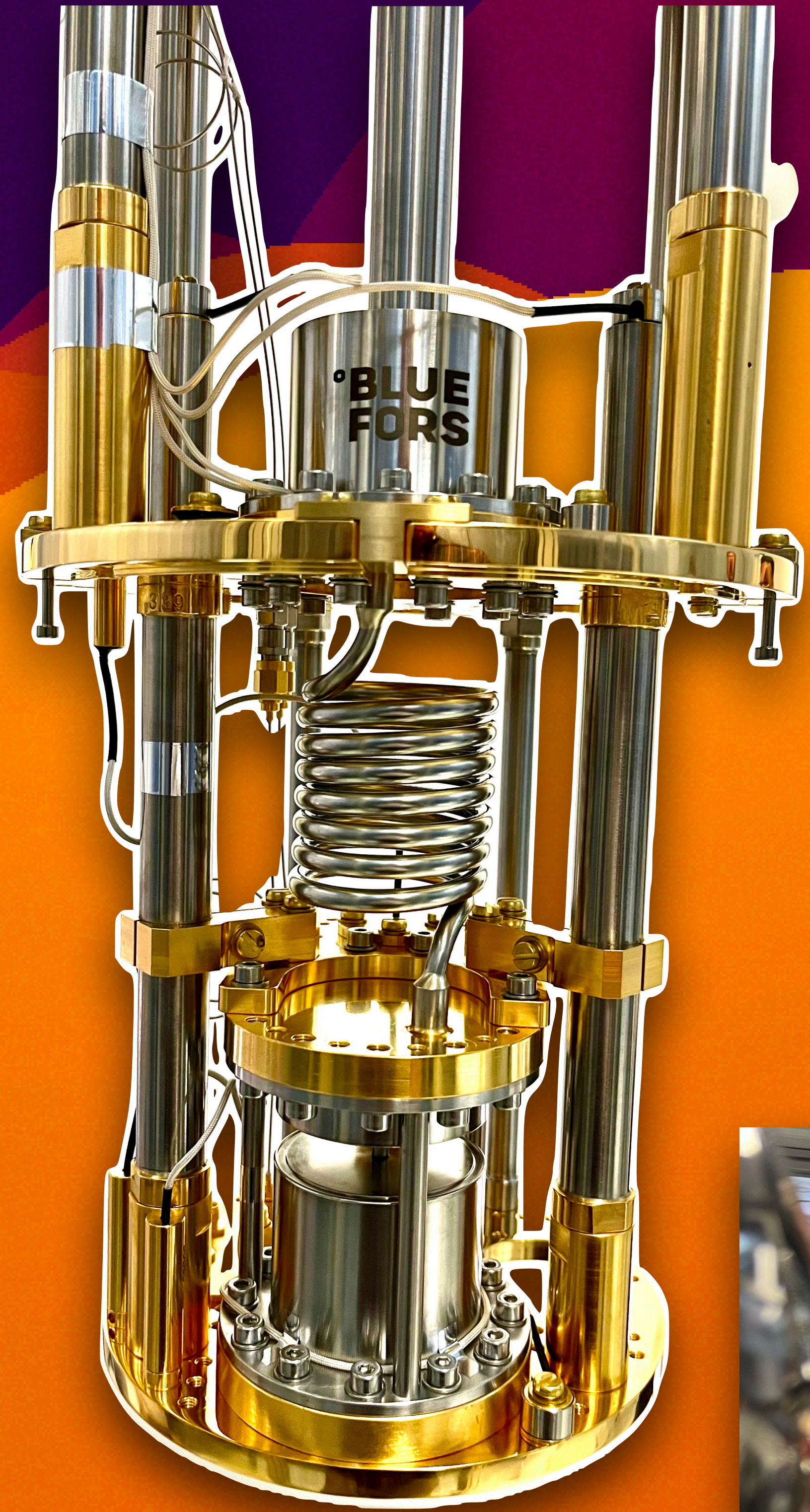
Graphic from Katharina-Sophie Isleif

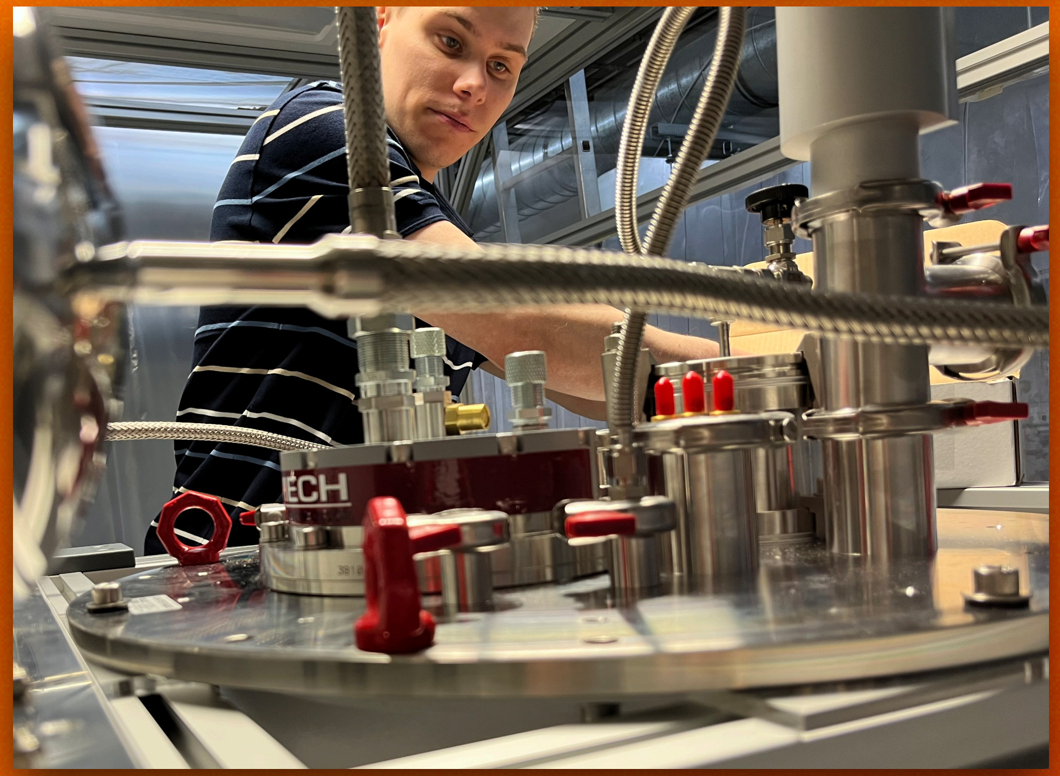
Future: New Modules, Second Fridge

- Parallel characterization and measurement campaigns
  → more science!
  - Modules packaged by PTB, TES chips by NIST
- New module being designed without fiber sleeves
  - Lower radioactive backgrounds for more sensitive direct dark matter searches
- Using Machine Learning to better discriminate backgrounds
  - Poster by Elmeri Rivasto

Jörn Beyer / PTB



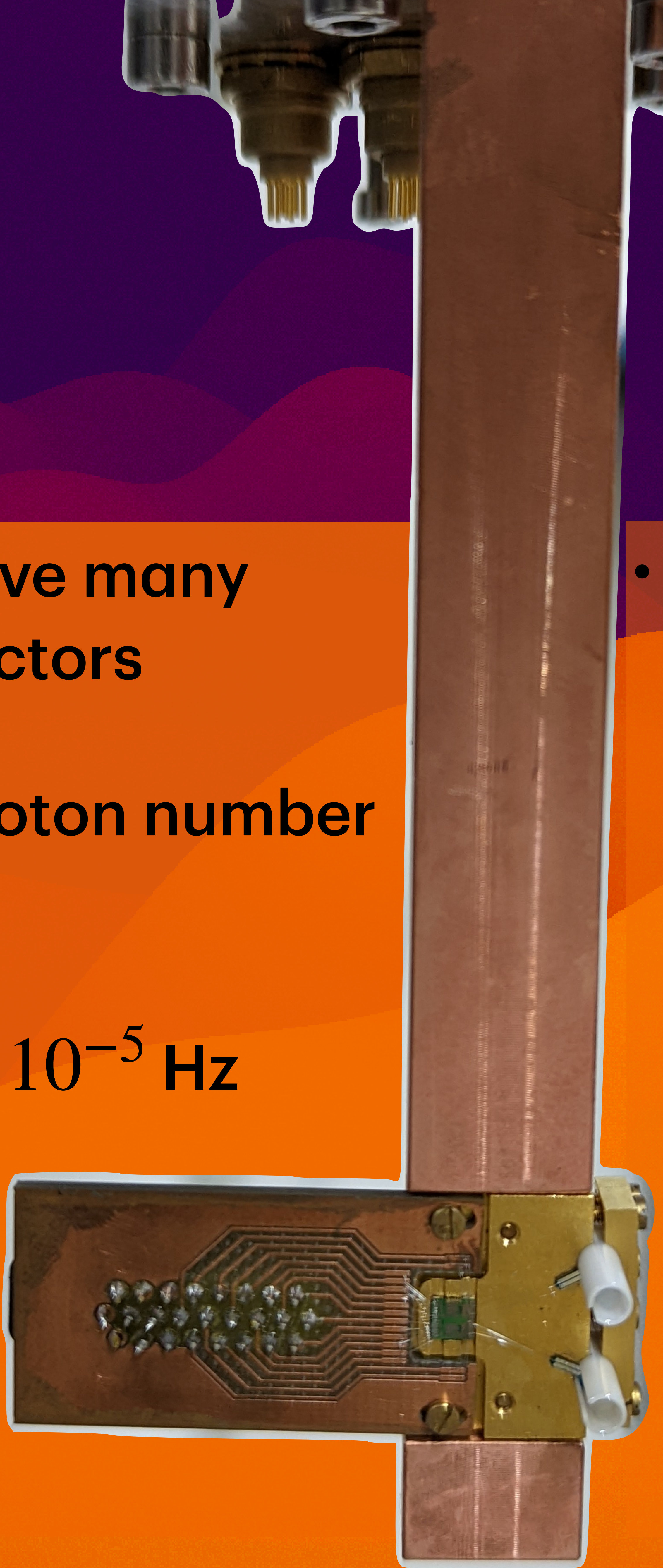




PTB
NIST
University of Glasgow

Summary

- Transition Edge Sensors have many beneficial qualities as detectors
  - Energy resolution and photon number resolution
  - Low dark-count rates: $\leq 10^{-5}$ Hz
    [Shah et al. 2022]
  - High quantum efficiency: $\geq$ 95% (near infrared)
    [Lita et al. 2008]



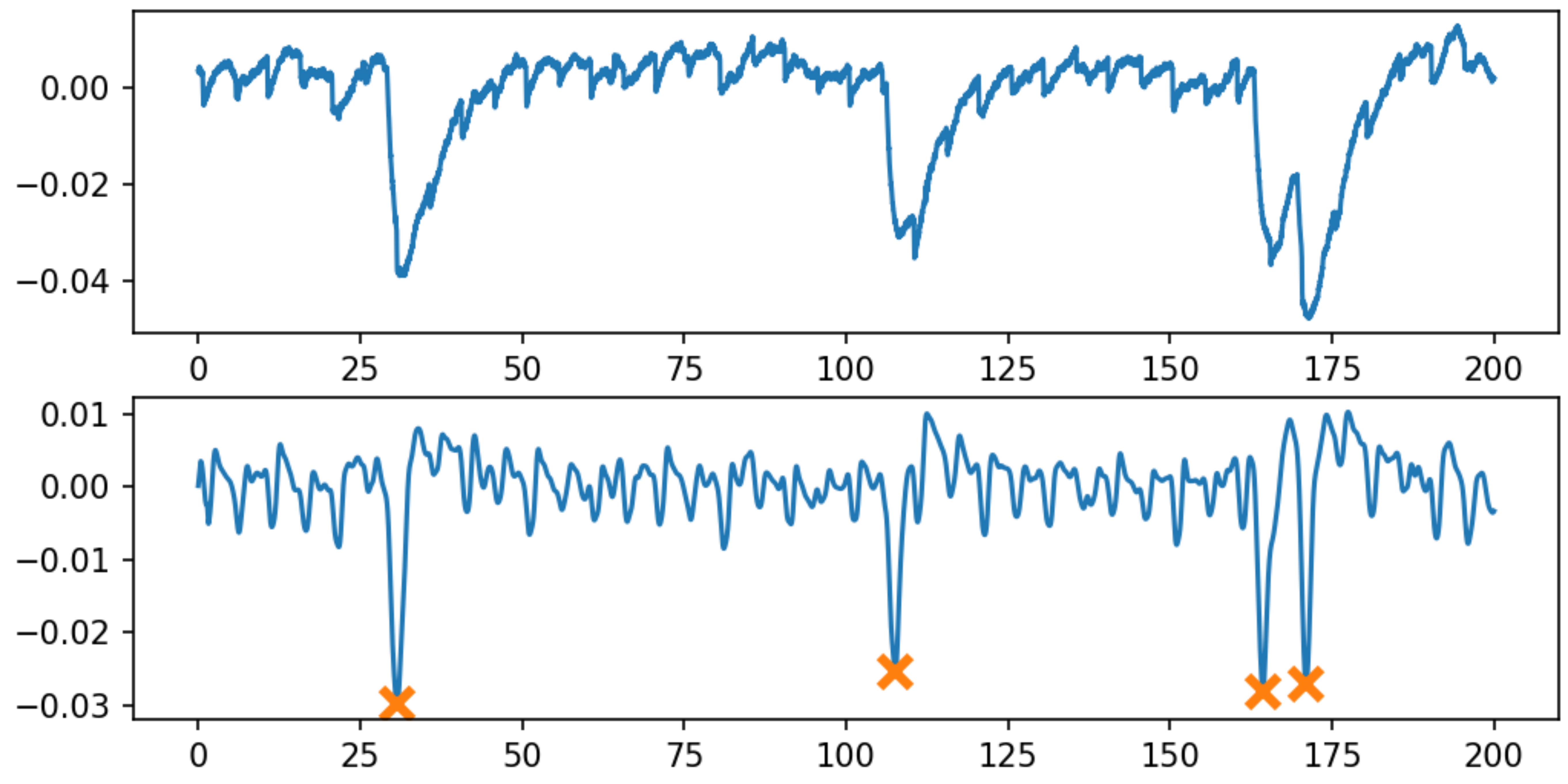
- TESs at DESY
  - Characterization of TESs
    - Working closely with NIST and PTB to develop new sensors
  - Fundamental physics
    - Direct dark matter
    - Measurements of Quantum-Squeezed light
    - Secondary detector for ALPS II

Backup Slides

System Detection Efficiency

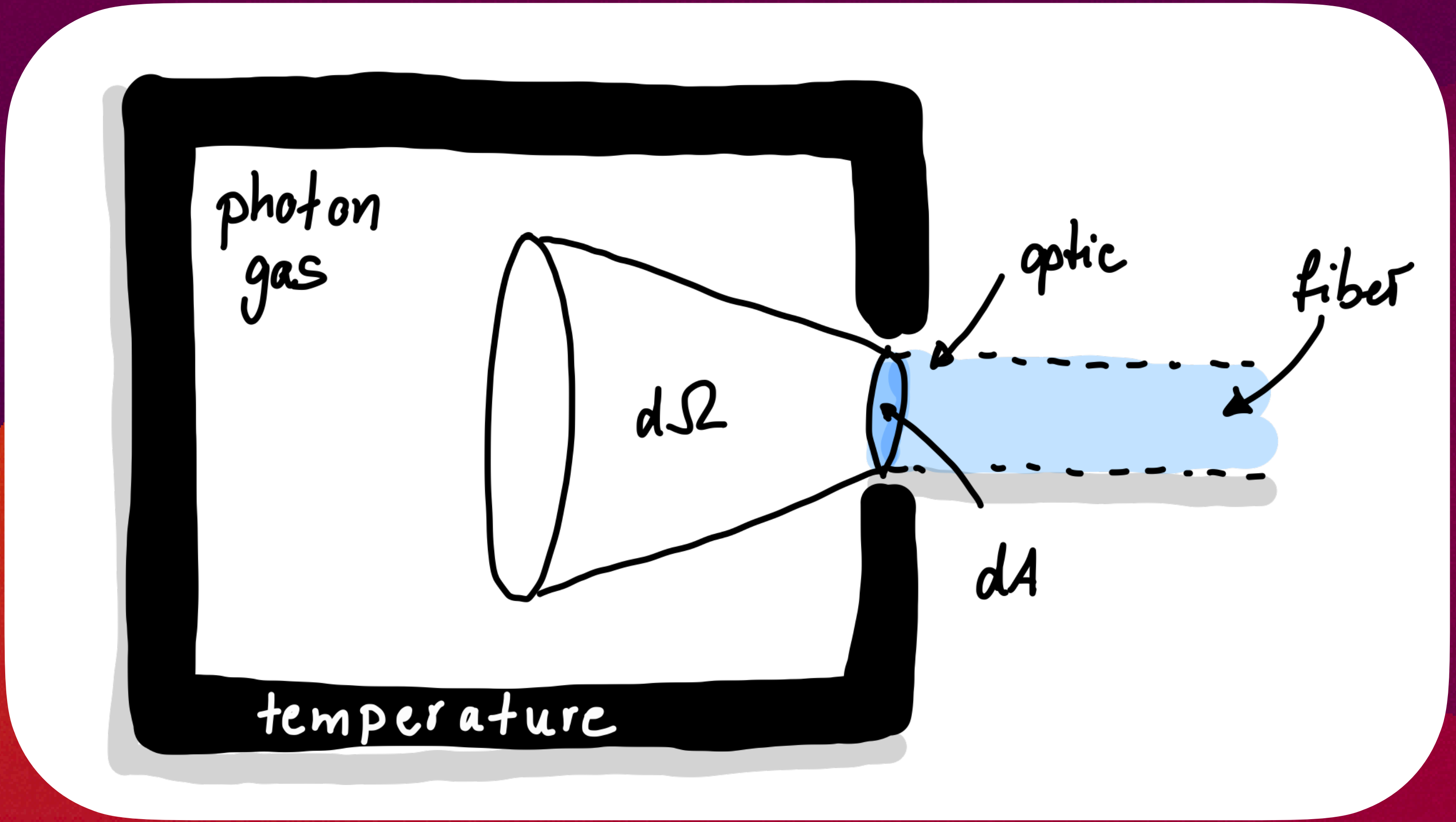
Pulse finding

- Take continuous timelines, 4 s
- Count peaks using trapezoidal filter algorithm
  - Helps to better distinguish signal from noise
  - Also helps with situations where there may be pileup

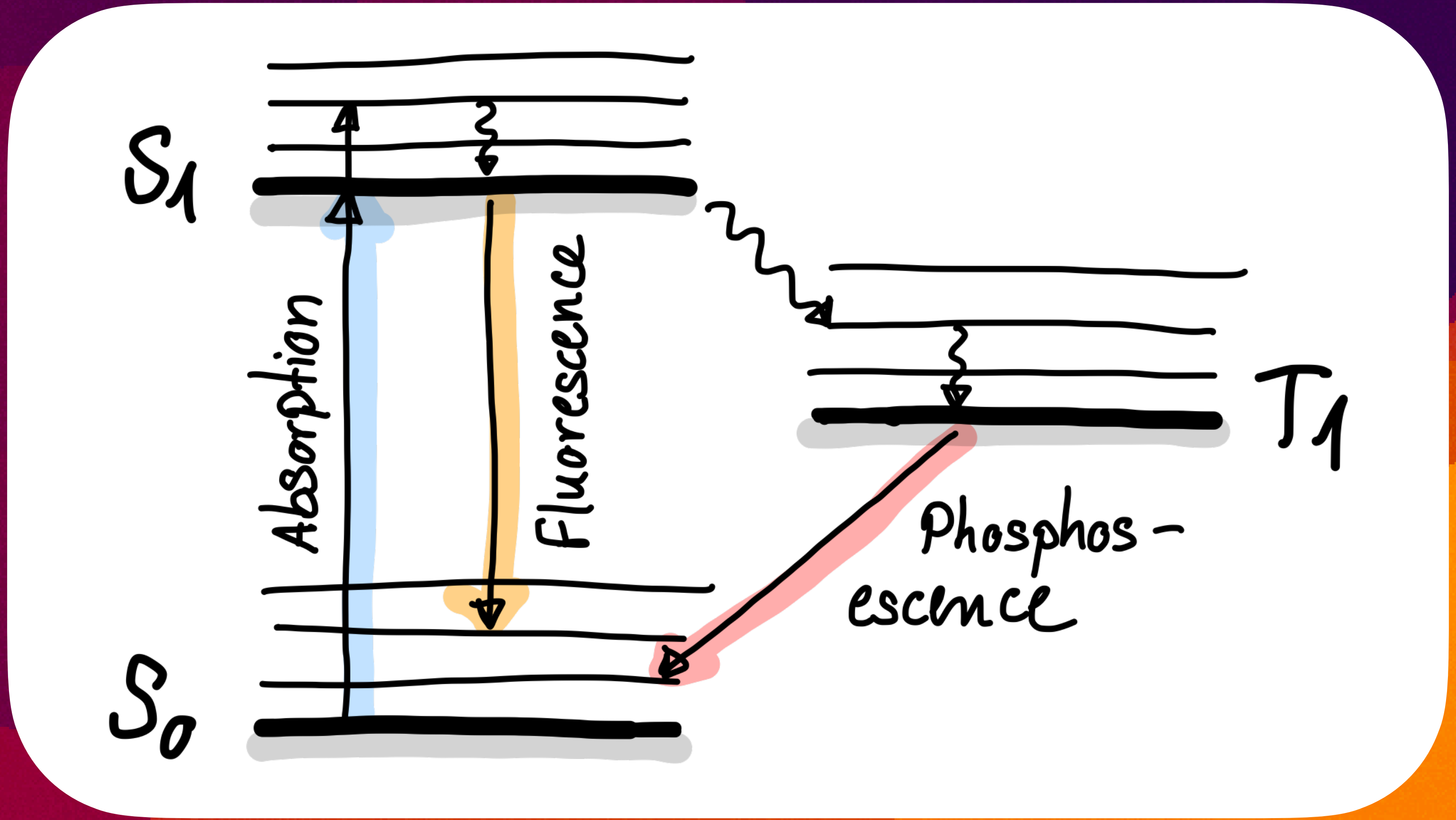


Expected Background Sources (fiber-coupled)

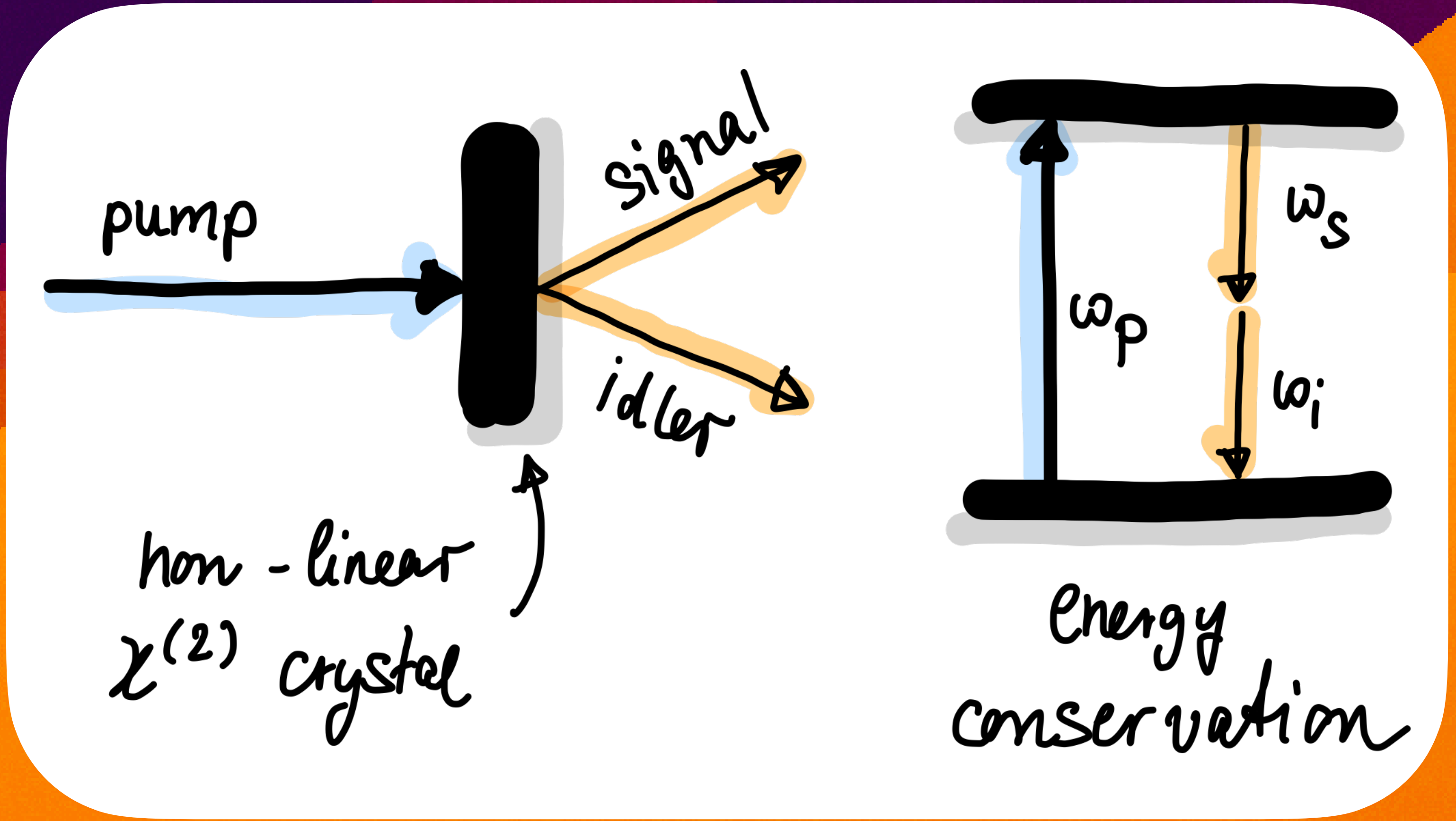
Black body radiation from laboratory, components @300K



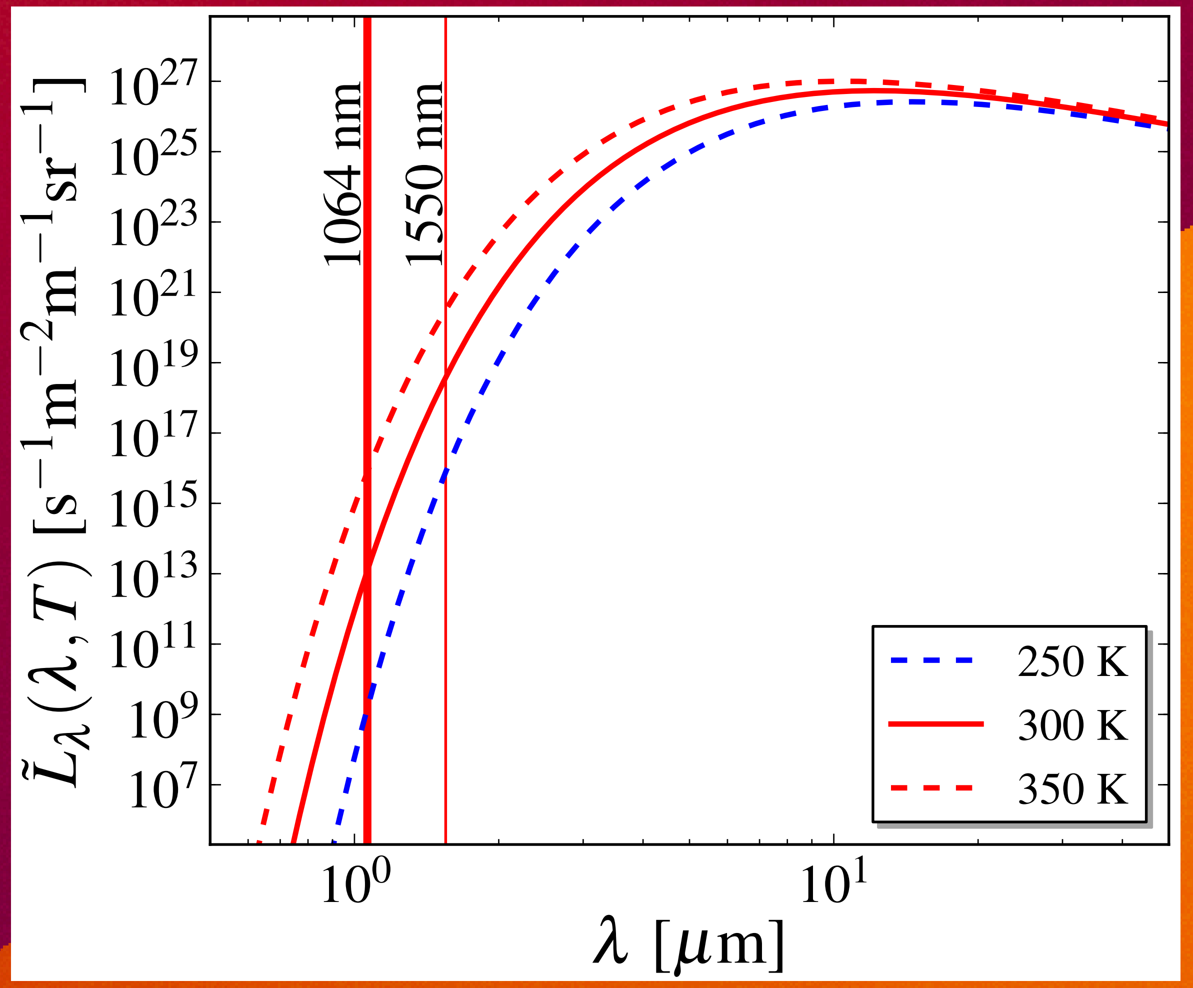
Luminescence in optical components or fibers



Parametric noise in non-linear optical components or fibers



Courtesy of Katharina-Sophie Isleif



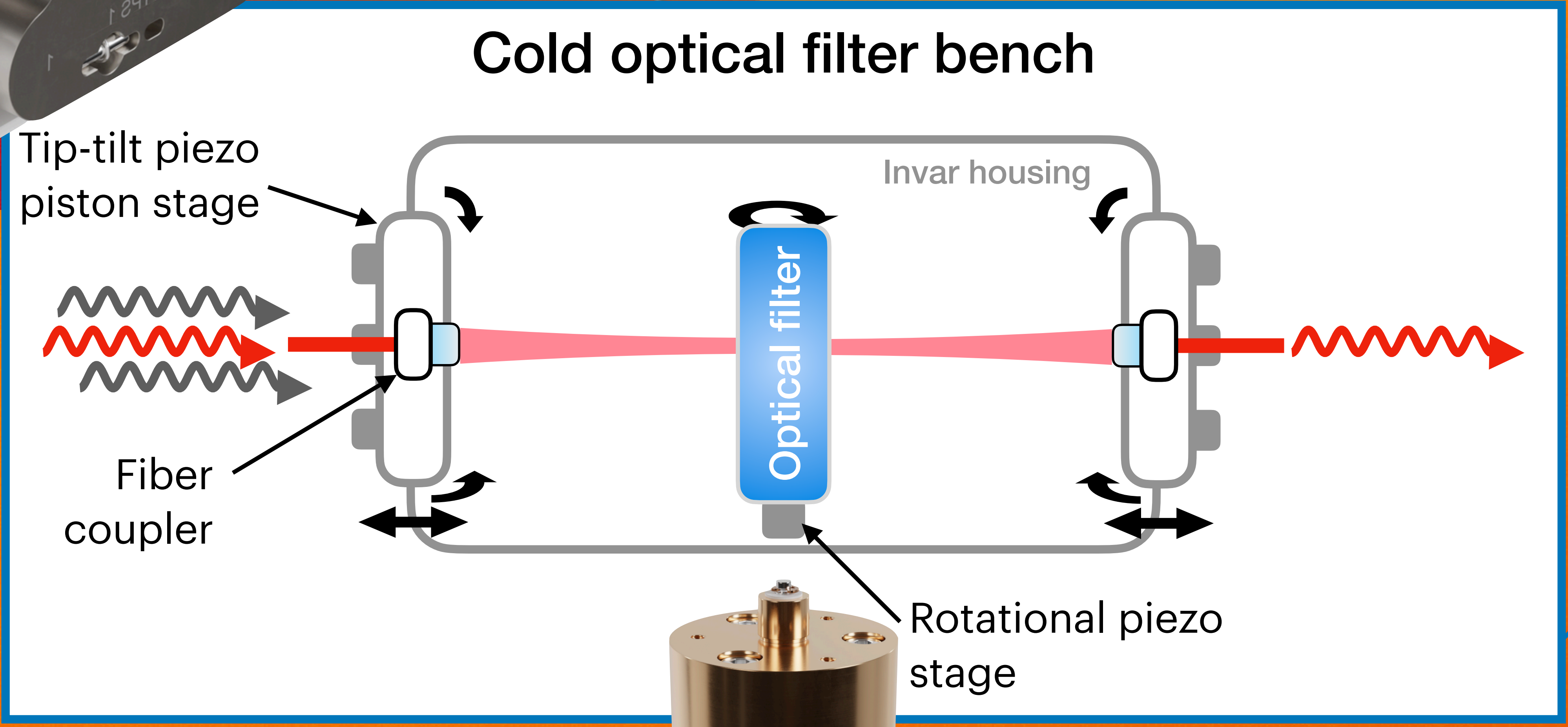
- **Without fiber connected:** radioactivity, cosmic rays
- With fiber connected:
  - Blackbody photons from warm components
  - Luminescence within the fiber itself and optical components
  - Parametric noise
- Suppressing backgrounds also relevant to other quantum sensing applications

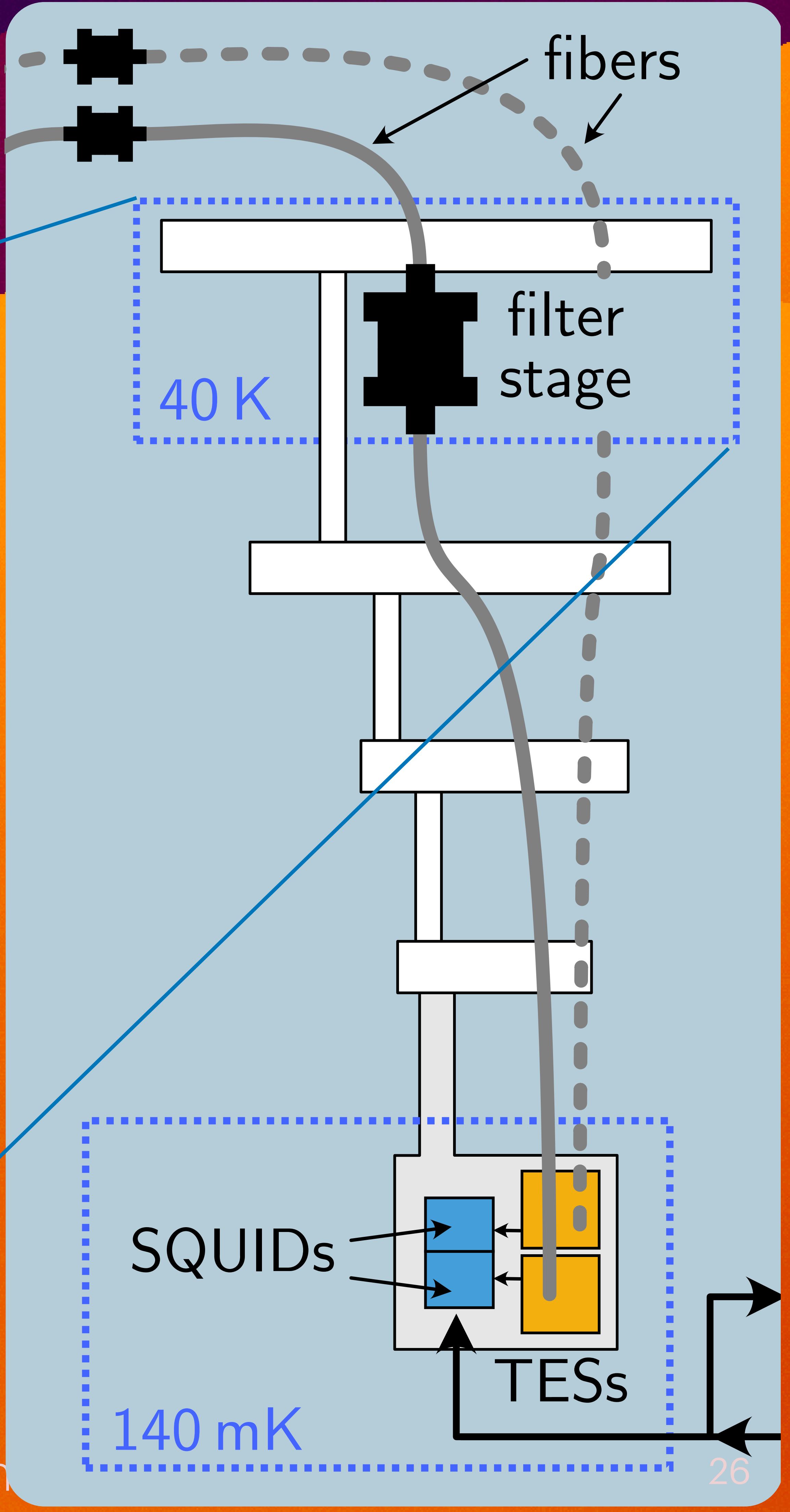
Background suppression: Cold optical filter bench

Design under development

- **Filter can be aligned with piezo stages inside cryostat**
- **Rotational stage to compensate for wavelength shift of filter**
- **Vibrational isolation and housing made of Invar**

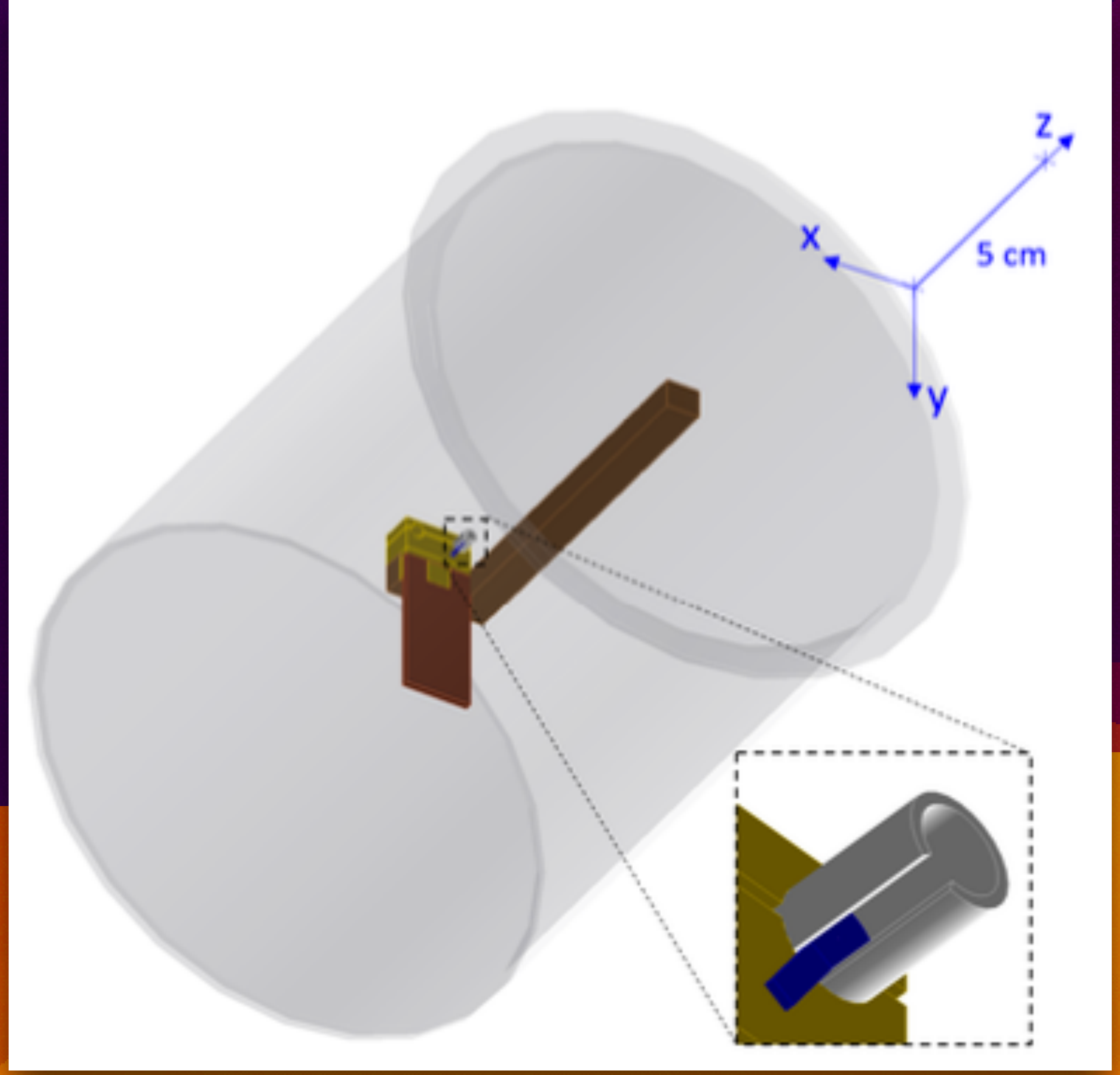
Vibrational isolation



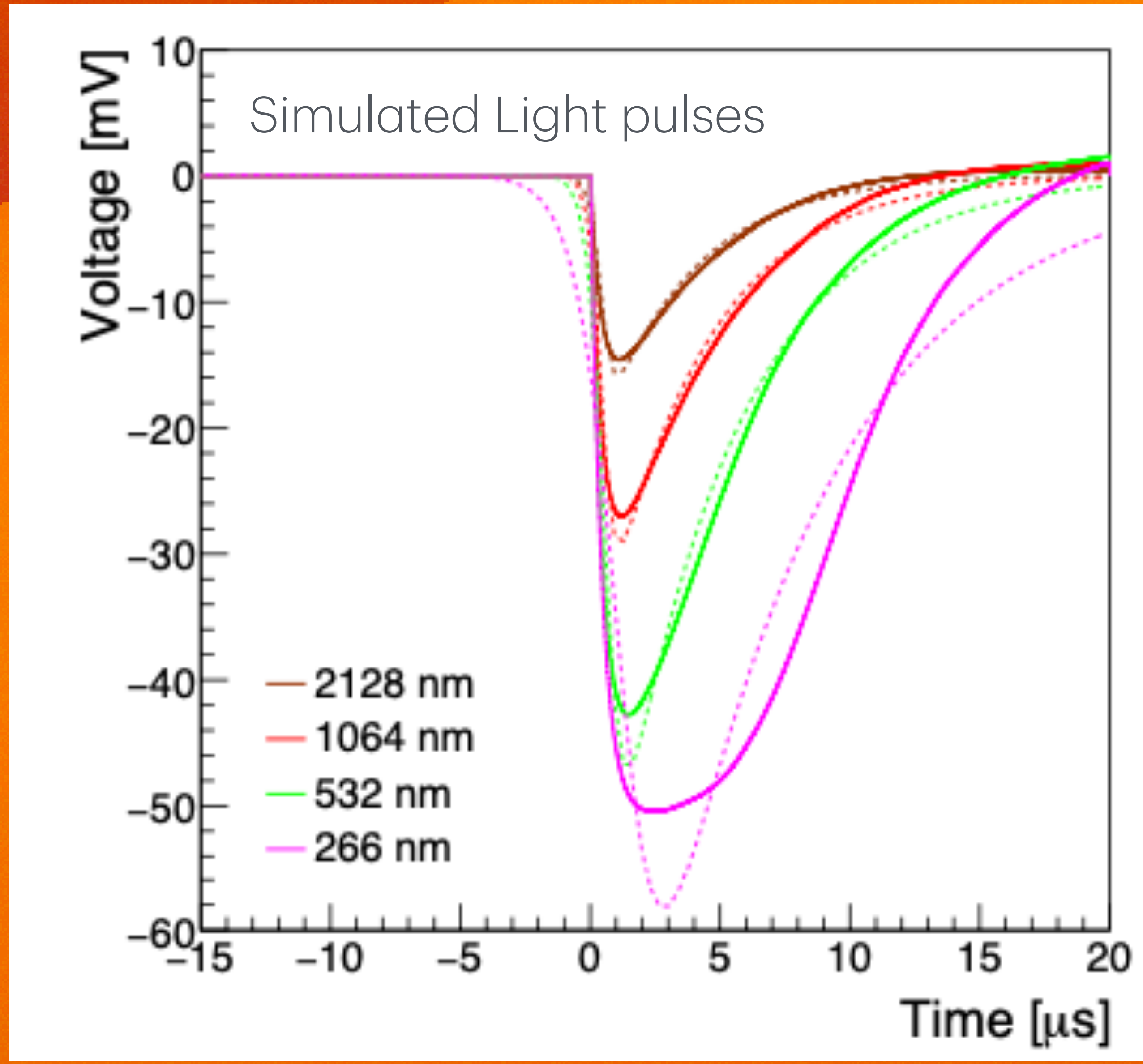


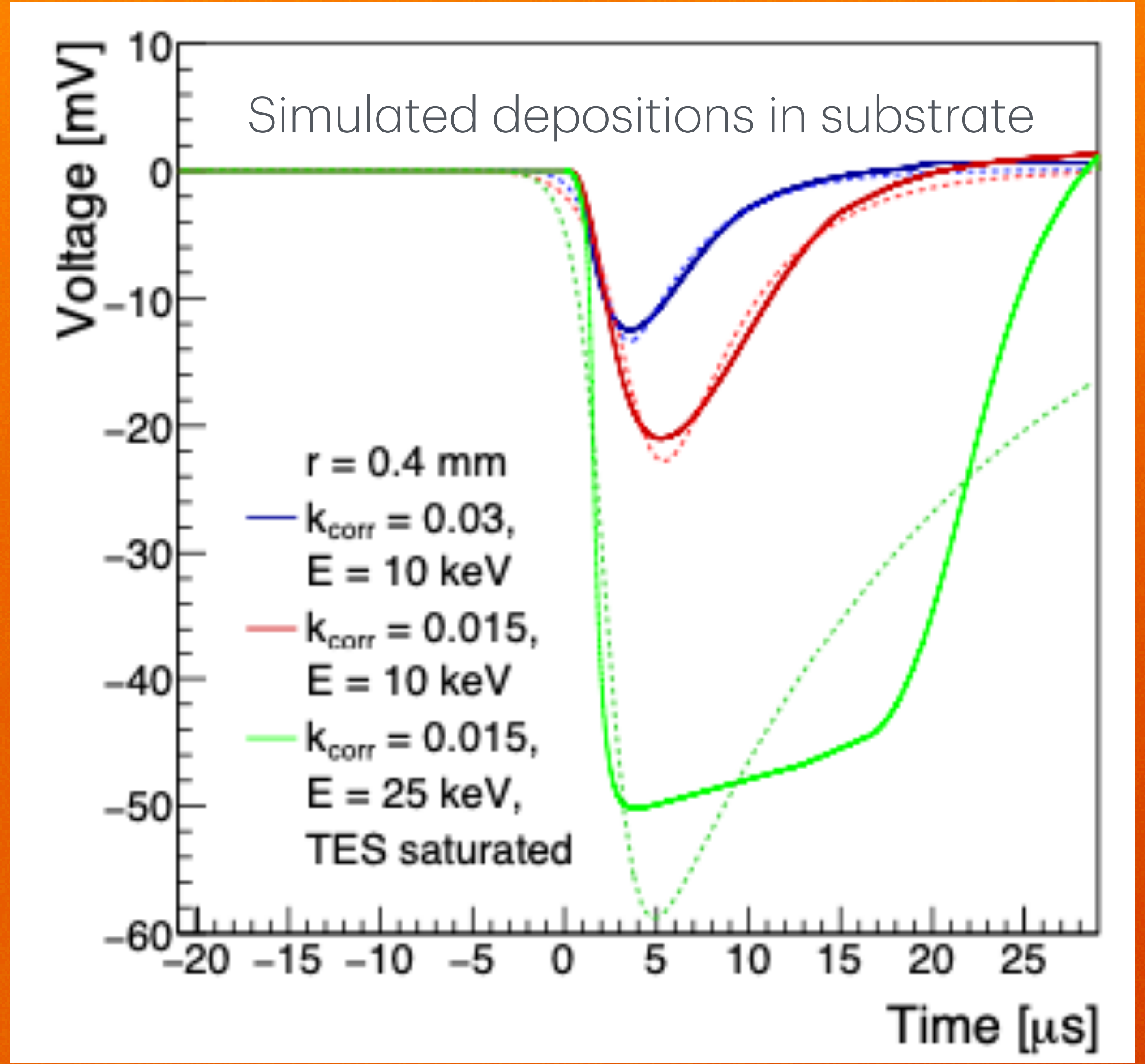
Simulations

- 3-fold simulations:
  - GEANT4: simulate radioactive backgrounds, such as cosmic muons, intrinsic radioactivity
  - COMSOL: simulate heat transfer from energy depositions in the substrate around the TES
  - Simulate pulses based on the heat transfer
- Energy deposition in substrate exhibit different behavior



PhD thesis of José Alejandro Rubiera Gimeno, finished 2024 at DESY

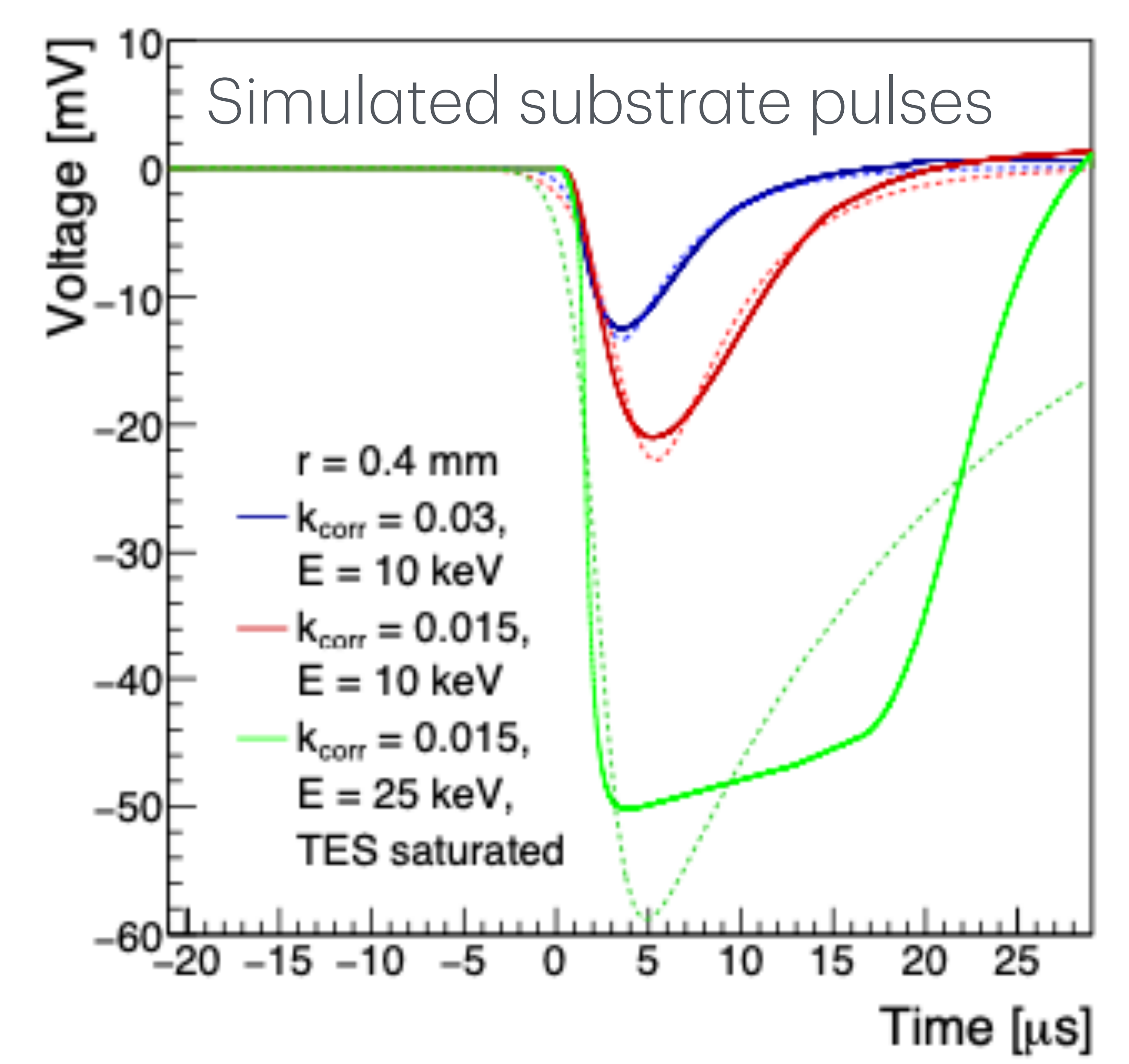




Simulations

PhD thesis of José Alejandro Rubiera Gimeno, finished 2024 at DESY

- **3-fold simulations:**
  - **GEANT4: simulate radioactive backgrounds, such as cosmic muons, intrinsic radioactivity**
  - **COMSOL: simulate heat transfer from energy depositions in the substrate around the TES**
  - **Simulate pulses based on the heat transfer**
- **Simulations predict a dominant background is Zirconia in the fiber sleeve**

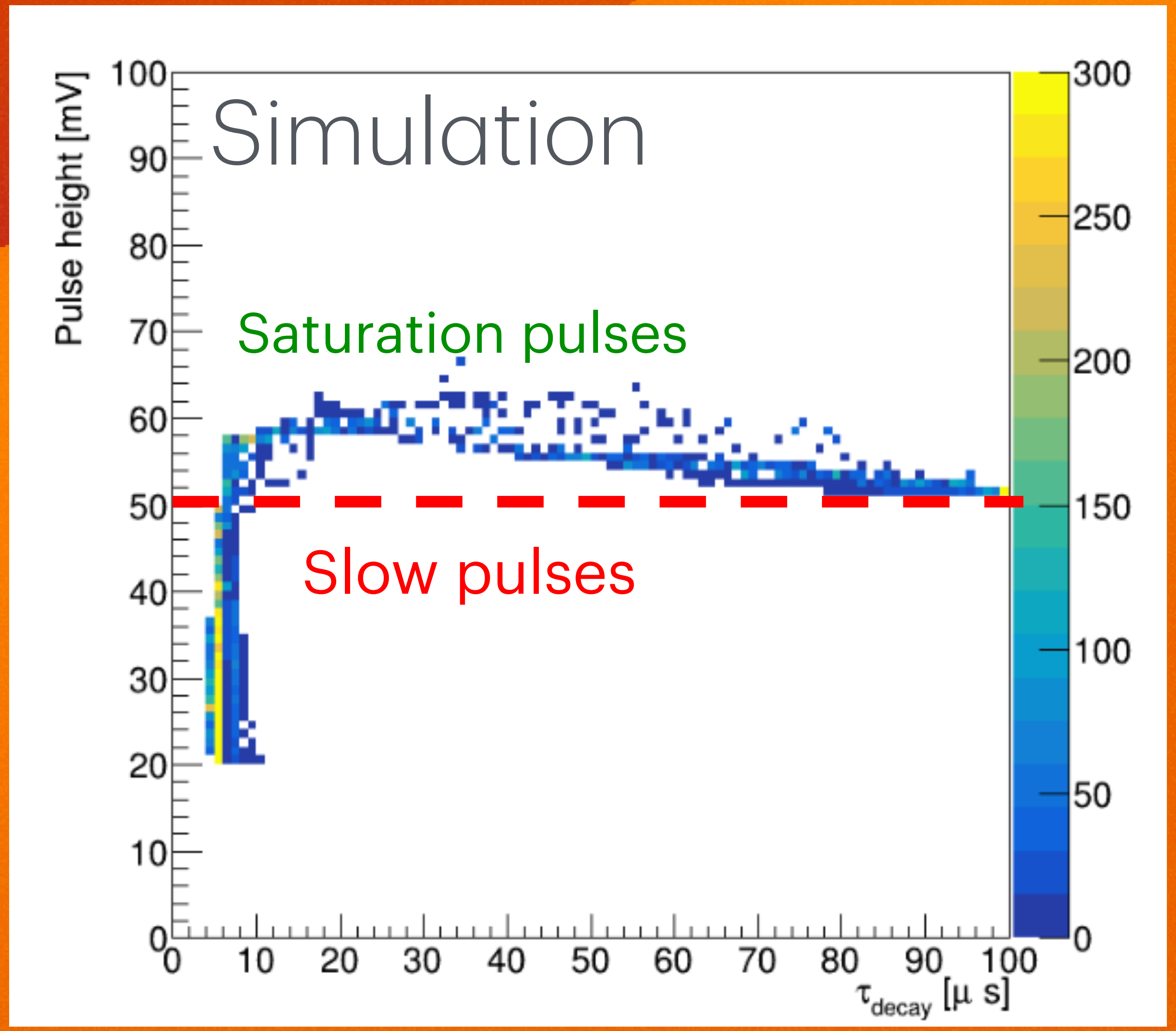


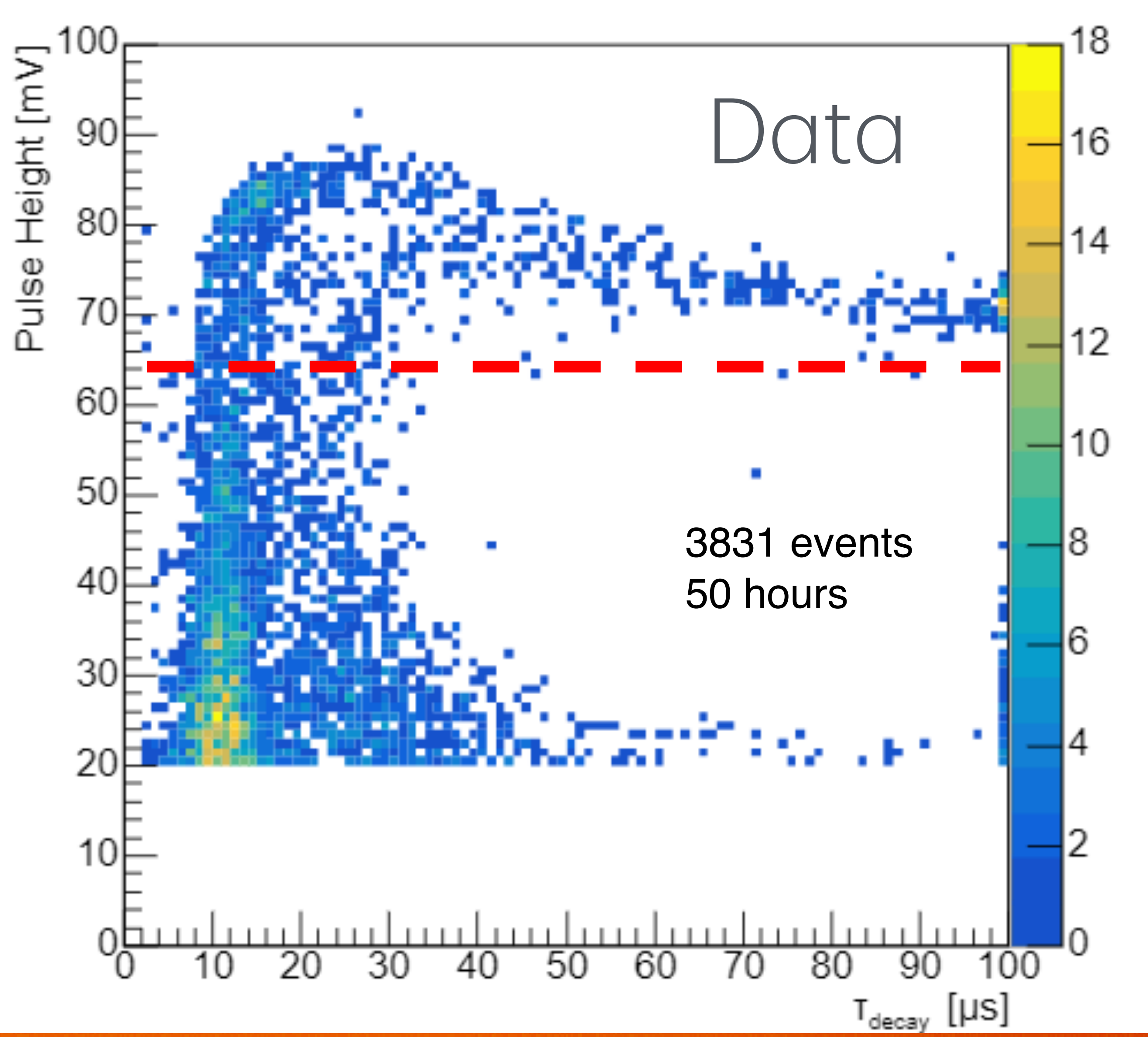
Rates from Geant4 + COMSOL simulation

Zirconia: rate $\in [0.33\ ;\ 2.1] \cdot 10^{-2}$ cps

Muon: rate = $8 \cdot 10^{-5}$ cps

Rate from data: $2.1 \cdot 10^{-2}$ cps

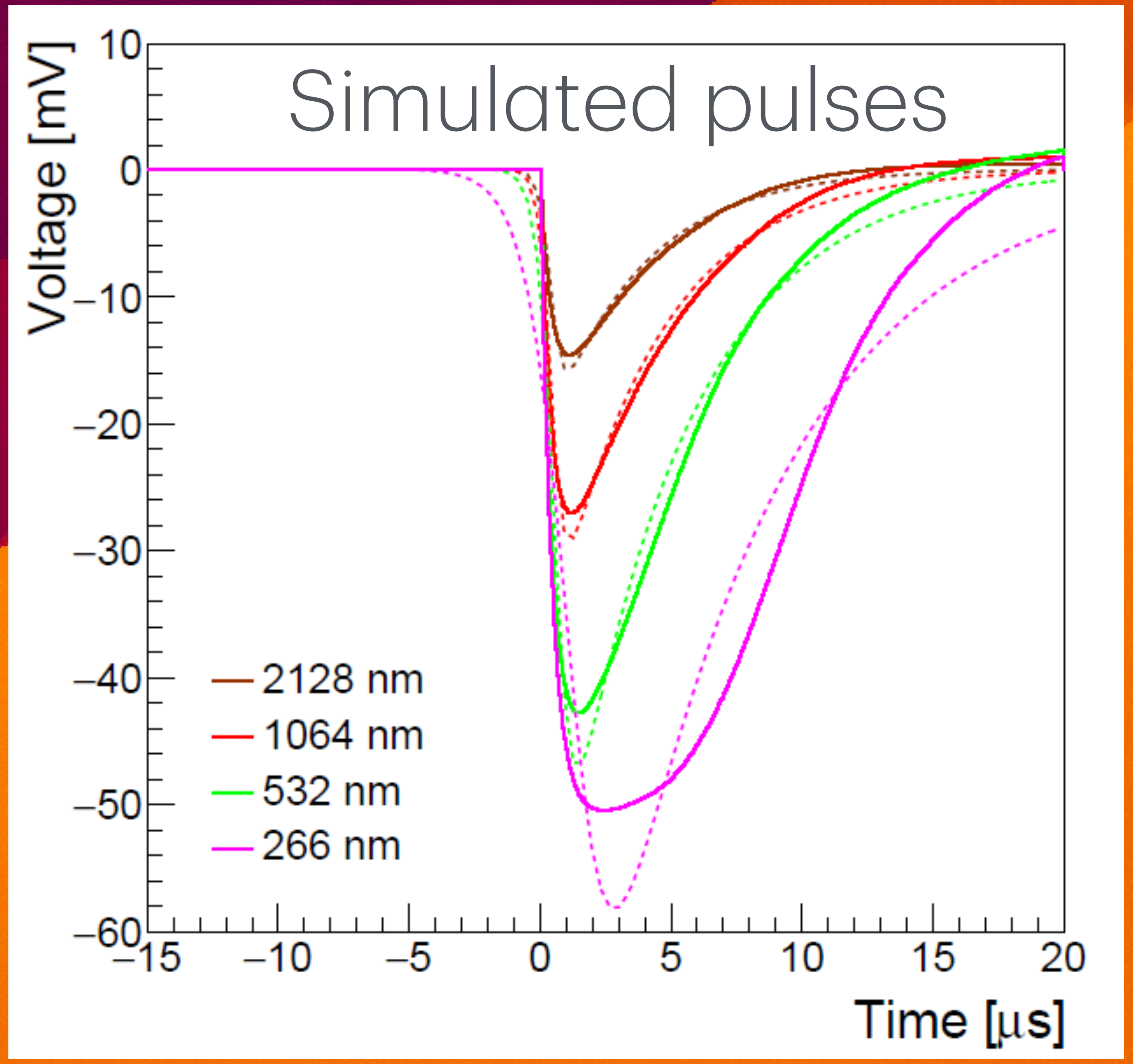


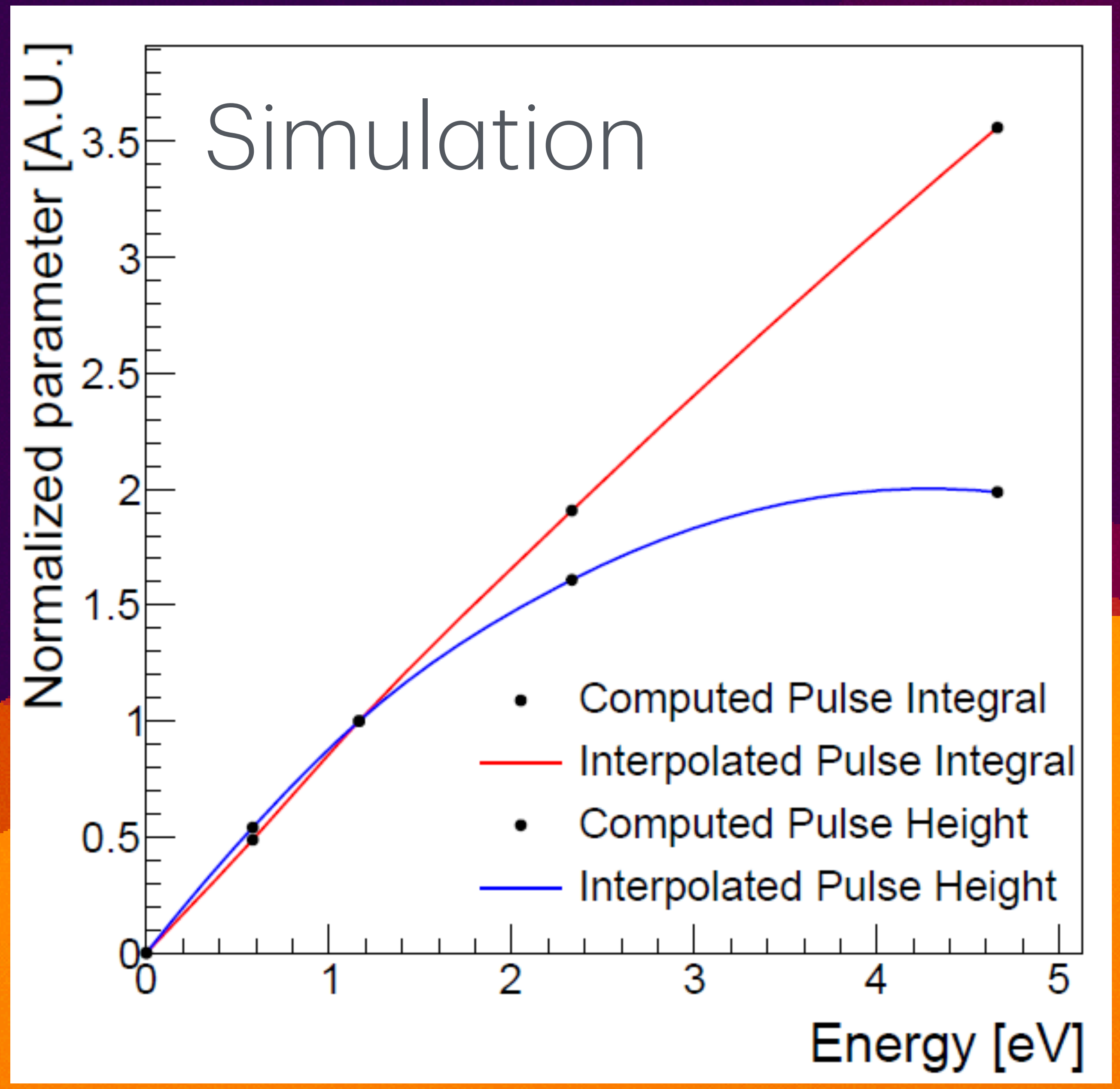


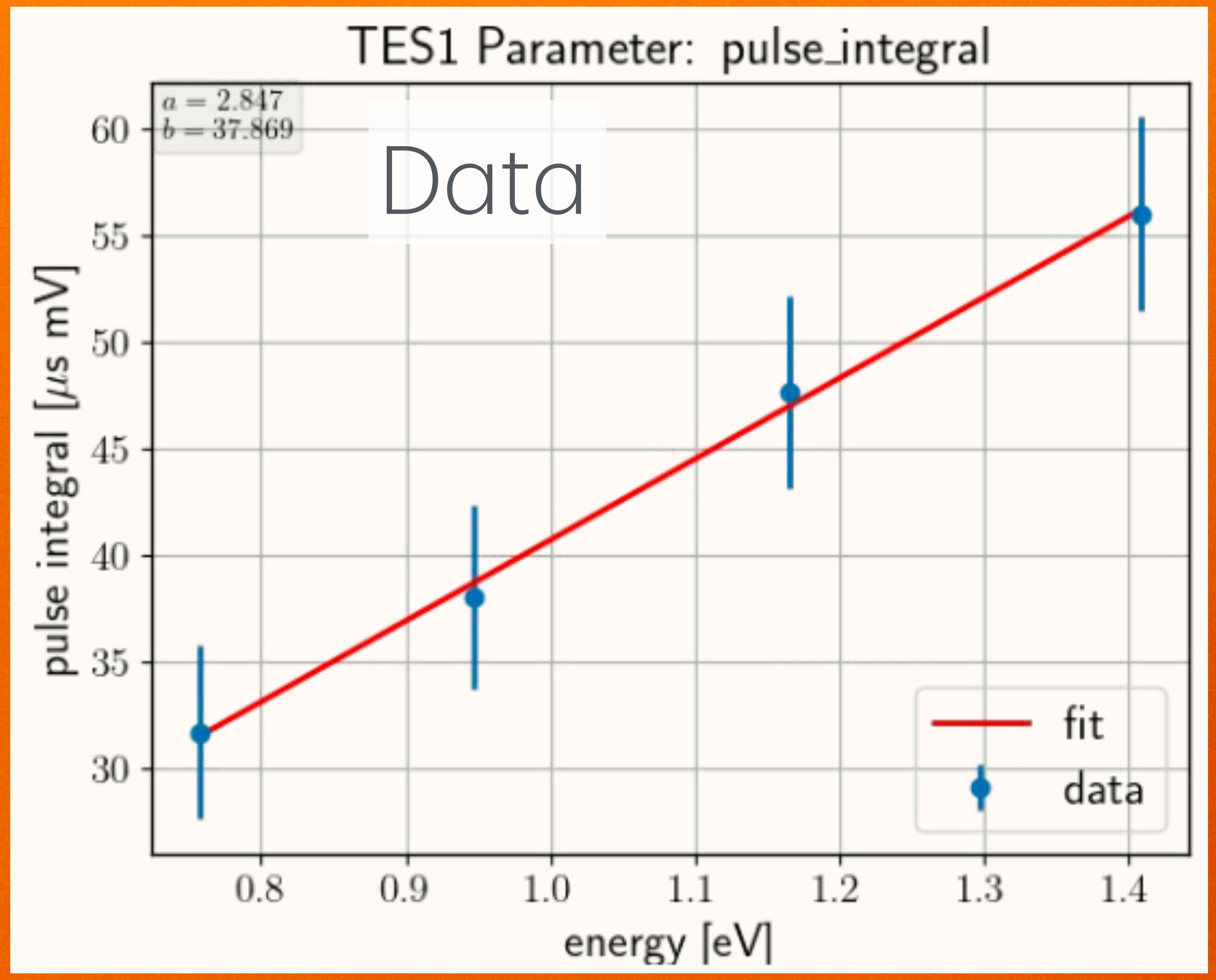
Simulations

Agreement with Calibration

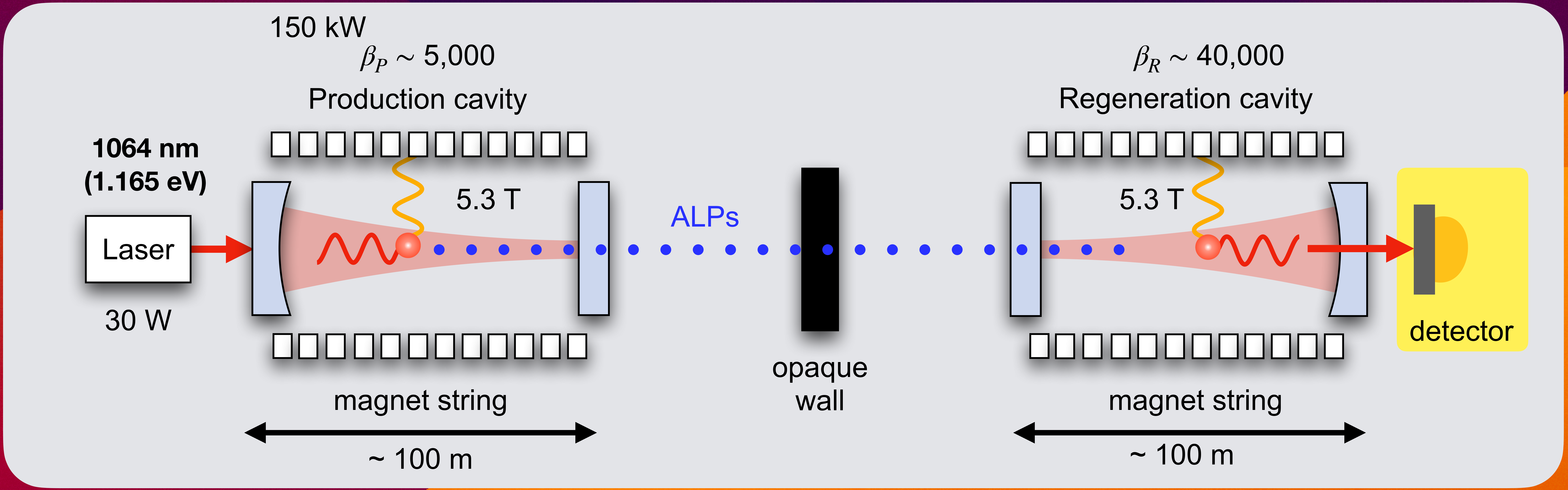
- **Simulations also predict the energy response is linear with the pulse integral**







ALPS II



Graphic from Katharina-Sophie Isleif

- **Using 24 straightened HERA magnets**
- **Fabry-Perot resonators in production *and* regeneration region**
- **150 kW → 10^{-24} W (~1 photon/day)**

$$g_{a\gamma} \sim 2 \times 10^{-11} GeV^{-1}$$

$$N_\gamma = \frac{1}{16}(g_{a\gamma}BL)^4 \frac{\mathscr{P}_i}{\omega} \beta_P \beta_R \tau$$