A Cryogenic Single-Photon Detector for ALPS II

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On behalf of the ALPS II collaboration

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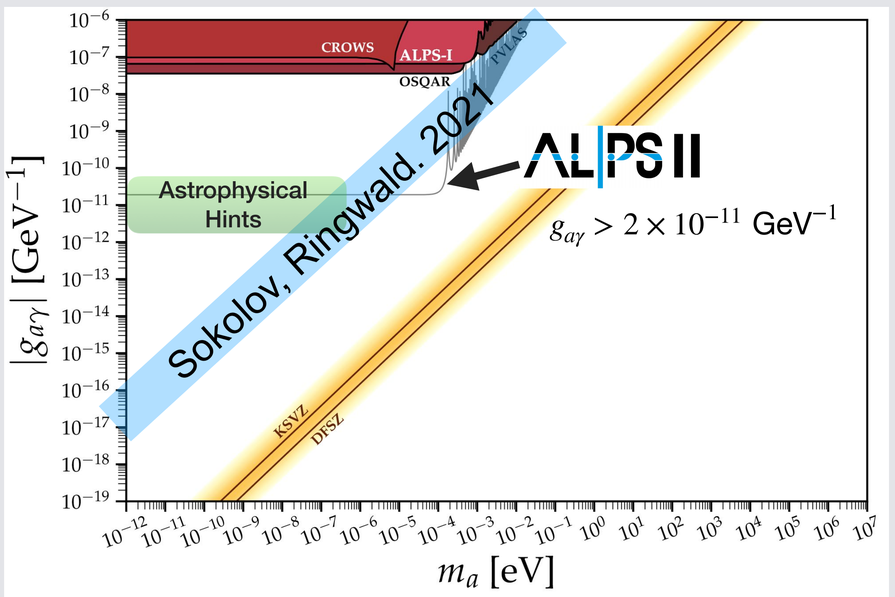
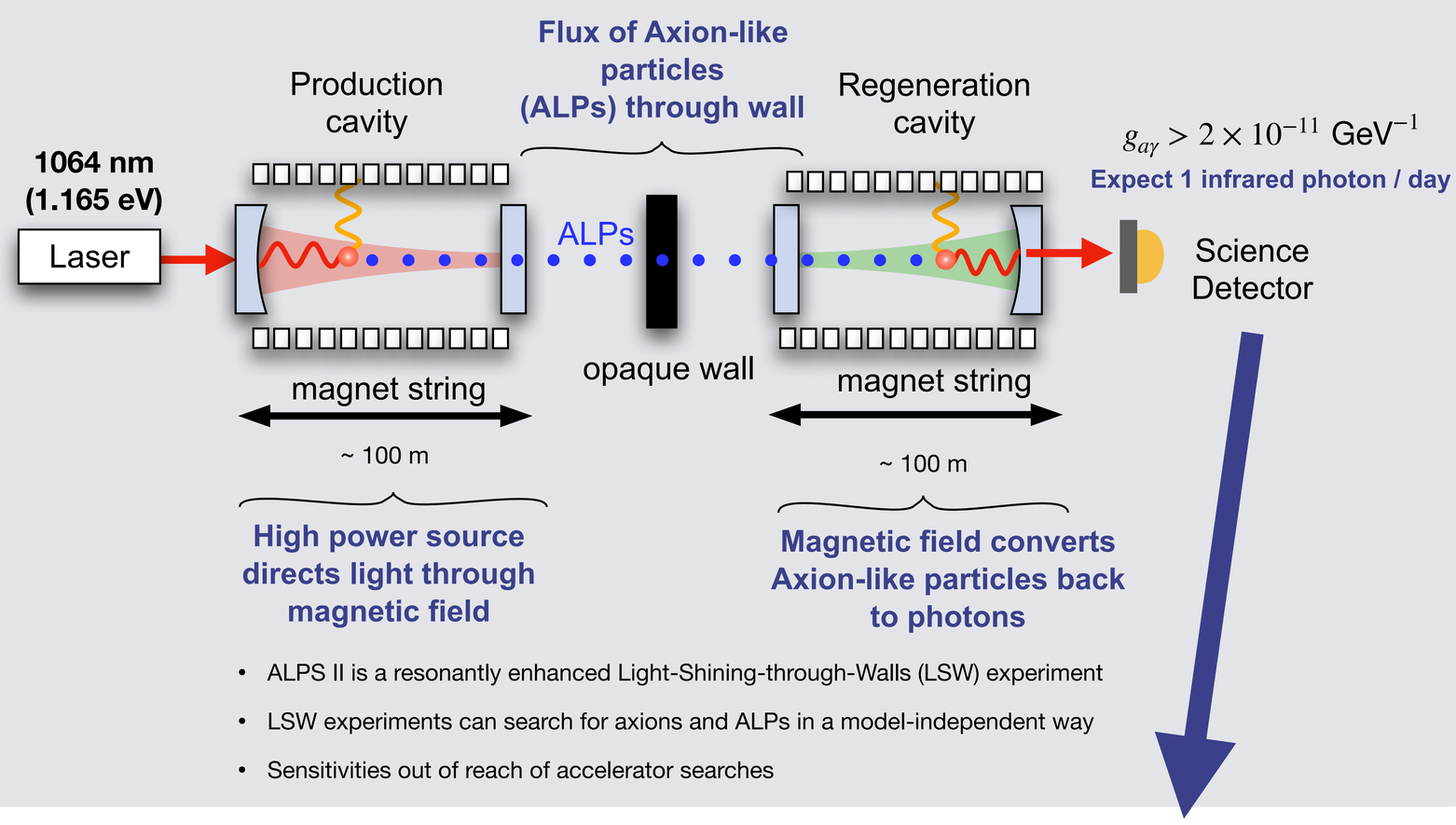
The ALPS II Experiment: Shining Light Through Walls

Graphic courtesy of Katharina-Sophie Isleif





Theoretical Motivation

- 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
- Probe regions with astrophysical hints in model-independent manner

- ALPS II is a resonantly enhanced Light-Shining-through-Walls (LSW) experiment
- LSW experiments can search for axions and ALPs in a model-independent way
- Sensitivities out of reach of accelerator searches

Transition Edge Sensors

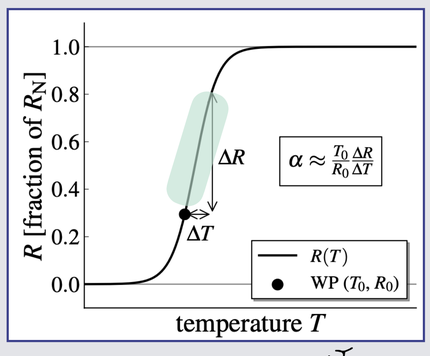
Transition Edge Sensors (TESs) are superconducting single-photon detectors

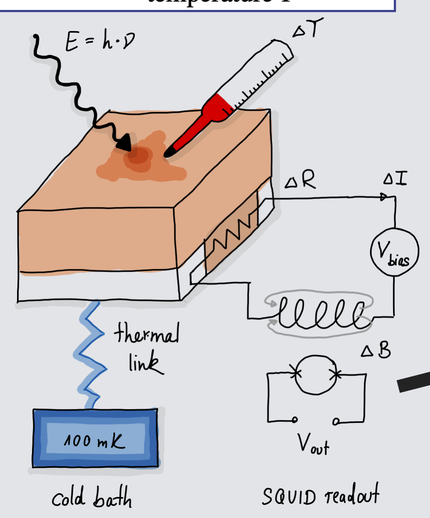
Working principle:

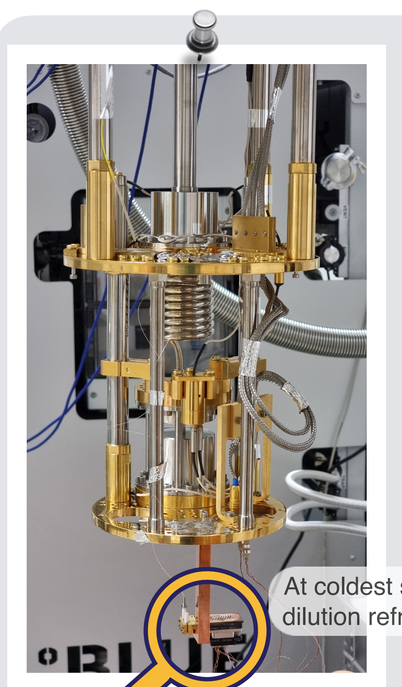
- TES biased in a region between superconducting and normal conducting → energy deposition from particle → small change of temperature → larger change in resistance and current → read out using SQUID electronics

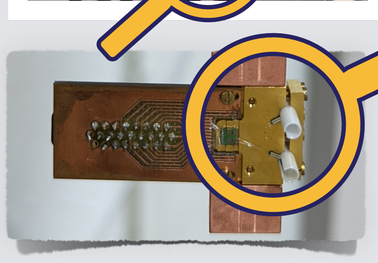
Our TESs:

- Tungsten → critical temperature of 140 mK
- Optimized for 1064 nm (~1.165 eV)

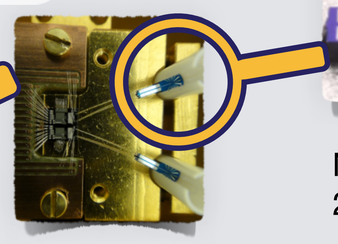






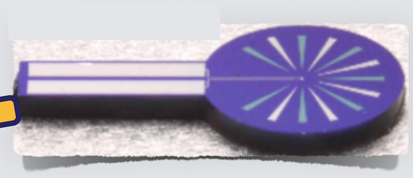


TES Module (PTB)



2 TES chips (NIST)

+ SQUID readout (PTB)



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

Detector Requirements

High Quantum Efficiency

- **> 95% at wavelength of interest (1064 nm ~ 1.165 eV)**

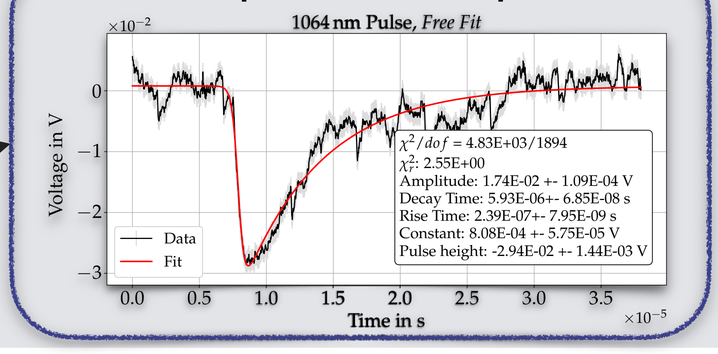
Good energy resolution

- 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)

Example 1064 nm TES pulse

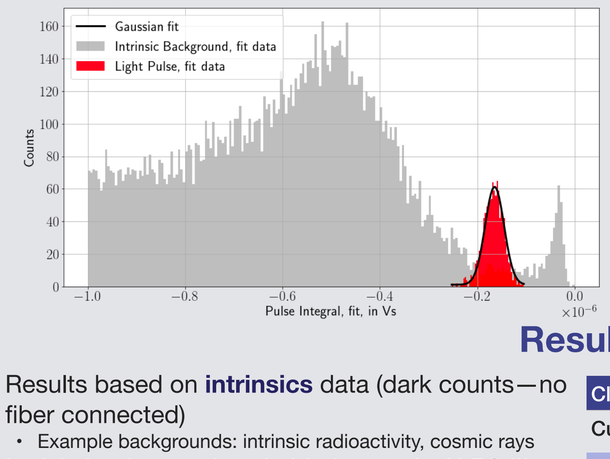


Pulse-Shape-Based Background Reduction

Complimentary analyses:

Cut-based analysis[1]

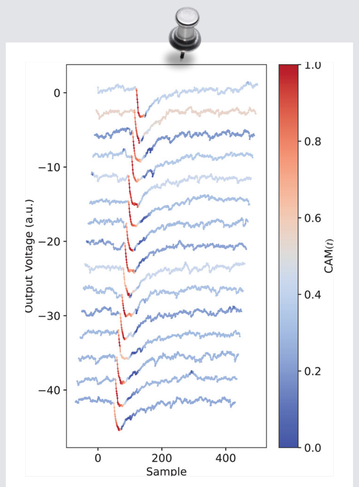
Compare pulse fit parameters from 1064 nm laser data—for example **rise time, decay time, and pulse integral**— to parameters from data with no laser (i.e. dark counts)



Machine learning[2]

Supervised learning: feed in fit parameters, use Random Forest (RF) or Multilayer Perceptron (MLP)

Deep learning: use Convolutional Neural Network (CNN) algorithm to extract important features

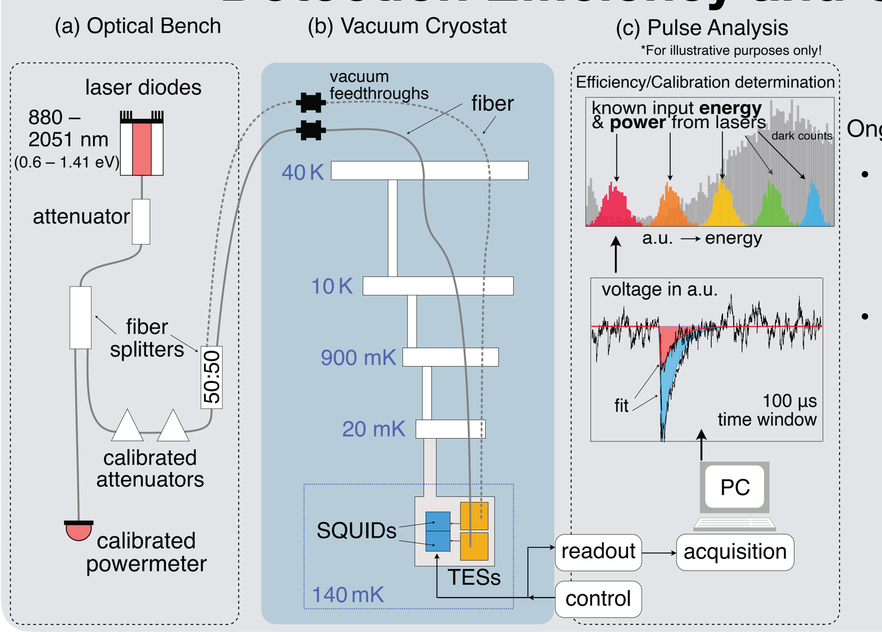


Results:

- Results based on **intrinsics** data (dark counts—no fiber connected)
  - Example backgrounds: intrinsic radioactivity, cosmic rays
- Intrisic backgrounds suitable for use in ALPS II!
- **To-do:** Repeat analyses with **extrinsics** data (no laser, but fiber connected)
  - Example background: blackbody photons from warm fiber tip

Classifier	Background Rate (10^{-6} Hz)	Signal Efficiency
Cut-based analysis[1]	$6.9^{+2.62}_{-1.47}$	> 0.9
RF[2]	2.1 ± 2.02	0.66 ± 0.15
MLP[2]	5.93 ± 5.23	0.9 ± 0.07
CNN[2]	< 8.54	0.42 ± 0.18

Detection Efficiency and Calibration



Ongoing work:

- Verify high detection efficiency for 1064 nm photons, for full setup including fiber feedthroughs
- Understand the detector response and efficiency at other wavelengths for searches beyond ALPS II

Want to get in touch?

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LinkedIn:

Conclusions and Future Work

Intrinsic backgrounds (no fiber connected) suitable for ALPS II

Still determining:

- Extrinsic backgrounds (with fiber connected)
- Full-system detection efficiency and calibration

Further science opportunities with the ALPS II TES:

- Direct detection of light dark matter particles, independent of ALPS II
- Explore using TESs in photonics Quantum Computing applications
- Explore using TESs in high-frequency gravitational wave searches
- Developing new TES modules in collaboration with group in Glasgow, UK

References and Acknowledgements

[1] Shah, R., Isleif, KS., Januschek, F. *et al.* Characterising a Single-Photon Detector for ALPS II. *J Low Temp Phys* **209**, 355–362 (2022). https://doi.org/10.1007/s10909-022-02720-0

[2] Meyer, M., Isleif, K., Januschek, F., Lindner, A., Othman, G., Rubiera Gimeno, J. A., Schwemmbauer, C., Schott, M., Shah, R., A First Application of Machine and Deep Learning for Background Rejection in the ALPS II TES Detector. *ANNALEN DER PHYSIK* 2023, 2200545. https://doi.org/10.1002/andp.202200545

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