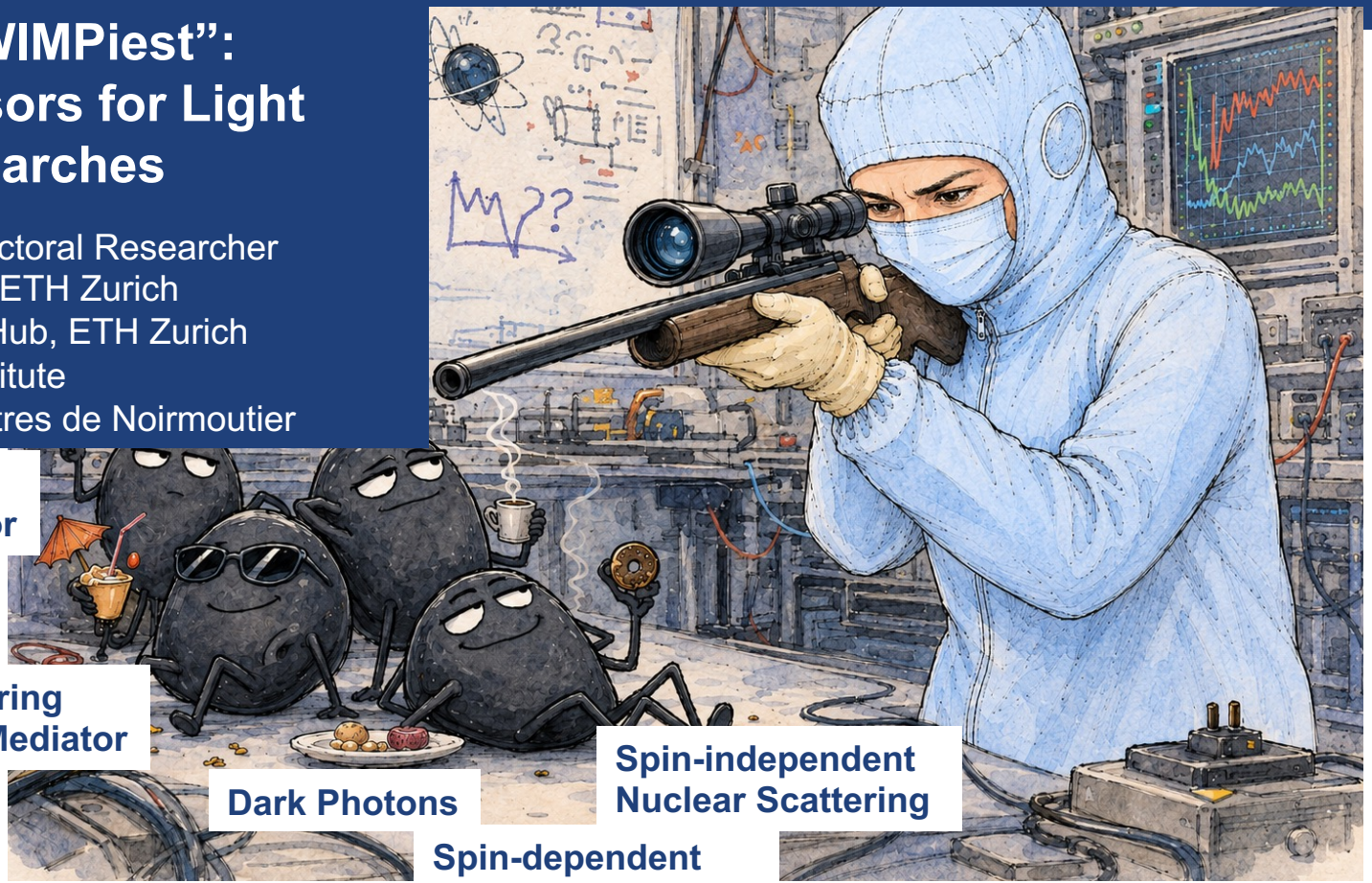
ETH zürich

Hunting the “WIMPiest”: Quantum Sensors for Light Dark Matter Searches

Felix Wagner, Postdoctoral Researcher
Quantum Device Lab, ETH Zurich
Quantum Computing Hub, ETH Zurich
and Paul Scherrer Institute
5/6/2026, Les Rencontres de Noirmoutier



The Quantum Device Lab @ ETH Zurich

Article | Published: 27 May 2026

Experimental randomness amplification

Anatoly Kulikov ✉, Simon Storz, Josua D. Schär, Martin Sandfuchs, Ramona Wolf, Florence Berterottière, Christoph Hellings, Andreas Wallraff & Renato Renner

Nature **653**, 1033–1038 (2026) | Cite this article

Article | Open access | Published: 10 May 2023

Loophole-free Bell inequality violation with superconducting circuits

Simon Storz ✉, Josua Schär, Anatoly Kulikov, Paul Magnard, Philipp Kurpiers, Janis Lütolf, Theo Walter, Adrian Copetudo, Kevin Reuer, Abdulkadir Akin, Jean-Claude Besse, Mihai Gabureac, Graham J. Norris, Andrés Rosario, Ferran Martin, José Martinez, Waldimar Amaya, Morgan W. Mitchell, Carlos Abellan, Jean-Daniel Bancal, Nicolas Sangouard, Baptiste Royer, Alexandre Blais & Andreas Wallraff ✉

Nature **617**, 265–270 (2023) | Cite this article

Article | Published: 25 May 2022

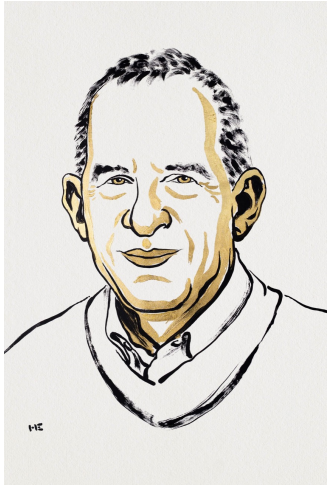
Realizing repeated quantum error correction in a distance-three surface code

Sebastian Krinner ✉, Nathan Lacroix, Ants Remm, Agustin Di Paolo, Elie Genois, Catherine Leroux, Christoph Hellings, Stefania Lazar, Francois Swiadek, Johannes Herrmann, Graham J. Norris, Christian Kraglund Andersen, Markus Müller, Alexandre Blais, Christopher Eichler & Andreas Wallraff

Nature **605**, 669–674 (2022) | Cite this article

Quantum Science with Superconducting Circuits

John Clarke

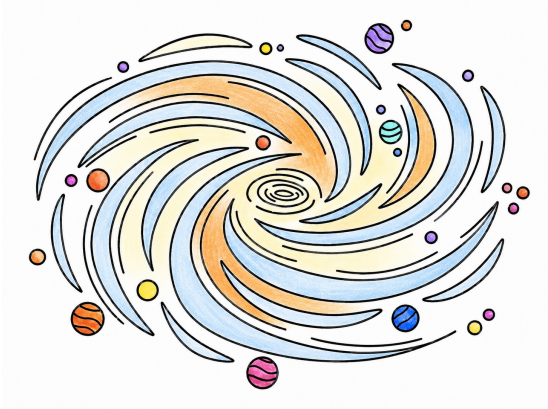


Michel H. Devoret

John M. Martinis

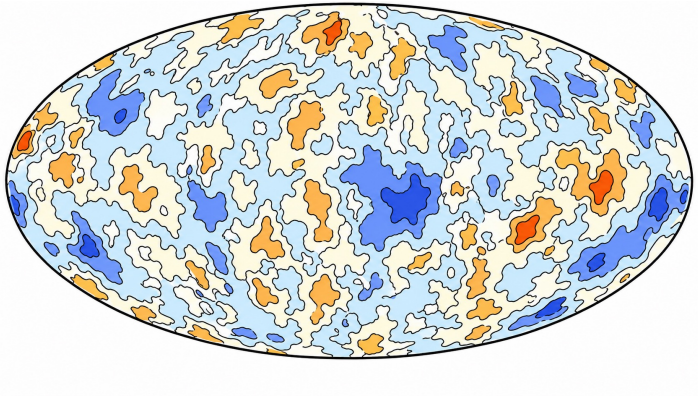
Nobel prize in physics 2025

Evidence for Dark Matter in our Universe



Galactic rotation curves: galaxies contain far more mass than their visible baryons

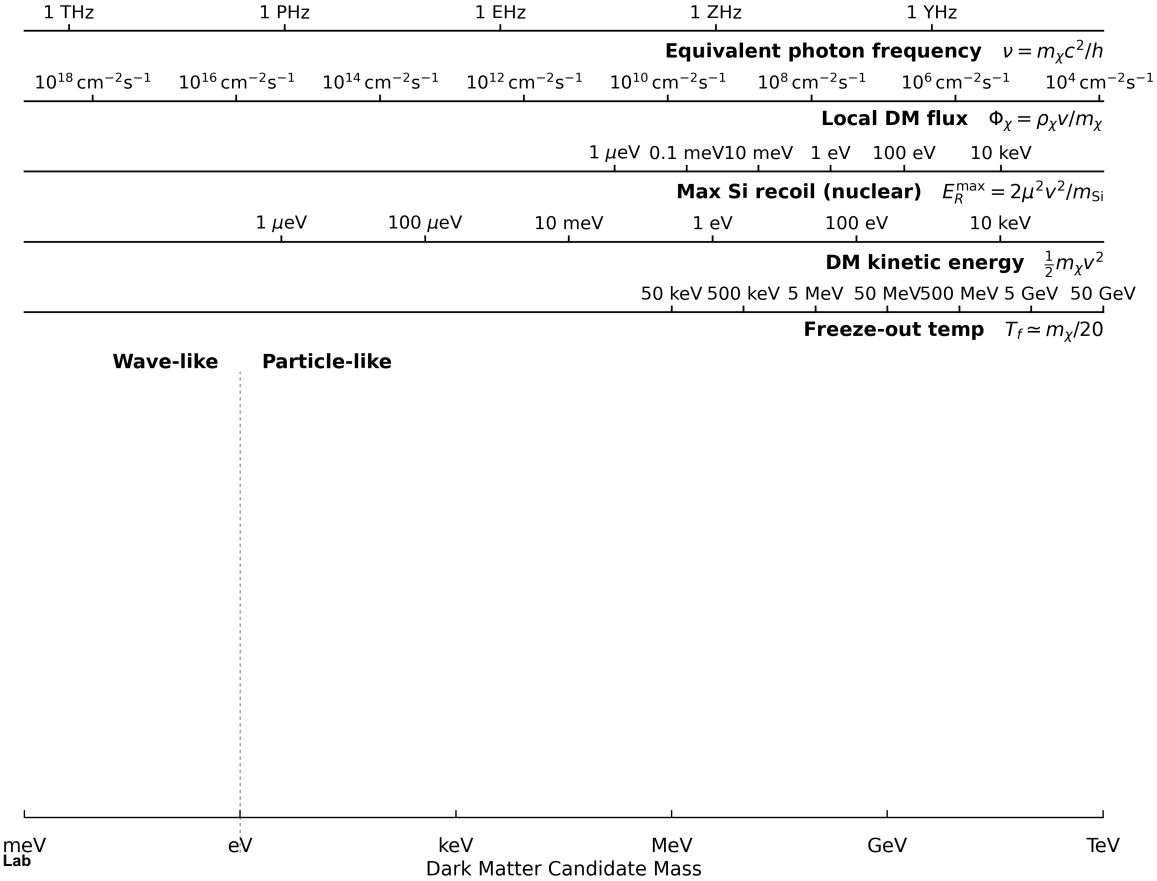
Lelli, AJ 152, 157 (2016)
Li, AJ SS 247, 31 (2020)



Cosmic Microwave Background: (84.27 ± 0.13) % of matter not subject to radiation pressure

Planck, AA 641, A6 (2020)

Selected Dark Matter Models



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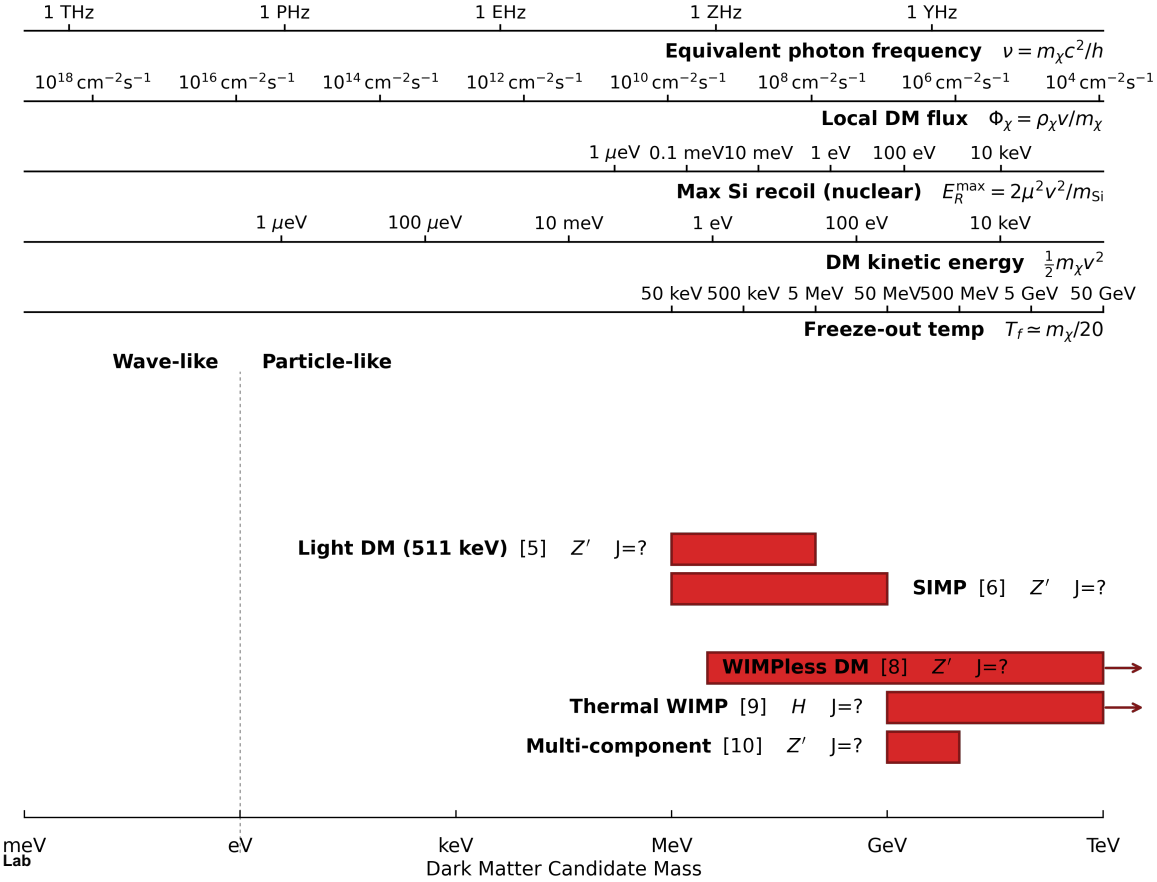

Production

thermal freeze-out

Coupling mechanism

H Higgs / electroweak

Z' hidden mediator

References

[5] Boehm & Fayet, NPB 683, 219 (2004)
[6] Hochberg, Kuflik, Volansky & Wacker, PRL 113, 171301 (2014)
[8] Feng & Kumar, PRL 101, 231301 (2008)
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[10] Zurek, PRD 79, 115002 (2009)

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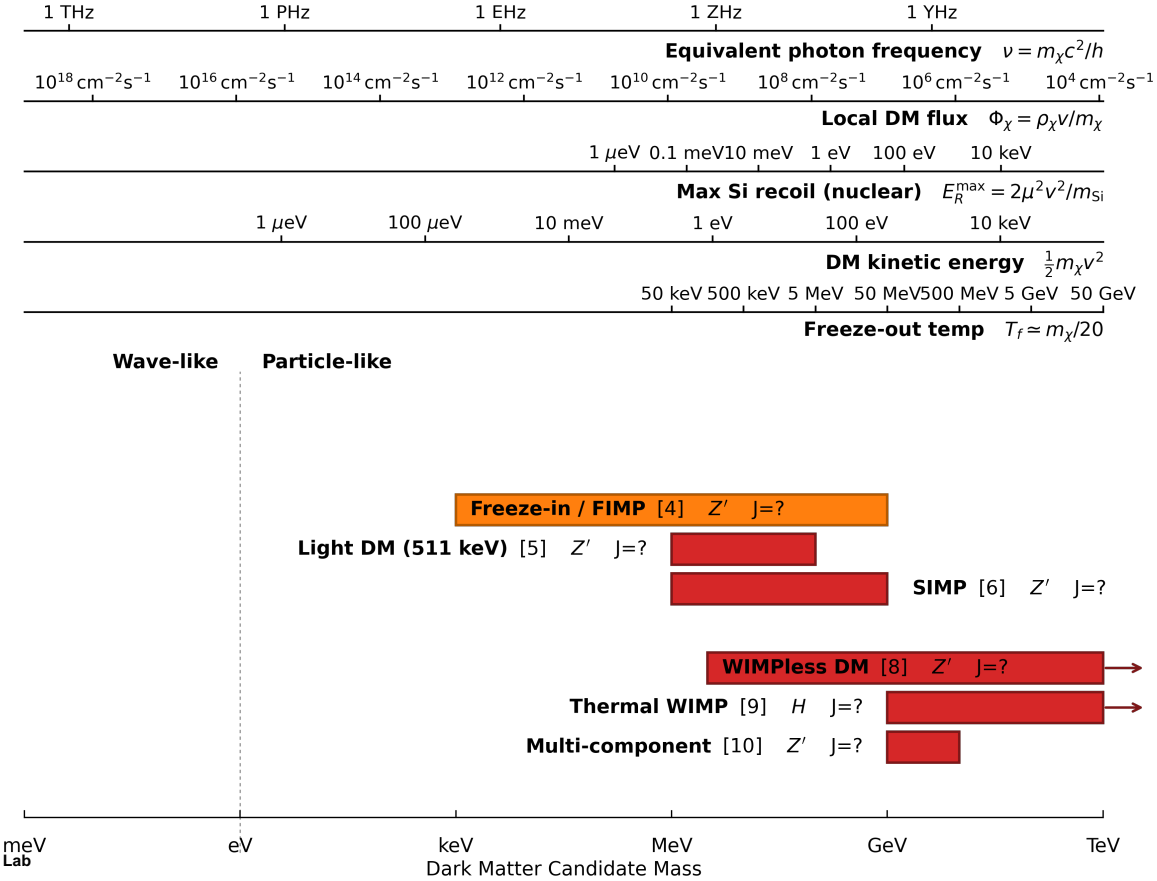

Production

- thermal freeze-out
- freeze-in (feeble)

Coupling mechanism

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[4] Hall, Jedamzik, March-Russell & West, JHEP 03, 080 (2010)
[5] Boehm & Fayet, NPB 683, 219 (2004)
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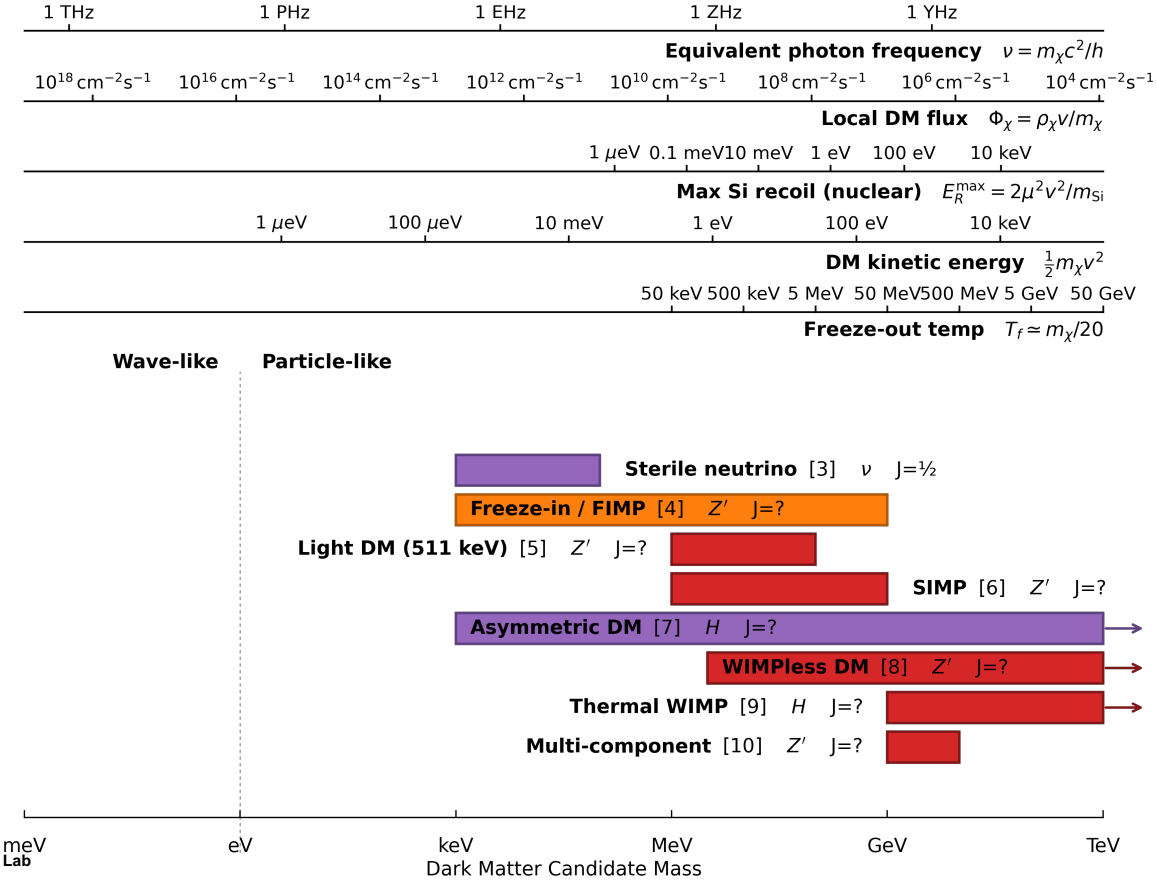

Production

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[3] Dodelson & Widrow, PRL 72, 17 (1994)
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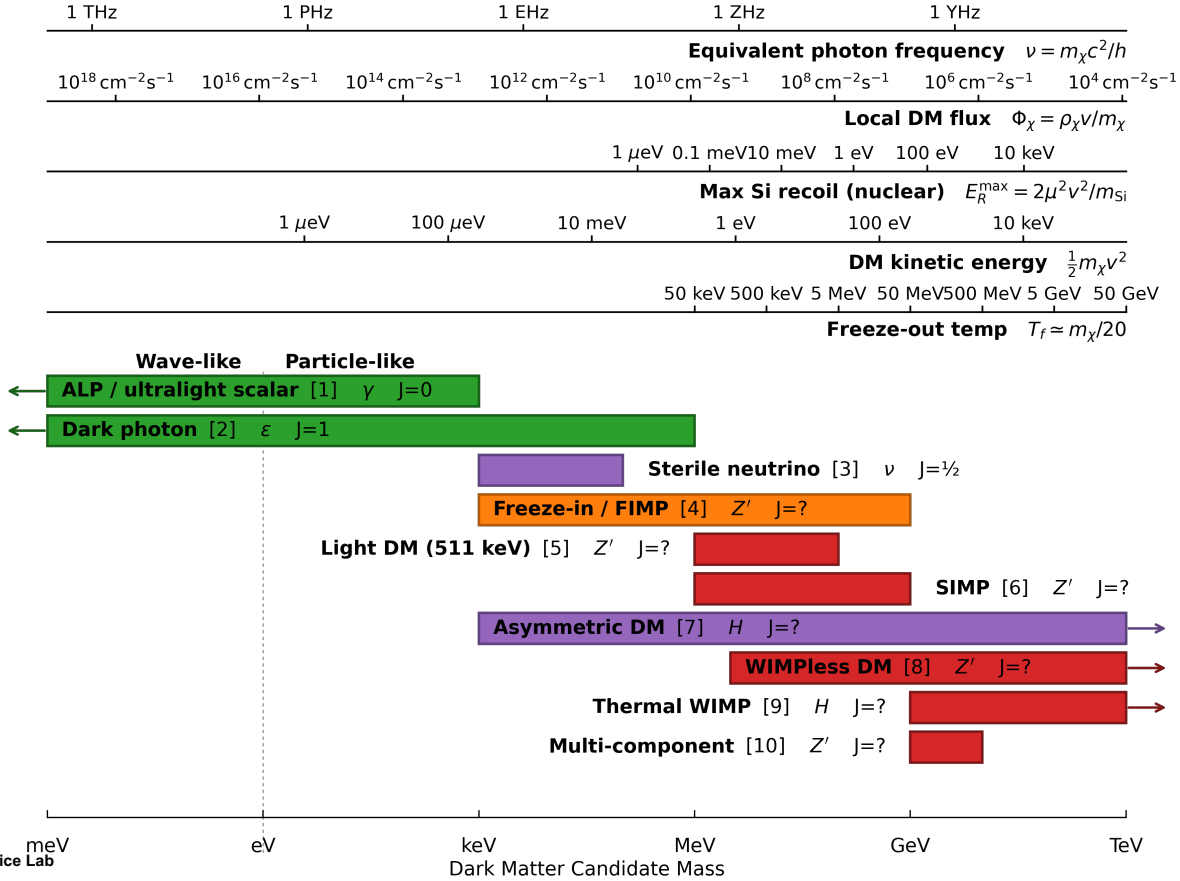

Production

- misalignment / non-thermal
- thermal freeze-out
- asymmetry / oscillation
- freeze-in (feeble)

Coupling mechanism

ε	kinetic mixing
γ	axion-photon
ν	neutrino mixing
H	Higgs / electroweak
Z'	hidden mediator

References

[1] Preskill, Wise & Wilczek, PLB 120, 127 (1983)
[2] Nelson & Scholtz, PRD 84, 103501 (2011)
[3] Dodelson & Widrow, PRL 72, 17 (1994)
[4] Hall, Jedamzik, March-Russell & West, JHEP 03, 080 (2010)
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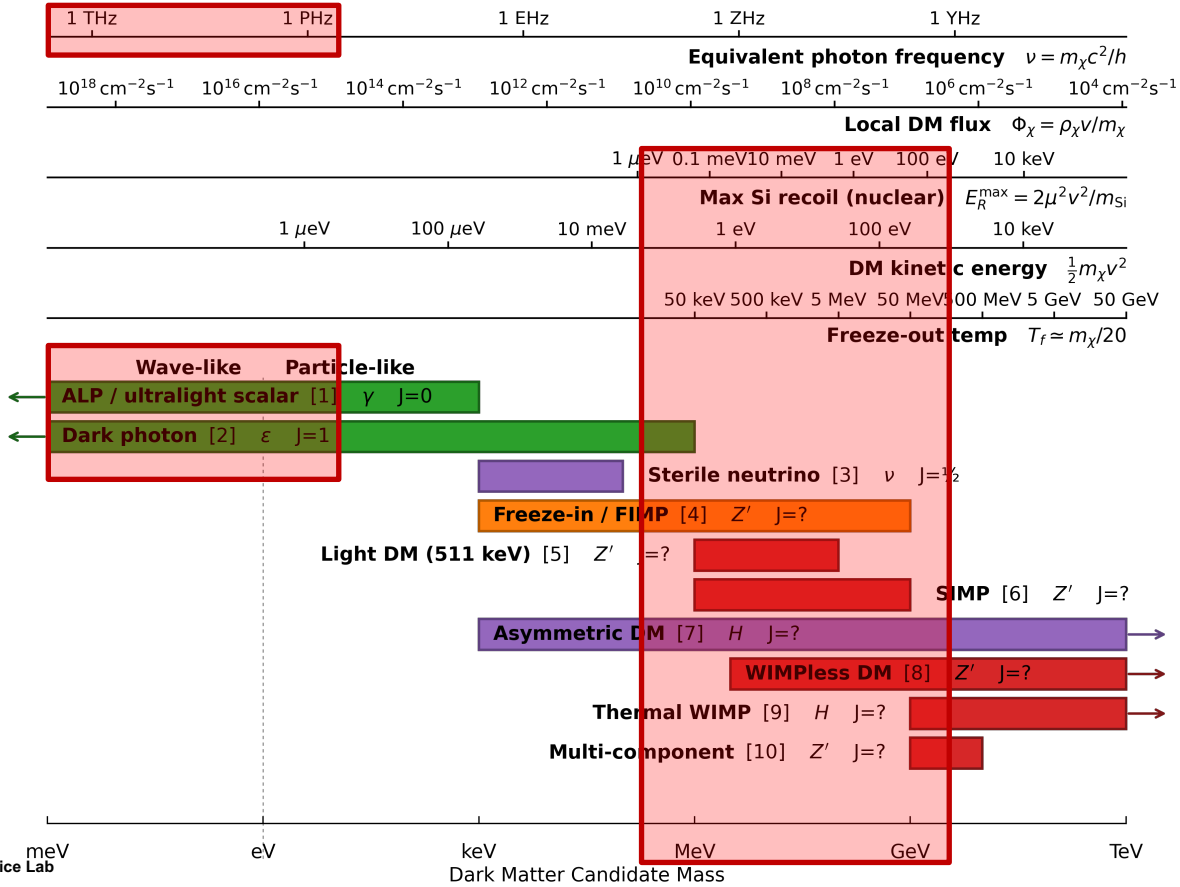

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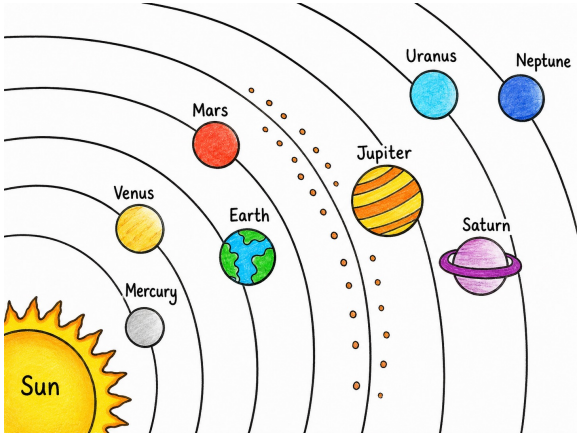
[8] Feng & Kumar, PRL 101, 231301 (2008)
[9] Lee & Weinberg, PRL 39, 165 (1977)
[10] Zurek, PRD 79, 115002 (2009)

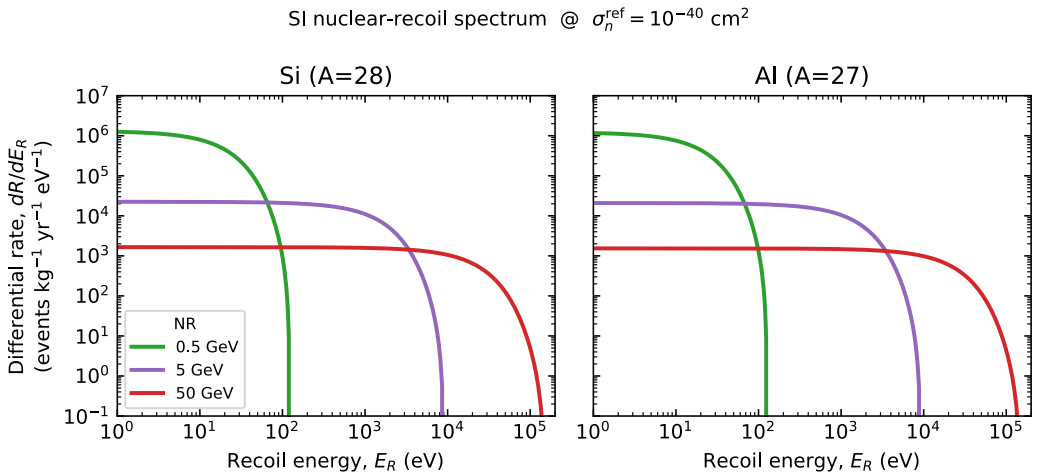
Direct Detection of Dark Matter with Earth-based Detectors

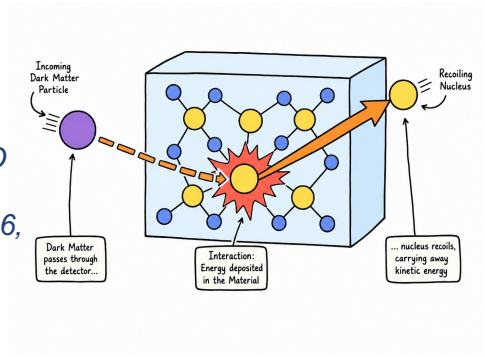


Significant **local dark matter density** exists, 0.3-0.4 GeV/c^3

Read, J. Phys. G: Nucl. Part. Phys. 41, 063101 (2014)

Dark Matter-Nucleus Scattering





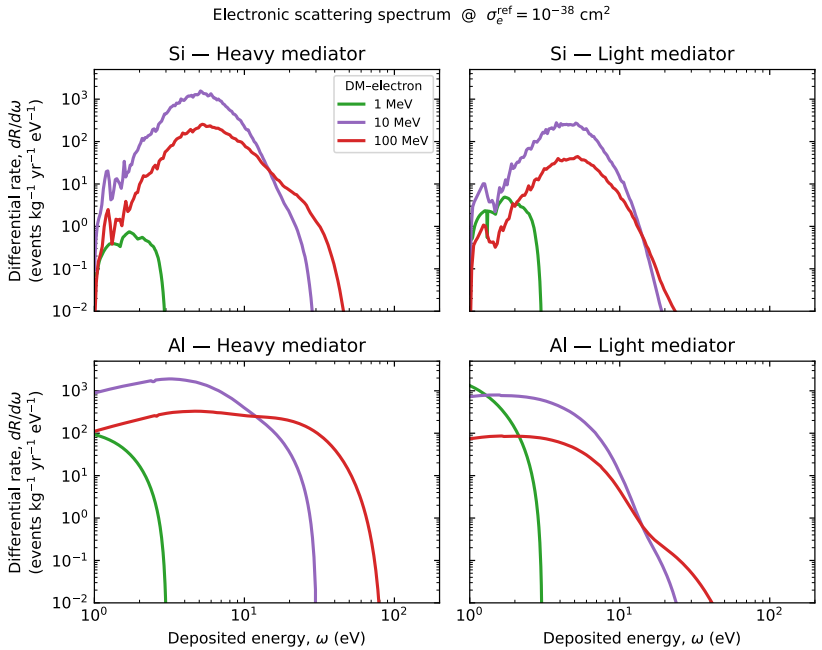
Goodman, Phys. Rev. D 31, 3059 (1985)
Lewin, Astropart. Phys. 6, 87 (1996)

Spin-dependent formalism:
Engel et al., Int. J. Mod. Phys. E 1, 1 (1992)
Bednyakov et al., Phys. Part. Nucl. 37, S106 (2006)

Spin-independent Nuclear Scattering Differential Rate

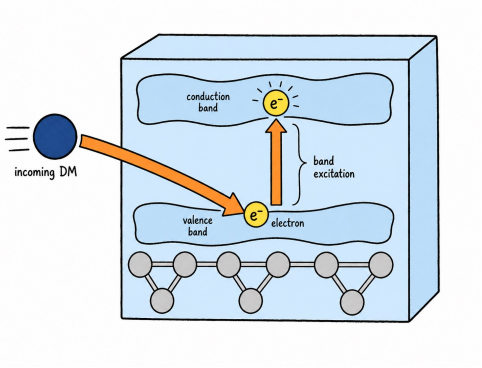
$$\frac{dR}{dE_R}(E_R; m_\chi) = \frac{1}{2}\frac{\rho_\chi}{m_\chi}\frac{A^2\sigma_n}{\mu_p^2}F(q)^2\eta\left(v_{\min}(E_R)\right)$$

Dark Matter-Electron Scattering



Knapen, Phys. Rev. D 104, 015031 (2021)

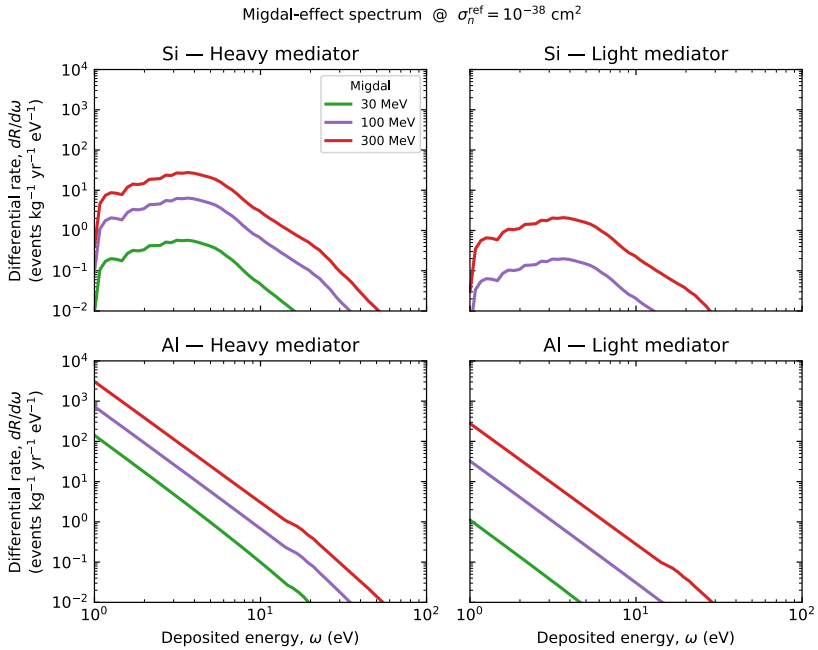
Plots produced with "DarkELF" package:
Knapen, Phys. Rev. D 105, 015014 (2022)



Electron Scattering Differential Rate

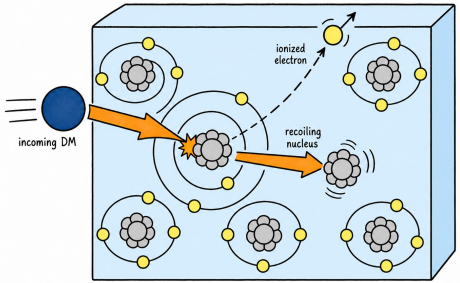
$$\frac{d^2R}{d\omega dk} = \frac{\rho_\chi}{m_\chi}\frac{1}{\rho_T}\frac{\overline{\sigma_e}}{\mu_{\chi e}^2}\frac{1}{8\pi\alpha}k^3 F_{\text{med}}(k)^2 \eta\left(v_{\text{min}}(\omega,k)\right)\text{Im}\left[\frac{-1}{\varepsilon(\omega,k)}\right]$$

Dark Matter-Nucleus Scattering (Migdal-only)



Ibe, JHEP 03, 194 (2018)
Knapen, PRL 127, 081805 (2021)

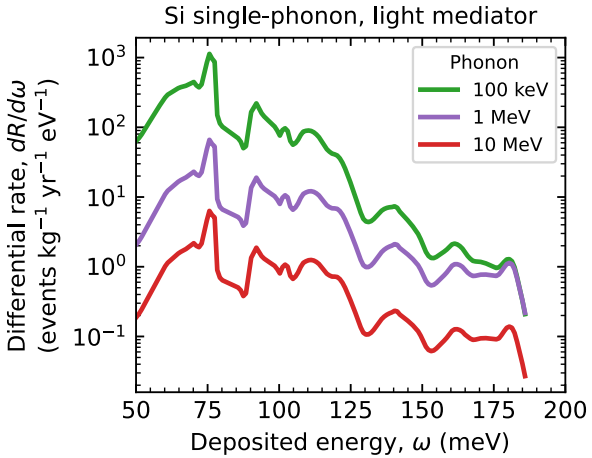
Plots produced with "DarkELF" package:
Knapen, Phys. Rev. D 105, 015014 (2022)



Nuclear Scattering (Migdal) Differential Rate

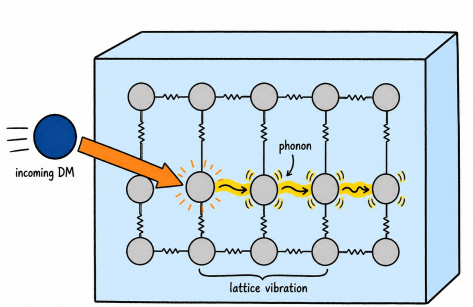
$$\left.\frac{dR}{d\omega}\right|_{\text{Migdal}} = \frac{\rho_\chi}{m_N m_\chi} I(\omega) \int_{v_{\min}}^{v_{\max}} d\,v v f(v) J(v,\omega)$$

Dark Matter-Phonon Scattering



Knapen, PLB 785, 386 (2018)
Griffin, PRD 98, 115034 (2018)
Campbell-Deem, arXiv:2205.02250 (2022)
Lin, arXiv:2411.03433 (2024)
Gori, arXiv:2506.11191 (2025)

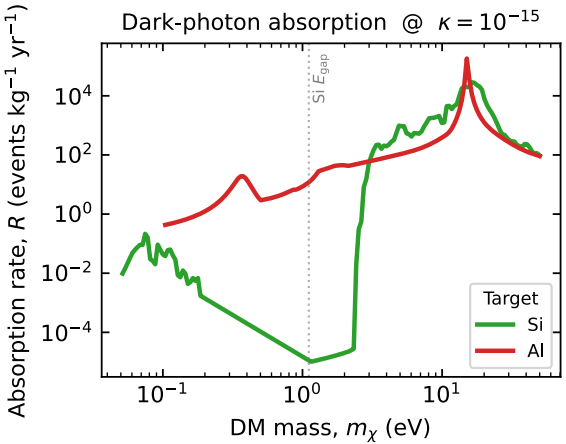
Plots produced with "DarkELF" package:
Knapen, Phys. Rev. D 105, 015014 (2022)



Phonon Scattering Differential Rate

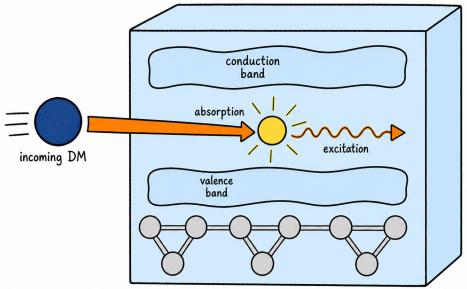
$$\frac{d^2R}{d\omega dk} = \frac{\rho_\chi}{m_\chi}\frac{1}{\rho_T}\frac{\overline{\sigma_e}}{\mu_{\chi e}^2}\frac{1}{8\pi\alpha}k^3 F_{\mathrm{med}}(k)^2 \eta\left(v_{\mathrm{min}}(\omega,k)\right)\mathrm{Im}\left[\frac{-1}{\varepsilon_{\mathrm{phonon}}(\omega,k)}\right]$$

Dark Matter Absorption



Hochberg, PRD 95, 023013 (2017)
Bloch, JHEP 06, 087 (2017)

Plots produced with "DarkELF" package:
Knapen, Phys. Rev. D 105, 015014 (2022)



Dark Photon Absorption Rate

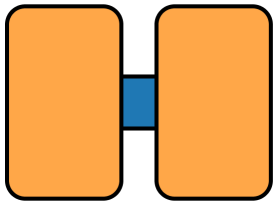
$$R_{\mathrm{abs}}(m_\chi) \propto \kappa^2 \frac{\rho_\chi}{\rho_T} \mathrm{Im}\left[-\frac{1}{\varepsilon(m_\chi, q \to 0)}\right]$$

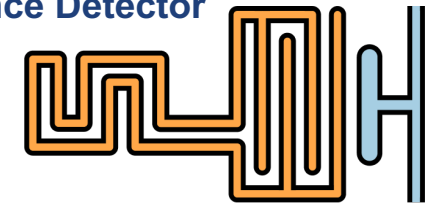
Sensors for Dark Matter Searches with Low Energy Thresholds

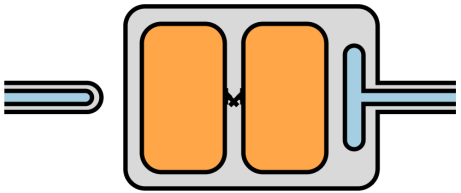
Microwave Kinetic Inductance Detector

Superconducting Qubit

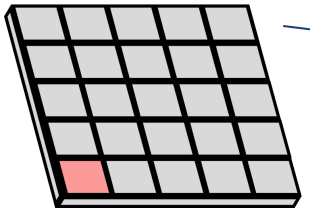
Transition Edge Sensor

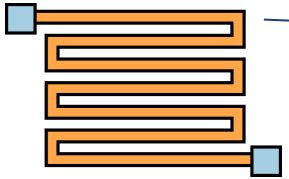




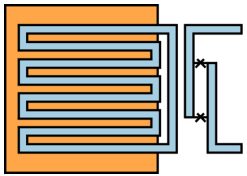


Charge Coupled Device



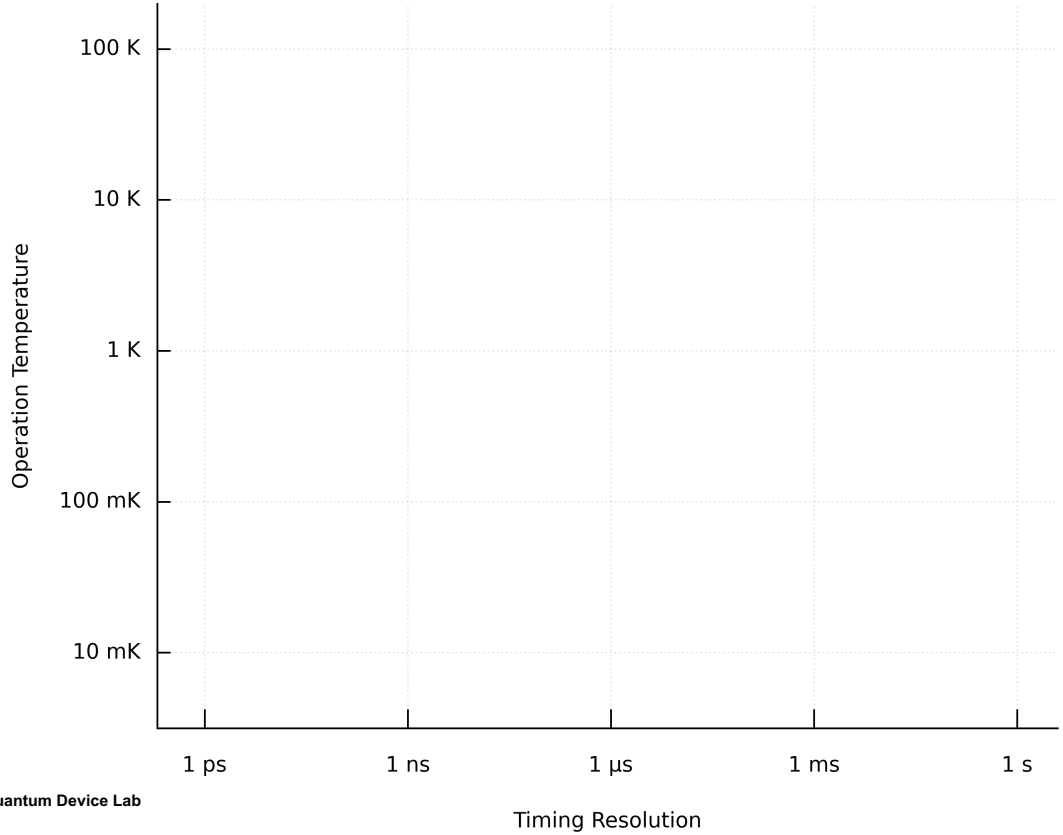


Superconducting Nanowires



Metallic Magnetic Calorimeters

Sensors for Dark Matter Searches with Low Energy Thresholds



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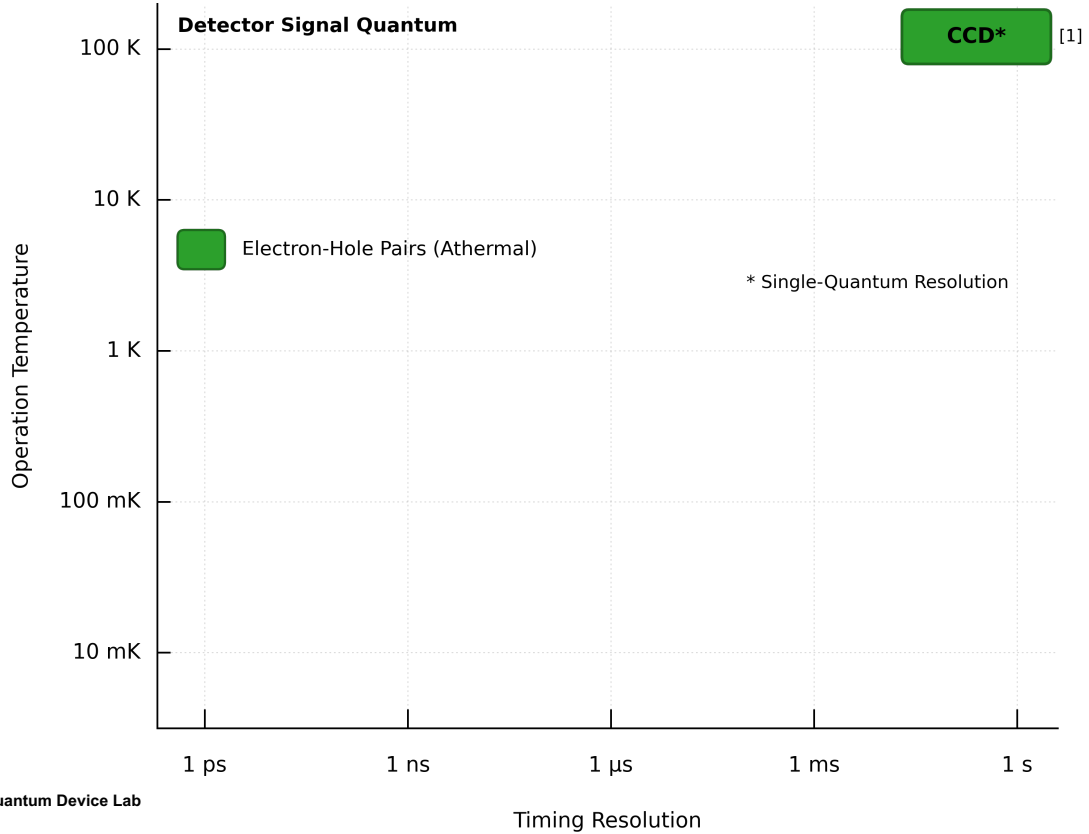

References

[1] Tiffenberg et al., PRL 119, 131802 (2017)

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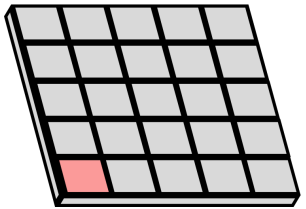

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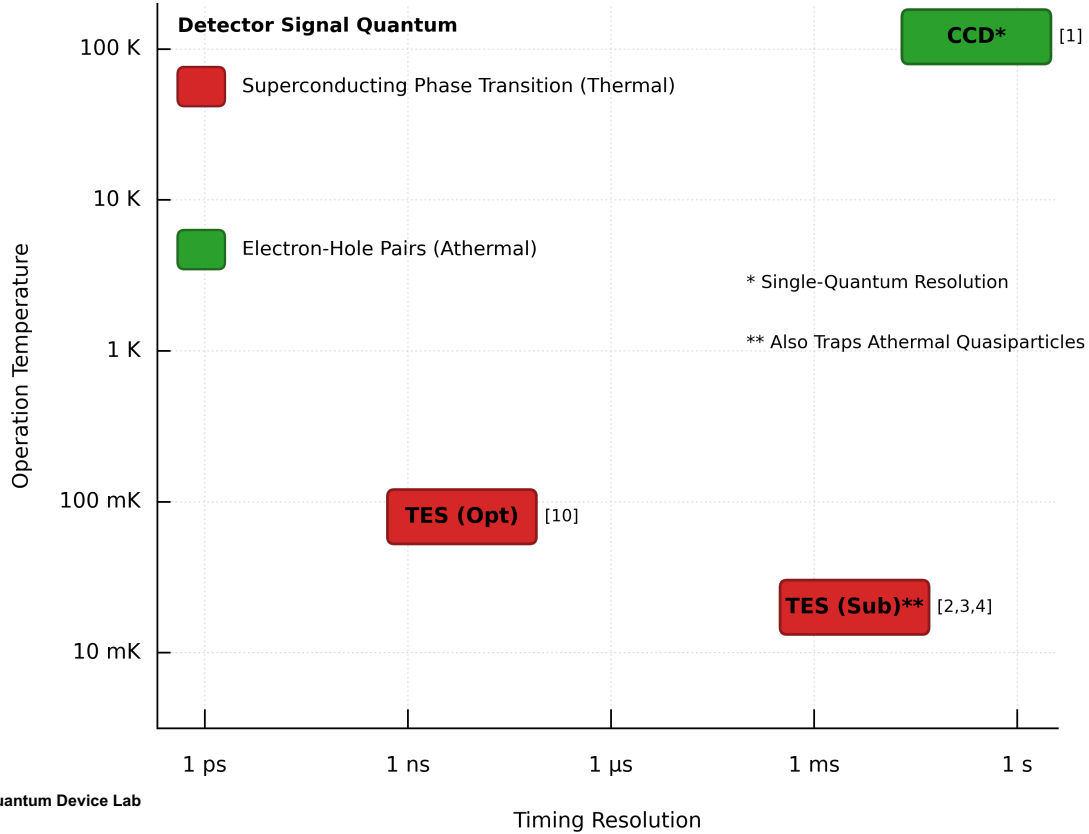

References

[1] Tiffenberg et al., PRL 119, 131802 (2017)

[2] Romani et al., APL 125, 232601 (2024)

[3] Alkhatib et al. (SuperCDMS), PRL 127, 061801 (2021)

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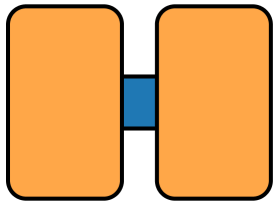
[10] Hattori et al., SST 35, 095002 (2022)

Transition Edge Sensor



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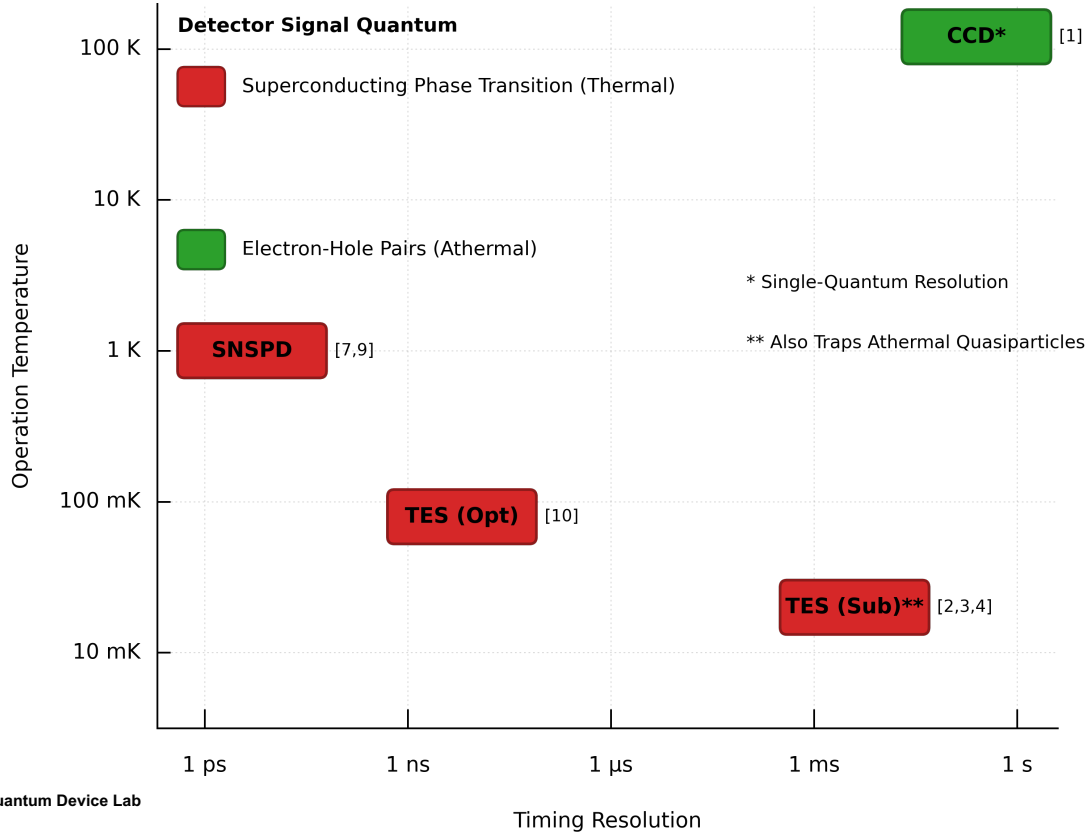

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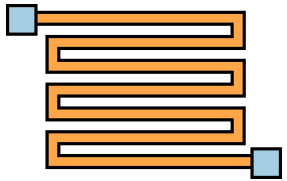
[4] Angloher et al. (CRESST), PRD 110, 083038 (2024)

[7] Baudis et al. (QROCODILE), PRL 135, 081002 (2025)

[9] Korzh et al., Nat. Photon. 14, 250 (2020)

[10] Hattori et al., SST 35, 095002 (2022)



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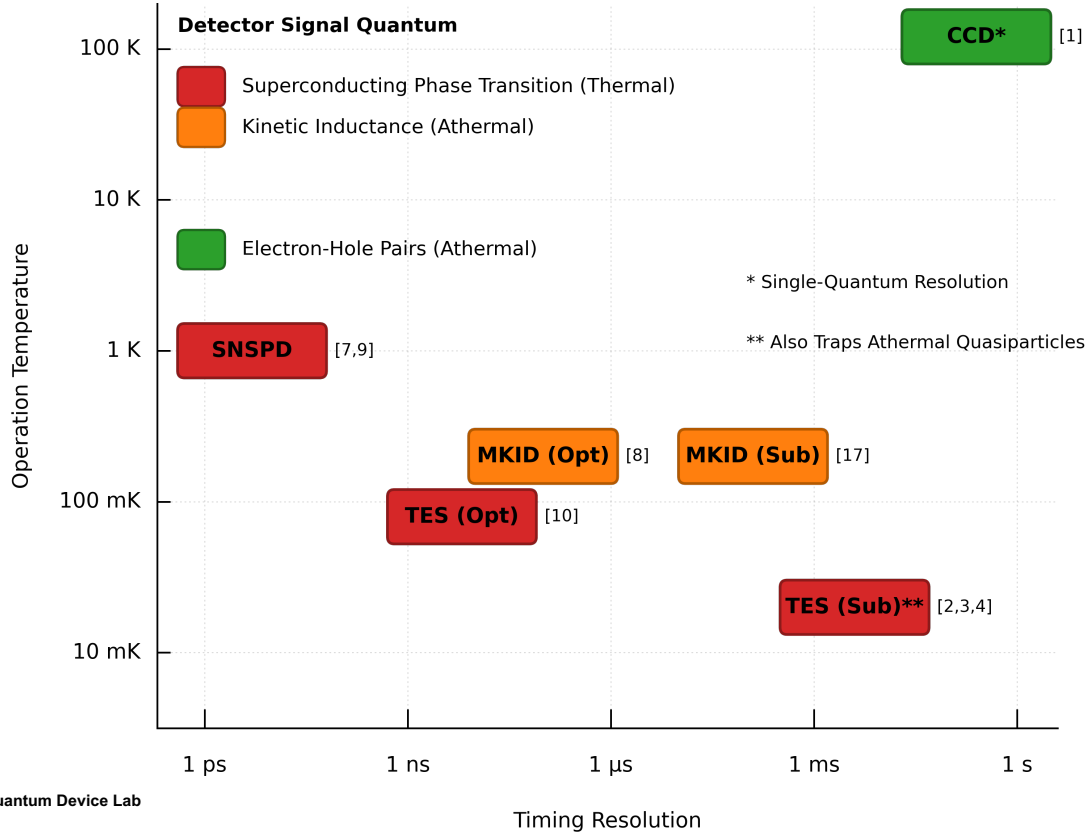

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[4] Angloher et al. (CRESST), PRD 110, 083038 (2024)

[7] Baudis et al. (QROCODILE), PRL 135, 081002 (2025)

[8] Day et al., PRX 14, 041005 (2024)

[9] Korzh et al., Nat. Photon. 14, 250 (2020)

[10] Hattori et al., SST 35, 095002 (2022)

[17] Pesce et al., arXiv:2601.08532 (2026)

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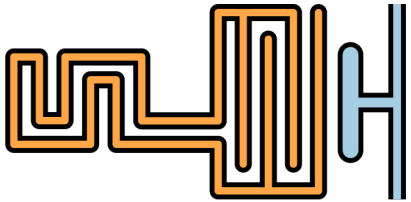
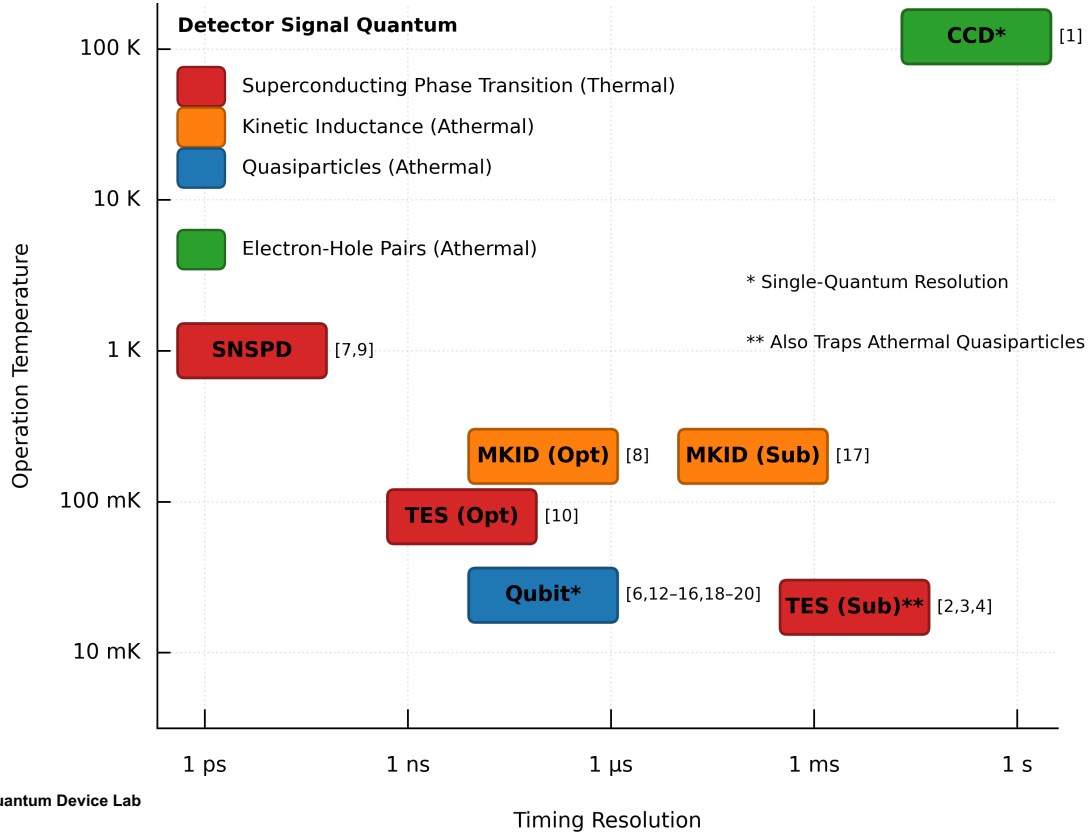
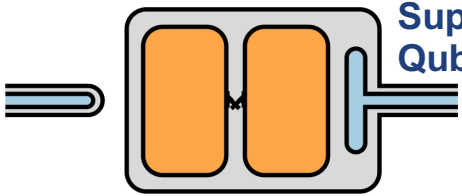


Sensors for Dark Matter Searches with Low Energy Thresholds





[6] Dixit et al., PRL 126, 141302 (2021)

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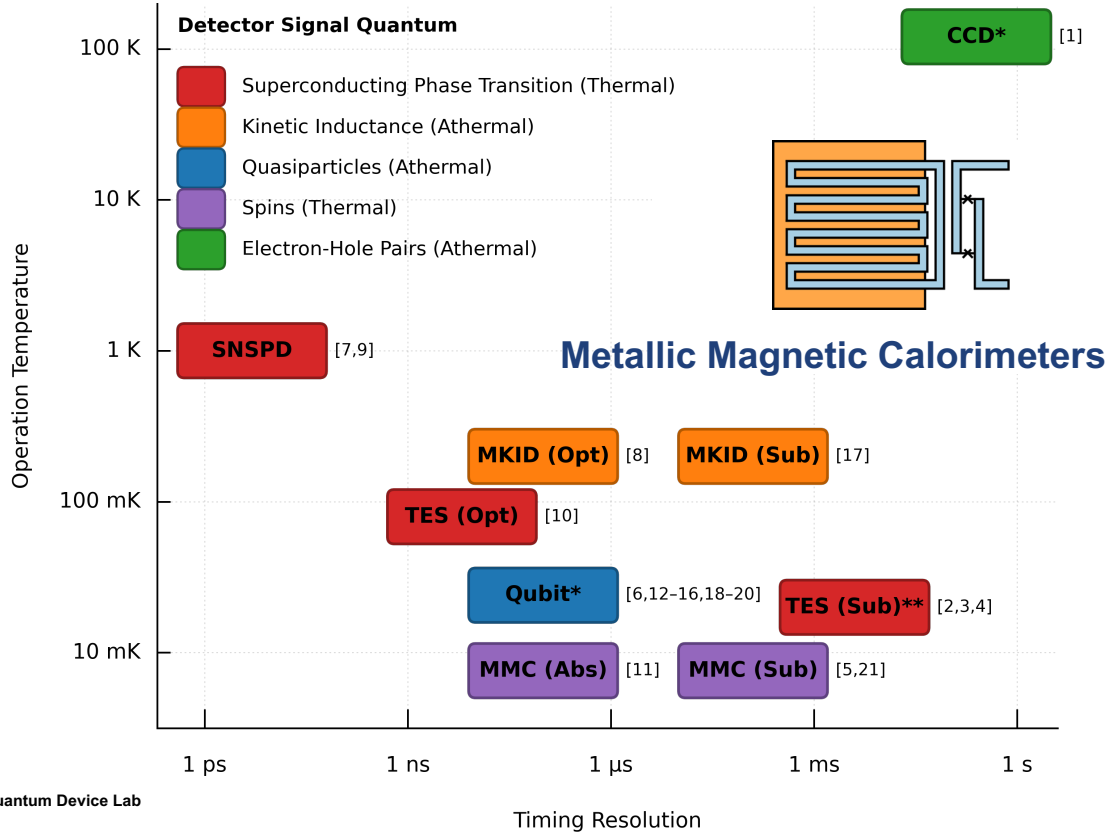

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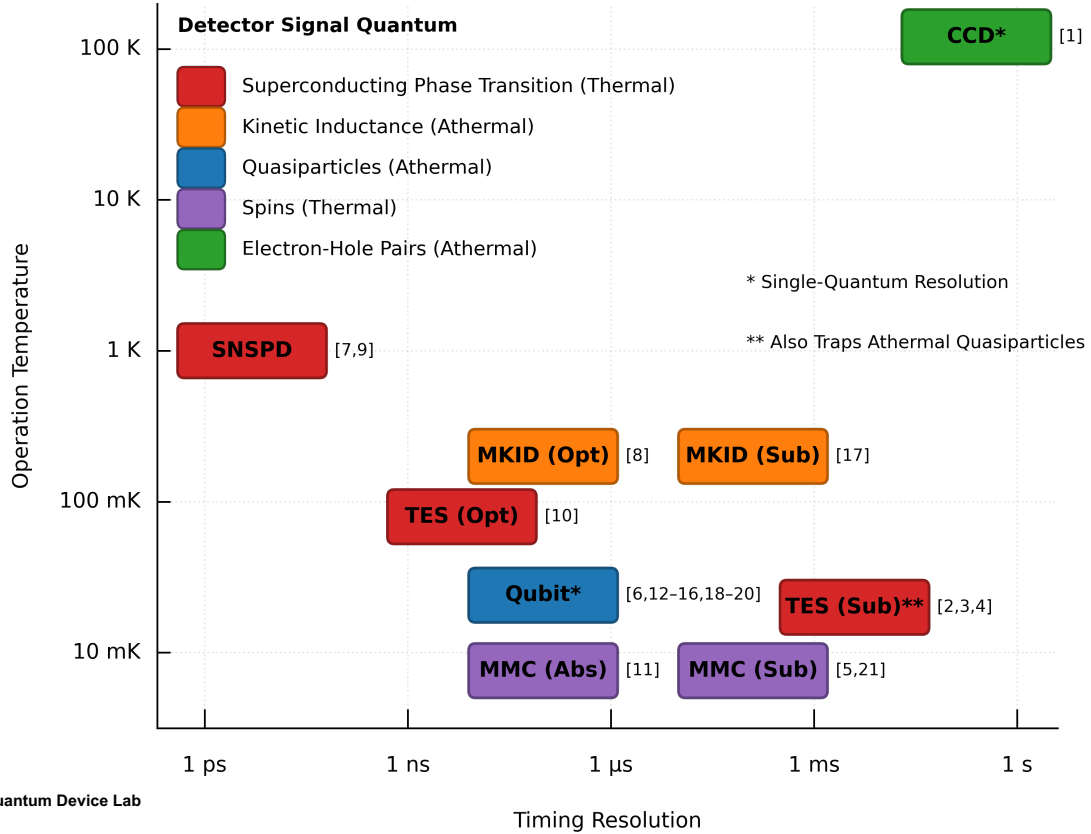

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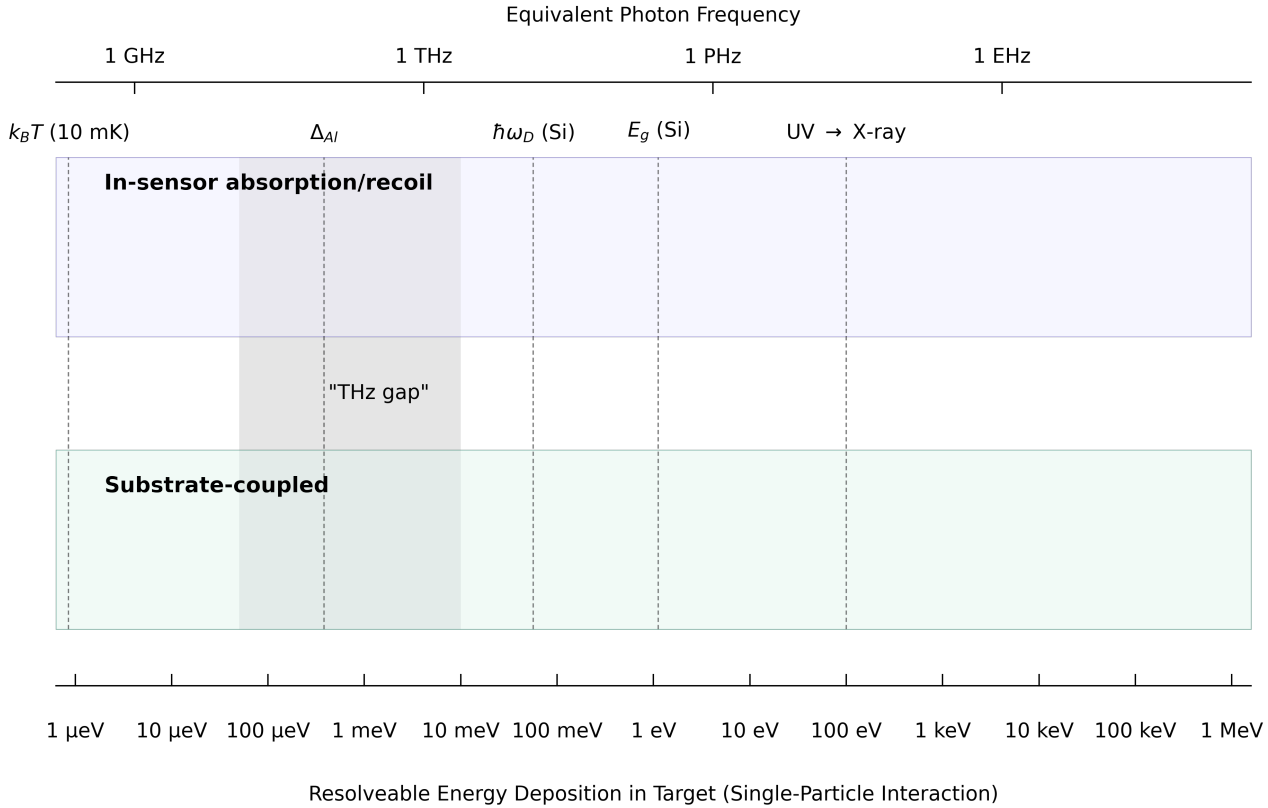
Demonstrated Sensitivities for Low-Threshold Devices



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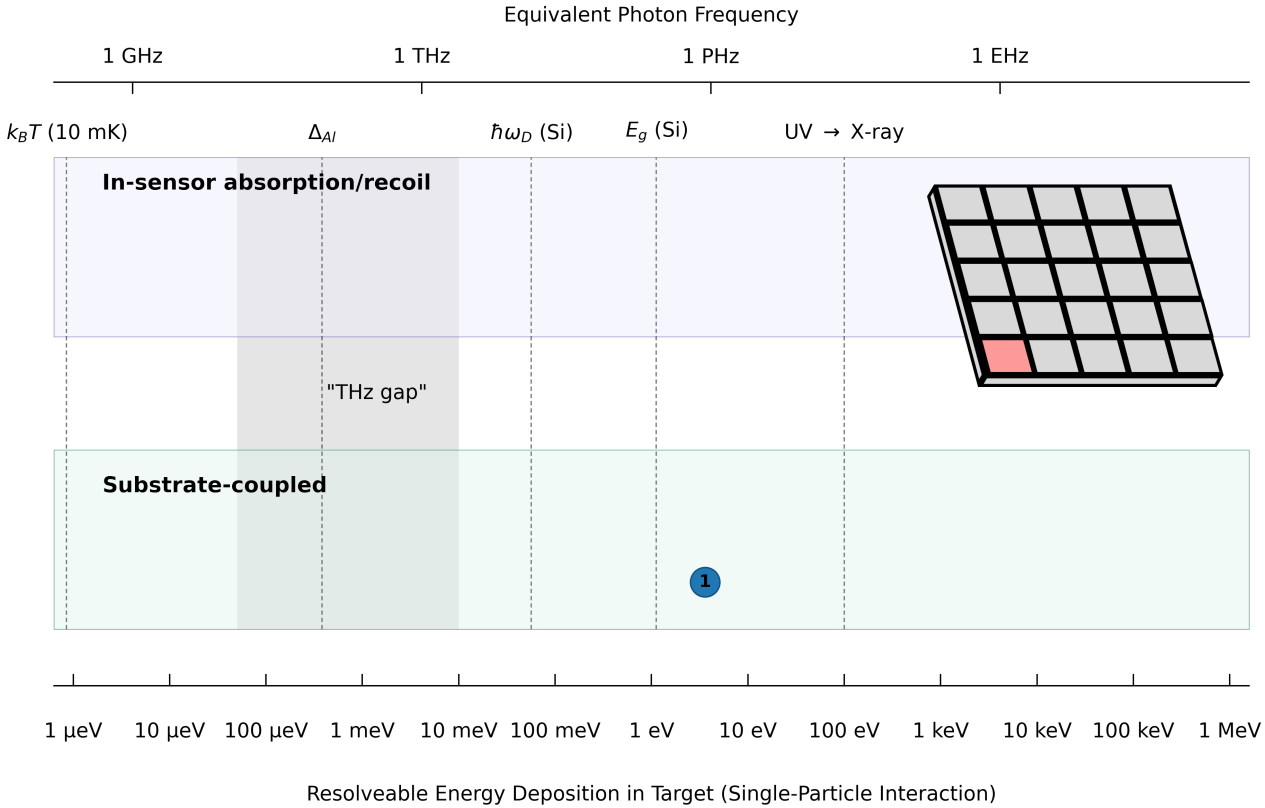

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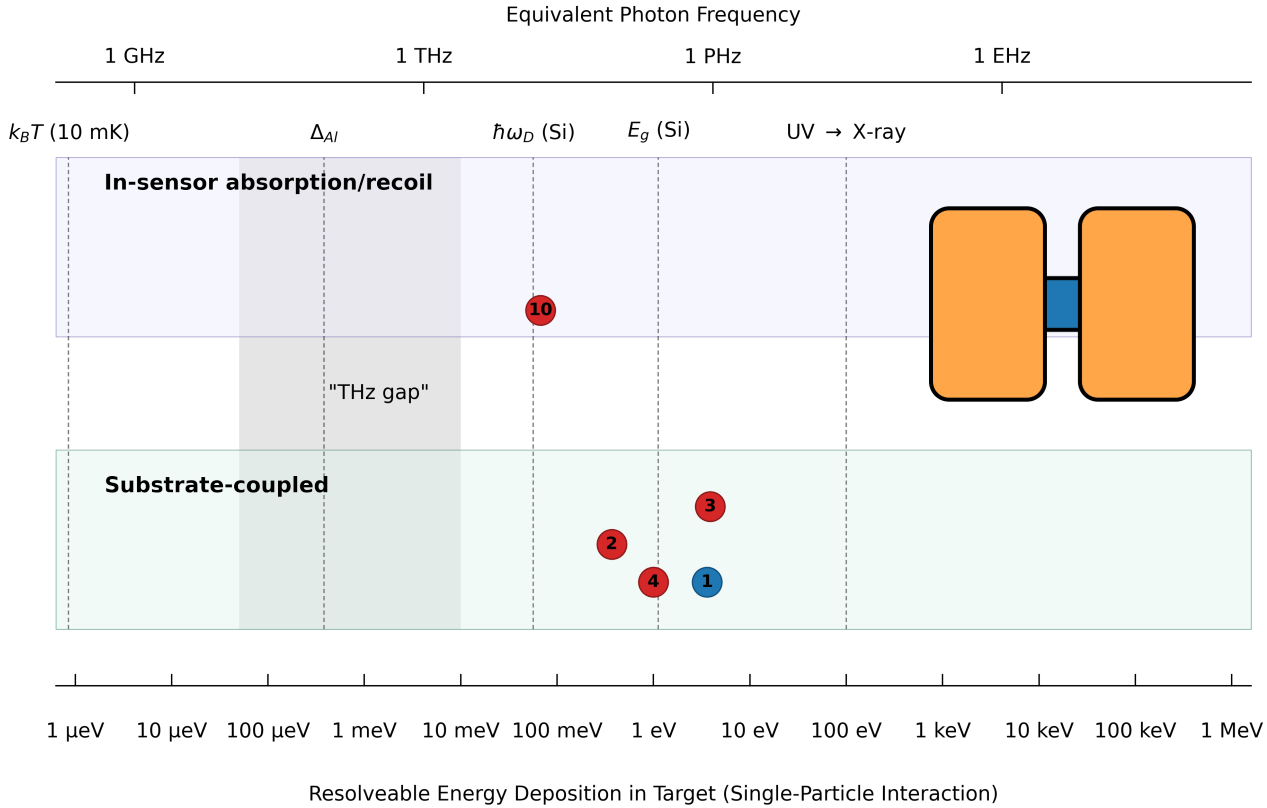

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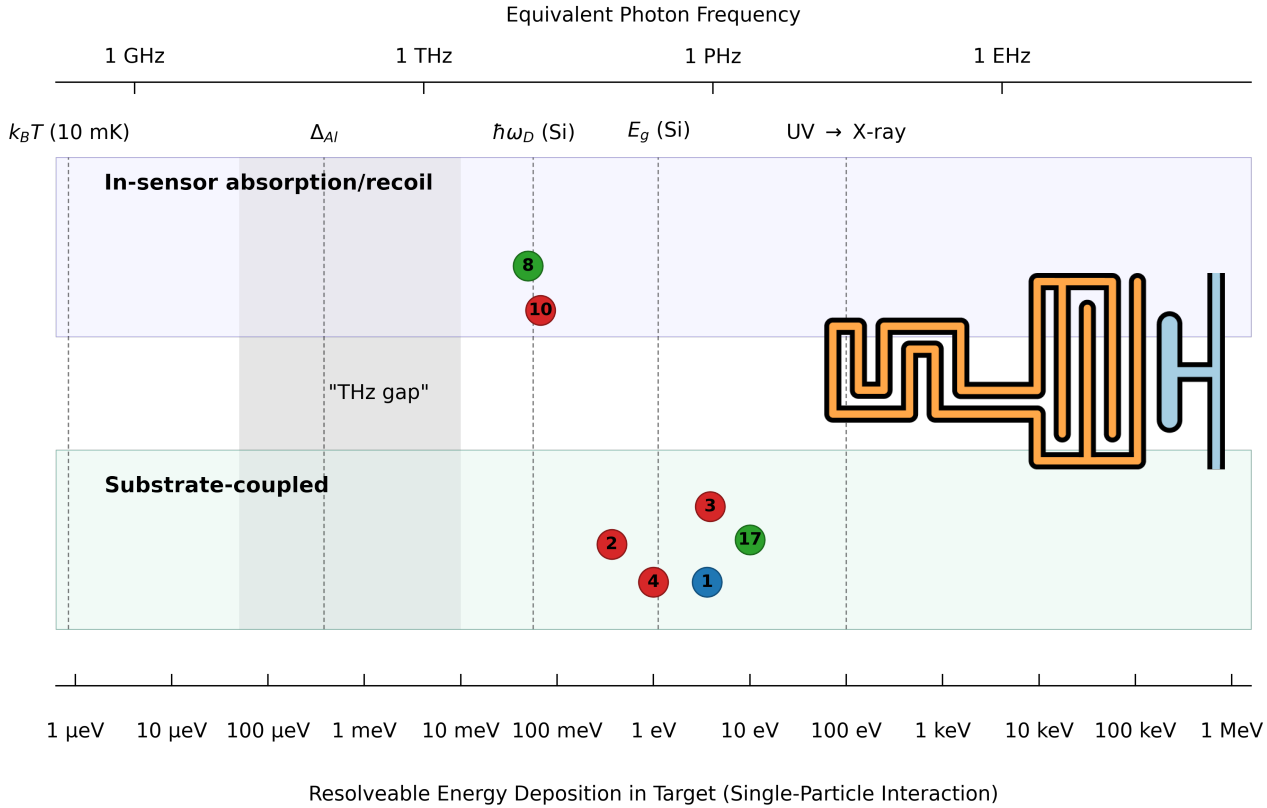

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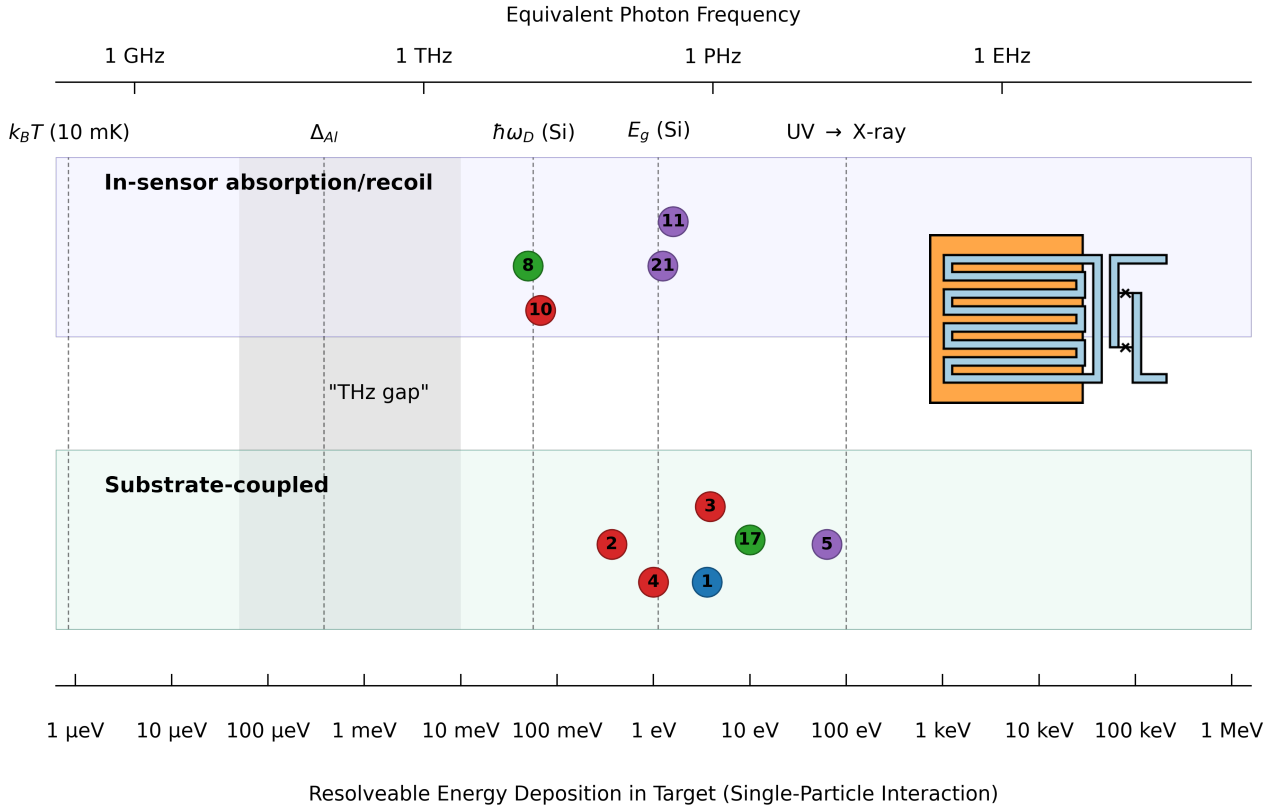

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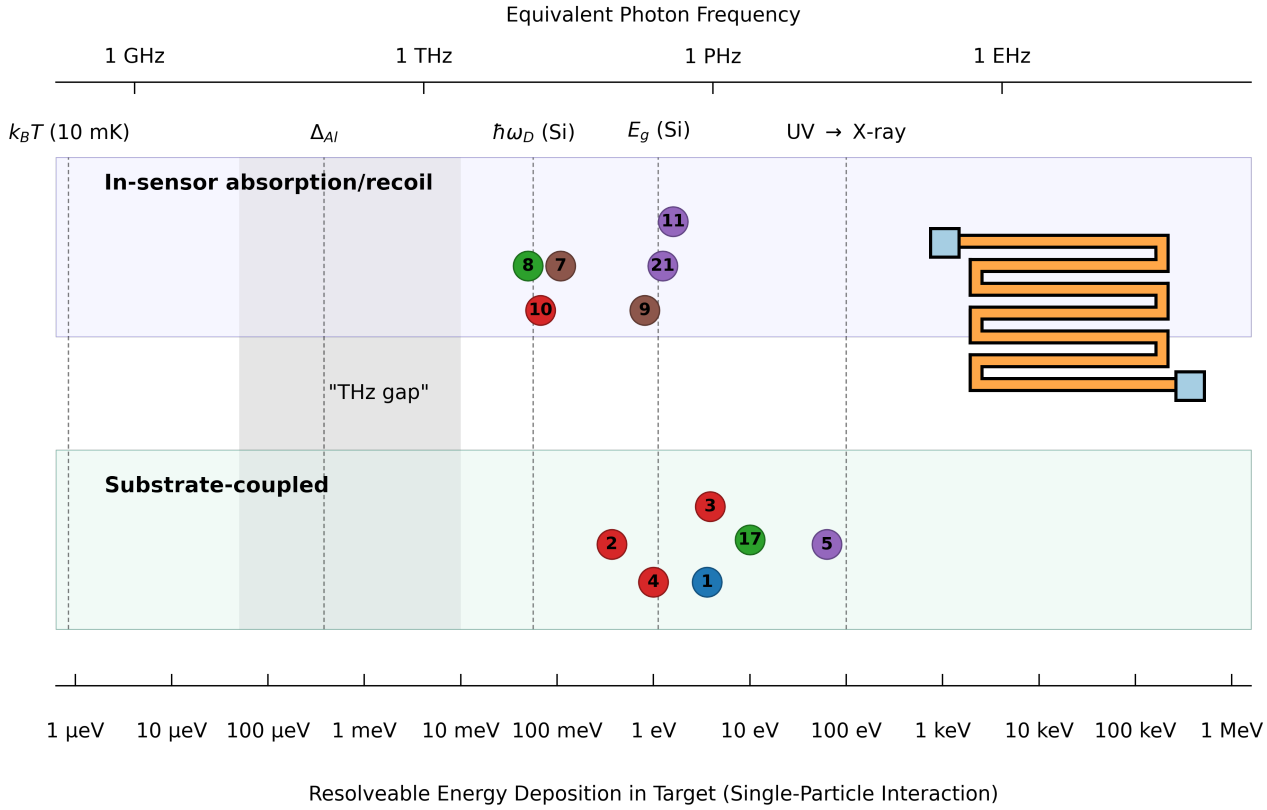

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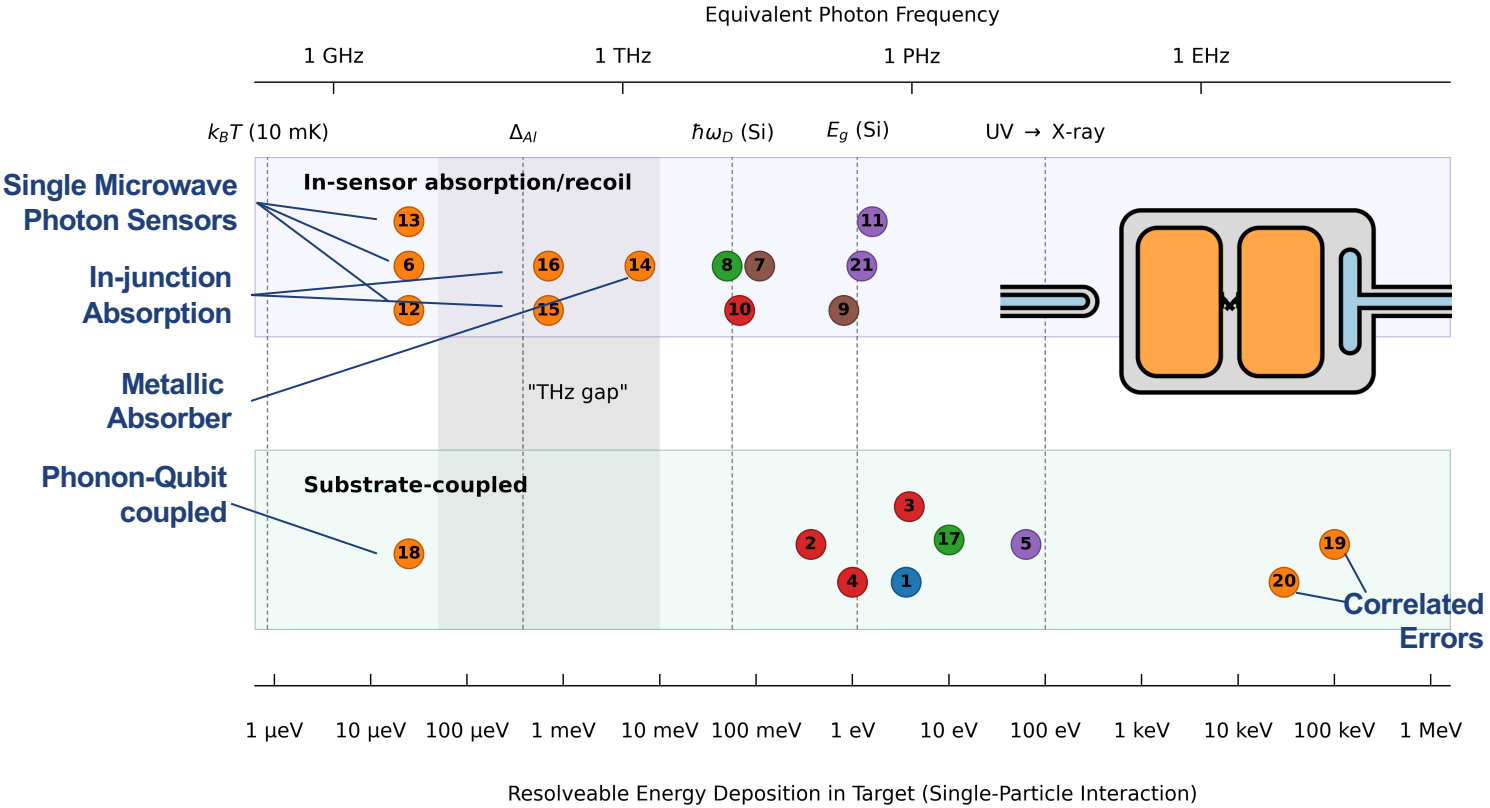

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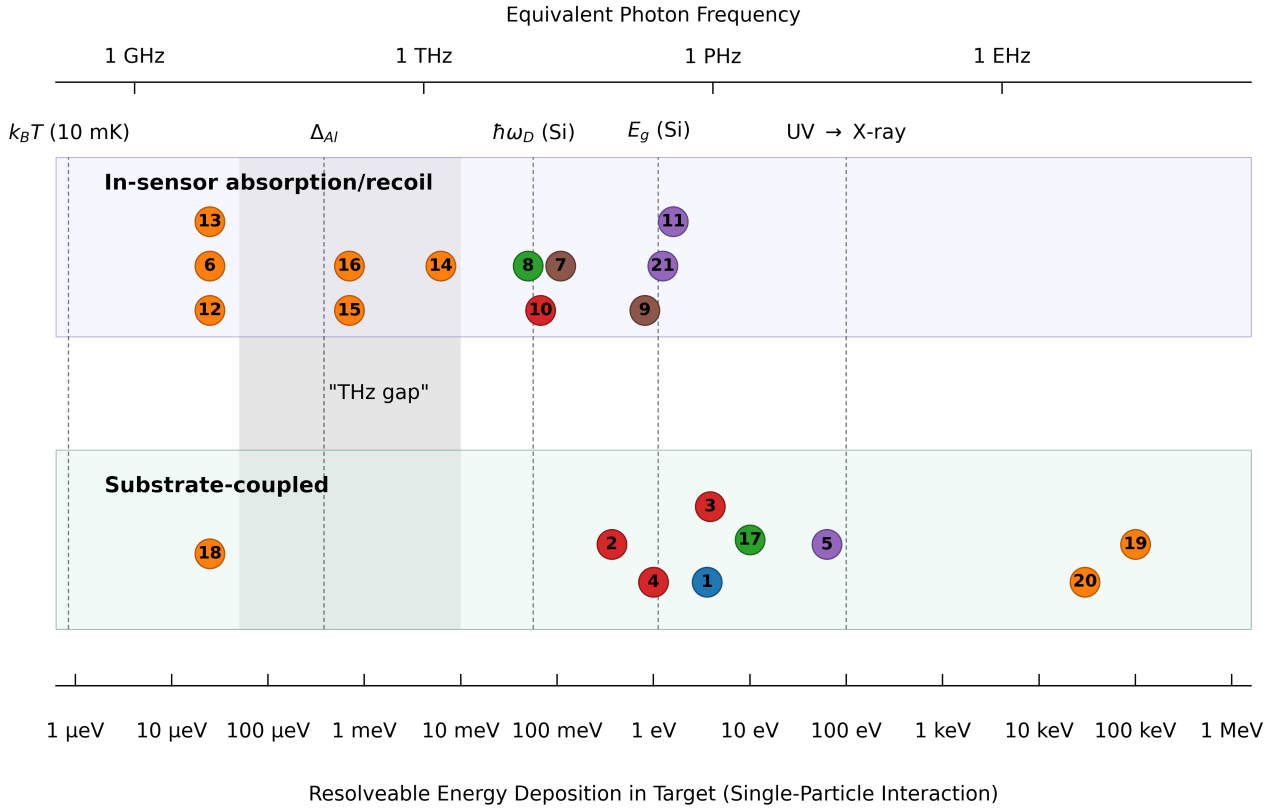

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Current State: Superconducting Qubits as Sensors

- Bogoliubov quasiparticles lead to qubit **relaxation and dephasing**
  - Catelani, PRB 84, 064517 (2011)
  - McEwen, PRL 133, 240601 (2024)
- **Single THz photon** absorption in qubit antenna or metallic absorber
  - Echternach, NA 2, 90 (2018)
  - Liu, PRL 132, 017001 (2024)
  - Diamond, PRX Q 3, 040304 (2022)
  - Kerschbaum, arXiv:2602.05806 (2026)
- **Substrate-coupled** sensors and event reconstruction
  - Magoon, arXiv:2601.16261 (2026)
  - Sandoval, arXiv:2509.18637 (2025)
  - Sundelin, arXiv:2602.01945 (2026)
  - Harrington, Nat. Commun. 16, 6428 (2025)
- **Single microwave photon and phonon** absorption in qubit mode
  - Dixit, Phys. Rev. Lett. 126, 141302 (2021)
  - Braggio, Phys. Rev. X 15, 021031 (2025)
  - Besse, Phys. Rev. X 8, 021003 (2018)
  - Omahen, arXiv:2507.02653 (2025)
- Sensitivity **projections** for future dark matter experiments
  - Hochberg, arXiv:2601.02474 (2026)
  - Li, arXiv:2512.20309 (2025)
  - Fink, PRA 22, 054009 (2024)
  - Linehan, PRD 112, 115005 (2025)

QuDev Lab’s Superconducting Qubits as Quantum Sensors

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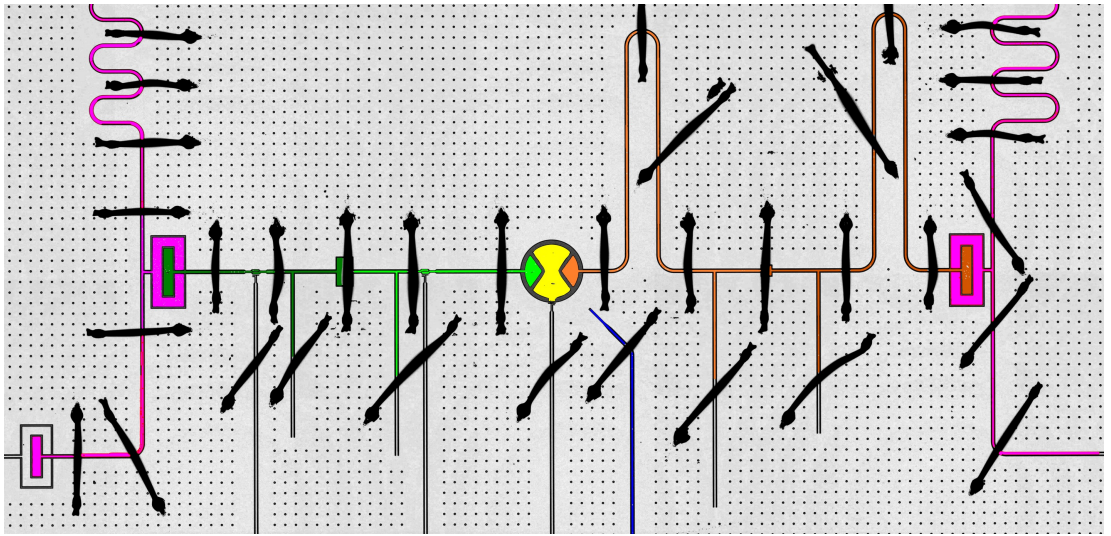
Single Microwave Photon Detectors (Four Wave Mixing)

- Based on Balembois PRA 21, 014043 (2024):
  7 GHz photon counter
  85 Hz dark count rate
  50% efficiency
  (literature values)



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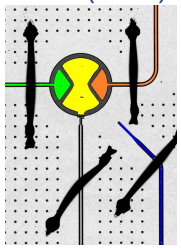

Single Far-Infrared Photon Detectors (Quasiparticles)

- Study IR in QC setups
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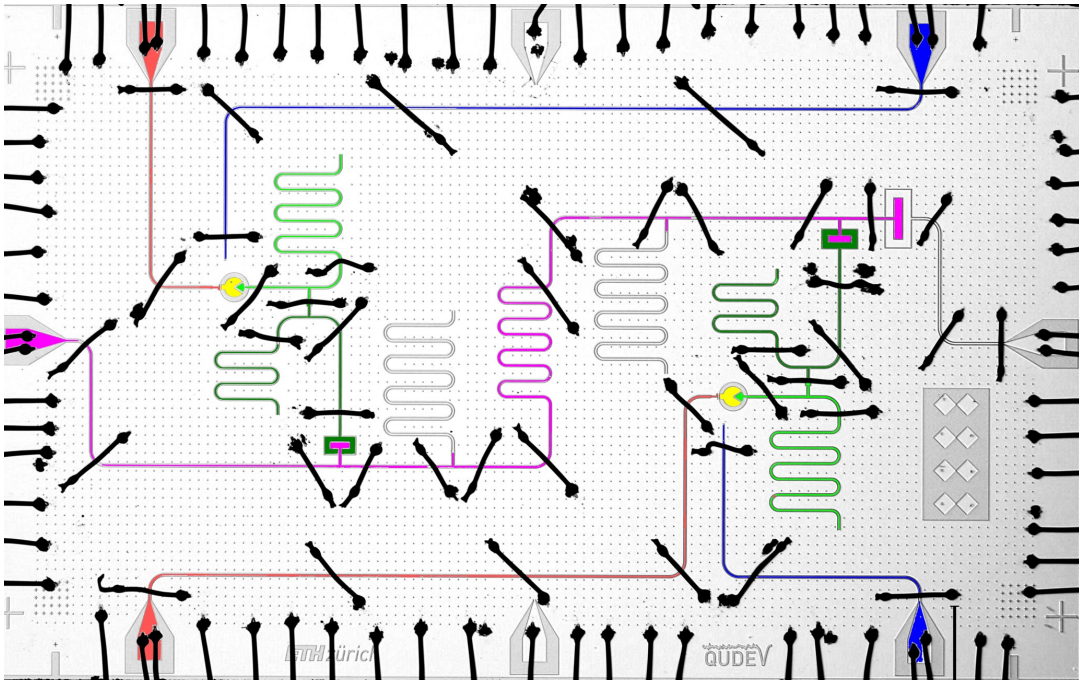

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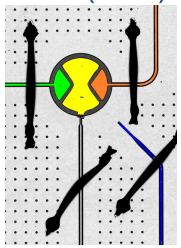

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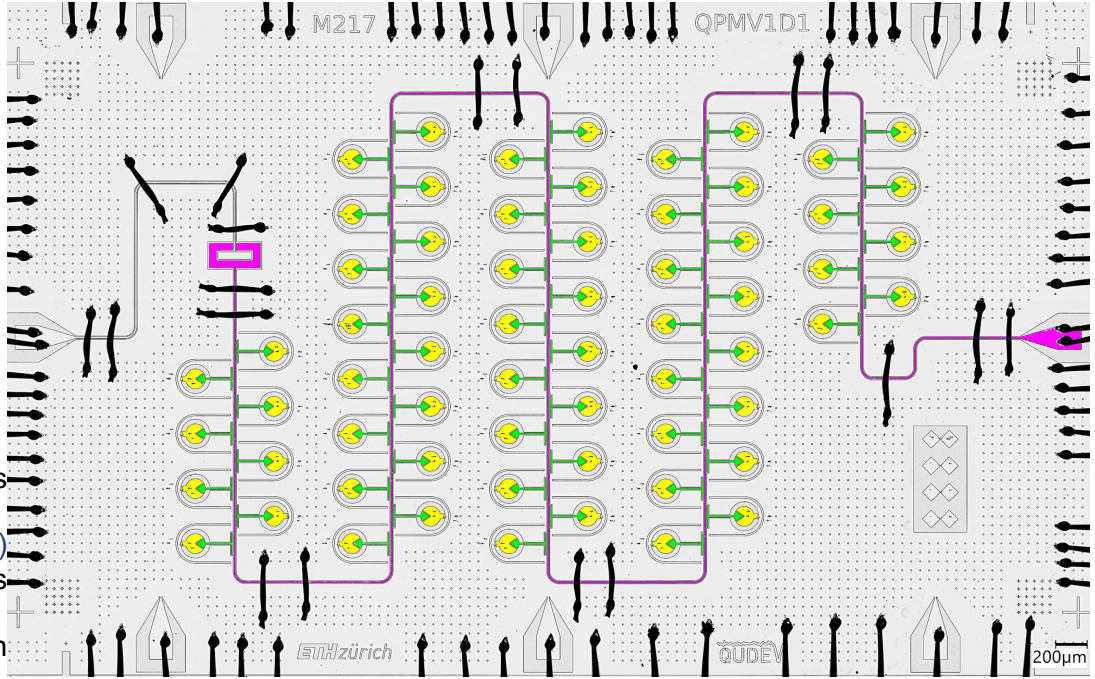

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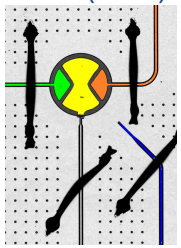

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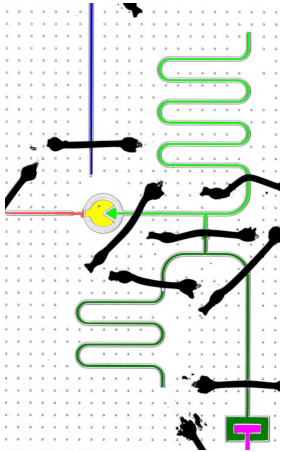
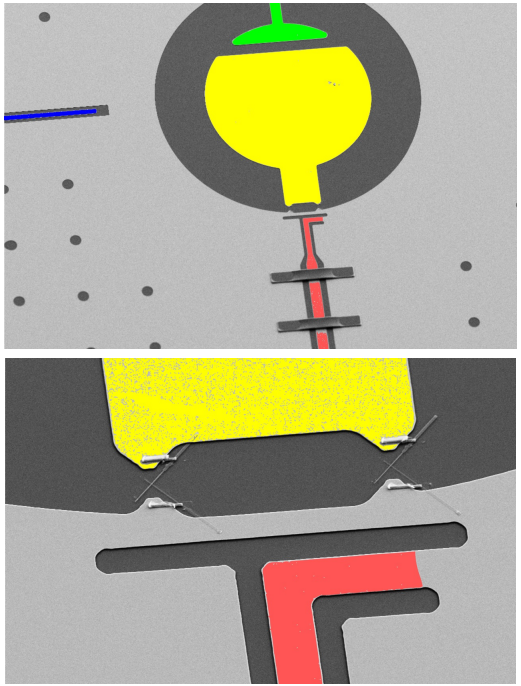
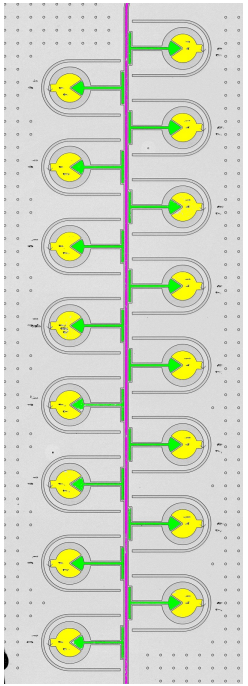
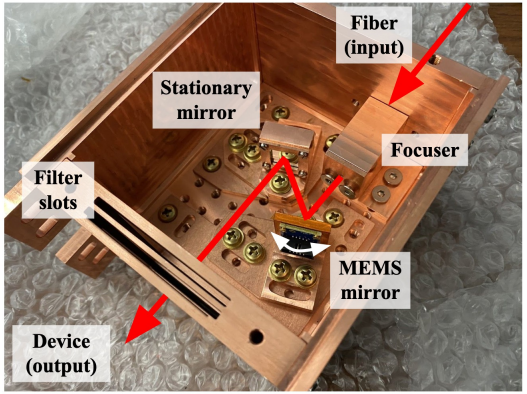






Low-Energy Calibration Methods



Glas fibres with micromirrors (~eV)
Stifter, arXiv:2405.02258 (2024)

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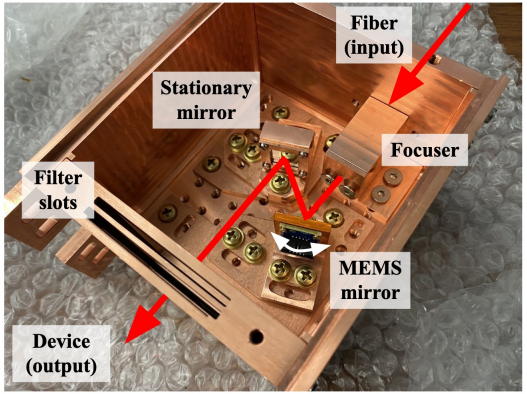

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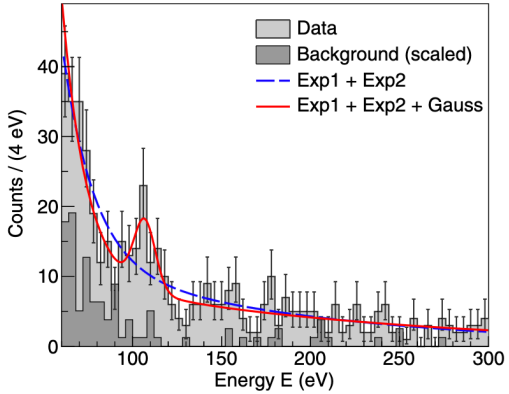
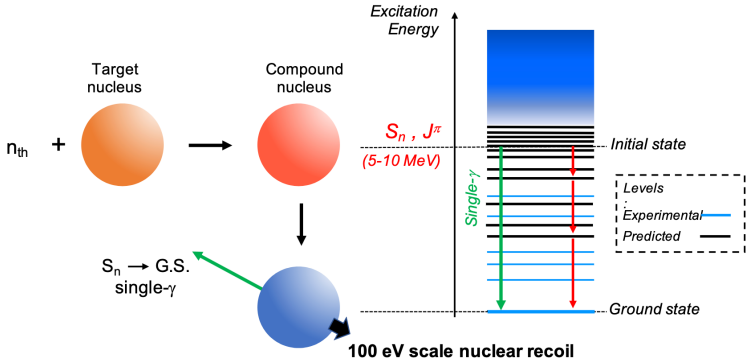


Neutron-induced nuclear recoils (~100 eV)
Abele, PRL 130, 211802 (2023)



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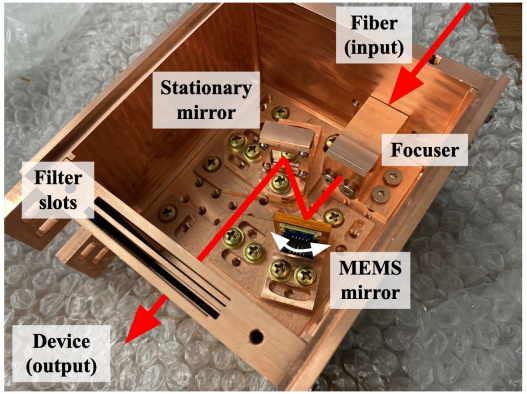

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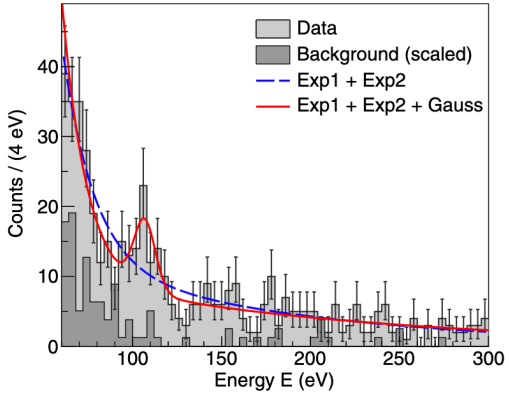

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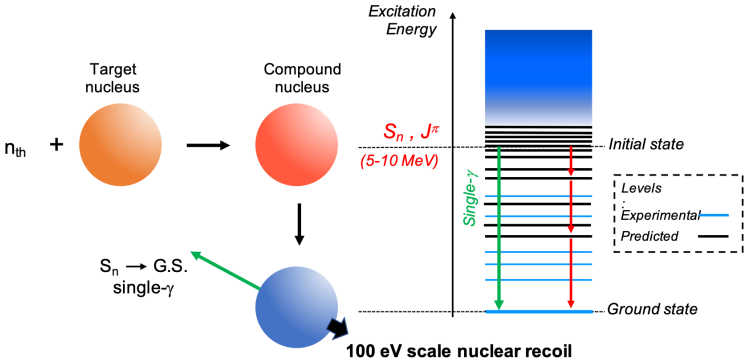
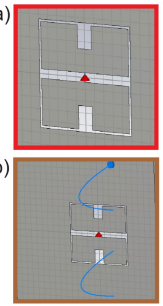
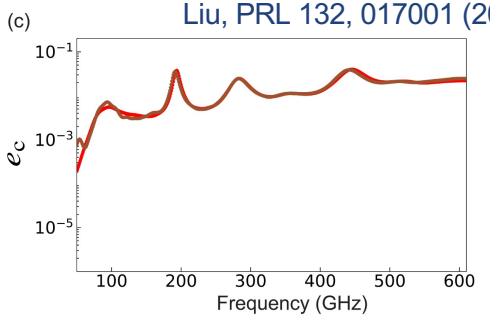


Biased Josephson Junction
Liu, PRL 132, 017001 (2024)

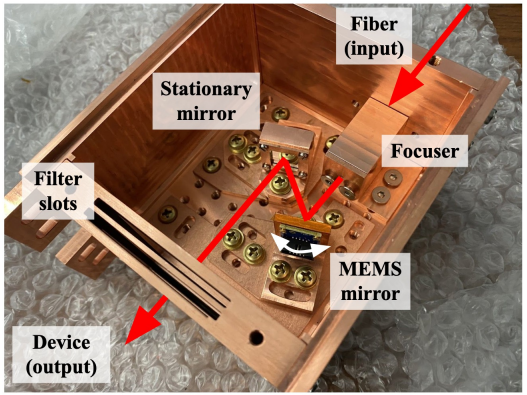
AC Josephson Effect

$$f_J = \frac{V}{\Phi_0} = \frac{2e}{h}V$$

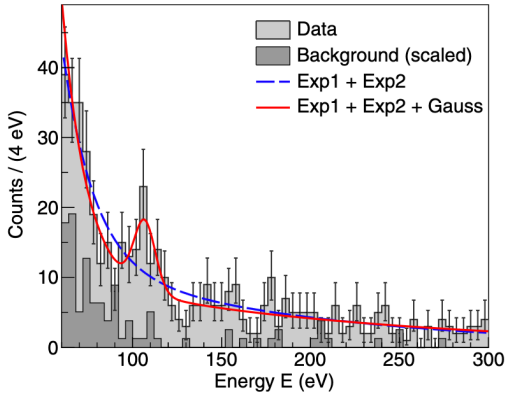




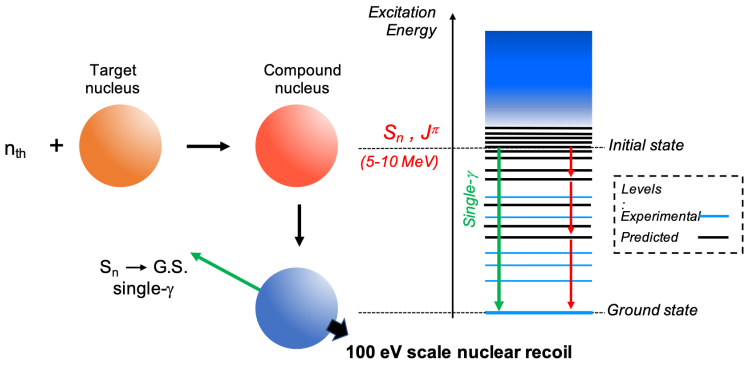
Low-Energy Calibration Methods



Glas fibres with micromirrors (~eV)
Stifter, arXiv:2405.02258 (2024)

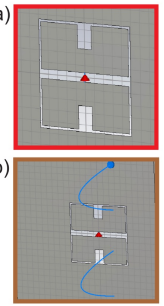


Neutron-induced nuclear recoils (~100 eV)
Abele, PRL 130, 211802 (2023)

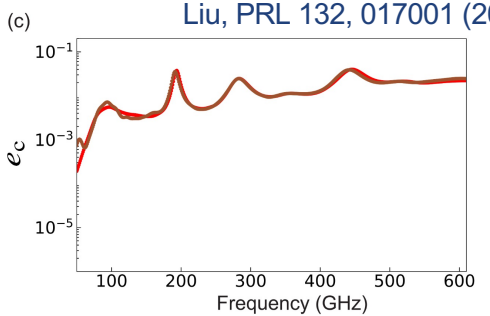


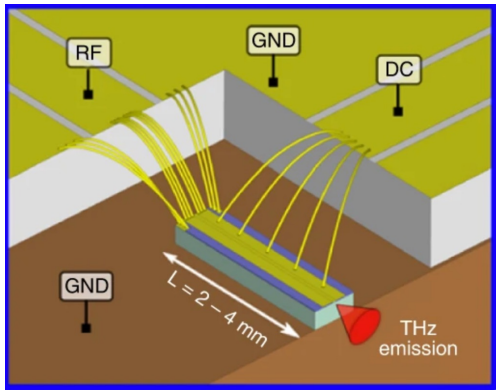
AC Josephson Effect

$$f_J = \frac{V}{\Phi_0} = \frac{2e}{h}V$$



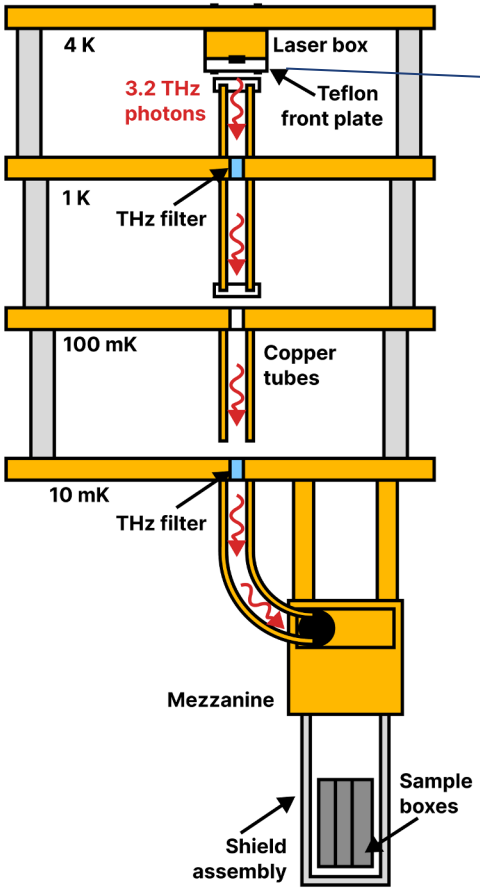
Biased Josephson Junction
Liu, PRL 132, 017001 (2024)

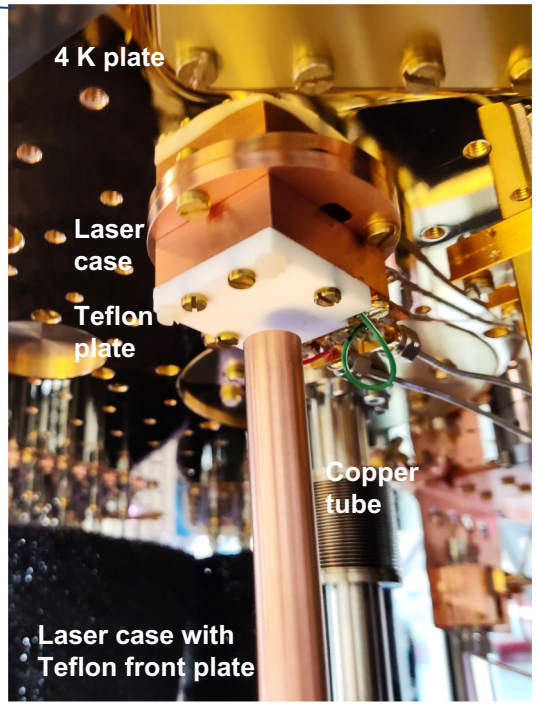


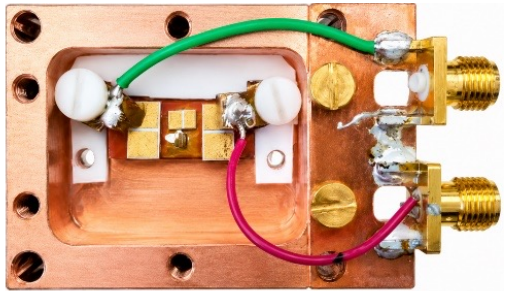


Quantum Cascade Laser
Senica, LSA 11, 347 (2022)

Cryogenic Operation of a Quantum Cascade Laser





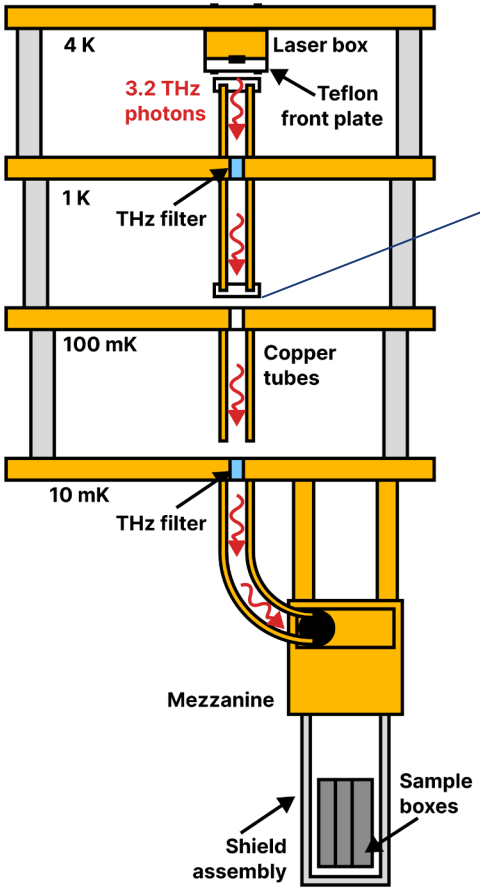


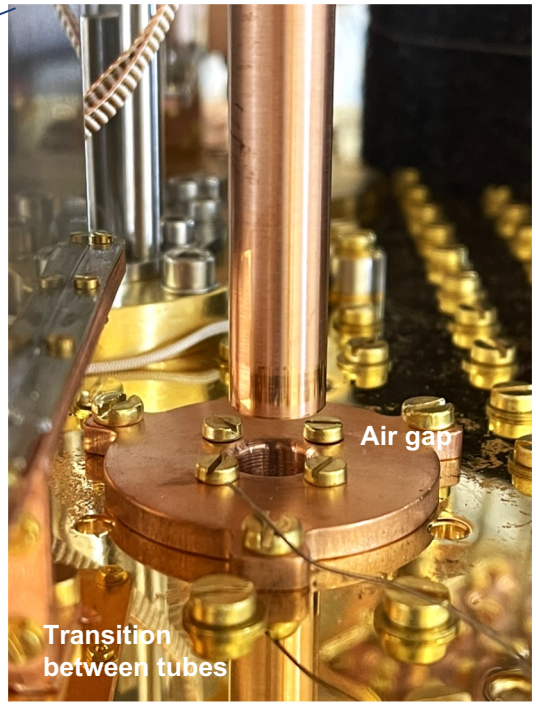
Quantum cascade laser

- **Thermal load** ≈ 1 W
- **Optical output** ≈ mW at **3.2 THz ≈ 13 meV**

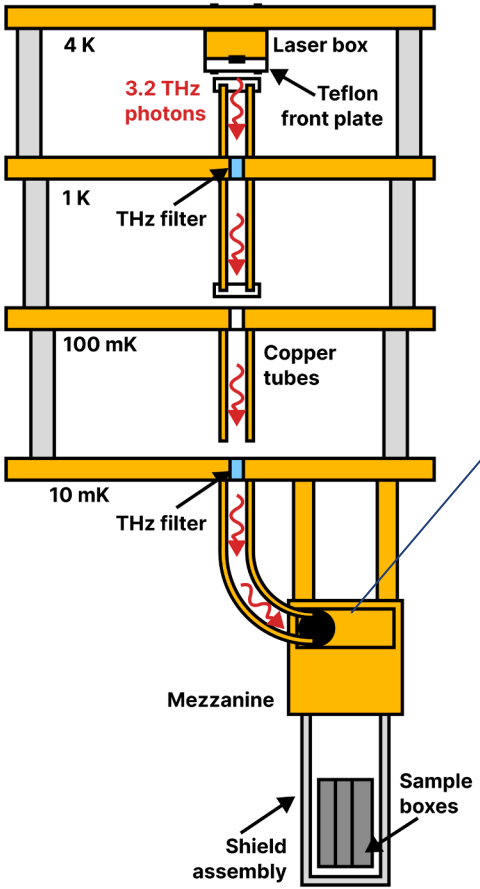
Similar device described in Senica, LSA 11, 347 (2022)

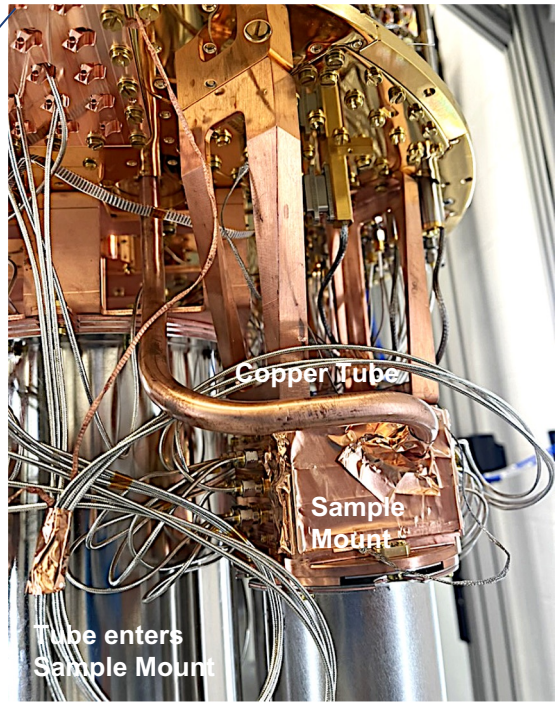
Cryogenic Operation of a Quantum Cascade Laser



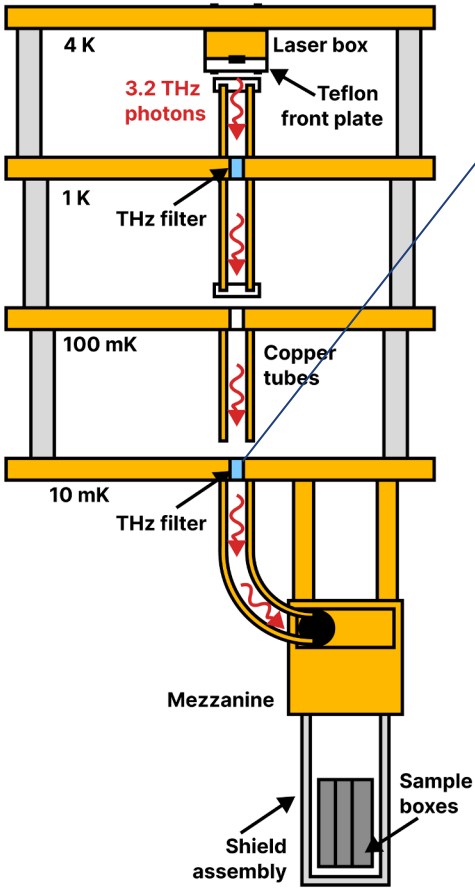


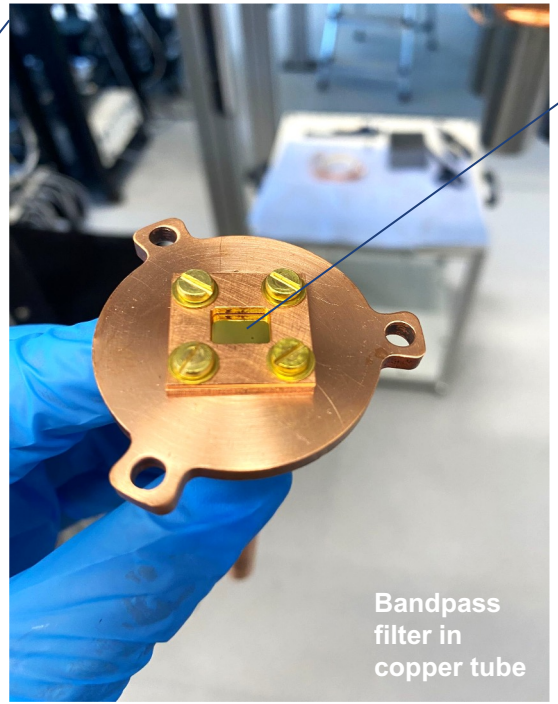
Cryogenic Operation of a Quantum Cascade Laser

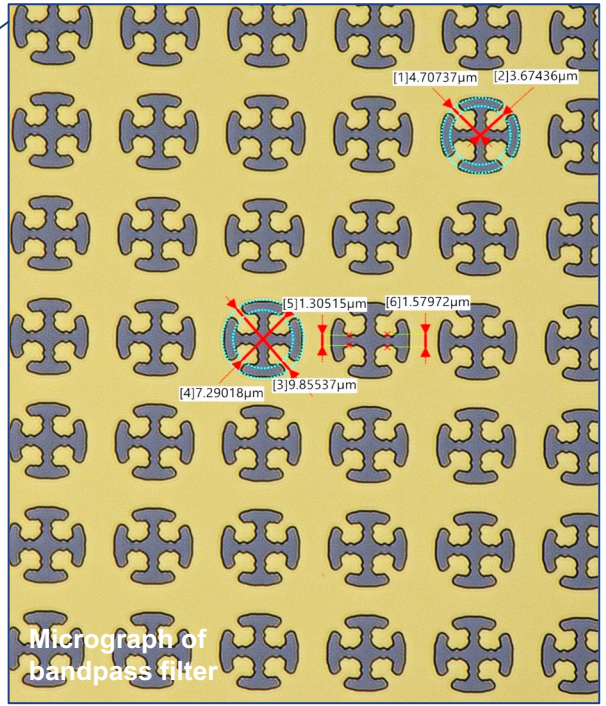




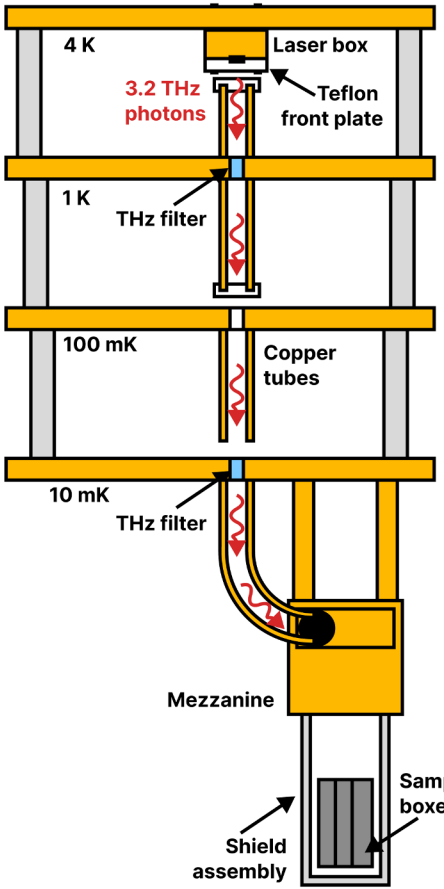
Cryogenic Operation of a Quantum Cascade Laser







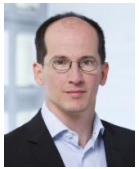
Cryogenic Operation of a Quantum Cascade Laser



Emre Vardar (Master Student)

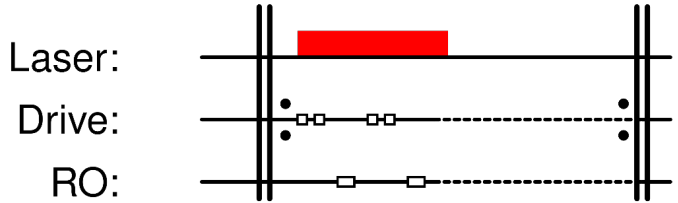
FW (PostDoc)

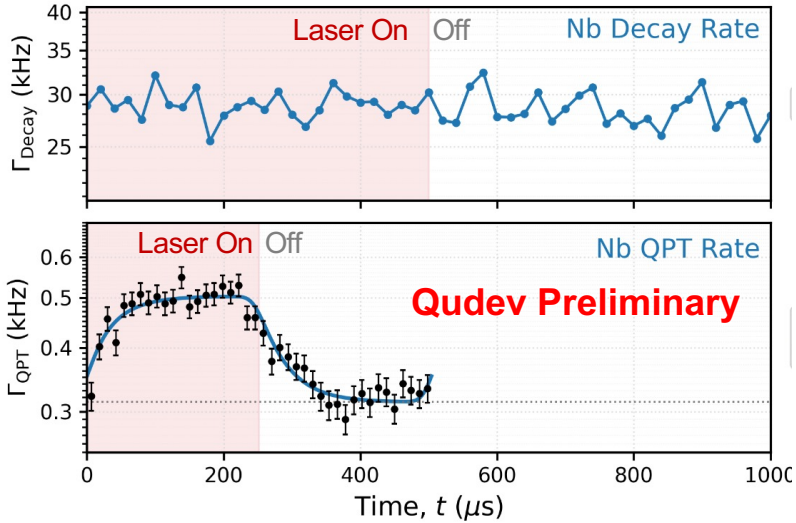
Jean-Claude Besse (Senior Assistant)



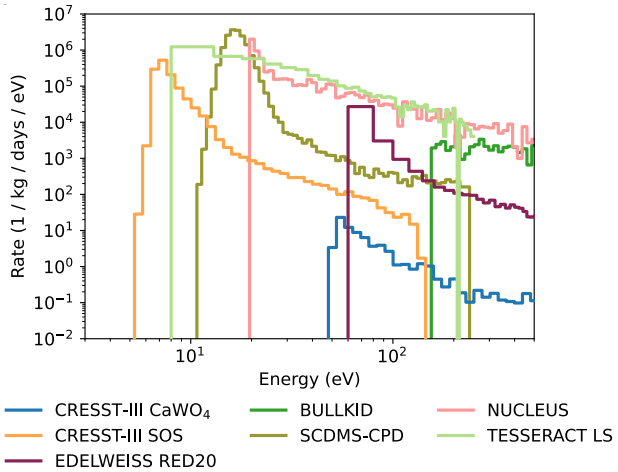
Andreas Wallraff (Group Leader)

Collarboration with **Valerio DiGiorgio**, **Giacomo Scalari** (ETHZ)





Low-Energy Phonon Backgrounds - “Low Energy Excess”



Angloher, PRD 110(8):083038 (2024)

Armengaud, PRD 99(8):082003 (2019)

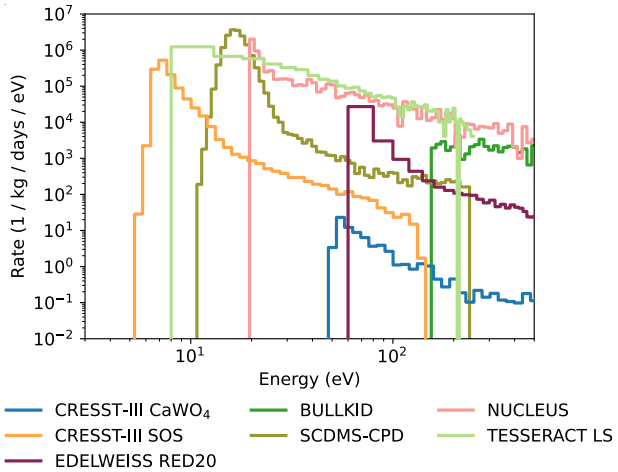
Cruciani, APL 121(21):213504 (2022)

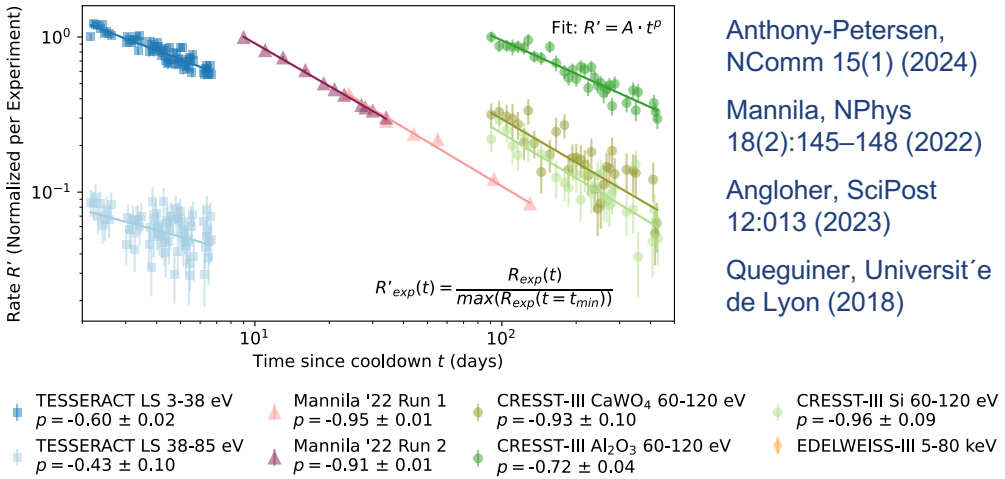
Alkhatib, PRL 127:061801 (2021)

Angloher, EPJ-C 77(9):637 (2017)

- One or multiple **power laws** in energy, onset **below ~200 eV**

Low-Energy Phonon Backgrounds - “Low Energy Excess”





Anthony-Petersen, NComm 15(1) (2024)

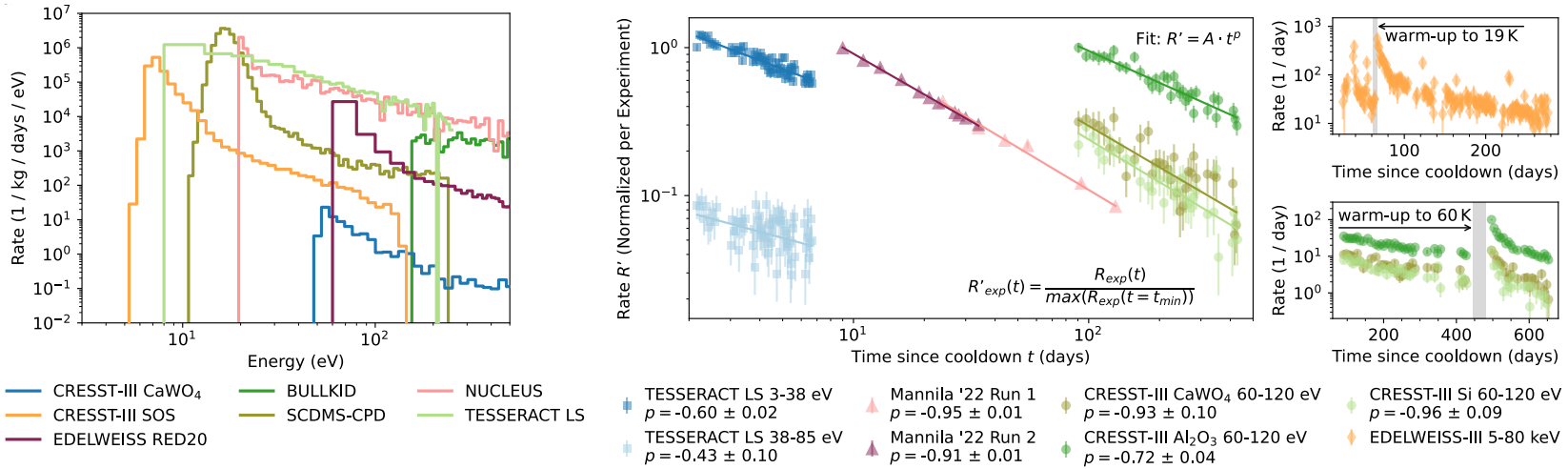
Mannila, NPhys 18(2):145–148 (2022)

Angloher, SciPost 12:013 (2023)

Queguiner, Universit´e de Lyon (2018)

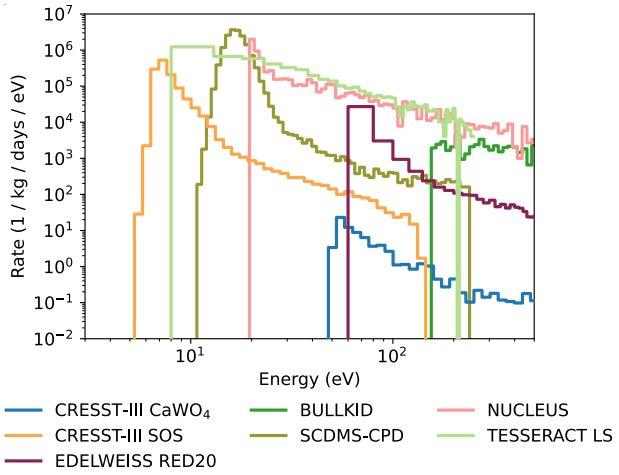
- One or multiple **power laws** in energy, onset **below ~200 eV**
- **Rate reduces** with time after cooldown

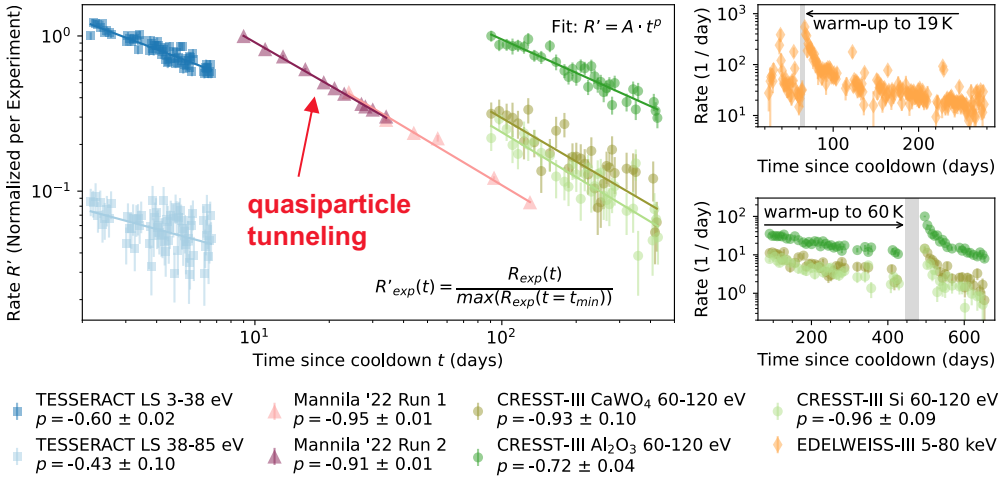
Low-Energy Phonon Backgrounds - “Low Energy Excess”



- One or multiple **power laws** in energy, onset **below ~200 eV**
- **Rate reduces** with time after cooldown
- Reset with **warm-up** of setup

Low-Energy Phonon Backgrounds - “Low Energy Excess”





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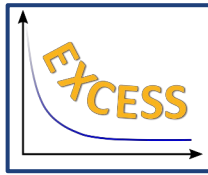


“EXCESS” workshop series on **low energy backgrounds**

Baxter, ARNPS 75, 301 (2025)

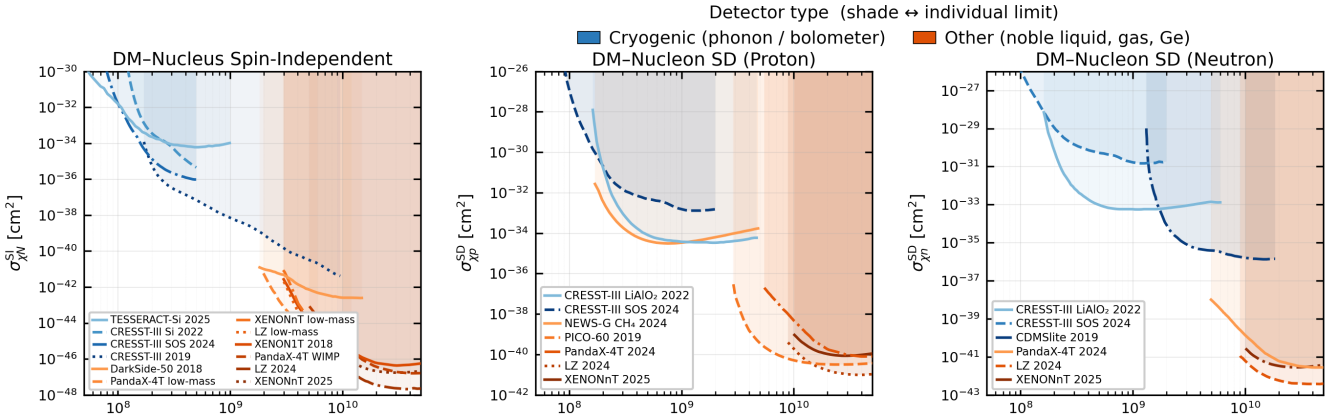
Time-dependence in quasiparticle density:

Yelton, arXiv:2503.09554 (2025)

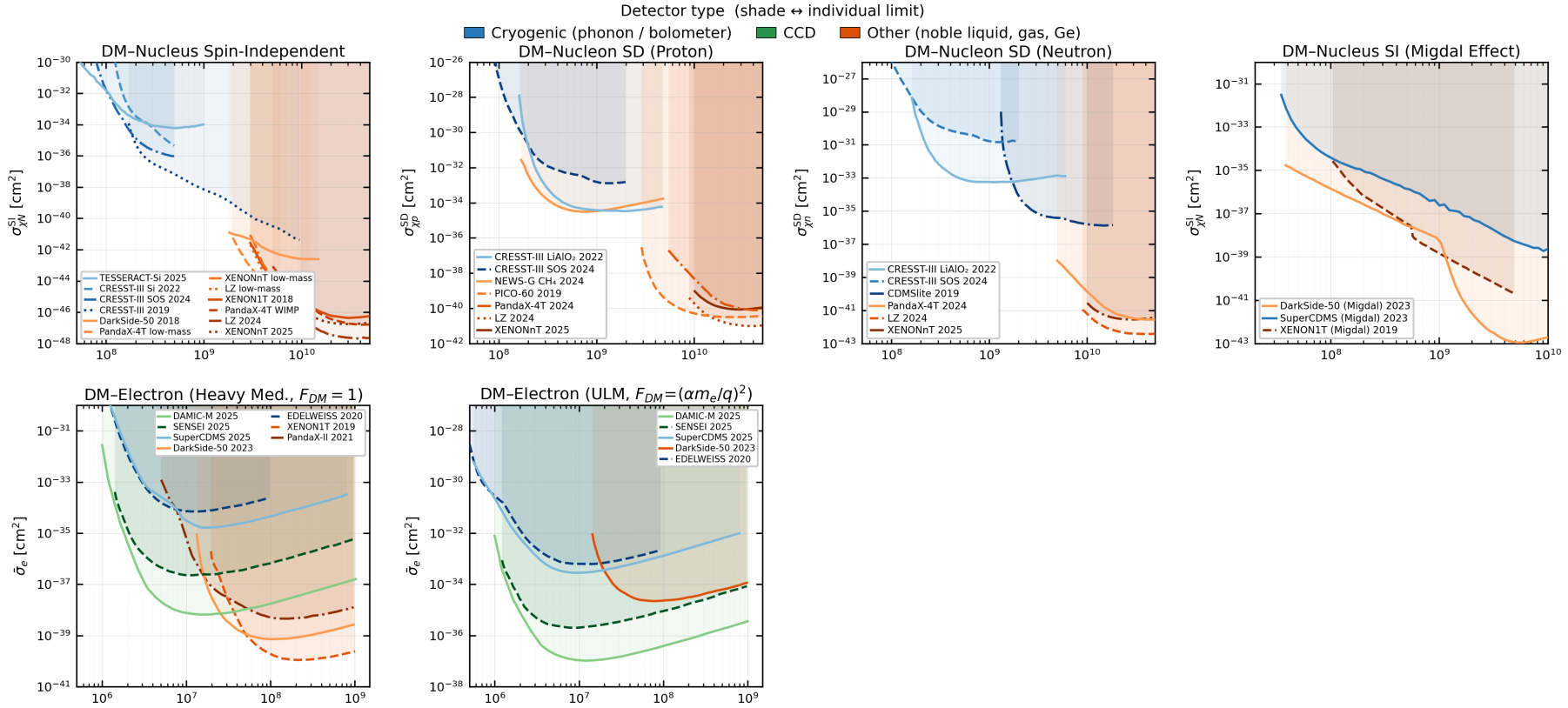
Kerschbaum, arXiv:2602.05806 (2026)

Experimental Limits on Light Dark Matter-Couplings

Experimental Limits on Light Dark Matter-Couplings



Experimental Limits on Light Dark Matter-Couplings



Experimental Limits on Light Dark Matter-Couplings