

Towards ultra-low backgrounds for high-efficiency transition edge sensors in optical and infrared axion searches

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Identification of Dark Matter 2026

Zaragoza, Spain



See overview talks by e.g. A.
Mirizzi and K. Van Bibber

Motivation for axions and axion- like particles (ALPs)

$$\mathcal{L}_a \supset -\frac{\alpha_s}{8\pi} G_{\mu\nu}^a \tilde{G}_a^{\mu\nu} \frac{\phi}{f_a} - \frac{1}{4} g_{a\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} + \partial_\mu \phi \sum_f g_{af} \bar{f} \gamma^\mu \gamma^5 f$$

QCD Axion only
Solves CP problem
Gives rise to potential
that generates axion mass

QCD Axion and ALPs,
 m_a and $g_{a\gamma}$ are independent for ALPs
ALPs predicted in many Standard Model extensions

Ringwald arxiv:1407.0546 for a review

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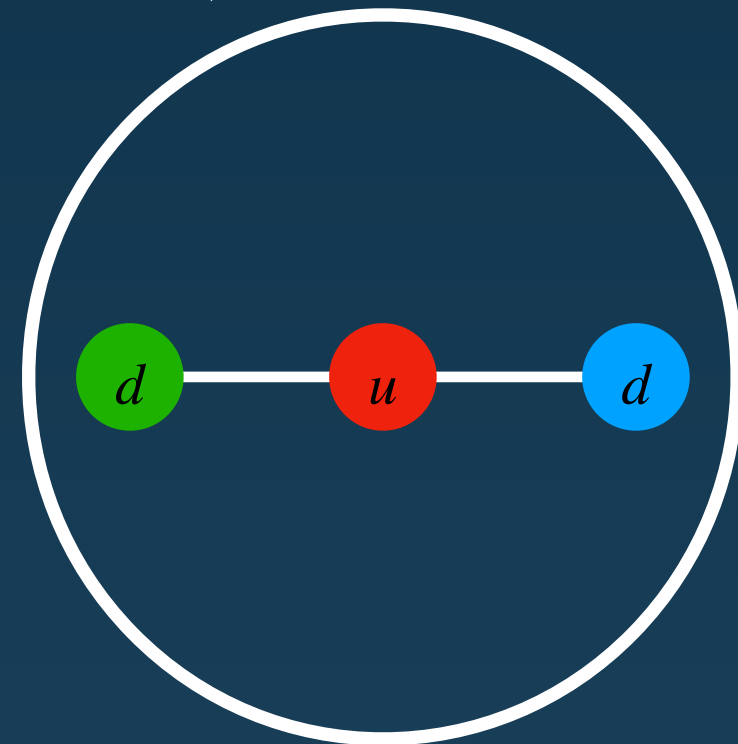
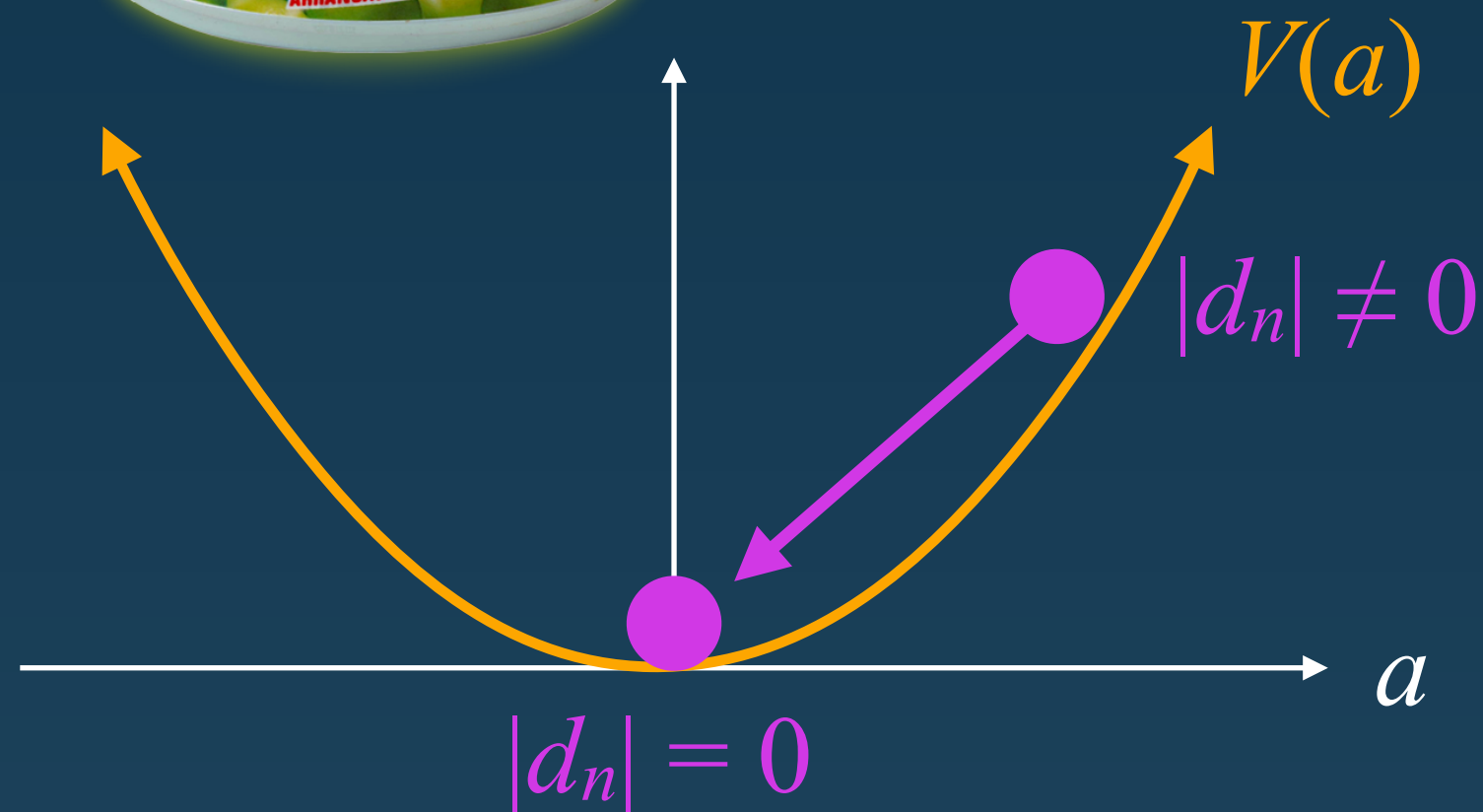
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Axions: dynamical Solution to the strong CP problem



$$m_a \approx 6 \mu\text{eV} \left(\frac{10^{12} \text{ GeV}}{f_a} \right)$$



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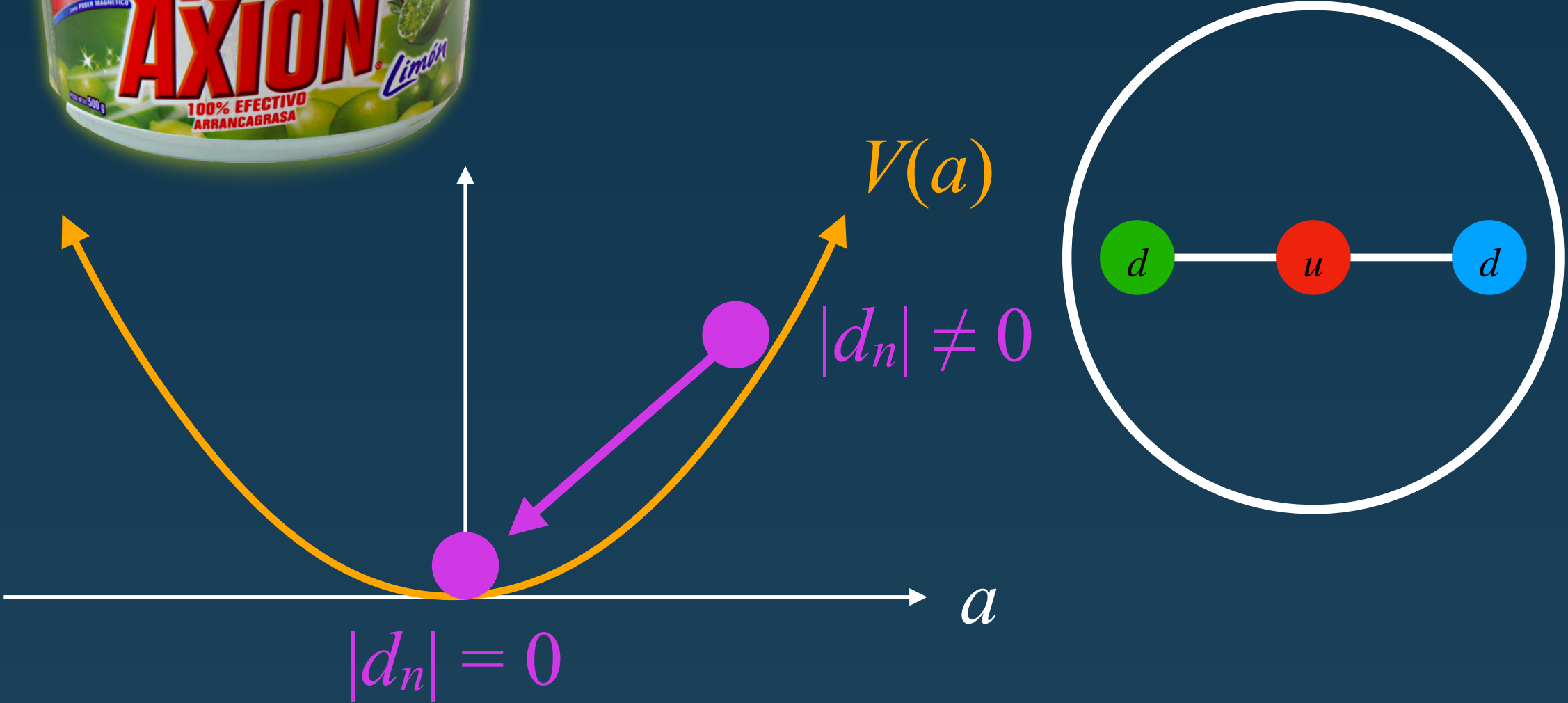
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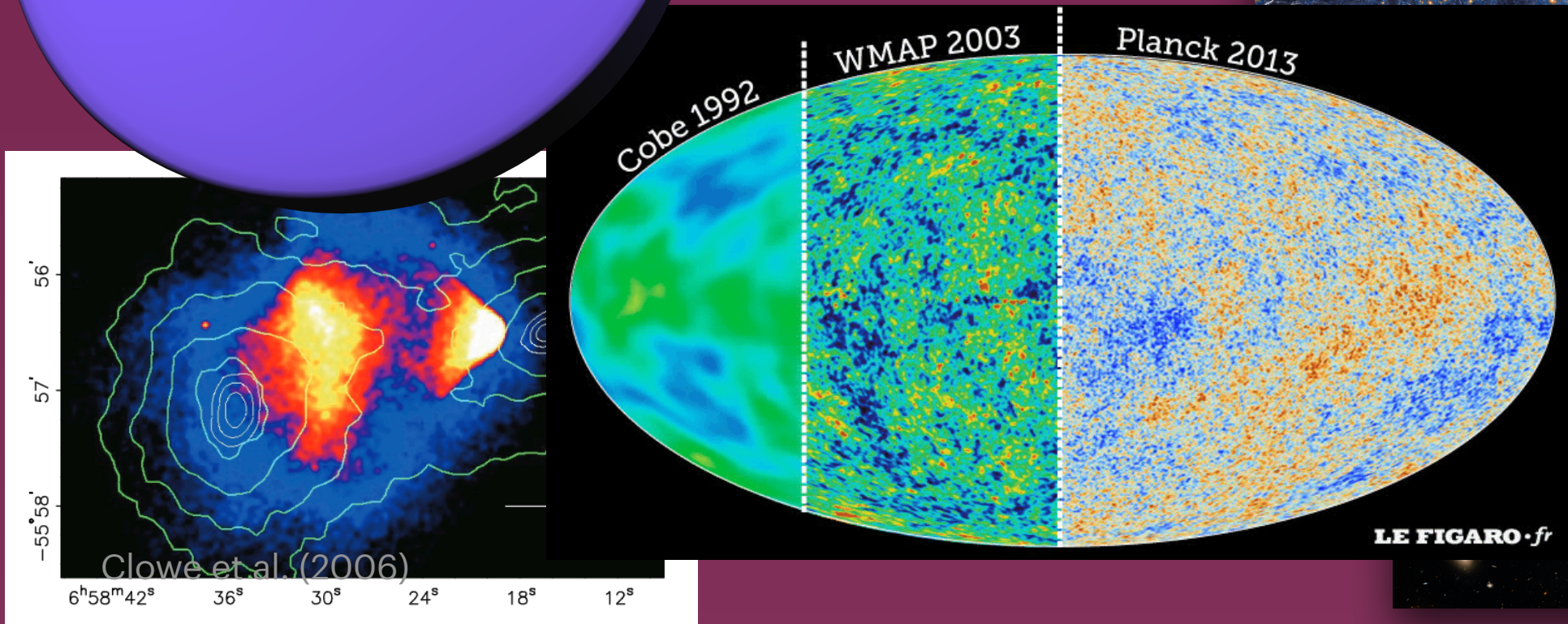
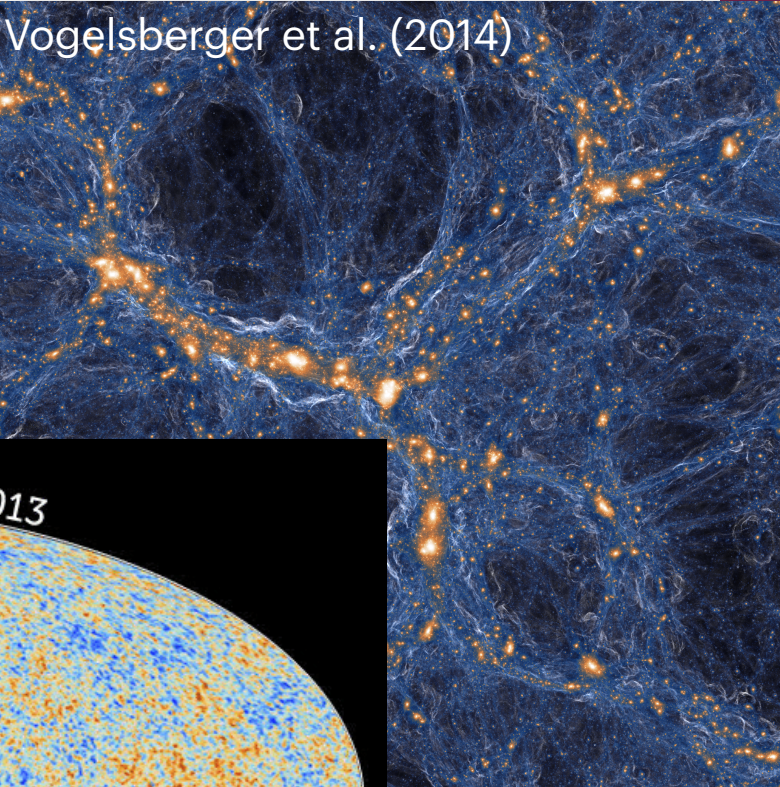
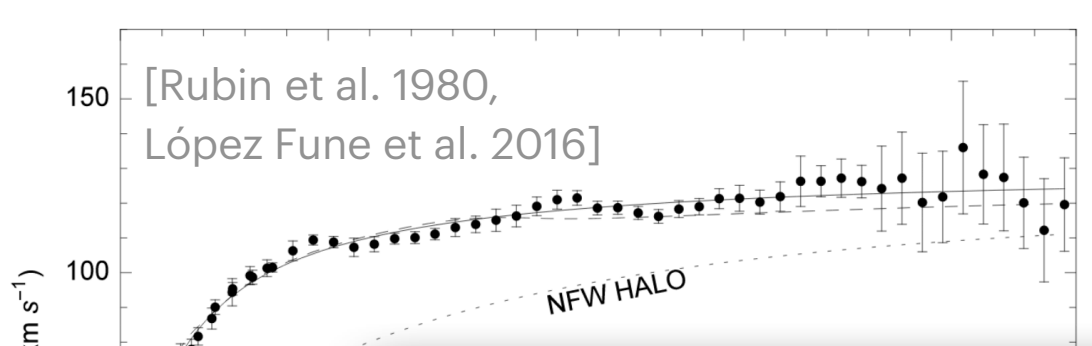
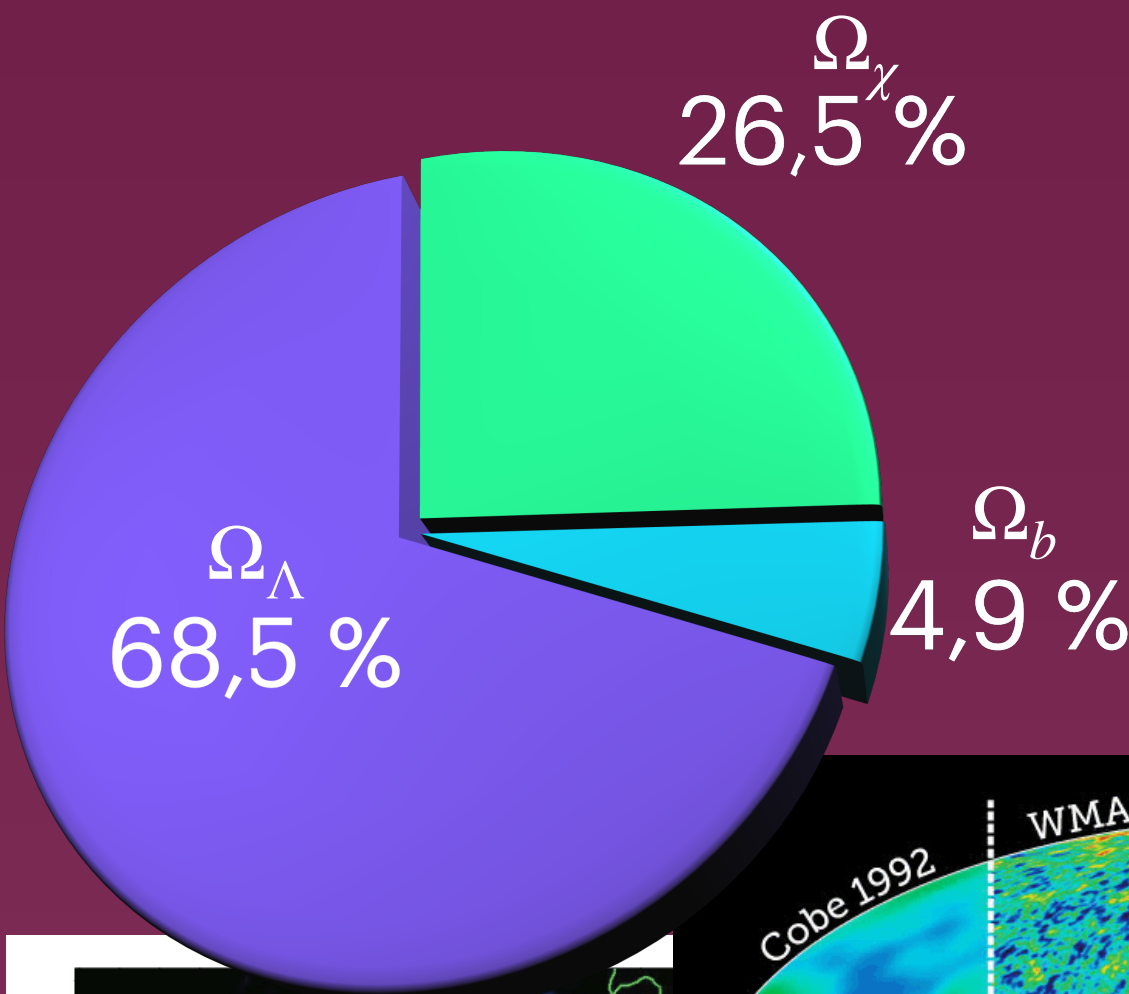


$$m_a \approx 6 \mu\text{eV} \left(\frac{10^{12} \text{ GeV}}{f_a} \right)$$



Peccei & Quinn 1977; Weinberg 1978; Wilczek 1978, Hook 2018

Axions and ALPs: dark matter particle candidates

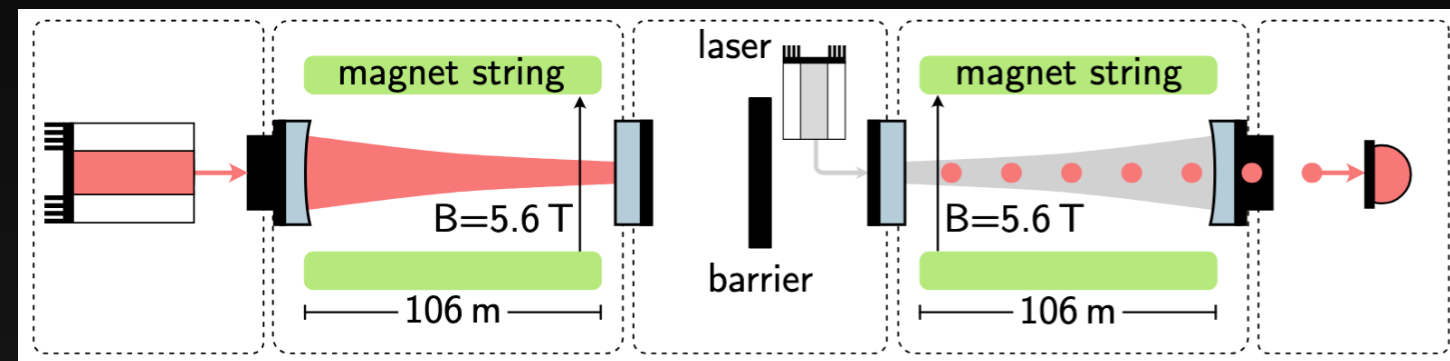


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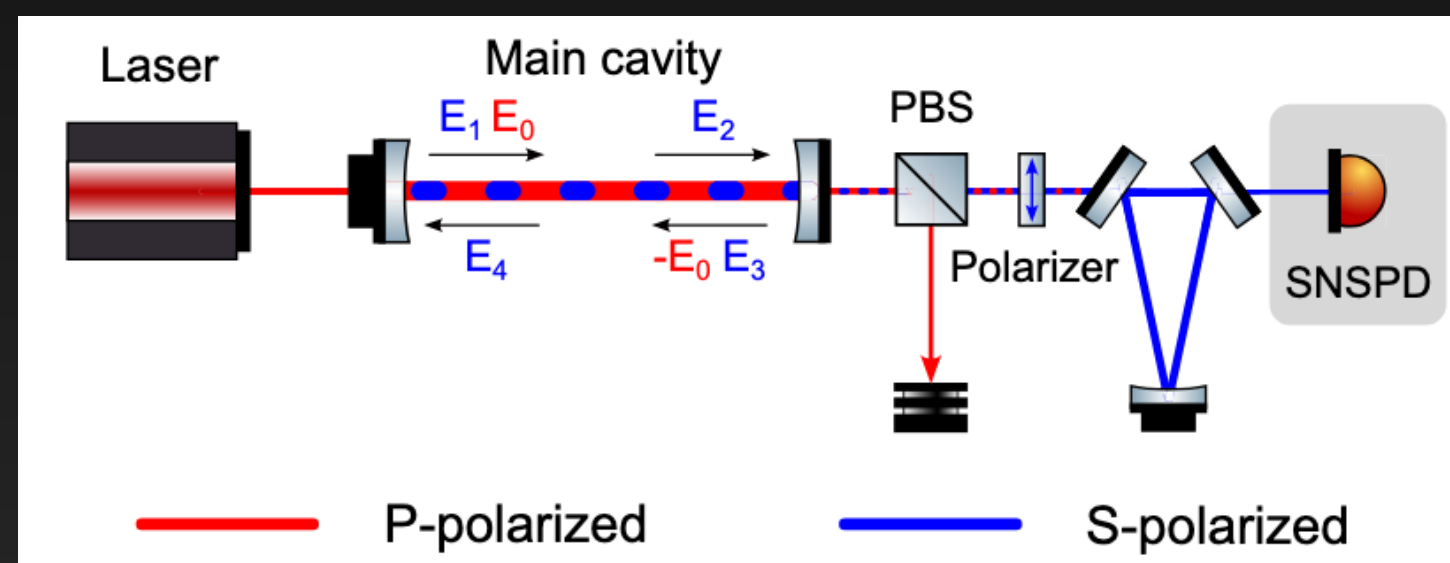
Zwicky 1933

Use cases for optical/infrared single photon detectors for axion experiments

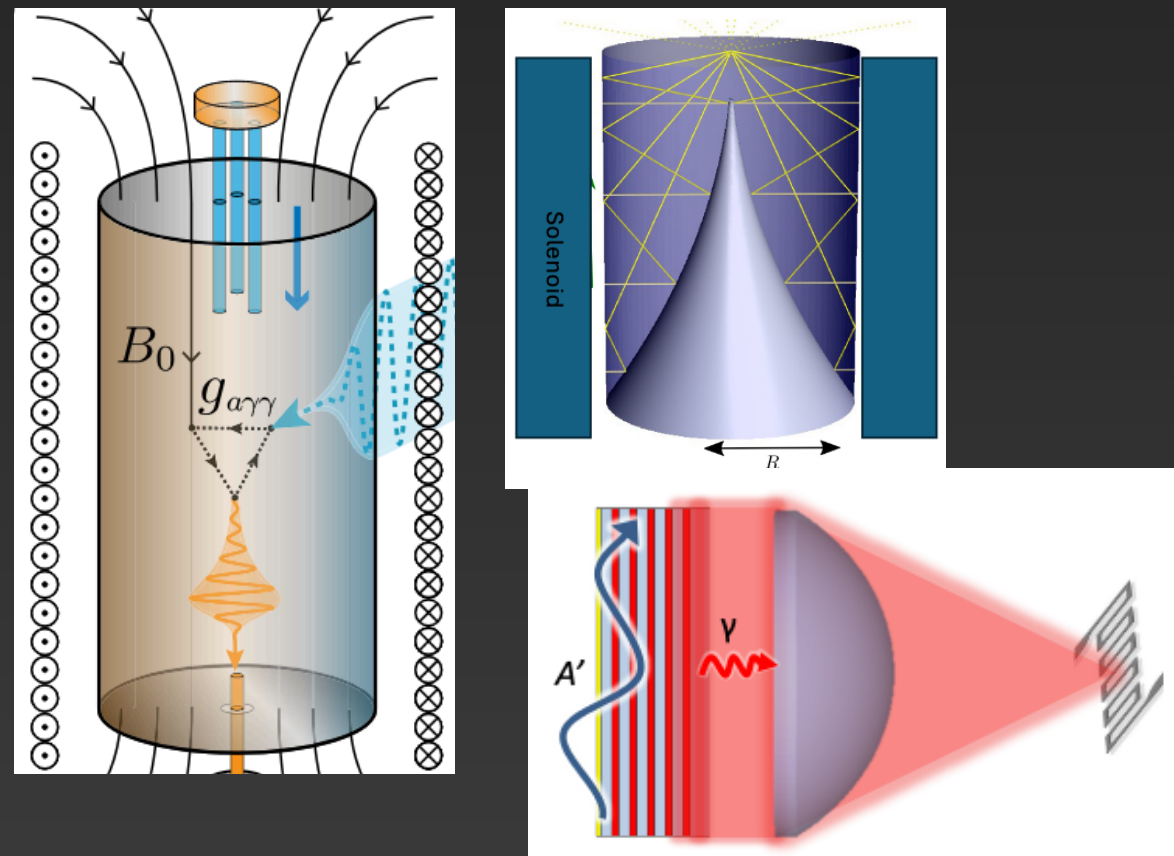
LSW



Interferometers

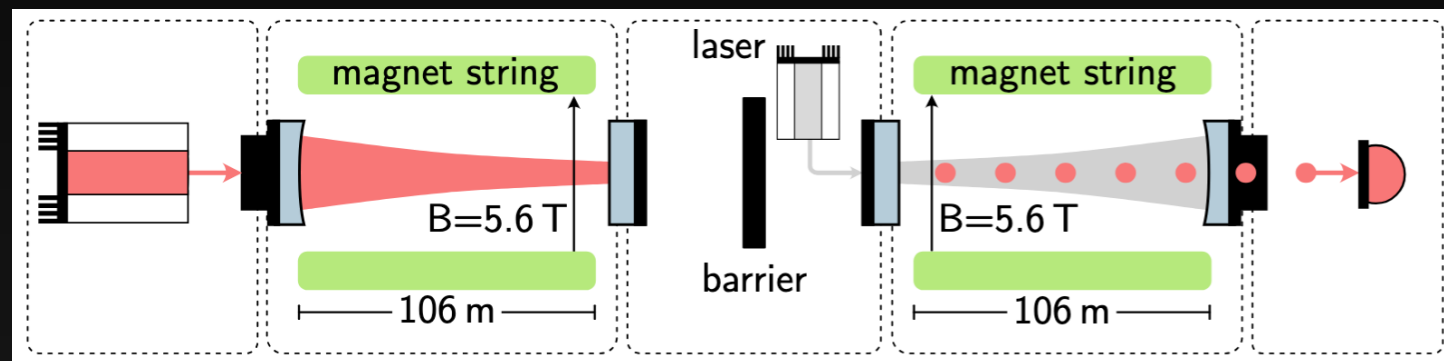


Haloscopes



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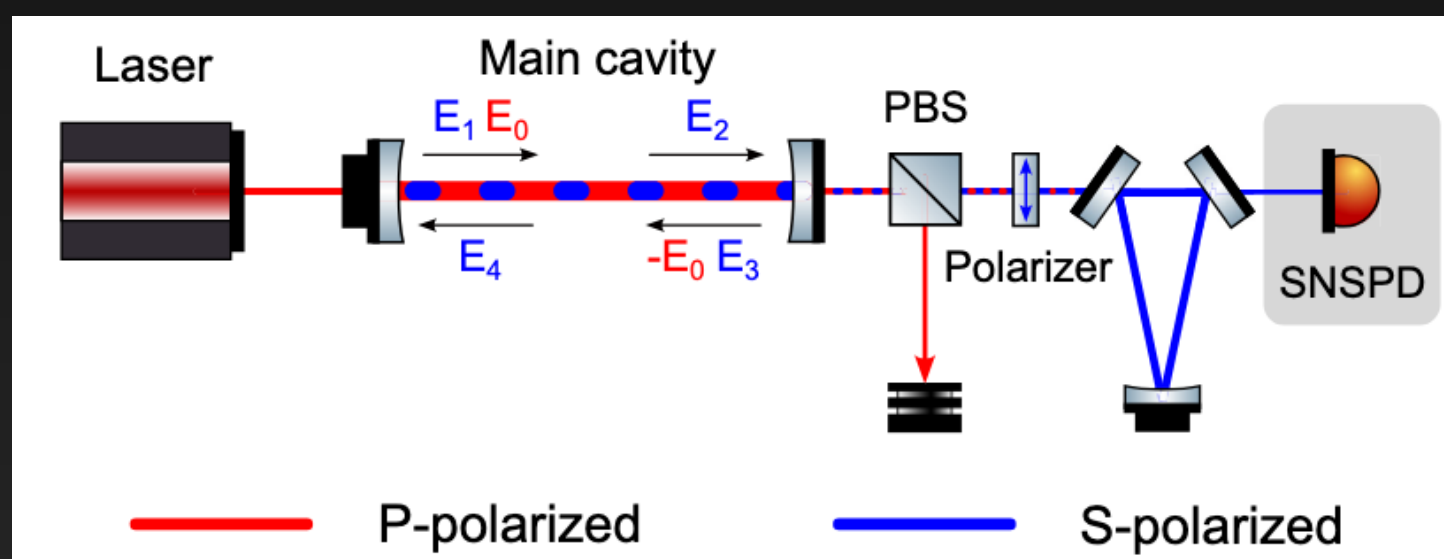
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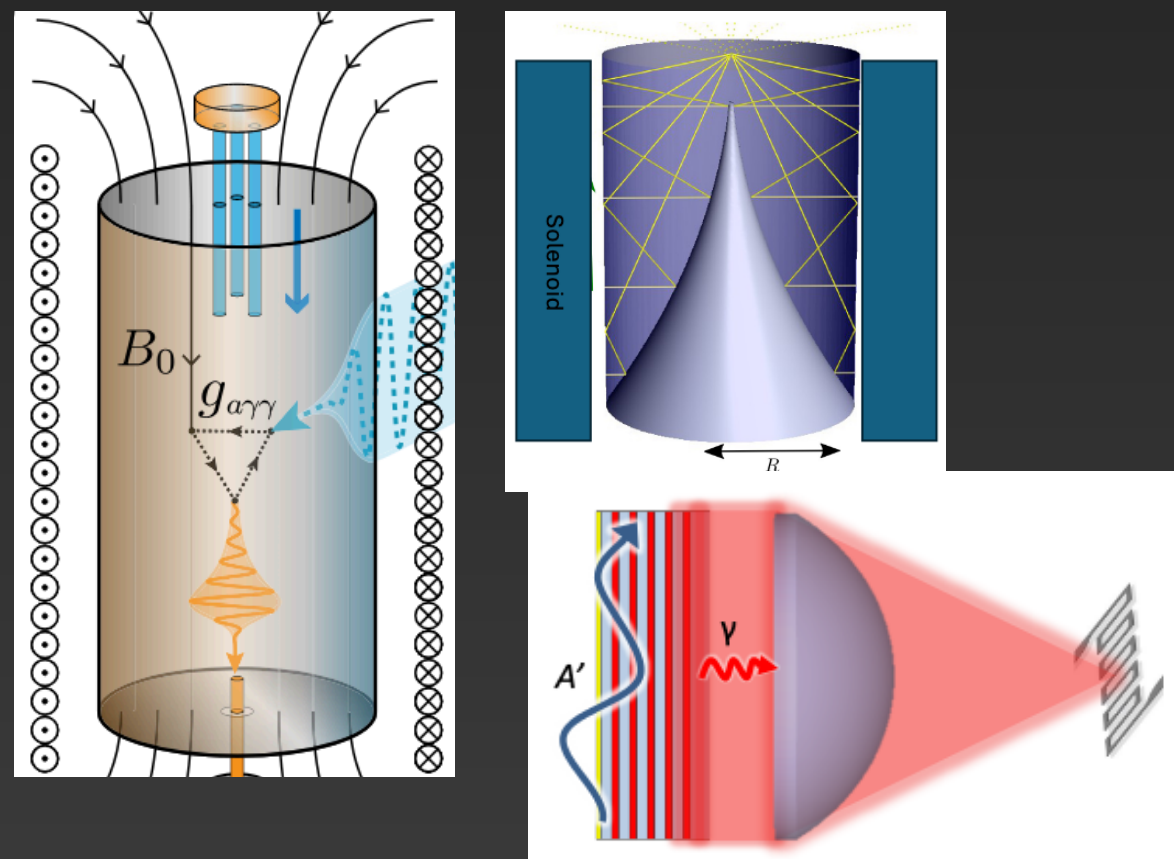
- **Idea:** produce axions and detect them behind light tight barrier; ALPS II experiment currently uses heterodyne detection scheme, laser @ 1064nm
- **With single photon counter:** possible to go below shot noise from local oscillator
- Requirements: **energy resolution** to filter out light for cavity alignment, **high detection efficiency, ultra-low dark current ≈ 1 photon / day**

ALPS II Collaboration,
arXiv:2512.14110
ALPS II Collaboration,
Moscow Univ.Phys.Bull.,
77 (2022) 2, 120-125

Interferometers

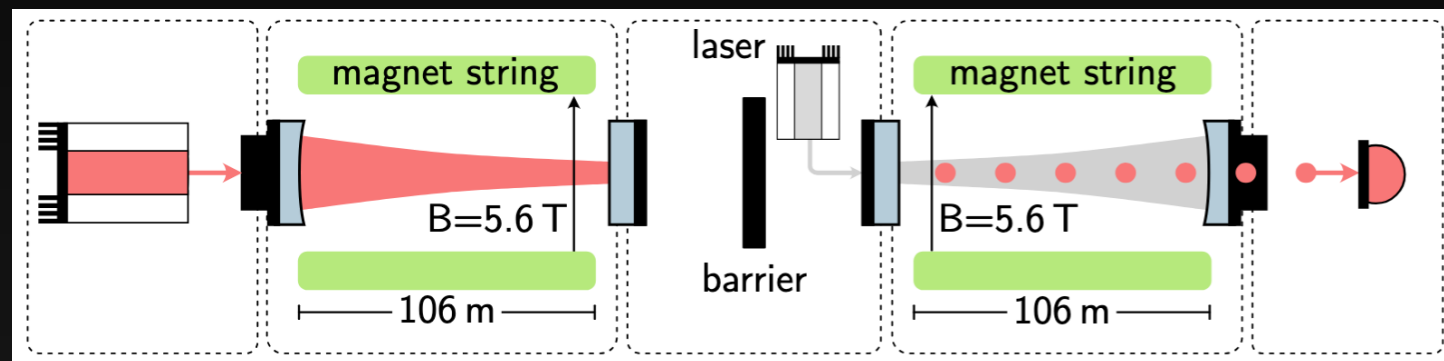


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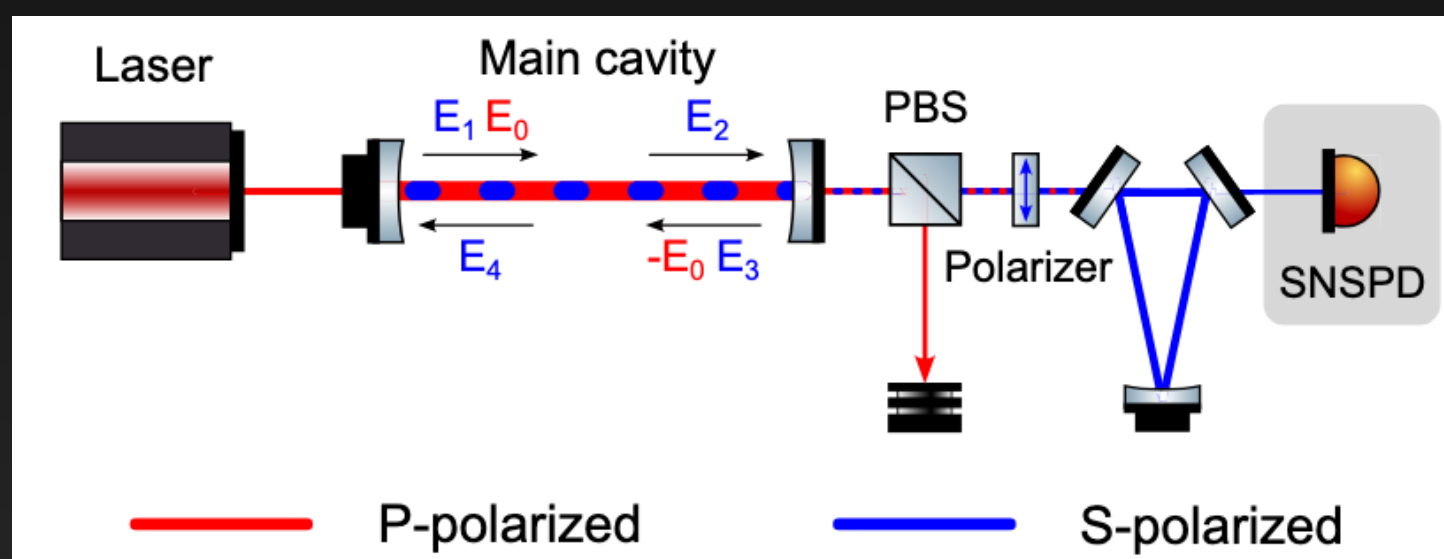
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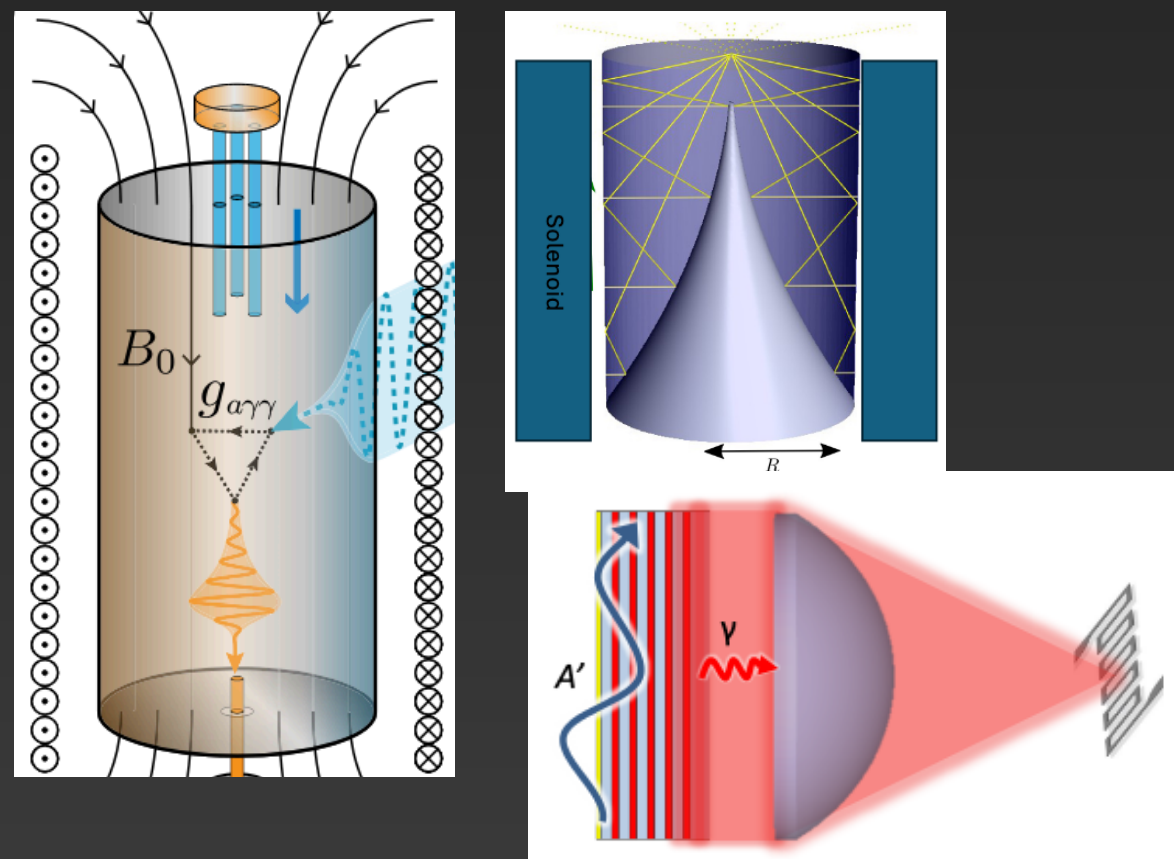


- **Idea:** propagation in axion field induces S-polarized light from P-polarized pump; experiments currently use heterodyne detection scheme, lasers @ 1064nm
- **With single photon counter:** Possible to go below shot noise from local oscillator, could improve sensitivity by factor 50
- Requirements: **P-polarized light can be filtered out, high detection efficiency, ultra-low dark current $\lesssim 1$ photon / day**

See talks by Camilo
Garcia Cely and Hinata
Takidera on Tuesday

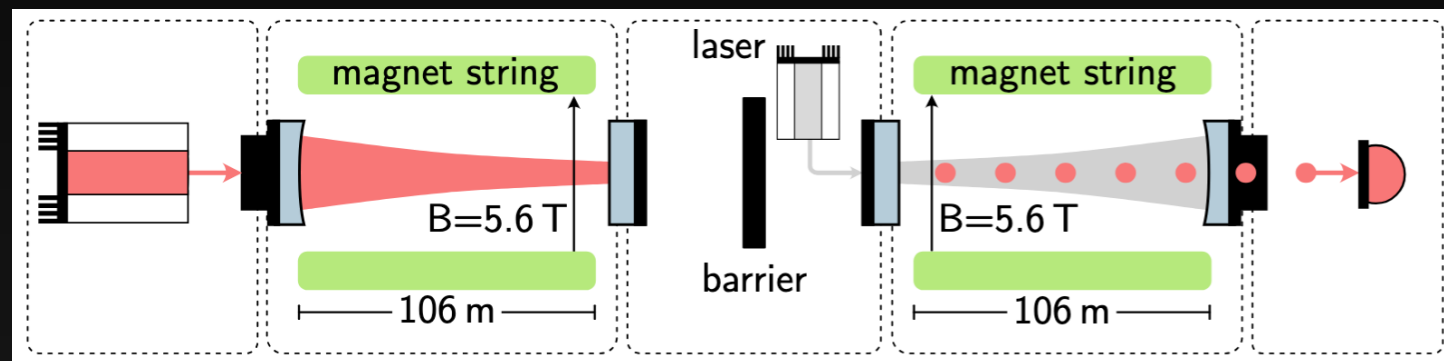
Yu et al., PRD 109,
(2024), 095042
Heinze et al., PRL 132
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Haloscopes



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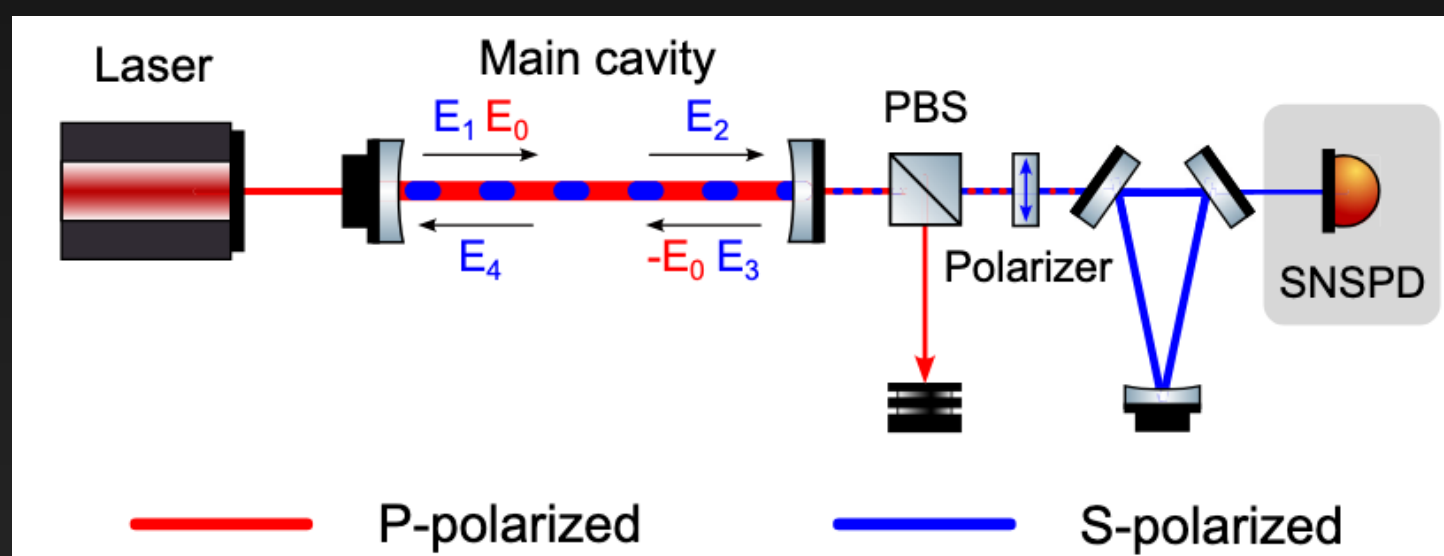
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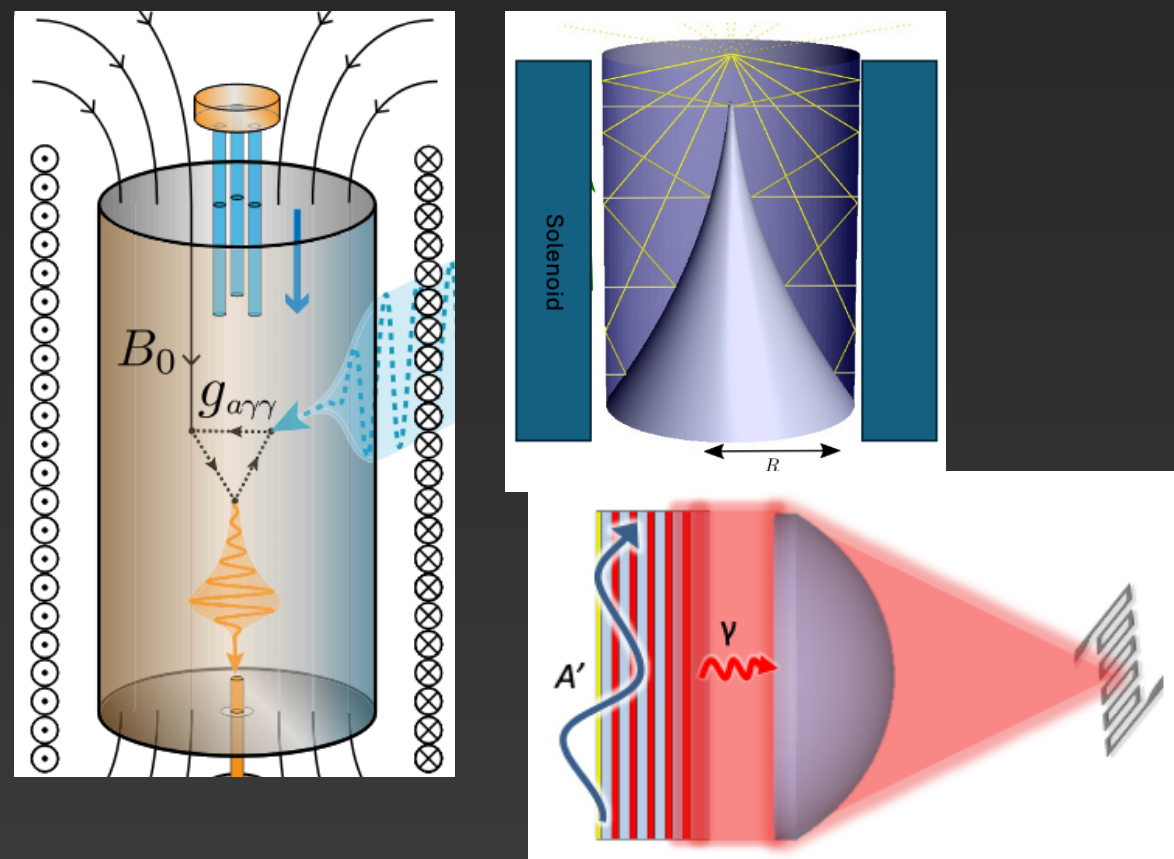


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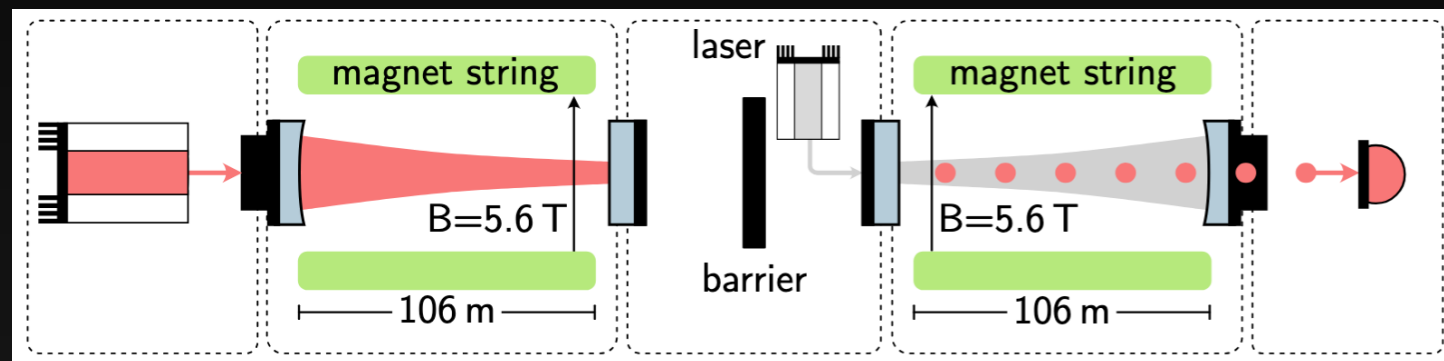


- Idea: look for dark matter axions converting to photons in strong magnetic field
- Boost conversion by using resonant cavities
- **With single photon detector:** potential to go below SQL
- Requirements: detectors that **withstand high B fields, high detection efficiency, low dark current**

BREAD Collaboration, PRL 128
(2022) 13, 131801
A. Sonnenschein's talk at UCLA DM
meeting 2025
Baryakhtar et al., PRD 98 (2018) 3,
035006
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Use cases for optical/infrared single photon detectors for axion experiments

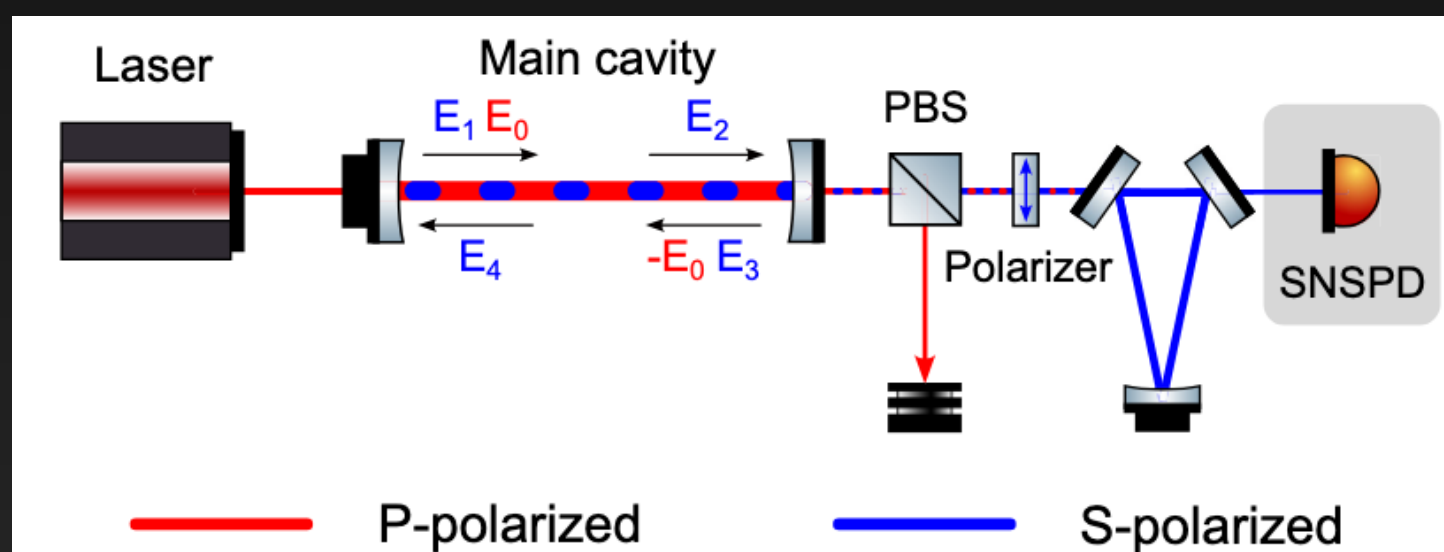
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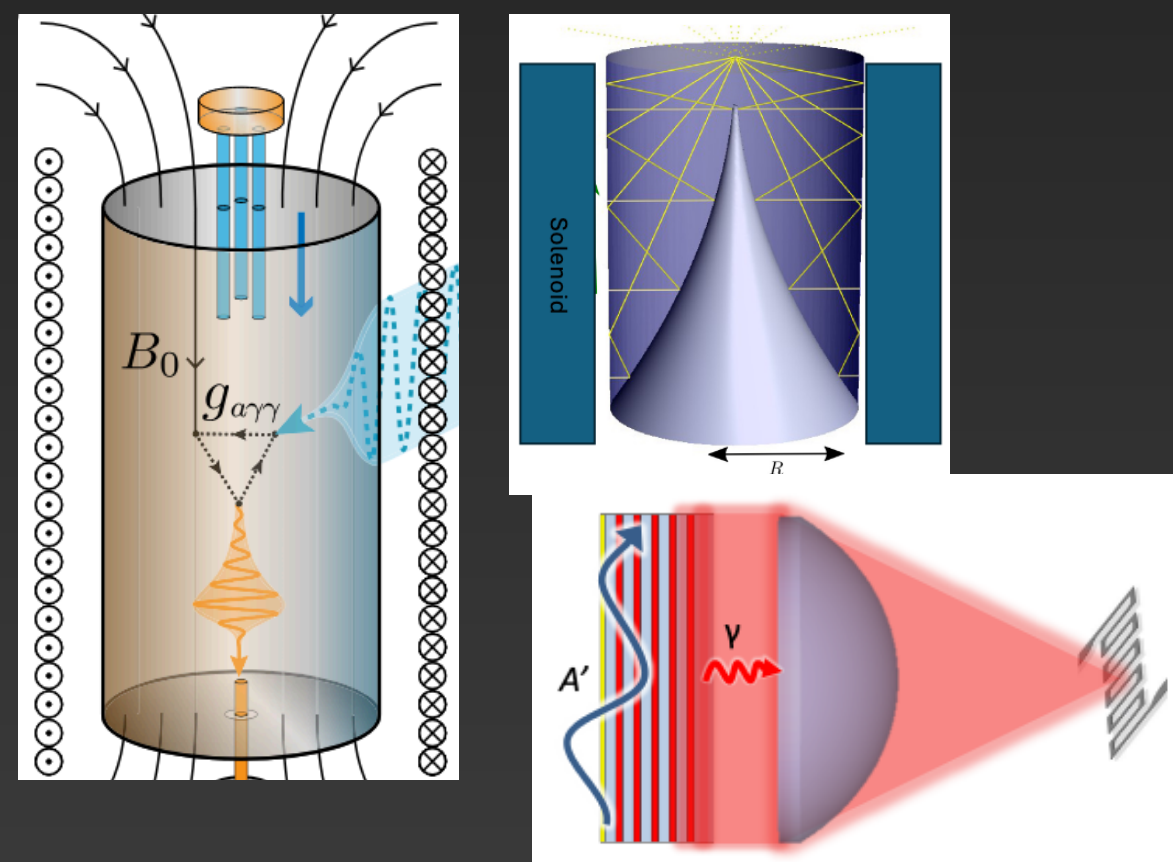


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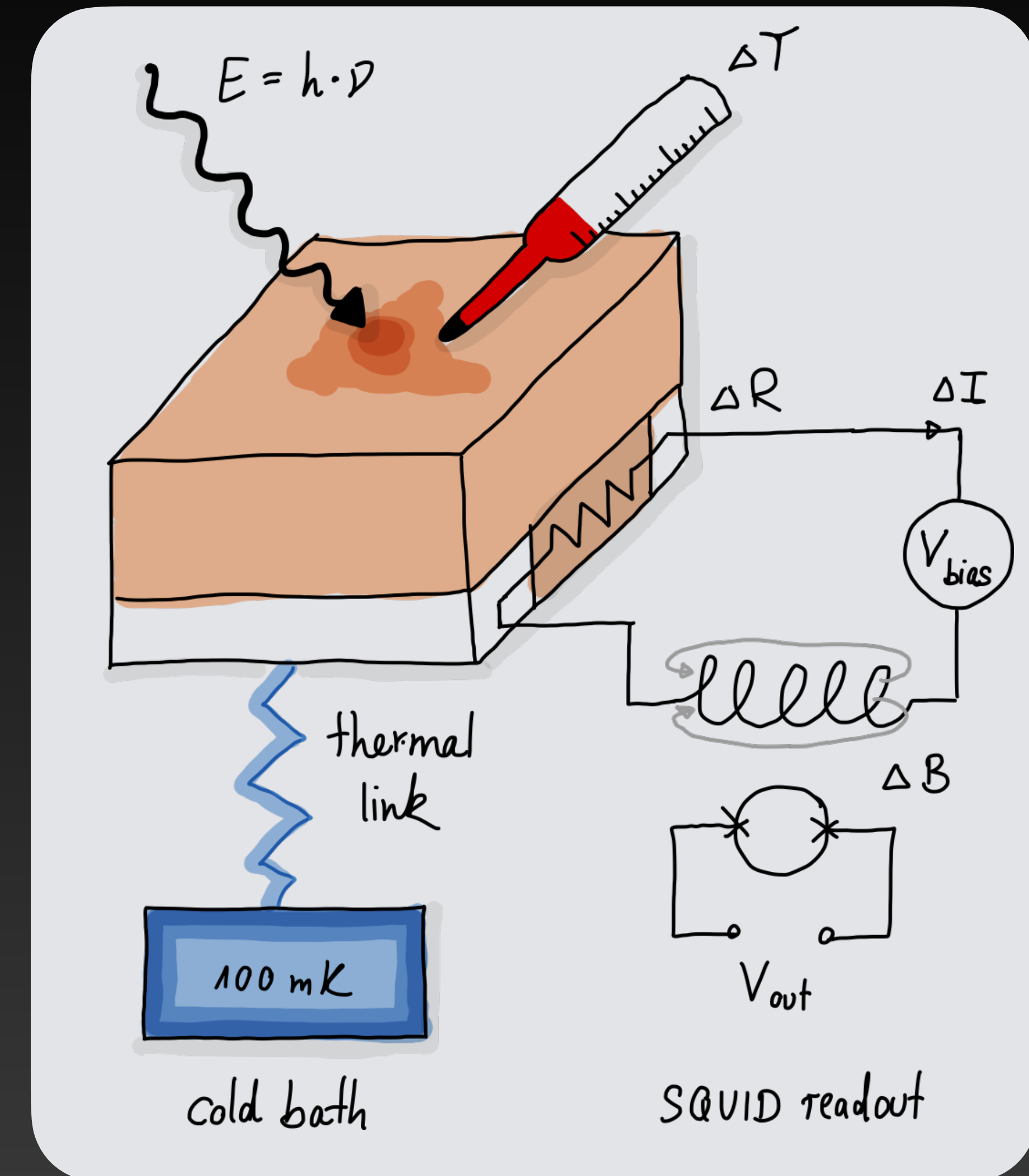
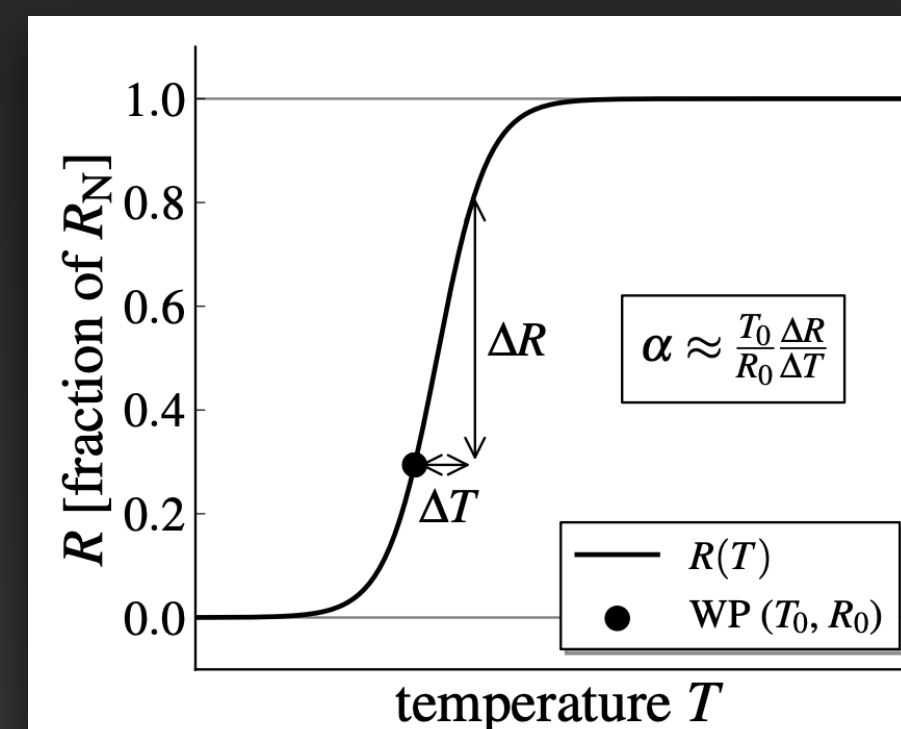
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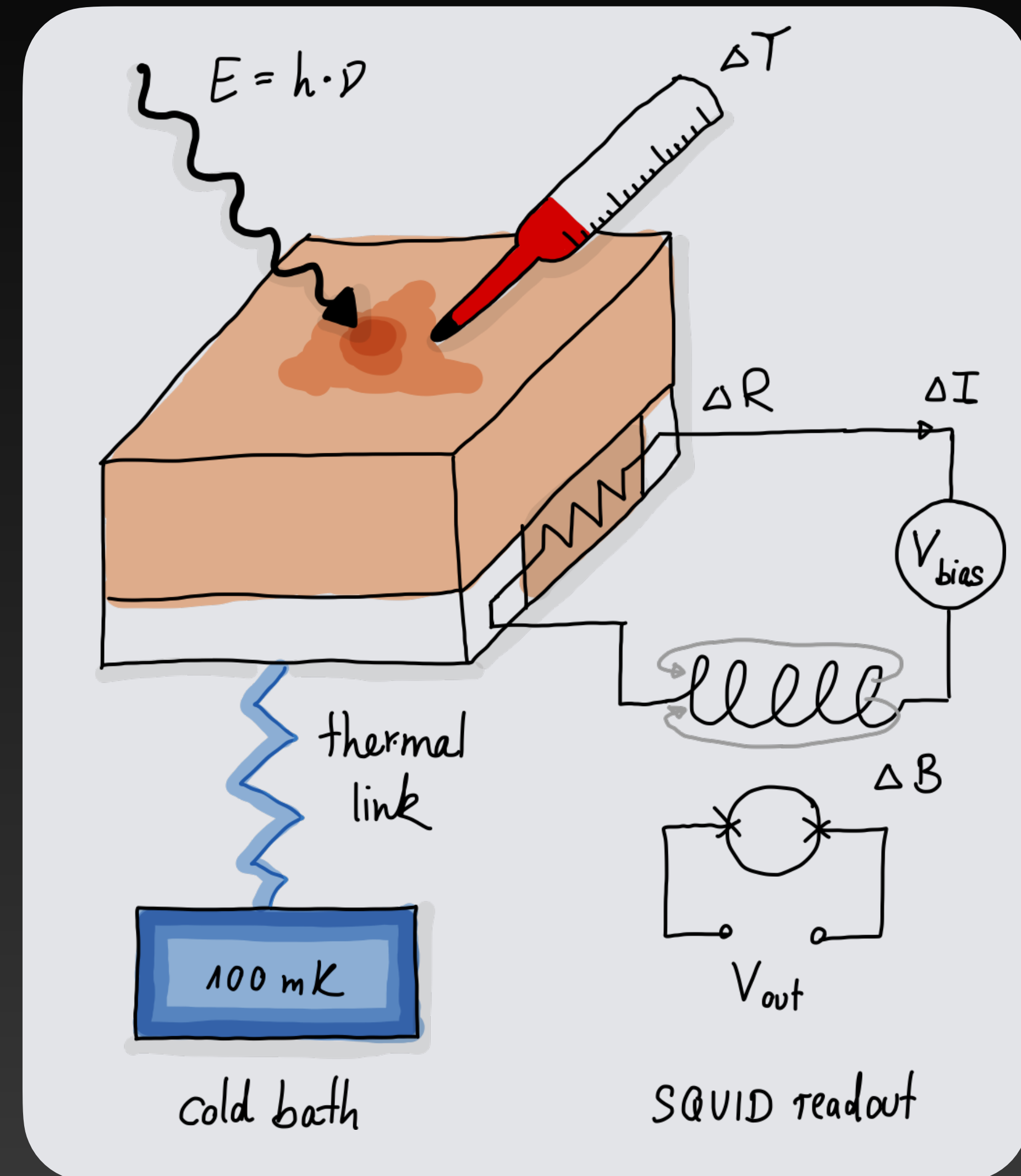
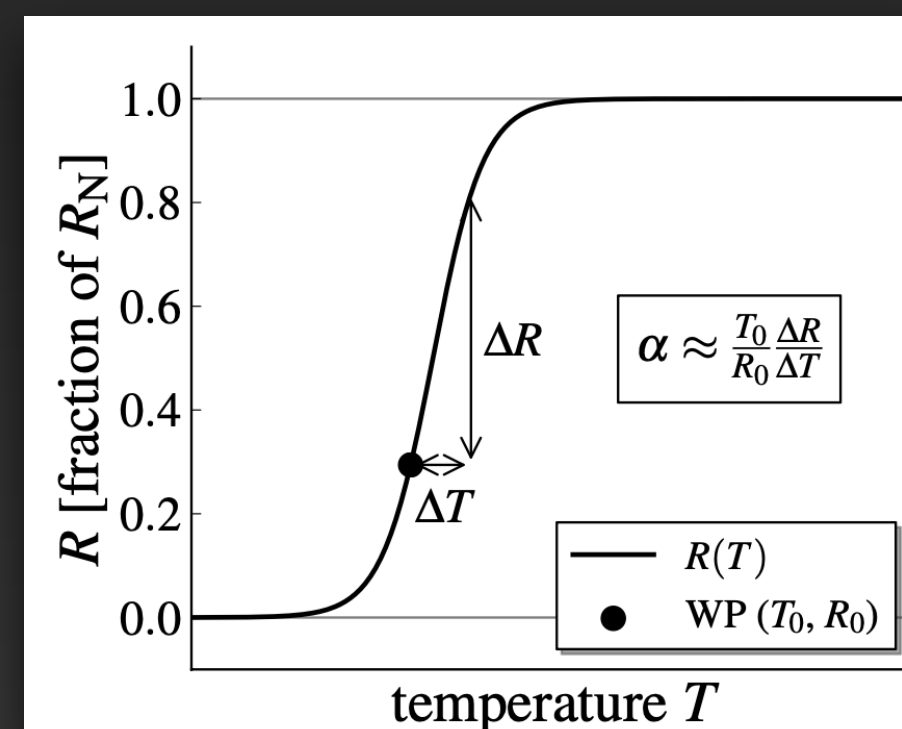


Drawing by K. Isleif

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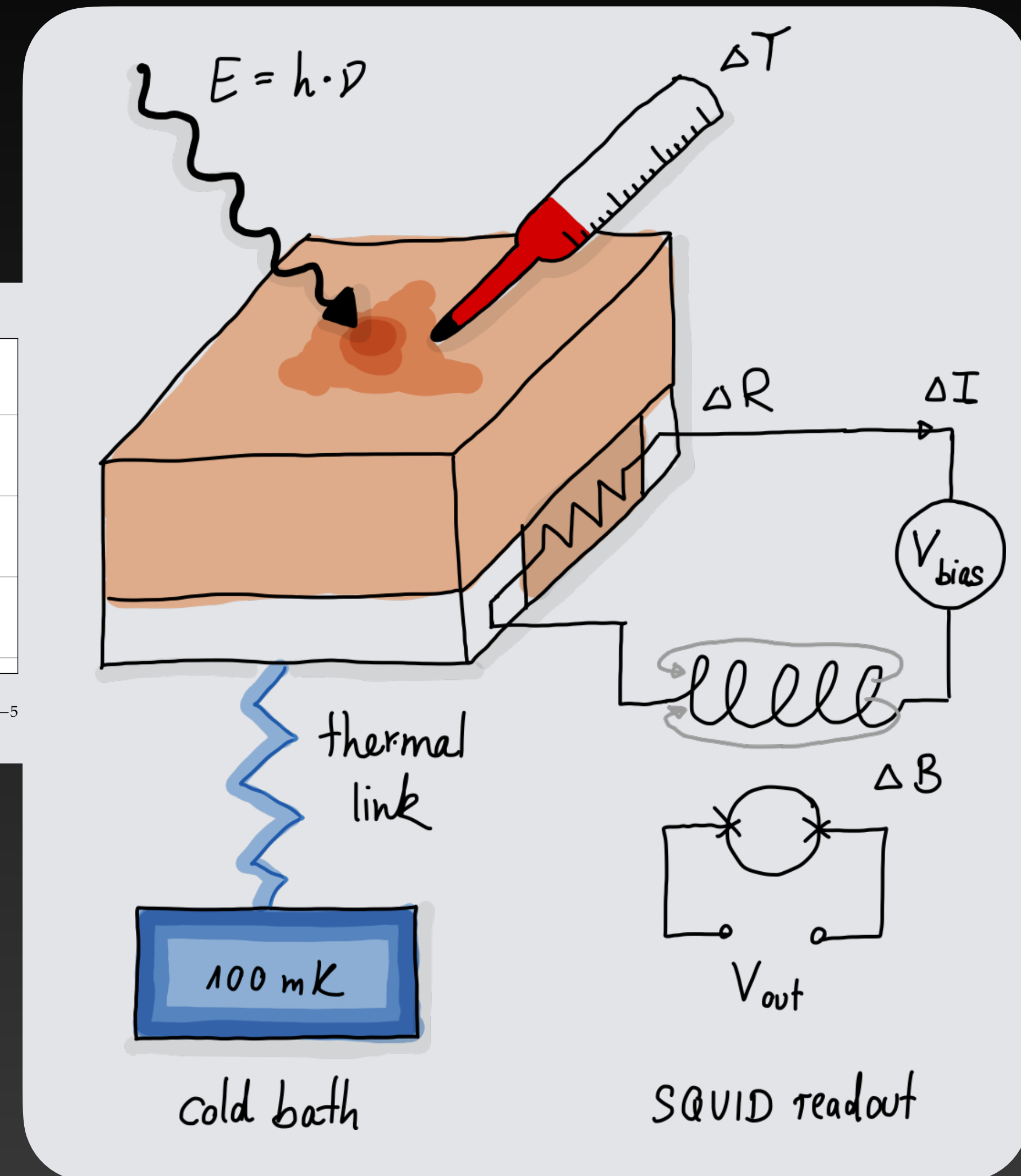
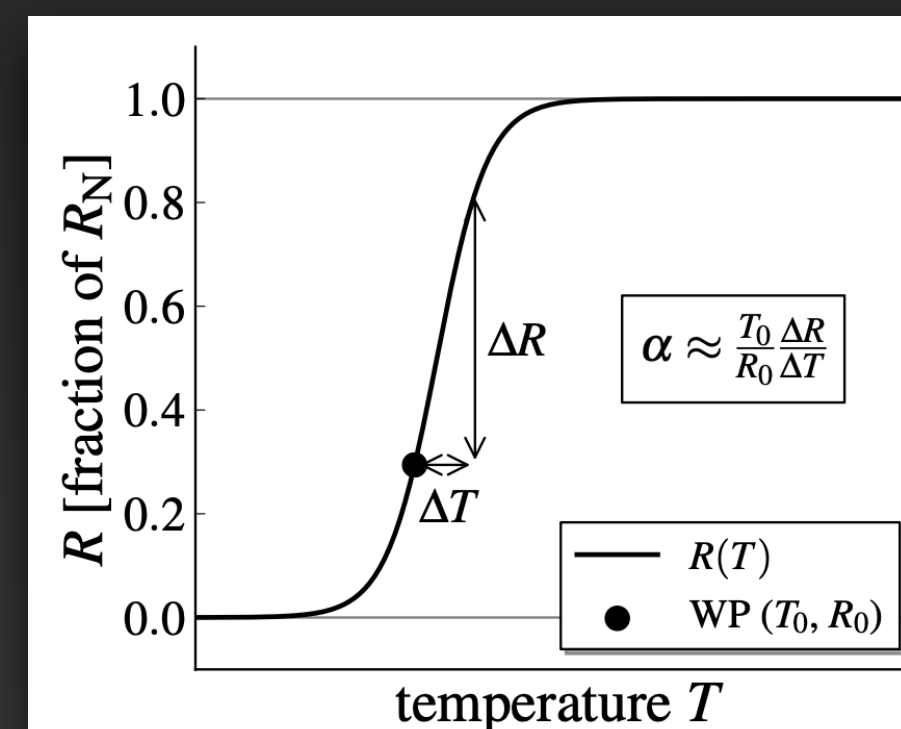
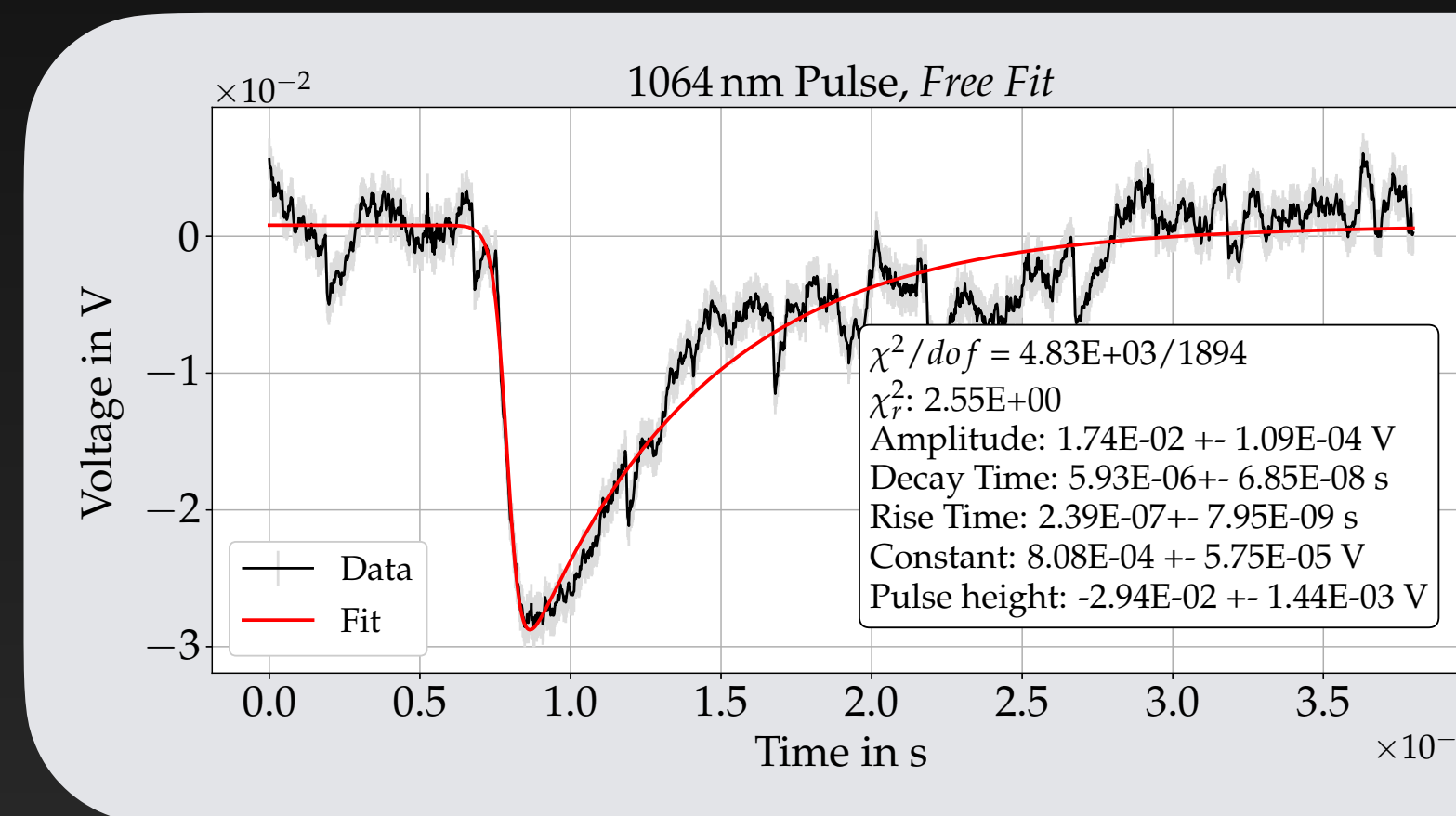


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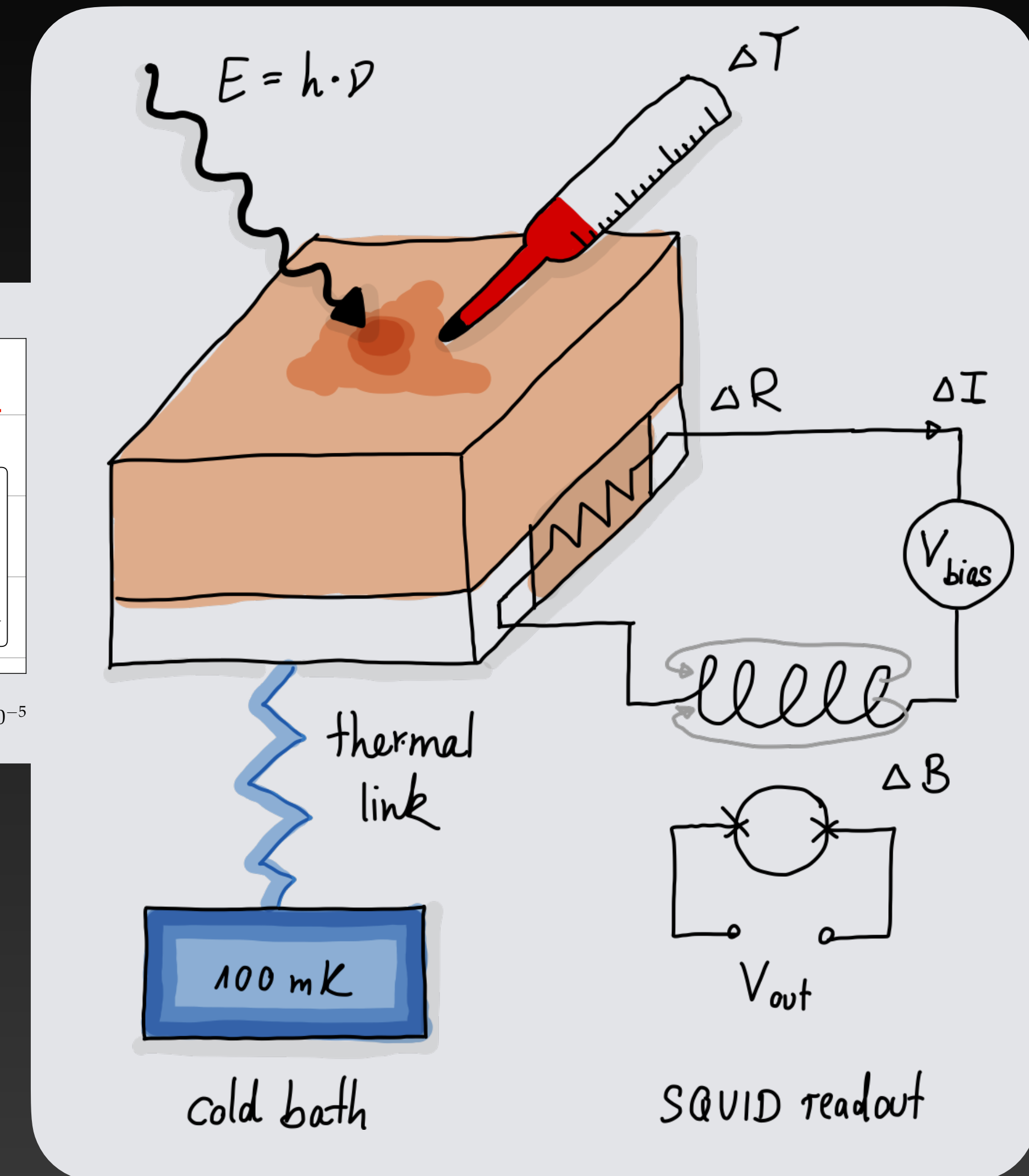
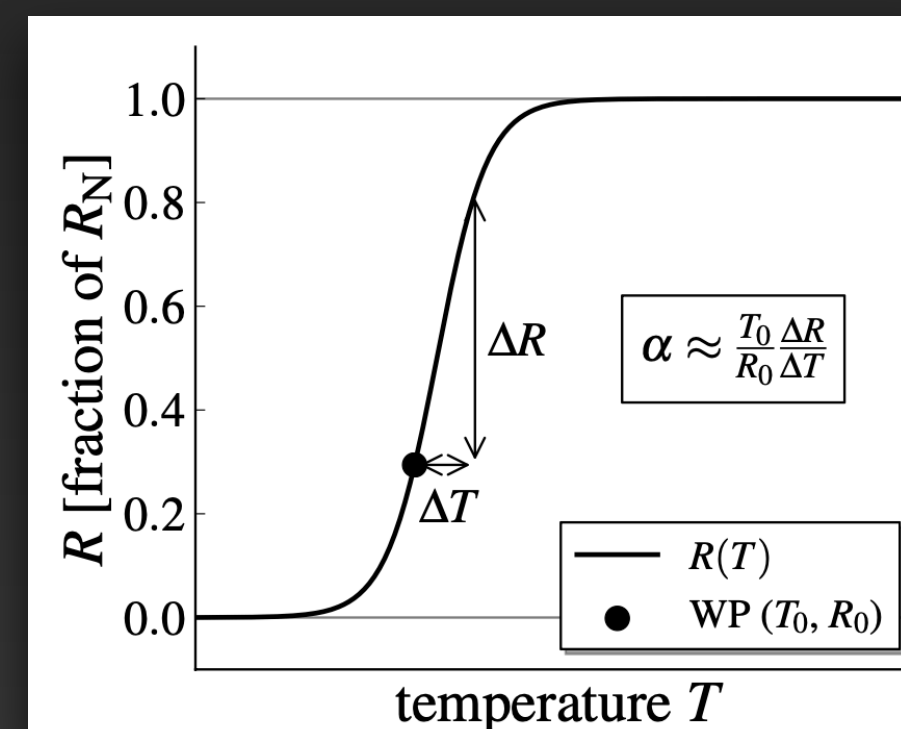
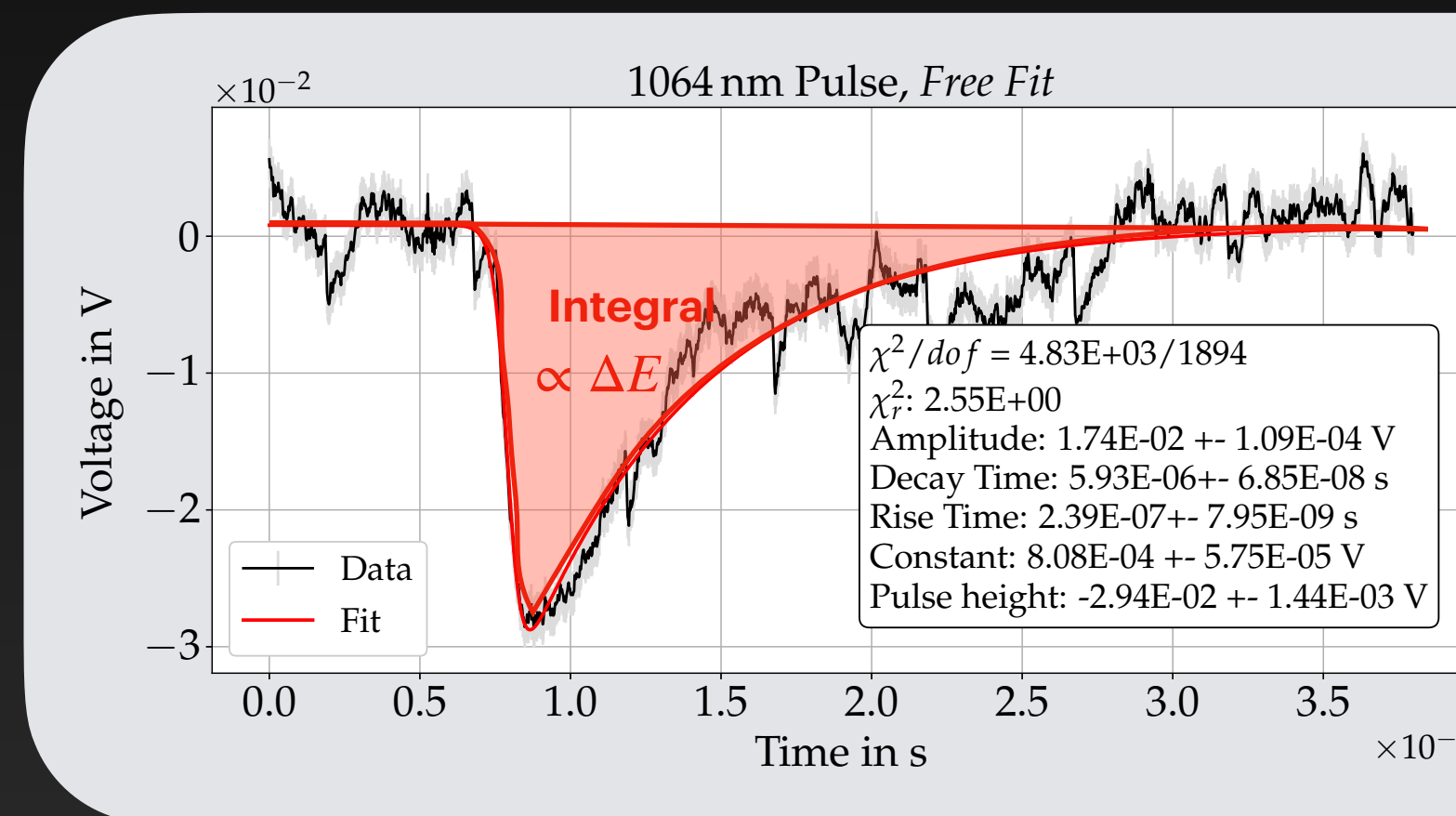


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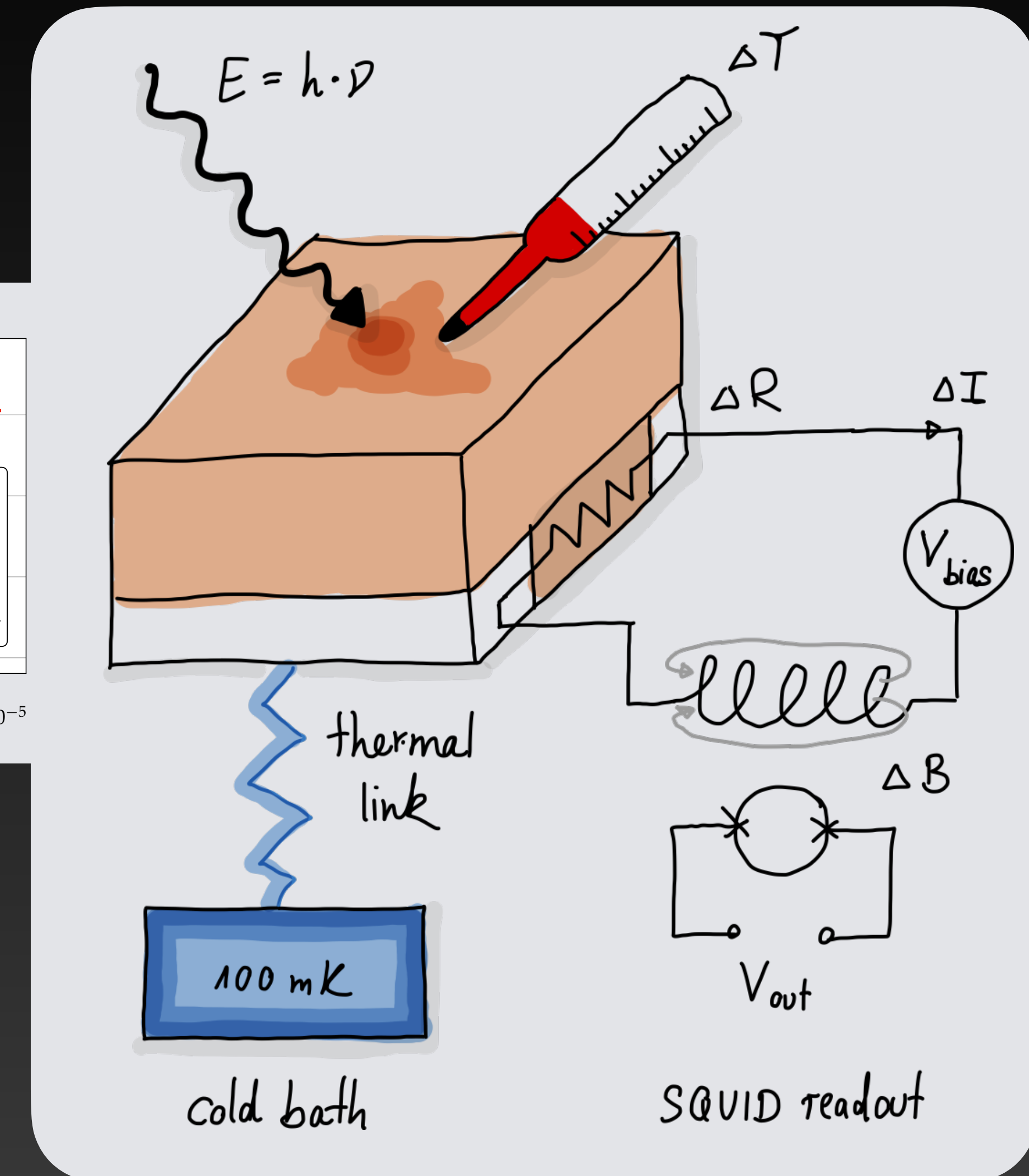
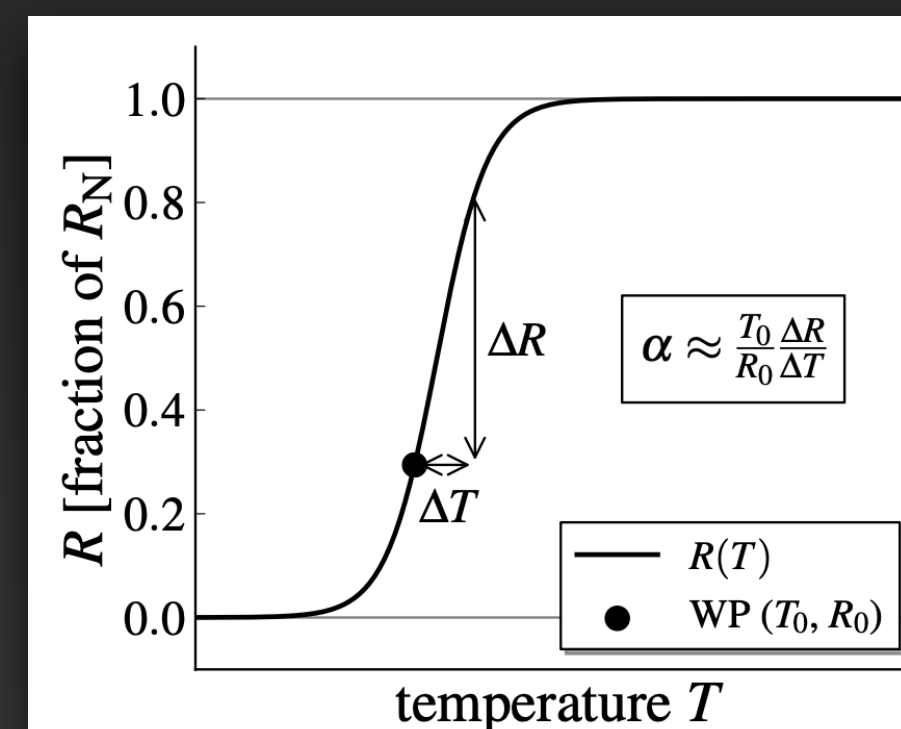
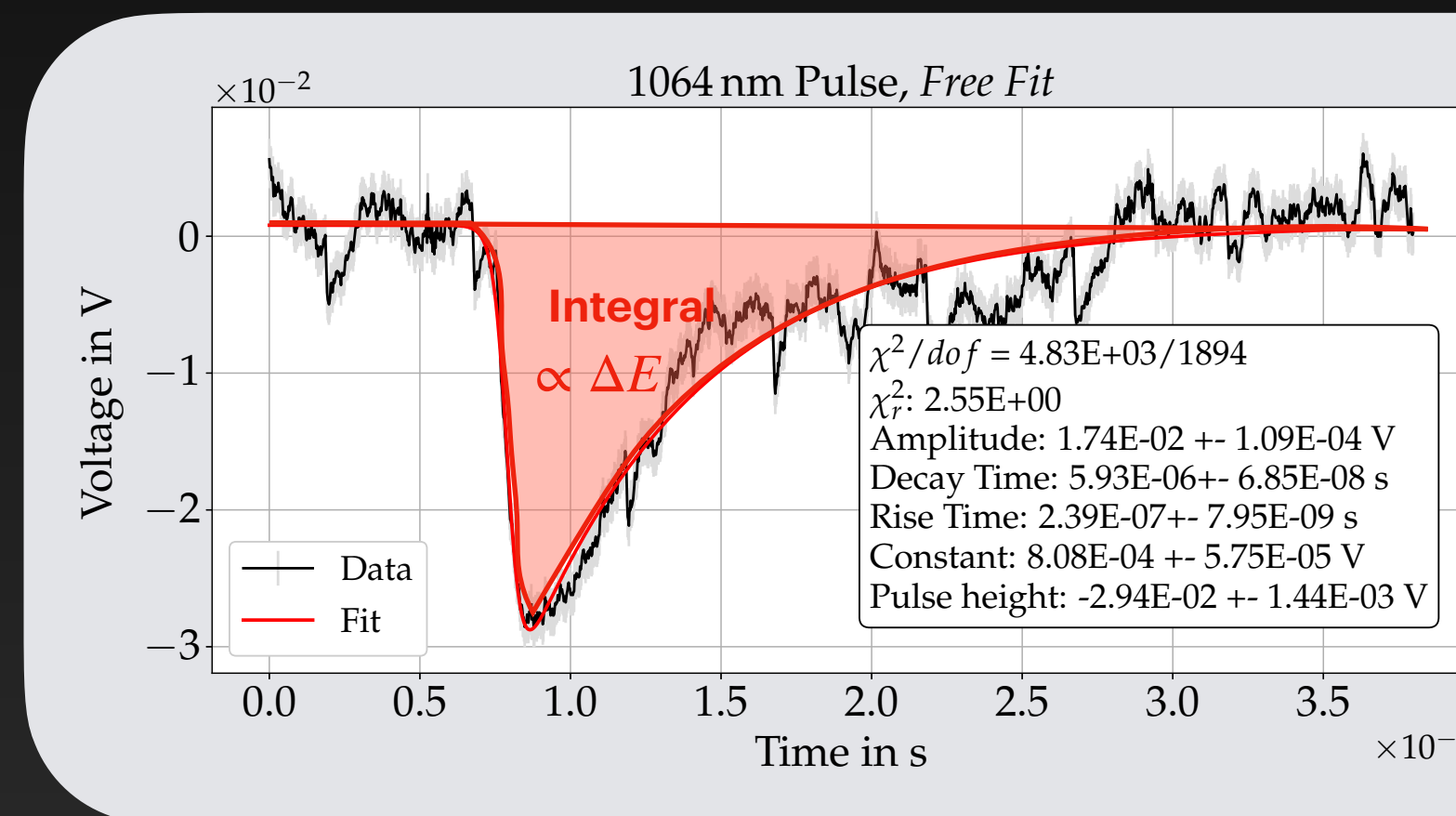


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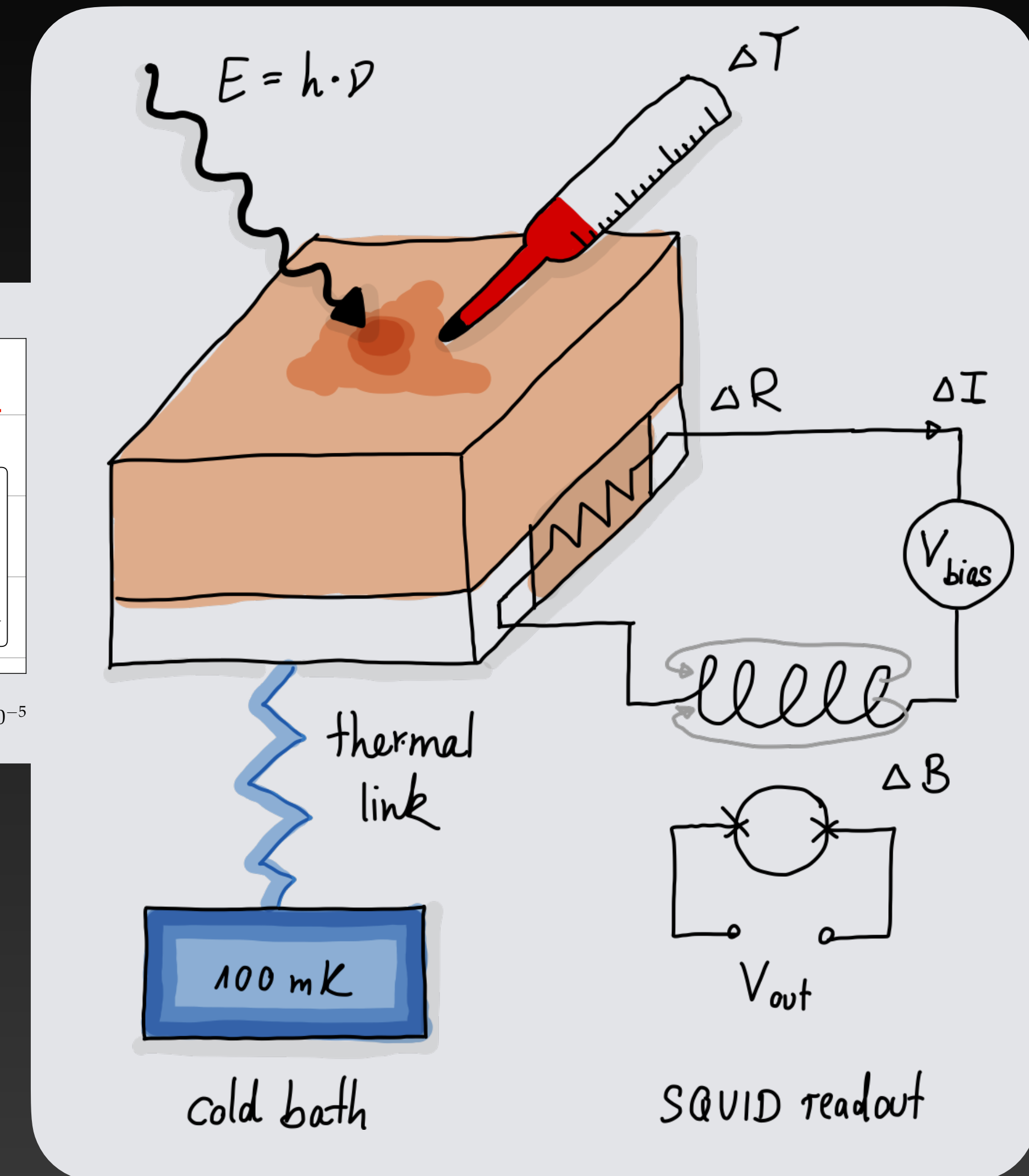
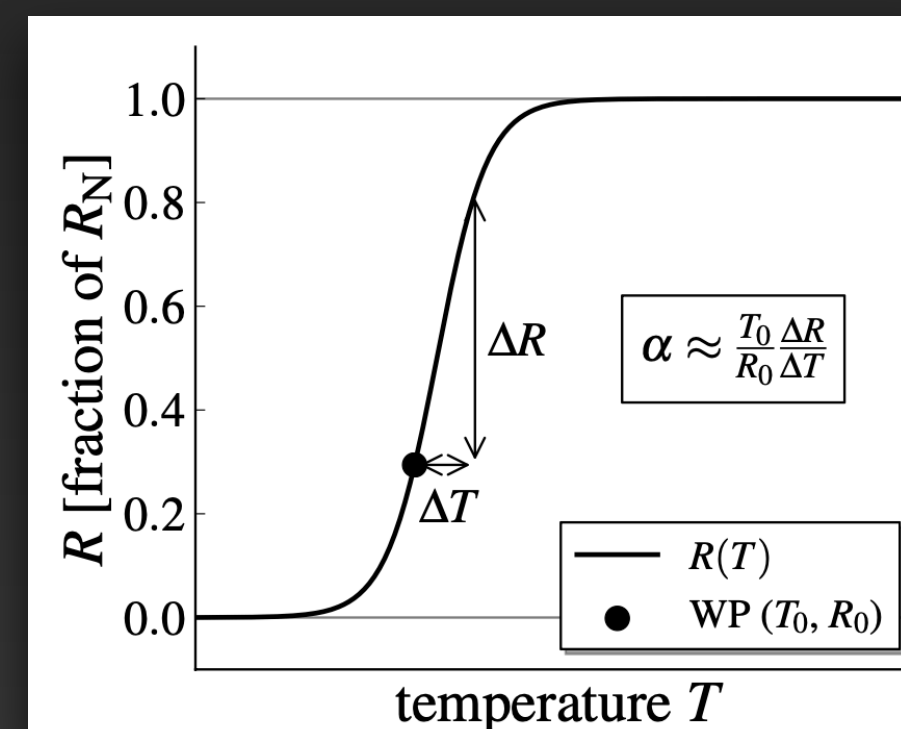
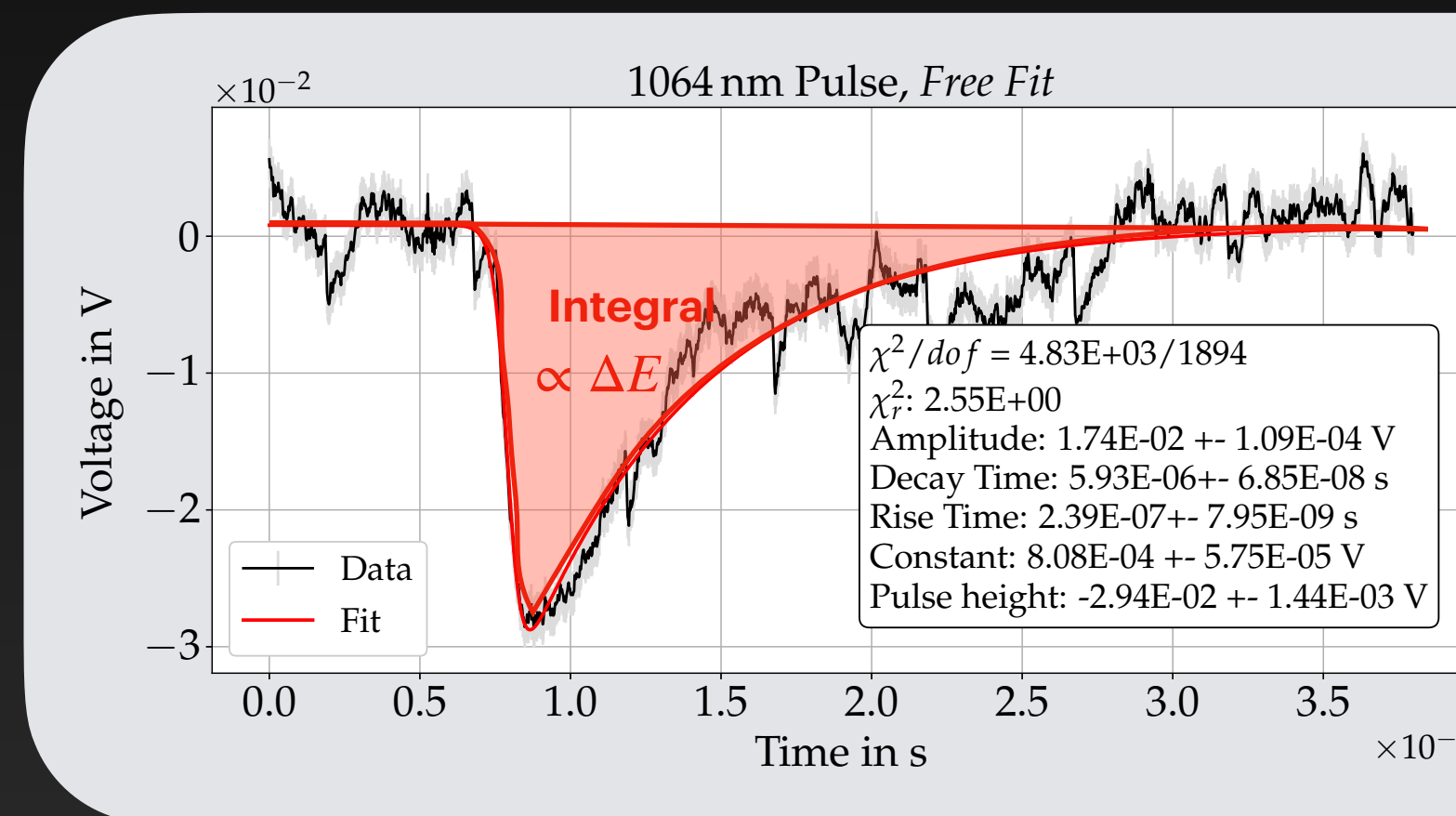


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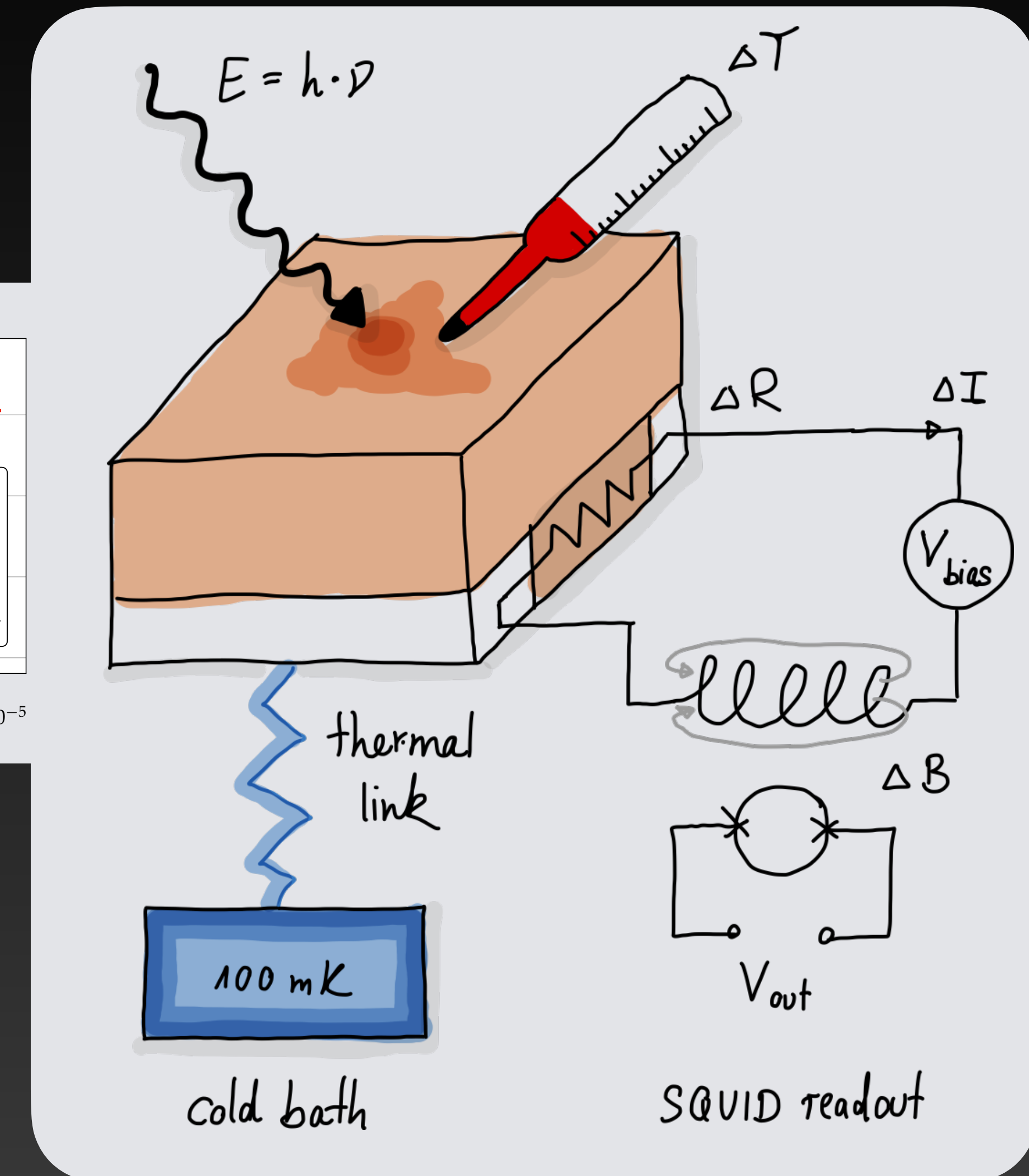
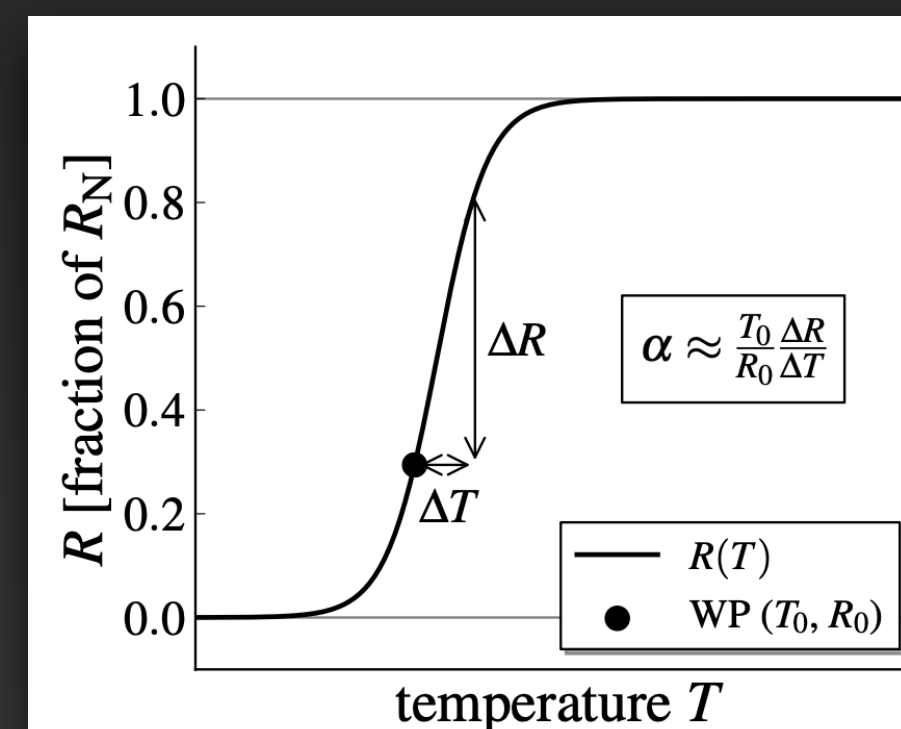
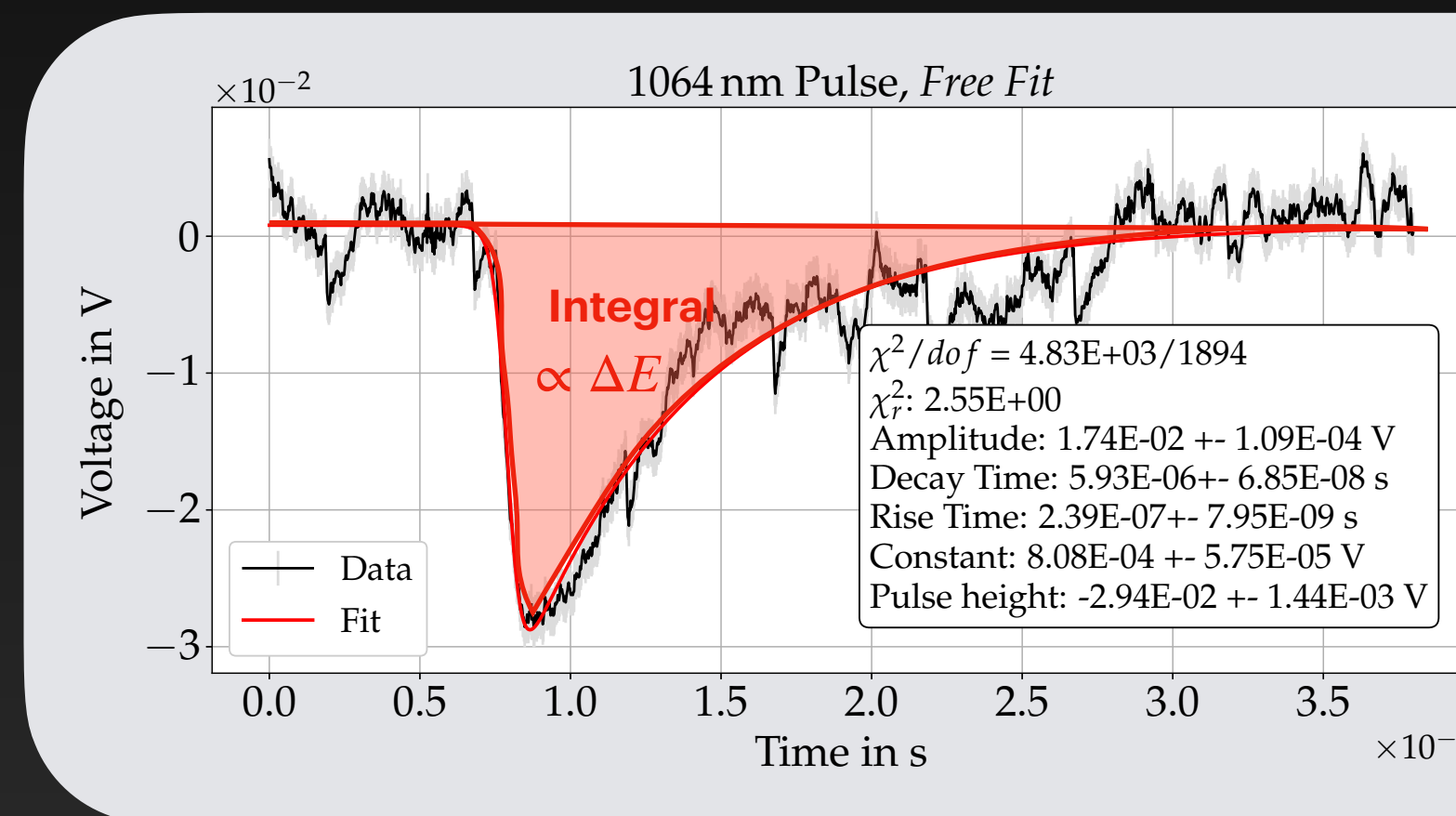


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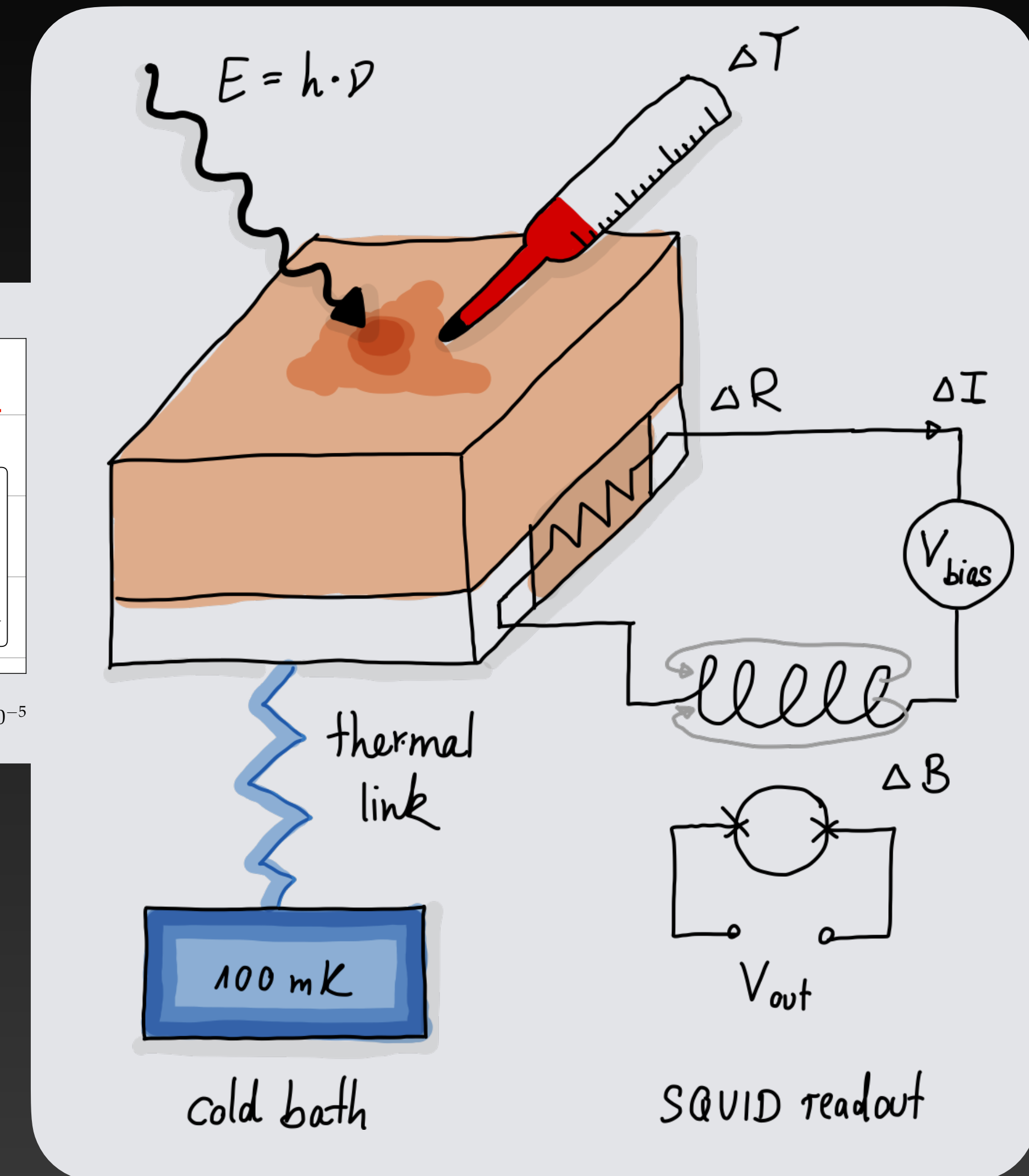
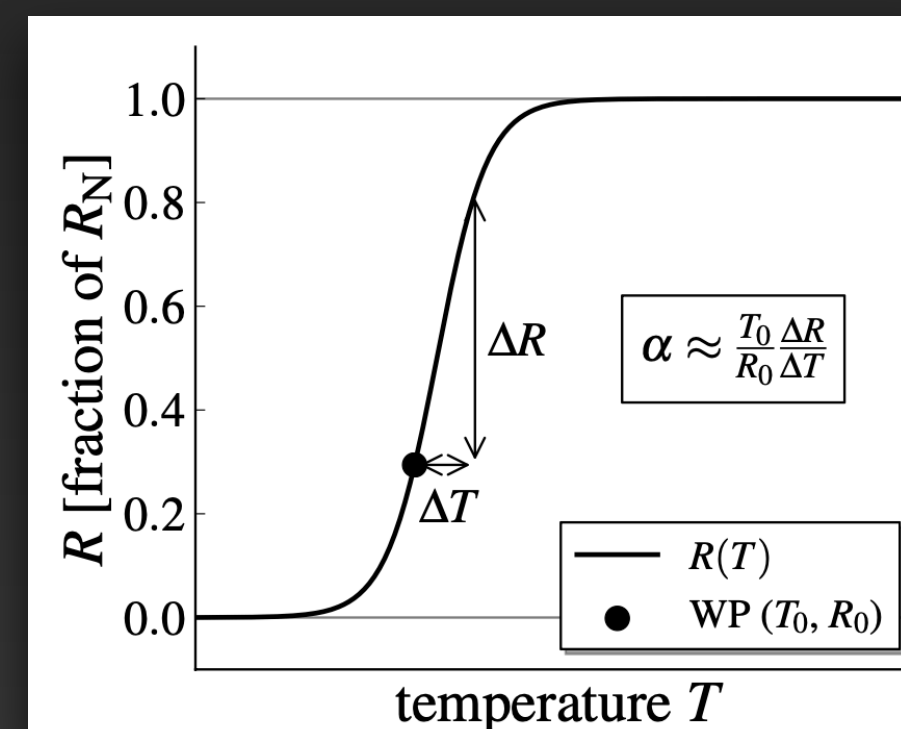
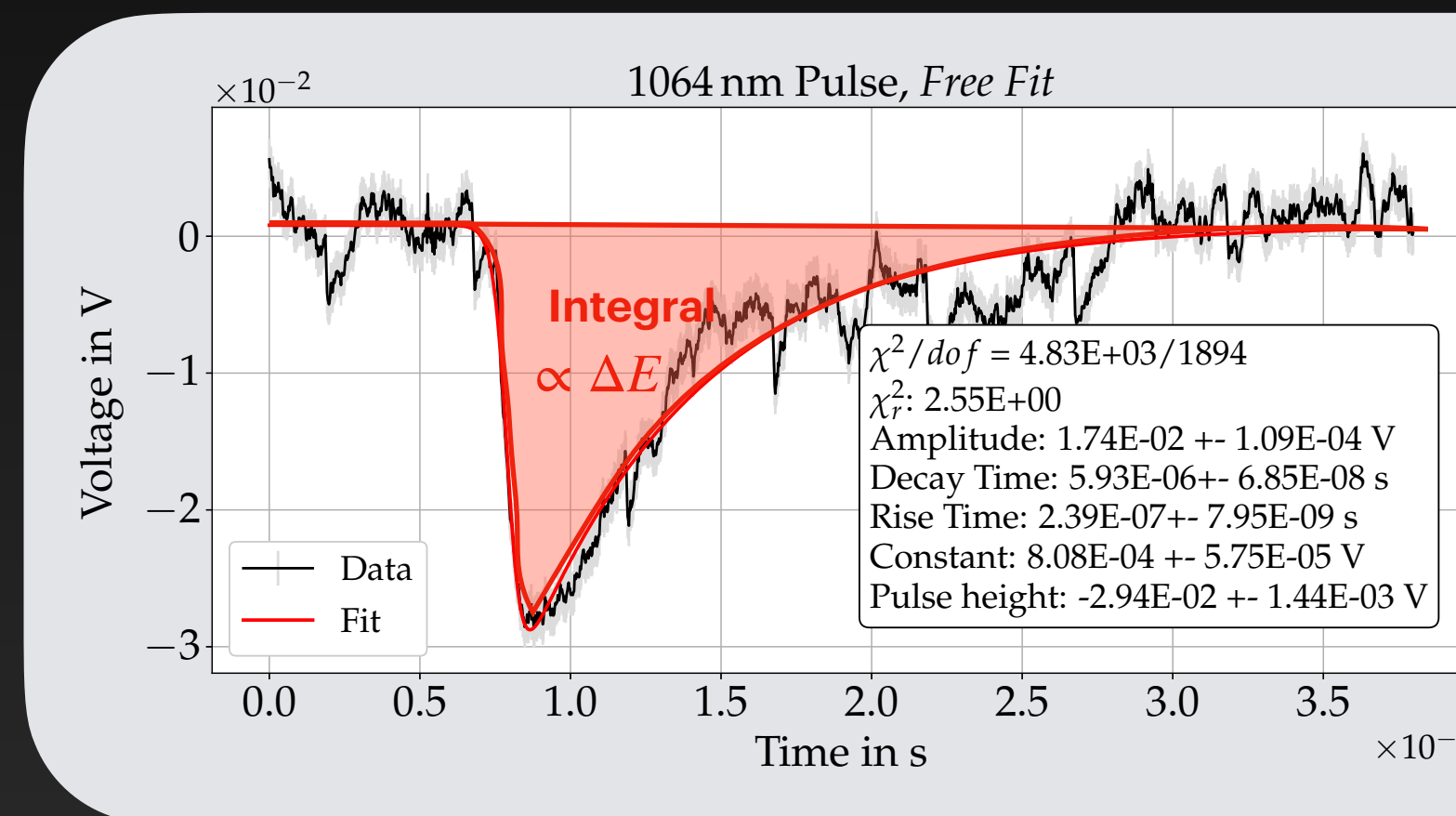


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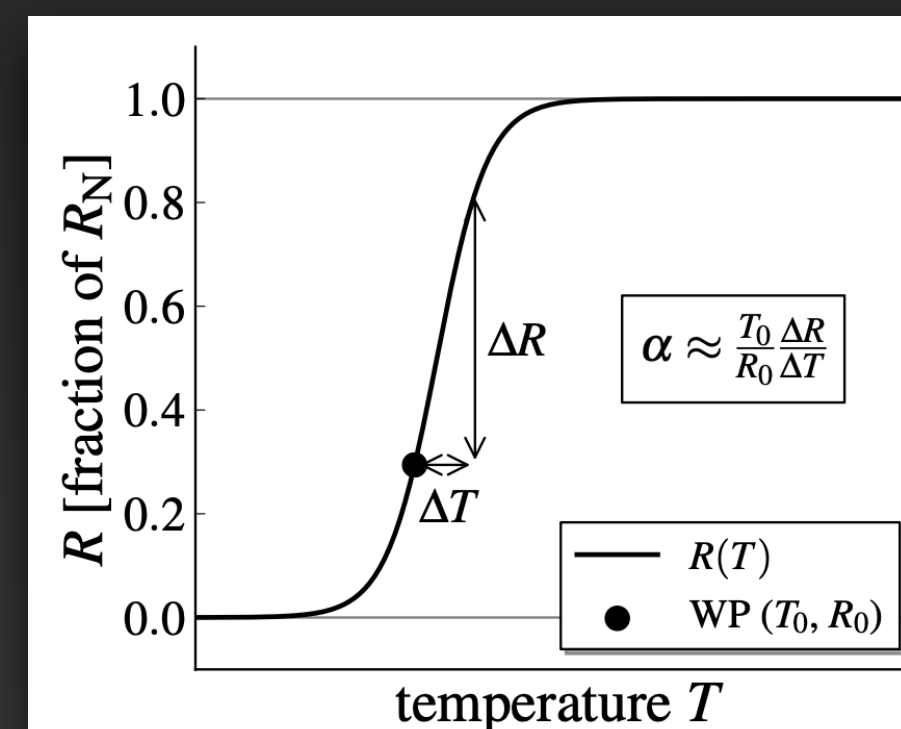
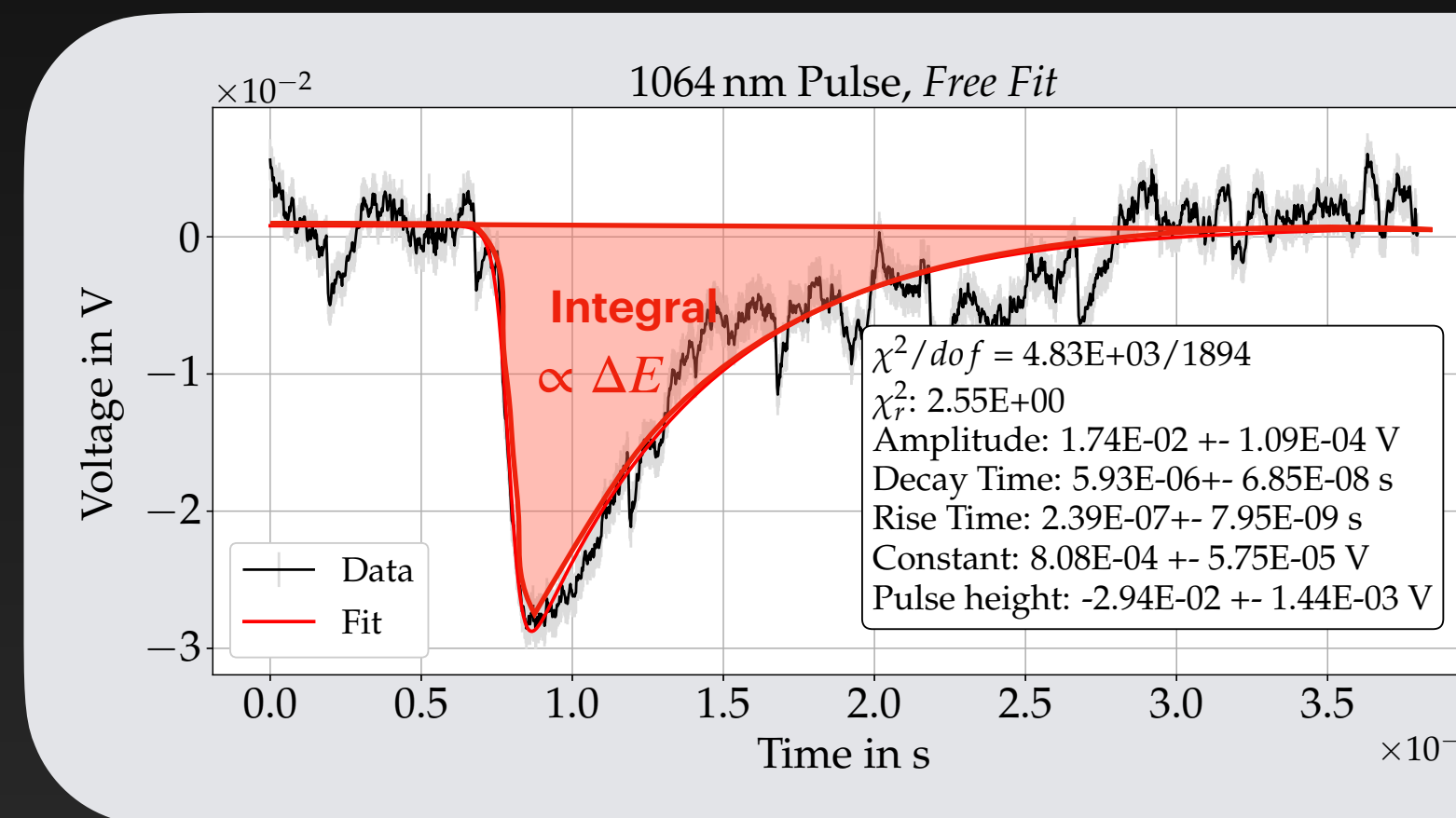


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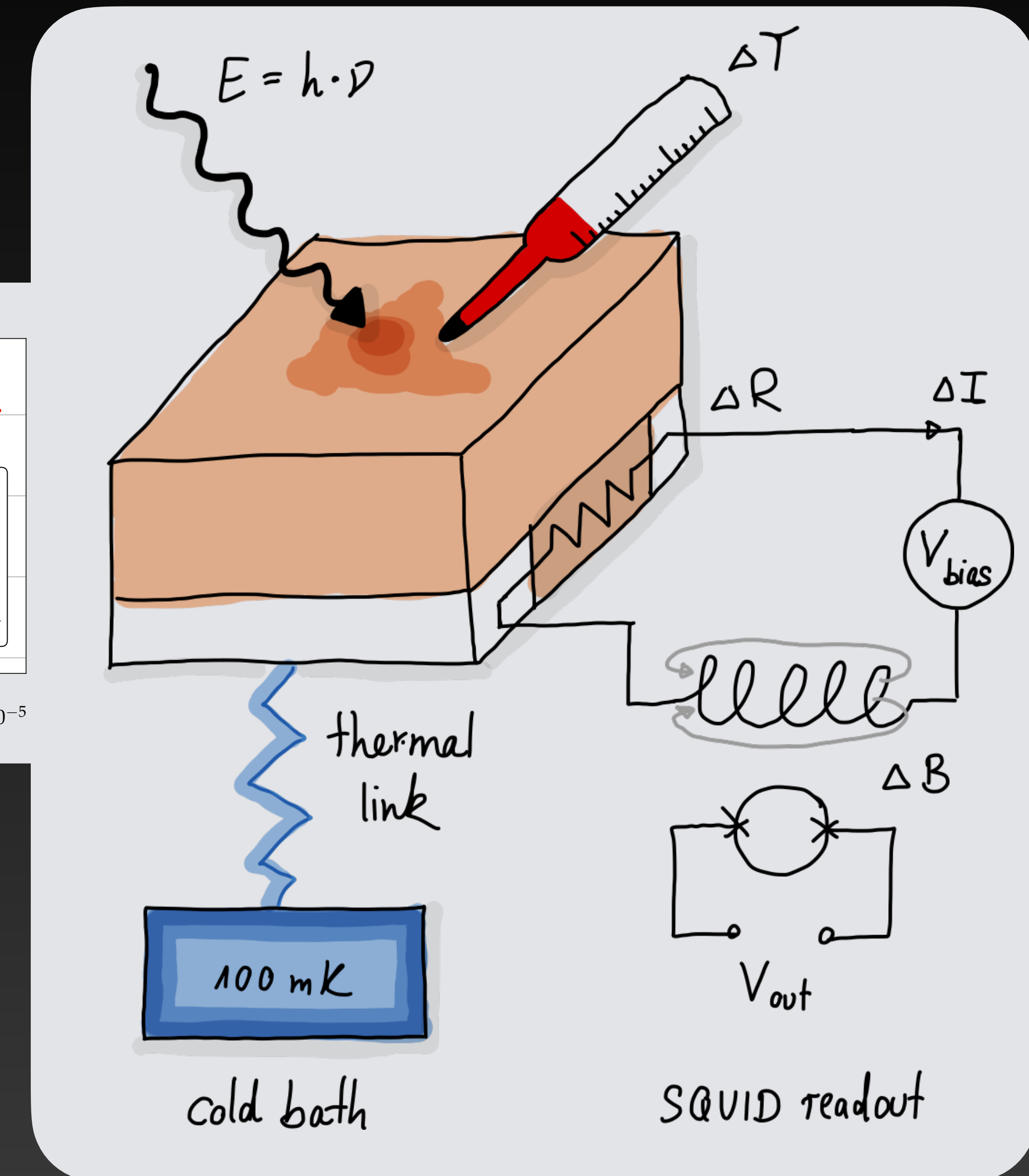
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- Demonstrated quantum efficiency: $\gtrsim 95\%$ at near infrared

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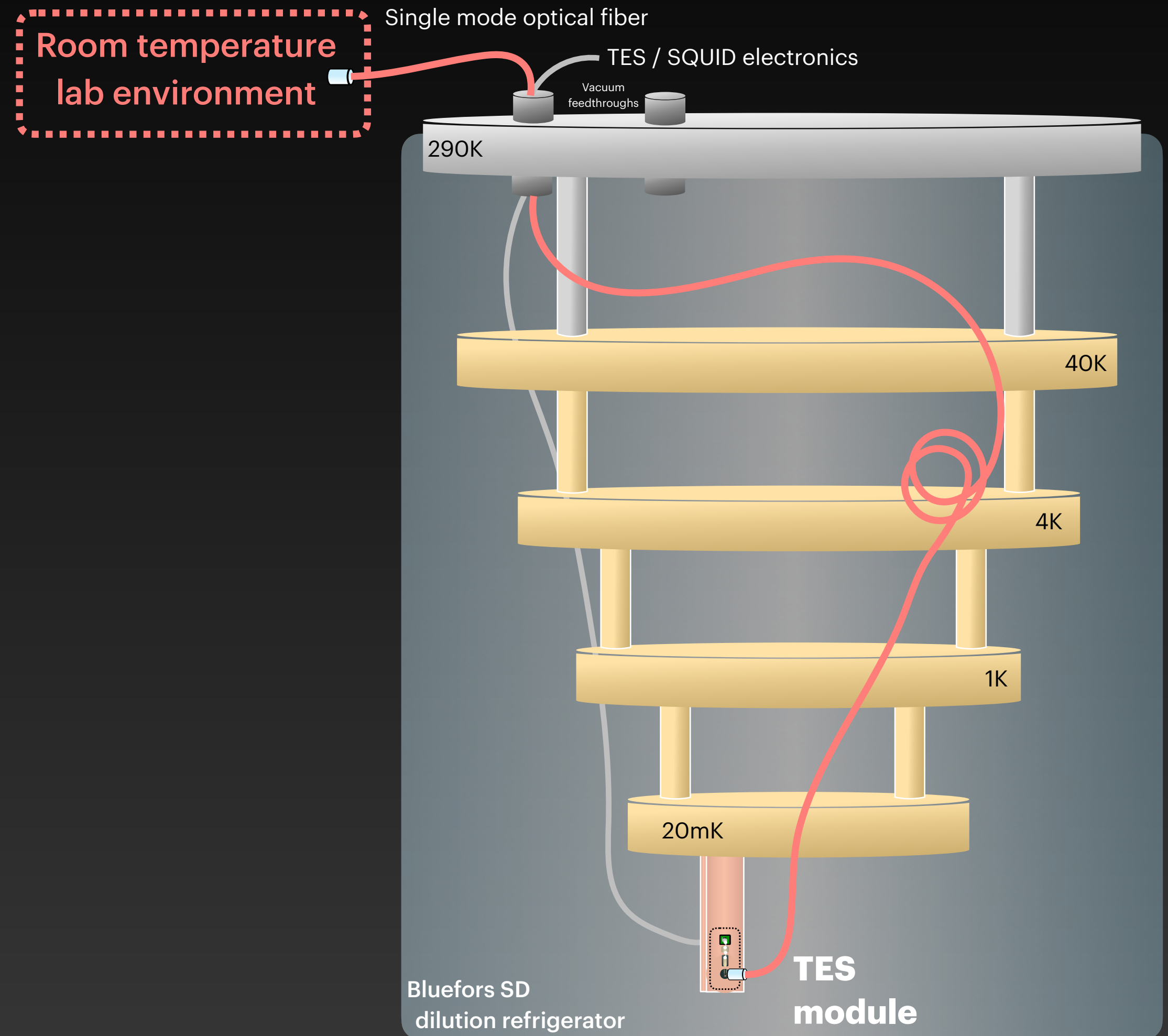
Lita et al. Opt. Exp. 16 (2008), 5



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ALPS II Transition Edge Sensor Module at

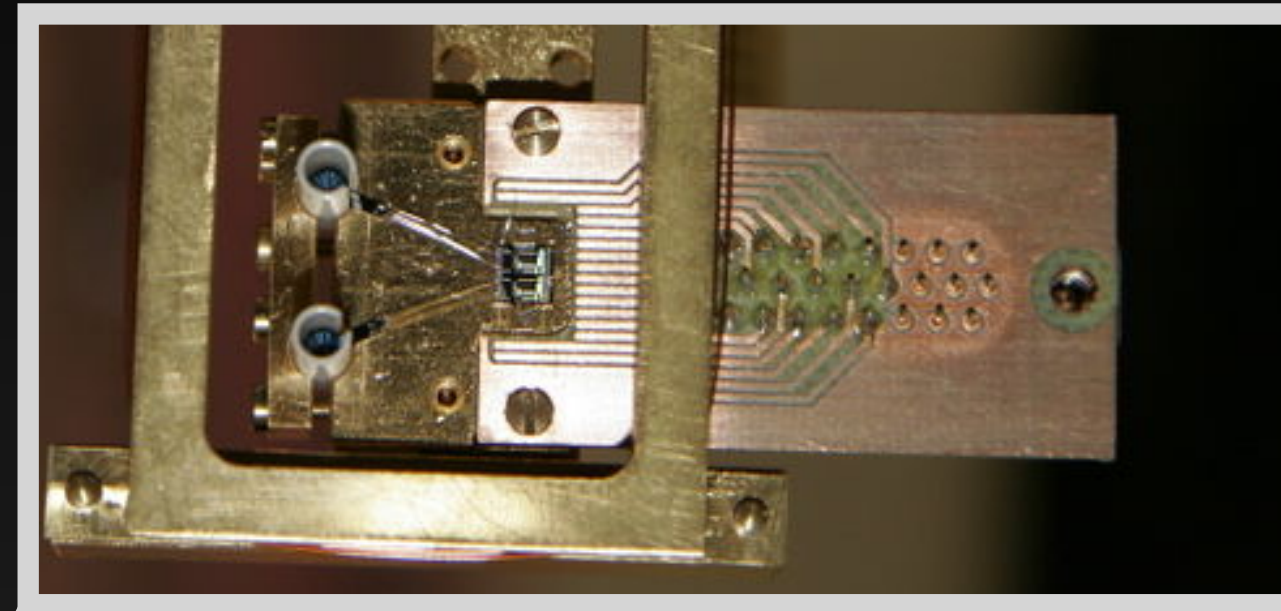
Two-channel system of tungsten-based TESs



ALPS II Transition Edge Sensor Module at



Two-channel system of tungsten-based TESs



Room temperature
lab environment

Single mode optical fiber

TES / SQUID electronics

Vacuum
feedthroughs

290K

40K

4K

1K

20mK

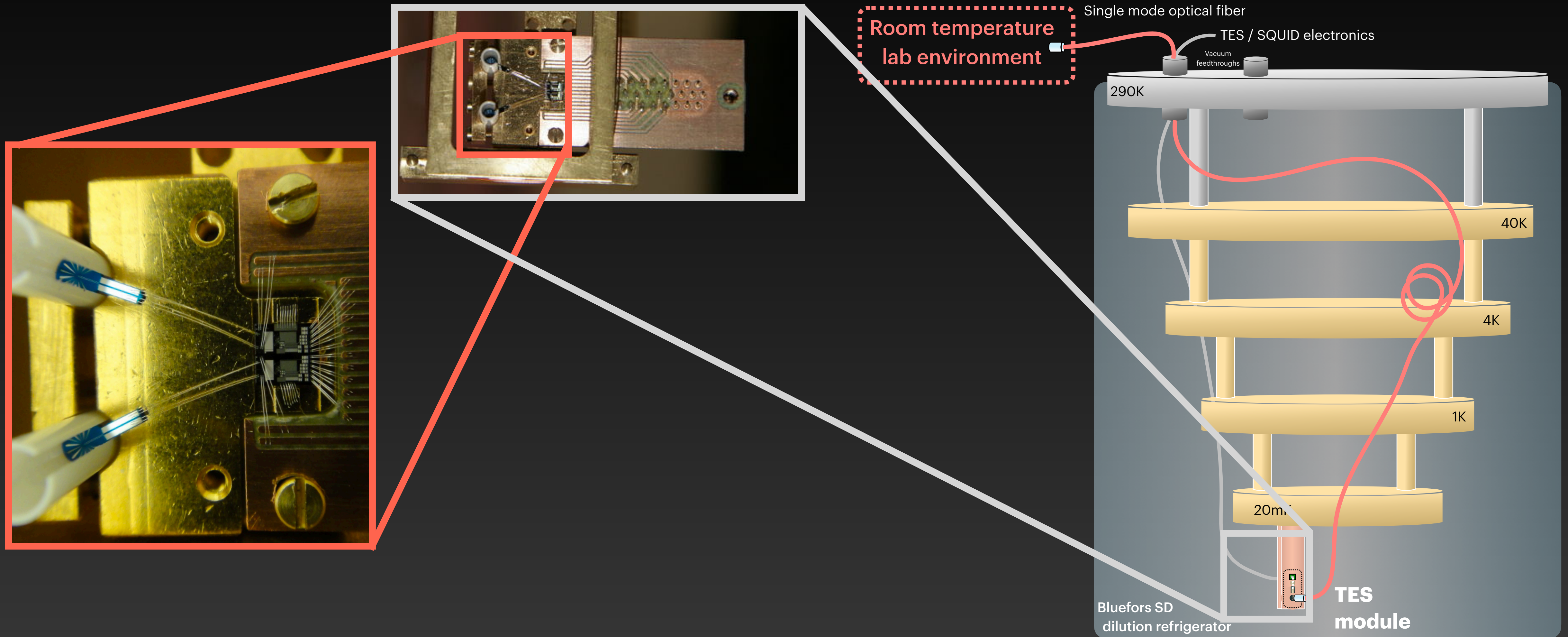
Bluefors SD
dilution refrigerator

TES
module

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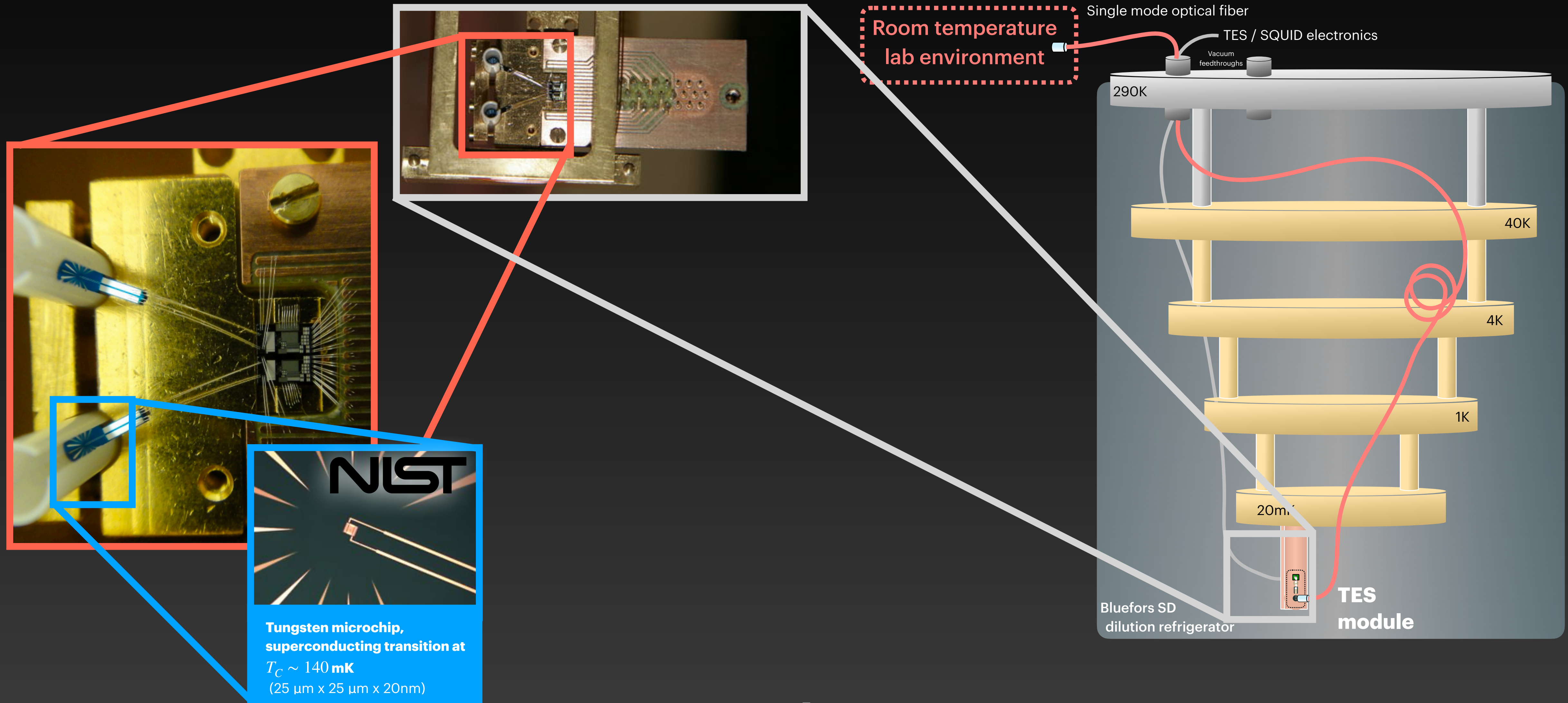
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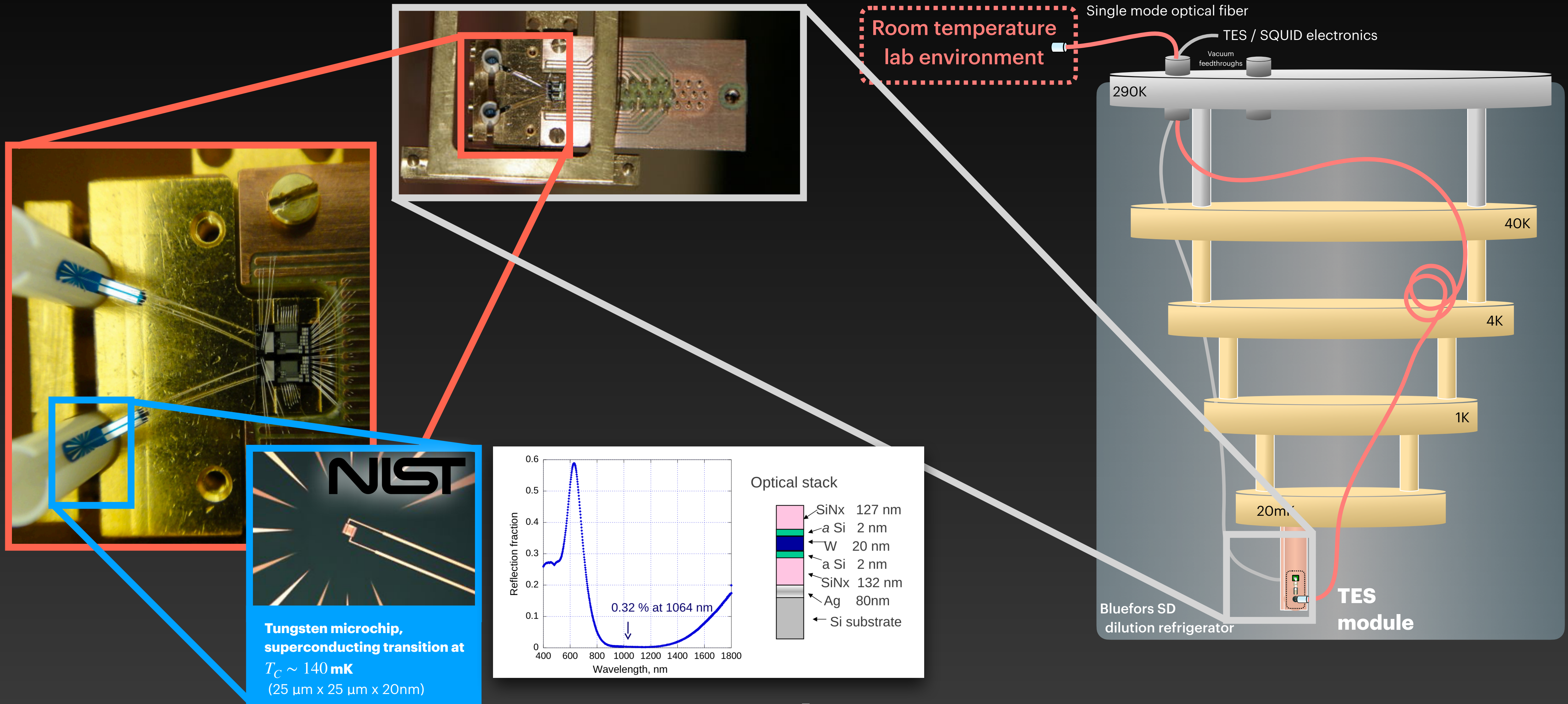
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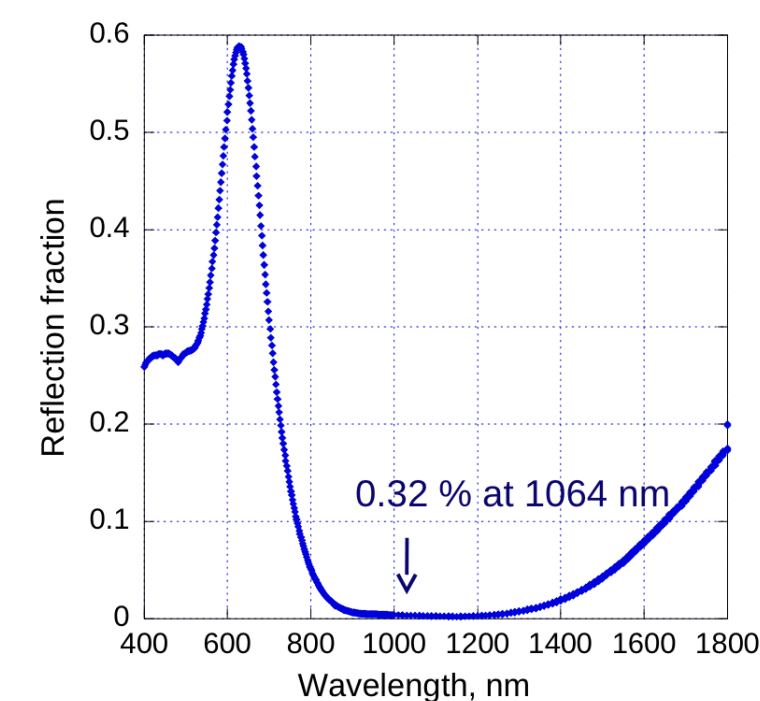
20m

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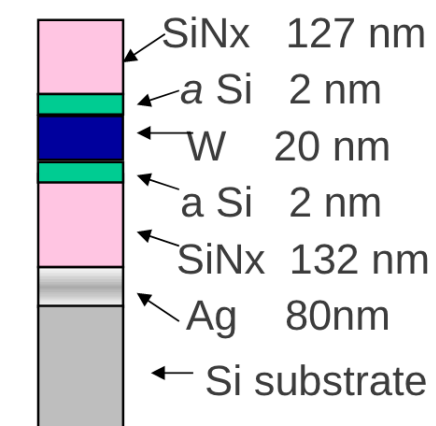
TES
module



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



Optical stack



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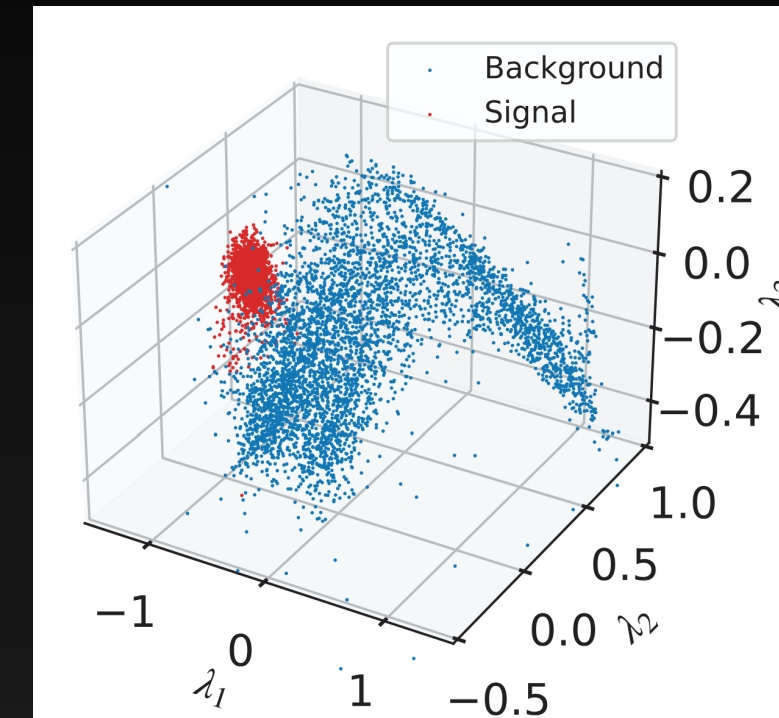
Shah et al., JLTP 209 (2022), 3-4

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MM et al. Annalen Phys. 536 (2024) 1, 2200545



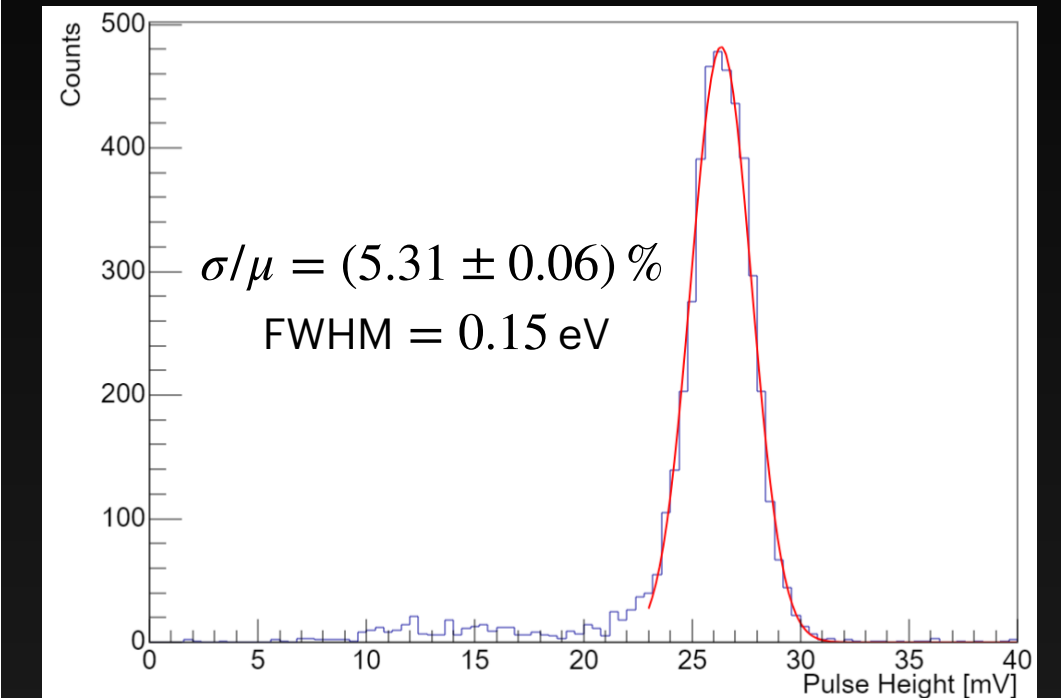
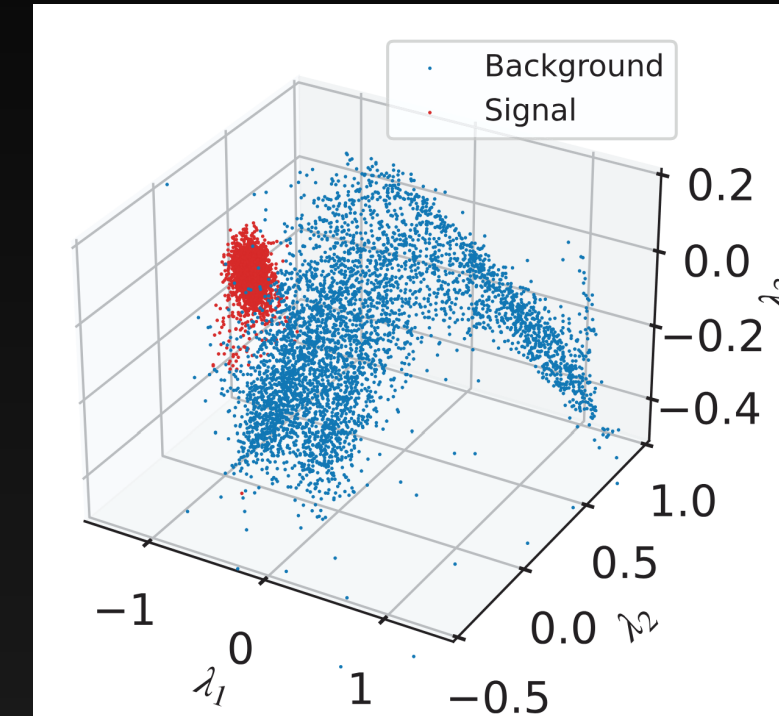
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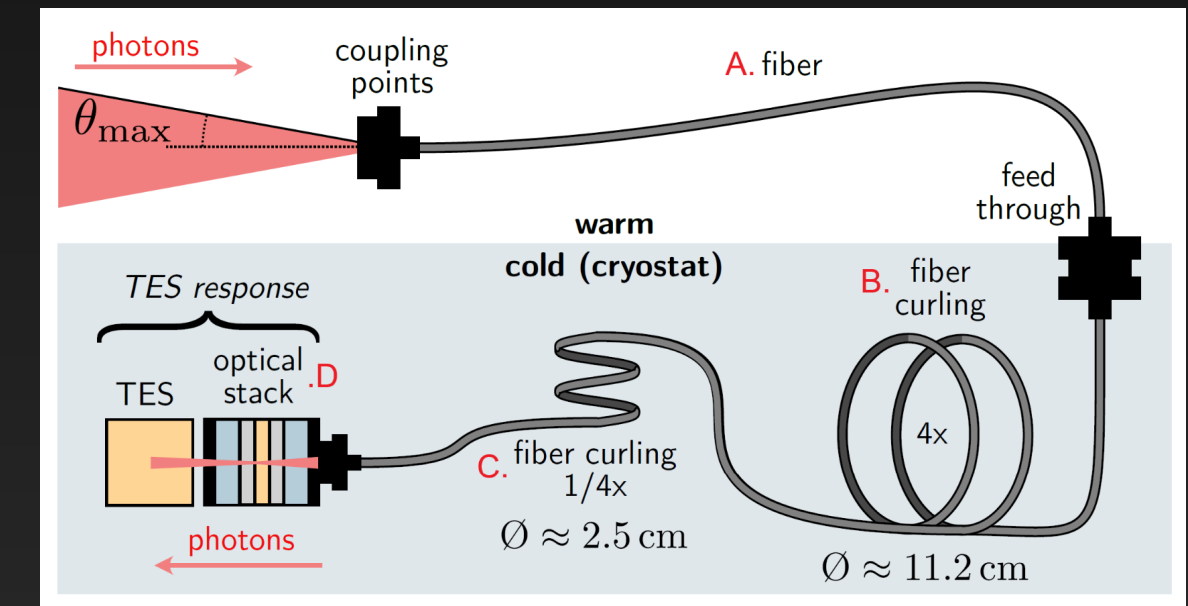
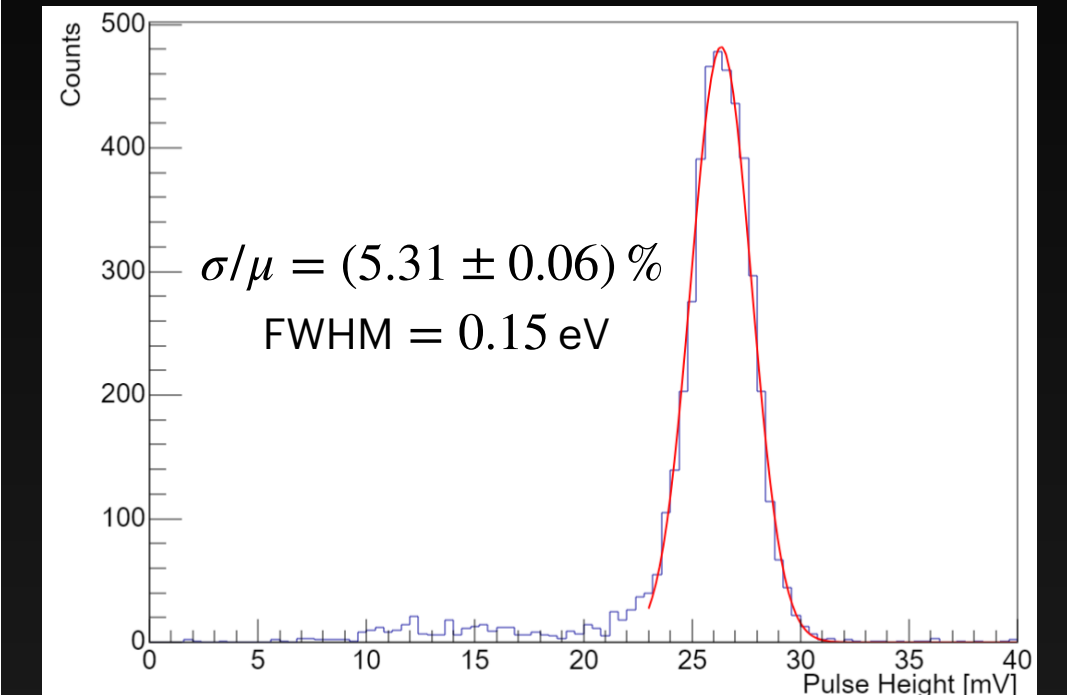
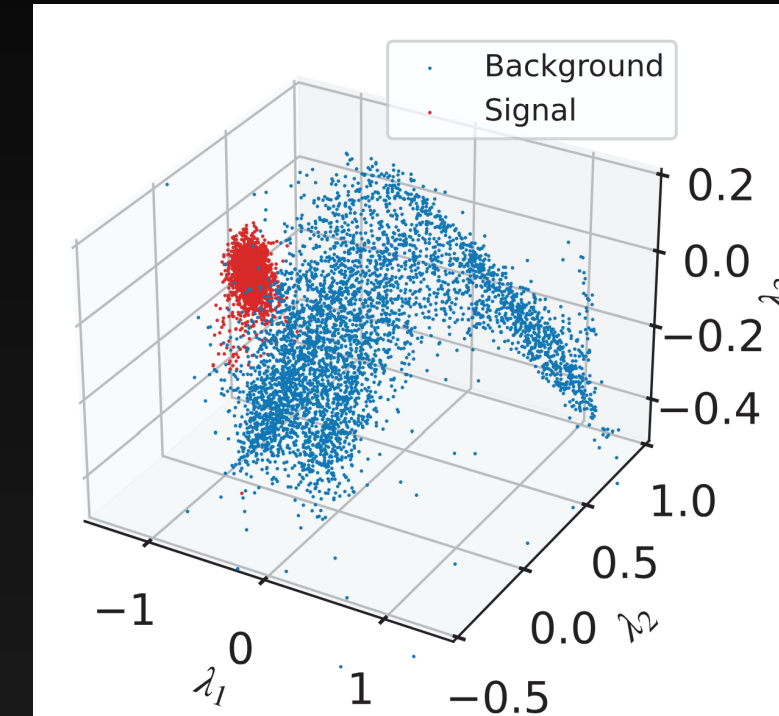
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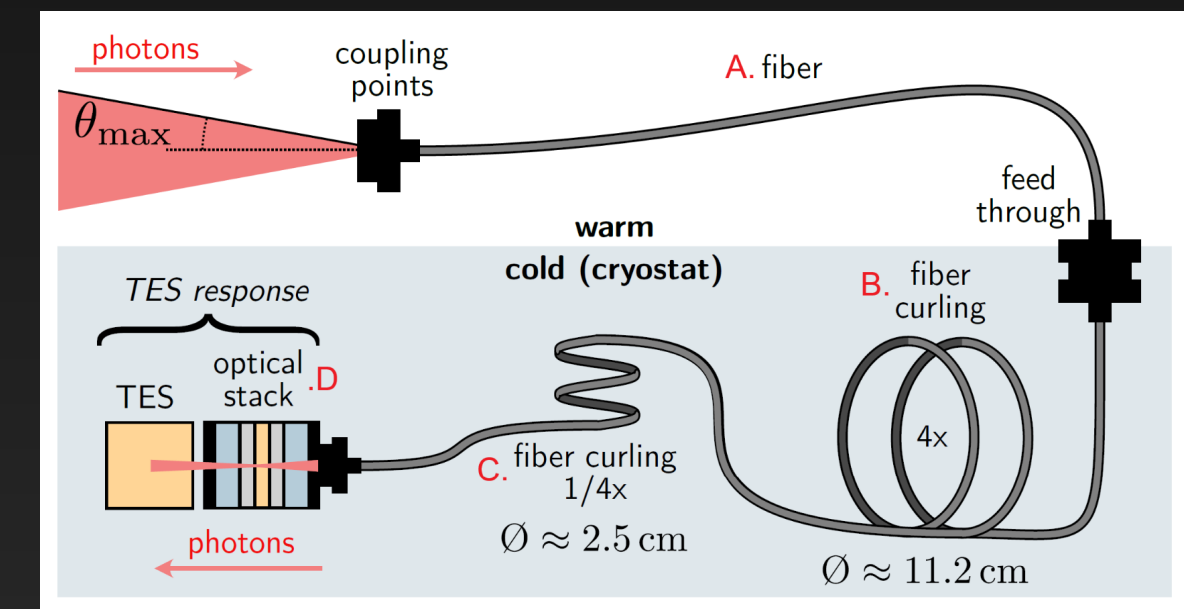
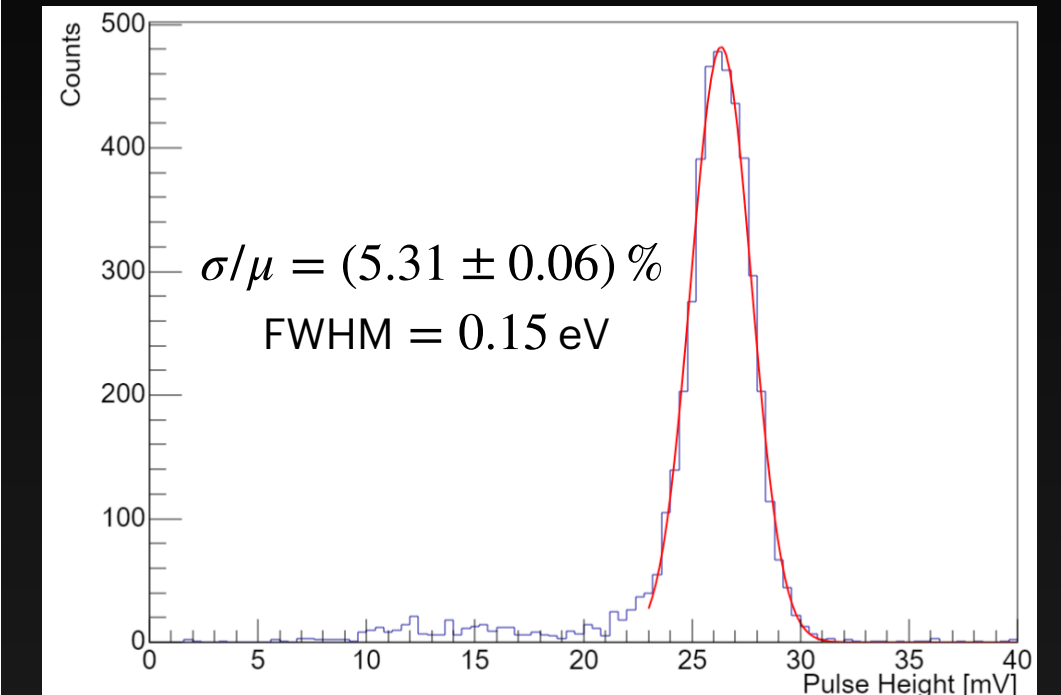
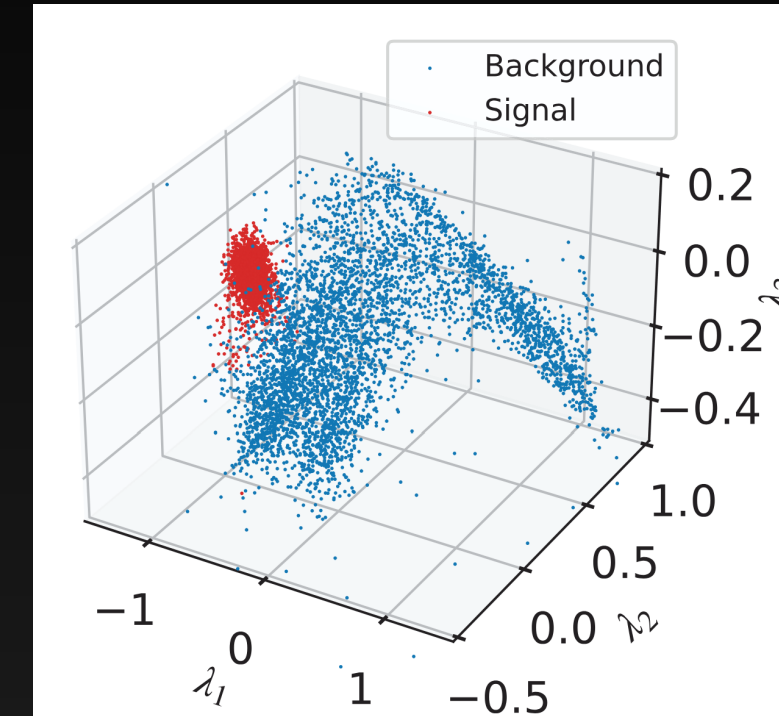
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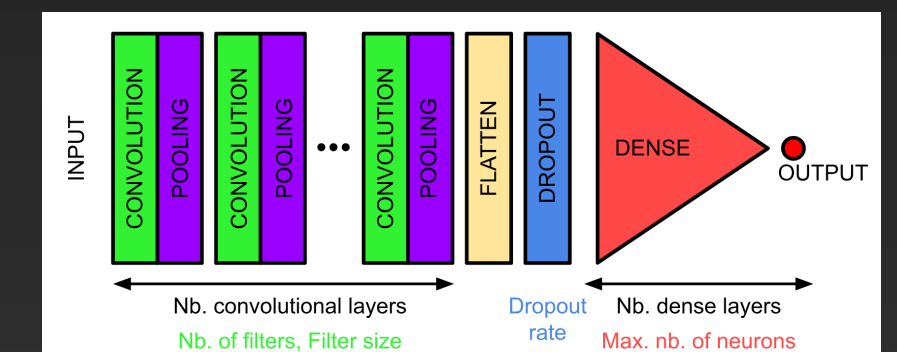
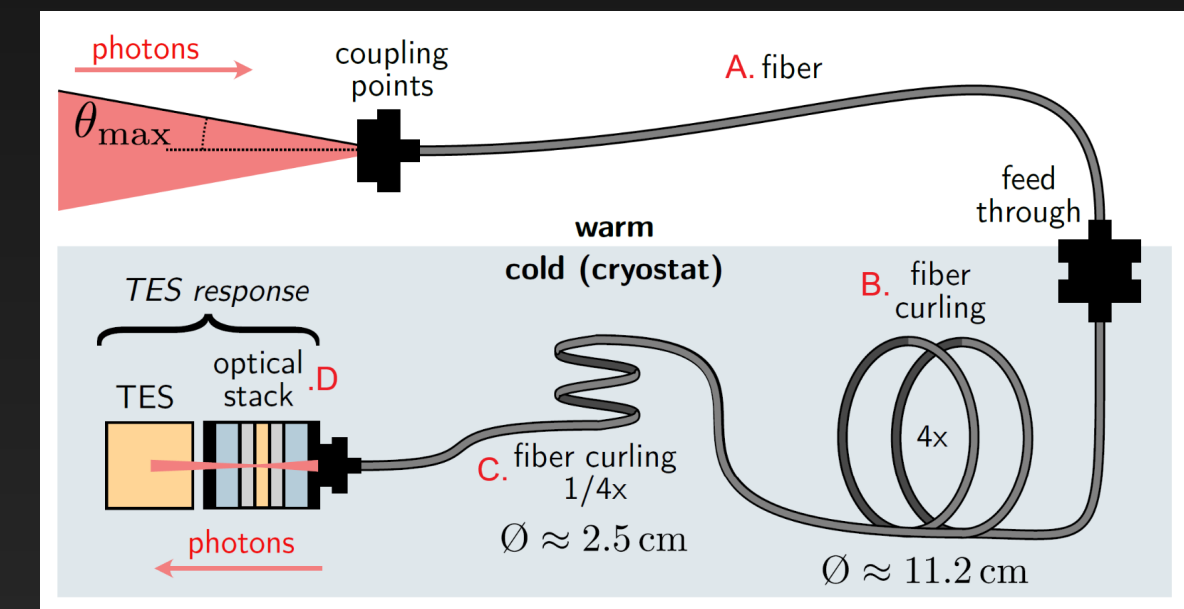
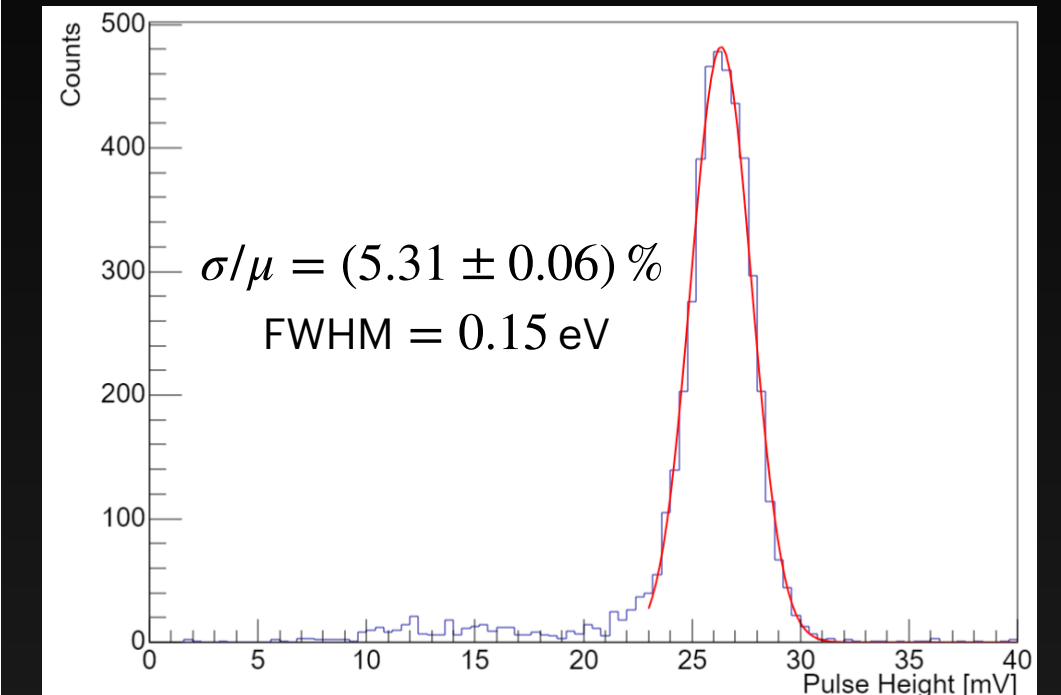
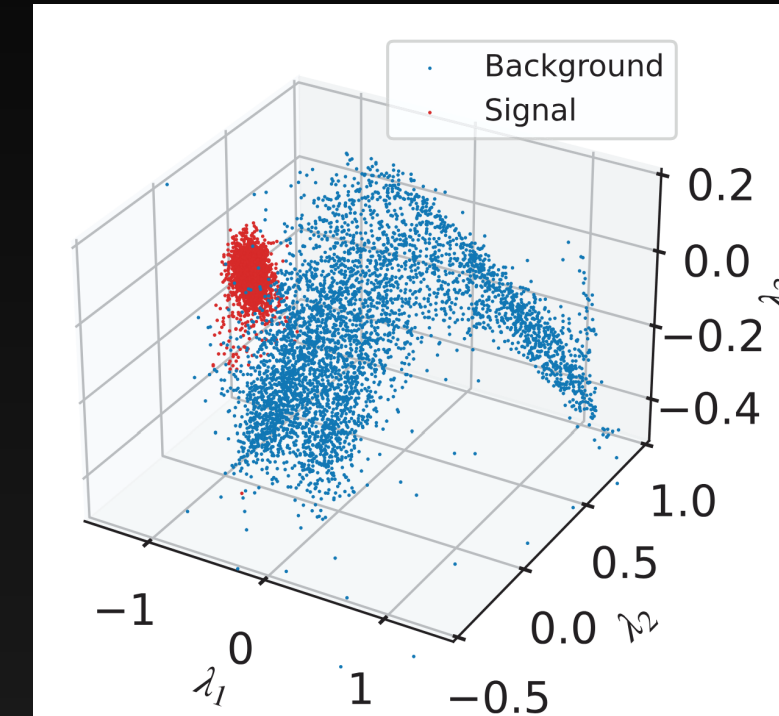
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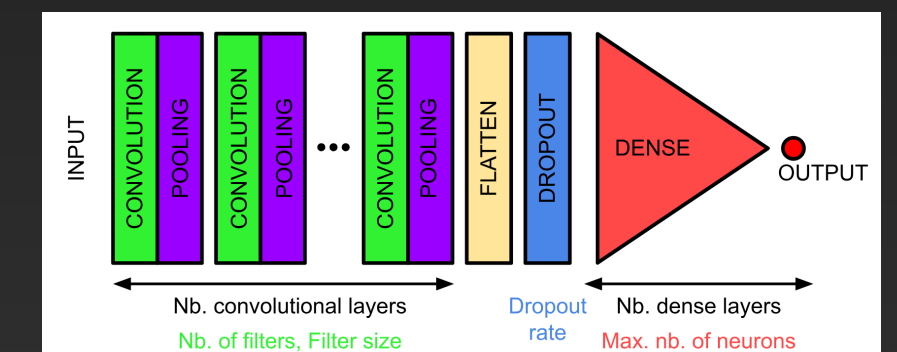
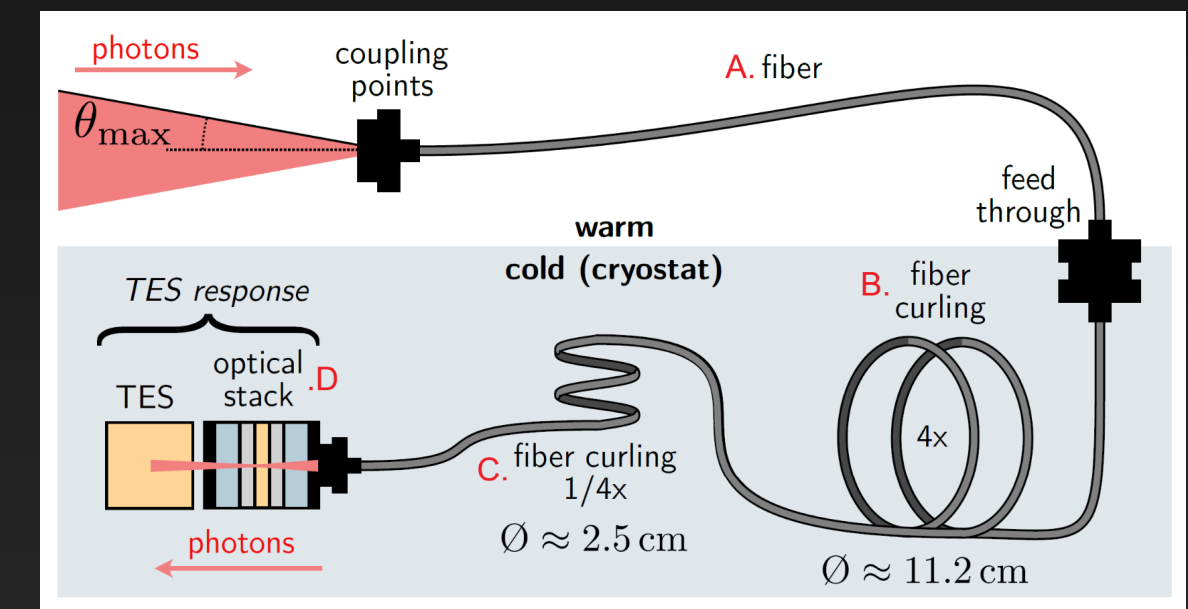
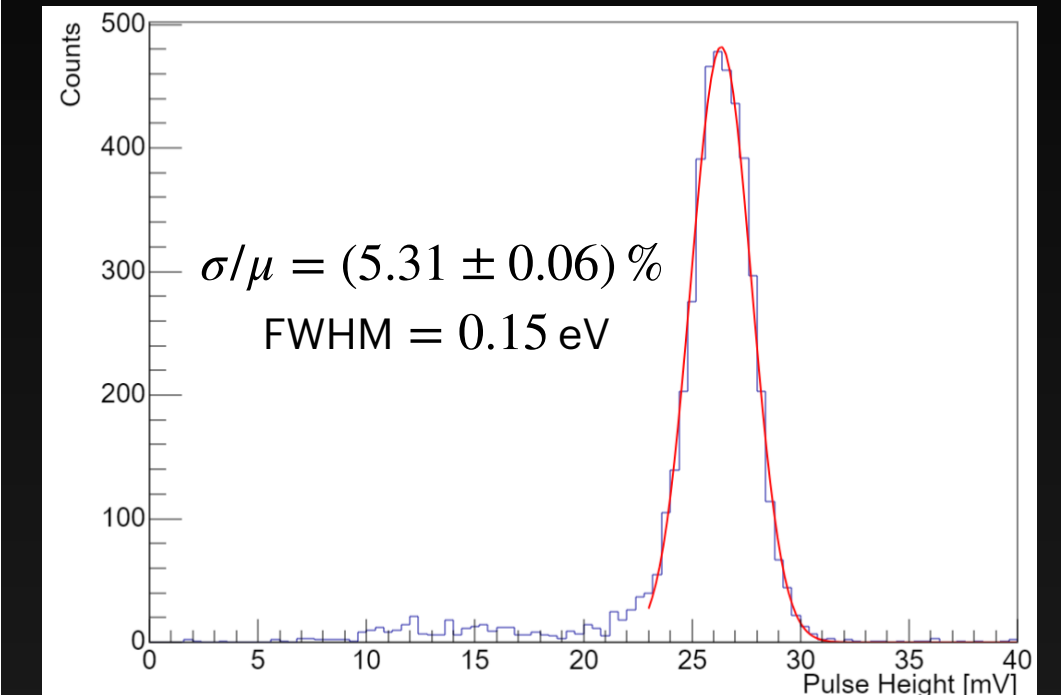
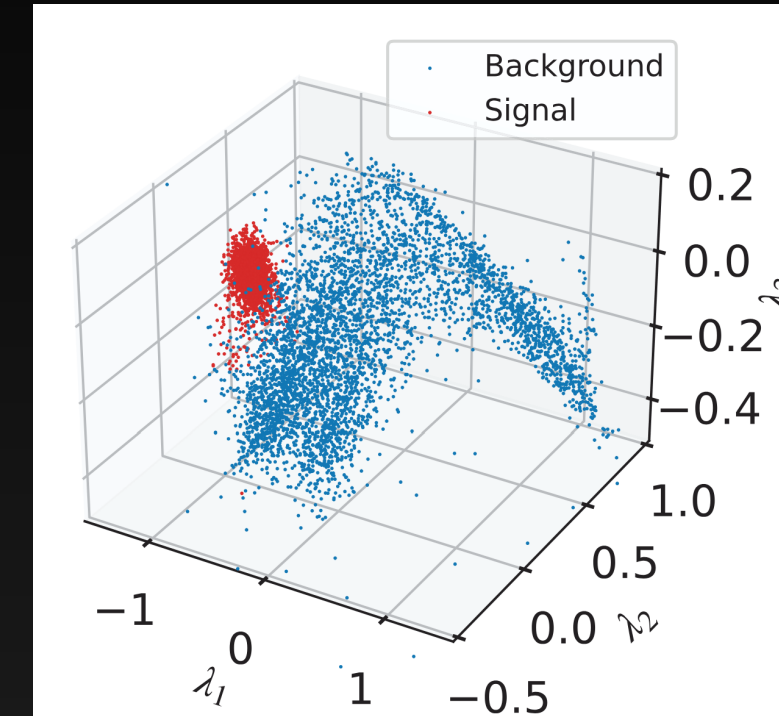
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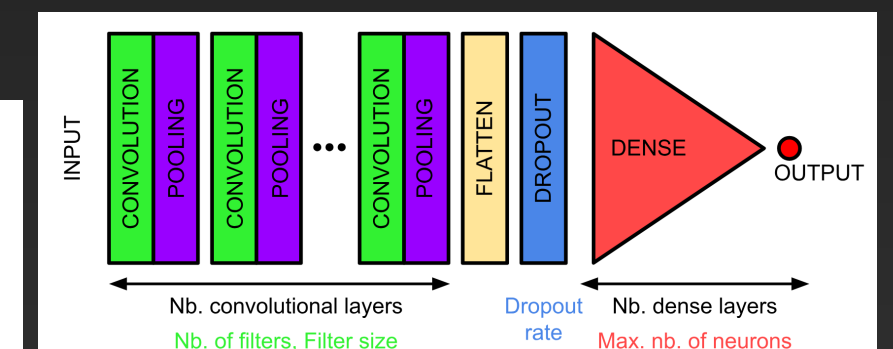
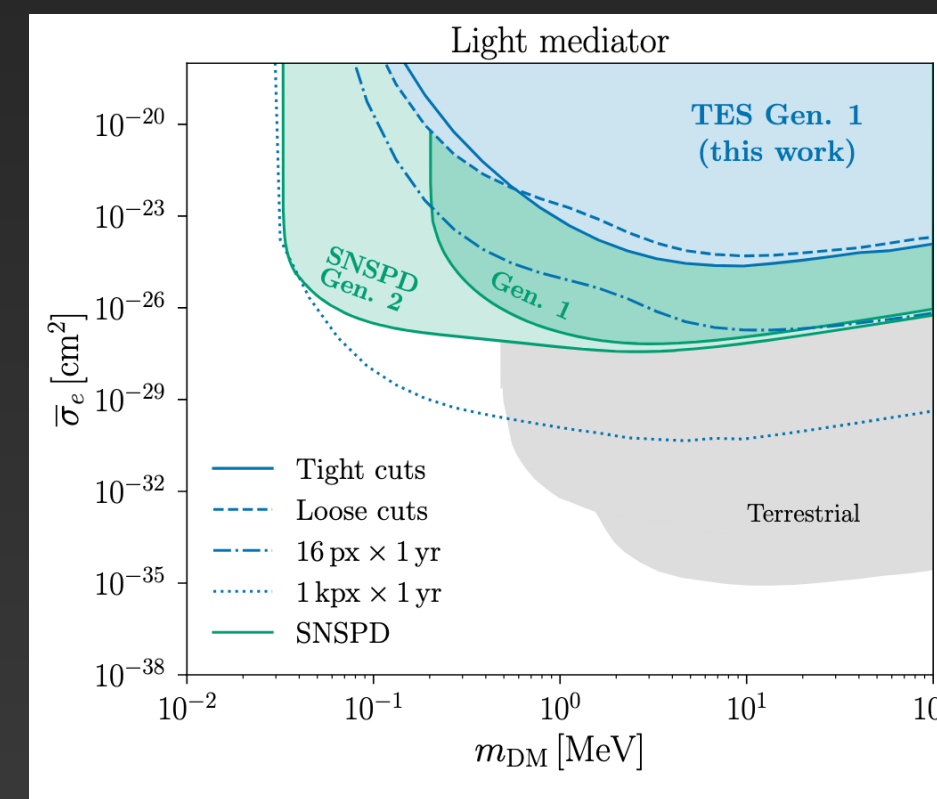
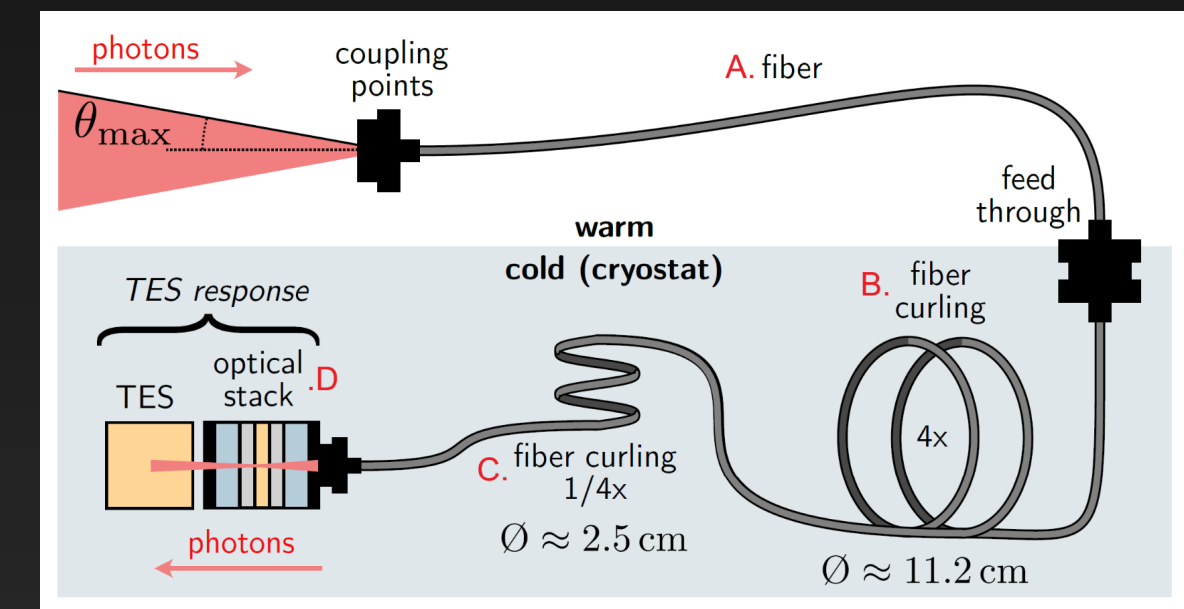
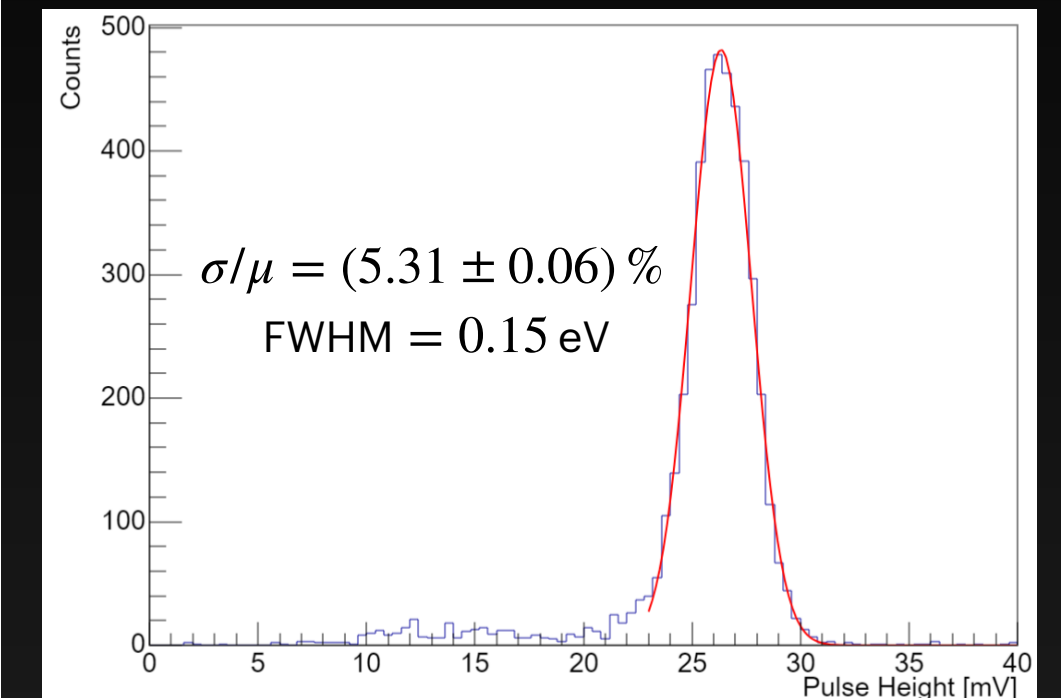
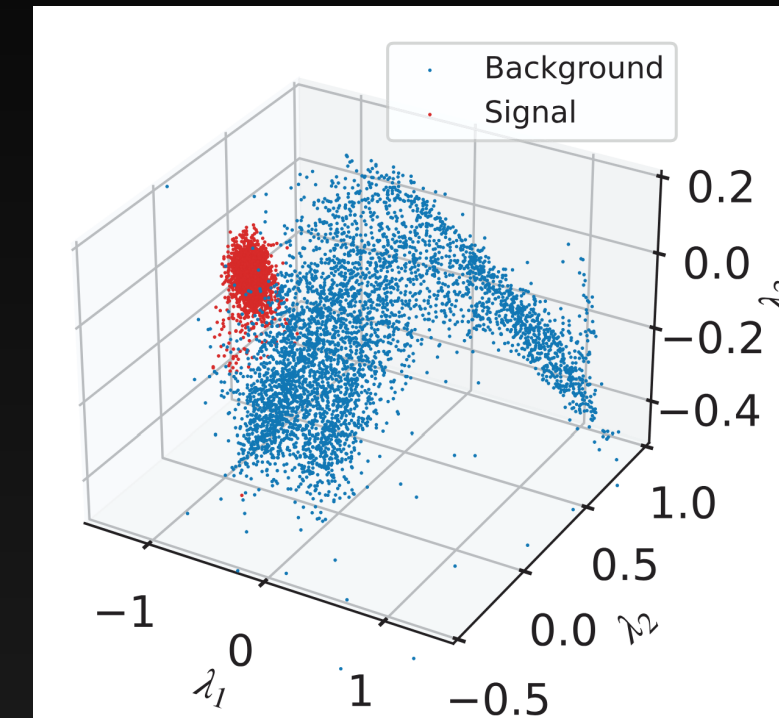
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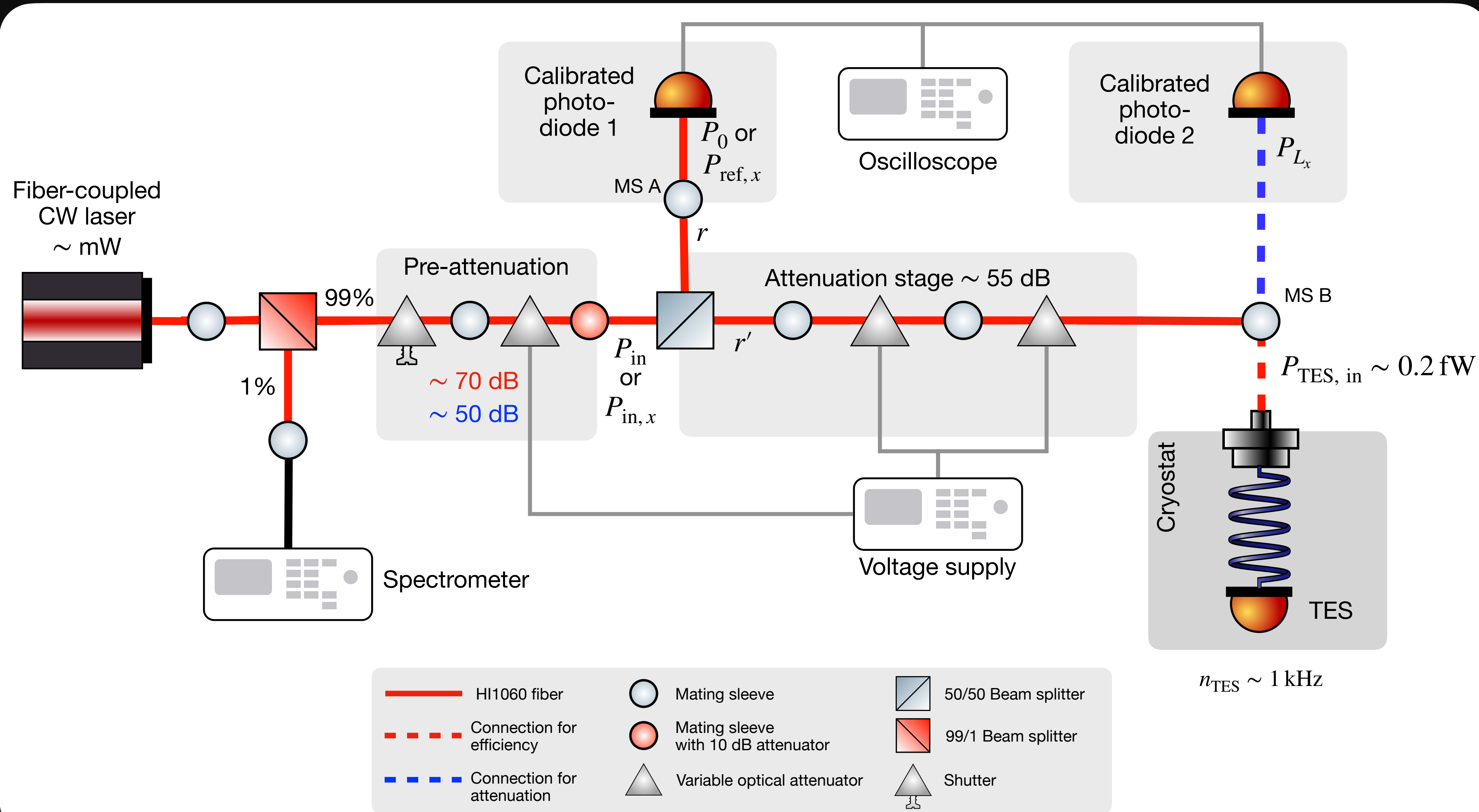
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- TES can also be used as target and detector for direct dark matter detection

Schwemmbauer et al., arxiv:2506.18982, accepted for publication in PRD (2026)



Determining the system detection efficiency



- SDE:

$$\eta = \frac{P_{\text{TES}}}{P_{\text{TES}, \text{in}}} = n_{\text{TES}} \frac{hc}{\lambda} \frac{1}{P_{\text{TES}, \text{in}}}$$
- Photon rate n_{TES} determined by counting photon pulses
- $P_{\text{TES}, \text{in}}$ determined from optical power at P_0 and calibrating attenuation stage
- Both channels show an SDE of $86\% \pm 1\%$**

Background spectrum

Preliminary results for TES1

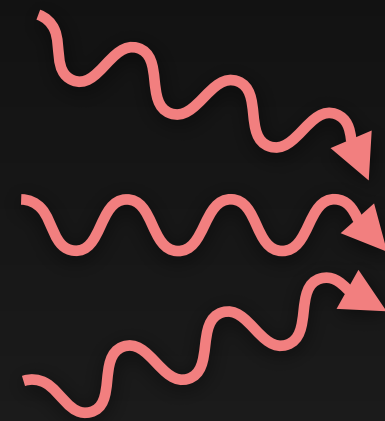
Background spectrum for TES1

Fitted with black body spectrum

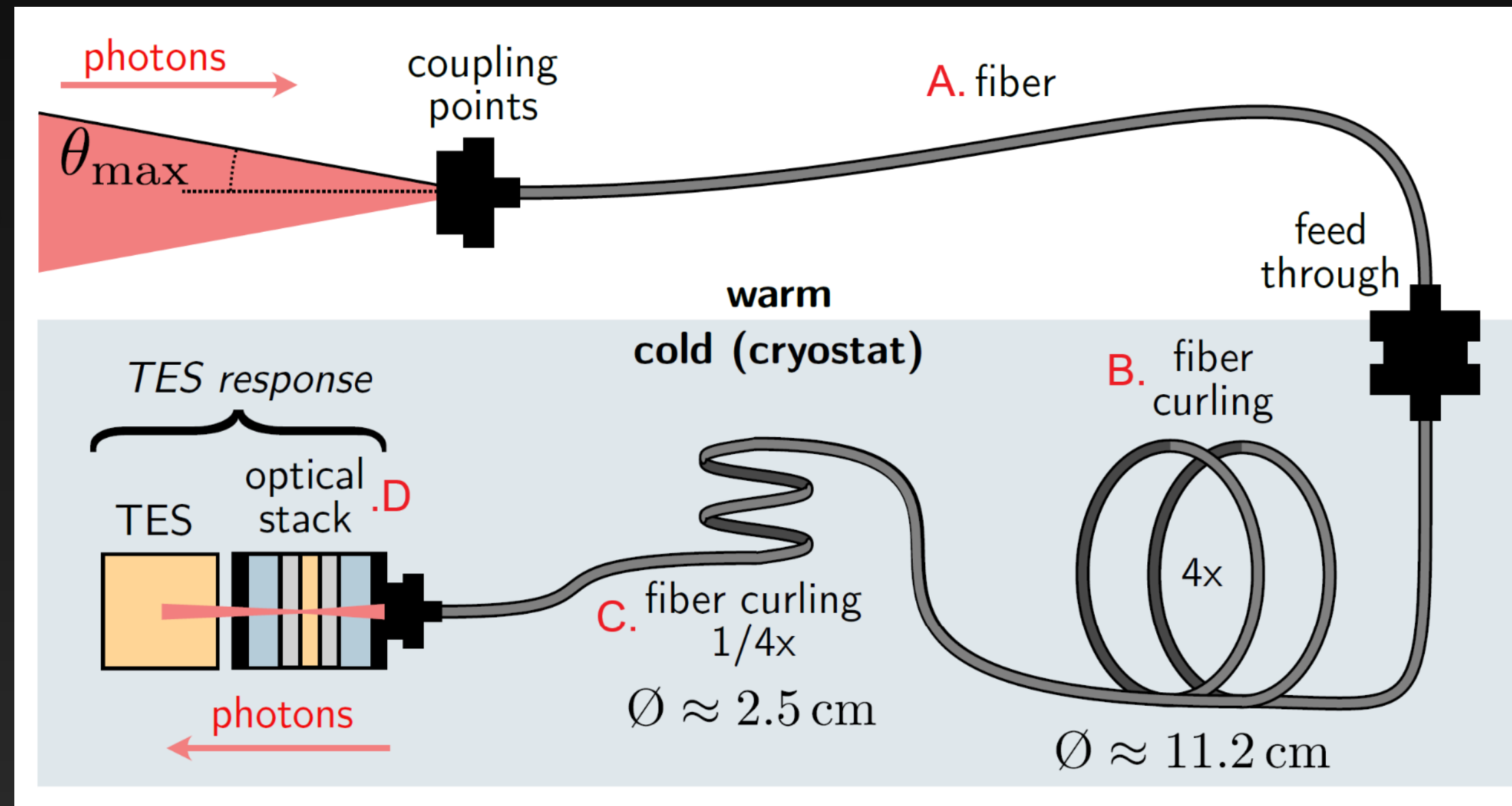
Black body spectrum

$T \sim 300$ K:

$$B(E', T) = \frac{2}{h^3 c^2} \frac{E'^2}{\exp\left(-\frac{E'}{k_B T}\right) - 1}$$



Rubiera Gimeno et al. PRD 112 (2025) 3, 032001



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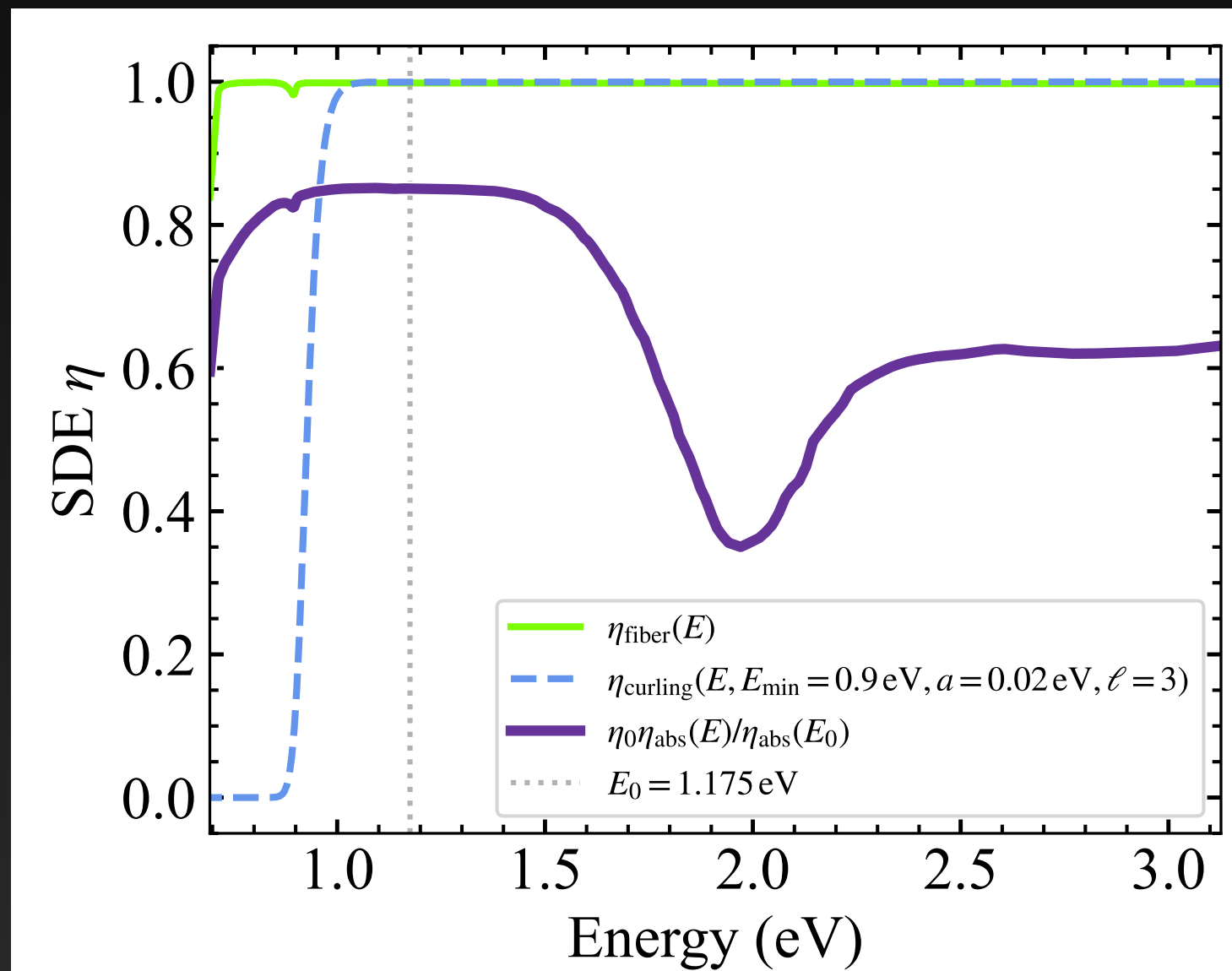
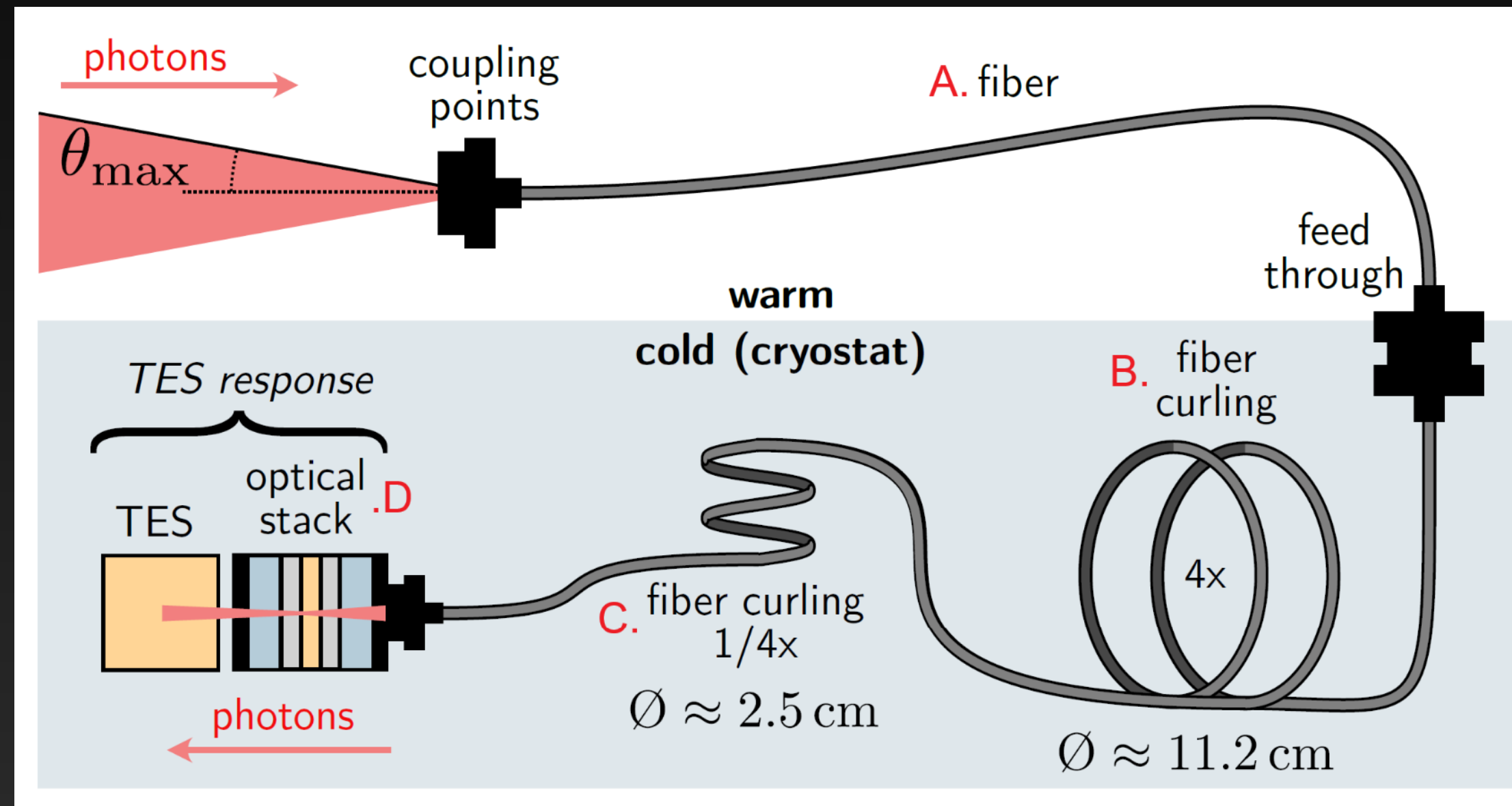
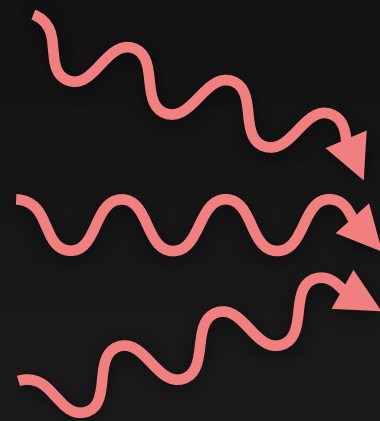
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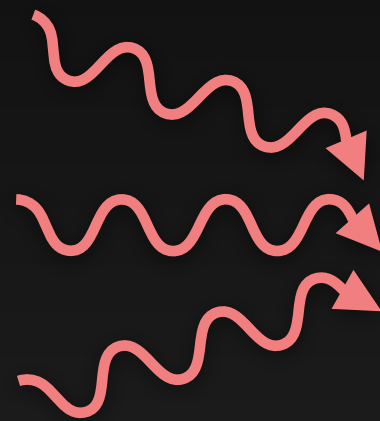
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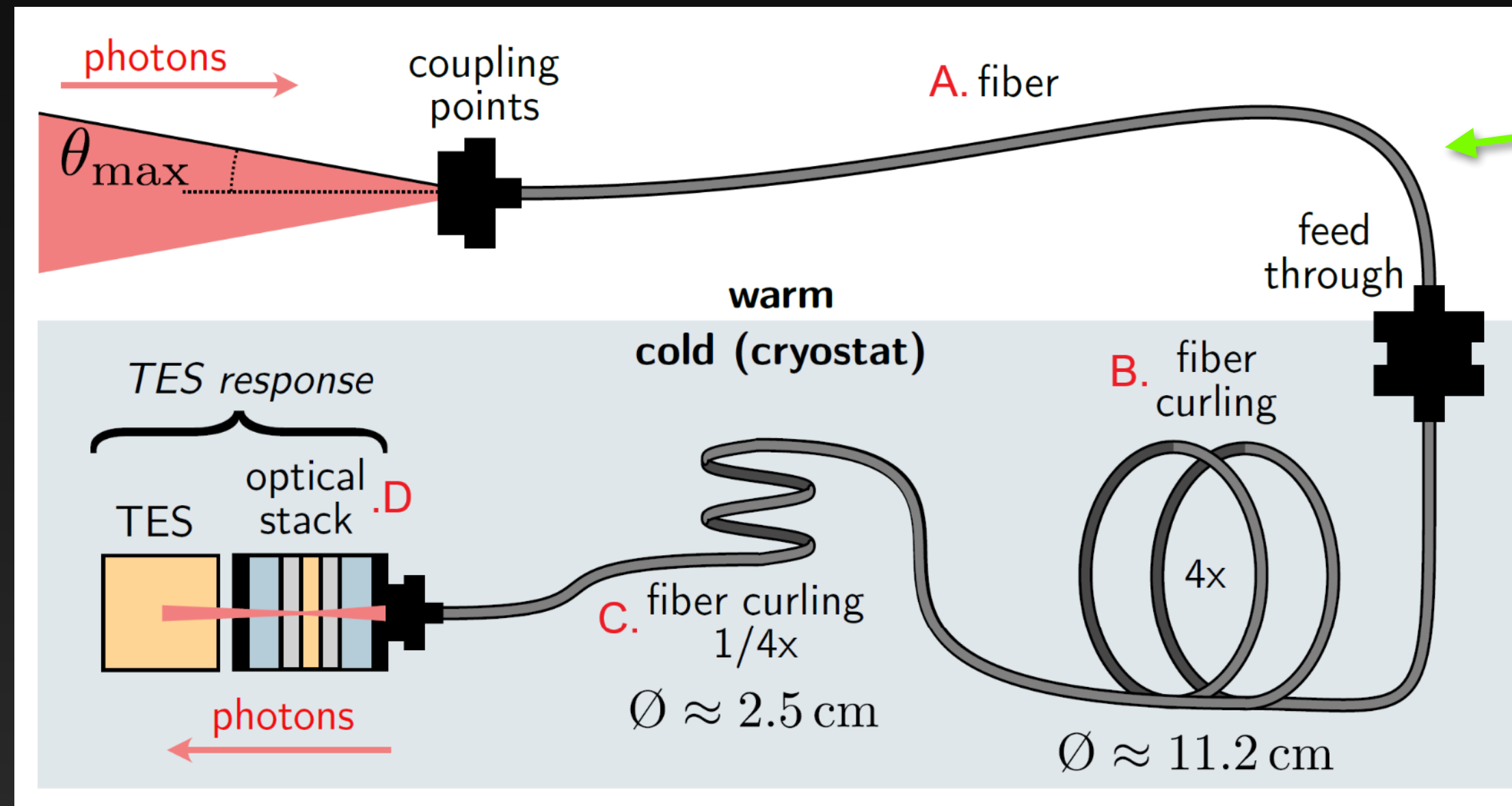
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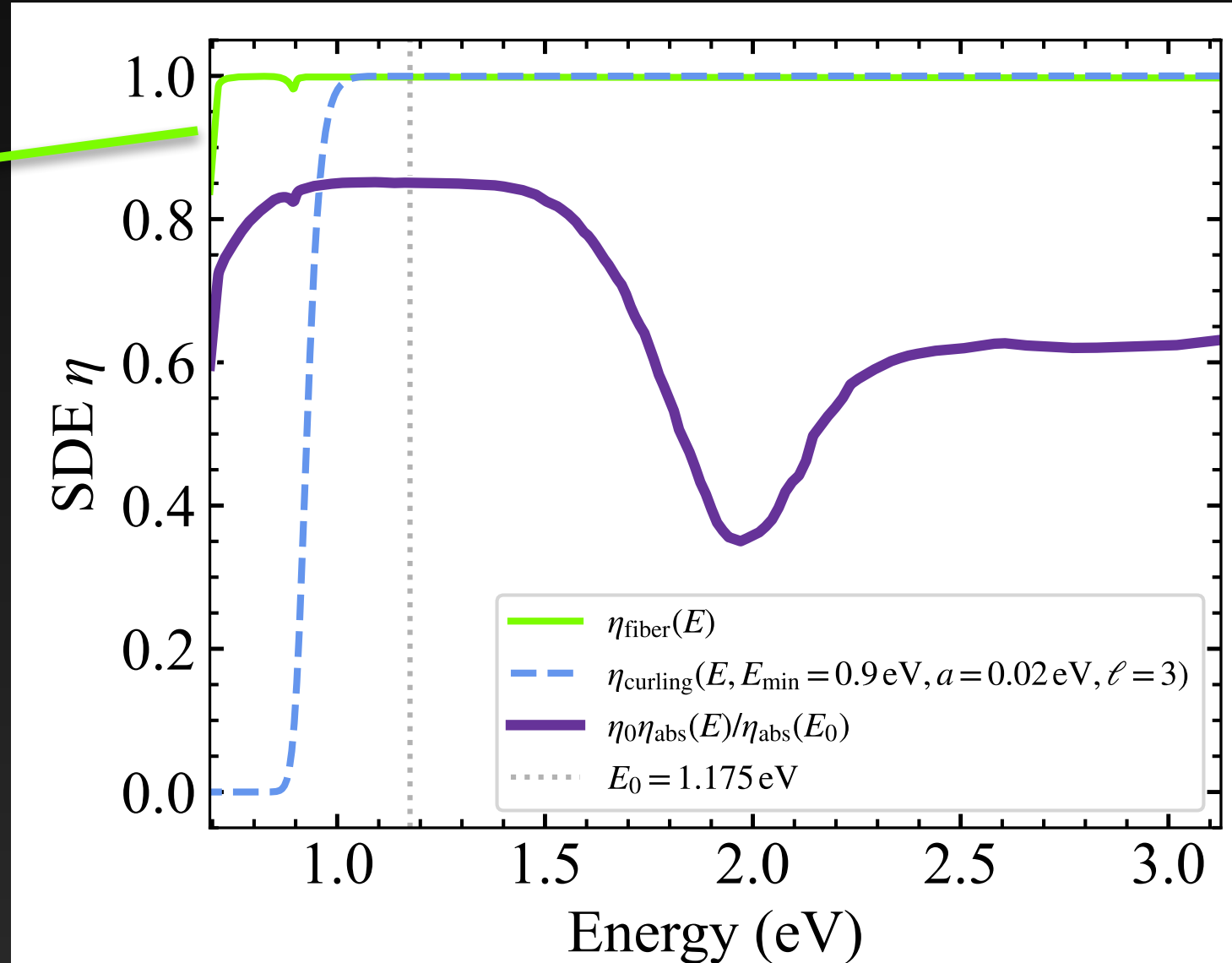
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Fiber transmission



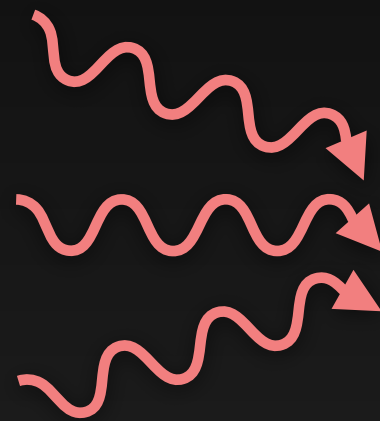
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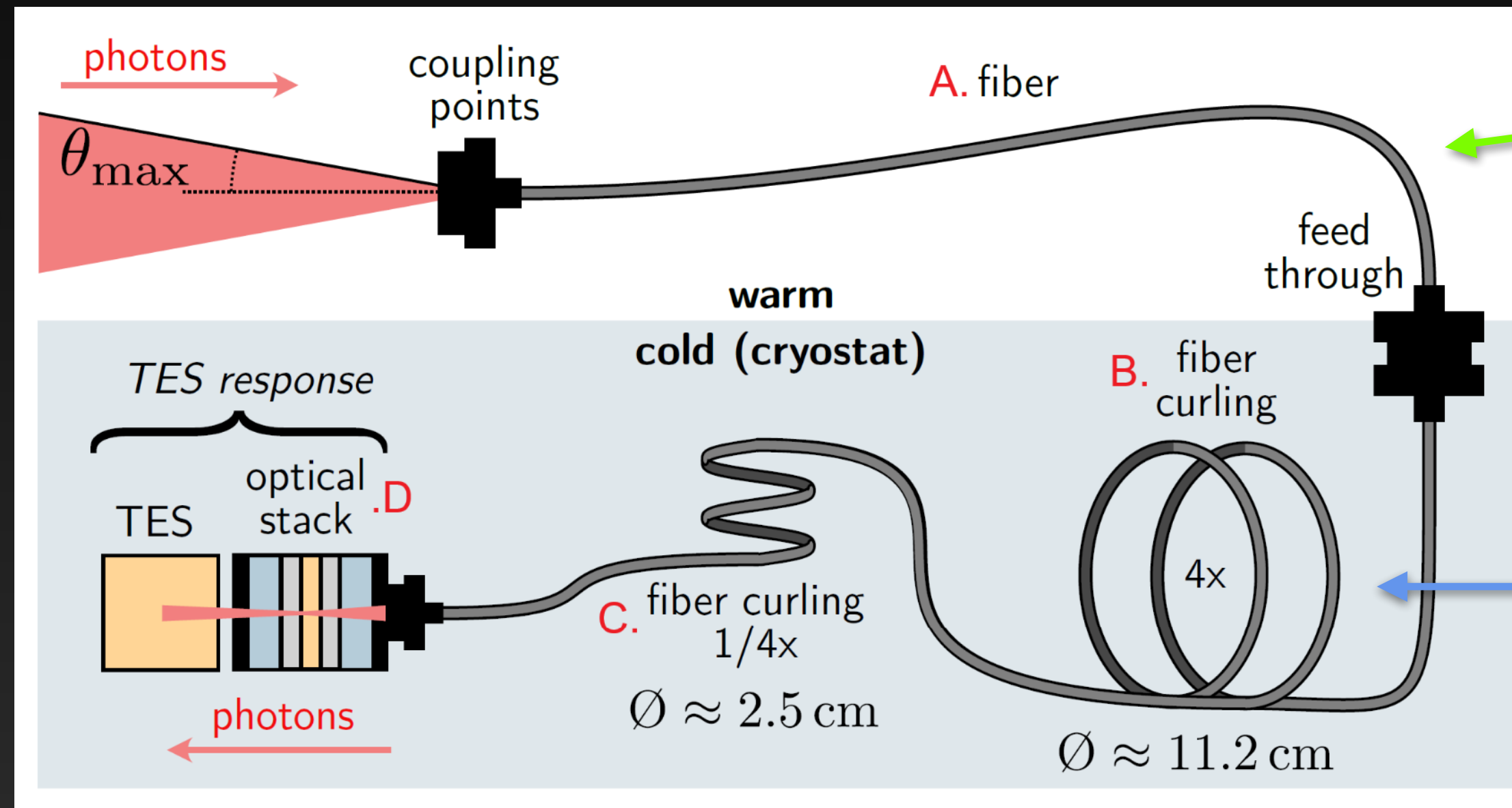
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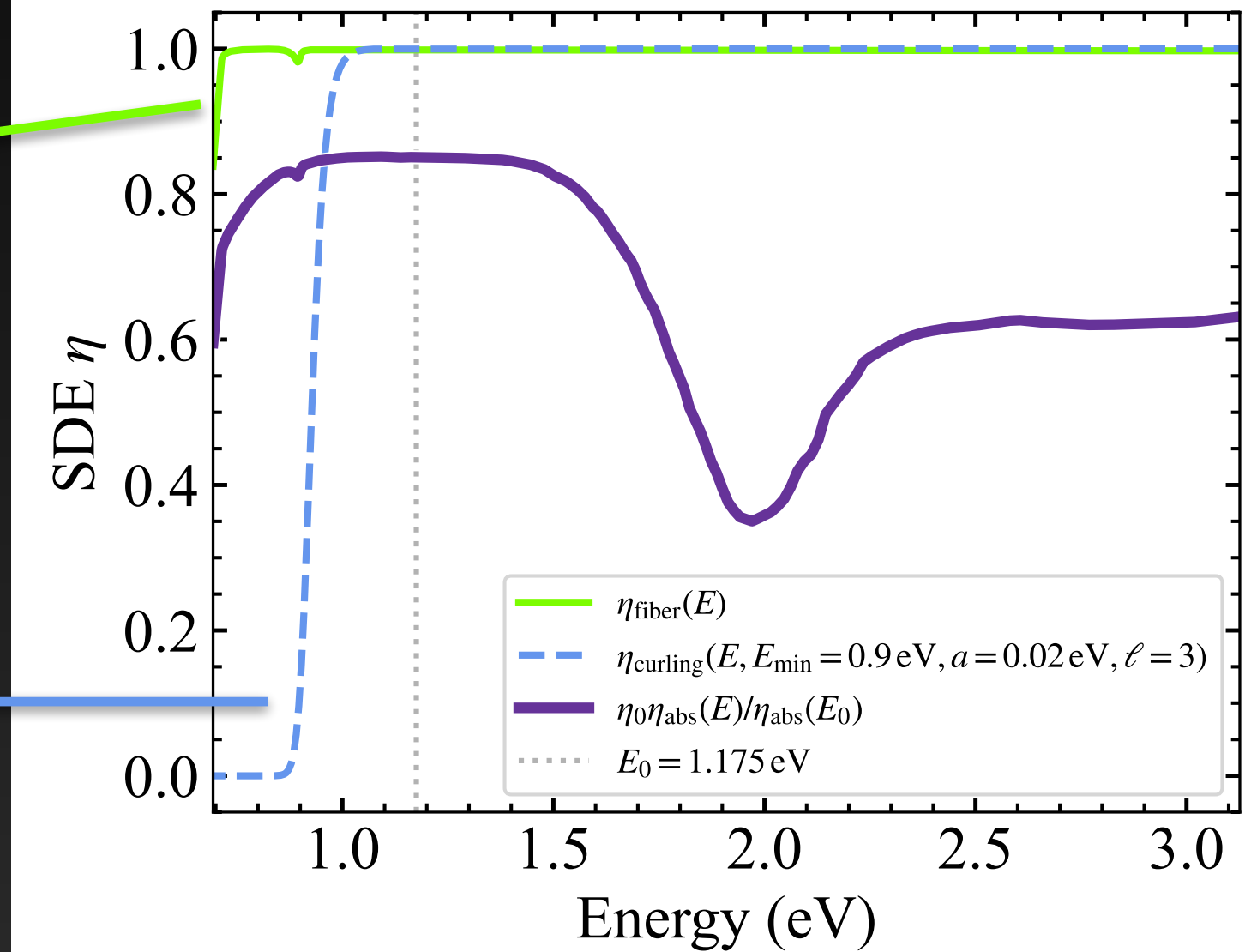
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Rubiera Gimeno et al. PRD 112 (2025) 3, 032001



Fiber transmission



Fiber curling

Background spectrum for TES1

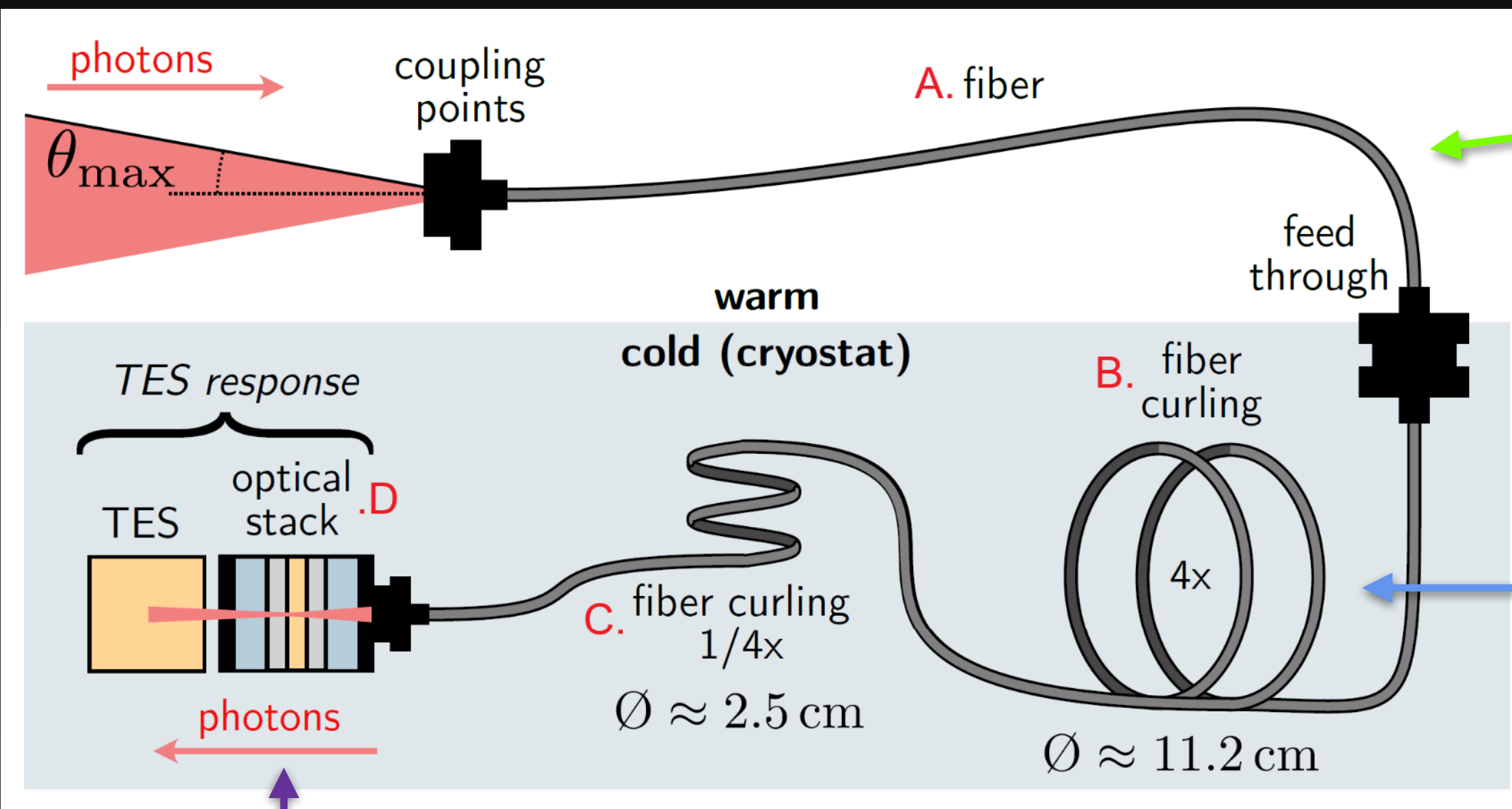
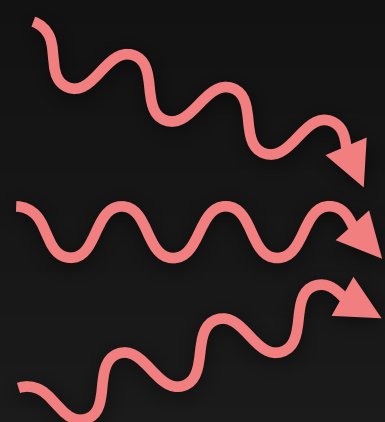
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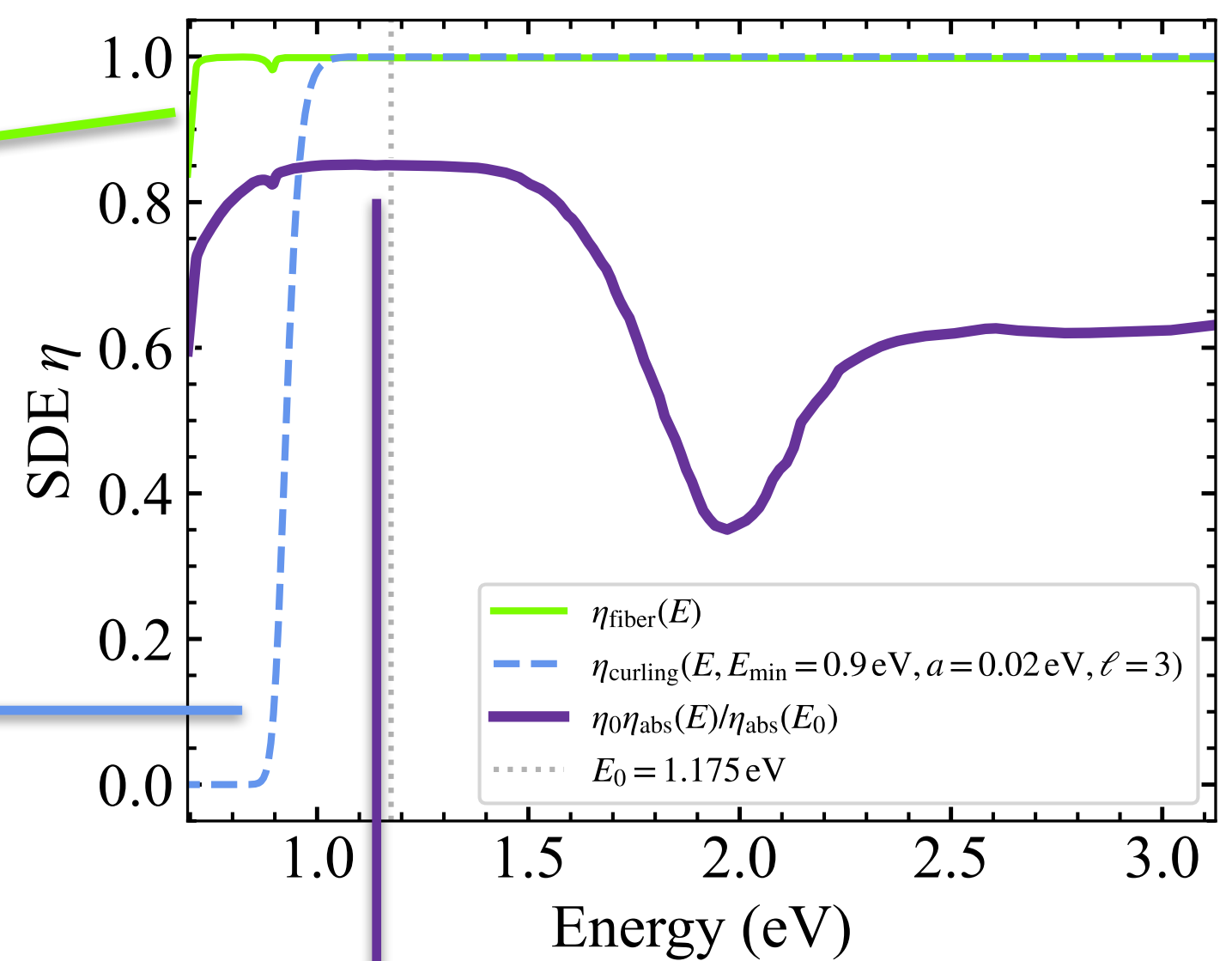
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Fiber transmission



Fiber curling

**Absorption in optical
stack scaled with
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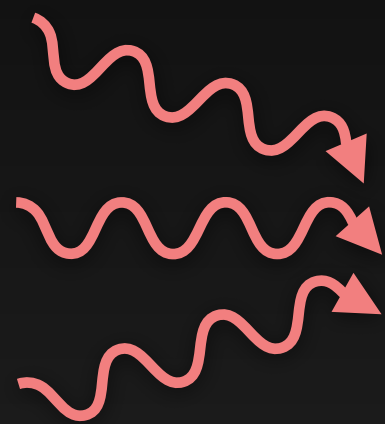
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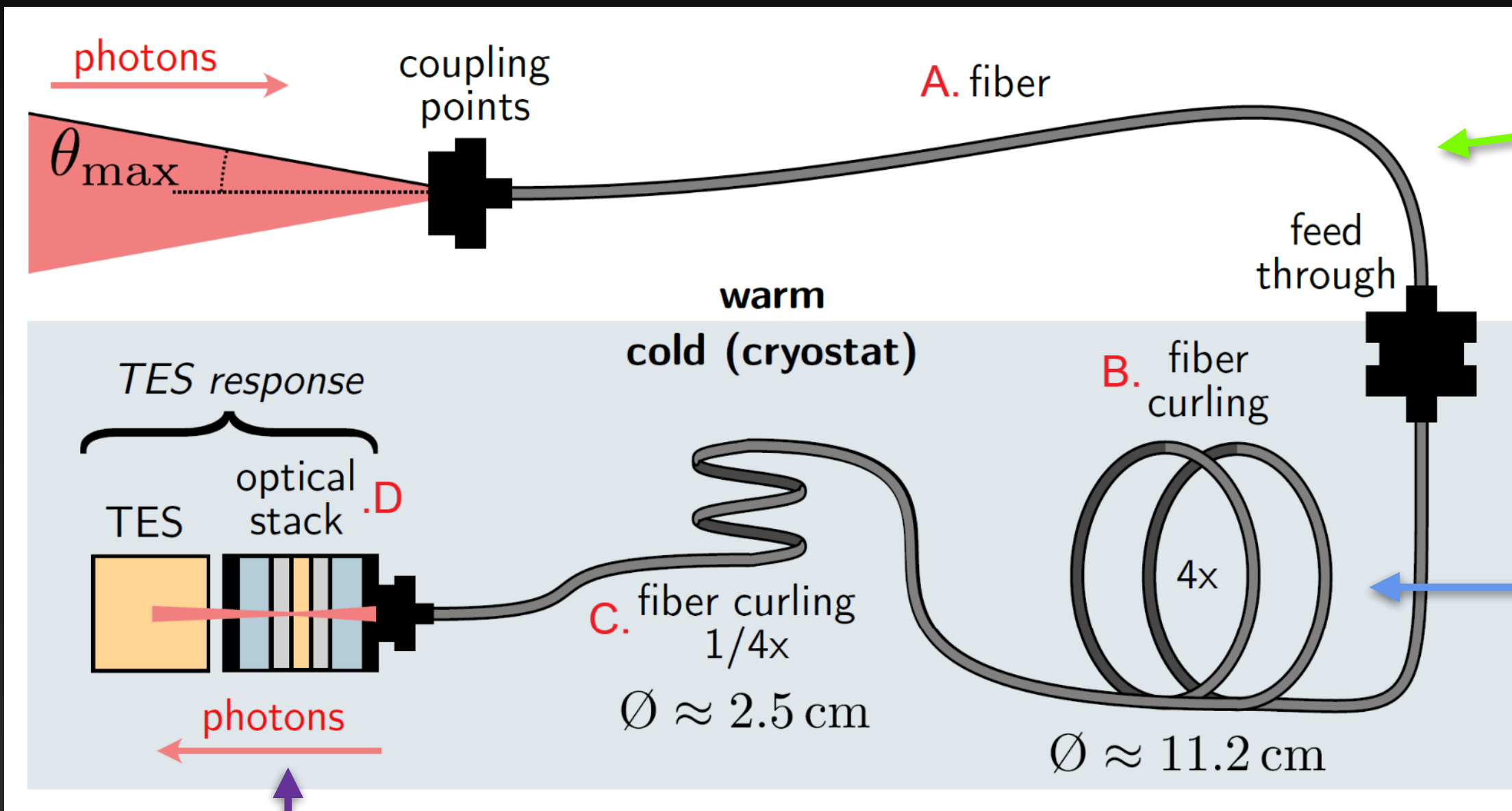
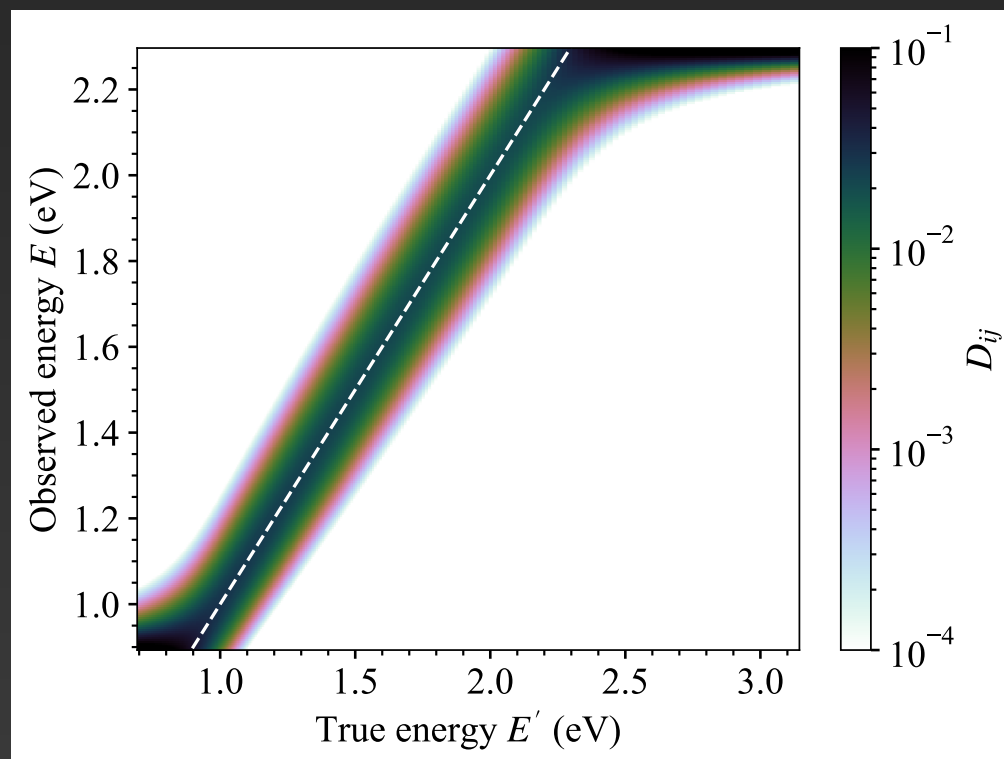
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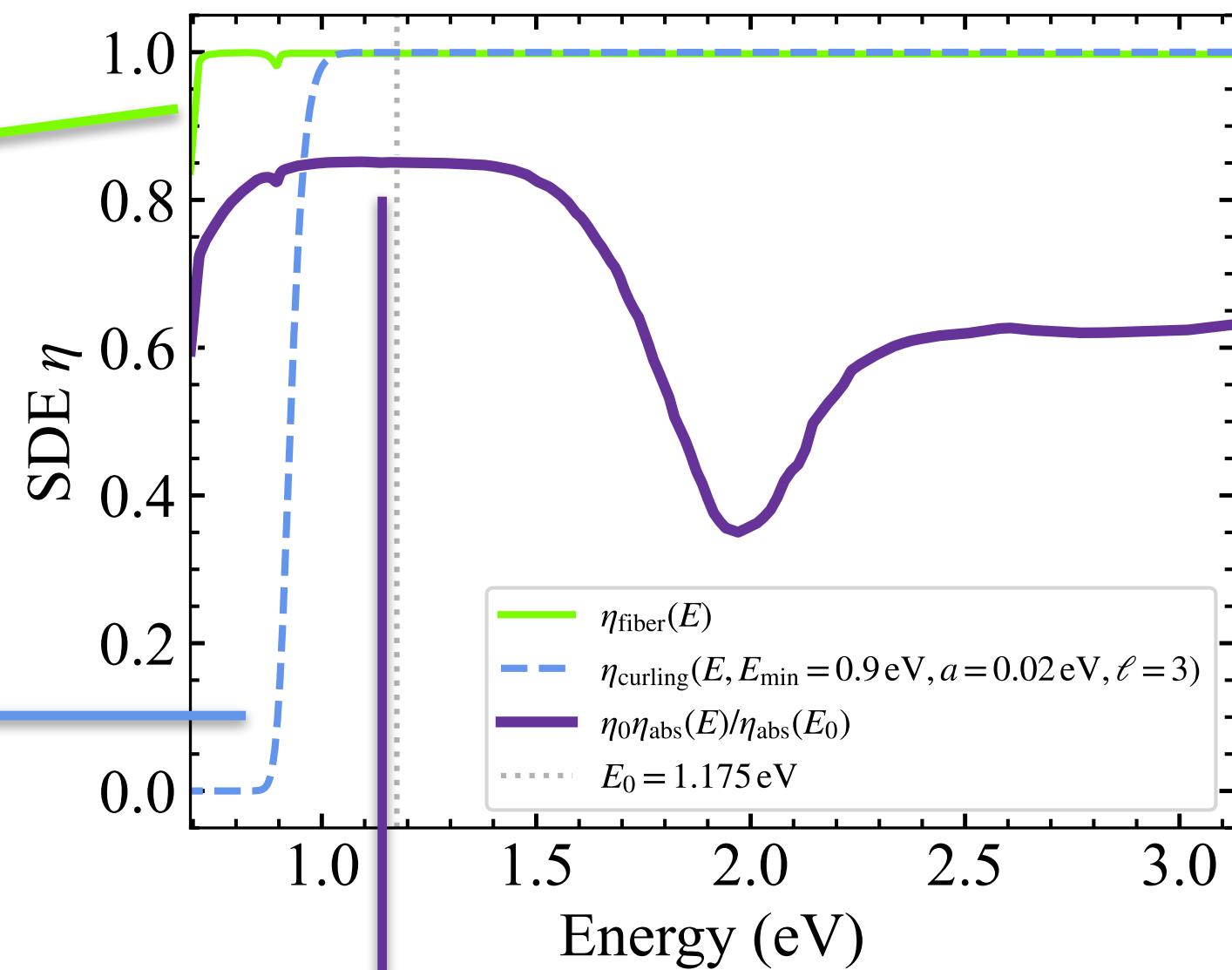
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Energy dispersion



Fiber transmission

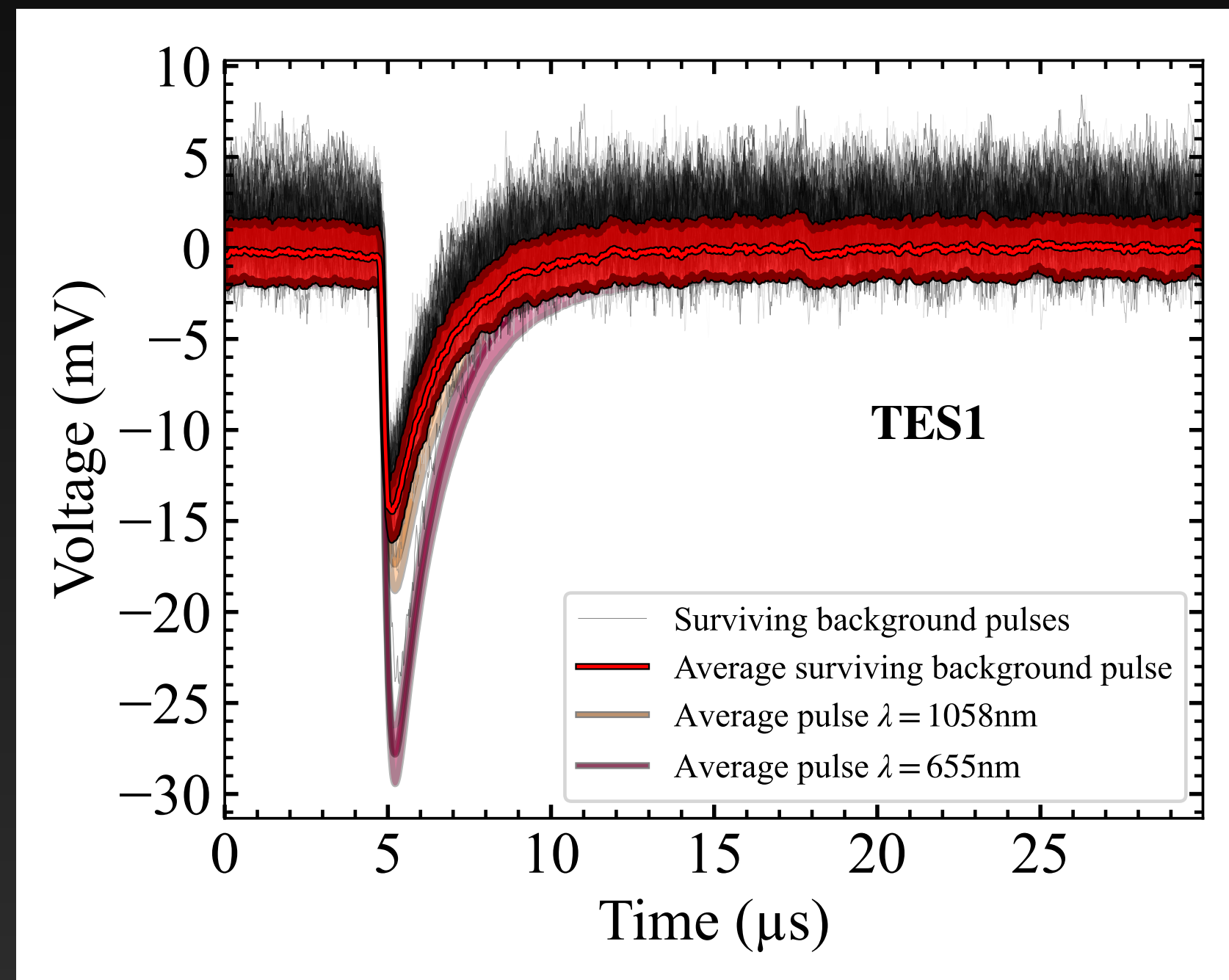


Fiber curling

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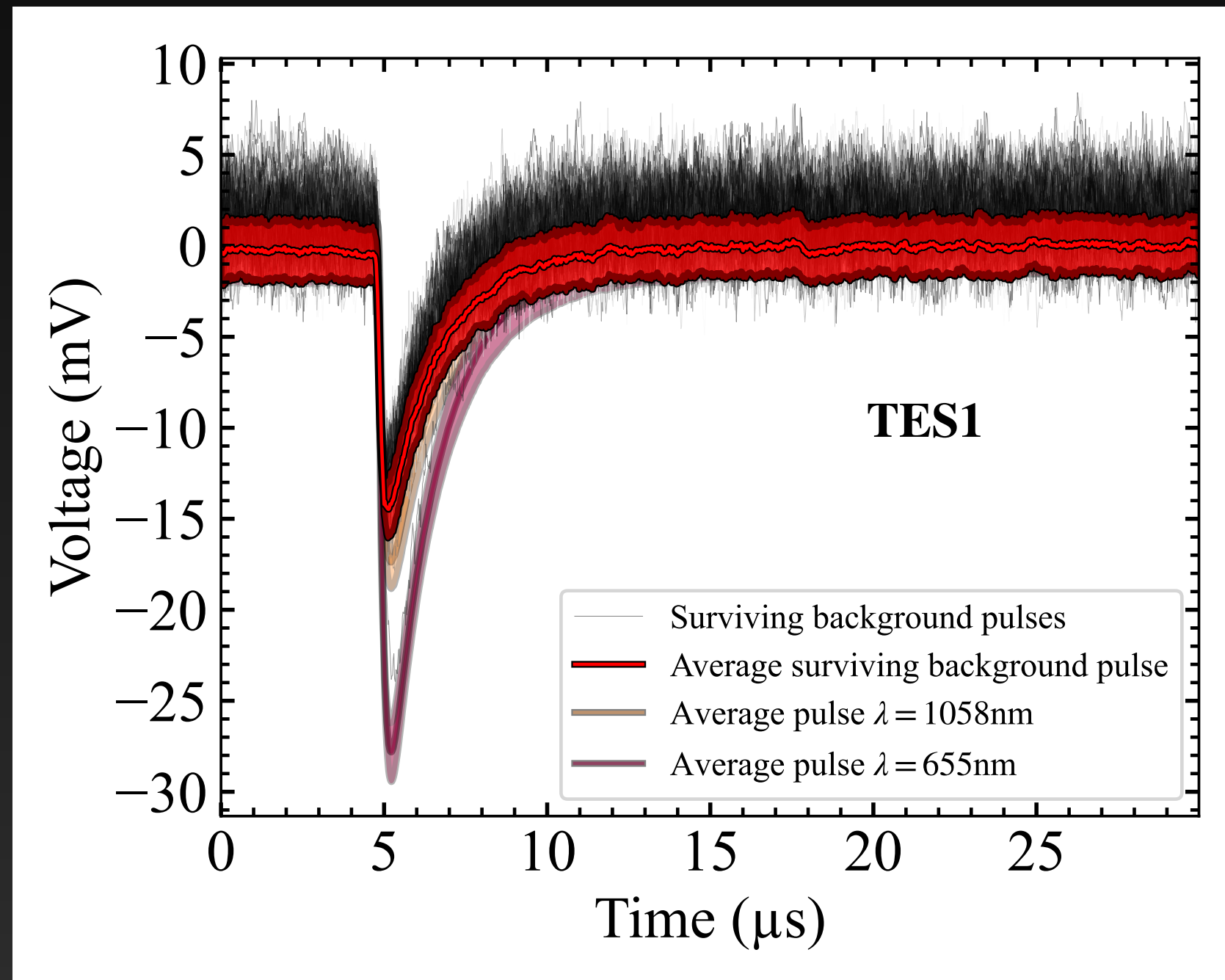
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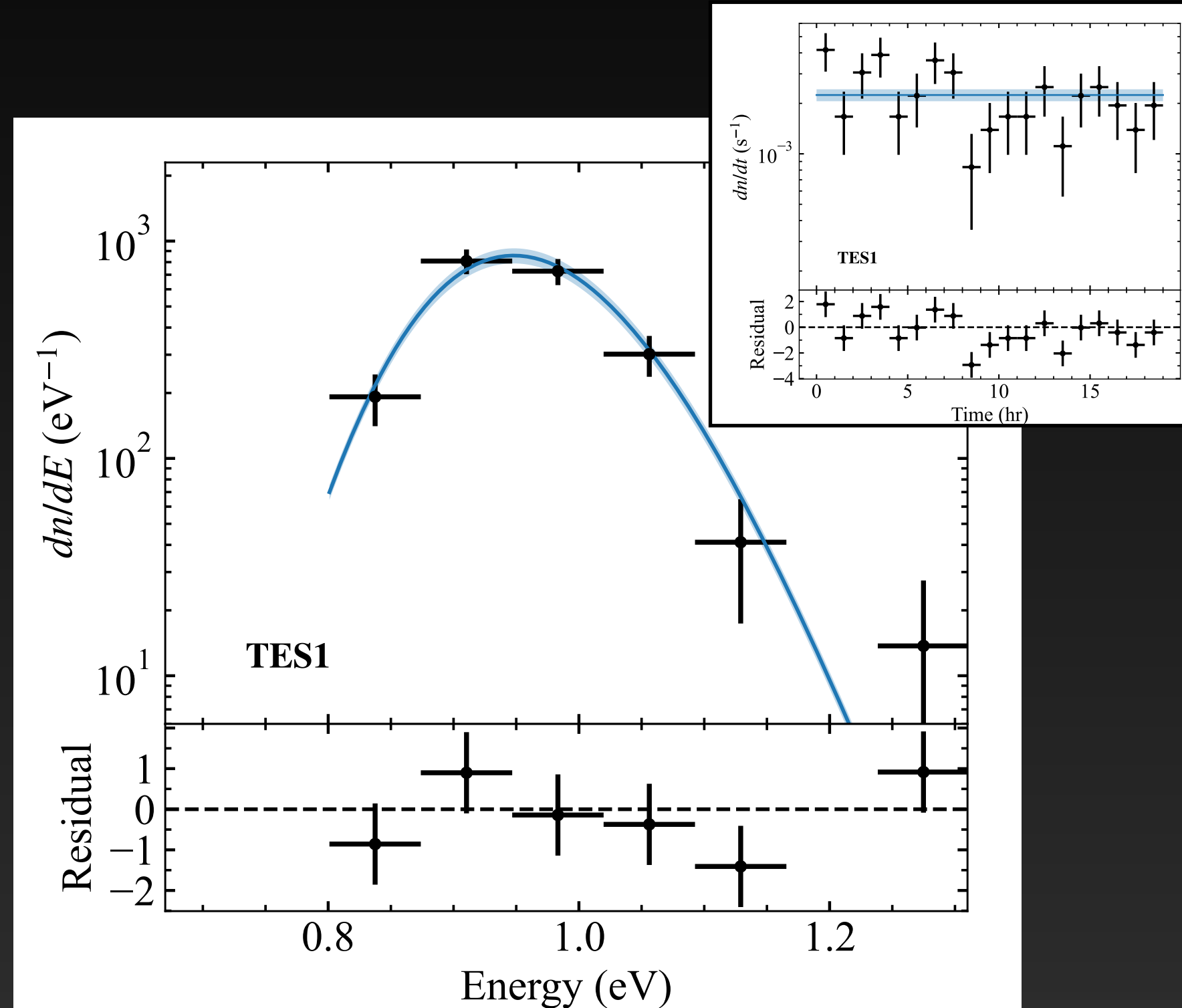
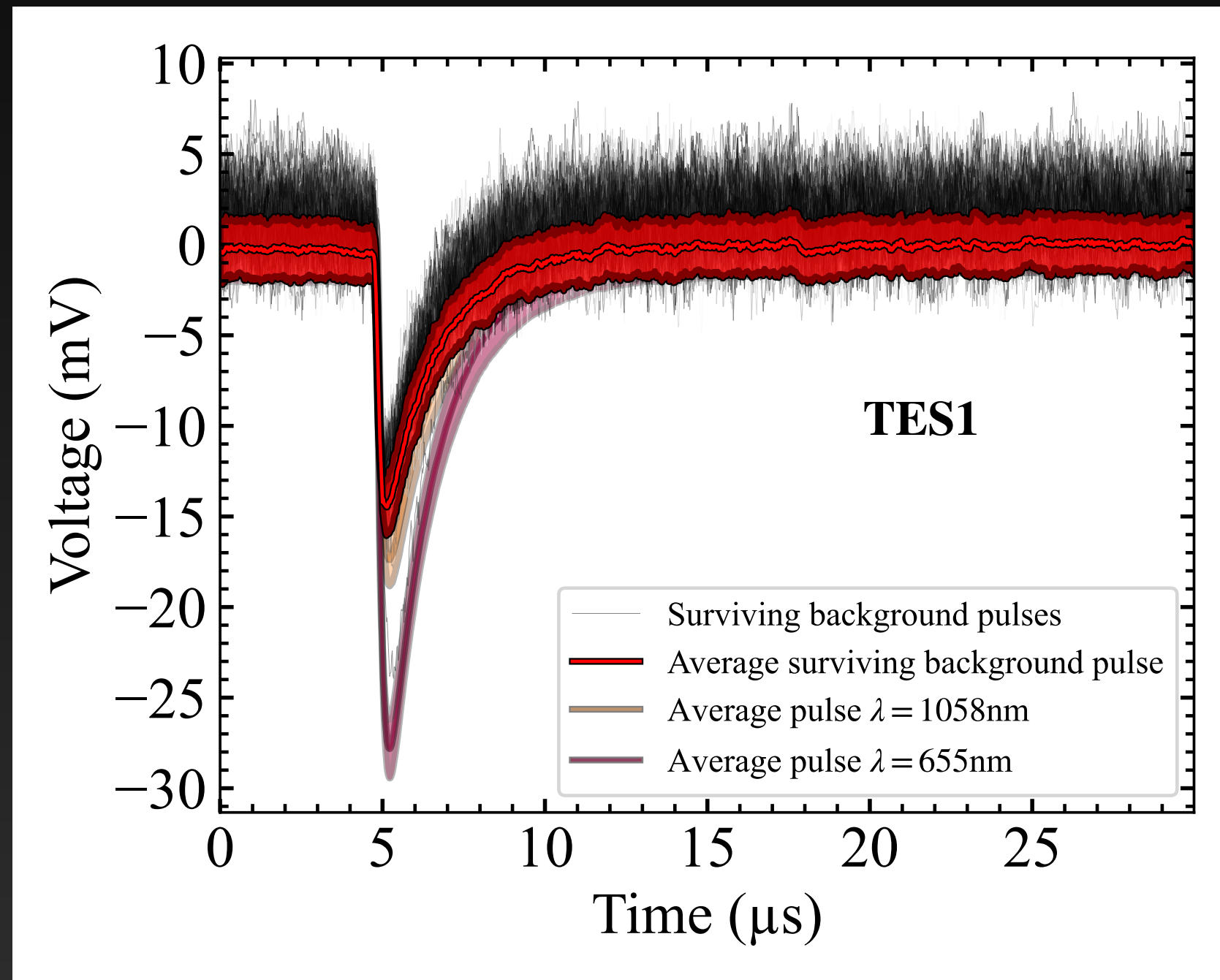
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- 19 hours of background data taken
- After photon selection: background rate
 $(2.2 \pm 0.2) \times 10^{-3} \text{ Hz}$

Background spectrum for TES1

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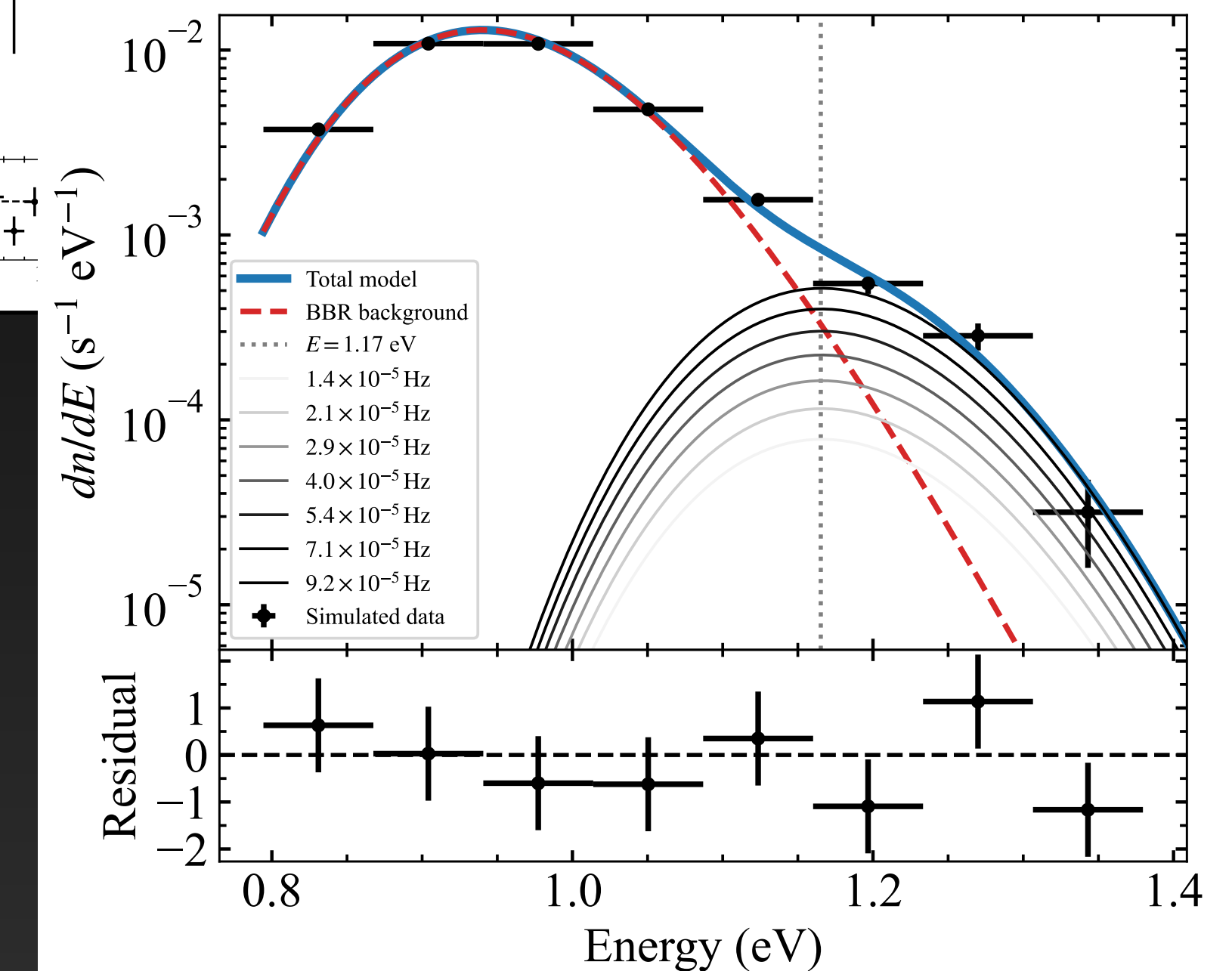
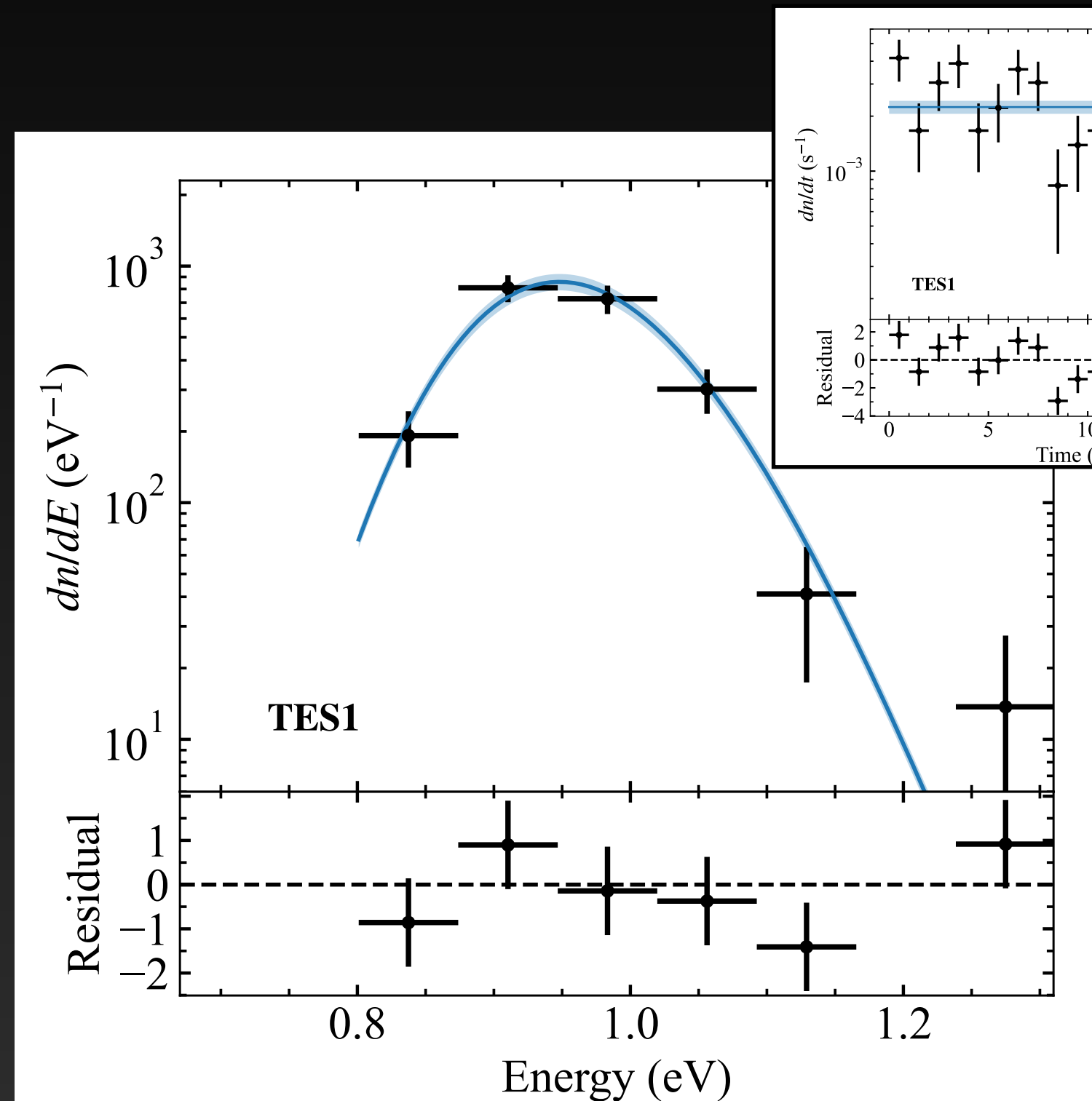
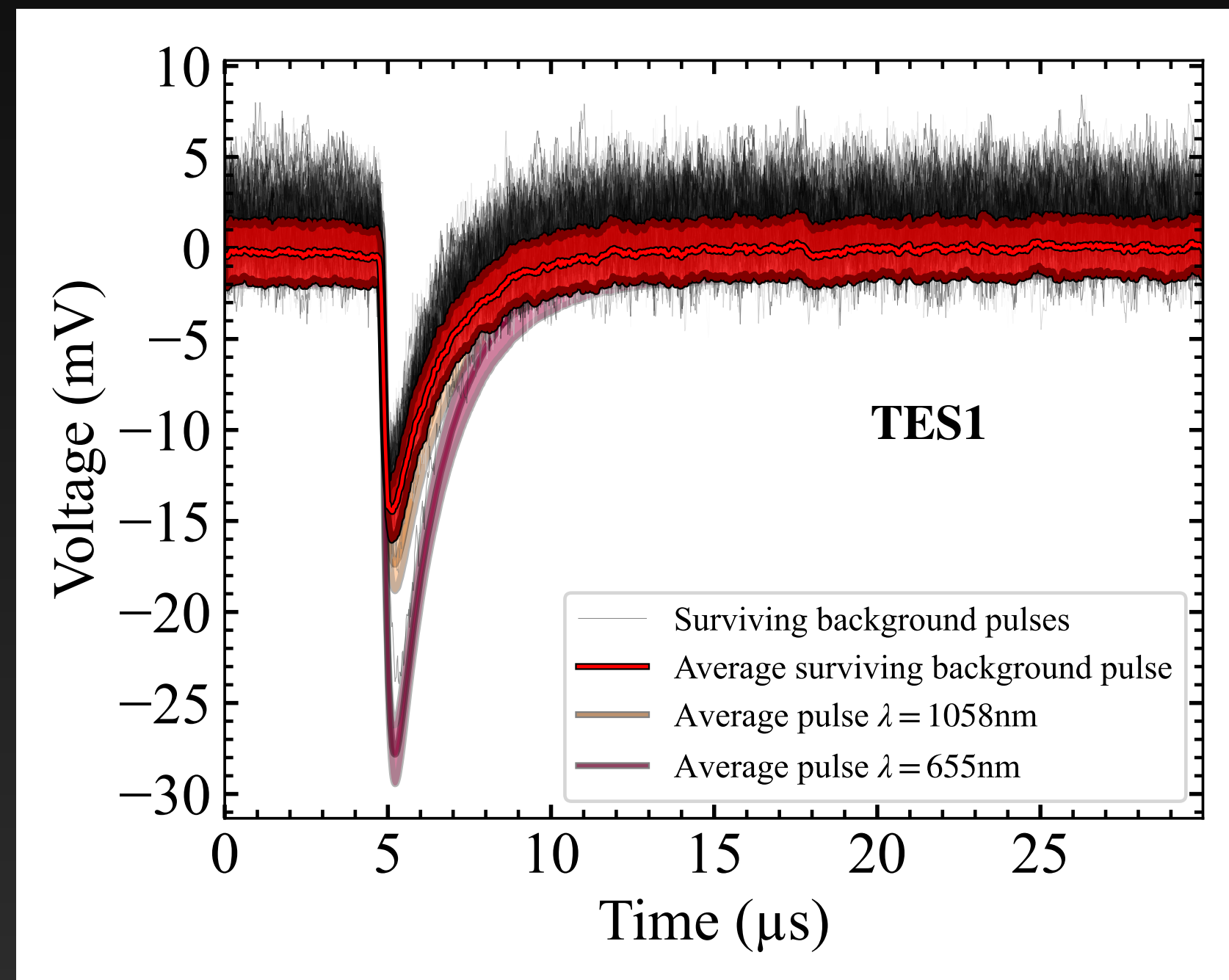


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- Blackbody temperature $T = (297 \pm 1) \text{ K}$

Background spectrum for TES1

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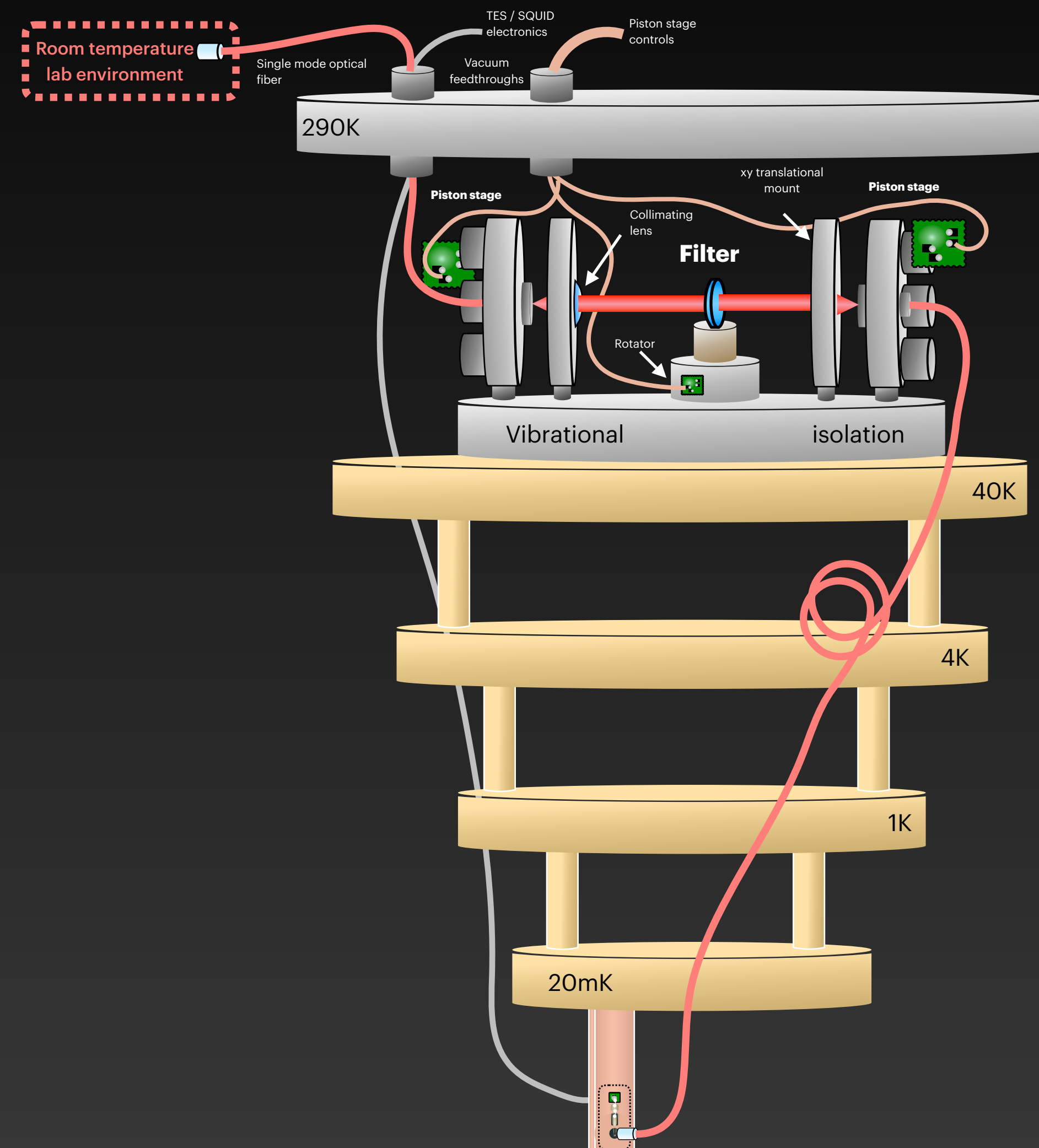
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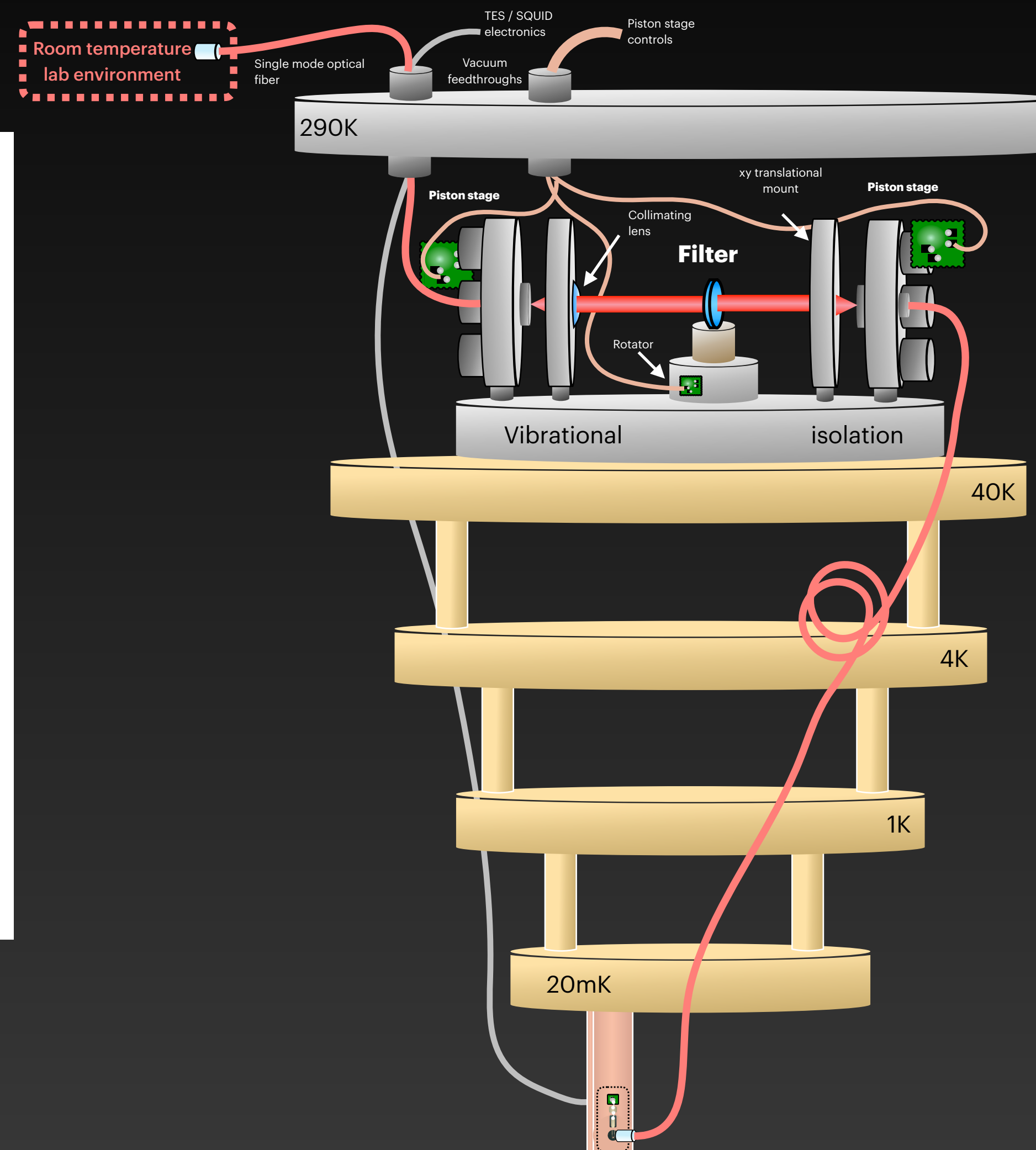
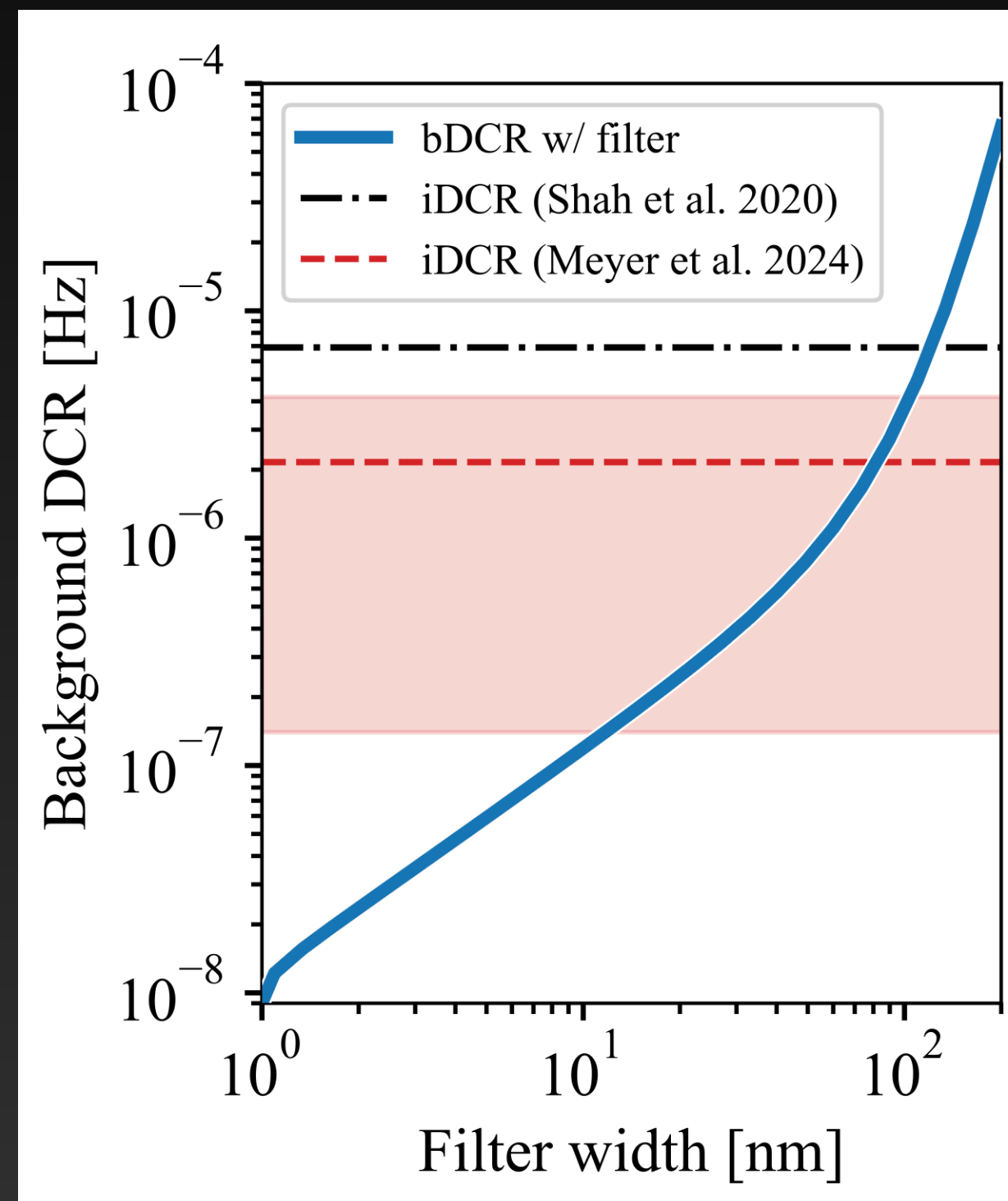
- Simulated 20 day measurement to determine detectable monochromatic line flux at 1064nm

Result: $n_0 \geq 2.7^{+0.8}_{-0.6} \times 10^{-5} \text{ Hz}$

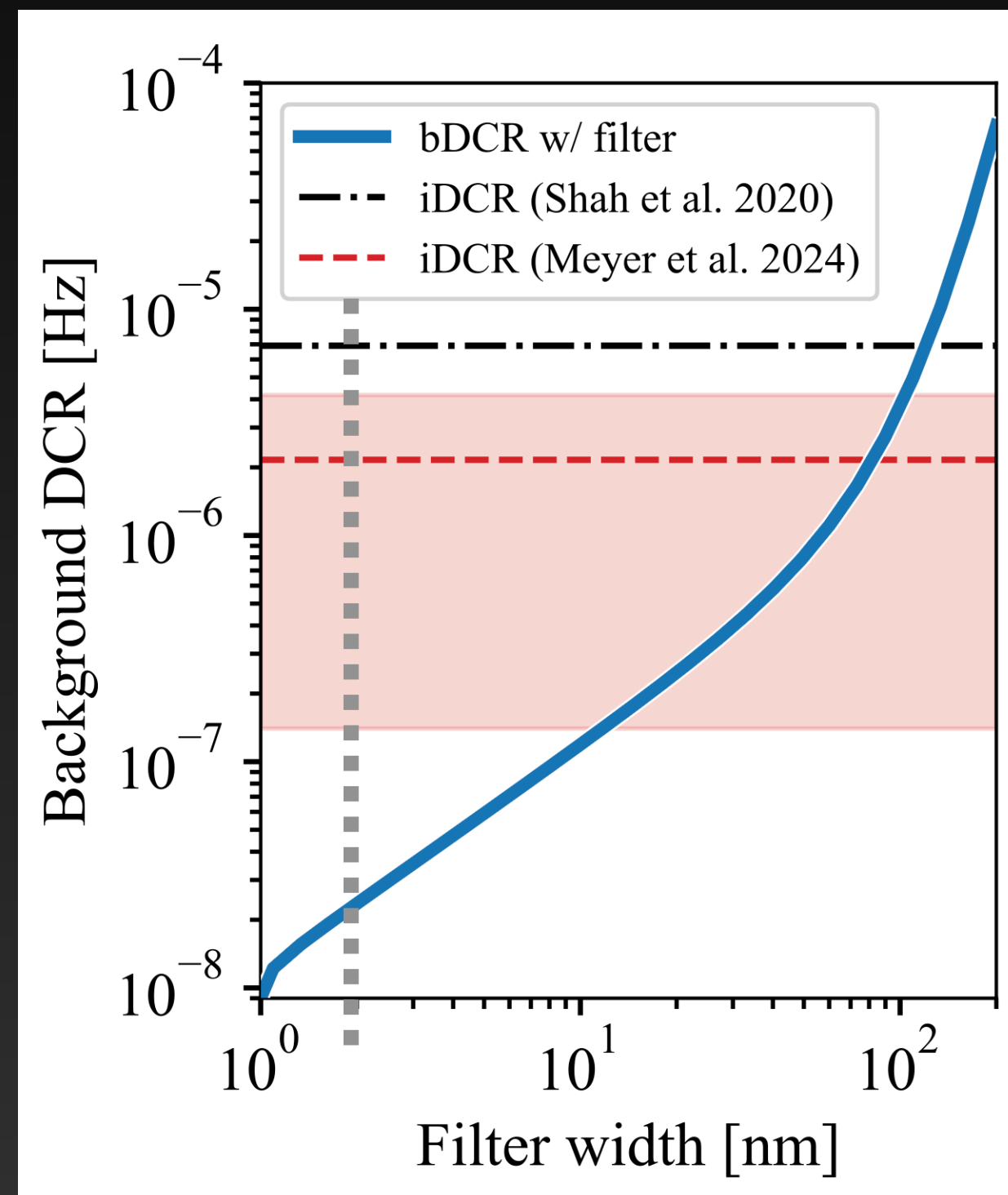
Improving energy resolution with cold optical filter bench



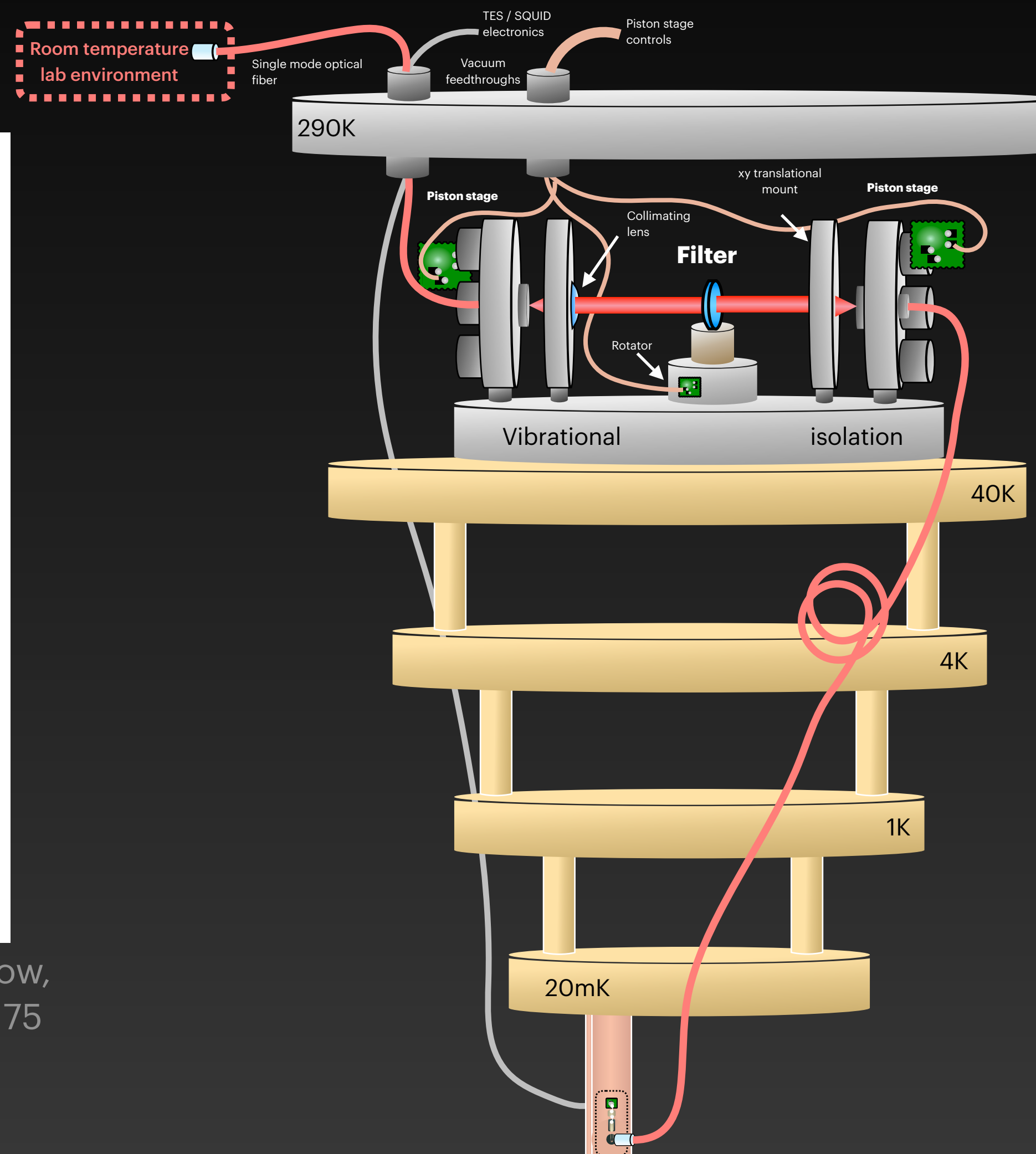
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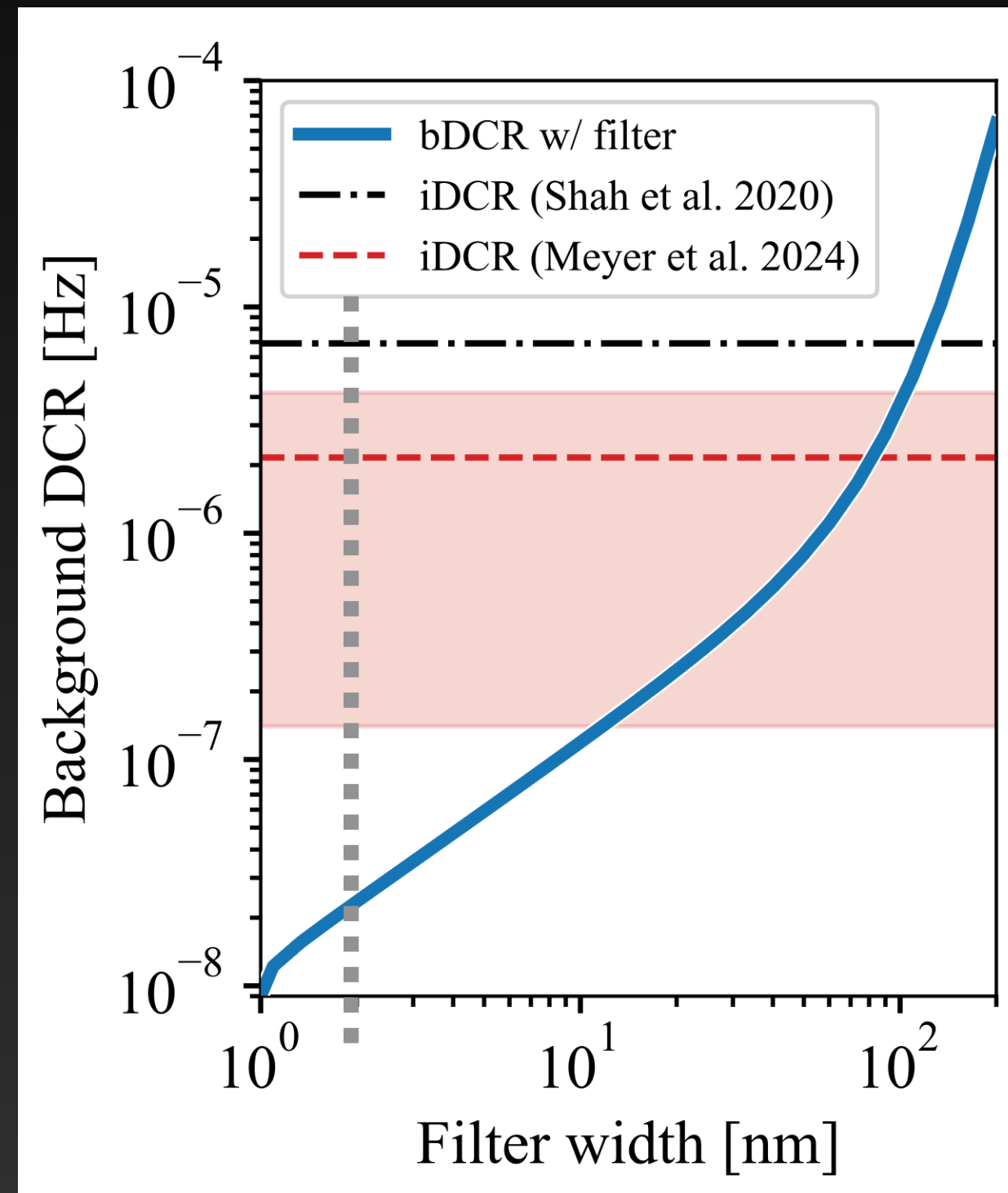
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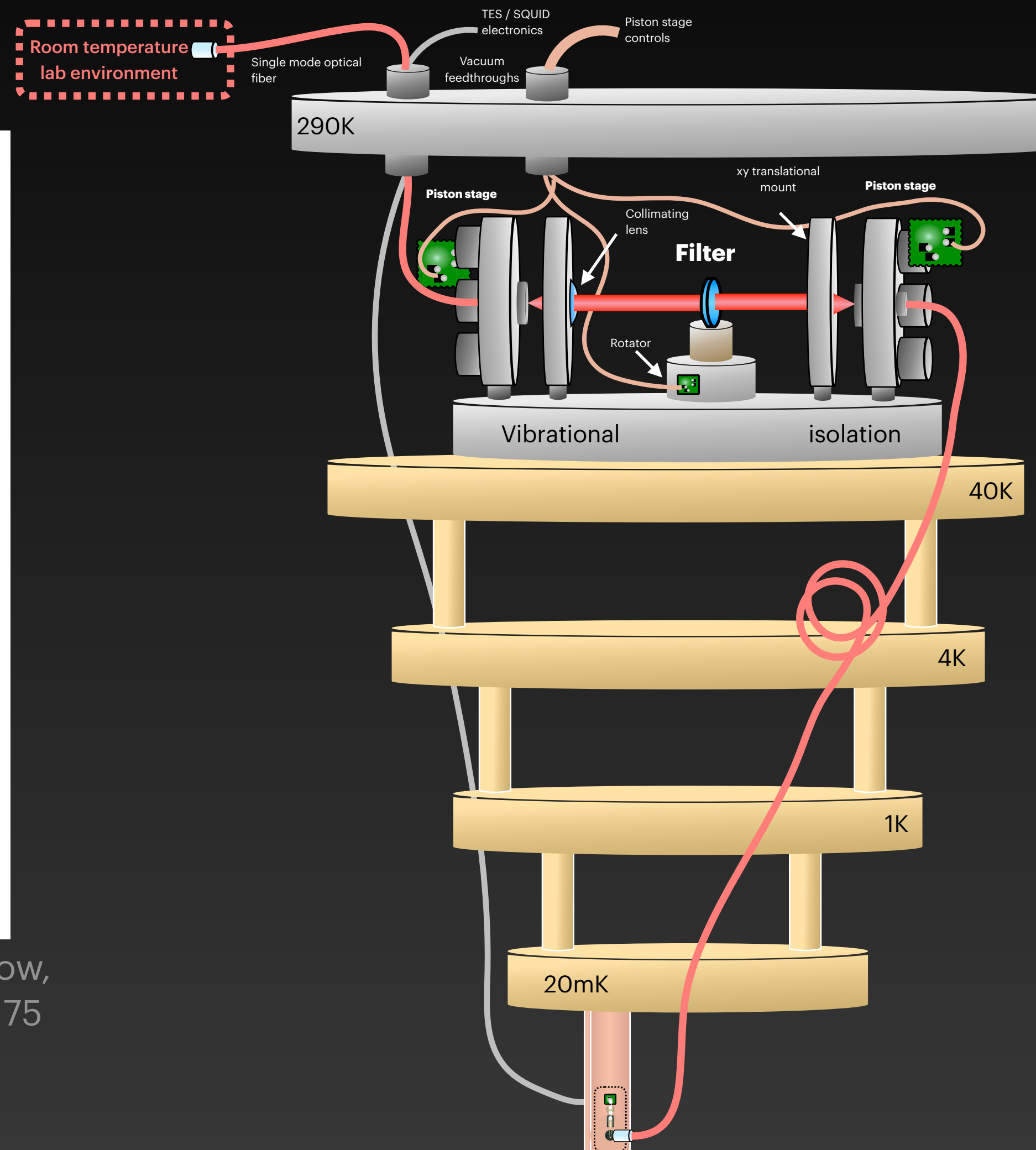
Filter in our lab has 2nm transmission window, could improve energy resolution by factor 75



Improving energy resolution with cold optical filter bench

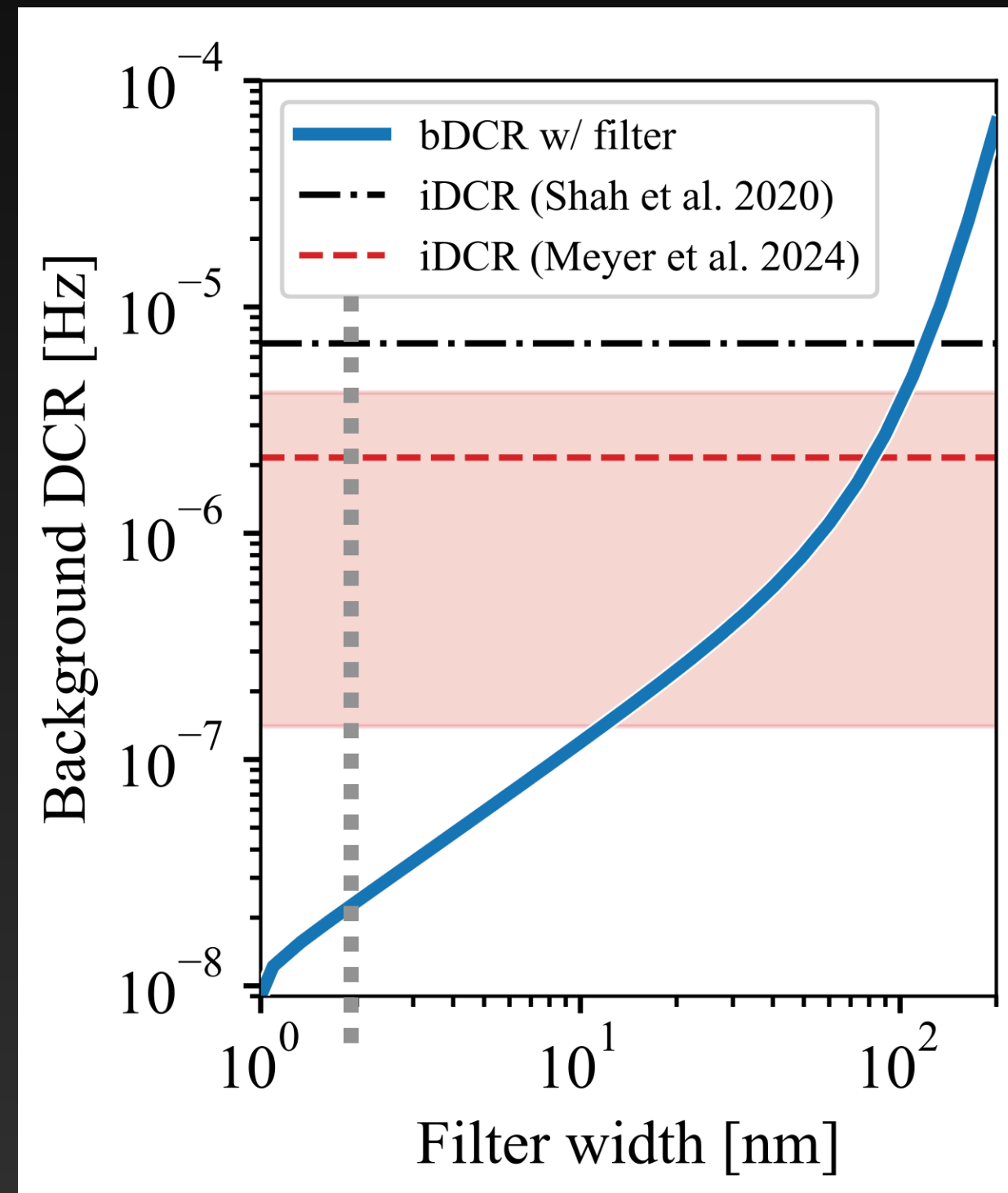


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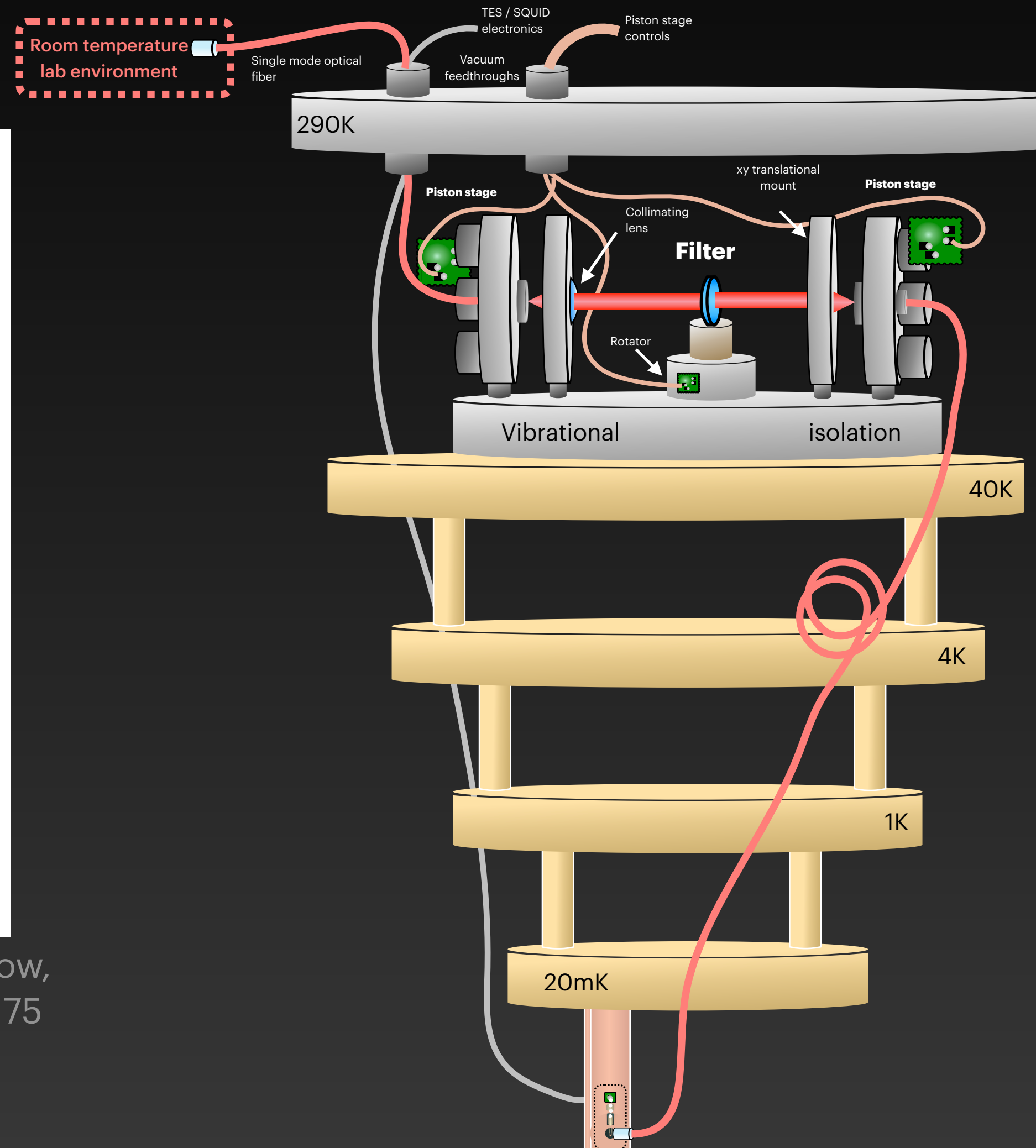


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Improving energy resolution with cold optical filter bench

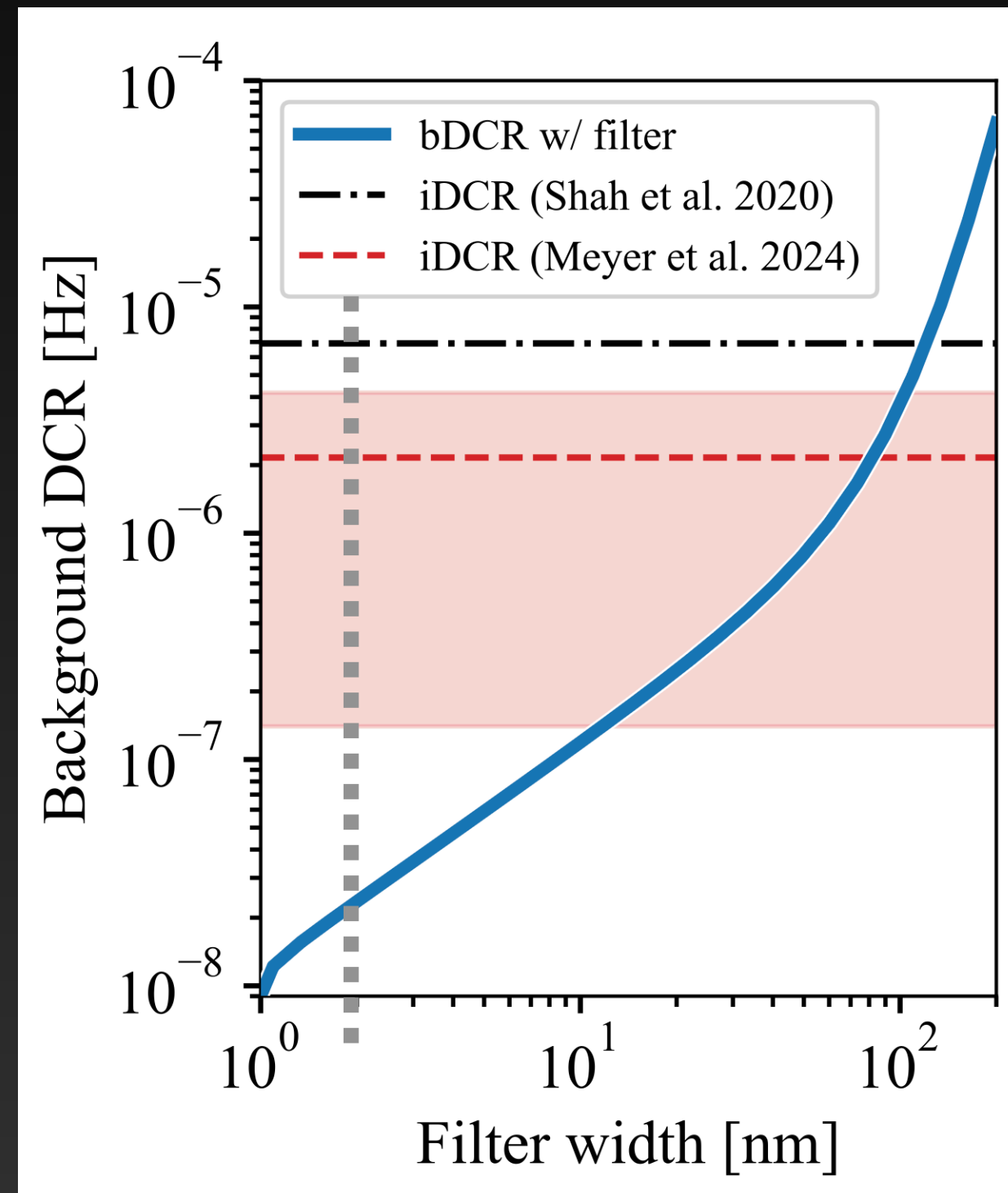


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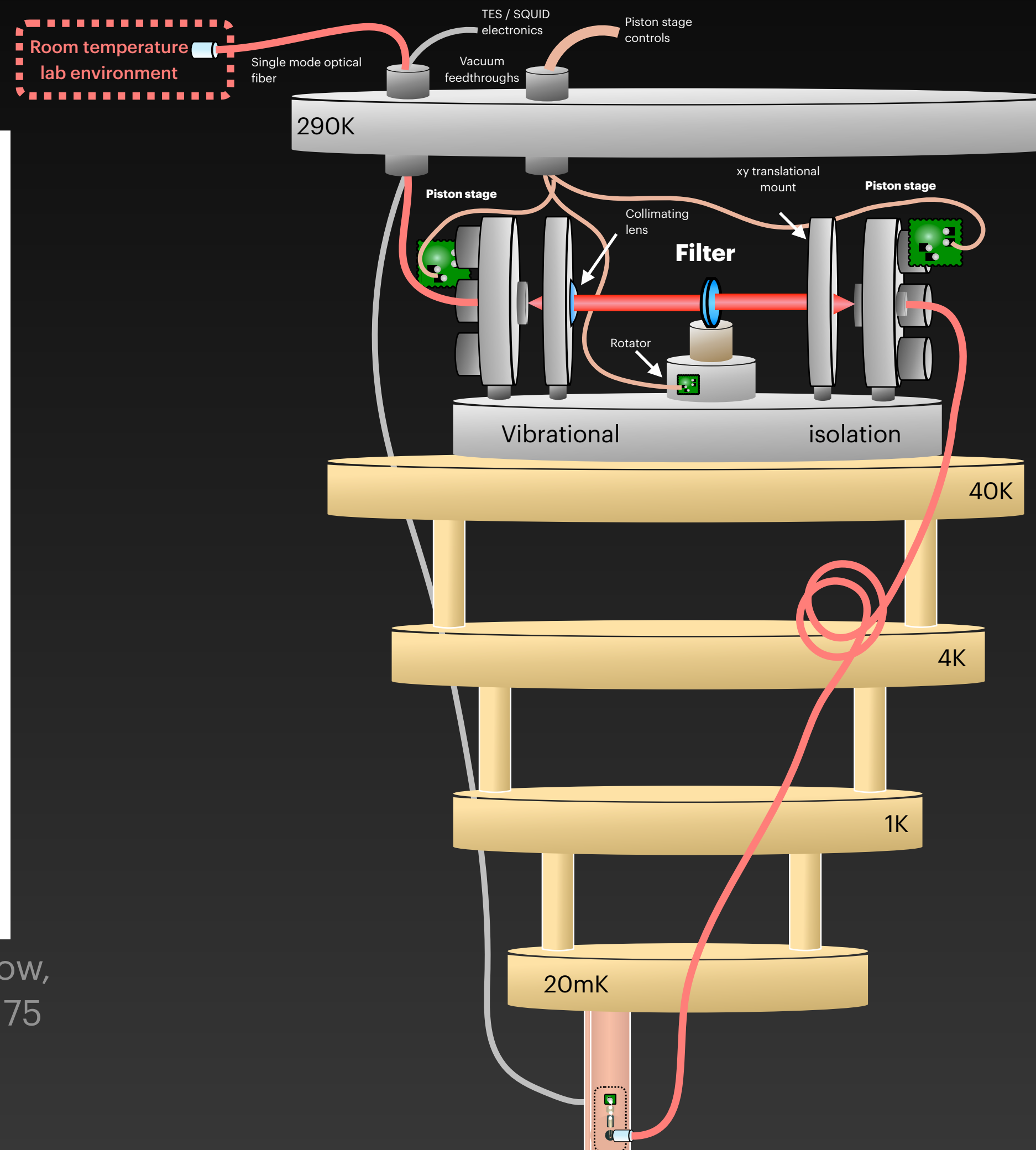


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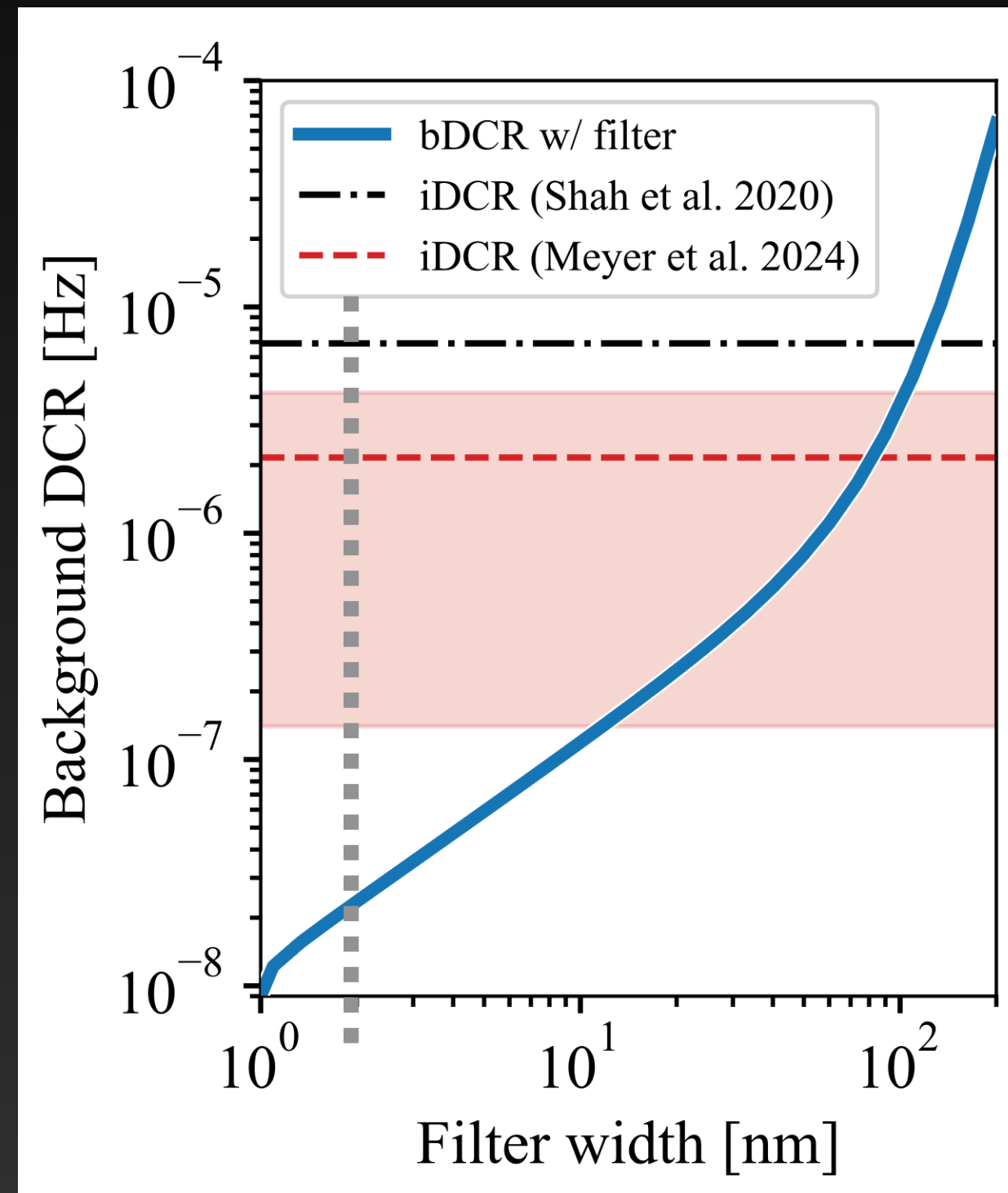


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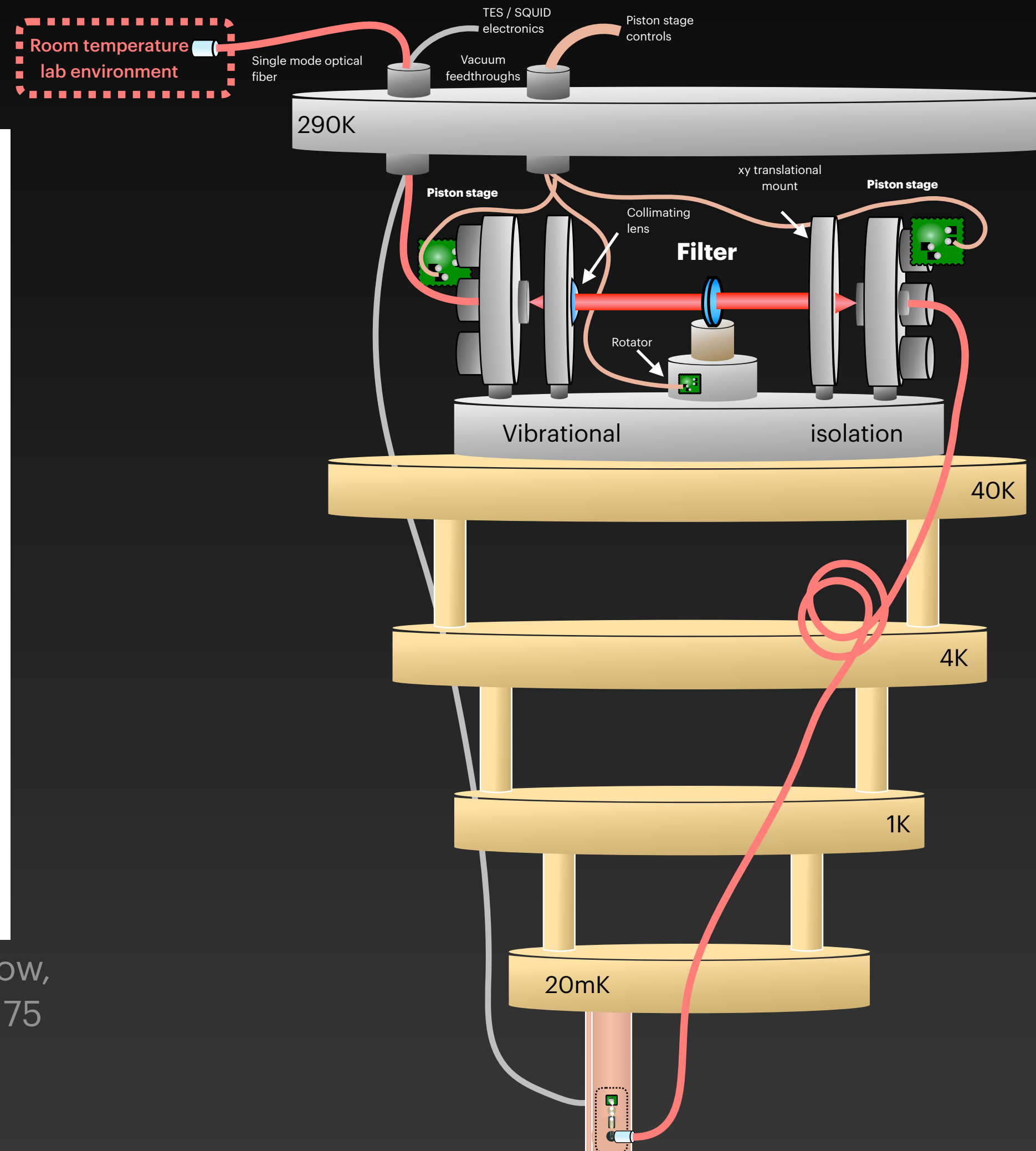


- Cryo-compatible piston stages for remote auto-alignment $\Rightarrow$ Compensates for misalignment by thermal contraction
- Transmission window shifts as a function of temperature $\Rightarrow$ Compensated by changing angle of incidence
- **Achieved above 80% transmission** for single-mode fibers (without filter) at room temperature

Improving energy resolution with cold optical filter bench

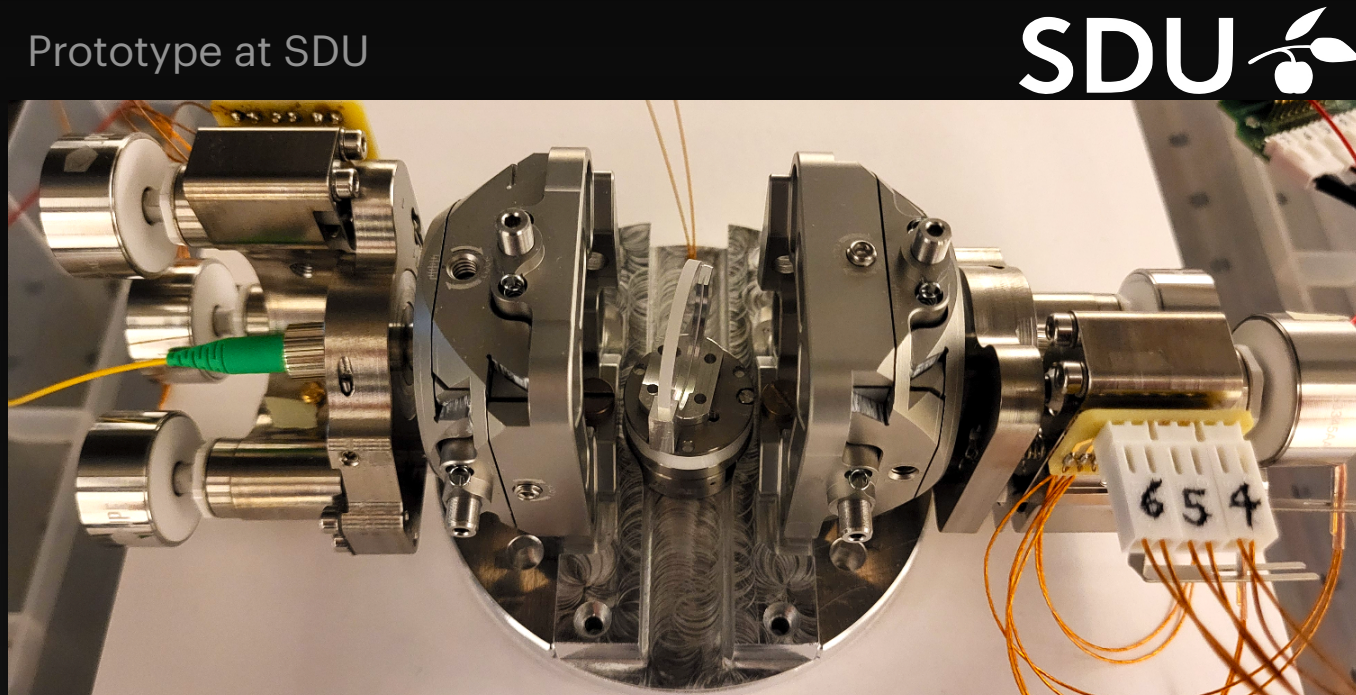


Filter in our lab has 2nm transmission window, could improve energy resolution by factor 75



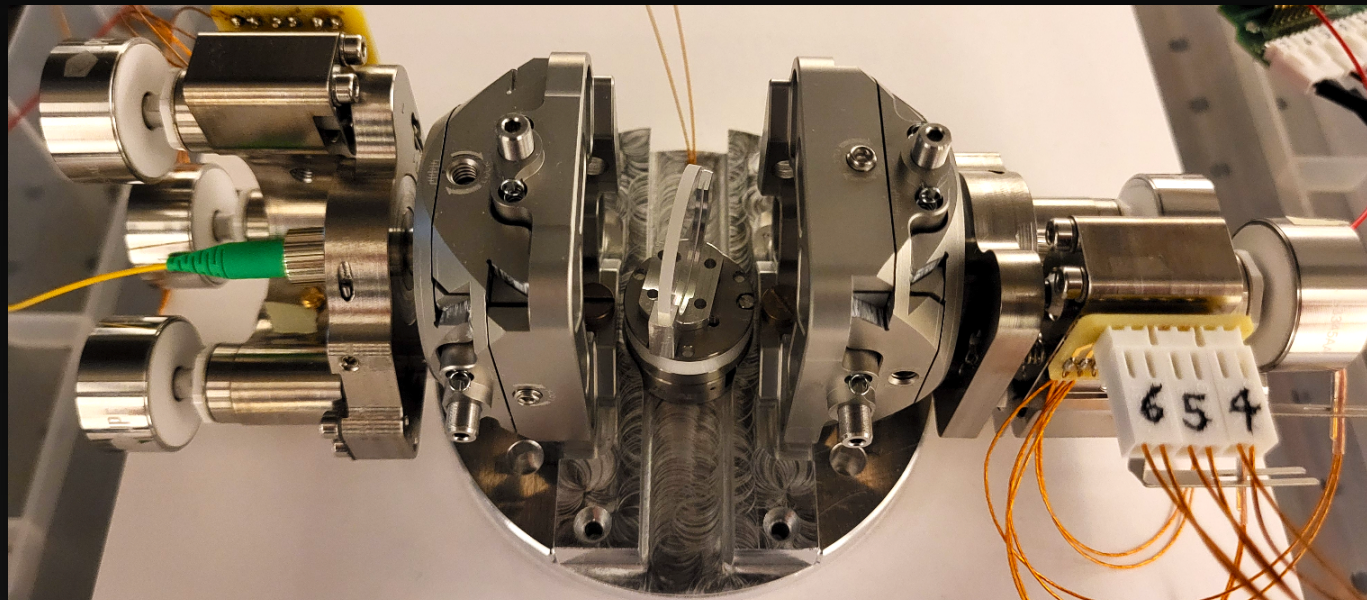
- Cryo-compatible piston stages for remote auto-alignment $\Rightarrow$ Compensates for misalignment by thermal contraction
- Transmission window shifts as a function of temperature $\Rightarrow$ Compensated by changing angle of incidence
- **Achieved above 80% transmission** for single-mode fibers (without filter) at room temperature
- Could enable photon energy selection for SNSPDs

Installation of first prototype in dilution refrigerator

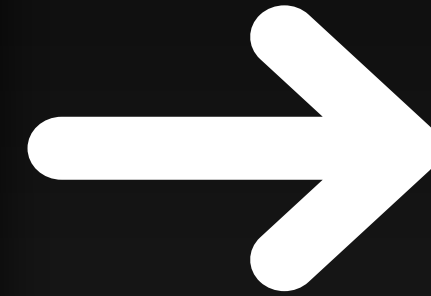


Installation of first prototype in dilution refrigerator

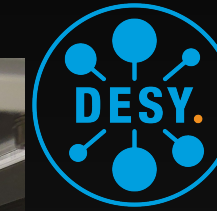
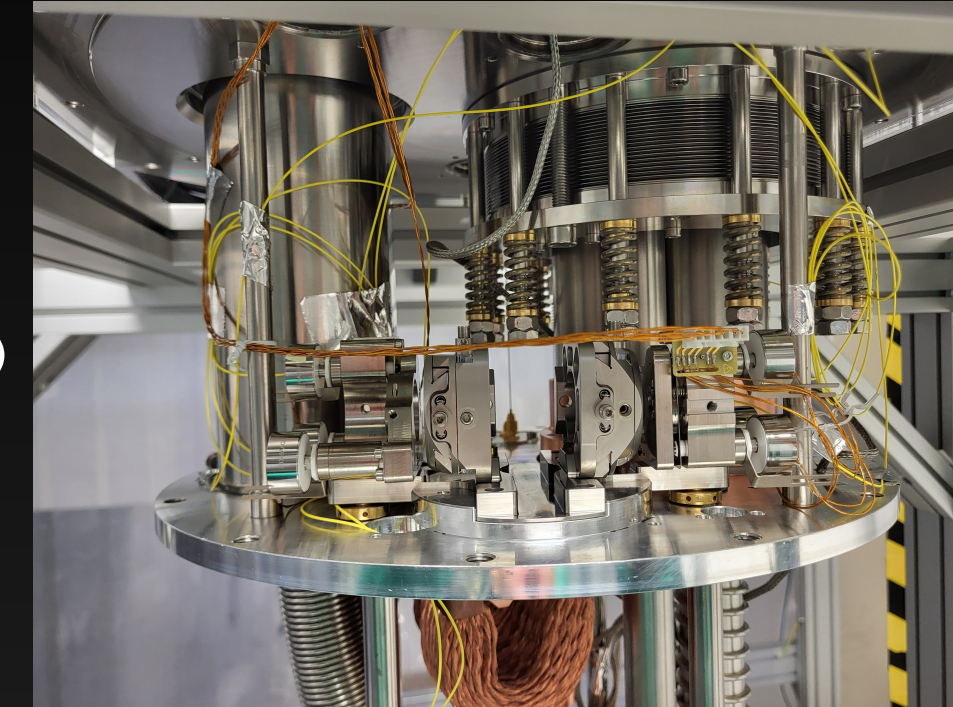
Prototype at SDU



SDU 



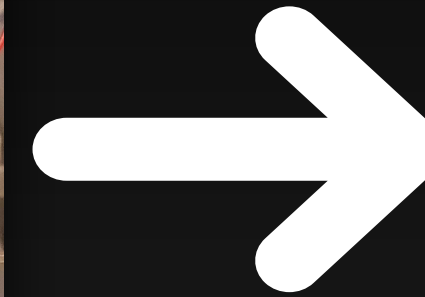
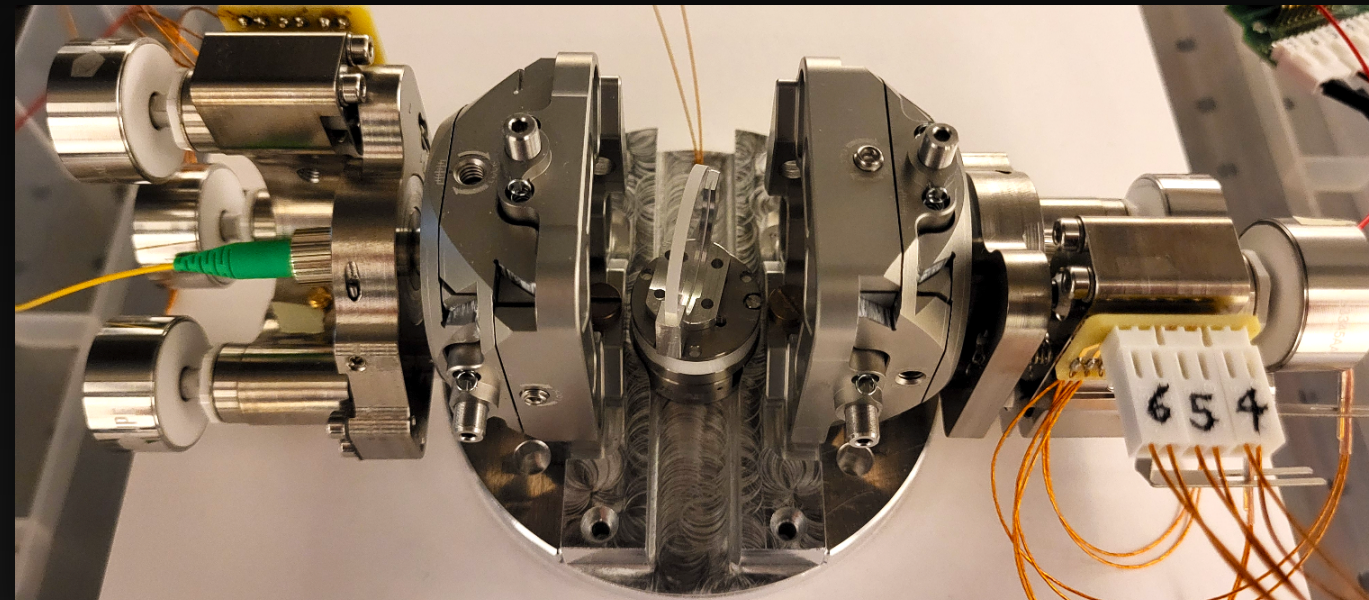
Installed at DESY in February 2026



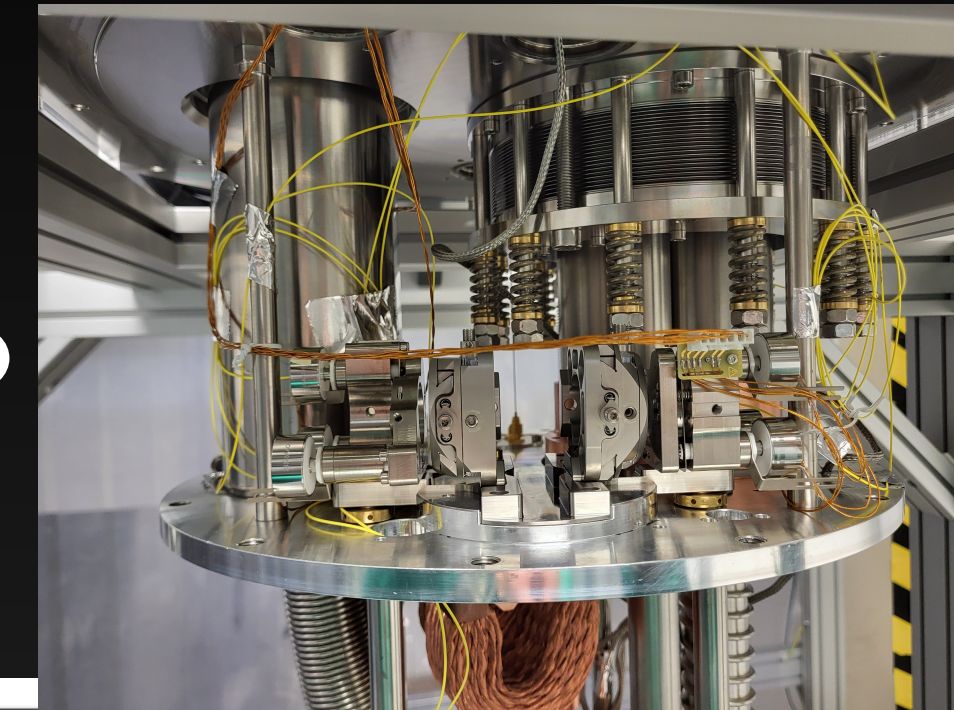
Installation of first prototype in dilution refrigerator

Prototype at SDU

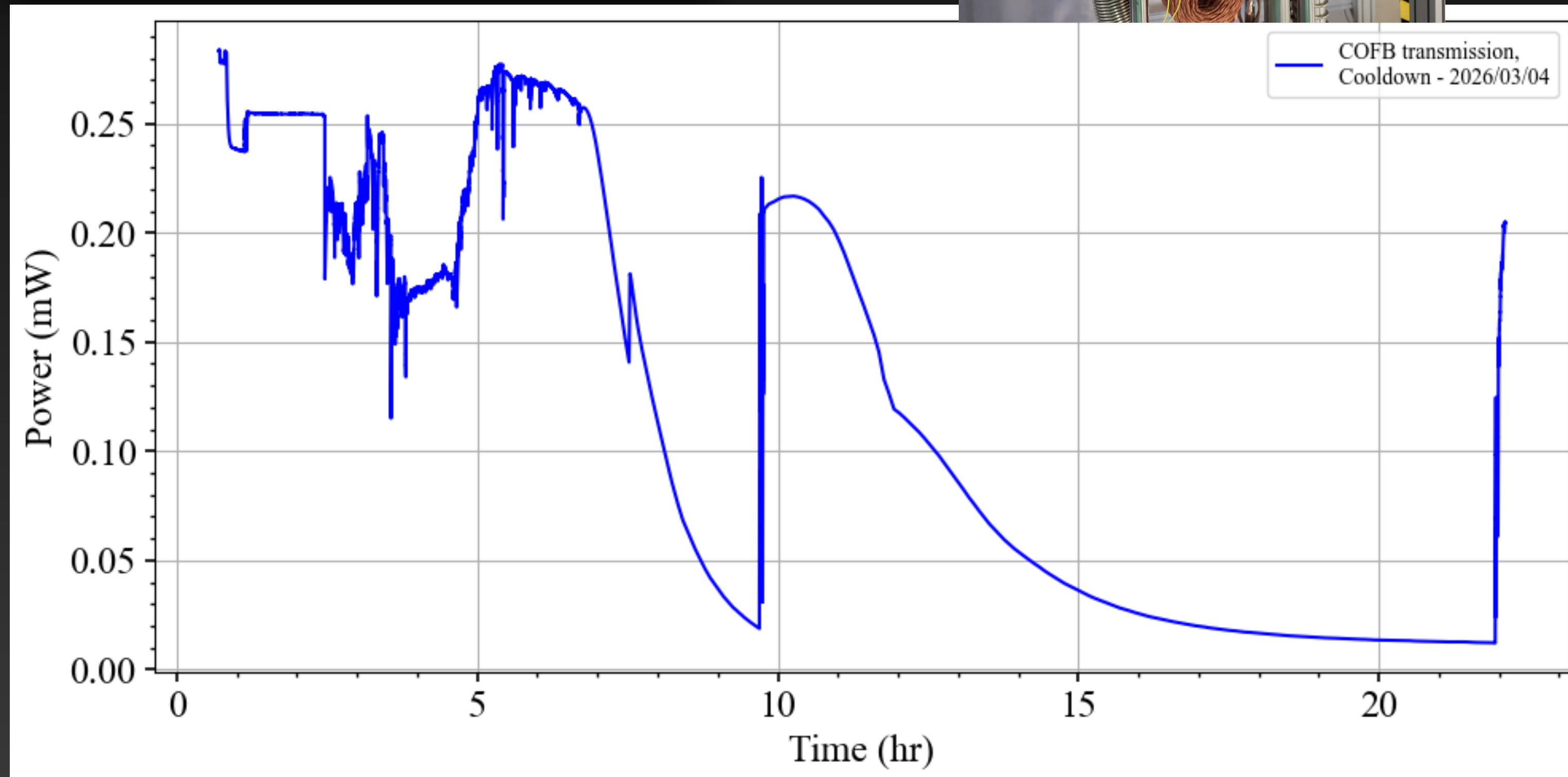
SDU 



Installed at DESY in February 2026



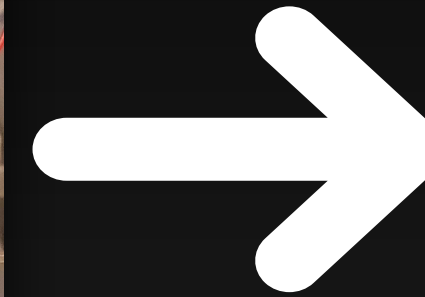
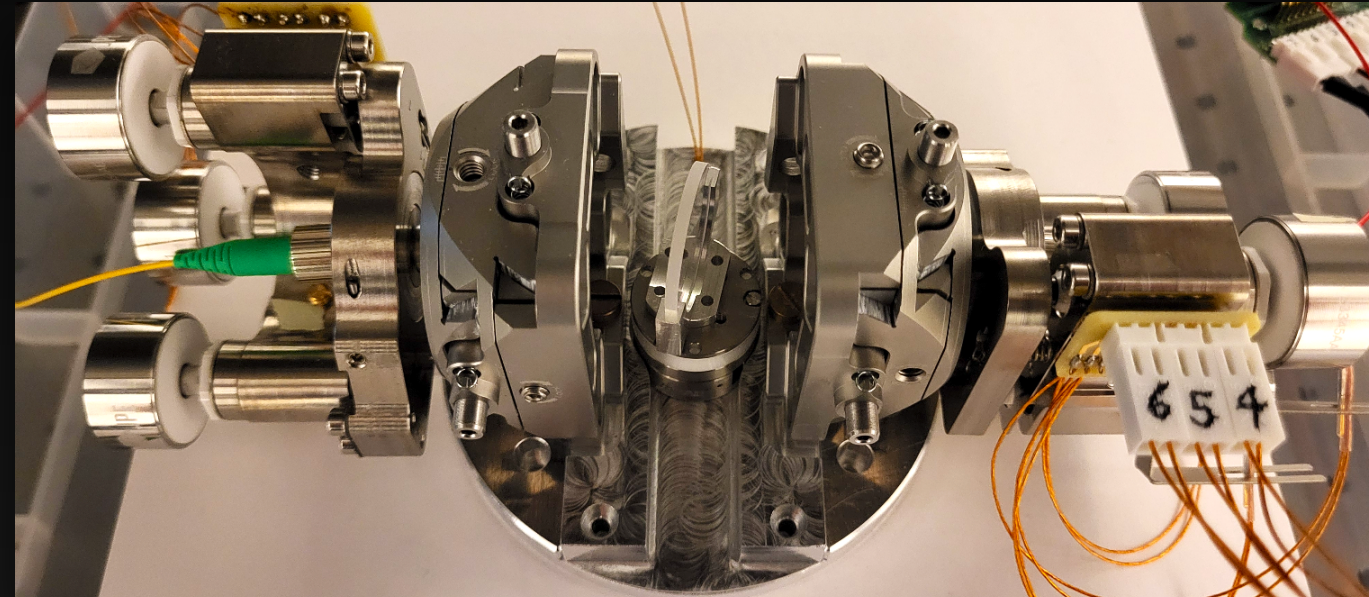
First test of
realignment
during
cooldown



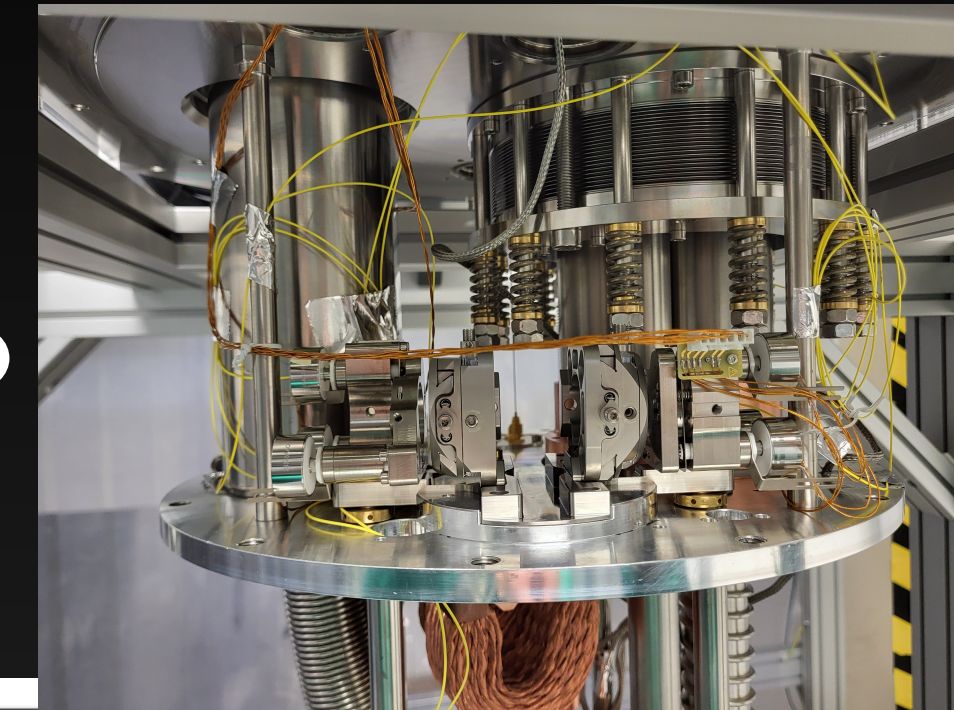
Installation of first prototype in dilution refrigerator

Prototype at SDU

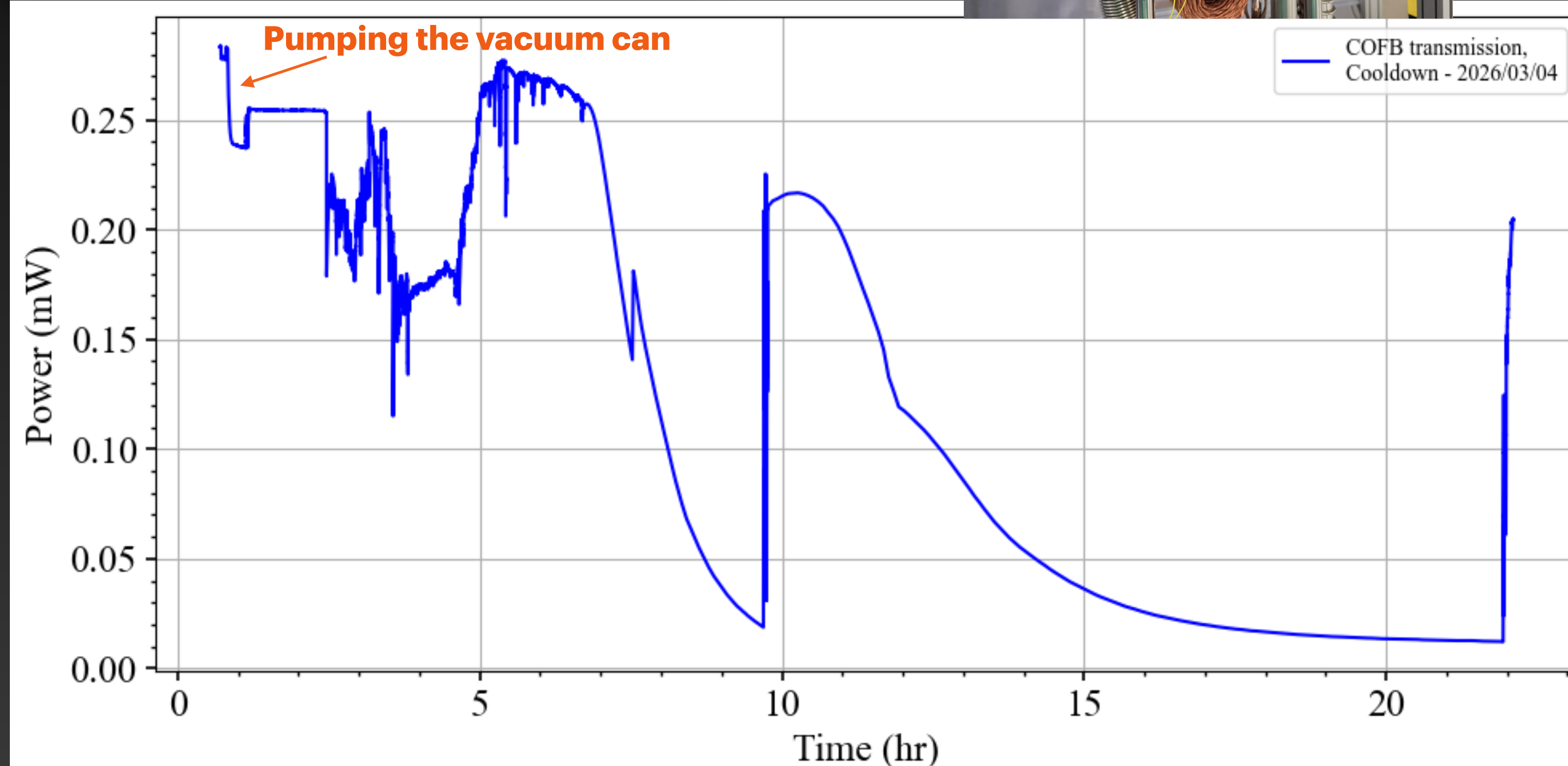
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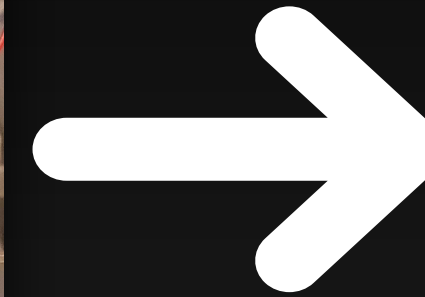
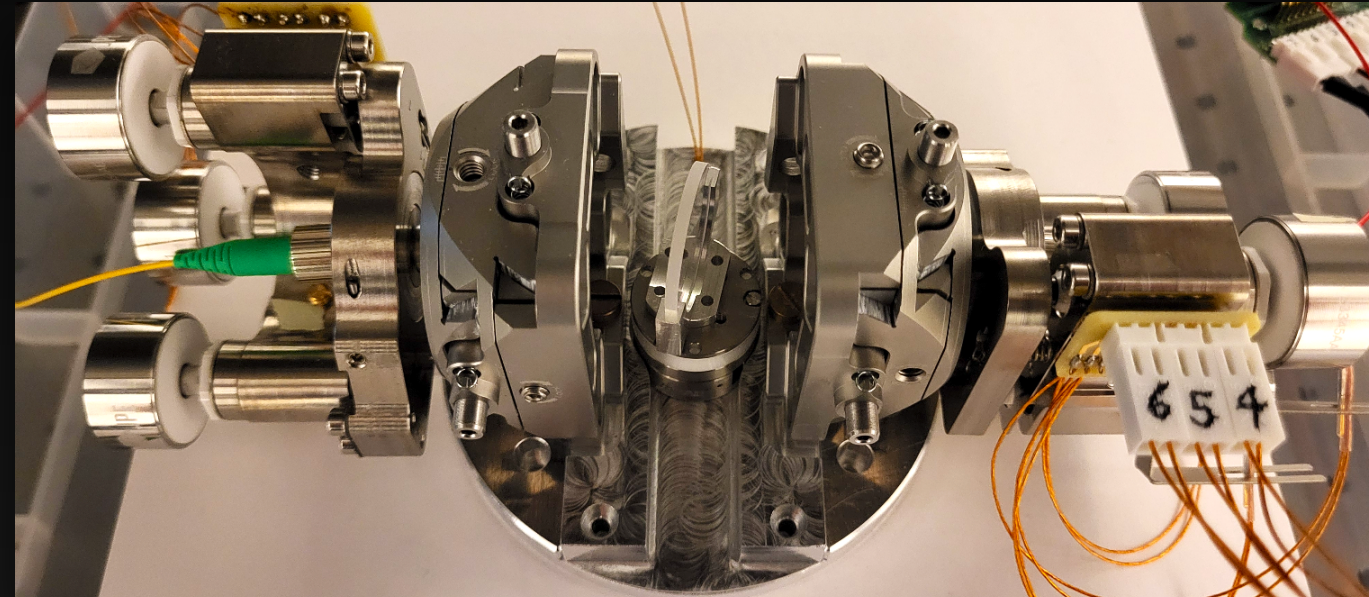
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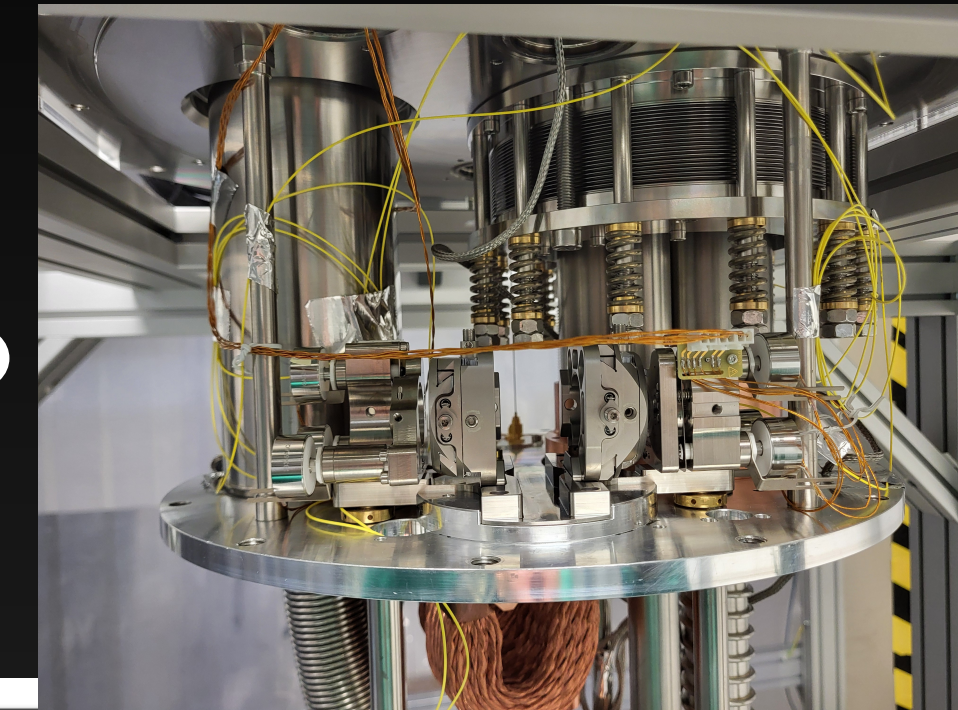
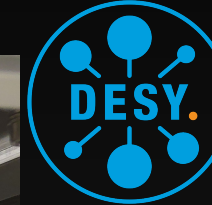
Installation of first prototype in dilution refrigerator

Prototype at SDU

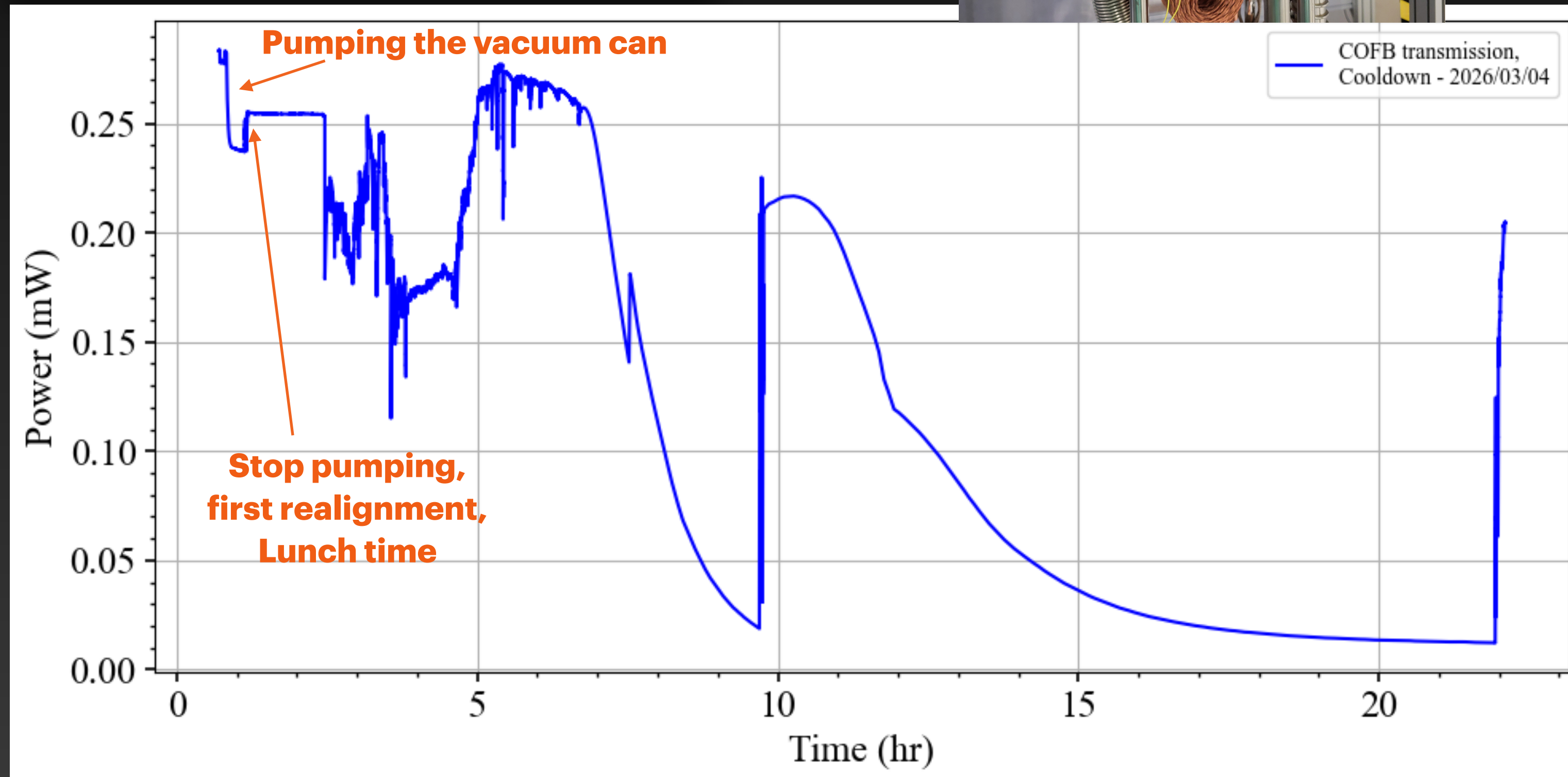
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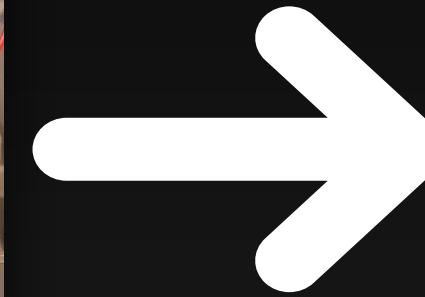
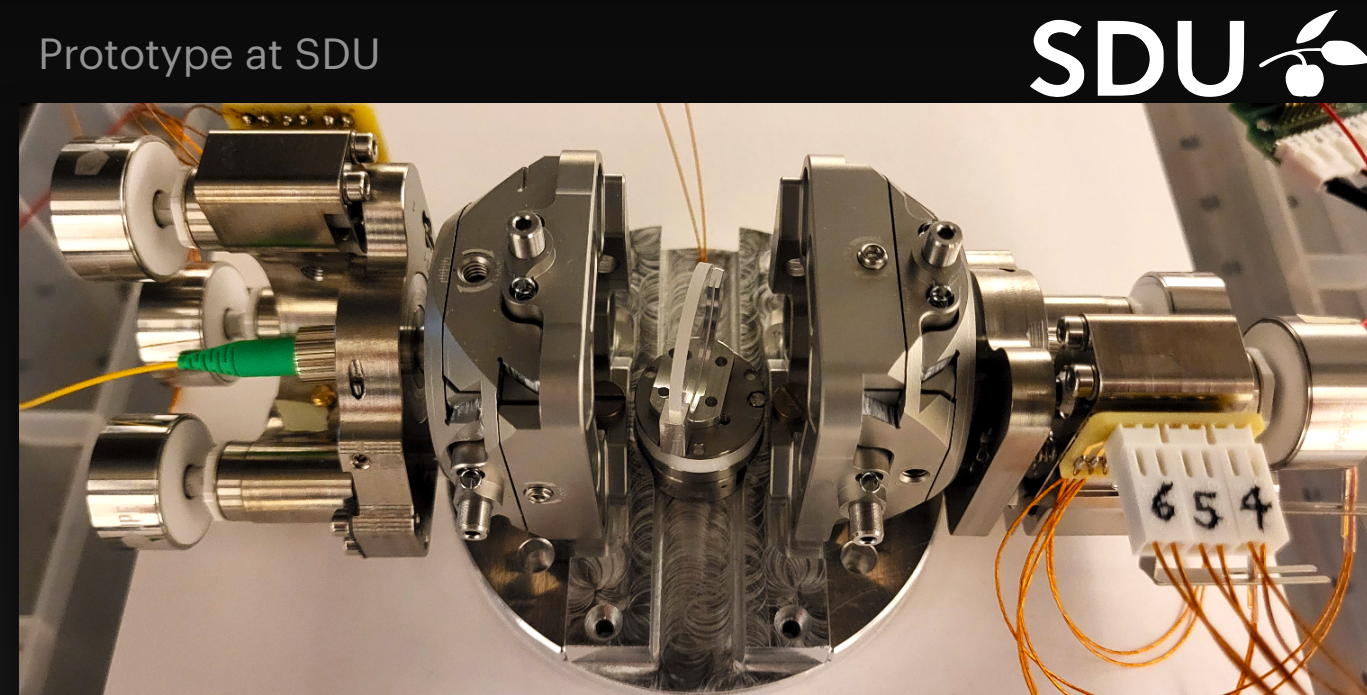
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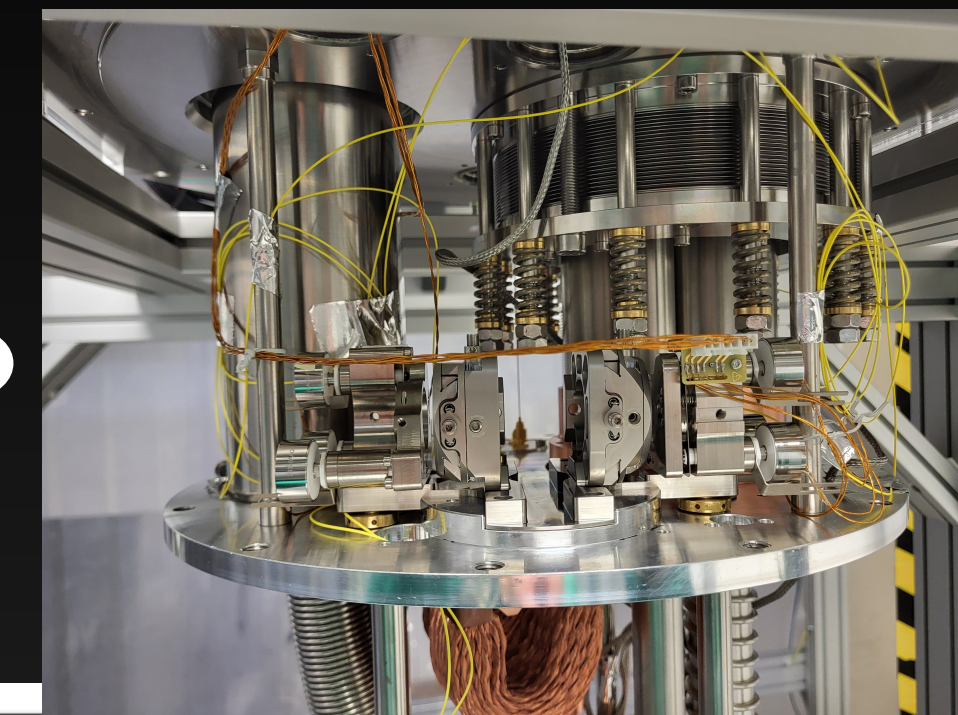
First test of
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during
cooldown



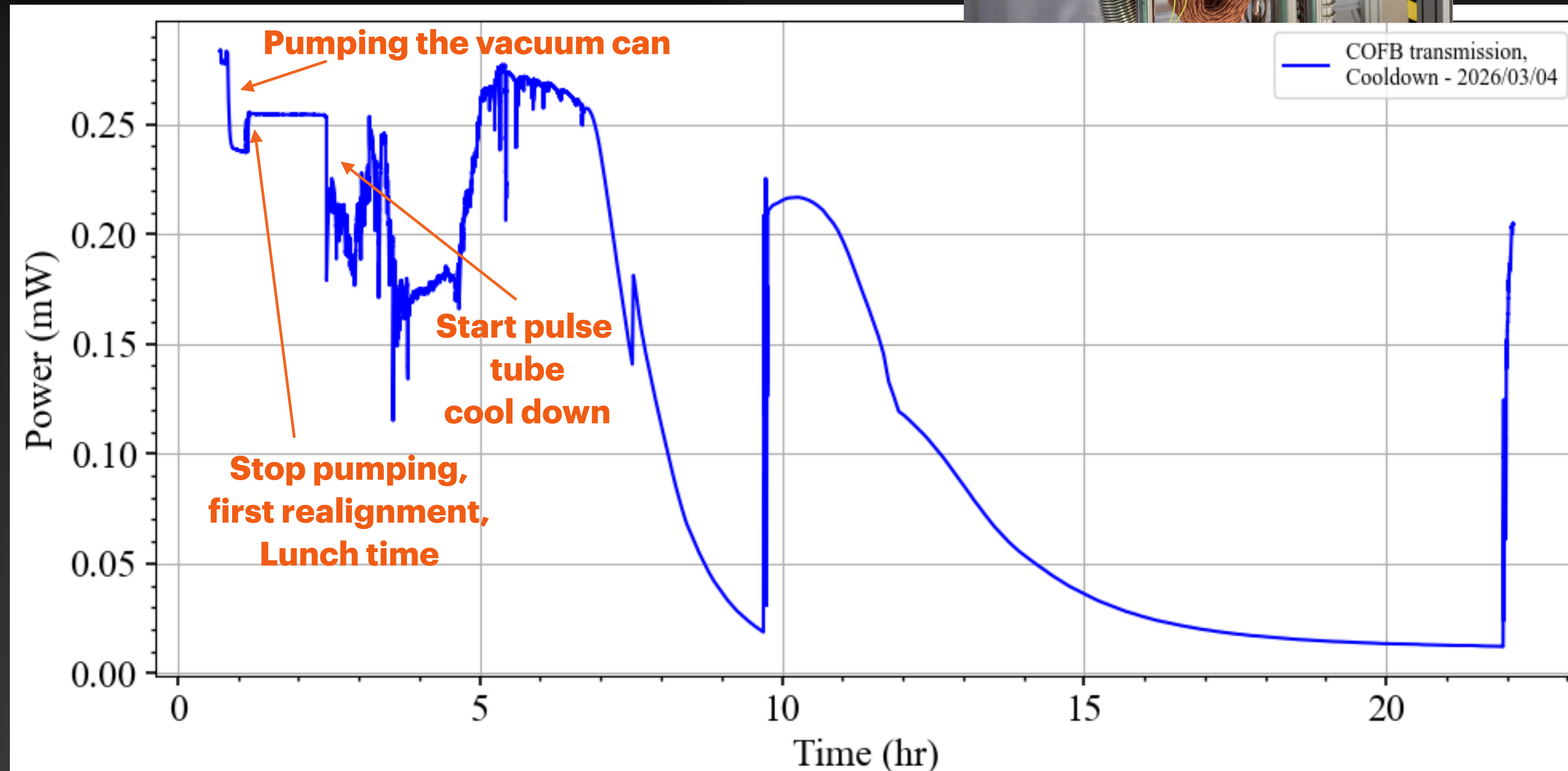
Installation of first prototype in dilution refrigerator



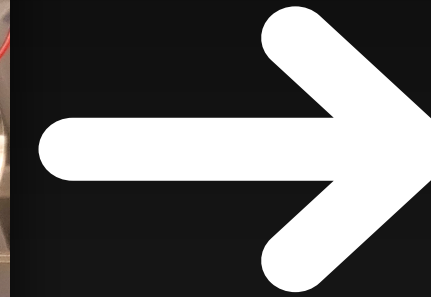
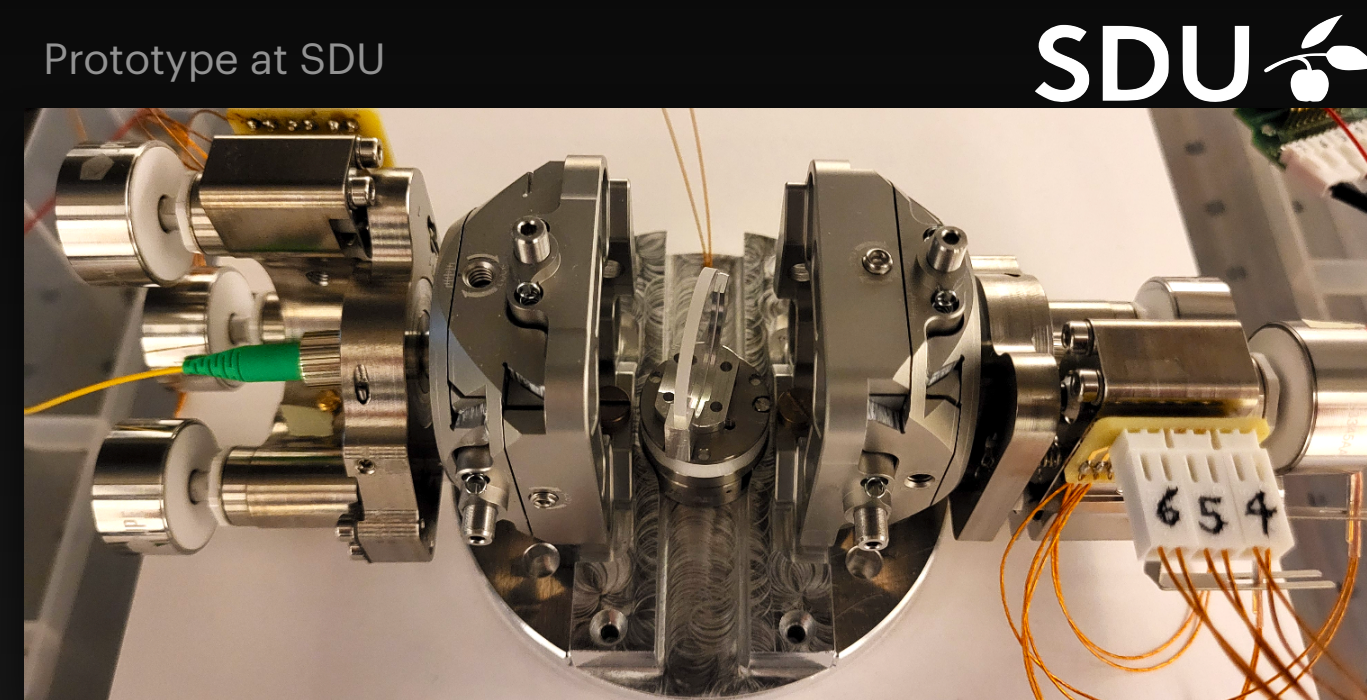
Installed at DESY in February 2026



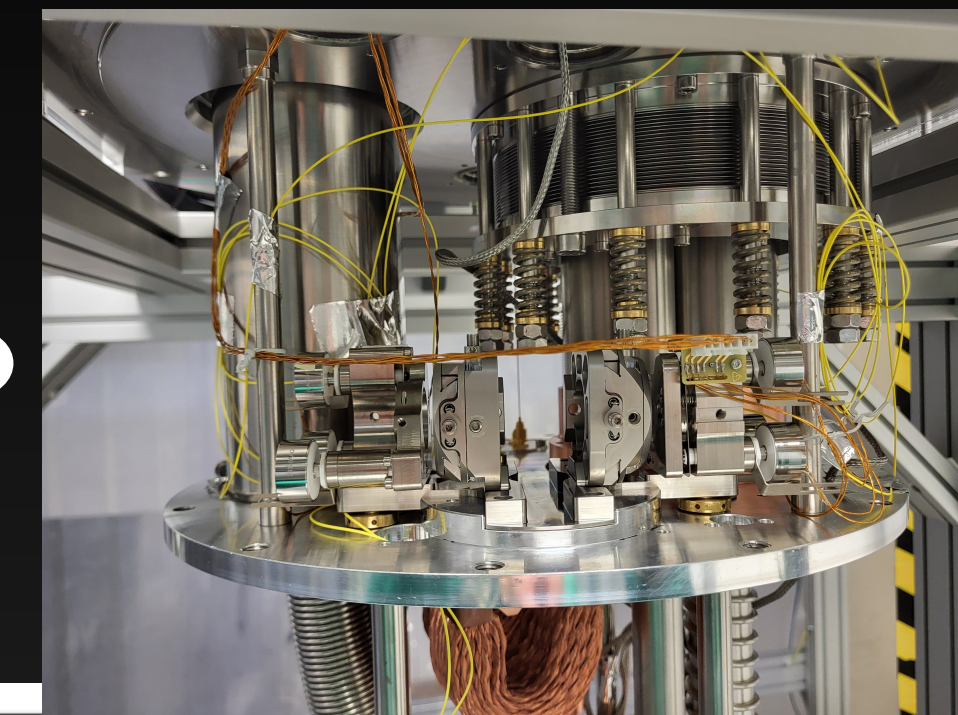
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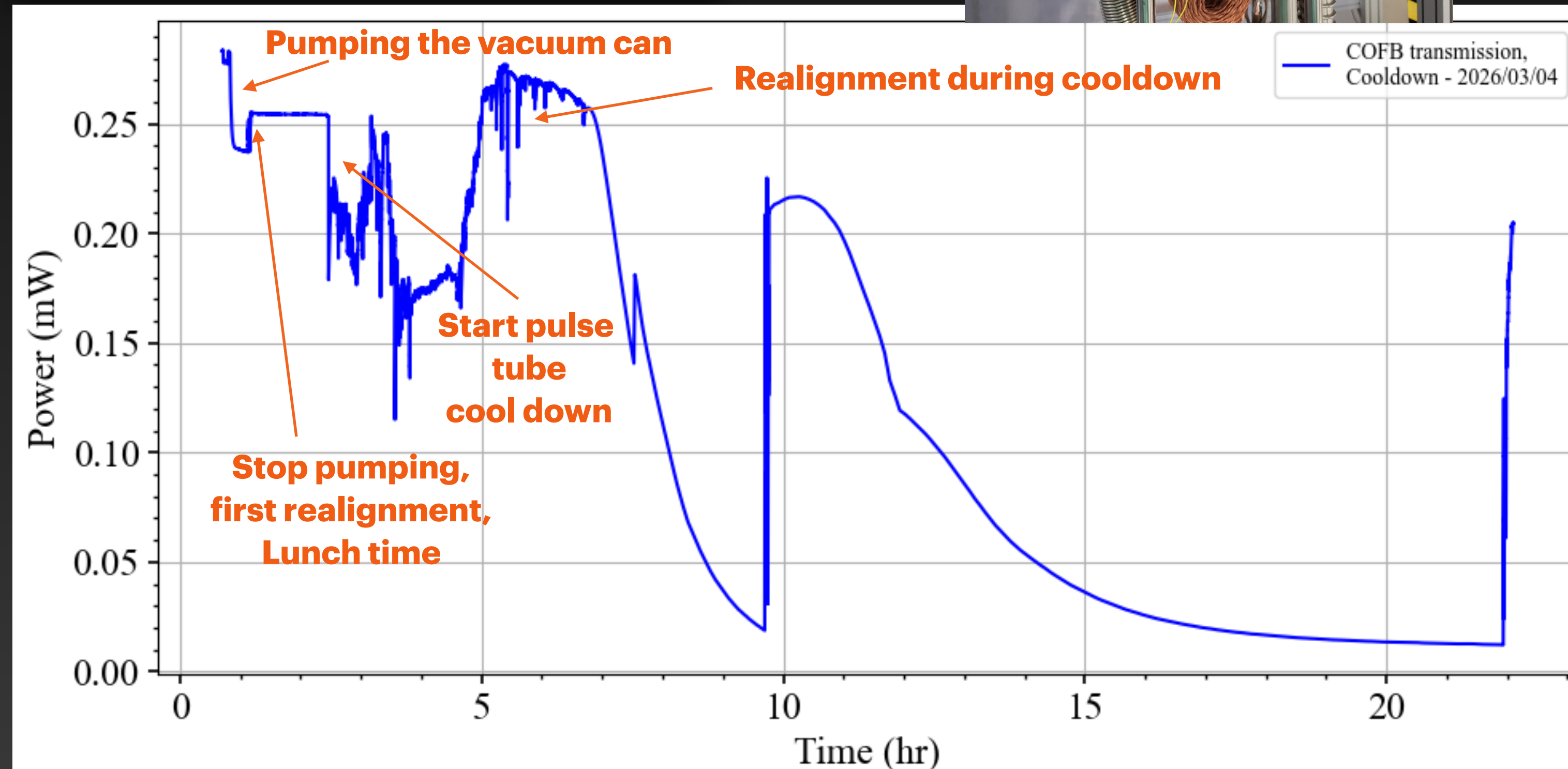
Installation of first prototype in dilution refrigerator



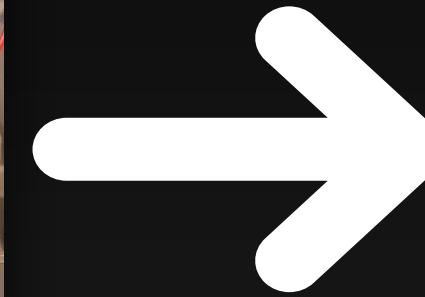
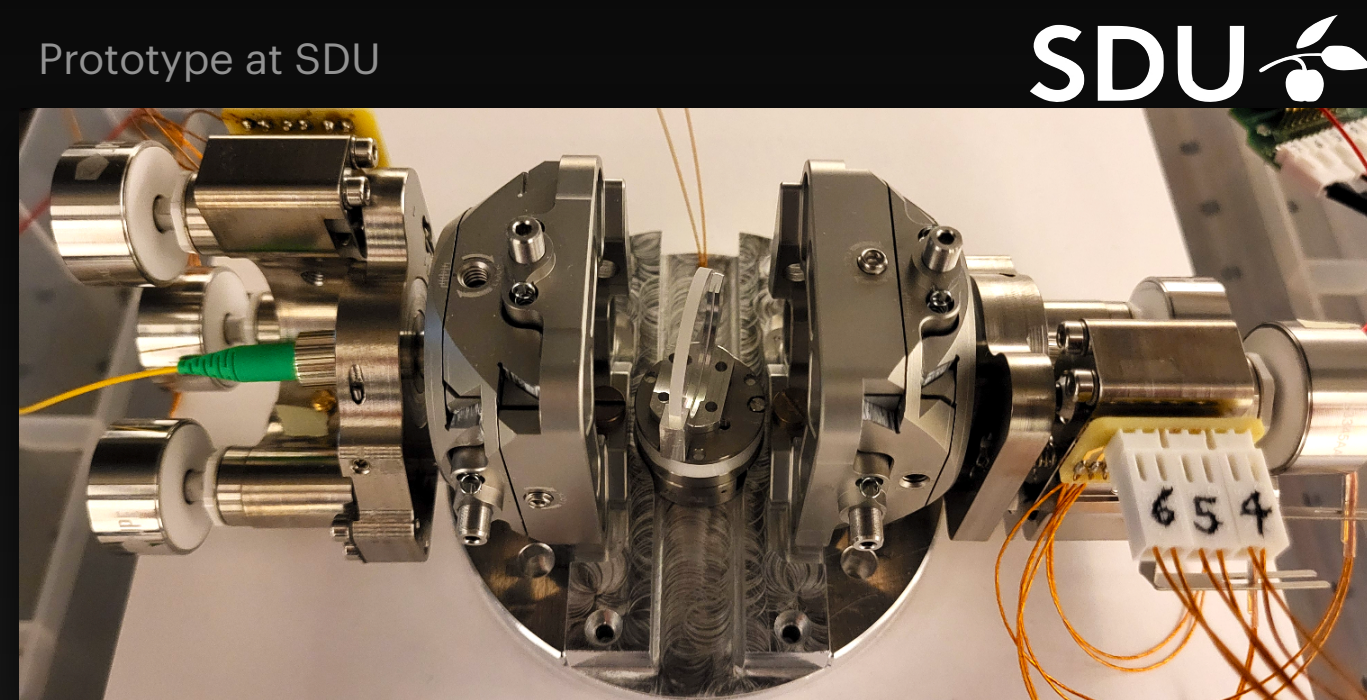
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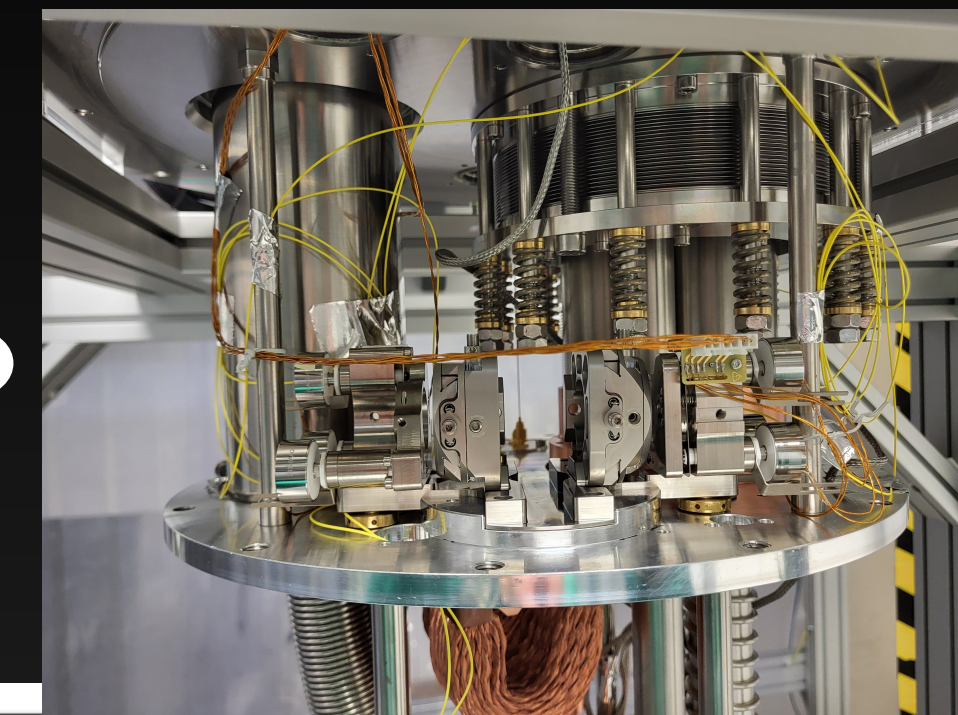
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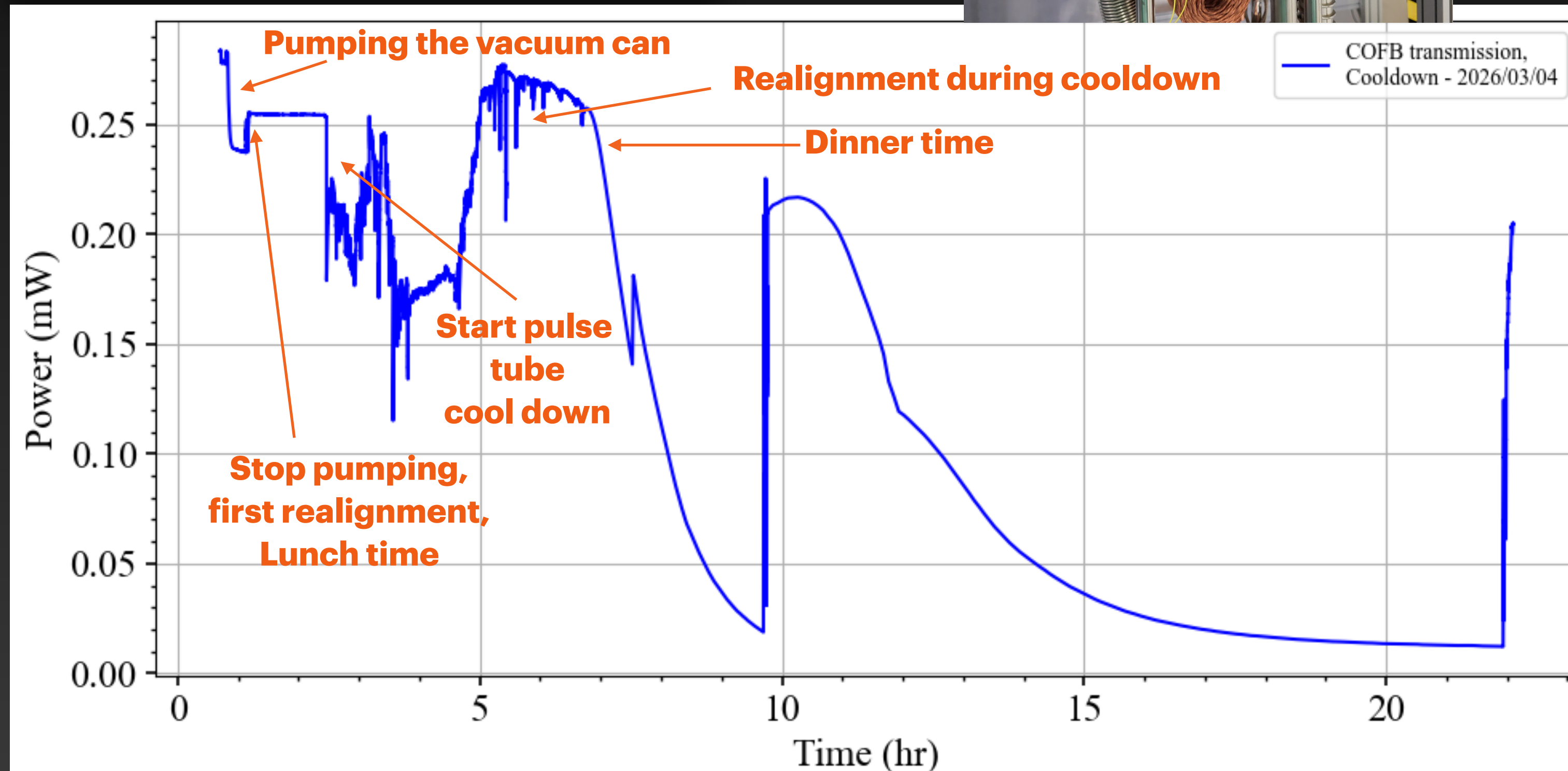
Installation of first prototype in dilution refrigerator



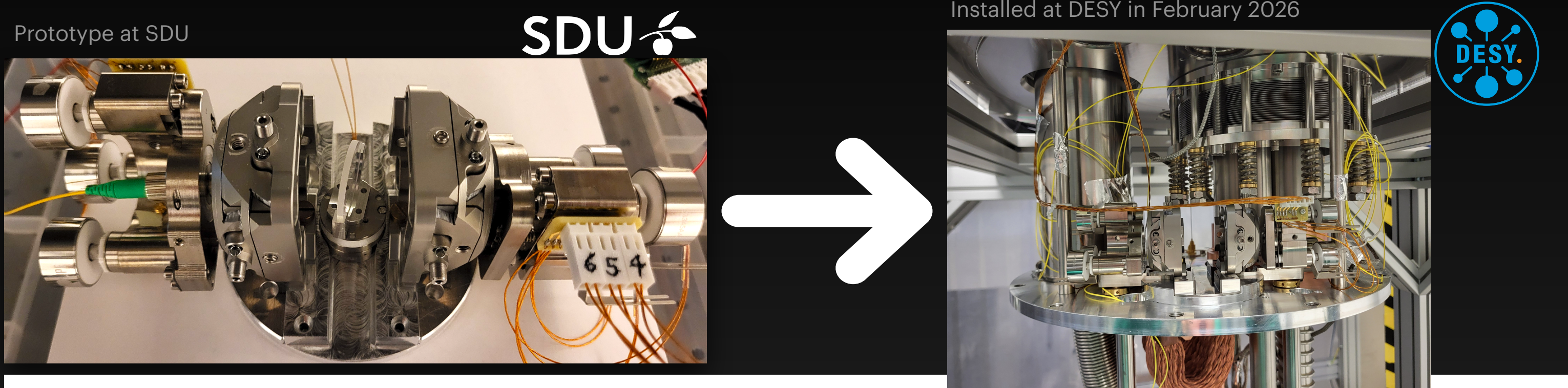
Installed at DESY in February 2026



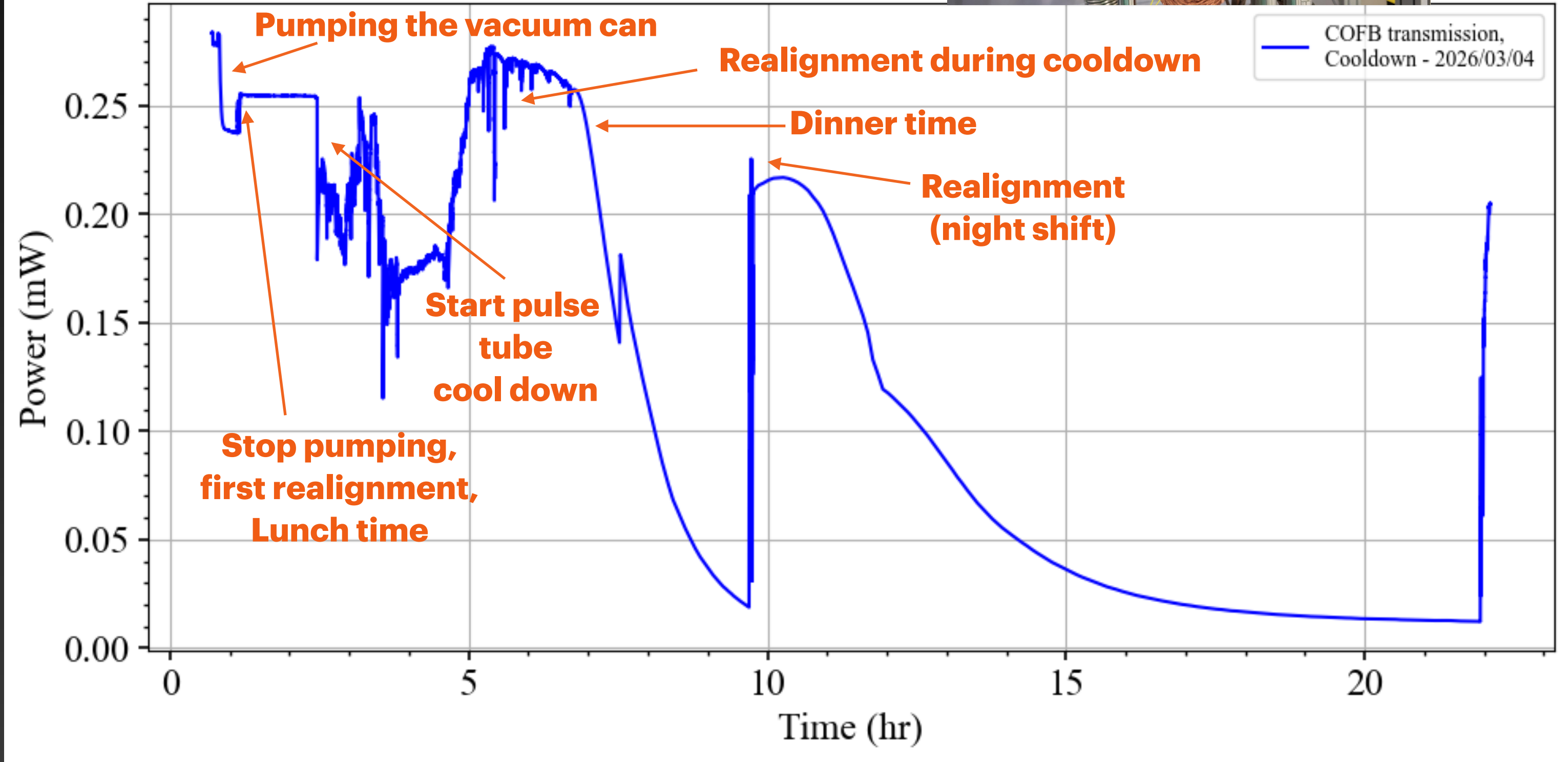
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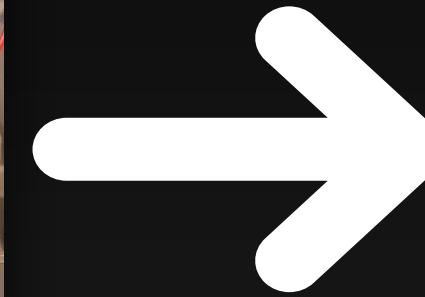
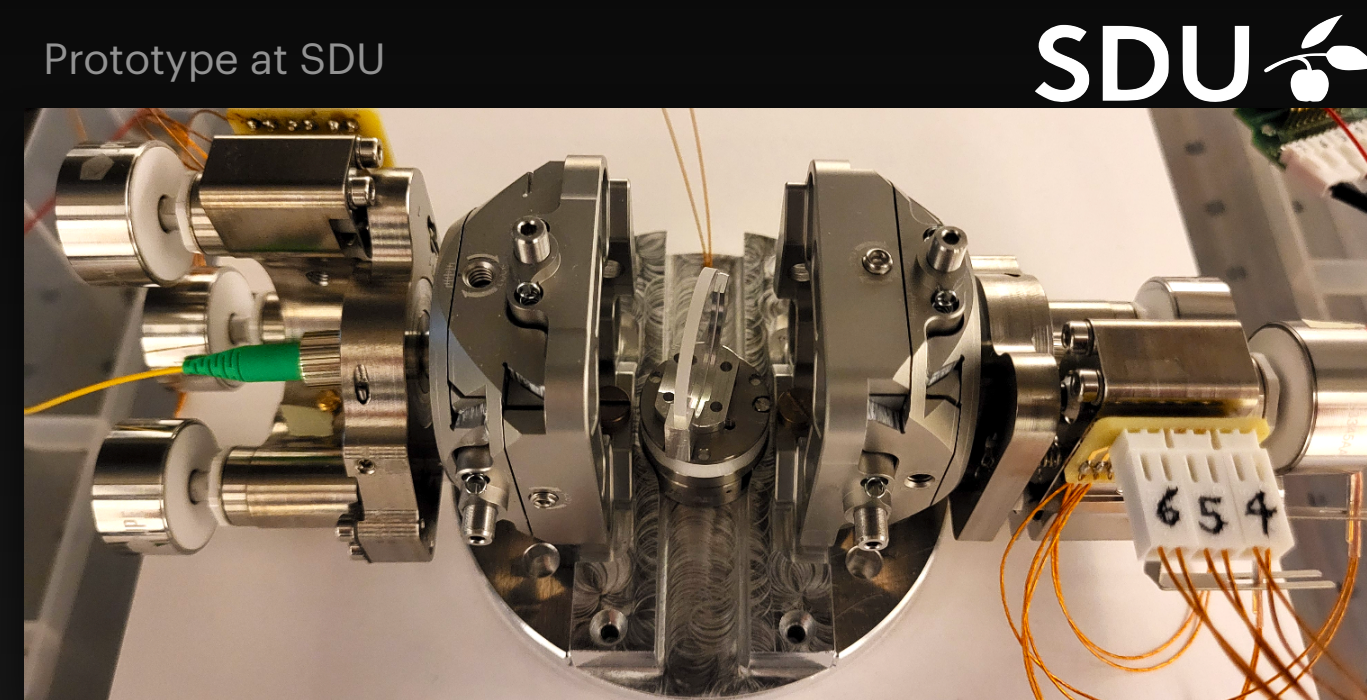
Installation of first prototype in dilution refrigerator



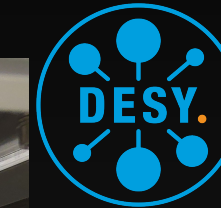
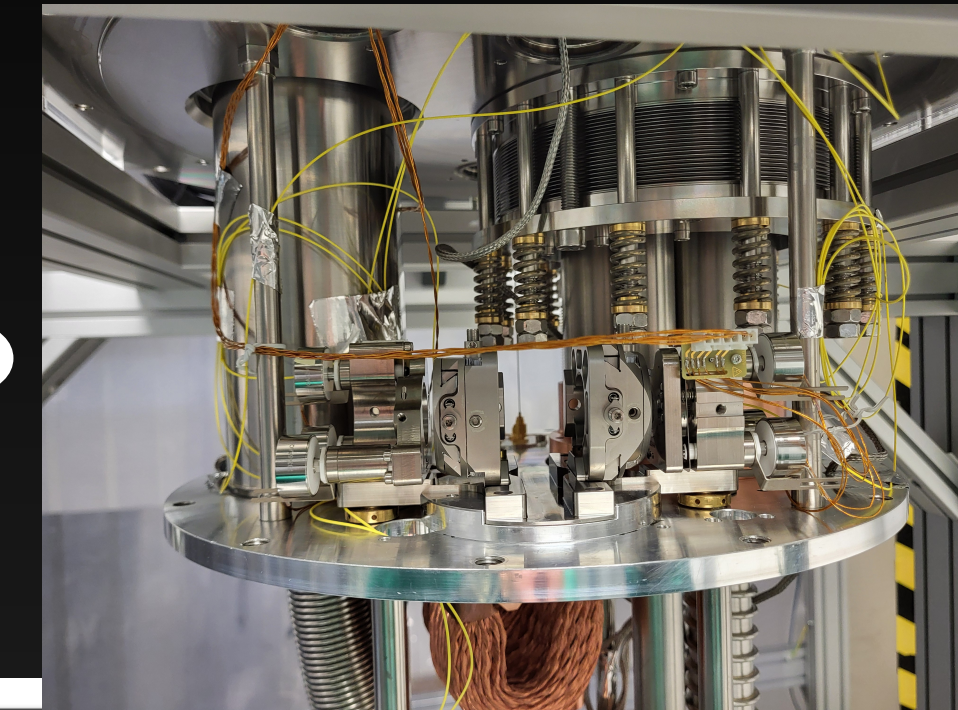
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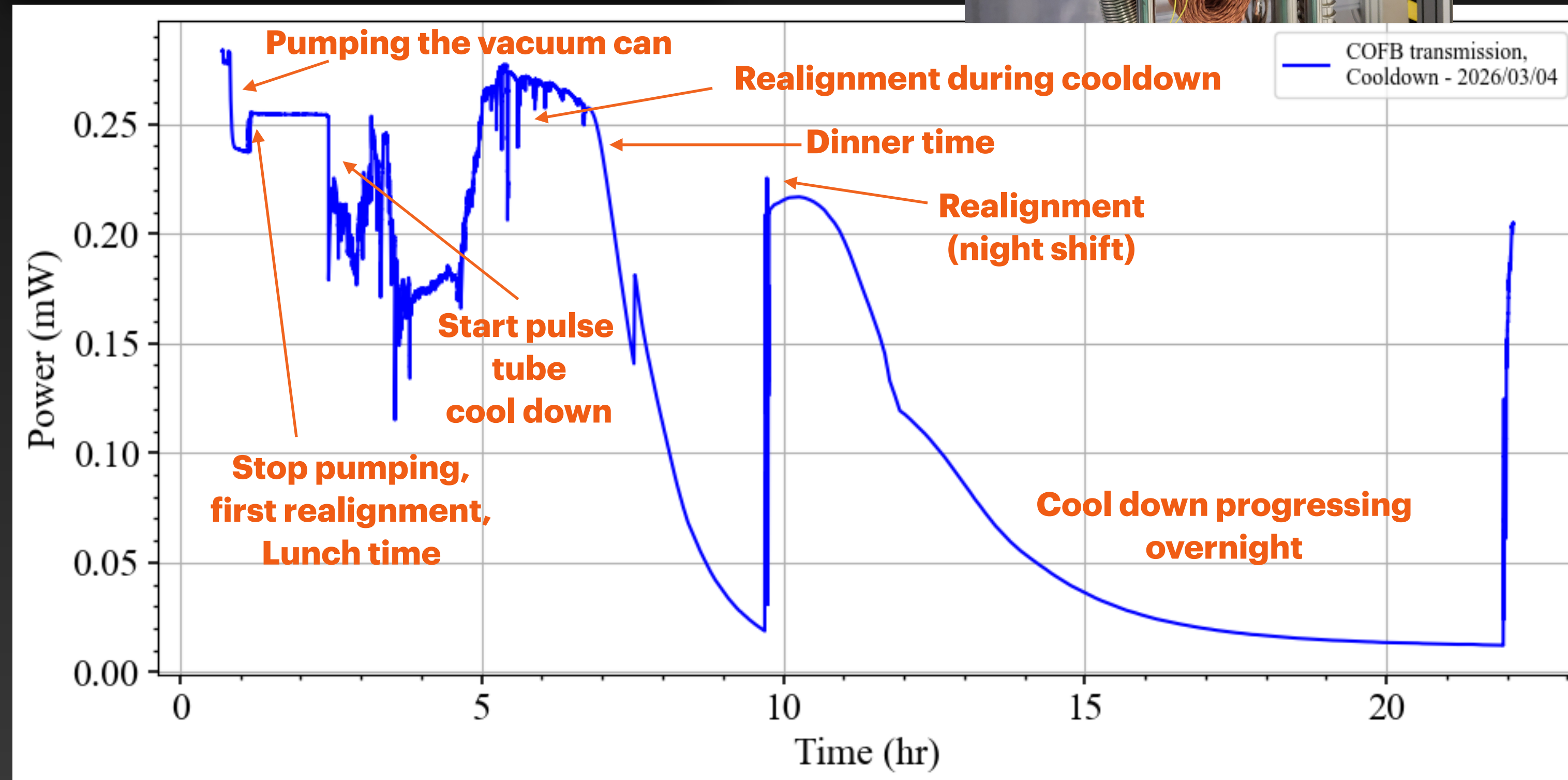
Installation of first prototype in dilution refrigerator



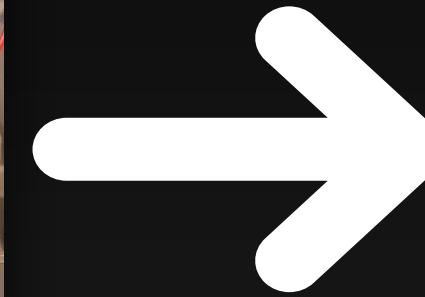
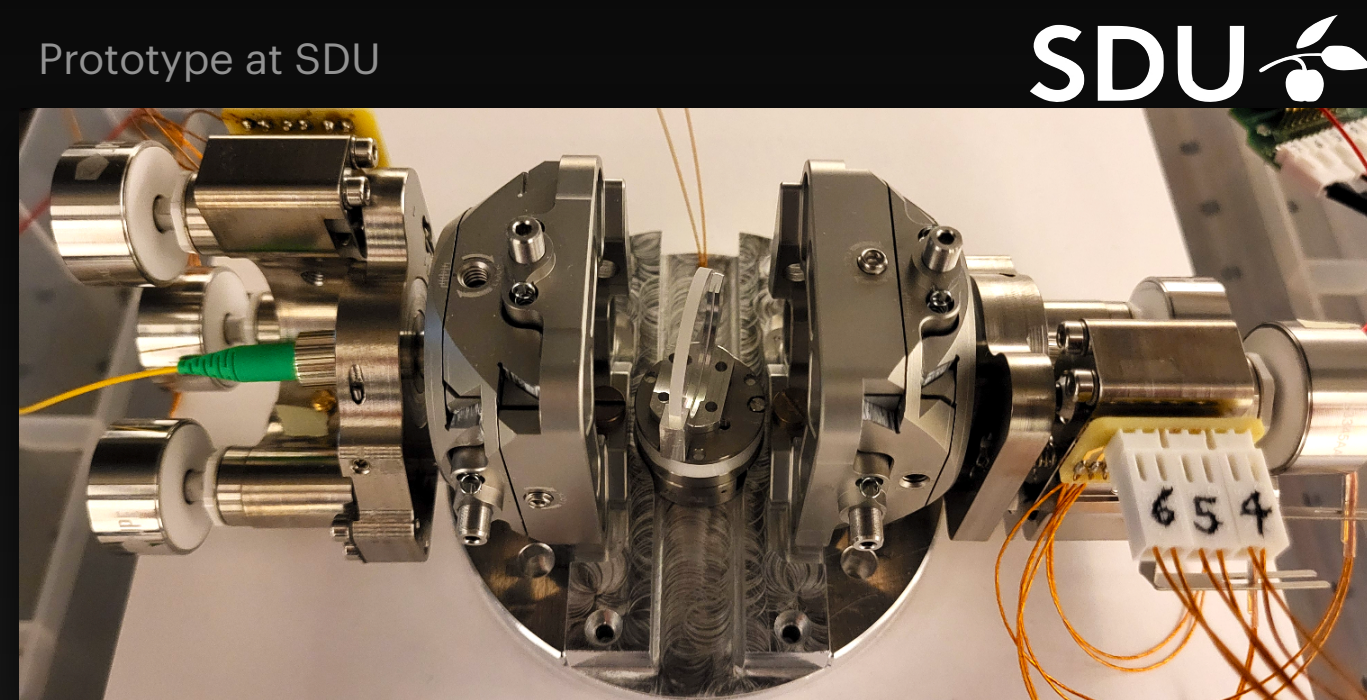
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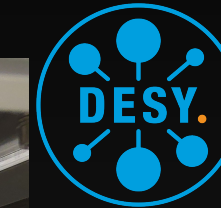
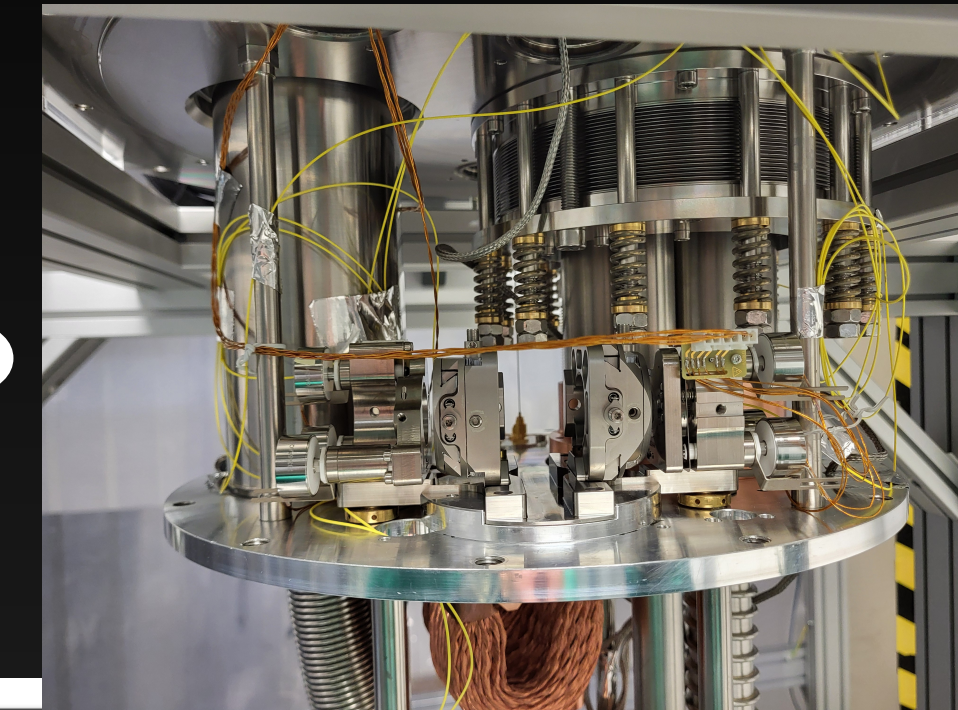
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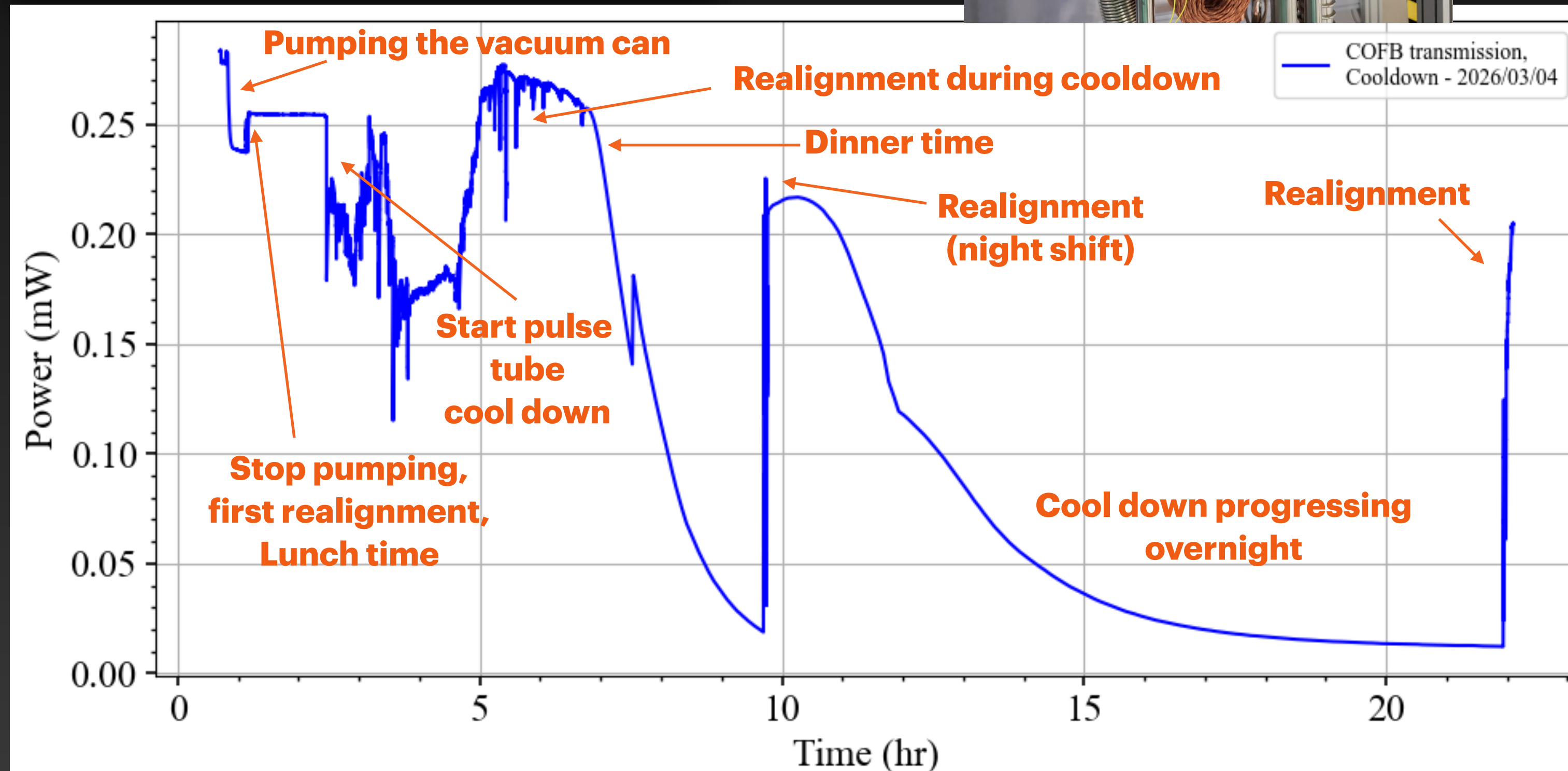
Installation of first prototype in dilution refrigerator



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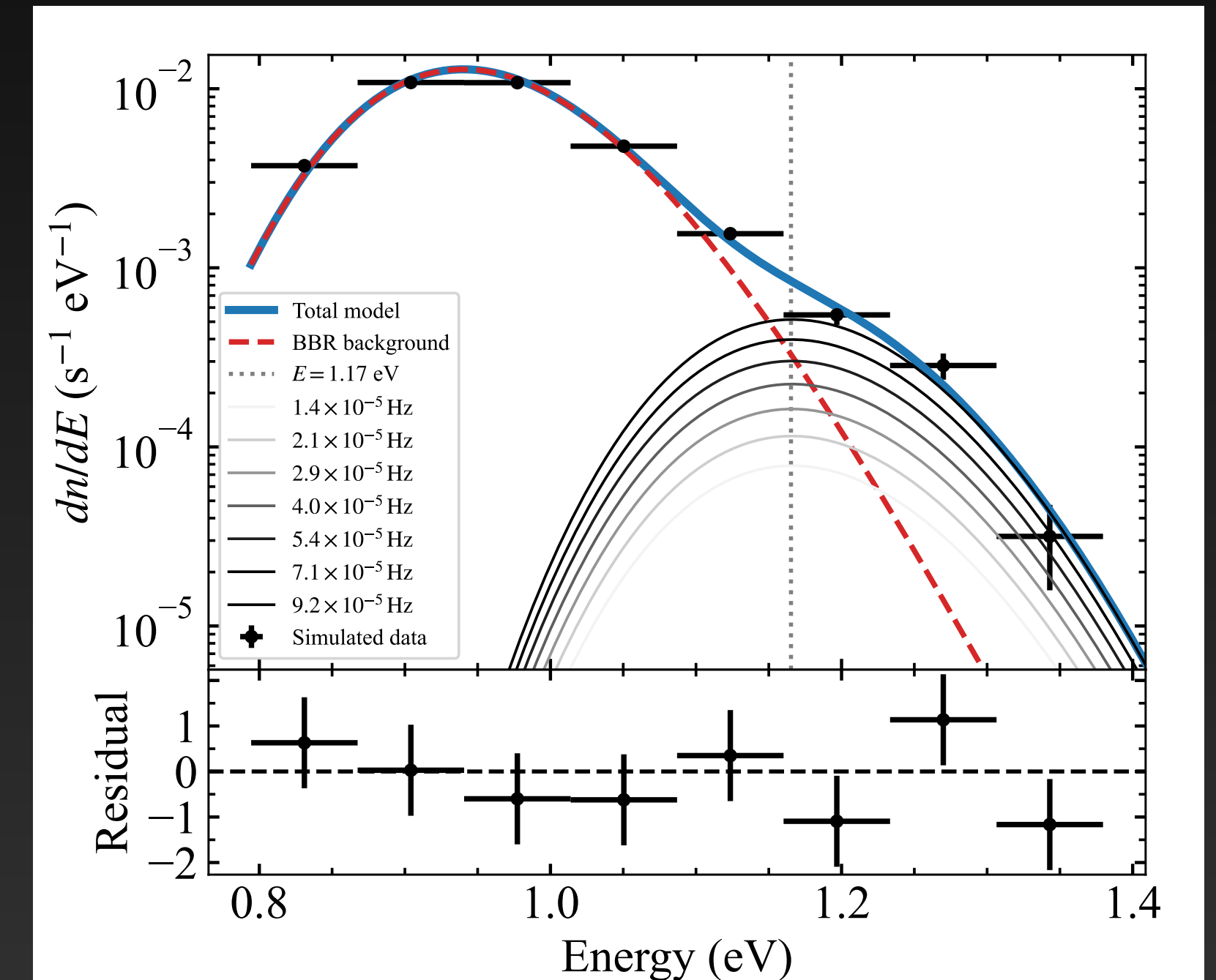


Conclusions



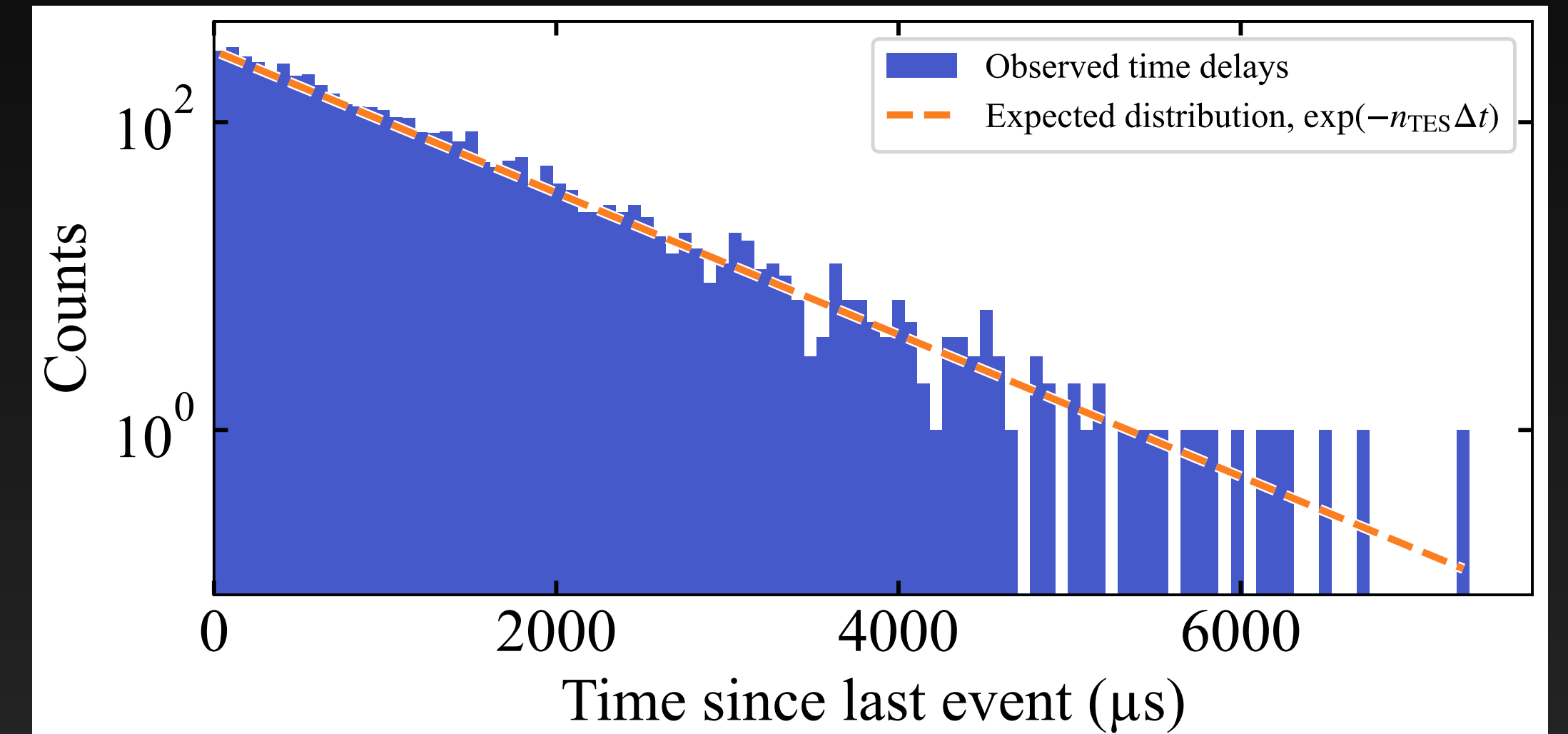
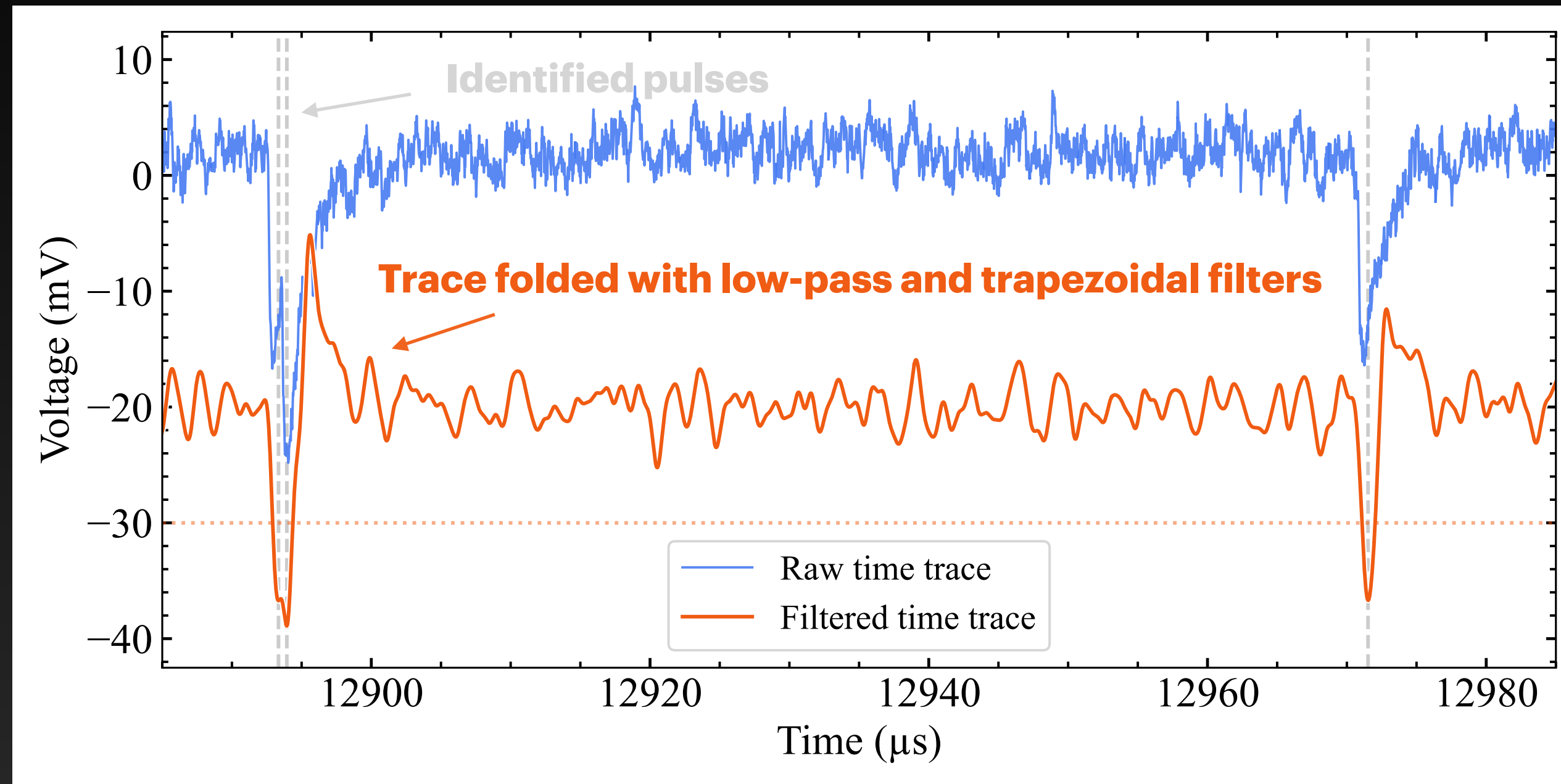
MM et al., arxiv:2605.07423

- Actively characterizing optical / infrared TESs for fundamental physics applications
- Have achieved an SDE of 86% and $bDCR = 2.2 \times 10^{-3}$ Hz
- Developing analysis and simulation frameworks for rare event searches with TESs
- 20 day measurement should be sensitive to:
 - Detection of $n_0 \geq 2.7^{+0.8}_{-0.6} \times 10^{-5}$ Hz photon flux at 1064nm
 - ALPS II: $g_{a\gamma}^{\text{ALPS II}} \gtrsim 2.38^{+0.16}_{-0.14} \times 10^{-11} \text{ GeV}^{-1}$
 - LIDA: $g_{a\gamma}^{\text{LIDA}} \gtrsim 2.57^{+0.35}_{-0.30} \times 10^{-14} \text{ GeV}^{-1}$
- Developing an auto-alignable cryogenic optical filter bench to suppress blackbody backgrounds



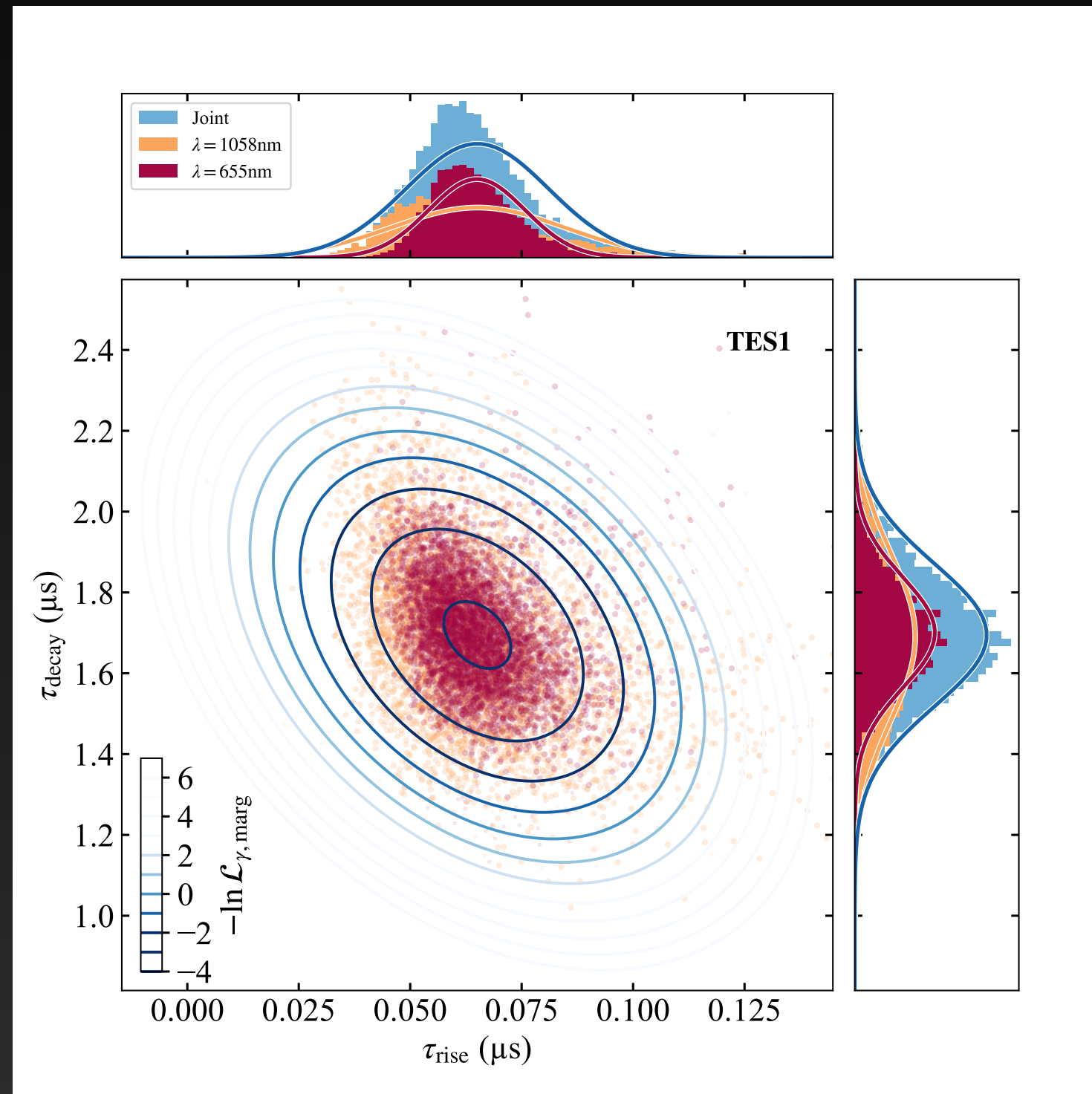
Backup

Counting photons and SDE results

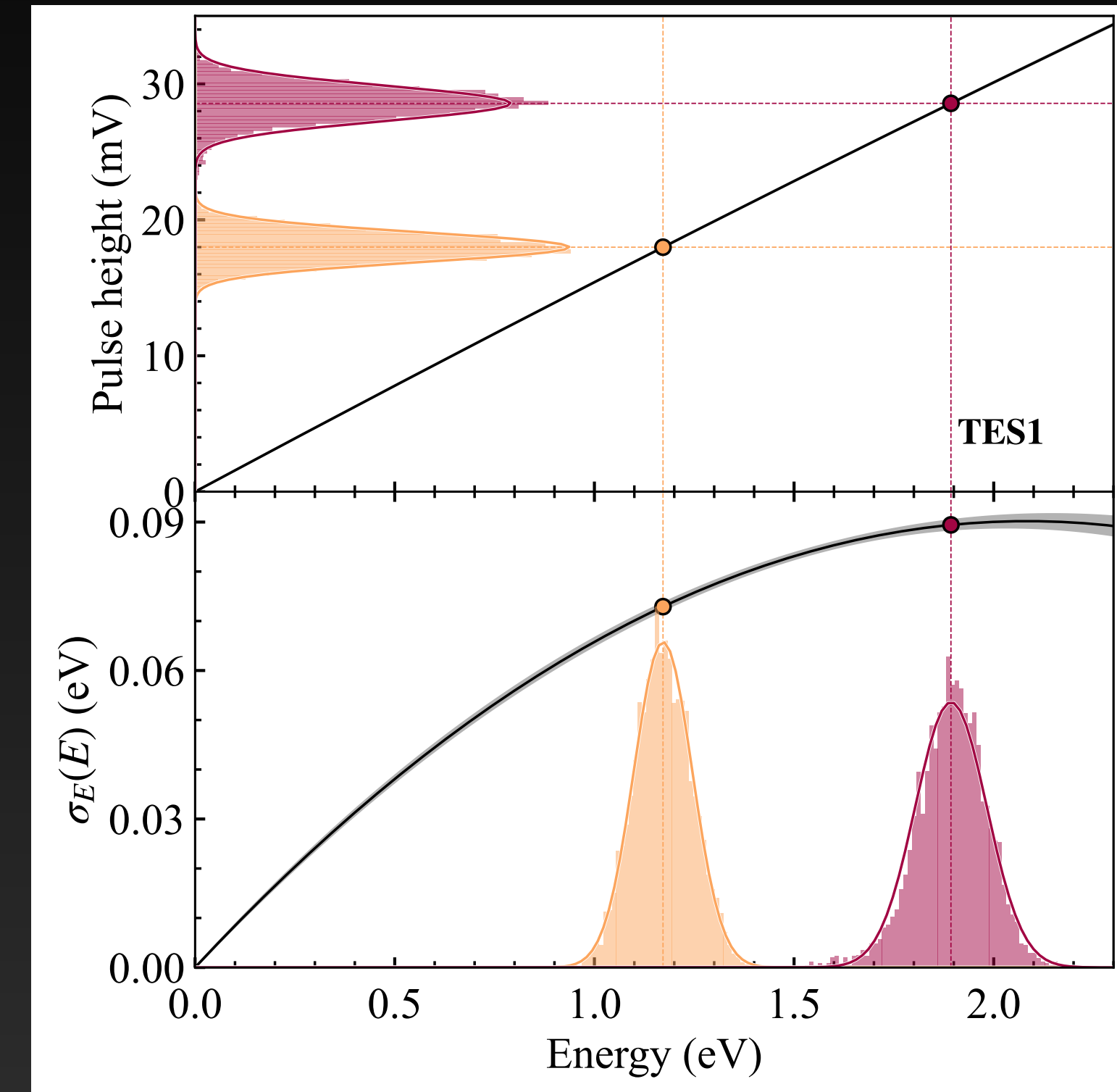


- We confidently identify pulses with separation $\gtrsim 0.5 \mu\text{s}$
- Time intervals follow expectation from Poisson process, no significant dead time
- **Both channels show an SDE of $86\% \pm 1\%$**

Photon selection and energy calibration



- Illuminated TESs with 1064nm and 655nm laser light
- Traces fit with exponential rise and decay function
- Selection of photon-like events based on best-fit parameters



- Pulse height of photon-like events used to calibrate energy
- Energy resolution @ 1064nm:
 - $\Delta E/E = 0.062 \pm 0.001$
 - $\text{FWHM} = (0.172 \pm 0.002) \text{ eV}$