A Superconducting Single-Photon Detector
for ALPS II and other new physics searches

Gulden (Joule) Othman for the ALPS II collaboration
University of Hamburg

14 April, 2023. World Quantum Day, DESY Hamburg

Any Light Particle Search (ALPS) II

Goal: To detect reconverted photons from axions and axion-like particles (ALPs)

- Axions and ALPs can constitute all or some of the **dark matter**
- Axions are a solution to the **Strong CP problem**

- **ALPS can access 5x smaller couplings than LHC for these particles**

DESY.

ALPS II

Any Light Particle Search (ALPS) II

DESY, Hamburg

7 institutions, ~30 members

Germany, US, UK, Denmark

Gefördert durch DFG Deutsche Forschungsgemeinschaft

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

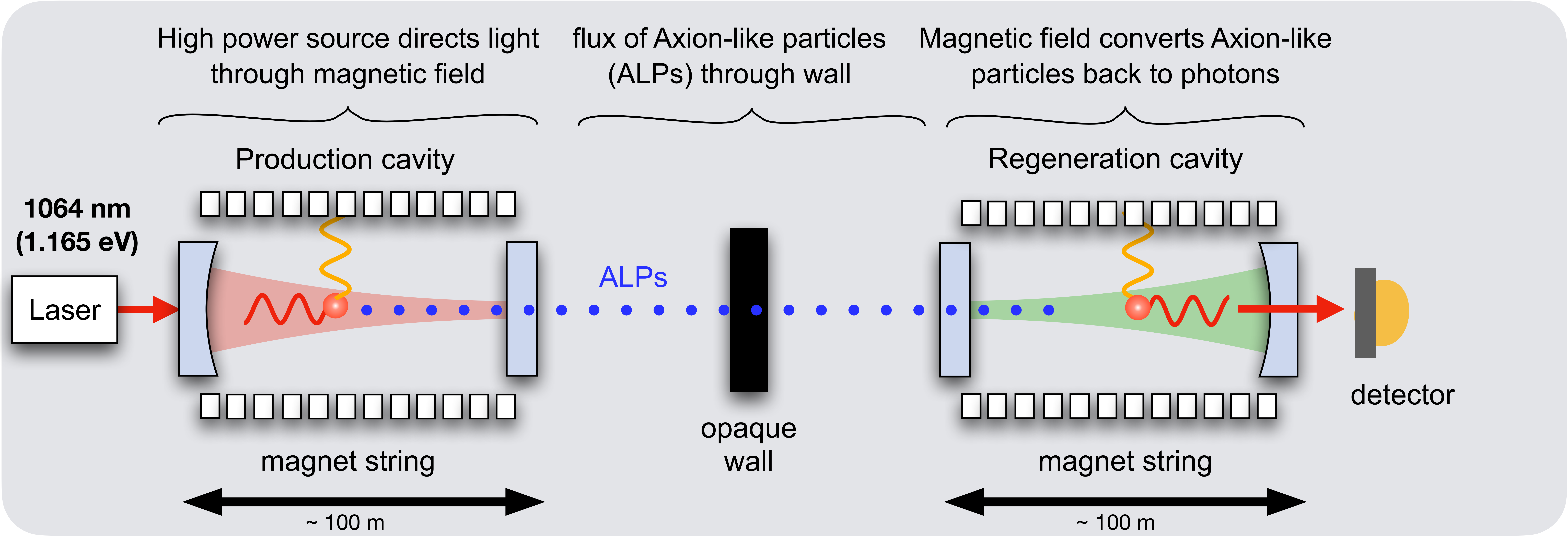
NSF

HEISING-SIMONS FOUNDATION

Science & Technology Facilities Council

erc

The ALPS II Experiment



Courtesy of Katharina-Sophie Isleif

Expect 1 infrared photon / day

First Science Run this Summer

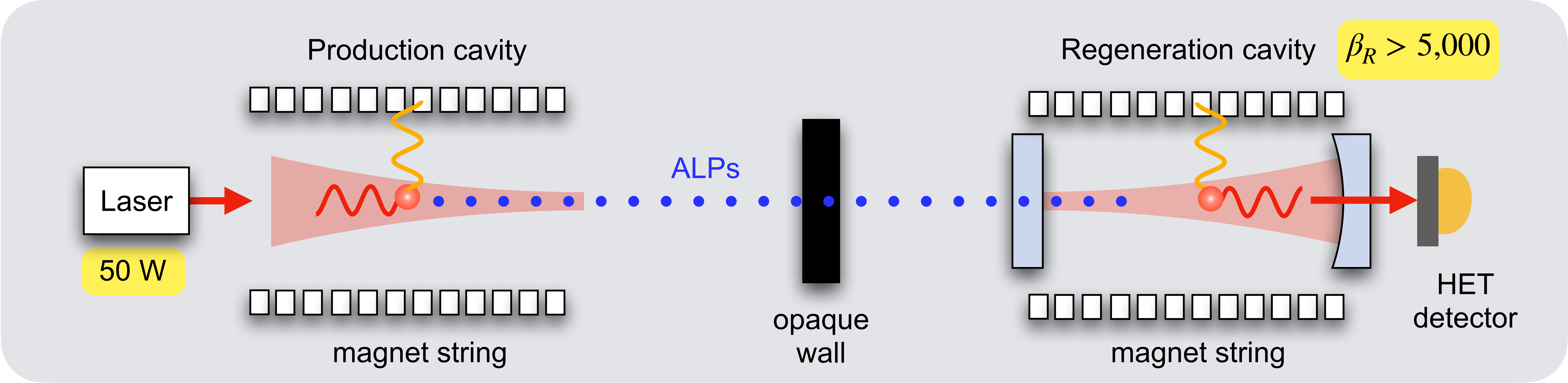
Commissioning optical setup without production cavity

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

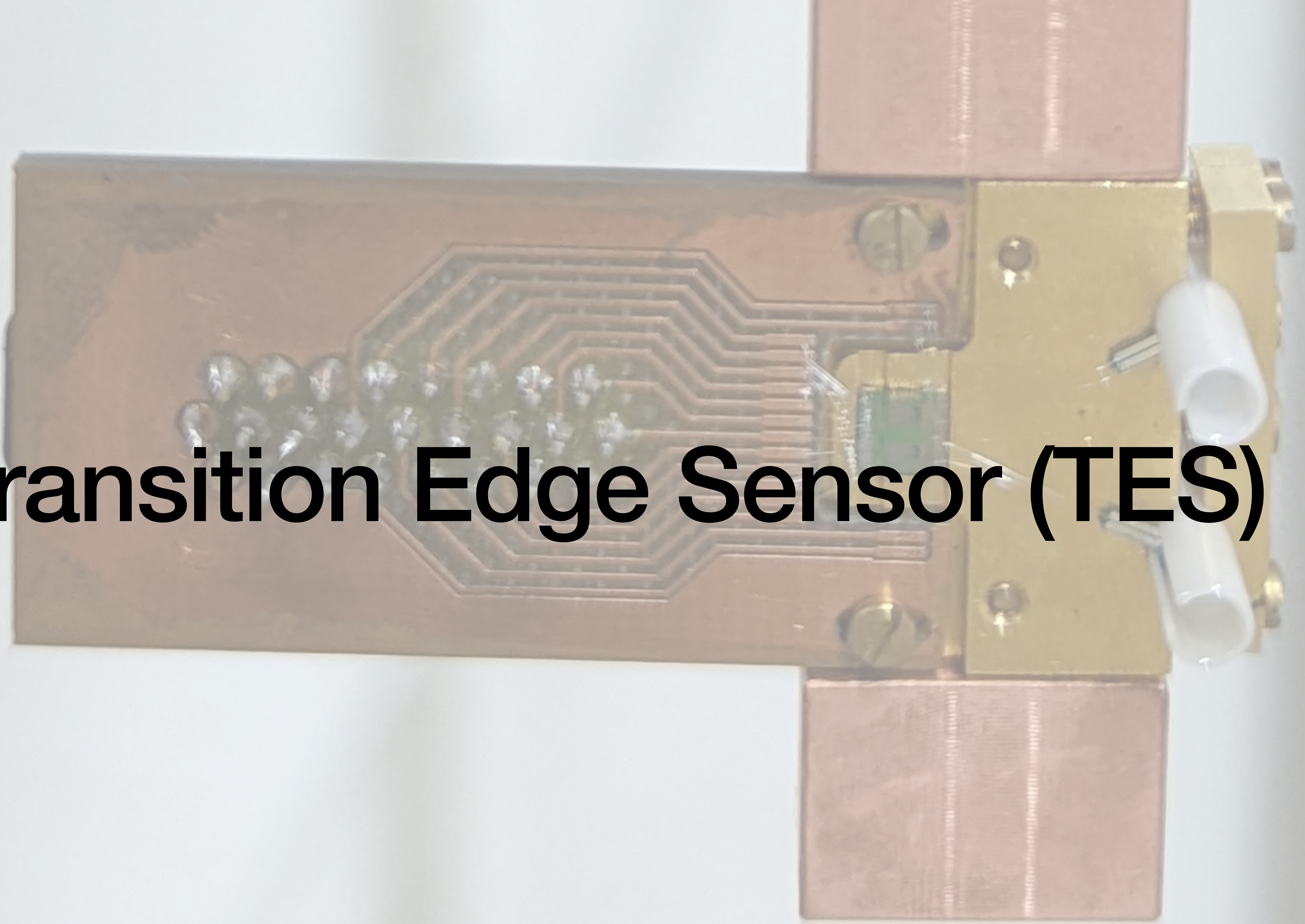
Stay tuned!

"ALPS Day" end of May

Graphic from Katharina-Sophie Isleif



Transition Edge Sensor (TES)



ALPS II Measurement Requirements

Goal: Single infrared photon detection, single photon per day

High Quantum Efficiency

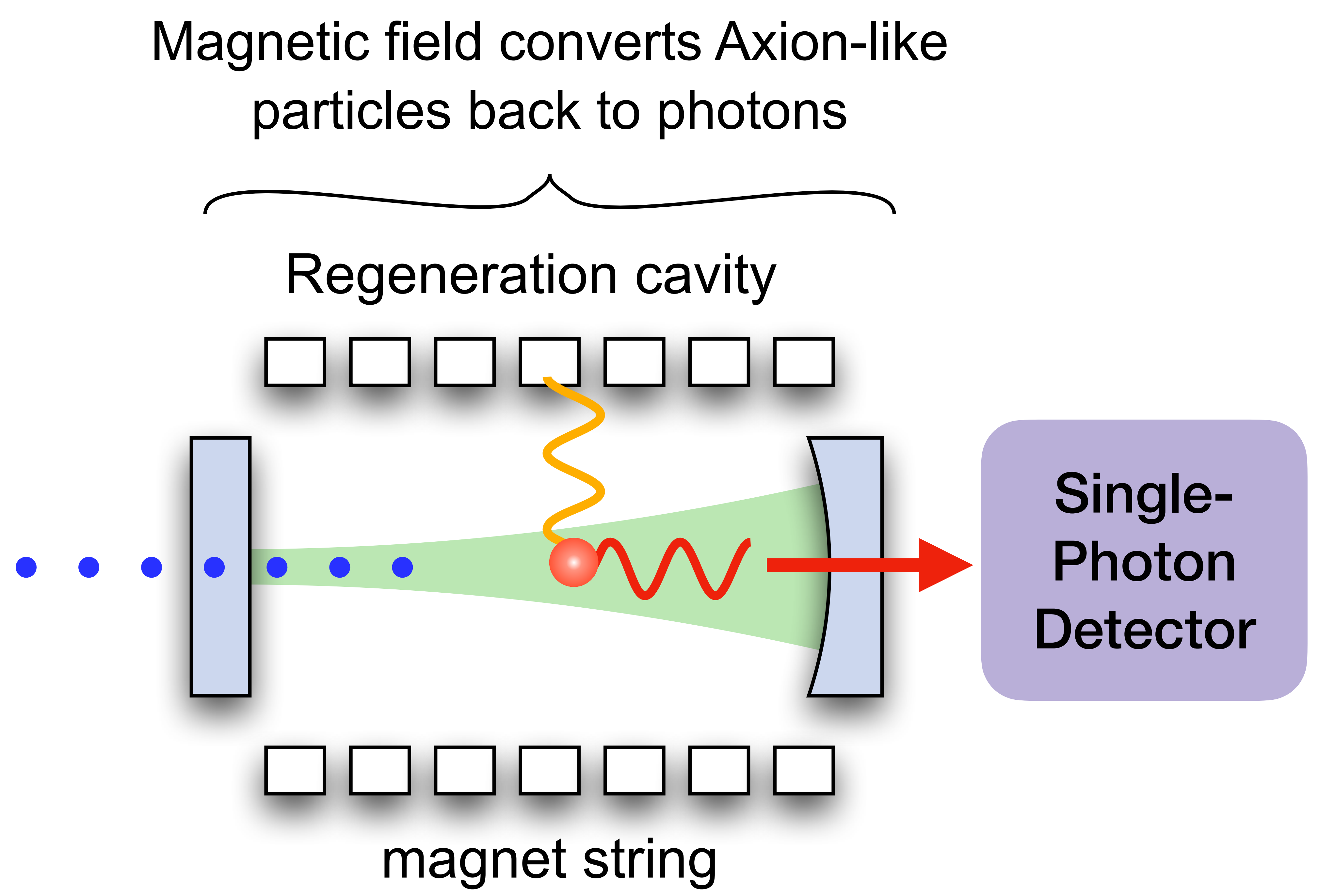
- **~ >99%** at wavelength of interest
  (1064 nm ~ 1.165 eV)

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)



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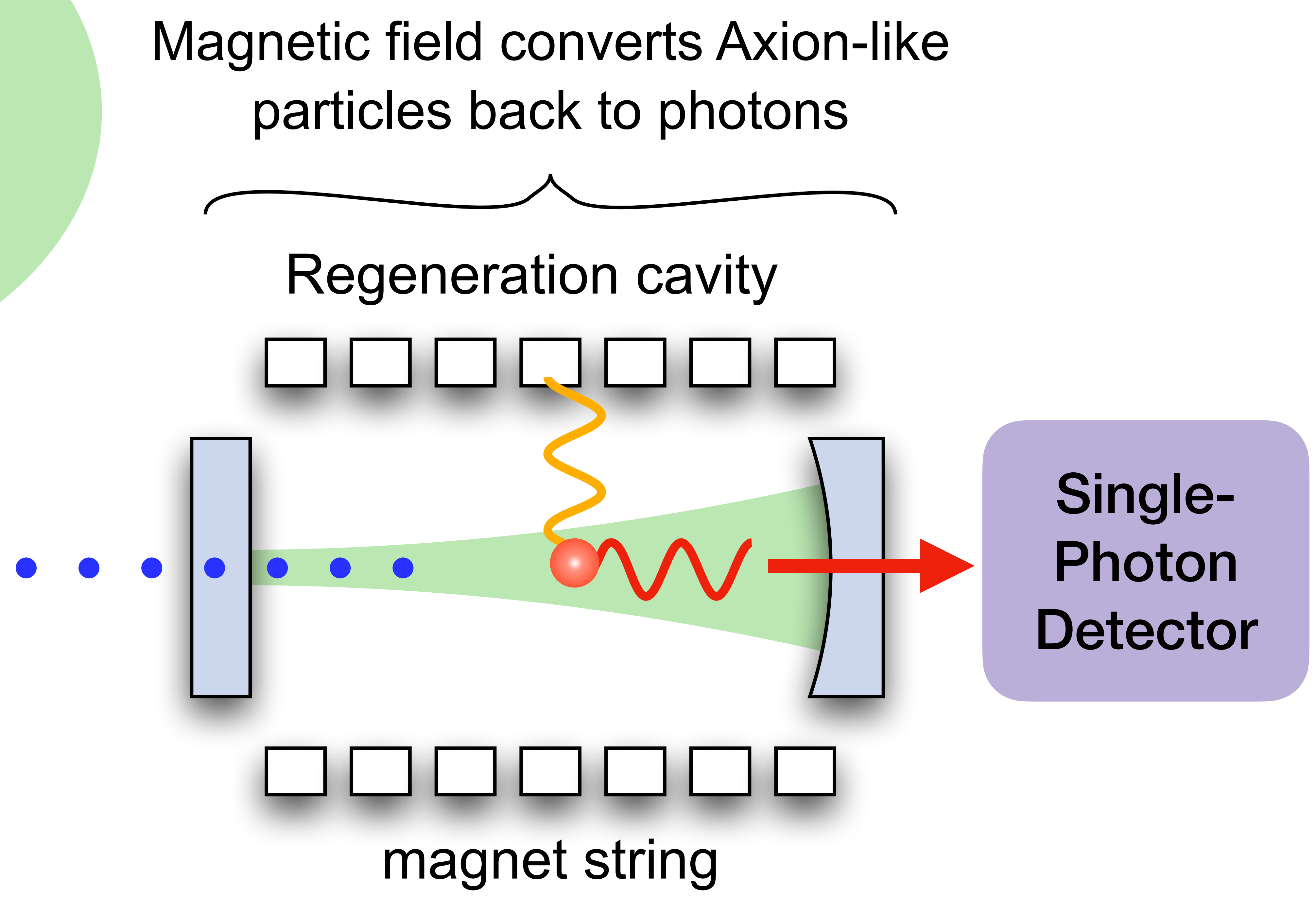
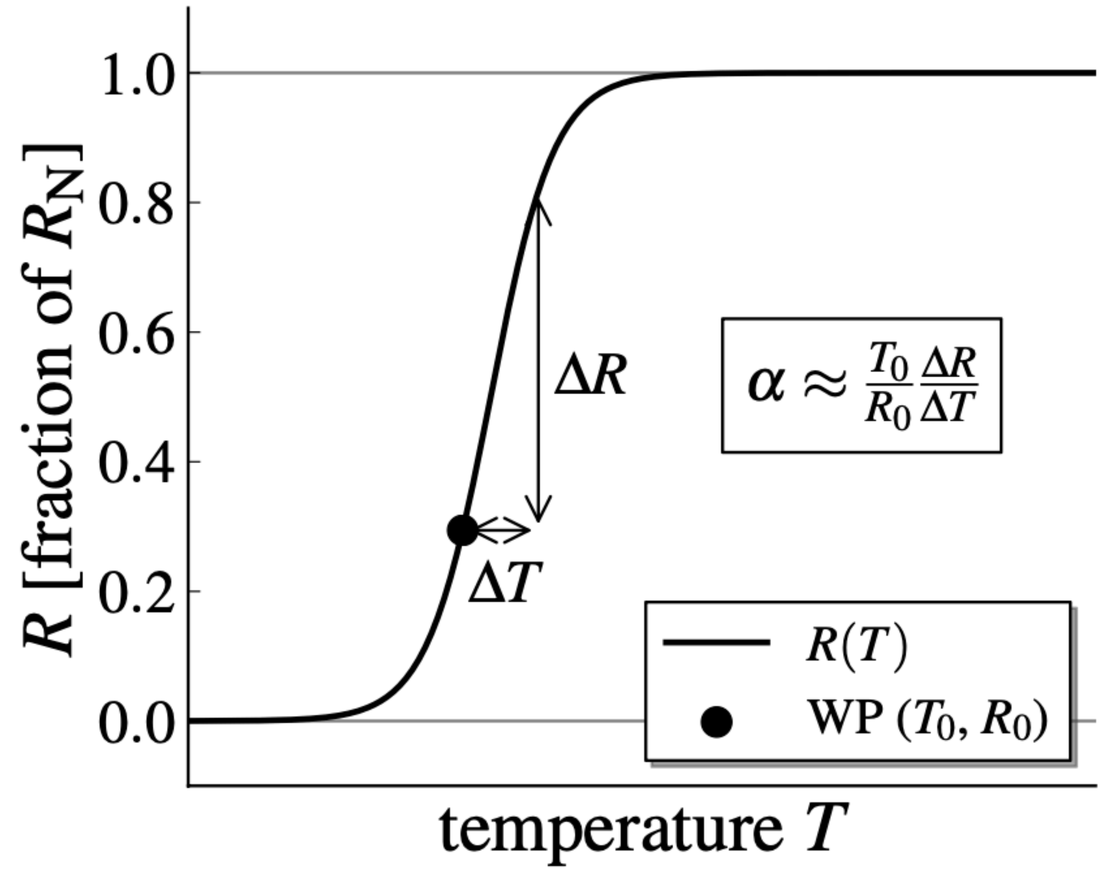
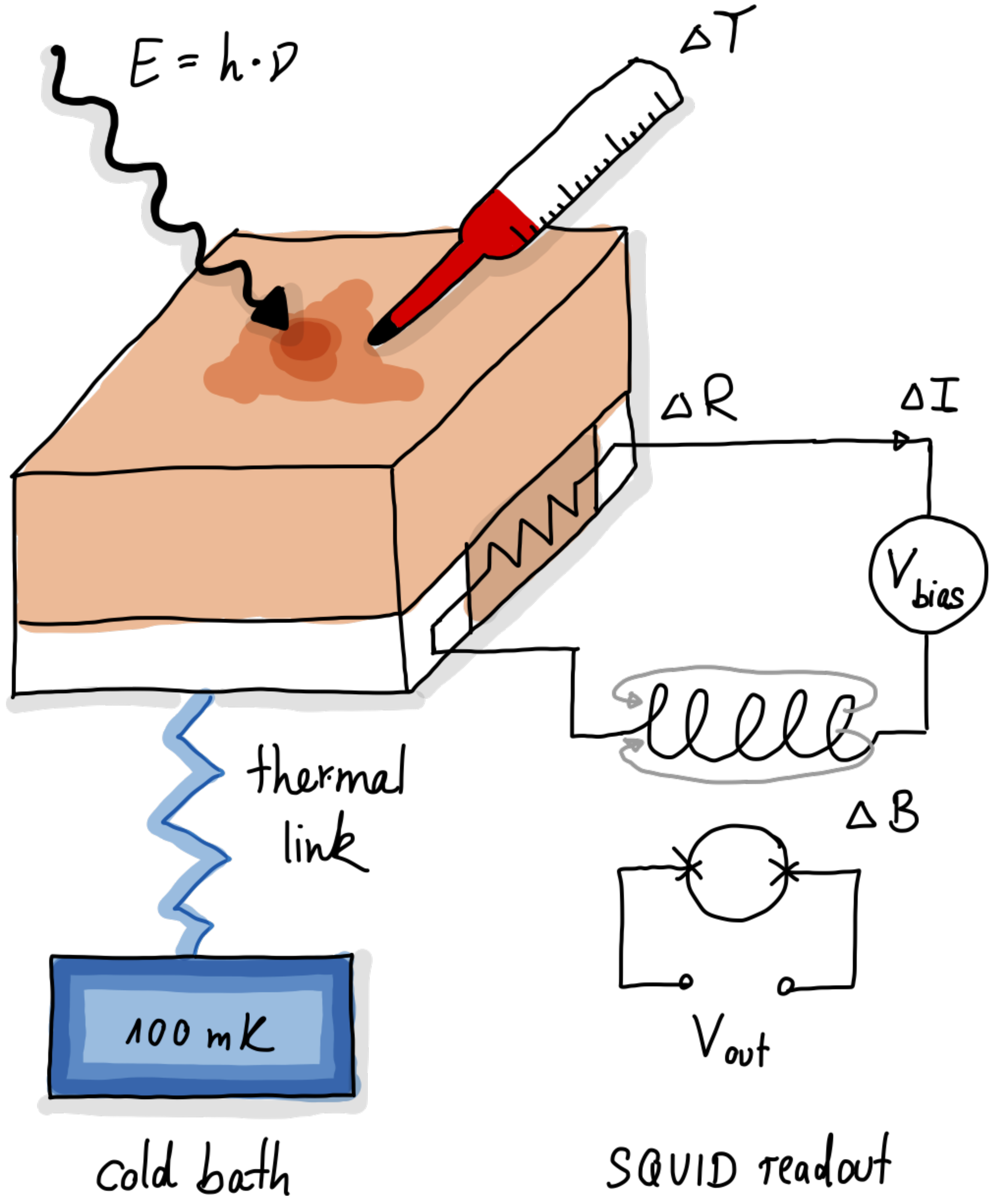
Transition Edge Sensors!



Transition Edge Sensor Working Principle

- Superconducting material held near transition (Tungsten: 140 mK)
- Incoming photon 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 change





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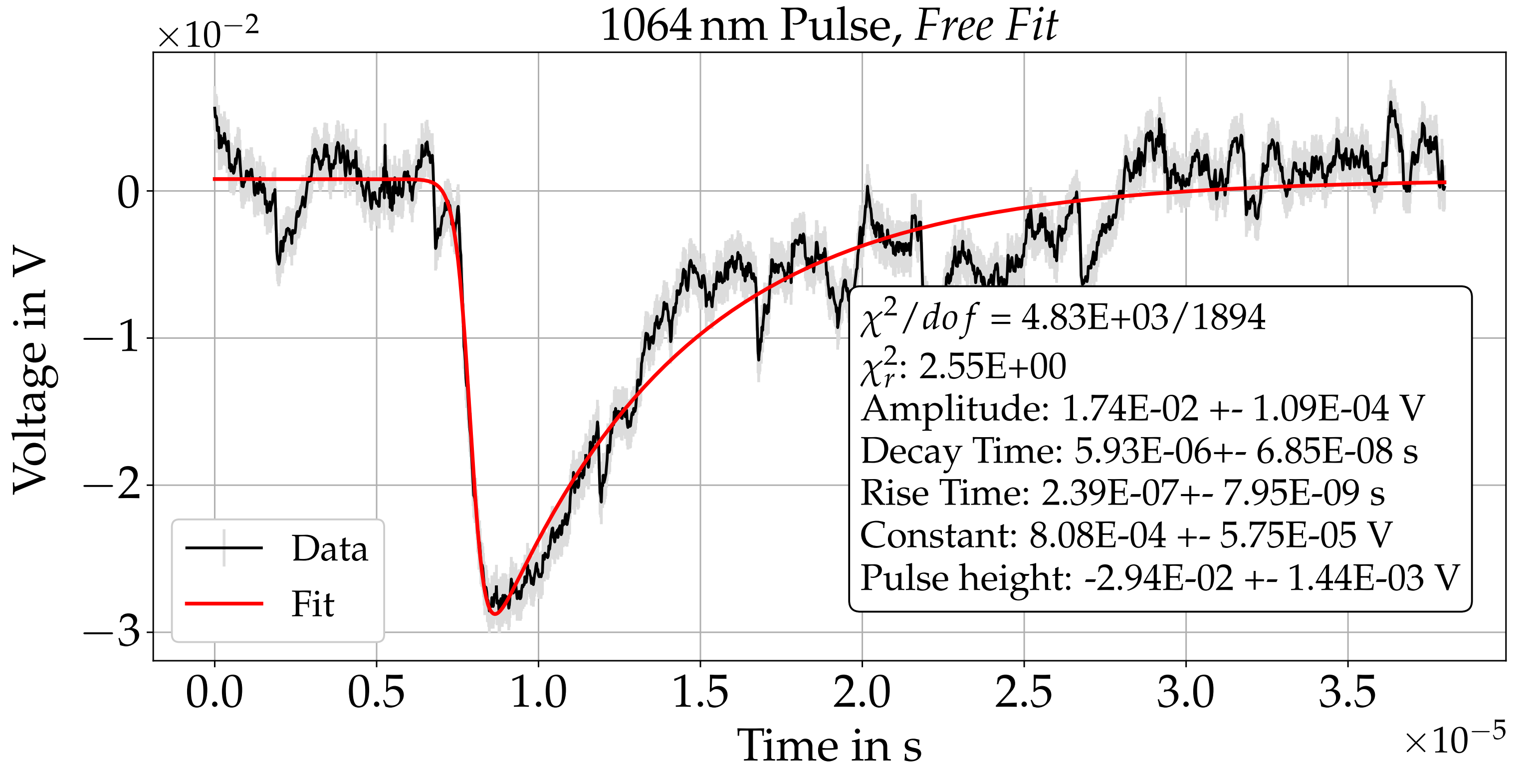
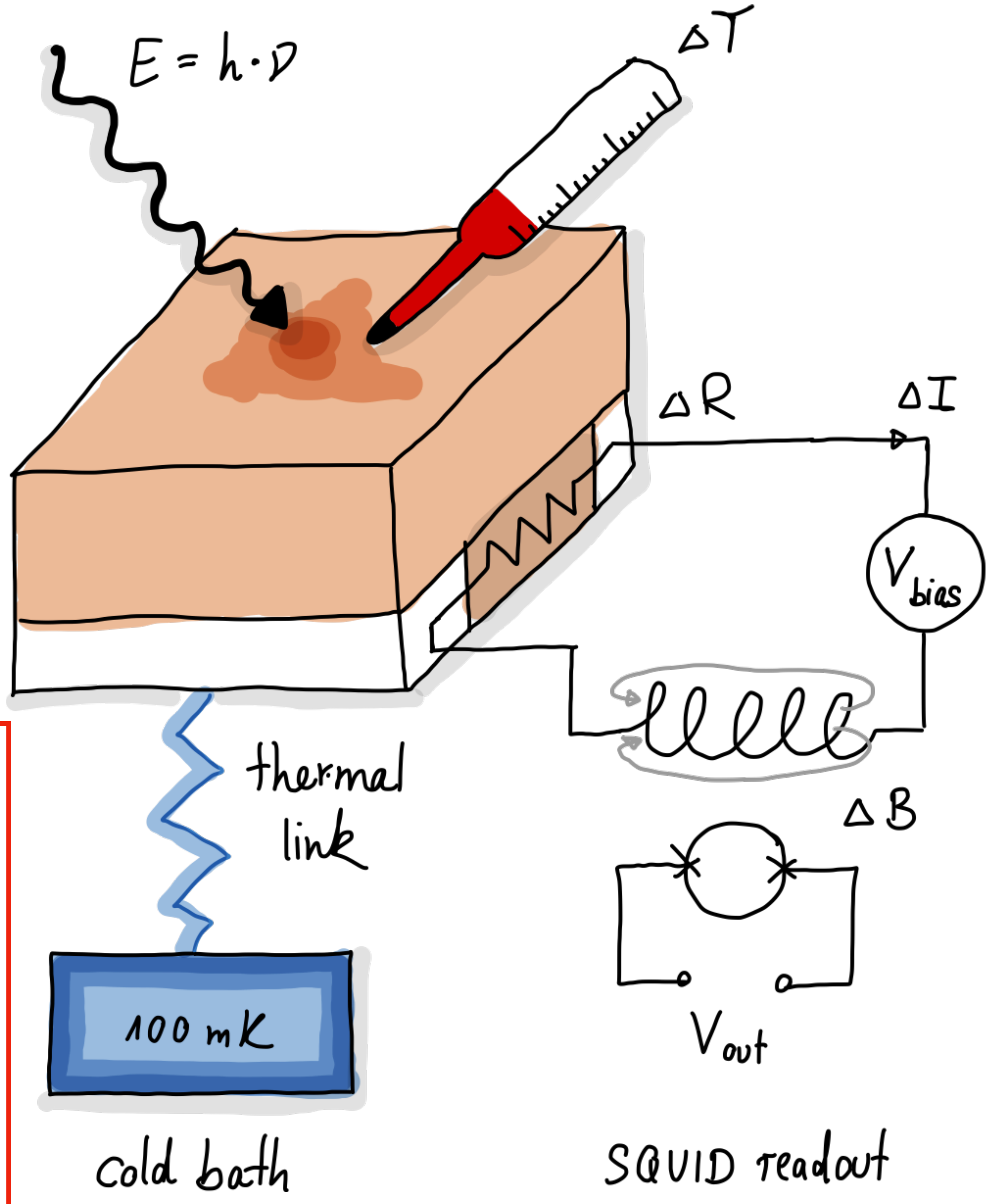
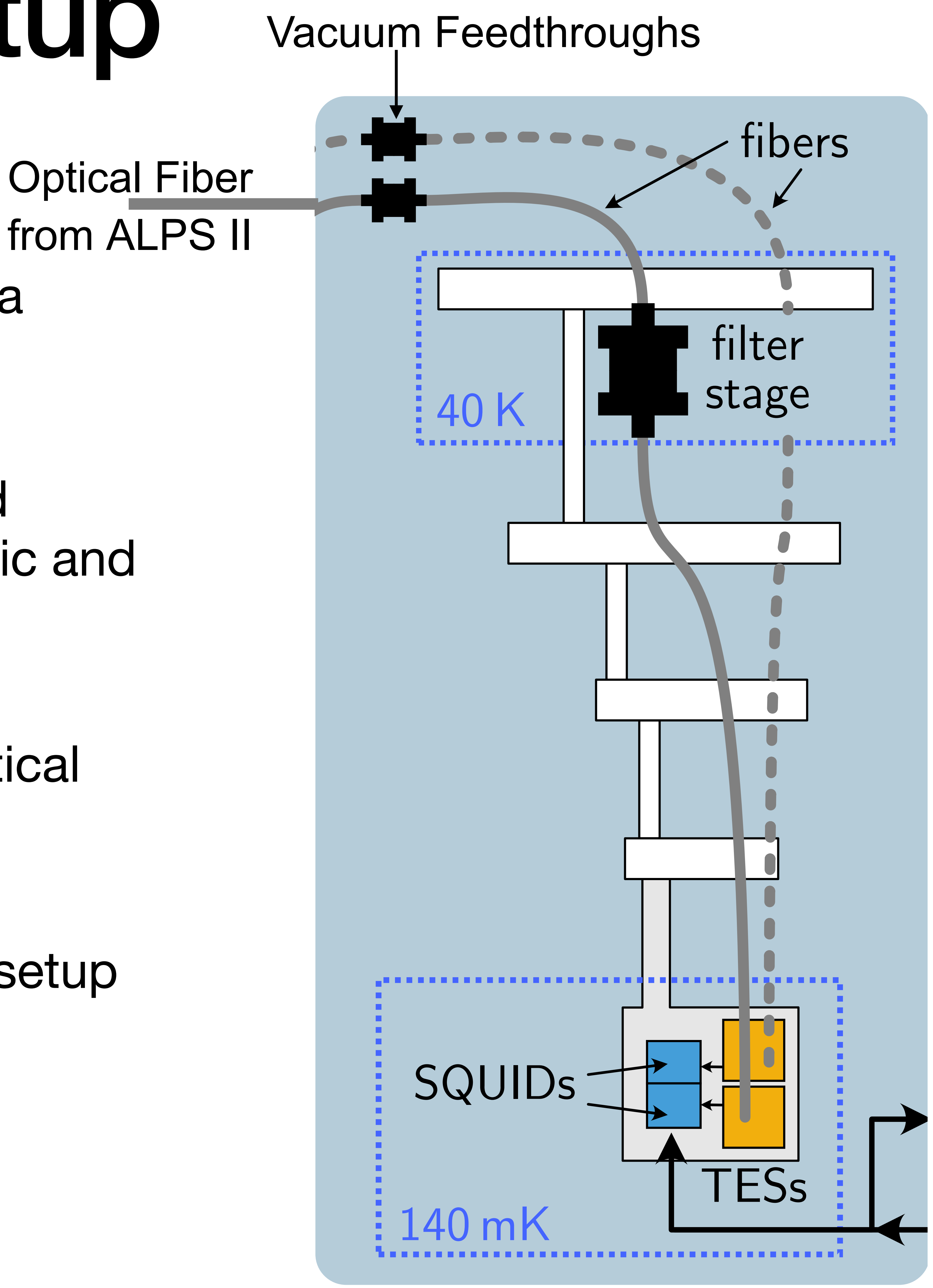
Example Light Pulse



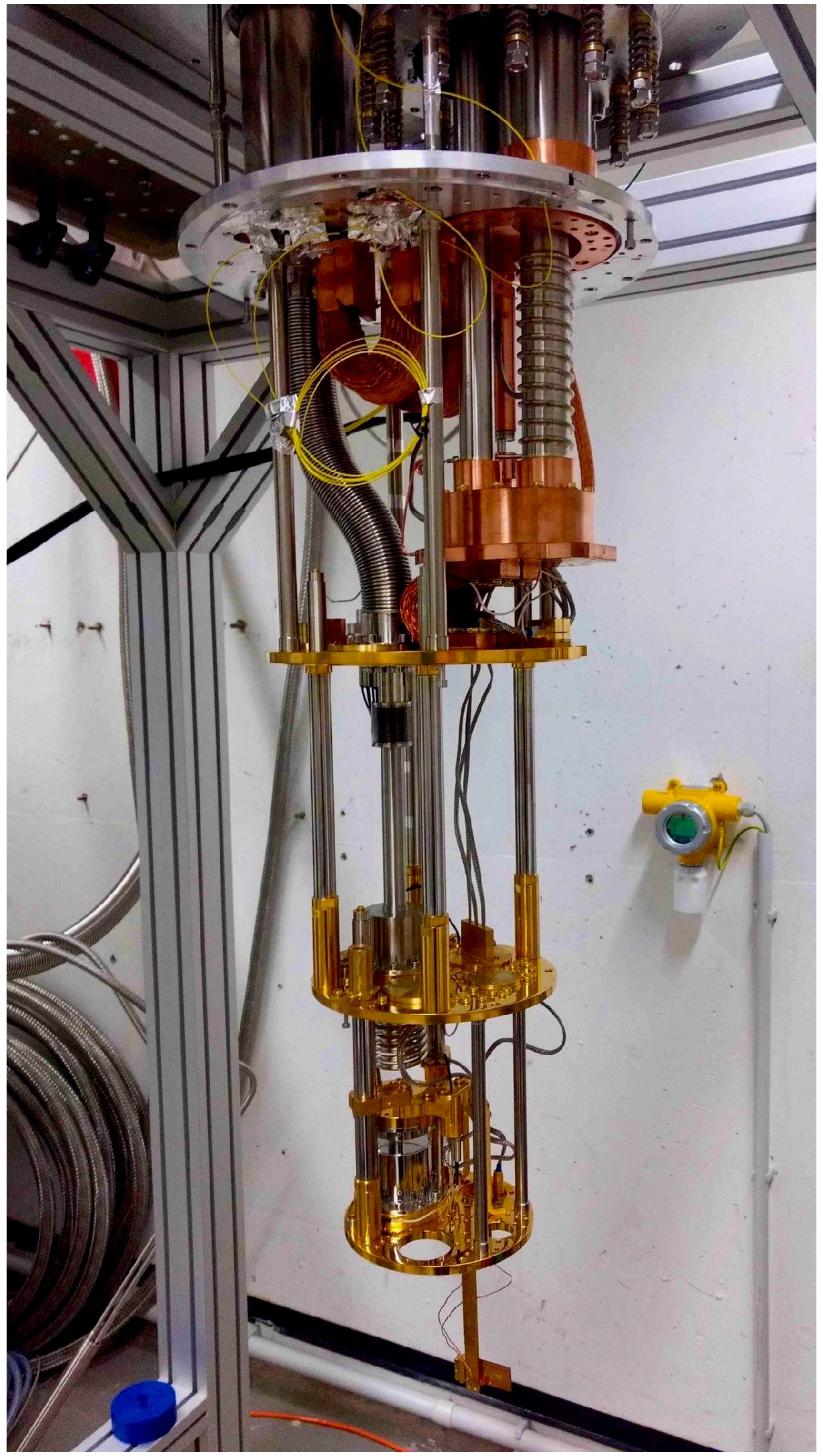


Experimental Setup

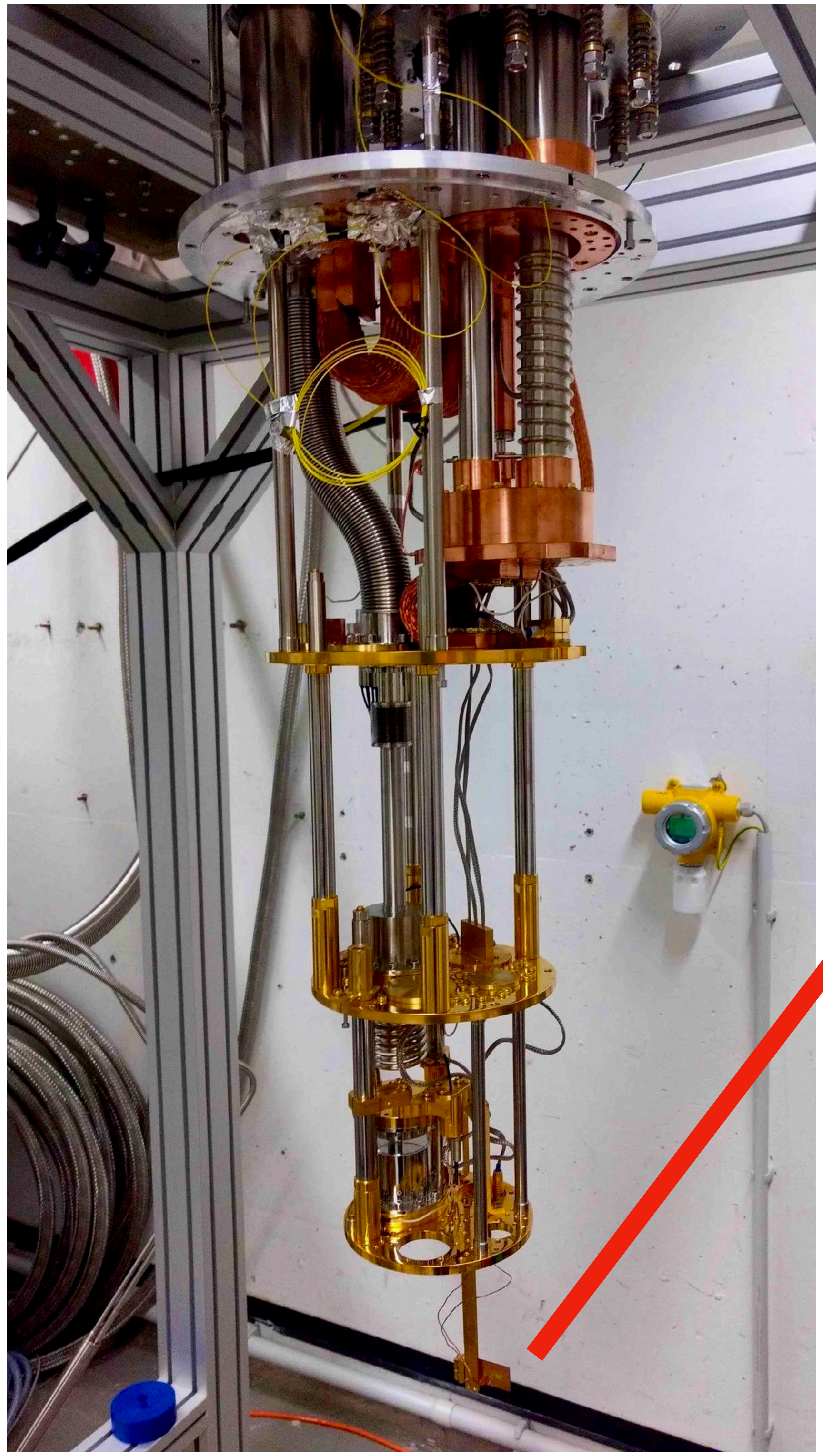
- Operate TES and SQUID electronics in a Dilution Refrigerator
- Light-tight, surrounded by muMetal and aluminium shielding against stray electric and magnetic fields
- **Current:** For initial characterization, optical fibers from reference 1064 nm laser
- **Future:** Optical fibers from the ALPS II setup

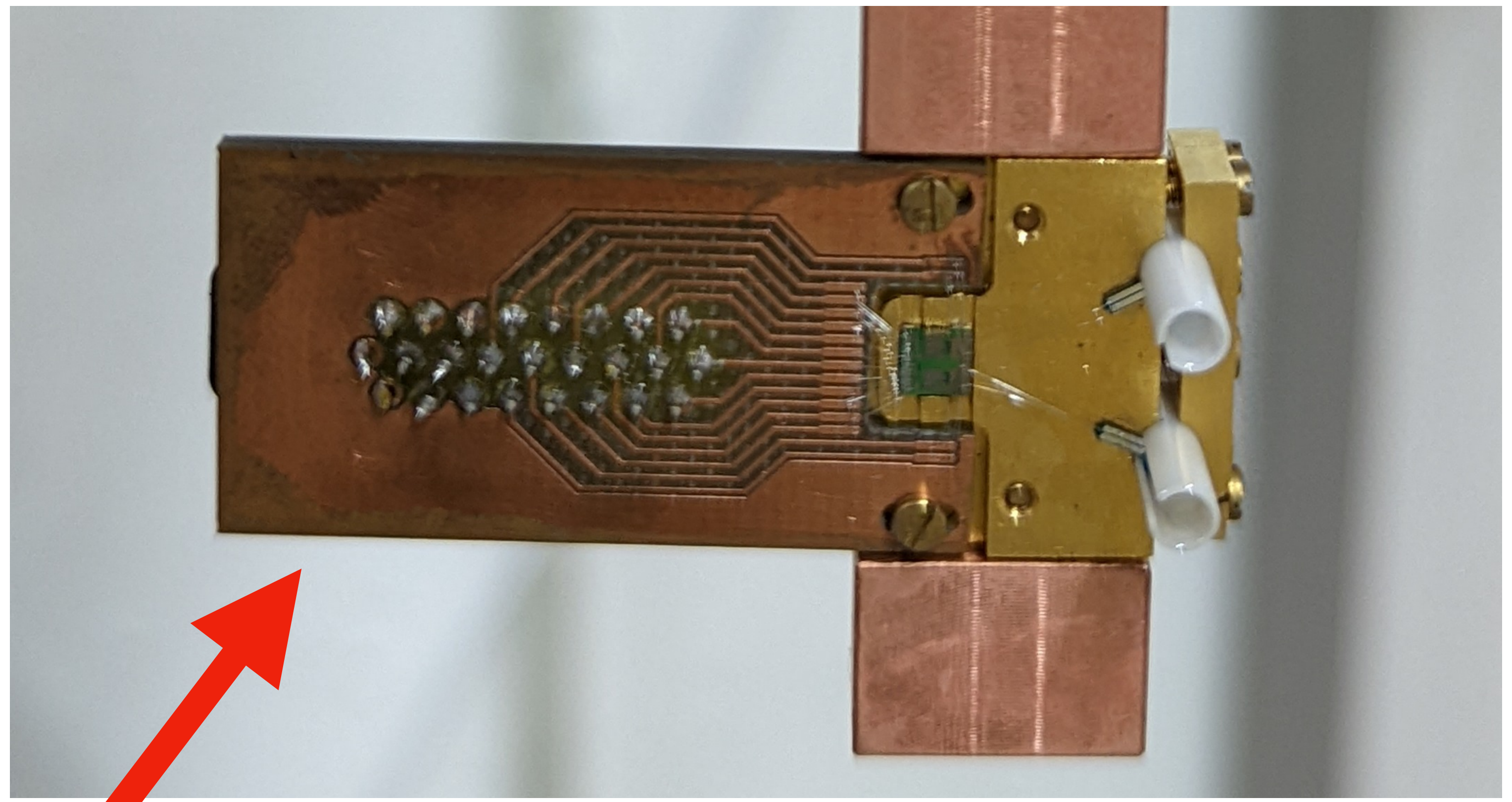


Courtesy of Katharina-Sophie Isleif



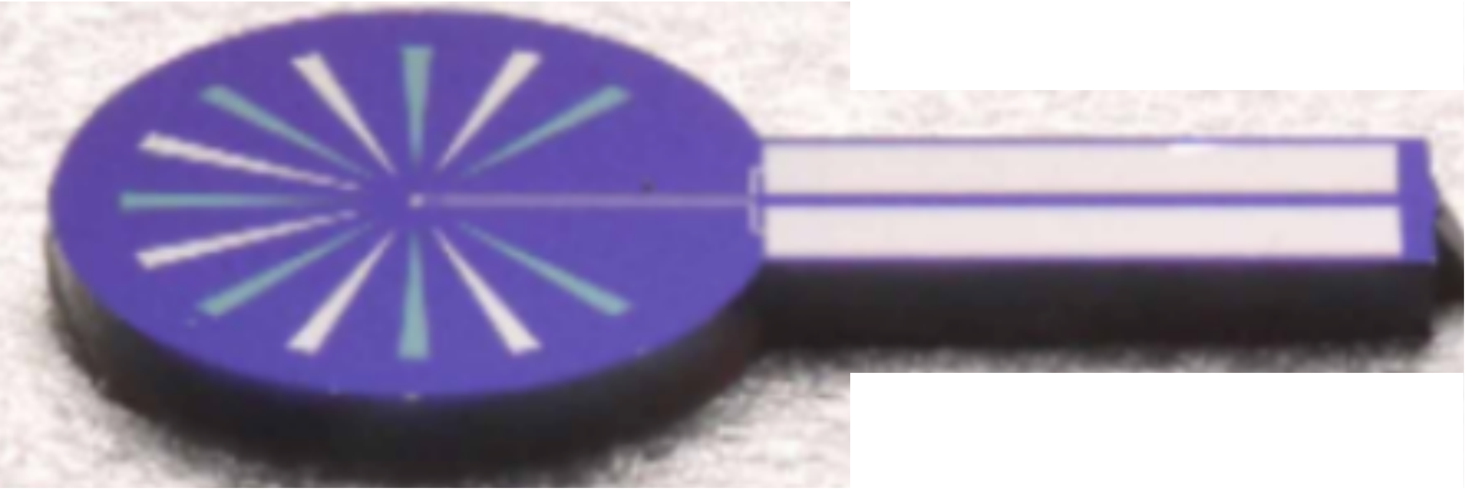
TES Module

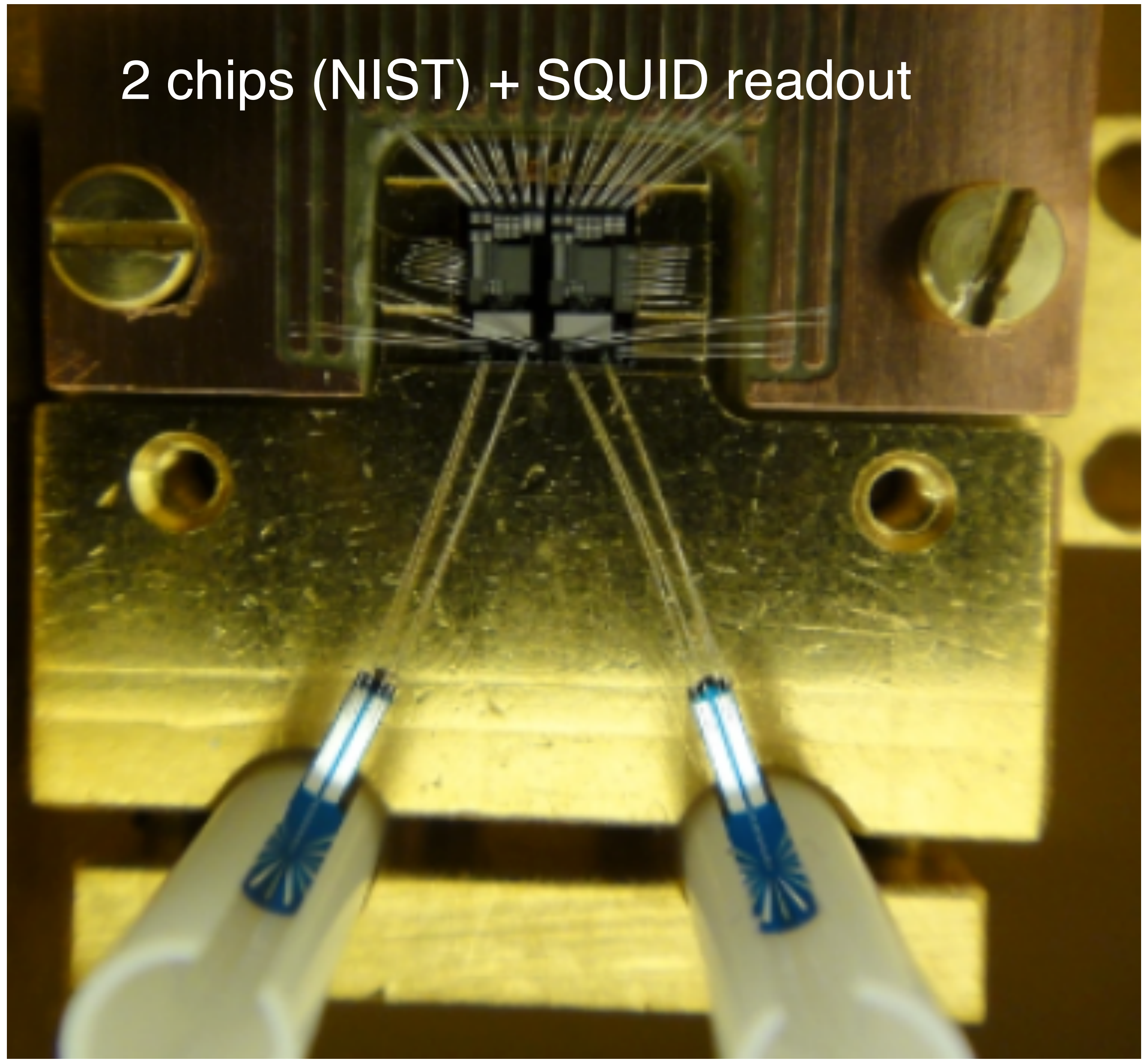




TES Module (PTB)

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





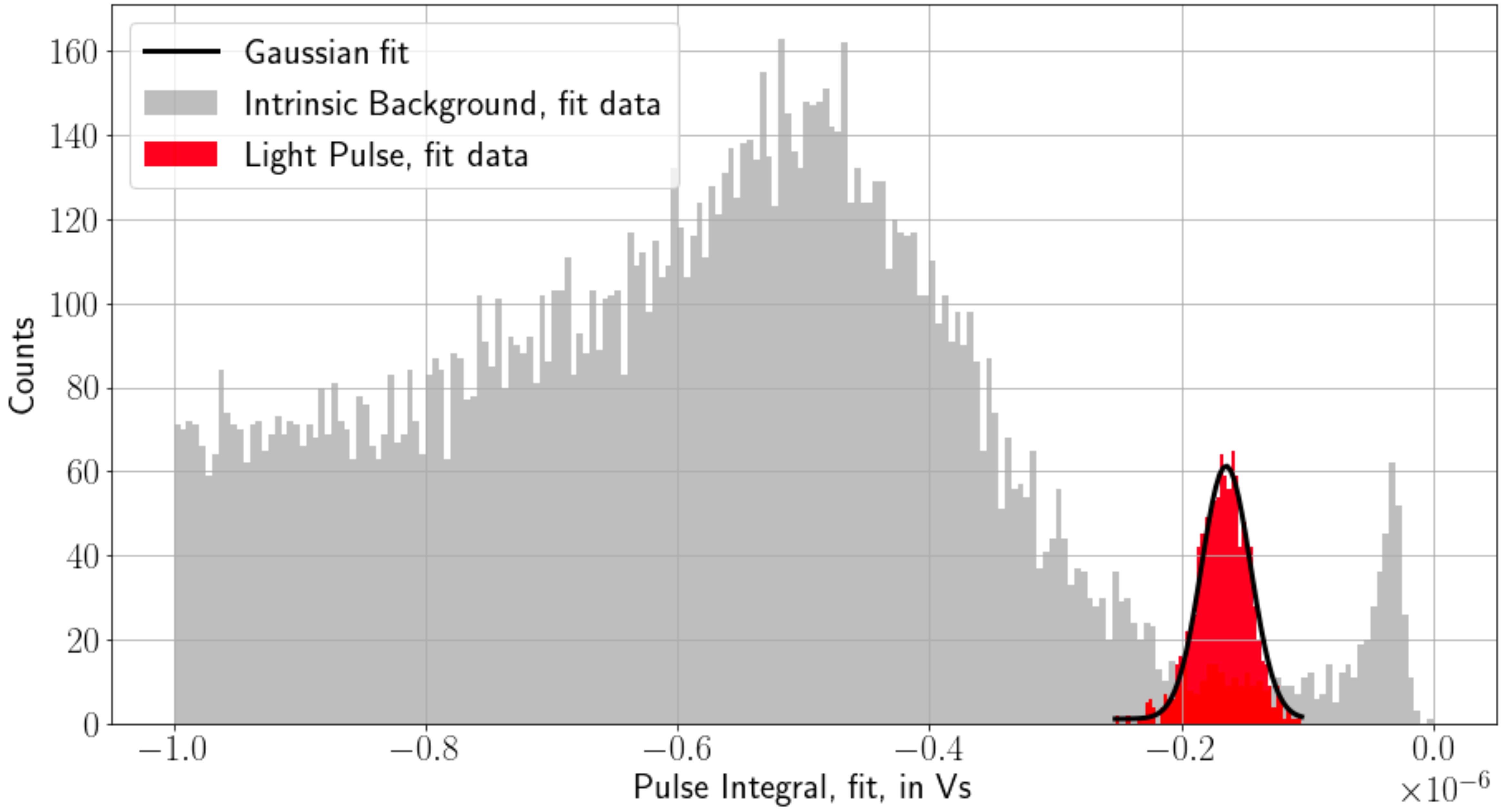
Backgrounds and Energy Resolution

No optical fiber connected:

- Intrinsic radioactivity, cosmic ray secondaries
- **μHz dark count rate over 20 days after pulse-shape based background rejection[1]**
- **~10% energy resolution**

Optical fiber connected:

- Blackbody photons from warm components
- Luminescence within the fiber itself
- Working to understand and characterize these backgrounds
- Still expect ~10% energy resolution



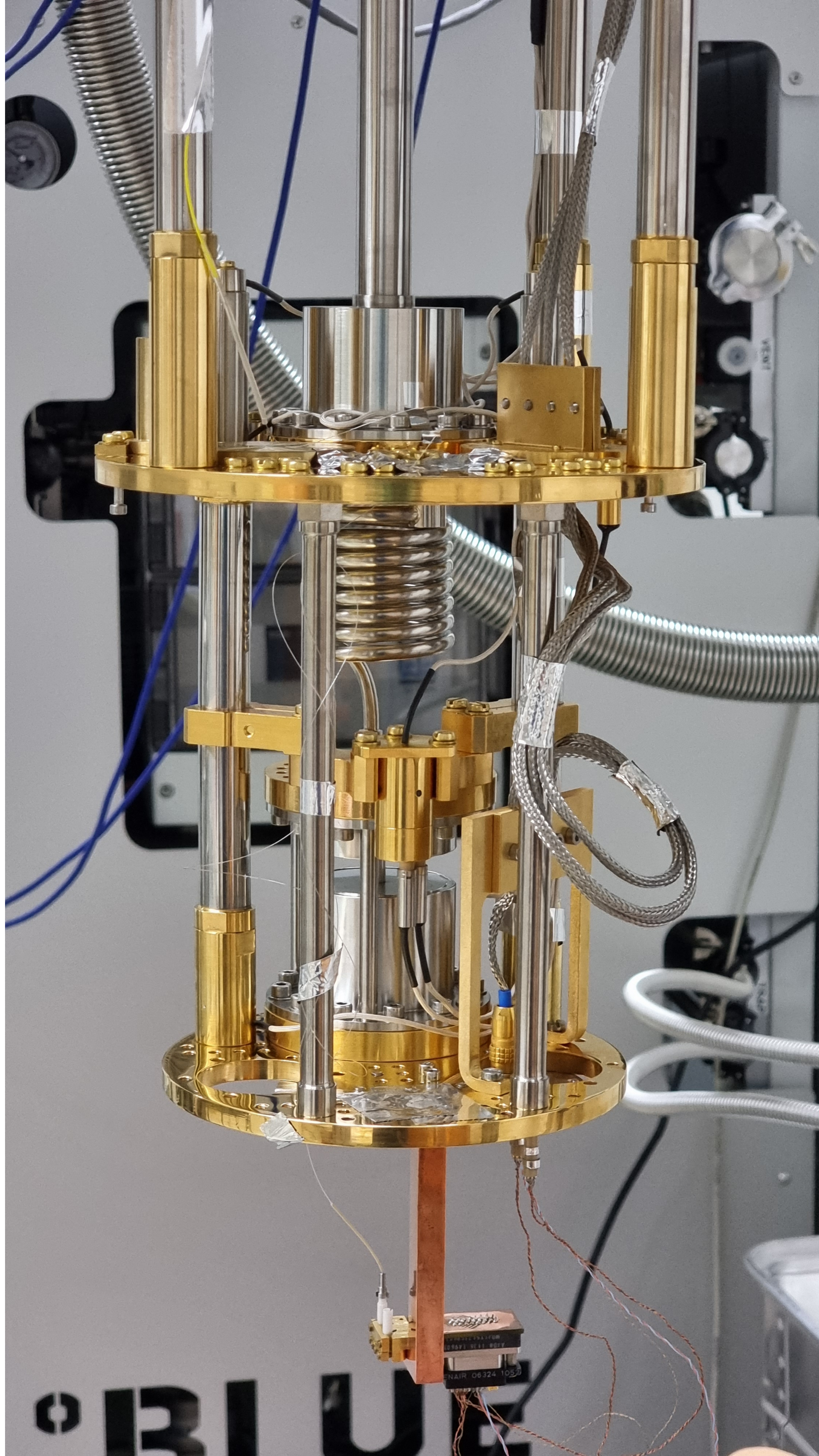
[1]Work by Rikhav Shah et. al: https://doi.org/10.22323/1.398.0801

Meets background rate and energy resolution requirements for ALPS II when no fiber attached

Backgrounds are relevant for quantum sensing and communication applications

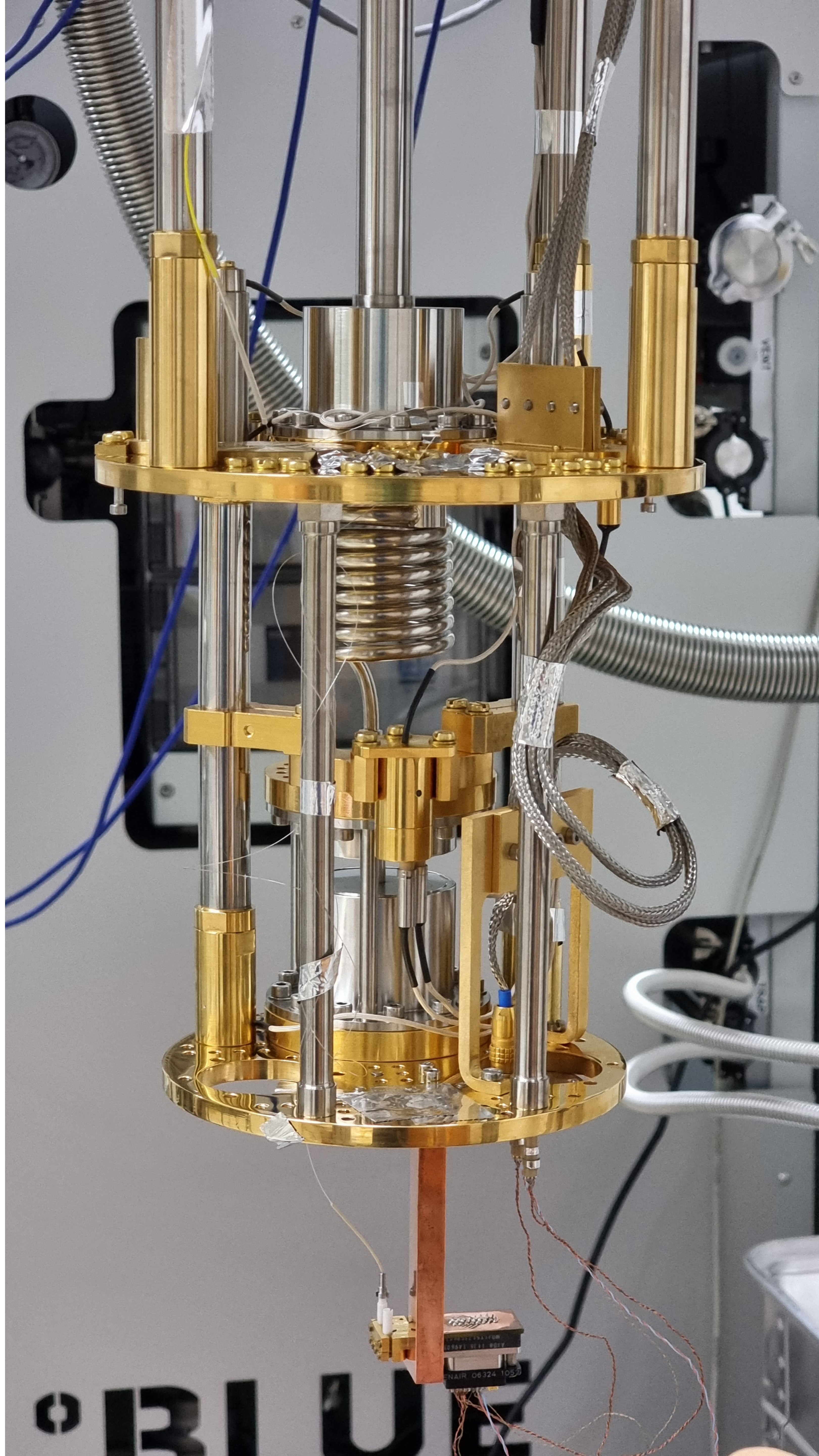
Current status, future plans

- For ALPS II:
  - Fiber-coupled efficiency measurements at 1064 nm
  - Further studies of backgrounds with fiber attached
  - Possibility for cryogenic optical filtering to reduce blackbody backgrounds
- Calibration, linearity, and efficiency studies across much of the dynamic range of the sensor (880 - 2050 nm)
- Direct dark matter search (independent of ALPS II)
- Characterization of other TES modules in collaboration with the UK consortium: *“Quantum-Enhanced Interferometry for New Physics”*
- **Possible quantum sensing application:** Characterization of 1550 nm Squeezed Light source by Roman Schnabel group at UHH



Summary

- Our TES detector is well-suited for the ALPS II experiment
  - With no fiber connected, μHz dark count rate after 20 days achieved
  - ~10% energy resolution
- Currently characterizing our TES at wavelengths other than 1064 nm
- Our facility is suited to test other TES modules— Collaboration with UK
- Our sensor(s) can be used in other Quantum Sensing applications
  - Ideas for collaboration? Talk with me!
  - gulden.othman@desy.de

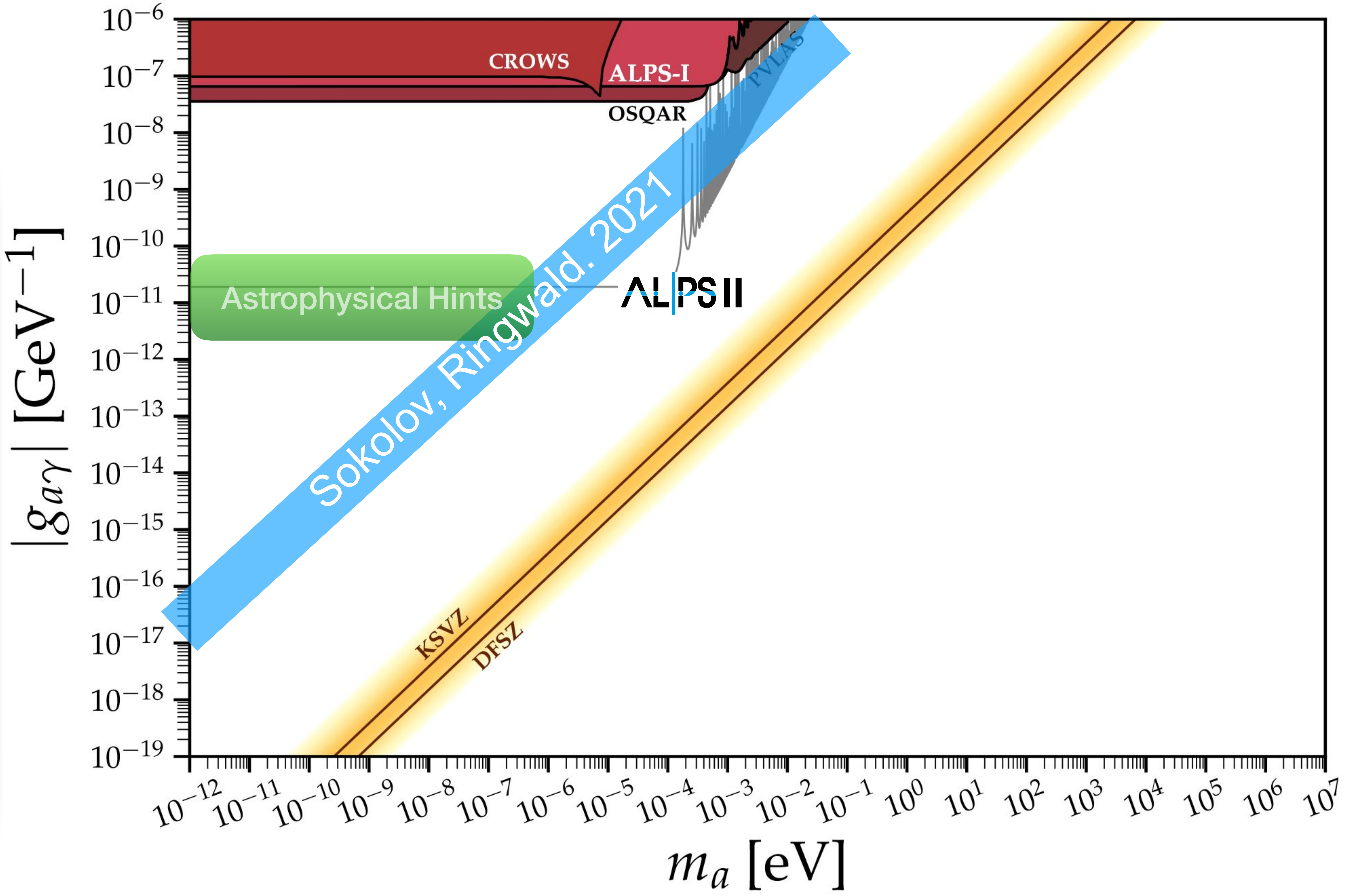


Backup: ALPS II

Motivation for Light Shining through Walls (LSW) Experiments

- Extensive observational evidence for the existence of dark matter
  - Axions and Axion-like particles (ALPs) can be dark matter candidates
  - Axions can additionally be a solution to the Strong CP problem
- LSW experiments can search for axions and ALPs in a model-independent way
- Sensitivities out of reach of accelerator searches
- Test astrophysical observations
  - Stellar cooling
  - TeV transparency

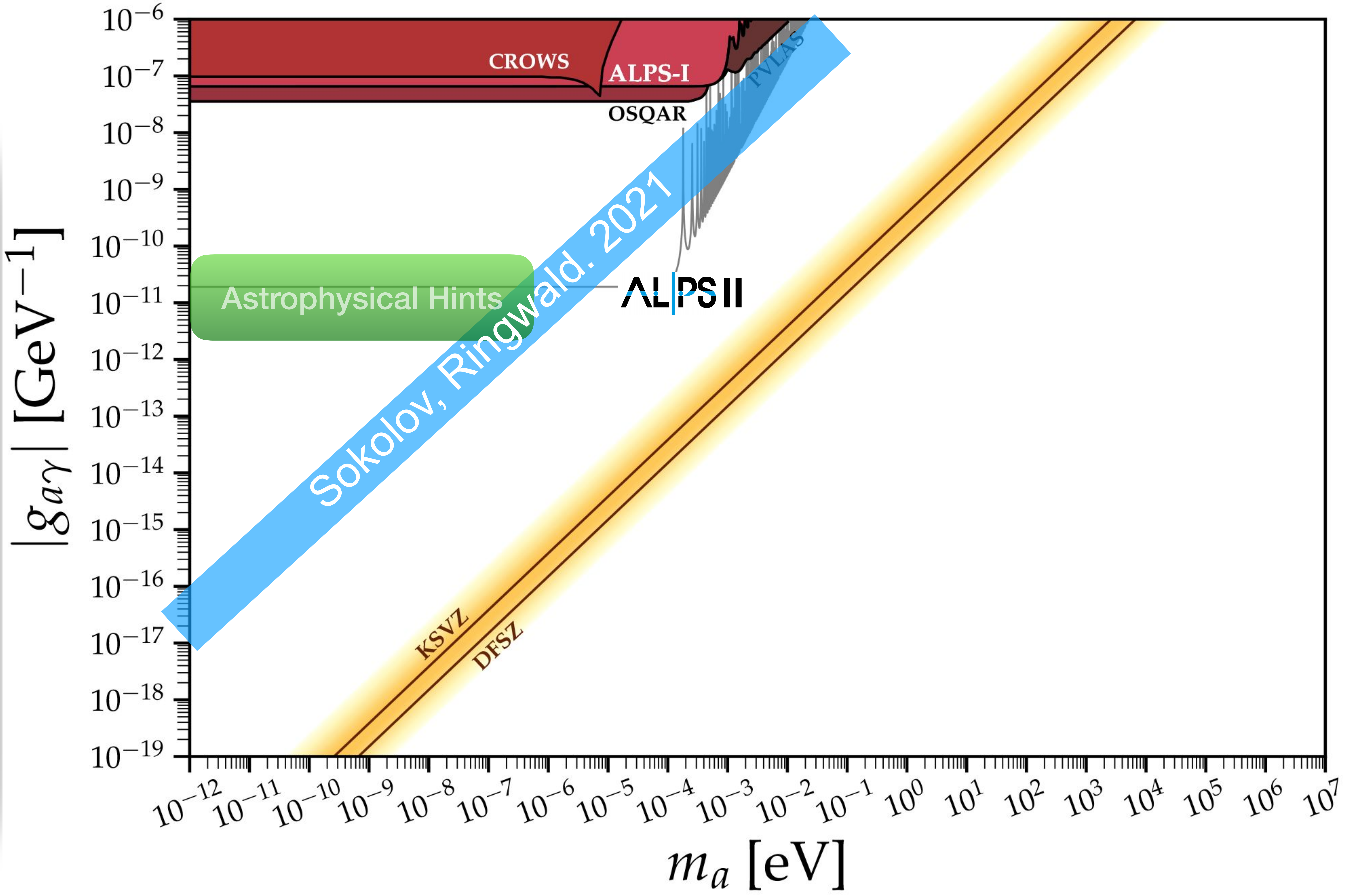
github.com/cajohare/AxionLimits/



ALPS II Sensitivity

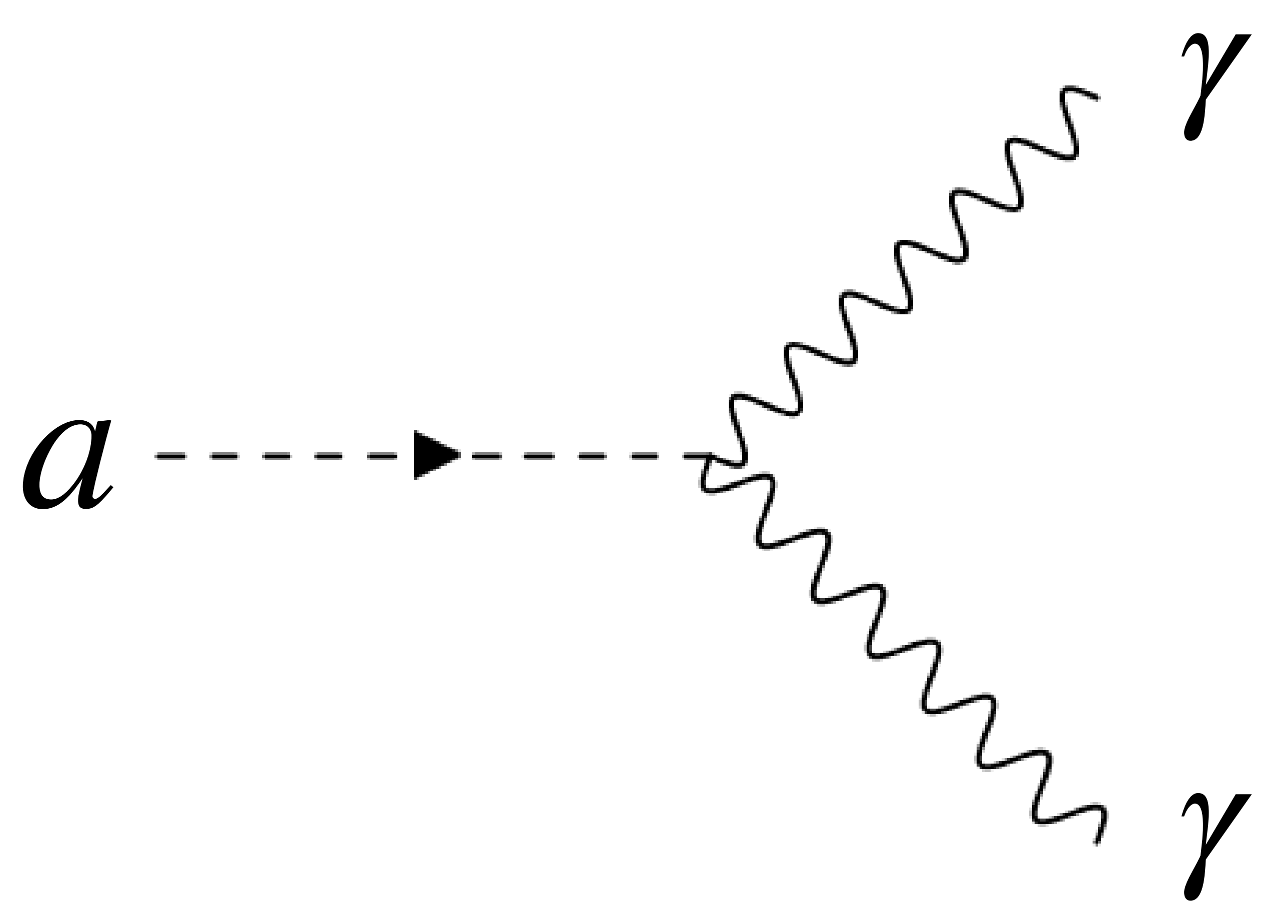
- $g_{a\gamma} > 2 \times 10^{-11} GeV^{-1}$
  - $m_a < 0.1$ meV
  - Increase sensitivity > 3 orders of magnitude over OSQAR, ALPS I
  - Factor of 3 over CAST
- Begin to probe astrophysical phenomena in model-independent way
  - Stellar cooling
  - TeV transparency
- Early science run with limited sensitivity later this summer

github.com/cajohare/AxionLimits/



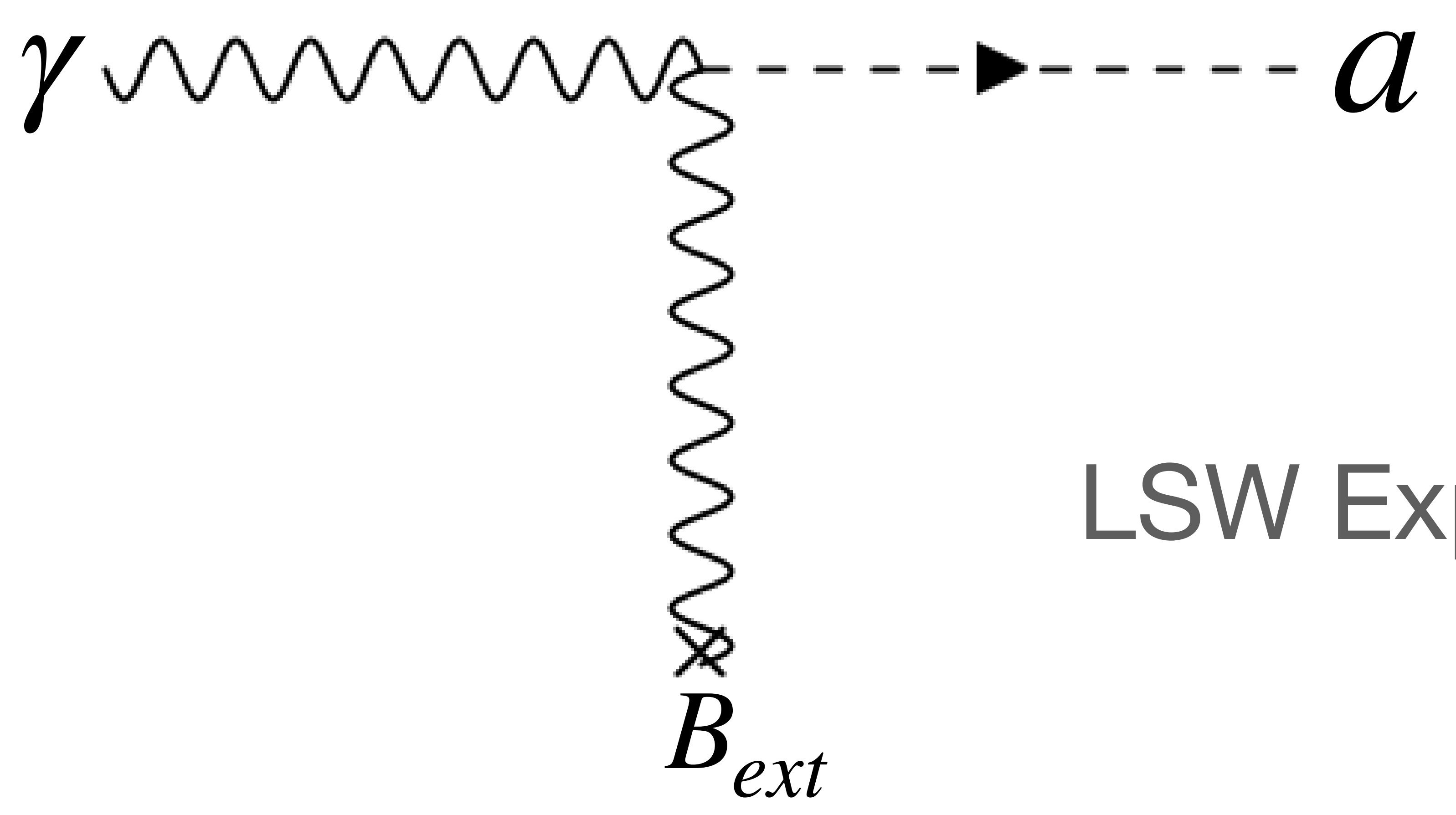
Axion coupling to photons

Axion decay

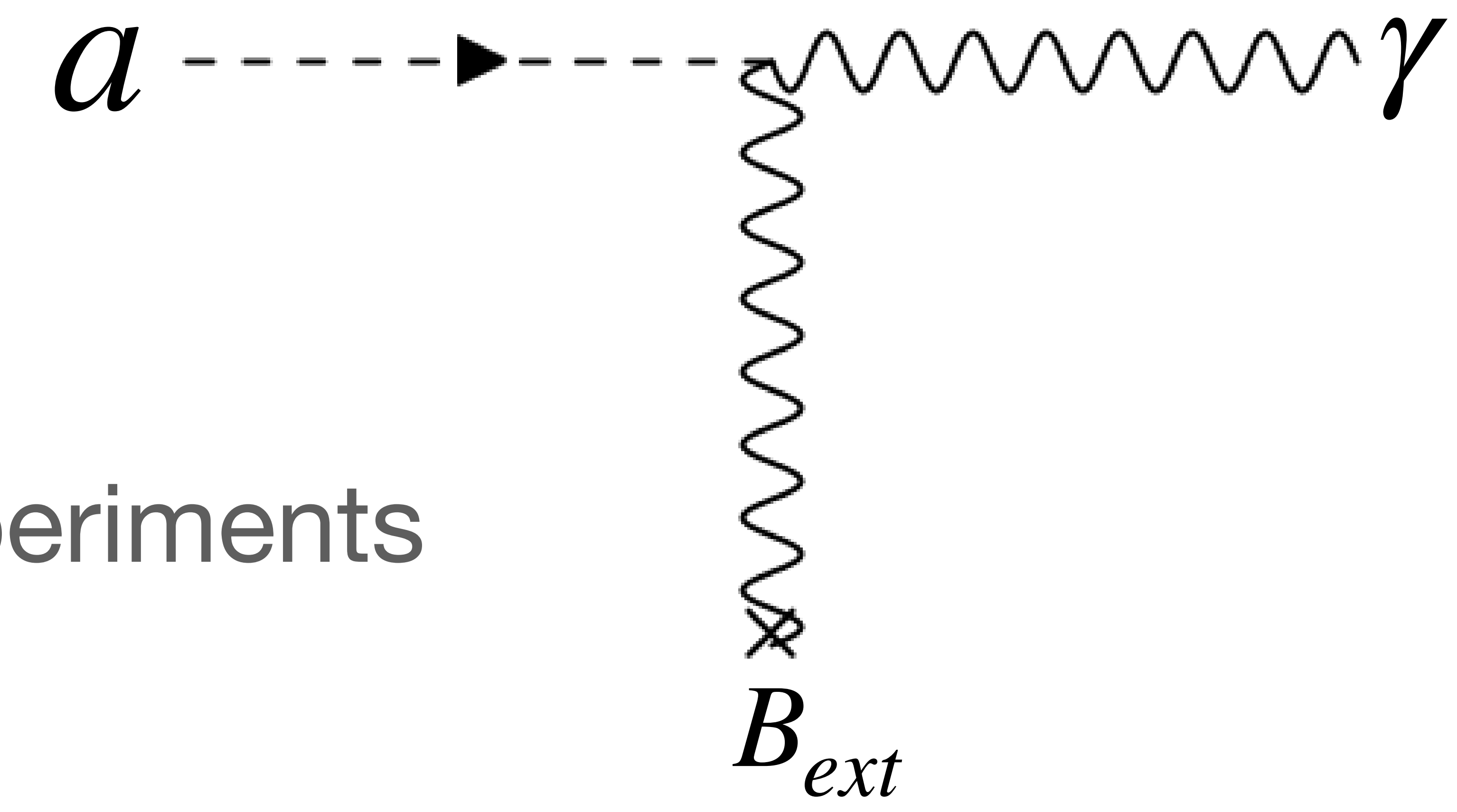


Astrophysics and cosmology

Inverse Sikivie effect



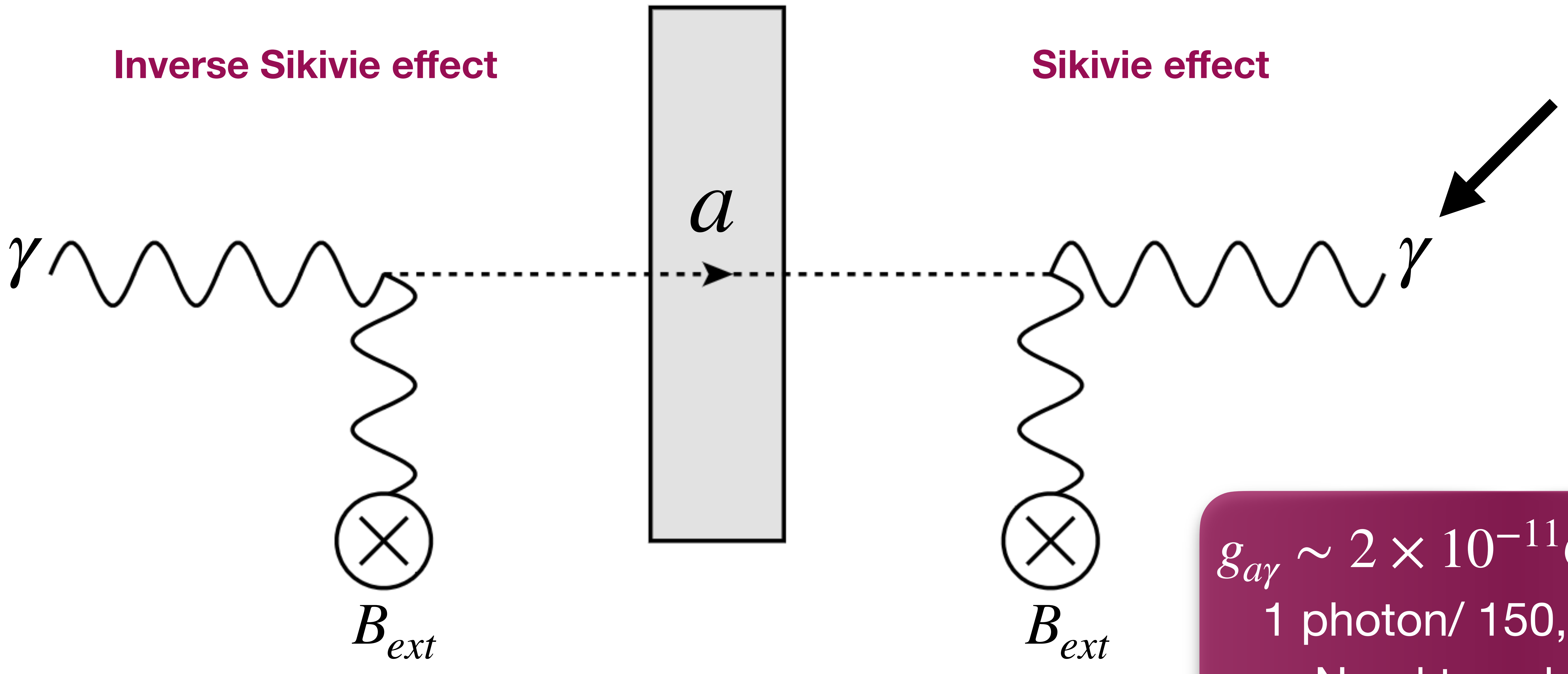
Sikivie effect



LSW Experiments

Haloscopes
Helioscopes

Light Shining Through Walls



$\mathscr{P}_i \rightarrow$ laser power
$h\nu \rightarrow$ laser photon energy
$\tau \rightarrow$ measurement time

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

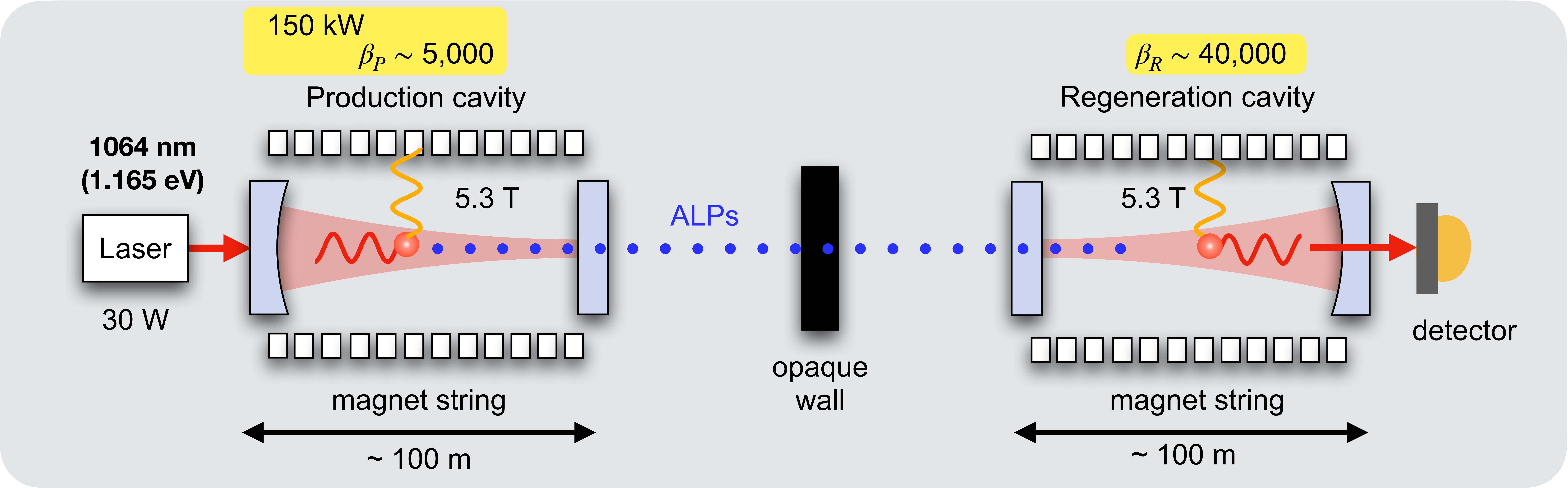
$g_{a\gamma} \sim 2 \times 10^{-11} GeV^{-1}$

1 photon/ 150,000 years!

→Need to enhance signal!

$B \sim 5.3\ T$
$L \sim 100\ m$
$\mathscr{P} \sim 30\ W$

Any Light Particle Search (ALPS) II



Graphic from Katharina-Sophie Isleif

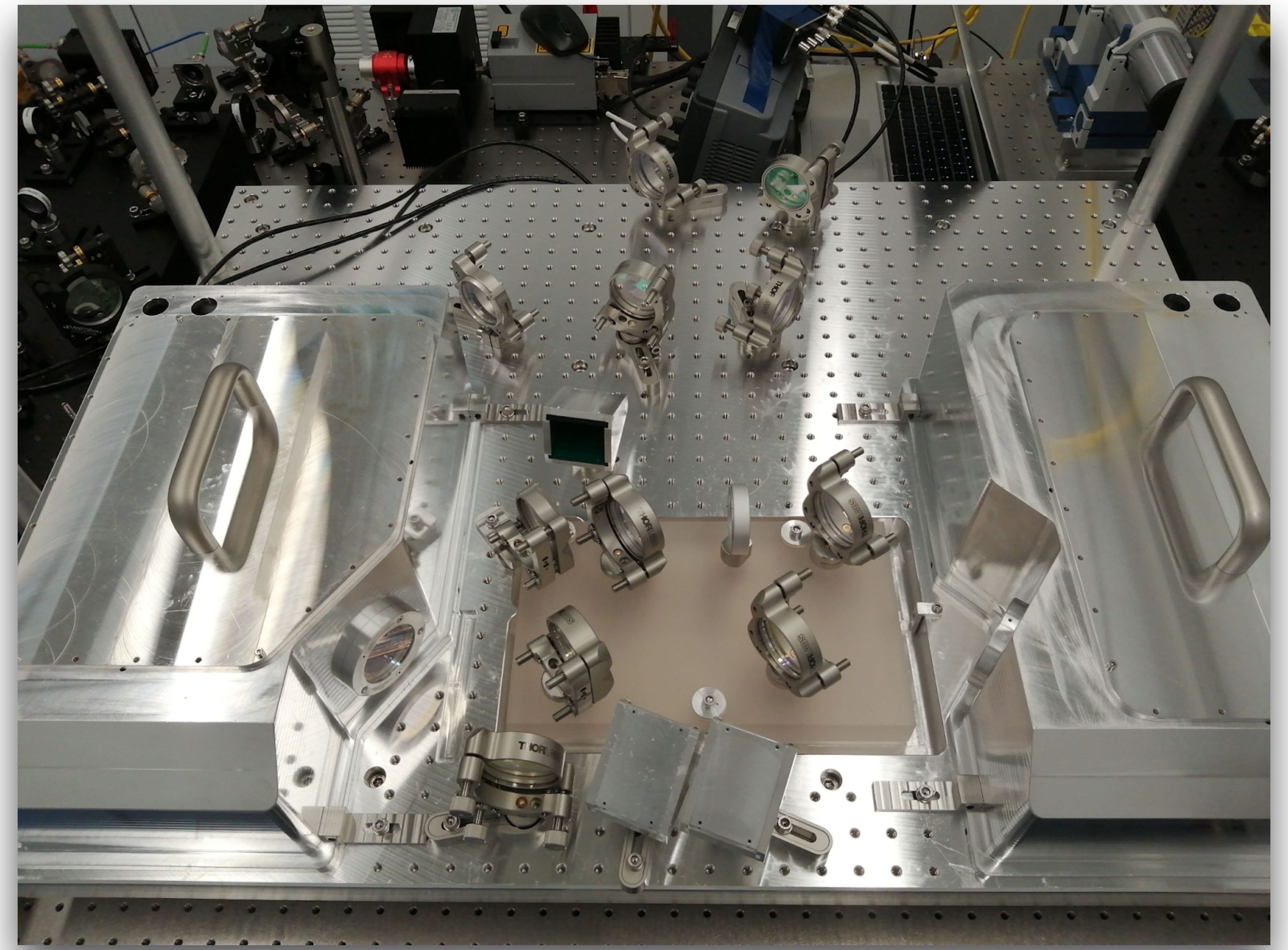
- Using 24 straightened HERA magnets
- Fabry-Perot resonators in production *and* regeneration region

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

Current Status

- Nearly fully operational (without production cavity)
- Magnet strings operational since March 2022
    - 24 straightened HERA dipole magnets
- Optical systems aligned and undergoing final testing

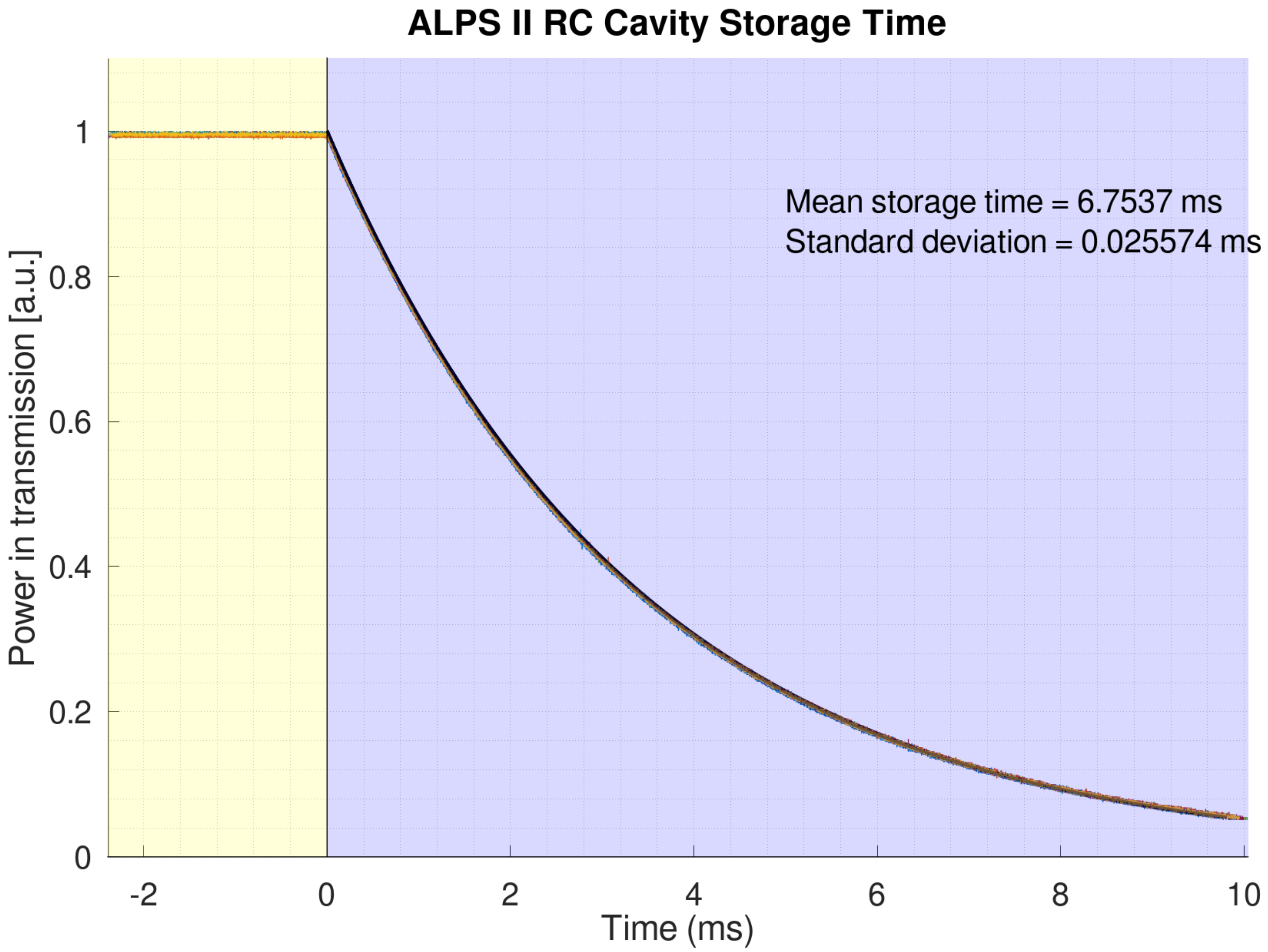
Photo by Heiner Müller-Elsner



Central Optical Breadboard

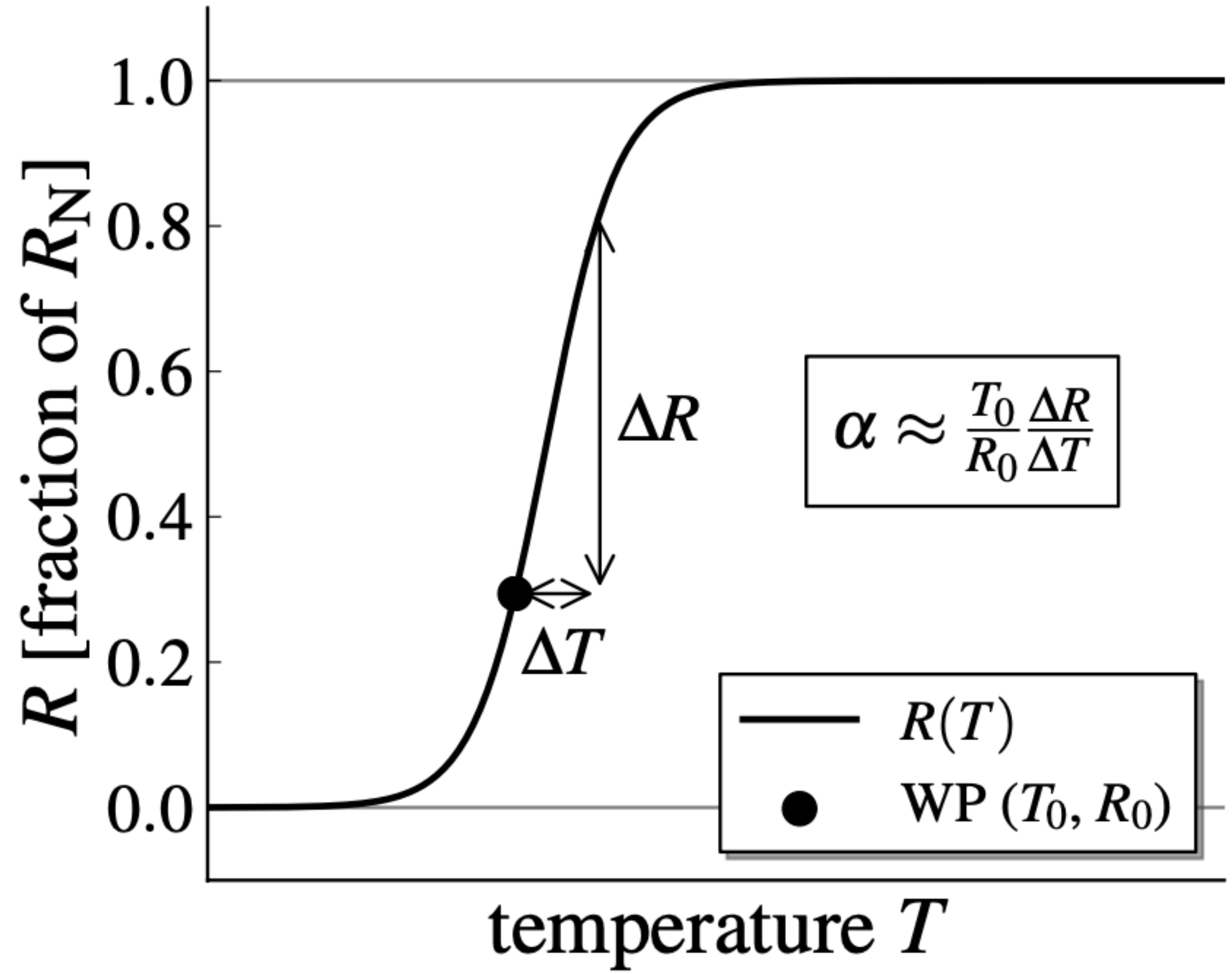
Longest storage time Fabry Perot cavity ever!

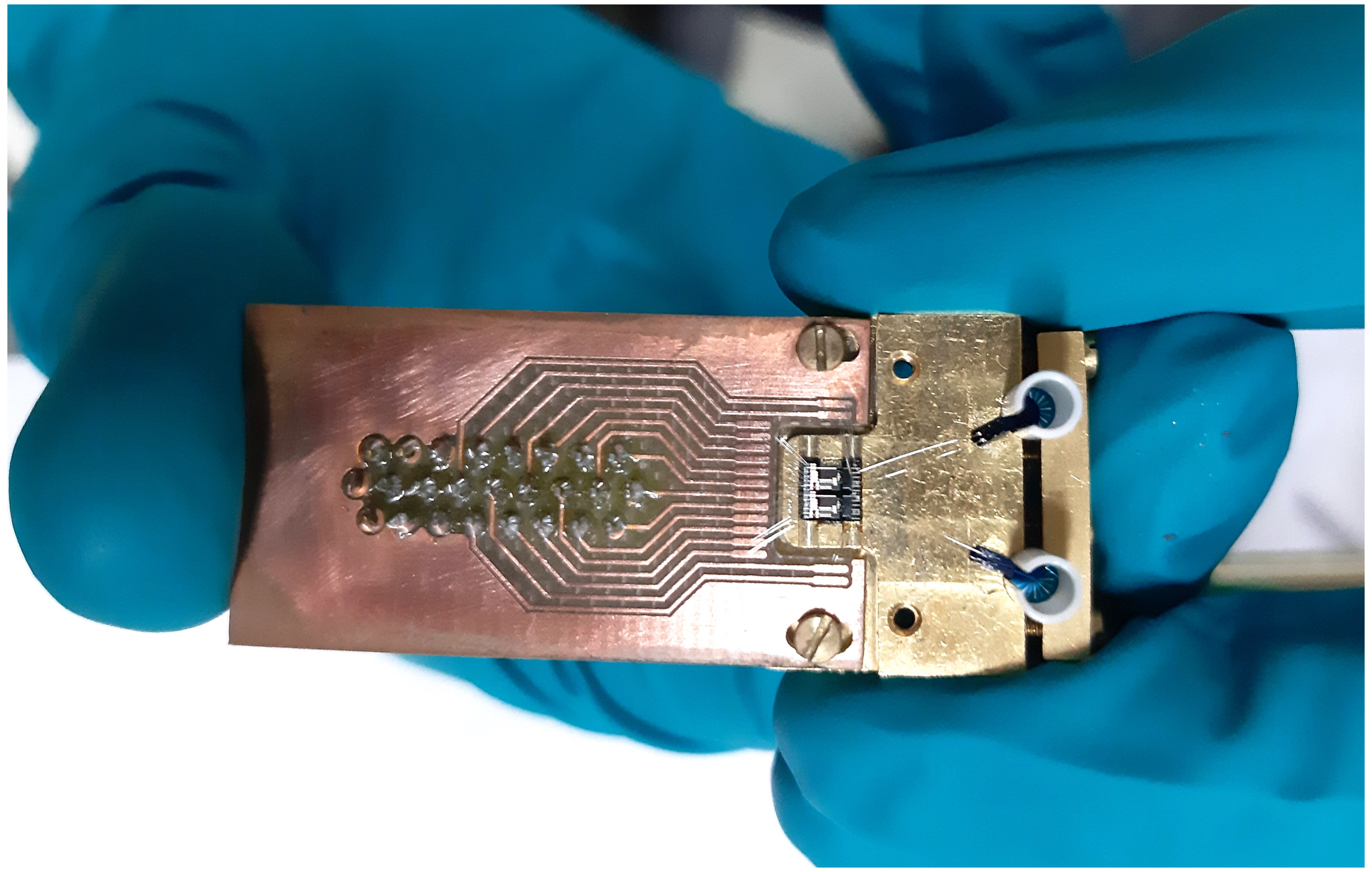
- Length: 124.6m, FSR: 1.22 MHz
- Storage time: 6.75 ms (*world record*)
- Power build up factor: β ~ 7000

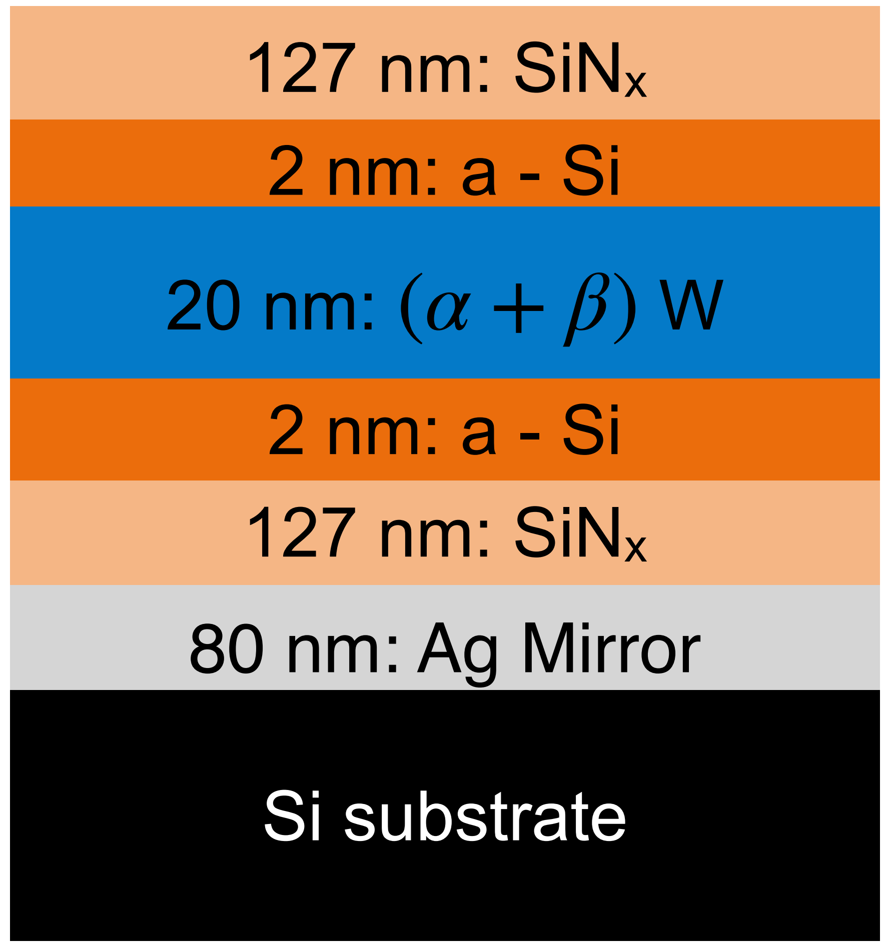


Backup: TES

TES Working Principle

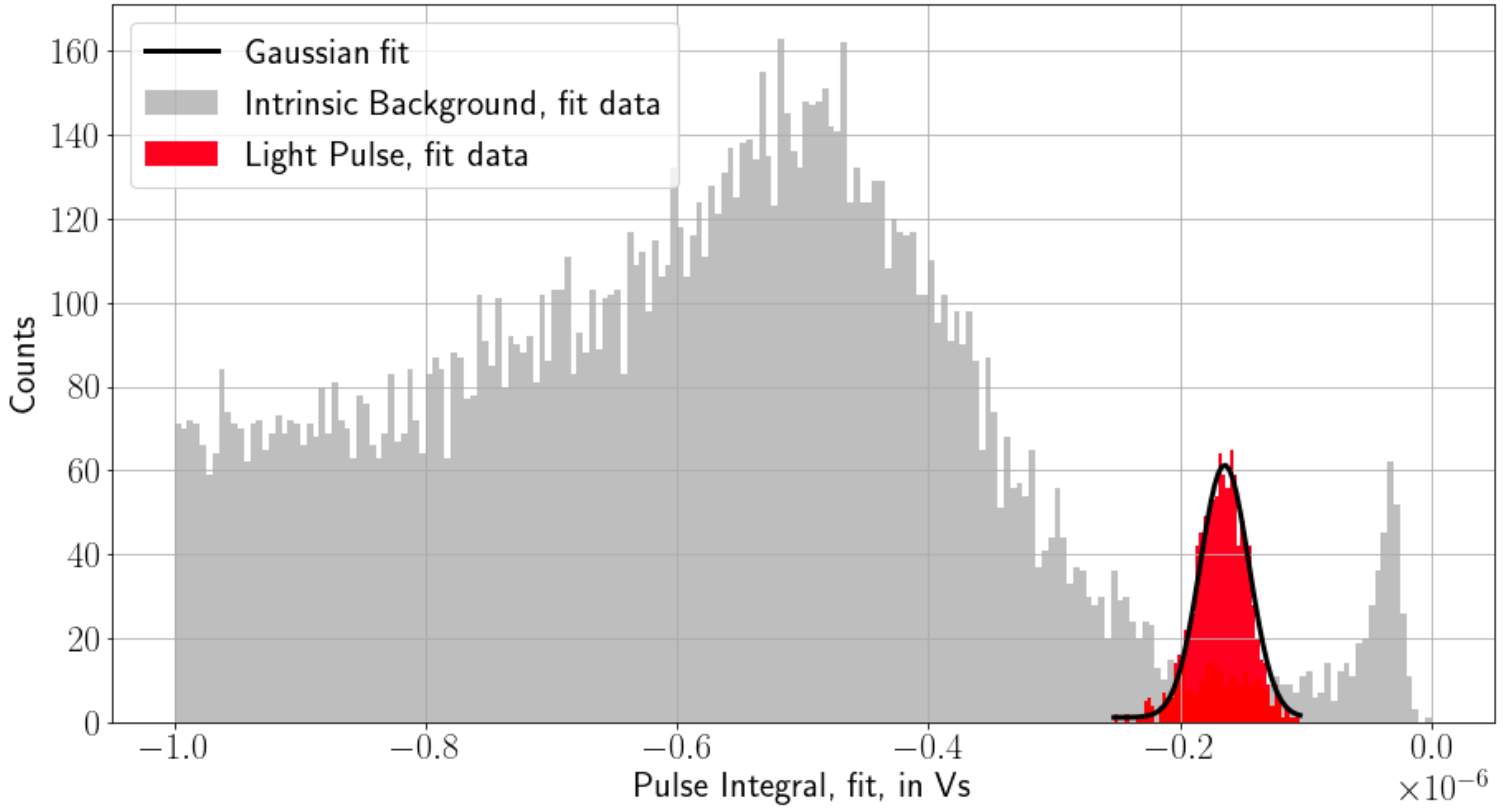


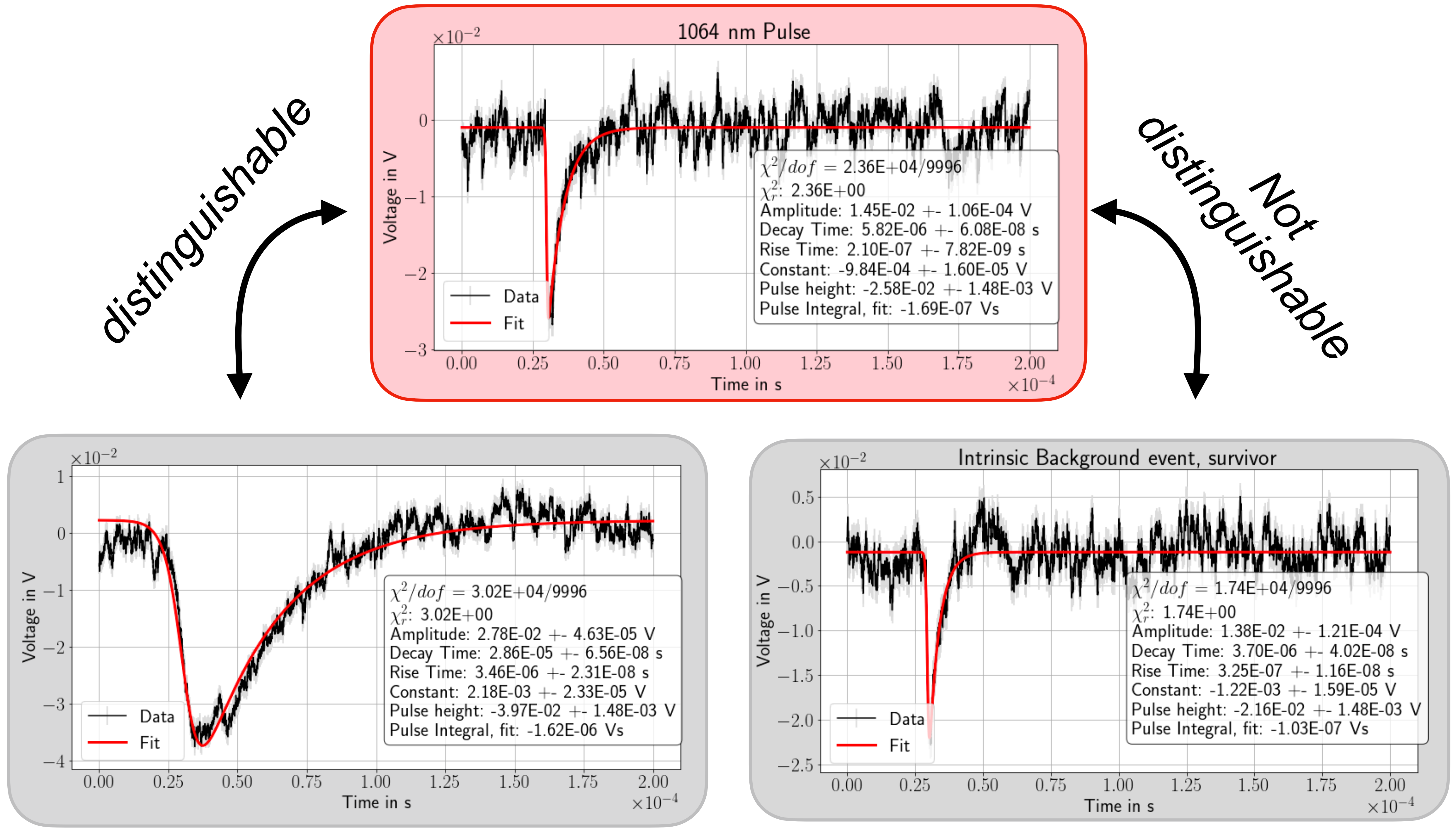




Courtesy of Katharina-Sophie Isleif

Background Sources





$6.9^{+5.18}_{-2.93} \cdot 10^{-6}\,\mathrm{Hz}$ (95% confidence level)

Rikhav Shah (JGU and DESY)

With no fiber connected:

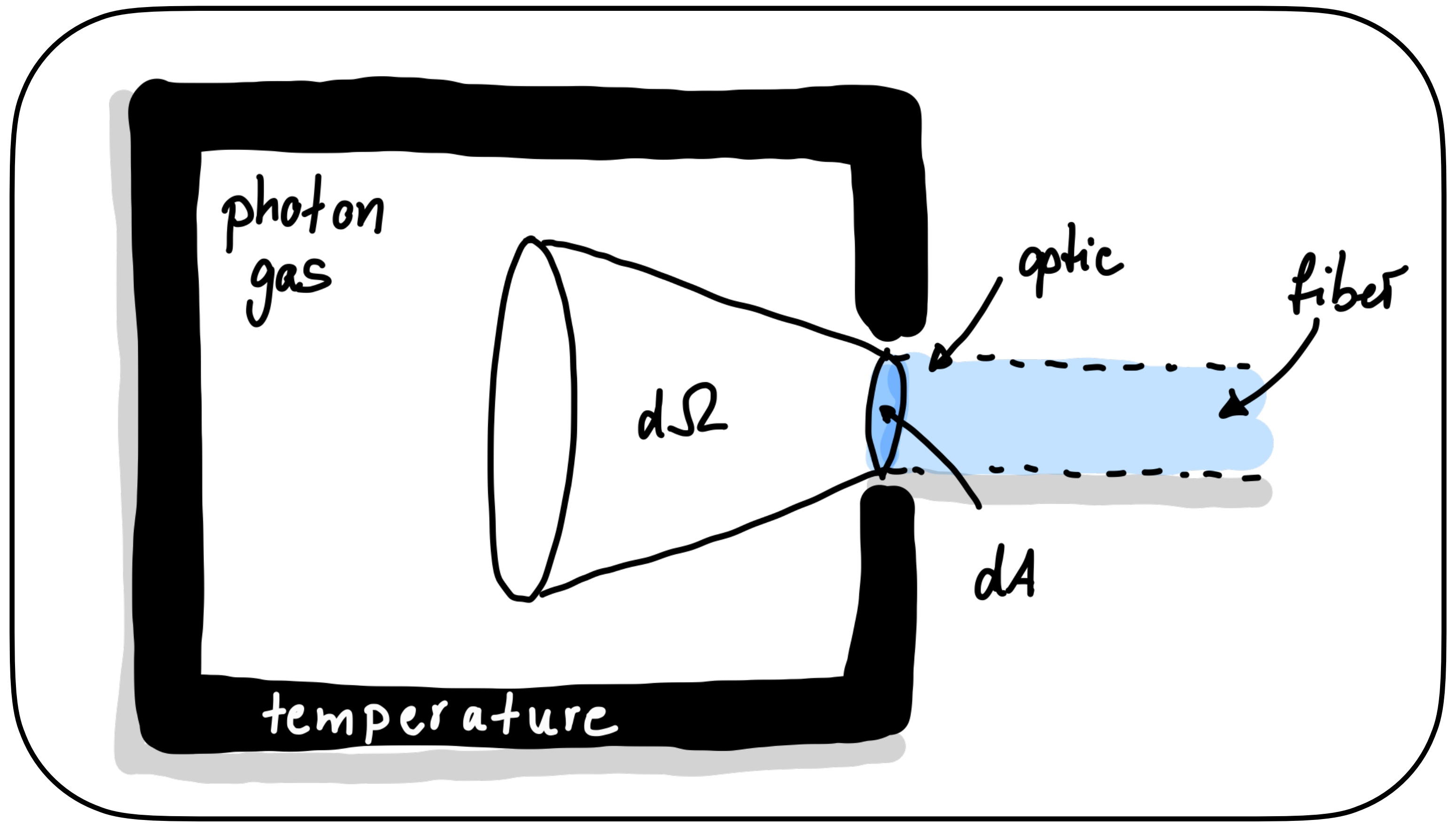
- Intrinsic radioactivity, cosmic ray secondaries
- μHz dark count rate over 20 days after pulse-shape based background rejection
- 11-15% energy resolution, depending on analysis method

- Relevant to other quantum sensing applications

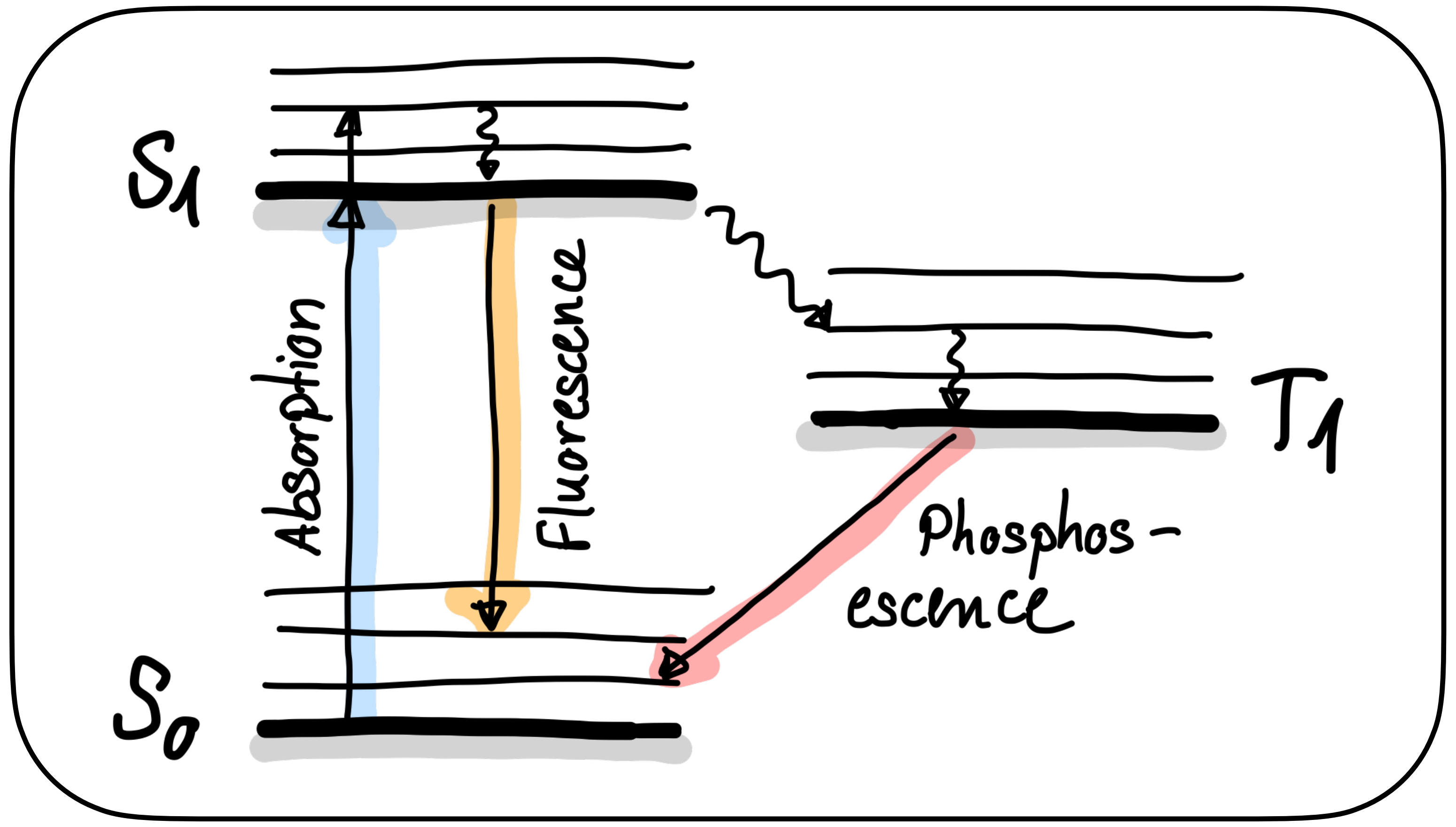
Meets the required background rate and energy resolution

Background Sources

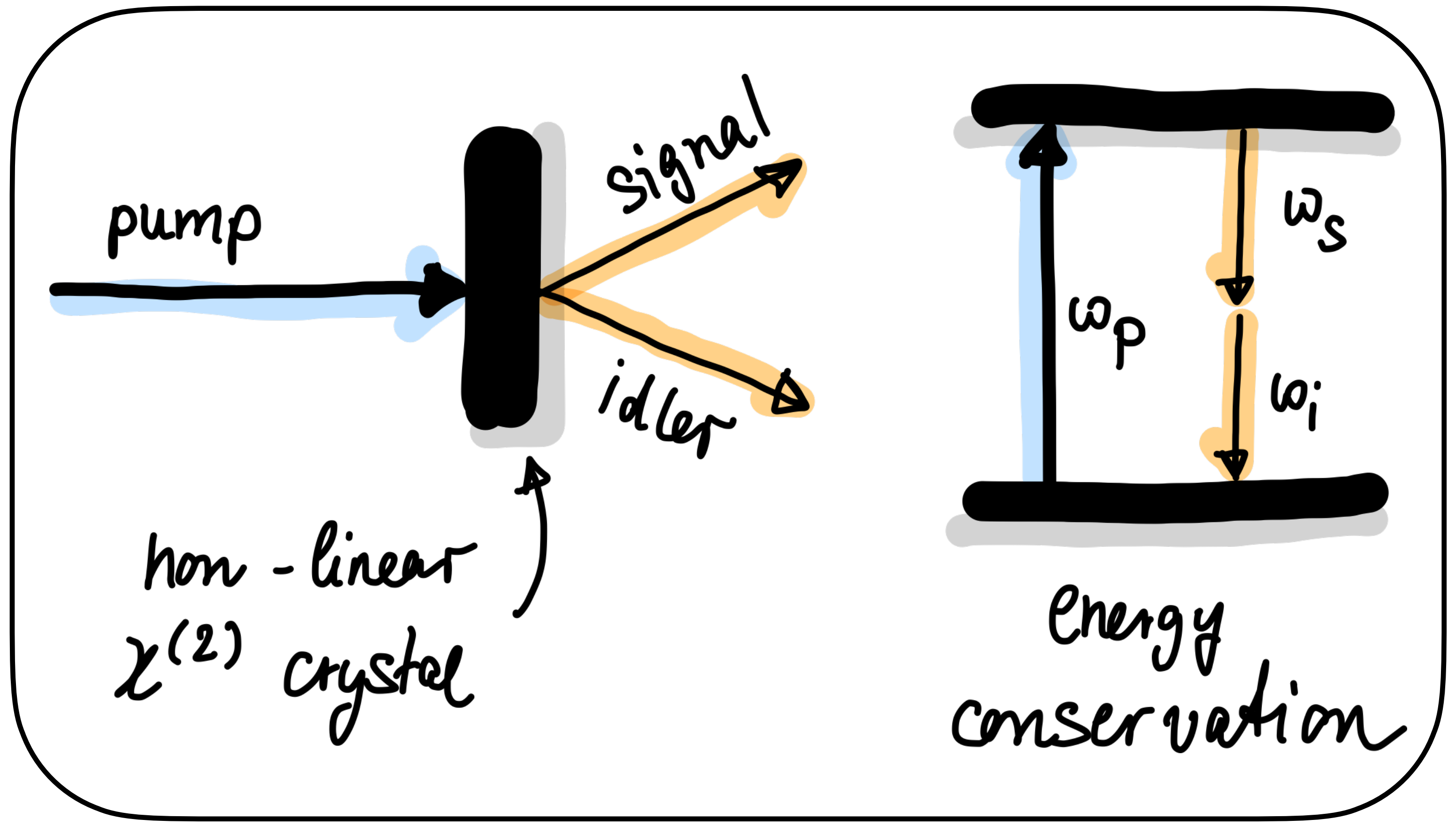
Black body radiation from laboratory, components @300K



Luminescence in optical components or fibers



Parametric noise in non-linear optical components or fibers



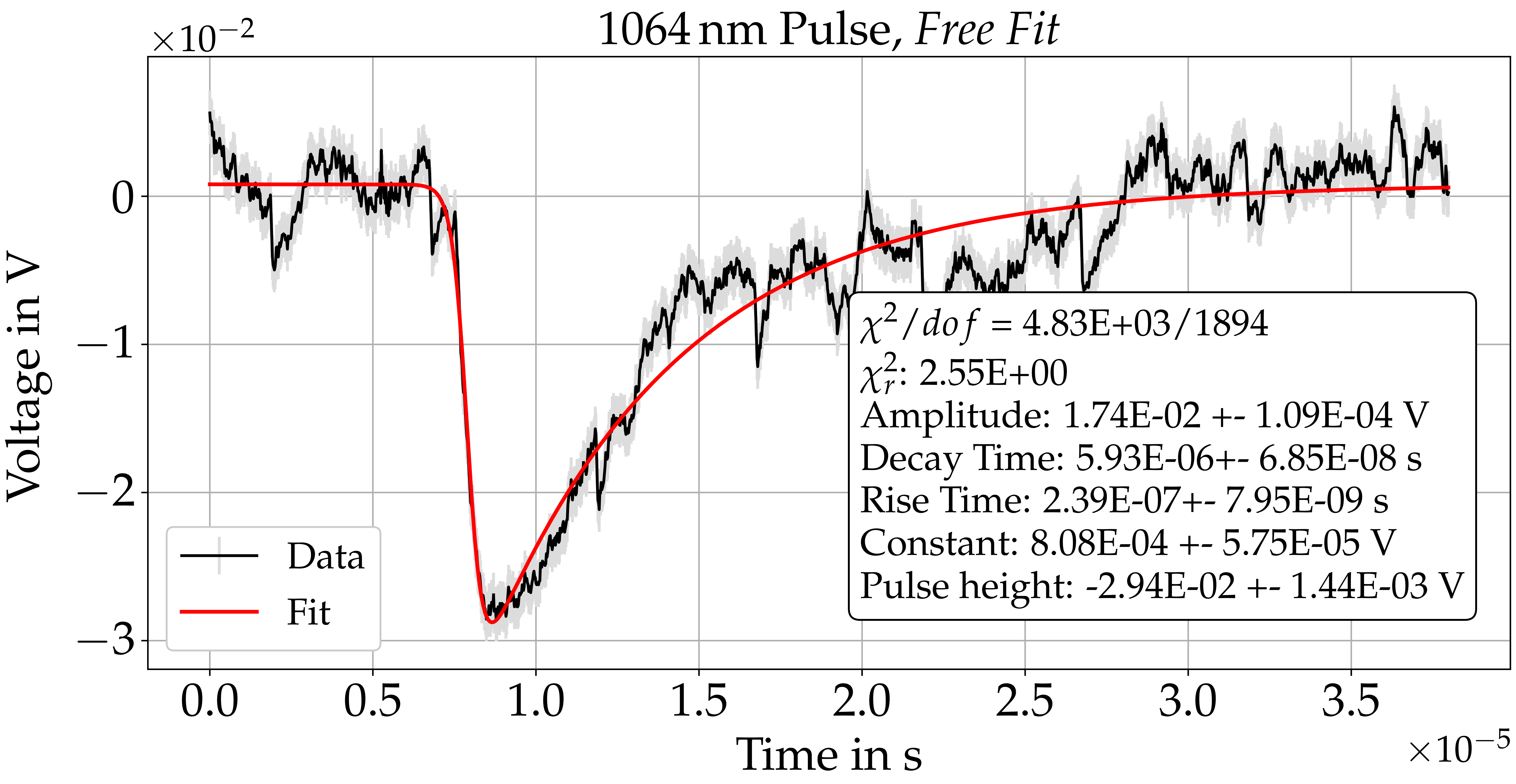
Courtesy of Katharina-Sophie Isleif

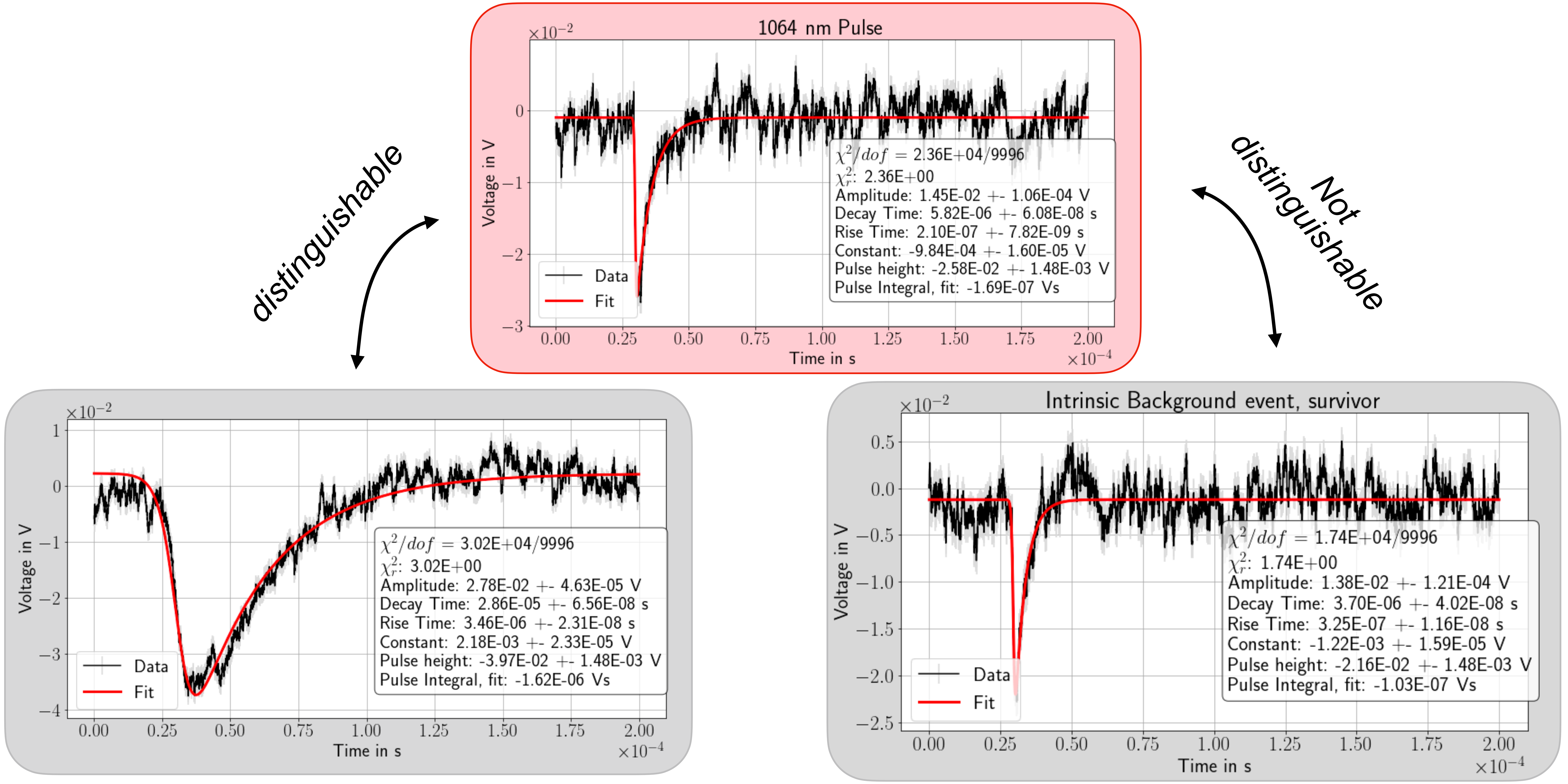
With fiber connected:

- Blackbody photons from warm components
- Luminescence within the fiber itself
- Working to understand and characterize these backgrounds

- Relevant to other quantum sensing applications

Example Light Pulse




1064 nm Pulse
χ^2/dof = 2.36E+04/9996
χ^2_r: 2.36E+00
Amplitude: 1.45E-02 +- 1.06E-04 V
Decay Time: 5.82E-06 +- 6.08E-08 s
Rise Time: 2.10E-07 +- 7.82E-09 s
Constant: -9.84E-04 +- 1.60E-05 V
Pulse height: -2.58E-02 +- 1.48E-03 V
Pulse Integral, fit: -1.69E-07 Vs
Data
Fit
Voltage in V
Time in s
distinguishable
Not distinguishable
χ^2/dof = 3.02E+04/9996
χ^2_r: 3.02E+00
Amplitude: 2.78E-02 +- 4.63E-05 V
Decay Time: 2.86E-05 +- 6.56E-08 s
Rise Time: 3.46E-06 +- 2.31E-08 s
Constant: 2.18E-03 +- 2.33E-05 V
Pulse height: -3.97E-02 +- 1.48E-03 V
Pulse Integral, fit: -1.62E-06 Vs
Intrinsic Background event, survivor
χ^2/dof = 1.74E+04/9996
χ^2_r: 1.74E+00
Amplitude: 1.38E-02 +- 1.21E-04 V
Decay Time: 3.70E-06 +- 4.02E-08 s
Rise Time: 3.25E-07 +- 1.16E-08 s
Constant: -1.22E-03 +- 1.59E-05 V
Pulse height: -2.16E-02 +- 1.48E-03 V
Pulse Integral, fit: -1.03E-07 Vs