A TES for ALPS II and further dark matter searches

8th MT Student Retreat

Christina Schwemmbauer on behalf of the ALPS II collaboration

ALPS, DESY
Hamburg, 28.09.2022

Dark Matter

Beyond the Standard Model

Dark **M**atter (DM)

- Makes up ~25% of the universe
- Mainly interacts gravitationally with ordinary matter

Indications include:

  - Galaxy rotational curves
  - Galaxy cluster dynamics
  - Gravitational lensing
  - … many more

Numerous DM models

  - Mass (30 solar masses to 10^{-21} eV)
  - SM coupling
  - Cross-section (in case of scattering experiments)

Techniques include direct detection and indirect detection (depending on model)

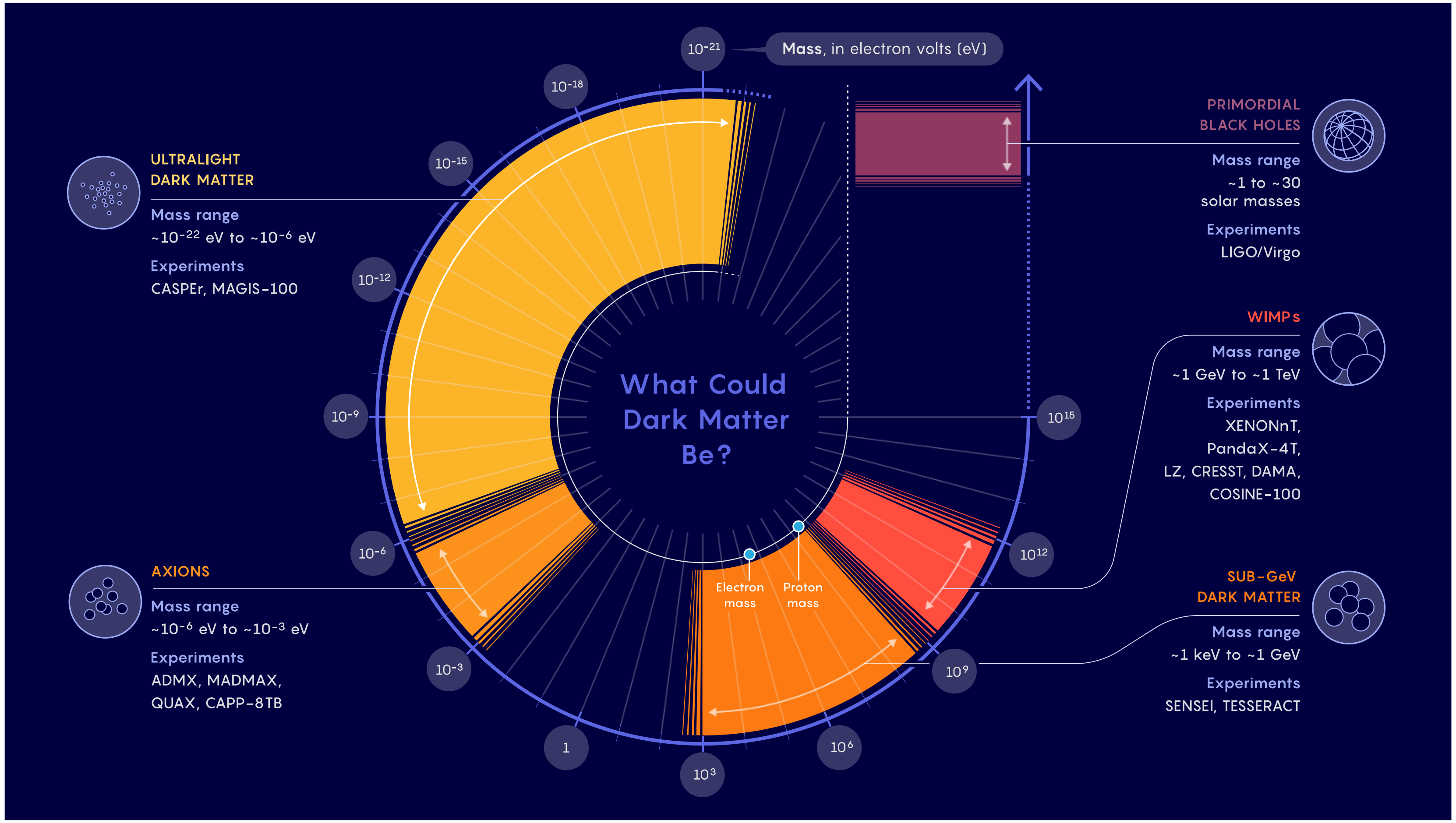

Image Credit: Samuel Velasco/Quanta Magazine

Countless theories: What can we actually detect?

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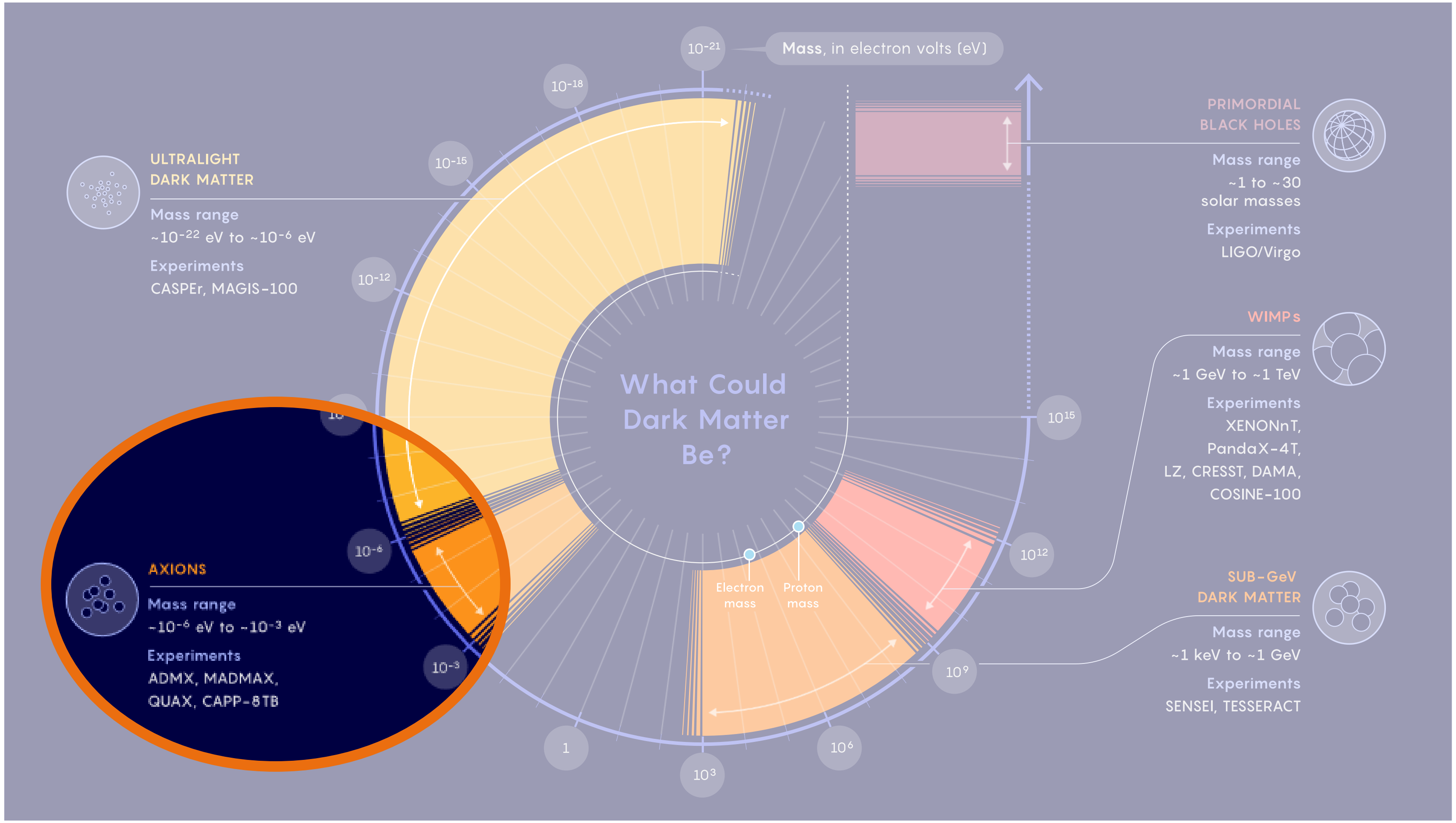

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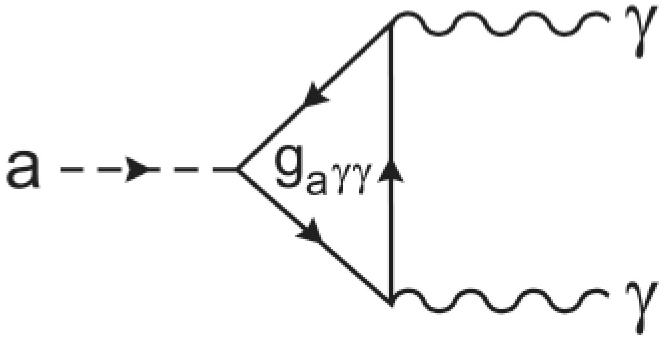
Countless theories: What can we actually detect?

Axions and Axion-like particles (ALPs)

Solving the strong CP problem

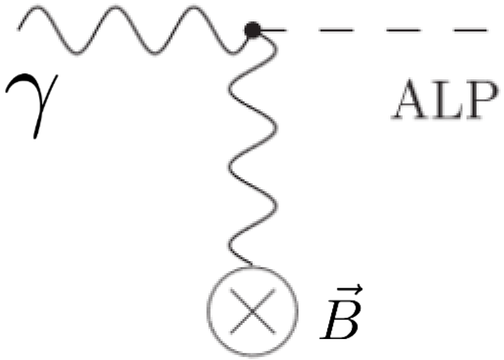
- Axions originally proposed to solve strong CP problem
- WISPs (**W**eakly **I**nteracting **S**ub-eV **P**articles)

- Axions or ALPs could constitute all or part of cold dark matter
- Many cosmological hints (e.g. anomalies in stellar evolution)
- 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

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



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

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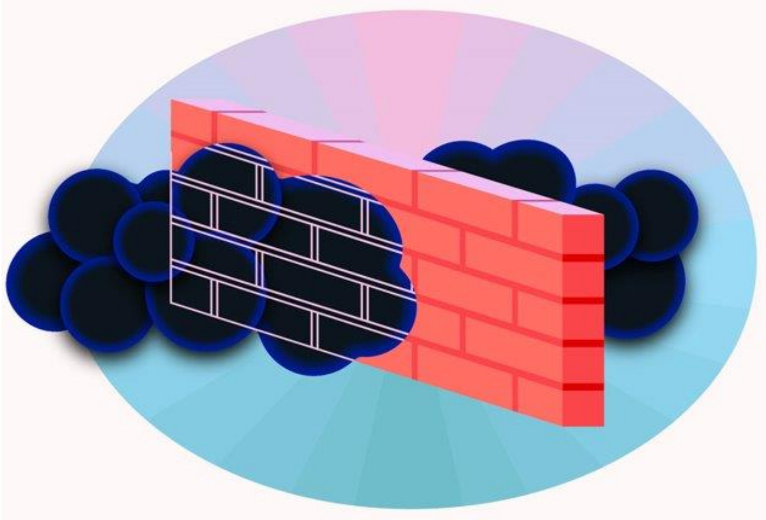
Solving the strong CP problem

Illustration by Sandbox Studio, Chicago with Ana Kova



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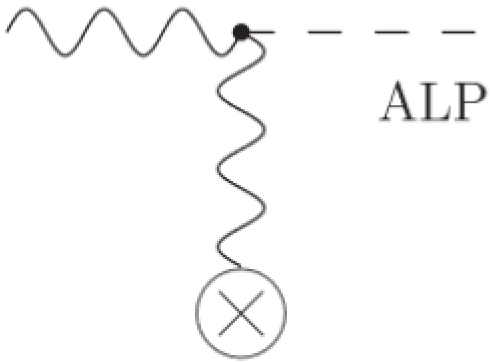
➡ **L**ight **S**hining Through **W**alls (LSW) experiments



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The ALPS II experiment

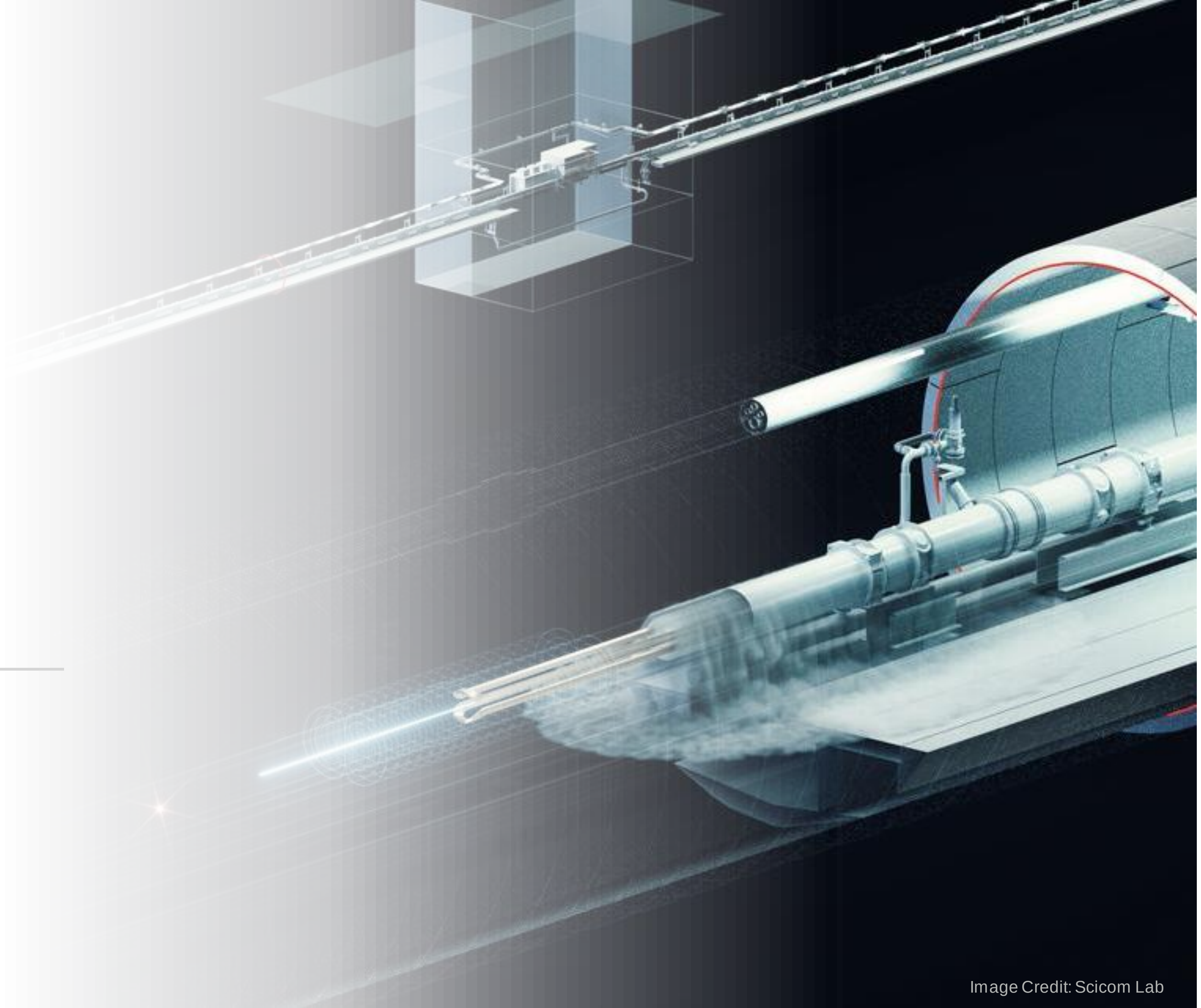
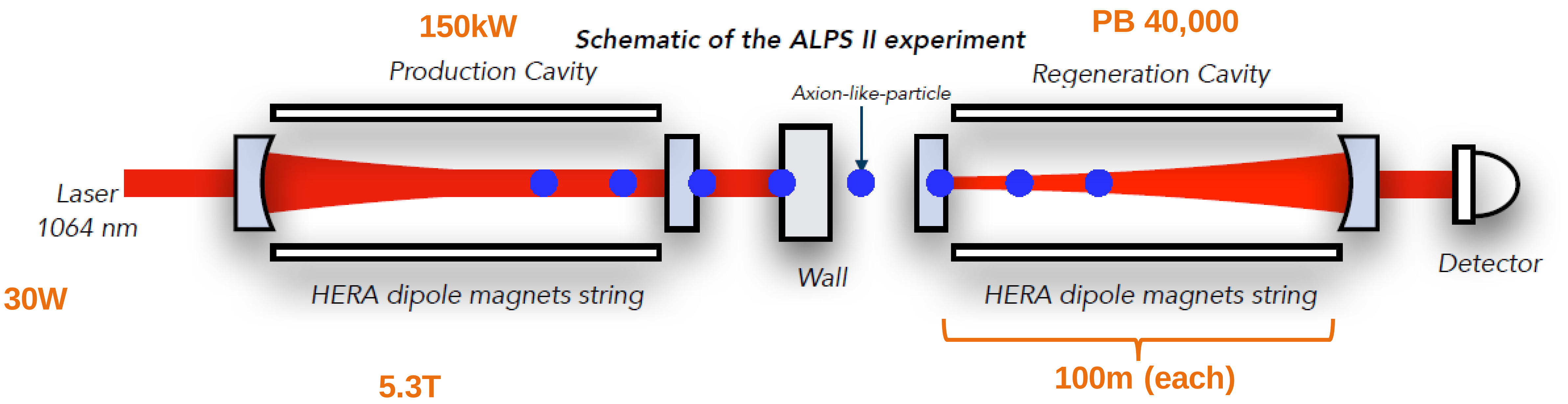


Image Credit: Scicom Lab

Any Light Particle Search with ALPS II

Searching for Axion-like Particles

Drawing courtesy of Rikhav Shah



150kW

PB 40,000

30W

5.3T

100m (each)

Detection probability:

$$P_{\gamma\to a\to\gamma} \propto PC \cdot RC \cdot g^4_{a\gamma\gamma} B^4 L^4$$

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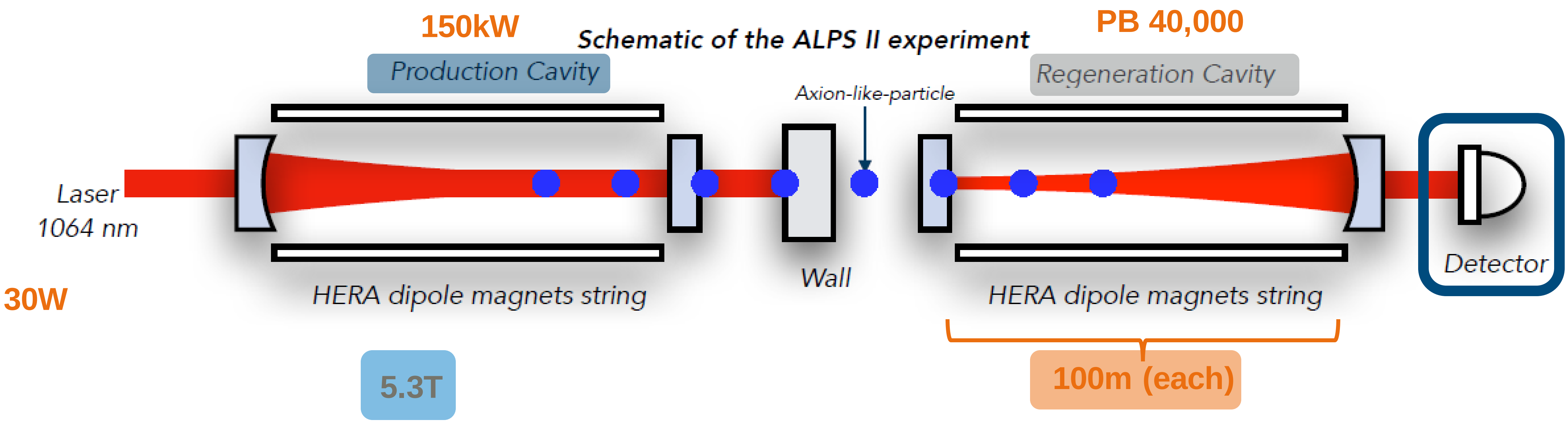

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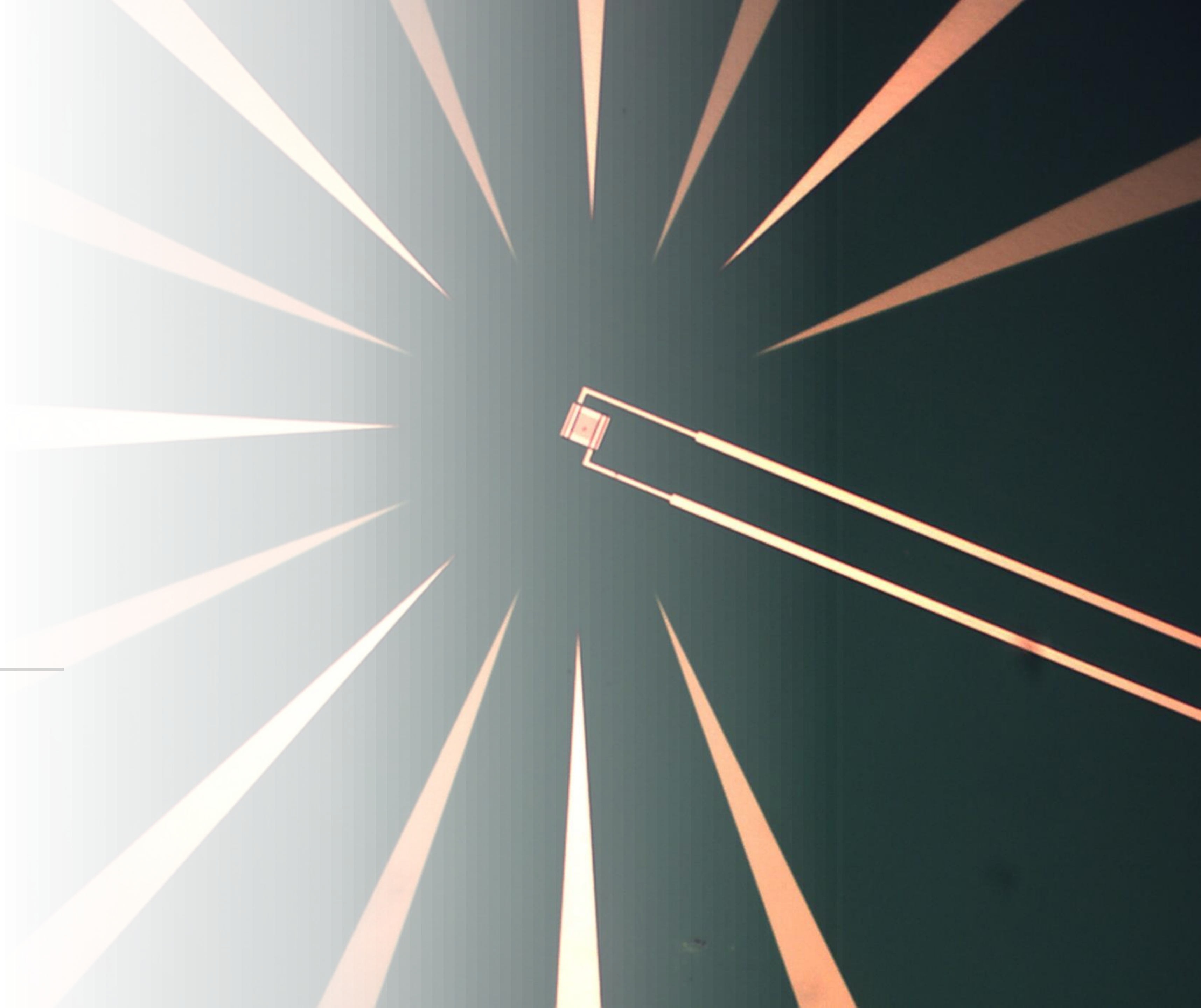
Expected rate of low energy ($\sim 1.16\,\mathrm{eV}$) photons: $\dot{N}_{\gamma} \approx 2.8 \cdot 10^{-5}\,\frac{\gamma}{\mathrm{s}} \approx 1\,\frac{\gamma}{\mathrm{day}}$
(for $g_{a\gamma\gamma} = 2 \cdot 10^{-11}\,\mathrm{GeV}^{-1}$)

Single-photon detection requirements for ALPS II:

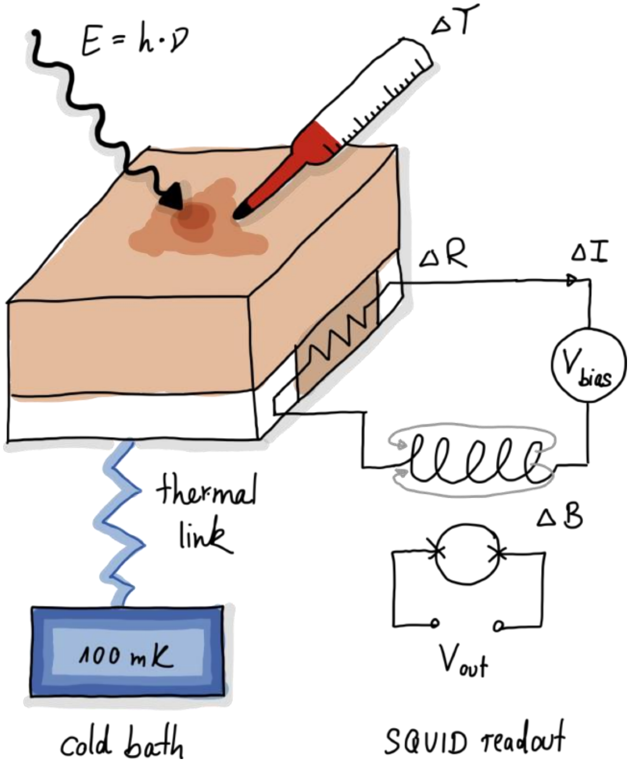
- Low energy photon detection
- Low background (less than 1 photon/day)
- High quantum efficiency
- High detection efficiency



TES single-photon detection

TES

Transition Edge Sensors

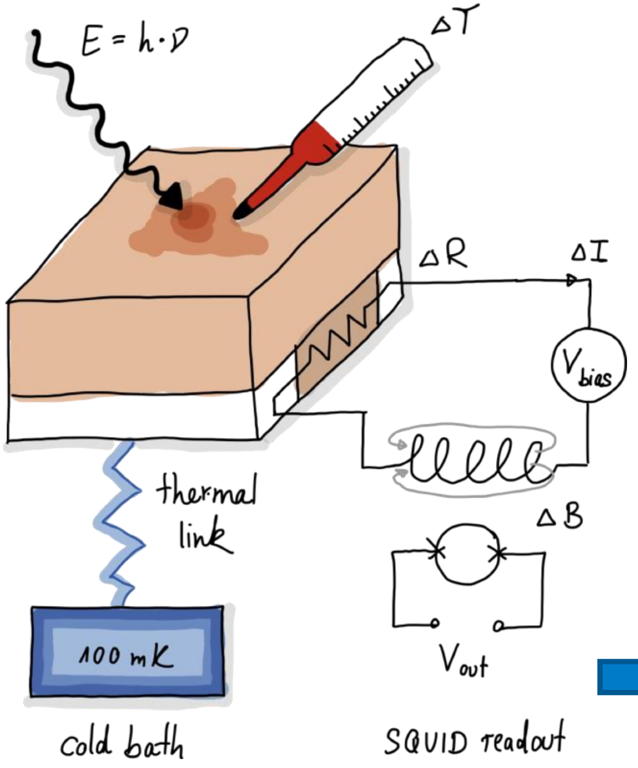


- Cryogenic microcalorimeters
- Operated at superconducting transition temperature
- Thermally connected to cold bath
- Read-out using **S**uperconducting **Q**uantum **I**nterference **D**evices (SQUIDs)

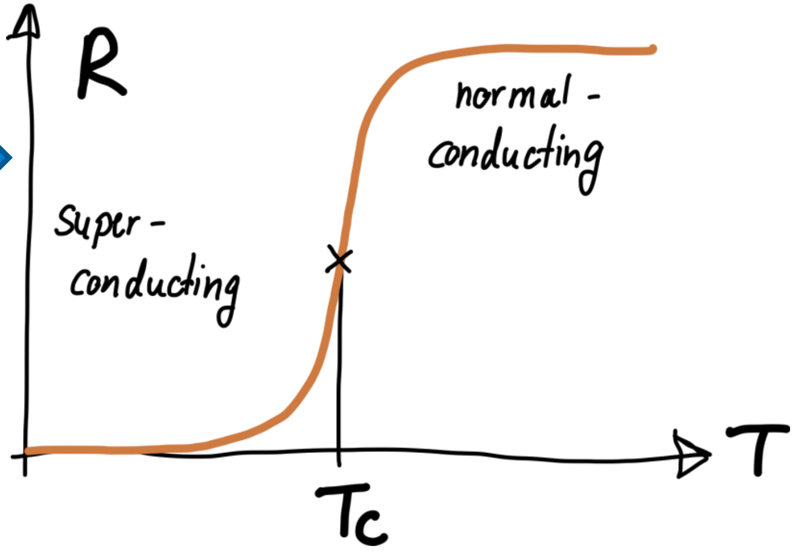
Sketches: Courtesy of K.-S. Isleif

TES

Transition Edge Sensors



- Operated at T_c ~ 140 mK
- Incident photon leads to temperature increase
- Small temperature increase leads to large variation in resistance



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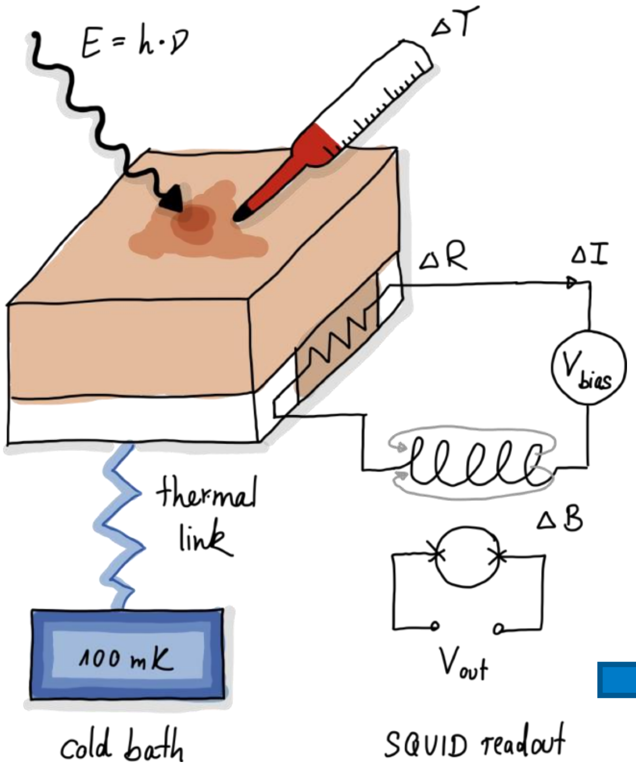
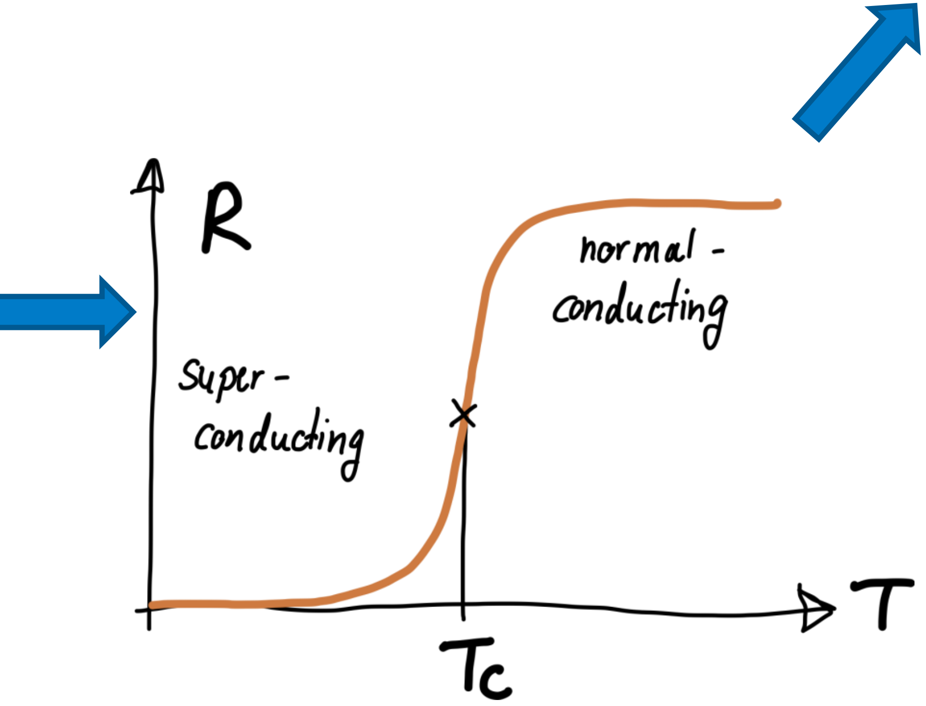
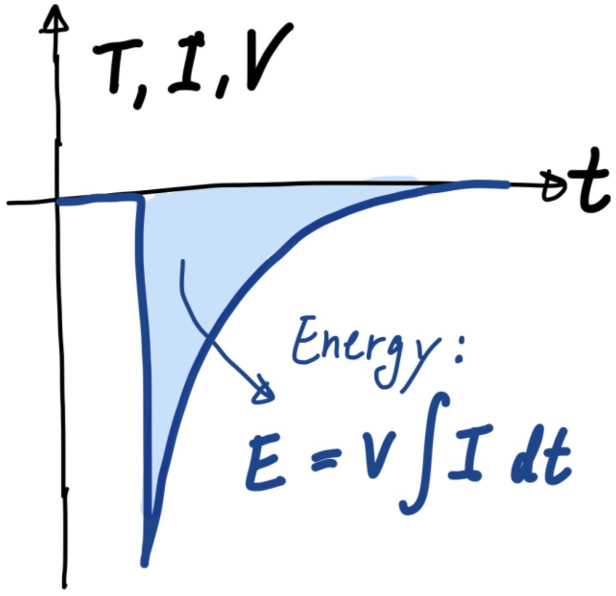




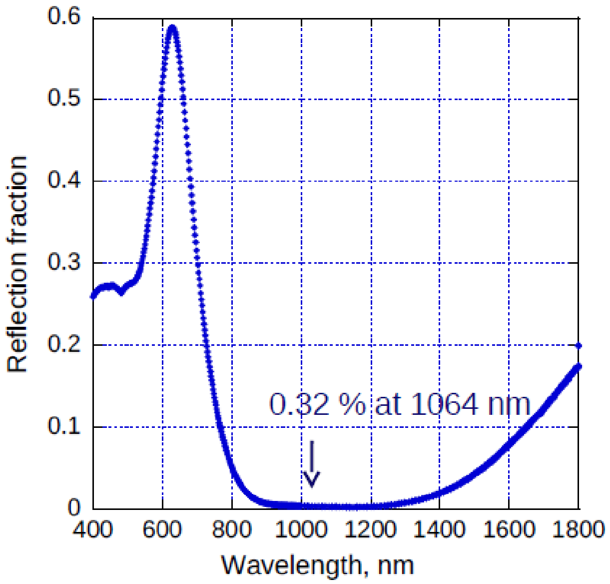


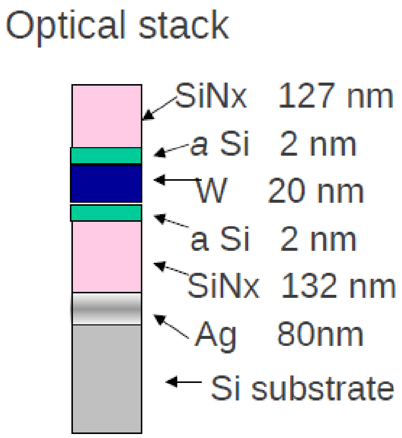
- Change in resistance is measured in changing current
- Signal is proportional to photon energy

Sketches: Courtesy of K.-S. Isleif

TES for ALPS II

Optimized optical stack

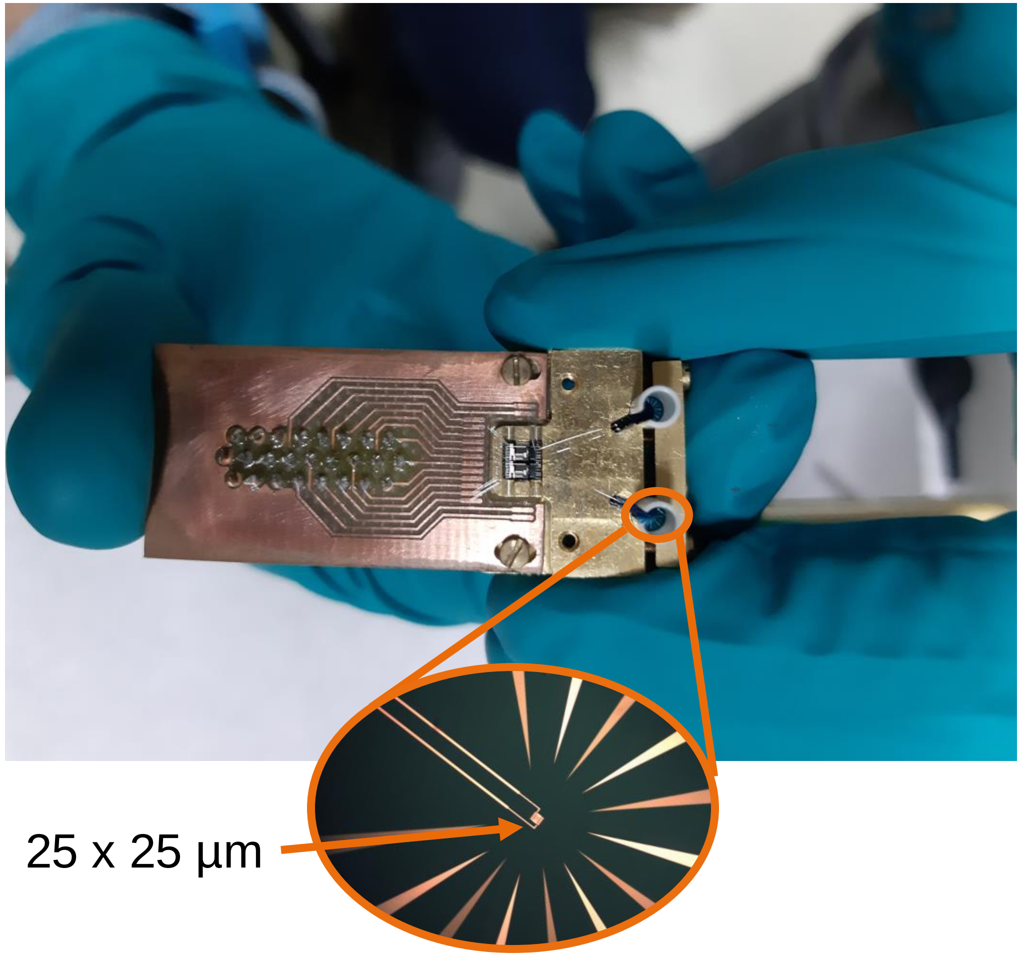




J. Dreyling-Eschweiler, Dissertation (2014)

- Optical stack optimized for 1064nm photons
- Higher reflection for other wavelengths
- Optimized efficiency

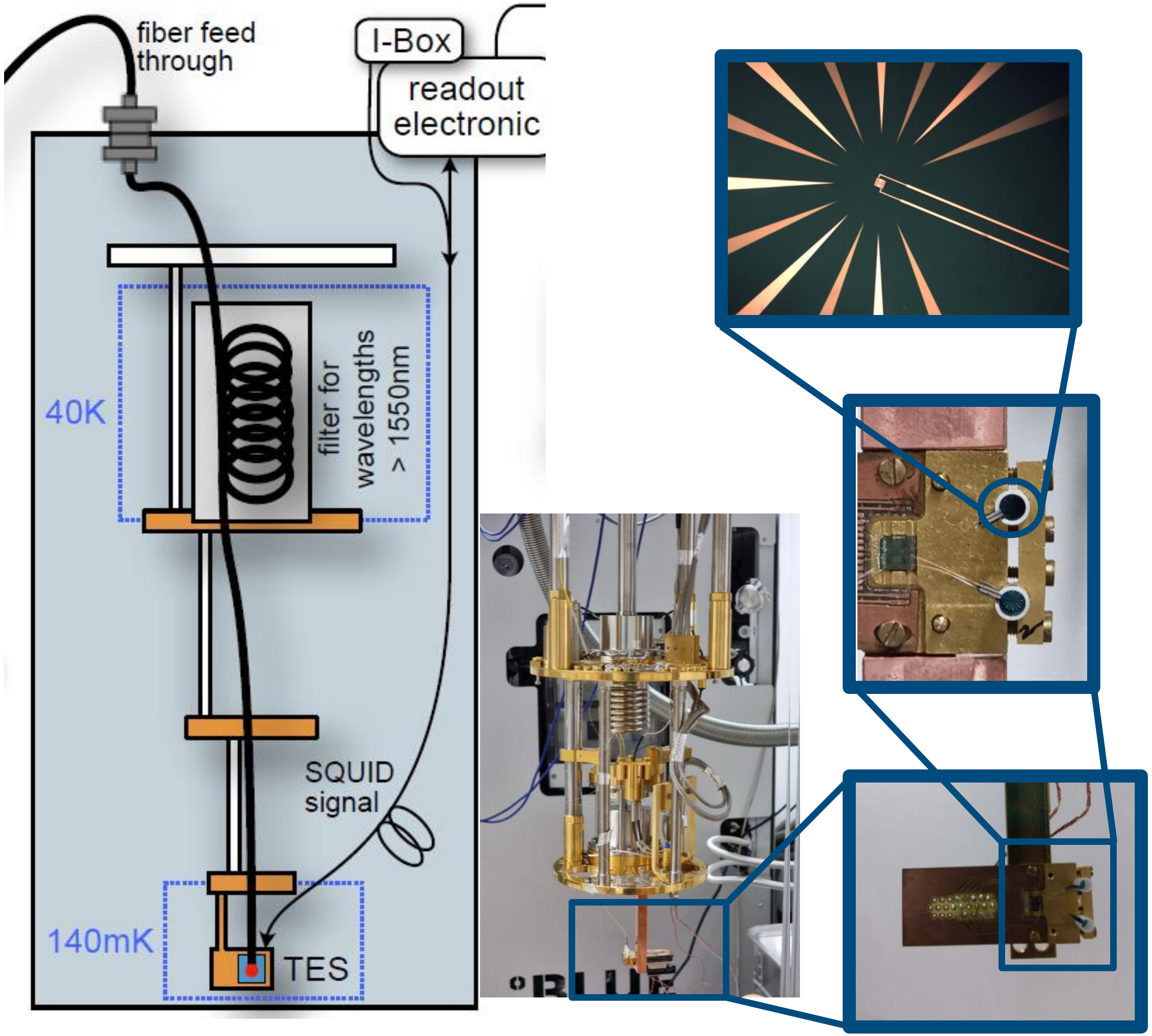
TES mount:
2x TES wire-bonded to SQUID-chips



TES for ALPS II

TES Setup

- TES mount in dilution refrigerator (cooling & shield)
- Background measurements:
  - **Intrinsic** (without fiber connection)
  - **Extrinsic** (with fiber connection)
- **Intrinsic** background (6.9 x 10^{-6} cps) viable for ALPS II!
- Good quantum efficiency and energy resolution (~8%)



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Still to do:
- Optimize and determine **system efficiency**
- Reduce extrinsic background (e.g. blackbody filtering, fiber curling)
- Determine **linearity** of TES response

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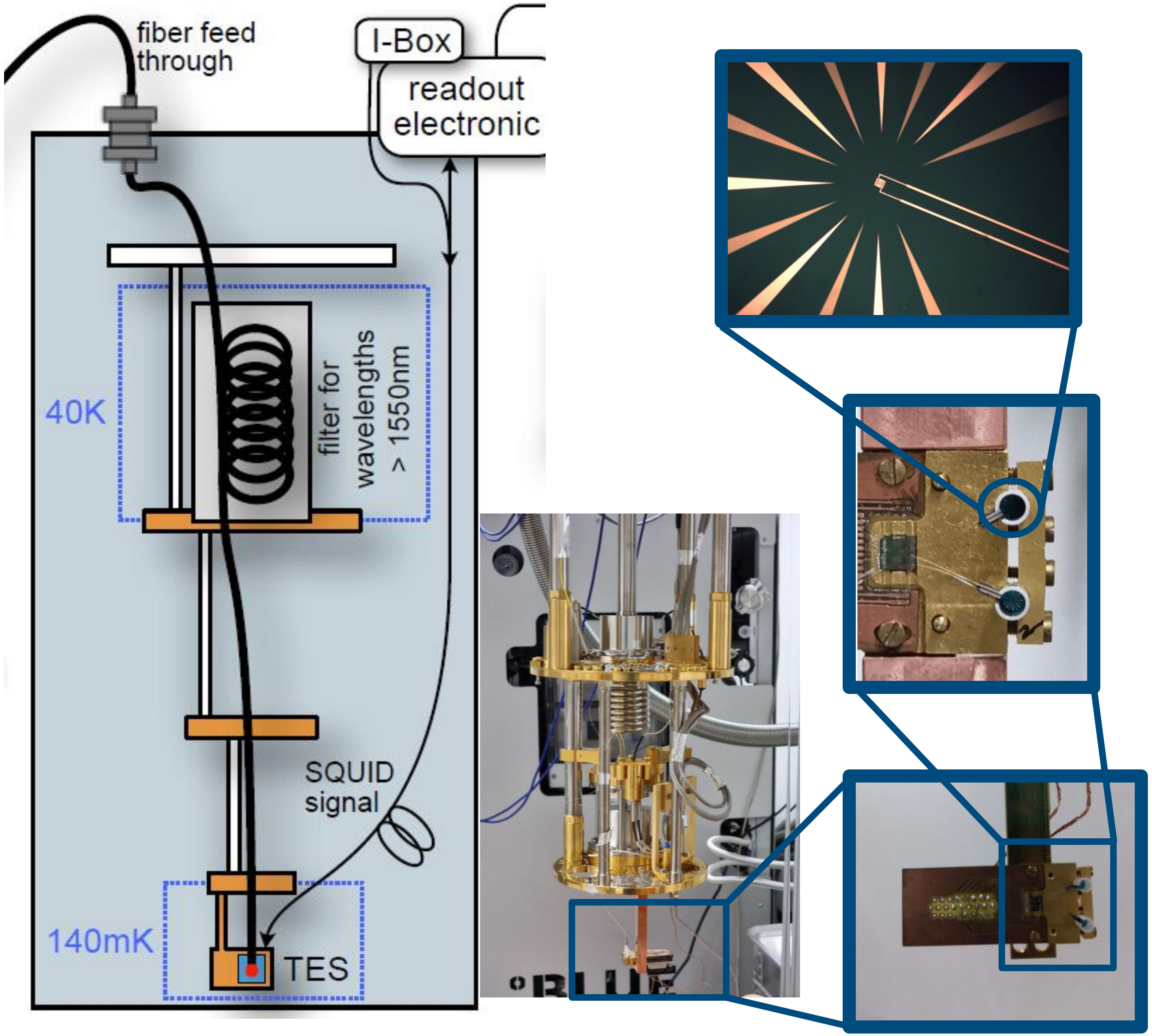

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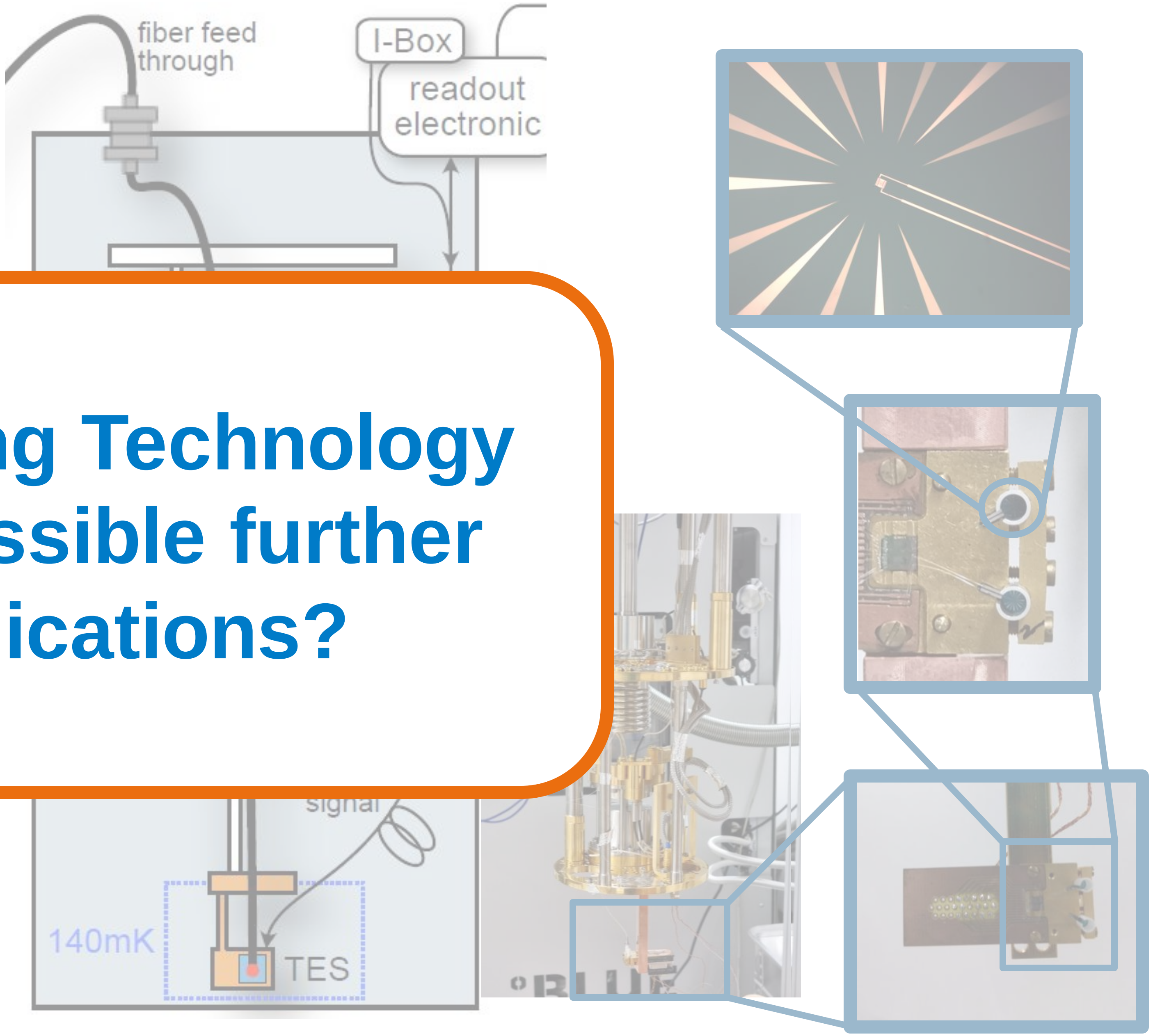

Promising Technology with possible further applications?

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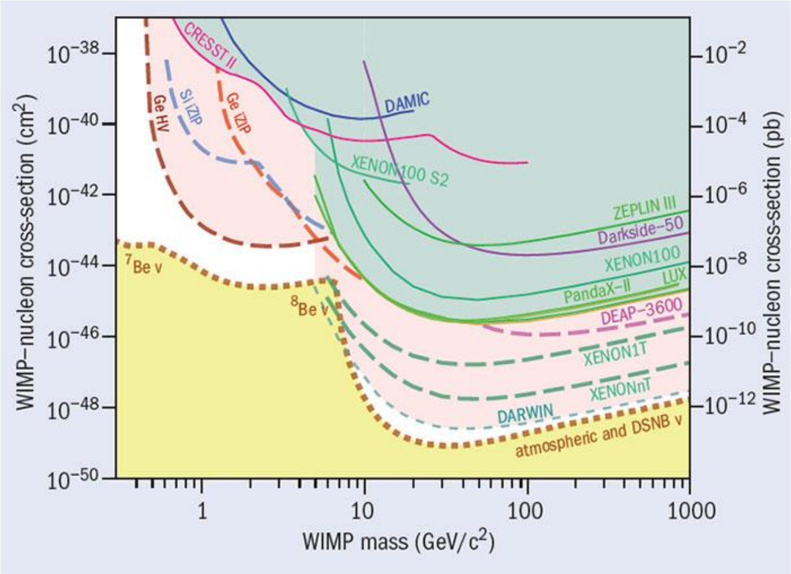
Detection of sub-MeV DM

Illustration by Sandbox Studio, Chicago with Ana Kova

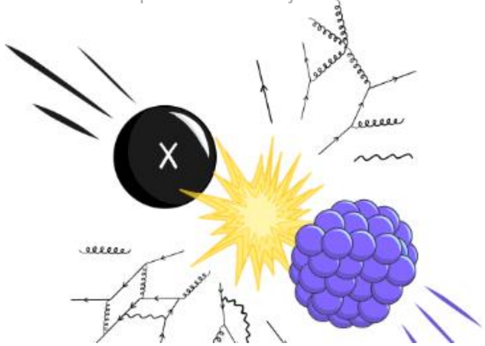
Sub-GeV dark matter?

Limits of nuclear recoil experiments



Cern Courier (2017)

Sketch adapted from Benjamin V. Lehman



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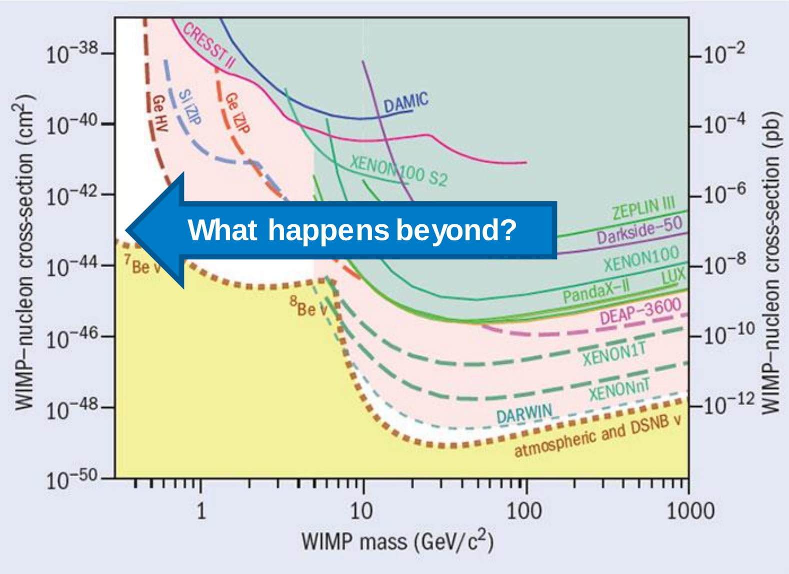

What happens beyond?

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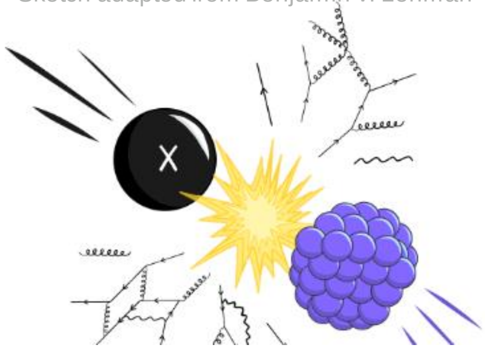

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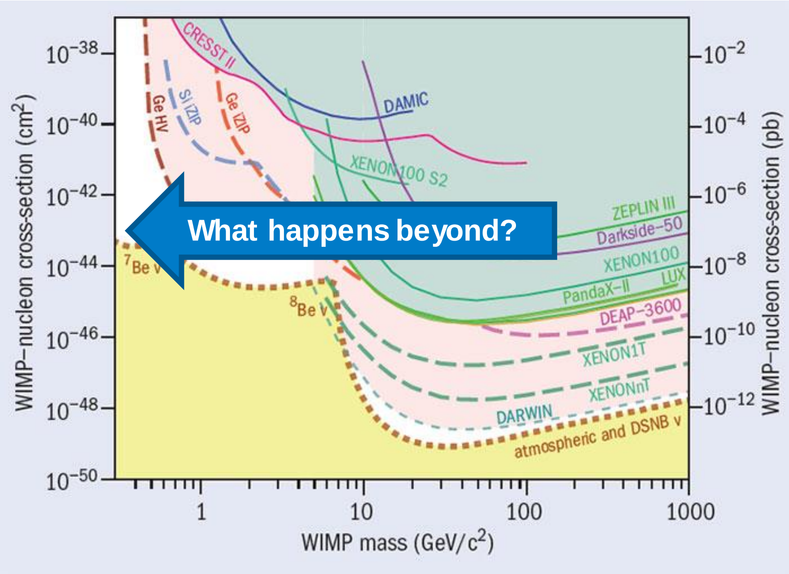

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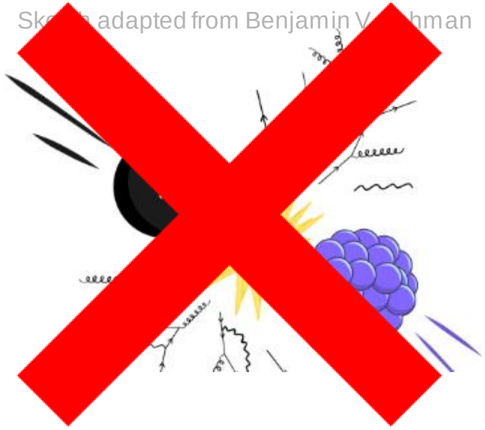

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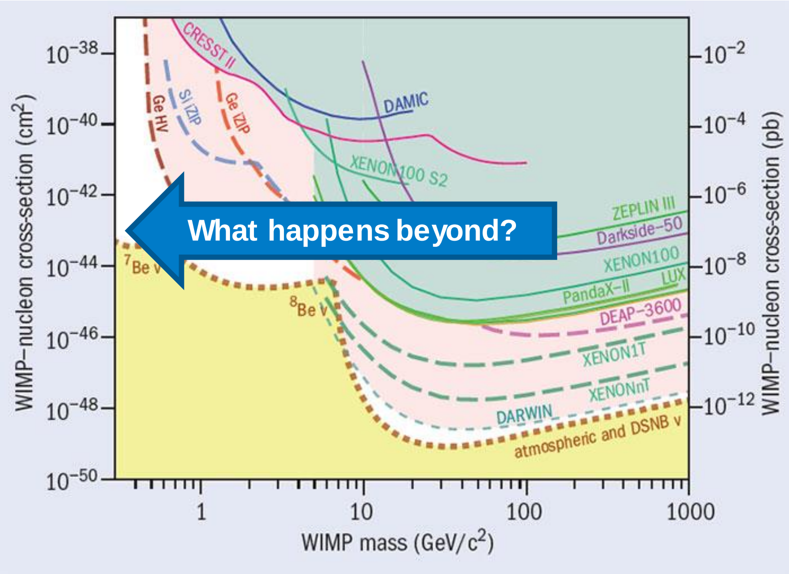

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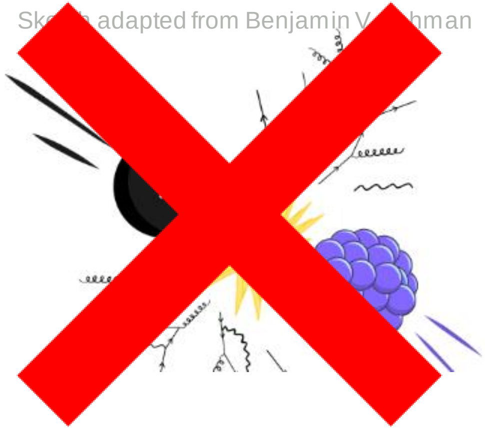
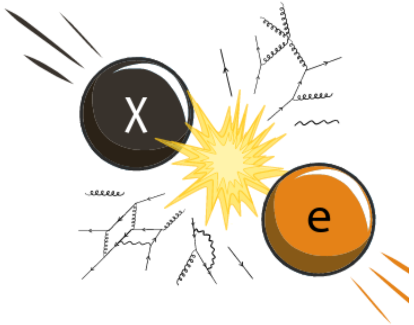
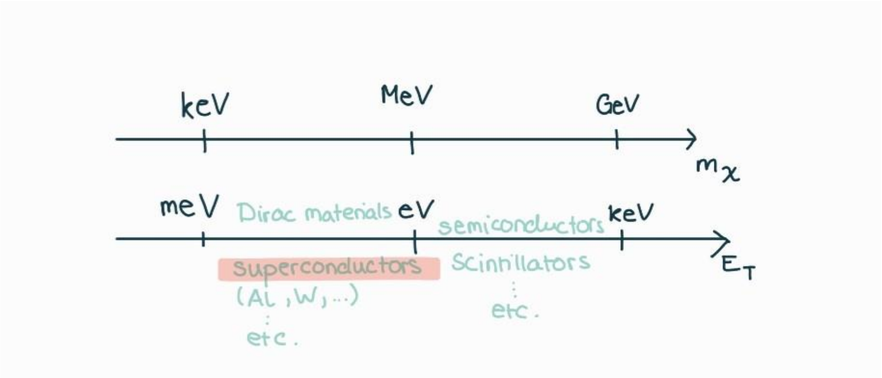


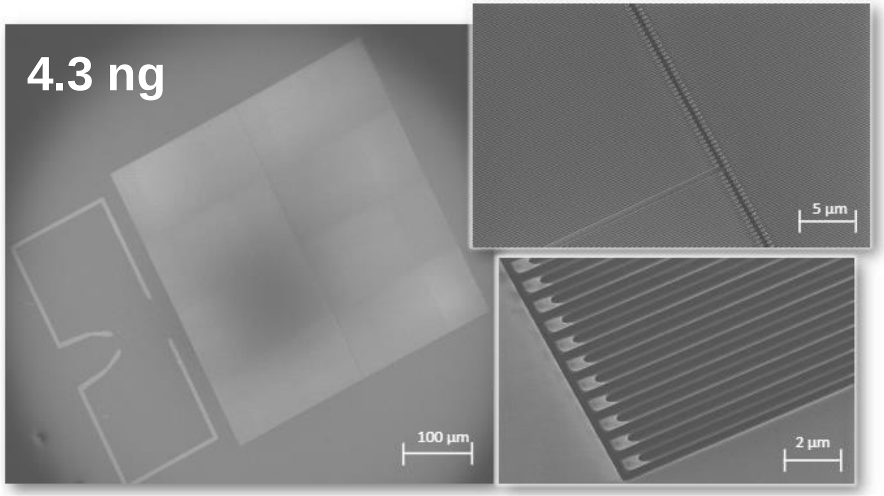




Direct DM detection

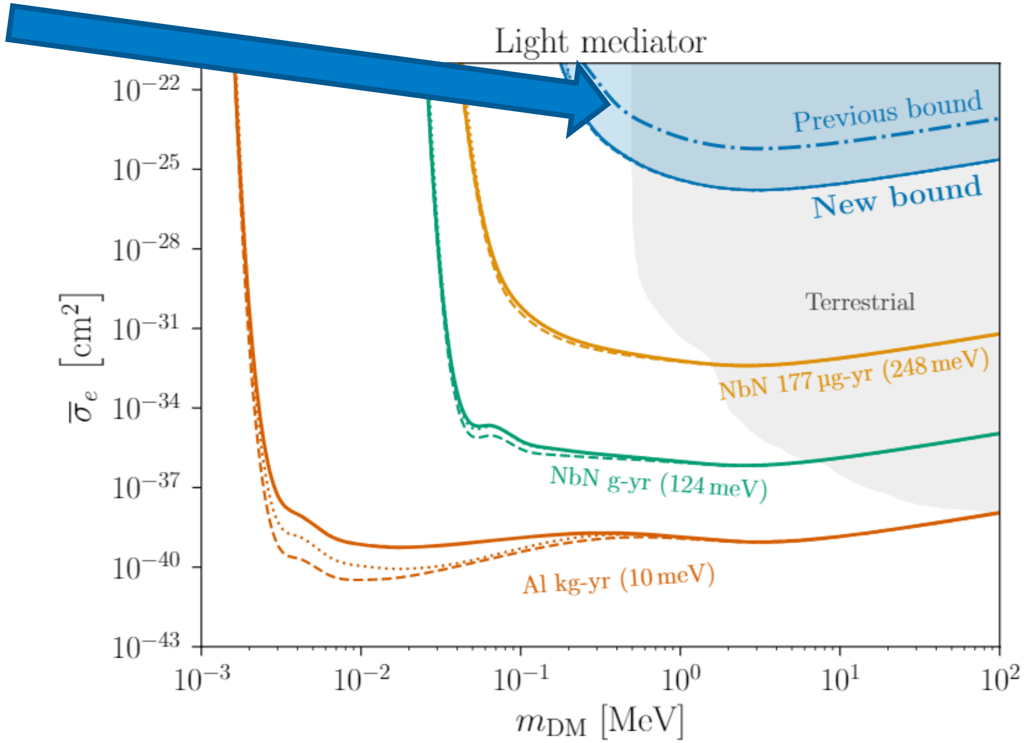
Suitable devices

- **Low noise**
- **‘Large’ target mass**
- **Low energy threshold**



Example: principle proven for SNSPDs
(**S**uperconducting **N**anowire **S**ingle **P**hoton **D**etector)

- New bounds on parameter space with one measurement
- No background signals in 3 hrs
- 0.76 eV energy threshold



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

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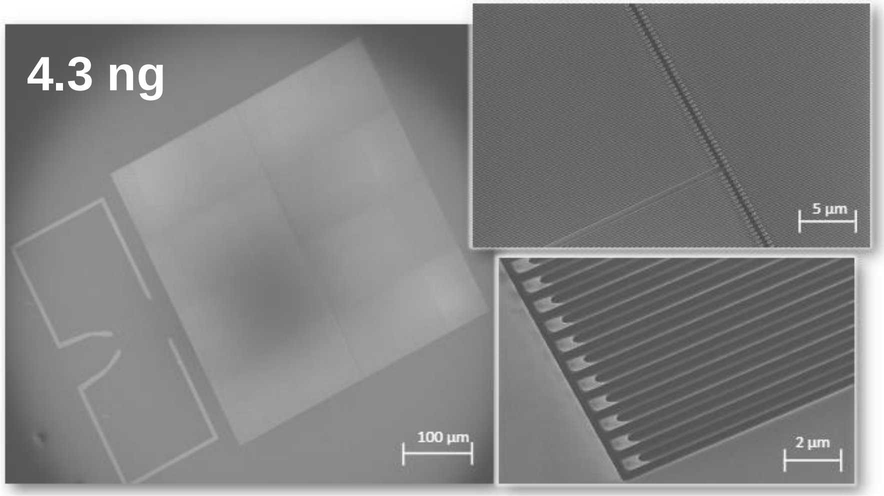

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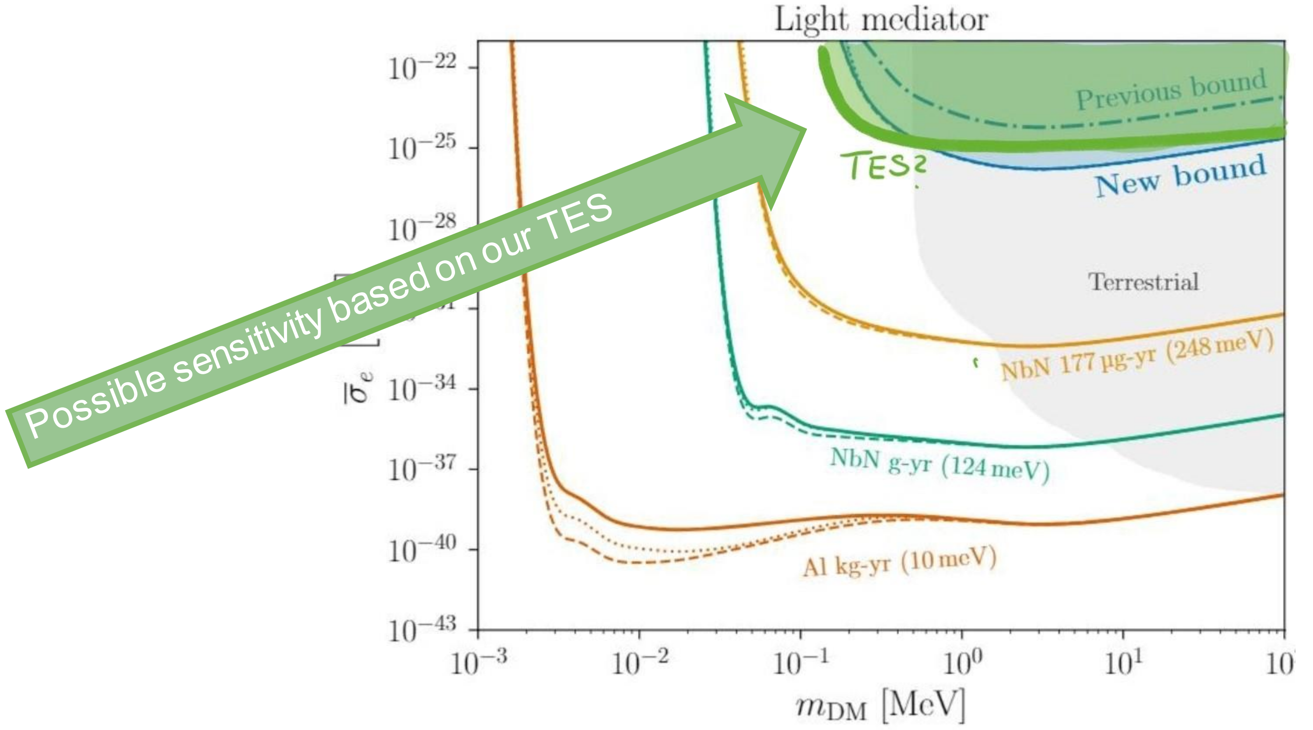
Proposal: Apply same idea to TES!

✓ Superconductor
✓ Low noise
✓ Energy resolution
✓ Lower energy threshold
✗ Lower mass (0.2 ng)
✗ Smaller target area



Possible sensitivity based on our TES

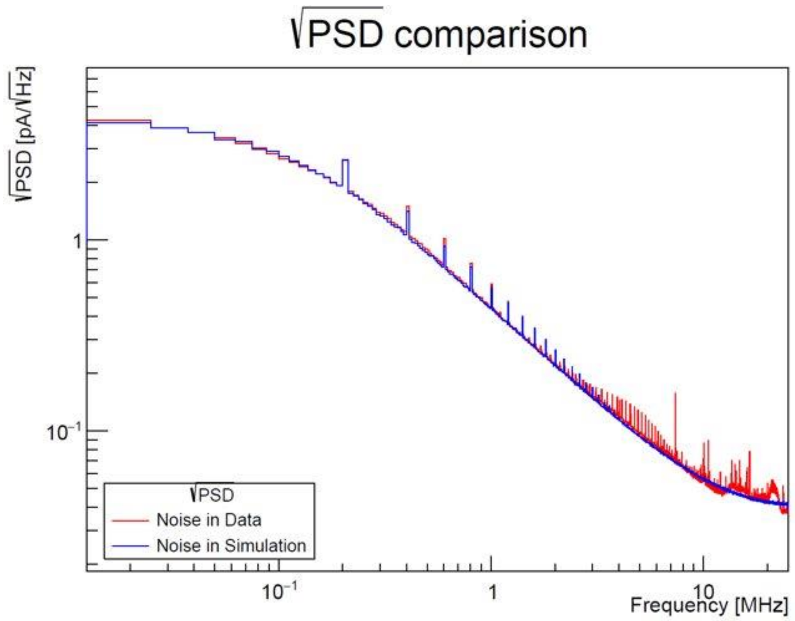
Hochberg, Y. et al. arXiv:2110.01586 (2021)

TES simulations

Simulating (electronic) noise background and low energy pulses

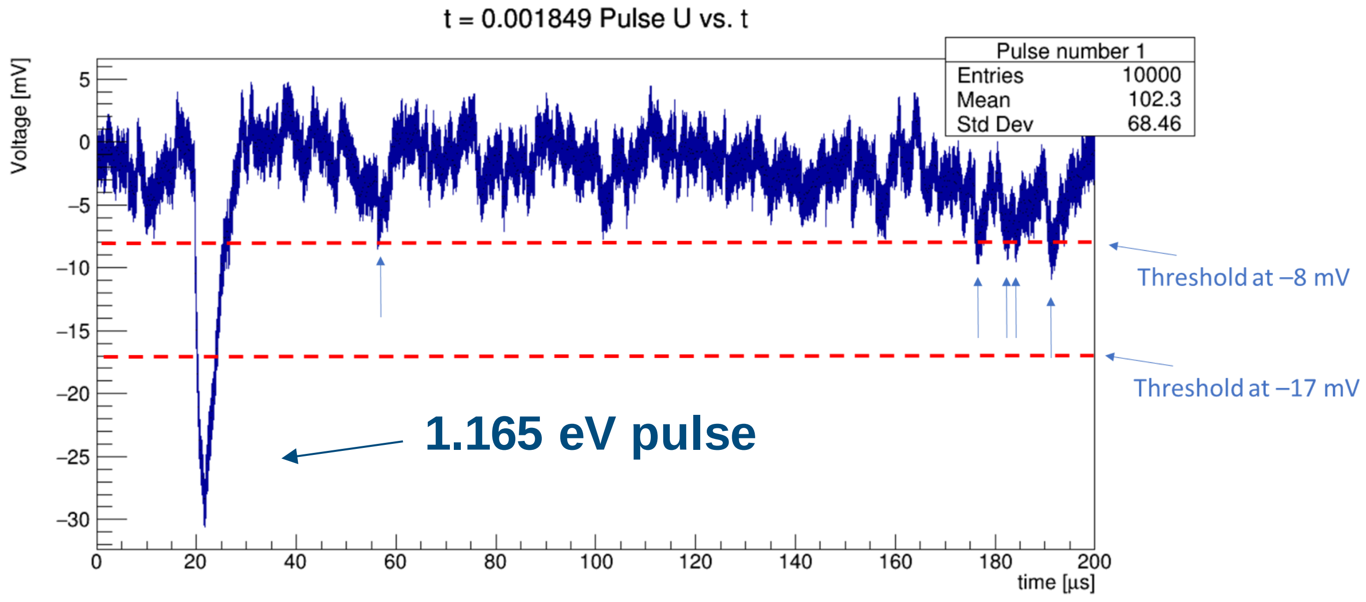
Simulate background

From fitting measured data set



Simulate background and pulses

To optimize analysis for certain energies



Can we discern low energy pulses from noise?

TES simulations

Simulating (electronic) noise background and low energy pulses

Simulate background

From fitting measured data set

Simulate background and pulses

To optimize analysis for certain energies

Test background rate for low triggers after analysis:

- Simulation of noise-only data
- Applying cuts & analysis optimized for 1.165eV and 0.583eV
- No noise passing analysis & cuts in 88 min of simulated time with **54.9%** acceptance of **0.583eV** pulses

Promising for direct DM searches!

Summary and Outlook

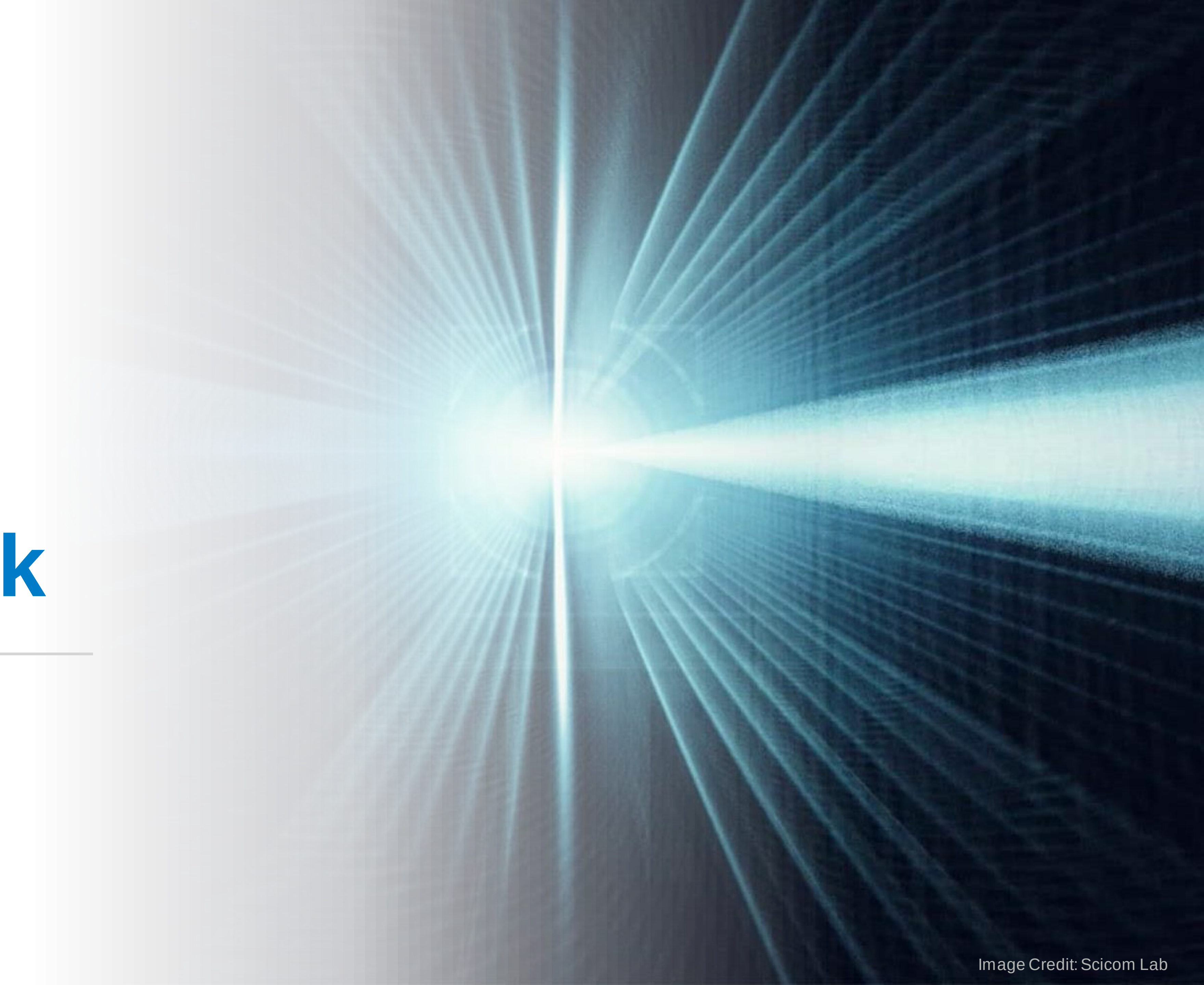


Image Credit: Scicom Lab

Summary and Outlook

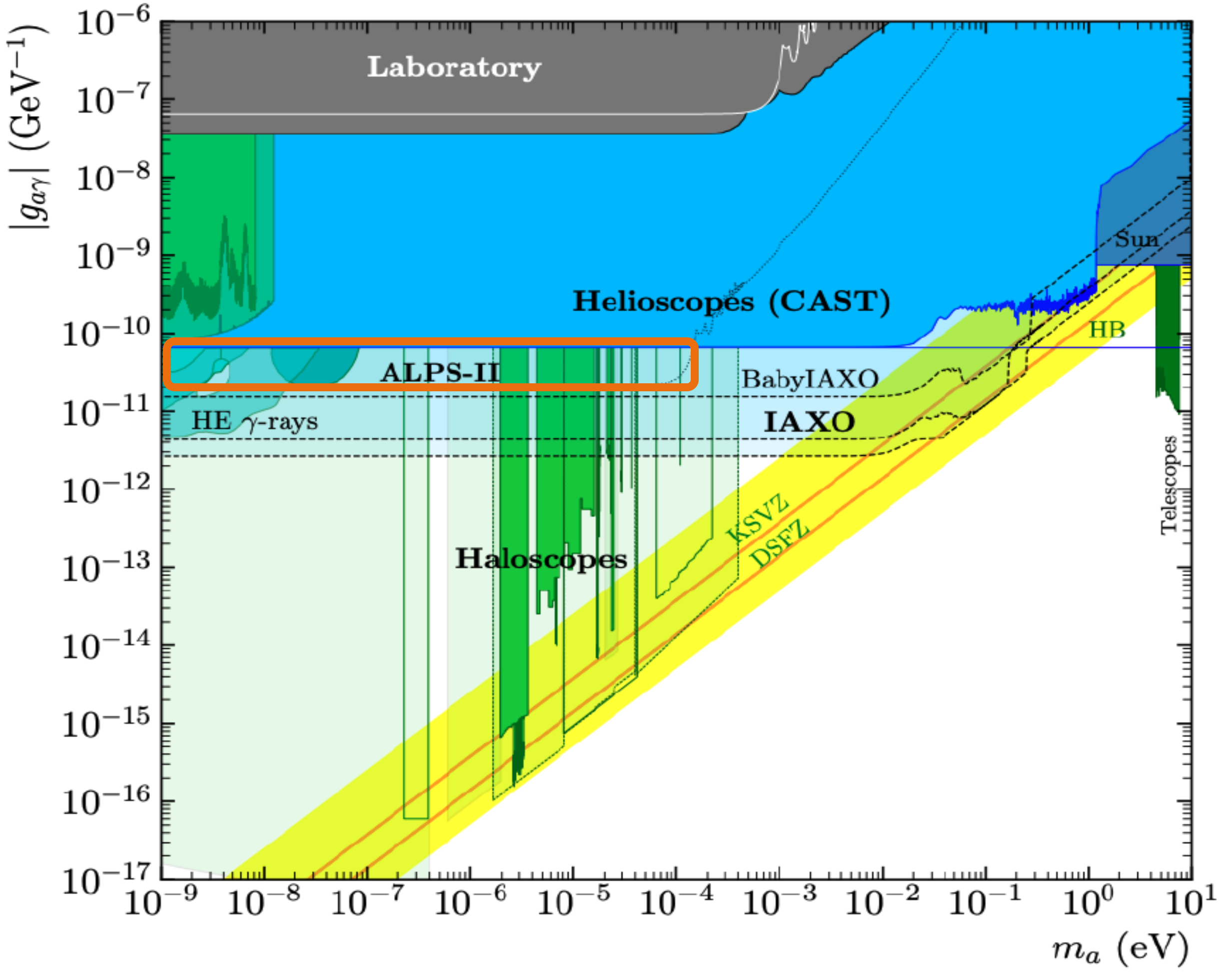
- TES technology will be used in **ALPS II**
- TES **intrinsic background viable** for ALPS II searches
- **But:** TES not only suitable for ALP searches
- Technology could be interesting for **direct dark matter searches** in the **sub-MeV DM** mass range (electron-DM scattering)
- Similar measurements have been conducted using **SNSPDs**
- Usage of TESs has been proposed in **literature**
- **Would our TES be viable?**

- Perform **intrinsics measurement** as comparison
- Investigate **linearity** of TES response for different energies
- Investigate and optimize **system efficiency**
- Investigate **alternative TES modules**

Thank you

Backup

Sensitivity Projection



IAXO Collaboration, arXiv:2010.12076v1 (2020)

Application of two photon-measurement schemes:

Heterodyne detection:

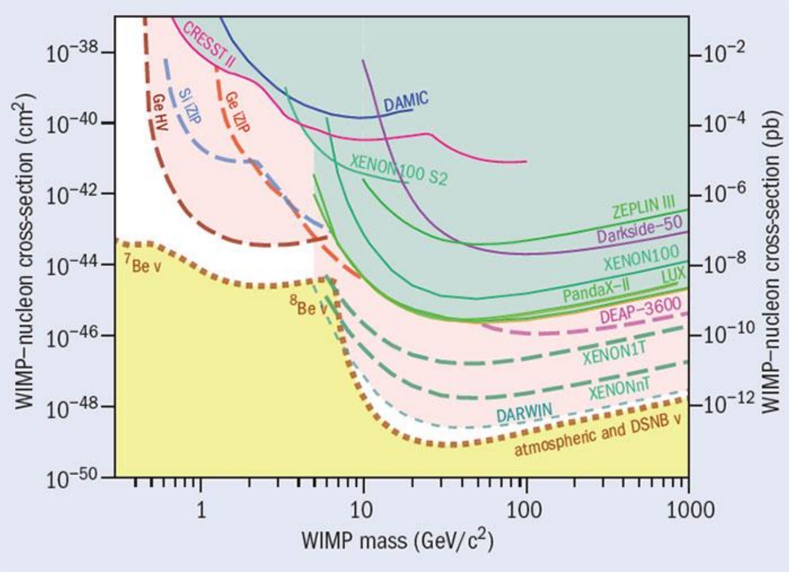
- Detects photon fields
- Mixing of regenerated fields with a local oscillator and measurement of resulting beat note

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

- Single photon detection
- Using superconducting tungsten chip

Backup

Sub-GeV dark matter – nucleon scattering?



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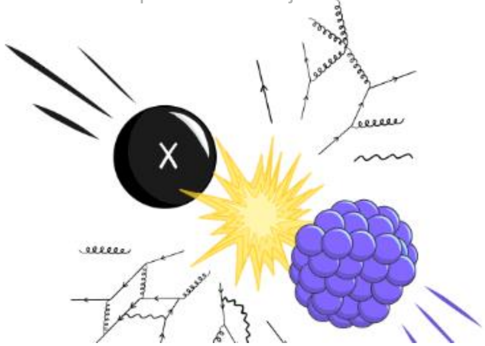


DM mass: m_χ, target mass: m_T

reduced mass: $\mu = \frac{m_\chi m_T}{m_\chi + m_T}$

recoil energy: $E_R = \frac{|q|^2}{2m_T} = \frac{\mu^2 v^2}{m_T}(1 - \cos(\theta_R))$

For $m_\chi \ll m_T$: $\mu \approx m_\chi$

$\rightarrow E_R \sim \frac{m_\chi^2}{m_T}$

Backup

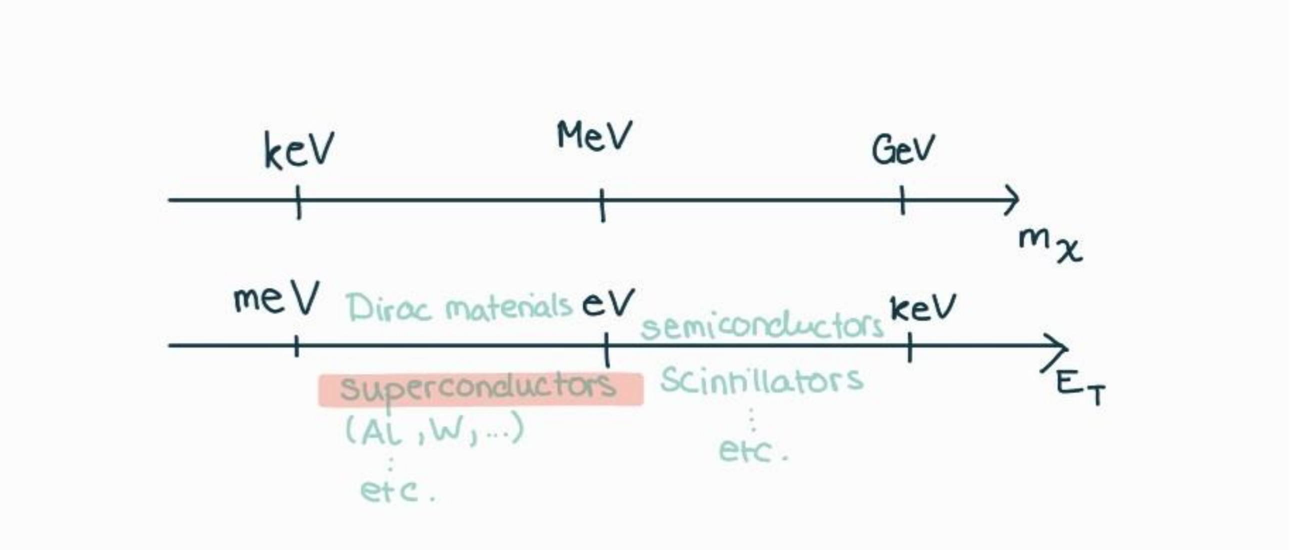
DM – electron scattering

Assume:

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

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

Energy range for given mass range: $E_{T_{\max}} = E_{\text{kin}} \sim m_\chi v^2 \sim 10^{-6} m_\chi$



Backup

Dielectric function

Energy loss function of dielectric materials $\Im(-\epsilon_L^{-1}(\omega, k))$ depends on longitudinal dielectric permittivity
Longitudinal dielectric permittivity responds to

- Charge density perturbations with frequency ω
- Momentum transfer q

After Lasenby, R., & Prabhu, A. (2022)electromagnetic sum rules and Kramers-Kronig relation lead to rules that must be satisfied by materials in which DM – electron scattering happens:

$$\int_0^\infty \frac{d\omega}{\omega} \Im(-\epsilon^{-1}(\omega, q)) \leq \frac{\pi}{2}(1 - \epsilon^{-1}(0, q))$$

Which gives the maximum possible material response during scattering.
Leads to g_χ constraints on maximum average DM scattering rate in a material with DM-mediator coupling strength and mediator-EM coupling strength g_e leading to:

$$\bar{\Gamma} \lesssim g_\chi^2 g_e^2 m_\chi v_\chi$$

Materials saturating this rate will be good candidates for direct DM detection!

Backup

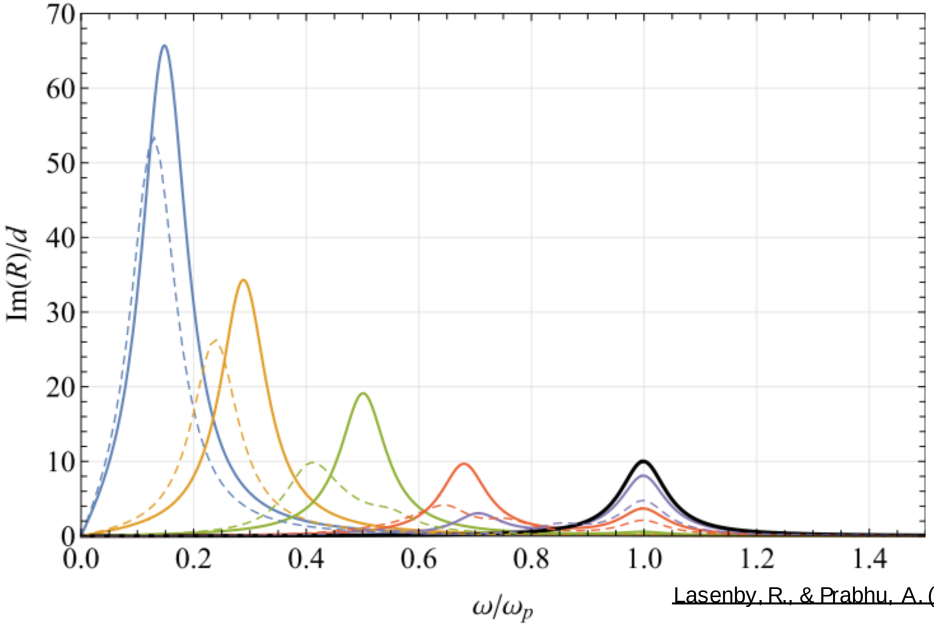
Thin films and plasma frequency

For thin layers per area scattering rate dependency on response function $\Im(R)$ can be used instead of per volume scattering rate relying on $\Im(-\epsilon^{-1})$ moves material response to lower frequencies

Material response governed by **plasma frequency** ω_p, above which dielectric function of a conductor $(\epsilon \simeq -\omega_p^2/\omega^2)$ is positive (e\m waves can penetrate material). Waves with frequencies below plasma frequency are reflected.

Thin layer response function for $k_z d$ values between 0.05 and 10. Black line corresponds to bulk material $(\omega = \omega_p)$

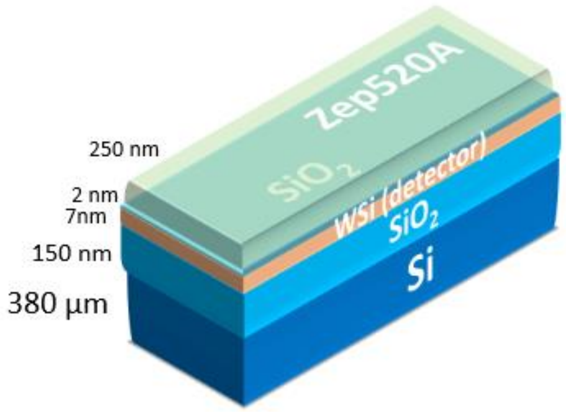
→ Larger response for small thicknesses even below plasma frequency

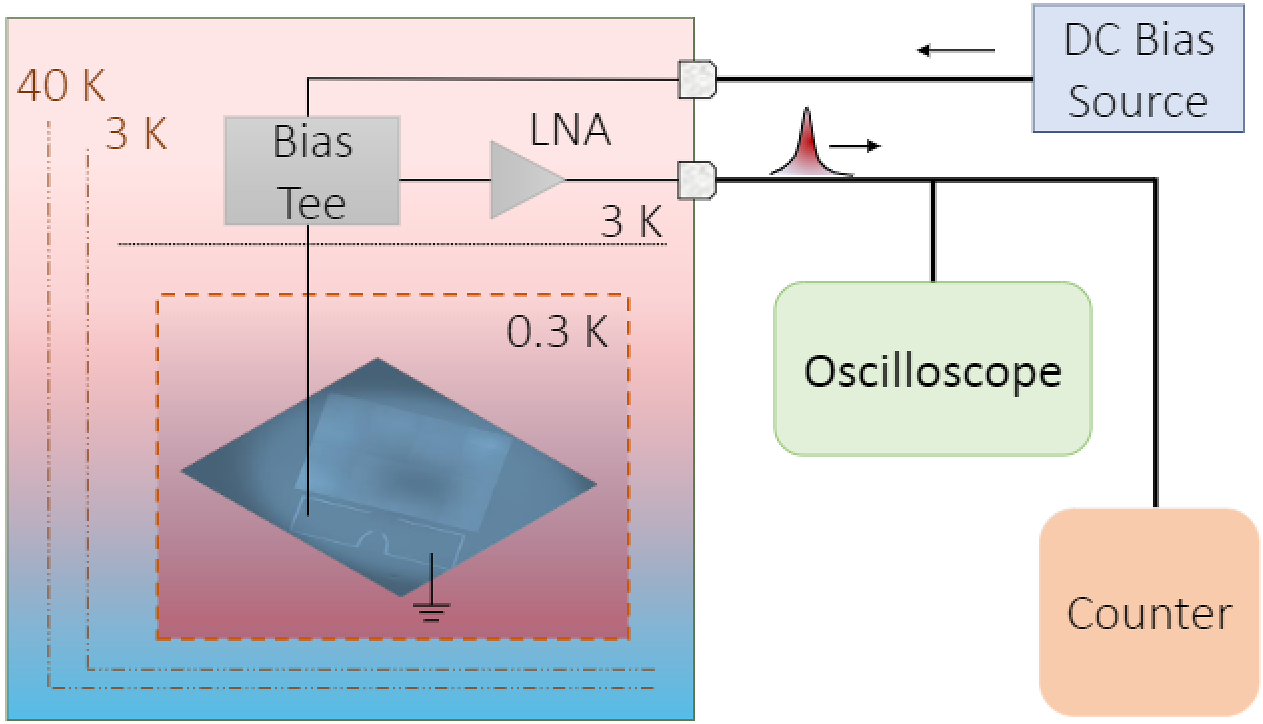


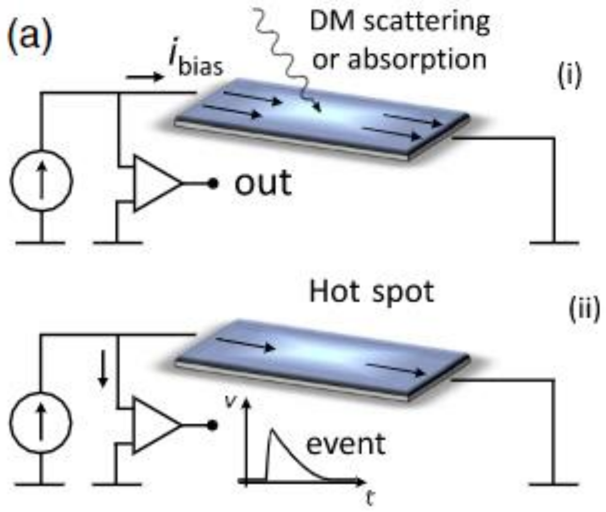
Lasenby, R., & Prabhu, A. (2021)

Backup

SNSPDs





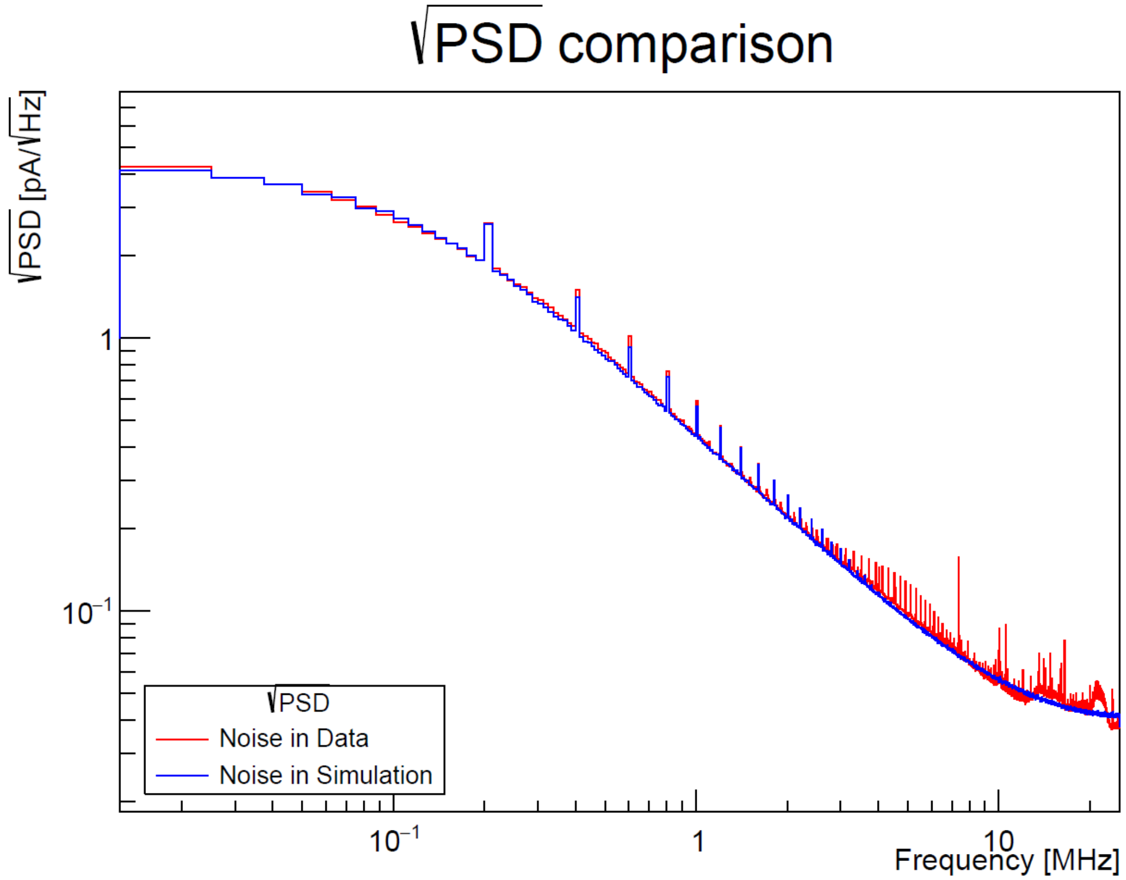


Hochberg, Y. et al., *Physical Review Letters, 123*(15). (2019)

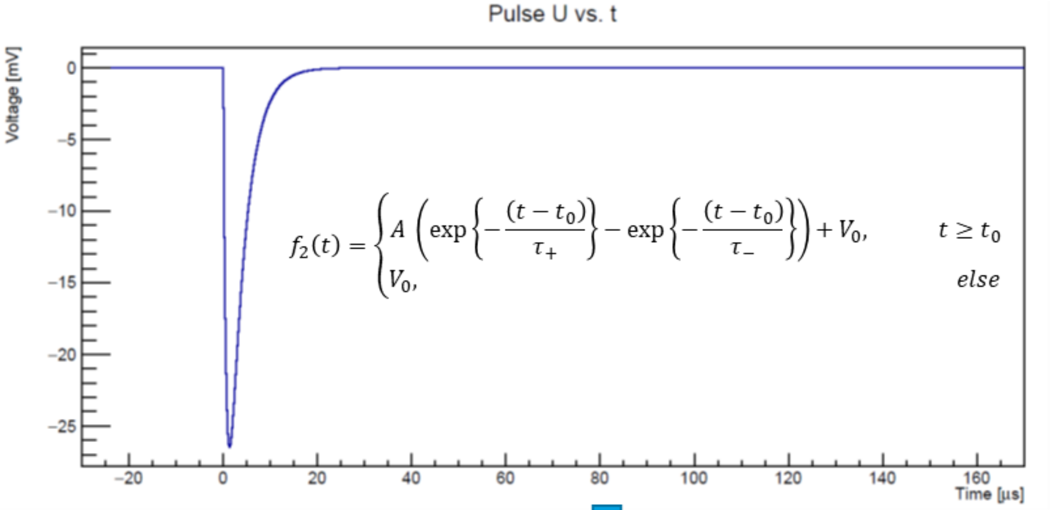
Hochberg, Y. et al. arXiv:2110.01586 (2021)

Backup

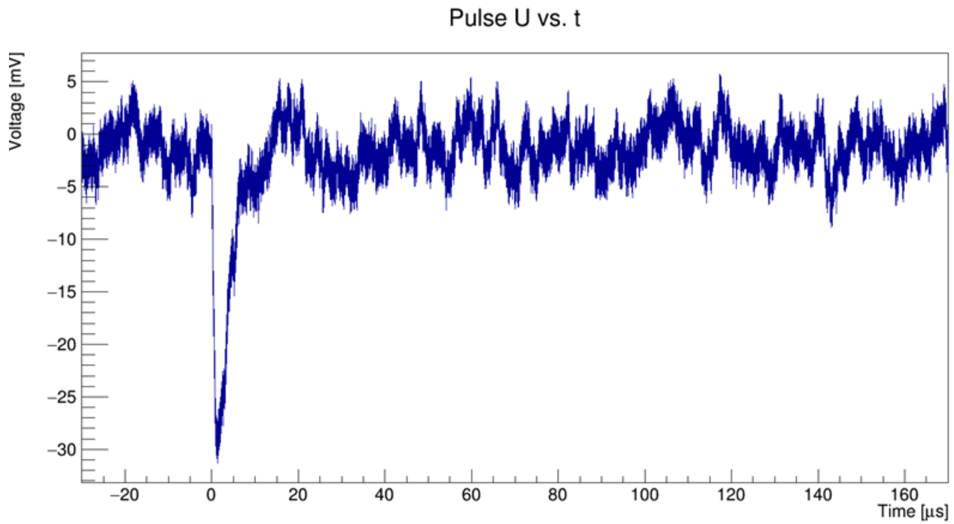
Simulation of pulses



+



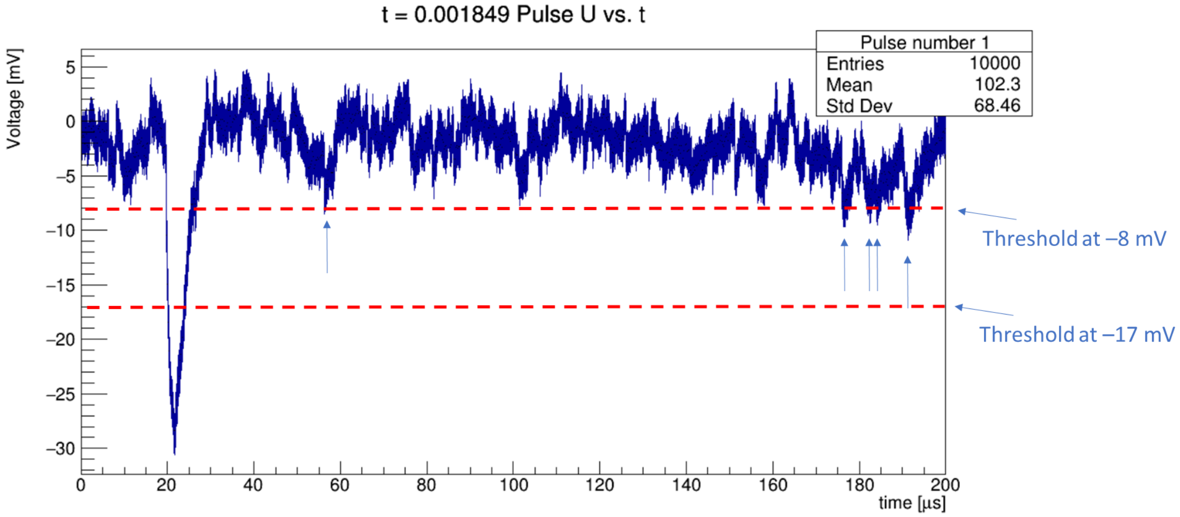
$$f_2(t) = \begin{cases} A\left(\exp\left\{-\frac{(t-t_0)}{\tau_+}\right\} - \exp\left\{-\frac{(t-t_0)}{\tau_-}\right\}\right) + V_0, & t \geq t_0 \\ V_0, & else \end{cases}$$



Backup

False trigger simulations

- Rate of triggered noise pulses for different thresholds and sample sizes
- Without simulated pulses – only noise contributions



False Triggers - Rate of noise pulses passing different trigger thresholds

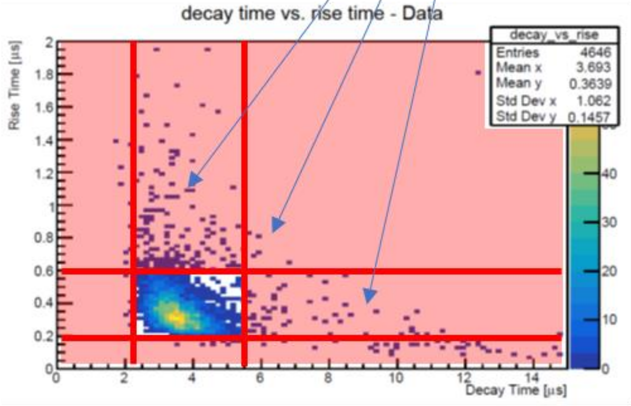
		Usual trigger thresholds for 1064nm pulses					Threshold/mV				
		-17	**-16**	**-15**	**-14**	**-13**	**-12**	**-11**	**-10**	**-9**	-8
Simulated time	**# Samples**	**Rate 1/s (+/- statistical uncertainties)**									
9 sec	**45 000**	0	0	0	0	0	0.33 (0.19)	4.2 (0.7)	36 (2)	241 (5)	/
8 min 20 sec	**2.5e6**	0	0	0	0	0.014 (0.005)	0.32 (0.03)	4.21 (0.09)	38.8 (0.3)	251.1 (0.7)	974 (1)

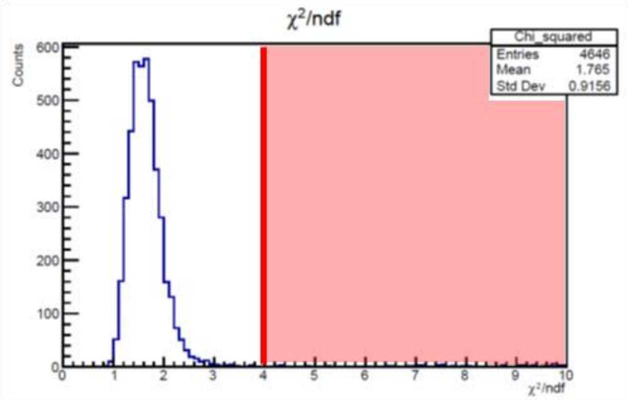
Backup

Cut-based analysis 1064nm signals

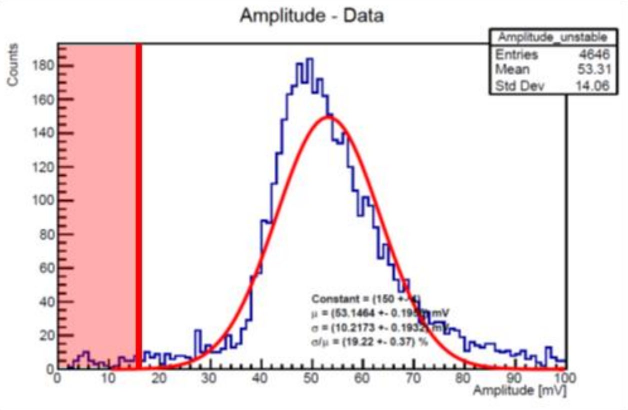
Pileup candidates

Method 1 – Time domain



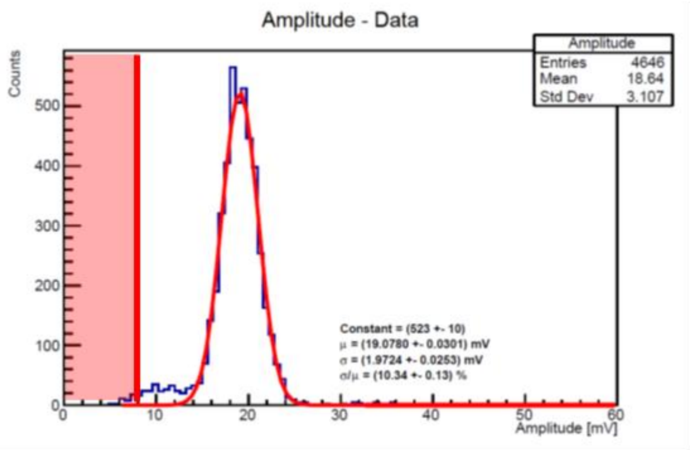


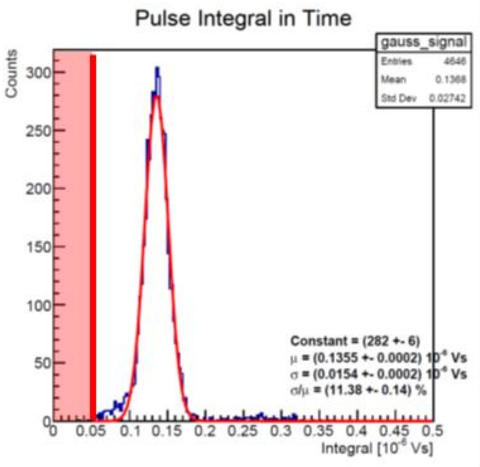
Method 2 – Frequency domain



if 1064nm

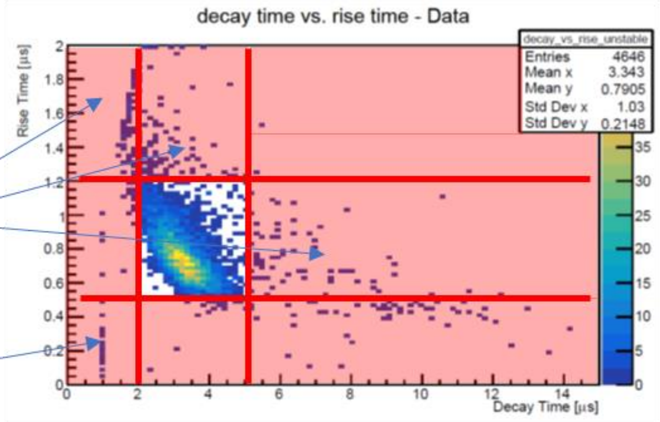
Mean pulse height: 28mV





Pileup candidates

Noise triggers



Backup

True trigger simulations and analysis - example

Example:
0.583 eV (2127 nm)

- **Before analysis:** Simulated trigger acceptance for different low energies and trigger threshold
- **Assumption:** Pulse-shape does not change for lower energies → only pulse height

True Triggers - Acceptance of triggered pulses - 5000 samples each									
				trigger threshold / mV (+/- statistical uncertainties)					
Energy / eV	**-17**	**-16**	**-15**	**-14**	**-13**	**-12**	**-11**	**-10**	**-9**
0.583	16.8 (0.6)%	29.2 (0.8)%	44.9 (1.0) %	62.7 (1.1)%	77.1 (1.2)%	88.6 (1.3)%	95.3 (1.4)%	98.5 (1.4)%	100.0 (1.4)%

- Perform **cut based analysis** on pulses accepted by the trigger
- Analysis reduces acceptance based on pre-defined cuts (e.g. pulses with long decay times)
- Analysis initially optimized for 1.165 eV

→ Comparison with additional cuts on pulse-height for 0.583 eV

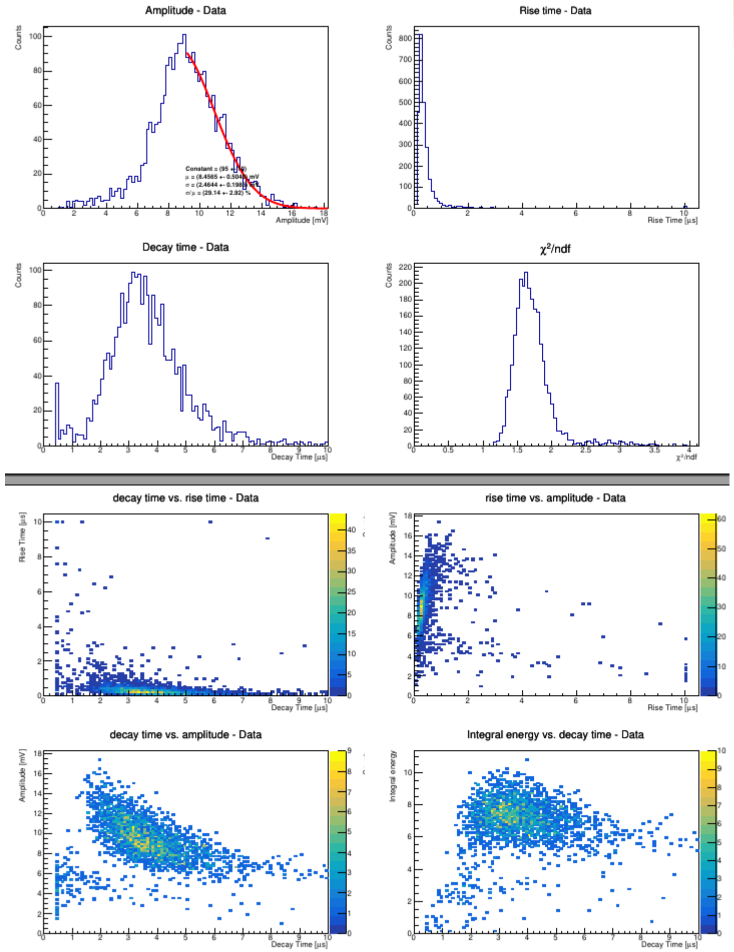
Trigger threshold	-11 mV
non optimized	37.6 (1.2)%
optimized	54.9 (1.5)%

Acceptance improvement

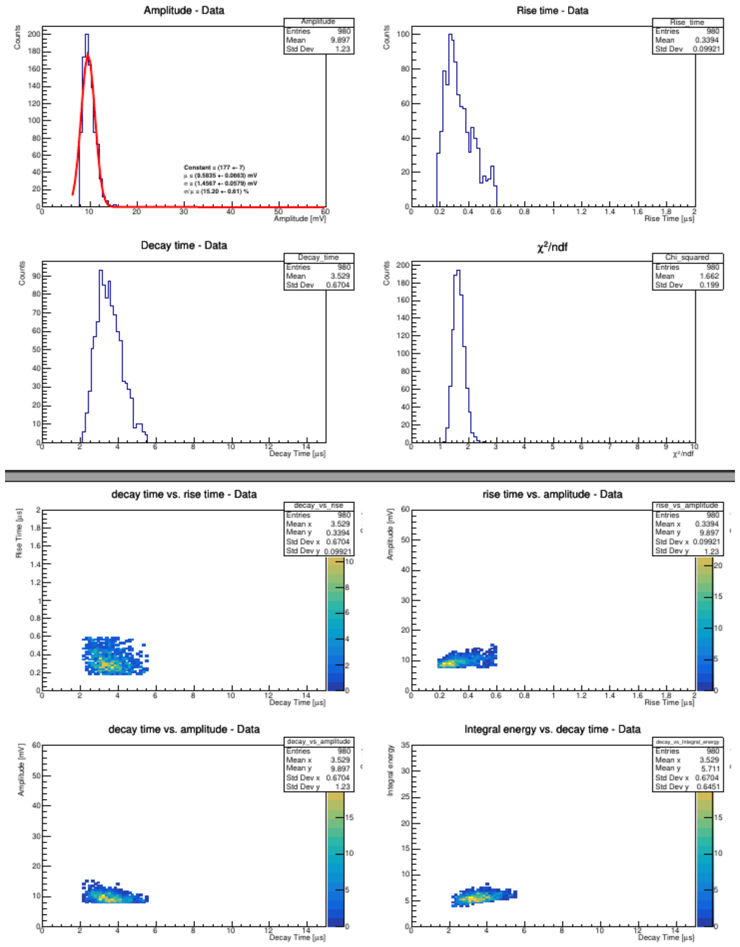
Backup

Simulation – Analysis and Cuts 0.583 eV

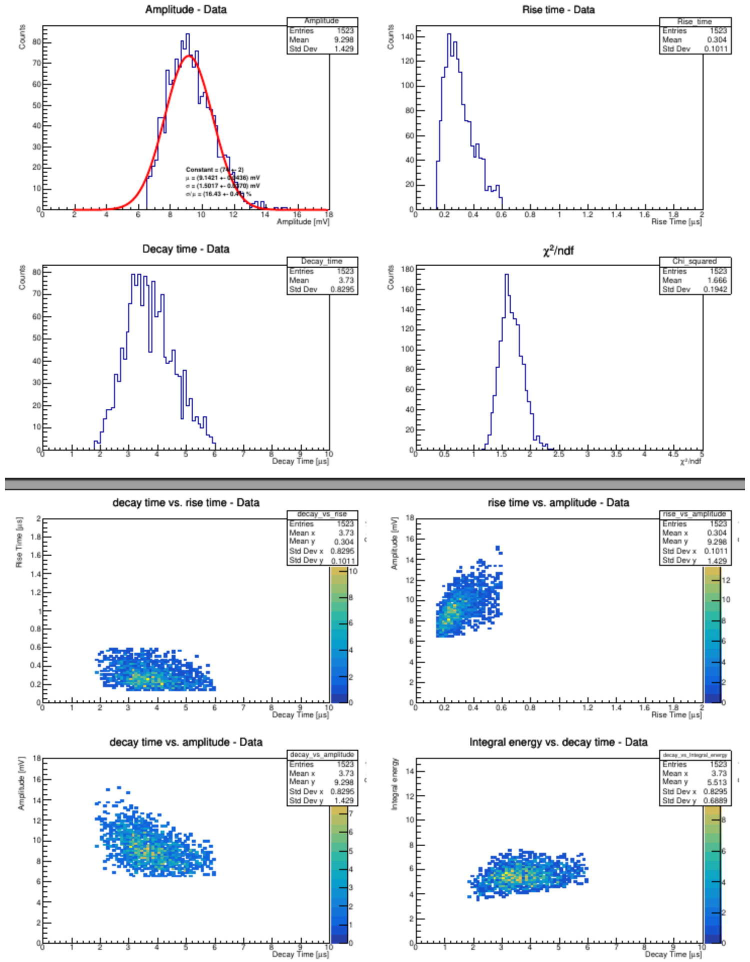
- Pre Cuts



- Post – 1.165eV optimized - Cuts



Post – 0.583eV optimized - Cuts



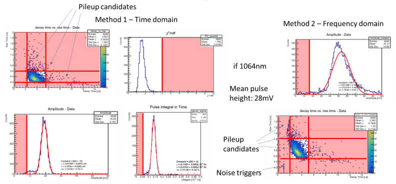
Examples in time domain

Backup

ALPS II analysis optimized for lower energies

Using Simulations:

1. w/o pulses – only electronic noise: rate after trigger
2. With light pulses to optimize analysis and cuts for different energies
   - Assumption: Only pulse amplitude changes for different energies



Test (electronic) background rate for low triggers after analysis:

- Simulation of noise-only data
- Applying cuts & analysis optimized for 1.165eV and 0.583eV
- No noise passing analysis & cuts in 88 min of simulated time with **54.9%** acceptance of **0.583eV** pulses

Promising for direct DM searches!

Noise-only simulations

Rate for -11 mV threshold
4.21(0.09) Hz

Noise-only simulations & analysis

Cuts based on	Rate for -11 mV threshold
1.165 eV	0.0000(0.0004) Hz
0.583 eV	0.0000(0.0004) Hz

Backup

Current planning

- Commissioning of different laser sources
- Check functionality & specs
- Check safety requirements and permissions

Re-commissioning of cryostat (hopefully)

- Intrinsics measurements with current setup
- Additional measurements (backup)

- Linearity measurements with different lasers

- Further TES modules/improvements?
- Tunable laser source?

Wavelength	Power	#	Laser
3200 Kelvin	150W	1x	tunable (intensity) White Light Source LQ1600
~630nm	4mW	3x	SuK 57FCM
pulsed, 1064nm, 532 SHG		1x	LASER SYSTEM YAG CFR 200-MINI-ICE/SHG
pulsed, 1064nm, 532 SHG		1x	LASER SYSTEM YAG CRF 200-20 ND
pulsed, 1064nm, 532 SHG		1x	LASER SYSTEM YAG CFR 400-25-OPO
355nm	1mW	1x	Laser CNI-355-1 cw-TTL10kHz
405nm	10mW	1x	Laser CNI-405-10-TTL10kHz-5
808nm	8W	2x	Laser CNI-808WS-8000-TTL-AC
1550nm	10-30mW?	1x	Rio Laser

Contact

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