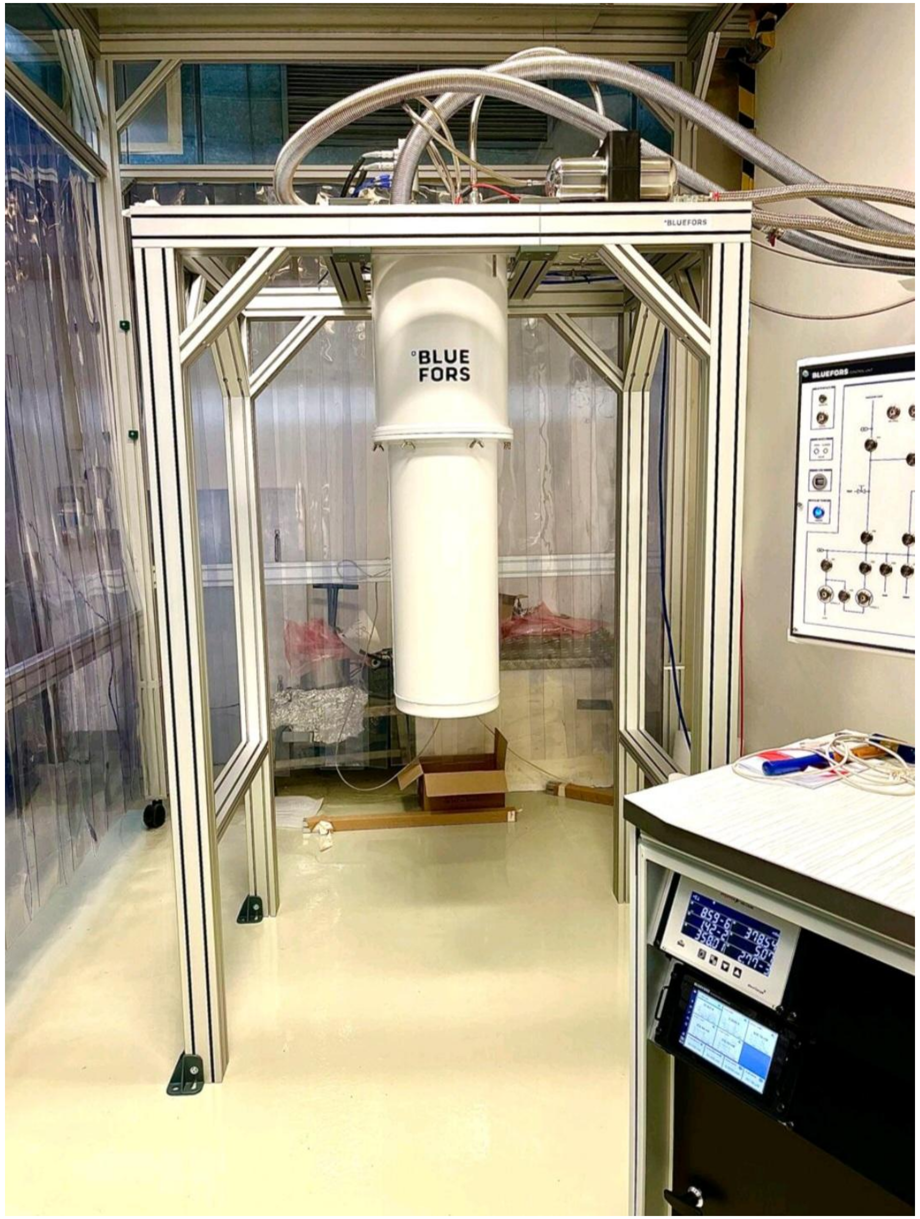
How to directly detect Dark Matter with a Transition Edge Sensor



Christina Schwemmbauer

for the TES Team of the ALPS Collaboration

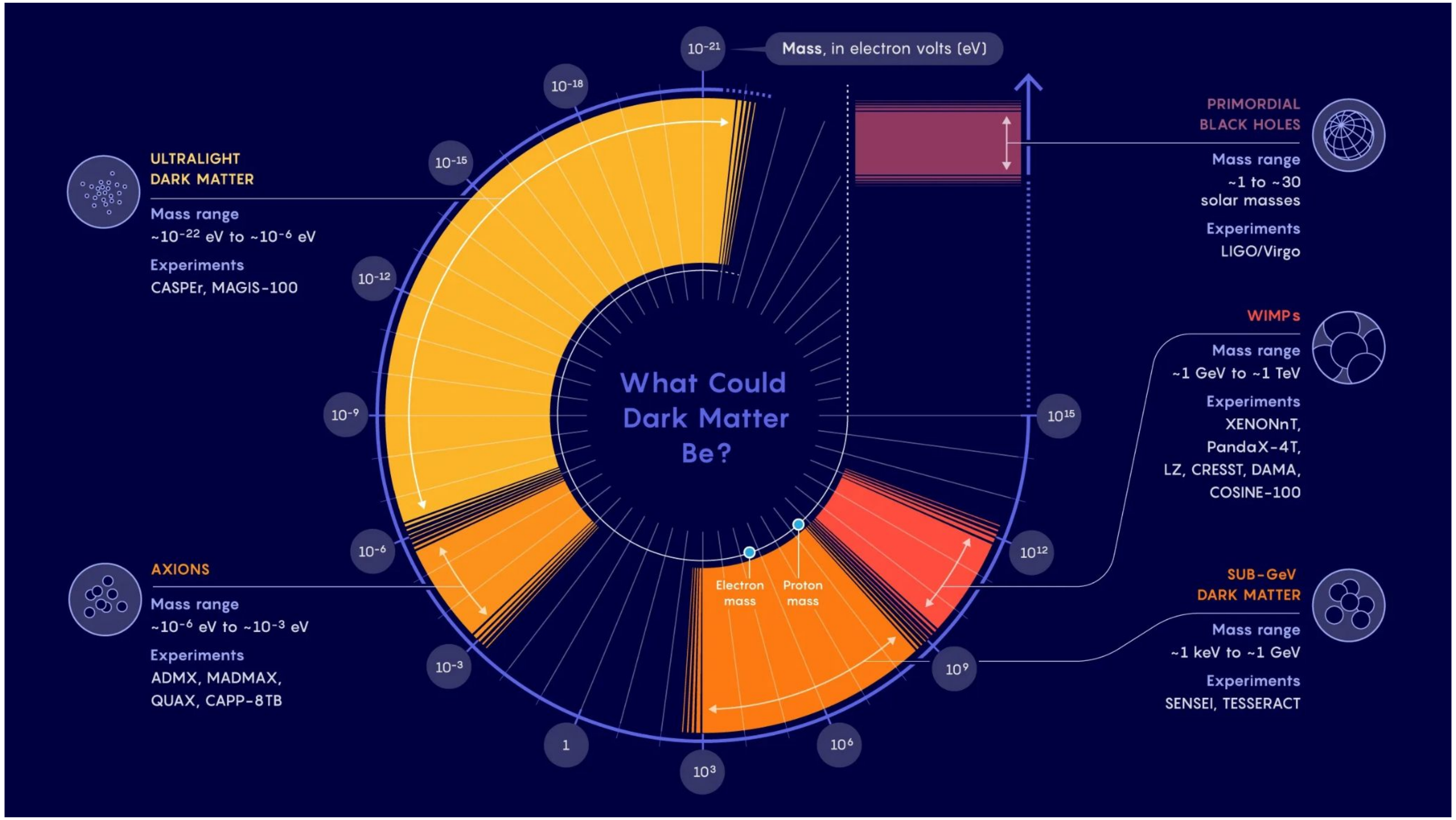
DESY Detector R&D Retreat, 19.01.2024

HELMHOLTZ UHH SDU University of Southern Denmark ALPS DESY.

Dark Matter

…and it's Particle Zoo

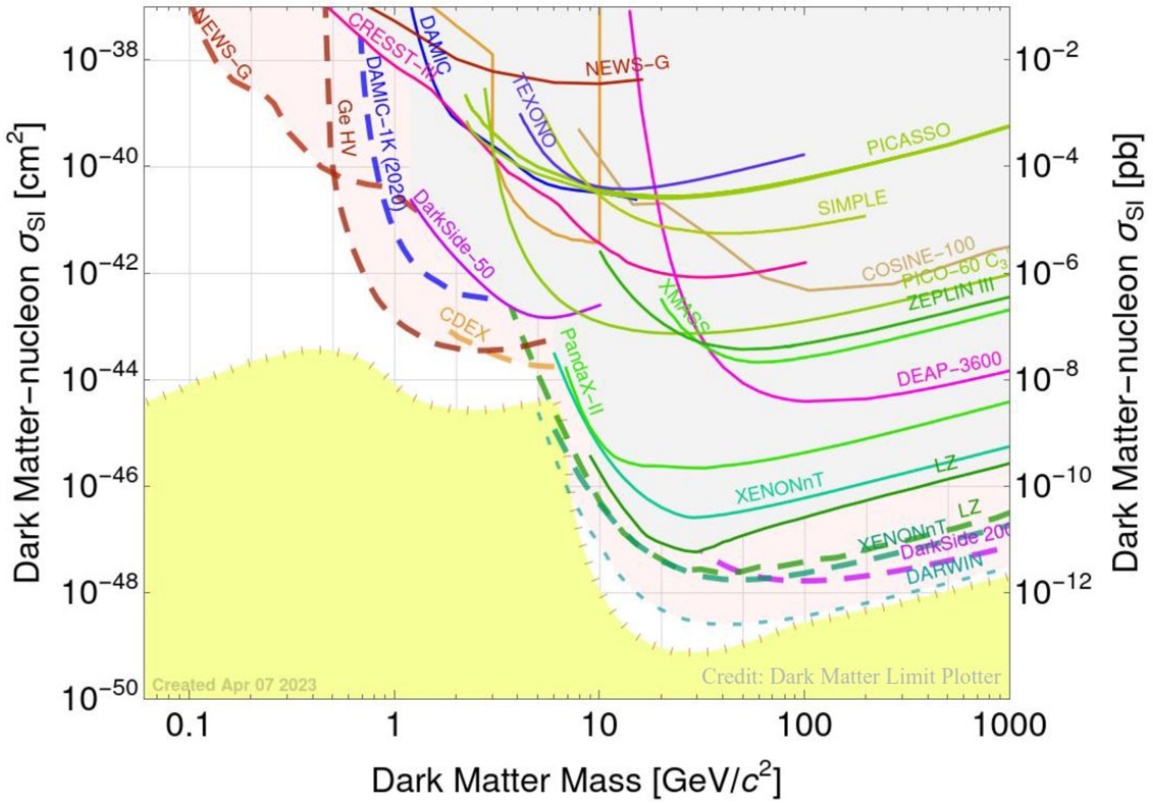
- Dark Matter (DM) makes up ~25% of the universe, mainly interacts gravitationally with ordinary matter
- many (particle) DM models exist, differing in mass/coupling/scattering cross-section/etc.
- searches for Weakly Interacting Massive Particles (WIMPs) in the GeV-mass range have not found new particles as of yet



https://www.wired.com/story/the-search-for-dark-matter-is-dramatically-expanding/

Detection of sub-GeV Dark Matter

Dark Matter – nucleon scattering



from S. Lindemann, "WIMP direct detection experiments", 18th PATRAS Workshop on Axions, WIMPs and WISPs, Rijeka 2023

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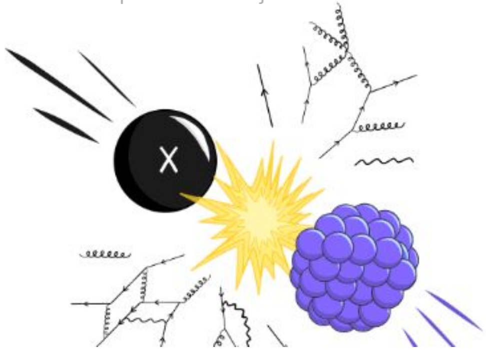

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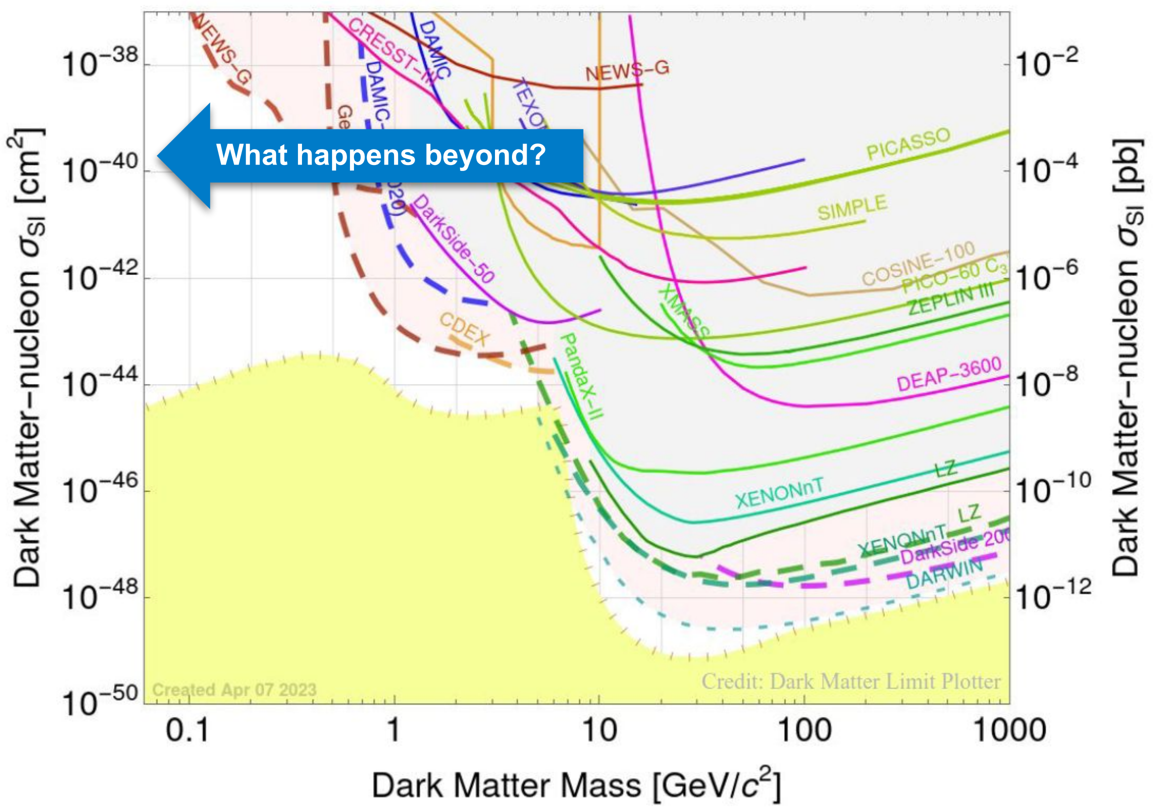

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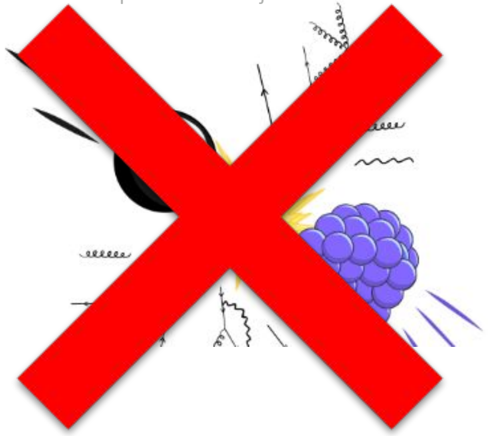

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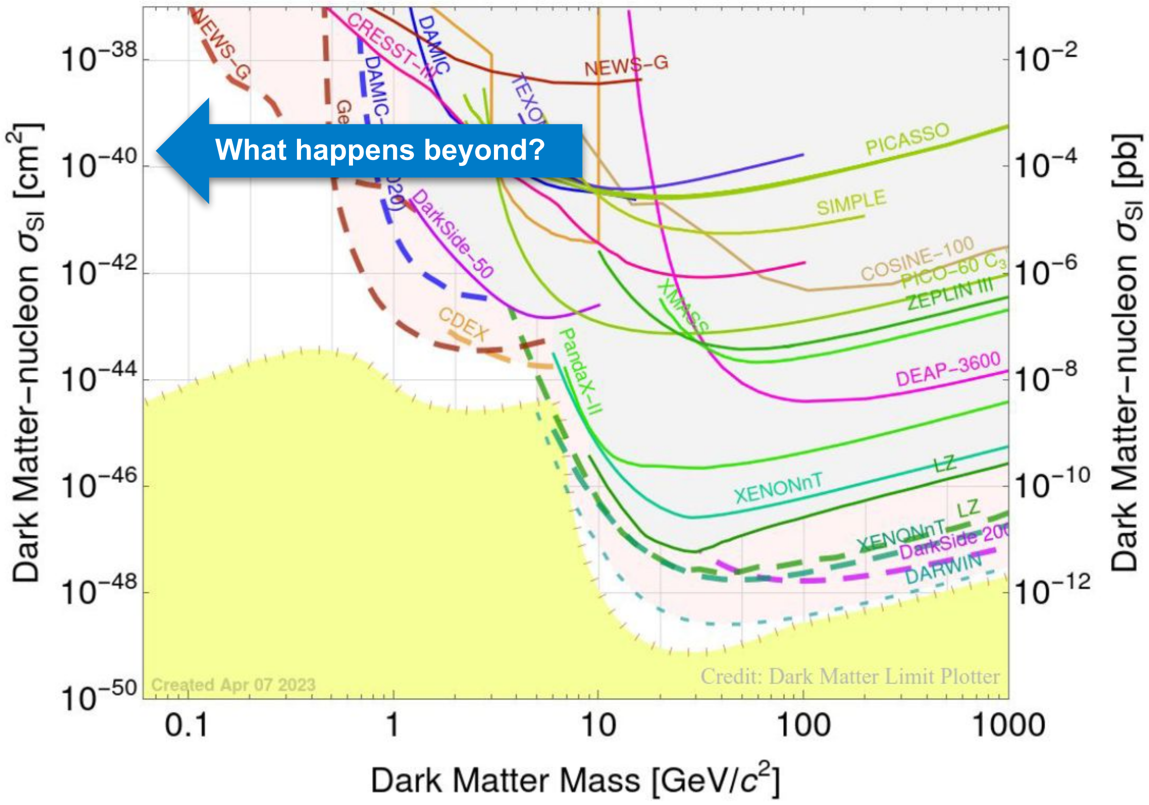

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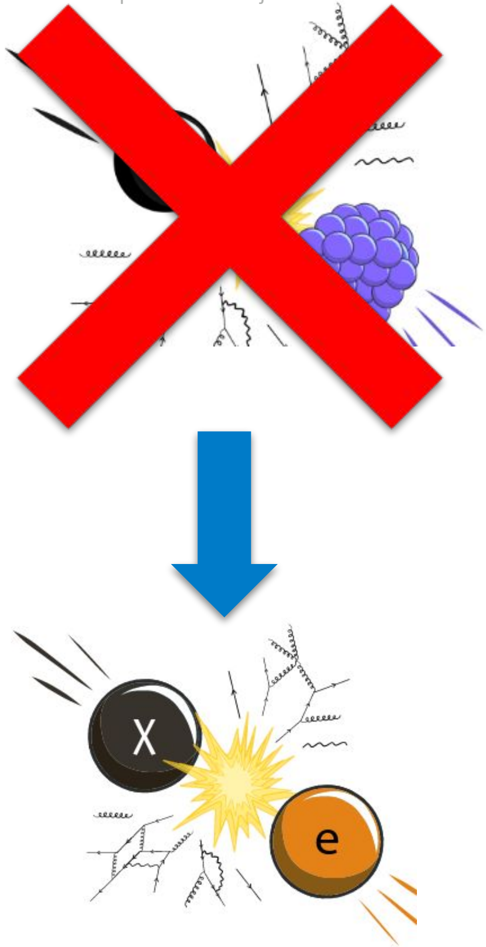

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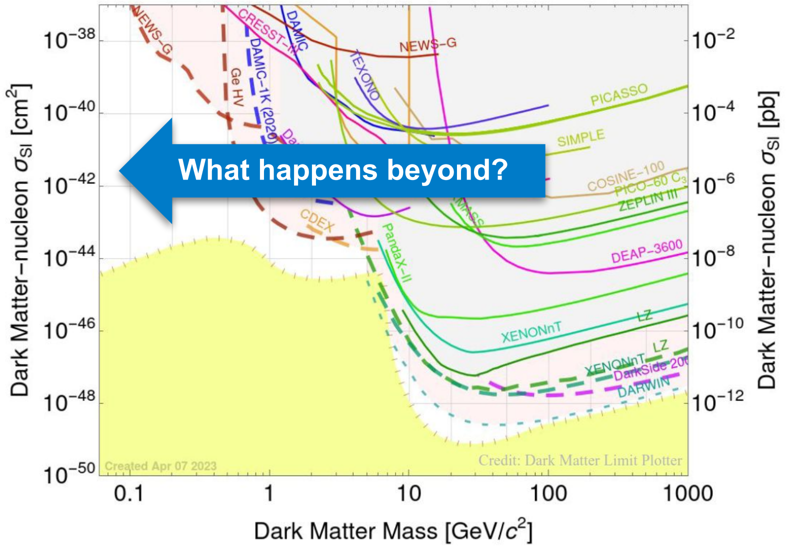

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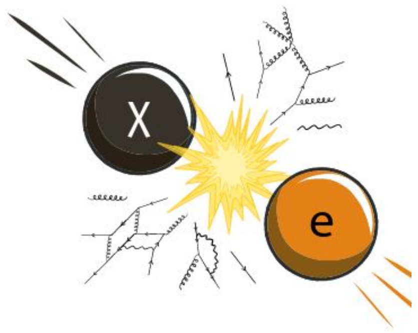

Assume:

- Characteristic DM halo velocity $v_\chi \sim 10^{-3}c$
- Scattering via mediator (heavy or light) coupling to electrons (e.g. dark photon as massless mediator)

Maximum Energy transfer E_T in scattering event is entire kinetic energy of DM particle with mass m_χ :

$$E_{T_{\max}} = E_{\rm kin} \sim m_\chi v^2 \sim 10^{-6} m_\chi$$

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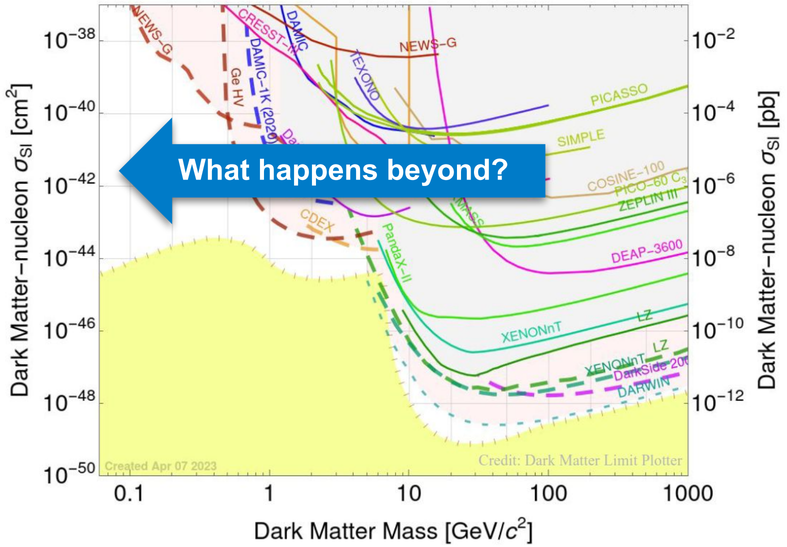

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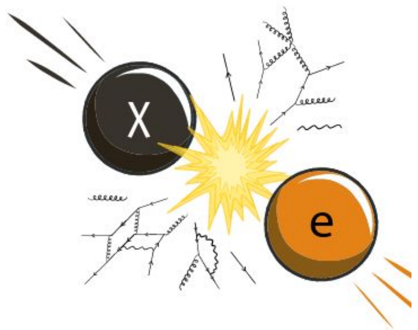

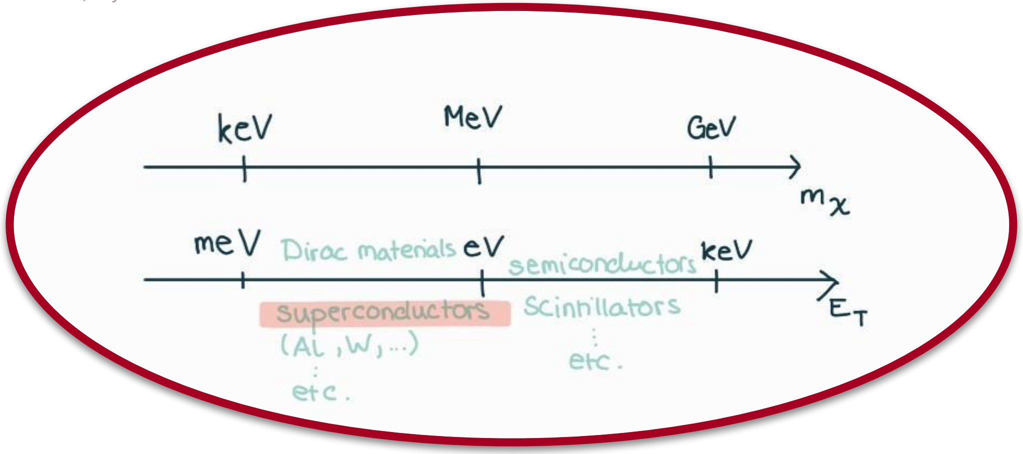

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DARK MATTER SEARCHES WITH SUPERCONDUCTORS

Illustration by Sandbox Studio, Chicago with Abigail Malate

DM Searches with Superconductors

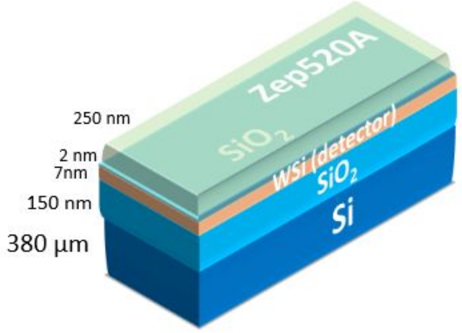
Role model: SNSPDs

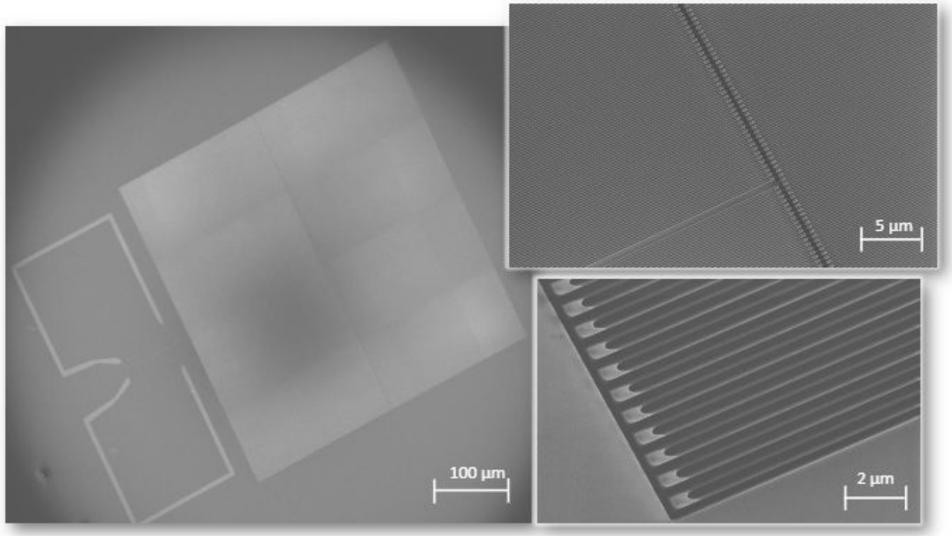
Example: principle proven for SNSPDs

(**S**uperconducting **N**anowire **S**ingle **P**hoton **D**etector)

- First measurements already set new bounds
- Only 4 dark counts in 180 hrs
- 0.73 eV energy threshold
- Allows to exclude DM-electron scattering parameter space

- **Low noise**
- **'Large' target mass (4.3 ng)**
- **Low energy threshold**





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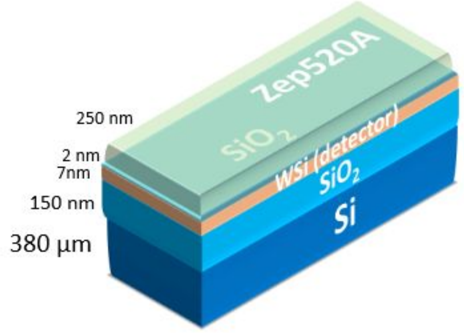

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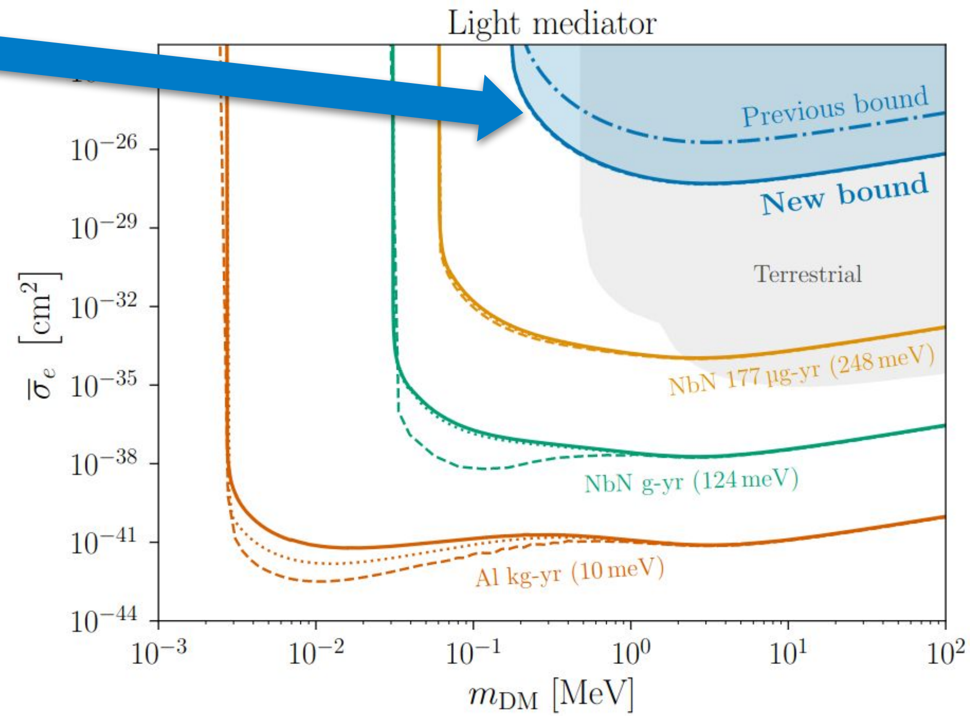

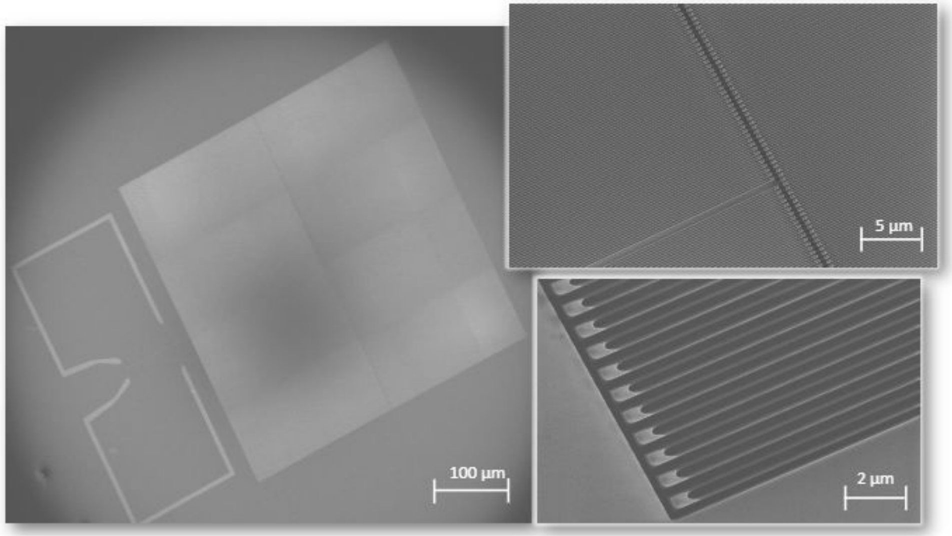

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SNSPD vs TES

Limits of SNSPDs:

Works like a Geiger counter

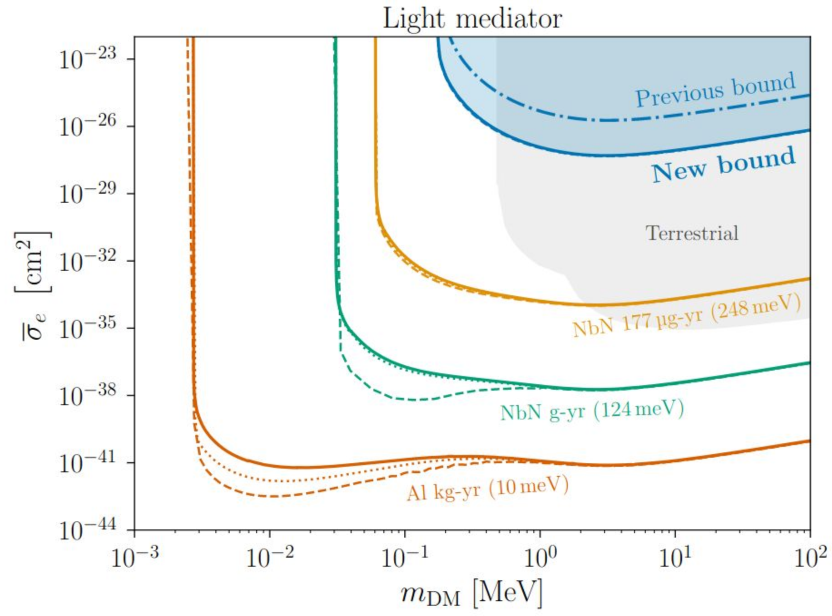
No pulse-shape discrimination

Superconducting Detectors for Super Light Dark Matter

Yonit Hochberg,[1] Yue Zhao,[2] and Kathryn M. Zurek[1]

[1] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720*
Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720
[2] *Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, CA 94305, U.S.A.*

We propose and study a new class of of superconducting detectors which are sensitive to $\mathcal{O}$(meV) electron recoils from dark matter-electron scattering. Such devices could detect dark matter as light as the warm dark matter limit, $m_X \gtrsim 1$ keV. We compute the rate of dark matter scattering off of free electrons in a (superconducting) metal, including the relevant Pauli blocking factors. We demonstrate that classes of dark matter consistent with terrestrial and cosmological/astrophysical constraints could be detected by such detectors with a moderate size exposure.



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- ✓ Energy information (Pulse shape analysis)
- ✓ Possibly lower energy threshold
- ✗ Lower mass (0.2 ng)

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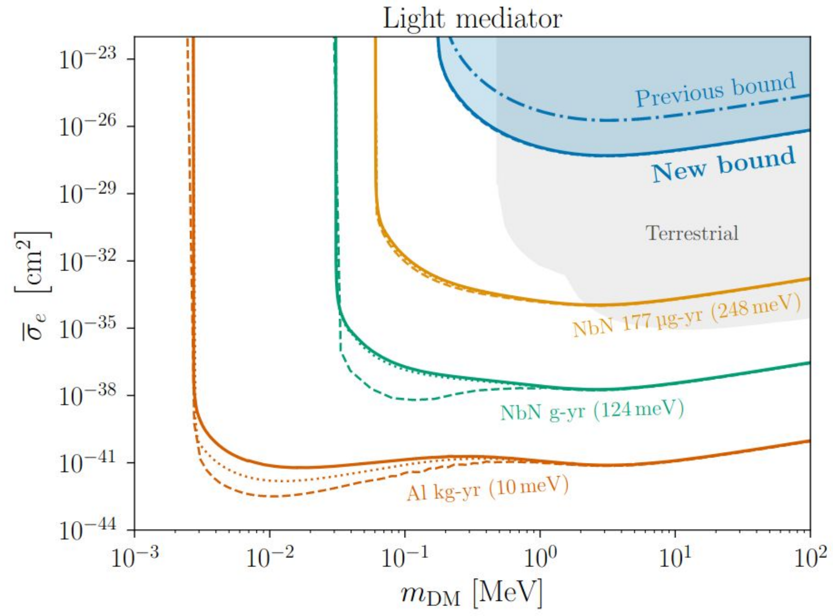

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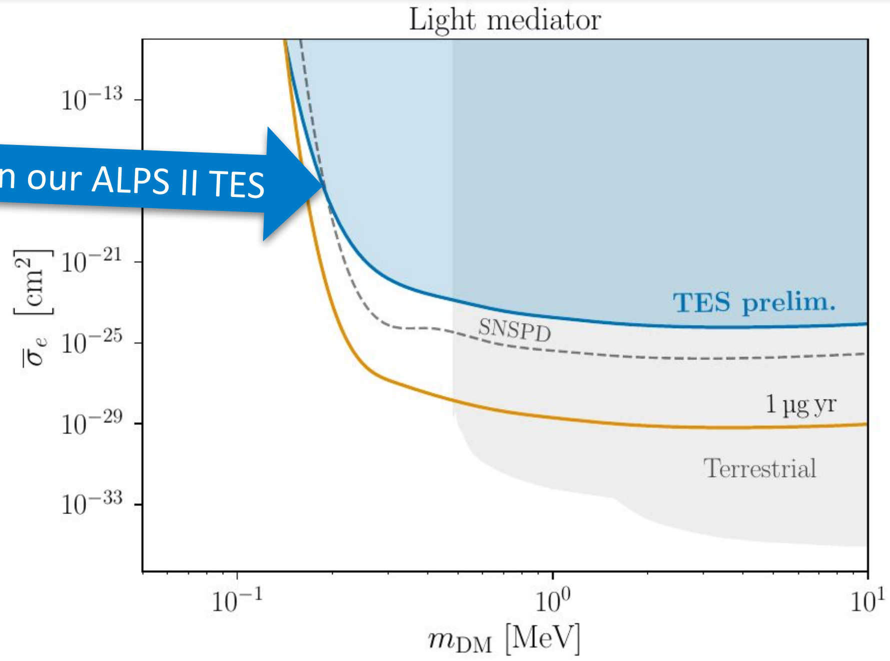
Possible sensitivity based on our ALPS II TES



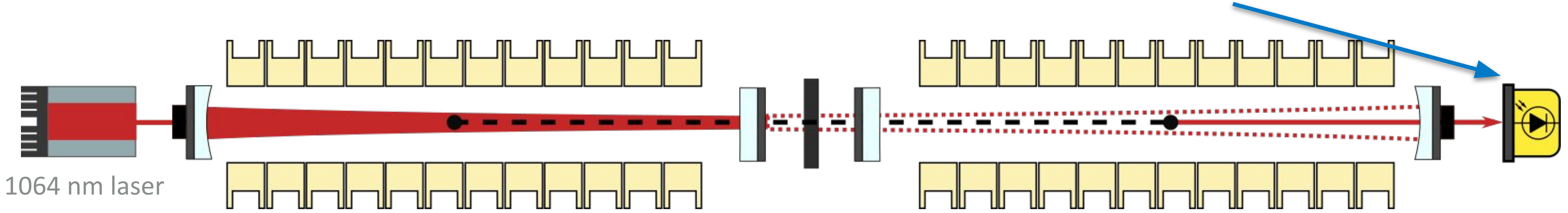
Projections and plot by Benjamin V. Lehmann

TES @ ALPS II

Illustration by Sandbox Studio, Chicago with Abigail Malate

TES Single Photon Detection
Detection techniques in the ALPS II experiment

Light Shining through a Wall experiment
Challenge: Detect single photon from axion-photon conversion



Goal: Detection of Axions/ALPs (Axion-Like-Particles) - possibility of producing and detecting dark matter

Drawing courtesy of Todd Kozlowski

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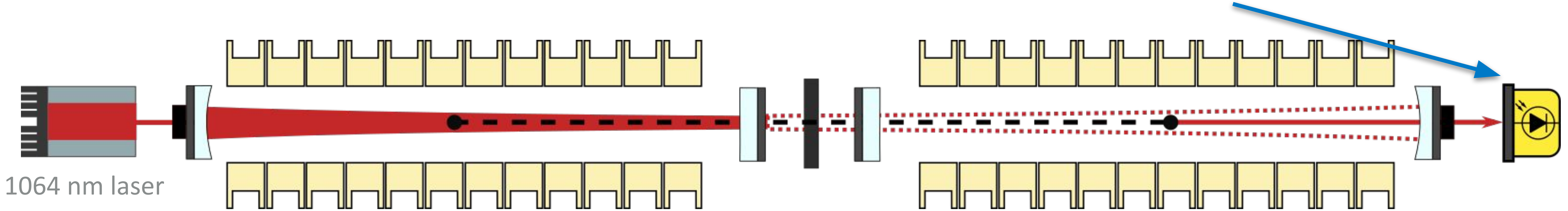


Application of two photon-measurement schemes:

HETerodyne interferometry (HET)

- detects photon fields
- mixing of regenerated fields with local oscillator
- measurement of resulting beat note

Transition **E**dge **S**ensor (TES):

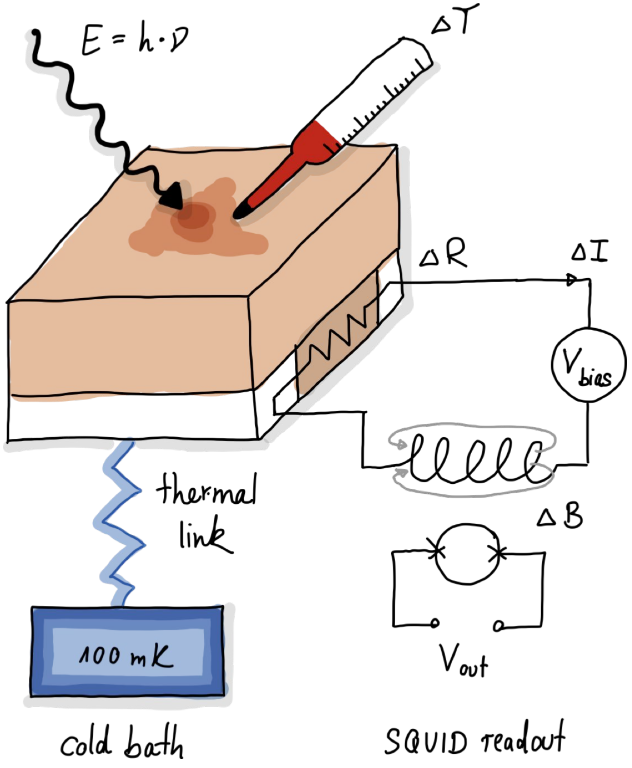
- Single photon detection
- Using **superconducting** tungsten chip

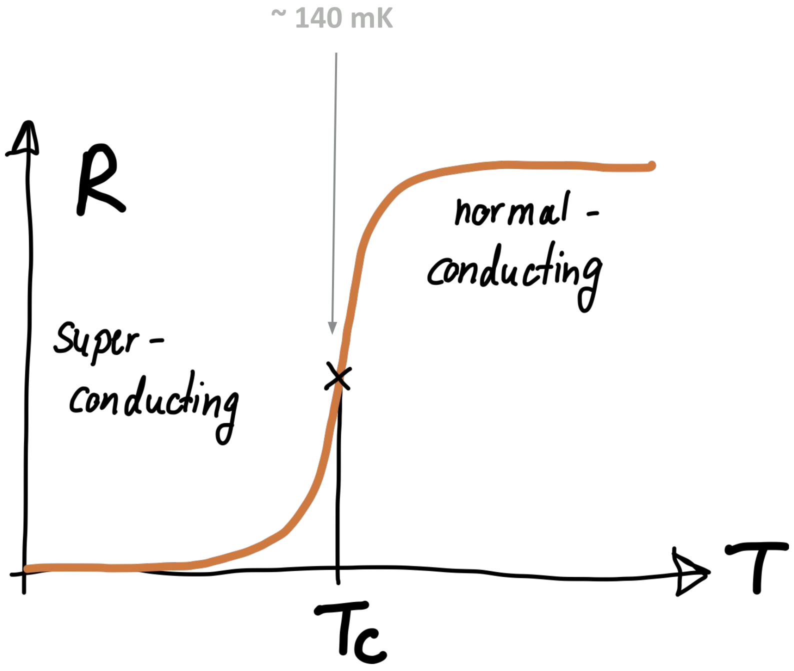
More details: "Characterisation of a TES detector for ALPS II" – José Alejandro Rubiera Gimeno

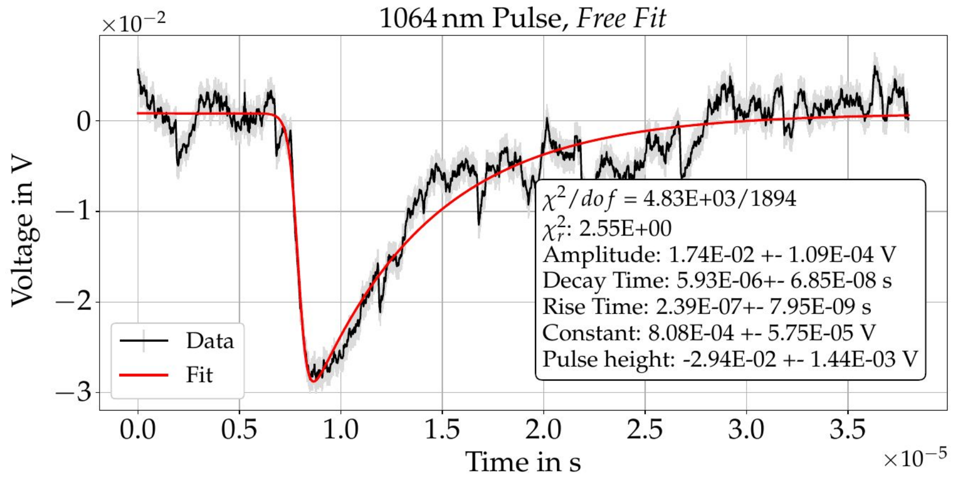
Drawing courtesy of Todd Kozlowski

TES Single Photon Detection

Transition Edge Sensors







Courtesy of Rikhav Shah

- Cryogenic microcalorimeters
- Operated at superconducting transition temperature
- Read-out using **S**uperconducting **Q**uantum **I**nterference **D**evices (SQUIDs)

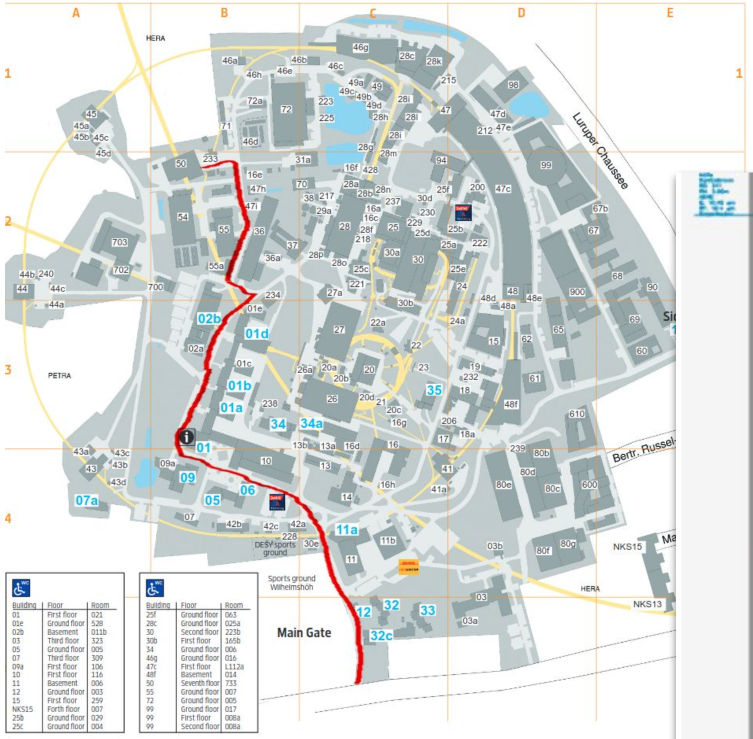
- Incident photon leads to temperature increase
- Small temperature increase leads to large variation in resistance

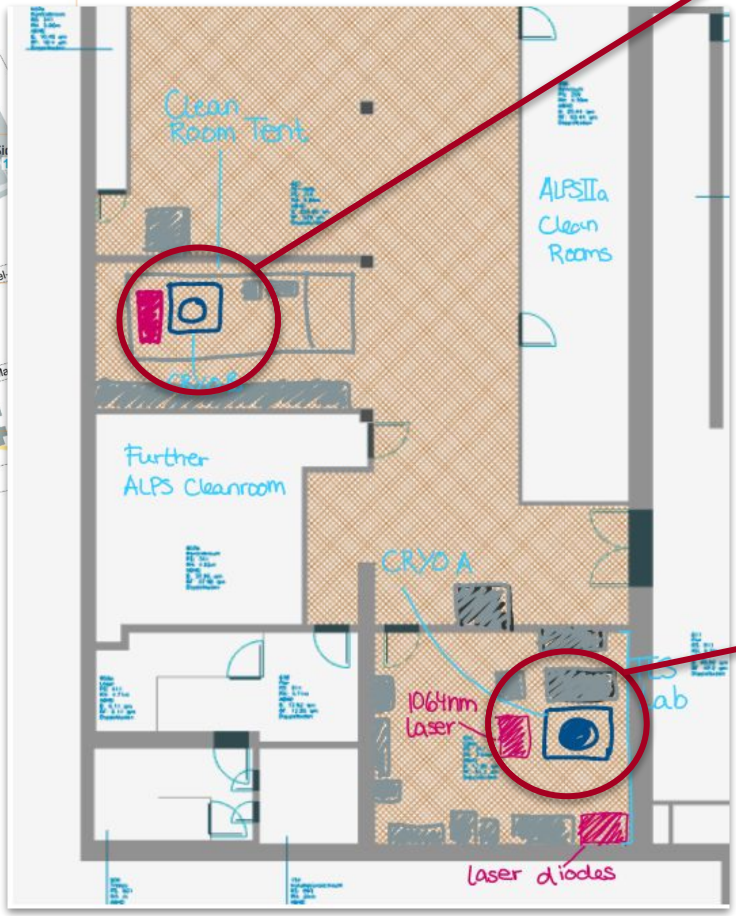
- Change in resistance is measured in changing current
- Signal is proportional to photon energy
- Energy resolution ≤ 10%
- DM signal expected to look like photon

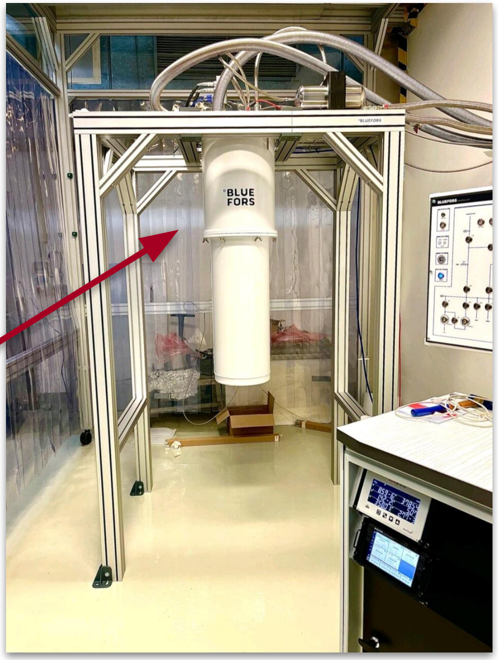
Drawings courtesy of Katharina-Sofie Isleif

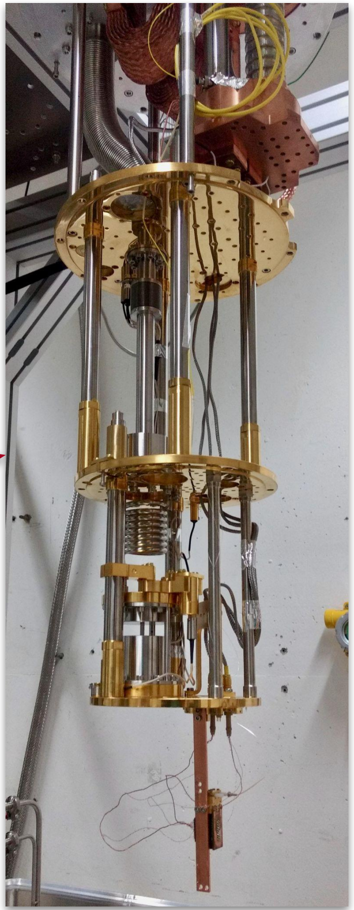
TES Single Photon Detection

Infrastructure









TES as Dark Matter Detector

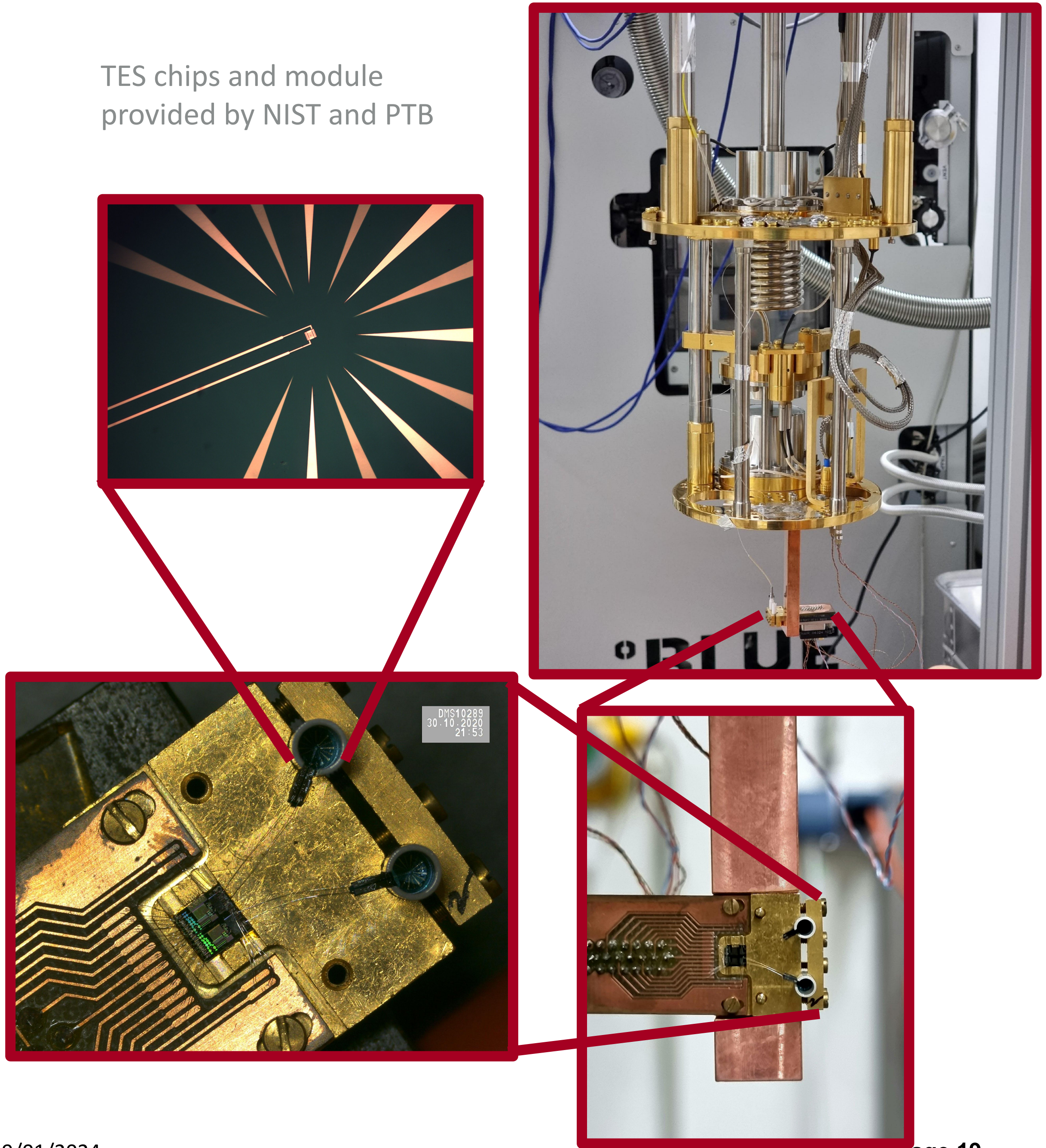
Current Challenges

TES @ ALPS II Status

- Optimized infrastructure (setup, analysis) for signals at 1064 nm→**1.165 eV**
- Limited knowledge about response to other wavelengths

Low background
(electronic noise, radioactivity, cosmic backgrounds)
→ currently: 6.9×10^{-6} cps[1]
(intrinsic background for 1.165 eV signals)

TES chips and module provided by NIST and PTB



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- Determine TES response at different (lower, sub – eV) energies
- Calibration measurements currently using different wavelengths (880 nm – 2000 nm)

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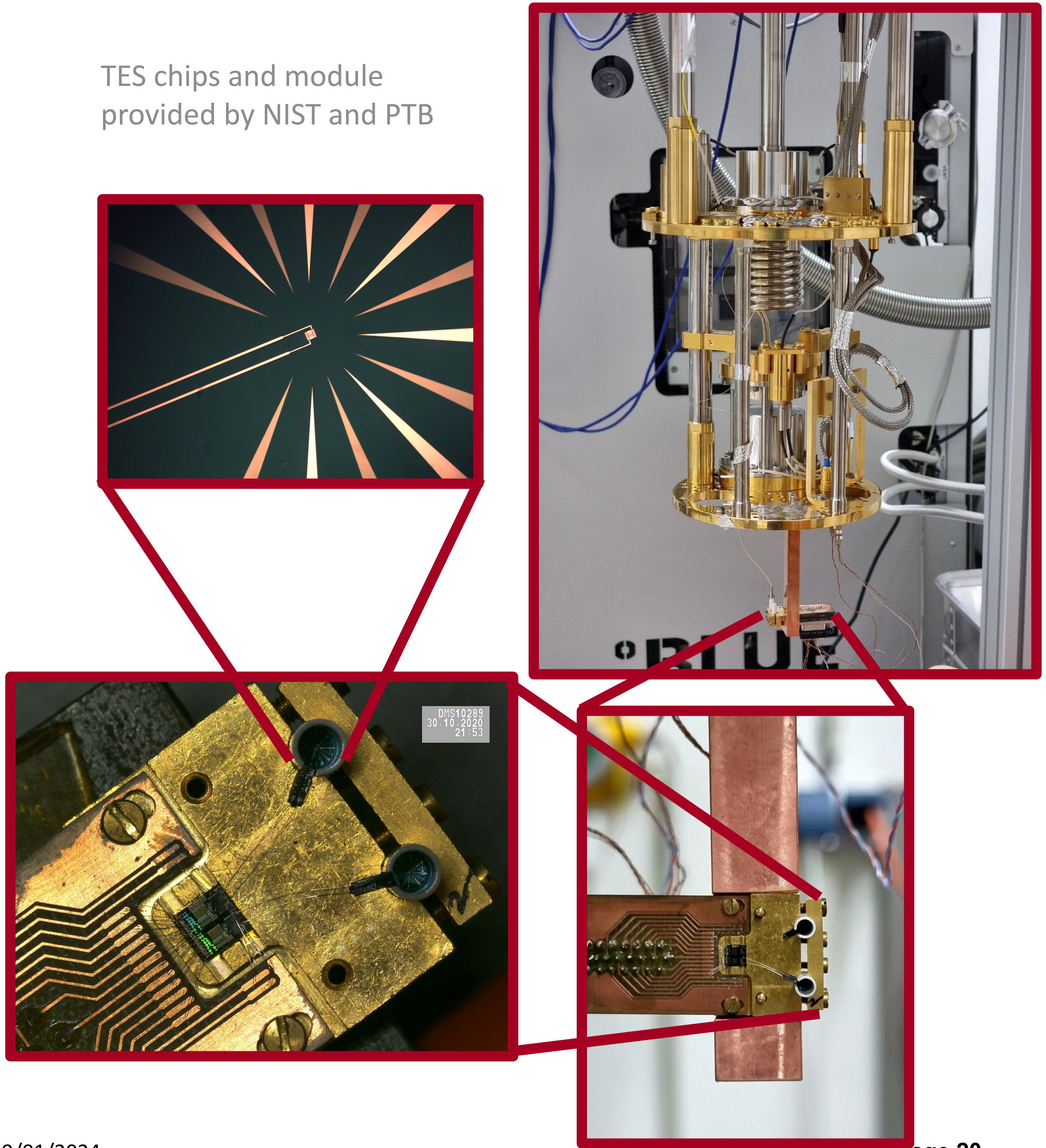

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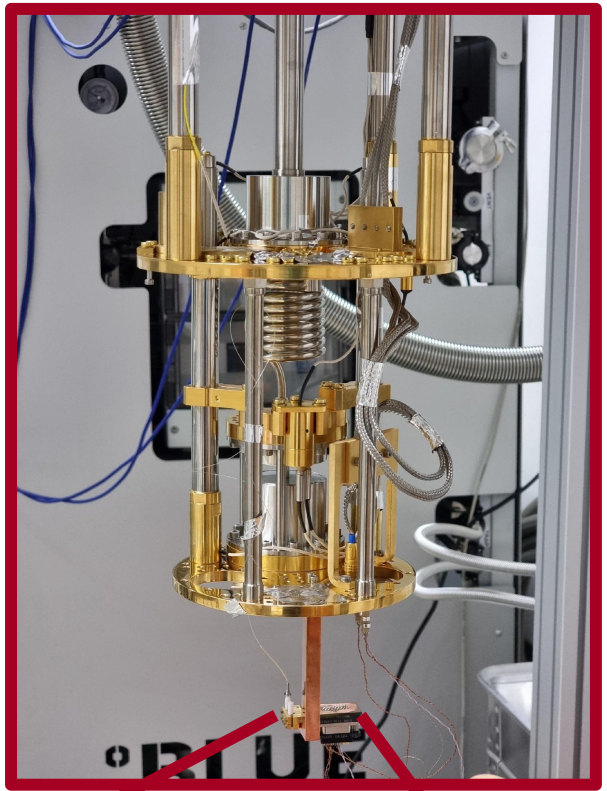

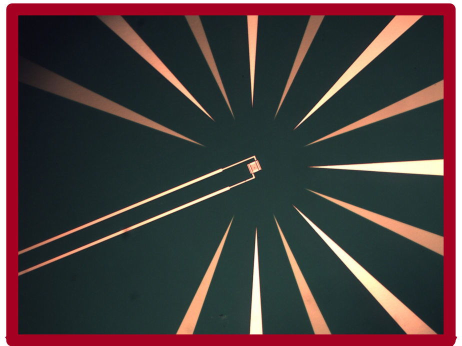

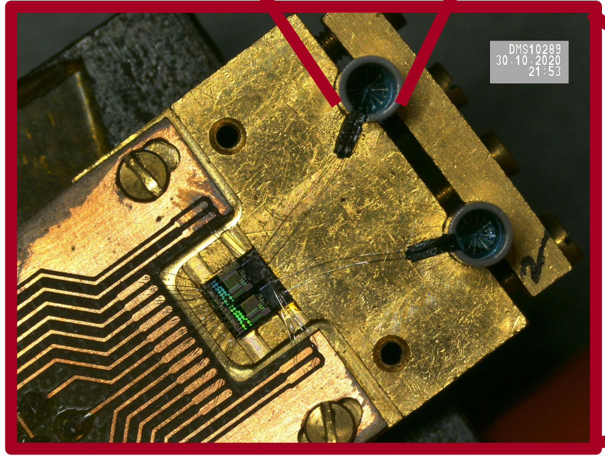

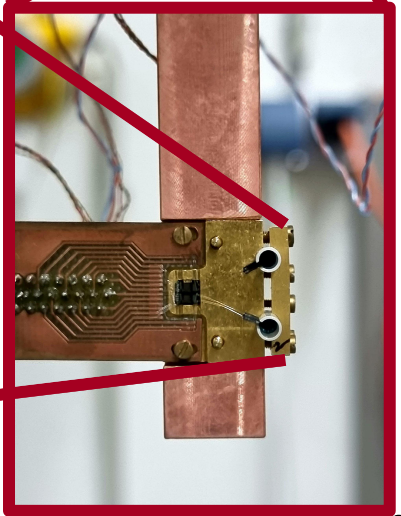

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Low background (electronic noise, radioactivity, cosmic backgrounds) → currently: 6.9×10^{-6} cps[1] (intrinsic background for 1.165 eV signals)	• Further investigate intrinsic backgrounds • Investigate alternative TES modules with lower noise background

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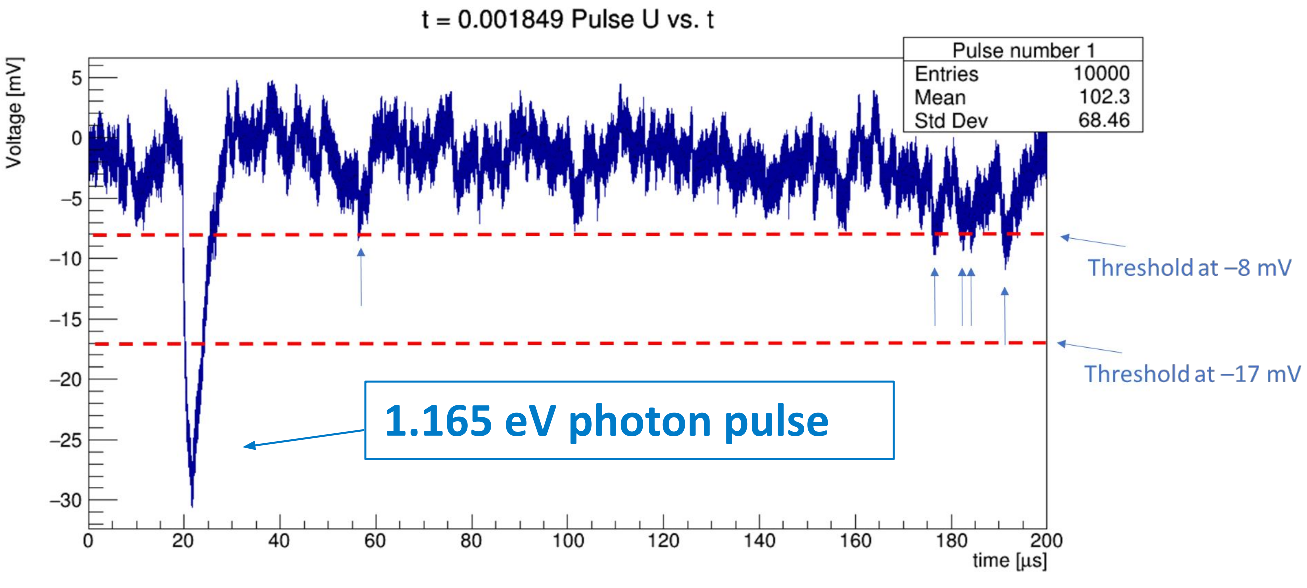
DIRECT DARK MATTER SEARCHES WITH TES - SIMULATIONS

Illustration by Sandbox Studio, Chicago with Abigail Malate

TES pulses - simulation and analysis
How low can we go?

- Based on laser (1.165 eV) calibration (recording single-photon pulses of an attenuated laser)
- and noise measurements

Simulation of electronic noise & pulses



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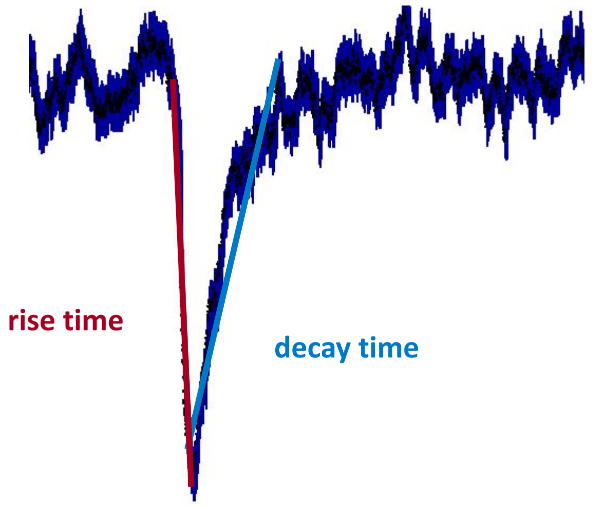

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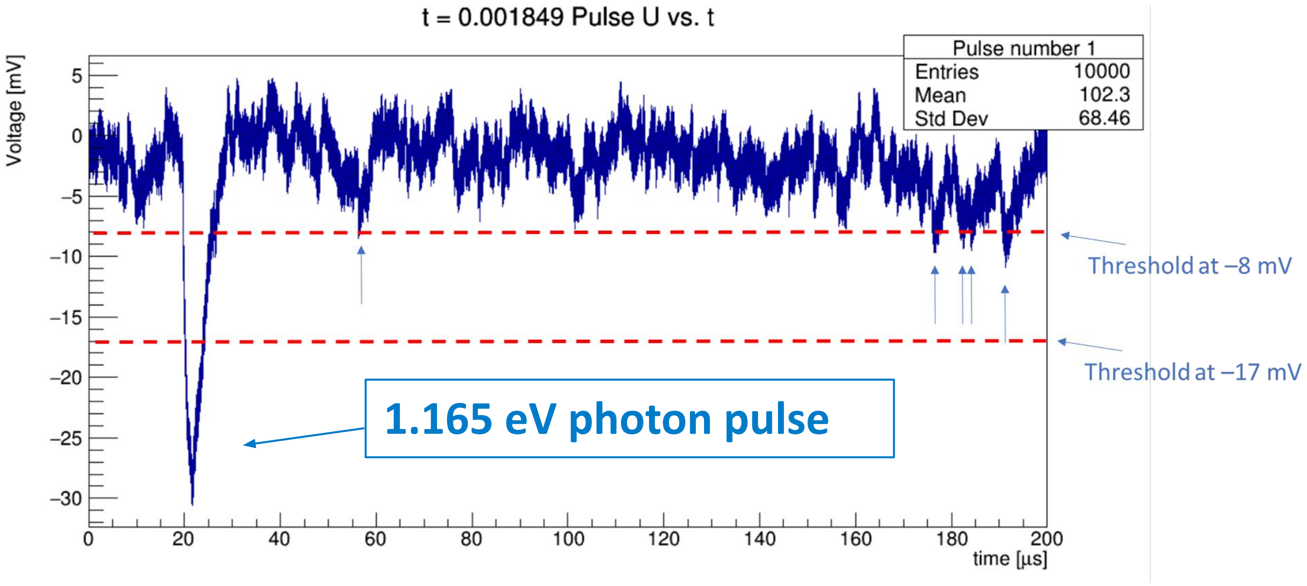


$$U(t) = -\frac{2A}{e^{-\frac{1}{\tau_{\mathrm{rise}}}(t-t_0)} + e^{\frac{1}{\tau_{\mathrm{decay}}}(t-t_0)}} + V_0$$

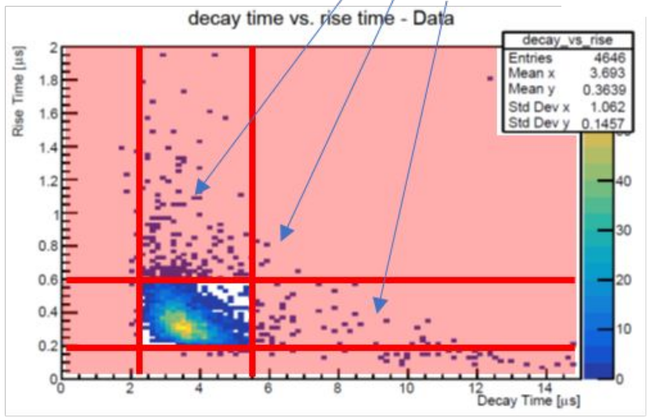
→ known pulse shape fitted to all triggered pulses

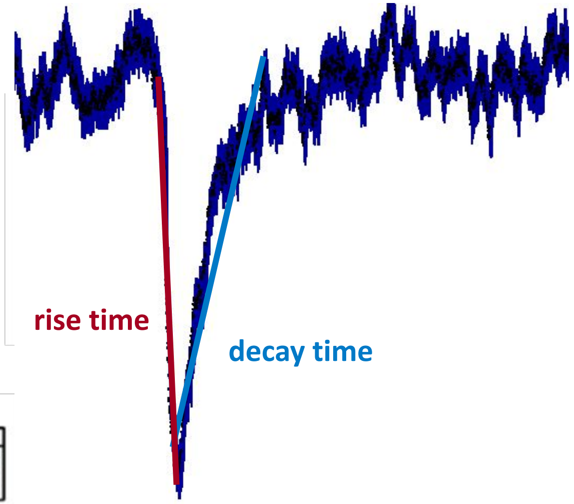
For sub-eV: Can we discern low energy pulses from noise?

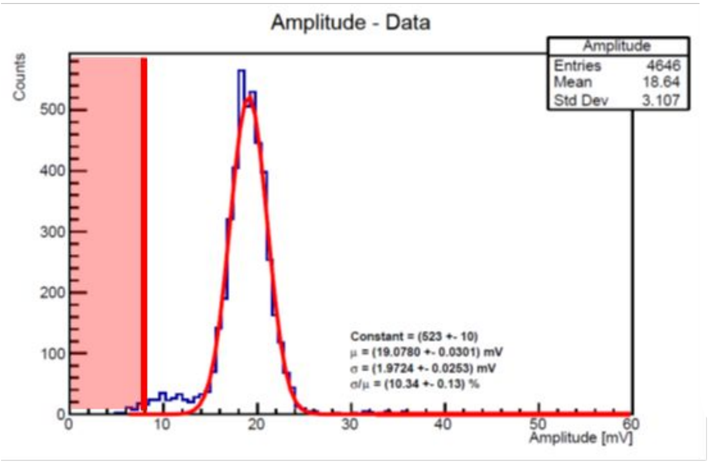
TES pulses - cut-based analysis

Example: 1.165 eV photon pulses

cutting away signals outside of central region







Assumptions for DM-electron scattering:

→ expect similar rise and decay time of pulses (governed by TES circuit)

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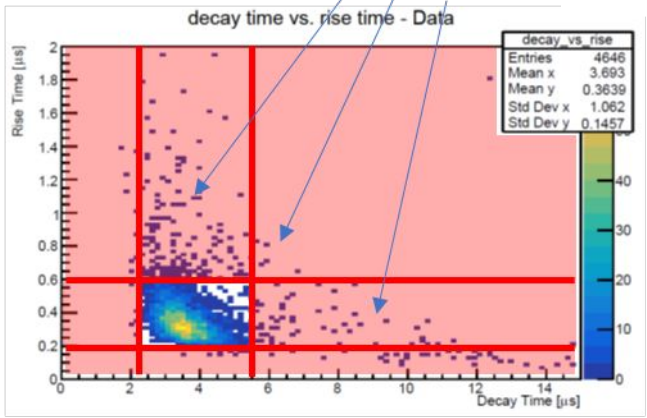

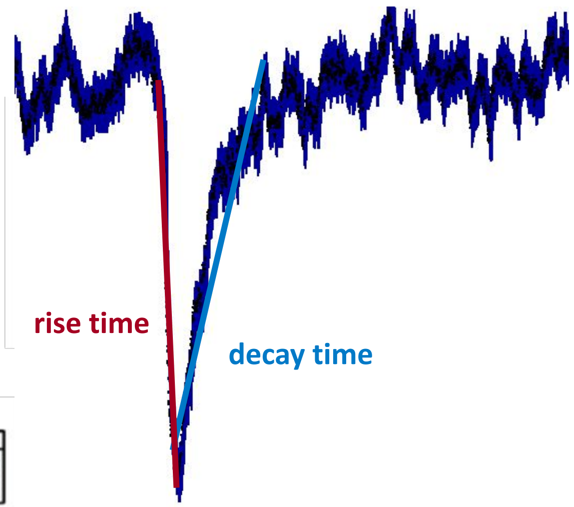

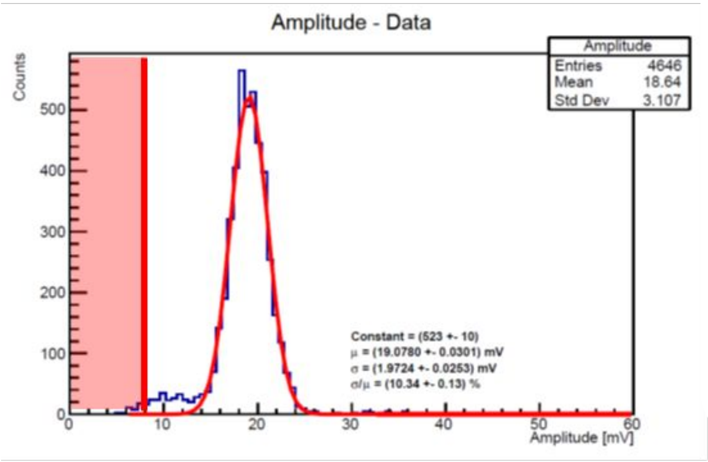

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Simulating lower energy pulses:

→ simulate pulses based on 1.165 eV calibration and assumptions above

→ adjust cut-based analysis for different energies

Baseline simulations

Using cut-based analysis for lower energy pulses

Noise-only simulations

Trigger Rate for -12 mV threshold
0.422 (0.010) Hz

after analysis & cuts

Based on these assumptions, for now we can

test background rate for lower triggers after analysis:

- ~ 70 min noise-only simulation
- Applying cuts optimized for 1.165eV and **0.583eV**

Baseline simulations

Using cut-based analysis for lower energy pulses

Noise-only simulations

Trigger Rate for -12 mV threshold
0.422 (0.010) Hz

after analysis & cuts

Cuts based on	Trigger Rate for -12 mV threshold
1.165 eV	< 0.0007 Hz
0.583 eV	< 0.0007 Hz

Based on these assumptions, for now we can

test background rate for lower triggers after analysis:

- ~ 70 min noise-only simulation
- Applying cuts optimized for 1.165eV and **0.583eV**

No noise passing analysis & cuts with
~56% acceptance of 0.583eV pulses
Promising for sub-MeV direct DM searches!

DIRECT DARK MATTER SEARCHES WITH TES

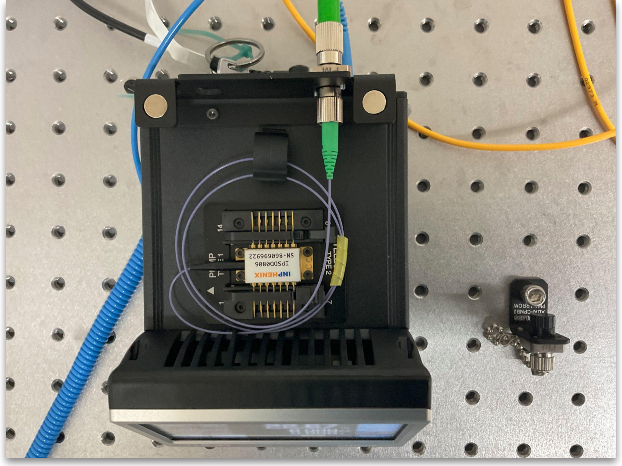
-

CALIBRATION

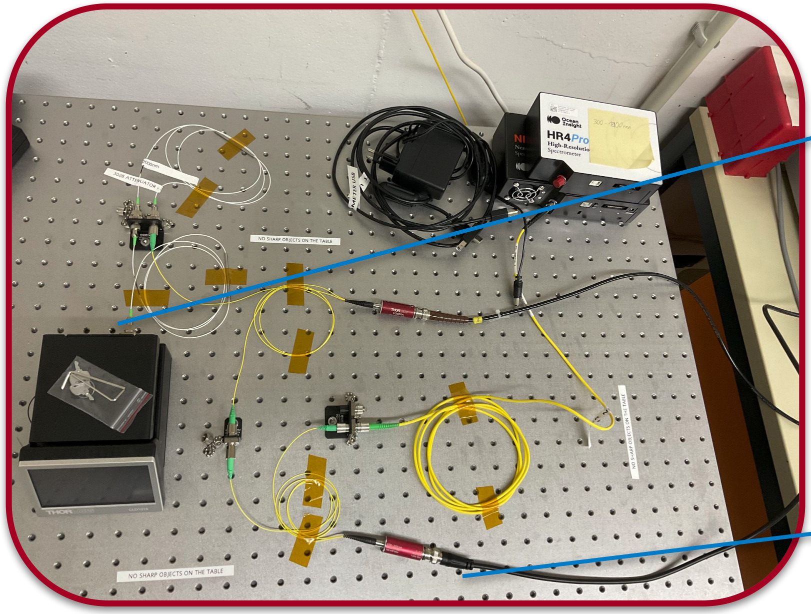
Illustration by Sandbox Studio, Chicago with Abigail Malate

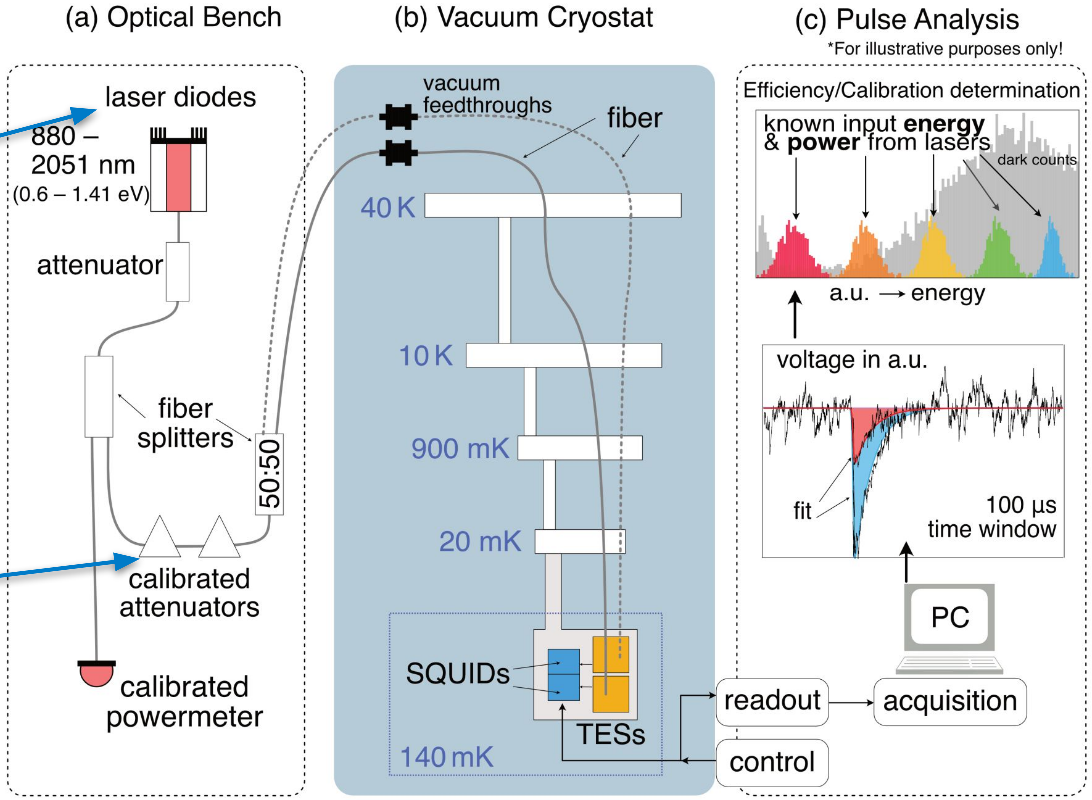
TES Calibration

Experimental setup: Using laser diodes of different wavelengths



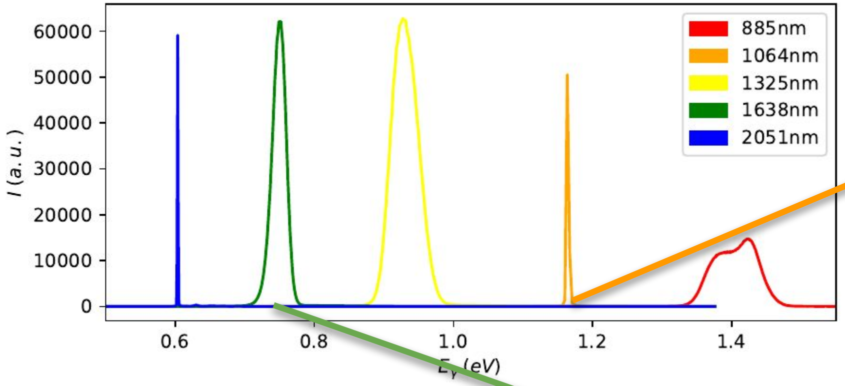
Goal: Determine calibration curve e.g. pulse height vs. energy



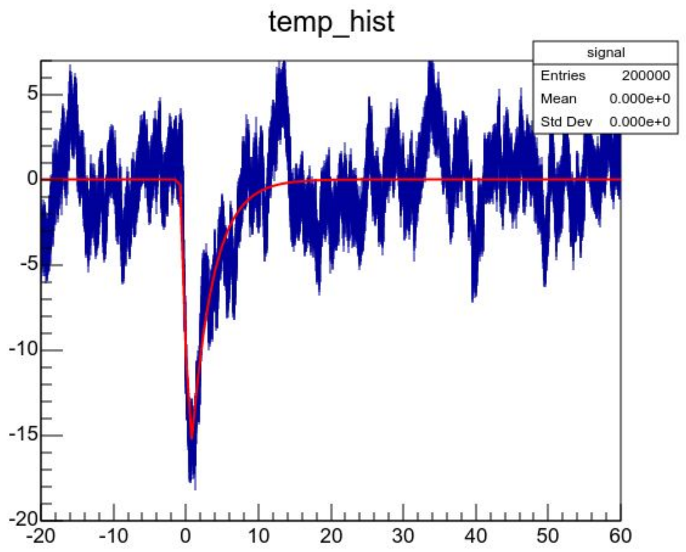


TES Calibration
Measured with laser diodes

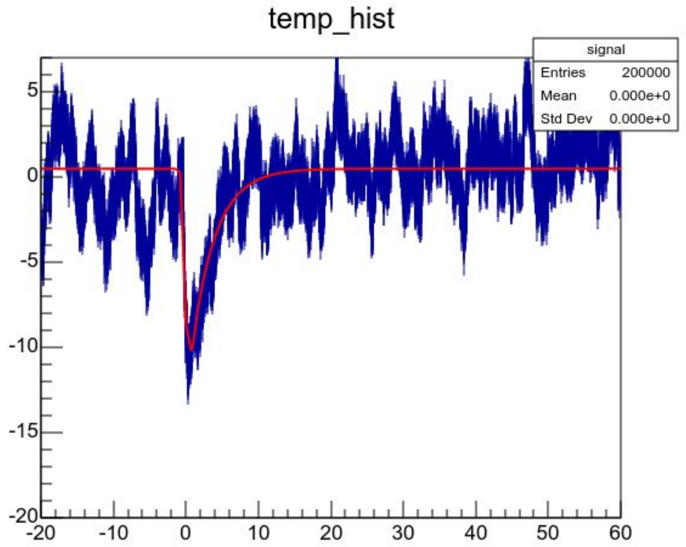
measured energy spectrum from laser diodes



Example: 1064 nm



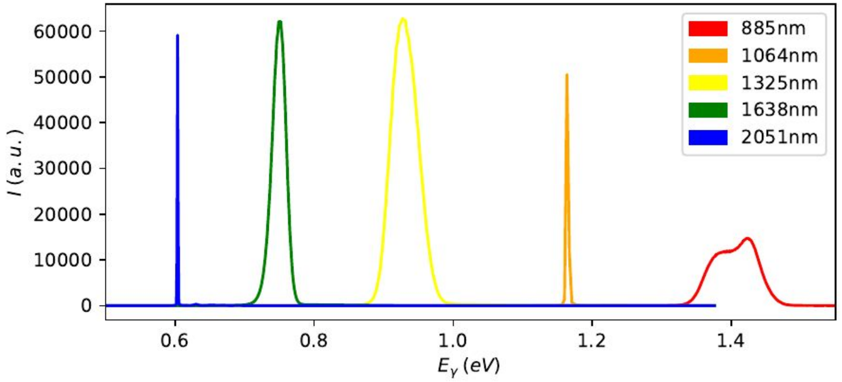
Example: 1640 nm



TES Calibration

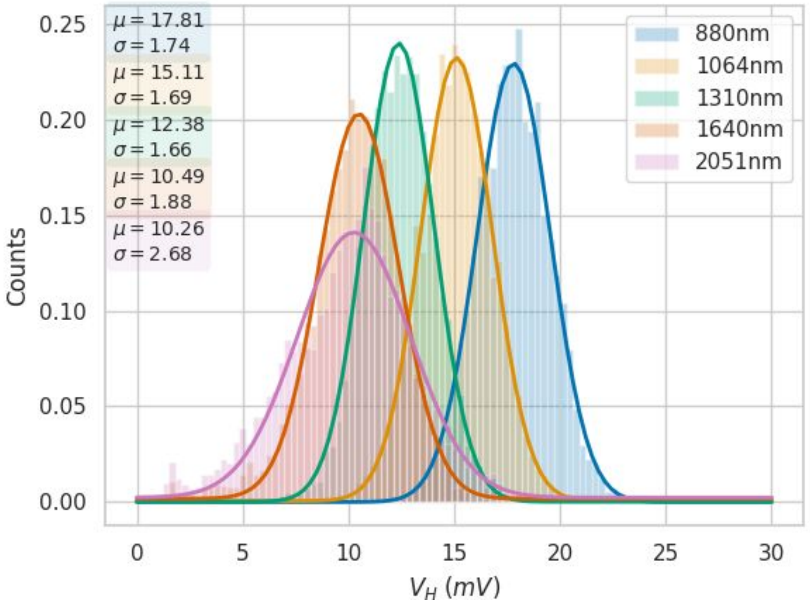
Measured with laser diodes

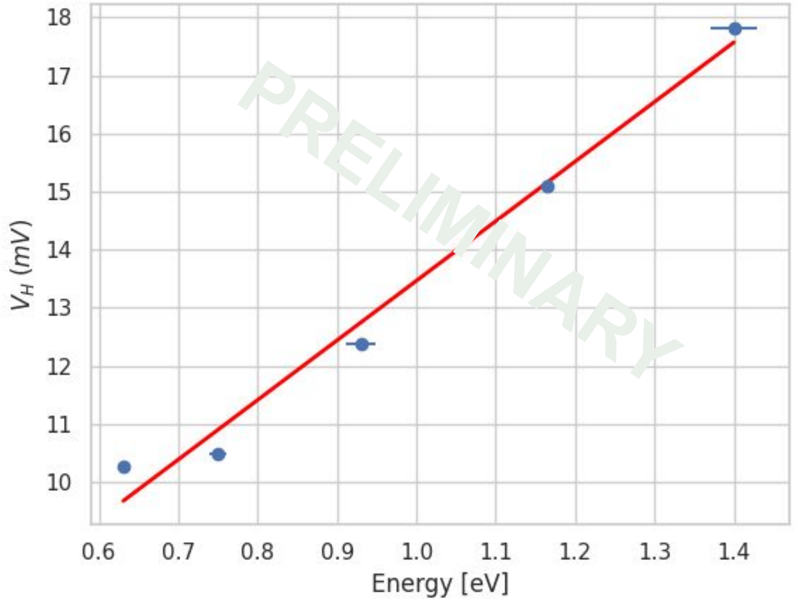
measured energy spectrum from laser diodes



Measure TES response

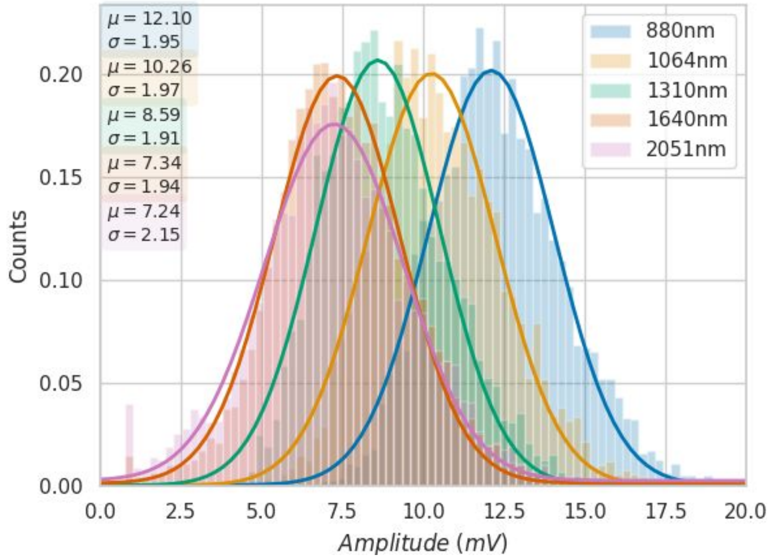
Example: Pulse height



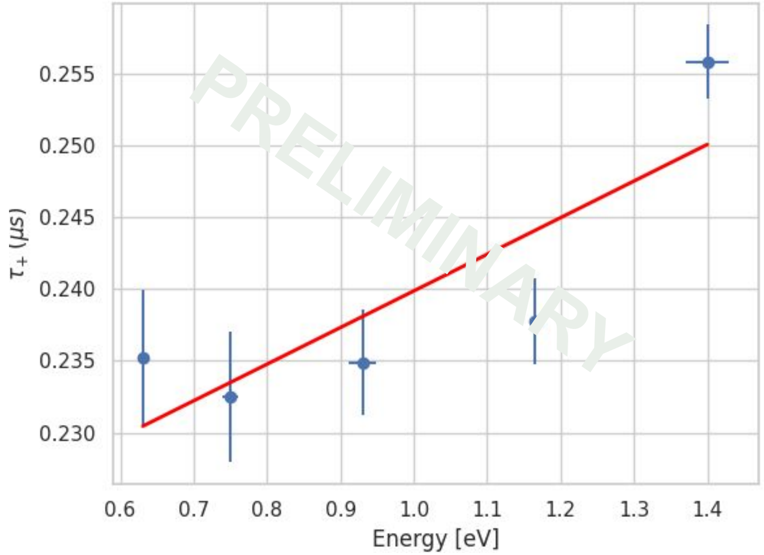


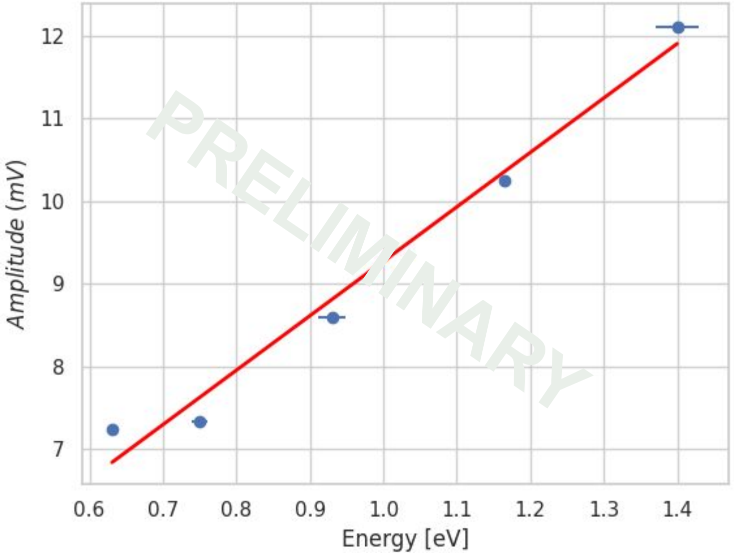
TES Calibration

Preliminary results



- parameters like pulse height or amplitude show energy dependent behavior (possibly linear)
- non-linearities at lower energies (so far)

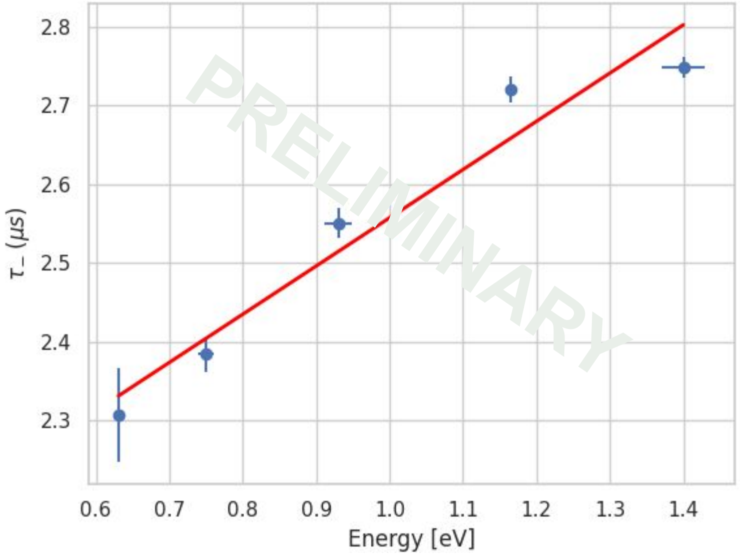




Supposedly less energy dependent parameters:

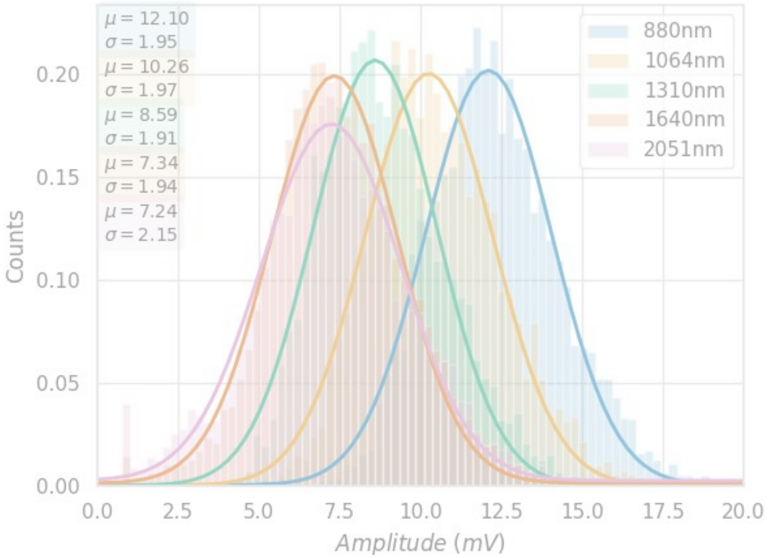
- rise time: no clear dependency, might be constant
- decay time: energy dependency possible

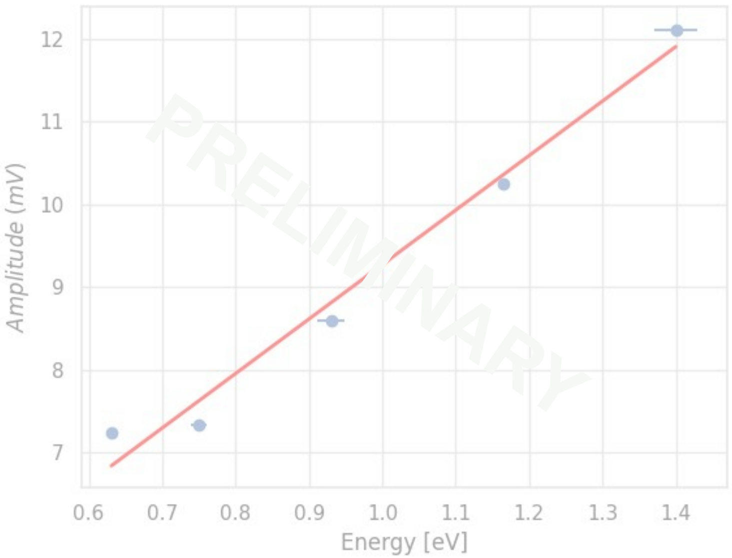
→ further investigation necessary



TES Calibration

Preliminary results





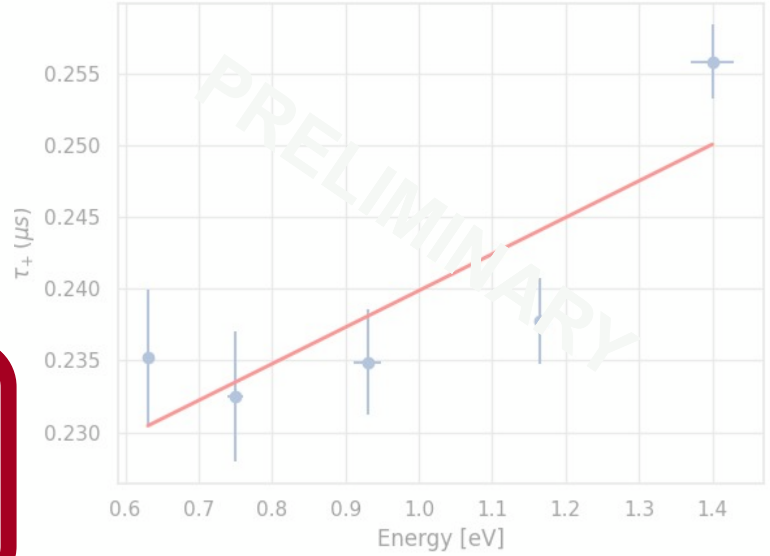
parameters like pulse height or amplitude show energy dependent behavior (possibly linear)
non-linearities at lower energies (so far)

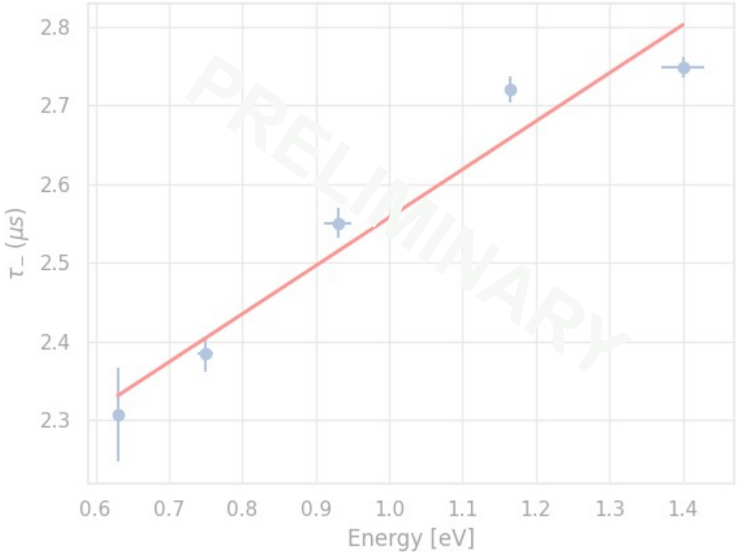
Promising first results, but need to further investigate response at lower energies

Supposedly less energy dependent parameters:

- rise time: no clear dependency, might be constant
- decay time: energy dependency possible

→ further investigation necessary





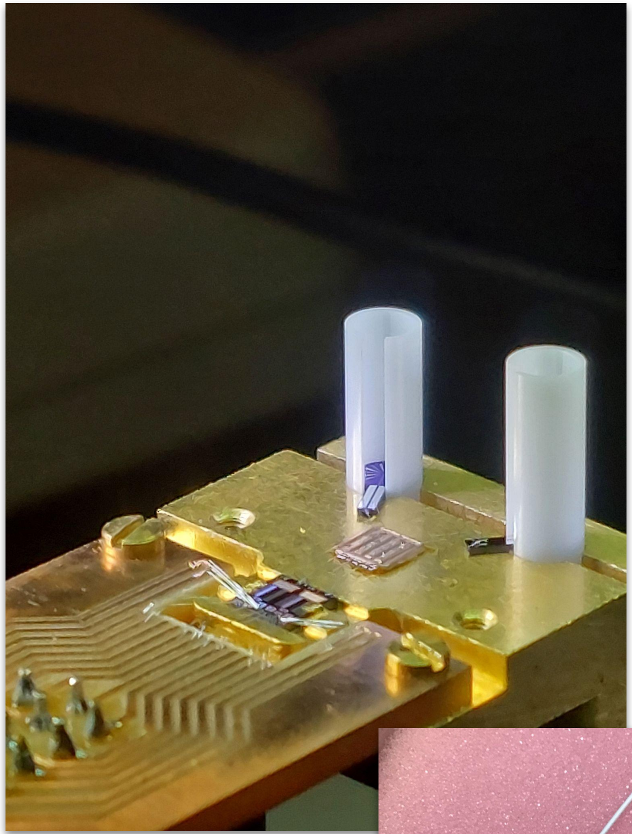
Summary and Outlook

- TES technology used in **ALPS II** may be viable for **direct dark matter searches** in the **sub-MeV DM** mass range
- Could reach new sensitivities **without dedicated hardware development**
- Could be a **proof of principle** for similar technologies as dark matter detectors

- **First calibration results** confirm some expectations, but need further investigation
- Perform **calibrated intrinsic background measurements** to compare with SNSPD results

- Recently received **4 new sensors!** → characterization ongoing
- Currently intensifying **partnership with NIST & PTB**
- plan to test improved sensor types (1550nm, without fiber sleeves,...)

→ **PERFORM DEDICATED DM SEARCHES SOON**

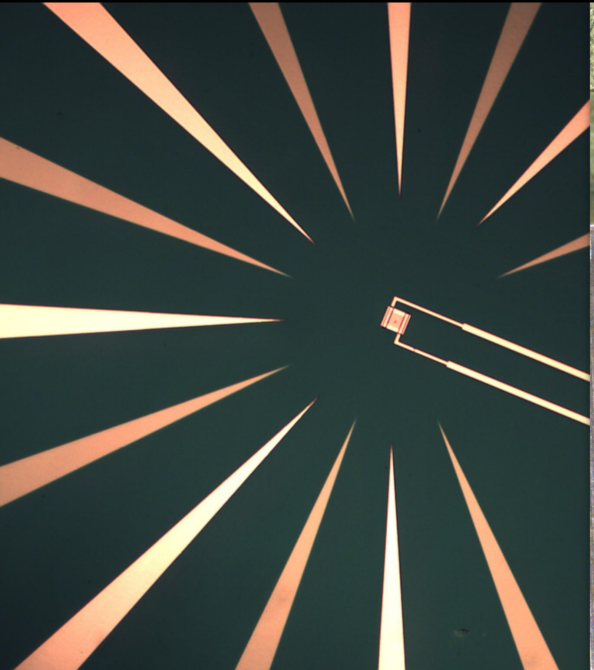


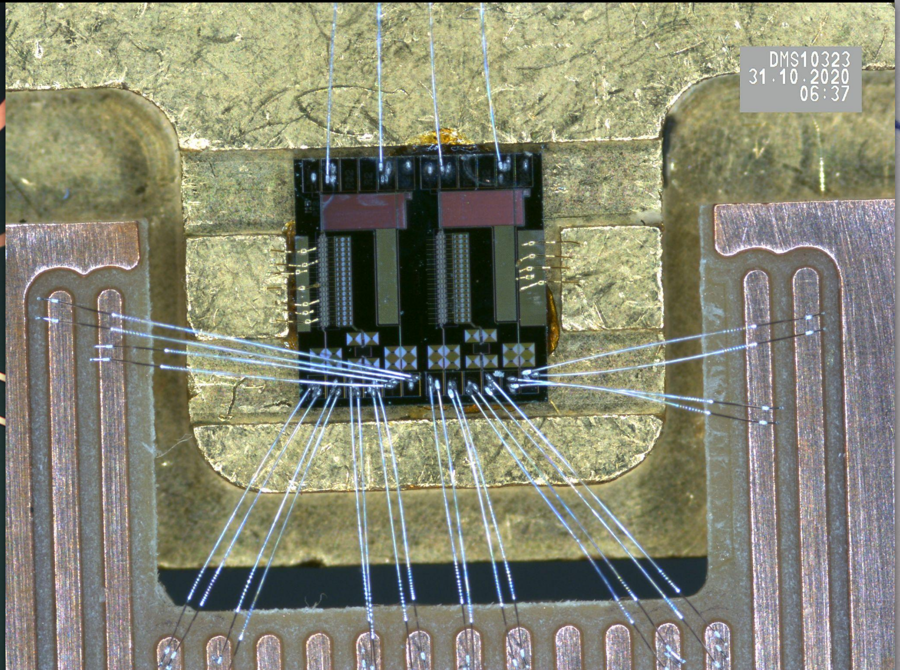
Thank you

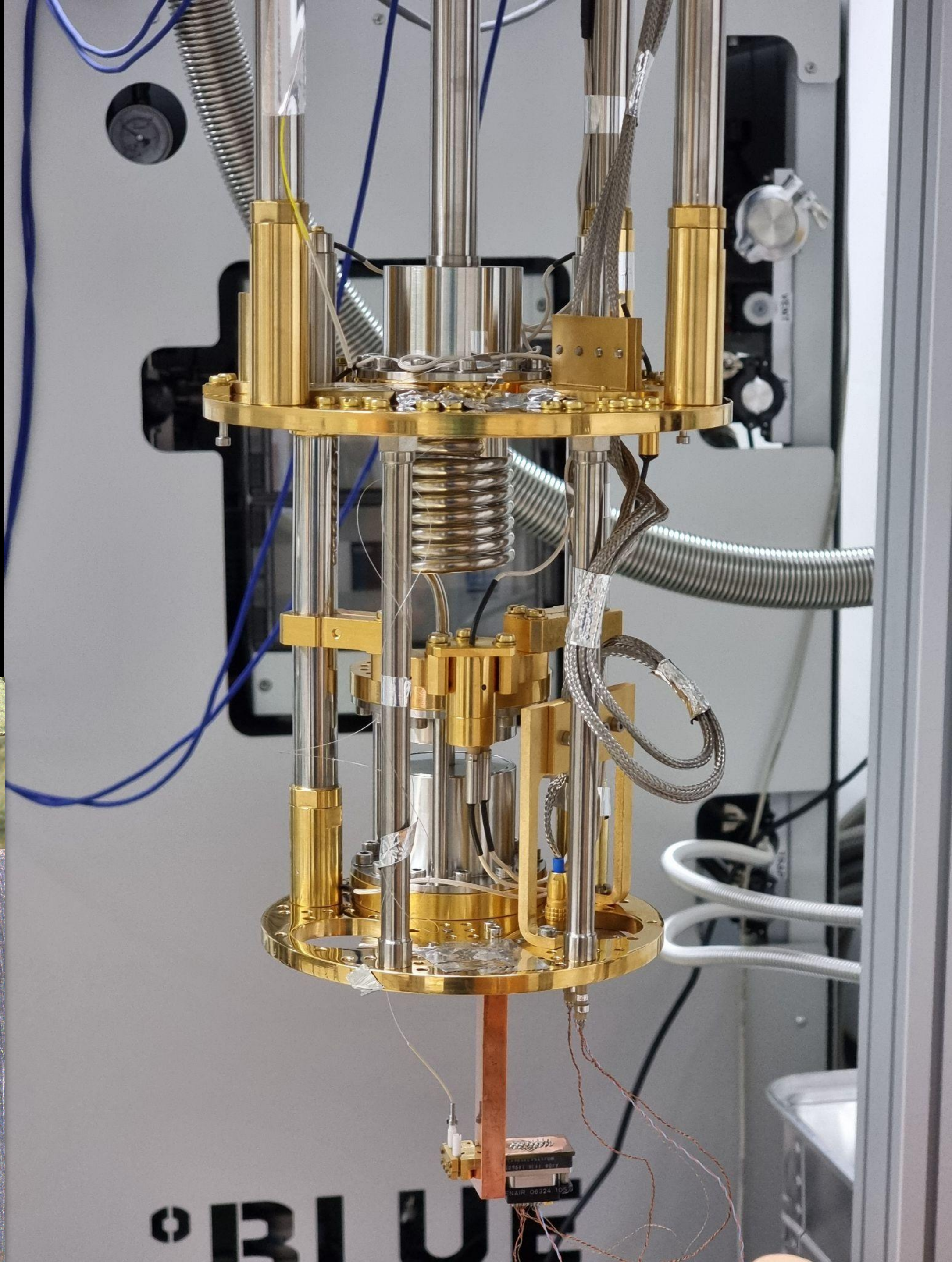
Other related talks:

"Characterisation of a TES detector for ALPS II" –
José Alejandro Rubiera Gimeno

Contact:
Christina Schwemmbauer
ALPS Group
christina.schwemmbauer@desy.de

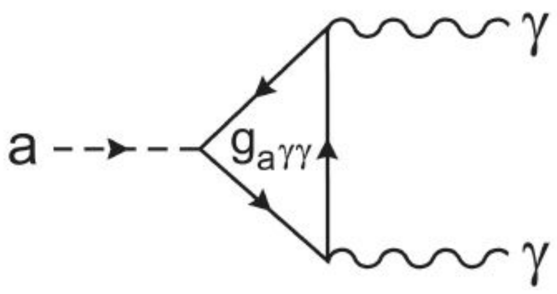




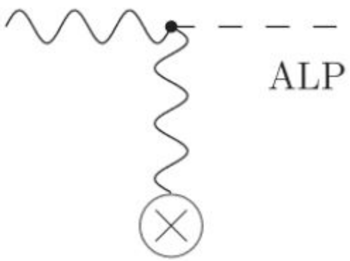


Backup
ALPS II - General Idea

- SM-coupling to two photons



- Detection via Primakoff-like Sikivie effect
- Possible ALP **production** by photon-ALP – oscillation in the presence of strong magnetic fields



K. Ehret et.al., NIMA 612(1)83-960 (2009)

Light **S**hining Through **W**alls (LSW) experiments

$$\rightarrow P_{\gamma\to a} \propto g_{a\gamma\gamma}^2 B^2 L^2$$

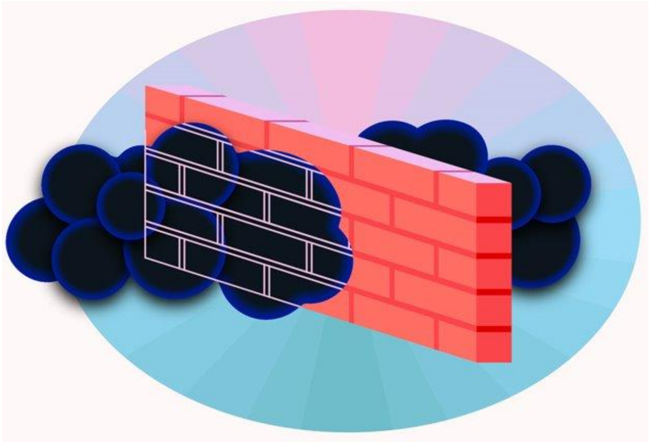
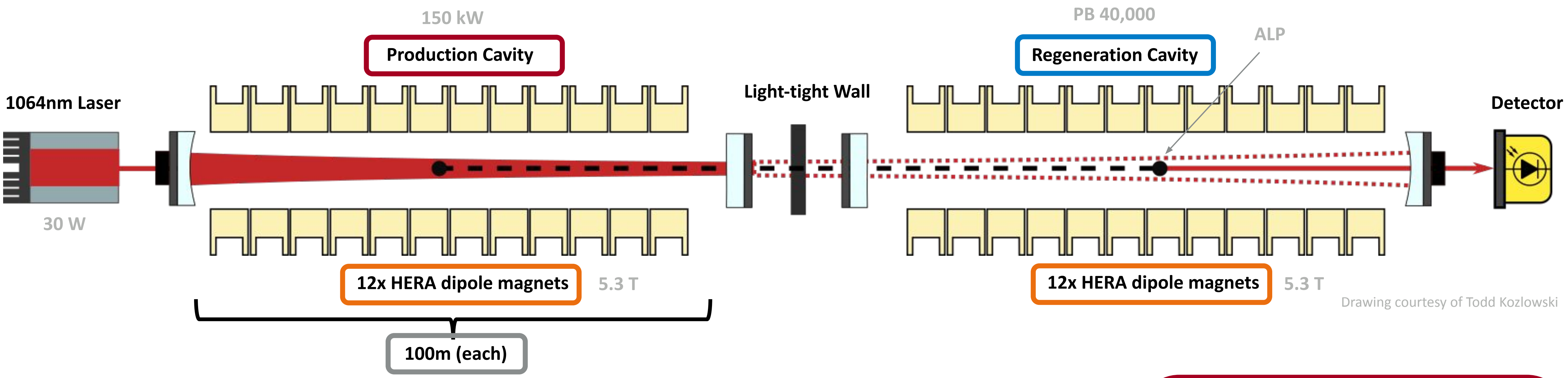


Illustration by Sandbox Studio, Chicago with Ana Kova

Backup

Any Light Particle Search with ALPS II - Experimental Setup



Drawing courtesy of Todd Kozlowski

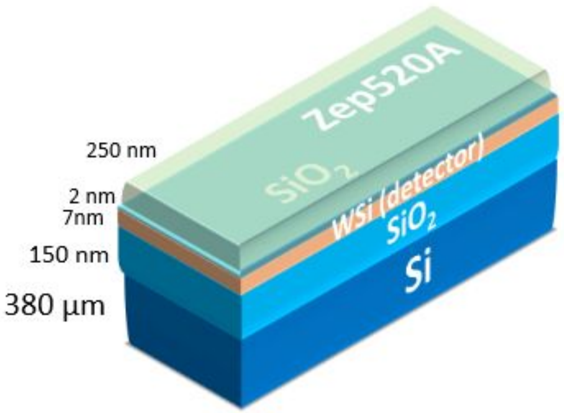
Single-photon detection requirements for ALPS II:

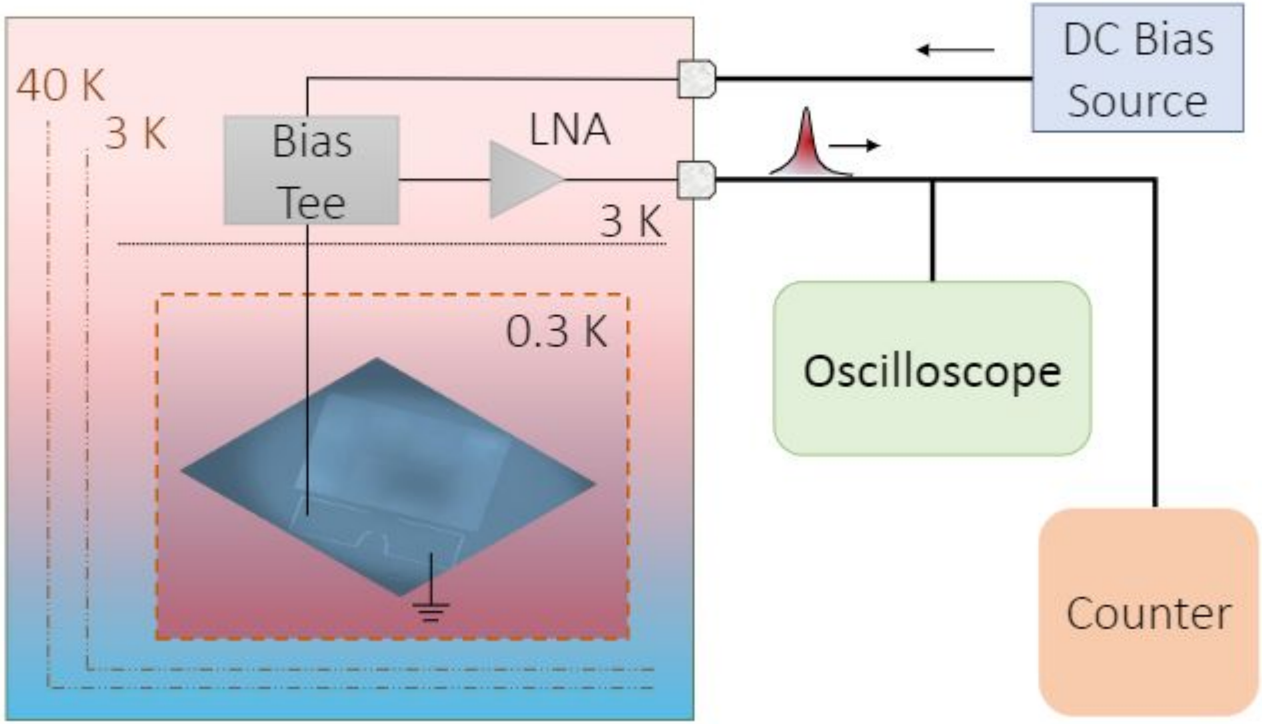
- Low energy photon detection
- Low background (< 1 photon/day)
- High detection efficiency

Detection probability: $$P_{\gamma\to a\to\gamma} \propto \boxed{PC} \cdot \boxed{RC} \cdot g_{a\gamma\gamma}^4 \boxed{B^4} \boxed{L^4}$$

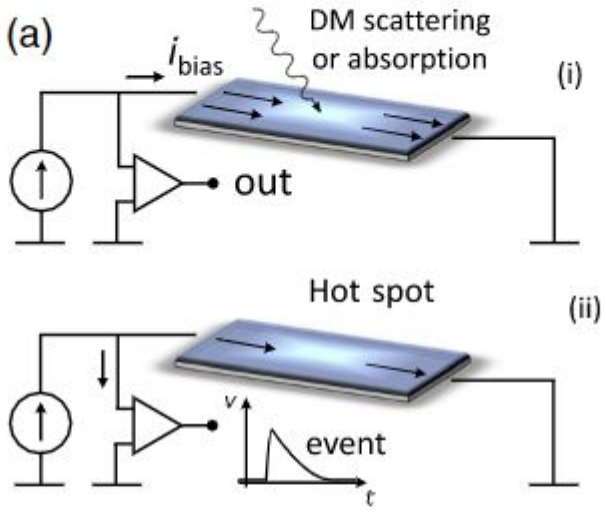
Expected rate of low energy ($\sim 1.16\,\mathrm{eV}$) photons: $\dot{N}_\gamma \approx 2.8 \cdot 10^{-5}\,\frac{\gamma}{\mathrm{s}} \approx 1\,\frac{\gamma}{\mathrm{day}}$
(for $g_{a\gamma\gamma} = 2 \cdot 10^{-11}\,\mathrm{GeV}^{-1}$)

Backup
SNSPDs





Hochberg, Y. et al. arXiv:2110.01586 (2021)

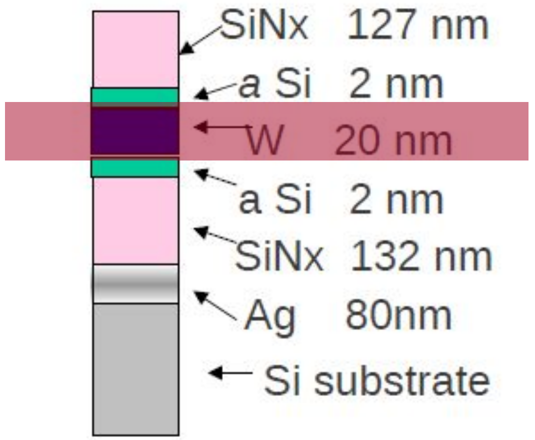


Hochberg, Y. et al., *Physical Review Letters, 123*(15). (2019)

Backup

Quantum Sensing Details

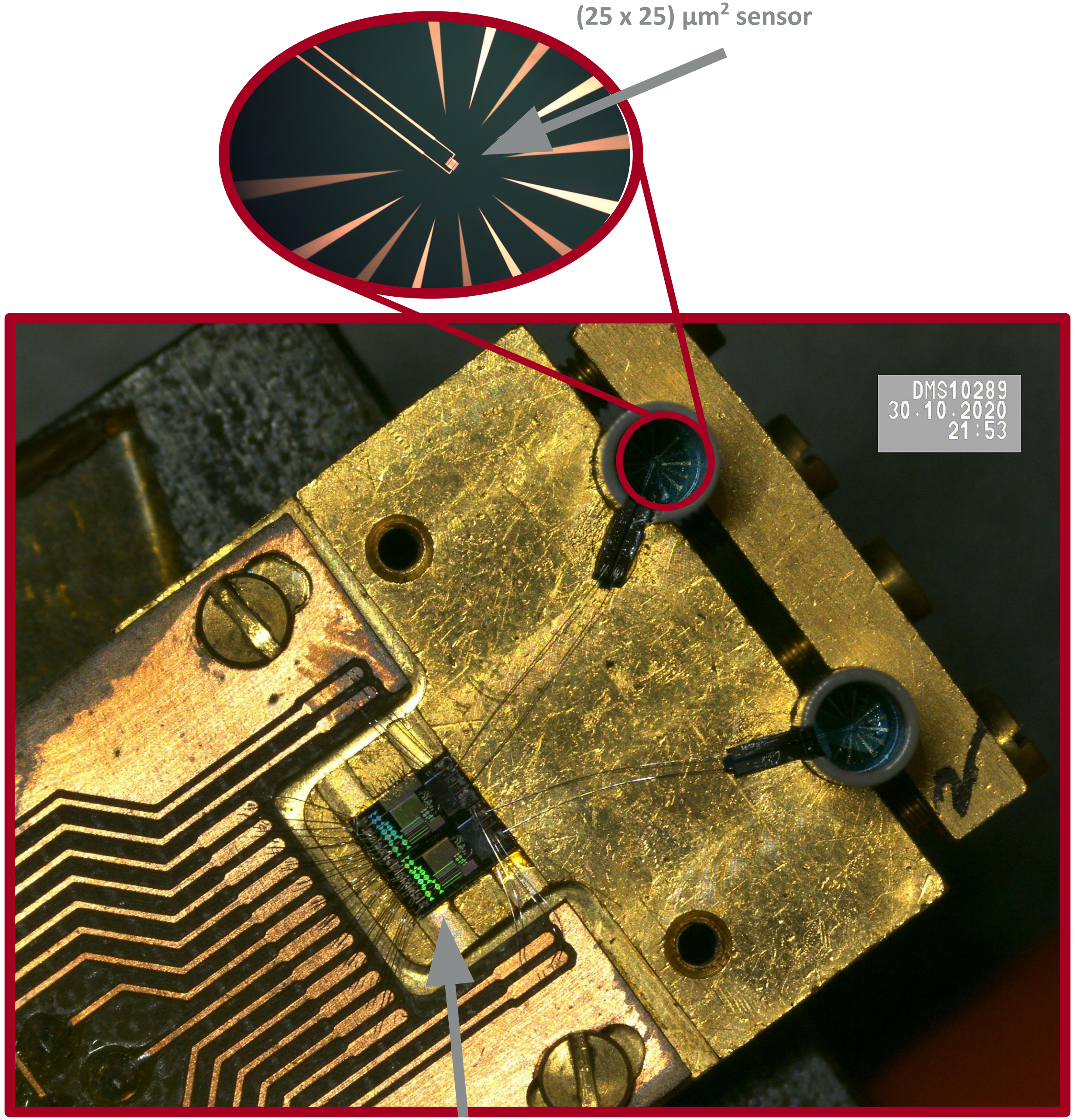
Optical stack



Sensitive tungsten mass

A. Lita, NIST

(25 x 25) μm^2 sensor



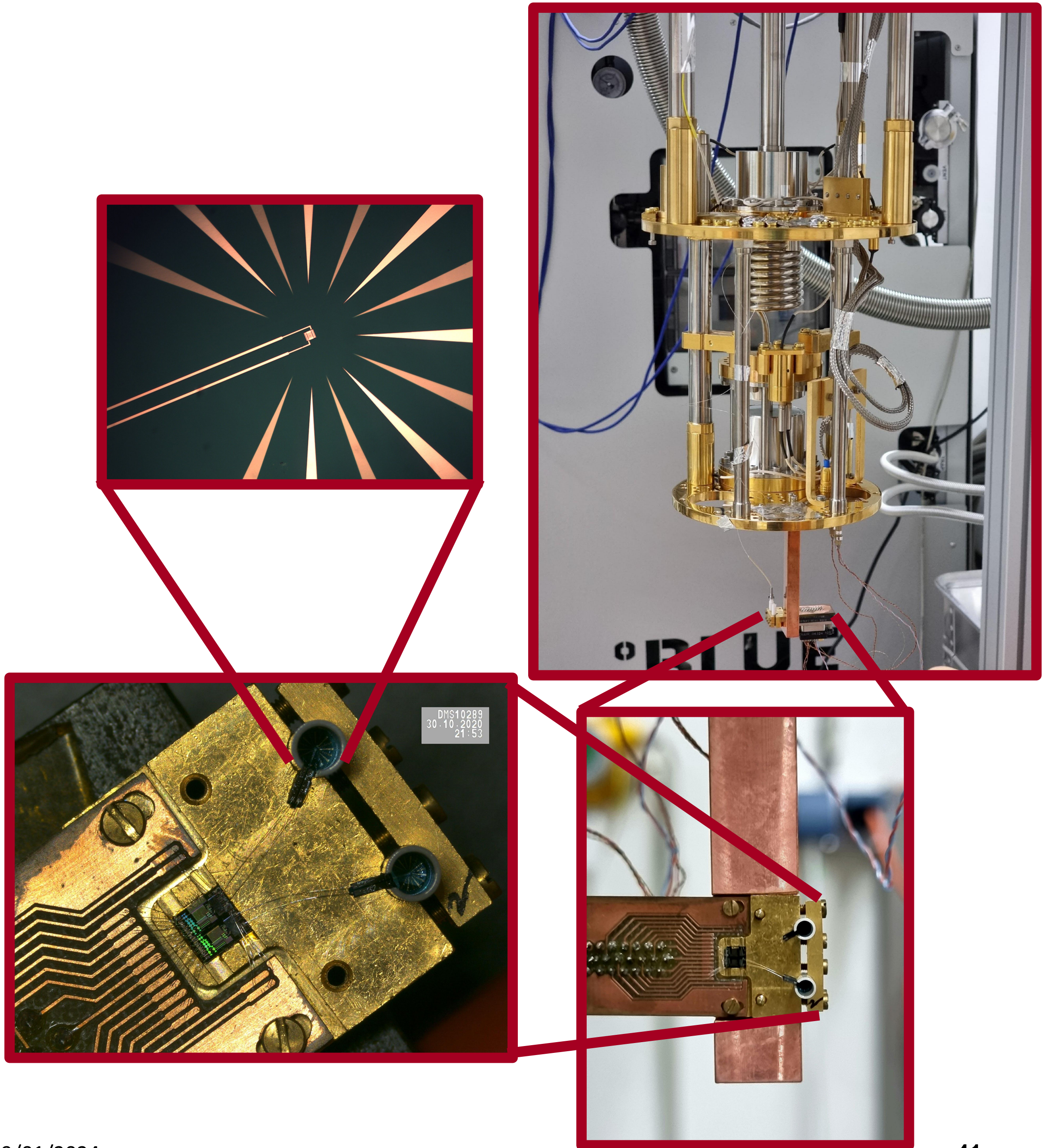
SQUID chips

- Very small active area – energy deposition in tungsten layer
- Option for fiber coupling
- Optical stack & efficiency optimized for 1064nm (1.165 eV) photons
- Wider range of energies interesting for direct DM searches

Backup

ALPS II Setup

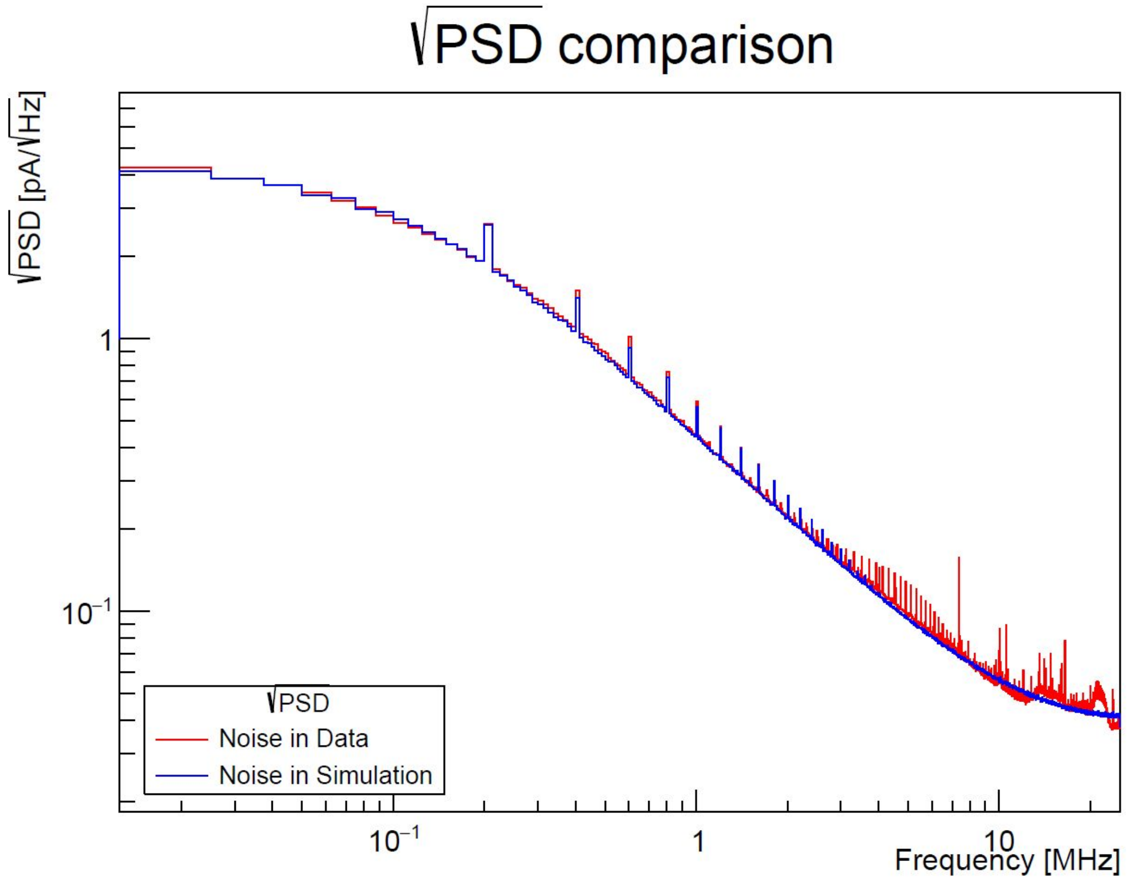
Detection requirements	TES solution
• Photon detection at low energies (1064 nm → 1.165 eV) • High quantum efficiency	optimized optical structure to increase absorption at 1064 nm
Low background (electronic noise, radioactive backgrounds, photons from black-body radiation) < 1 photon/day	shielding in cryostat and tests to reduce background: • fiber curling • filtering of black-body photons → currently: 6.9×10^{-6} cps[1] (intrinsic background)
High detection efficiency	preliminary results suggest at least 80% efficiency



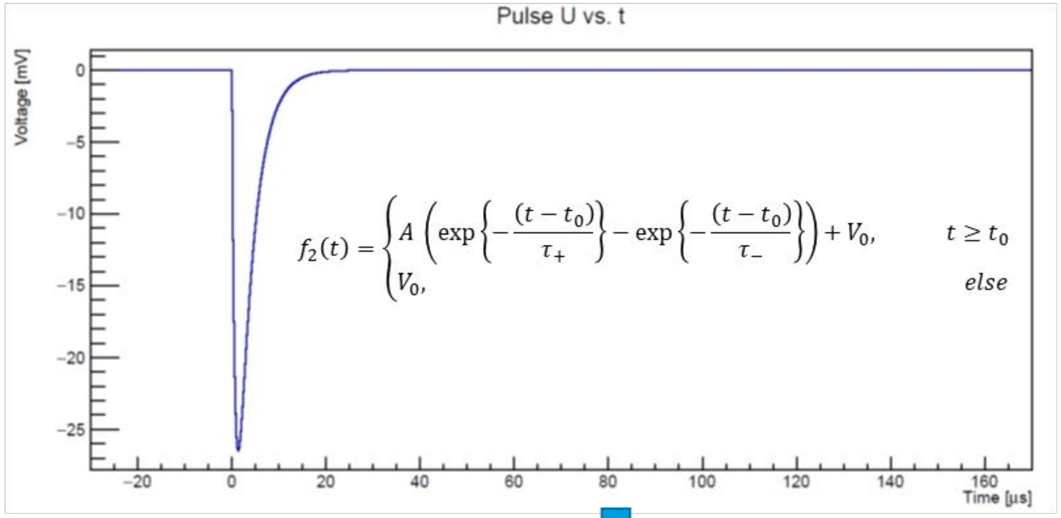
[1] R. Shah et al., PoS, EPS-HEP2021, 801 (2022)

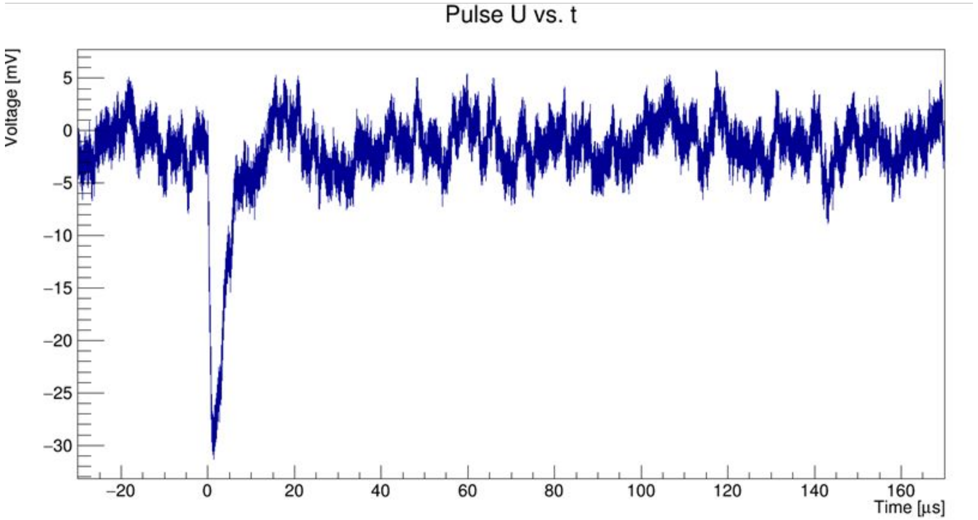
Backup

Simulation of pulses



+

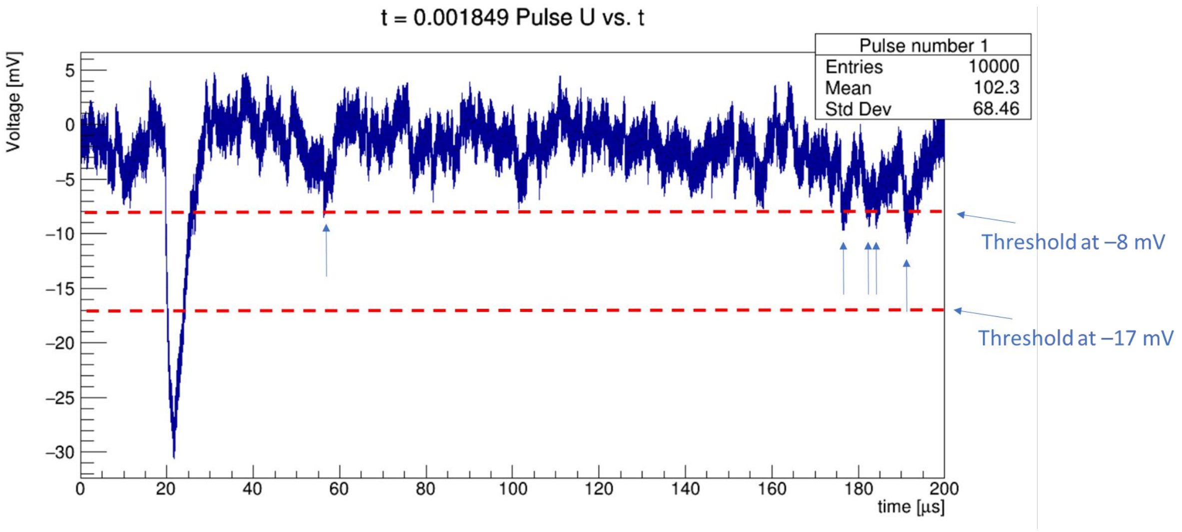




Backup

False trigger simulations

- Simulated rate of triggered noise pulses for different thresholds
- Without simulated pulses ⟶ expect only noise contributions
- Simulation fits order of magnitude of 3 day intrinsic measurement with -12mV threshold



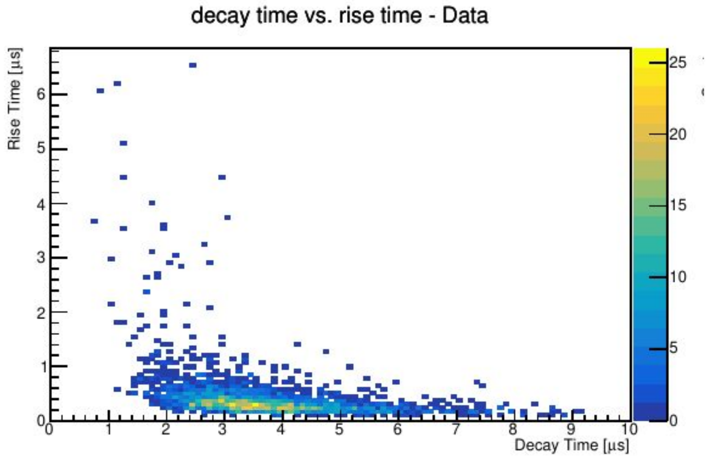
False Triggers - Rate of noise pulses passing different trigger thresholds

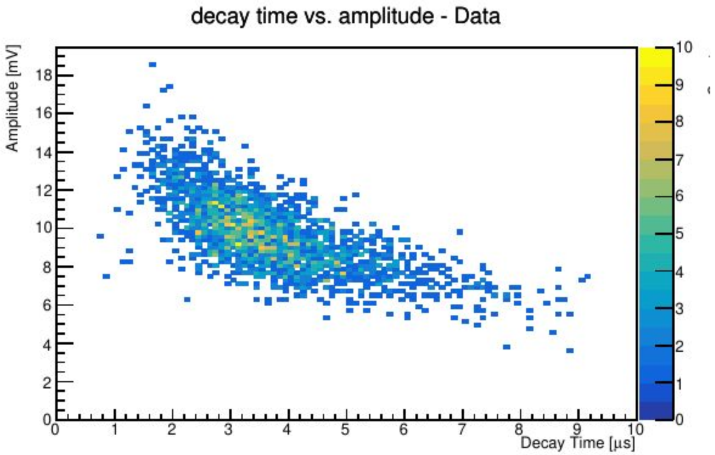
		Threshold [mV] (Usual trigger thresholds for 1064nm pulses: -17, -16, -15)								
		-17	**-16**	**-15**	**-14**	**-13**	**-12**	**-11**	**-10**	**-9**
Simulated time	**# Samples**	**Rate [1/s]**								
500 sec	**2.5e6**	0	0	0	0	0.014 (0.005)	0.32 (0.03)	4.21 (0.09)	38.8 (0.3)	251.1 (0.7)
72 hours	**no simulation**						0.5070 (0.0014)			

Backup

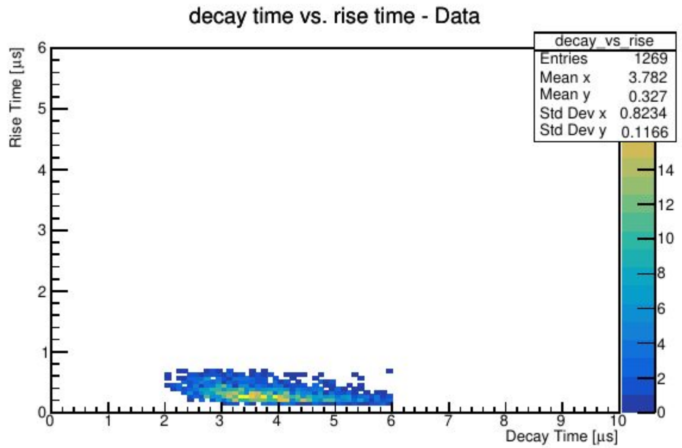
Simulation – Cut-based analysis for lower energy pulses

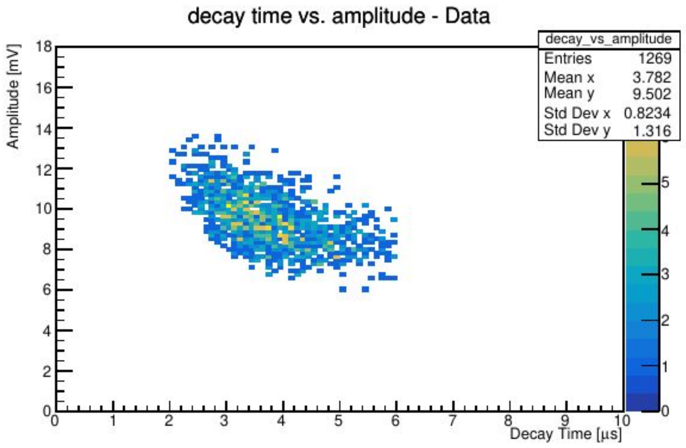
Pre Cuts





Post – 0.583eV optimized - Cuts





Contact

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www.desy.de

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