Quantum Sensors for New Physics

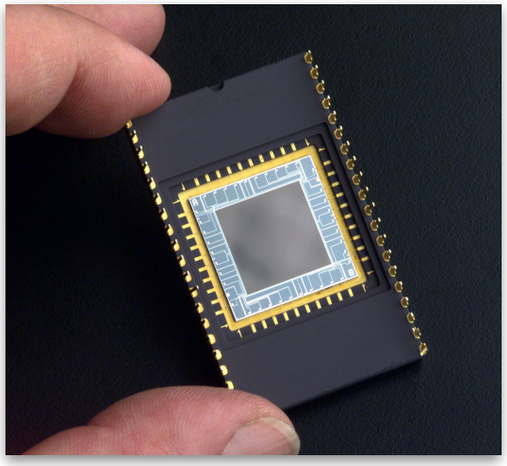
Asher Berlin - Fermilab

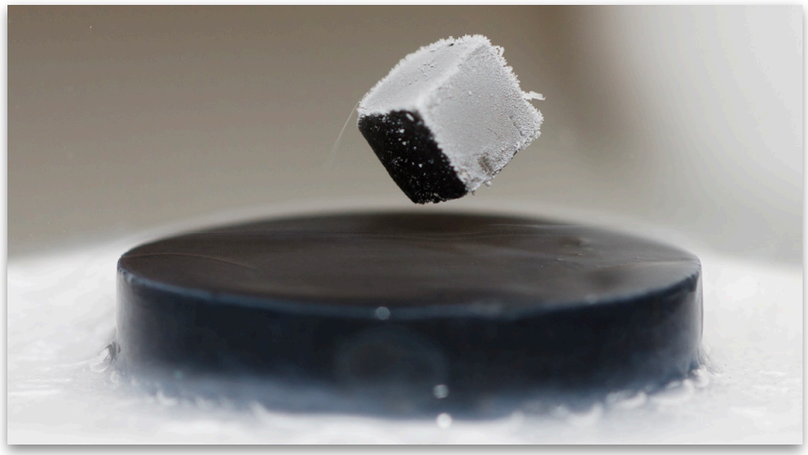
Seattle Snowmass Summer Meeting
July 23, 2022

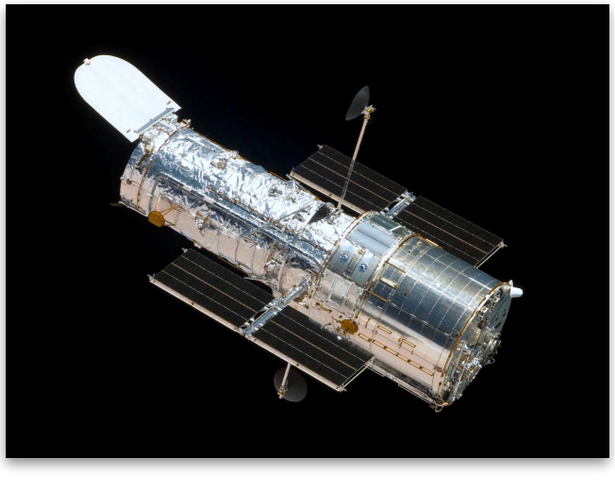
See also:
arXiv:2203.10089, arXiv:2203.14923
arXiv:2203.14915, arXiv:2203.07250
arXiv:2203.11846, arXiv:2203.09488
arXiv:2203.12714, ...

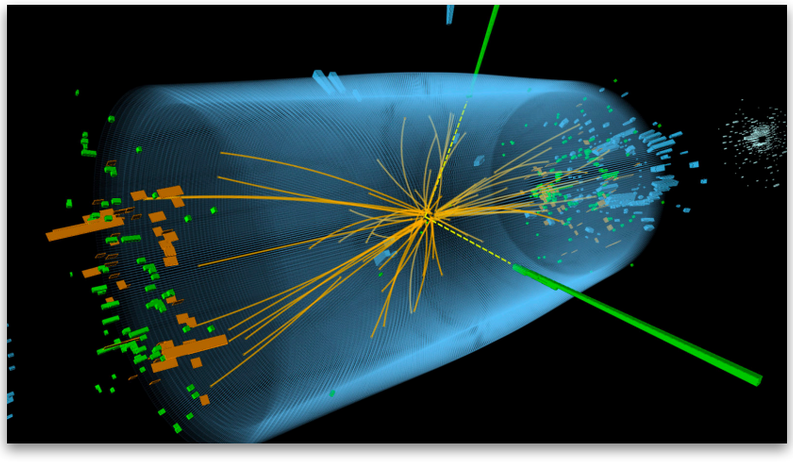
Technology and Fundamental Physics

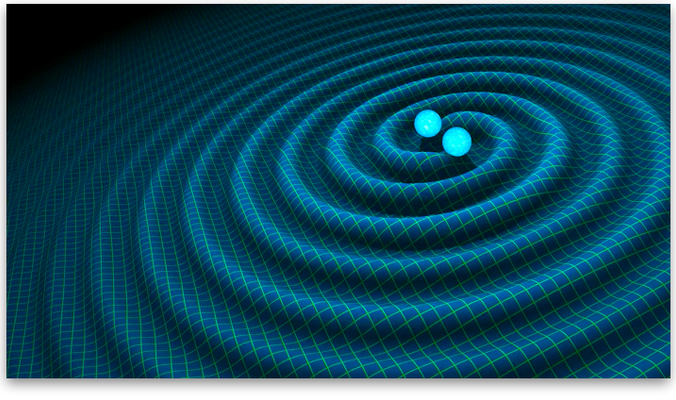
New technology opens windows into new physics.











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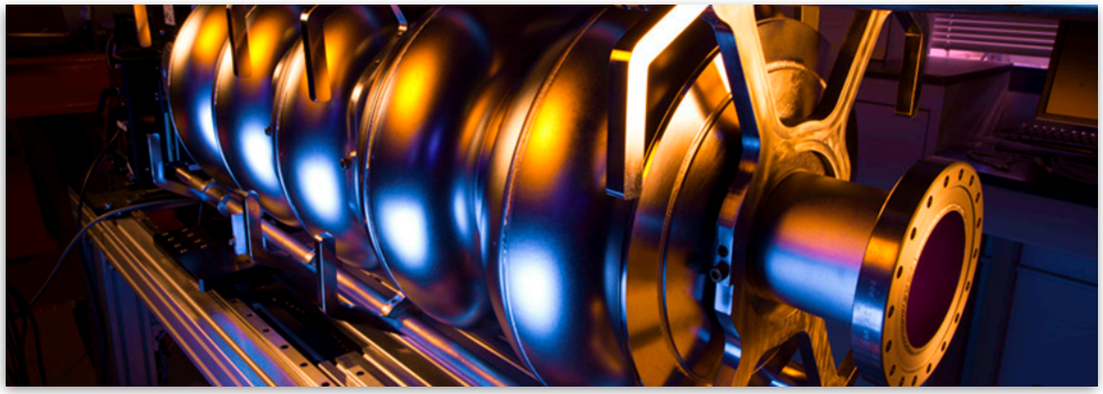
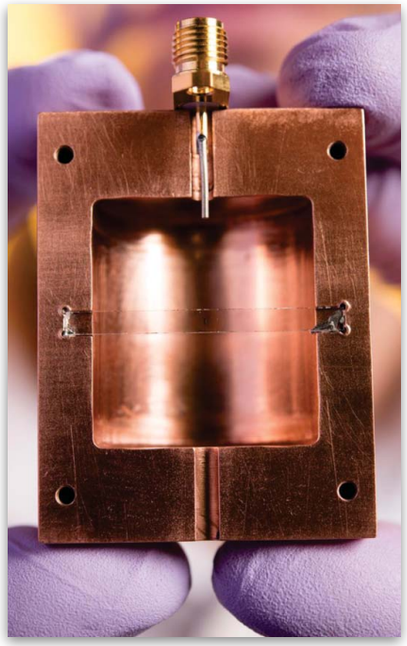




There is an opportunity to explore new physics
at previously inaccessible scales with developing technology.

How can developments in quantum sensing be steered
to make the biggest impact on fundamental physics?

What is the nature of dark matter?

What Have We Learned?

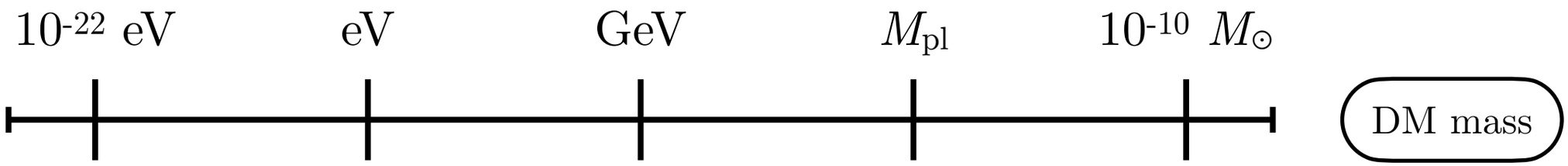
dark matter resides in galaxies (including our own)

velocity: $v_{\rm DM} \sim 100$ km/s $\sim 10^{-3}\ c$

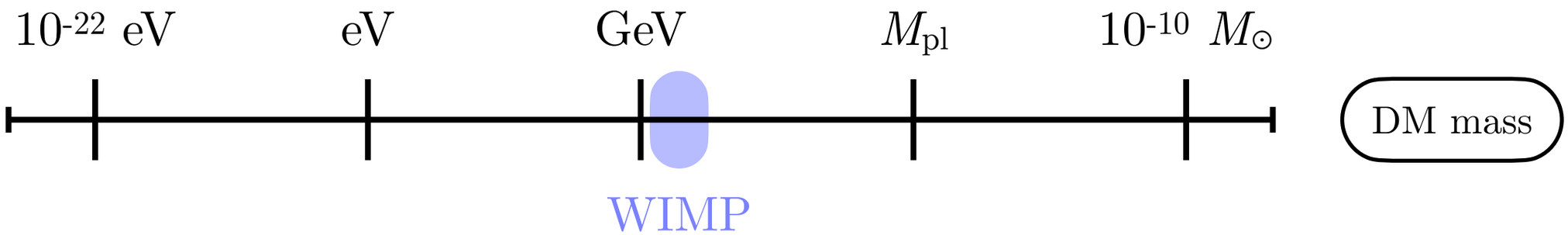
mass density: $m_{\rm DM}\, n_{\rm DM} \sim$ GeV/cm^3

Few heavy particles or many light particles?
What is the dark matter mass?

What Have We Learned?

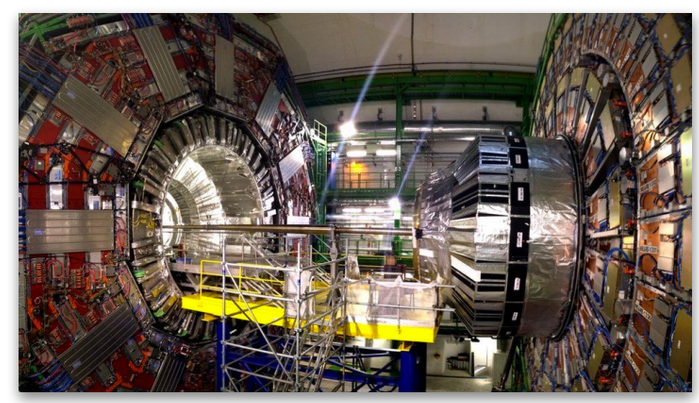


What Have We Learned?



The search for WIMPs has been an incredible success.

What now?



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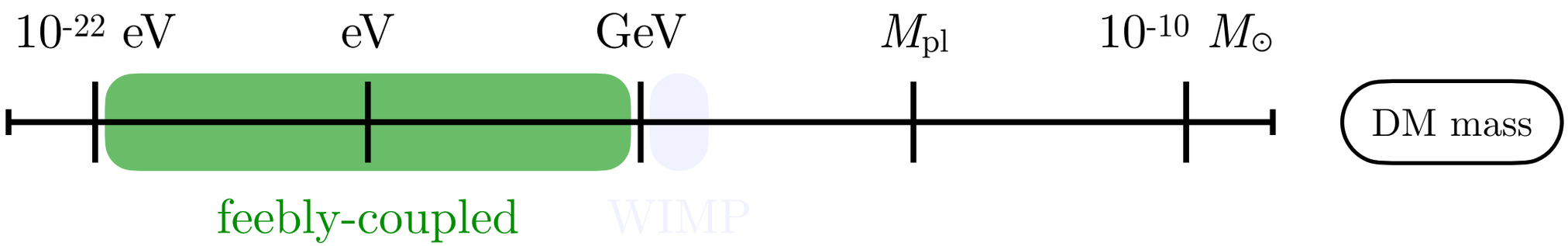


<u>quantum/precision detectors</u>

Quiet and coherent enough to build up a detectable signal.

We can now explore a wide range of previously inaccessible scales.

Maybe the dark matter and hierarchy problem are not solved together.

↓

If so, the space of motivated signals is dramatically enlarged.

↓

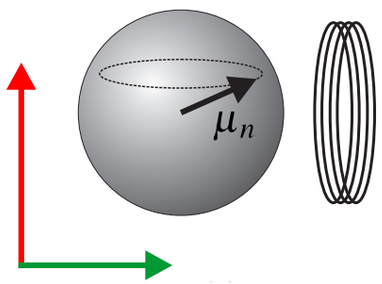
This motivates a strong diversification of the experimental program.

Going Further

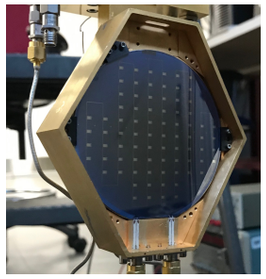
QIS for BSM physics

a ~~single catch-all experiment~~ → multitude of bang-for-buck experiments

NMR

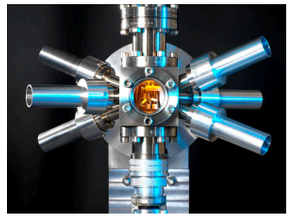


KIDs



SRF cavities

atomic clocks/interferometers



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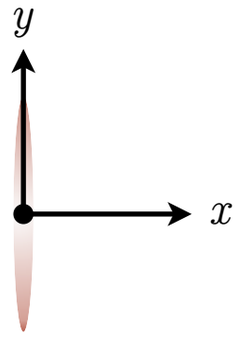
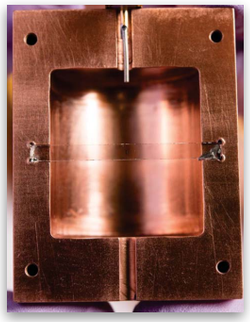
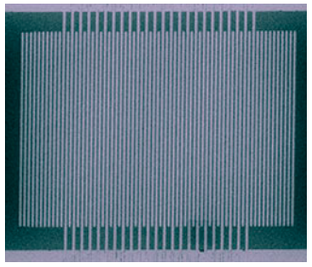


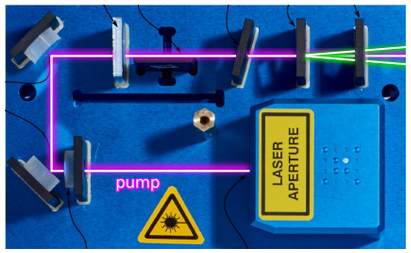
SC qubit



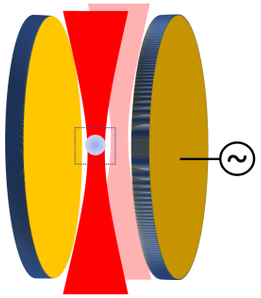
SNSPDs



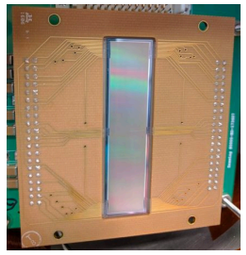
nonlinear optics



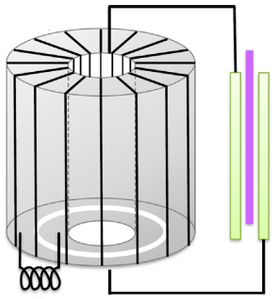
optically levitated dielectrics



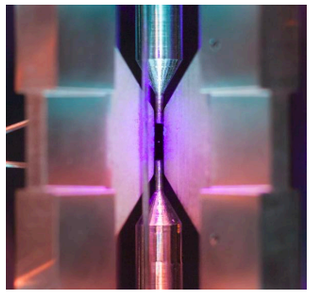
skipper CCDs



LC circuits



ion traps



+... many more

See also:
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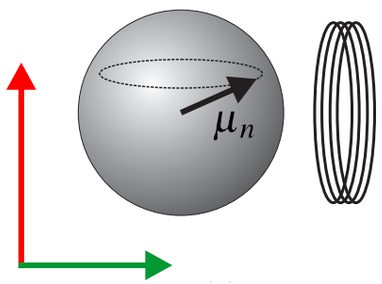

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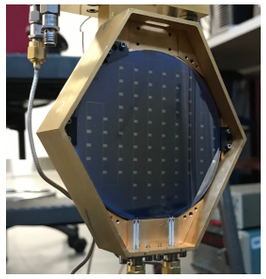

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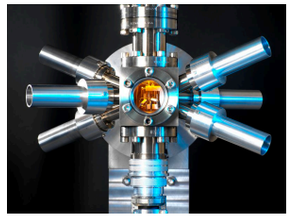

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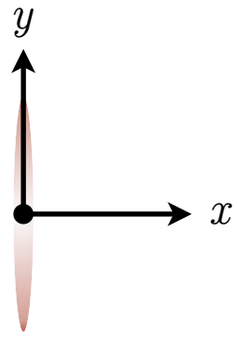

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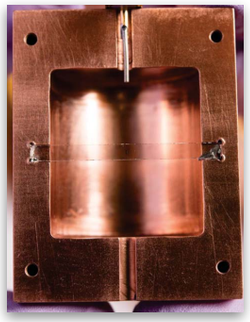

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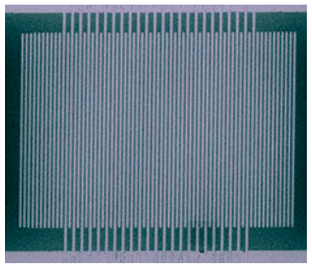

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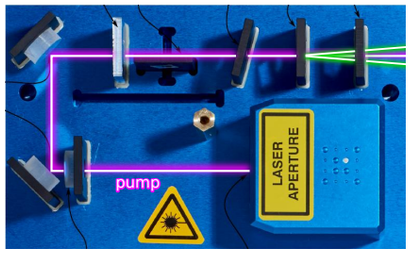

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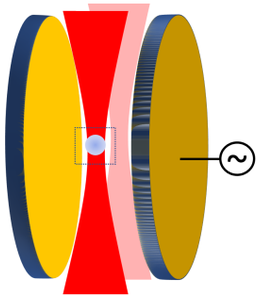

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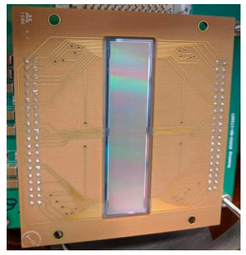

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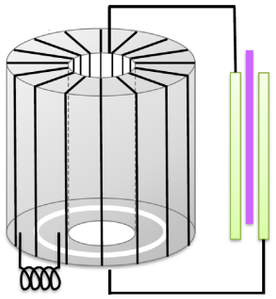

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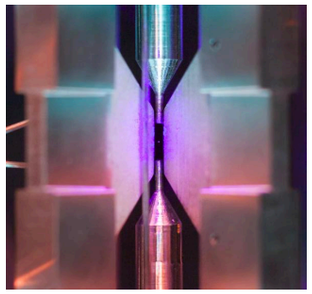

What is the role of a theorist?

Creative repurposing of existing detectors.

Motivating/conceiving/designing new small-scale experiments.

This is especially crucial in emerging fields.

see arXiv:2203.10089

Outline

Quantum Manipulation

I.

atomic clocks
atomic interferometers
< SQL for axions
ion traps, ...

Detecting Individual Quanta

II.

skipper CCDs
supercond. nanowires
supercond. qubits, ...

Supercond. RF cavities

III.

axions
dark photons
photon mass
millicharged particles
gravitational waves, ...

**some of these boundaries are blurry*

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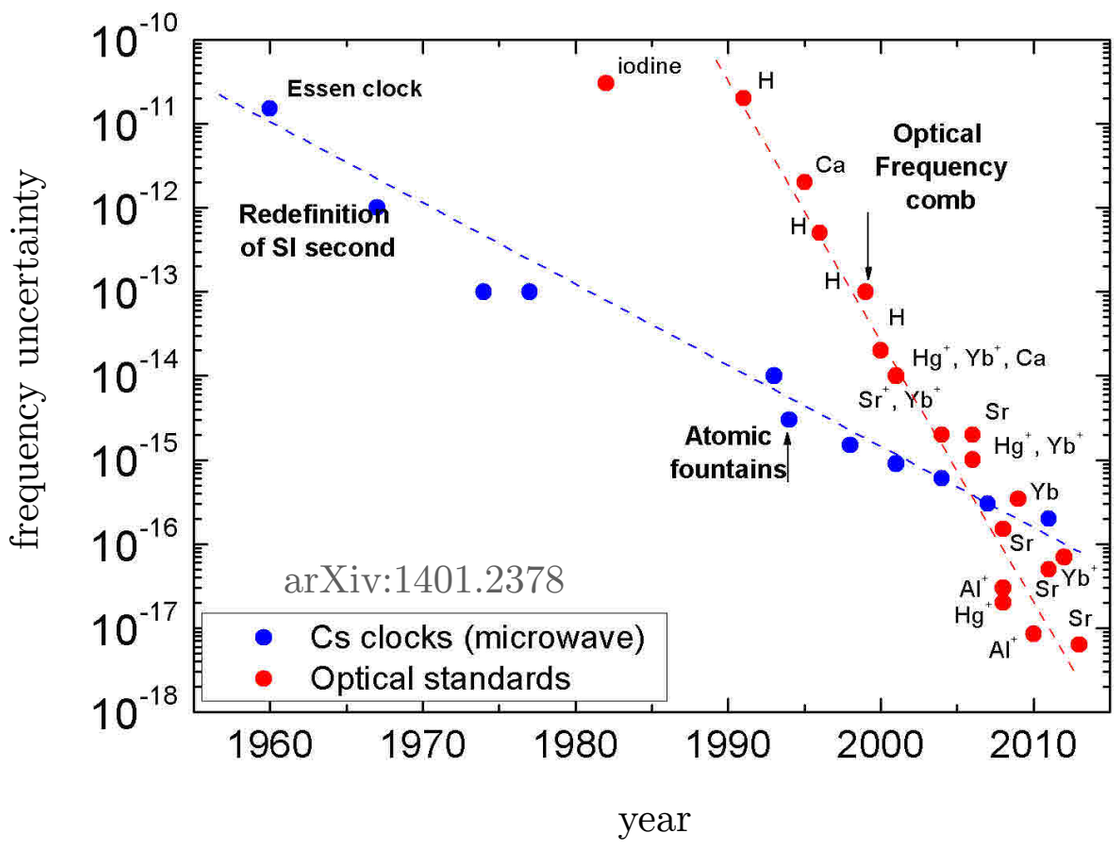
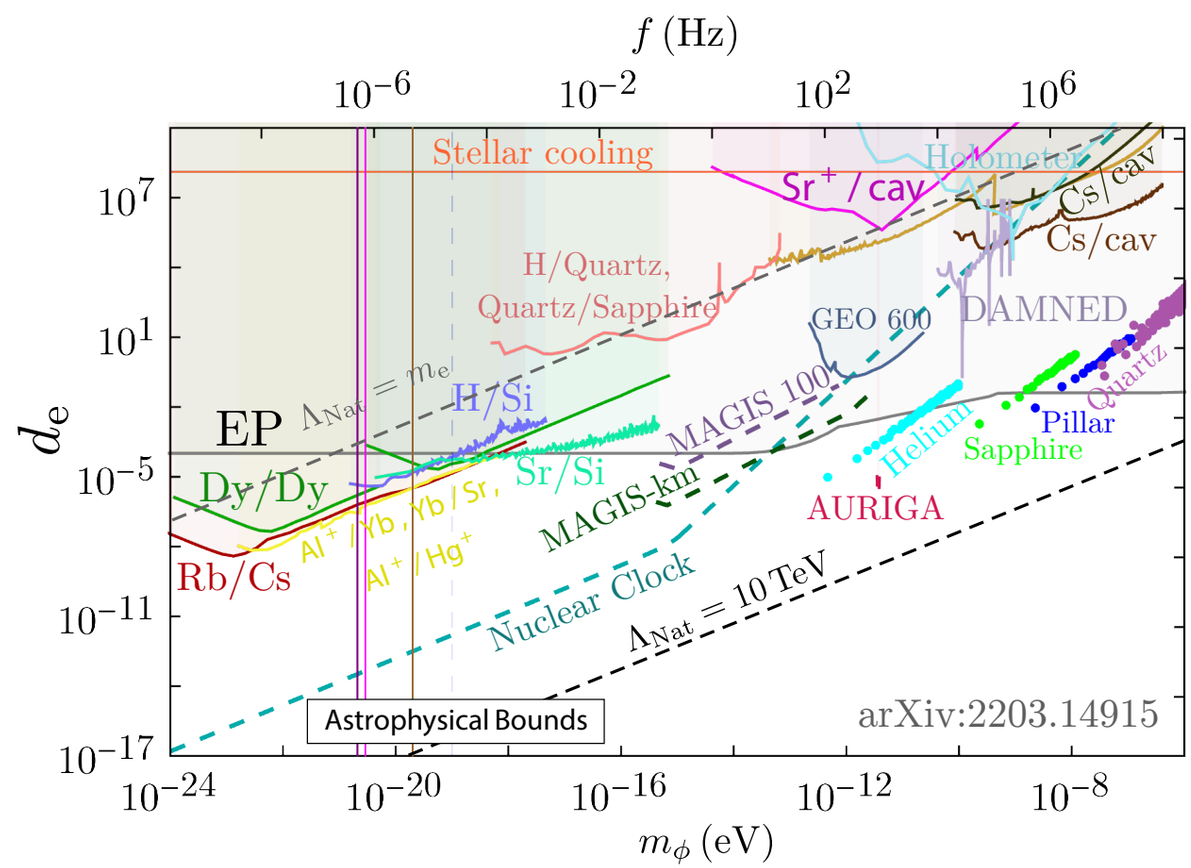
I. Quantum Manipulation

Atomic Clocks

oscillation of fundamental constants

$$\mathscr{L} \sim \frac{\phi}{M_{\rm pl}}\left(d_e\, F_{\mu\nu}F^{\mu\nu} + d_{m_e}\, m_e\, \bar{e}e\right)$$



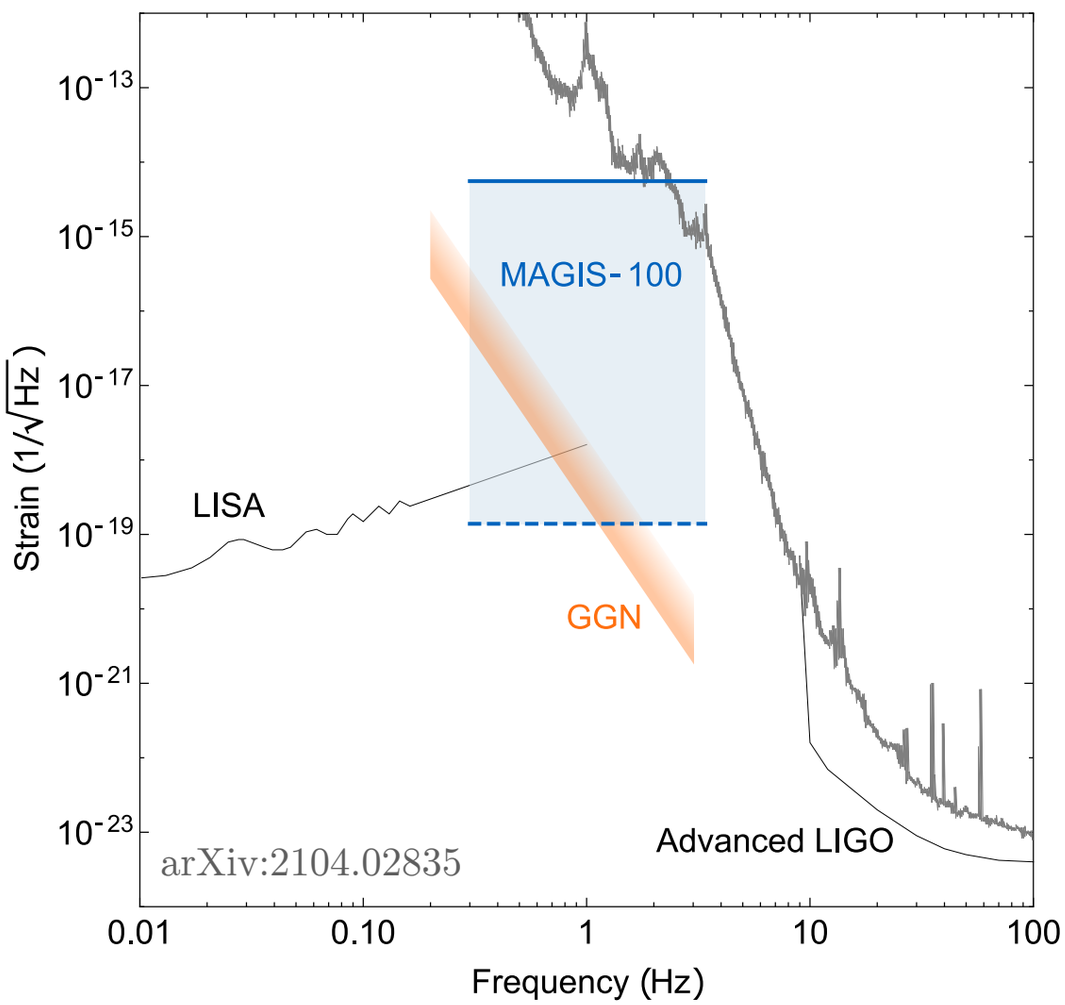


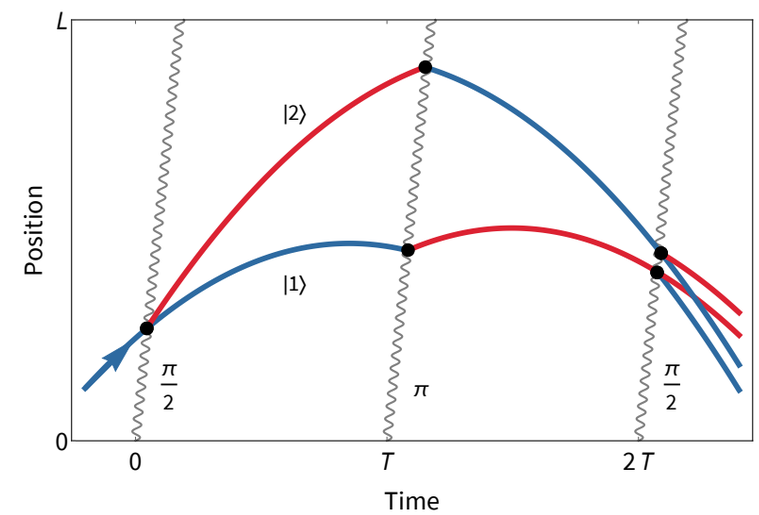
future

- improvement of existing clocks
- nuclear clocks, molecular clocks
- quantum-entangled clocks, < SQL

Atomic Interferometers

+ gravitational waves





future

- MAGIS-100 at Fermilab
- MAGIS-km, space-based, ...

Role of Theorists

Hunting for topological dark matter with atomic clocks

A. Derevianko[1] and M. Pospelov[2,3]
[1] *Department of Physics, University of Nevada, Reno, Nevada 89557, USA*
[2] *Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia V8P 1A1, Canada*
[3] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2J 2W9, Canada*

Searching for dilaton dark matter with atomic clocks

Asimina Arvanitaki*
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada

Junwu Huang† and Ken Van Tilburg‡
Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, CA 94305, USA
(Dated: February 3, 2015)

Searching for dark matter and variation of fundamental constants with laser and maser interferometry

Y. V. Stadnik* and V. V. Flambaum†
School of Physics, University of New South Wales, Sydney 2052, Australia
(Dated: March 24, 2015)

Testing General Relativity with Atom Interferometry

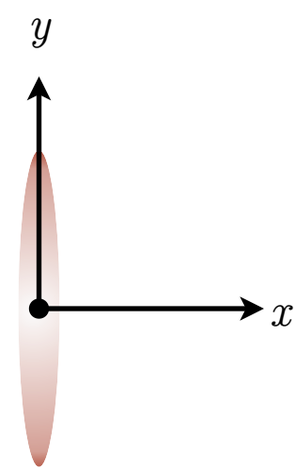
Savas Dimopoulos, Peter W. Graham, Jason M. Hogan, and Mark A. Kasevich
Department of Physics, Stanford University, Stanford, California 94305
(Dated: February 6, 2008)

Gravitational Wave Detection with Atom Interferometry

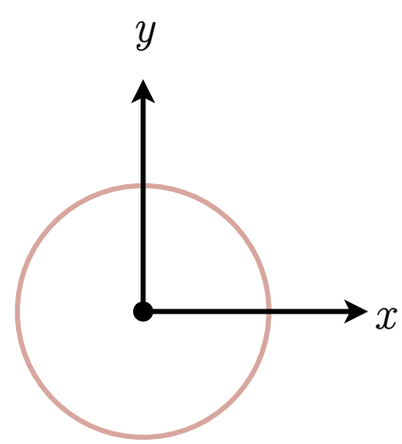
Savas Dimopoulos,[1] Peter W. Graham,[2,1] Jason M. Hogan,[1] Mark A. Kasevich,[1] and Surjeet Rajendran[2,1]
[1] *Department of Physics, Stanford University, Stanford, California 94305*
[2] *SLAC, Stanford University, Menlo Park, California 94025*
(Dated: October 22, 2018)

Beyond the Standard Quantum Limit

$<$ SQL



measure x not y



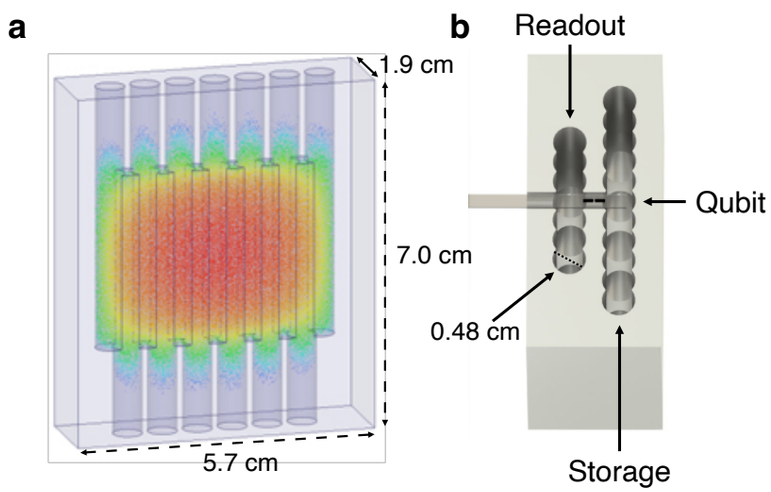
measure amplitude not phase

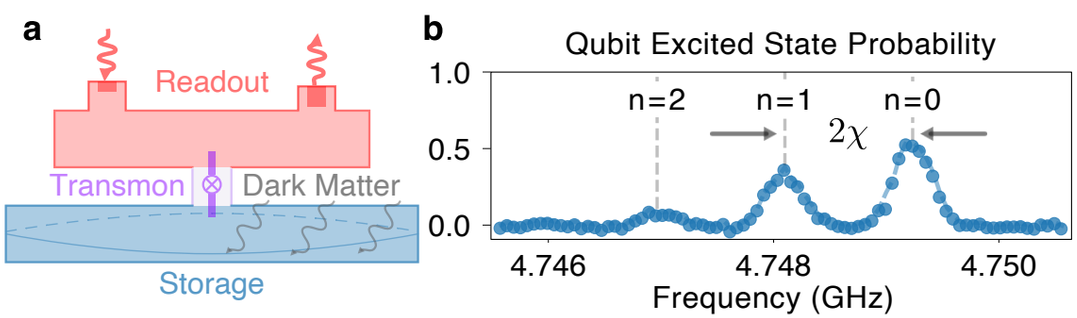
Beyond the Standard Quantum Limit

Axion Dark Matter Detection

superconducting qubits

arXiv:2008.12231

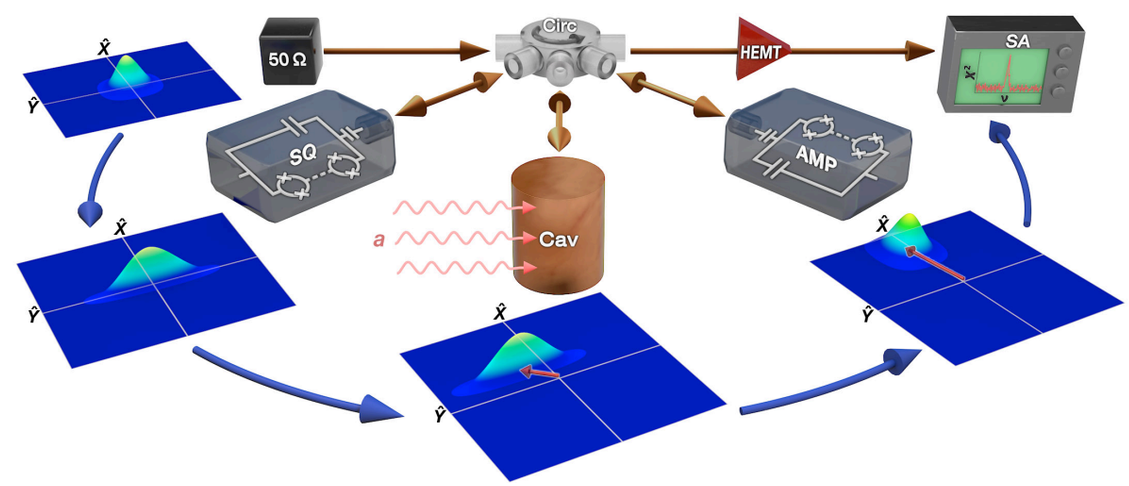




non-destructive photon counting
(search rate × 10^3)

HAYSTAC

arXiv:2008.01853



vacuum squeezing
(search rate × 2)

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axions
dark photons
photon mass
millicharged particles
gravitational waves, ...

II. Detecting Individual Quanta

Detecting Individual Quanta

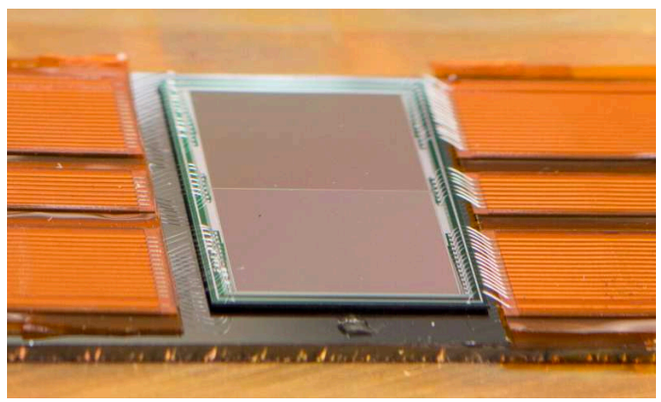
low-energy quanta, low dark counts

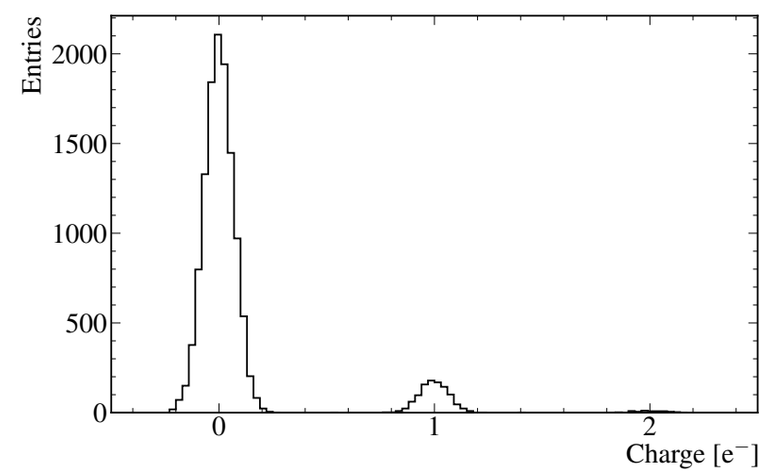
skipper CCDs, SENSEI

arXiv:1706.00028

$E_{\rm th} \sim 1$ eV

non-destructive repeated charge counting, dark count < 10^{-3} e/pix/day





Single-electron and single-photon sensitivity with a silicon Skipper CCD

Javier Tiffenberg,[1,*] Miguel Sofo-Haro,[2,1] Alex Drlica-Wagner,[1] Rouven Essig,[3]
Yann Guardincerri,[1,†] Steve Holland,[4] Tomer Volansky,[5] and Tien-Tien Yu[6]

[1] *Fermi National Accelerator Laboratory, PO Box 500, Batavia IL, 60510*
[2] *Centro Atómico Bariloche, CNEA/CONICET/IB, Bariloche, Argentina*
[3] *C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, NY 11794*
[4] *Lawrence Berkeley National Laboratory, One Cyclotron Rd, Berkeley, CA 94720*
[5] *Raymond and Beverly Sackler School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv 69978, Israel*
[6] *Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland*

(Dated: June 2, 2017)

Detecting Individual Quanta

low-energy quanta, low dark counts

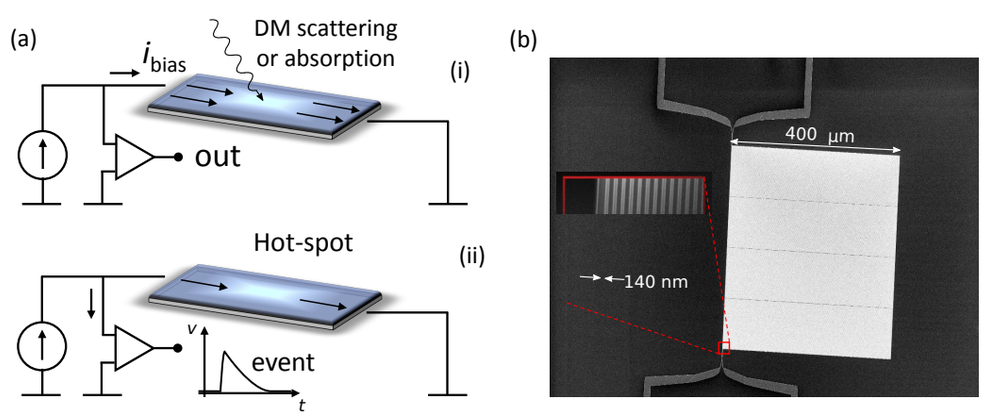
superconducting nanowires

MeV-scale dark matter scattering

arXiv:1903.05101

Detecting Dark Matter with Superconducting Nanowires

Yonit Hochberg[1],* Ilya Charaev[2],† Sae-Woo Nam[3],‡ Varun Verma[3],§ Marco Colangelo[2],¶ and Karl K. Berggren[2]**
[1]*Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem 91904, Israel*
[2]*Massachusetts Institute of Technology, Department of Electrical Engineering and Computer Science, Cambridge, MA, USA and*
[3]*National Institute of Standards and Technology, Boulder, CO, USA*

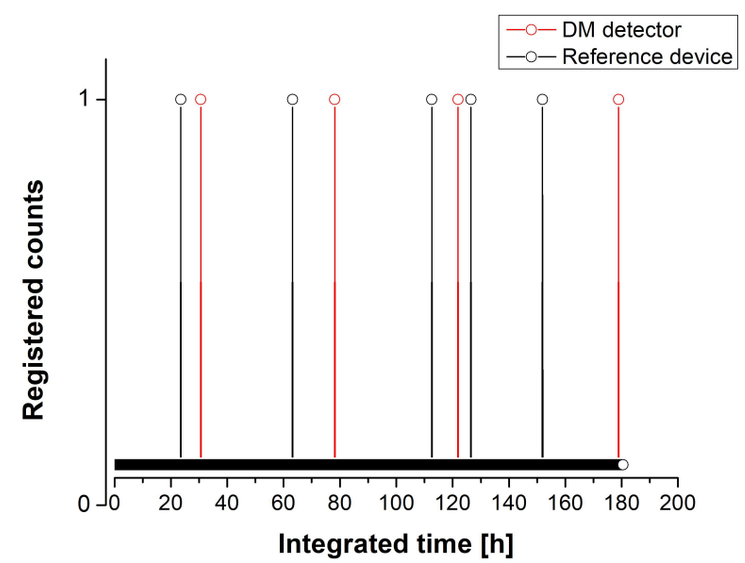


LAMPOST (axions)

arXiv:2110.01582

New Constraints on Dark Photon Dark Matter with Superconducting Nanowire Detectors in an Optical Haloscope

Jeff Chiles,[1,*] Ilya Charaev,[2,3,*] Robert Lasenby,[4] Masha Baryakhtar,[5] Junwu Huang,[6] Alexana Roshko,[1] George Burton,[1] Marco Colangelo,[2] Ken Van Tilburg,[7,8] Asimina Arvanitaki,[6] Sae Woo Nam,[1] and Karl K. Berggren[2]



$E_{\rm th} \sim 1$ eV

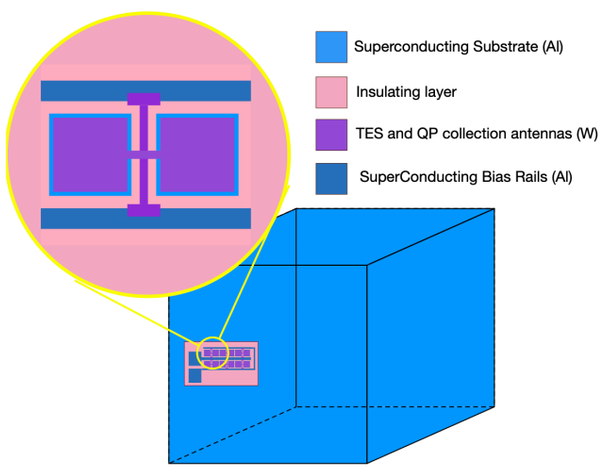
infrared/optical photon counting, dark count ~1 per day

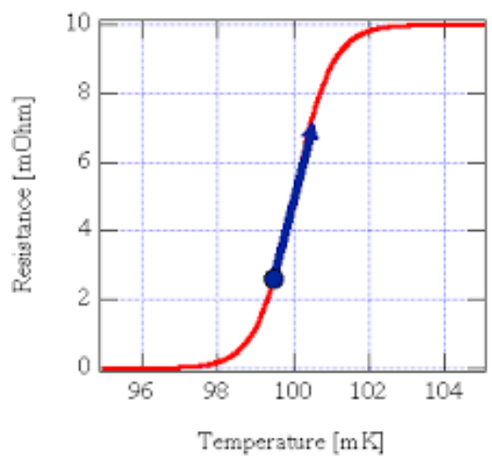
Detecting Individual Quanta

Future Developments

Single-Phonon Detectors

arXiv:1512.04533



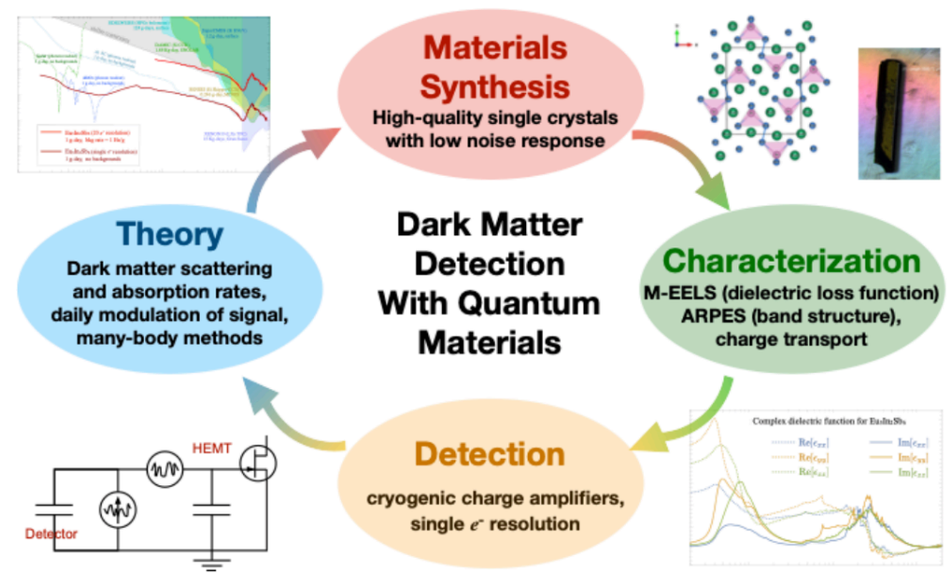


Transition-edge sensor:

(single optical phonons, $E_{\rm th} \sim 50$ meV)

Exotic Narrow-Gap Semiconductors

SPLENDOR collaboration



arXiv:2203.08297

Outline

Developing even a single technology opens up a versatile array of new physics opportunities.

Quantum Manipulation

I.

atomic clocks
atomic interferometers
< SQL for axions
ion traps, ...

Detecting Individual Quanta

II.

skipper CCDs
supercond. nanowires
supercond. qubits, ...

Supercond. RF cavities

III.

axions
dark photons
photon mass
millicharged particles
gravitational waves, ...

III. SRF Cavities

SRF Cavities

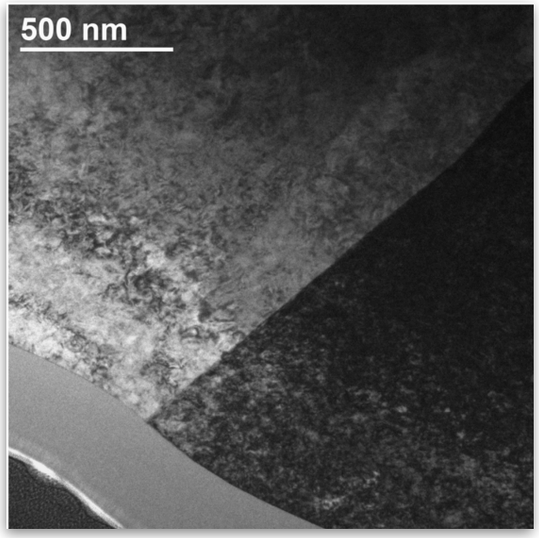
Why superconducting RF cavities?

1. most efficient engineered oscillators
$Q \sim 10^{12}$
long coherence for quantum computation

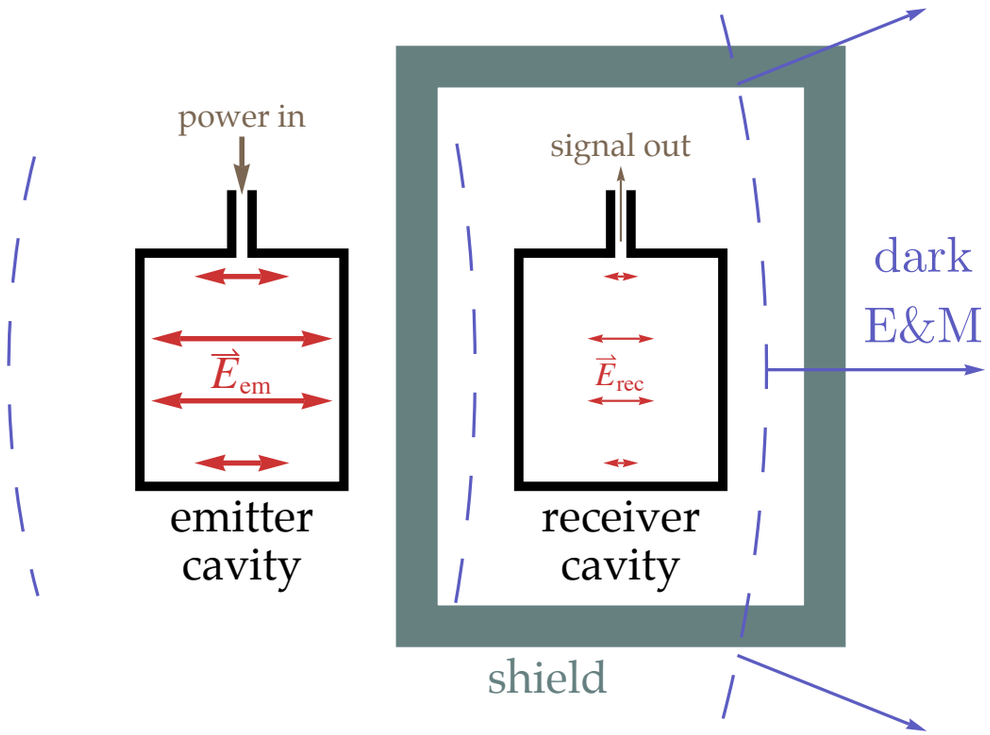
2. large oscillating fields
(0.2 T, ~GHz)

3. precisely manufactured and operated
(nm-precision)

4. already used for new physics searches
(experimentalists)



SRF Cavities



("light-shining-through-wall")

DarkSRF (Fermilab)

A Parametrically Enhanced Hidden Photon Search

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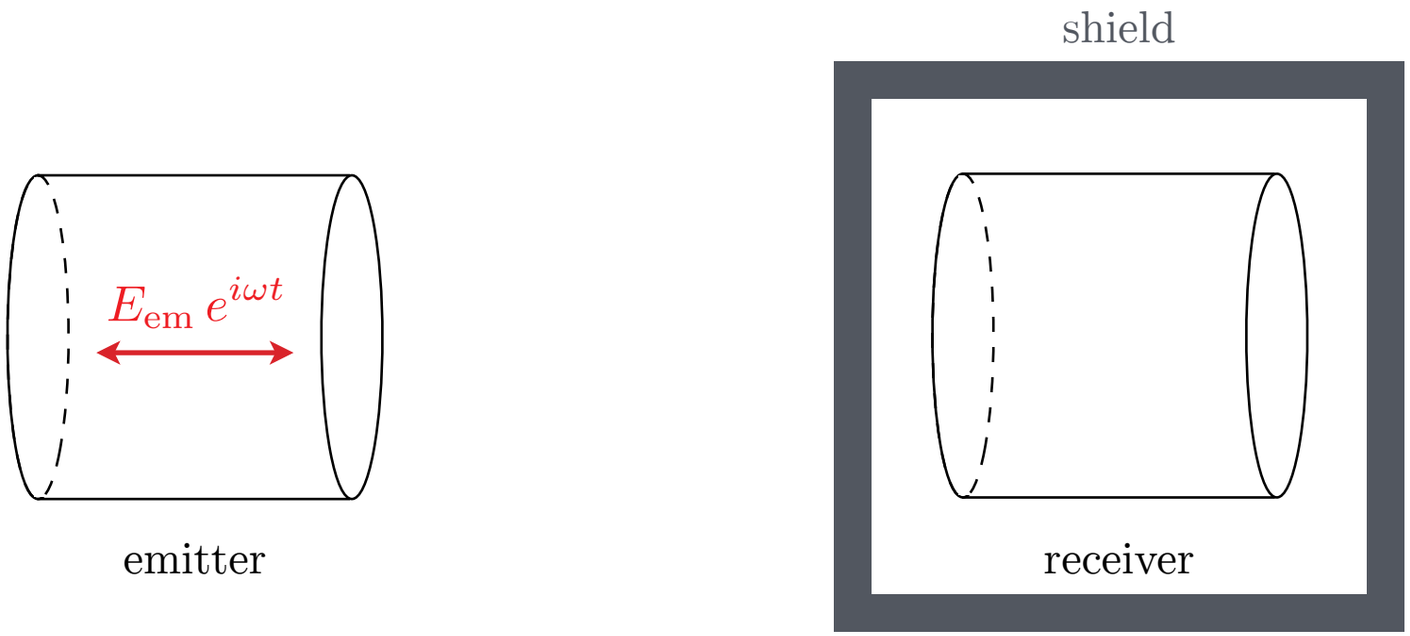
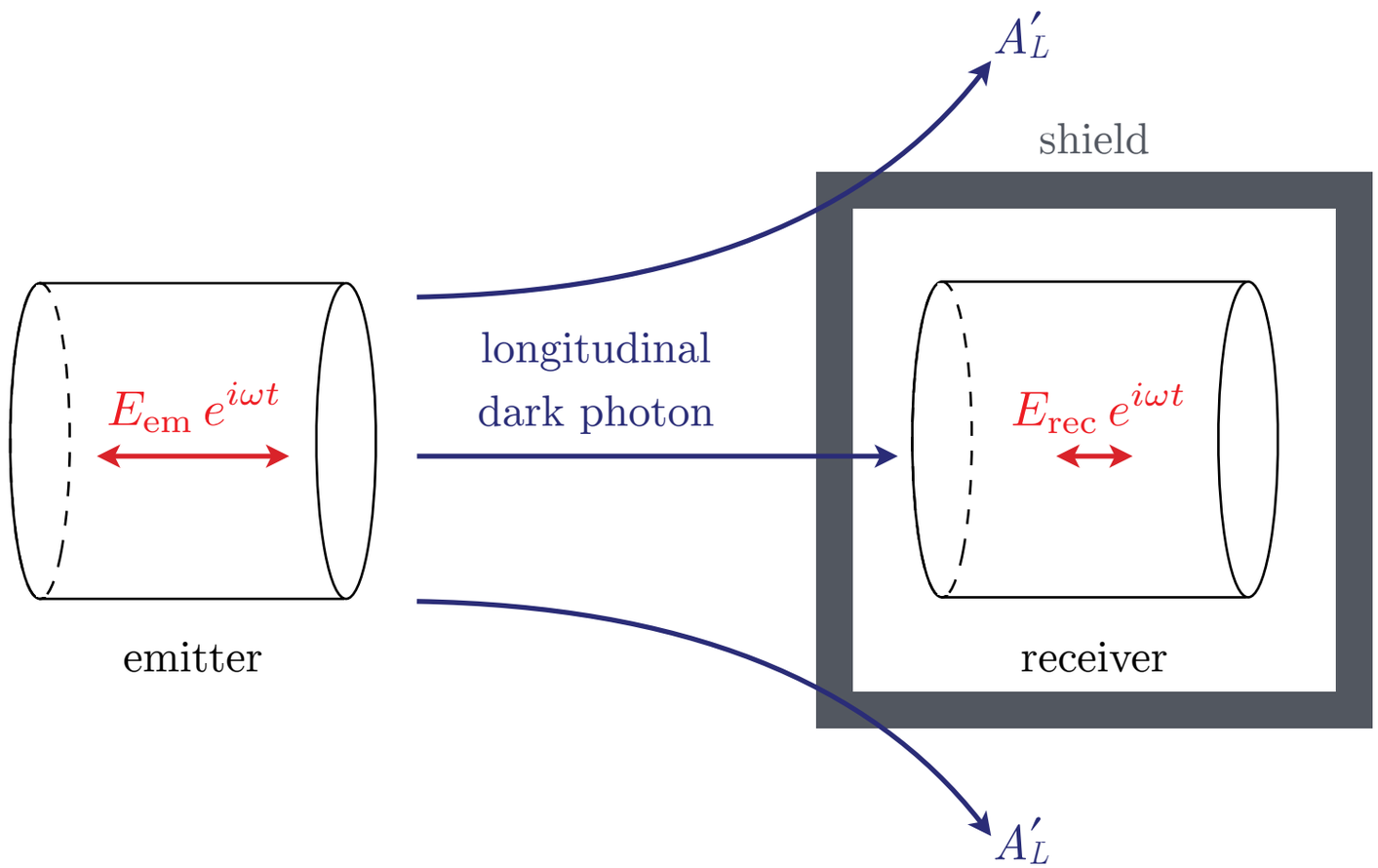
[2]*Berkeley Center for Theoretical Physics, Department of Physics, University of California, Berkeley, CA 94720*

- sub-Hz frequency wobble
- resolved thermal noise
- plan for a week run

New Physics for Free at DarkSRF

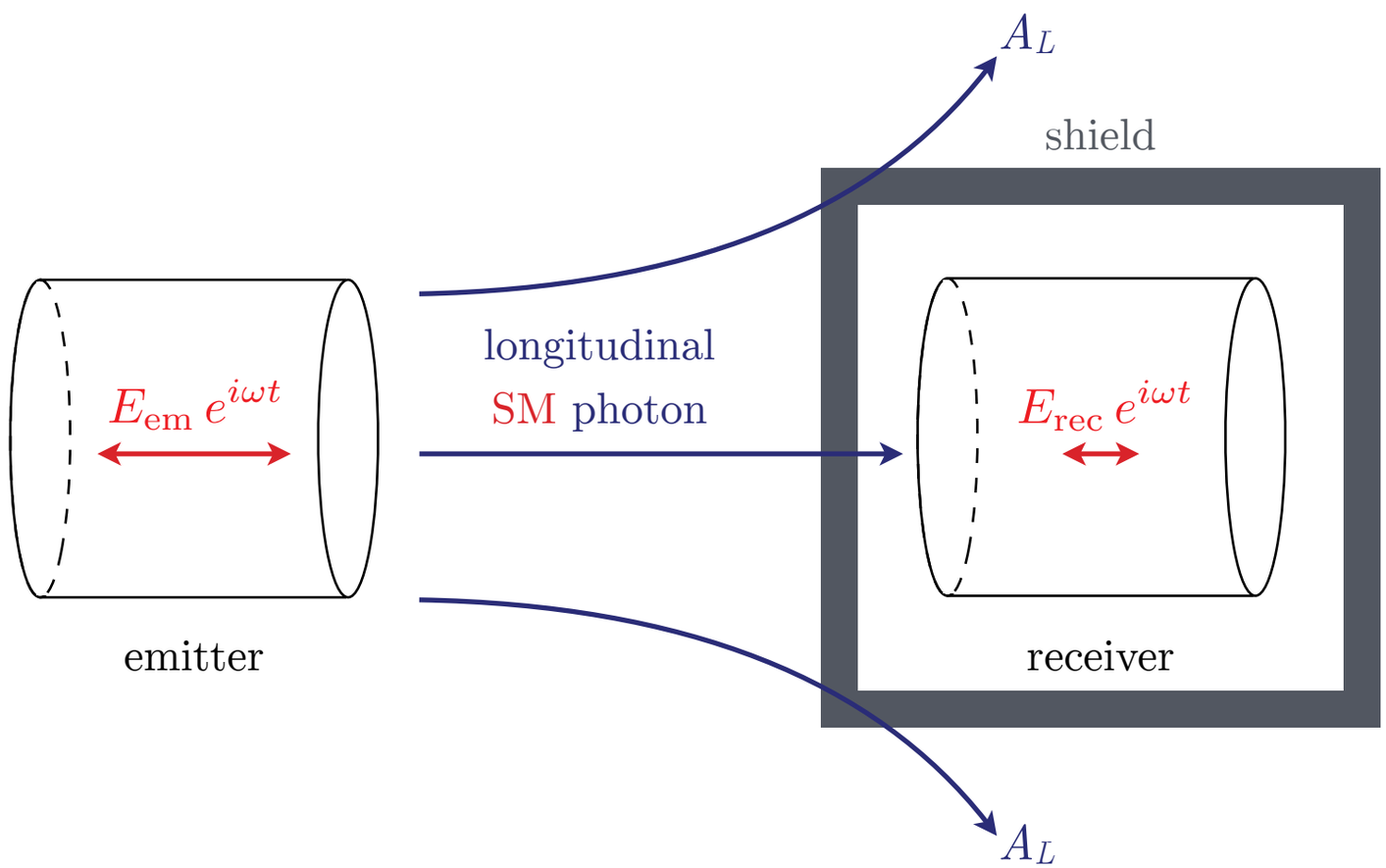


New Physics for Free at DarkSRF



$$\epsilon\, m_{A'} \lesssim 6 \times 10^{-16}\ \text{eV} \simeq 10^{-48}\ \text{g}$$

New Physics for Free at DarkSRF: SM Photon Mass



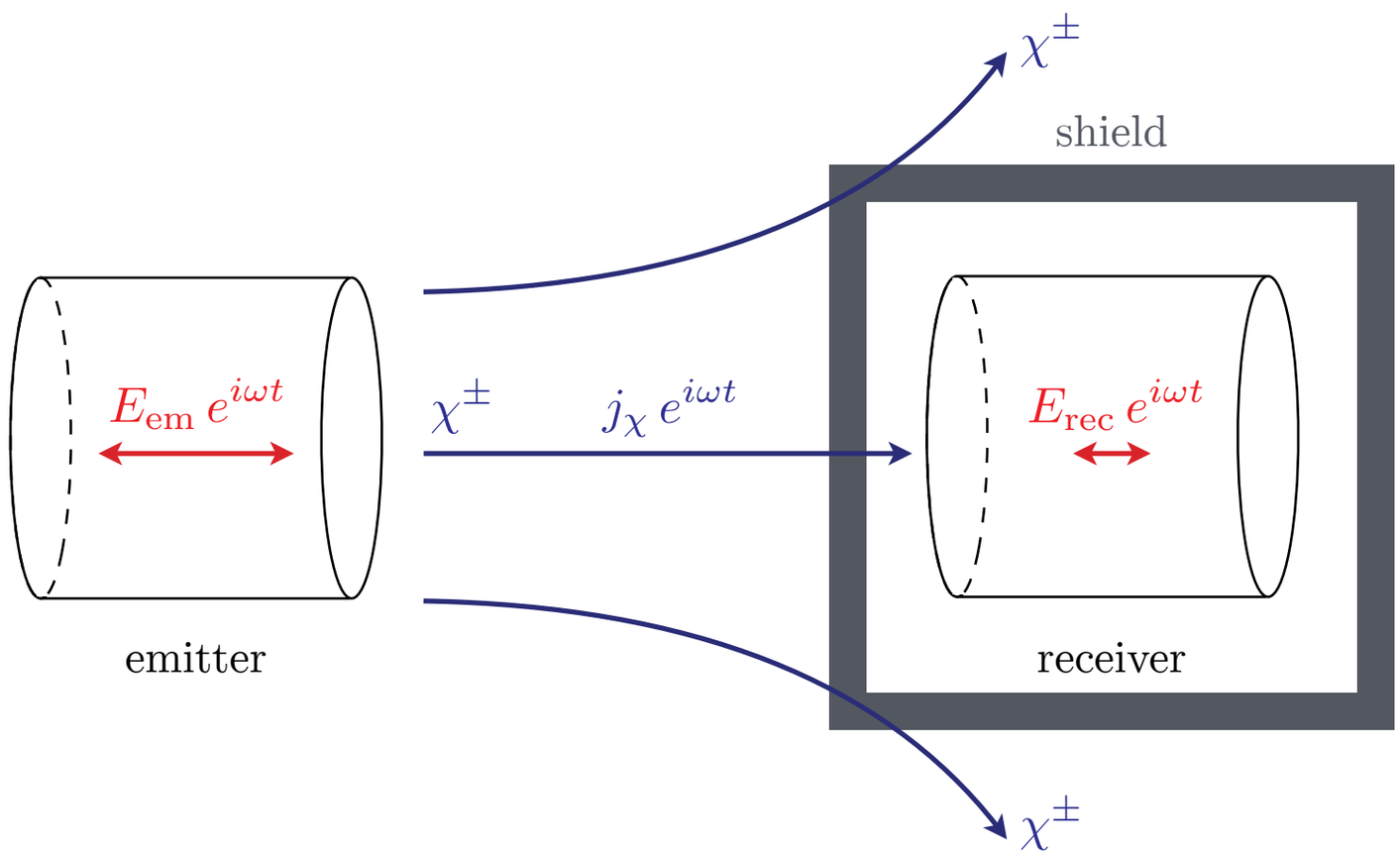
<u>a longitudinal mode is a longitudinal mode</u>

$$m_\gamma \lesssim 6 \times 10^{-16}\ \text{eV} \simeq 10^{-48}\ \text{g}$$

(best direct laboratory bound on the SM photon mass in 50 years)

A. Berlin, A. Hook

New Physics for Free at DarkSRF: Ultralight Millicharges



Schwinger pair-production of millicharged particles

$$E_{\rm cr} \sim 50\ {\rm MV\ m^{-1}} \times \left(\frac{m_\chi}{\rm meV}\right)^2 \left(\frac{q_\chi}{10^{-7}}\right)^{-1}$$

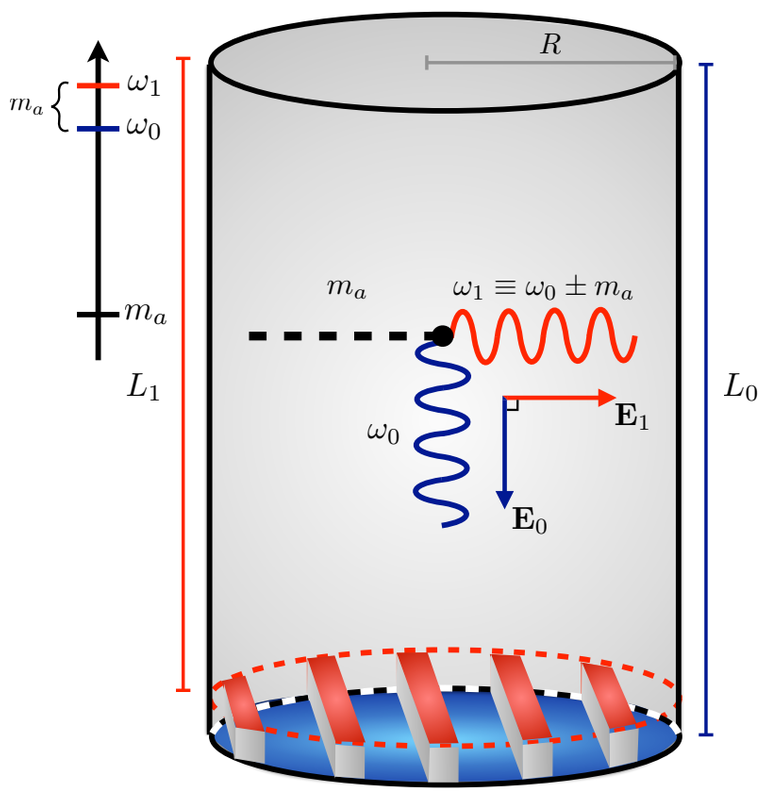
(best laboratory sensitivity to light millicharges by > five orders of magnitude)

arXiv:2001.02679

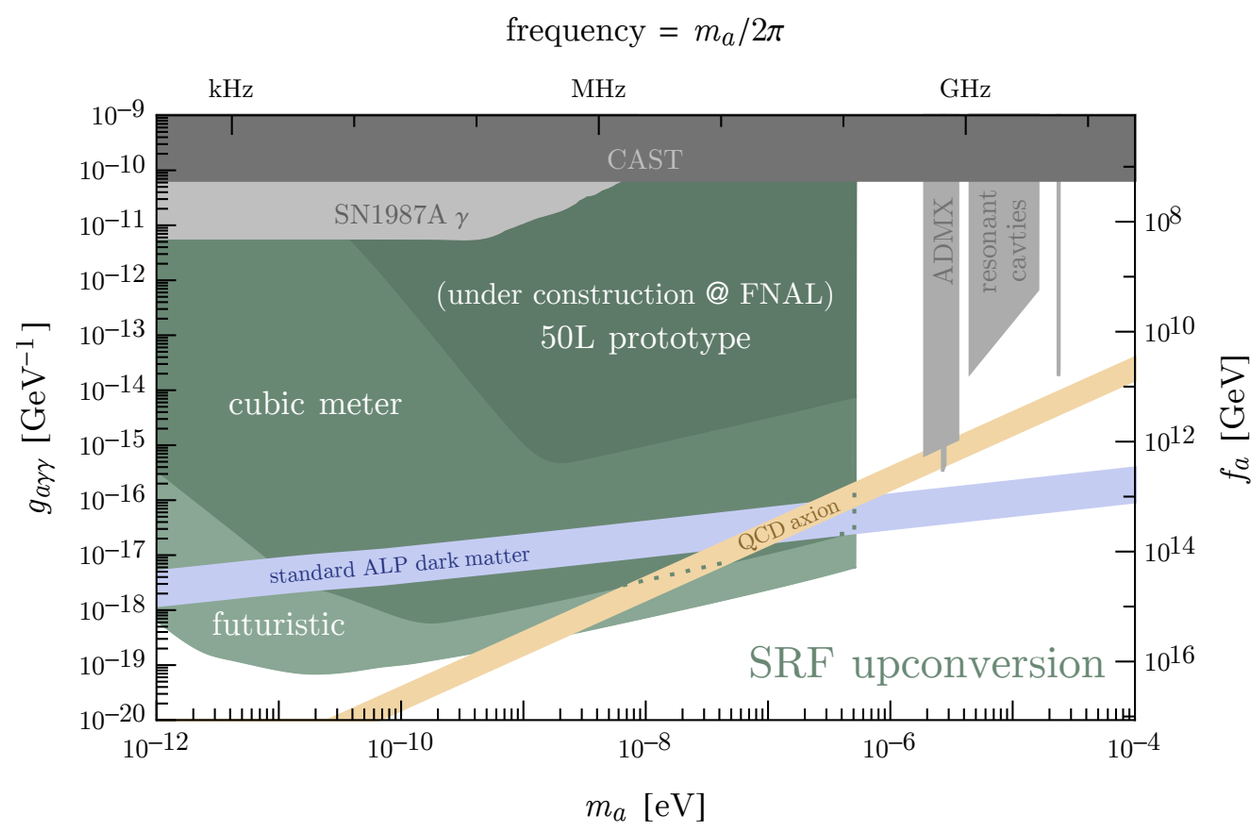
Heterodyne Frequency Conversion

Axion Dark Matter

arXiv:1912.11048, arXiv:1912.11056, arXiv:2007.15656



Axion transfers power
from driven mode to quiet mode.



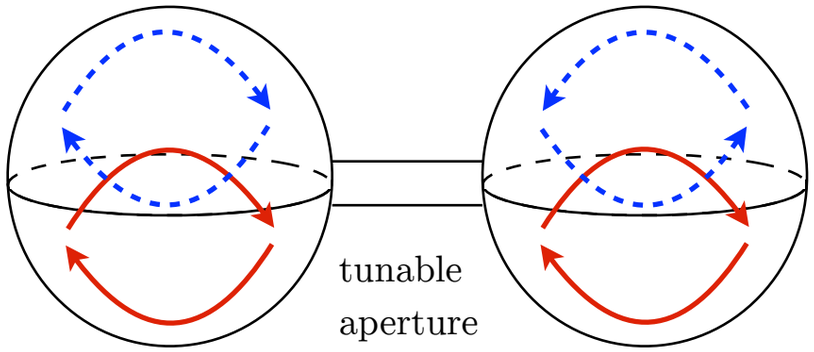
Enhanced signal for light axions: GHz$/m_a$ >> 1 and $Q \sim 10^{12}$

Heterodyne Frequency Conversion

High-Frequency Gravitational Waves (MAGO)

arXiv:gr-qc/0103006 arXiv:gr-qc/0203024, arXiv:gr-qc/0502054

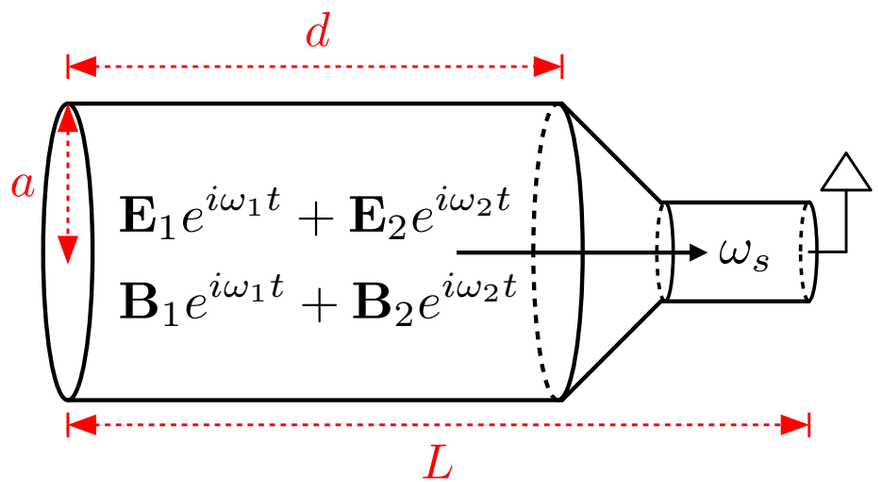
Gravitational wave transfers power from driven mode to quiet mode.

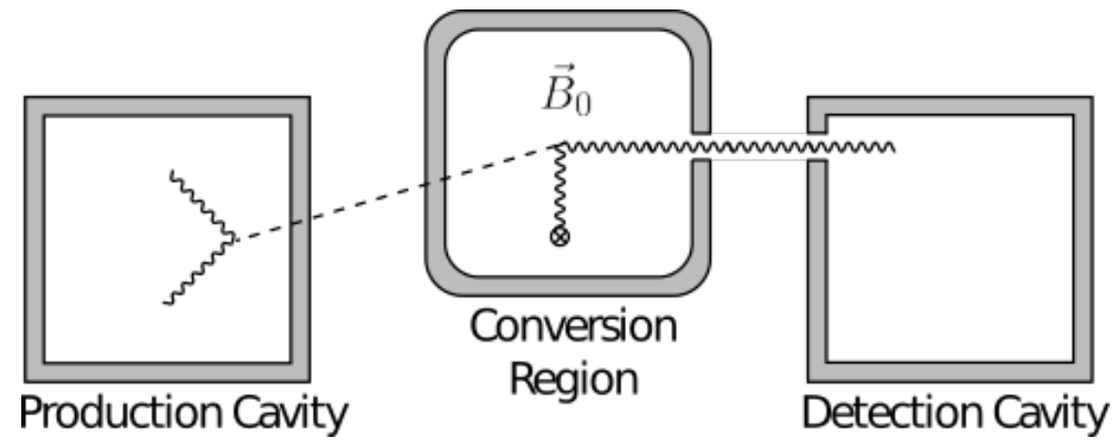


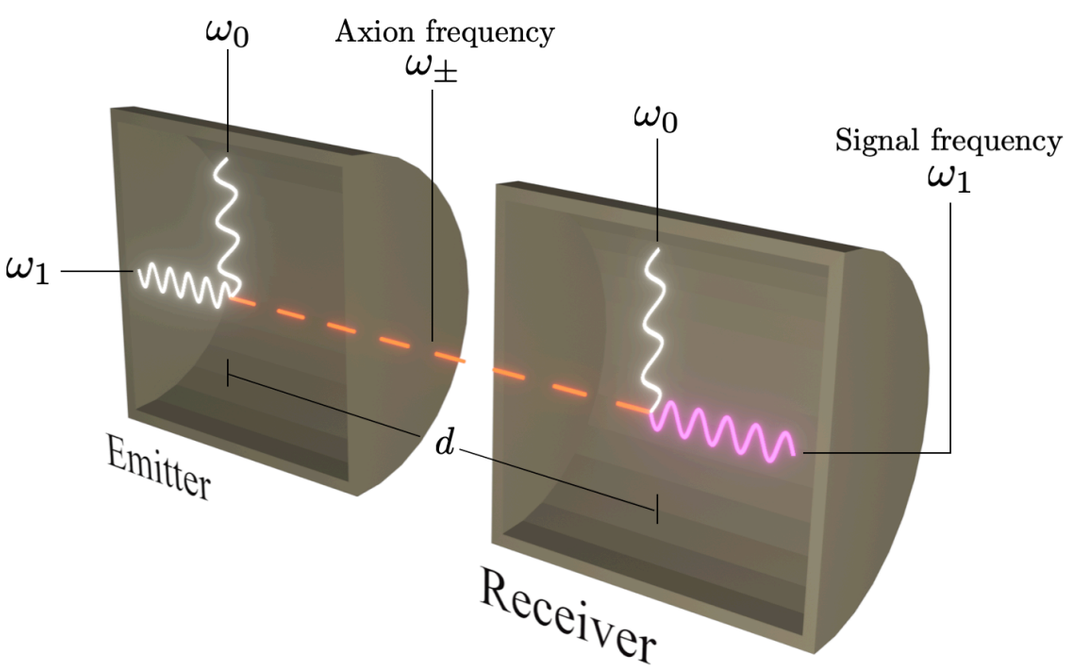
transition between symmetric and antisymmetric modes

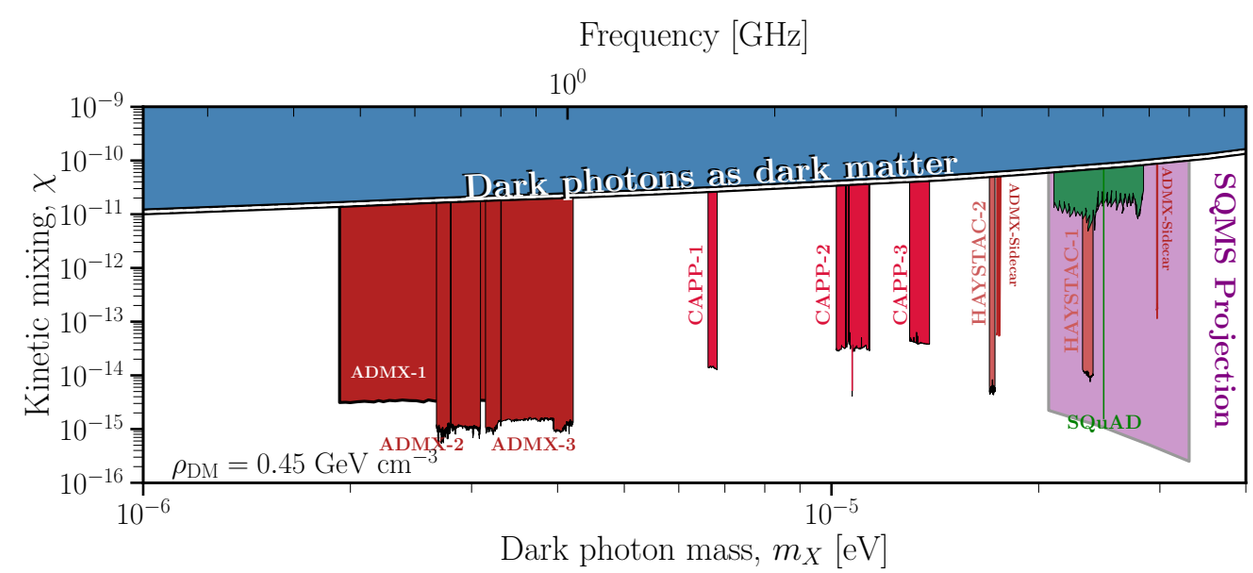
strain sensitivity ~ 10^{-20} for kHz - MHz frequencies

Many Other Applications









Searches for New Particles, Dark Matter, and Gravitational Waves with SRF Cavities
arXiv:2203.12714

Role of Theorists

Axion Dark Matter Detection by Superconducting Resonant Frequency Conversion

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Institut de Physique Théorique, Université Paris Saclay, CEA, F-91191 Gif-sur-Yvette, France

Sebastian A. R. Ellis, Christopher Nantista, Jeffrey Neilson, Philip Schuster, Sami Tantawi, Natalia Toro, and Kevin Zhou

Microwave cavity searches for low-frequency axion dark matter

Robert Lasenby*

Heterodyne Broadband Detection of Axion Dark Matter

Asher Berlin,[1] Raffaele Tito D'Agnolo,[2] Sebastian A. R. Ellis,[3] and Kevin Zhou[3]

On the operation of a tunable electromagnetic detector for gravitational waves

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Microwave Apparatus for Gravitational Waves Observation

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INFN and Università degli Studi di Genova, Genova, Italy

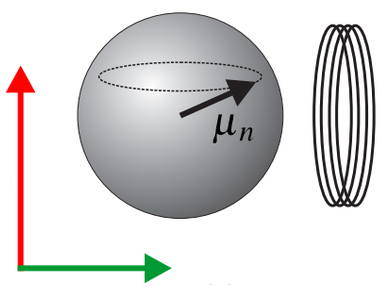
Ph. Bernard, S. Calatroni, E. Chiaveri, and R. Losito
CERN, Geneva, Switzerland

R.P. Croce, V. Galdi, V. Pierro, and I.M. Pinto
INFN, Napoli, and Università degli Studi del Sannio, Benevento, Italy

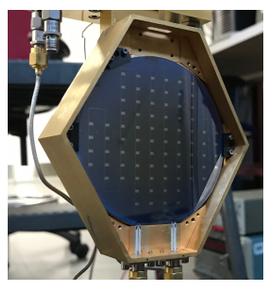
E. Picasso
INFN and Scuola Normale Superiore, Pisa, Italy and CERN, Geneva, Switzerland

Outlook

NMR

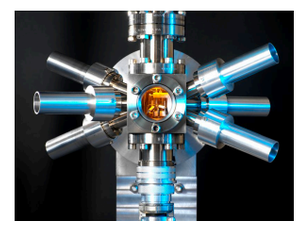


KIDs



SRF cavities

atomic clocks/interferometers



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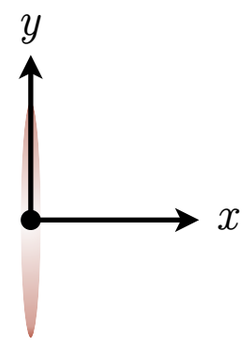
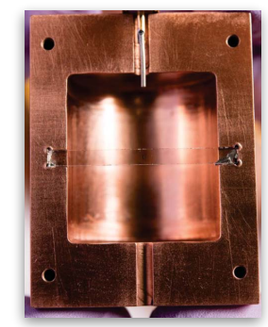
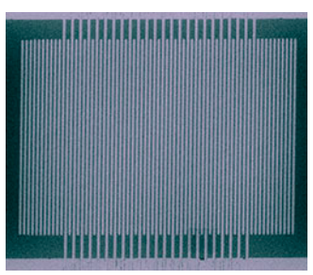


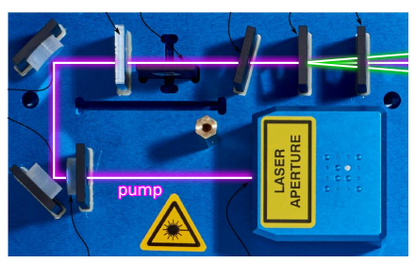
SC qubit



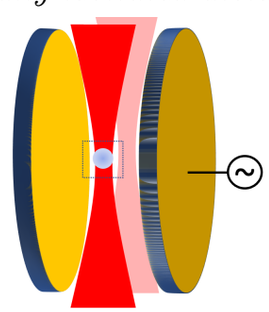
SNSPDs



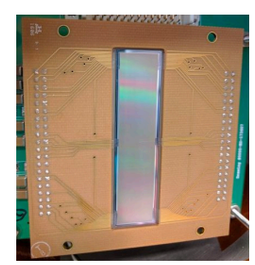
nonlinear optics



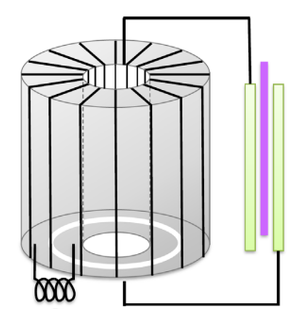
optically levitated dielectrics



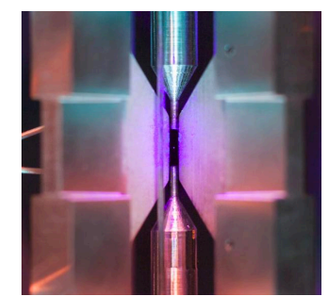
skipper CCDs



LC circuits



ion traps



+... many more

Outlook

Now is an important time

We are now beginning to explore physics beyond the Standard Model at scales currently inaccessible with previous technology.

How can technologies coming online be steered to make the biggest impact on fundamental physics?

A shift in our priors has motivated a larger set of signals.
Many bang-for-buck experiments > single catch-all experiment.

Theory and experiment are evolving together in this effort.
The role of theorists is crucial in emerging fields.

see "Snowmass2021 Theory Frontier: Theory Meets the Lab"
arXiv:2203.10089

NMR

SC qubit

SNSPDs

ion traps