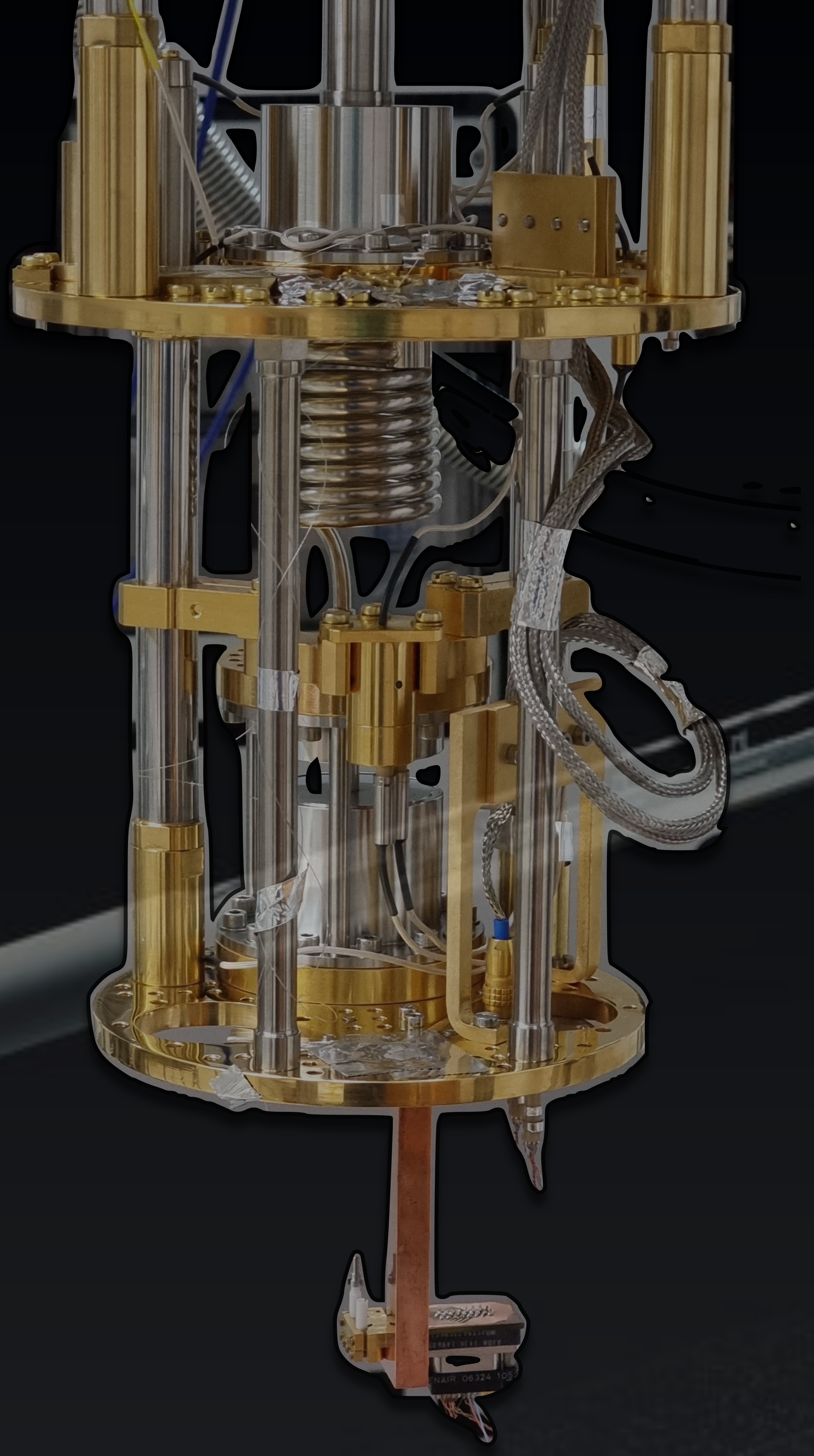


Transition edge sensors for axion searches in ALPS II and beyond

Manuel Meyer[1], Katharina Isleif[2], Friederike Januschek[3], Axel Lindner[3], Gulden Othman[4], José Rubiera Gimeno[3], Elmeri Rivasto[1], Christina Schwemmbauer[3]

[1]CP3 Origins, University of Southern Denmark
[2]Helmut-Schmidt-Universität
[3]Deutsches Elektronen-Synchrotron DESY
[4]Institut für Experimentalphysik, Universität Hamburg

axion-alp-dm.github.io
@me_manu
Manuel Meyer

mey@sdu.dk, September 6, 2024

COST Meeting Istanbul

Outline

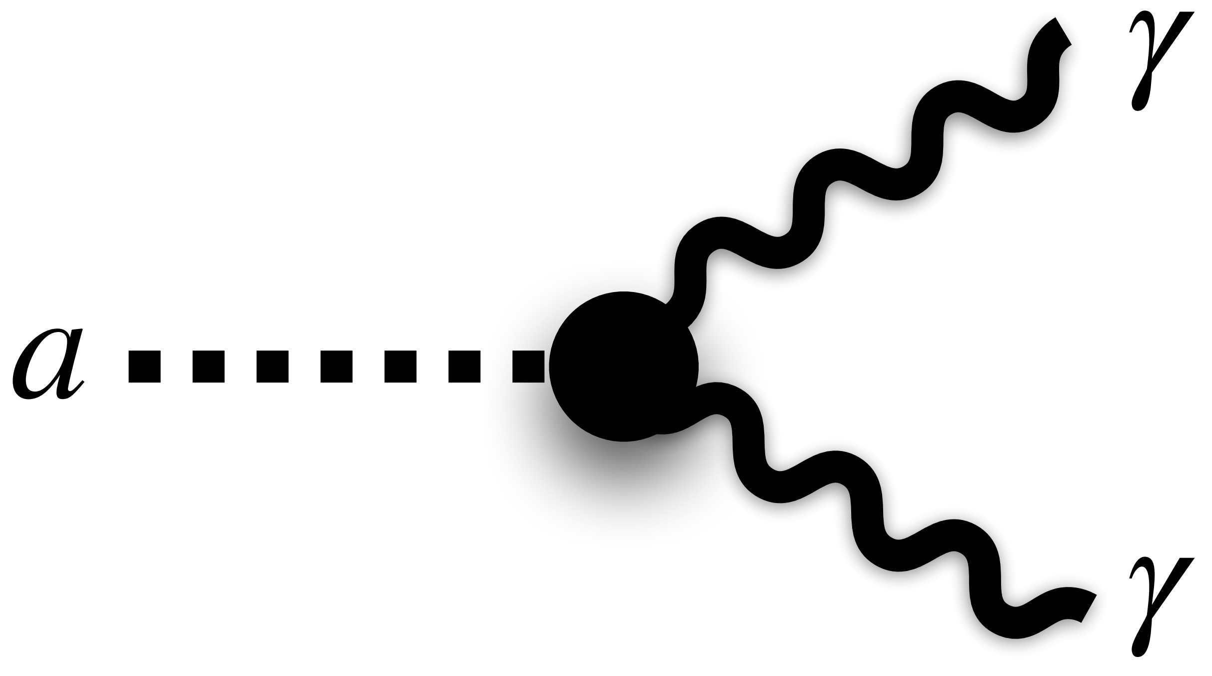
1. The ALPS II experiment
2. The Transition Edge Sensor (TES) detector for ALPS II at DESY
3. Going beyond ALPS II

How to search for the axion / an ALP?

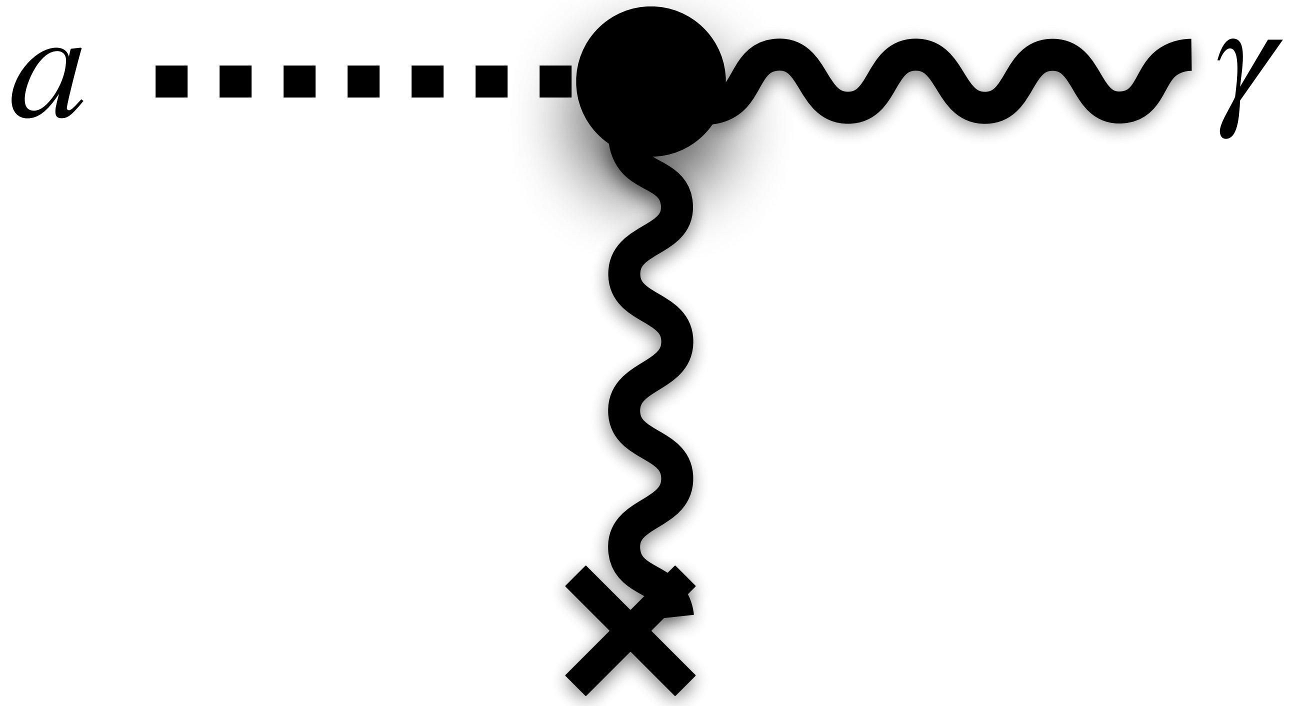
$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma}\, \phi\, F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$g_{a\gamma} = C_{a\gamma} \frac{\alpha}{2\pi f_a}$$

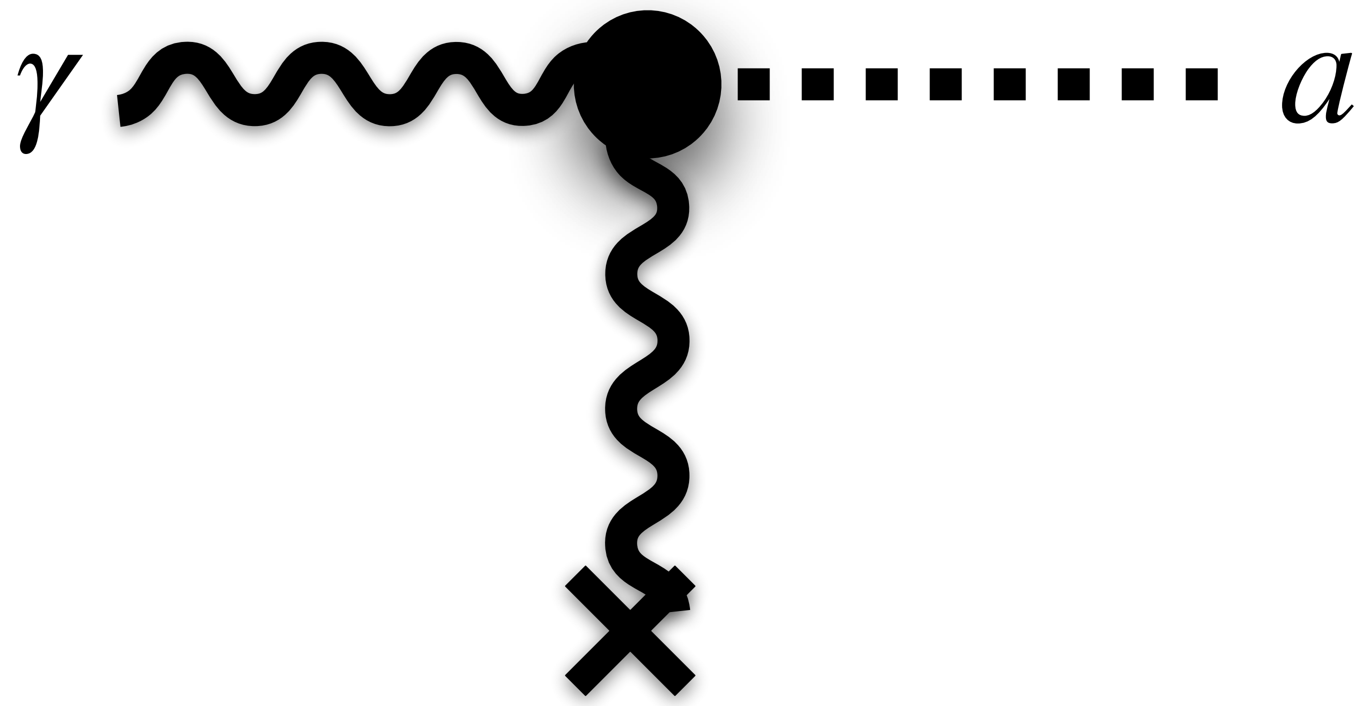
Decay



Sikivie / Inverse Primakoff



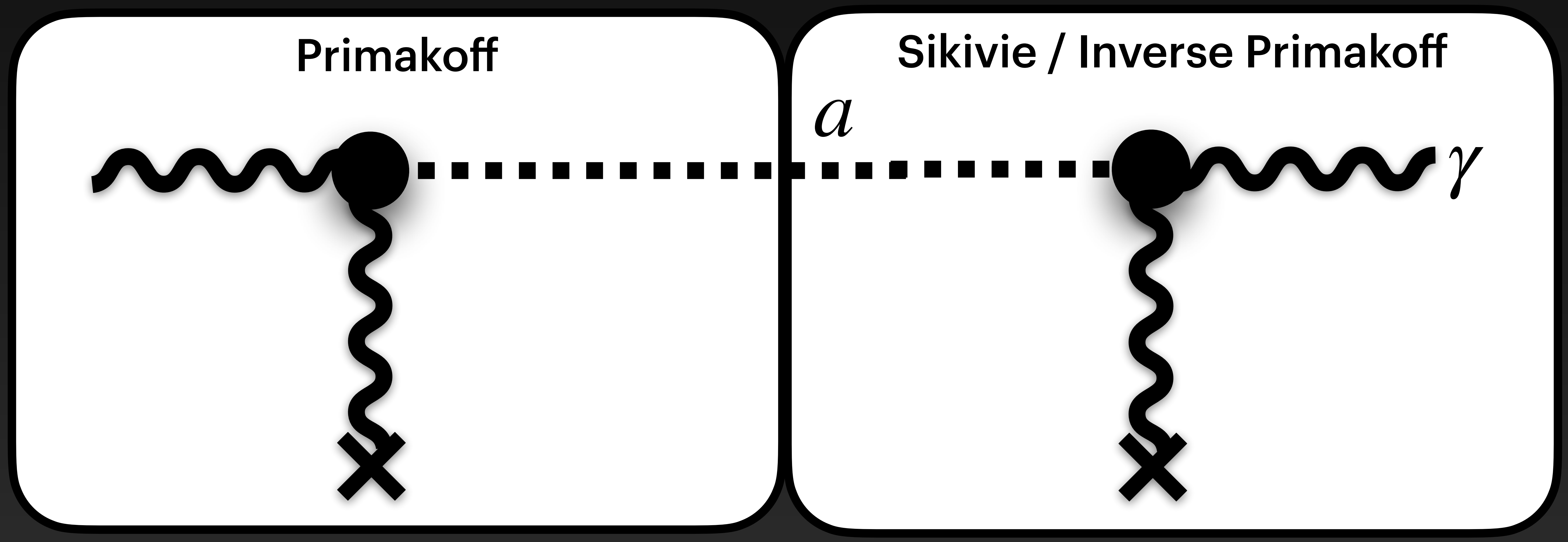
Primakoff



Axion dark matter

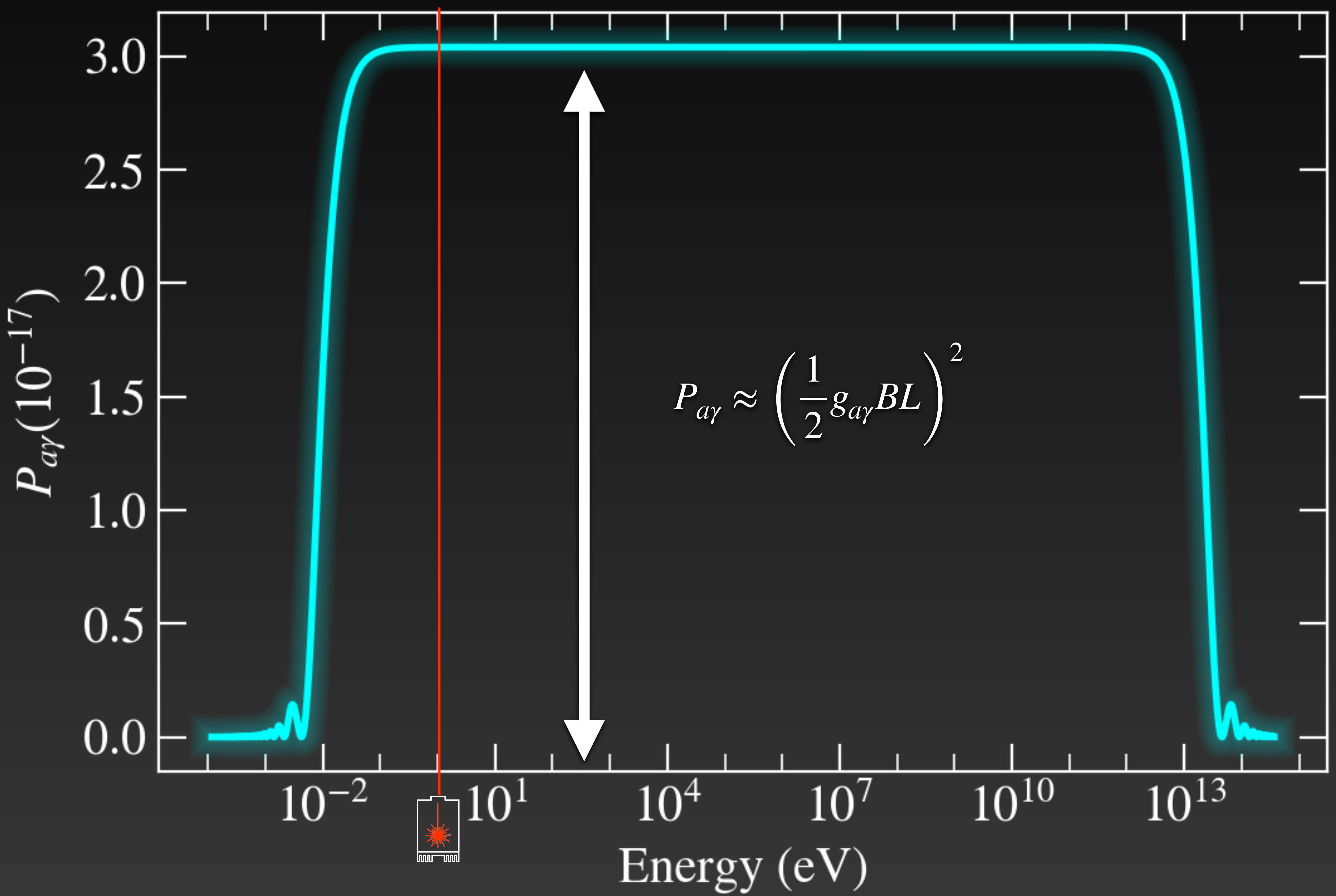
Artificial axion production

Light shining through a wall experiments



Energy dependence of Photon-ALP oscillations

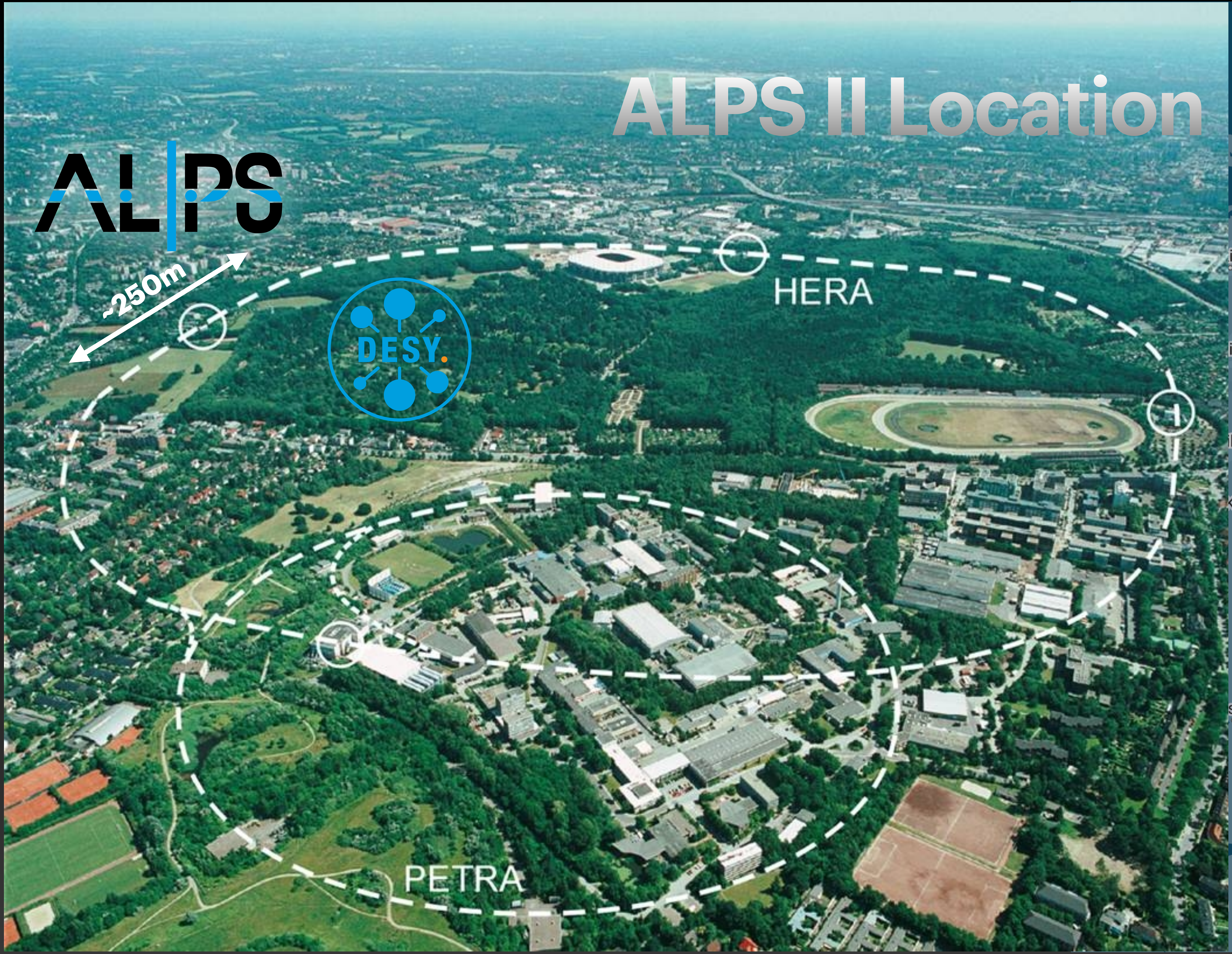
B = 5.3T, L = 12 x 8.8m, $g_{a\gamma} = 2 \times 10^{-11}\,\mathrm{GeV}^{-1}$, $m_a = 10^{-5}\,\mathrm{eV}$

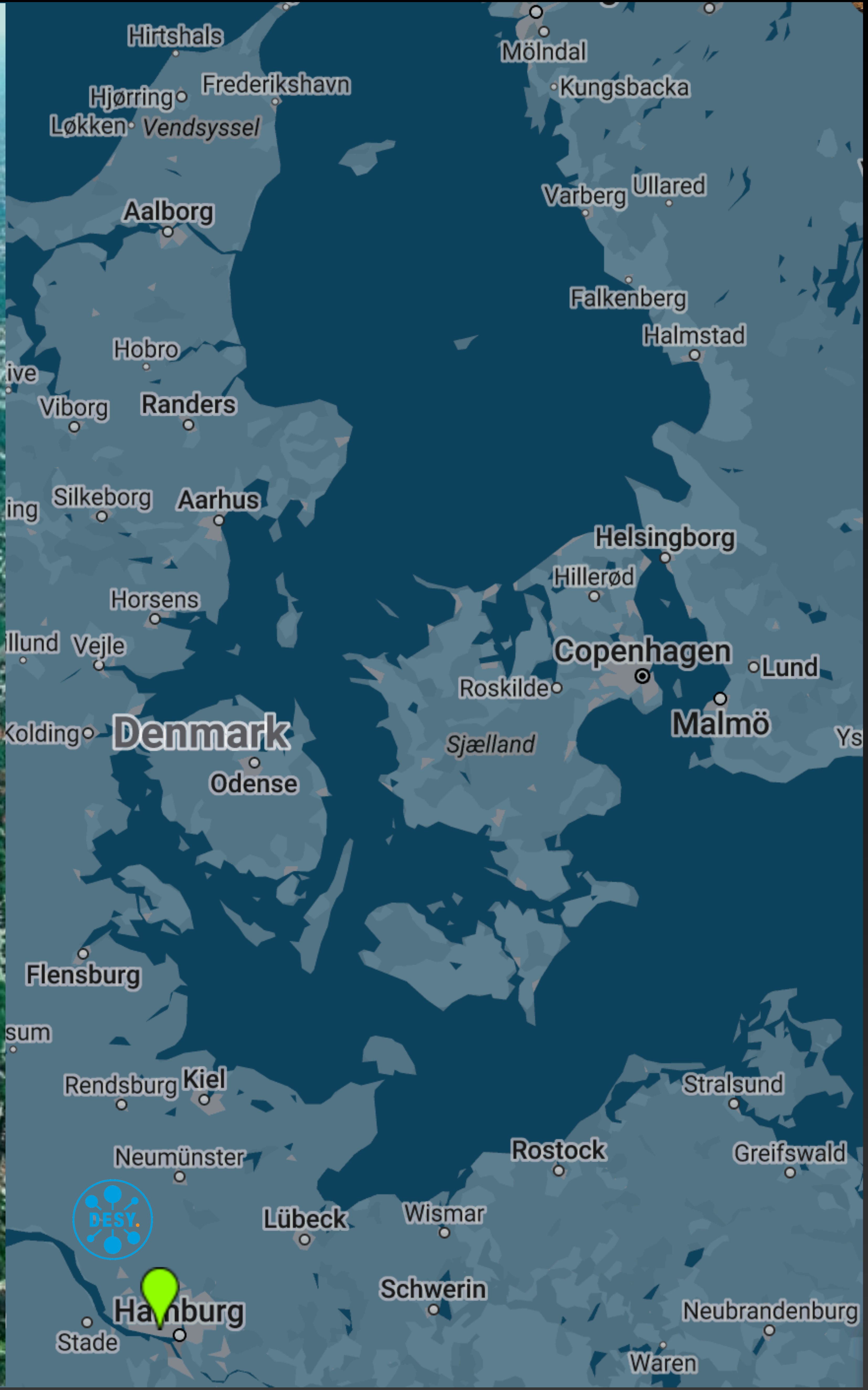


Plot produced with gammaALPs

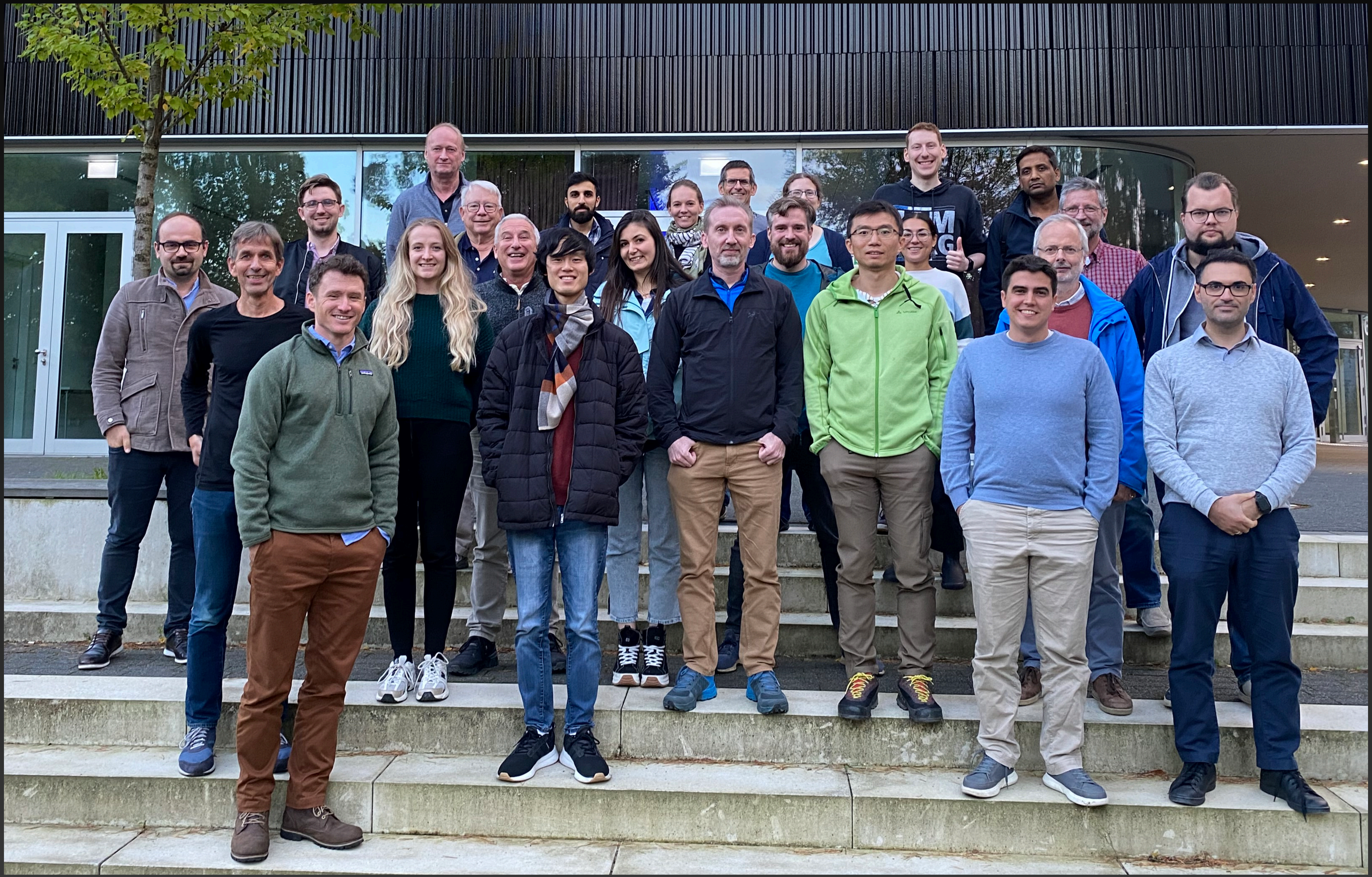
ALPS II Experiment

ALPS II Location



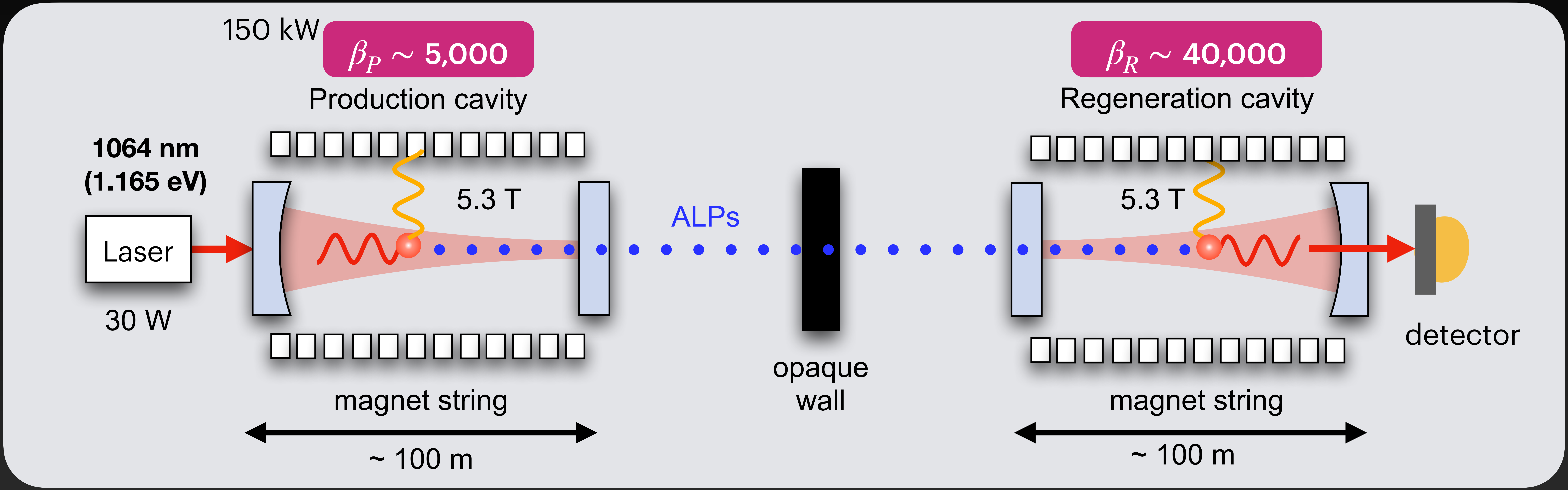


ALPS II Collaboration



ALPS II Collaboration meeting in Hamburg, October 2023

Any Light Particle Search (ALPS) II



Graphic from Katharina-Sophie Isleif

$$N_\gamma = \frac{1}{16}\left(g_{a\gamma}BL\right)^4 \frac{\mathscr{P}_{\text{laser}}}{h\nu} T_{\text{obs}} \, \eta \, \beta_P \beta_R$$

$= P_{a\gamma}^2$

Number of photons hitting wall

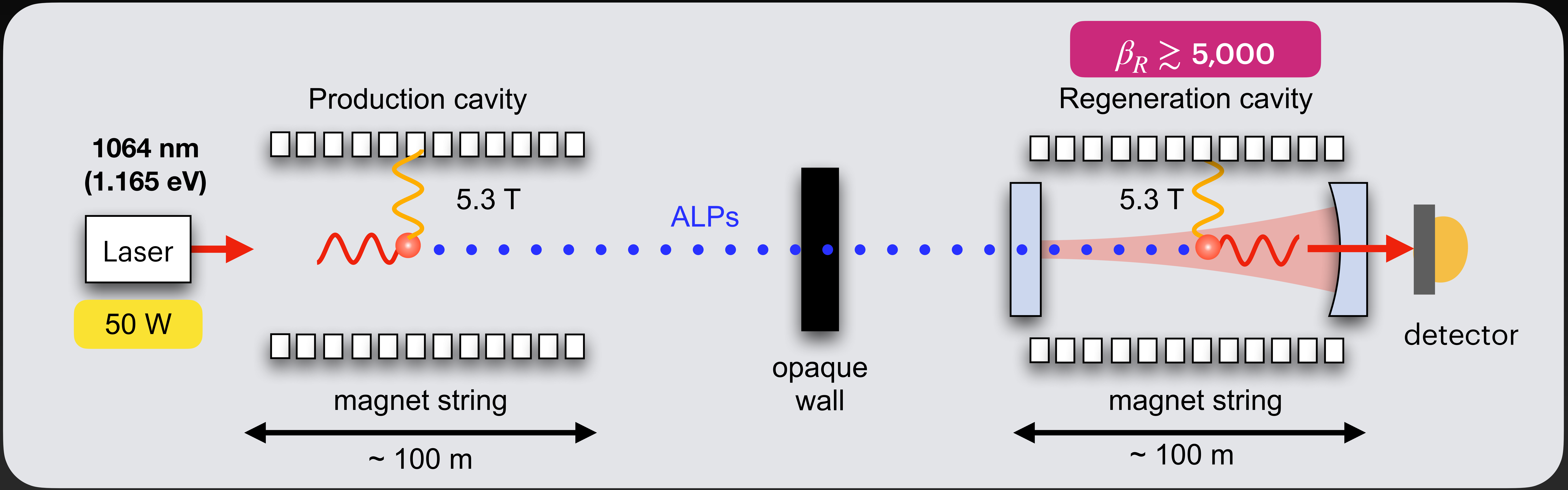
Detector efficiency

$g_{a\gamma} \sim 2 \times 10^{-11}\,\text{GeV}^{-1} \rightarrow$ 1 photon / day

- Using 24 straightened HERA magnets
- Fabry-Perot resonators in production *and* regeneration region

First science run started in May 2023

Axel Lindner (DESY) ALPS II Spokesperson



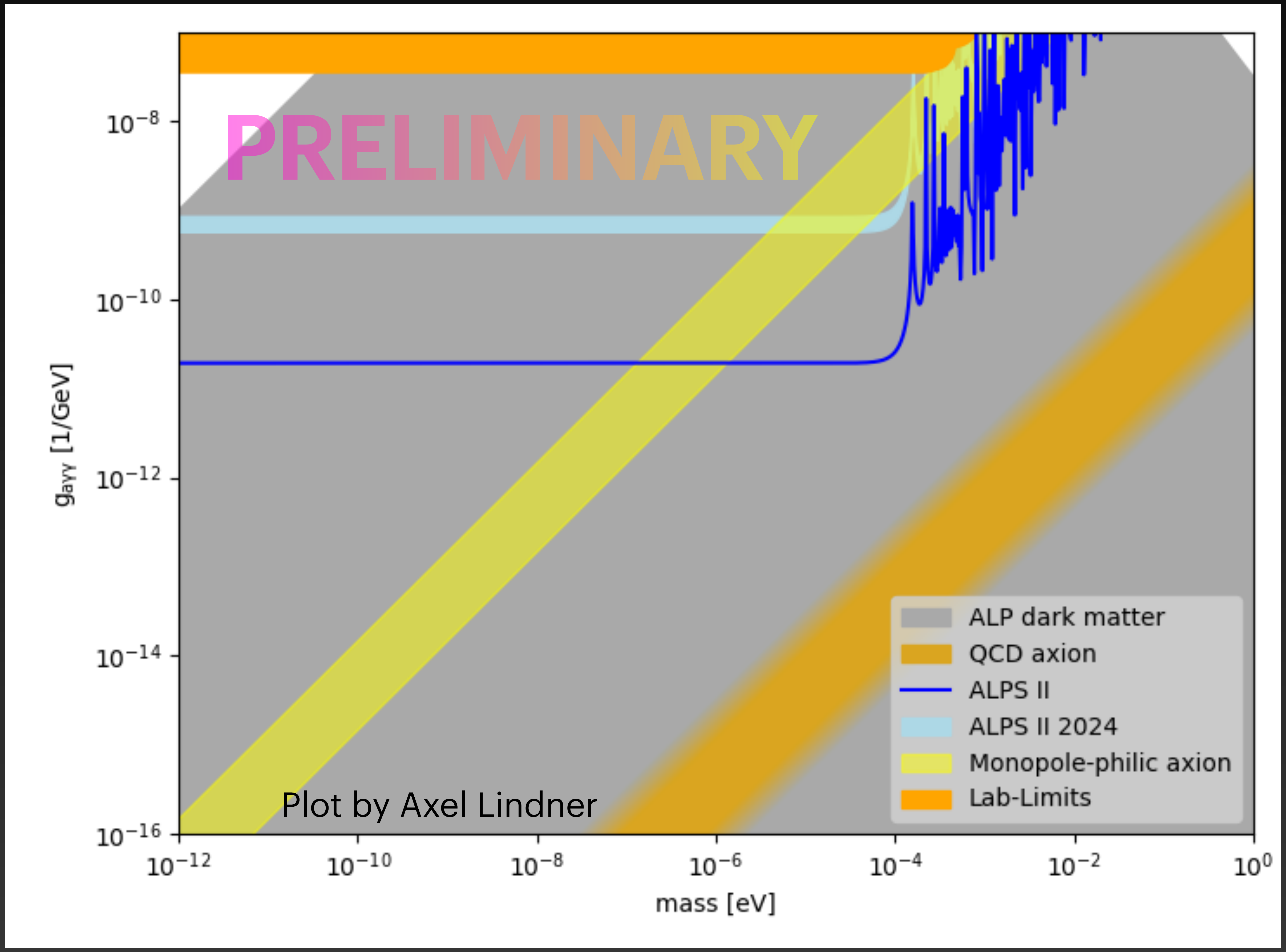
Graphic from Katharina-Sophie Isleif

Commissioning optical setup without production cavity

- Simpler control scheme
- Stronger signals for stray light hunting
- Heterodyne (HET) Detector

Preliminary ALPS II sensitivities

Initial science run for scalar and pseudo-scalar particles completed



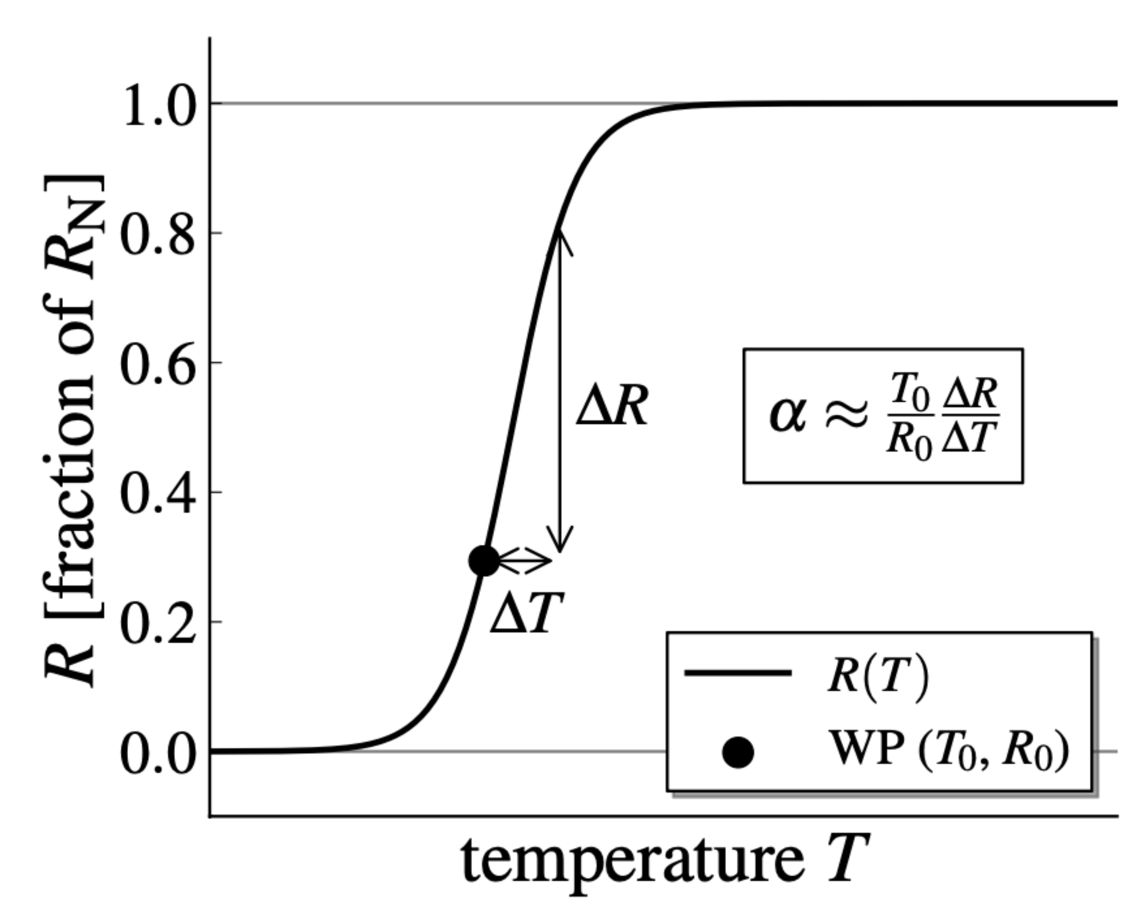
Next steps:

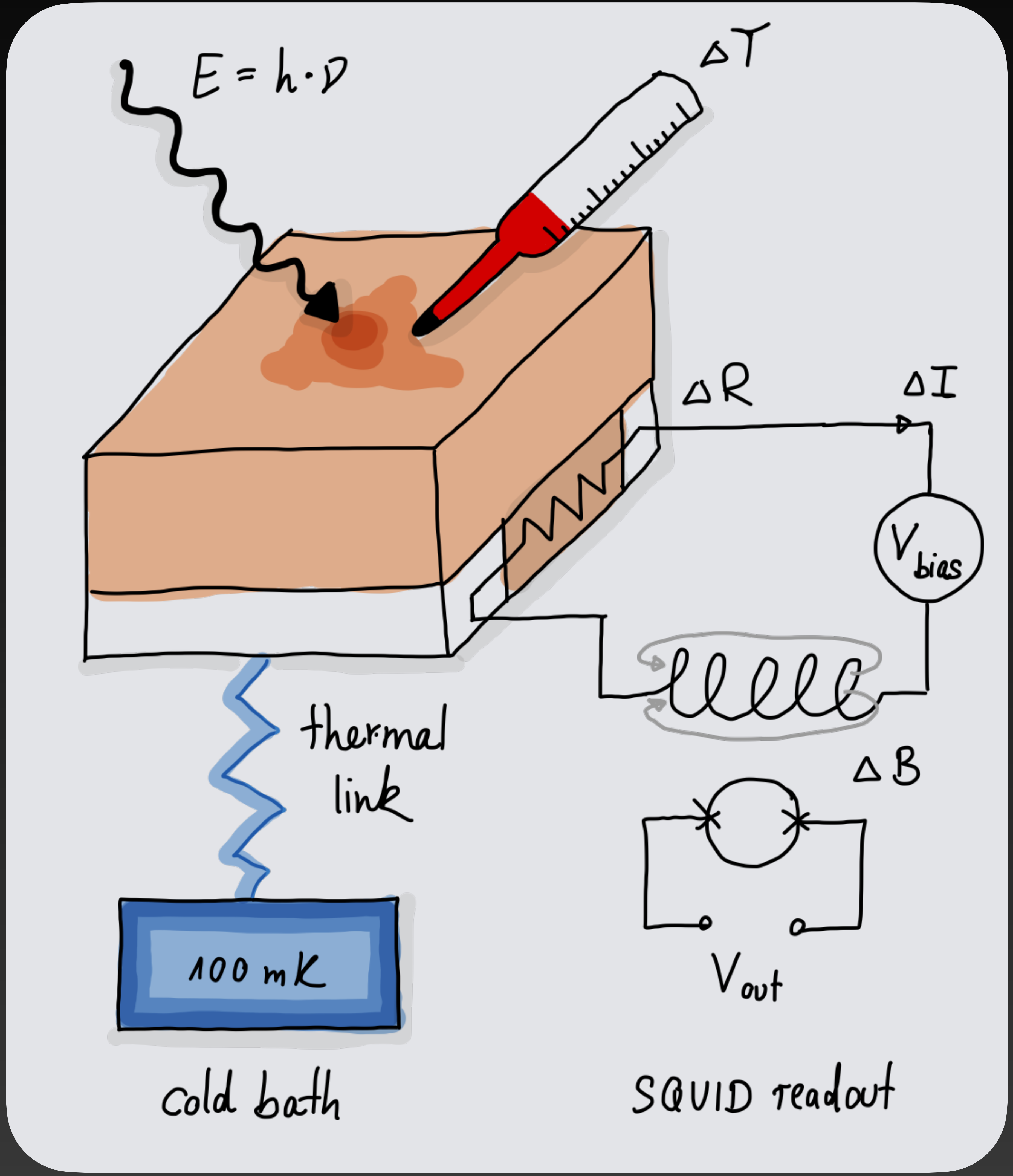
- Installation of production cavity
- Upgrade optics
- Full science run
- Possible full science run with alternative detector
(depending on initial results and funding)

See also Aaron Spector's talk at
Axions beyond the dark matter paradigm Conference
January 2024

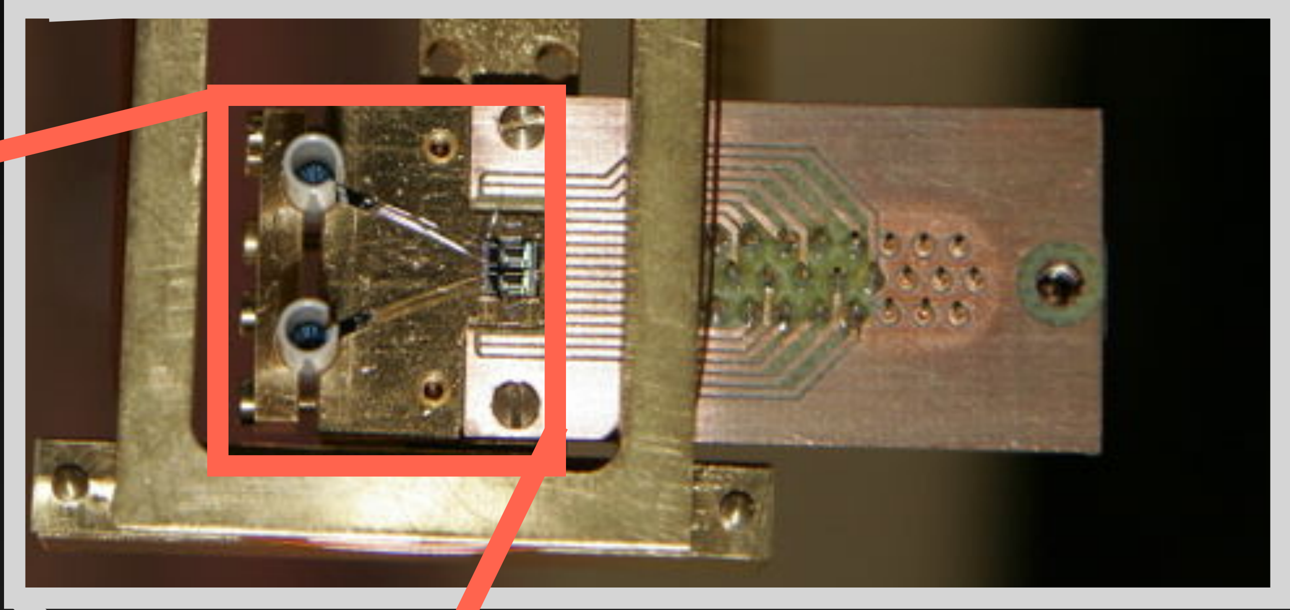
Transition Edge Sensor

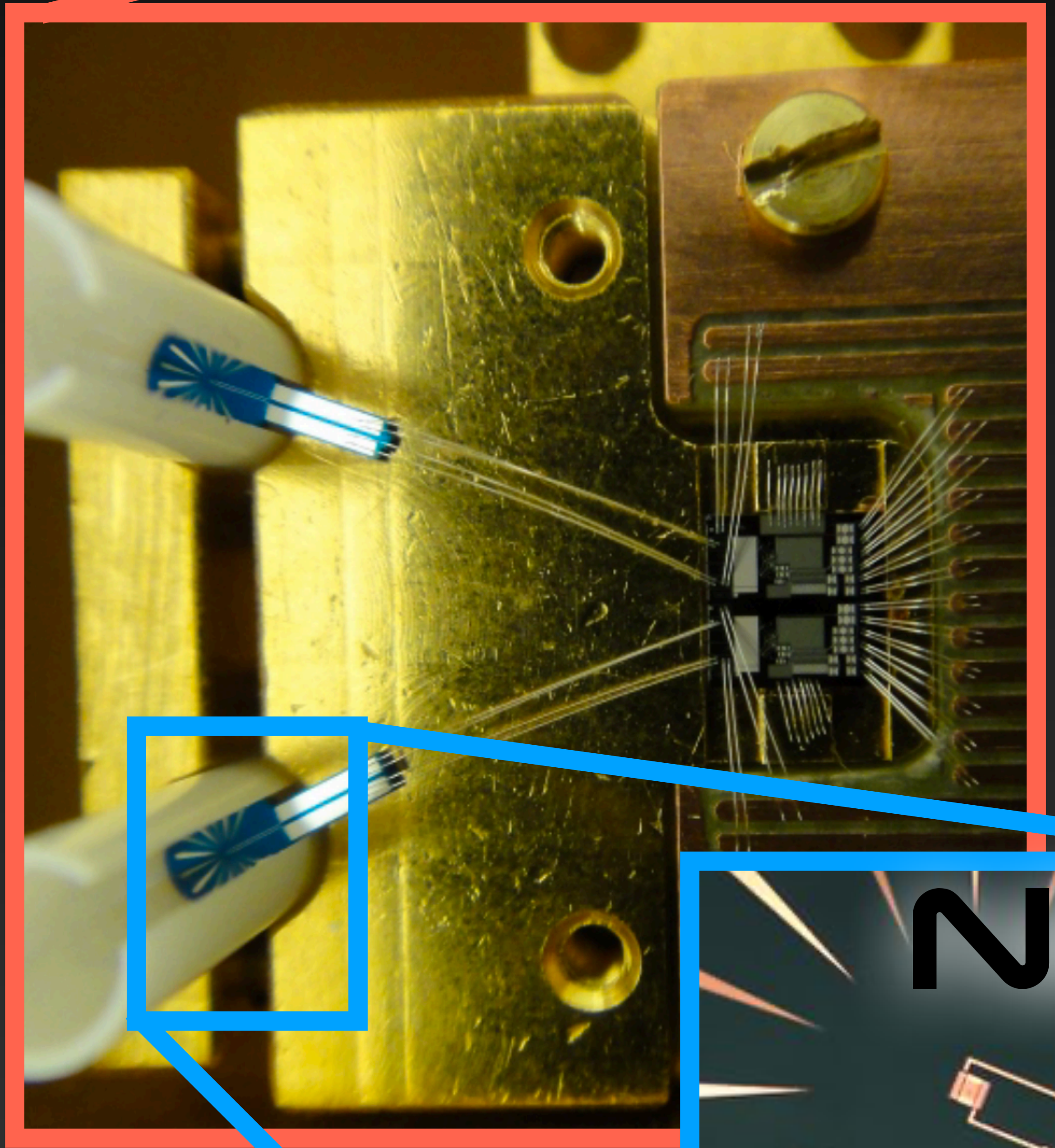
- Superconducting single photon detector
- Demonstrated quantum efficiency: $\gtrsim 95\,\%$ at near infrared
  [Lita et al. 2008]
- Demonstrated low dark current $\lesssim 10^{-5}\,\mathrm{Hz}$
  [Shah et al. 2022]

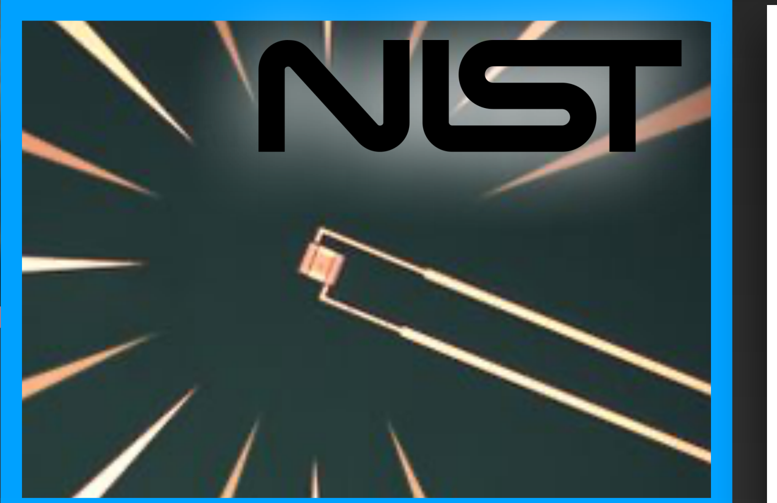




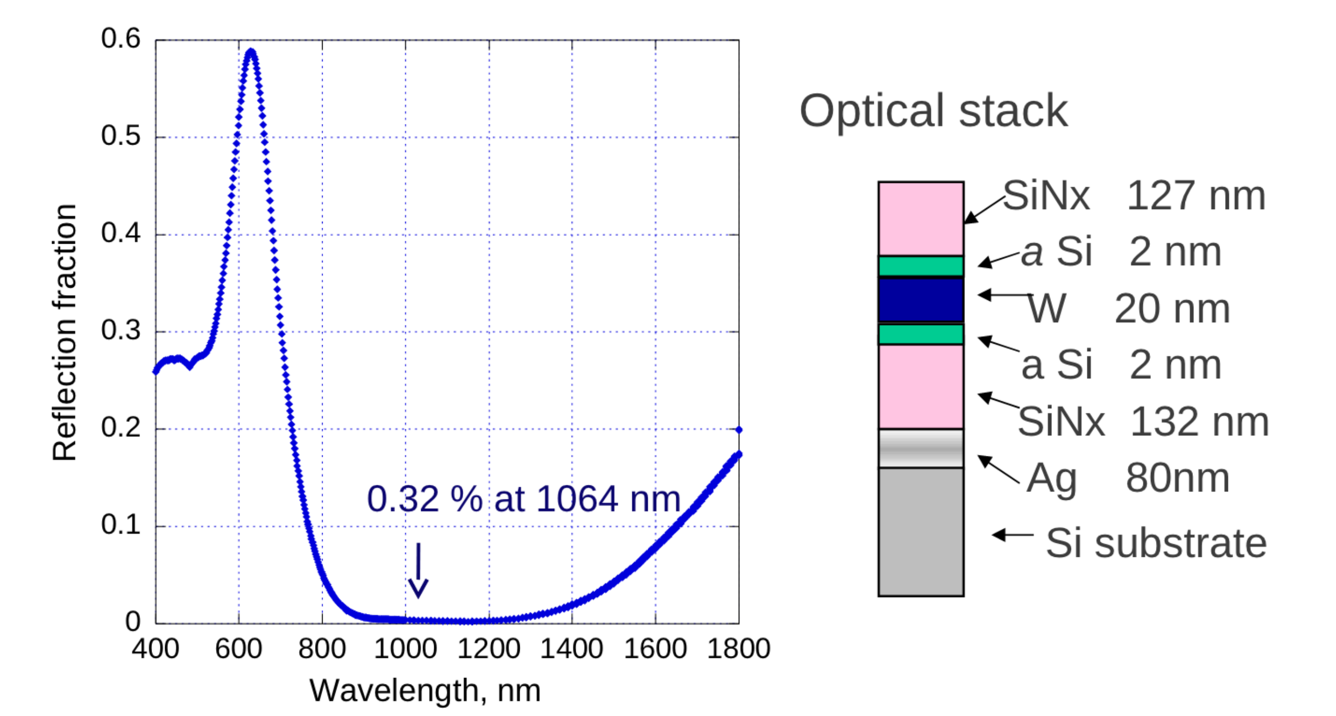
Transition Edge Sensor

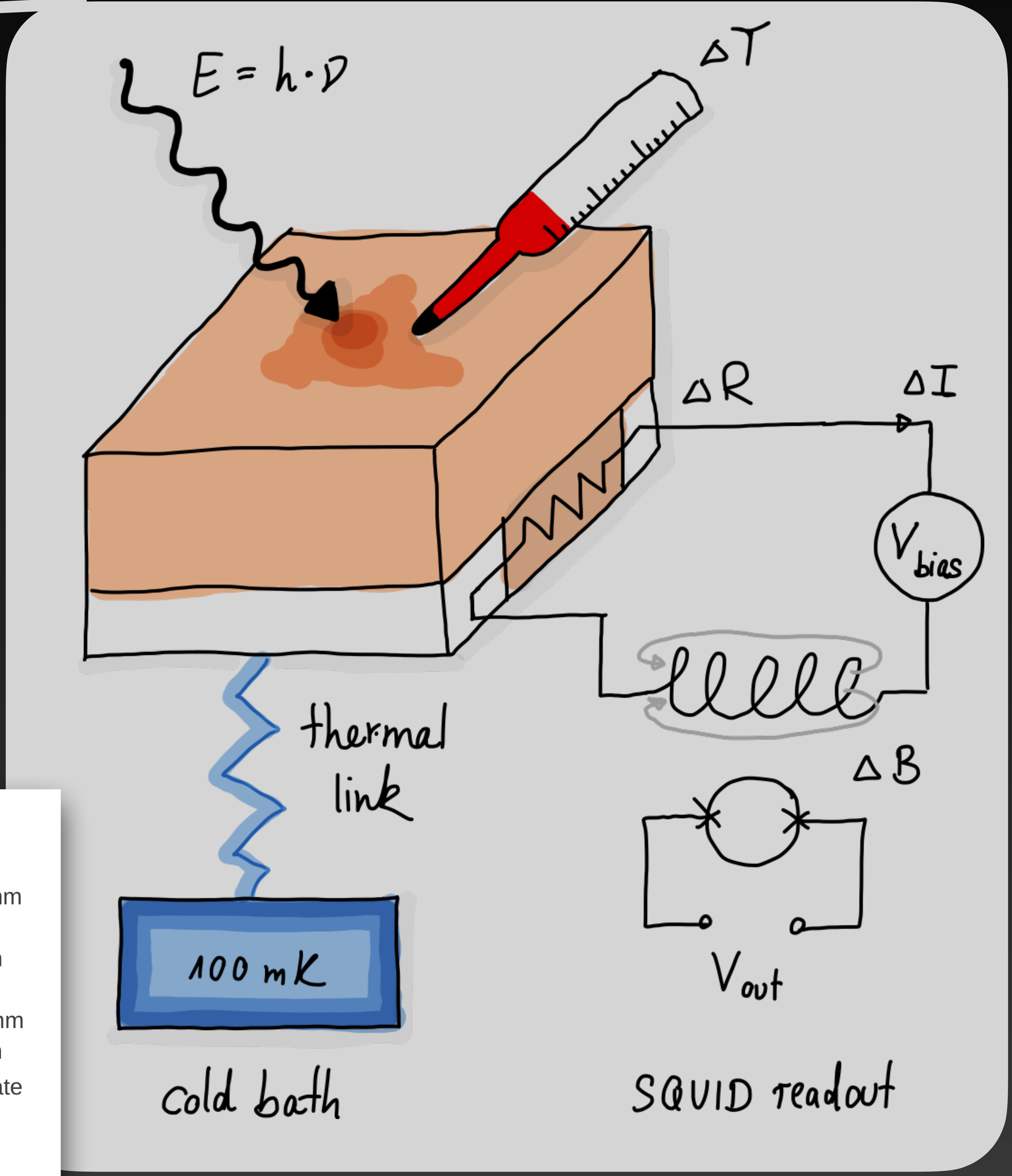




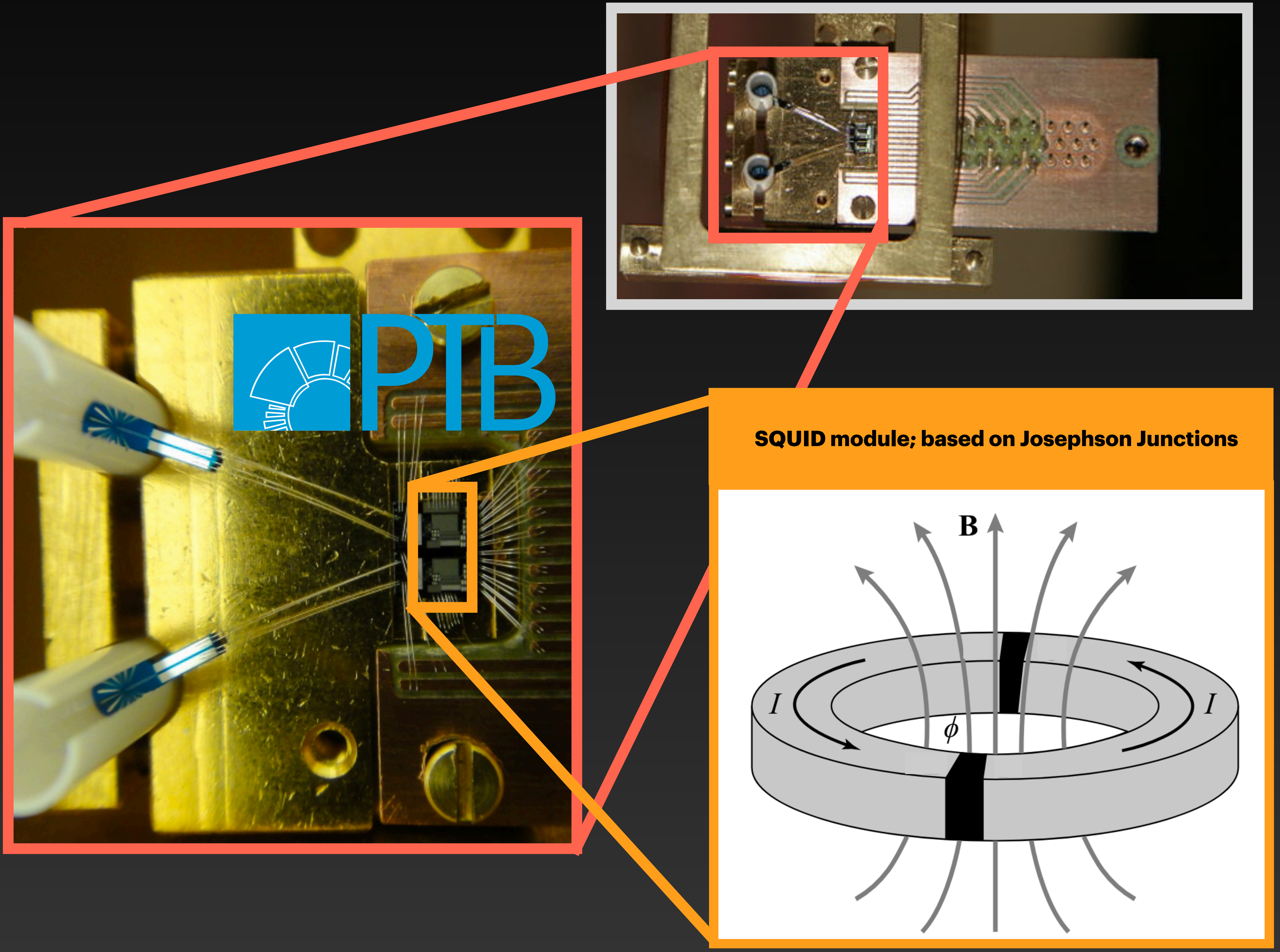


Tungsten microchip, superconducting transition at $T_C \sim 140$ mK
(25 µm x 25 µm x 20nm)





Transition Edge Sensor

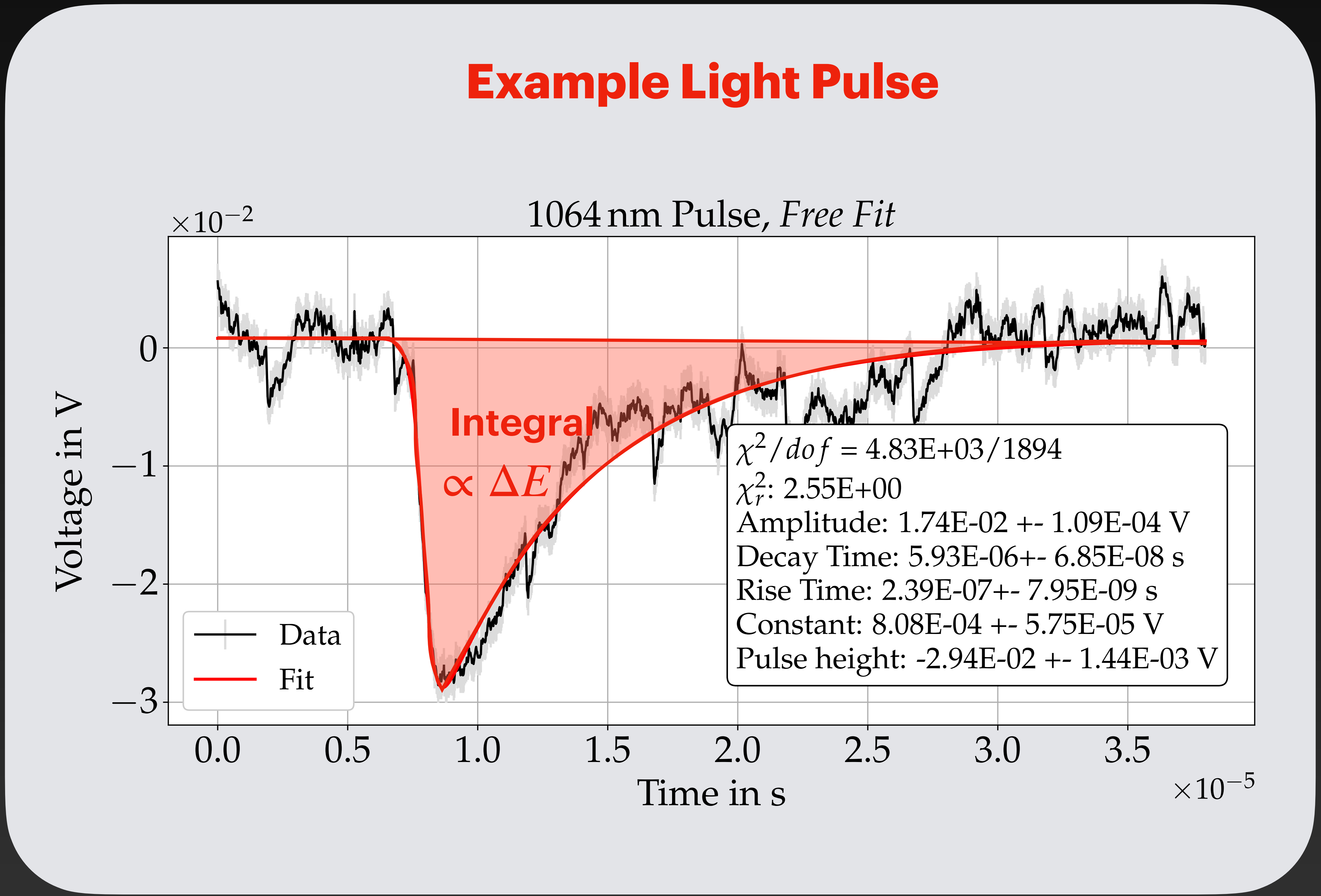


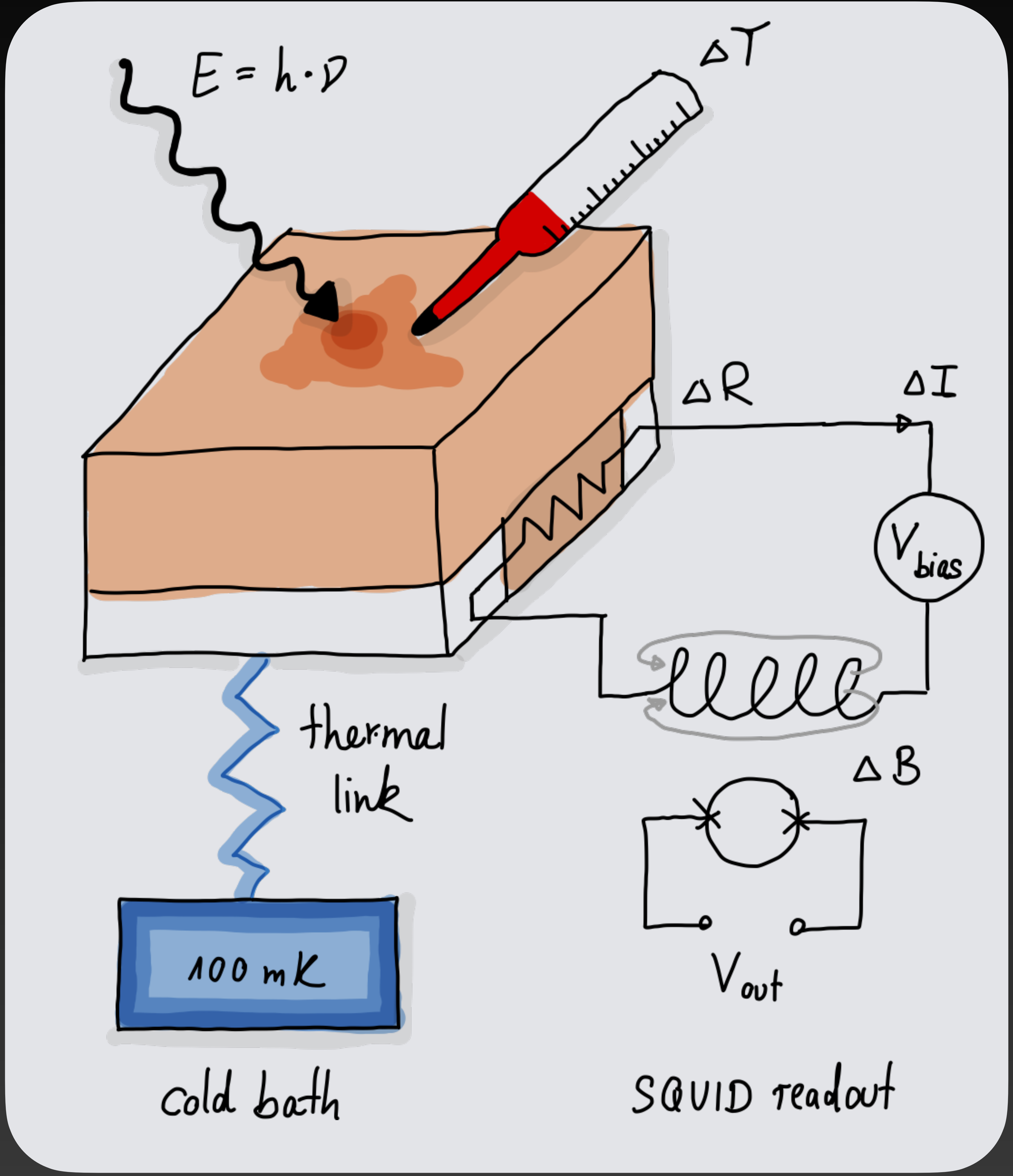
- Tunneling current through junctions experiences phase shift in presence of external magnetic field:

$$\delta^{\mathrm{mag}} = \frac{2e}{\hbar} \oint \mathbf{A} \cdot d\mathbf{l} = \frac{2e}{\hbar} \int_S \mathbf{B} ds = 2\pi \frac{\Phi}{\Phi_0}$$

- Makes SQUIDs extremely sensitive magnetometers sensitive to $\lesssim 1 \text{ nT}$

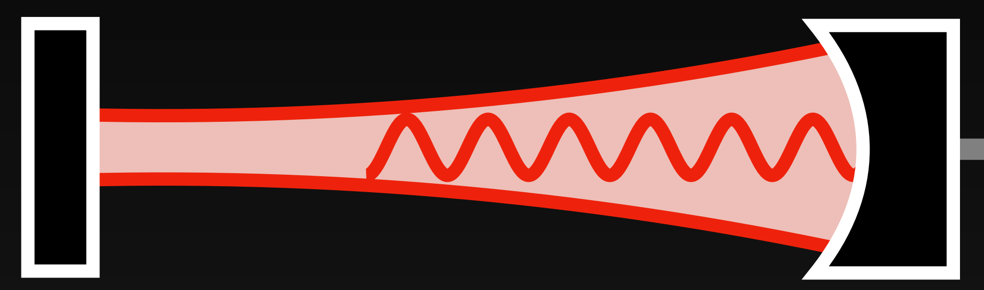
Single photon pulses



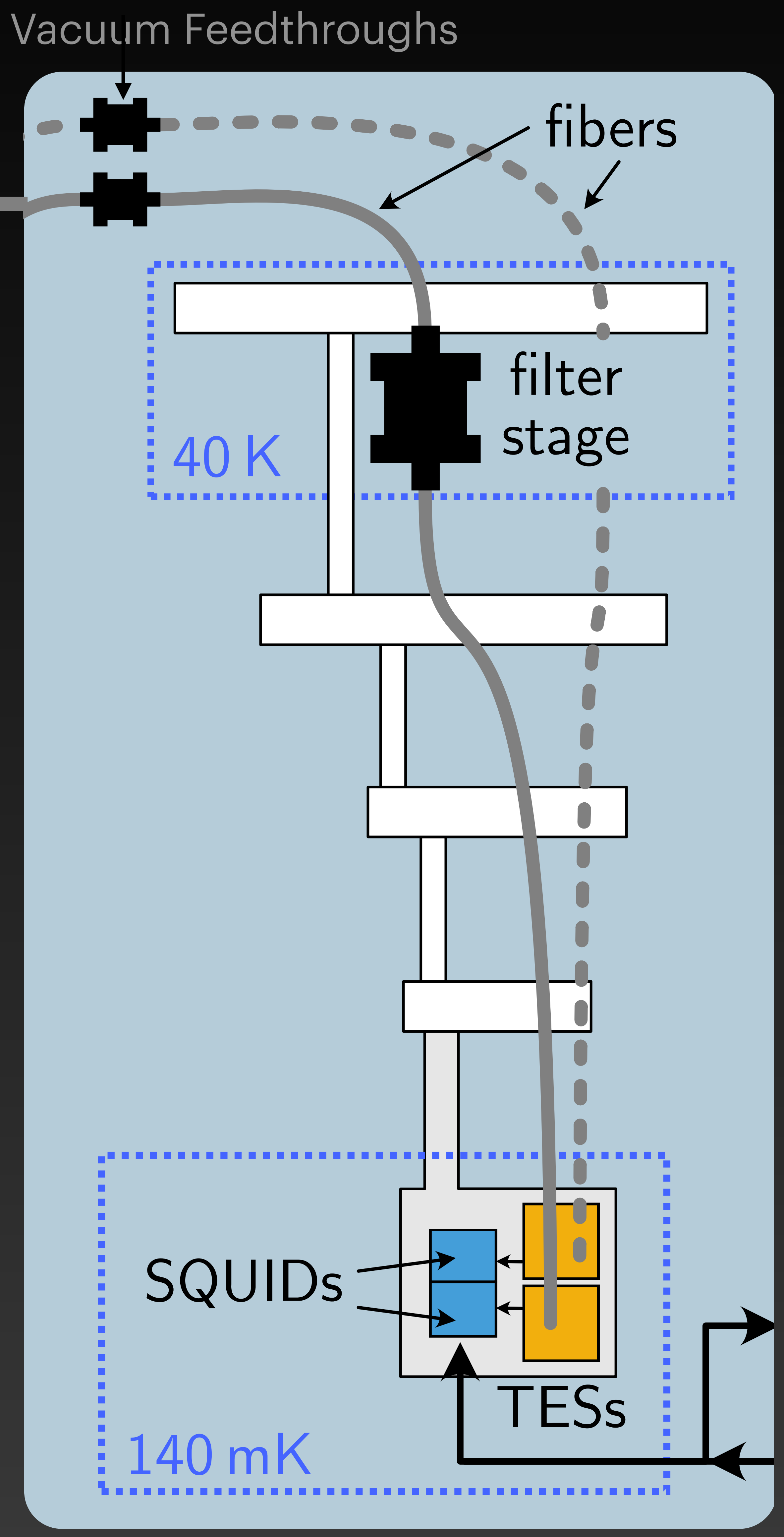


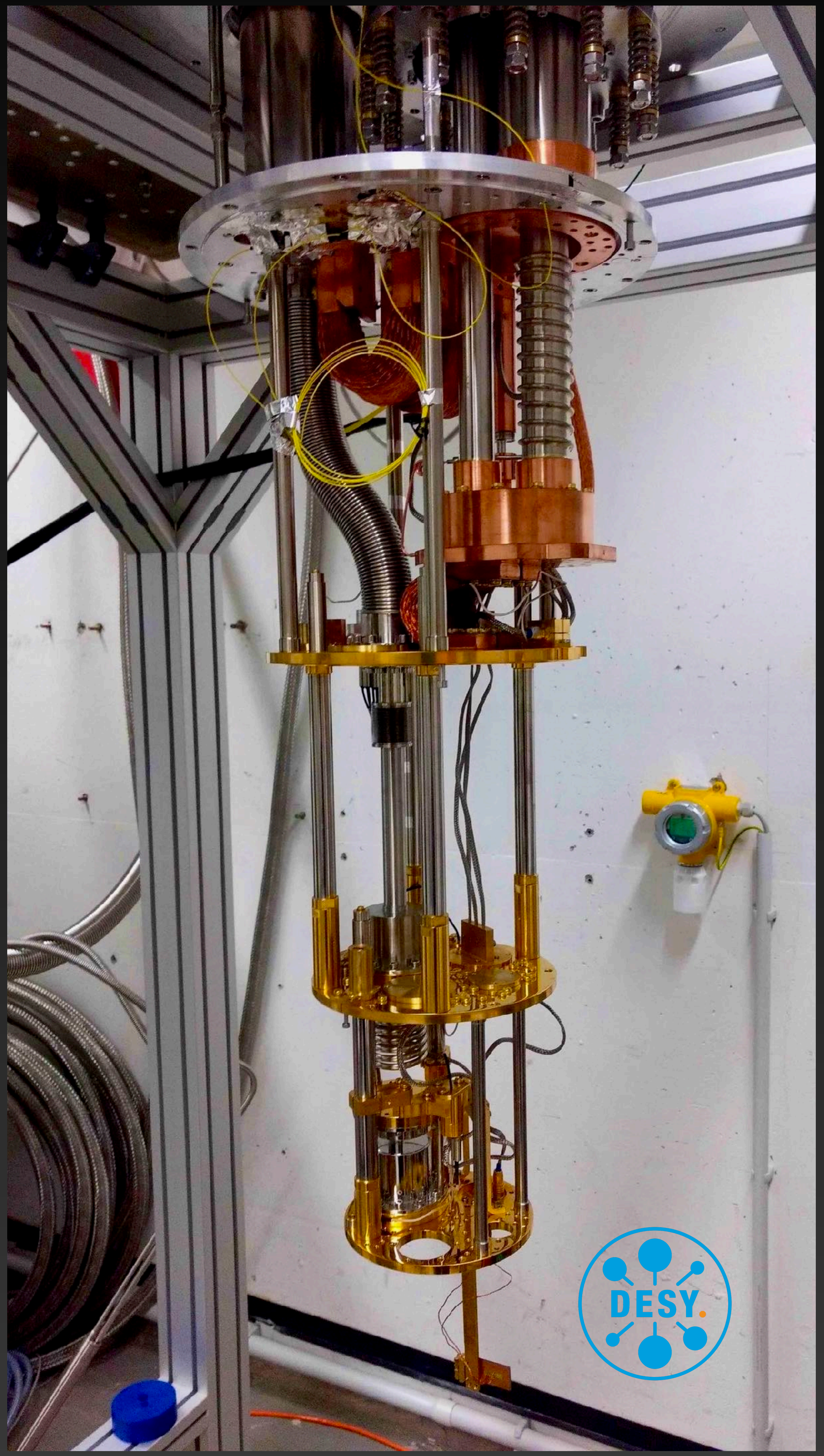
Experimental Setup at DESY

Friederike Januschek
TES team lead
at DESY



Optical Fiber
from ALPS II

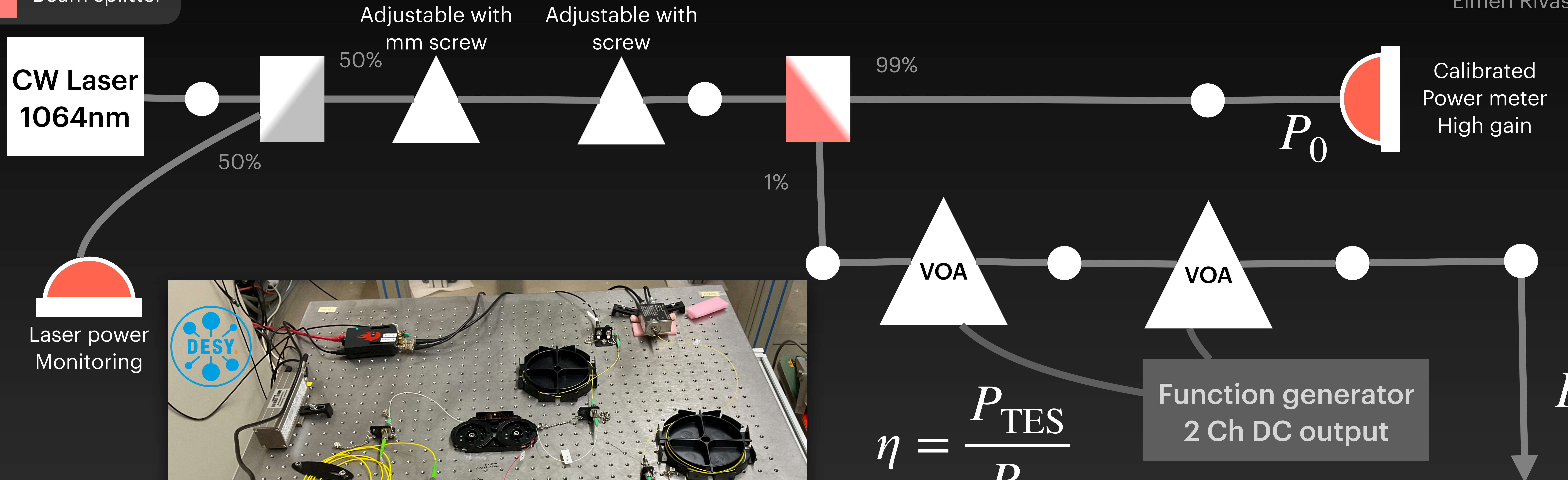


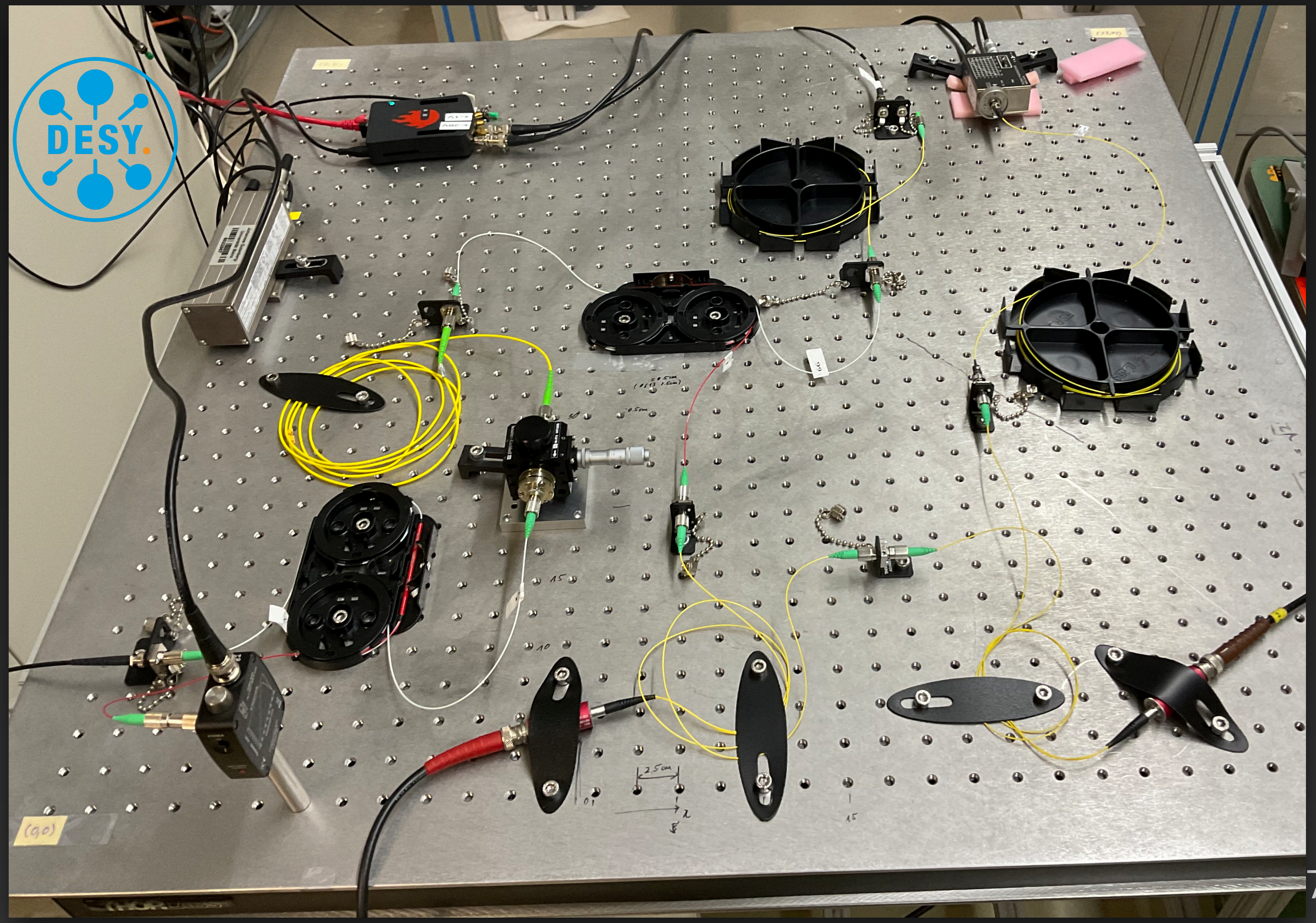


- Operate TES and SQUID electronics in a Dilution Refrigerator
- BlueFors SD system, reaching base temperature of $T \lesssim 30\,\mathrm{mK}$
- **Current:** For initial characterization, optical fibers from reference 1064 nm laser
- **Future:** Optical fibers from the ALPS II setup

Determining the system detection efficiency

UHH and SDU Post docs
Gulden Othman
Elmeri Rivasto





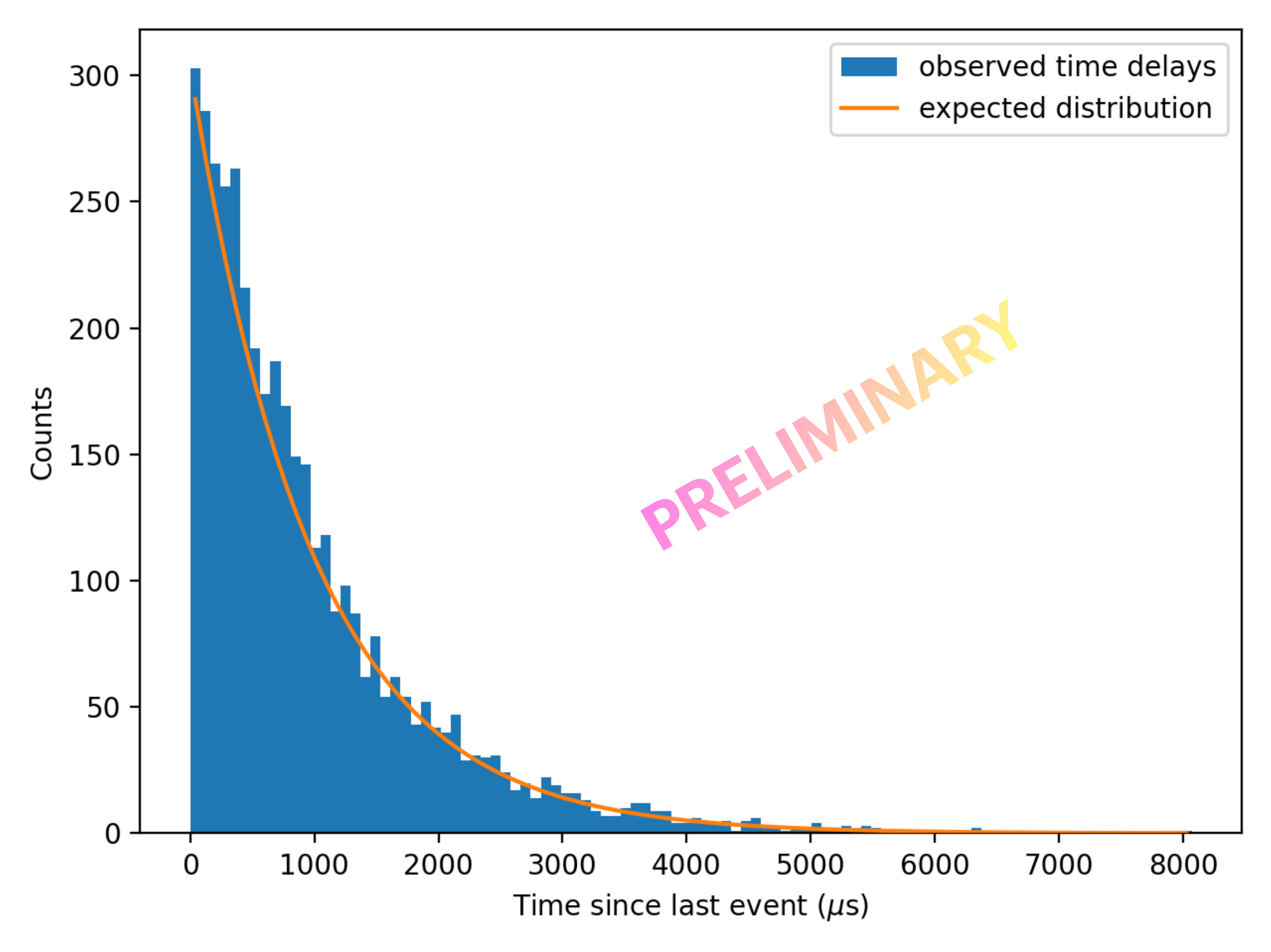
$$\eta = \frac{P_{TES}}{P_{in}}$$

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

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

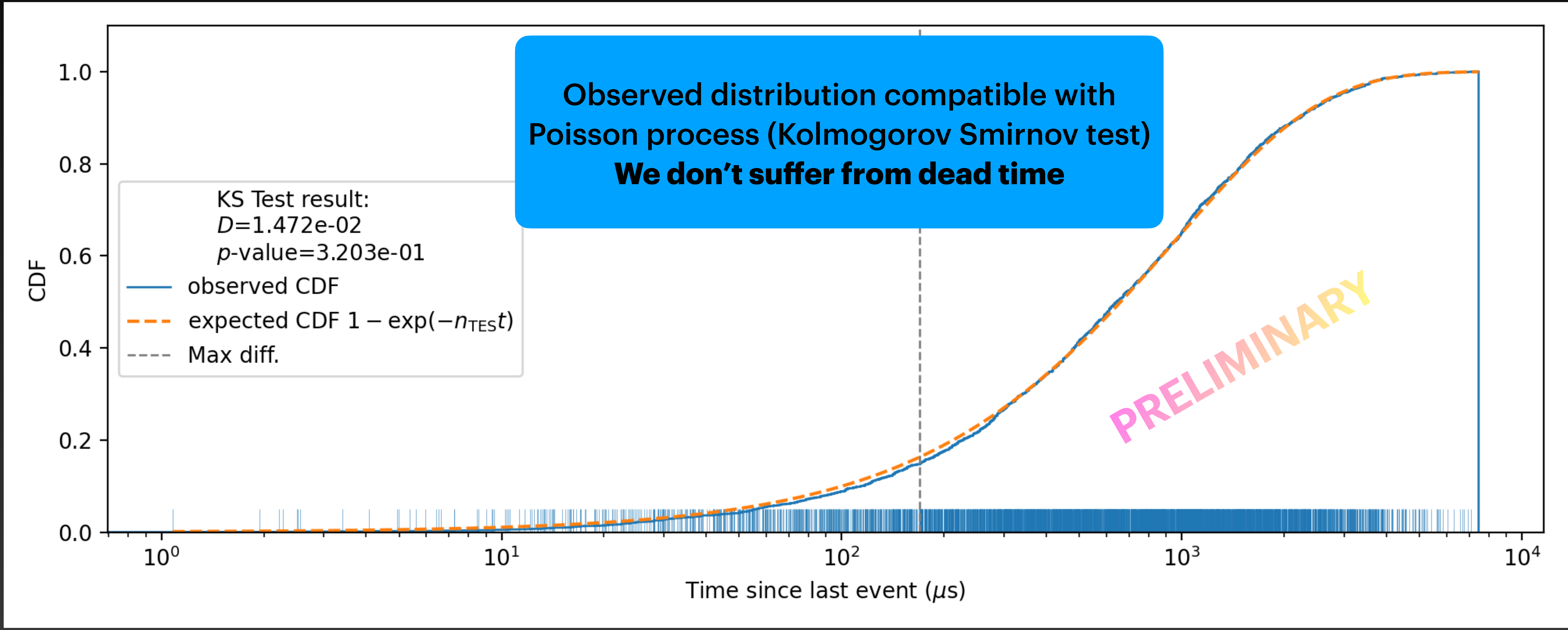
Arrival times: Poisson distributed?

Example for one 4s measurement



Arrival times: Poisson distributed?

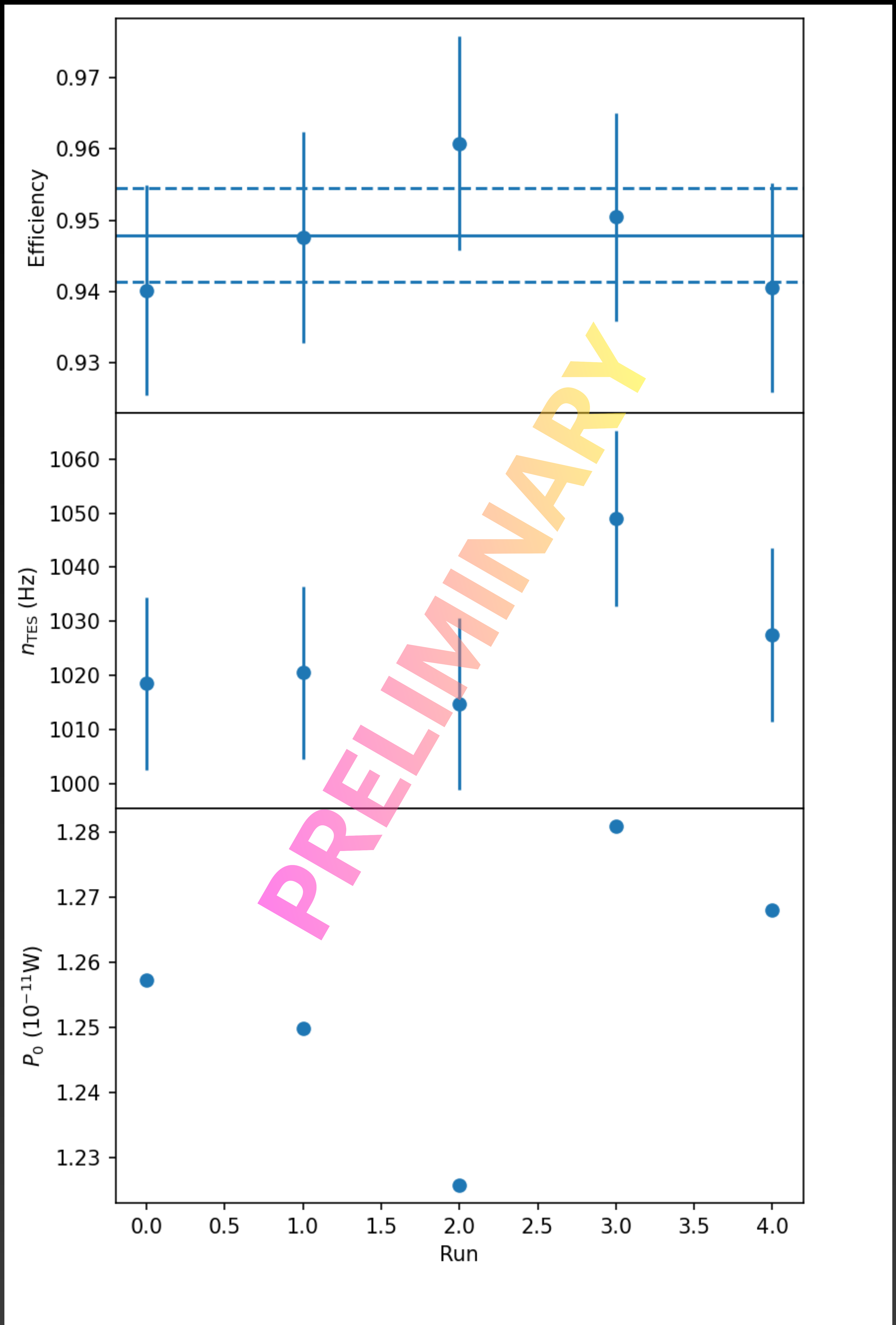
Example for one 4s measurement



Results
Using trapezoidal filter for pulse finding

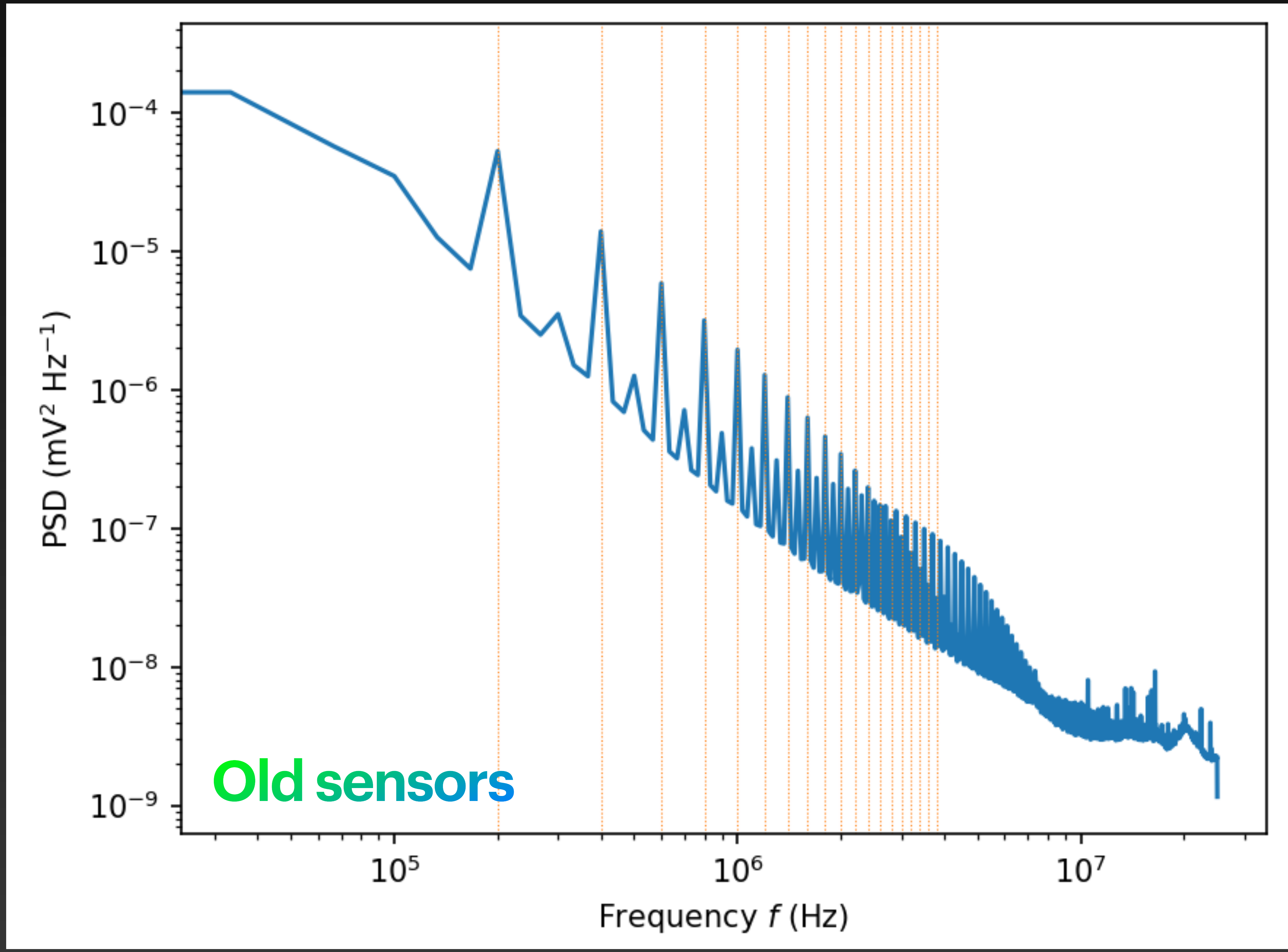
- 5 x 4s time lines taken
- P_0 appears to correlate with n_{TES} as expected
- Large fluctuations in P_0, under investigation

$$\eta \gtrsim 0.9$$

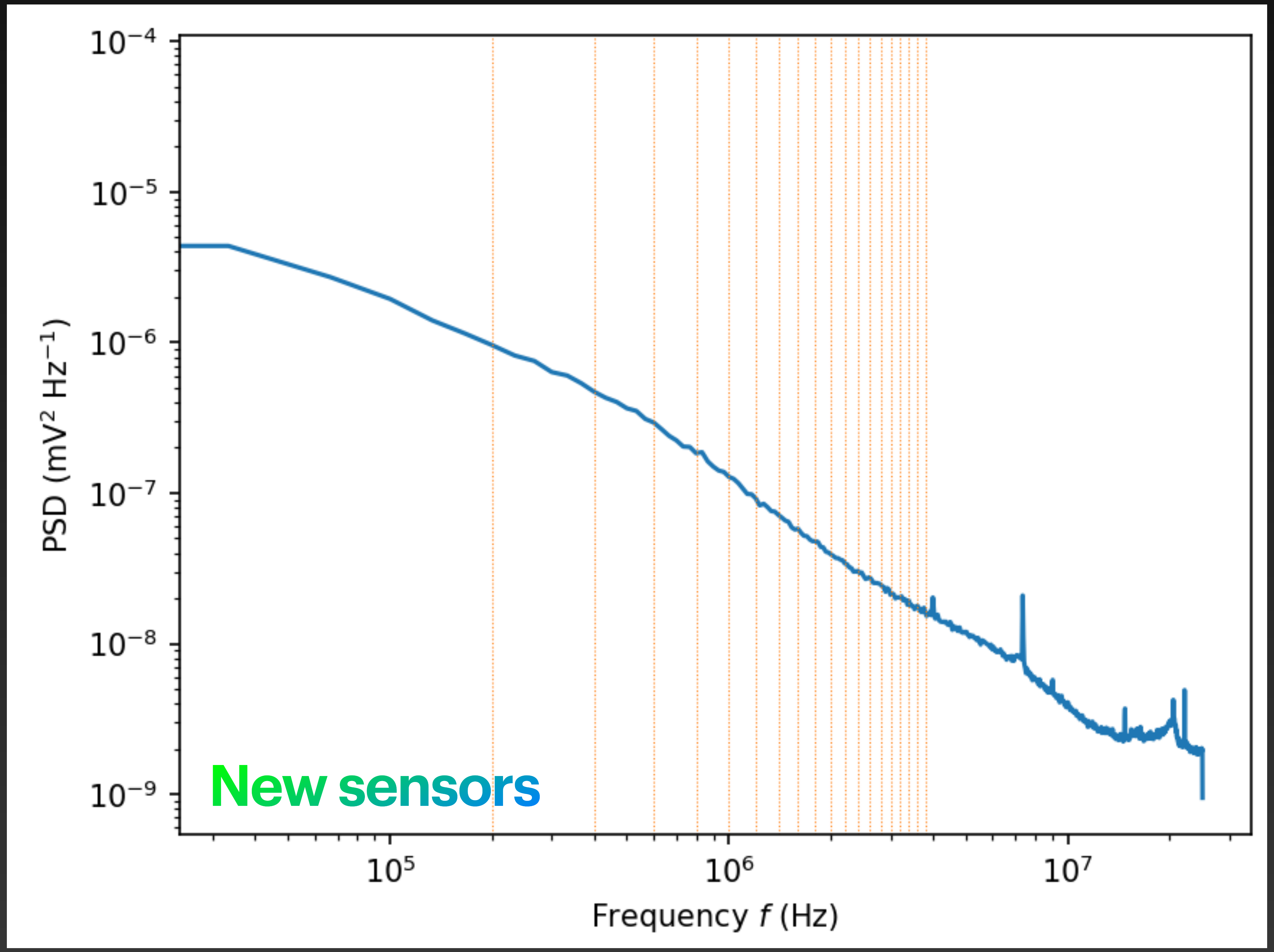


New Sensors with single stage SQUIDs

- Currently redoing measurements with new sensors

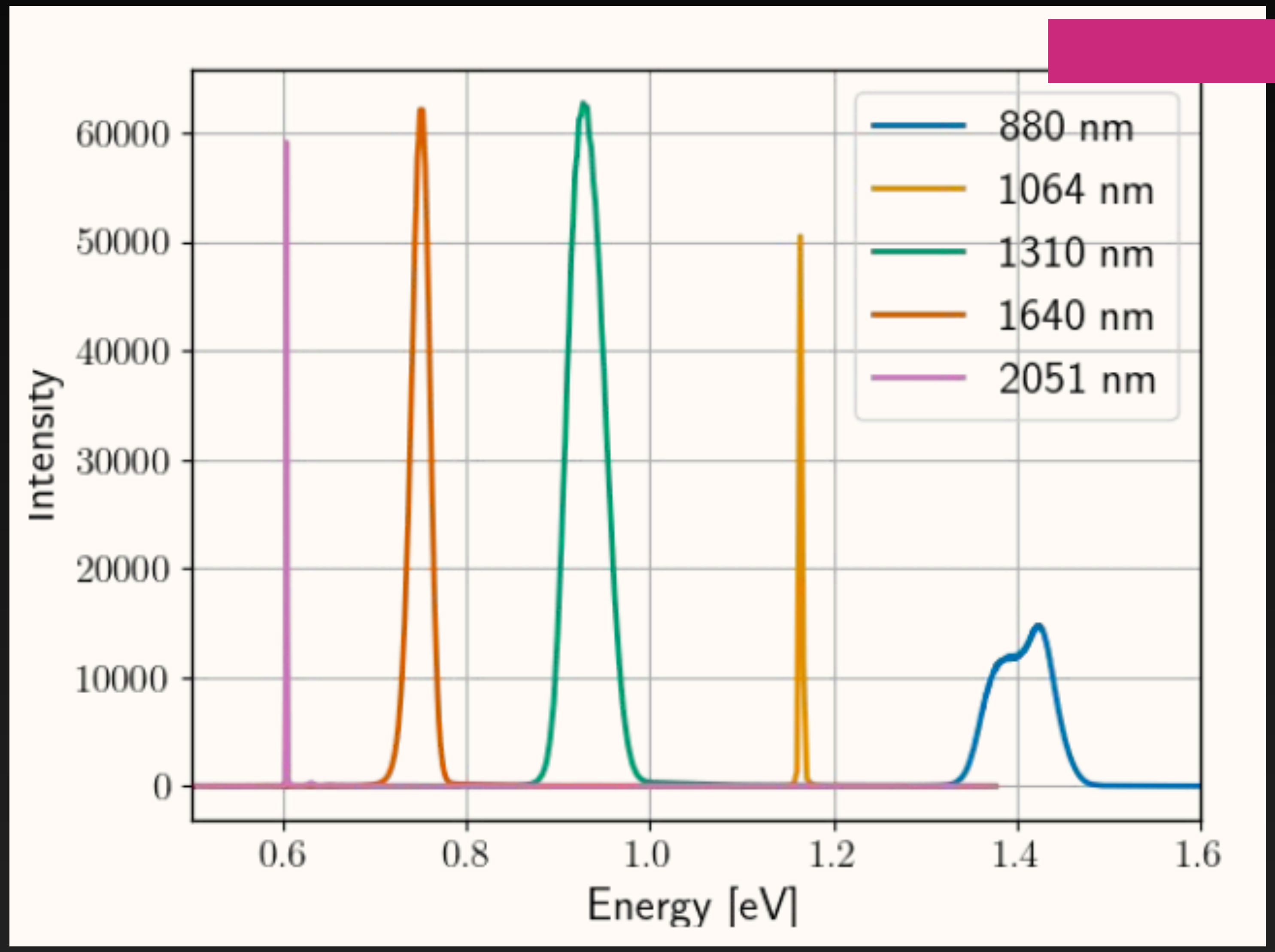


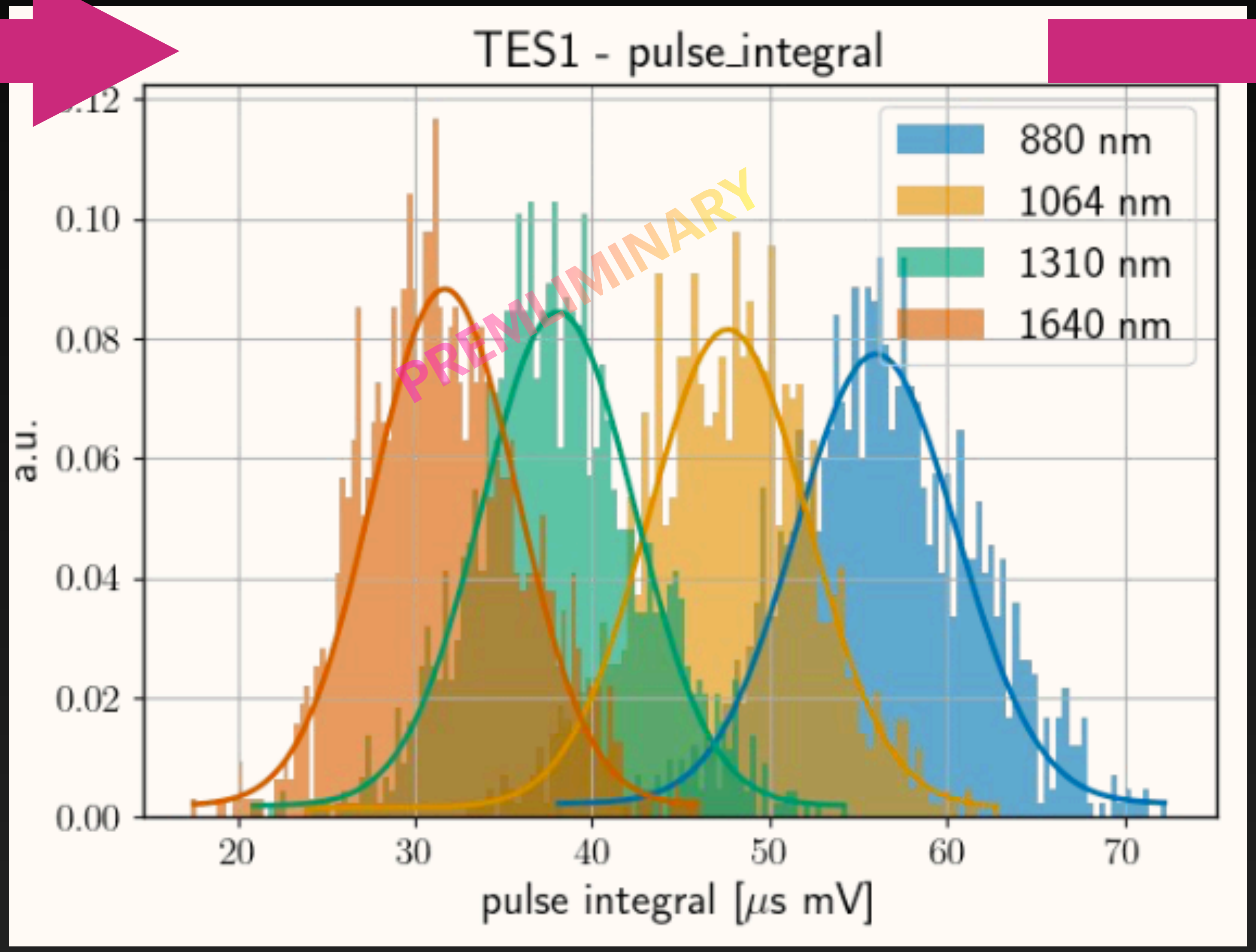
- Only one-stage SQUIDs, less amplification but much reduced 200kHz noise

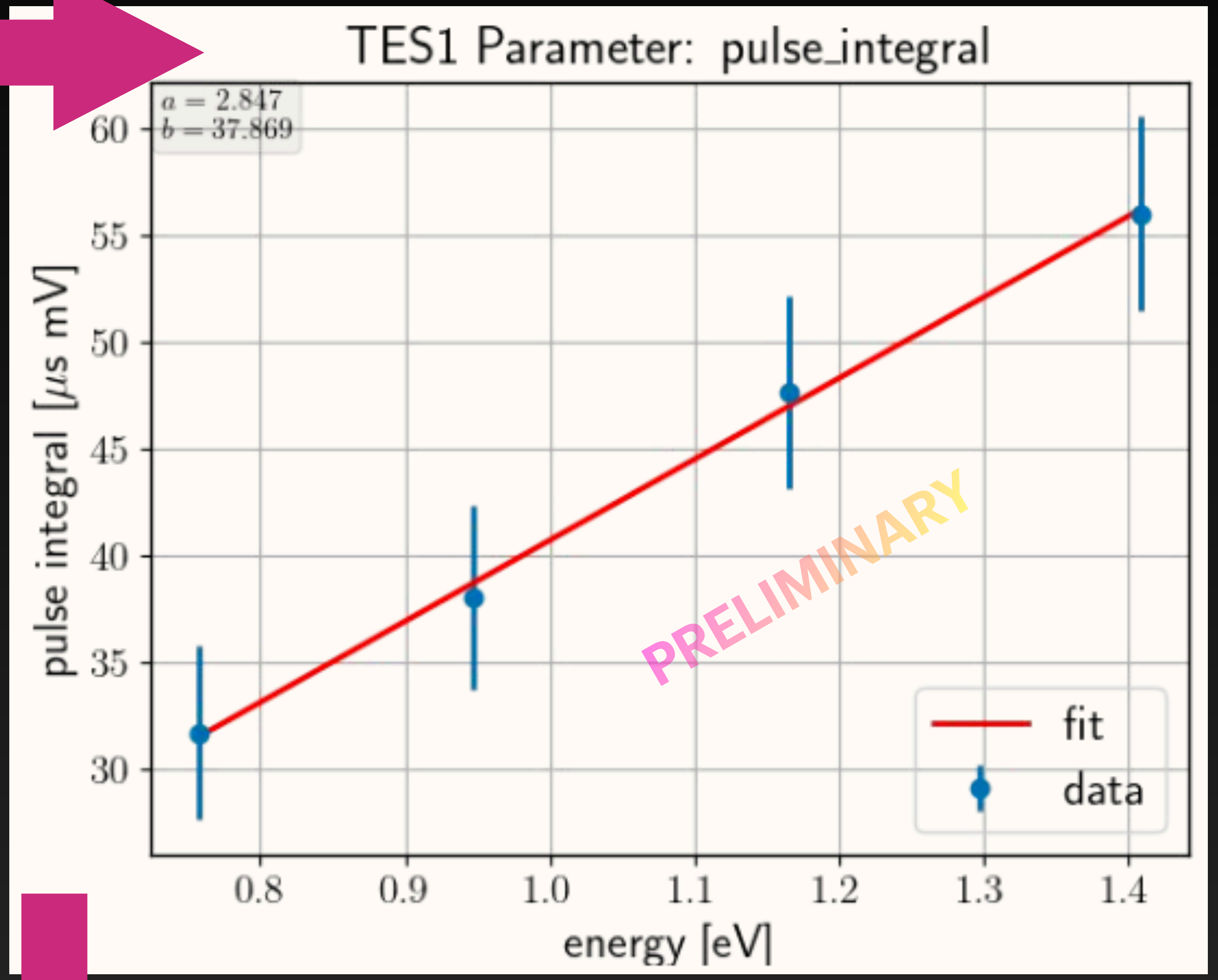


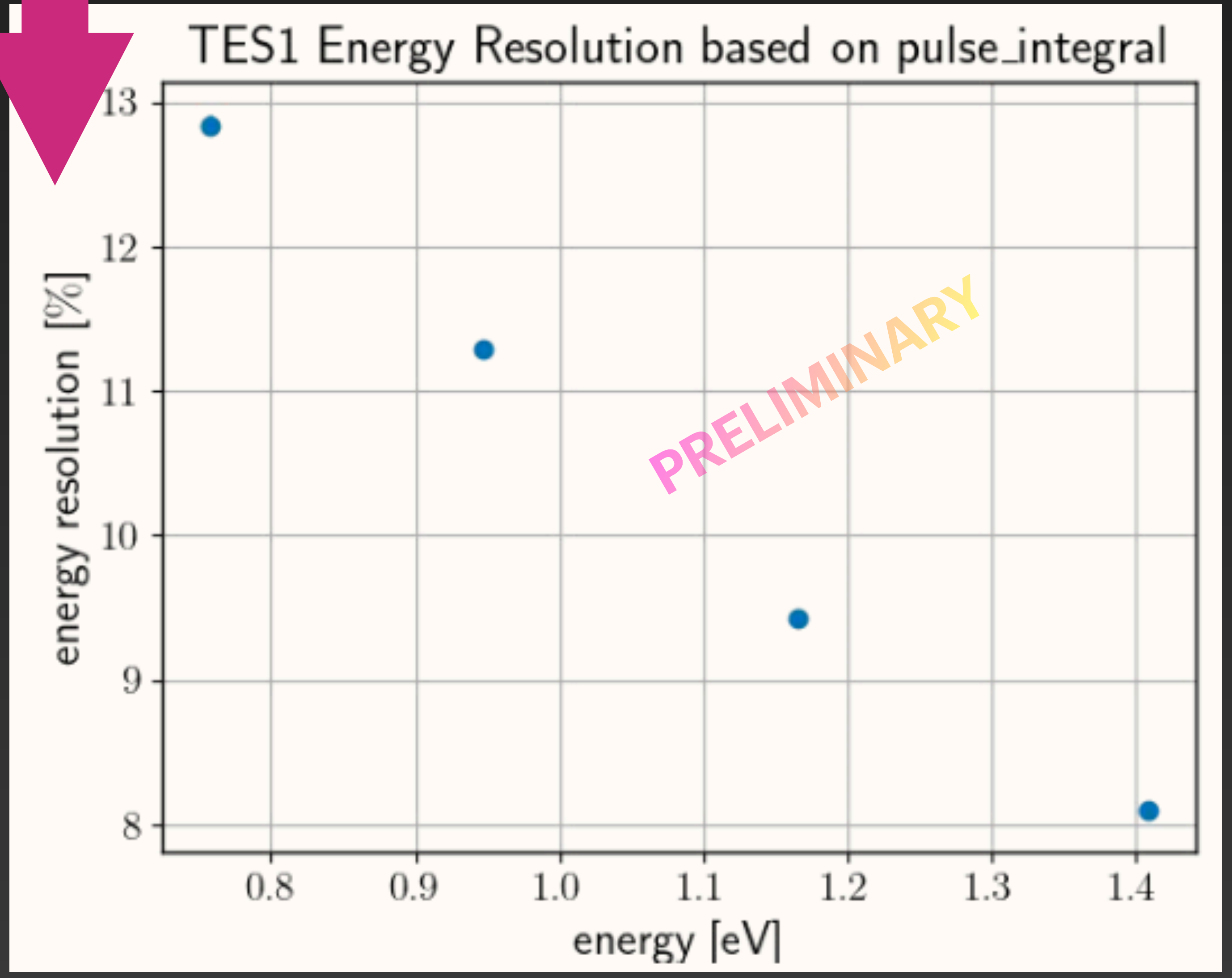
Calibration and energy resolution

Gulden Othman
PhD student
Christina Schwemmbauer









- Different laser diodes used for calibration
- Also determines energy resolution as $\Delta E / E = \sigma / \mu$
- σ, μ determined from histogram of pulse integral

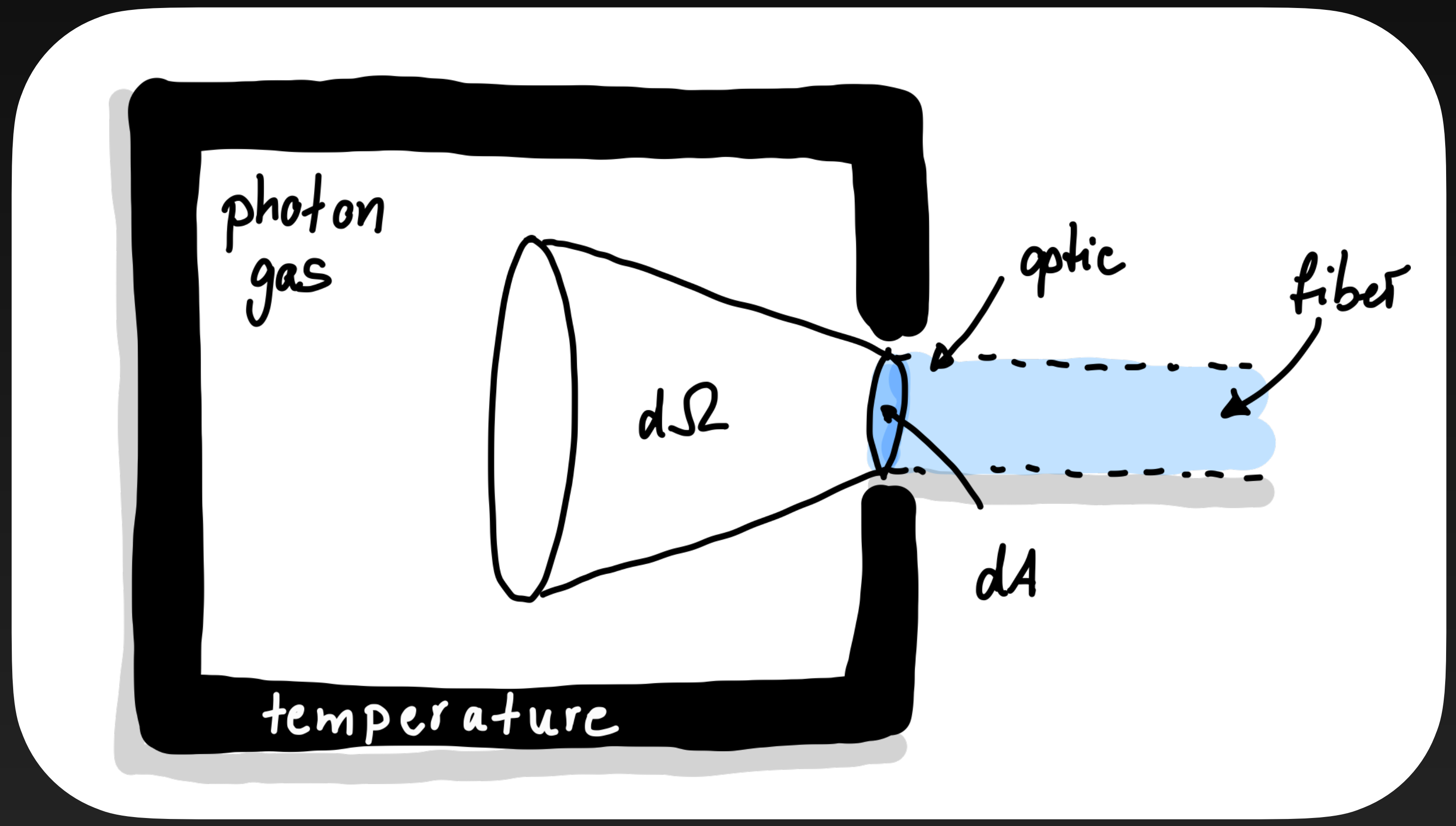
See C. Schwemmbauer's talk at IDM2024

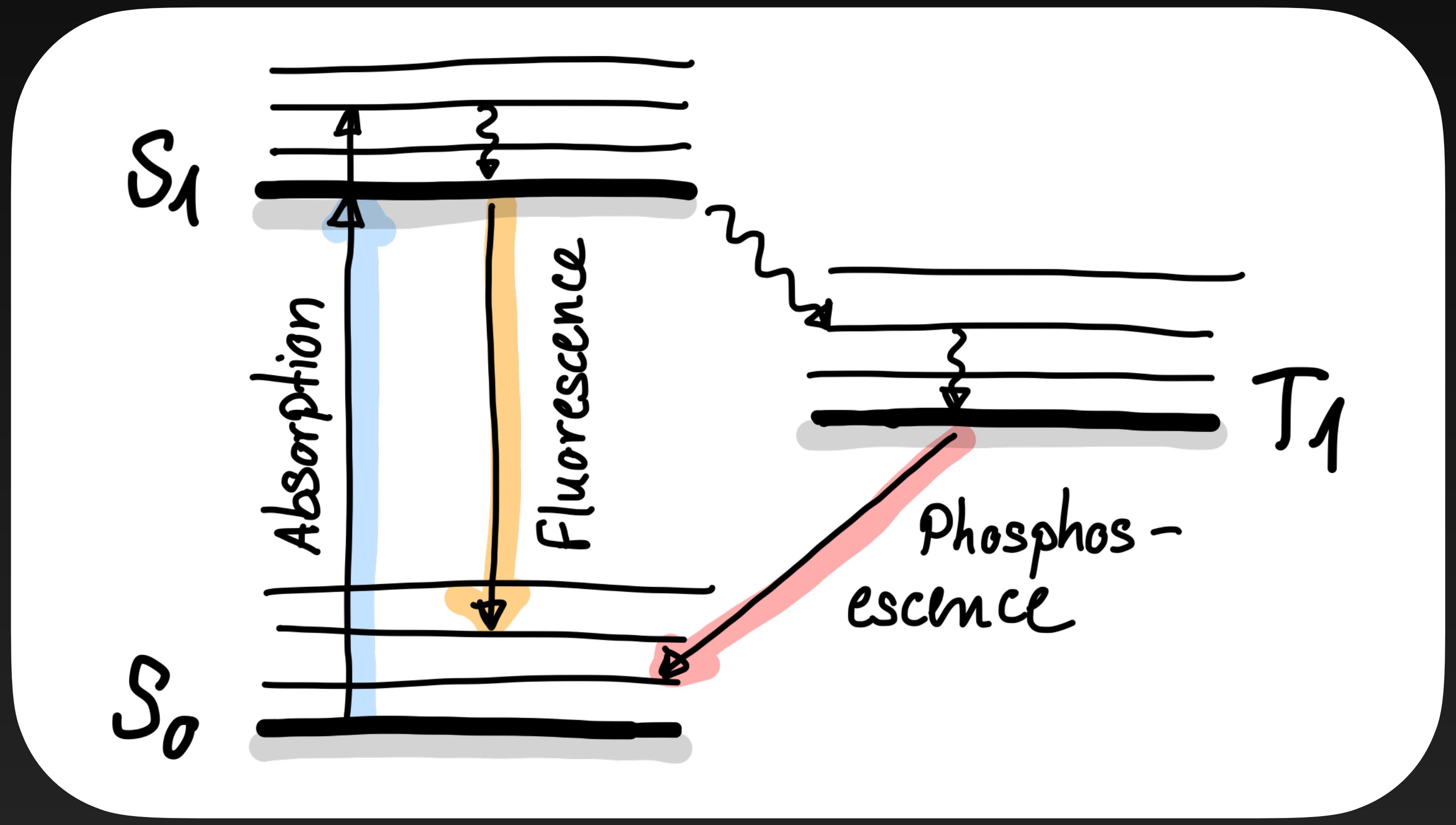
External background Sources for TES

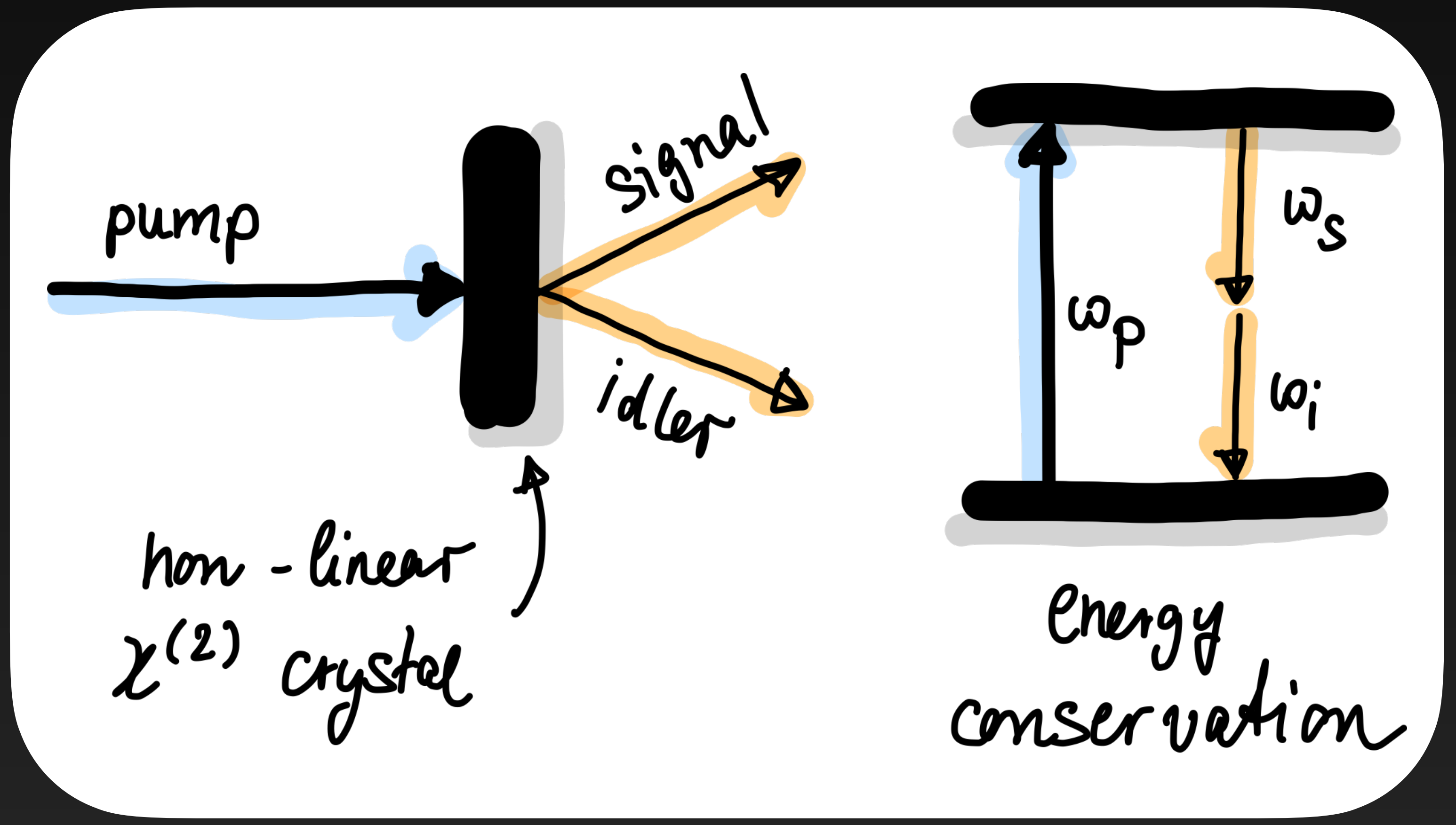
Black body radiation from laboratory, components @300K

Luminescence in optical components or fibers

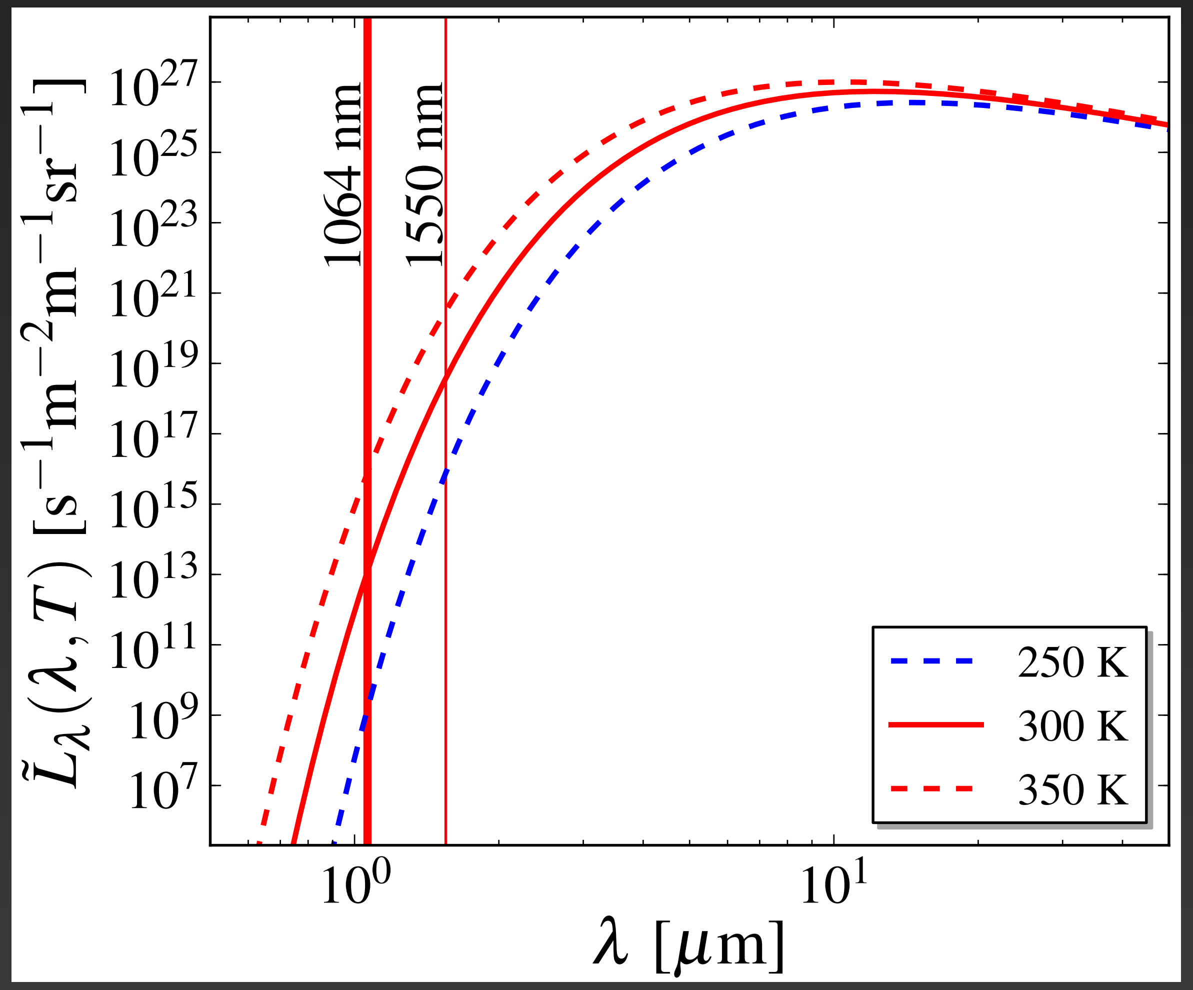
Parametric noise in non-linear optical components or fibers







Courtesy of Katharina-Sophie Isleif

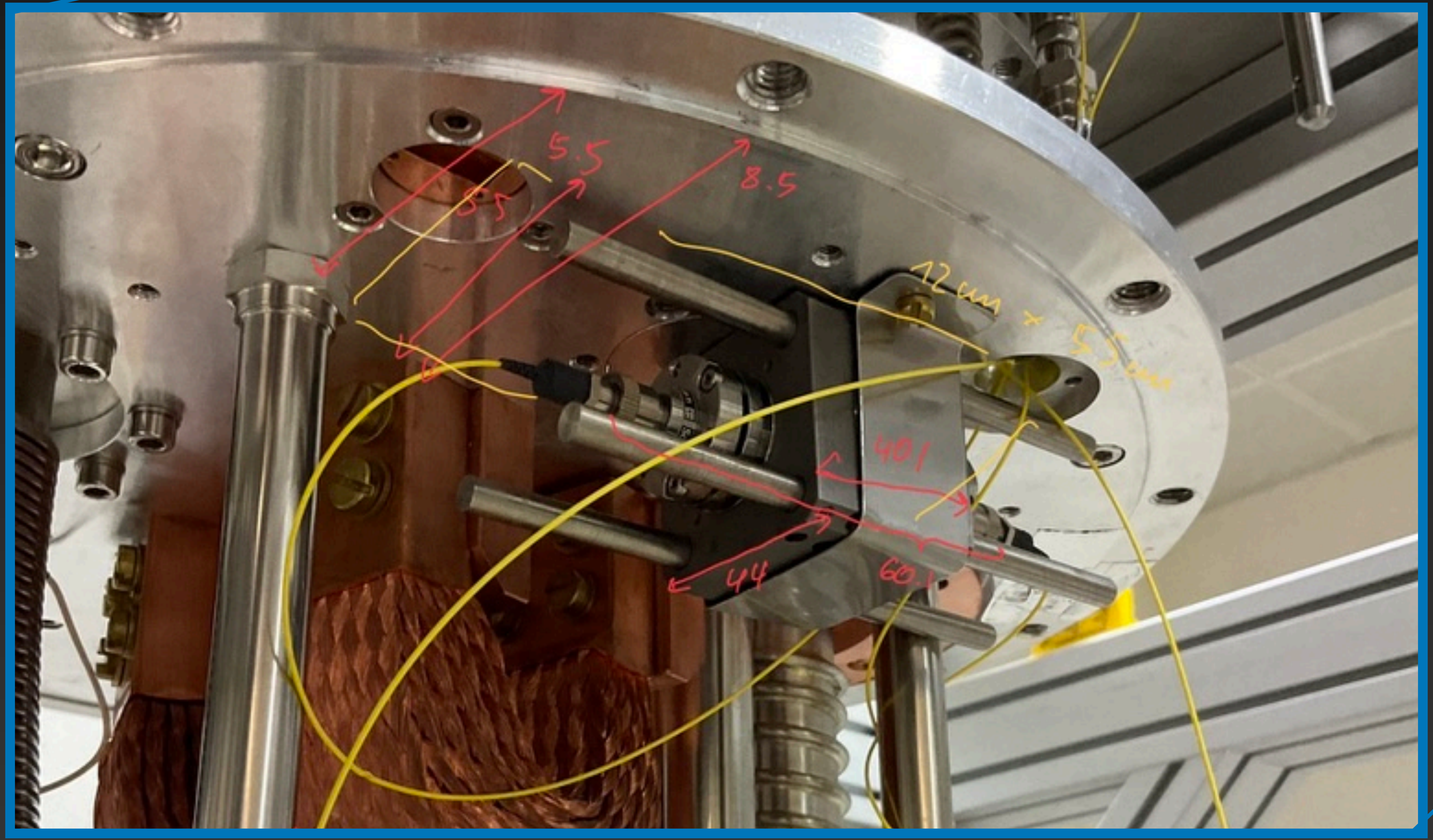


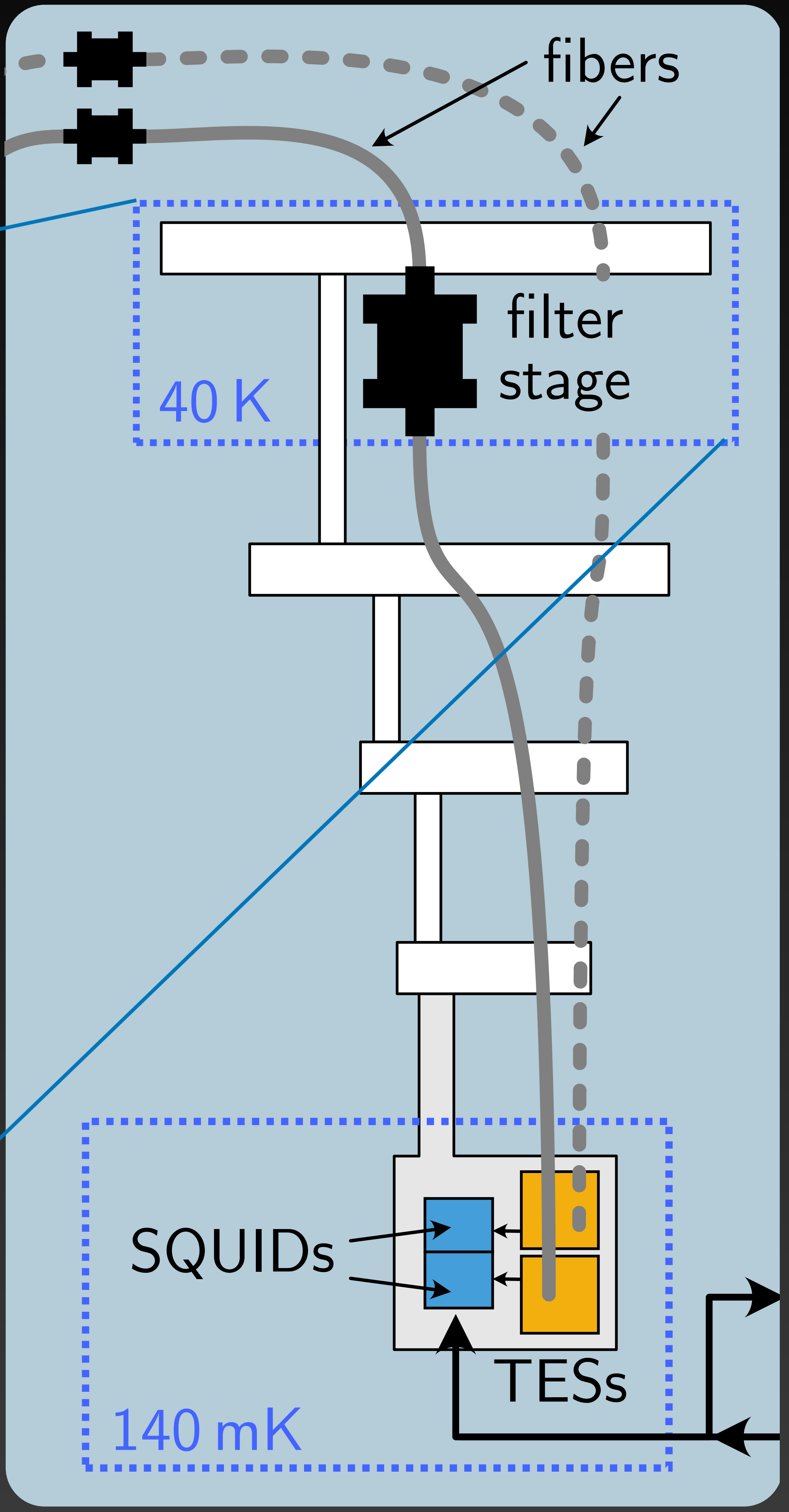
- Without fiber disconnected: radioactivity, cosmic rays
- With fiber connected:
  - Blackbody photons from warm components
  - Luminescence within the fiber itself and optical components
  - Parametric noise
- Suppressing backgrounds also relevant to other quantum sensing applications

Background suppression: Cold optical filter bench

Current design (by Katharina Isleif — Initial design by Benno Willke, Aaron Spector, Jan Pohl)

- Idea:
  - narrow bandpass filter
  - suppress photons at wrong wavelength at level below energy resolution
- Alignment of Ti fiber couplers performed at room temperature
- Misalignment during cool down (thermal contraction)
- Transmission drops to $\lesssim 20\%$

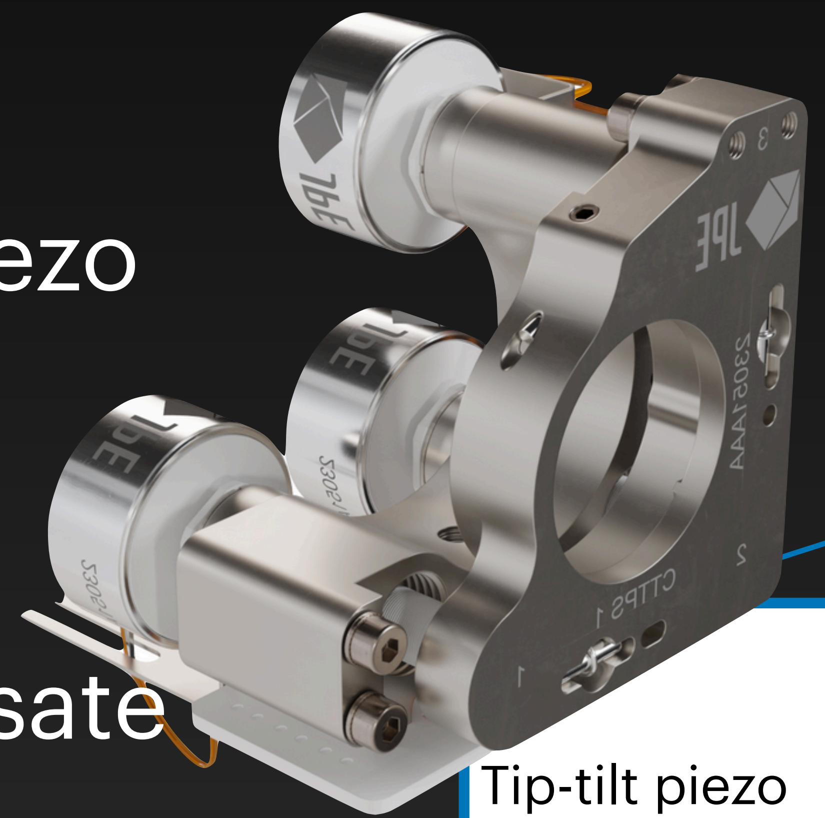




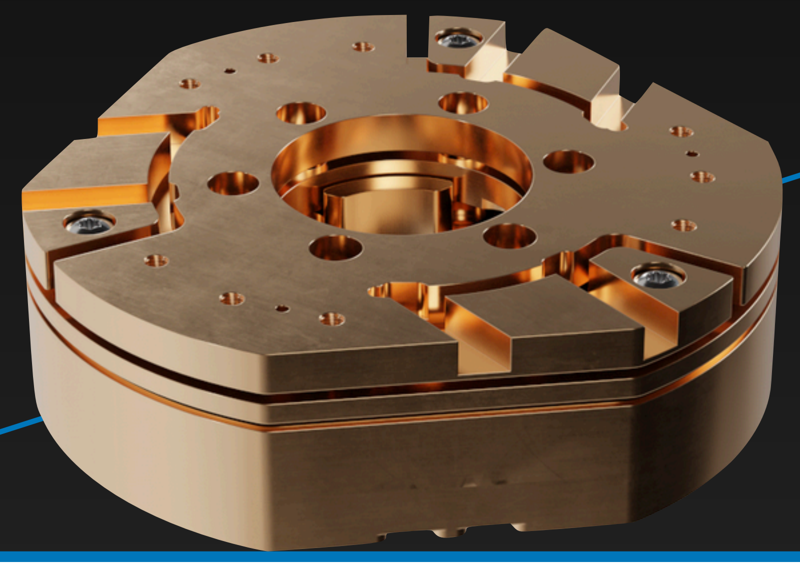
Background suppression: Cold optical filter bench

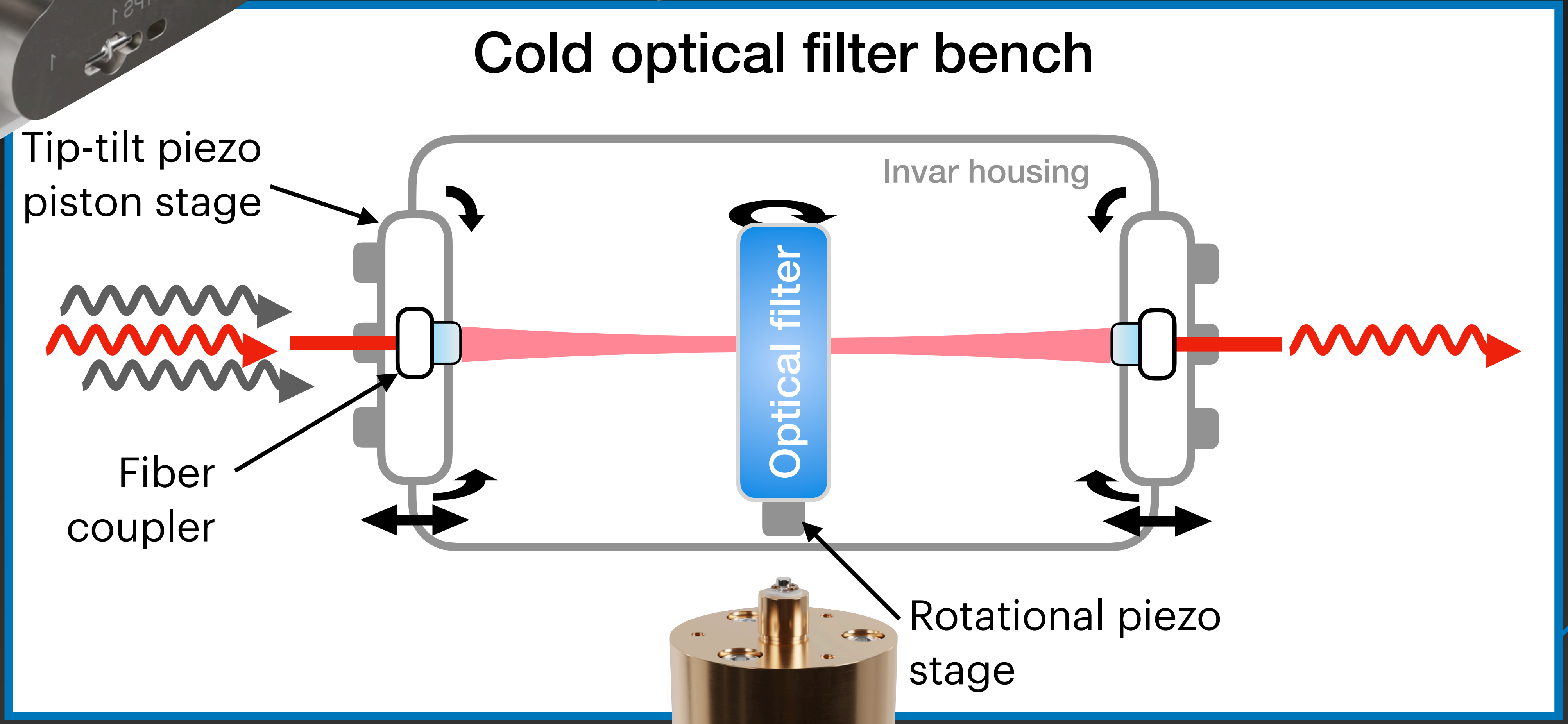
Design under development

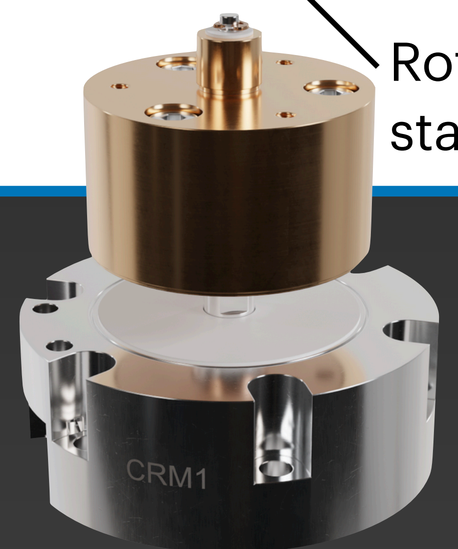
- Filter can be aligned with piezo stages inside cryostat
- Rotational stage to compensate for wavelength shift of filter
- Vibrational isolation and housing made of Invar

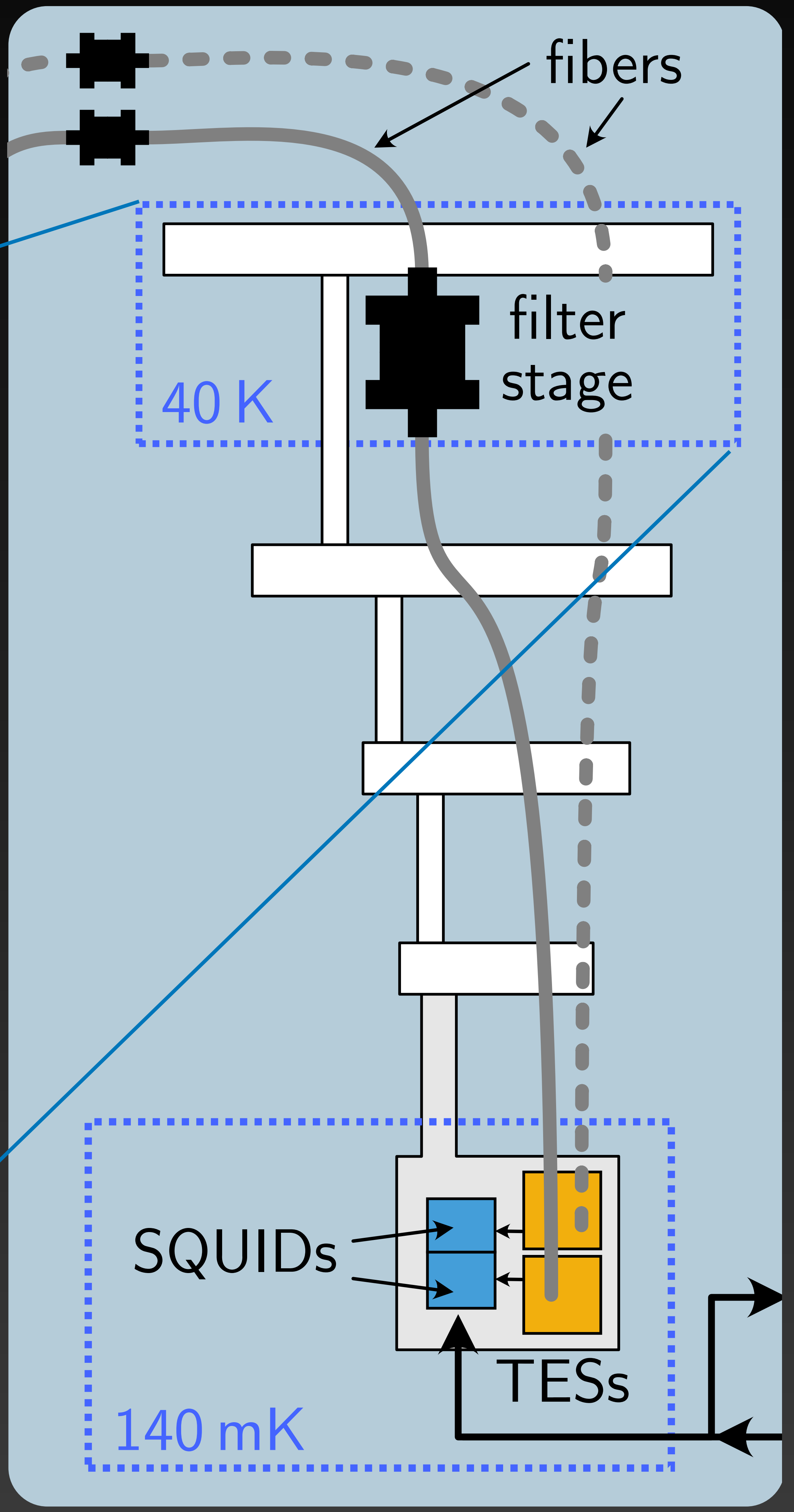


Vibrational isolation







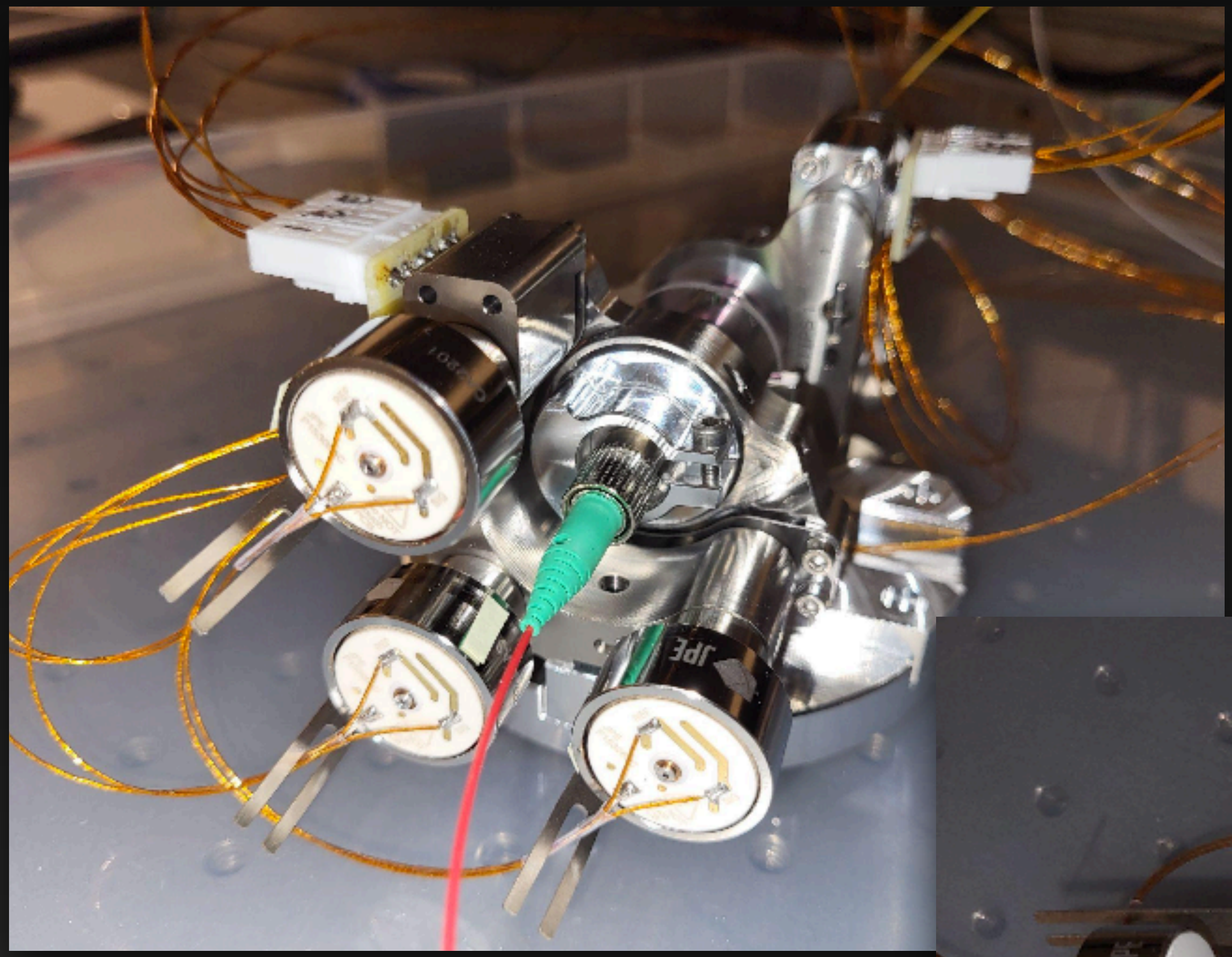


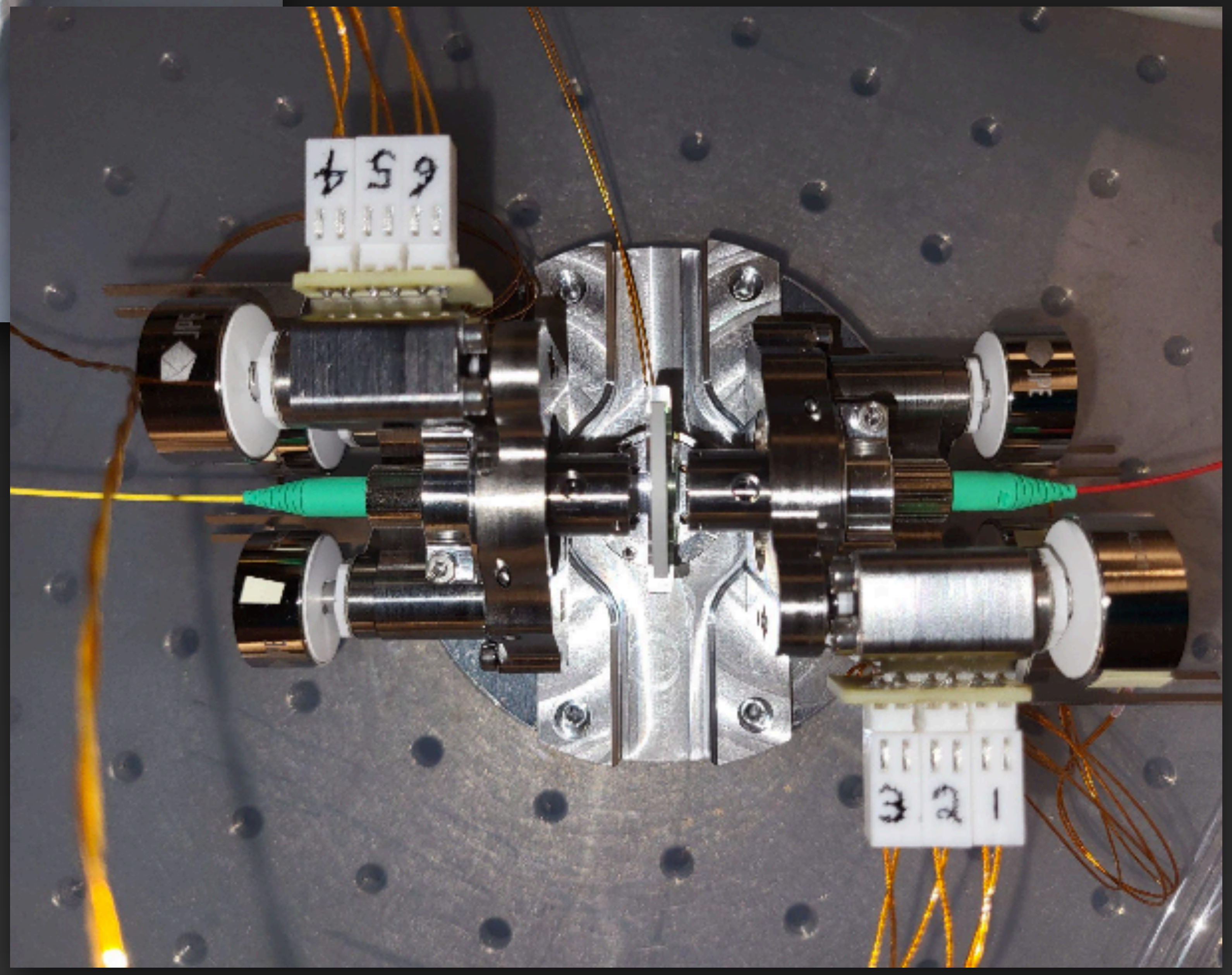
Development at SDU

Optimization started in the warm with preliminary filter design
Will then be tested in cryostat at DESY

SDU Post doc
Elmeri Rivasto

- 3 angles + distance between fibre-end and lens
- Rotator tunes filters transmission window
- Vibrational damper stabilizes the system
- Expecting 70-80% transmission coefficient





Machine learning approaches

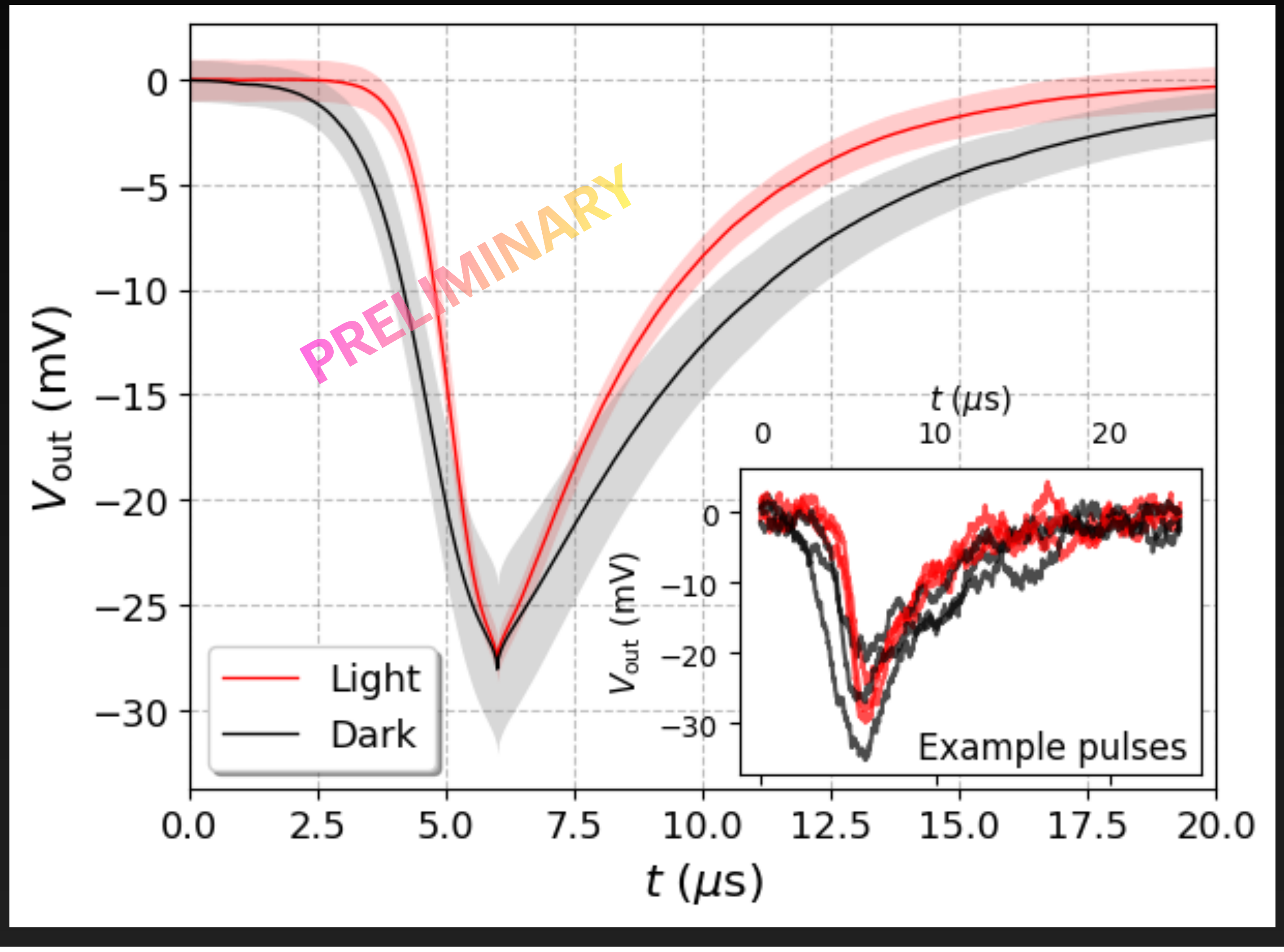
For improved signal and background rejection (no fiber attached)

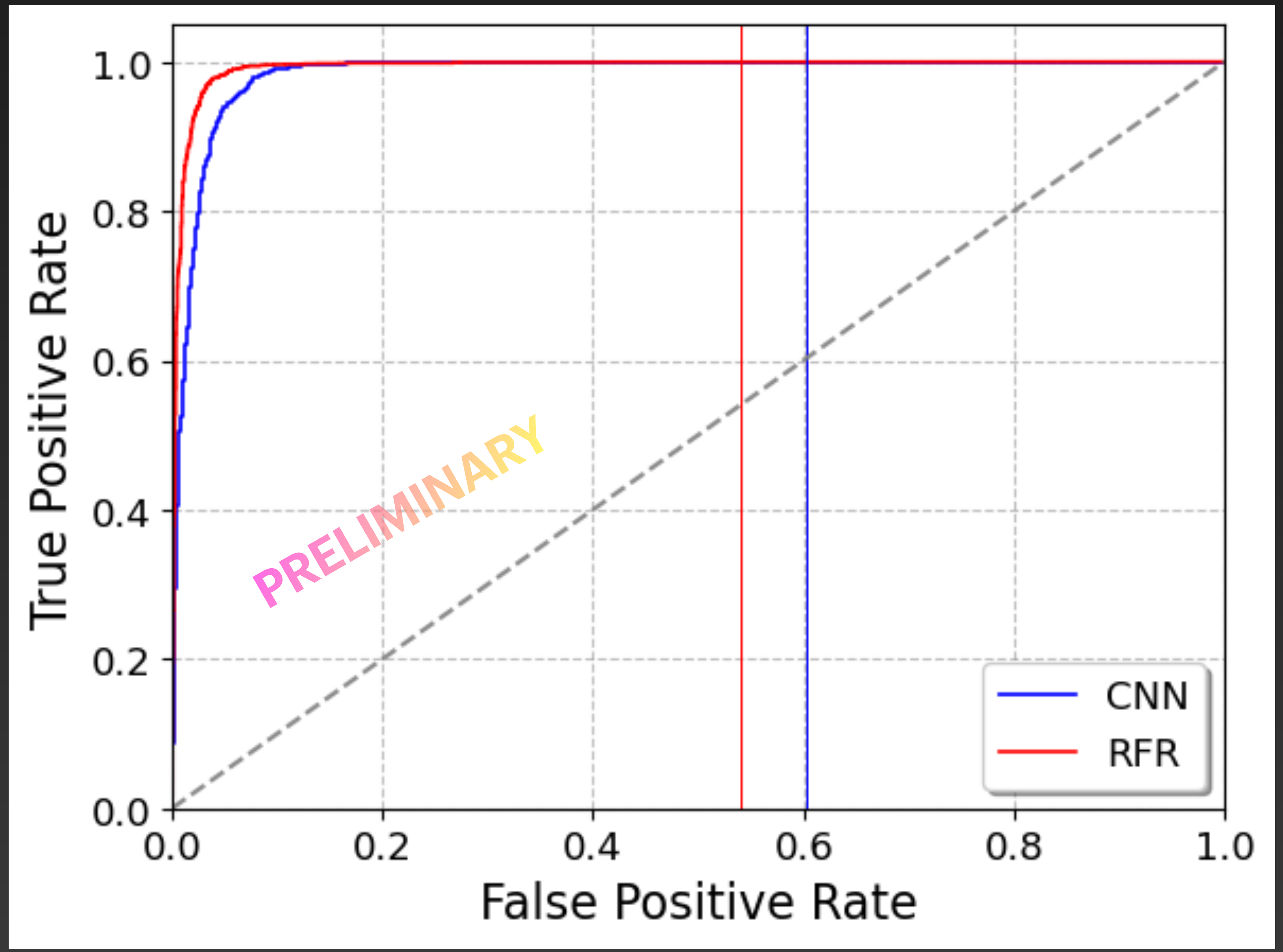
[MM et al., arXiv:2304.08406]

Background discrimination with CNNs with fiber connected

SDU Post doc
Elmeri Rivasto

- Data sets simulated to find best architecture of convolutional neural network
- Background simulation to produce light pulses at slightly wrong energy
- Simulated data set of 50,000 time lines
- CNN appears to outperform random forest





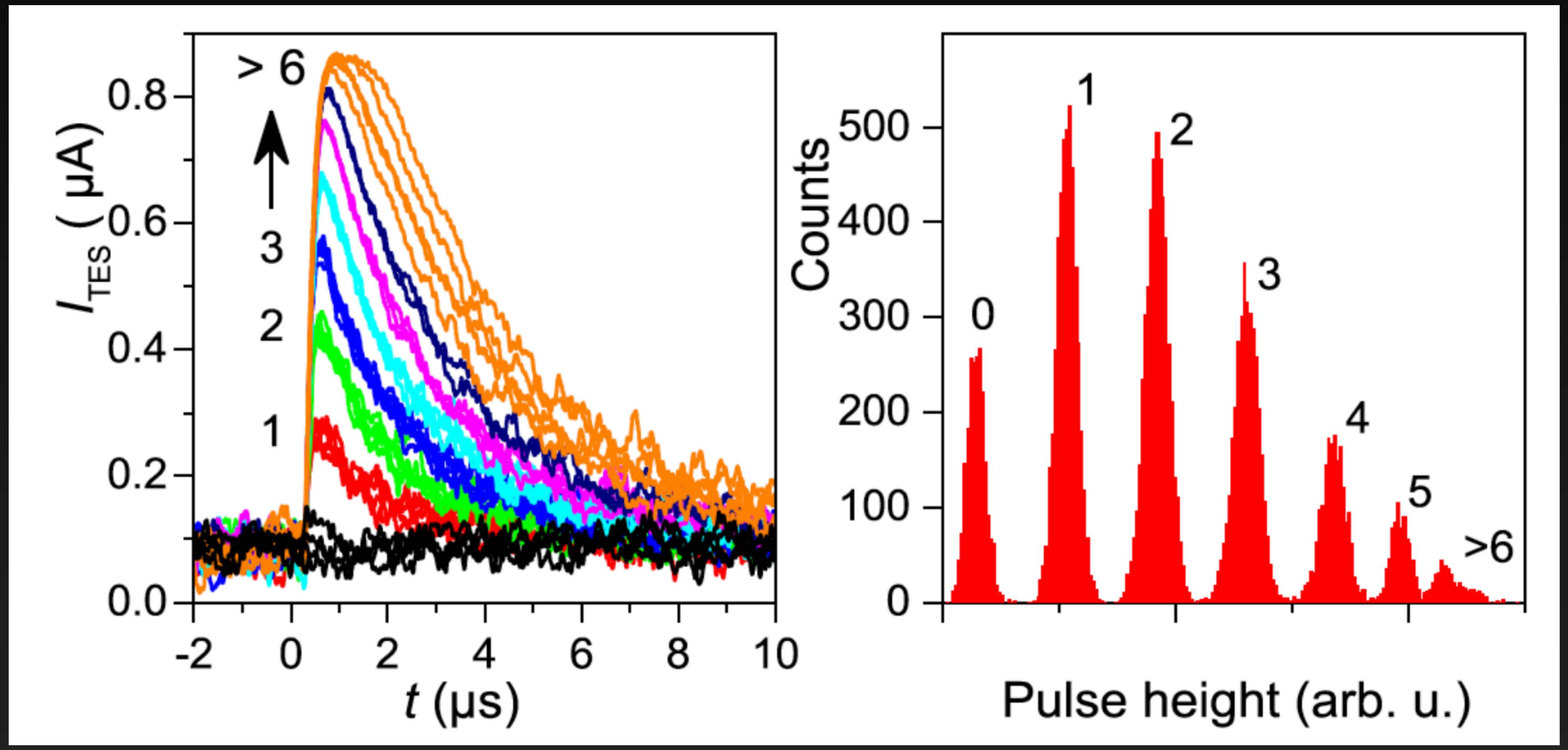
Beyond ALPS II

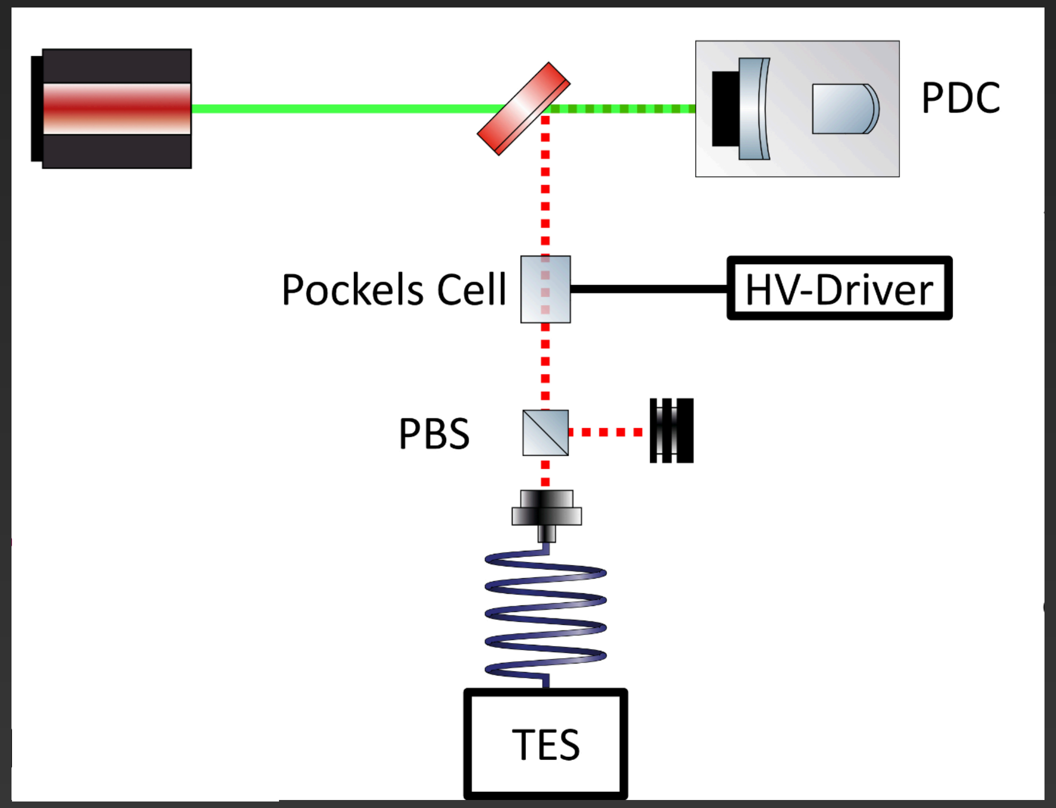
Measuring photon number distribution of squeezed light at DESY

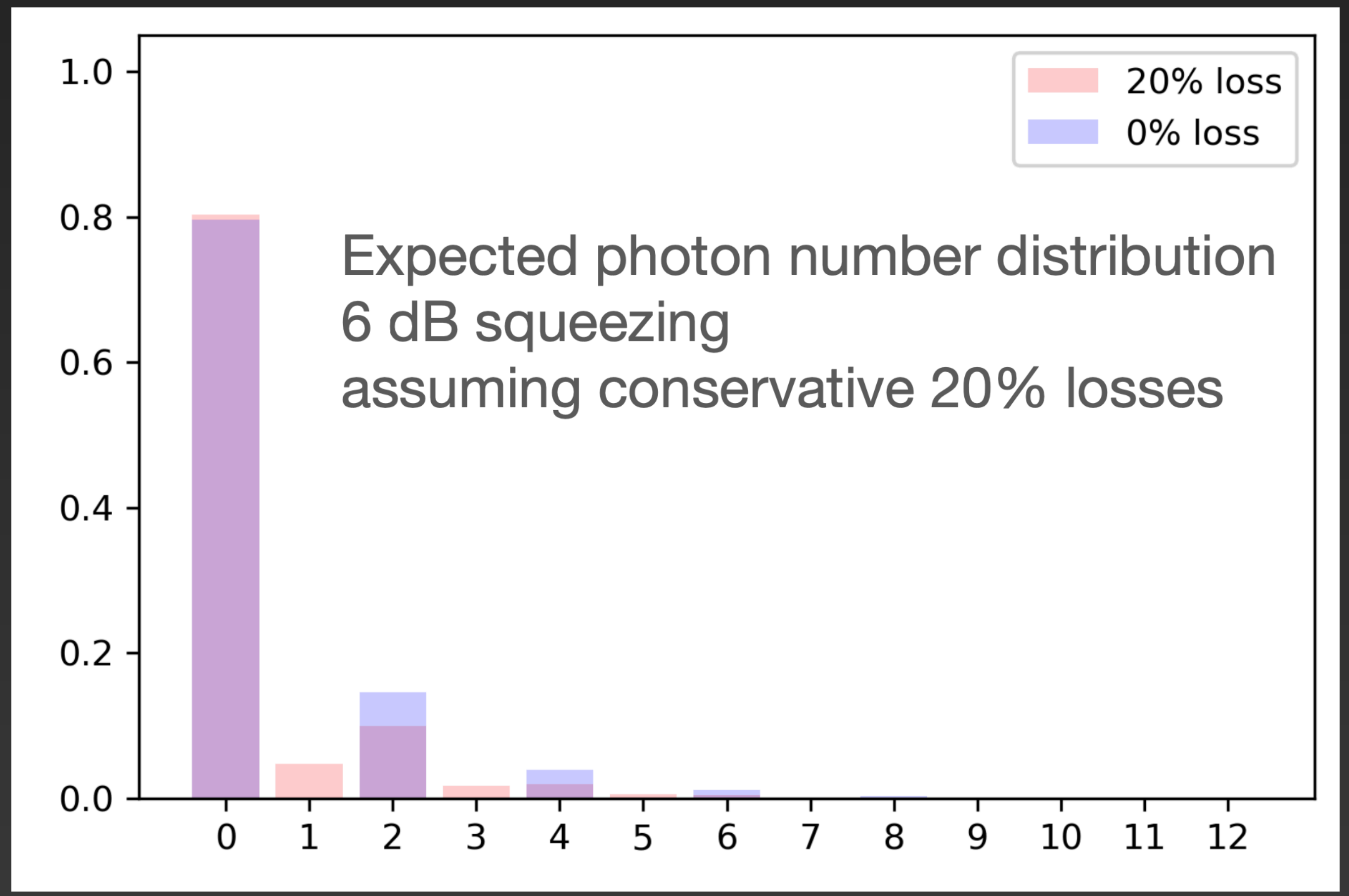
UHH
Post doc
Gulden
Othman

- TES can measure photon number distribution
- Idea: Measure even number photon distribution of squeezed light source at 1064nm
- Necessary step to realizing Gottesman–Kitaev–Preskill (GKP) States for Quantum Computation (QC)
- GKP qubits have not yet been realized in photonic QC
- In cooperation with Roman Schnabel's group at University of Hamburg (hold world record in squeezing)

Schmidt et al. (2018)



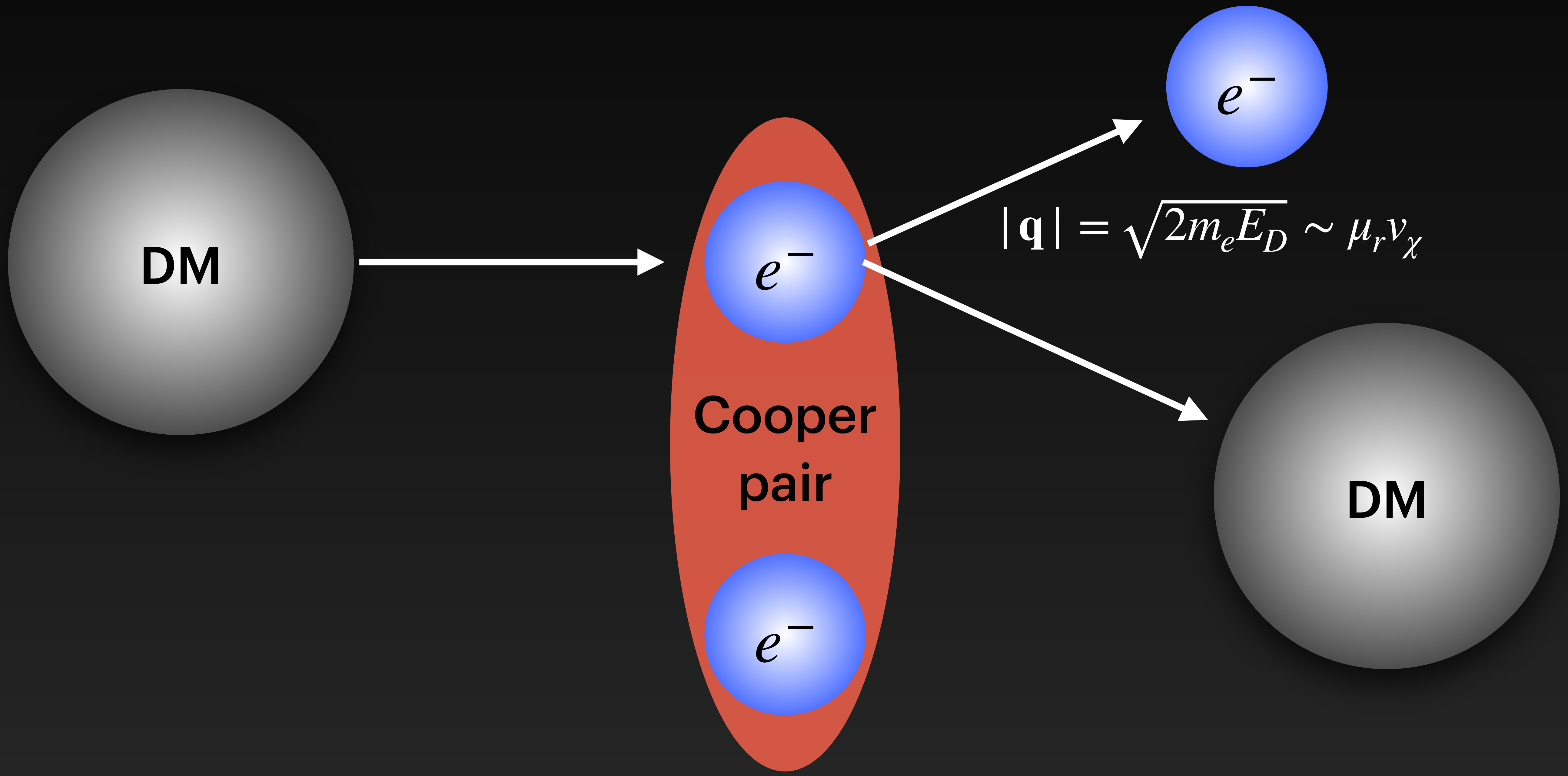


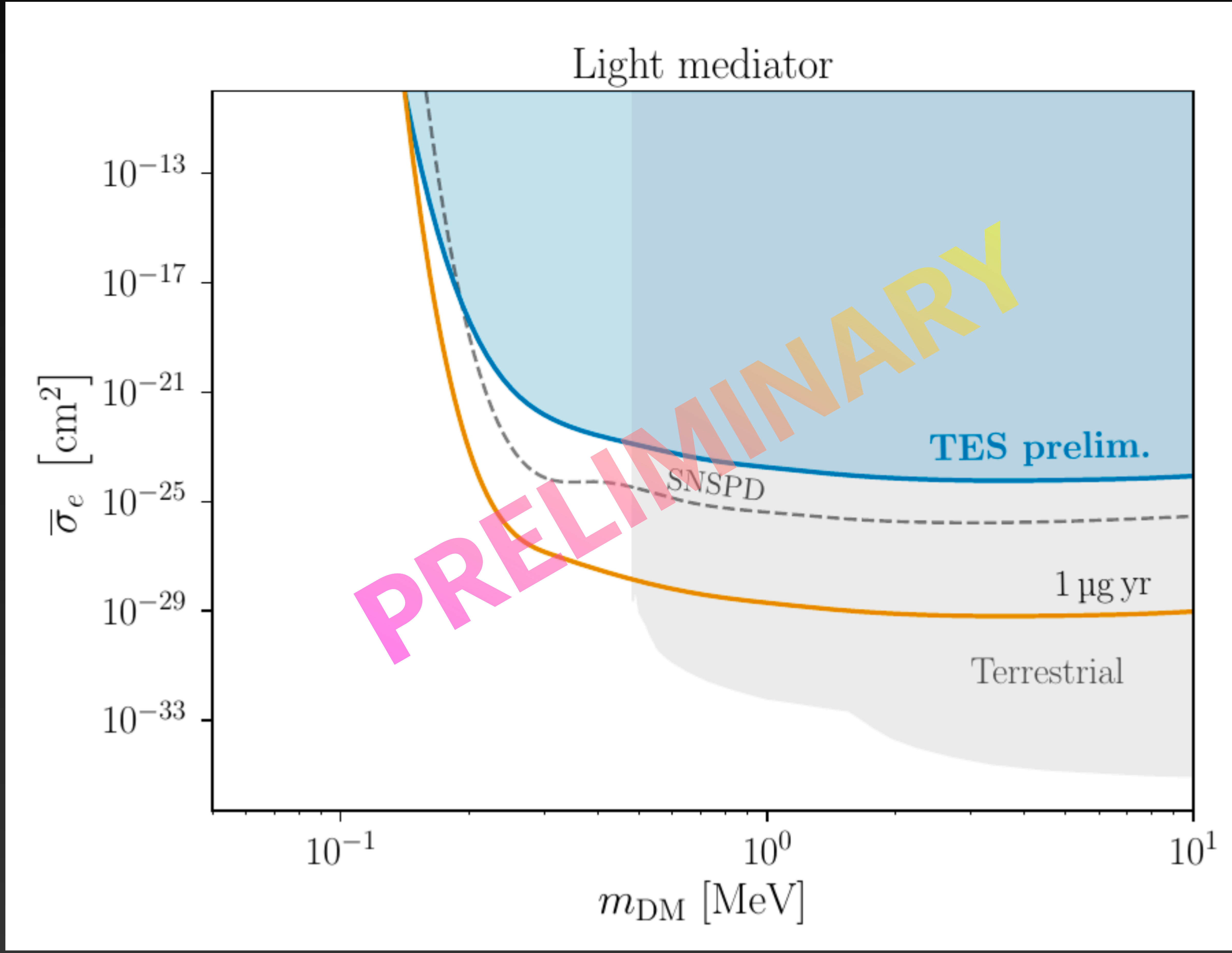


Plots and simulations by PhD student Stephan Grebien, seed funding obtained by Gulden Othman

TES as direct dark matter detector

DESY PhD student
Christina
Schwemmbauer



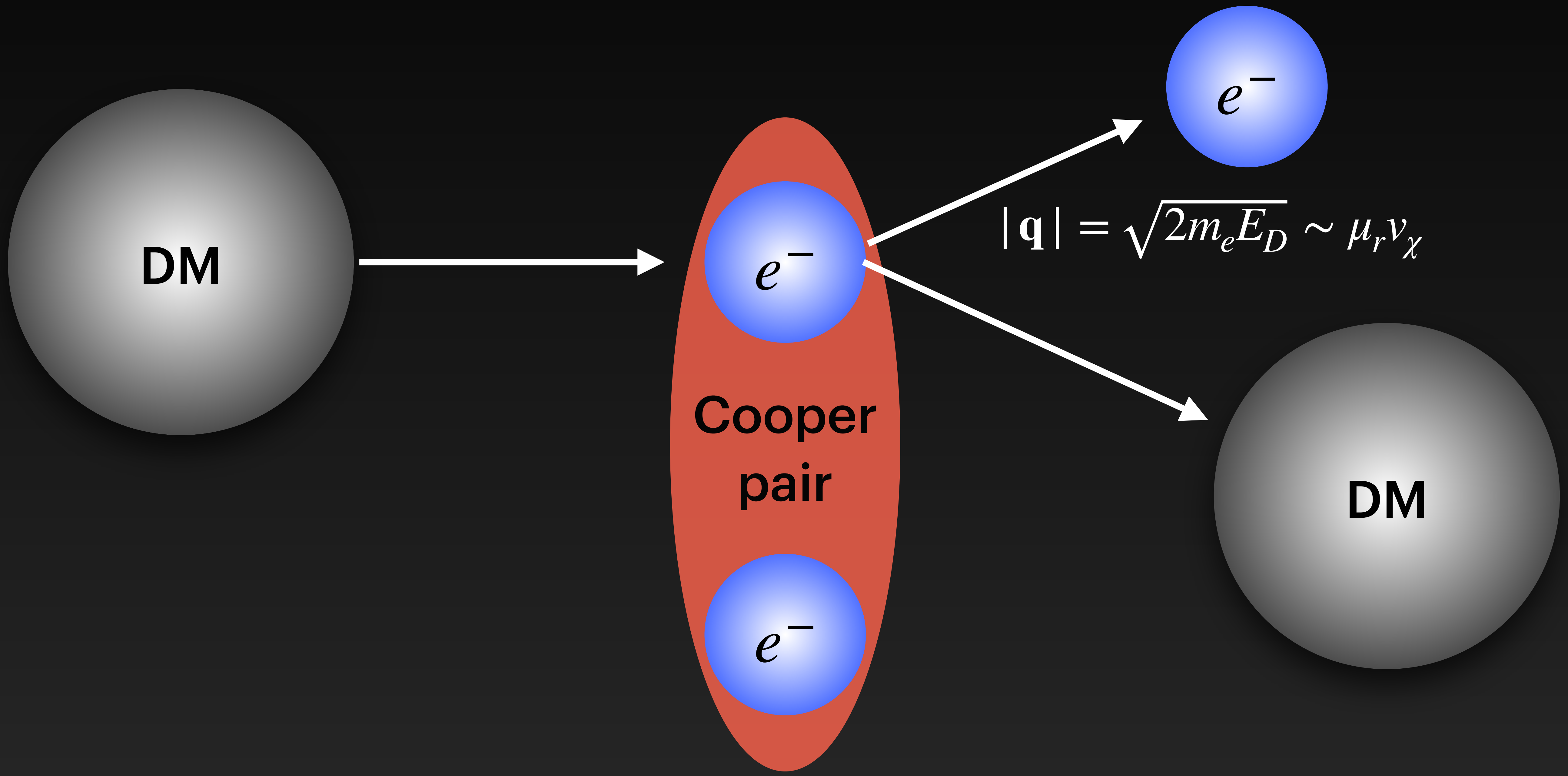


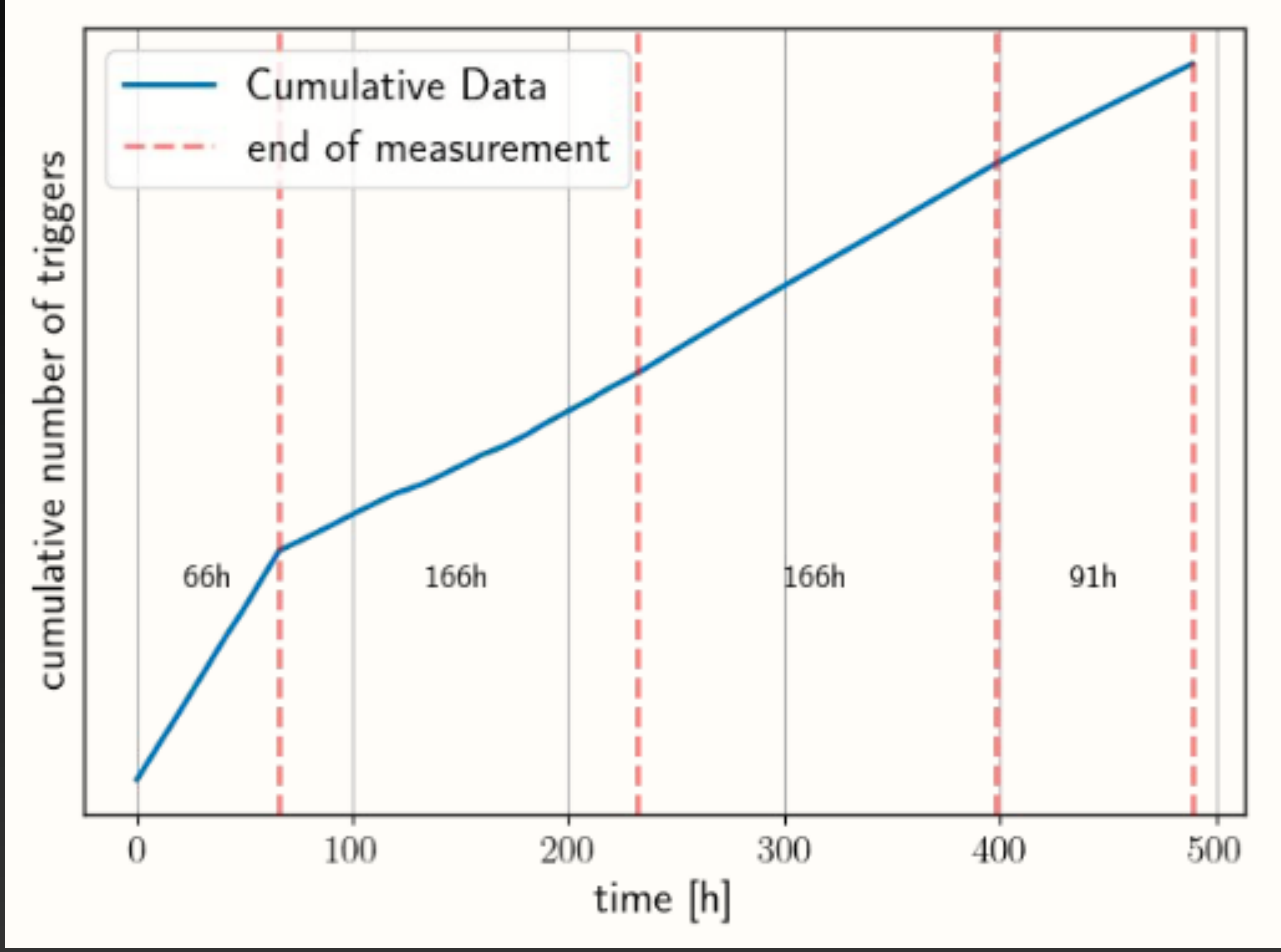
- DM-electron scattering could break Cooper pairs
- O(100 meV) threshold, sensitive to light dark matter
- TES dark current measurements can be used to set limits
- TES never been used in direct dark matter searches before
- Finished ~1 month of data taking at DESY, analysis on-going

See C. Schwemmbauer's talk at IDM2024

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

TES as direct dark matter detector





- DM-electron scattering could break Cooper pairs
- O(100 meV) threshold, sensitive to light dark matter
- TES dark current measurements can be used to set limits
- TES never been used in direct dark matter searches before
- Finished ~1 month of data taking at DESY, analysis on-going

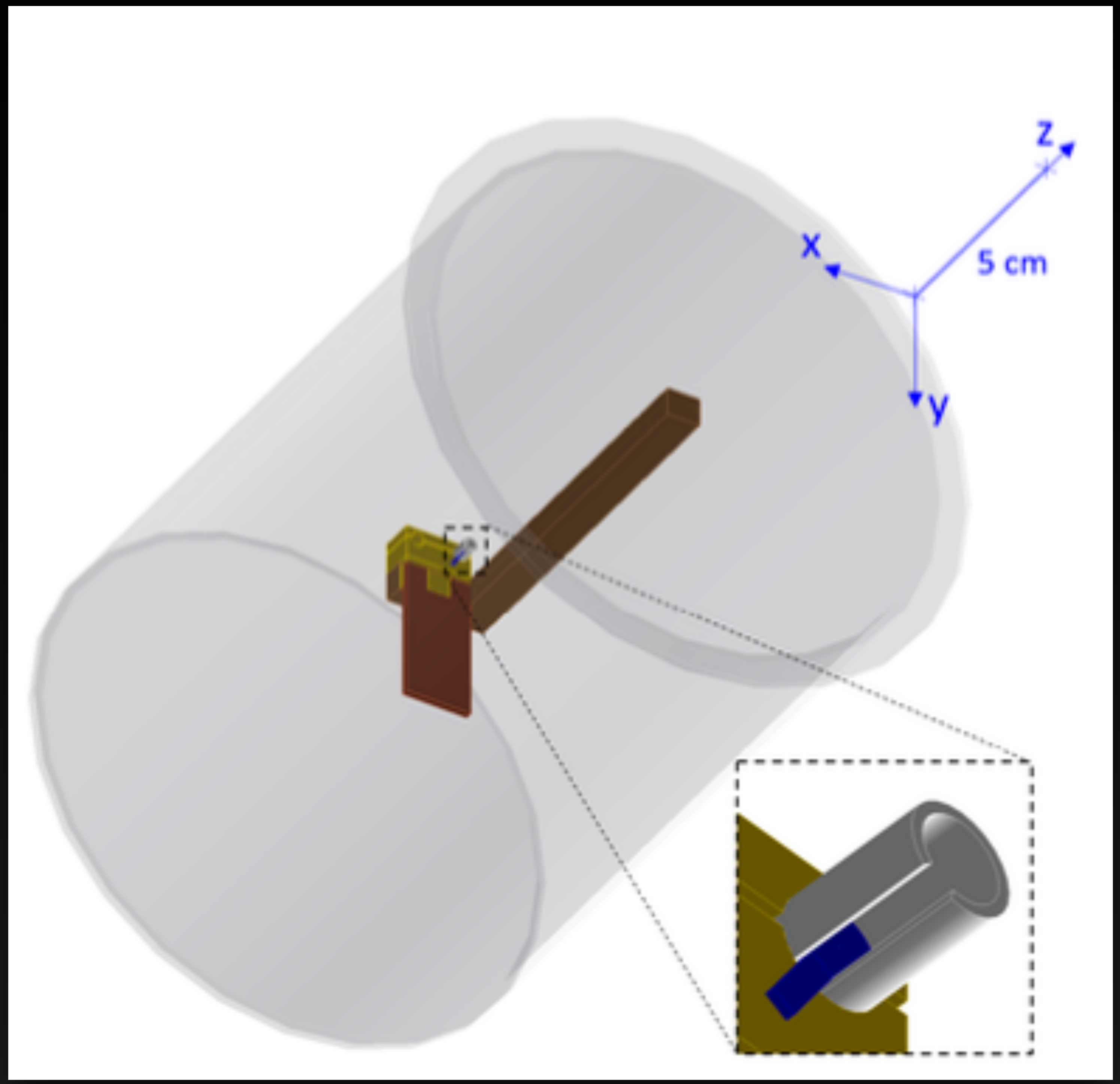
See C. Schwemmbauer's talk at IDM2024

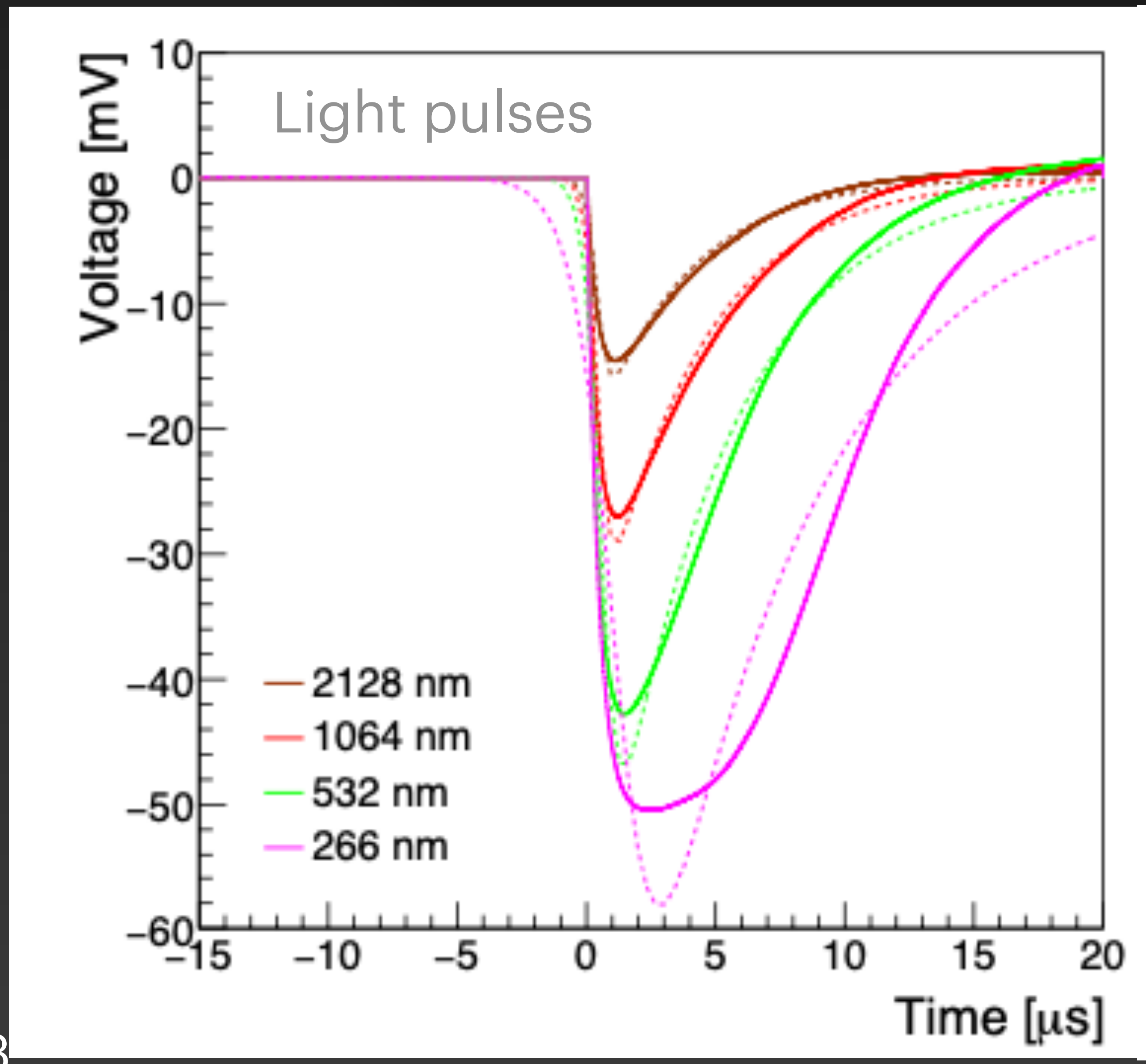
[Schwemmbauer et al. (2024), Hochberg et al. (2016)]

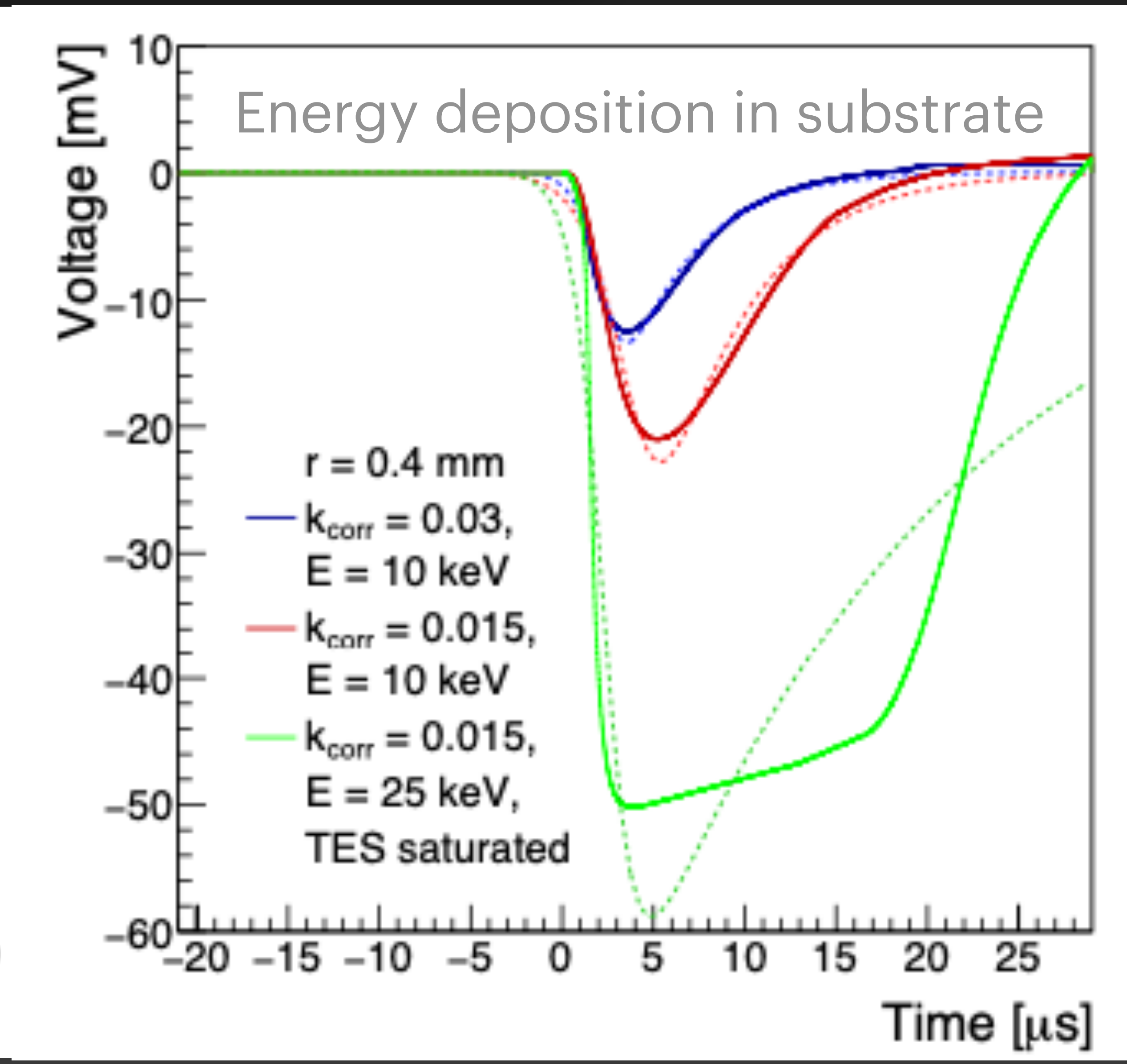
Simulation of backgrounds

- Coupled GEANT4 and COMSOL simulations
- Simulations produce light pulses well
- Possible to simulate different energy depositions on detector
- Decay of radioactive isotopes in Zr fiber sleeve probably main background contribution for dark matter searches

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



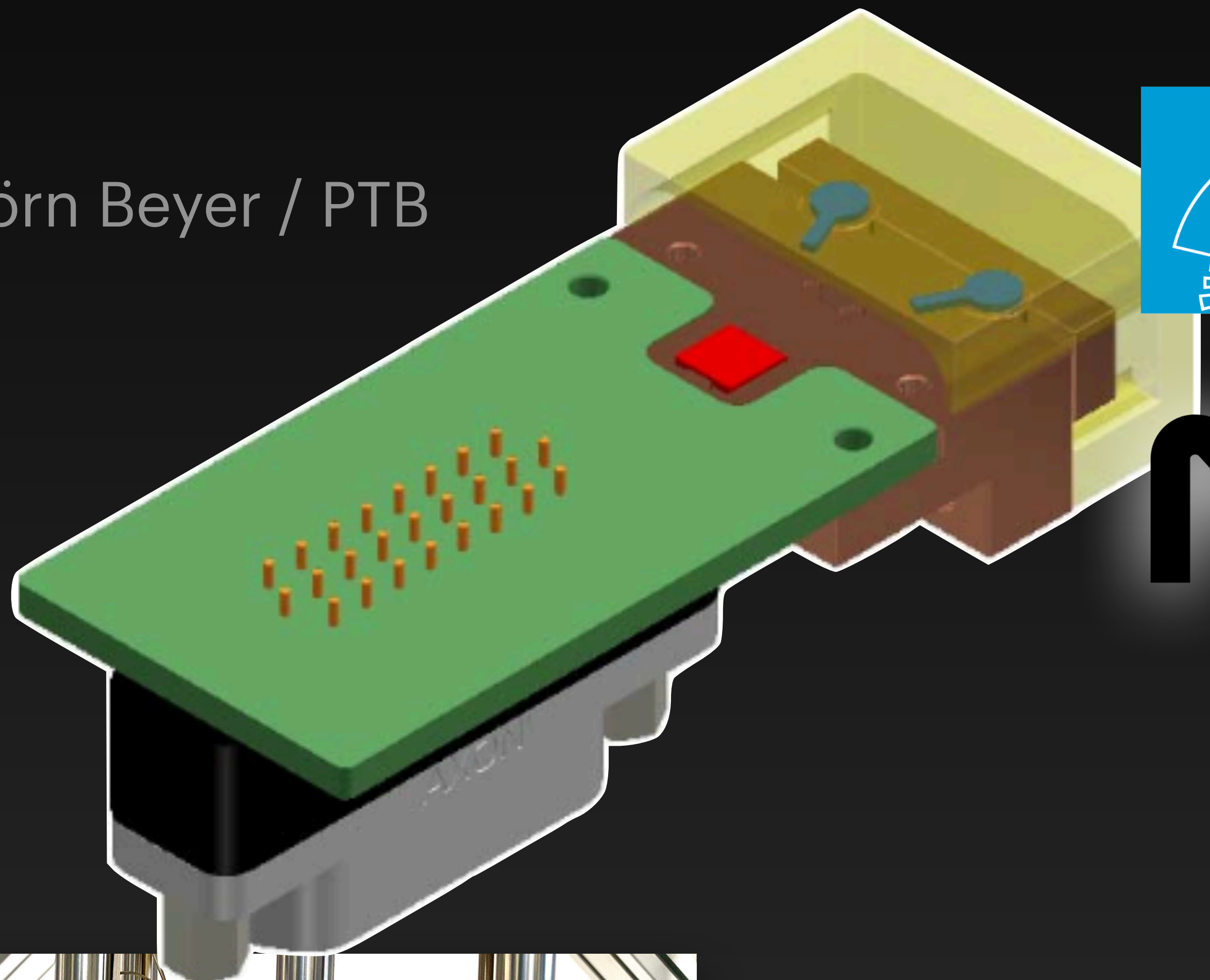




Second cryostat at DESY and new TES modules

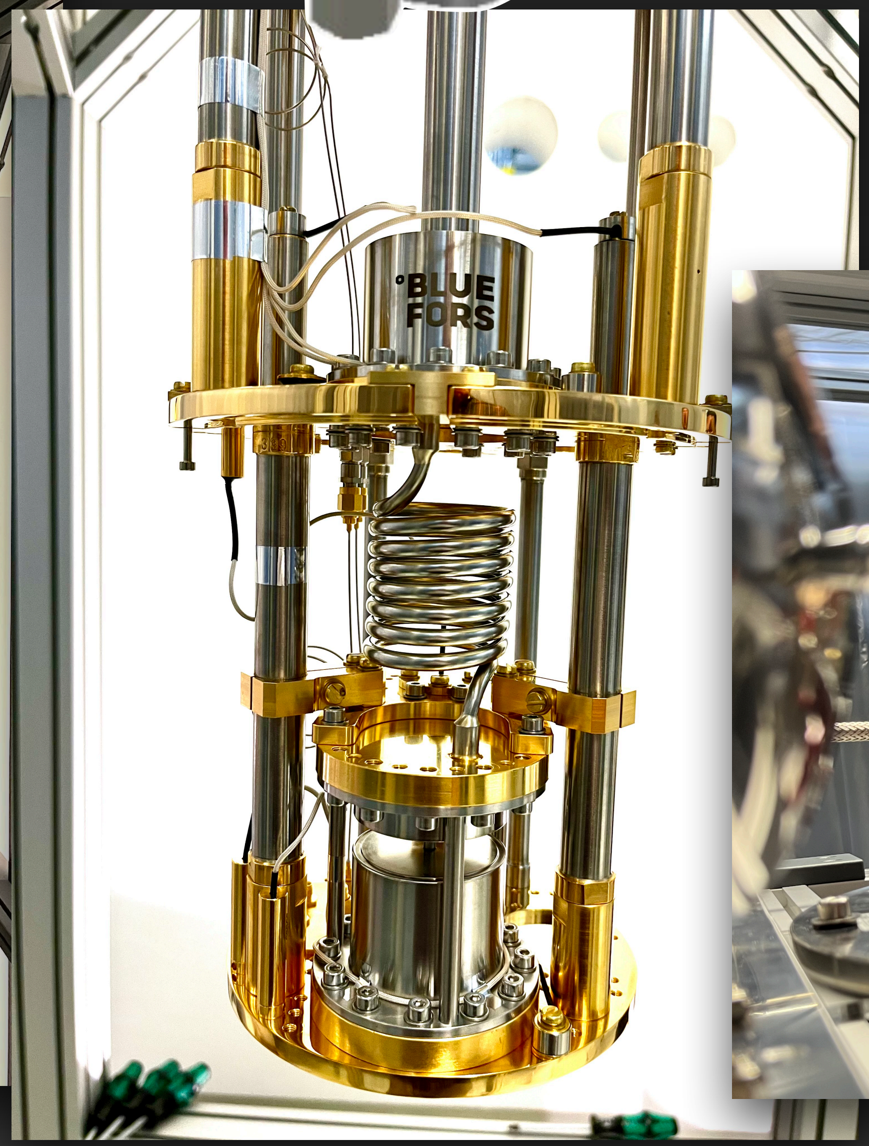
Improved TES detectors for DM searches

Jörn Beyer / PTB



- TES detectors without fiber sleeves to be delivered

- Will be tested on 2nd BlueFors cryostat installed in 2023 at DESY

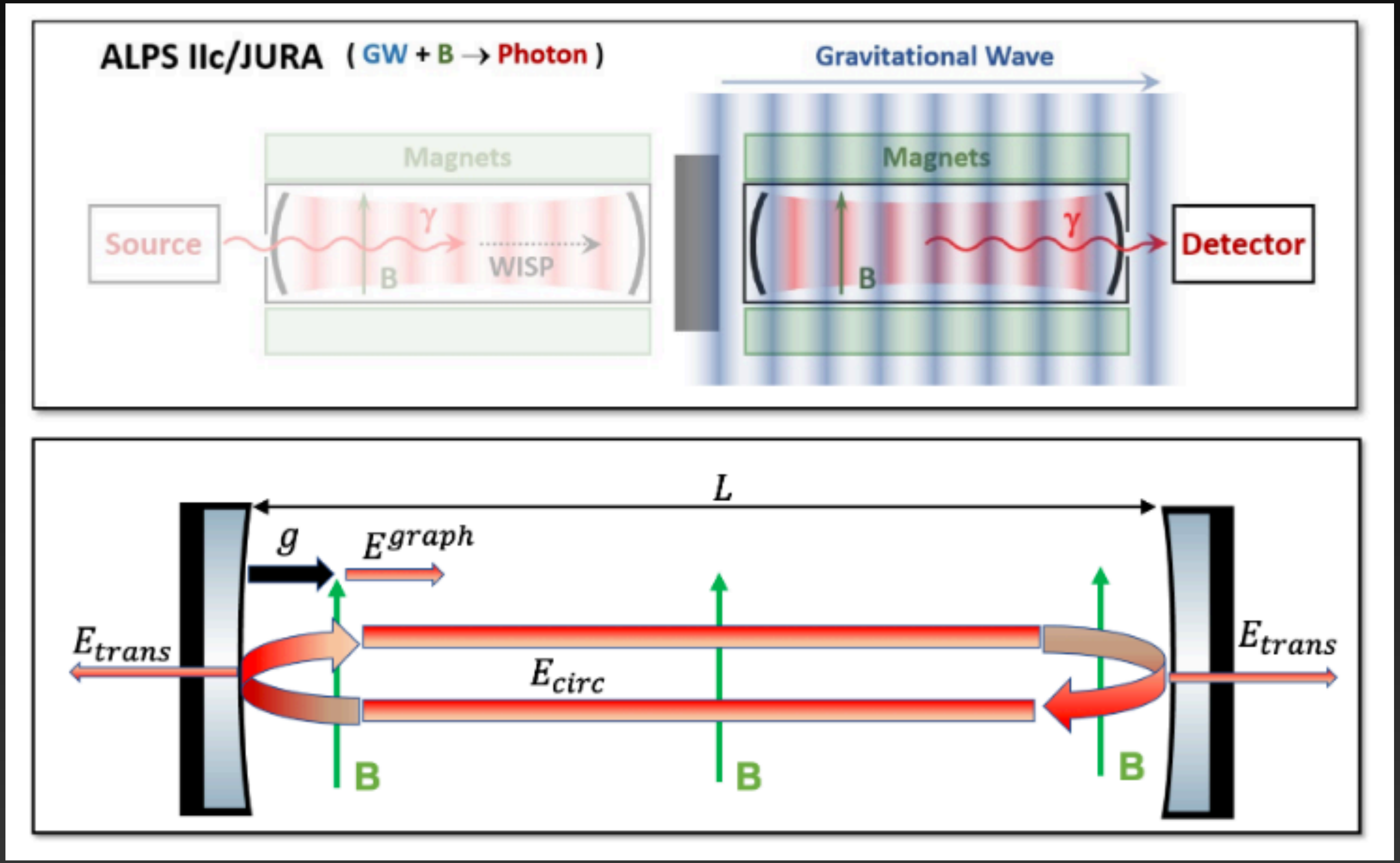


GW signals detectable with ALPS II?

Inverse Gertsenshtein effect

See also Aldo Ejlli's talk on Tuesday

- Detection of GW through conversion to photons in external B field
- Current design: possible to detect ultra-high frequency GWs at $f \sim 2 \times 10^{14}\,\mathrm{Hz}$
- No known astrophysical sources
- Close-by mergers of primordial black holes with asteroidal masses
- Current theoretical study by ISA master student Constant Peeters on going

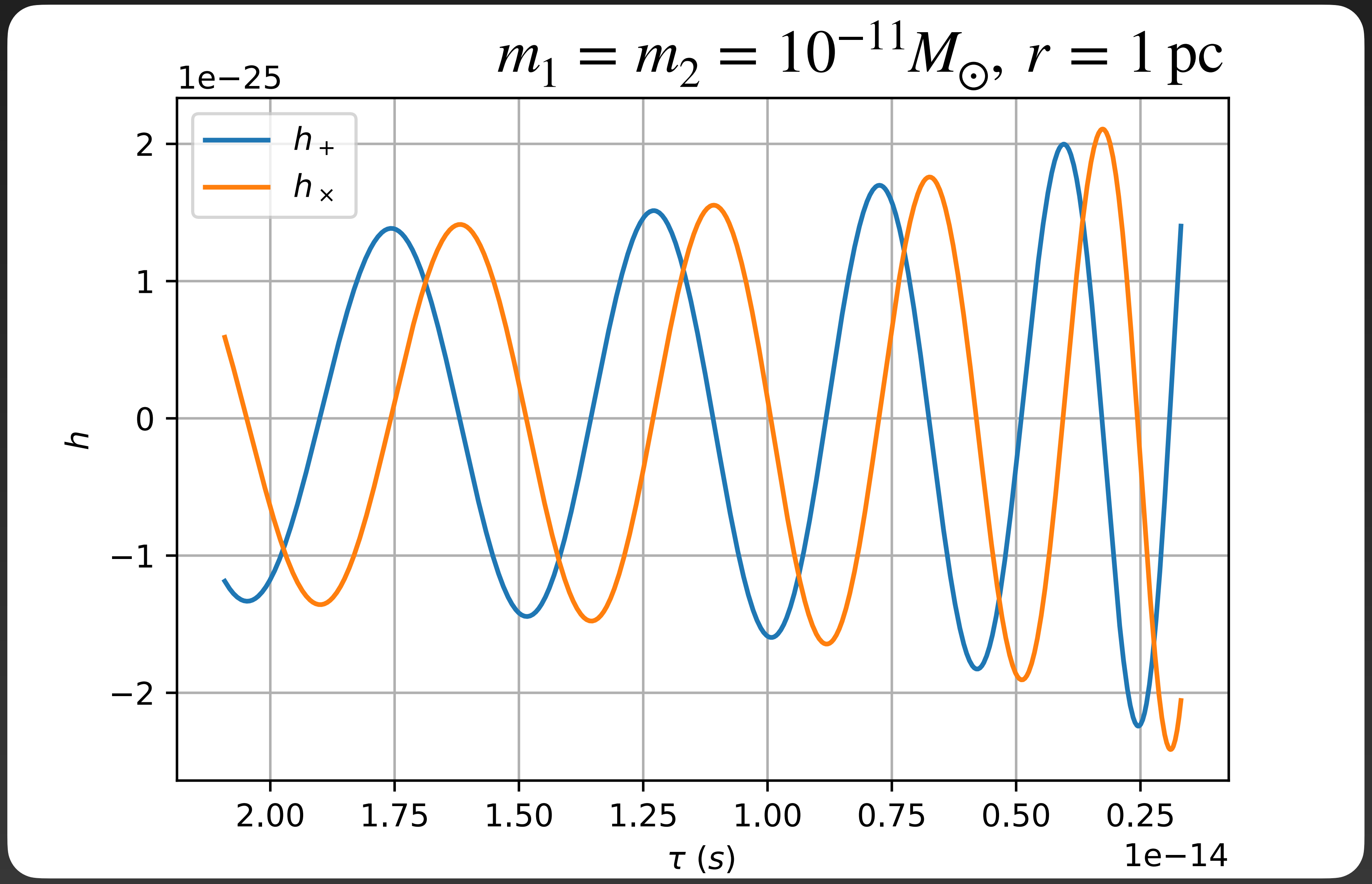


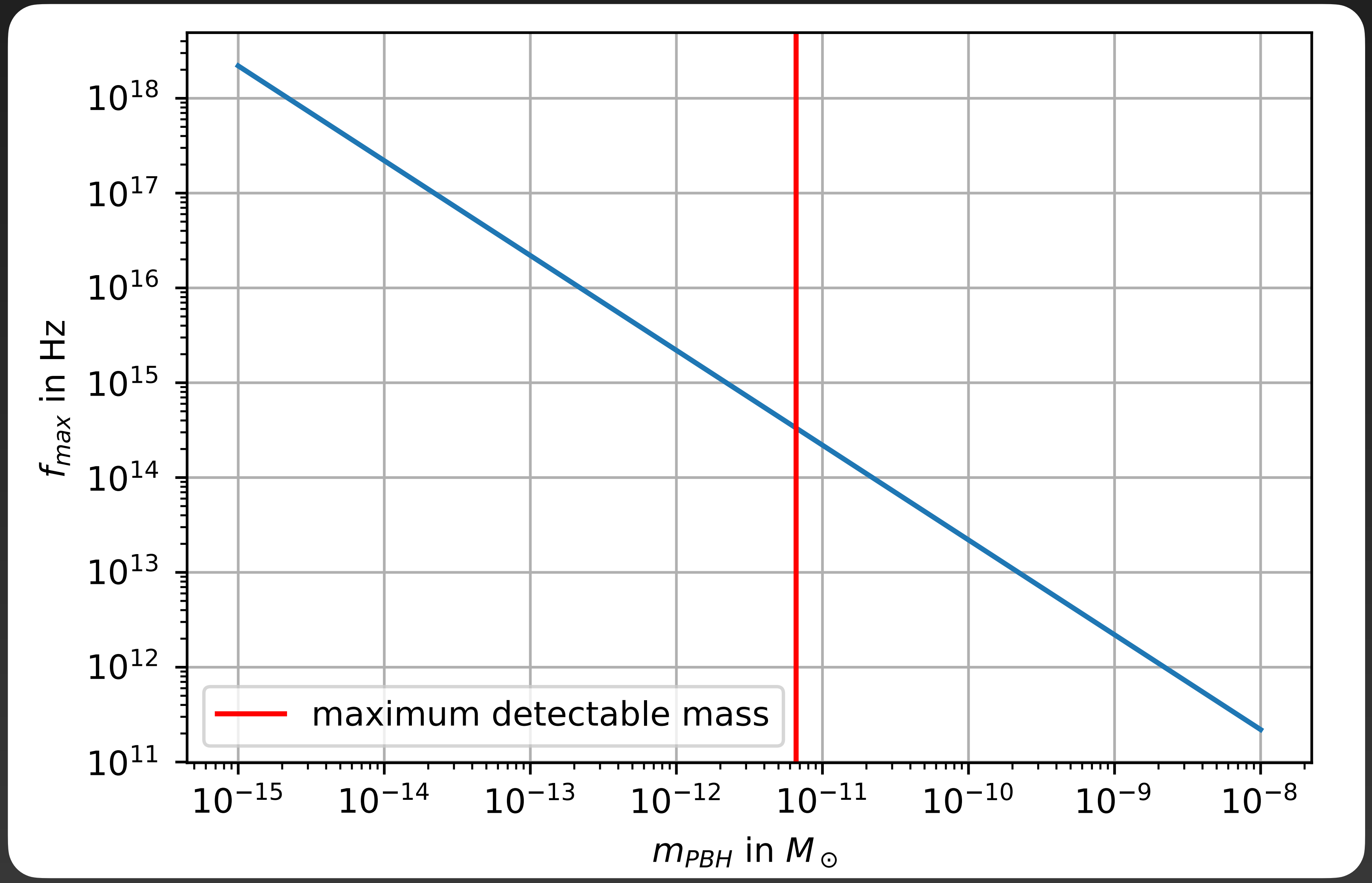
Ejlli et al. (2019) arXiv: 1908.00232v2

What could we expect from PBH mergers?
[work in progress]

SDU Master student
Constant Peters

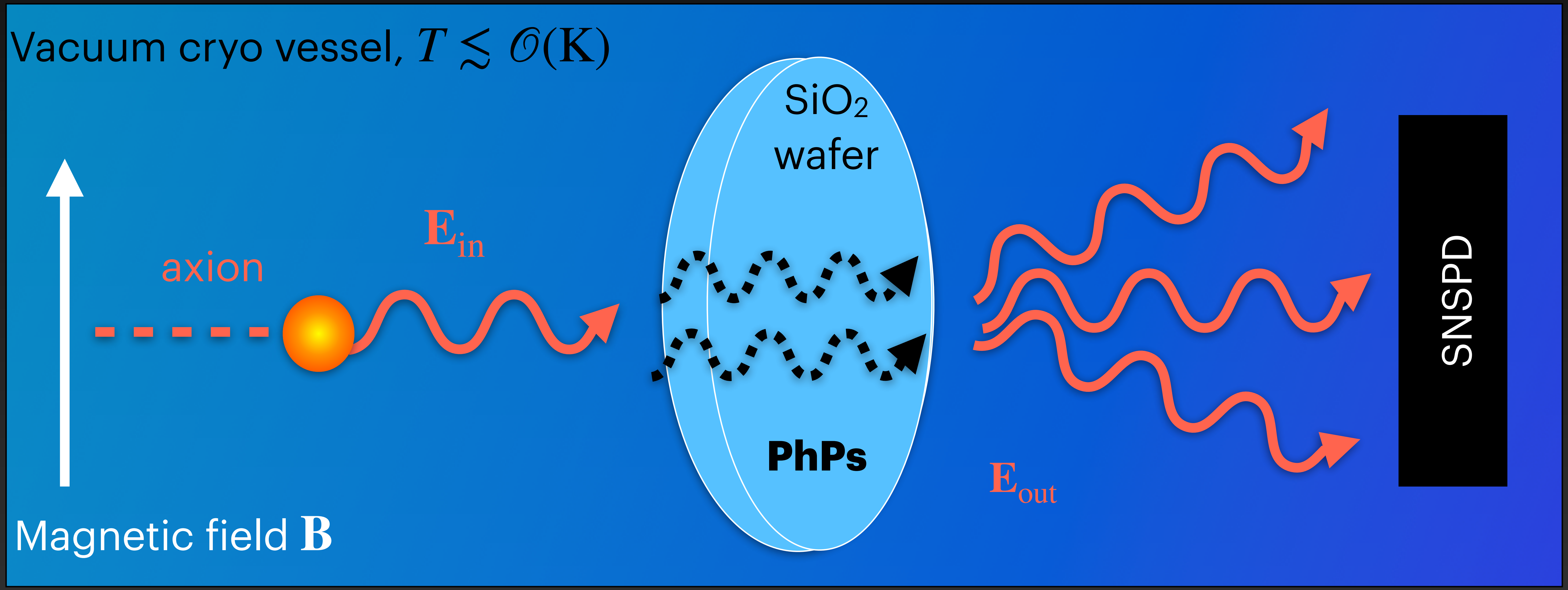
- ALPS II might be able to detect close-by merger of primordial black holes
- Masses must be $m \lesssim 10^{-11} M_\odot$ for current TES detector





Future direction: search for a phonon-polariton enhanced dark-matter axion signal

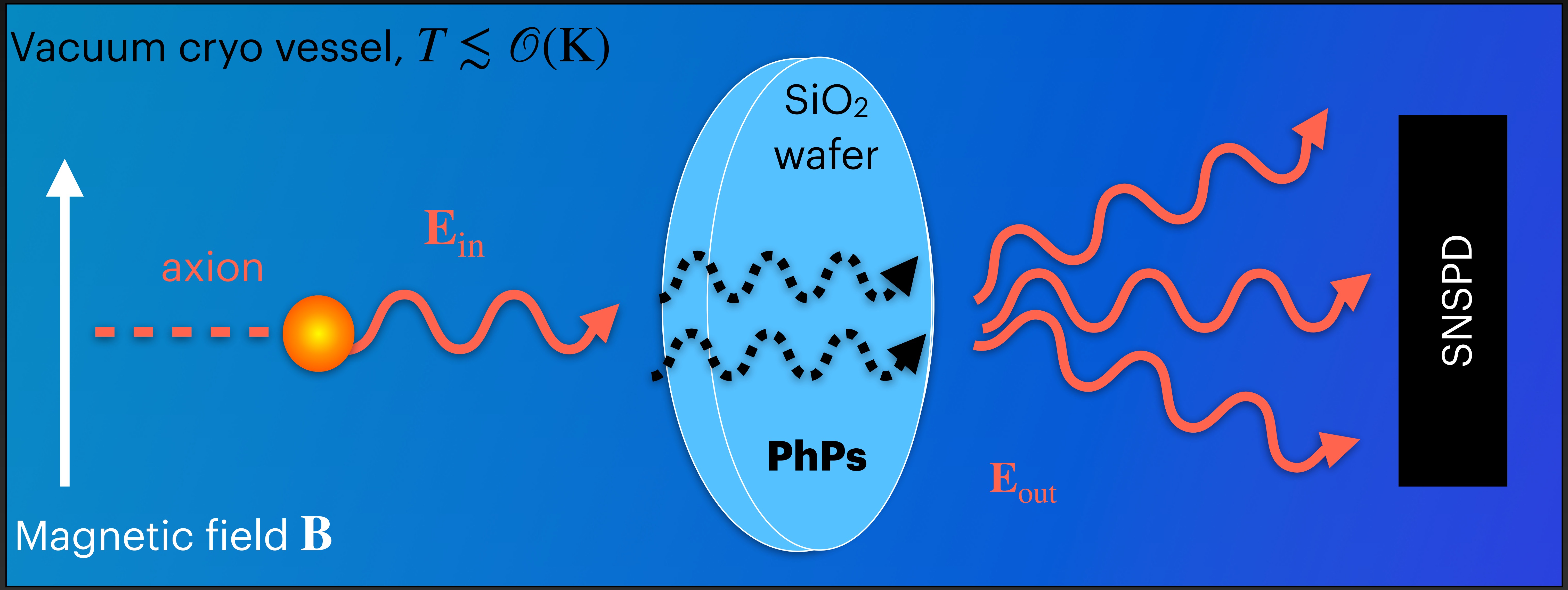
- Axions in B field generate weak E field
- E field can couple to atomic lattice with dipole molecules and excite lattice vibrations
- Excitations called phonon-polaritons
- Can resonantly enhance incoming field



DJE March et al. 2023

Future direction: search for a phonon-polariton enhanced dark-matter axion signal

- Boost $\beta = E_{\mathrm{out}}/E_{\mathrm{in}}$ depends on dielectric permittivity $\epsilon(\omega)$
- β experiences resonances close to longitudinal optical frequency ω_{LO} of phonons
- For SiO_2: ω_{LO} at MIR wavelengths
- Requires single photon detection at MIR within high B field



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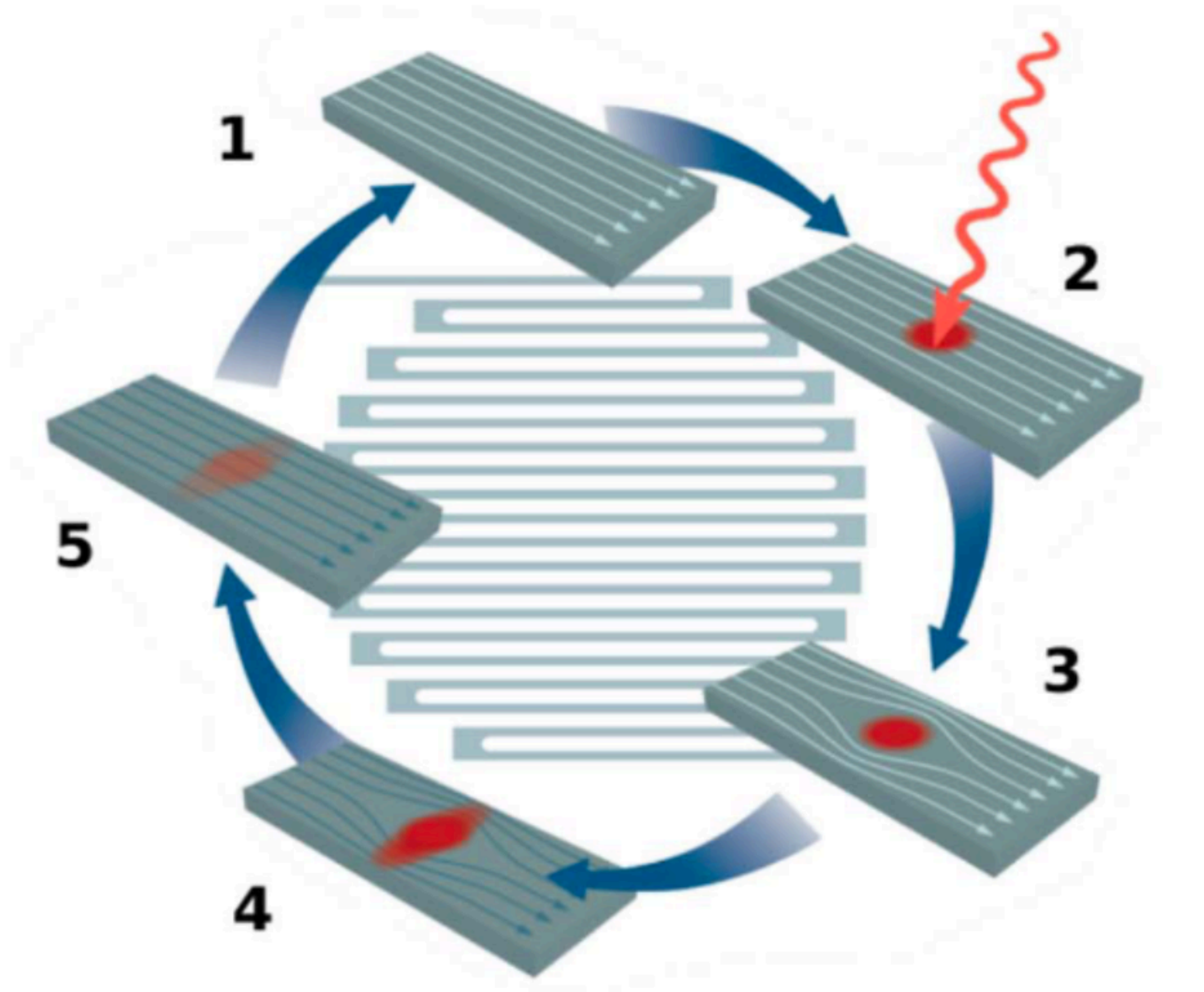
SNSPDs

Superconducting Nanowire Single-Photon Detectors

- Absorption of photon increases resistance by $\sim \mathrm{k}\Omega$ on timescale of ps
- Produces digital pulse
- No energy resolution, only photon counting
- Might withstand high magnetic fields
- Sensitive at MIR
  [Verma et al., 2022]

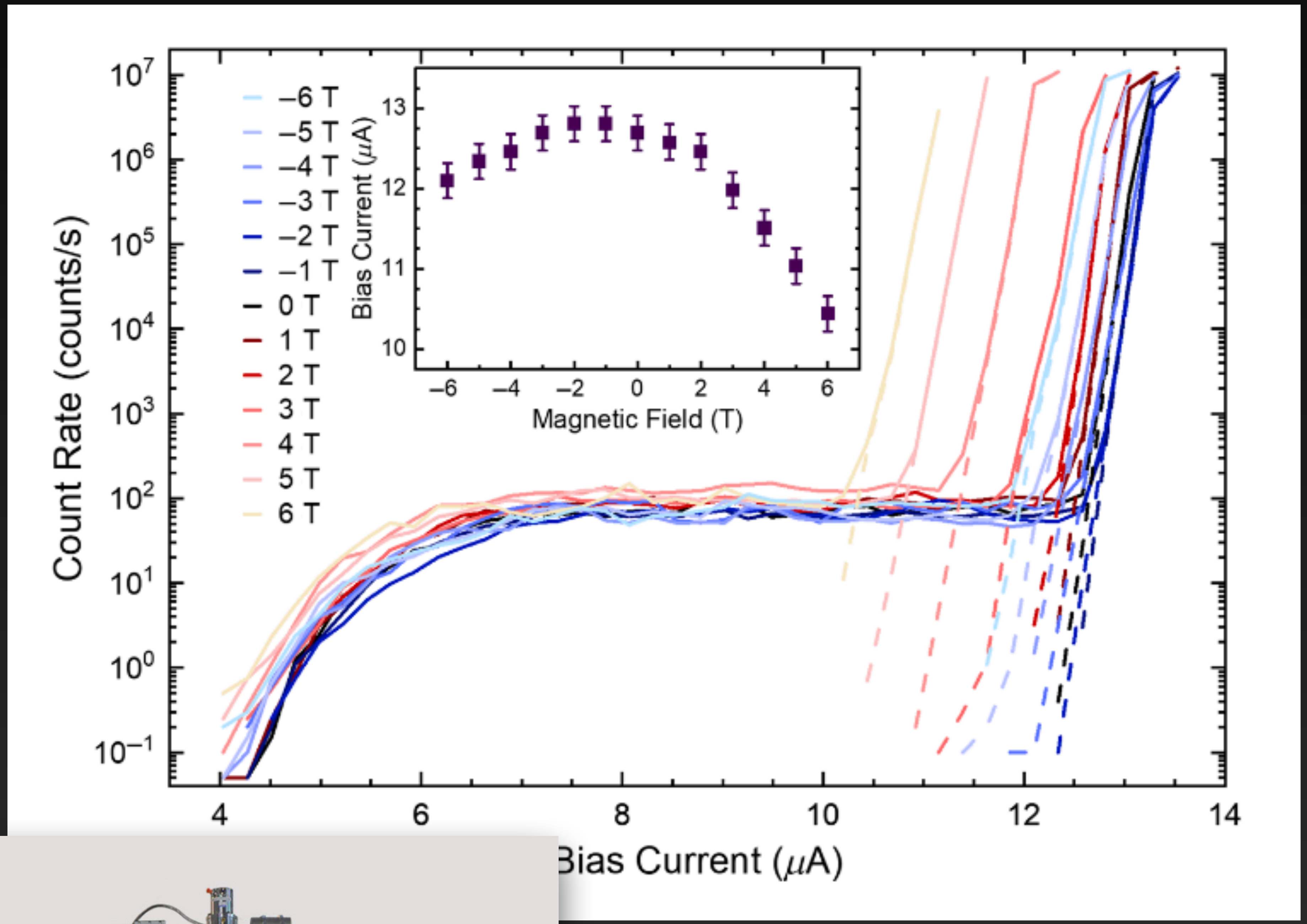


[See review by Lita et al. (2022)]

Plans at SDU: measure SNSPD performance in high magnetic field

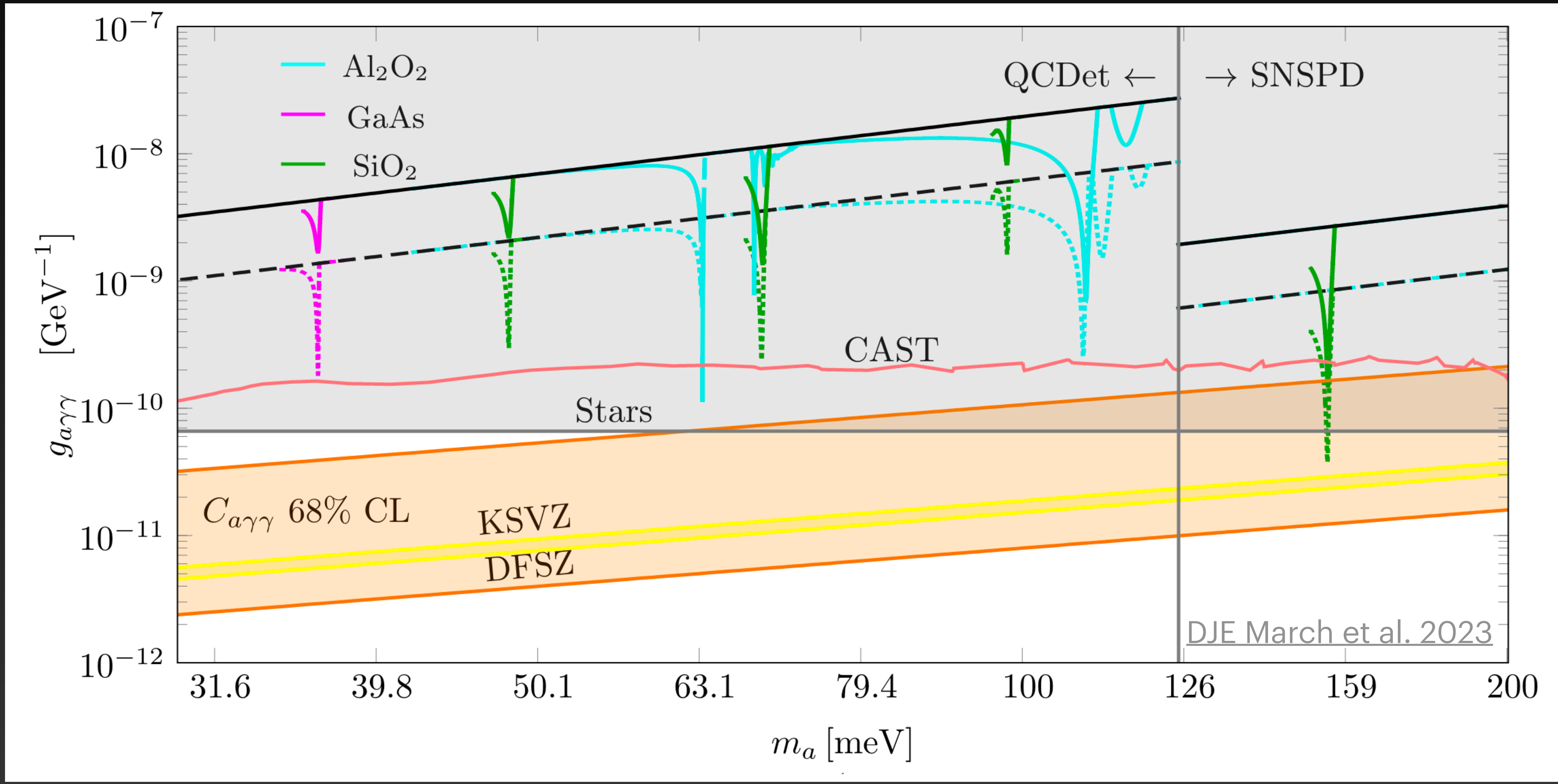
[Lawrie et al. 2021]

- First studies suggest that SNSPDs can be operated at fields up to 6T
- Cryostat with $B \leqslant 8\,\mathrm{T}$ will be delivered to SDU in October
- Launch pilot experiment for phonon-polariton enhanced axion signal



Sensitivity estimates for phonon-polariton enhanced DM signal

- Sensitivity estimates for disks of radius of 10cm and thickness of 0.01mm
- Might allow challenging parameter space $m_a \sim \mathcal{O}(100\,\mathrm{meV})$
- Tuning could be challenging



DJE March et al. 2023

Summary and outlook

- ALPS II has started data taking, full sensitivity down to $g_{a\gamma} \gtrsim 2 \times 10^{-11}\,\mathrm{GeV}^{-1}$ to be reached in next years
- Single photon detection with TES as alternative detector
- Characterization of TES at DESY is ongoing
- Working on soft- and hardware based background suppression
- TES many applications beyond ALPS II: squeezed light, searches for light WIMPs, ultra-high frequency GWs
- Will start up working on SNSPDs in Q4 2024