Quantum Sensors for HEP

Kent Irwin

Dept. of Physics, Stanford University
SLAC National Accelerator Laboratory

CPAD
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Outline

New breakthroughs in QIS are driving a revolution in measurement for HEP.

1. Quantum Sensors for High Energy Physics workshop report
2. The quest to fully search the QCD axion band:
   illustrates that quantum sensing is *required* to achieve HEP science goals

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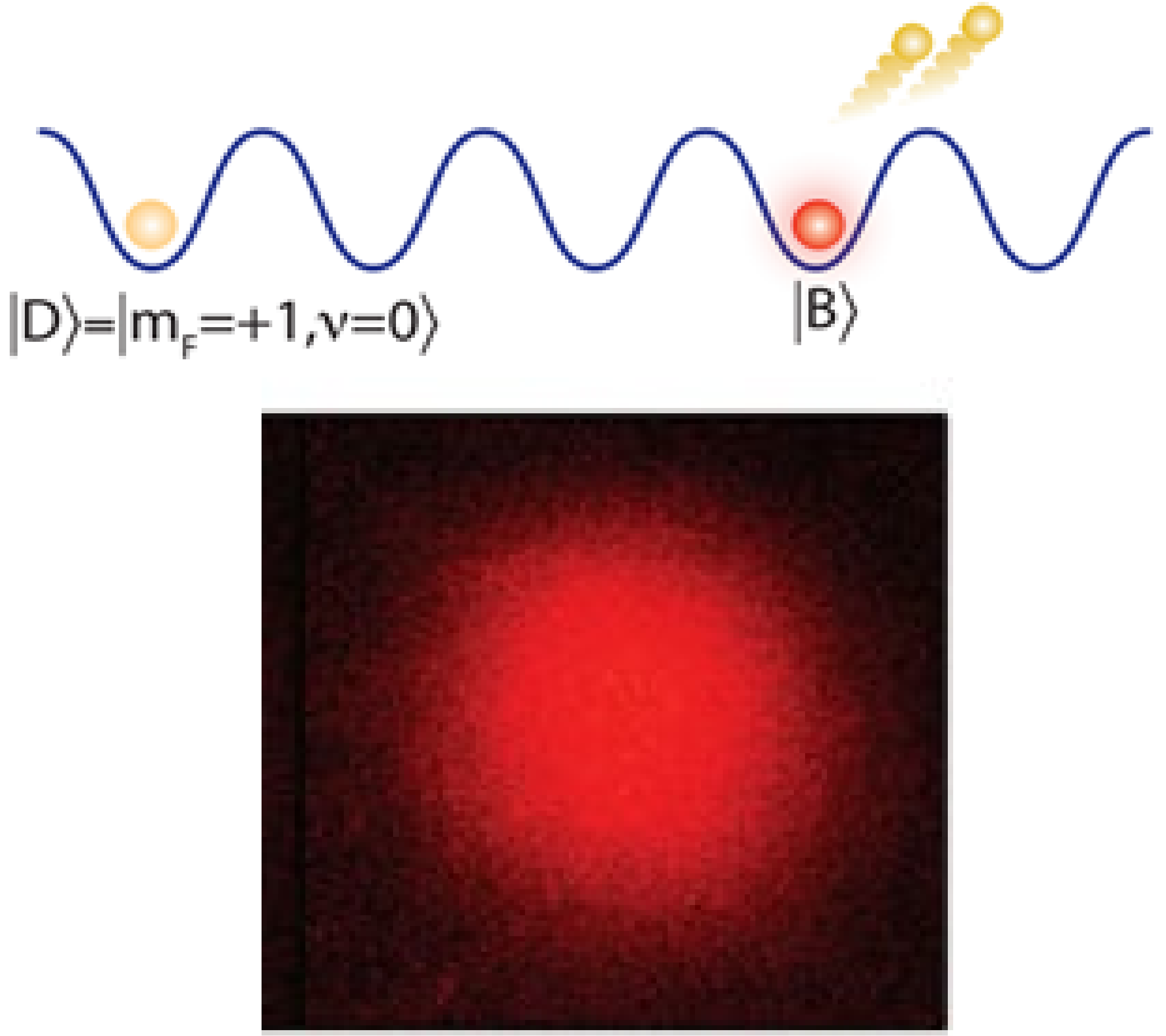
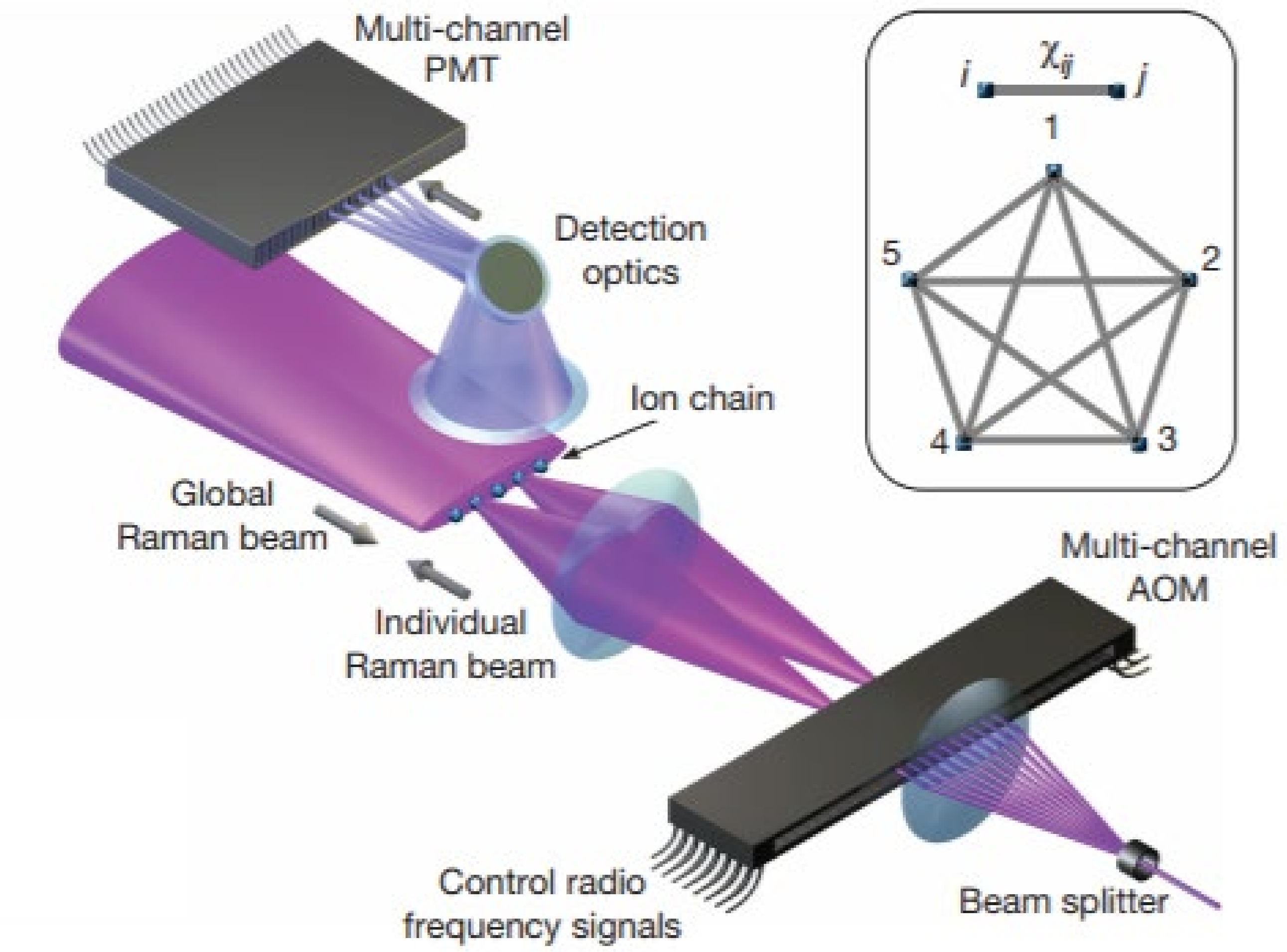
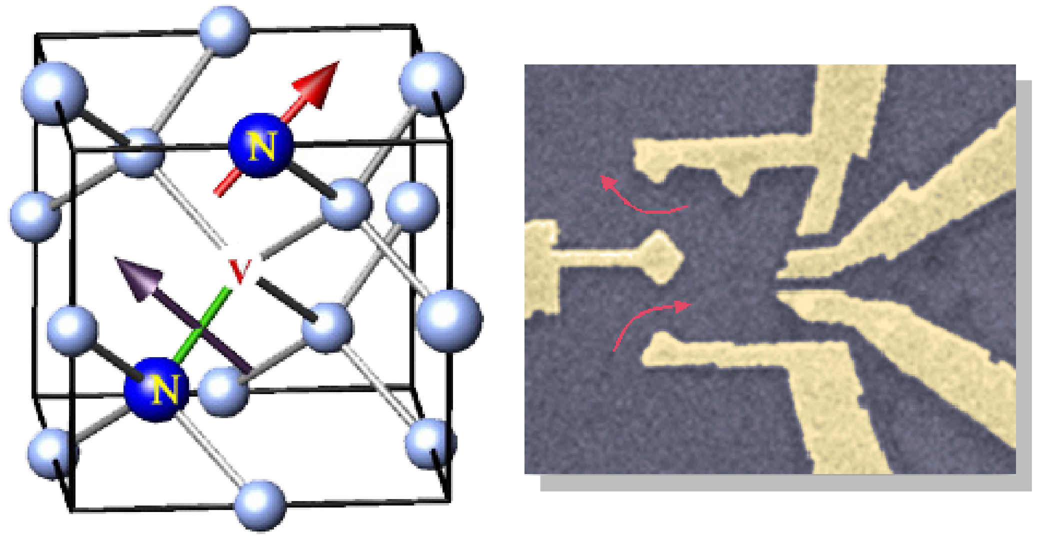
Diverse quantum sensing modalities



Cold atoms

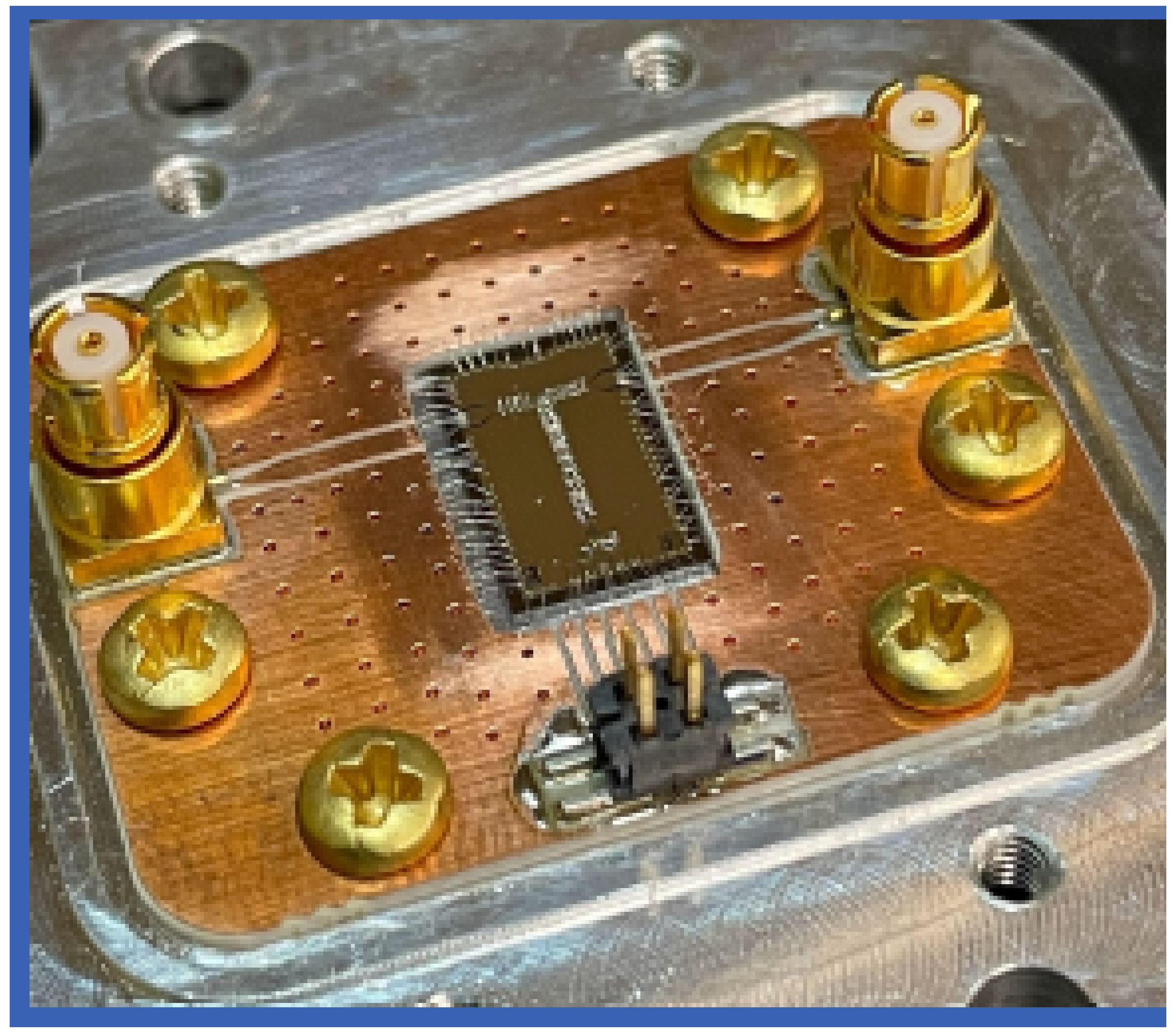


Trapped ions

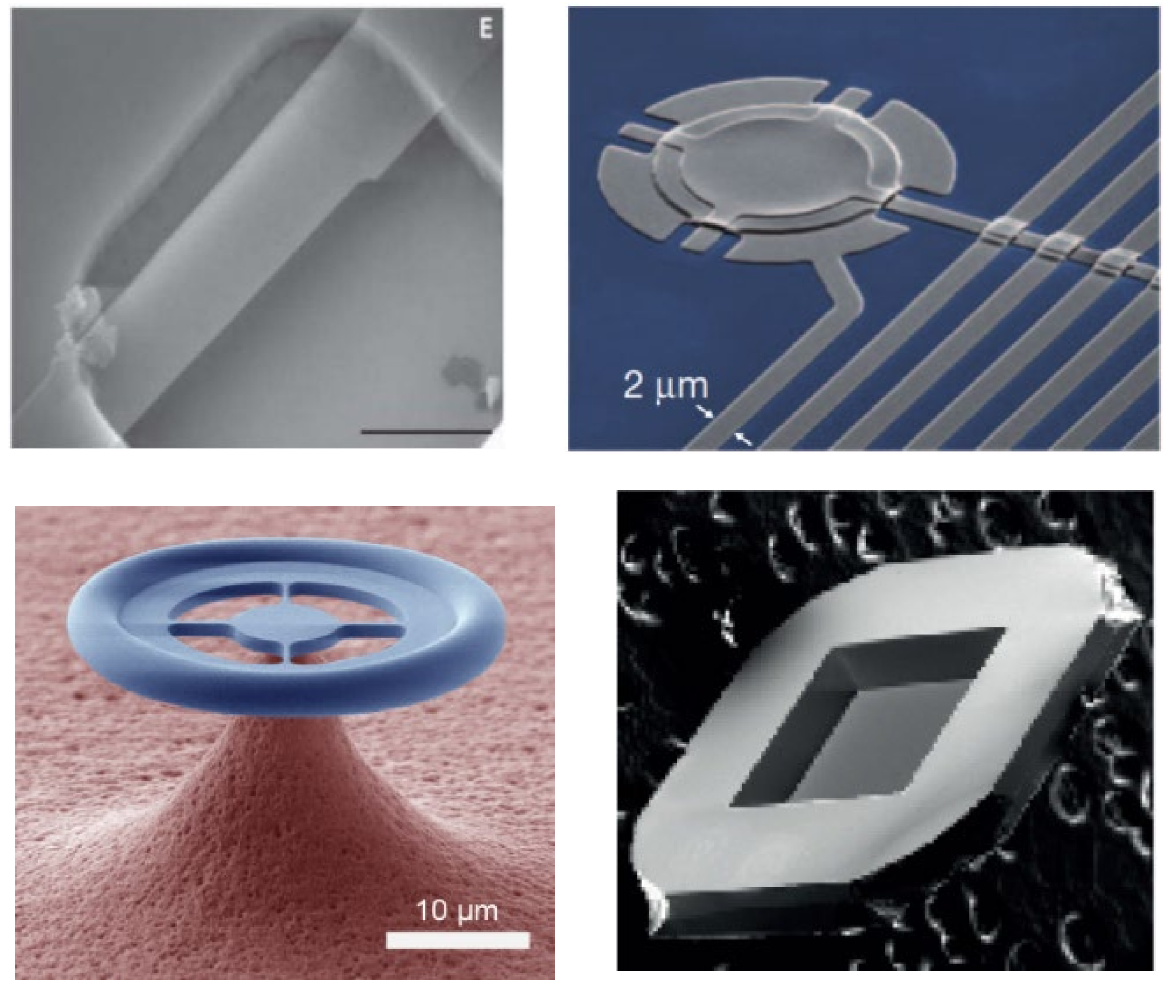


Spins (electron / nuclear)

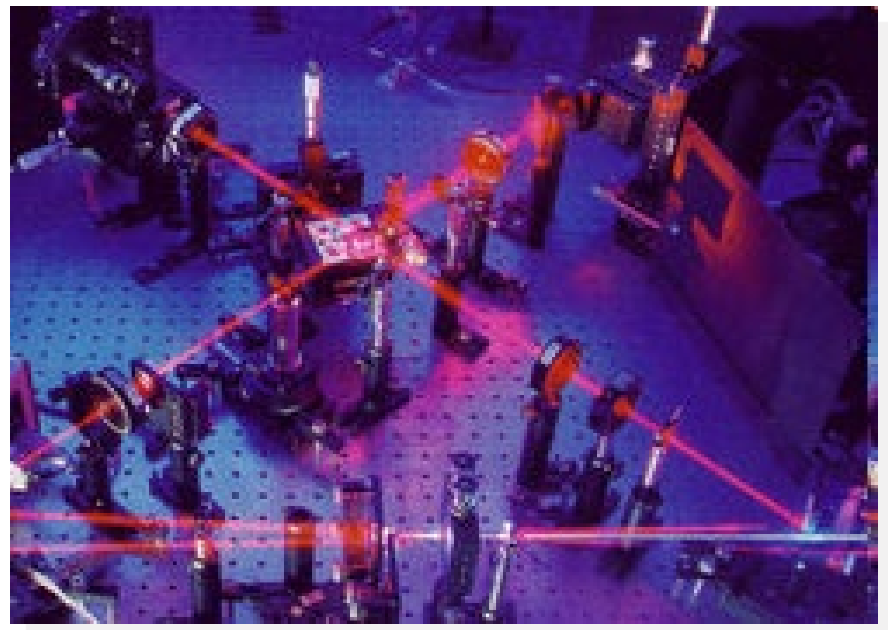
. . .



Superconducting



Optomechanical



Optical

DOE workshop report

- Workshop charged by DOE oHEP to “identify particularly promising approaches in the domain of quantum sensing that can be utilized by future HEP applications to further the scientific goals of the community as outlined by the P5 Report and in the recent Snowmass 2021 Report.”
- Workshop held at the Yale Quantum Institute April 26-28, 2023.
- Participants drawn from the DOE QuantISED Program, the National Quantum Initiative Science Research Centers, and a mix of DOE laboratory staff, NIST and NASA researchers, and university faculty.
- Workshop coordinated by Aaron Chou, Kent Irwin, and Reina Maruyama
- Workshop report: **Arxiv:2311.01930 (Nov. 3, 2023)**

arXiv:2311.01930v1 [hep-ex] 3 Nov 2023

Quantum Sensors for High Energy Physics

Aaron Chou[1], Kent Irwin[2,3], Reina H. Maruyama[4,5], Oliver K. Baker[4], Chelsea Bartram[3], Karl K. Berggren[6], Gustavo Cancelo[1], Daniel Carney[7], Clarence L. Chang[8,9,10], Hsiao-Mei Cho[3], Maurice Garcia-Sciveres[7], Peter W. Graham[2], Salman Habib[10], Roni Harnik[1], J. G. E. Harris[4], Scott A. Hertel[11], David B. Hume[12], Rakshya Khatiwada[13,1], Timothy L. Kovachy[14], Noah Kurinsky[3], Steve K. Lamoreaux[4,5], Konrad W. Lehnert[15,16], David R. Leibrandt[17], Dale Li[3], Ben Loer[18], Julián Martínez-Rincón[19], Lee McCuller[20], David C. Moore[4,5], Holger Mueller[21,7], Cristian Pena[1], Raphael C. Pooser[22], Matt Pyle[21], Surjeet Rajendran[23], Marianna S. Safronova[24,25], David I. Schuster[2,3], Matthew D. Shaw[26], Maria Spiropulu[20], Paul Stankus[19], Alexander O. Sushkov[27], Lindley Winslow[28], Si Xie[1], and Kathryn M. Zurek[20]

[1]Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
[2]Department of Physics, Stanford University, 382 Via Pueblo Mall, Stanford, CA, 94305, USA
[3]SLAC National Laboratory, 2575 Sand Hill Rd., Menlo Park, CA 94025, USA
[4]Department of Physics, Yale University, New Haven, Connecticut 06520, USA
[5]Wright Laboratory, Department of Physics, Yale University, New Haven, Connecticut 06520, USA
[6]Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[7]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA
[8]Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA
[9]Kavli Institute for Cosmological Physics, University of Chicago, 5640 South Ellis Ave., Chicago, IL 60637, USA
[10]Argonne National Laboratory, Lemont, IL 60439, USA
[11]University of Massachusetts, Amherst Center for Fundamental Interactions and Department of Physics, Amherst, MA 01003-9337 USA
[12]Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO, USA
[13]Illinois Institute of Technology, Chicago, Illinois 60616, USA
[14]Department of Physics and Astronomy and Center for Fundamental Physics, Northwestern University, Evanston, IL 60208, USA
[15]JILA, National Institute of Standards and Technology and the University of Colorado, Boulder, Colorado 80309, USA
[16]Department of Physics, University of Colorado, Boulder, Colorado 80309, USA
[17]Department of Physics and Astronomy, University of California, Los Angeles, CA, USA
[18]Pacific Northwest National Laboratory, Richland, WA 99352, USA

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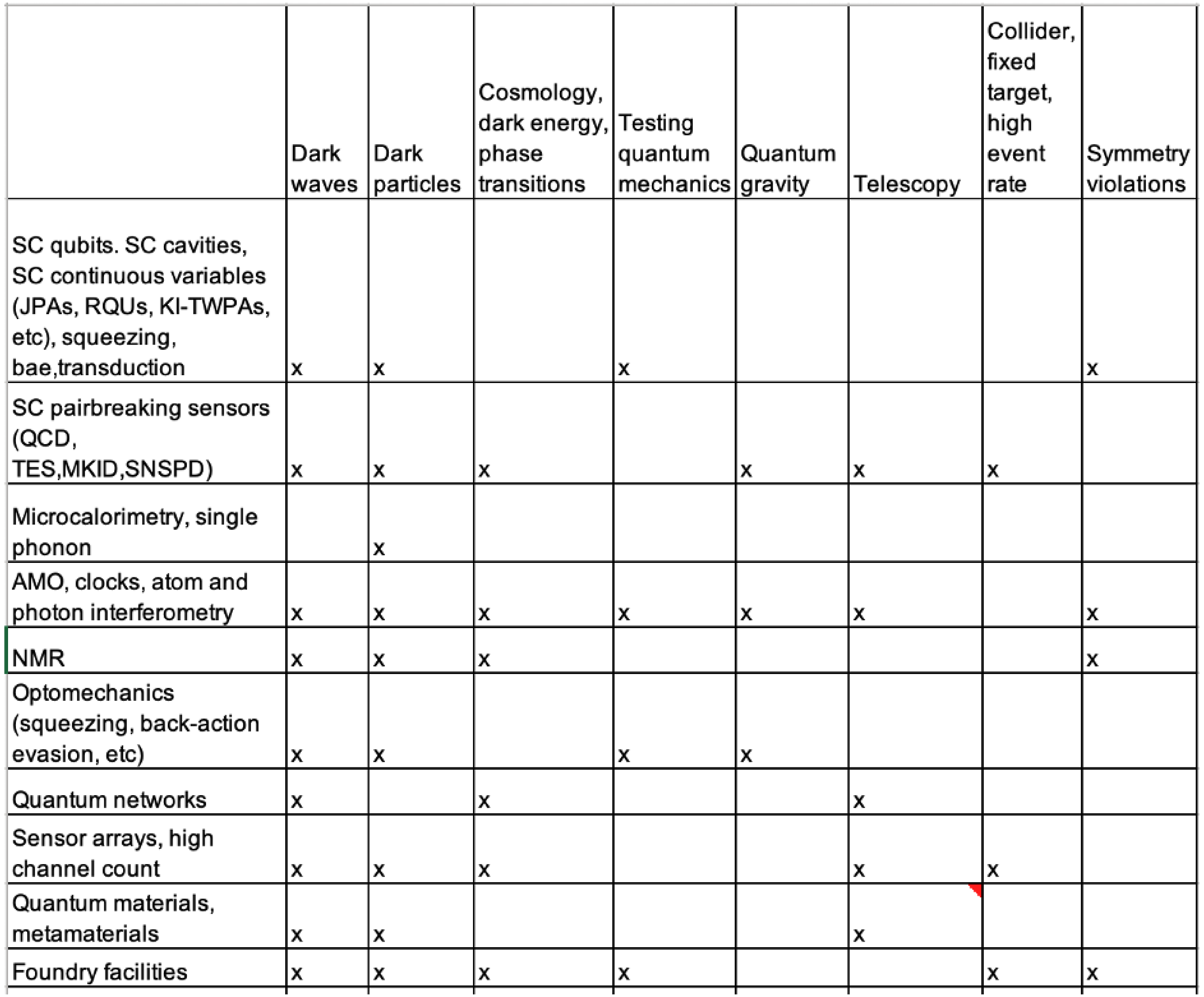
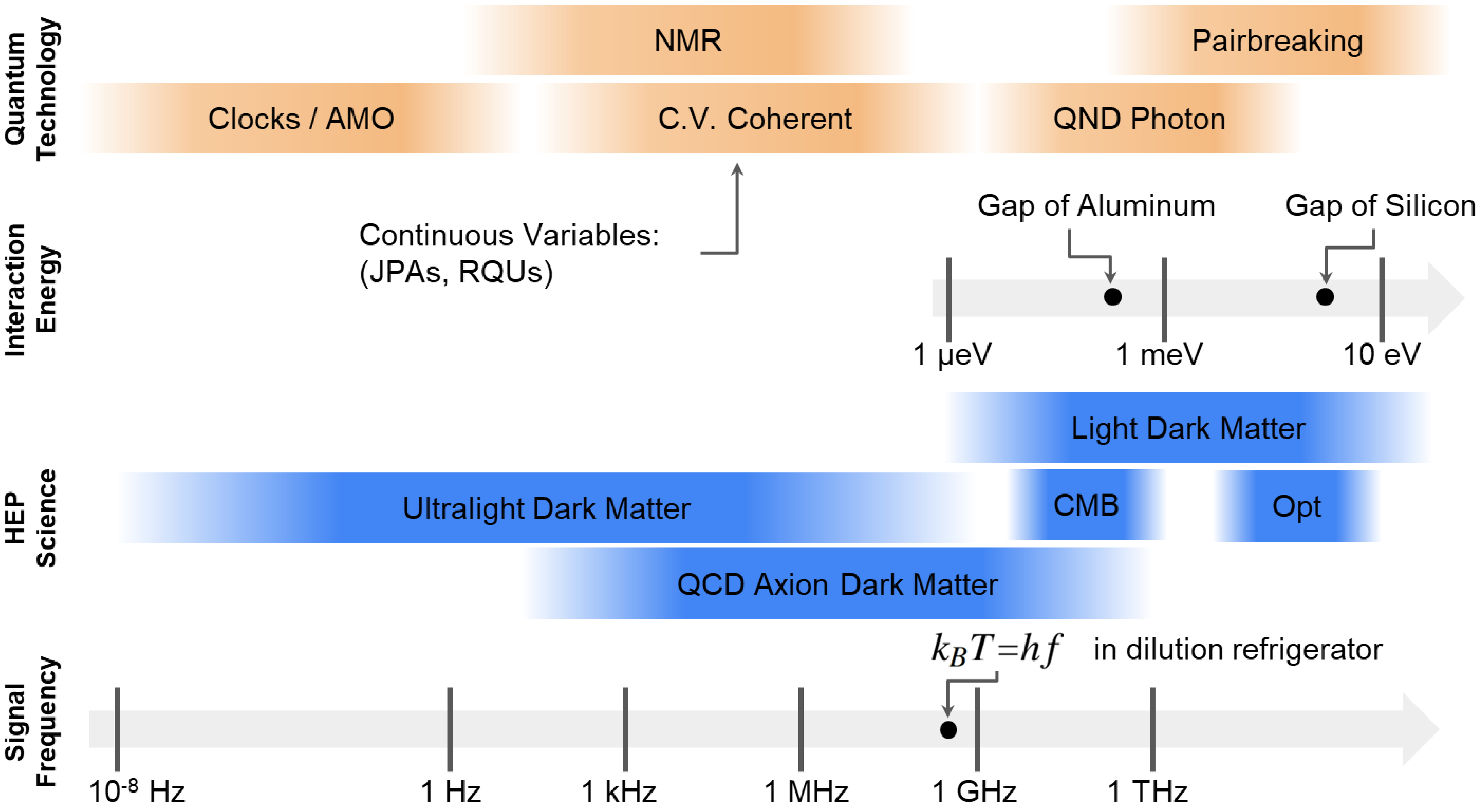
Fig. 2: Diverse HEP science targets and applicable quantum technologies

- Fig. 2 in Arxiv:2311.01930
- I don’t expect you to read the details on this slide – this is just a pointer to the report



	Dark waves	Dark particles	Cosmology, dark energy, phase transitions	Testing quantum mechanics	Quantum gravity	Telescopy	Collider, fixed target, high event rate	Symmetry violations
SC qubits. SC cavities, SC continuous variables (JPAs, RQUs, KI-TWPAs, etc), squeezing, bae,transduction	x	x		x				x
SC pairbreaking sensors (QCD, TES,MKID,SNSPD)	x	x	x		x	x	x	
Microcalorimetry, single phonon		x						
AMO, clocks, atom and photon interferometry	x	x	x	x	x	x		x
NMR	x	x	x					x
Optomechanics (squeezing, back-action evasion, etc)	x	x		x	x			
Quantum networks	x		x			x		
Sensor arrays, high channel count	x	x	x			x	x	
Quantum materials, metamaterials	x	x				x		
Foundry facilities	x	x	x	x			x	x

Quantum sensing and HEP science



Quantum Technology

NMR

Pairbreaking

Clocks / AMO

C.V. Coherent

QND Photon

Interaction Energy

Continuous Variables:
(JPAs, RQUs)

Gap of Aluminum

Gap of Silicon

1 μeV

1 meV

10 eV

HEP Science

Light Dark Matter

Ultralight Dark Matter

CMB

Opt

QCD Axion Dark Matter

Signal Frequency

$k_B T = hf$ in dilution refrigerator

10^{-8} Hz

1 Hz

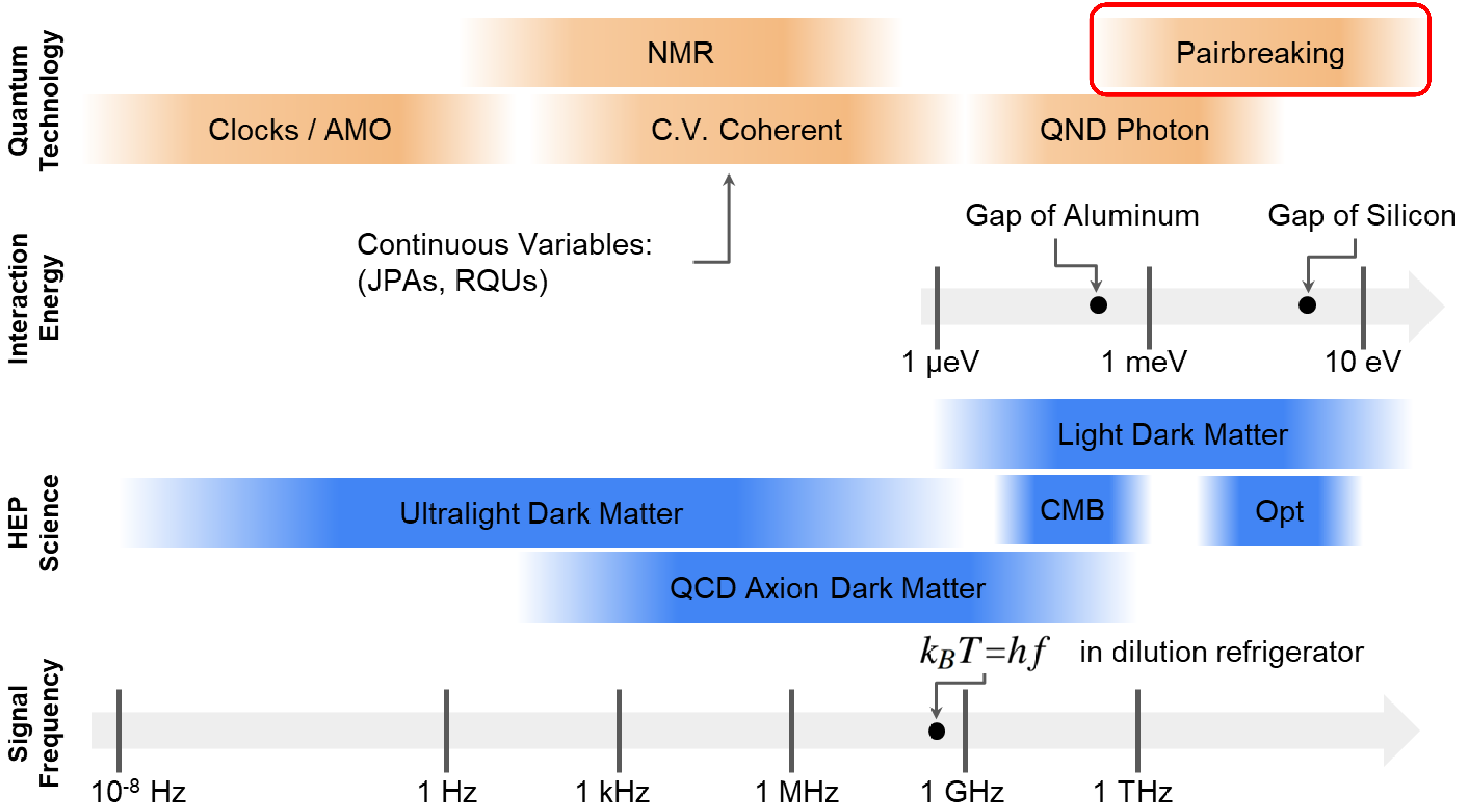
1 kHz

1 MHz

1 GHz

1 THz

Quantum sensing and HEP science



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Optical pairbreaking single photon detectors

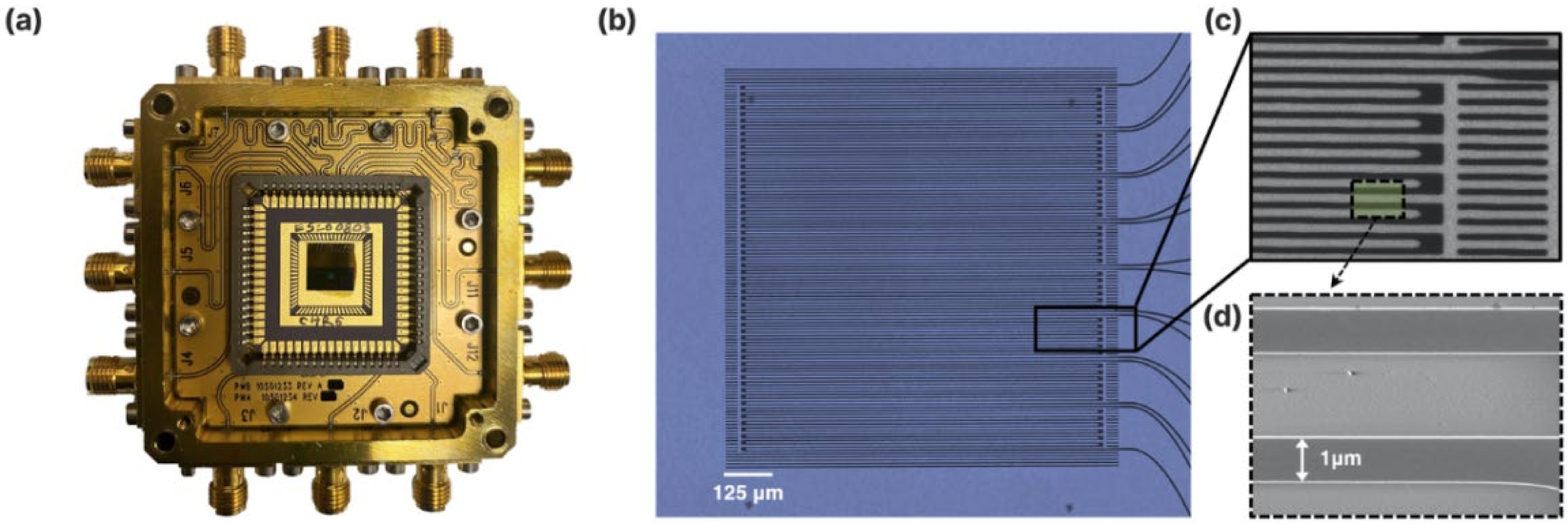
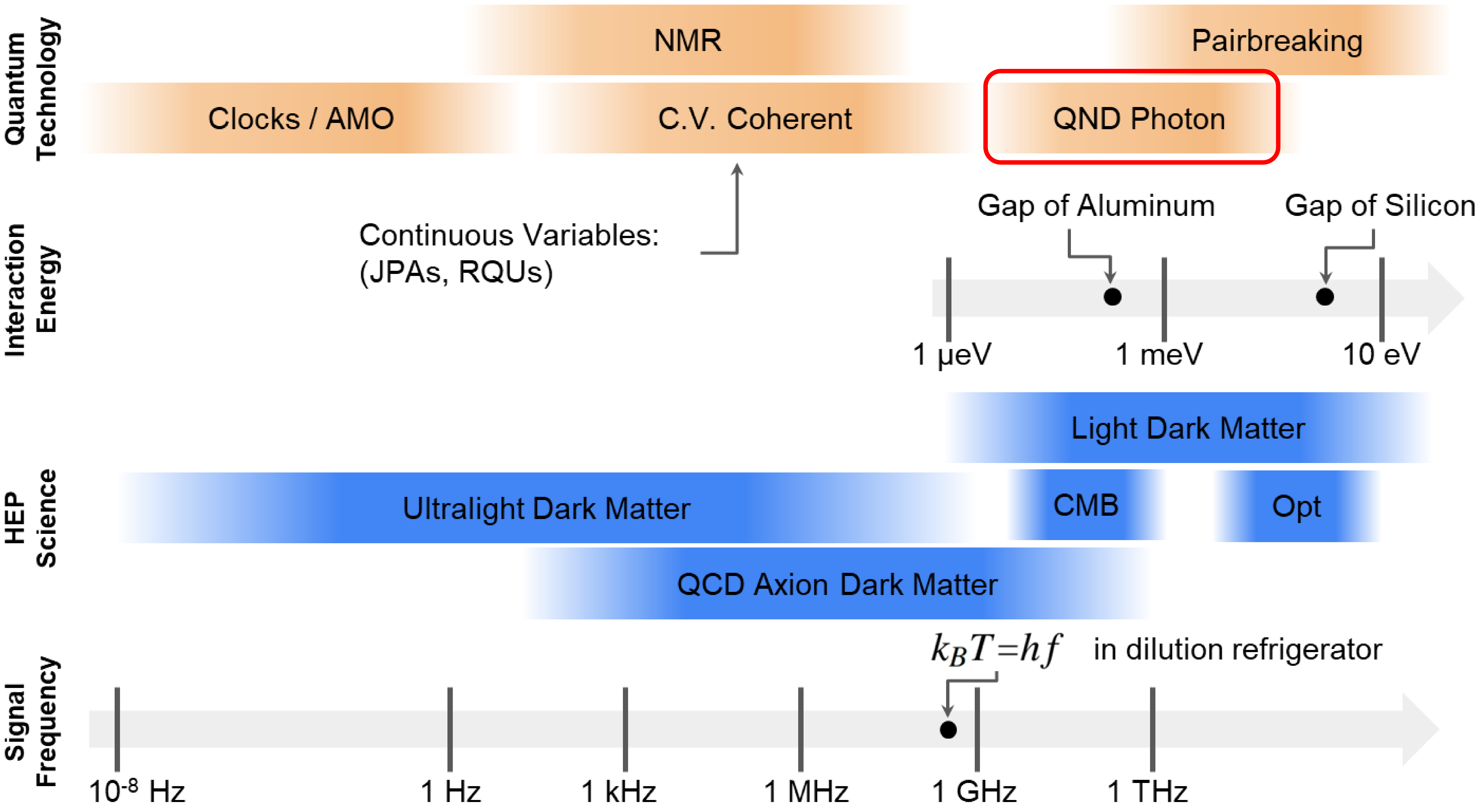


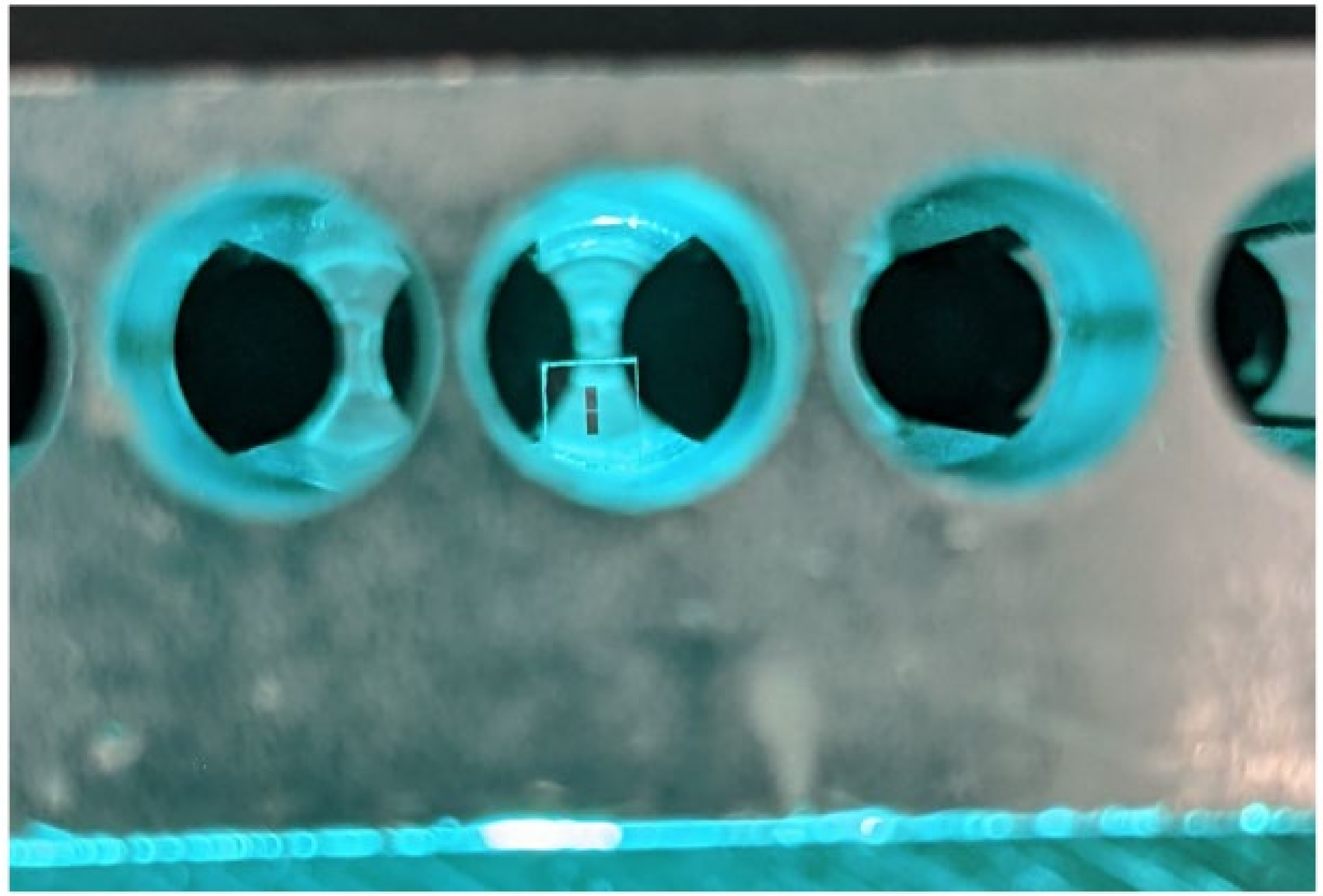
Figure 4: Superconducting nanowire single photon detectors.

- Example pairbreaking detector: superconducting nanowire single photon detectors (SNSPDs). The most advanced technology for ultra-low-noise, time-resolved single photon counting. Fig. 4 in Arxiv:2311.01930
- Effective pixel count as large as 400,000 (arXiv:2306.09473)
- Exciting applications in both particle-like and wave-like light dark matter
- Other pairbreaking detectors: quantum capacitance detectors, superconducting quasiparticle-amplifying transmon (SQUAT), Kinetic inductance detectors, Transition-edge sensors

Quantum sensing and HEP science



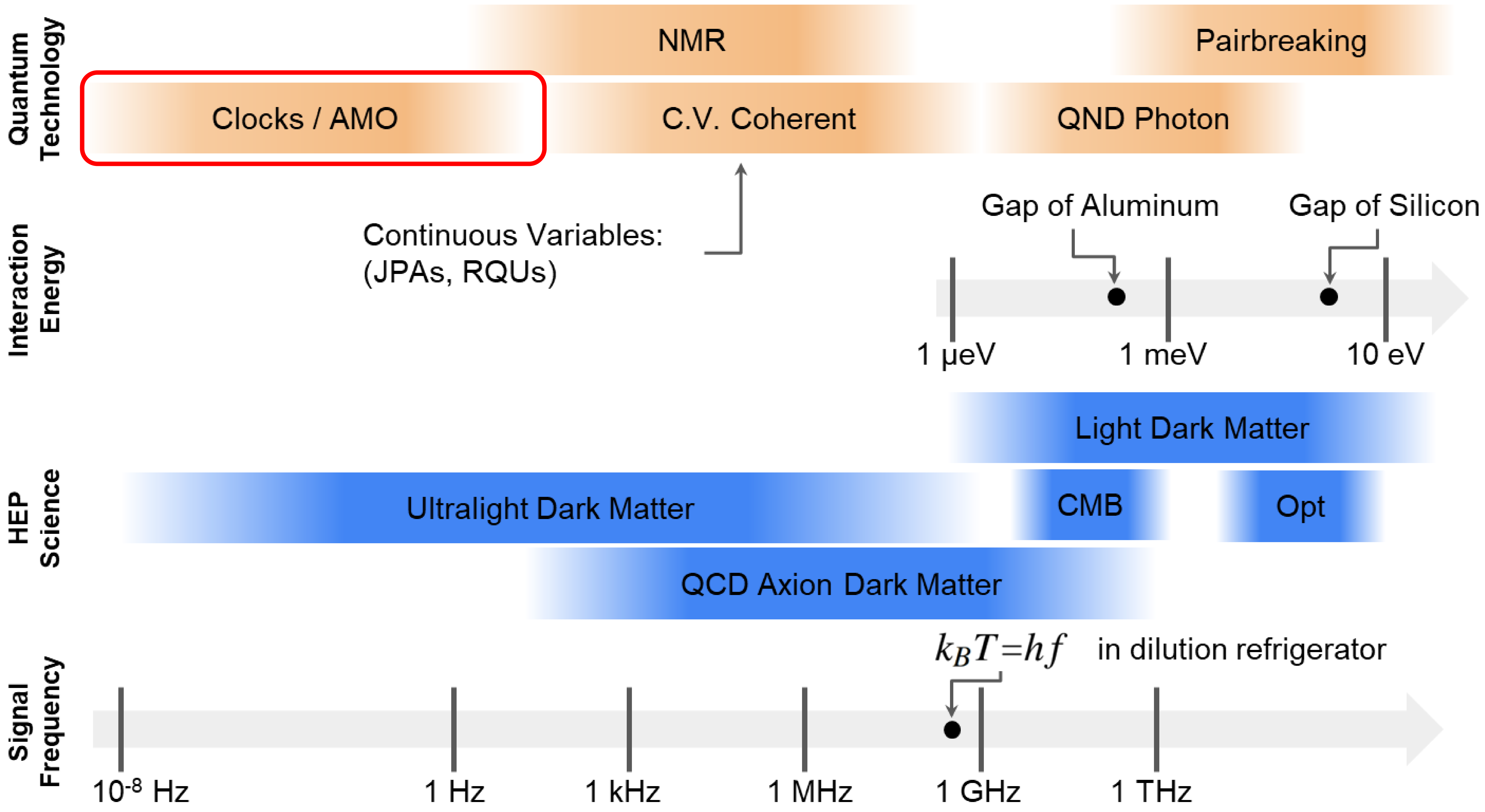
Quantum Non-Demolition (QND) photon detectors



Example of a QND photon detector: transmon qubit

- Fig. 5 in Arxiv:2311.01930 microwave “panflute” cavity with transmon qubit sensor
- Photon detection using quantum non-demolition techniques
- Can detect single photons down to ~ GHz
- Applications in wavelike dark-matter detection (including axions)

Quantum sensing and HEP science



Clocks / AMO

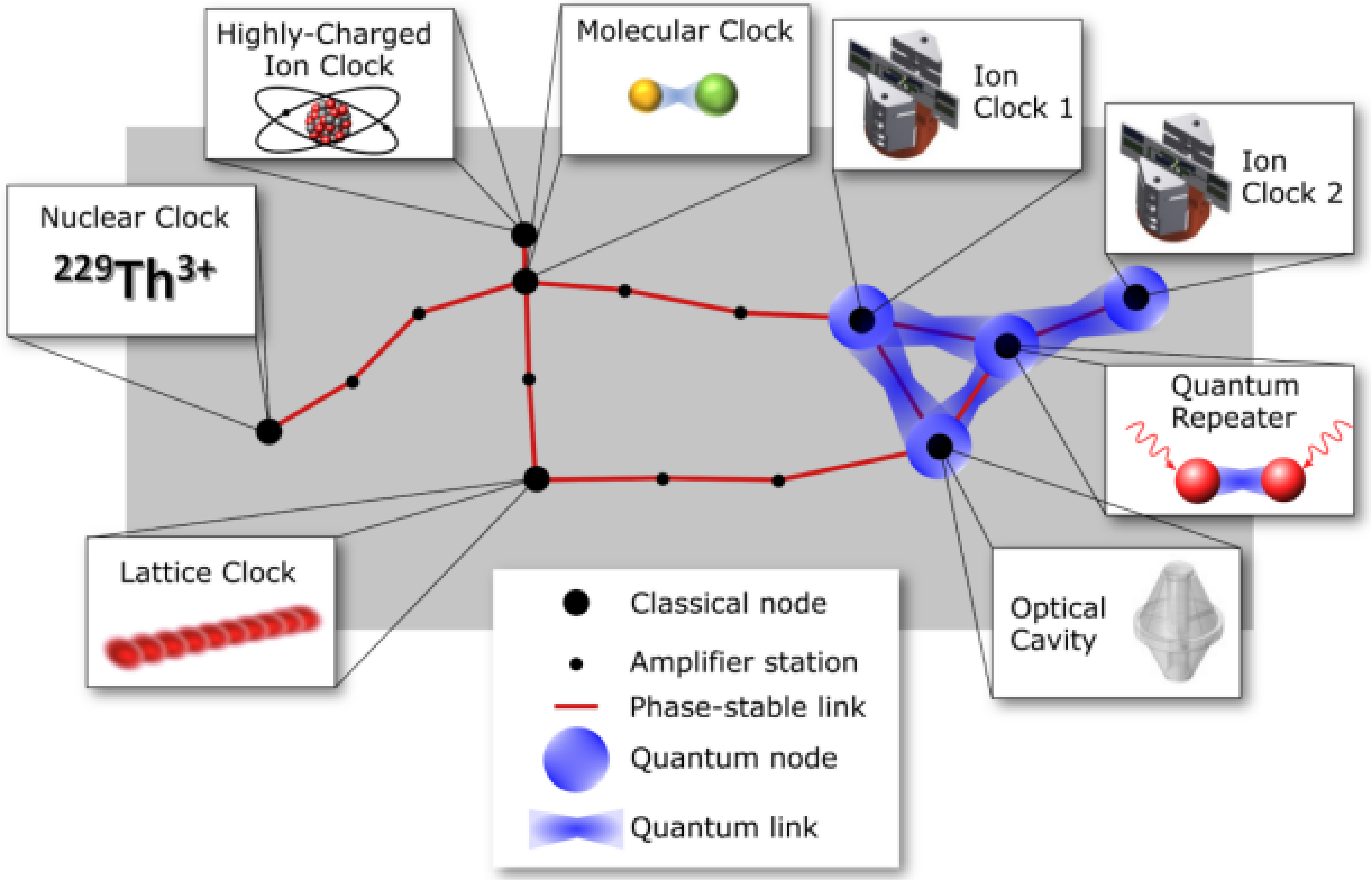


Figure 3: Conceptual picture of a clock network including both classical and quantum nodes and a wide variety of clock species to target various applications in fundamental physics.

- Fig. 3 in Arxiv:2311.01930: conceptual picture of a clock network
- Rapid progress in clock precision: more than 3 orders of magnitude in last 15 years
- 1 part in 10^{18} precision
- Tests of constancy and position invariance of fundamental constants, ultralight dark-matter searches, Lorentz invariance, general relativity, gravity
- Also: atom interferometry (e.g. MAGIS-100)

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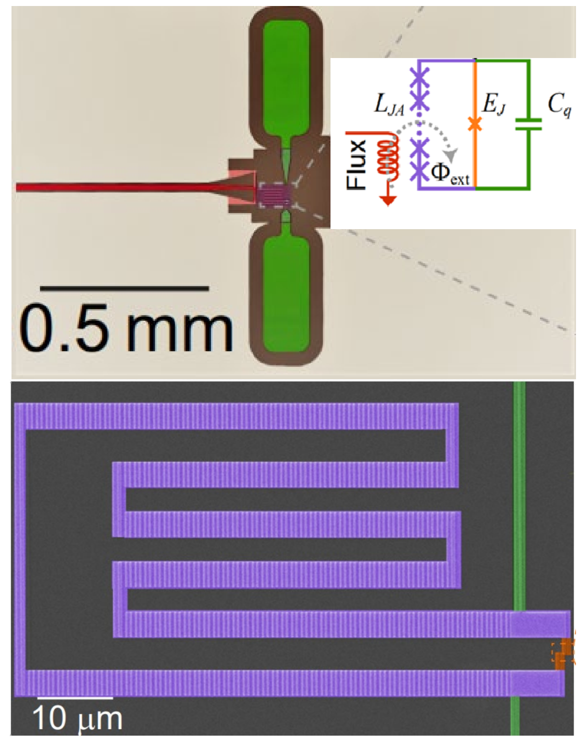
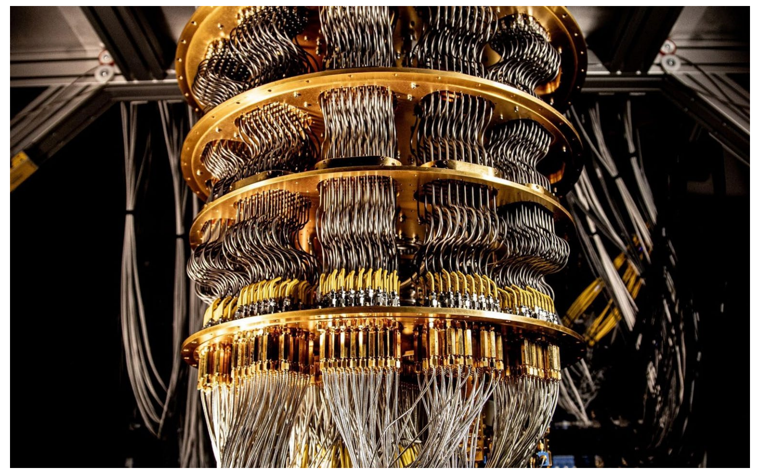
One Motivation: A Golden Age for QIS and Dark Matter

The Quantum Information Revolution



Qubit (Schuster)



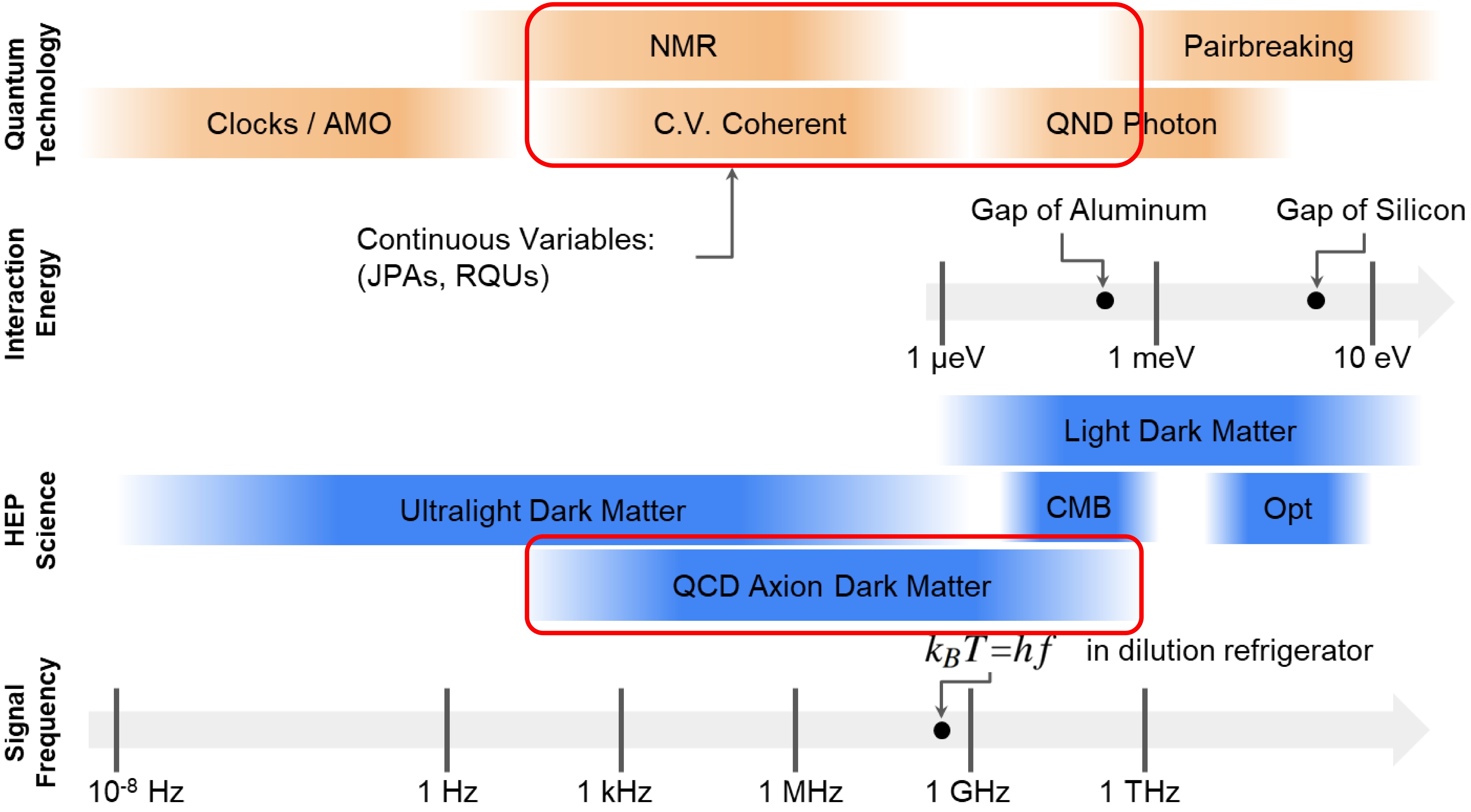
Quantum computer (Google)

- Advances in quantum control
  ⇒ Major governmental, industrial, and academic investment in new quantum technologies
- Near-term opportunities for leveraging quantum advantage:
  - Sensing with new modalities and beyond the standard quantum limit
  - Quantum simulations of physical phenomena intractable to classical computers

The Dark Matter Revolution

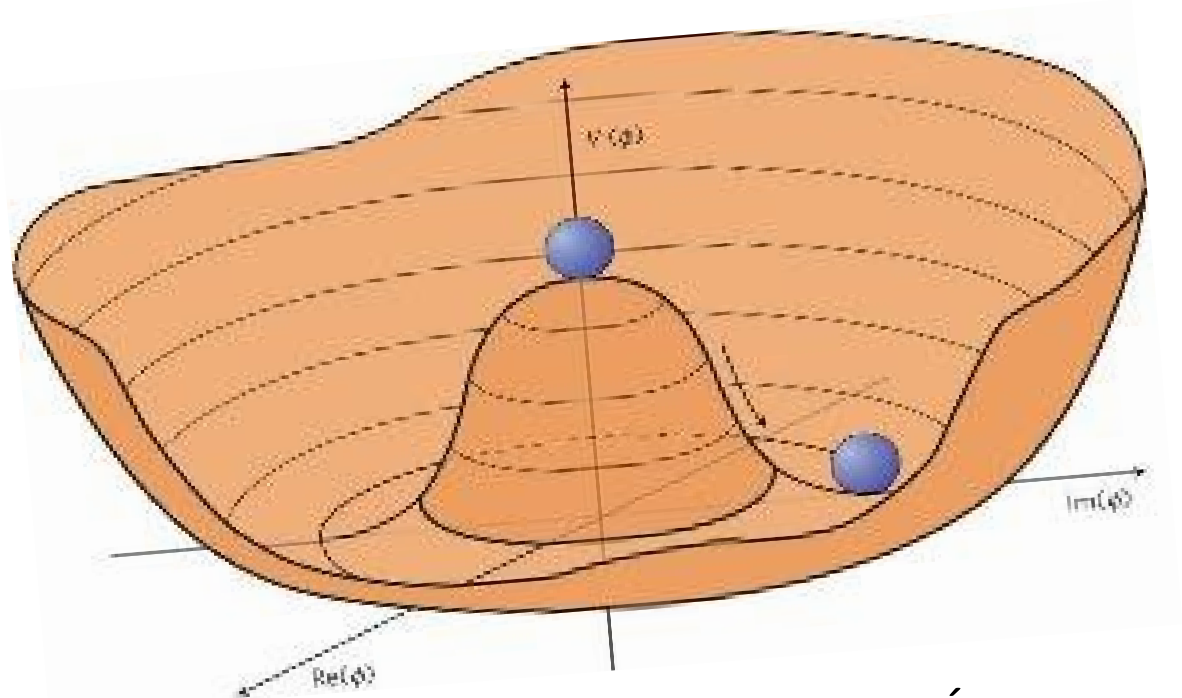
- Progress in theoretical understanding of:
  - Diverse range of dark-matter candidates
  - QCD axion: pre- and post-inflation
- Searching for diverse range of dark-matter candidates requires diverse new quantum sensor technologies (photon detectors, atomic clocks, spins, superconducting qubits, ...)
- Searching for QCD axion requires quantum enhancement: reduce time to fully measure QCD axion band from millennia to years

Quantum sensing and HEP science



QCD axion and the strong CP problem

- CP symmetry violation discovered in 1964 in the decays of neutral kaons: Nobel Prize in Physics in 1980 (Cronin & Fitch).
- CP violation should naturally occur in QCD; would result in an electric dipole moment of the neutron. Measured level of this dipole moment are >~10^9 smaller than natural scale. This fine-tuning problem is the “Strong CP Problem”.
- A natural relaxation mechanism was provided by Peccei and Quinn, who extended QCD to include a dynamic field (an angle $\bar{\theta}$). QCD drives $\bar{\theta}$ to zero after PQ symmetry breaking, explaining the smallness of neutron EDM.
- The particle associated with this field is the axion, and the energy of PQ symmetry breaking determines the axion mass. Axions would be expected to be produced in abundance in the early universe.
- Where are they? Why don’t we see them? *Do we see them gravitationally?*

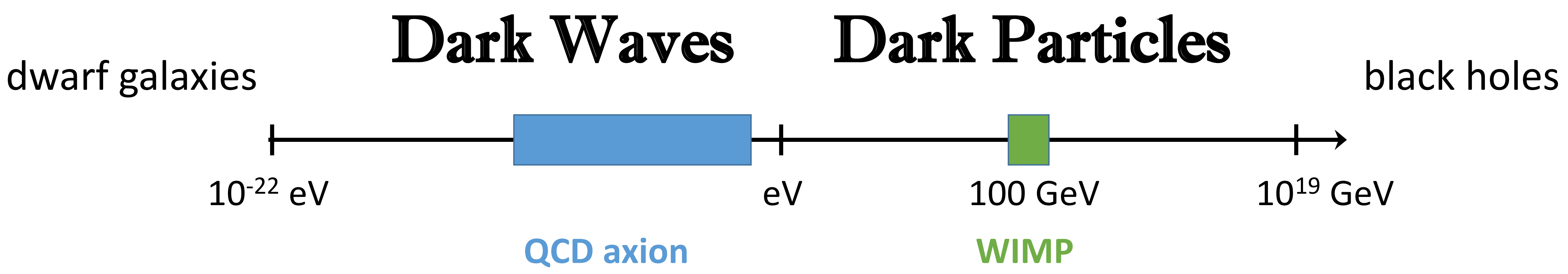


LUIS ÁLVAREZ-GAUMÉ & JOHN ELLIS, 2011

After 40+ years, the axion is the only ***widely*** *accepted solution for the strong CP problem (alternative theories include the existence of two time dimensions (Bars, 1998)).*

Slide credit: C.L. Kuo

Two “uniquely” motivated dark-matter candidates



Dark Waves **Dark Particles**

dwarf galaxies

black holes

10^{-22} eV

eV

100 GeV

10^{19} GeV

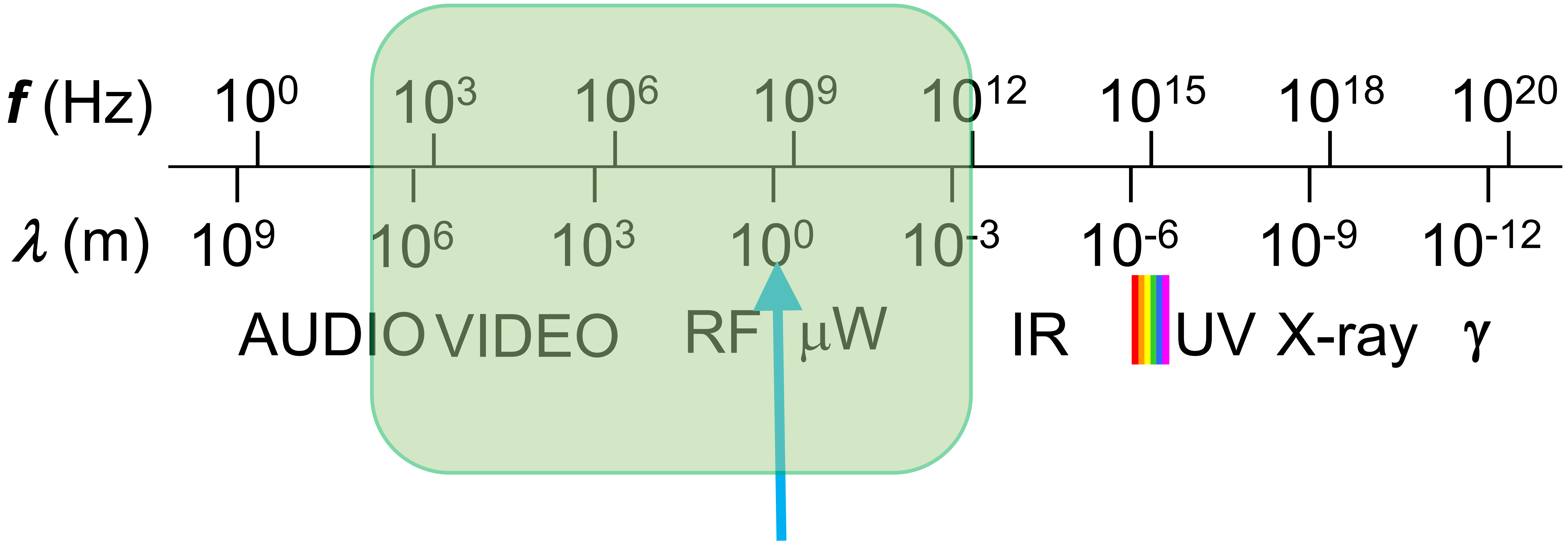
QCD axion

WIMP

- **Weakly Interacting Massive Particle (WIMP)**
  - *Motivated* by the theory of supersymmetry.
  - *Naturalness*: thermal production of observed abundances for WIMPs near 1-100 GeV.
  - Ongoing, 30-year effort to produce (supersymmetry at LHC) and detect (direct dark-matter searches). Much interesting phase space has been searched – and more to come.
- **Axion**
  - *Motivated* by the standard model, as solution to the strong CP problem in QCD.
  - *Naturalness*: natural, non-thermal production of observed abundances of dark matter.
  - Largely unexplored parameter space – emerging quantum technology will do it

Quantum Sensing Technology is emerging to fully search the QCD axion band over the next 20 years

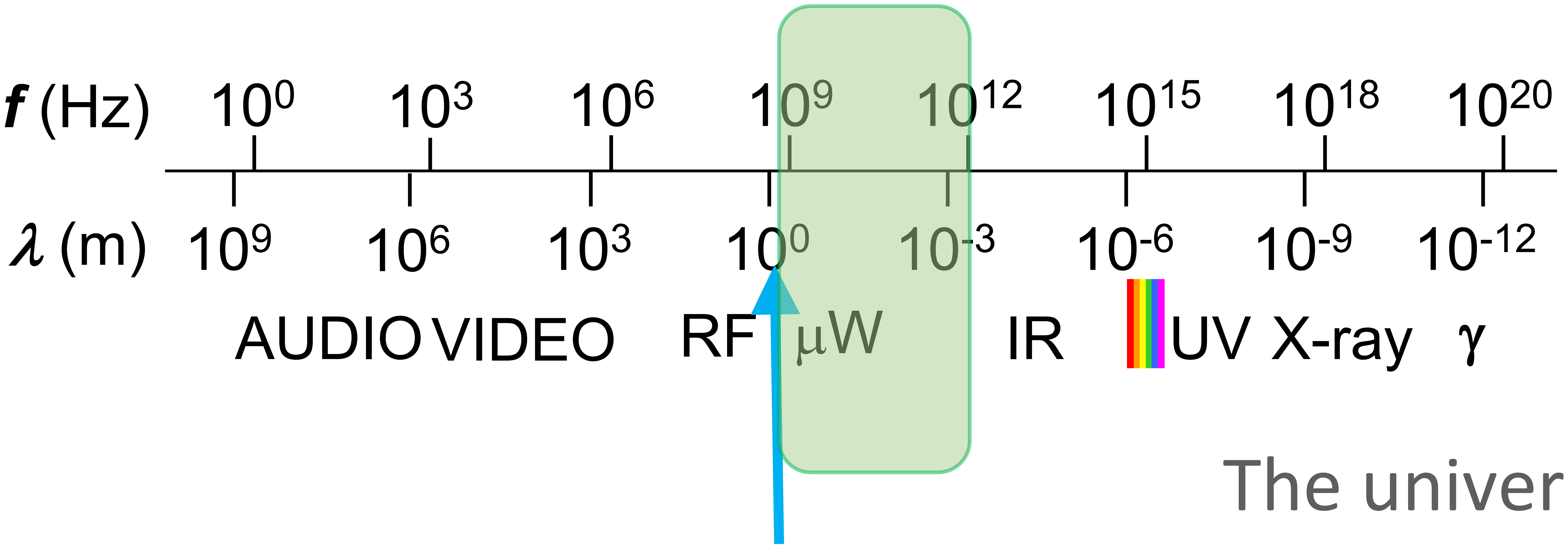
QCD axion band spans two regions of quantum technology: Smaller-than-human and larger-than-human scale



300 MHz ~ 0.015 Kelvin ~ 1 m

300 MHz ~ human scale ~ dilution refrigerator temperature

Larger than humans: post-inflationary axions

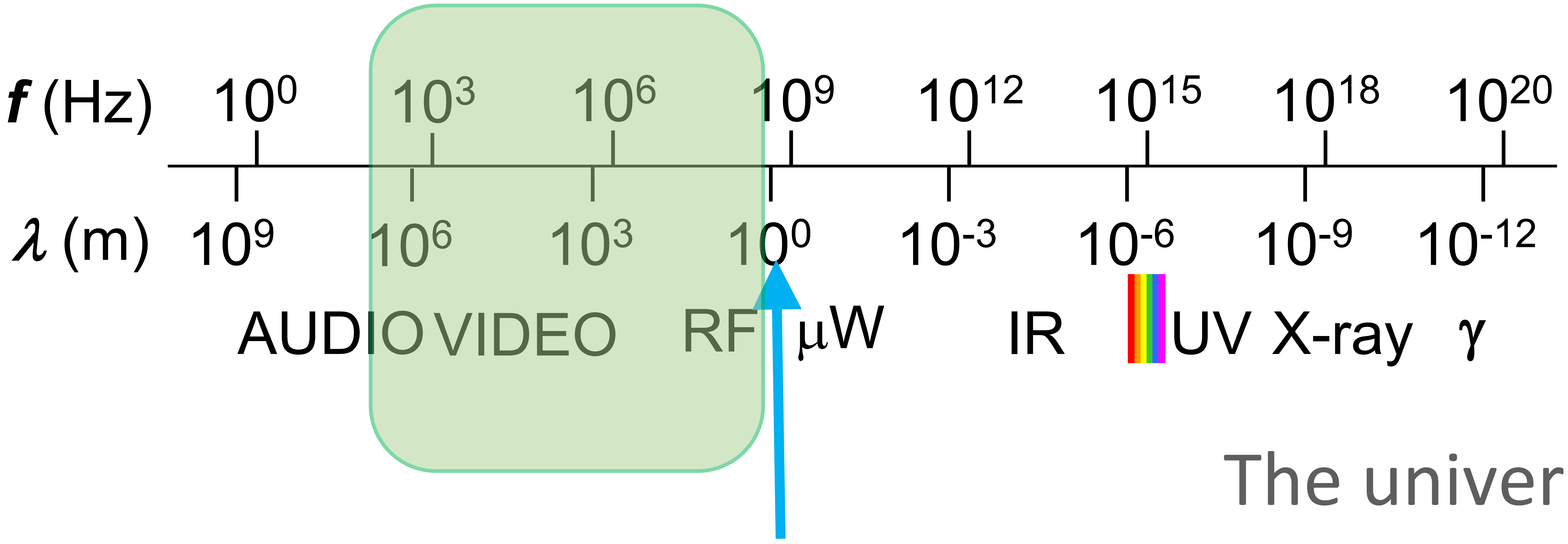


The universe ~ 2.7 K

300 MHz ~ 0.015 Kelvin ~ 1 m

- Top ~1/3 of QCD axion band
- CV superconducting detectors (JPA), photon counting, …
- ADMX, BREAD, MADMAX, ALPHA, etc.
- See G. Carosi, RDC8 coherent wave detectors summary, RC8 talks

Smaller than humans: pre-inflationary axions

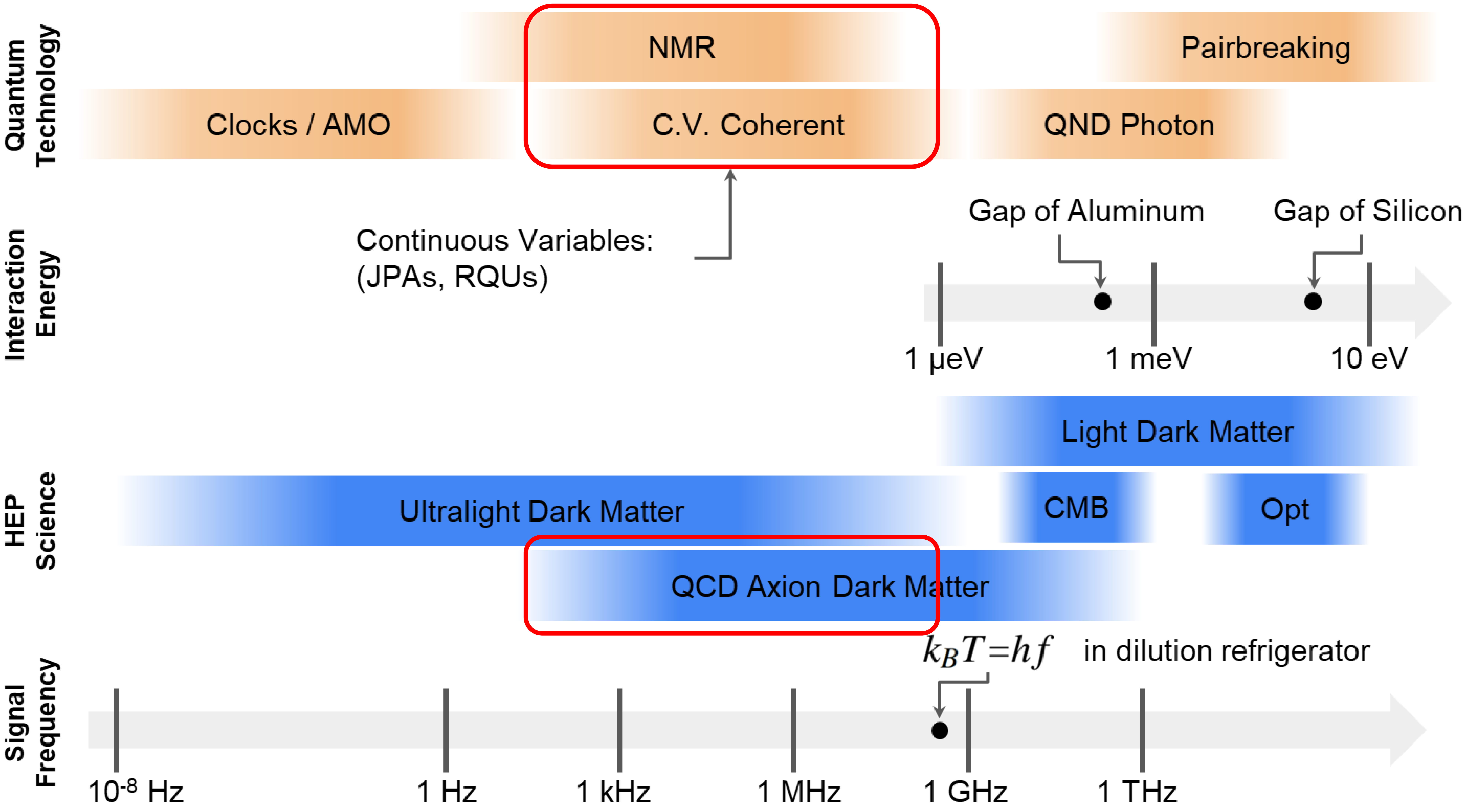


The universe ~ 2.7 K

300 MHz ~ 0.015 Kelvin ~ 1 m

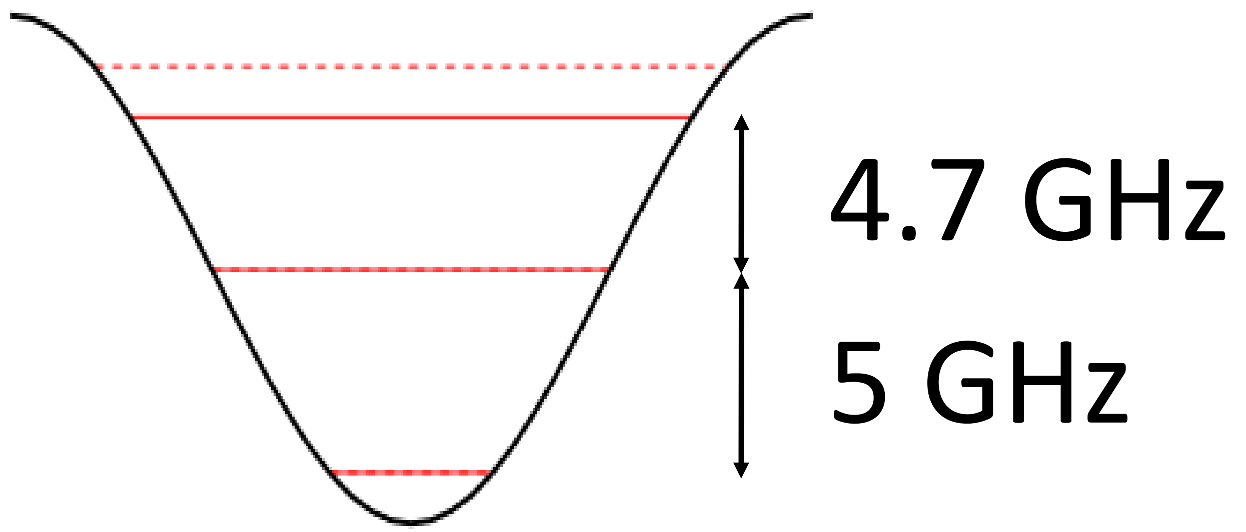
- Bottom ~2/3 of QCD axion band
- CV superconducting (RQUs), NMR, …
- Dark Matter Radio, CASPEr-electric, SRF-m3, etc...

Pre-inflationary axions

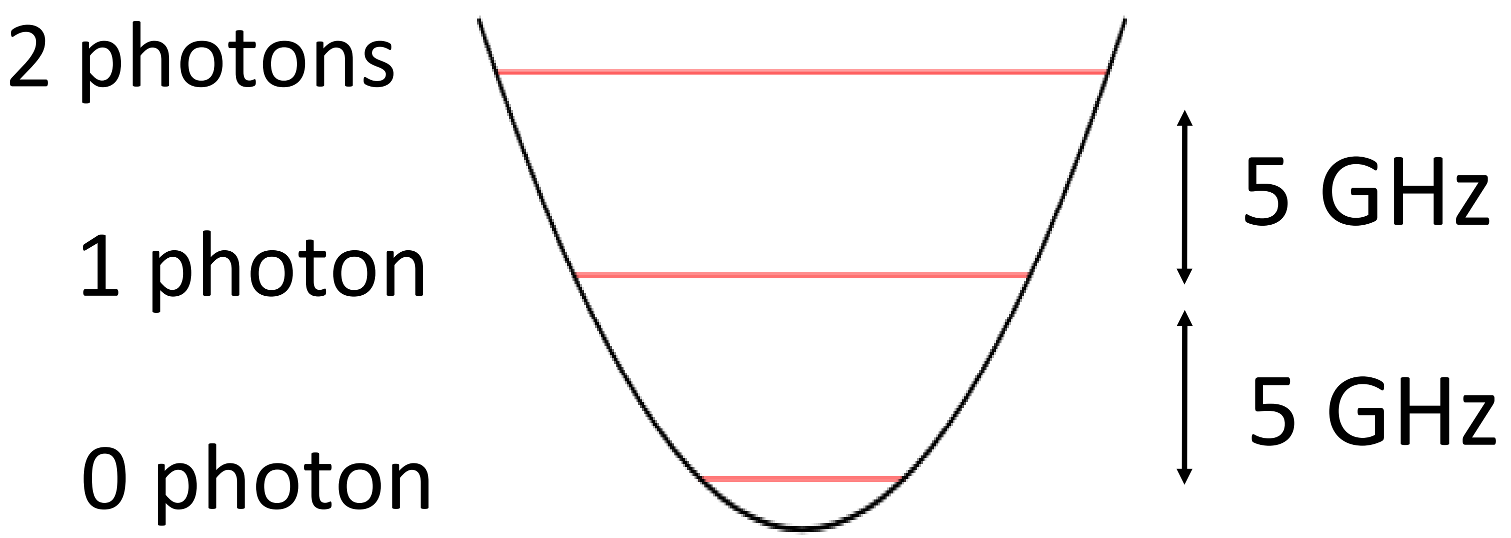


Continuous variables quantum information

- A qubit, or two-level system, is in some superposition of two states, |0> and |1>. It is "digital"-like.
- Physical observables (e.g. the strength of an electromagnetic field) have continuous intervals. They are "analog"-like.
- Often, continuous variables signals are sensed in a weak, continuous measurement, rather than a single projection. (the realized quantum limits are similar in either case).
- The state of the field can be expressed as a phasor diagram, with $\widehat{X}$ and $\widehat{Y}$ quadrature components



Qubit with nonlinear level spacing



Mode with linear level spacing

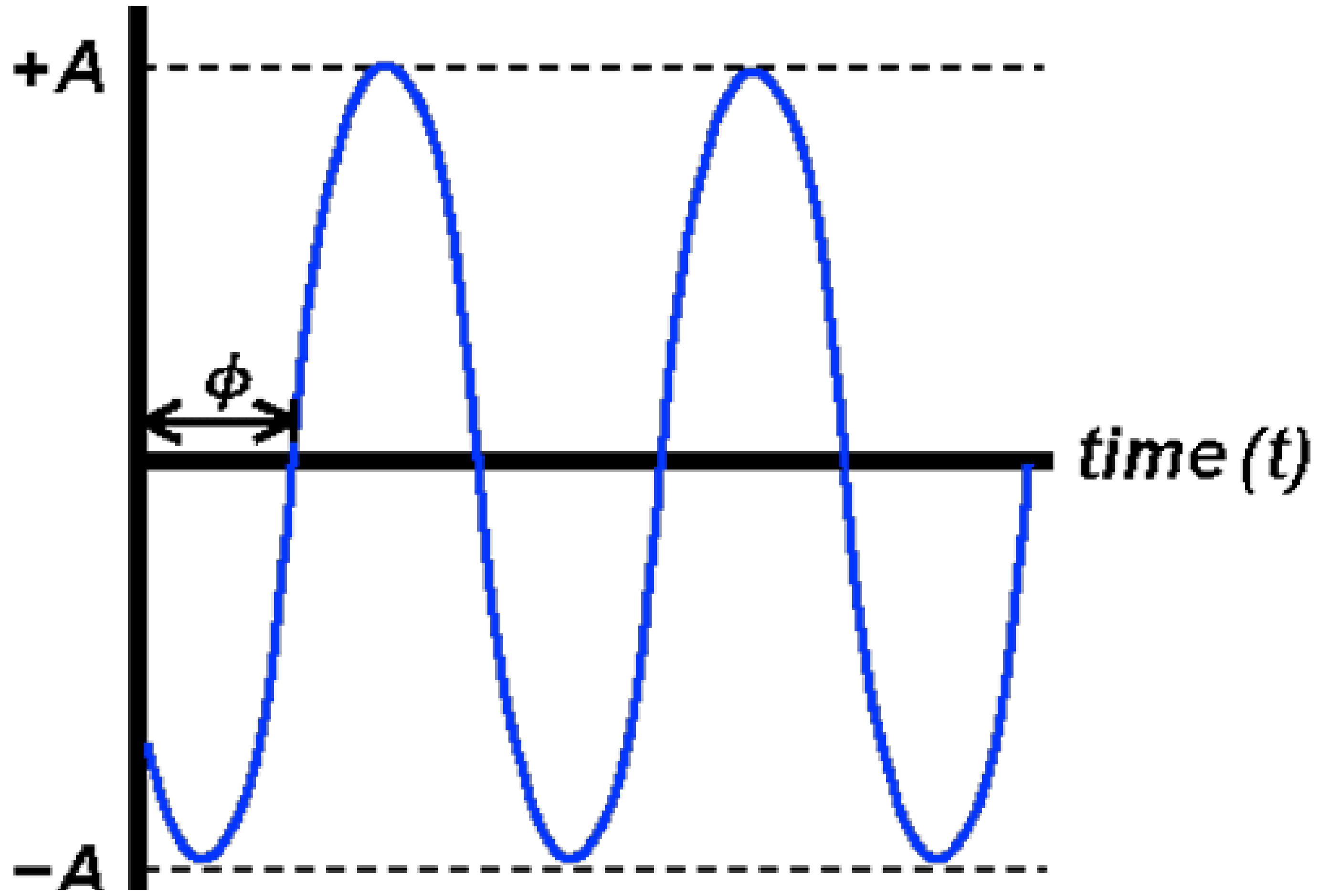
$$\widehat{H} = \hbar\omega\left(a^{\dagger}a + 1/2\right)$$

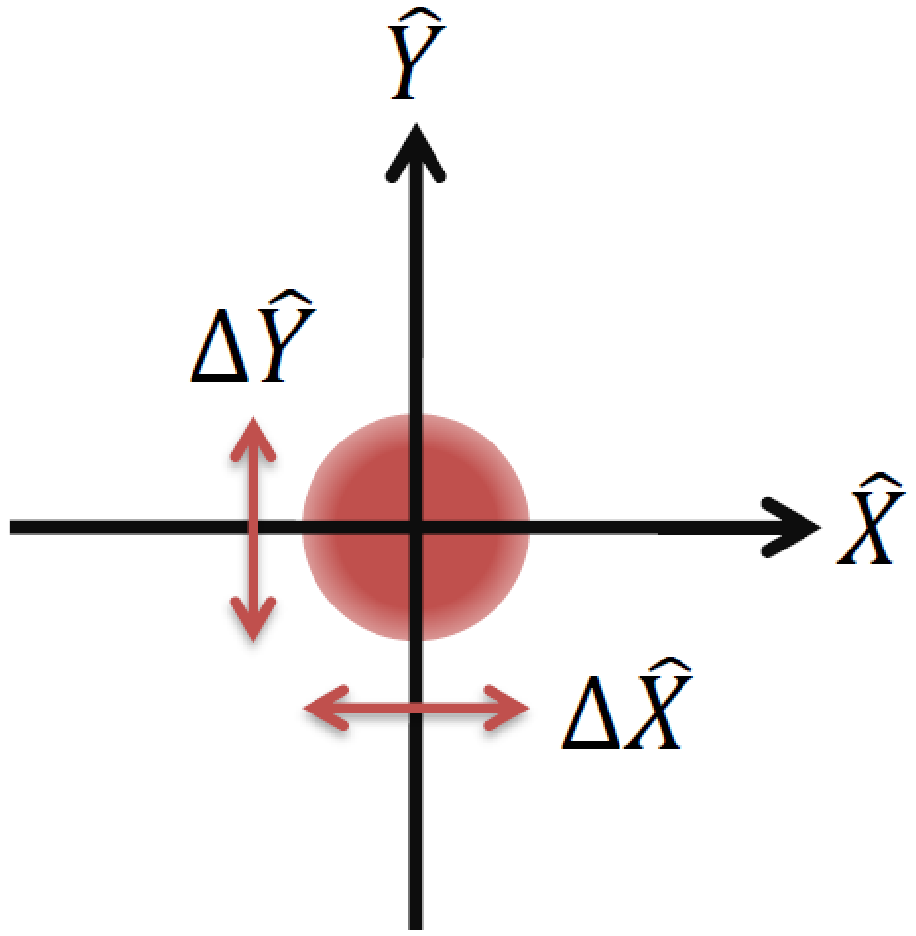
You can't know both amplitude and phase perfectly

Heisenberg tells us that you can't know the position and momentum of a particle perfectly at the same time:

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

$$A\cos(\omega t + \phi) = X\cos(\omega t) + Y\sin(\omega t)$$



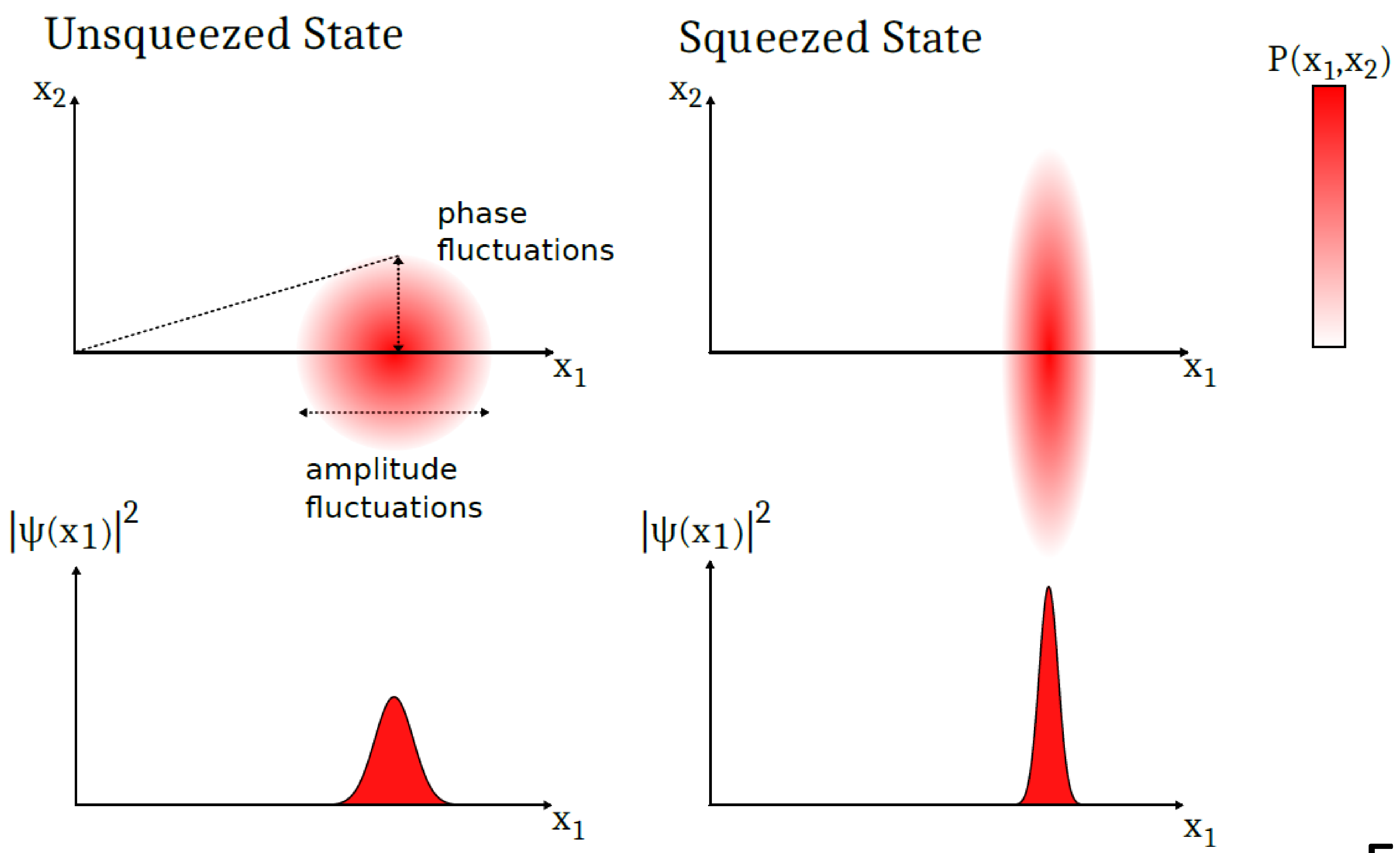


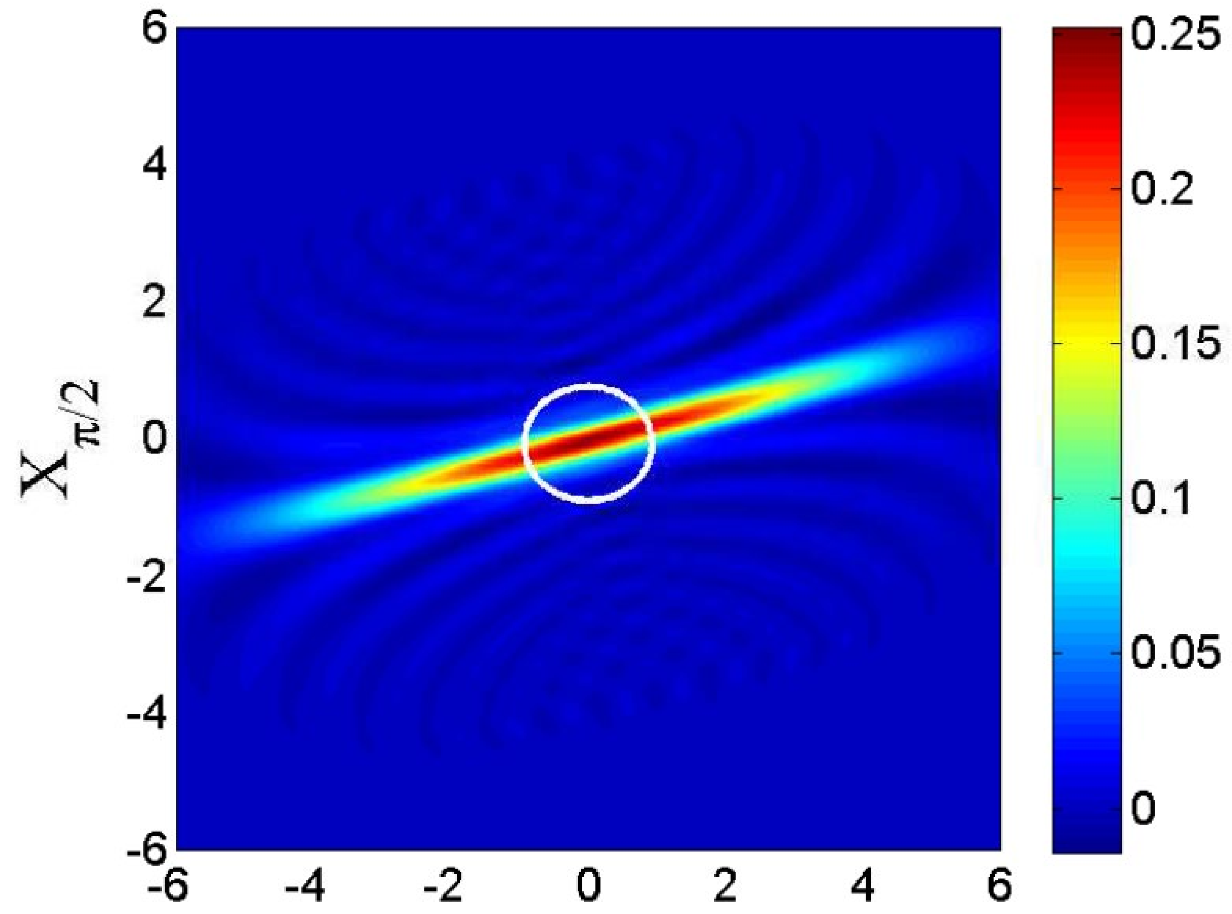
$$\Delta X \Delta Y \geq \frac{\hbar\omega}{4}$$

A "classical" sensor measures both amplitude and phase with equal sensitivity, limited by the Standard Quantum Limit of $\hbar\omega$

What if I don't care about phase???

One way to evade the SQL - squeezing

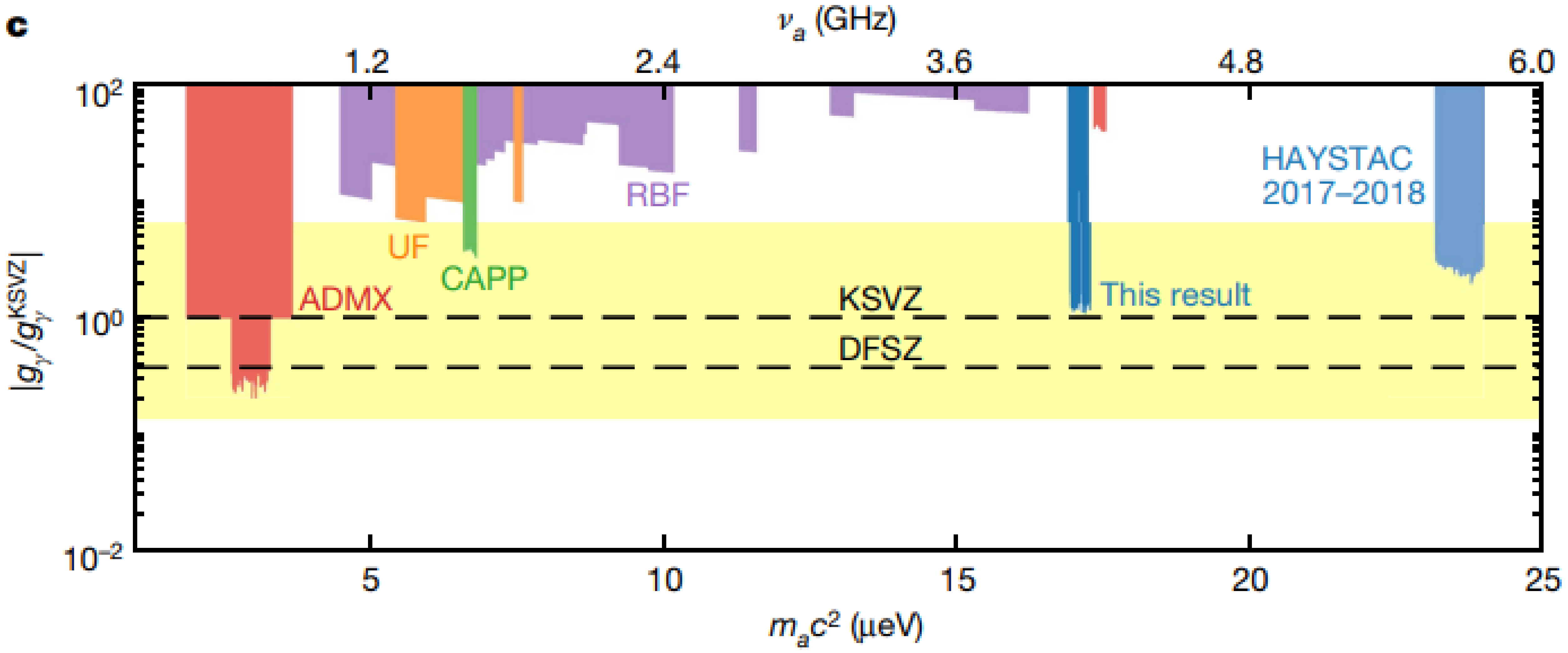




F. Mallet et al. *Phys. Rev. Lett.* **106**, 220502 (2011).

- Don’t measure both amplitude and phase. (Equivalently, don’t measure both sine and cosine quadratures)
- There are several ways to achieve this outcome. They are deeply inter-related (and involve entanglement), and all obey the Uncertainty Principle.

HAYSTAC: Faster science through squeezing

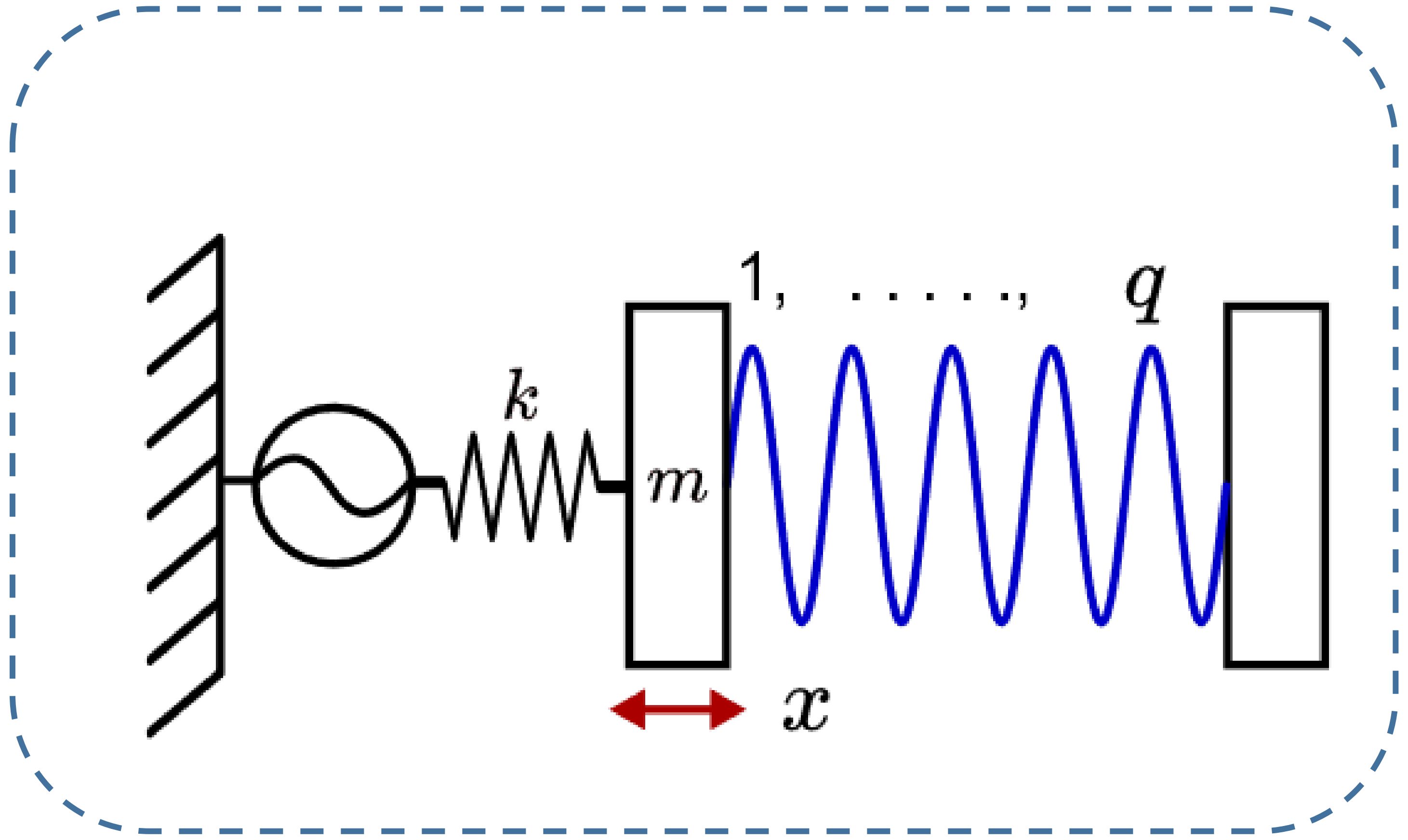


HAYSTAC quantum accelerated science reach

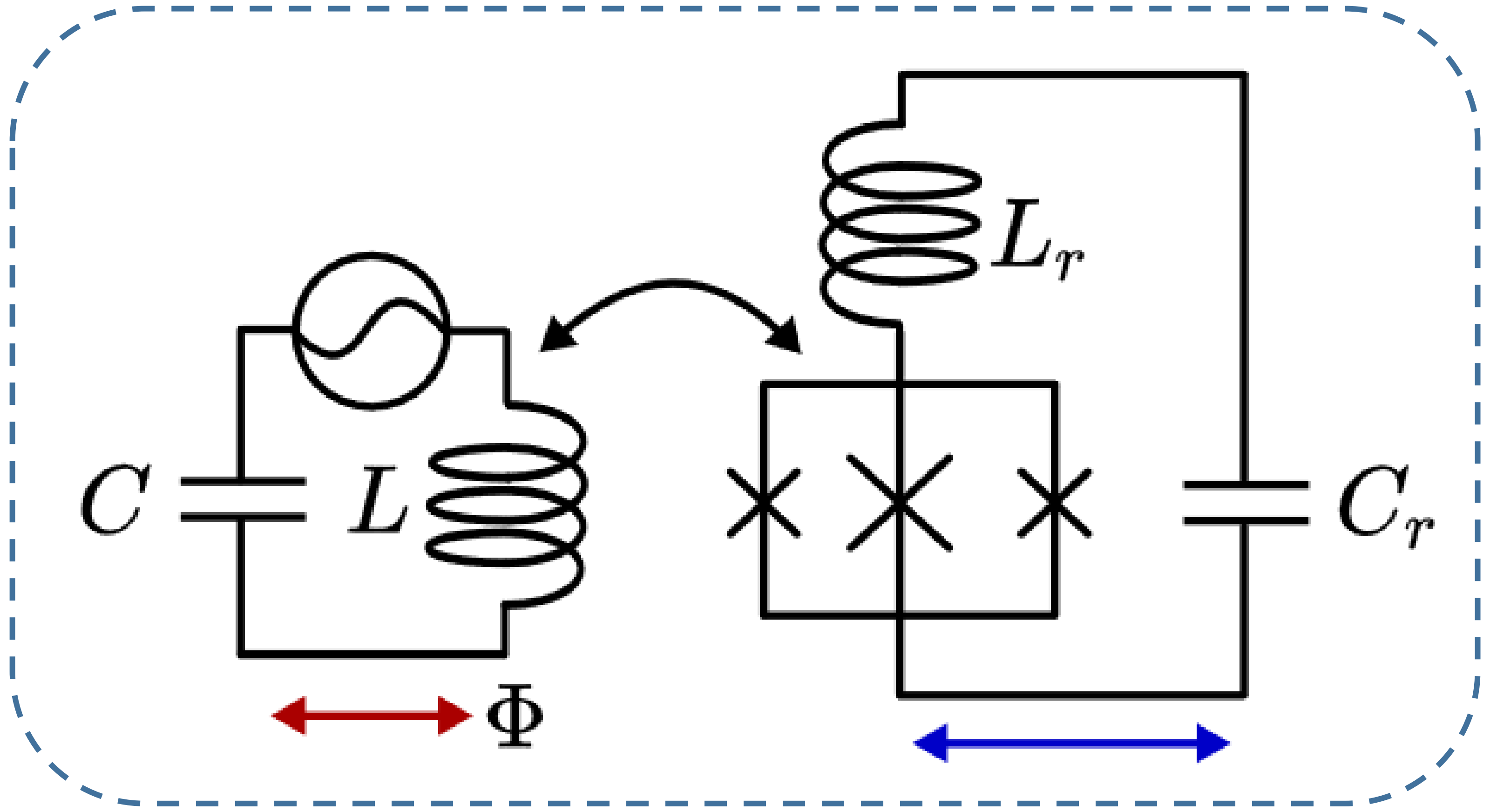
Backes, Kelly M., et al. "A quantum enhanced search for dark matter axions."
Nature 590.7845 (2021): 238-242.

Radio-Frequency Quantum Upconverters: Analogous to Optomechanical Systems

LIGO:



Axion detector with RQU:



$$\omega_a = \sqrt{\frac{k}{m}} \qquad \omega_b = \frac{2\pi q c}{l(x)}$$

$$\omega_a = \sqrt{\frac{1}{LC}} \qquad \omega_b = \sqrt{\frac{1}{L_r(\Phi)C_r}}$$

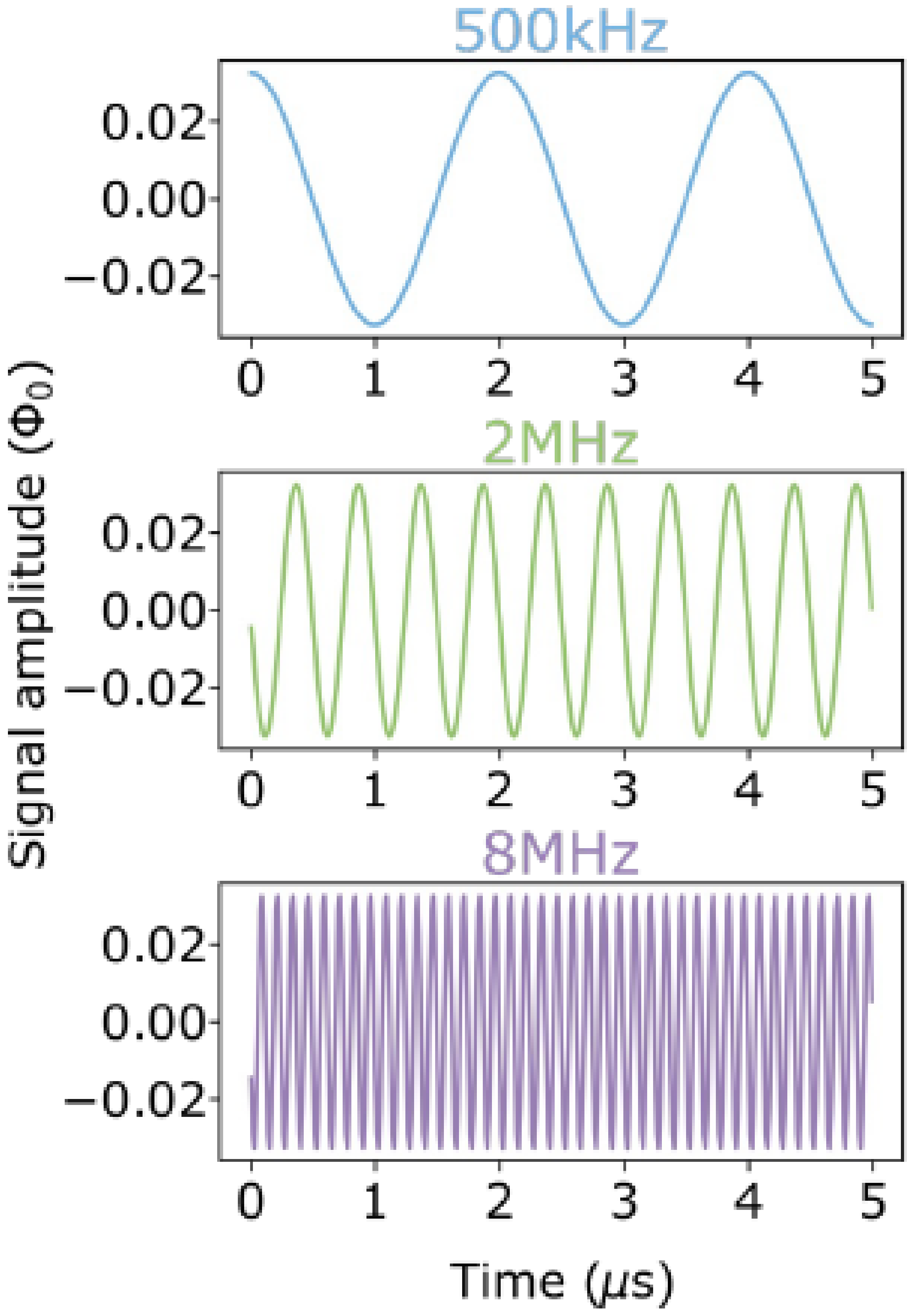
Optomechanical Hamiltonian

$$\hat{\mathrm{H}} = \hbar\omega_a\left(\hat{a}^\dagger\hat{a} + 1/2\right) + \hbar\omega_b\left(\hat{b}^\dagger\hat{b} + 1/2\right) + \hat{\mathrm{H}}_{\mathrm{INT}}$$

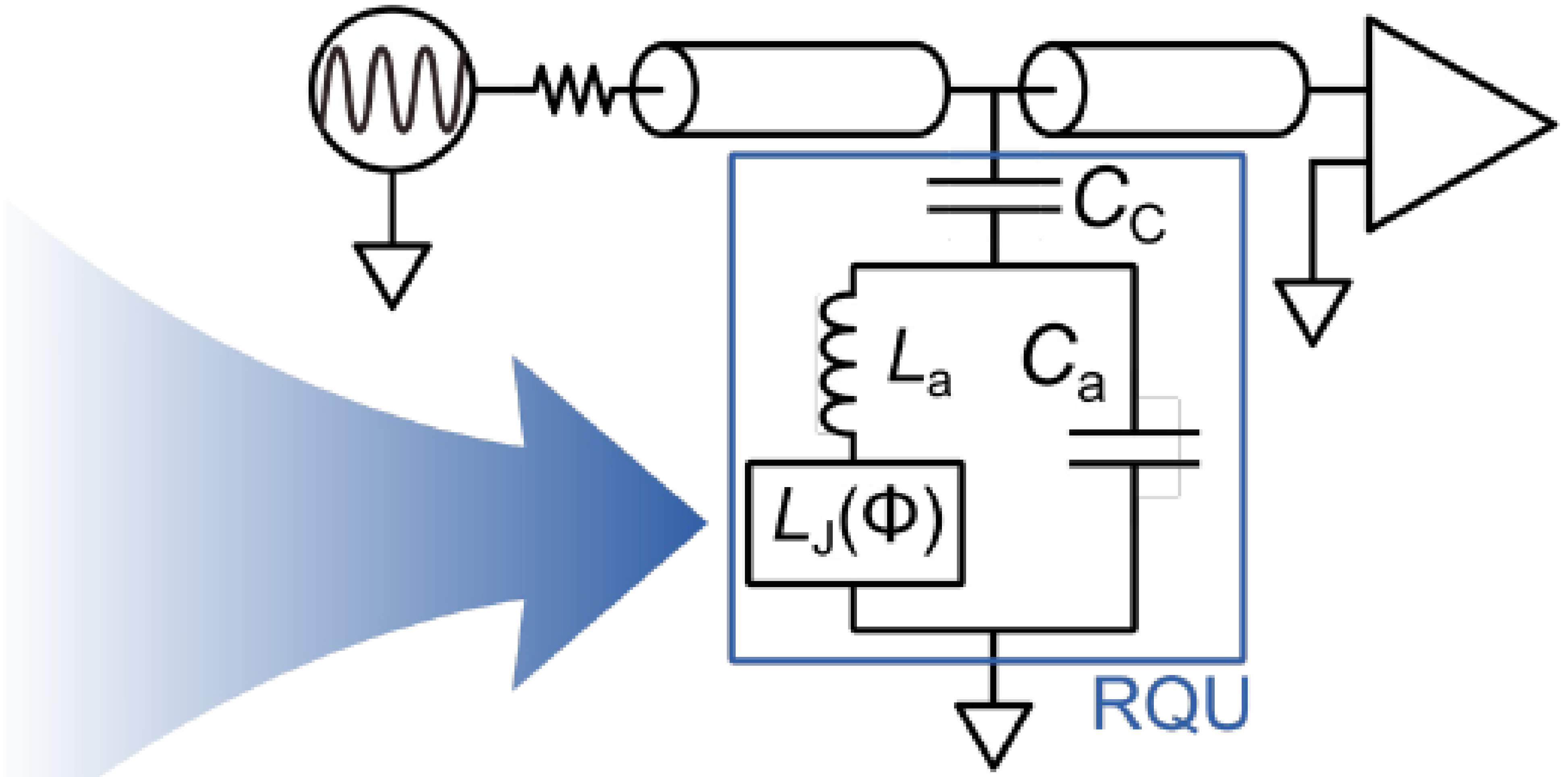
$$\hat{\mathrm{H}}_{\mathrm{INT}} = -\hbar\hat{F}\hat{b}^\dagger\hat{b}\left(\hat{a}^\dagger + \hat{a}\right)/\sqrt{2}$$

Data Illustrating RF Upconversion

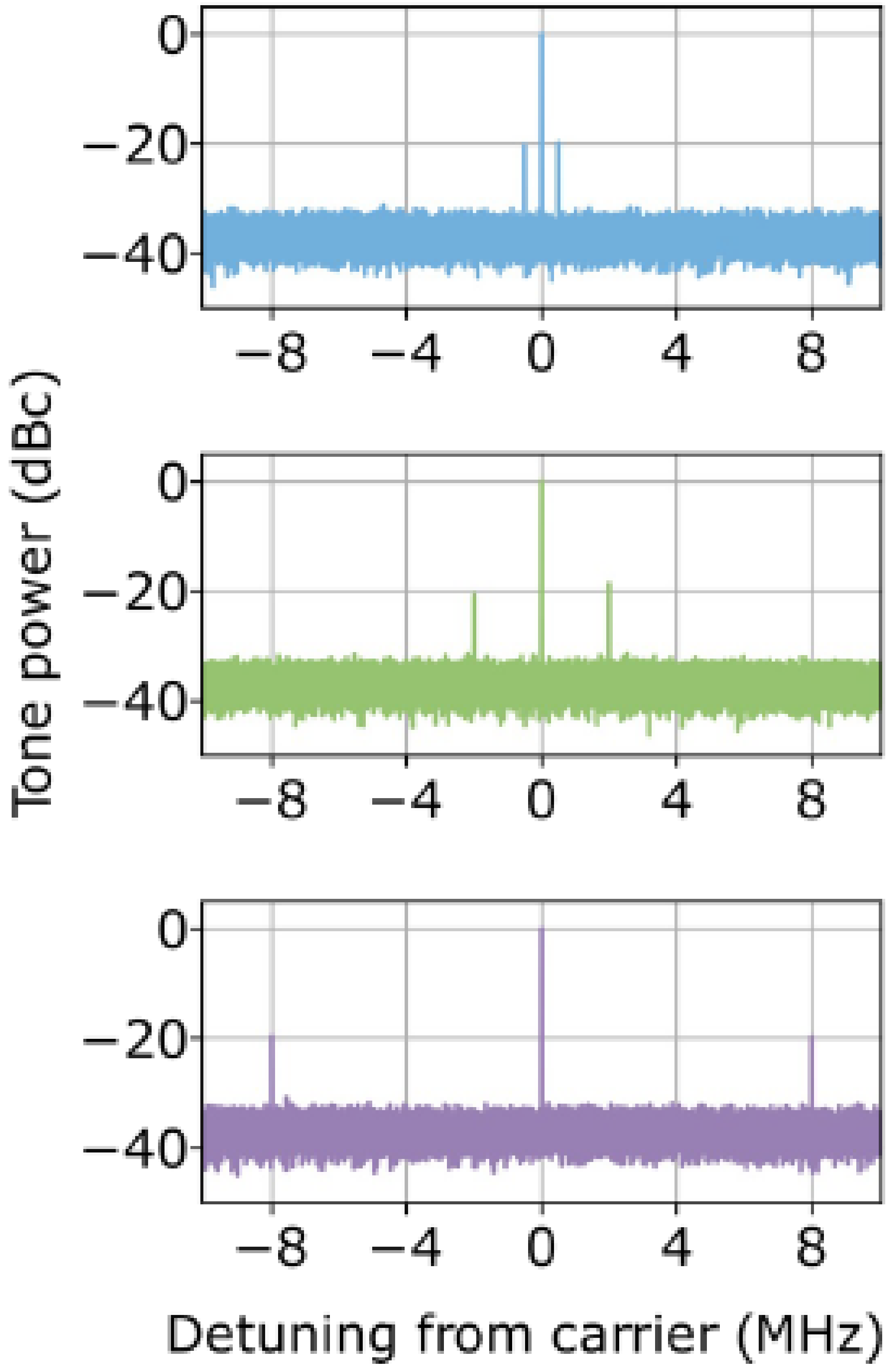
Inject low-f signal



Drive with microwave carrier

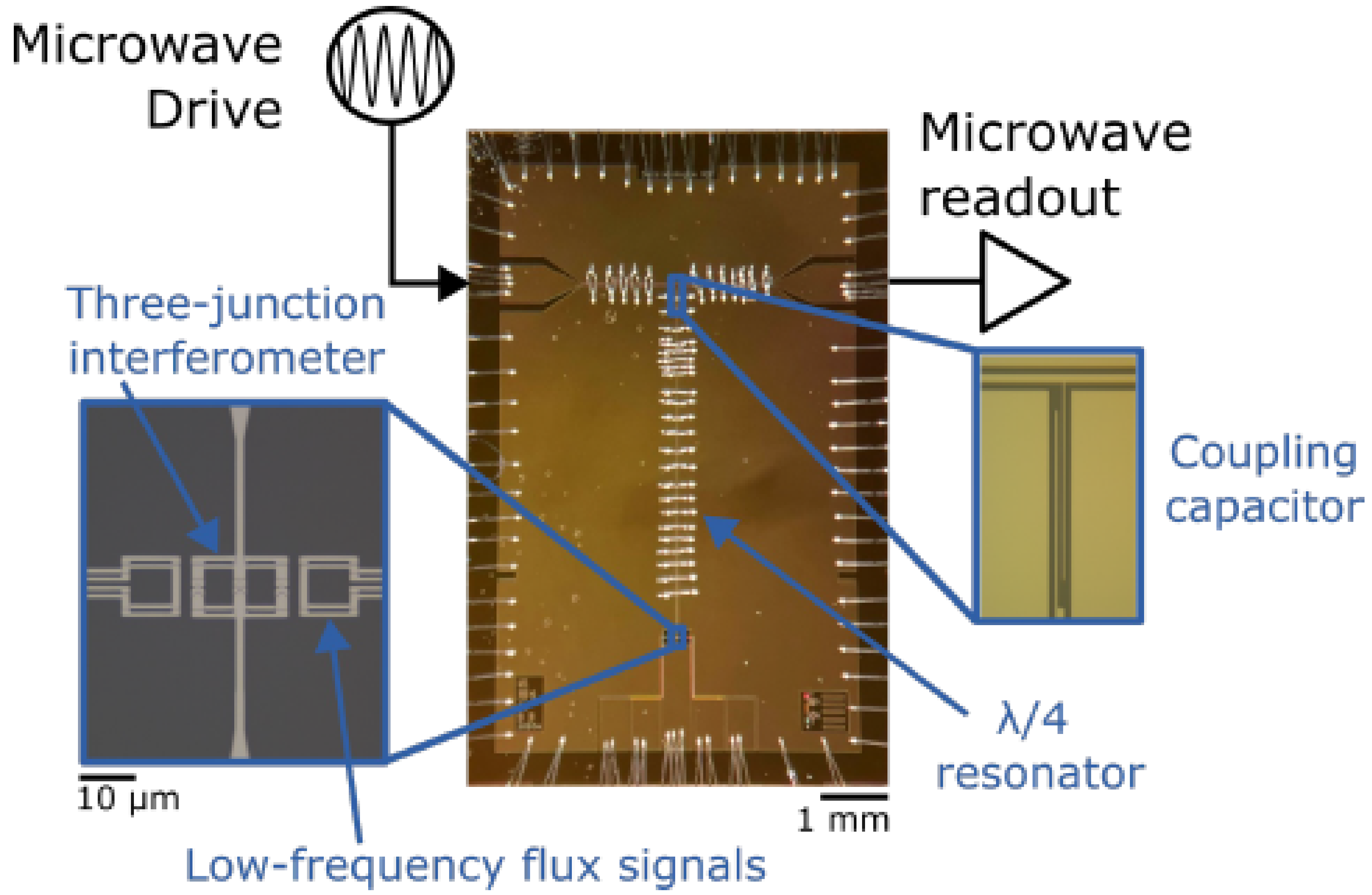


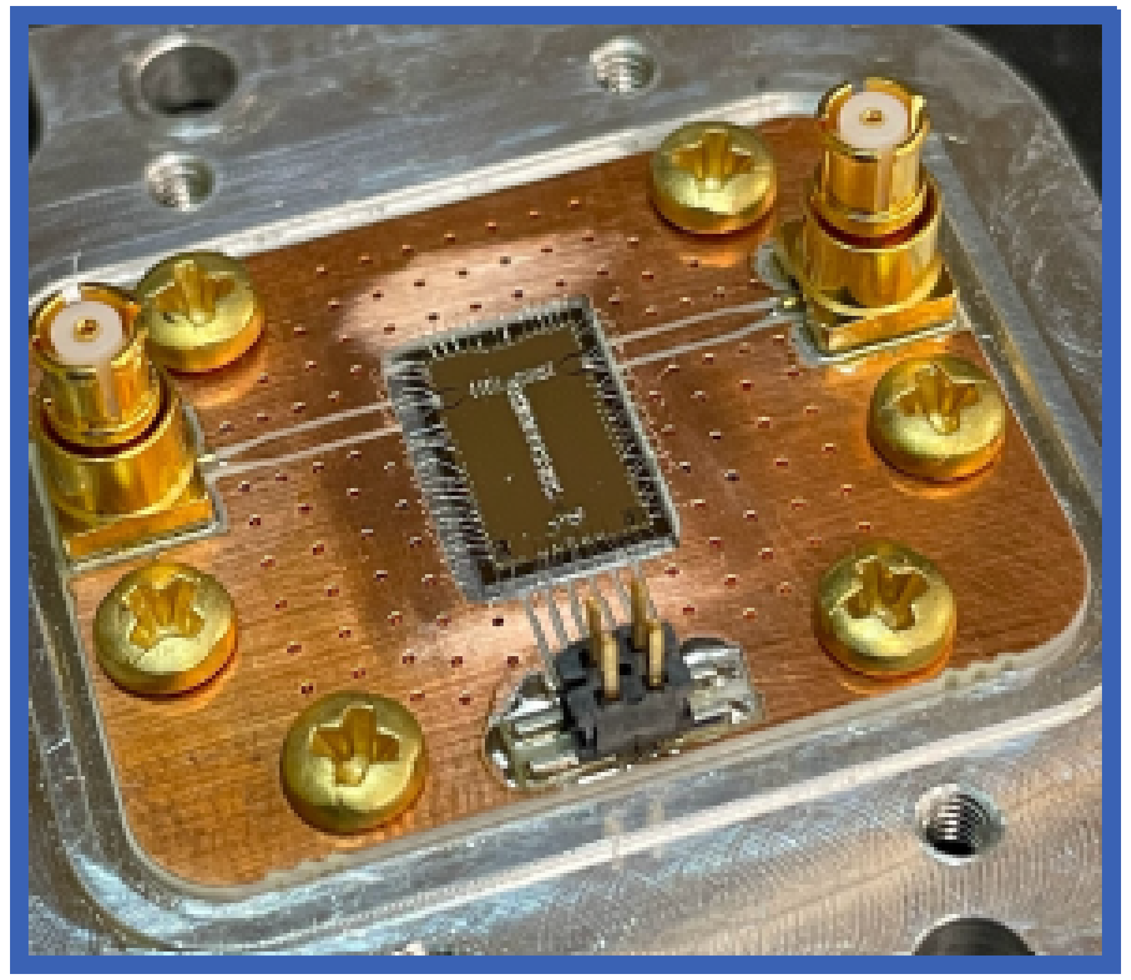
Sidebands carry low-f signal

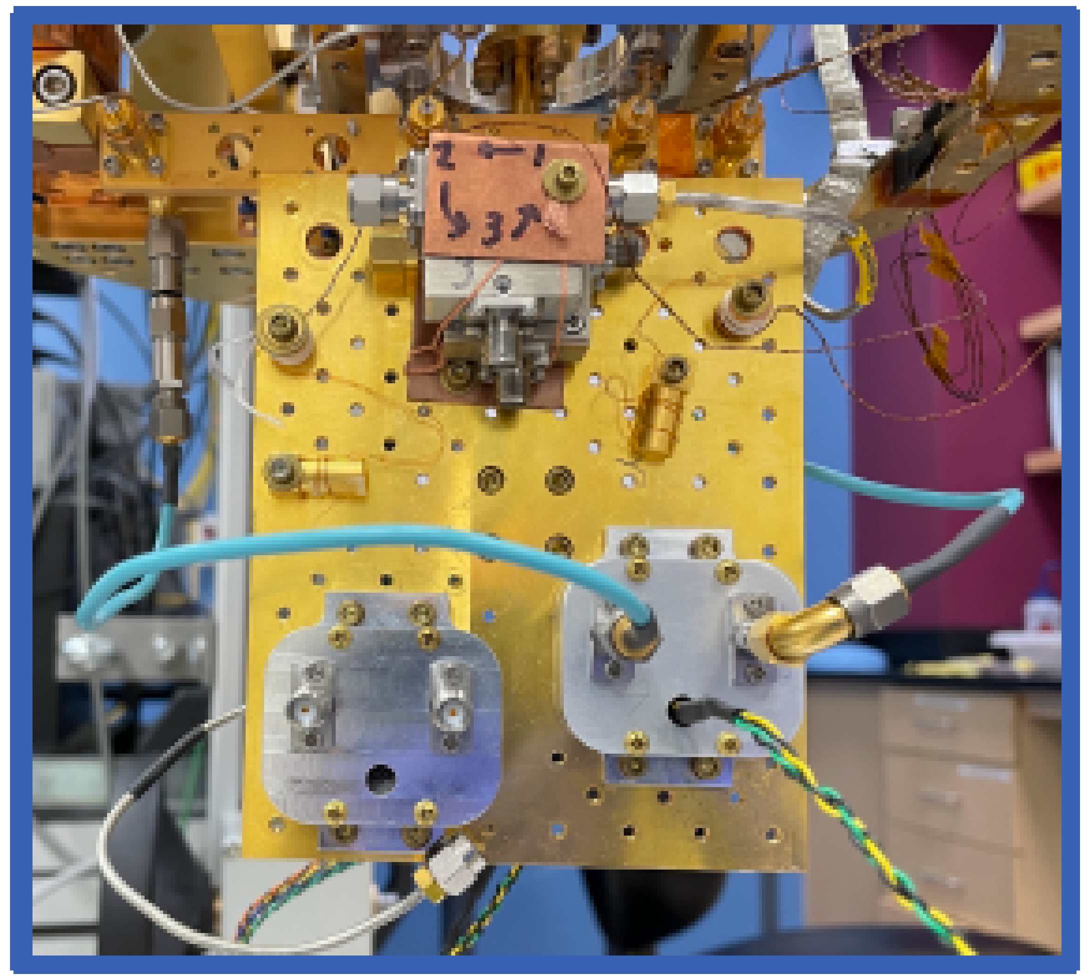


- Data illustrating upconversion in RQU
- The signal information is upconverted to symmetric sidebands on the microwave carrier tone.

RQU implementation







- Al-AlOx-Al on silicon substrate.
- Single deposition process using shadow evap.
- Symmetric 3-junction interferometer with larger central junction inductance.
- Single-turn flux signal input loops next to interferometer.
- Coplanar waveguide quarter-wave resonator.
- Capacitor couples the resonator to the transmission line.

arXiv:2210.05576

Demonstrated RQU phase-sensitive gain

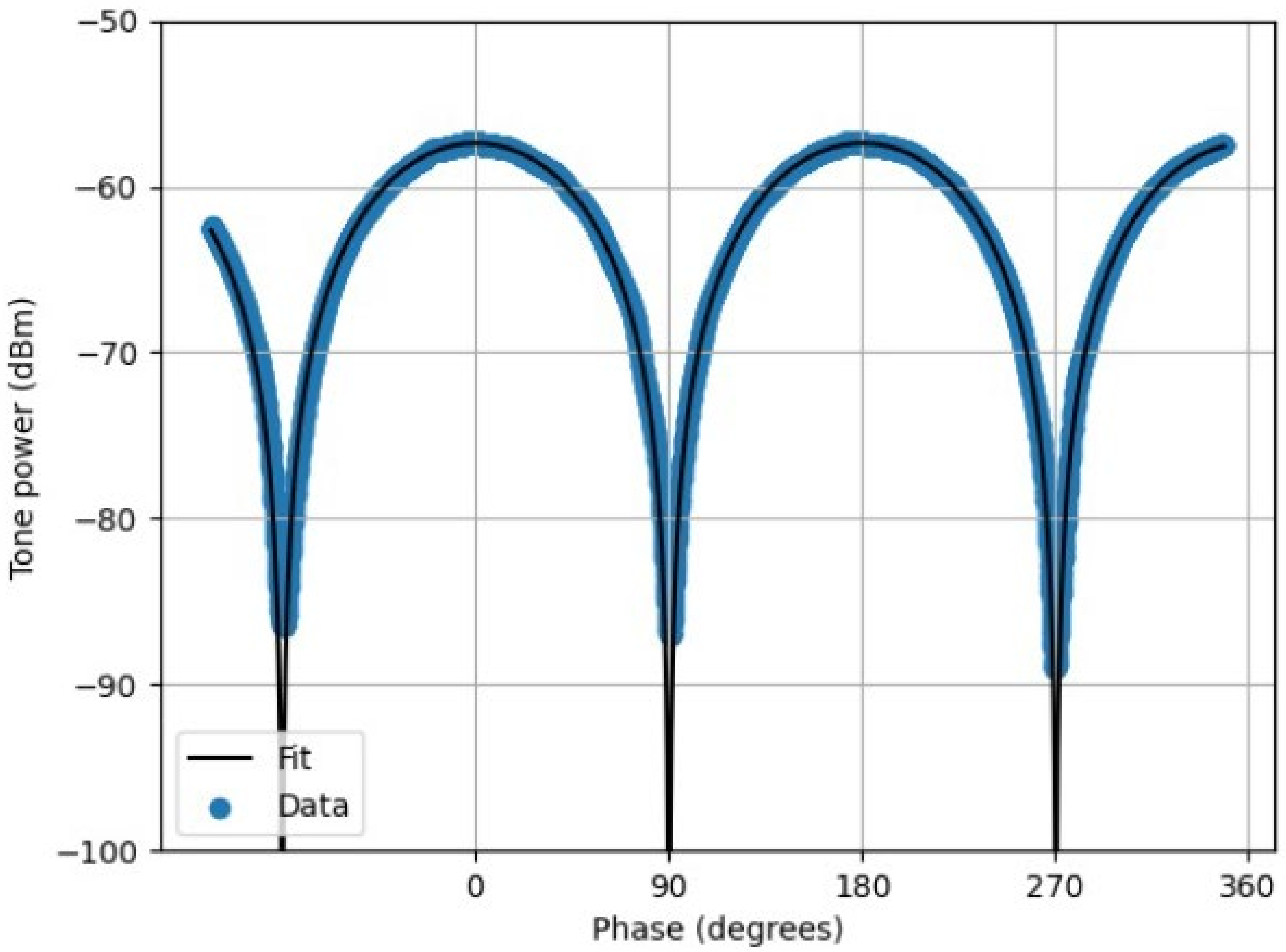
Input: 5 MHz flux signal into an RQU

Carrier: 5.26 GHz sinewave amplitude modulated at 5.26 GHz

Measure: output tone power as a function of phase shift between input sinewave and AM modulation

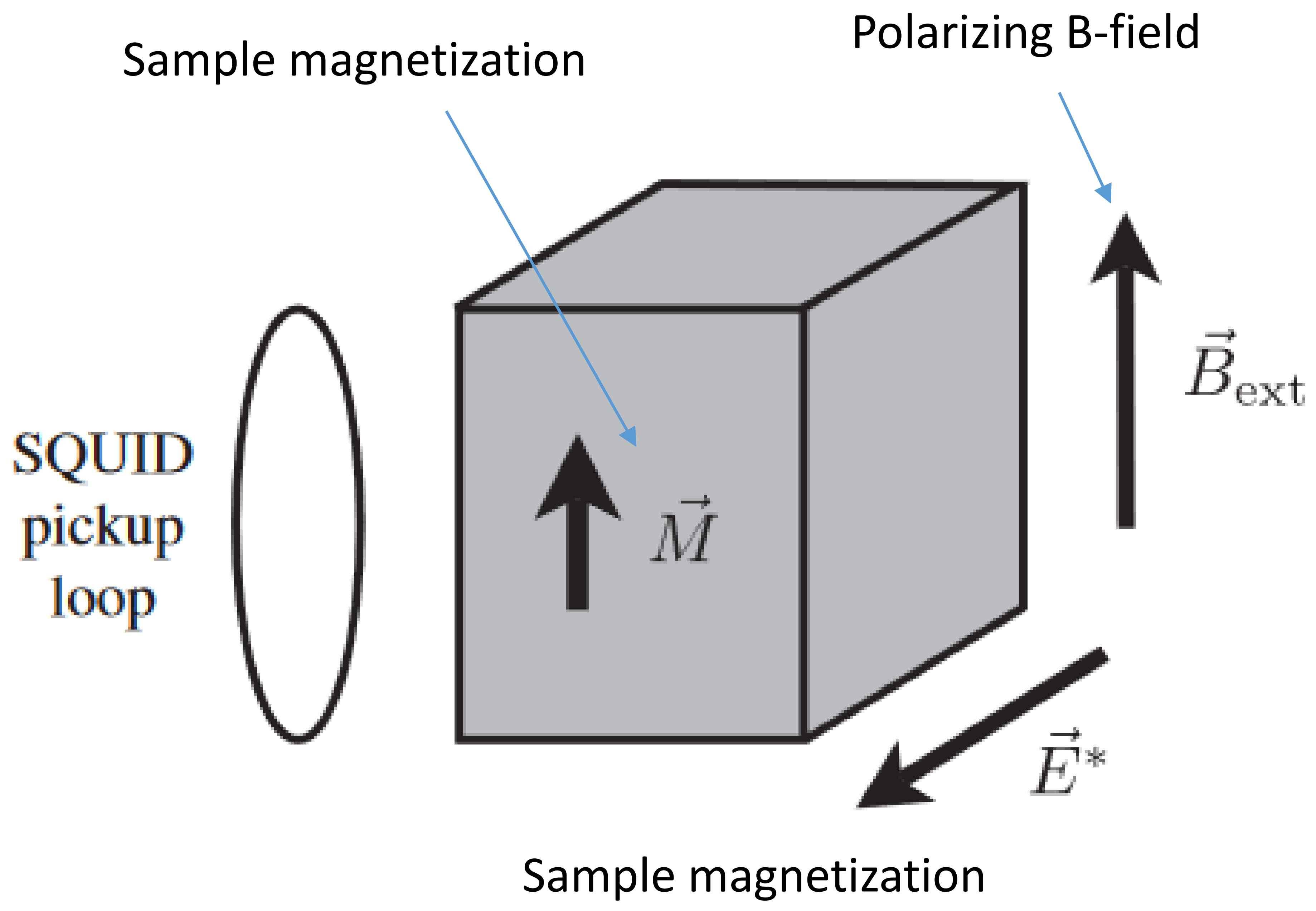
Extinction ratio: ratio of maximum gain to minimum gain:
> 50 dB

Phase sensitive gain: only measuring one quadrature, Heisenberg doesn't apply. Working towards full evasion of SQL



Searching for axions with NMR

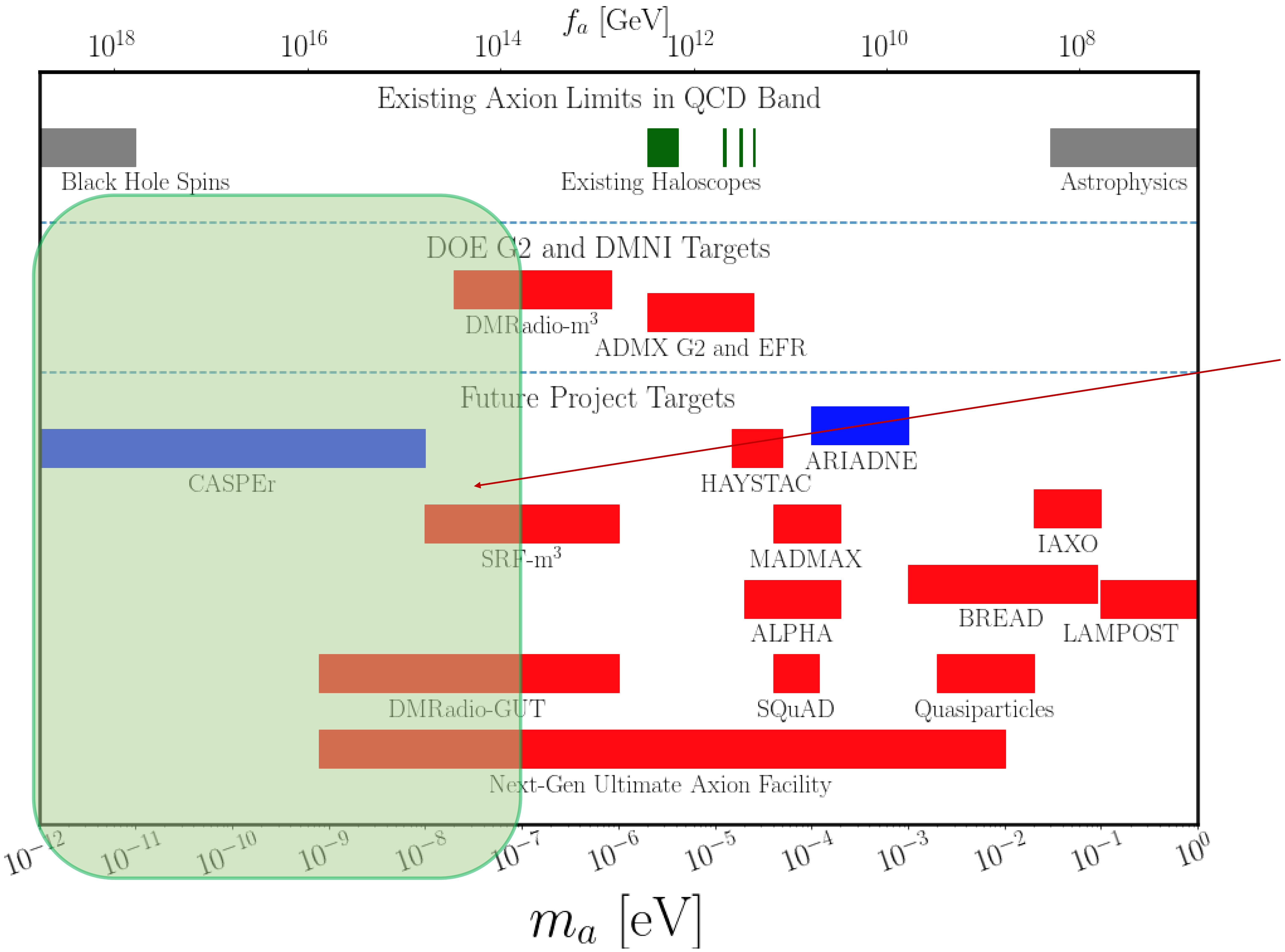
- Axions couple to nuclear spins through the strong force, inducing an effective nuclear electric dipole moment which oscillates at f_{ax}.
- A spin-polarized sample of nuclear spins will resonantly precess if f_{ax} matches their Larmor frequency.
- The precessing magnetization can be detected with a SQUID magnetometer or quantum sensor.



CASPEr-electric

Garcon, Antoine, et al. "The Cosmic Axion Spin Precession Experiment (CASPEr): a dark-matter search with nuclear magnetic resonance." *Quantum Science and Technology* 3.1 (2017): 014008.

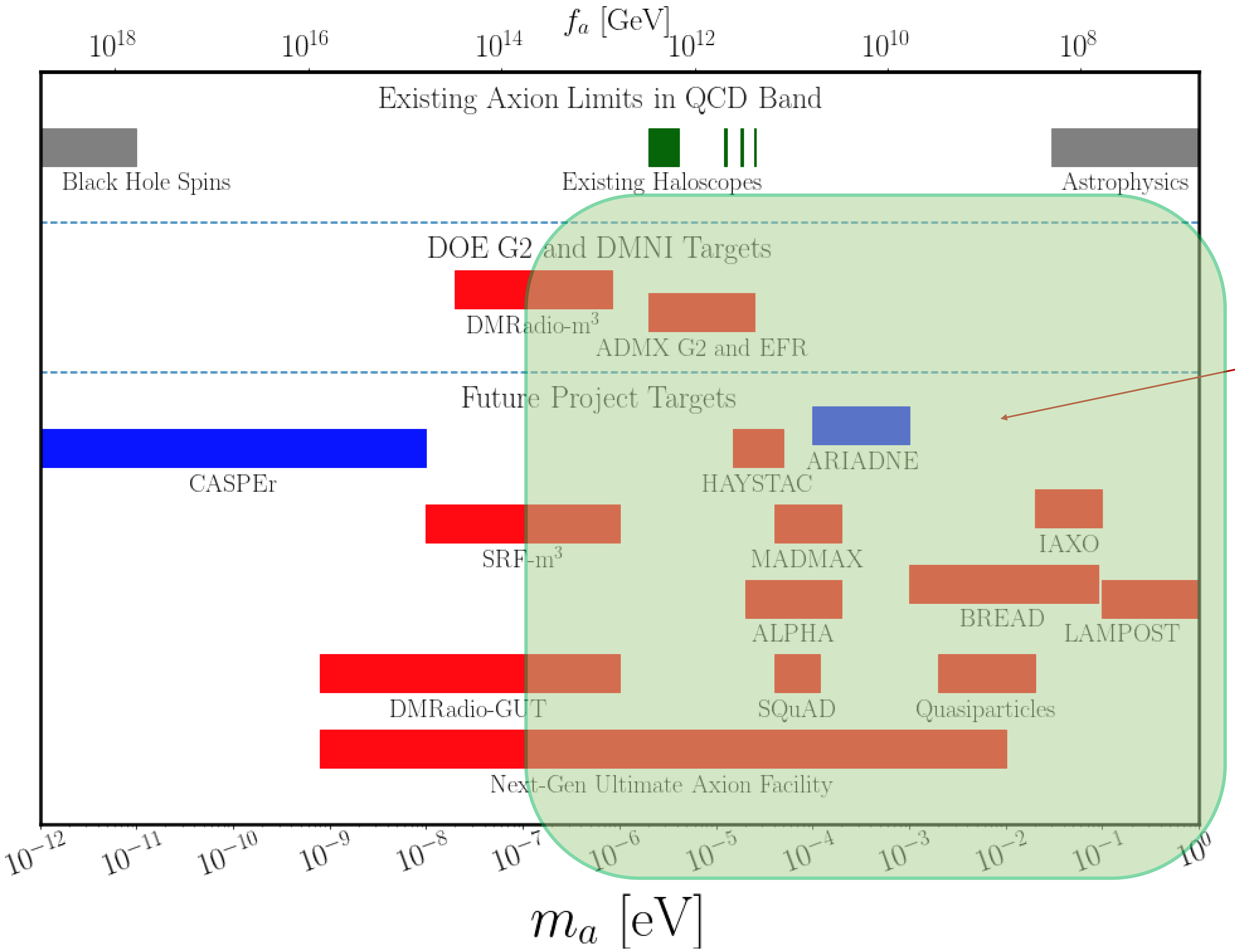
SNOWMASS: a comprehensive search for QCD axions



QCD axions here: measurement below the SQL to probe the best models

Figure 3 of Snowmass CF2 summary
https://snowmass21.org/_media/cosmic/repv1_cf2.pdf

SNOWMASS: a comprehensive search for QCD axions



QCD axions here: New quantum sensing modalities required to cover all frequency space efficiently

Figure 3 of Snowmass CF2 summary
https://snowmass21.org/_media/cosmic/repv1_cf2.pdf

Conclusions

New breakthroughs in QIS are driving a revolution in measurement for HEP.

- Workshop report: **Arxiv:2311.01930**
- Some HEP science goals provably require new quantum sensor technology
- Taking advantage of new quantum technology, the HEP community can fully search the QCD axion band over the next ~20 years
- Addressing the range of HEP science requires investment in a diverse portfolio of new quantum sensor technologies (photon detectors, atomic clocks, spins, superconducting qubits, Continuous variables quantum sensors ...)