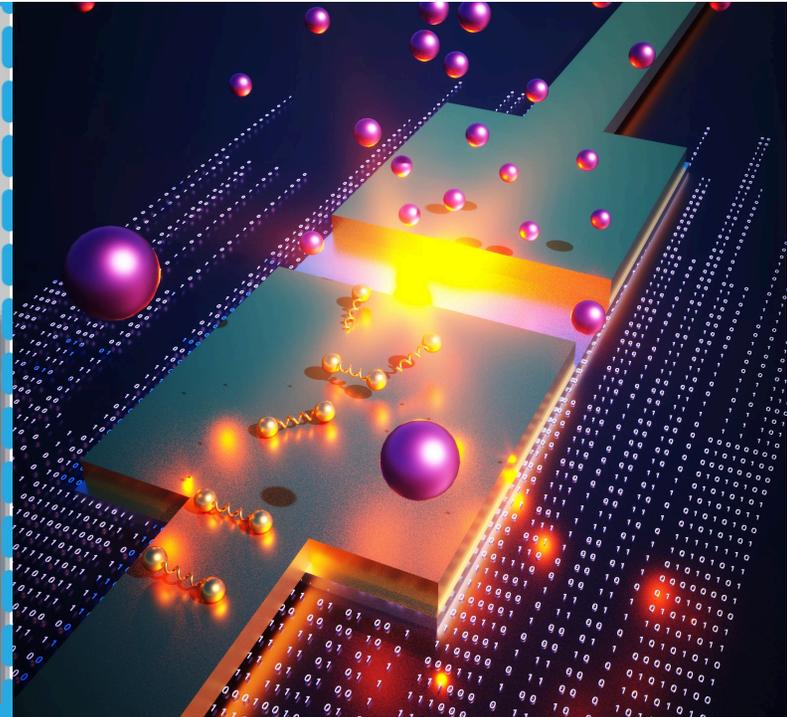
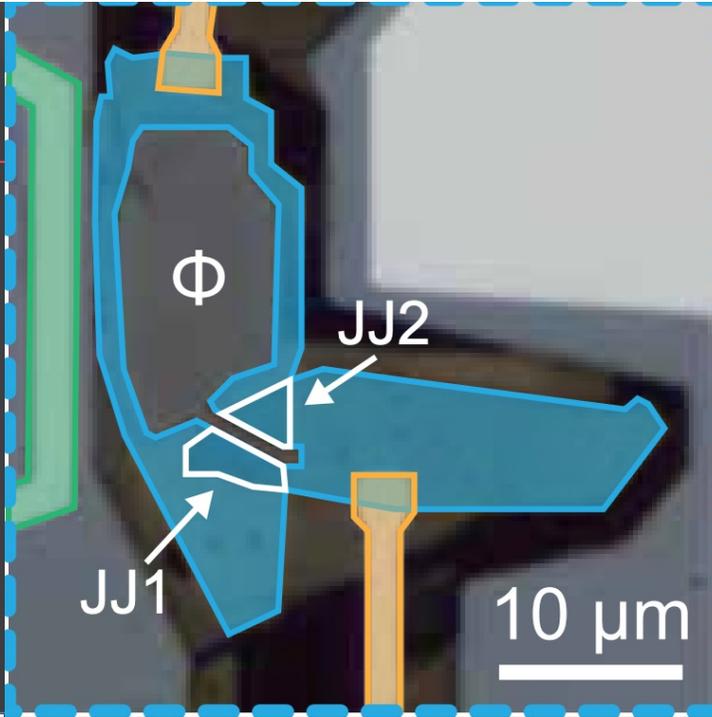


Associate member of



Sponsor:



Collaboration:



Graphene single photon detector for dark matter axion

Kin Chung Fong
@BREAD Collaboration Meeting
Harvard University Jan 2026

Team



D. Englund



B. Huang



E. Arnault



C. Fried



G-H.Lee



W-C.Jung

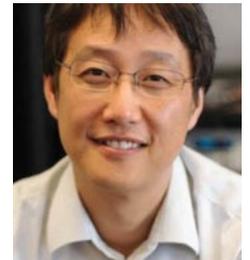
Early efforts and other SPD directions



L.Ranzani



D.Efetov



P. Kim



E.Walsh

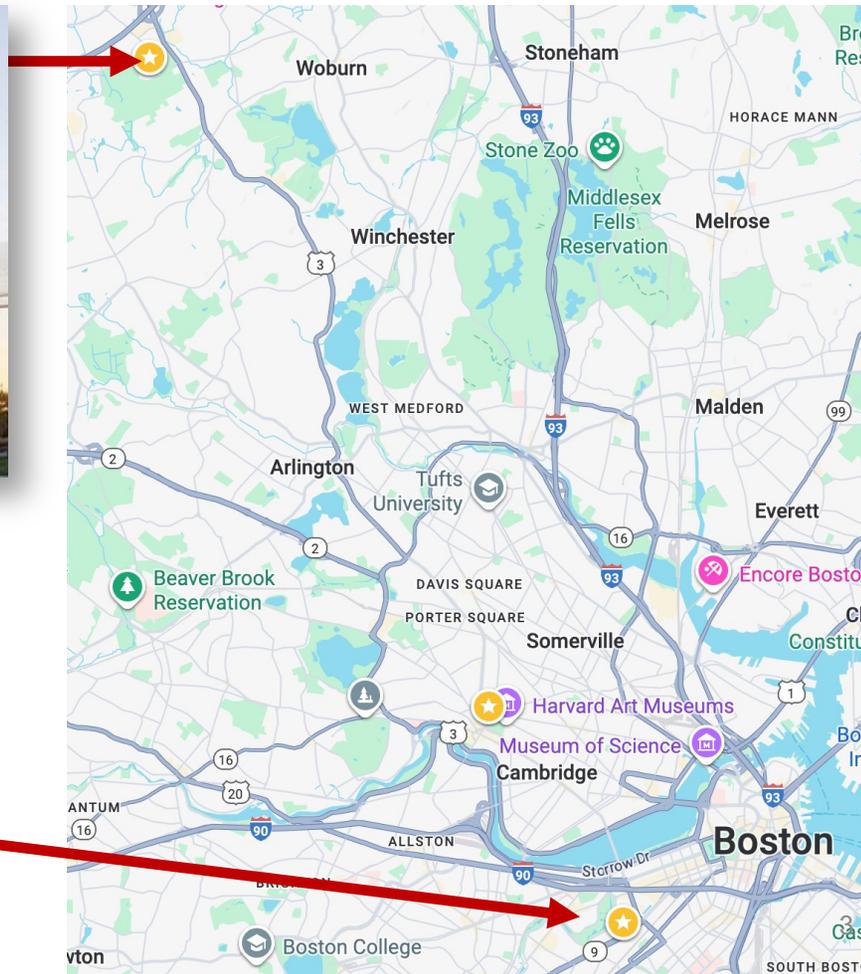


G. Battista



E. Henriksen

Quantum Materials and Sensing Institute



Hiring students and postdocs

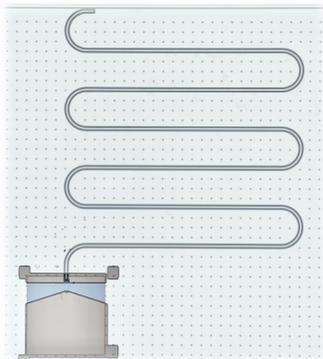
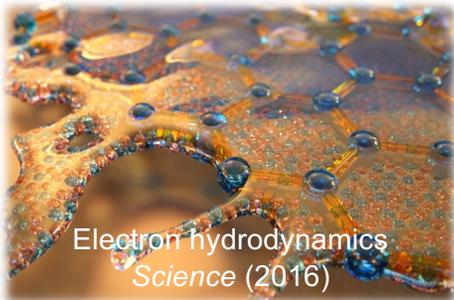


k.fong@northeastern.edu

Interdisciplinary research



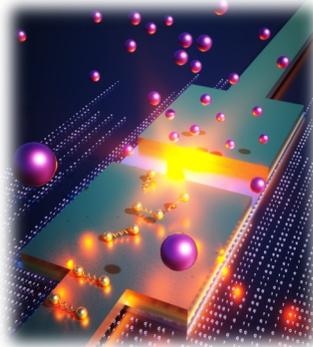
Quantum Matter



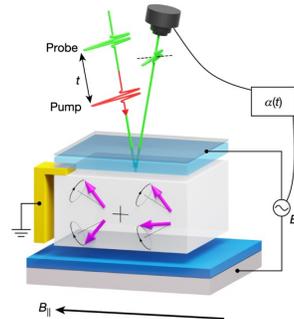
Superfluid stiffness, PRR (2024)
Nature (2025)

k.fong@northeastern.edu

Quantum Sensor

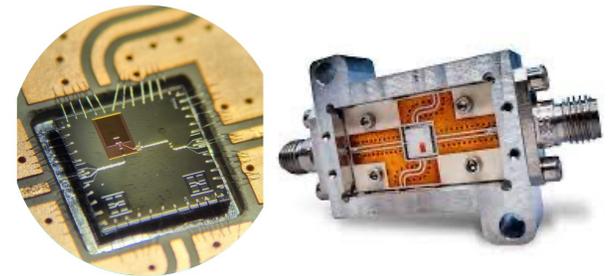


Single-photon detector
Nature (2020), *Science* (2021),
PRApplied (2017, 2024)

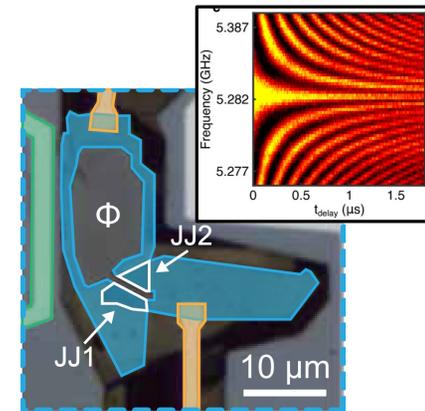


Axionic quasiparticles
PRL (2019), *Nature* (2025)

Quantum Devices



Parametric amplifier
APL (2018), *IEEE* (2022)

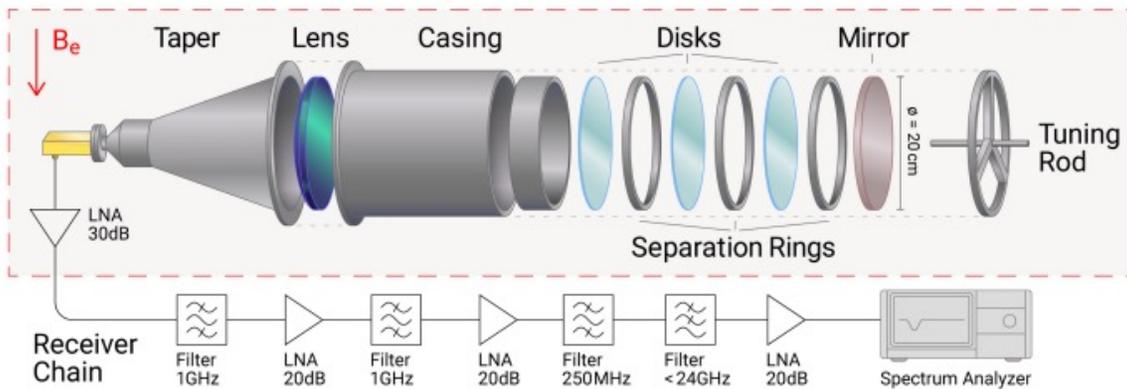


Qubit
Nano Lett. (2021), *PRApplied* (2025)

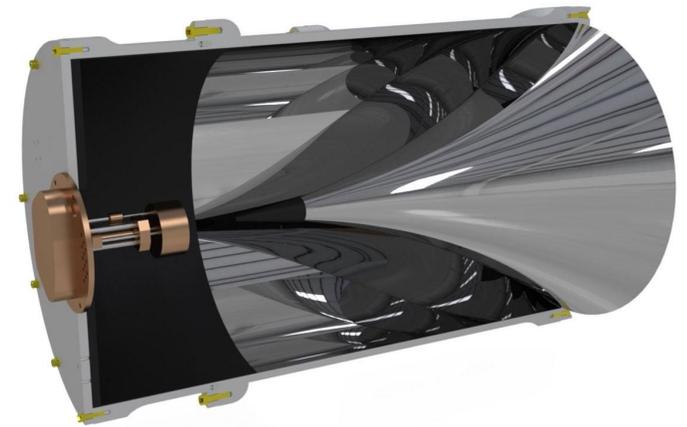
Speeding up with broadband single-photon detector



MADMAX

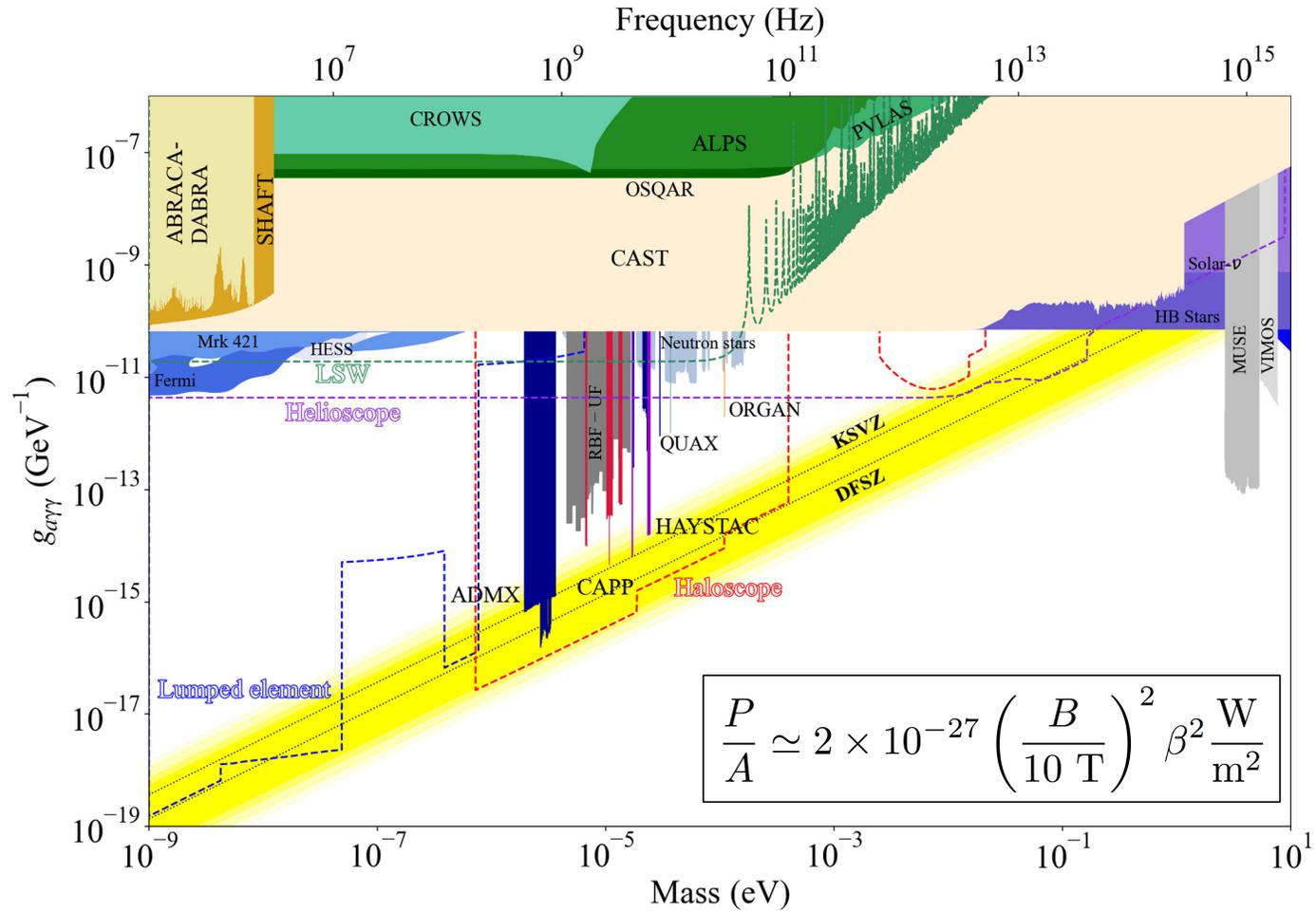


BREAD



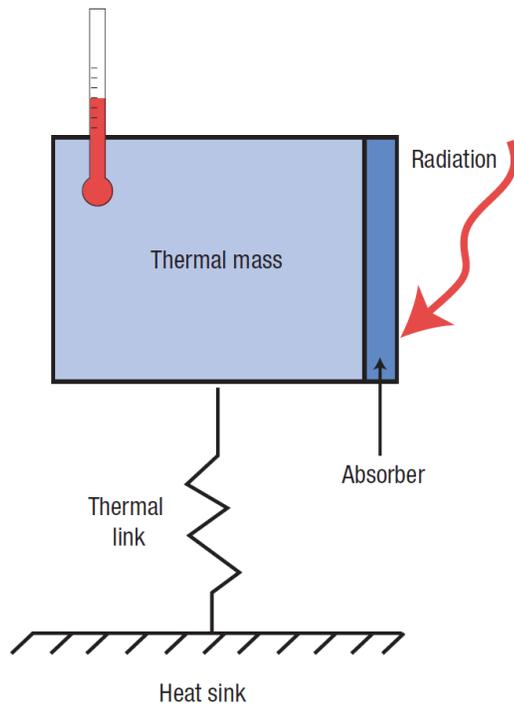
A pilot 0.7 m² barrel experiment planned at Fermilab is projected to surpass existing dark photon coupling constraints by over a decade with one-day runtime. Axion sensitivity requires $< 10^{-20} \text{ W}/\sqrt{\text{Hz}}$ sensor noise equivalent power with a 10 T solenoid and 10 m² barrel. We project BREAD sensitivity for various

Looking for dark matter axion



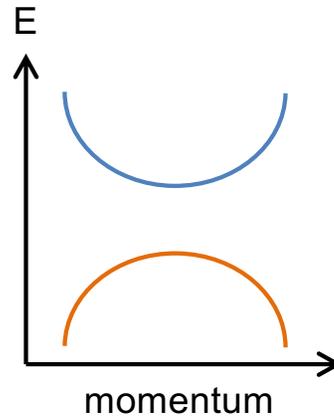
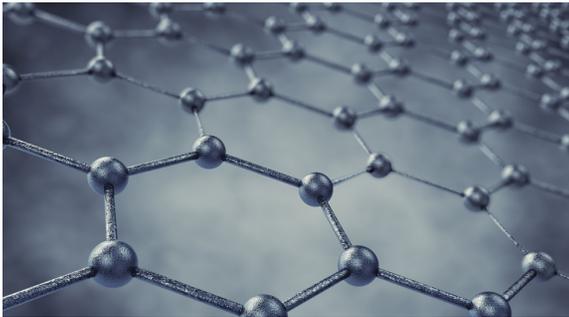


Bolometer and calorimeter

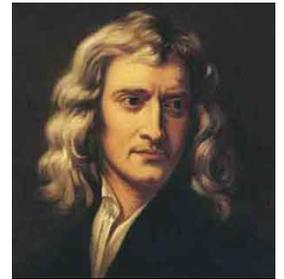


$$\Delta T = \frac{P}{G_{th}} \quad \Delta T = \frac{h\nu}{C_{th}}$$

Why graphene electrons?



$$E_{\text{Newton}} = \frac{p^2}{2m_0}$$

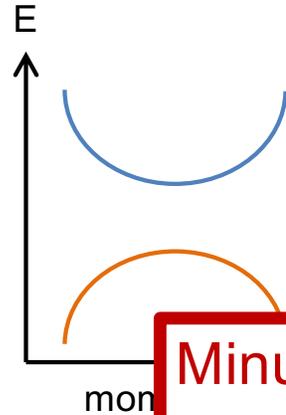
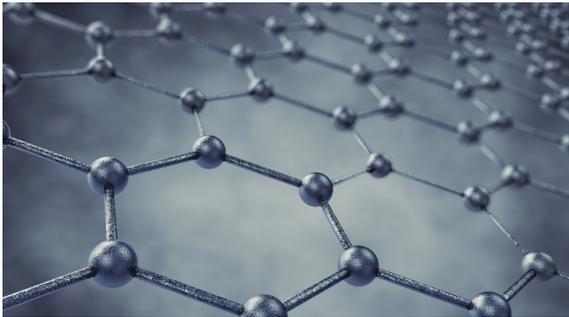


Newton

Ref:

- Vora, Kumaravadivel, Nielsen, and Du, APL 100, 153507 (2012)
- Fong and Schwab, PRX 2, 031006 (2012)
- J. Yan, et. al., Nature Nanotech. 7, 472 (2012)
- McKitterick, Prober, and Karasik, JPL 113, 044512 (2013)

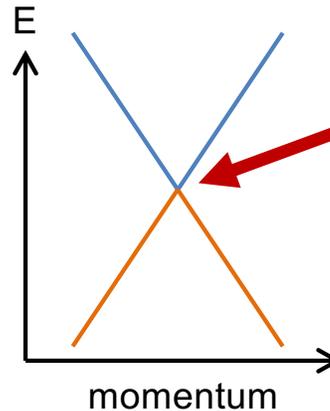
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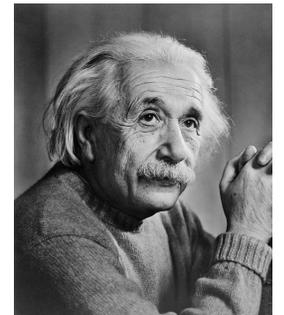


Minute density of states results in minute specific heat of massless Dirac fermions



$$E^2 = \cancel{(m_0c)^2} + (pc)^2$$

$$E = pc$$

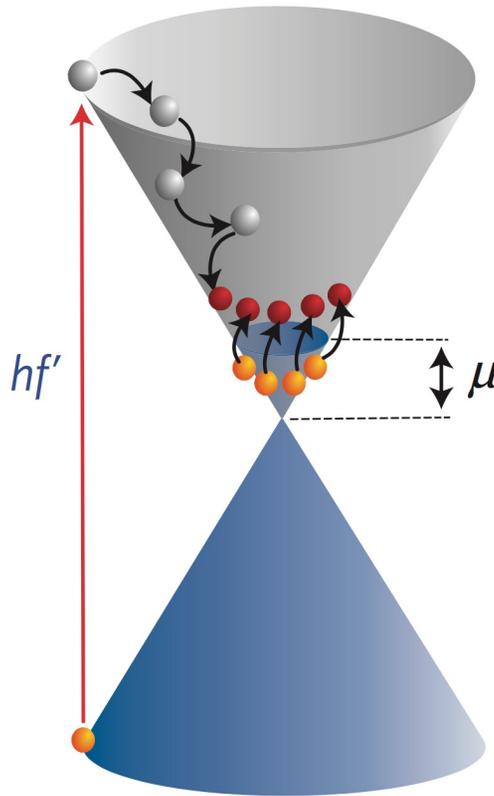


Einstein

Ref:

- Vora, Kumaravadivel, Nielsen, and Du, APL 100, 153507 (2012)
- Fong and Schwab, PRX 2, 031006 (2012)
- J. Yan, et. al., Nature Nanotech. 7, 472 (2012)
- McKitterick, Prober, and Karasik, JPL 113, 044512 (2013)

Graphene electron is ideal for photon detection

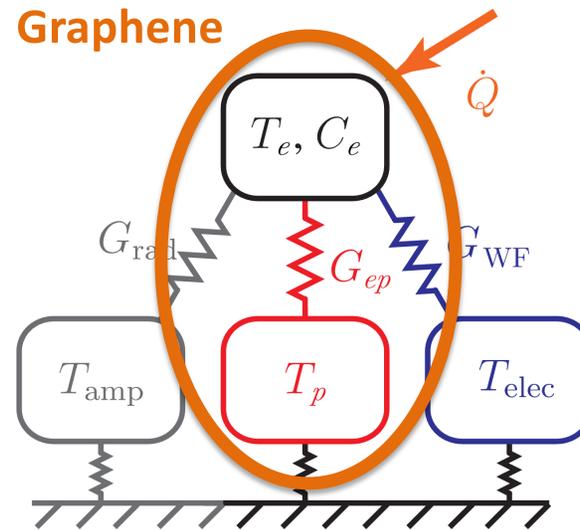
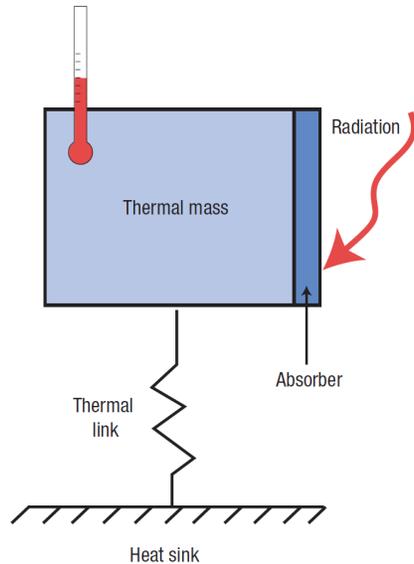


- Minute C_{th} on the order of k_B
- $DOS = 2E / (\pi(\hbar v_F)^2)$
- Small G_{th} due to weak electron-phonon coupling
- Wide EM bandwidth
- High absorption efficiency with impedance matching
- Fast thermalization due to short e-e scattering time
- $\alpha = \frac{Potential}{Kinetic} = \frac{e^2}{\epsilon_r \hbar v_F} \approx 0.5$

Ref:

- Vora, Kumaravadivel, Nielsen, and Du, APL 100, 153507 (2012)
- Fong and Schwab, PRX 2, 031006 (2012)
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Graphene electron is ideal for photon detection

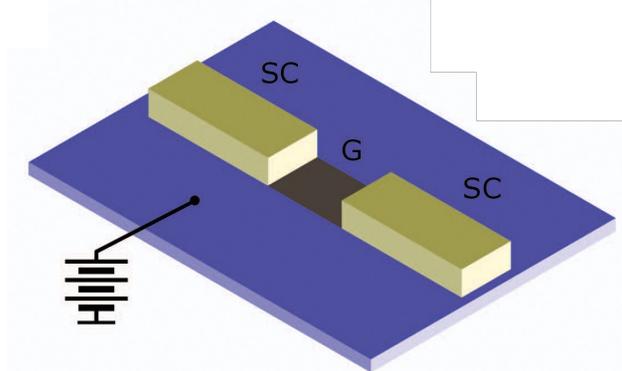


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- McKitterick, Prober, and Karasik, JPL 113, 044512 (2013)

Quantum sensing of the heat of a single photon



Ill. Niklas Elmehed © Nobel Prize Outreach
John Clarke
Prize share: 1/3



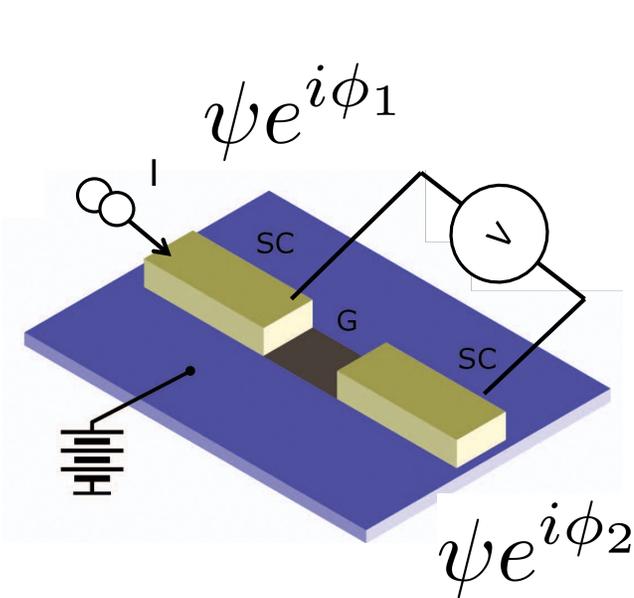
Ill. Niklas Elmehed © Nobel Prize Outreach
Michel H. Devoret
Prize share: 1/3



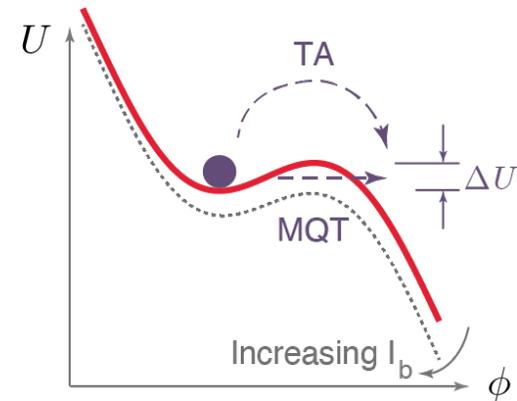
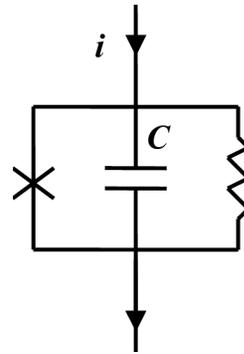
Ill. Niklas Elmehed © Nobel Prize Outreach
John M. Martinis
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“for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit”

Quantum sensing of the heat of a single photon



$$\phi = \phi_1 - \phi_2$$

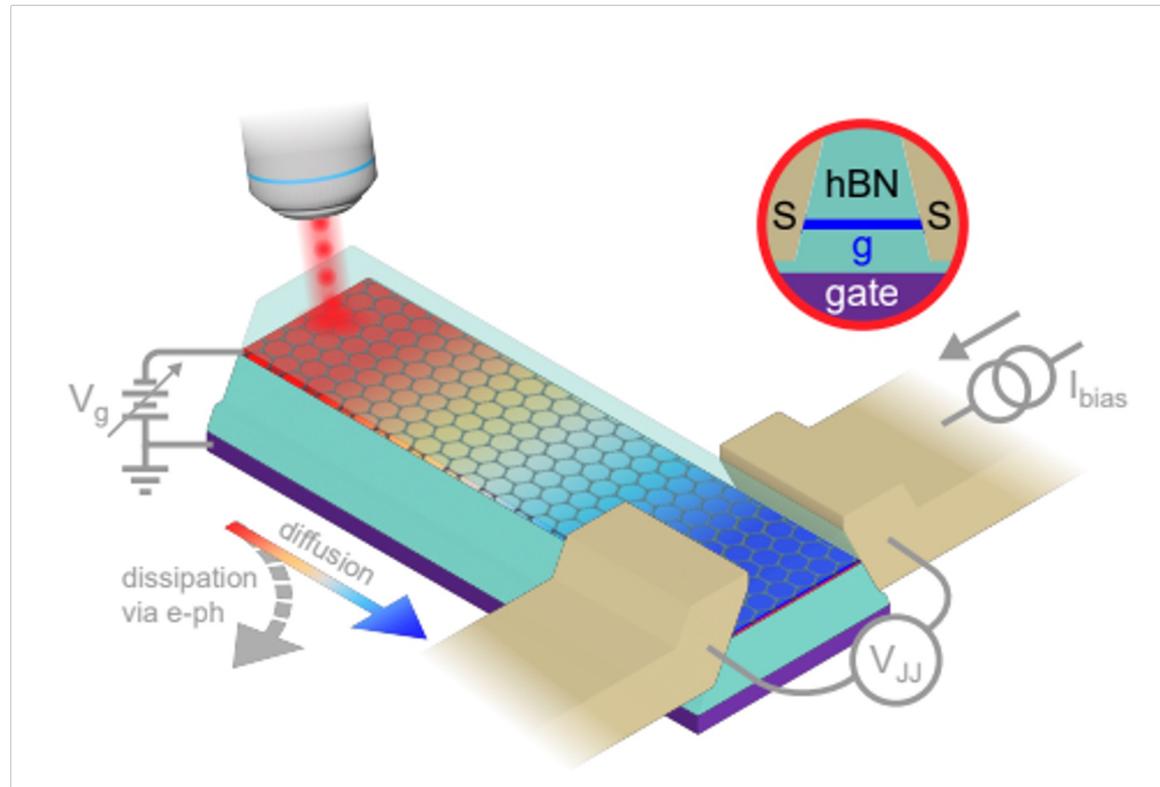
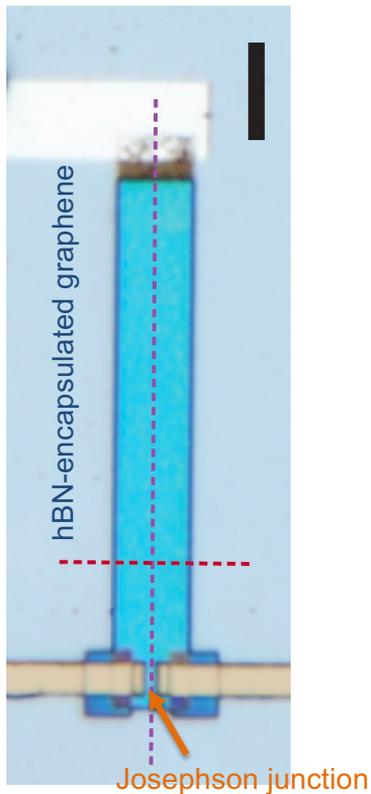


$$V_{JJ} = \frac{\hbar}{2e} \frac{d\phi}{dt}$$

$\rightarrow = 0$ No photon
 $\rightarrow \neq 0$ Photon!

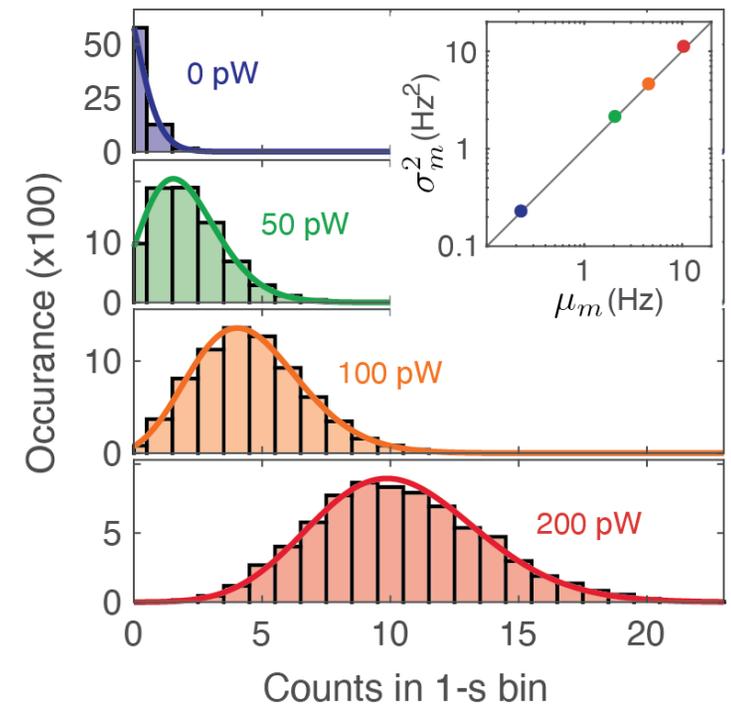
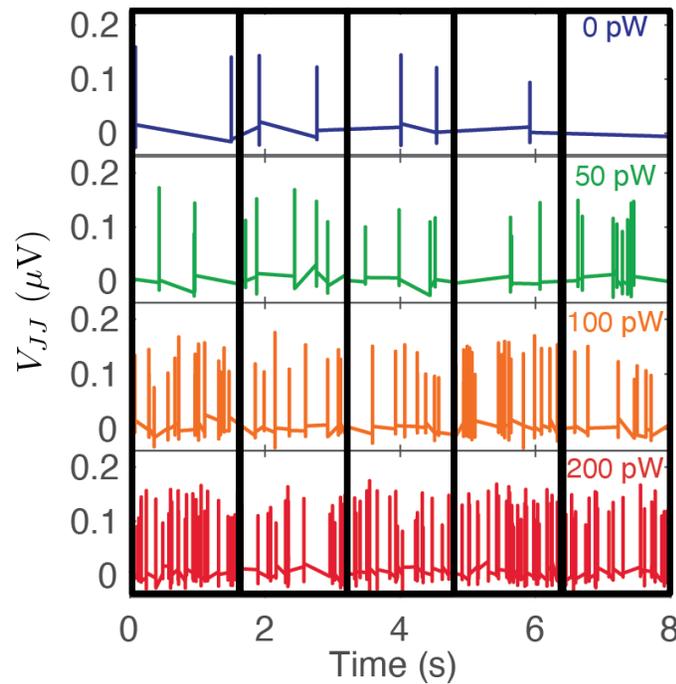
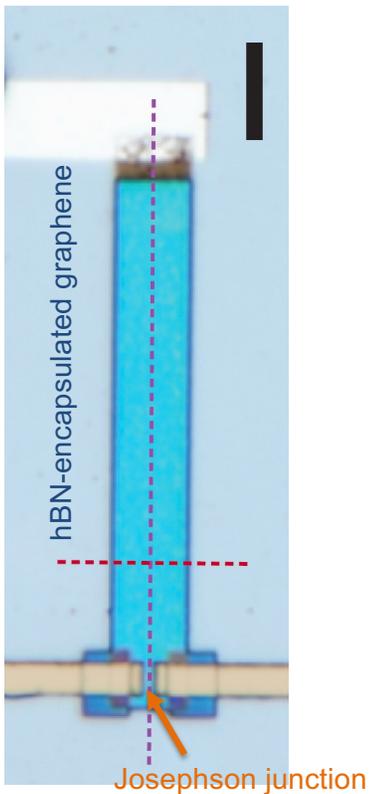
Walsh, ... KCE, Phys. Rev. Applied 8, 024022 (2017)
 See also: Giazotto, et. al., APL 92, 162507 (2008)

Detecting single-photon by massless Dirac fermions

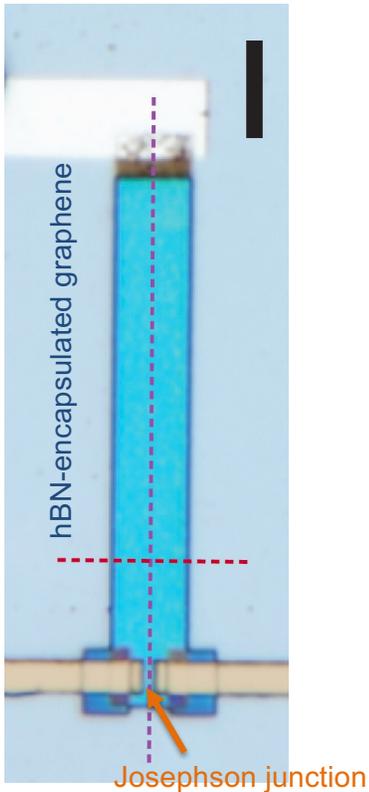


Huang, Arnault, Jung, ... Lee, KCF, arXiv:2410.22433

Detecting single-photon by massless Dirac fermions



Detecting single-photon by massless Dirac fermions

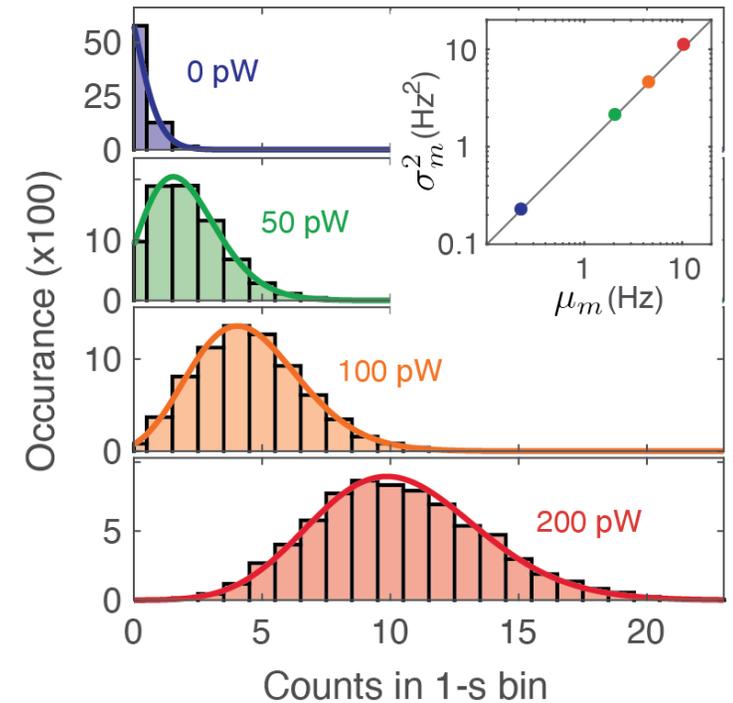


$$|\alpha\rangle = e^{-\frac{|\alpha|^2}{2}} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

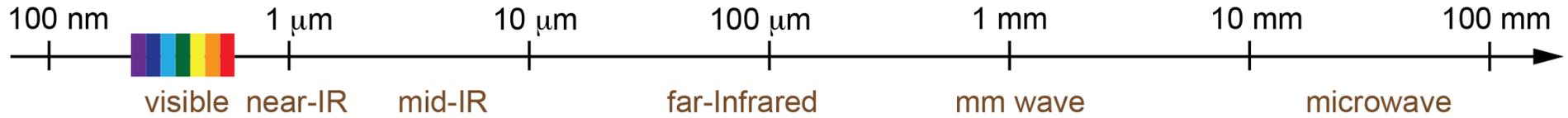
$$P(n) = |\langle n|\alpha\rangle|^2 = e^{-\langle n\rangle} \frac{\langle n\rangle^n}{n!}$$

Question in MADMAX:

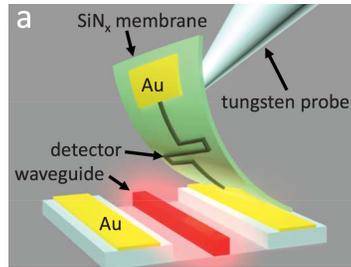
$$\frac{P}{A} \simeq 2 \times 10^{-27} \left(\frac{B}{10 \text{ T}} \right)^2 \beta^2 \frac{W}{\text{m}^2}$$



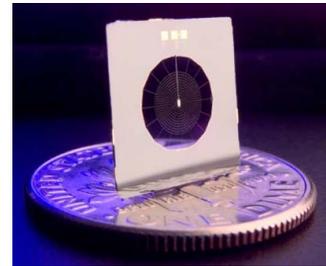
Fundamental limit of measurements



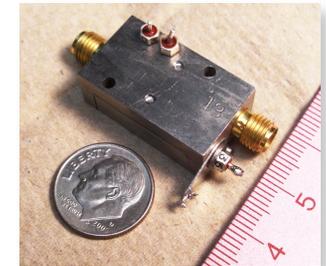
Photodiode



Cooper pair breaking detector



Bolometer



HEMT

Amplifier and heterodyne mixer

$$T_N \simeq \frac{\hbar\omega}{k_B}$$

Caves, PRD (1982)
Tucker and Feldman, RMP (1985)

Bolometer

$$NEP = \sqrt{4G_{th} k_B T^2}$$

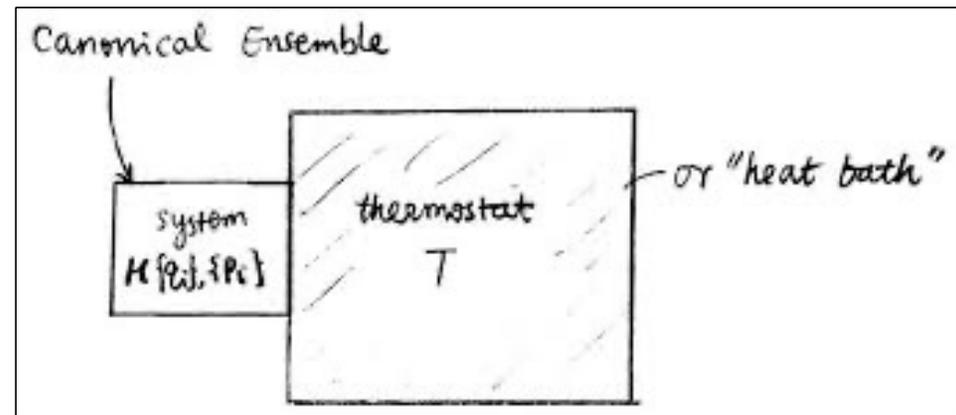
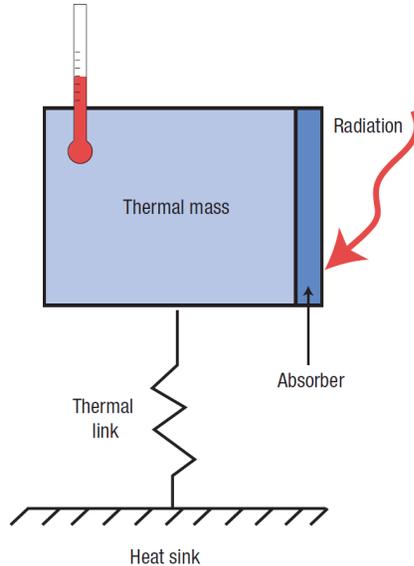
Lee... **KCF**, Nature (2020)
Mather, Appl. Opt. (1984)

Calorimetric SPD

$$\Delta\epsilon \sim \sqrt{C_{th} k_B T^2}$$

Moseley-Mather-McCammon, JAP (1984)

Fundamental limit of bolometer measurements



Amplifier and heterodyne mixer

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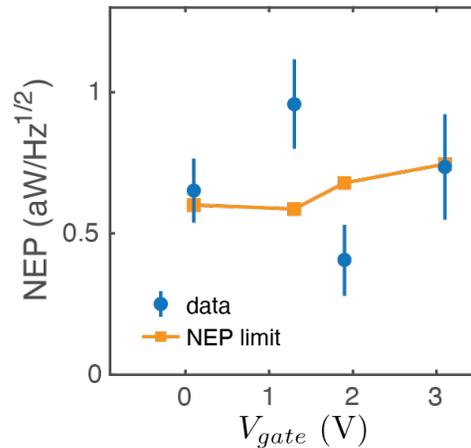
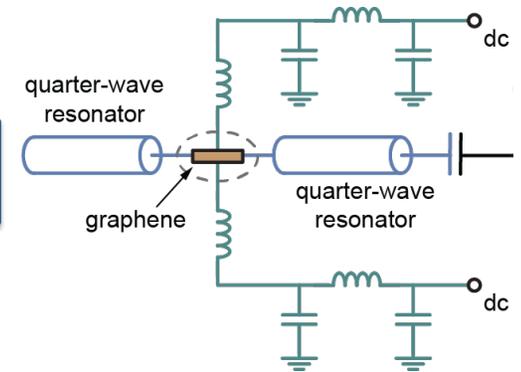
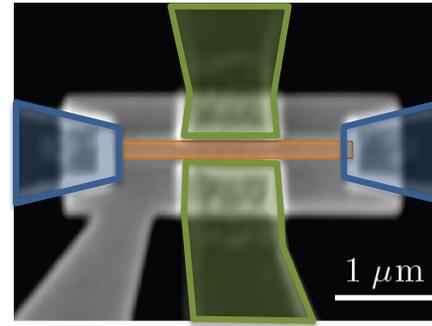
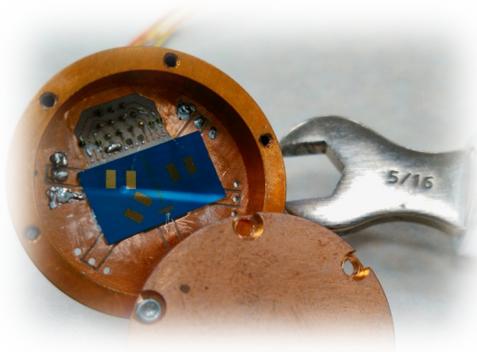
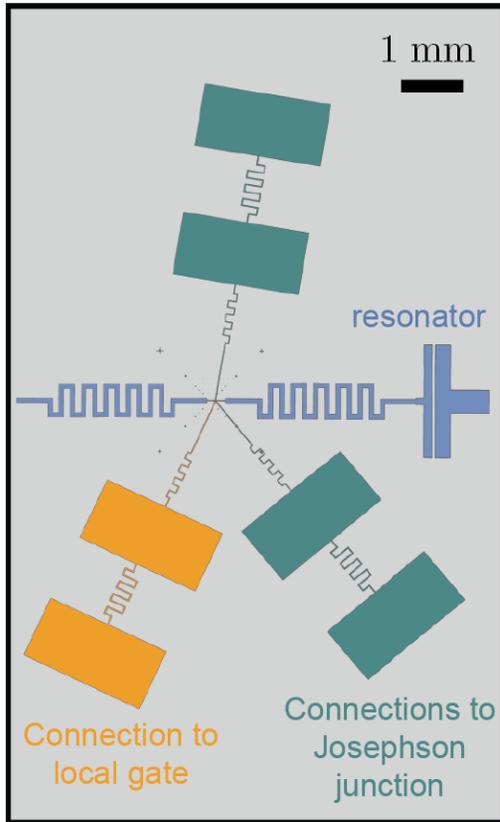
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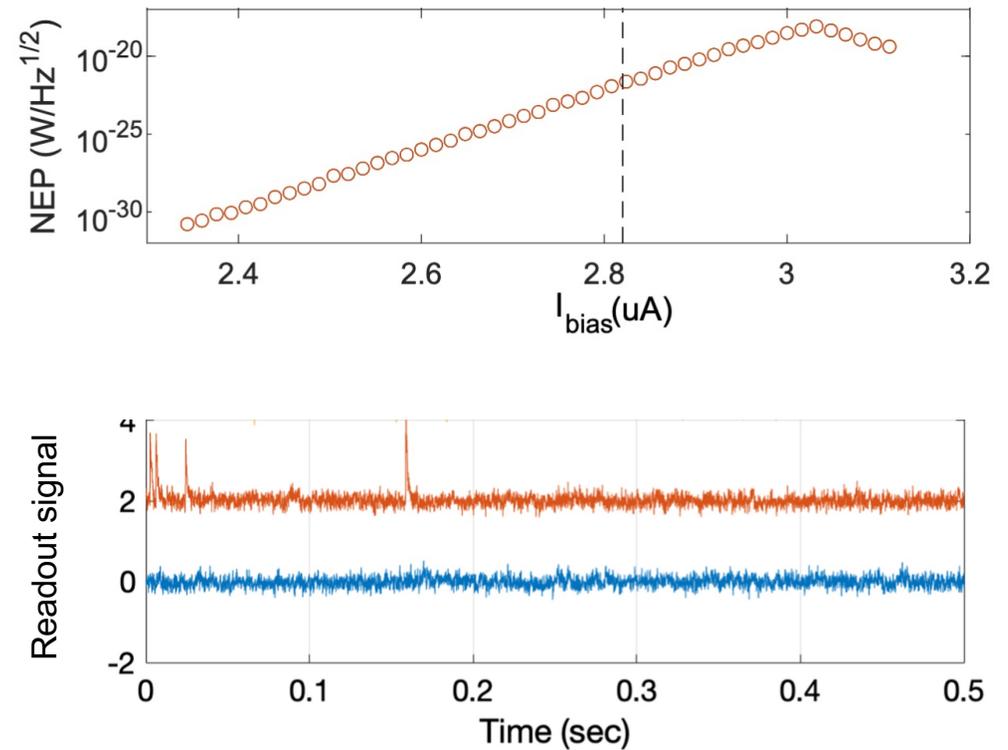
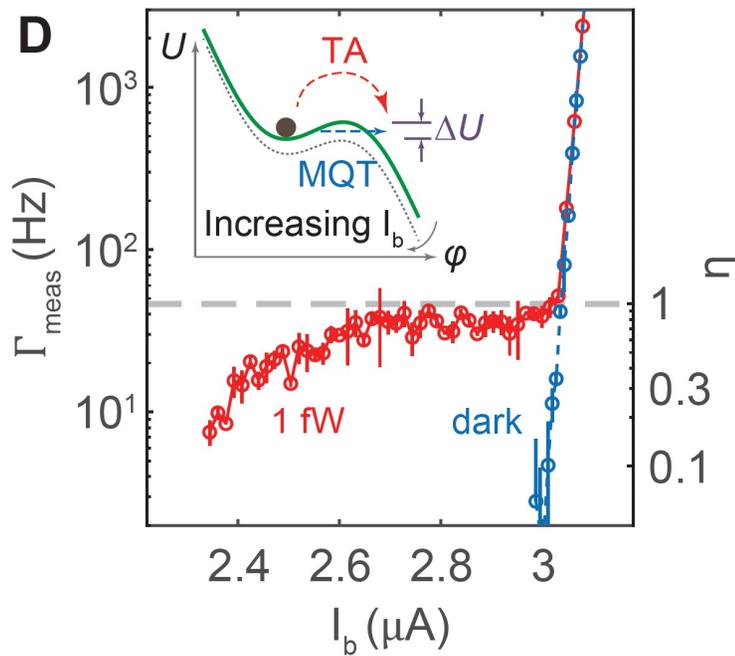
Lee... **KCF**, Nature (2020)
Mather, Appl. Opt. (1984)

$$\Delta E = 32 \text{ GHz}$$

Lee... **KCF**, Nature 586, 42 (2020)
See also: ibid 586, 47 (2020)

Surpassing the thermodynamic limit of bolometer

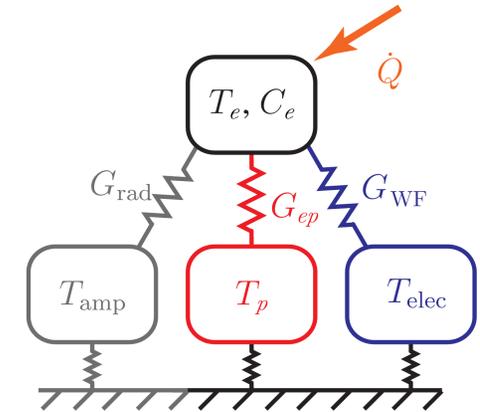
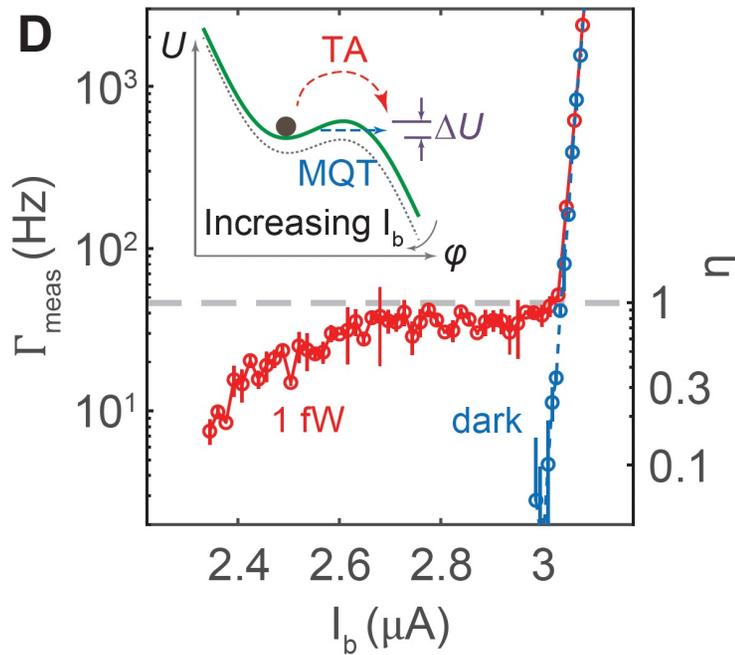
$$NEP_{\text{eff}} = \frac{\epsilon_P \cdot \sqrt{\Gamma_P}}{\eta}$$



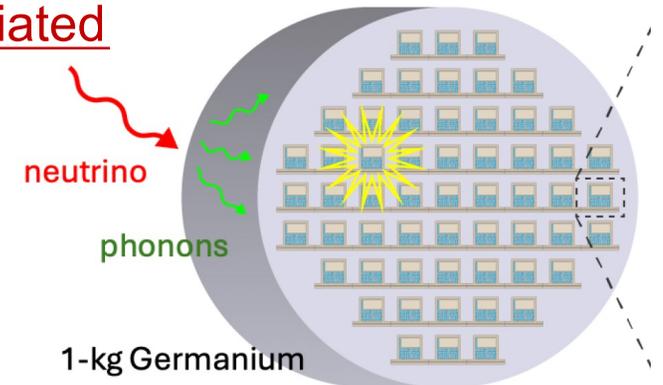
Graphene: to be or not to be?

$$\text{NEP}_{\text{eff}} = \frac{\epsilon_P \cdot \sqrt{\Gamma_P}}{\eta}$$

Graphene SPD



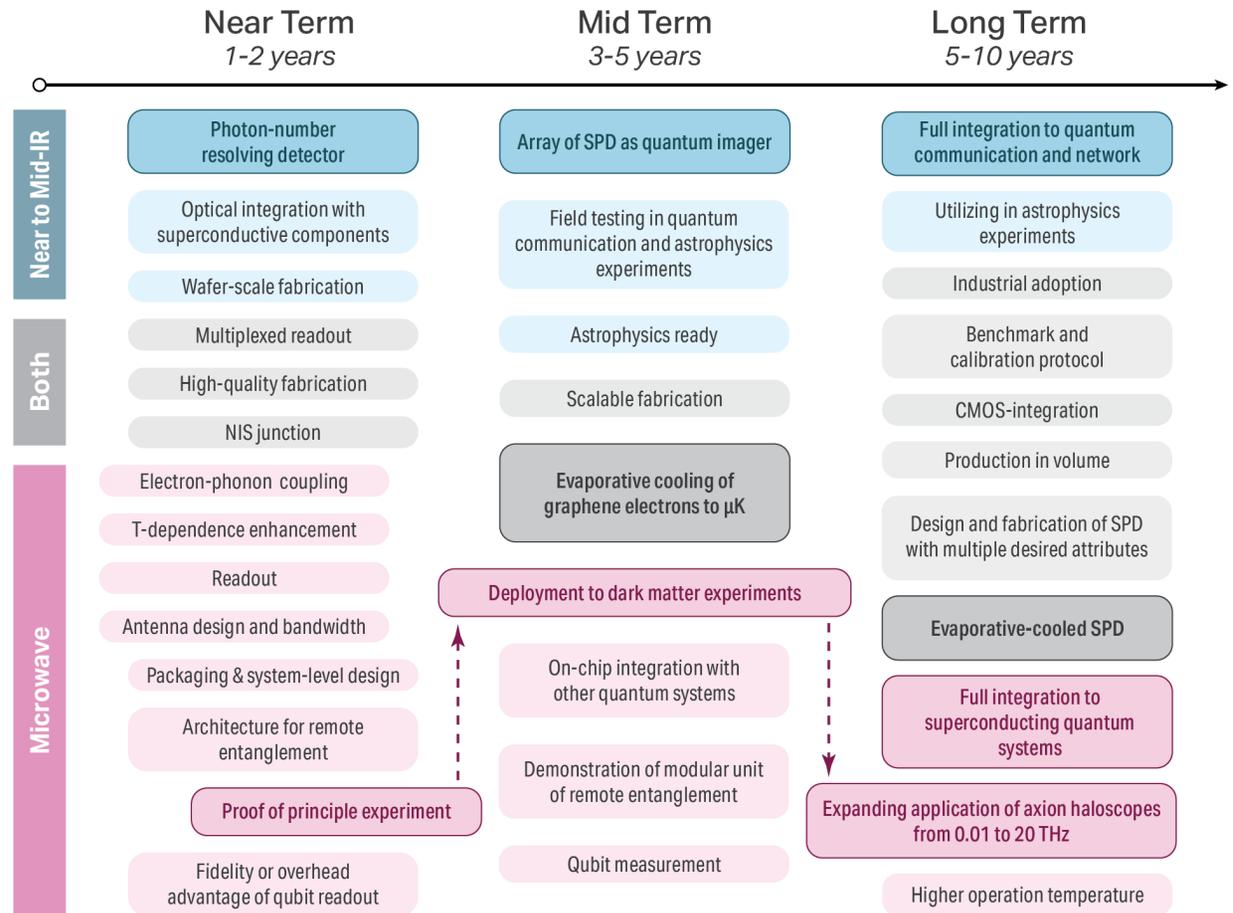
Phonon-mediated detector



Graphene-based SPD Roadmap for **BREAD** in arXiv:2512.14973

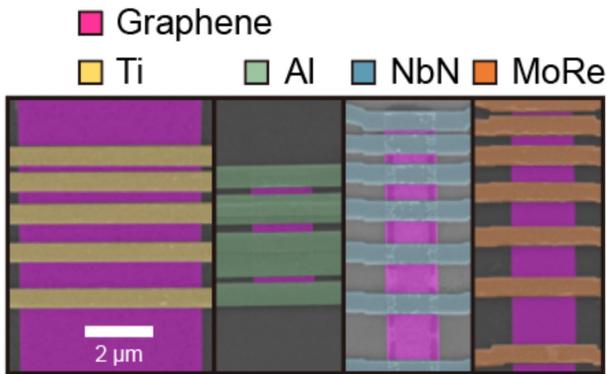


Graphene-based SPD Roadmap for BREAD in arXiv:2512.14973

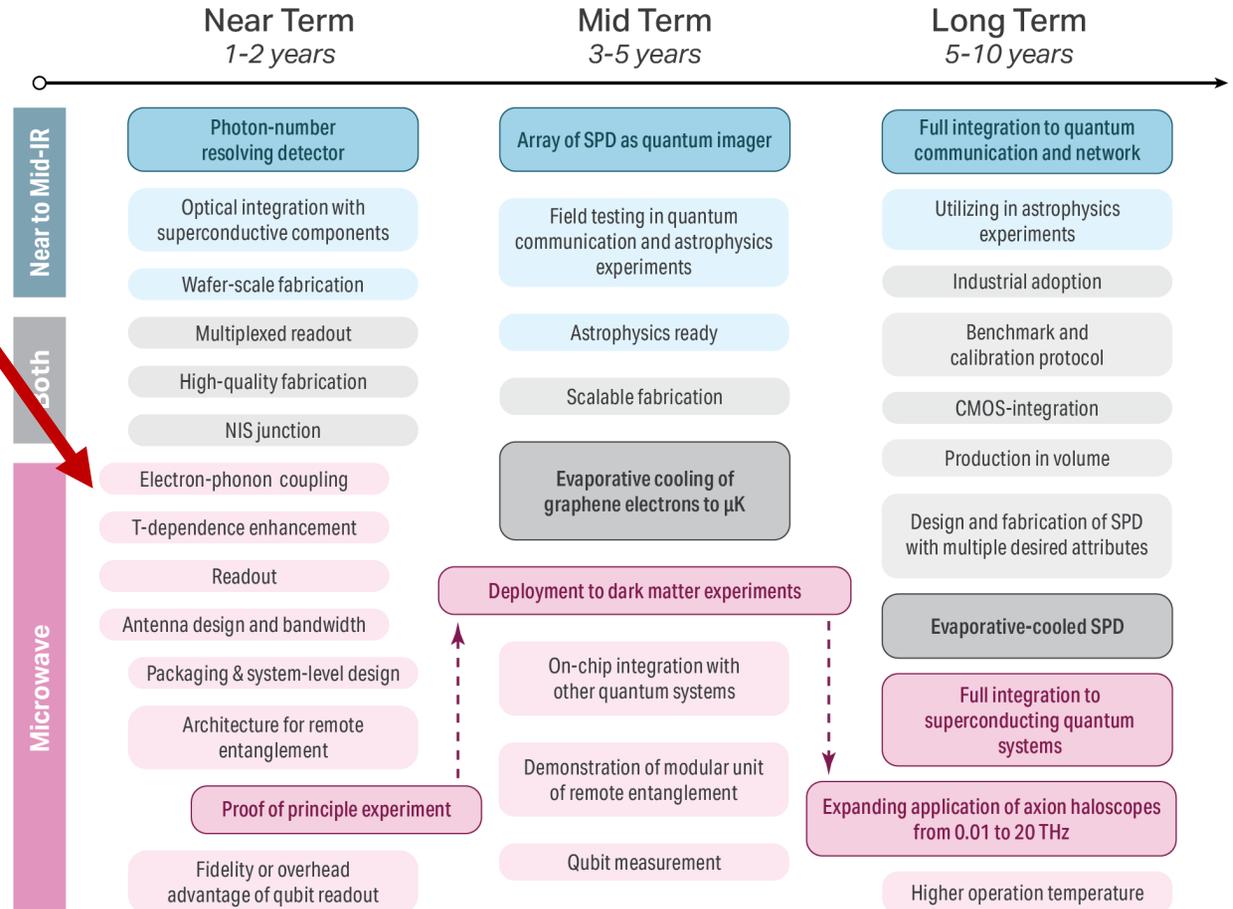


Graphene-based SPD Roadmap for BREAD in arXiv:2512.14973

Josephson optimization



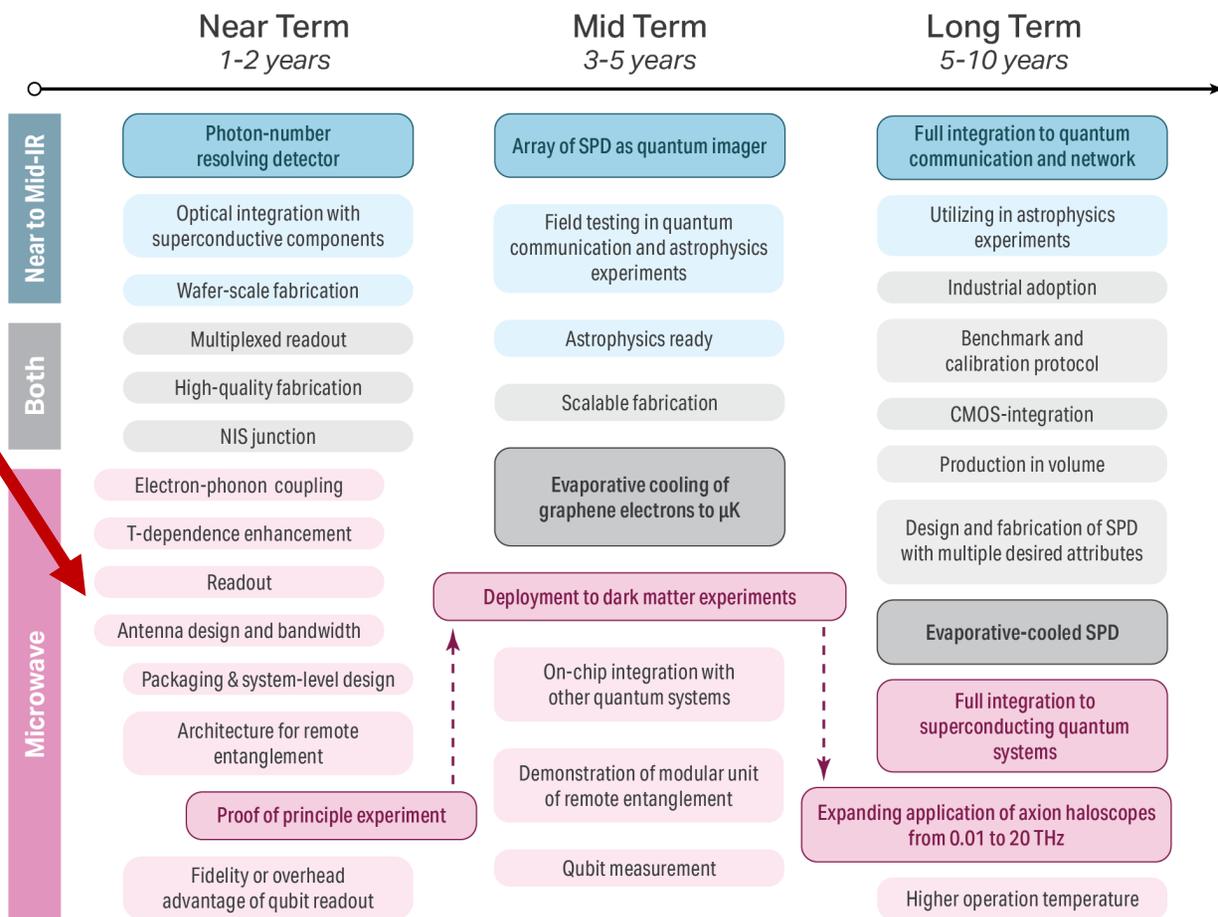
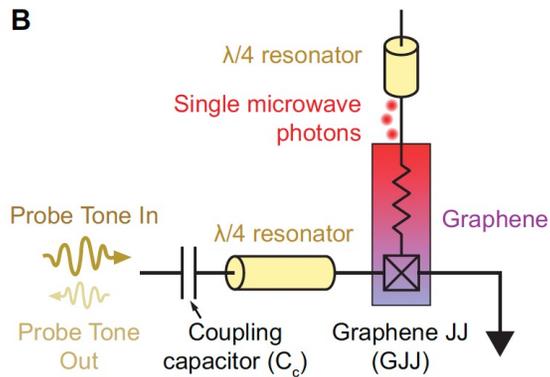
W.Jung, et. al., arXiv:2503.06850



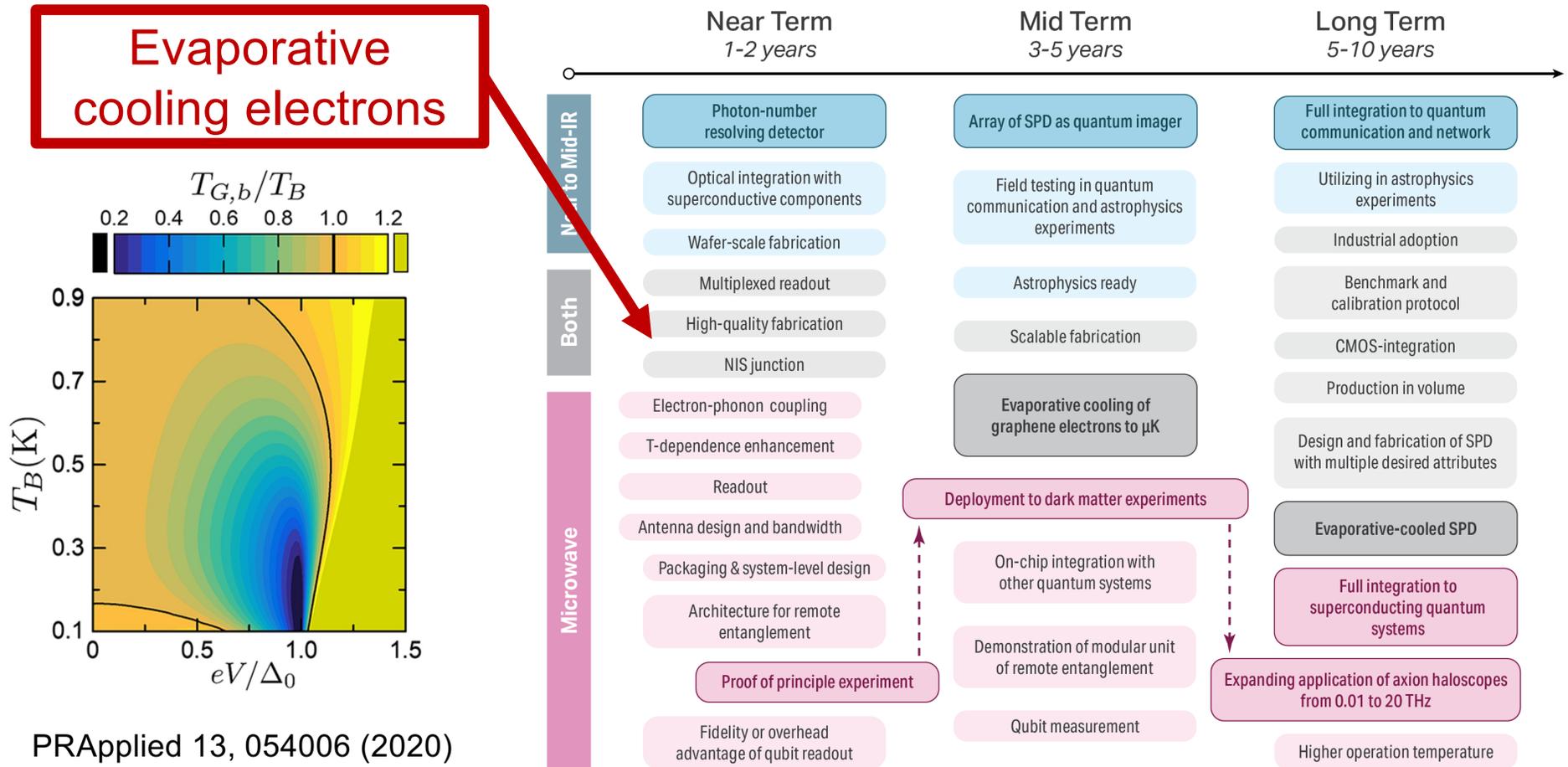
Graphene-based SPD Roadmap for BREAD in arXiv:2512.14973



readout



Graphene-based SPD Roadmap for BREAD in arXiv:2512.14973



New eyes to see dark matter

