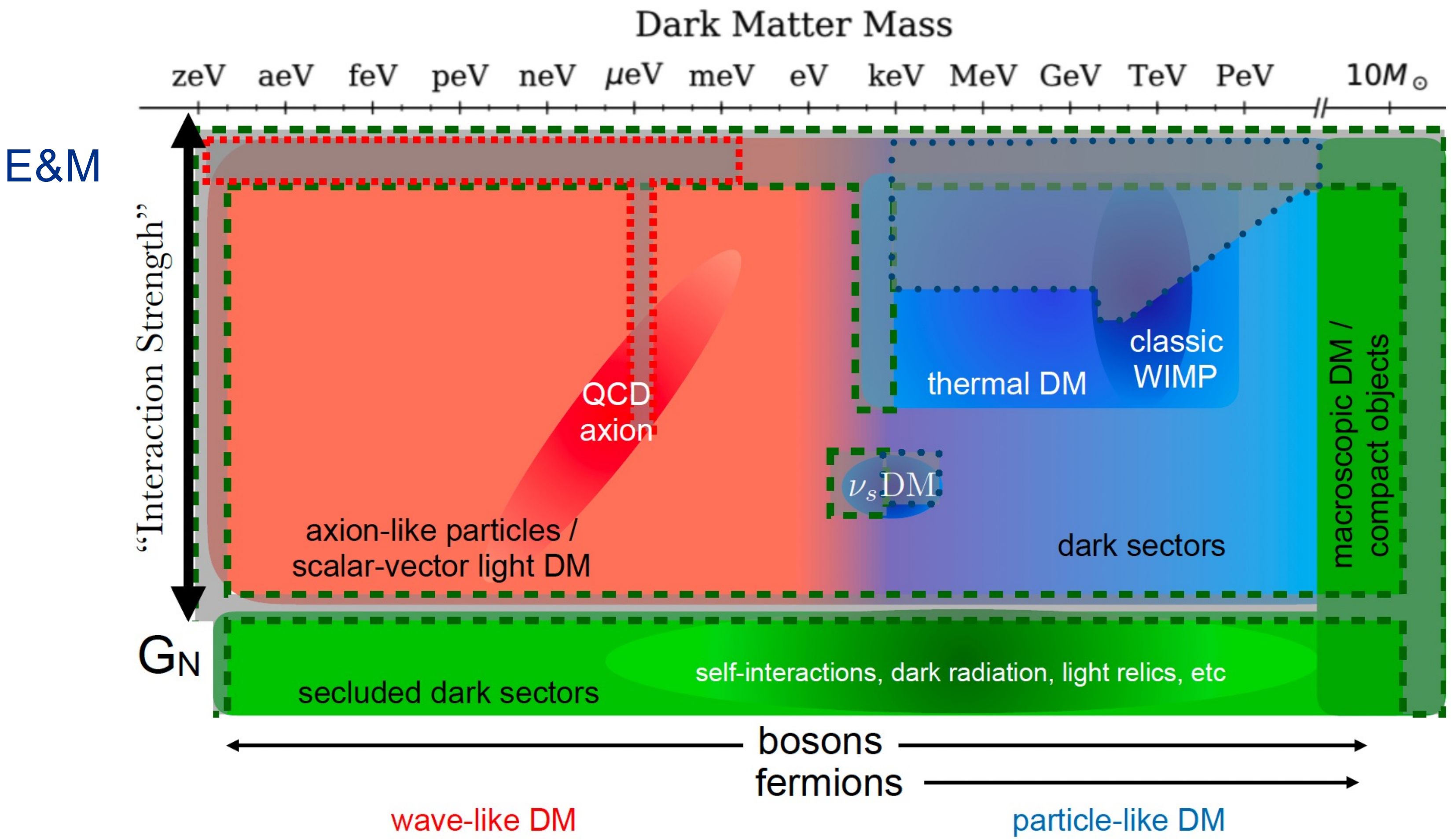
Dark Matter Strategy: Delve Deep, Search Wide … but how?

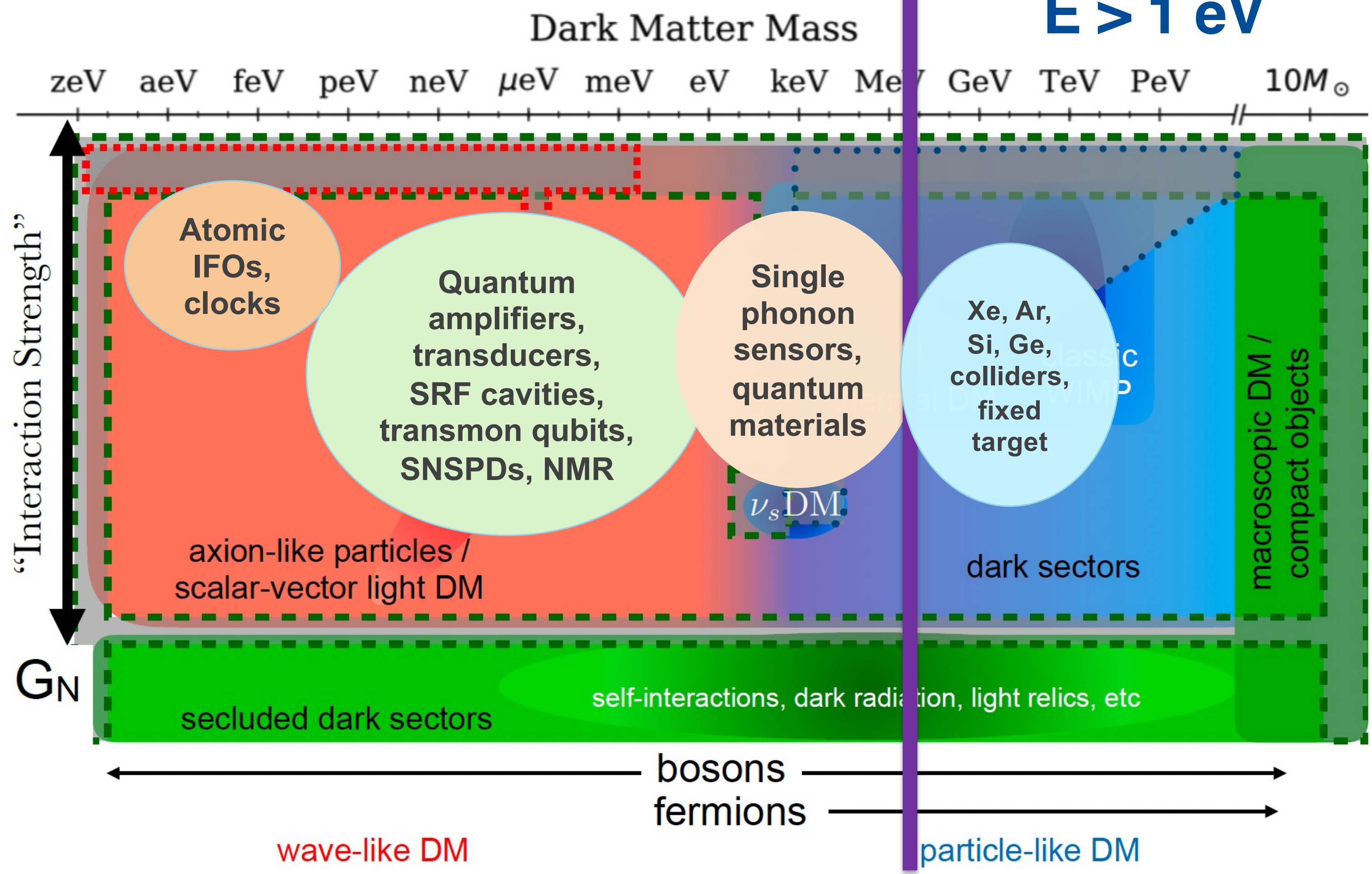


Cartoon from Snowmass

Quantum sensors: E < 1 eV

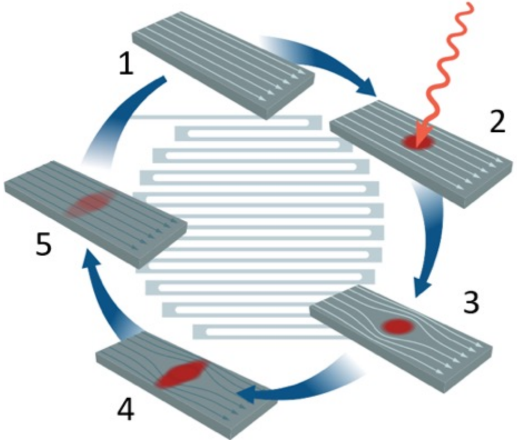
Conventional tech: E > 1 eV

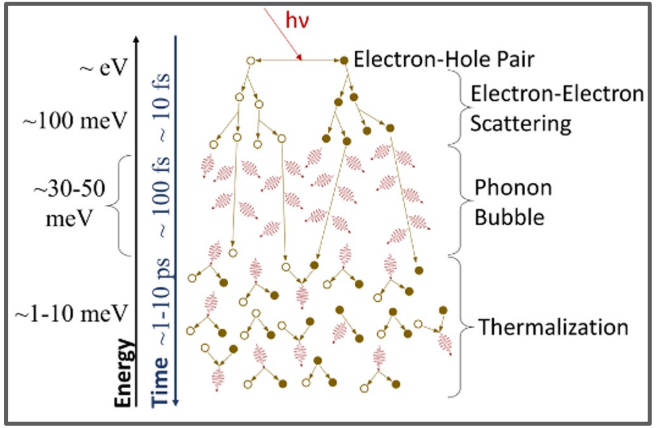
E&M



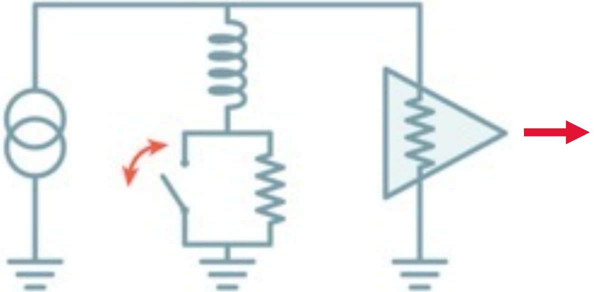
Cartoon from Snowmass

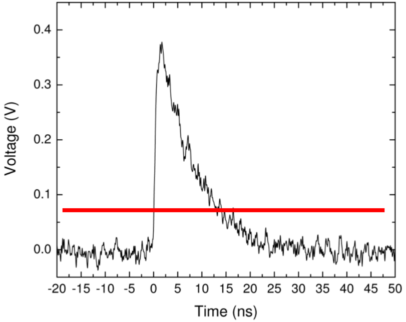
Superconducting Nanowire Single Photon Detectors Matt Shaw (JPL)

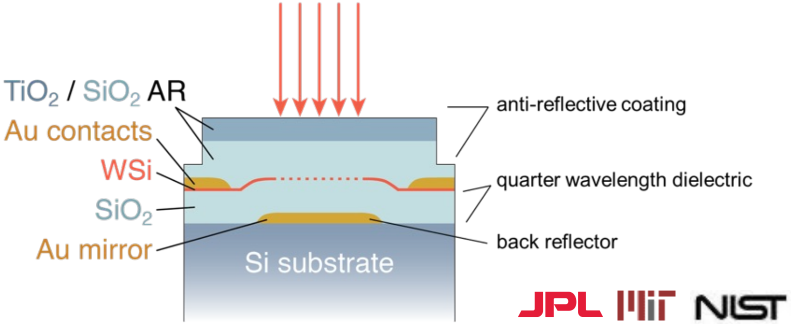




- 98% System Detection Efficiency at 1550 nm (NIST)
- 0.27 – 29 µm operating wavelength (JPL / NIST / MIT)
- <1e-5 cps dark count rate (MIT / NIST)
- mm^2 active area (JPL / NIST / MIT)
- 400 kpix camera format (NIST)
- 1.5 Gcps maximum count rate (JPL)
- <3 ps FWHM timing jitter (MIT / JPL / NIST)
- High radiation tolerance

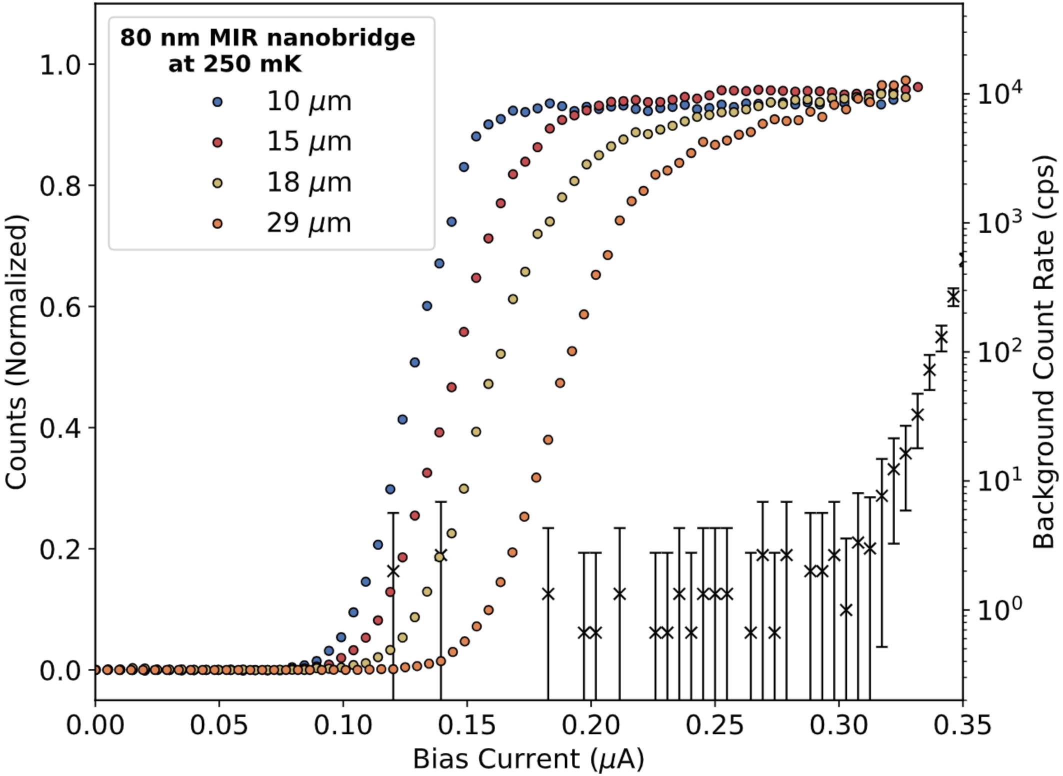






New Result: Single Photon Detection at 29 µm

Matt Shaw (JPL)

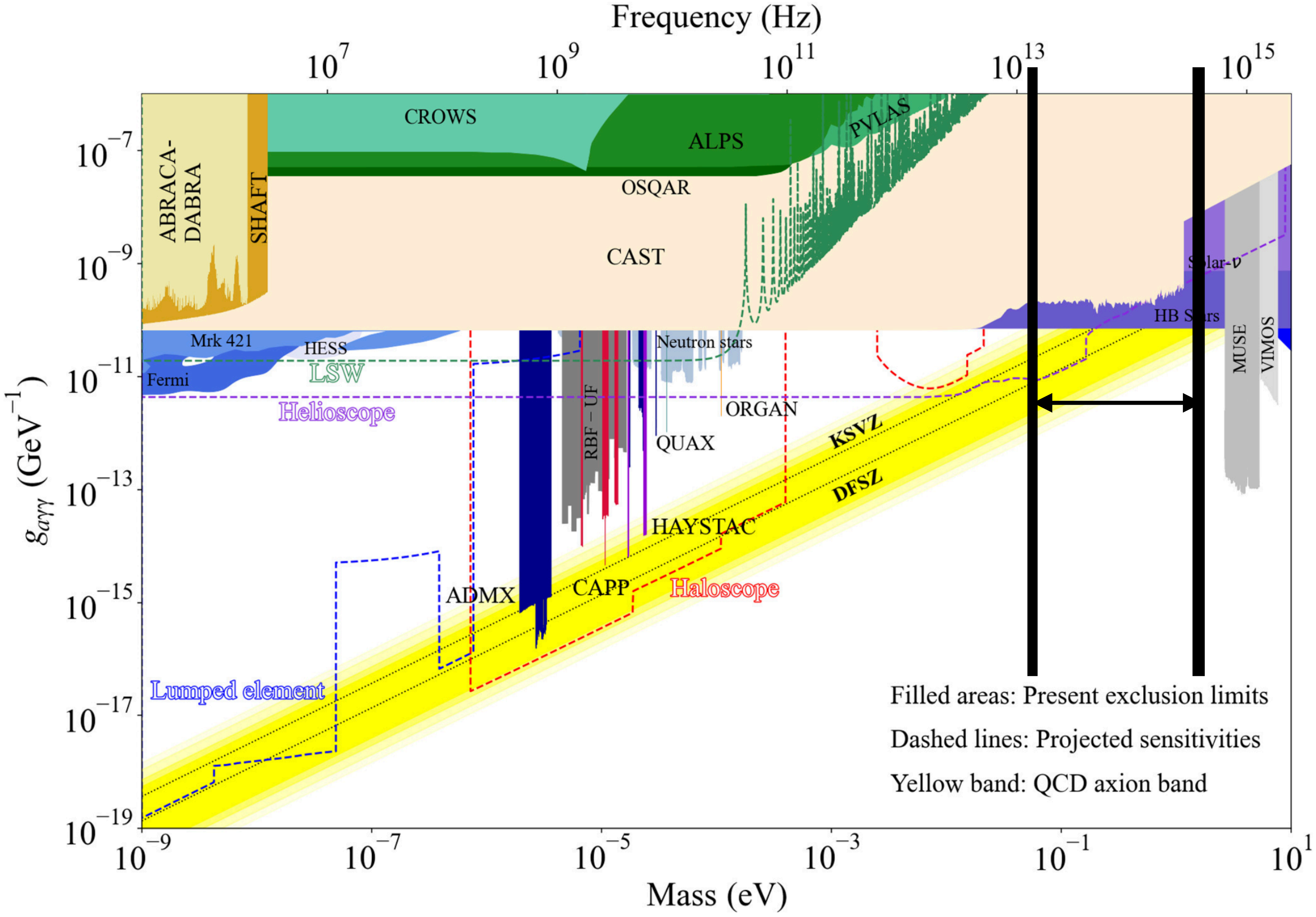


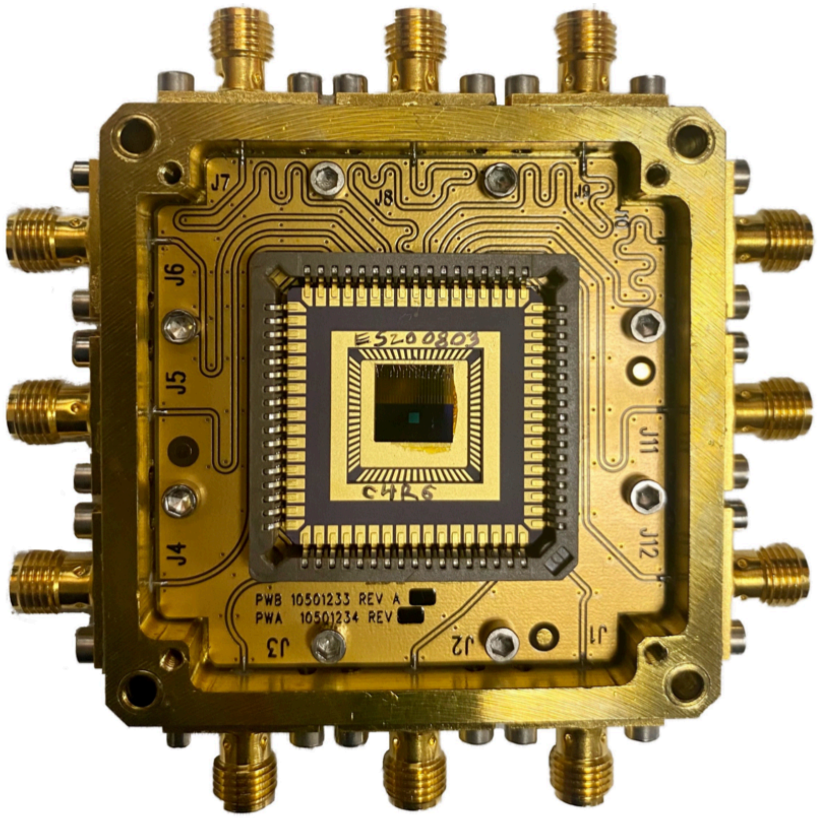
- SNSPD nanobridge with Si-rich WSi for reduced superconducting gap energy (1.3 K Tc, 80 nm nanobridge)
- First demonstration of single-photon counting at far-infrared wavelengths (43 meV, 10 THz)

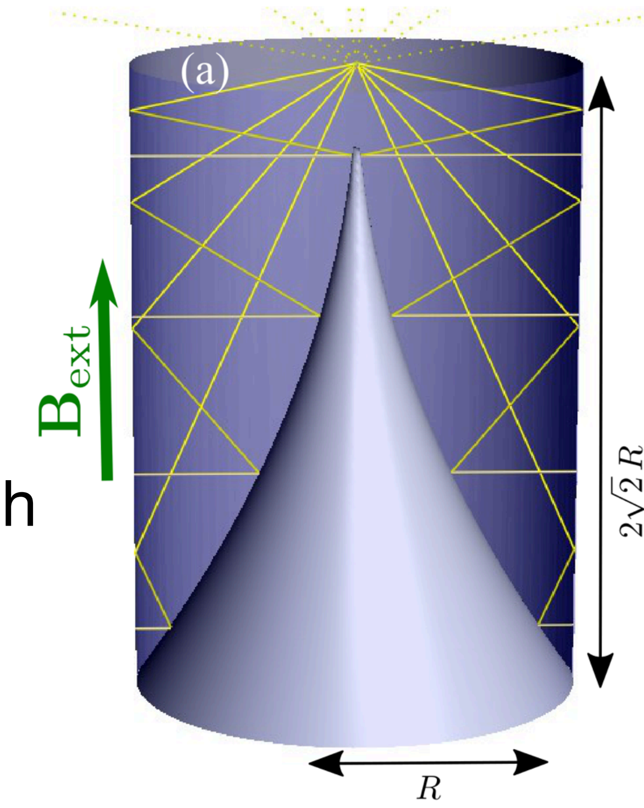
Axions with low-threshold SNSPD

SNSPD overview:
see M. Shaw's slides

Low-threshold photon detectors will play a key role in broadband axion detection







SNSPD demonstrated nanowire sensitivity to 0.04 - 1 eV → mass reach

Best DCR < 1e-5 c.p.s → axions coupling sensitivity

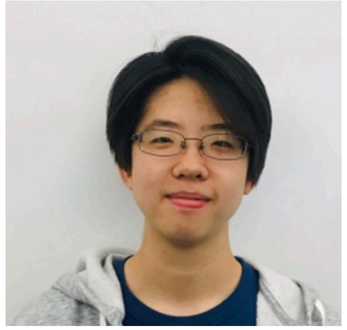
Final SNSPD to realize axion detection require challenging R&D

Cristián Peña — Fermilab

Axions with low-threshold SNSPD

BREAD
COLLABORATION

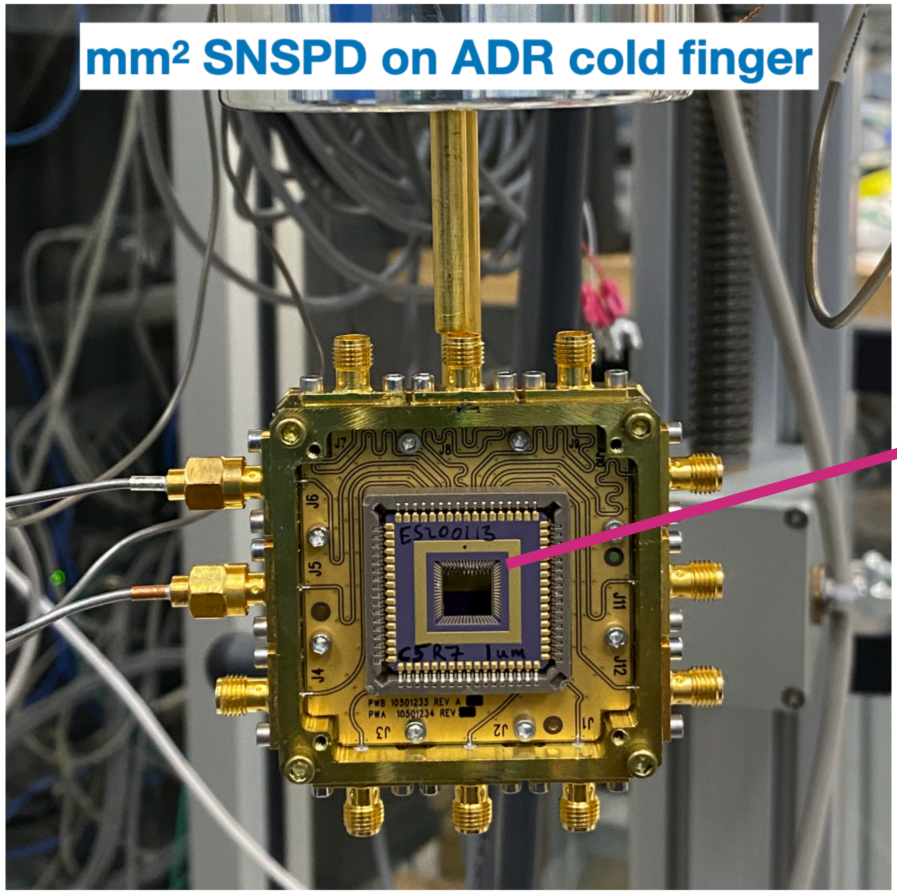
Jamie Luskin

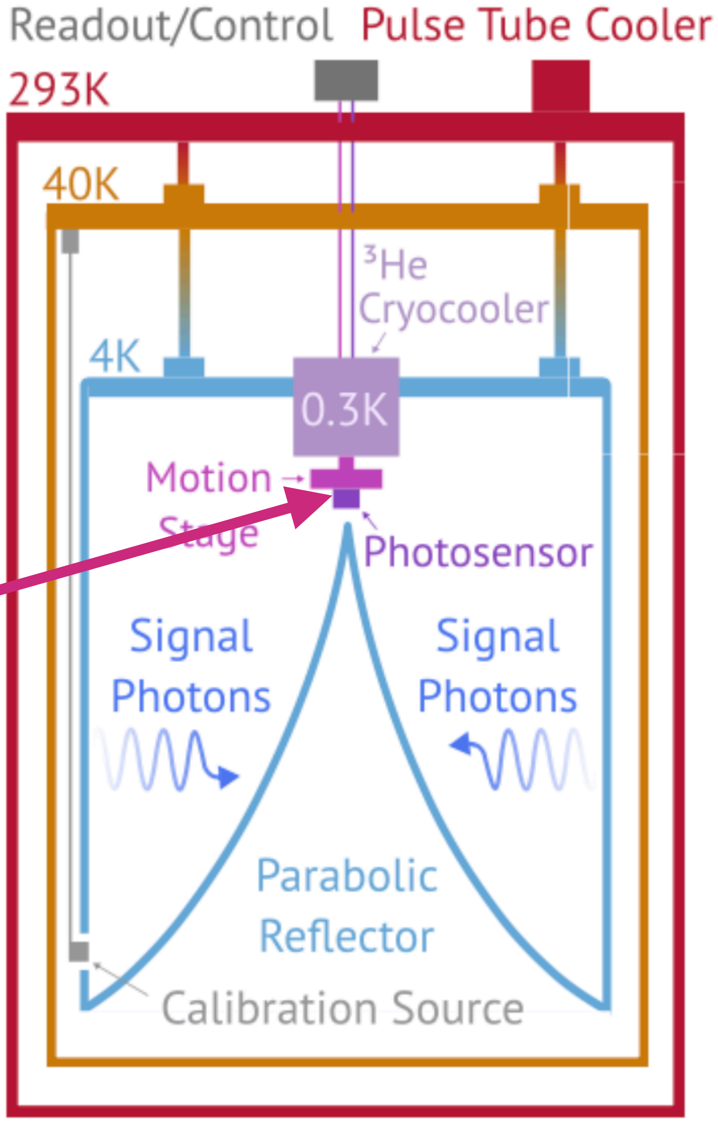


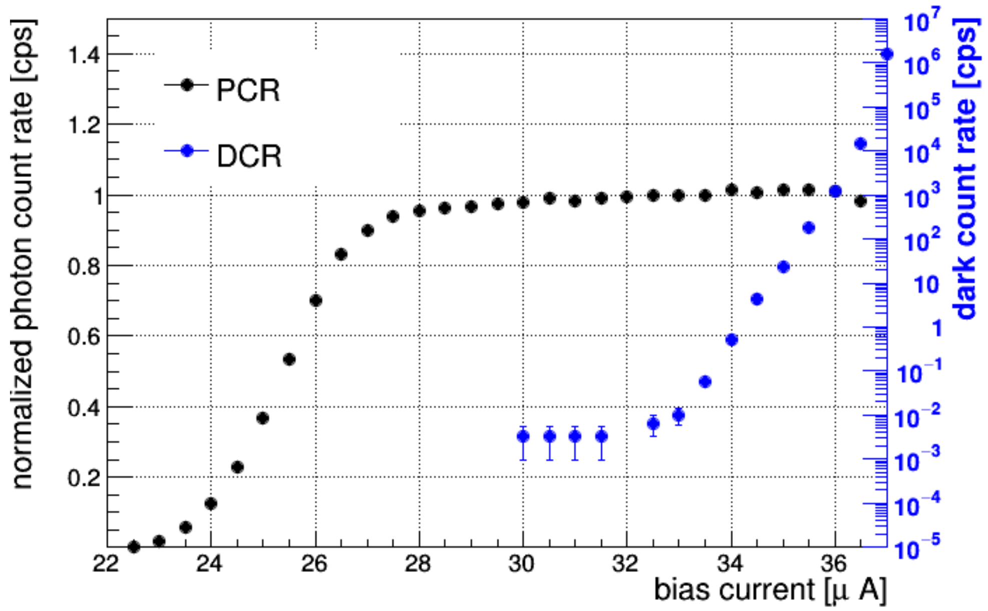
Christina Wang

ongoing R&D to meet sensor parameters

Arxiv:2303.10739

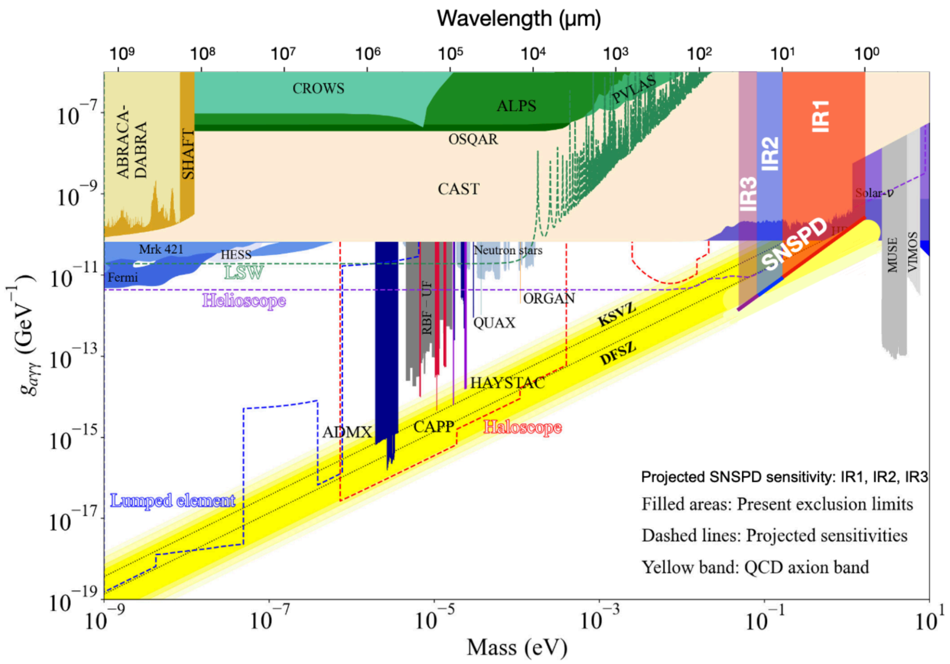






Towards new axion sensitivity

SNSPD area/channel scaling: see S. Xie's slides

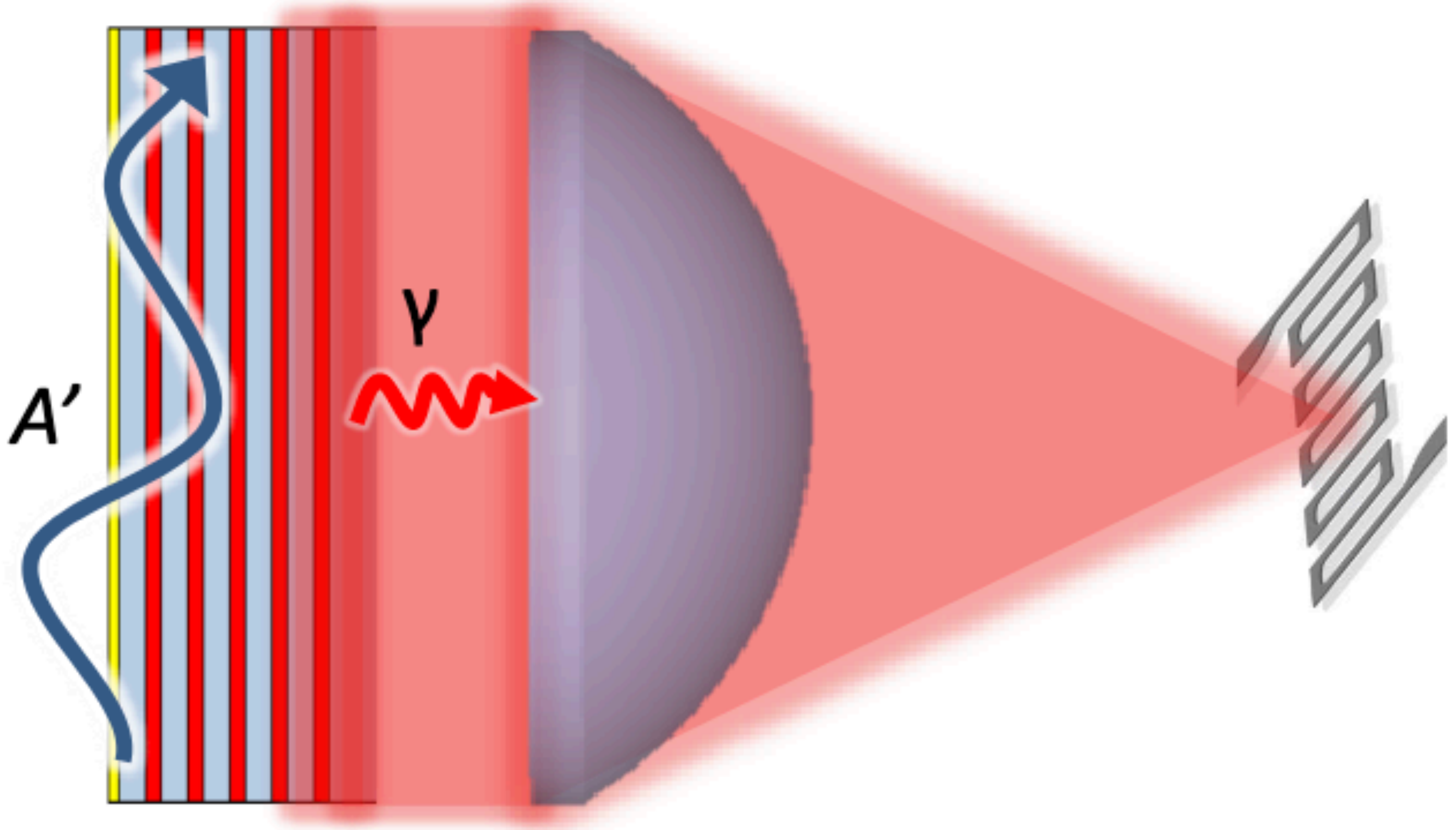


LAMPOST: Dielectric Haloscope with an SNSPD

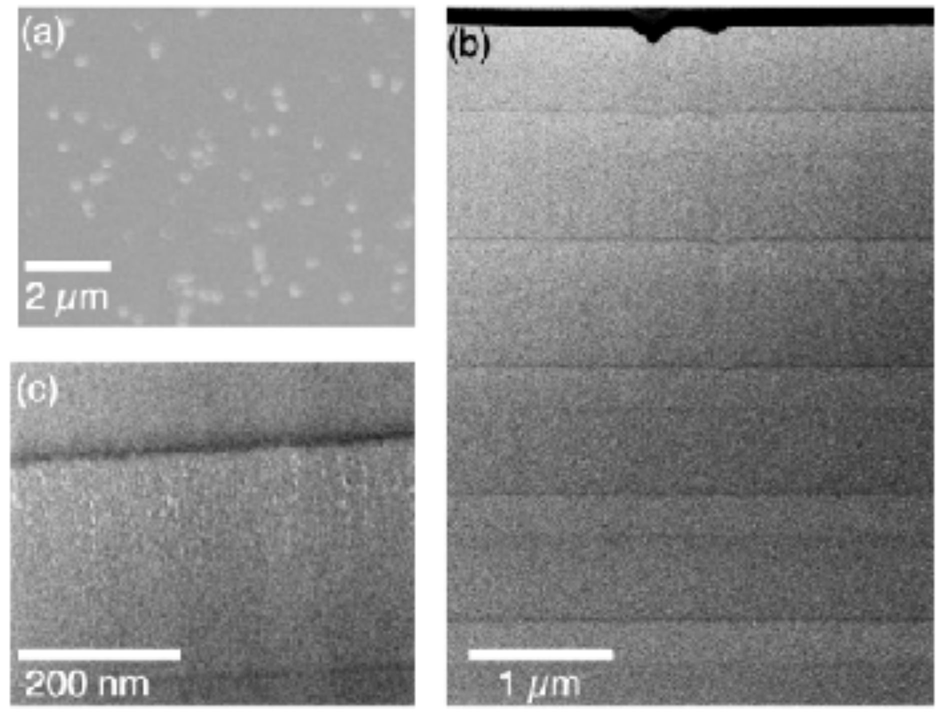
Stewart Koppell[1], Dip Joti Paul[1], Jeffrey Chiles[2], Junwu Huang[3], Masha Baryakhtar[4], Sae Woo Nam[2], Karl Berggren[1] (1. MIT, 2. NIST Boulder, 3. Perimeter Institute for Theoretical Physics, 4. University of Washington)

Ilya Charaev

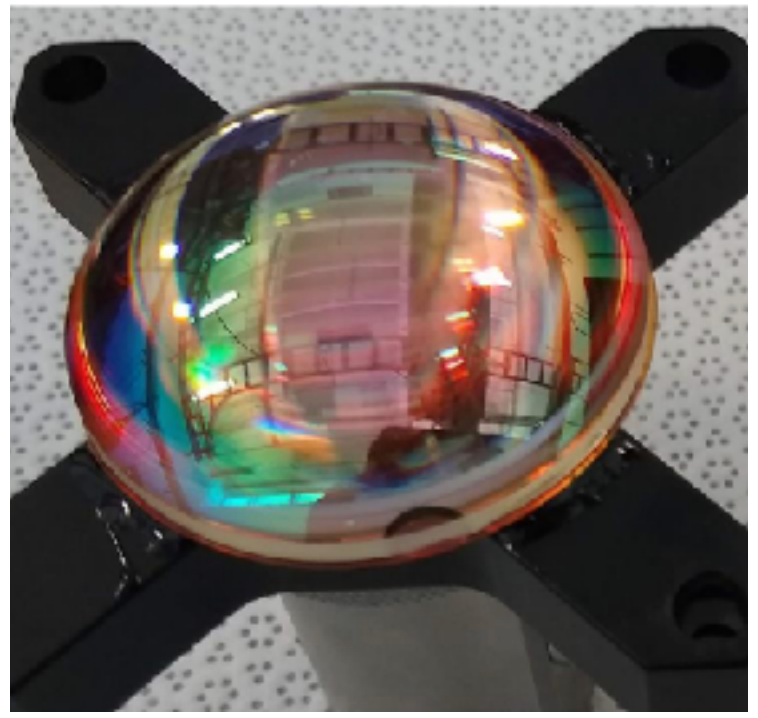
Jeffrey Chiles



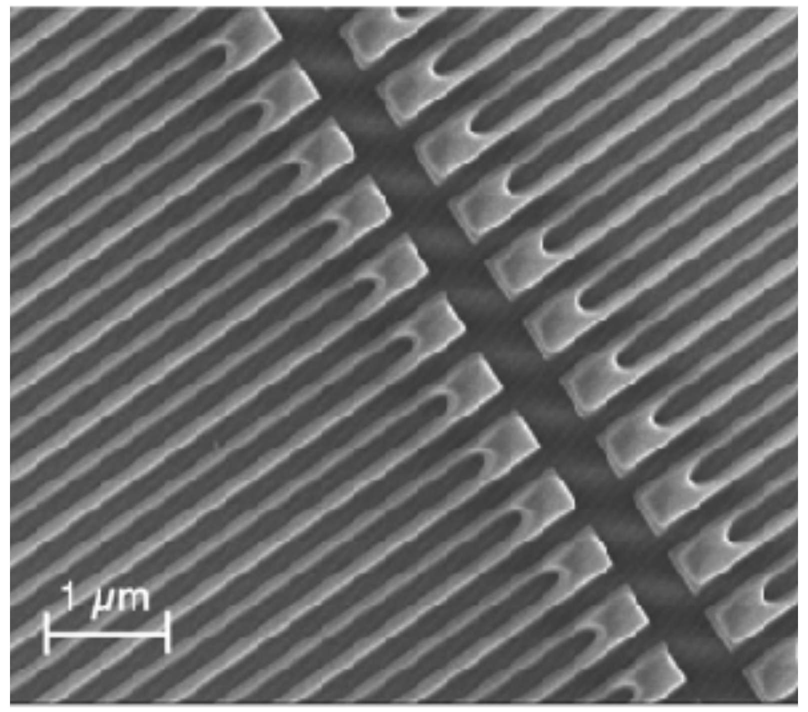
Dark Matter Absorber



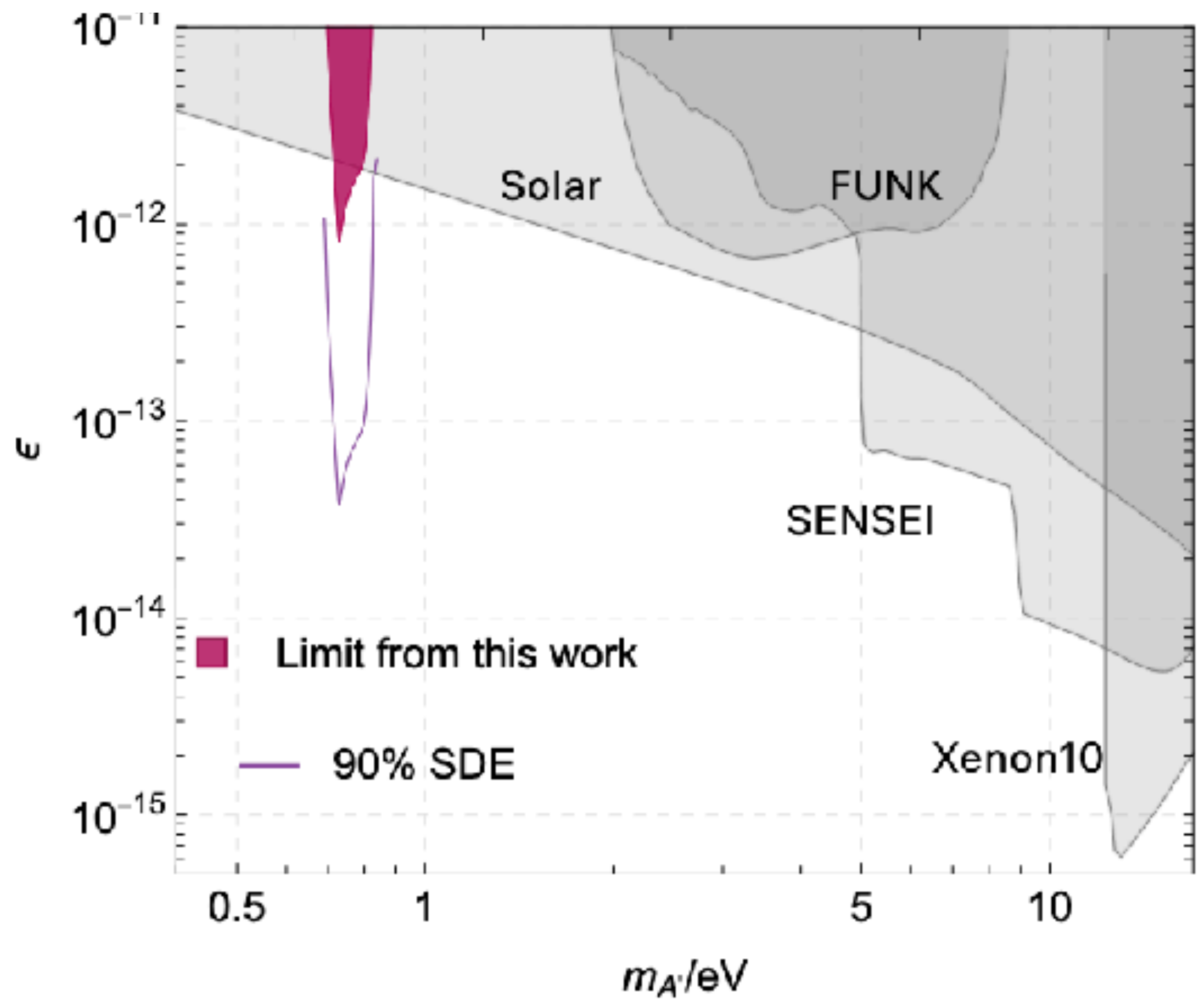
Lens

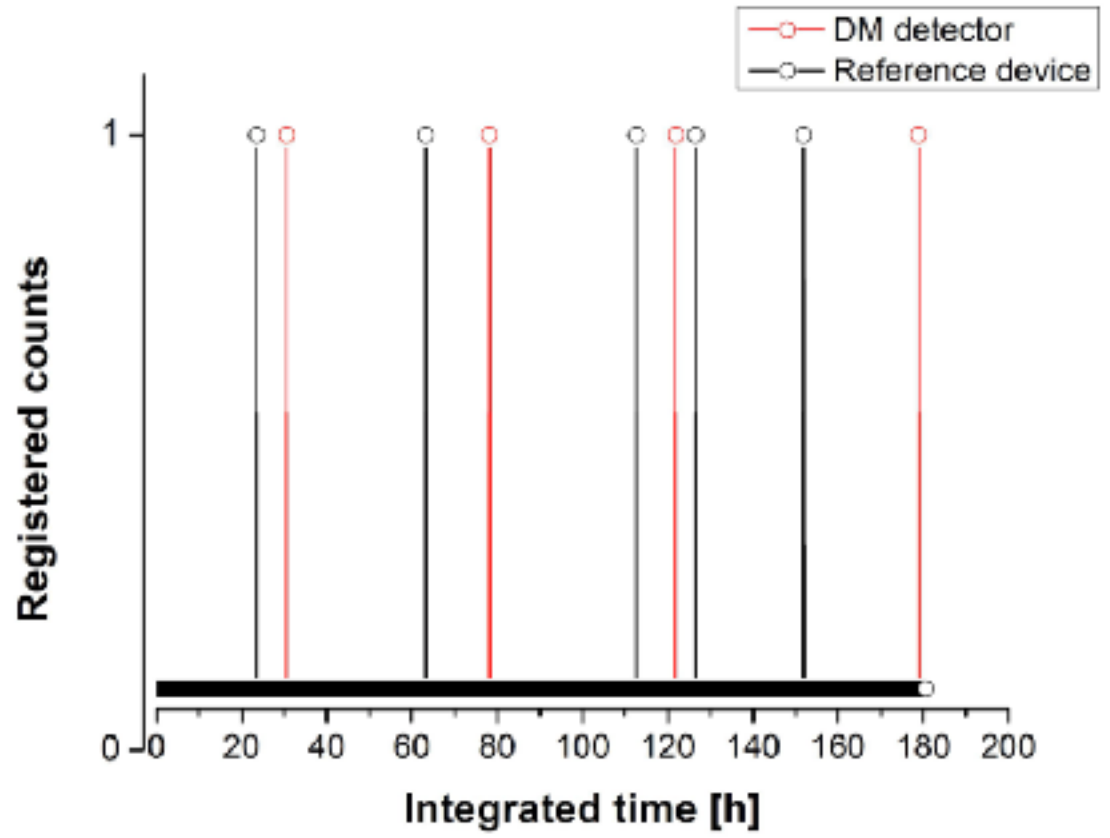


SNSPD



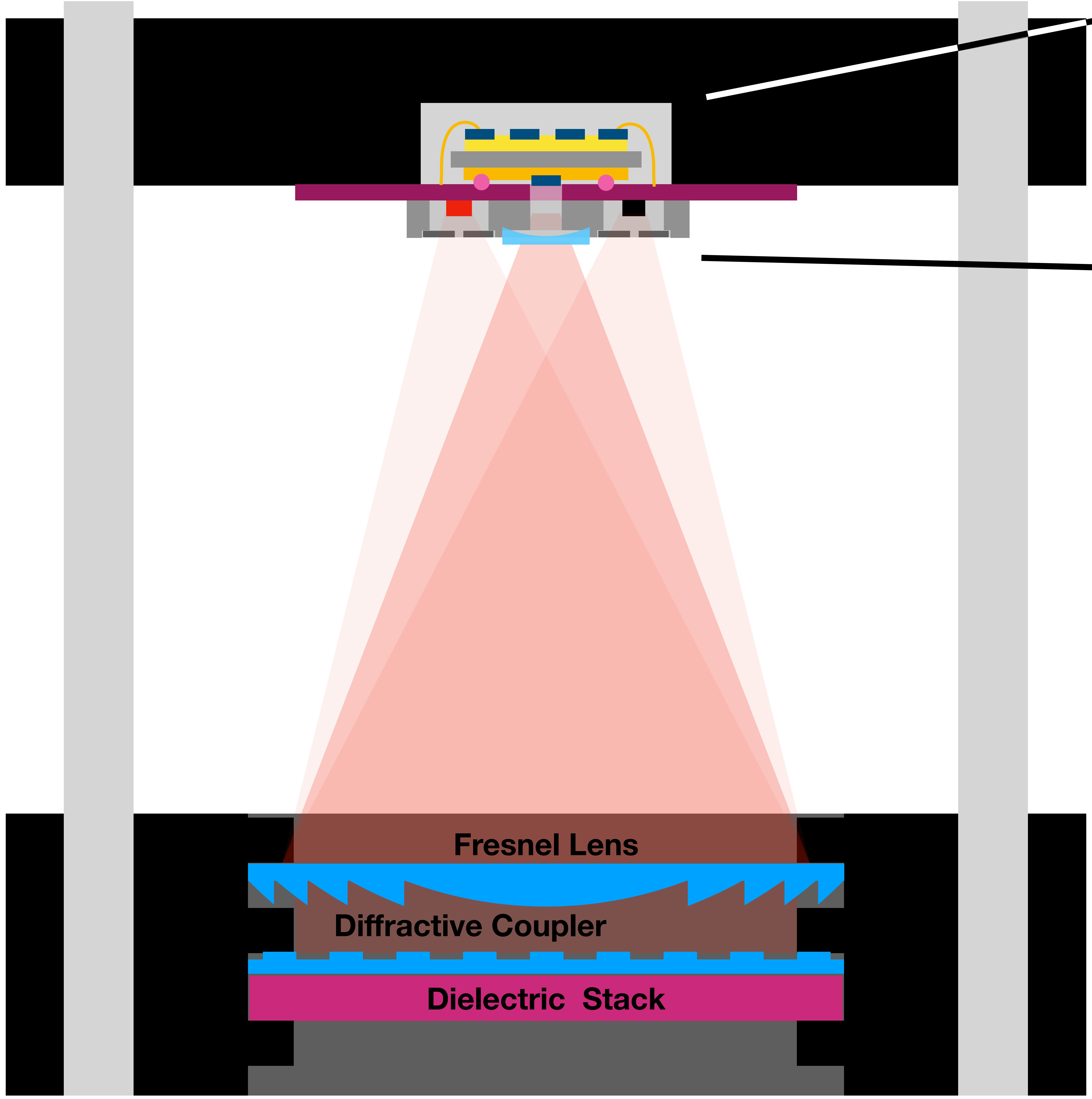
J. Chiles et al, Phys. Rev. Lett. 128 (2022)

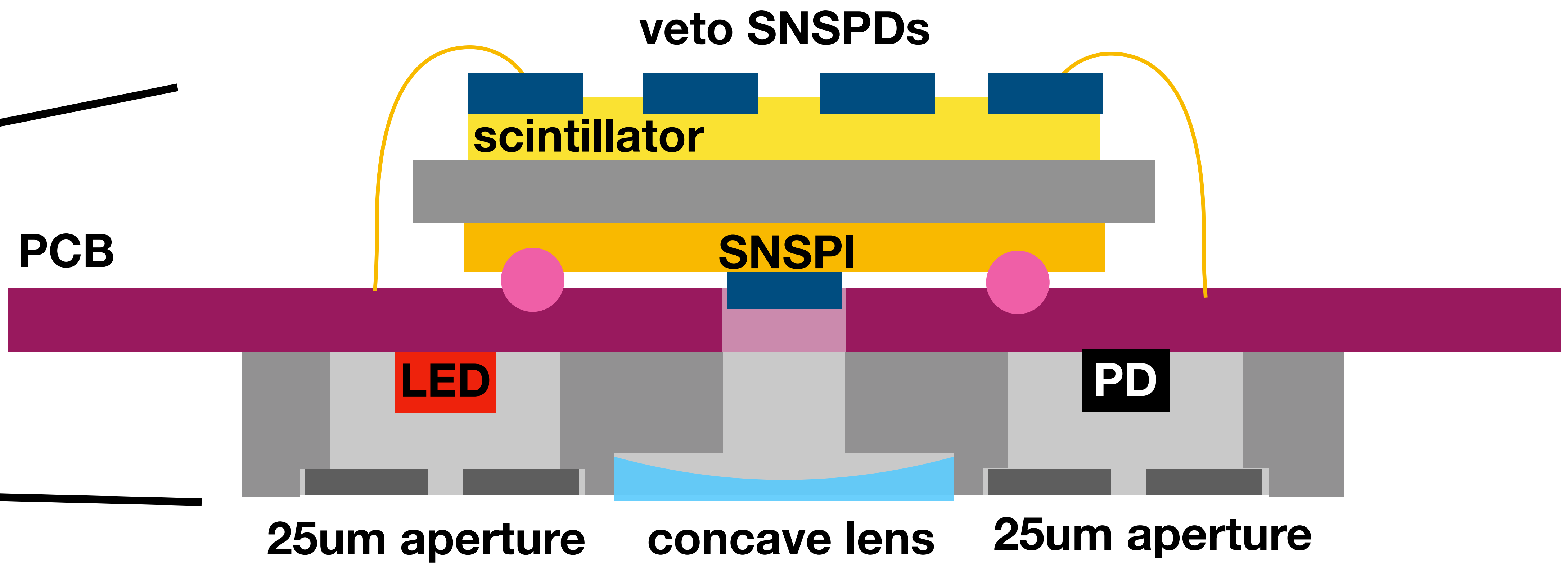




DCR $\sim 1/40$**hrs** $\sim 1/(730$**years** $\cdot$ **micron**$^2)$

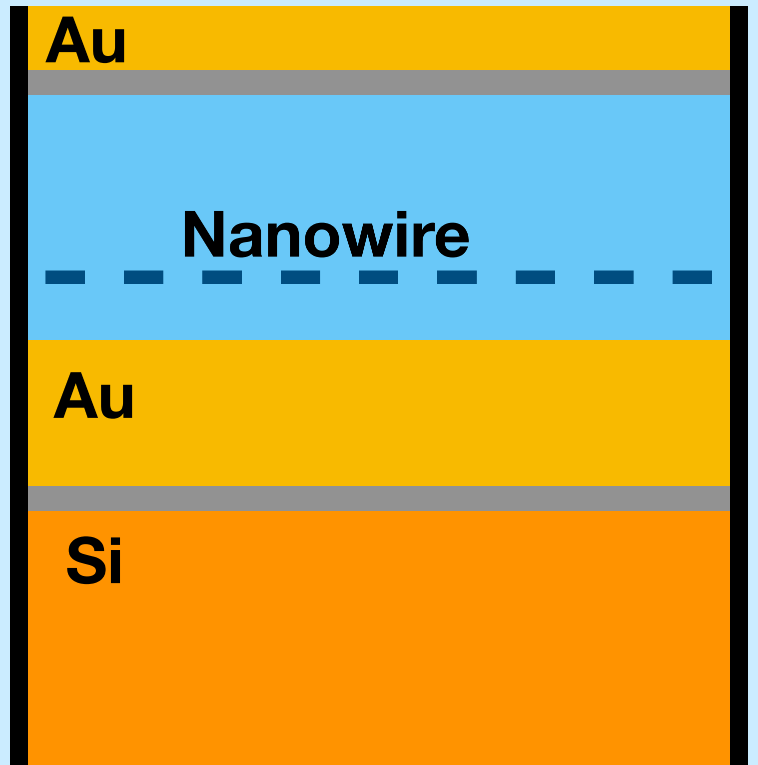
LAMPOST 2: Dielectric Haloscope with an SNSPI





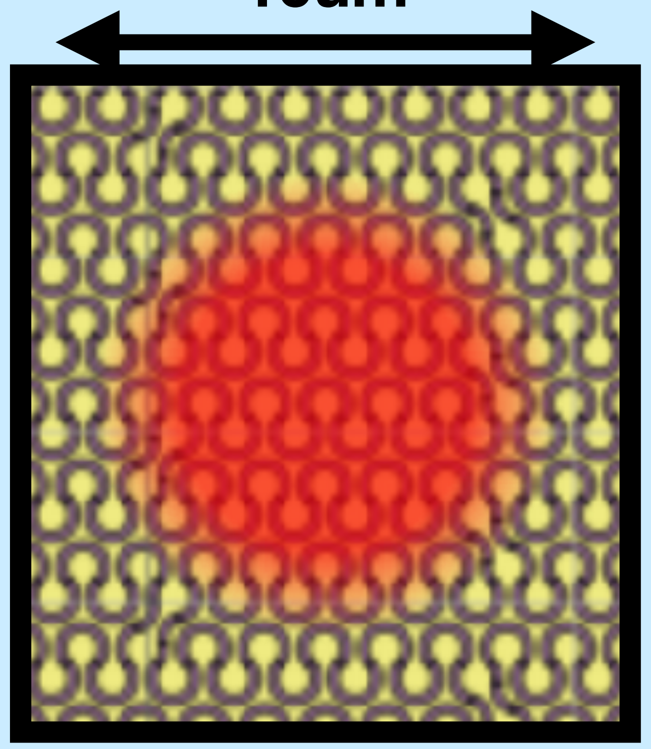
Background rejection with an SNSPI

Optical cavity:
spectral resolution

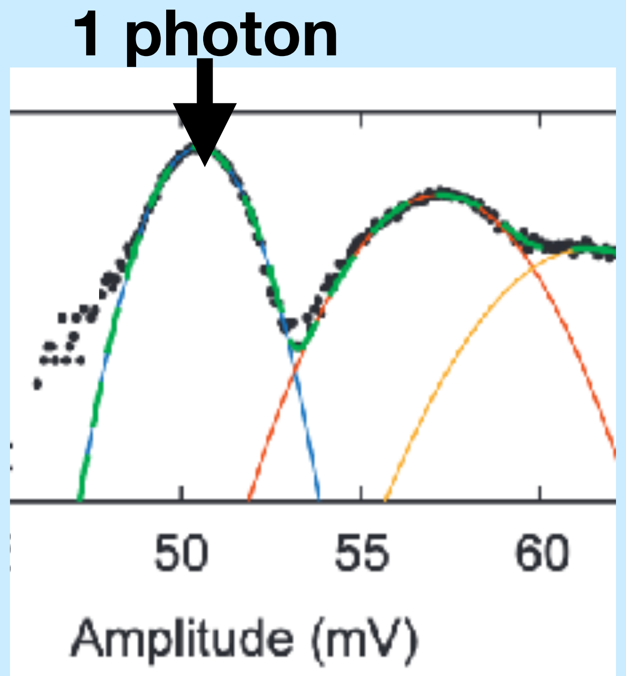


Impedance-matched output:

spatial resolution



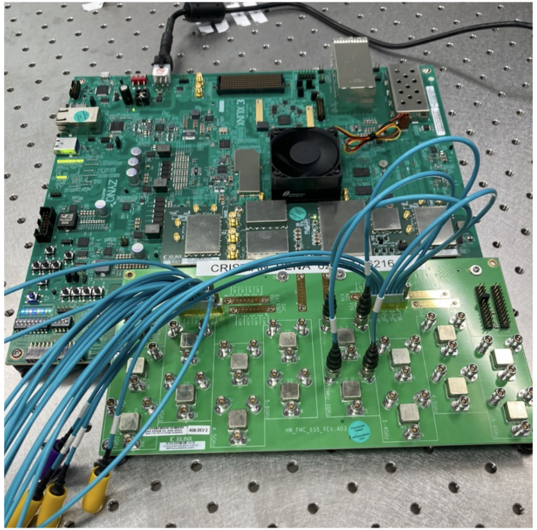
amplitude resolution



M. Colangelo, et al, "Impedance-matched differential SNSPDs for practical photon counting with sub-10 ps timing jitter,"

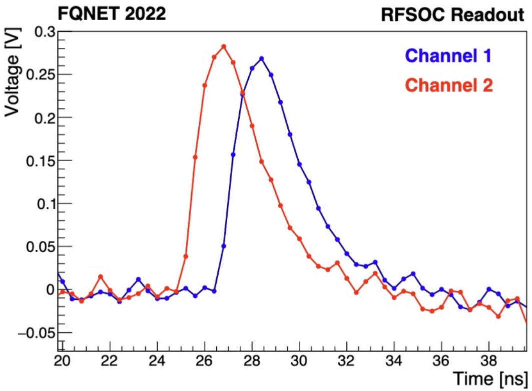
QICK SNSPD Readout Demonstrator

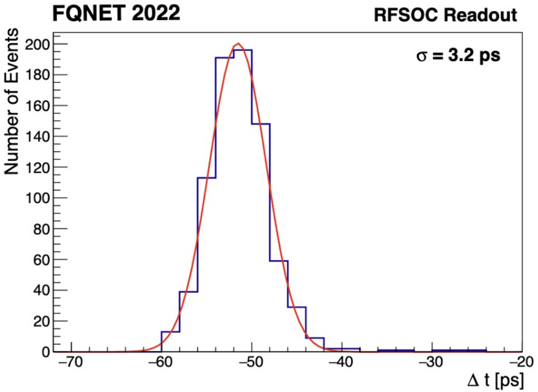
- SNSPDs are ideal low-threshold photodetectors for axion detection experiments (see talk by C.Pena)
- **Quantum Instrumentation Control Kit** System offers integrated solution to FPGA-based detector control and readout
- First demo of time-domain readout of SNSPDs sampled at 2.5Gsps, measured sync time resolution of 3ps



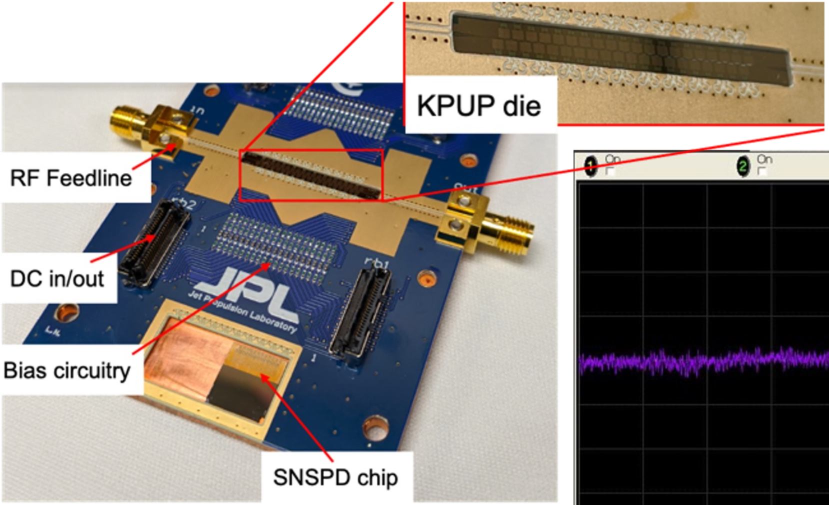
Entangled Photon Pair Source Demonstrator using the Quantum Instrumentation Control Kit System, S. Xie et al, arxiv:2304.01190, submitted to IEEE JQE.

- **Paving the way towards fast and scalable readout !**

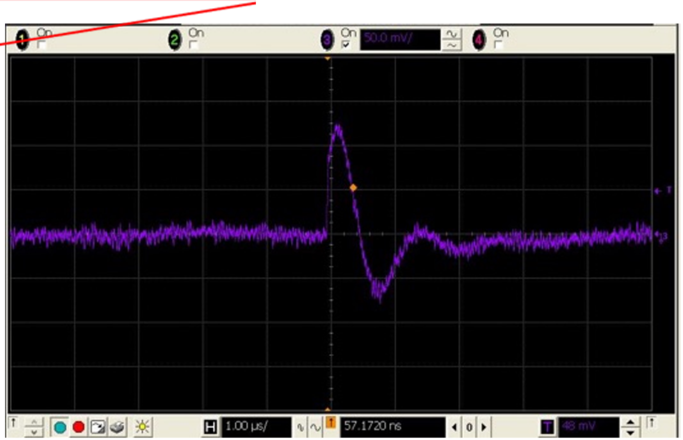




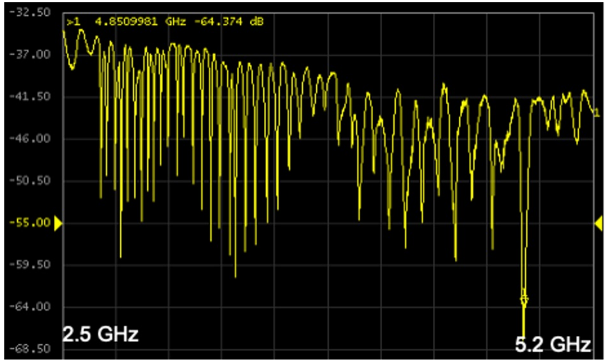
Frequency-Domain SNSPD Readout with QICK



SNSPD array interfaced to resonator chip

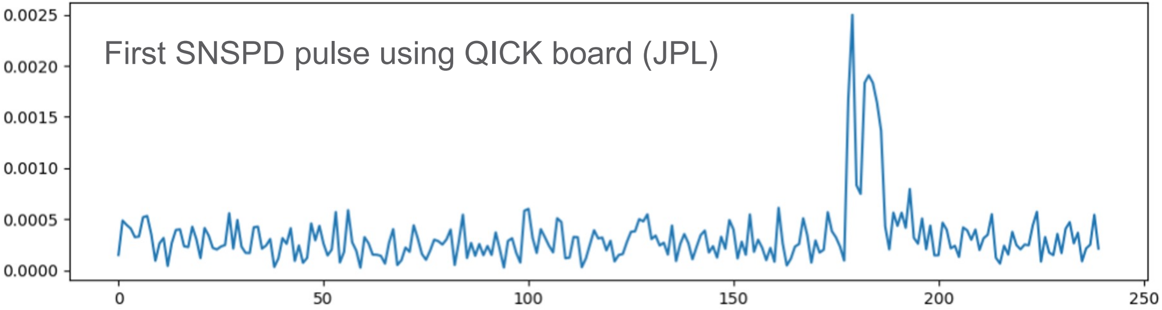


Frequency domain SNSPD readout with analog demux



40 resonators on one feedline

- Frequency-domain multiplexing is the best approach to scale to large arrays of long-wavelength (>10 μm) SNSPDs due to high current sensitivity
- Fermilab / JPL / Caltech / ASU collaboration is has recently measured first SNSPD pulses using QICK hardware and kinetic inductance parametric upconverter (KPUP)

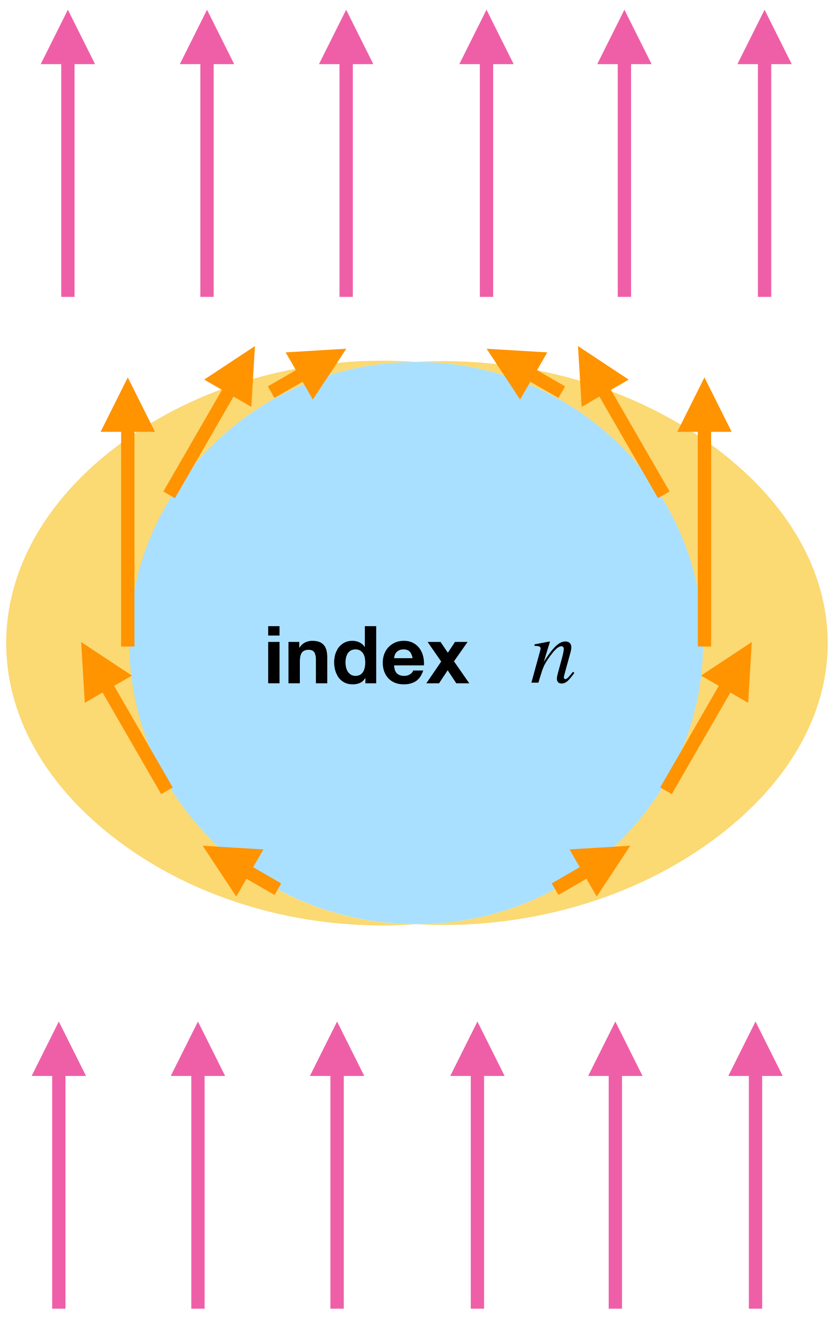


First SNSPD pulse using QICK board (JPL)

Sasha Sypkens

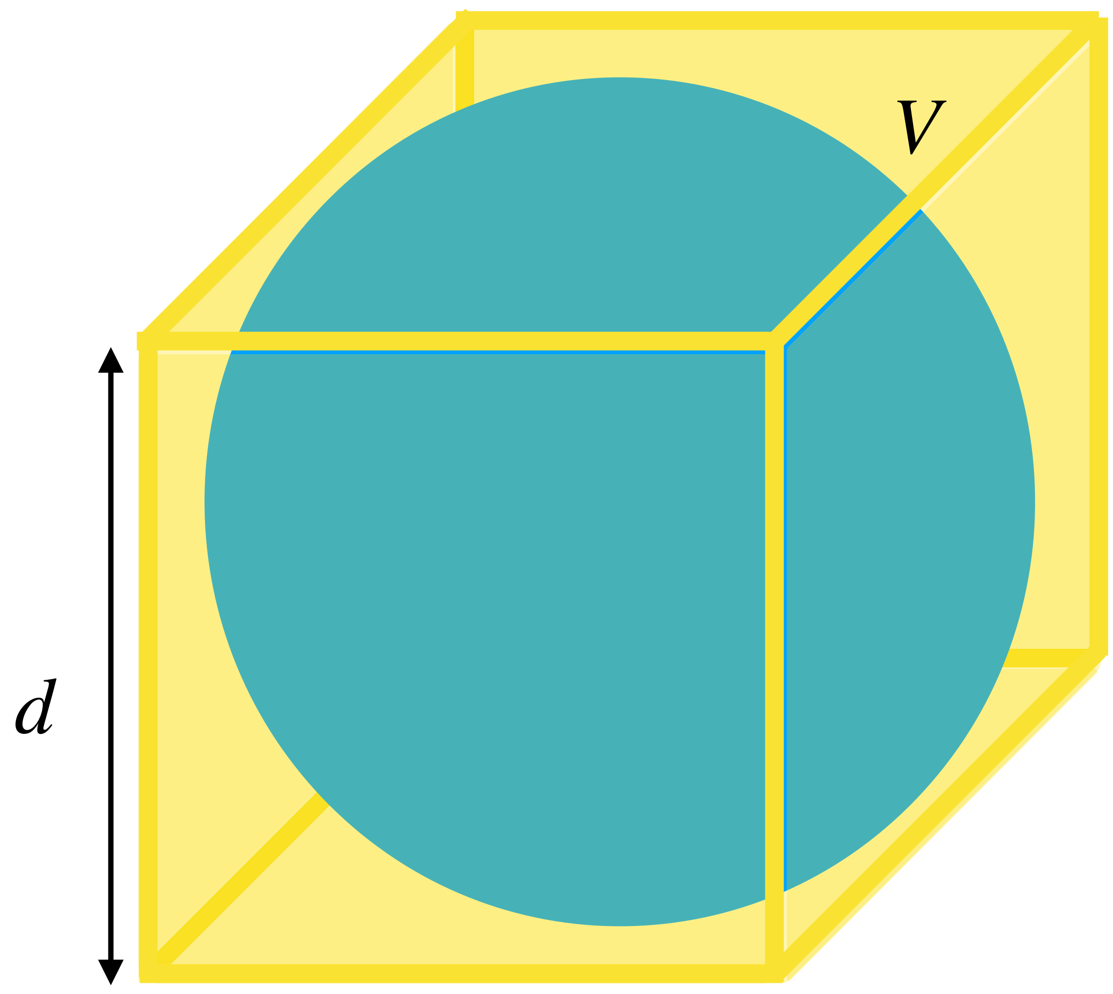
Dark Photon Absorption by a 3D Microstructure

Stewart Koppell[1], Dip Joti Paul[1], Junwu Huang[2], Karl Berggren[1] (1. Massachusetts Institute of Technology, 2. Perimeter Institute for Theoretical Physics)



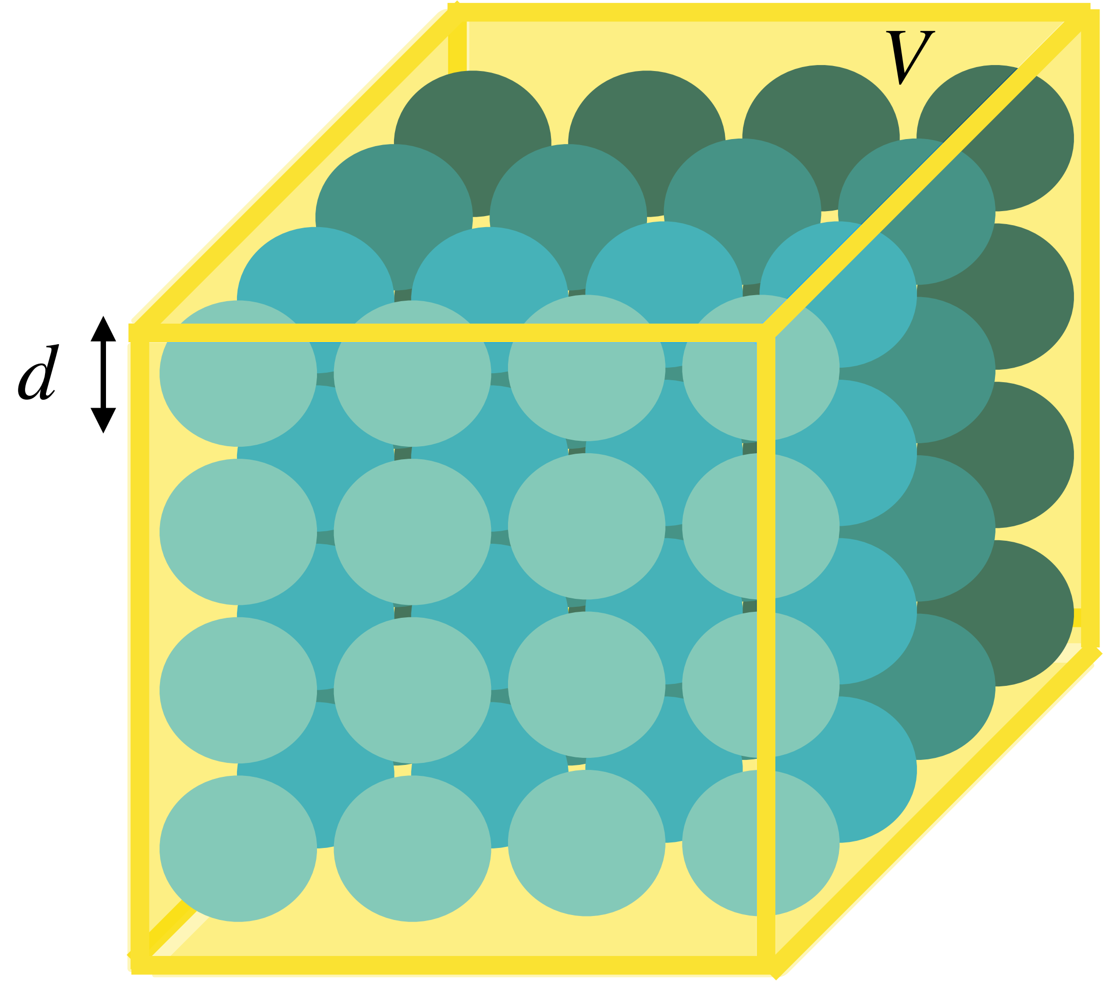
$$E_{\|} = E^a \cos(\theta)$$

$$P = \mathbf{SA}\, E_{\|}^2 \left(1 + \frac{1}{n}\right)\left(1 - \frac{1}{n}\right)^2$$



Above diffraction limit: $d \gg \lambda/2\pi$

$$\frac{P}{V} \equiv \rho \propto \frac{\mathbf{SA}}{V} \propto \frac{1}{d}$$



Below diffraction limit: $d \ll \lambda/2\pi$

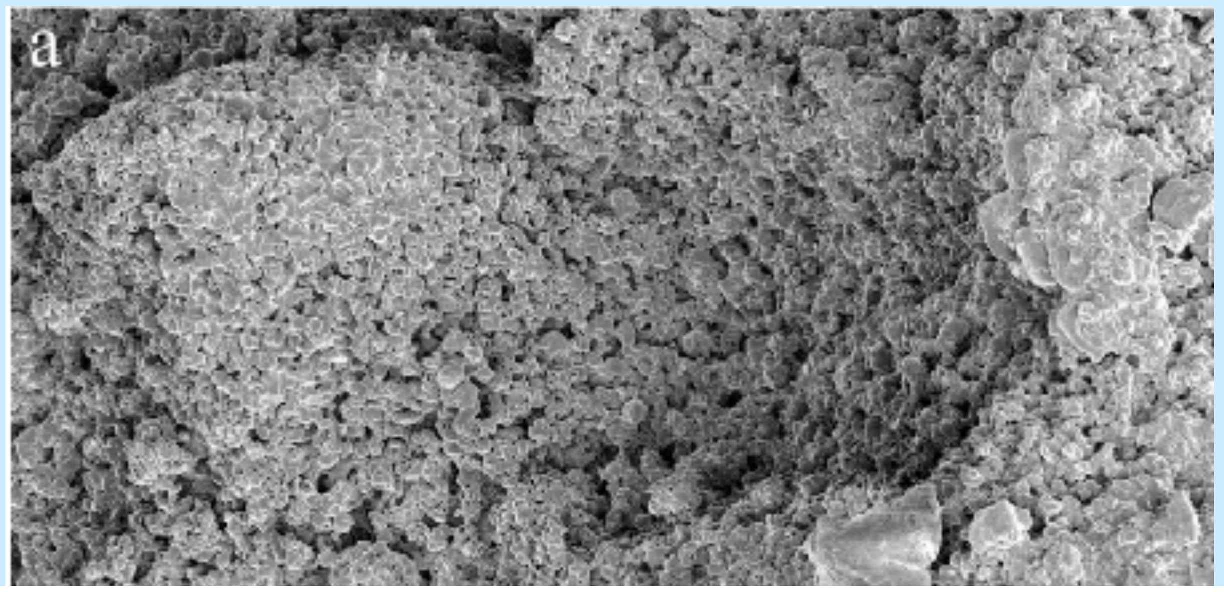
$$\rho \propto \frac{d^3}{\lambda^4}$$

Porous Alumina

Absorption $\alpha \sim 0.1m^{-1}$

Scattering $\beta \sim 0.2cm^{-1}$

Diffusion $\gamma \sim \sqrt{\alpha\beta}$



Near-infrared optical properties of a porous alumina ceramics produced by hydrothermal oxidation of aluminum

Aleksey V. Lisitsyn[a], Leonid A. Dombrovsky[b,*], Vladimir Ya. Mendeleyev[a], Anatoly V. Grigorenko[a], Mikhail S. Vlaskin[a], Andrey Z. Zhuk[a]

[a] Joint Institute for High Temperatures, NCHMT, Krasnokazarmennaya 17A, Moscow 111116, Russia
[b] Joint Institute for High Temperatures, Izhorskaya 13-2, Moscow 525003, Russia

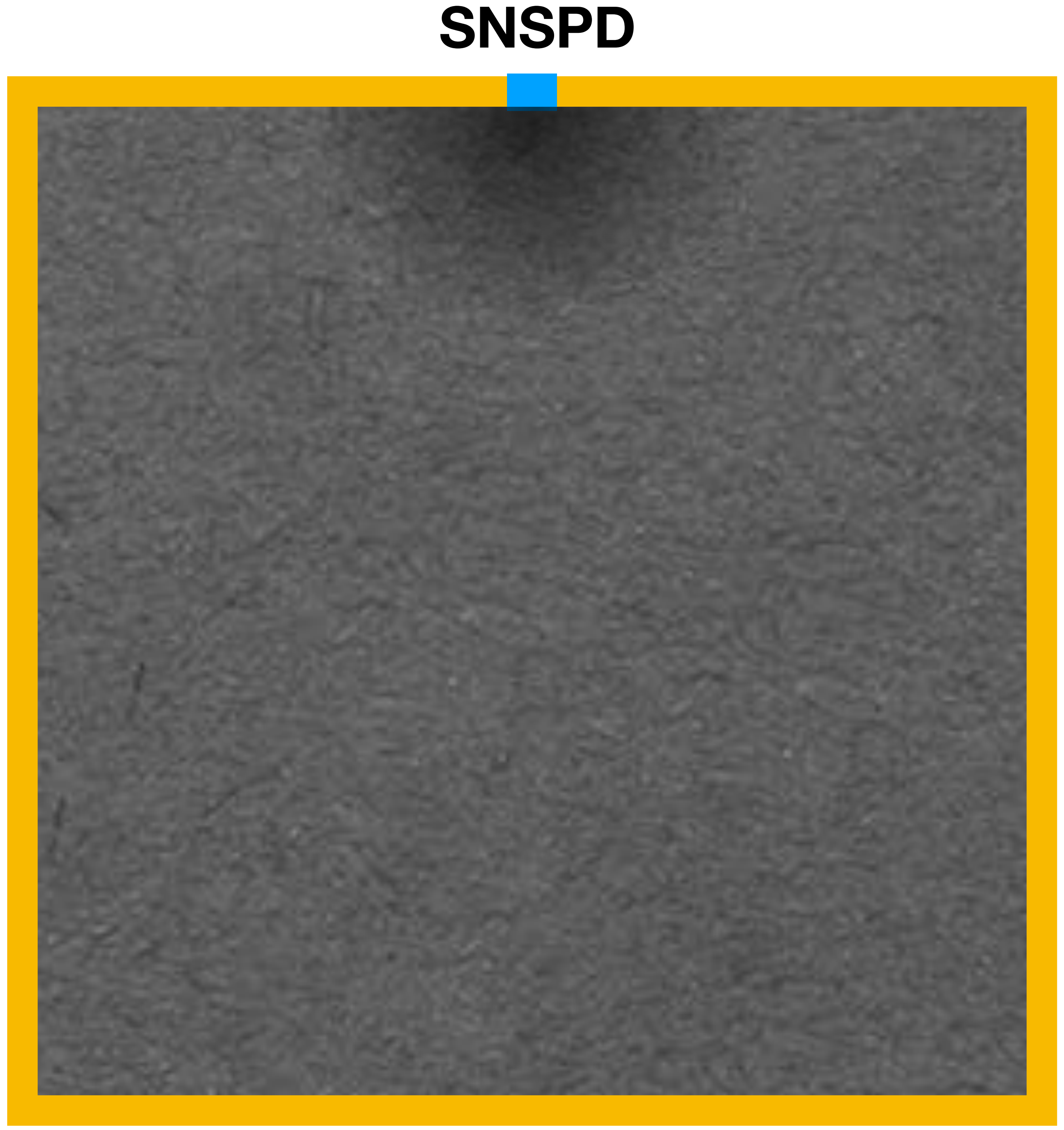
Collecting photons

0.7um Dielectric Powder

Diffusion Length $1/\gamma = 3mm?$ **Specific Surface area** $3m^2/cm^3$

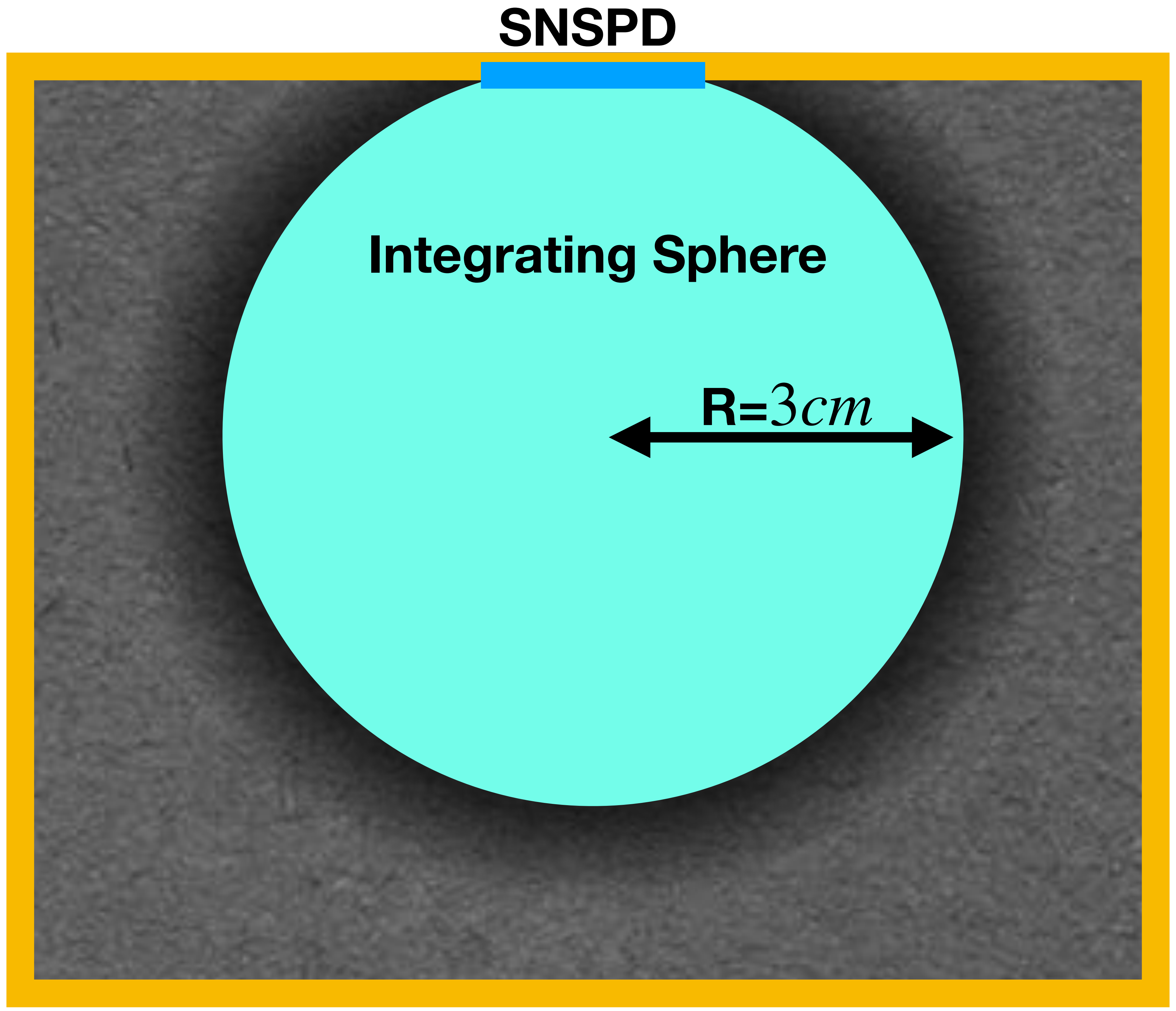
Effective volume:
$1/\gamma^3 = (3mm)^3$

Effective area:
$0.1m^3$

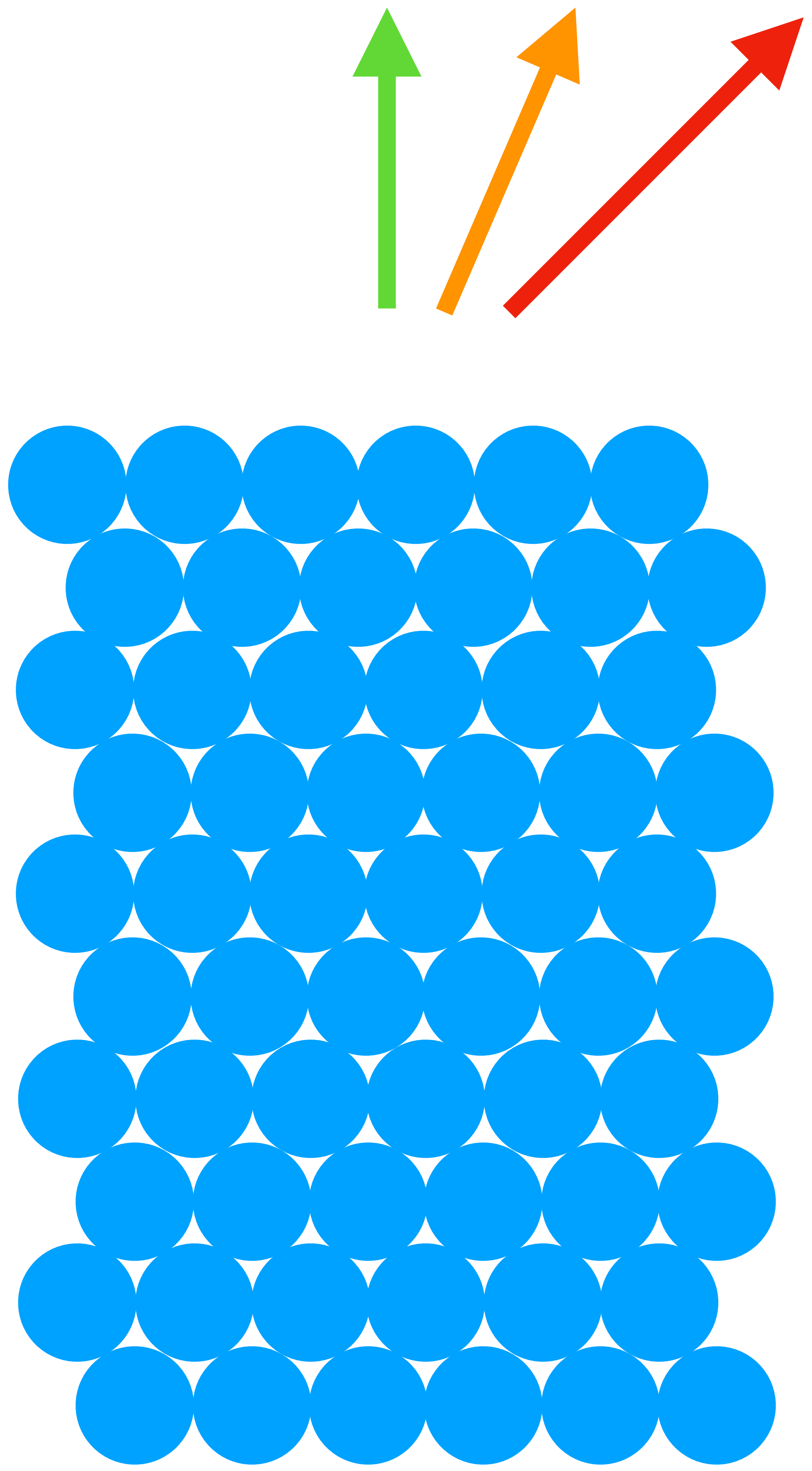


Effective volume:
$4\pi R^2/\gamma = 34cm^3$

Effective area:
$100m^2$



Photonic Crystal



Jet Propulsion Laboratory
California Institute of Technology

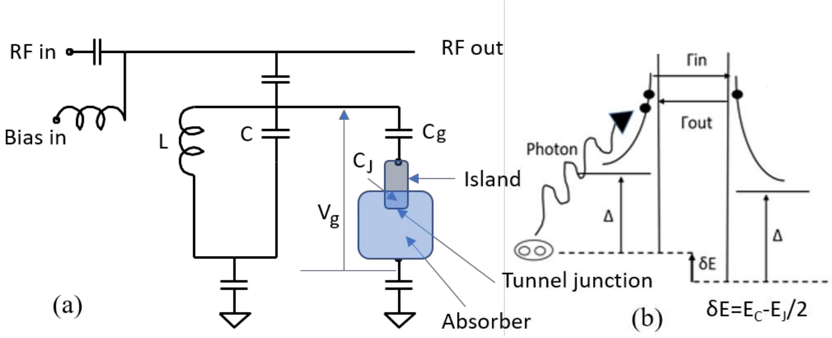
Fermilab

The Quantum Capacitor Detector for Terahertz Single Photon Counting

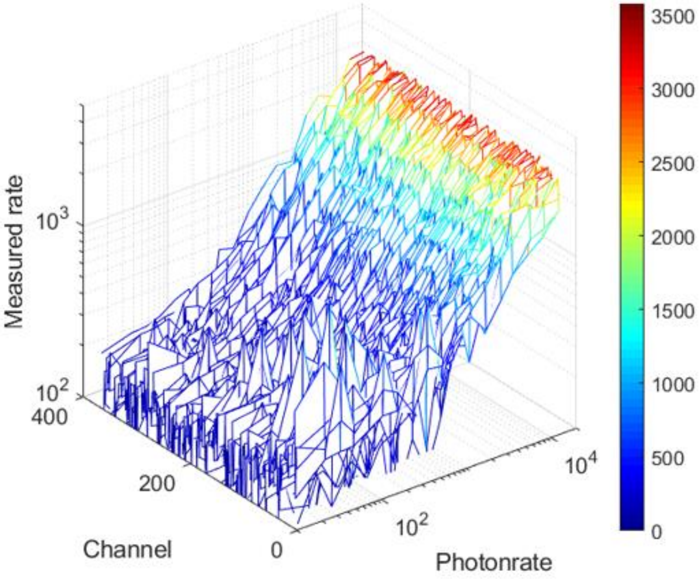
A.D. Beyer[1], A. Chou[2], P.M. Echternach[1], R. Khatiwada[3], J. Lu[3],M.D. Shaw , Sven van Berkel[1]

[1]Jet Propulsion Laboratory, California Institute of Technology,[2]Fermilab,[3]Illinois Institute of Technology

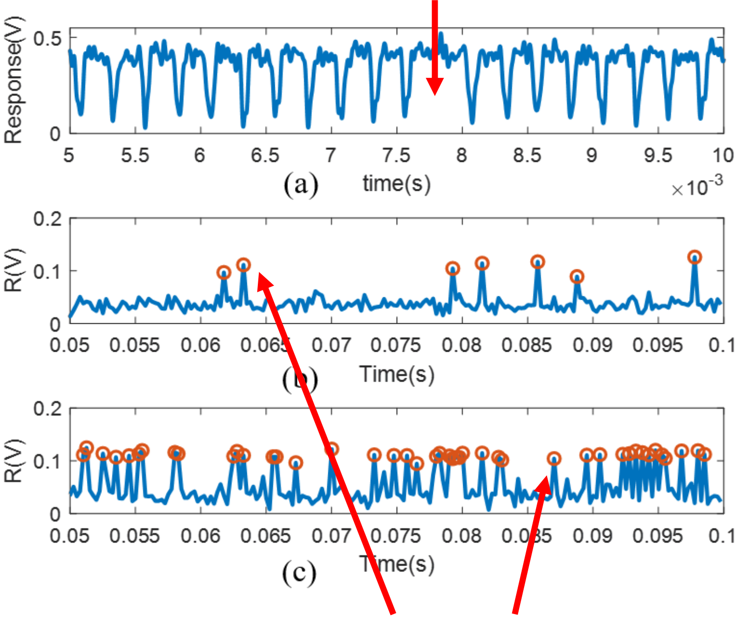
QCDs exploit the extreme susceptibility of a charge qubit to external influences to make an extremely sensitive far IR detector



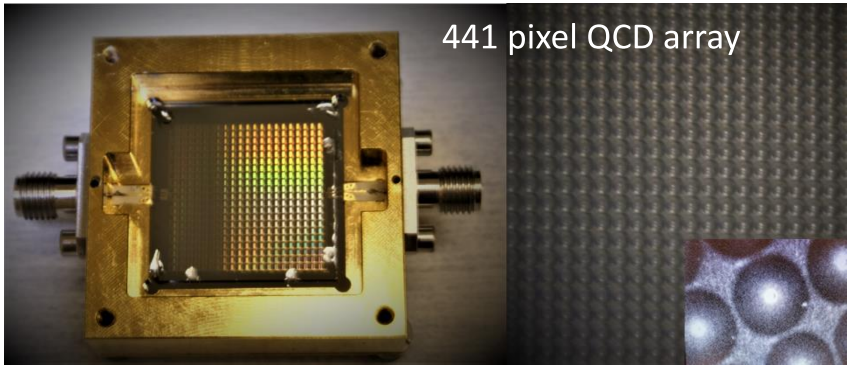
Measured photon rate as function
Of optical radiation power in 441 pixel array



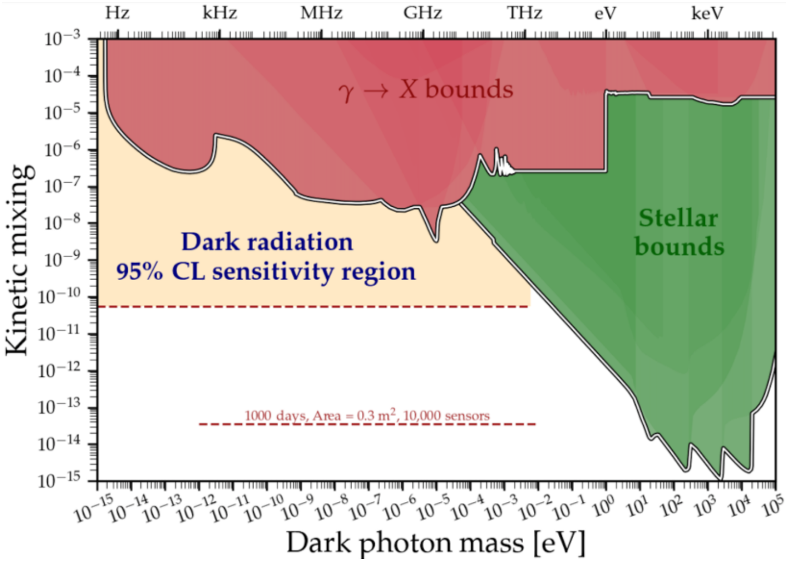
Missing quantum capacitance peak indicates photon detection event



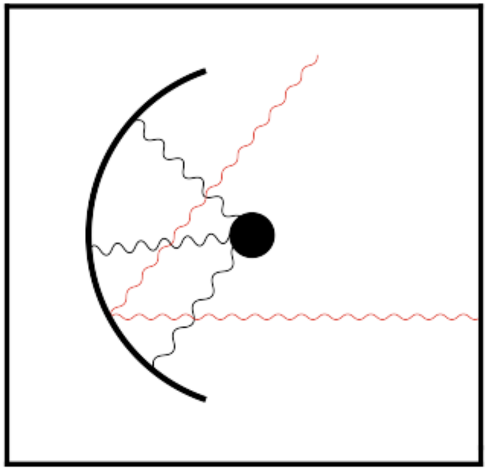
Photon events for cold and hot black body


441 pixel QCD array

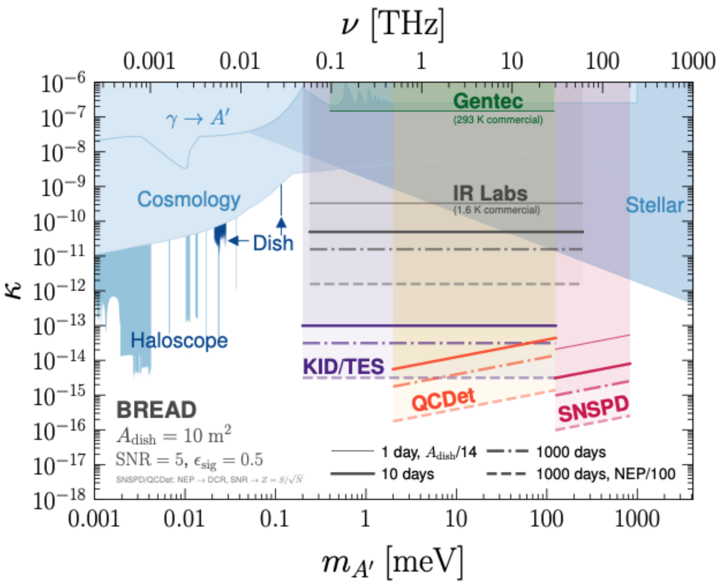
Applications - Dark Radiation, Hidden photon and axion dark matter



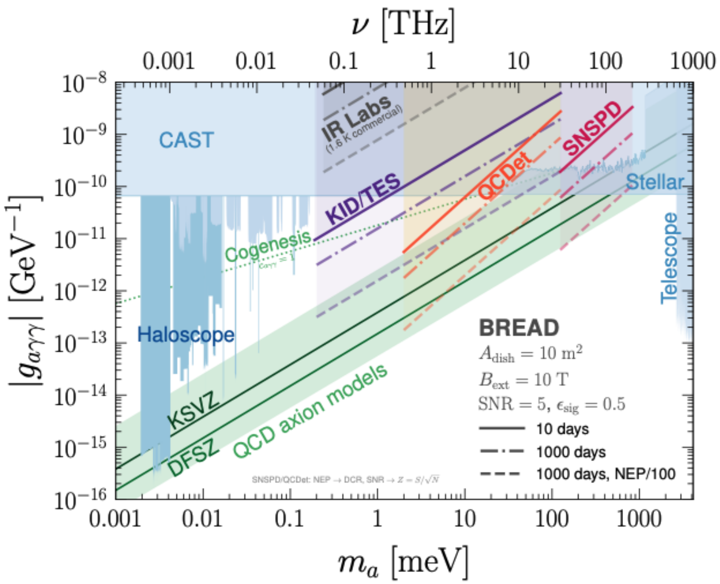
Dark photons convert to visible photons upon scattering on impedance mismatched materials



Dark Photon sensitivity



Axion sensitivity



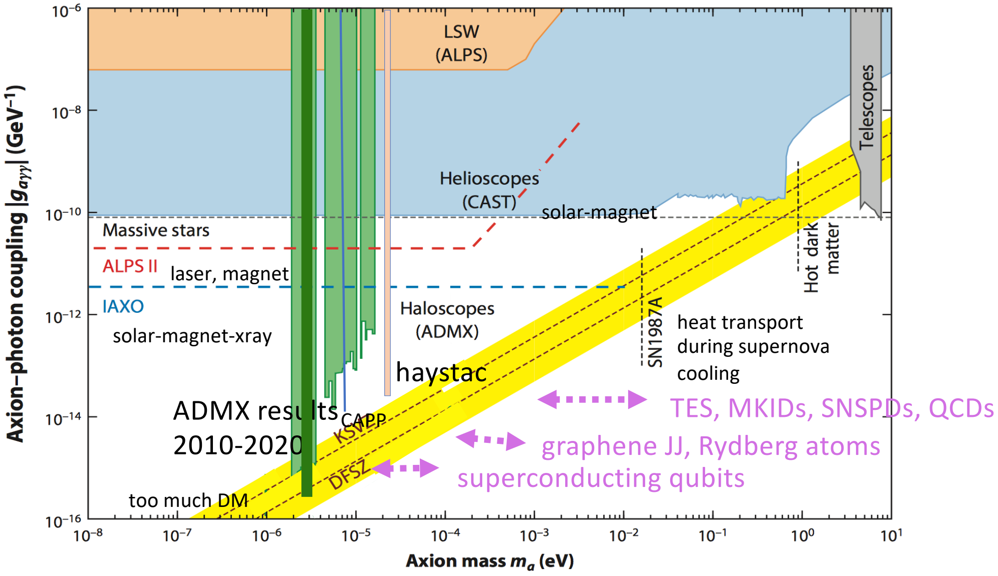
Dark Matter detection with Quantum Capacitance Detectors

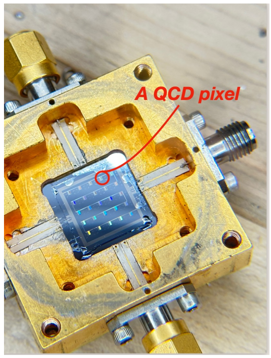
Rakshya Khatiwada

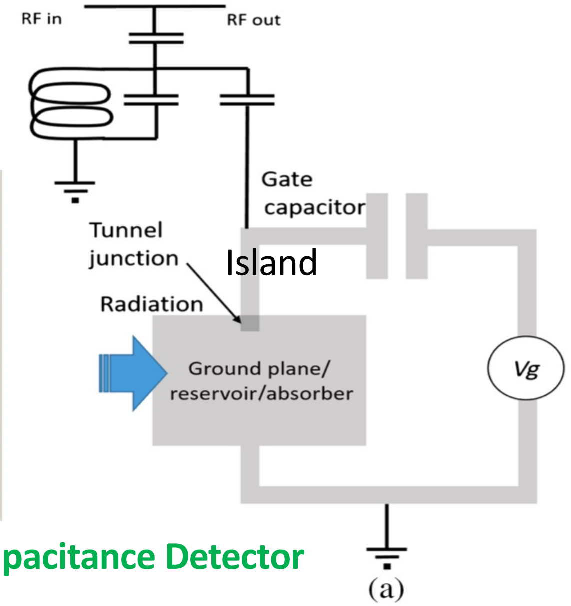
Illinois Institute of Technology

Fermilab

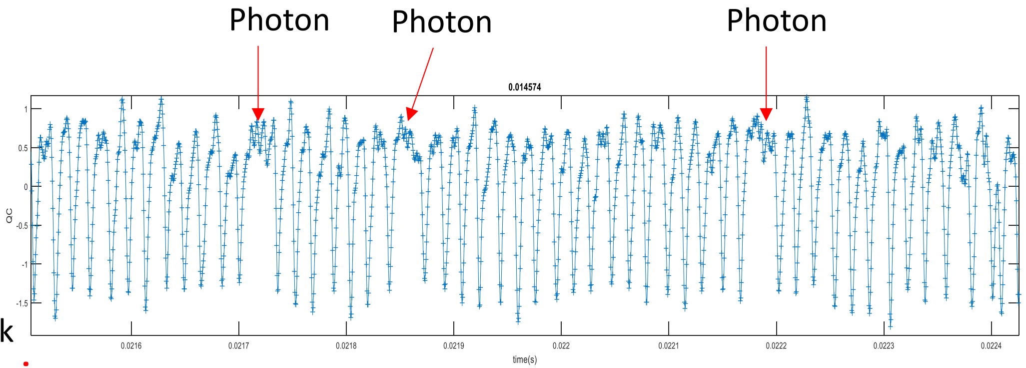
Motivation





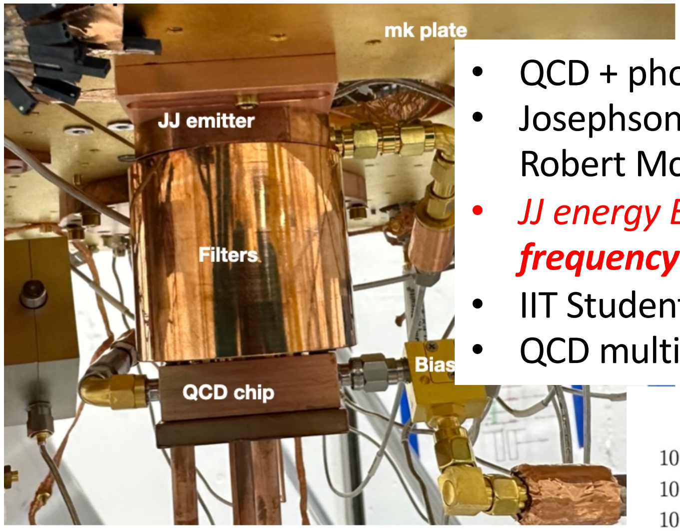


Quantum Capacitance Detector



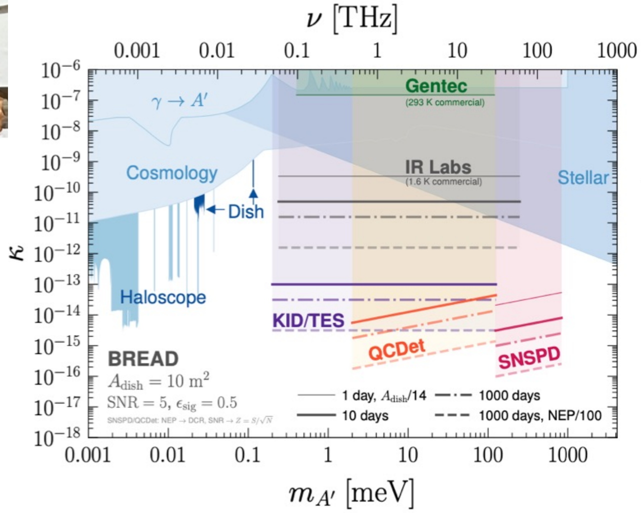
- ➢ How do we bridge the gap between ultralight to GeV Dark Matter?
- ➢ Most successful Haloscope experiments limited by quantum noise
- ➢ Lack of detection technology limiting the progress
- ➢ Qubits: great potential for low energy radiation detection
- ➢ Proven single photon counting with Qubits ~ few GHz
- ➢ Can we expand it further to probe even higher mass, wave like Dark Matter? **JPL (Echternack), Fermilab (Chou, Khatiwada, Yu), Wisconsin (McDermott, Harrison) collaboration**

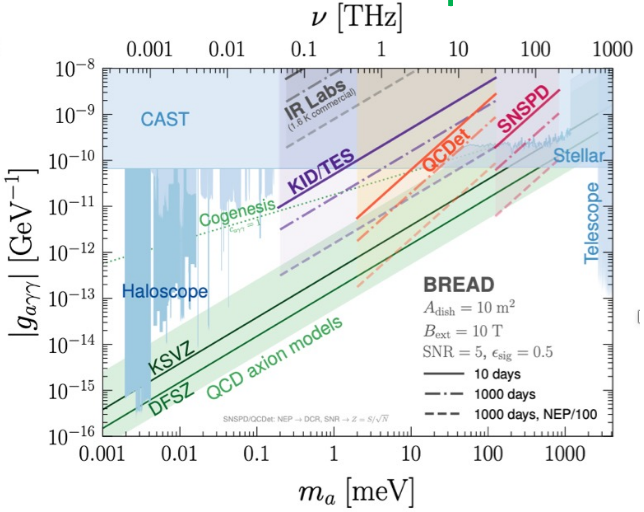
QCD single photon counter for Dark Matter



- QCD + photon emitter source integration in progress at FNAL/IIT
- Josephson Junction based photon emitter source for fab. by Robert McDermott's group
- *JJ energy $E_j = 2eV_{DC}$ => **$f = 2eV_{DC}/h$ produces photons at this frequency***
- IIT Student supported by FNAL LDRD
- QCD multiple array readout and characterization in progress

Projected sensitivity for Broadband Antenna BREAD experiment





(BREAD Collaboration)
Phys. Rev. Lett. **128**, 131801 – Published 28 March 2022

- QCD: great potential for THz photon detection
- **Map out:** **Energy deposited from DM photon in Al -> Broken cooper pairs -> quasiparticles tunneling rate higher -> qubit charge parity 'signal' readout**

Nonlinear Kinetic Inductance Devices for Cosmic Frontier Science

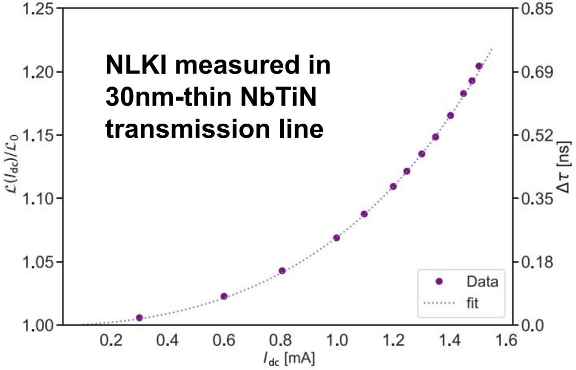
[a] Jet Propulsion Laboratory
California Institute of Technology
[b] Caltech

R. Basu Thakur [a,b], **P. K. Day**[a], **D. Cunnane**[a], **K. Ramanathan**[b], **J. Zumidzinas**[b]

Nonlinear Kinetic Inductance (NLKI)

Kinetic inductance in thin-film superconductors, NbTiN, MgB2 etc. varies non-linearly with supercurrent

$$\mathcal{L}(I) \approx \mathcal{L}_0 \left(1 + \left(\frac{I}{I_*}\right)^2 + \left(\frac{I}{I'_*}\right)^4 + \ldots\right)$$

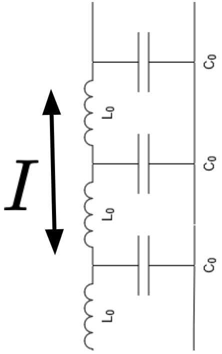


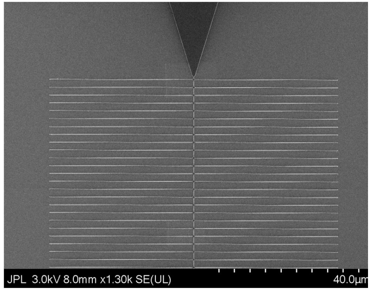
NLKI measured with resonators & transmission lines in 1-100 GHz

THz devices under R&D

Devices fabricated with phase velocities ~0.1%c & ~10% NLKI

NLKI in transmission lines





NbTiN transmission line
250nm-wide central conductor

- In dispersion-engineered transmission lines, NLKI can enable frequency mixing processes (akin to nonlinear crystals)

$$\frac{1}{\mathcal{L}_0 C}\frac{\partial^2 I}{\partial z^2} = \frac{\partial^2 I}{\partial t^2} + \boxed{\frac{1}{I_*^2}\frac{\partial}{\partial t}\left[I^2\frac{\partial I}{\partial t}\right]} \Rightarrow$$

Parametric amplification @ SQL & frequency conversion demonstrated

- In non-dispersive transmission lines, NLKI can enable field-tunable delay of the RF signal by applying DC current

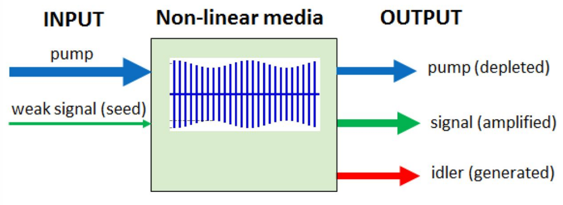
$$\Delta\tau(I) = \sqrt{\mathcal{L}(I)\mathcal{C}}$$

~1 ns achieved, targeting micro-seconds

ritoban@caltech.edu

Traveling Wave Parametric Amplifiers (TWPA)

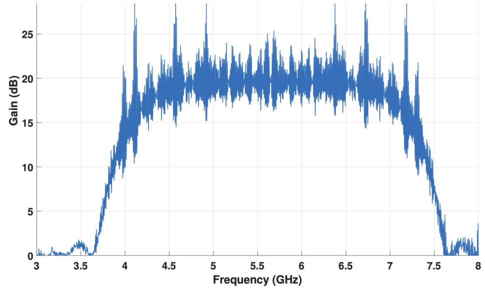
See arXiv: 2209.03419, 2103.00656, 2111.06558, 1909.02100, Klimovich 2002 (Caltech PhD thesis)



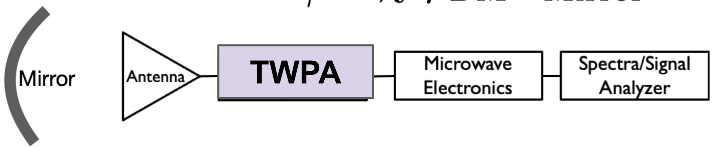
Transmission line with phase-matching & dispersion engineering, thus amplification

TWPAs used for dark matter searches

~17 dB gain = 3 x standard quantum limit noise, actively pushing to SQL

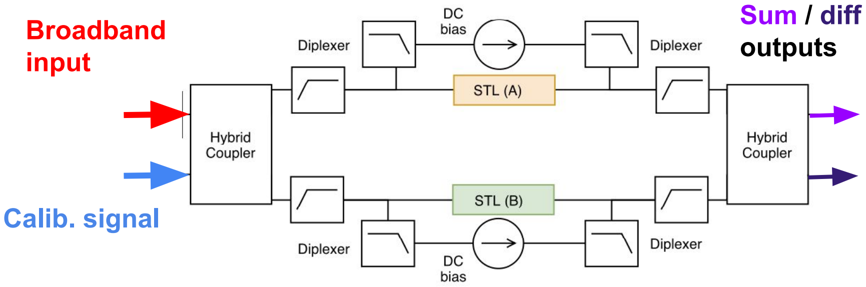


$$\text{Power}_\gamma \sim \chi^2 \rho_{\text{DM}} A_{\text{Mirror}}$$

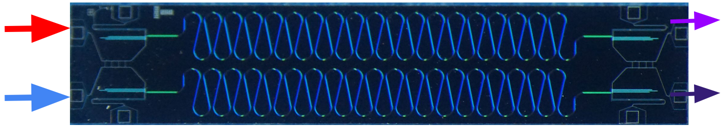


QUAntum **LI**mited **PH**otons **I**n the **D**ark **E**xperiment set leading limits on hidden photon dark matter in 20-30 ueV … planned expansion to 500 ueV

Superconducting On-chip Fourier Transform Spectrometer (SOFTS)



Tunable *electromagnetic* delay (no mirrors) via NLKI
Ultracompact as v_{phase} ~0.1%c, broadband and lossless
Integrable with TWPAs/ QCDs/ KIDs for photonic circuits



6mm prototype device for 20-40 GHz signals with 1GHz resolution

4-port Mach Zehnder form with two transmission lines
SOFTS does calibrated lossless broadband spectroscopy

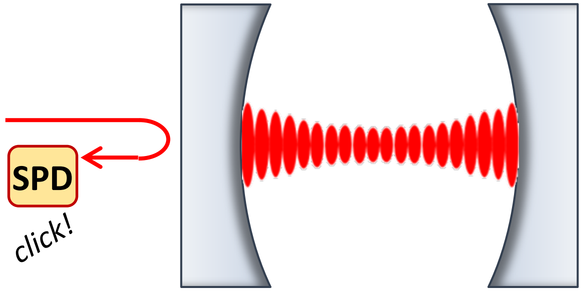
Line intensity, galaxy-cluster spectro-imaging, CMB spectral distortions, dark-sector searches, quantum-optics experiments

Quantum Optomechanics for HEP

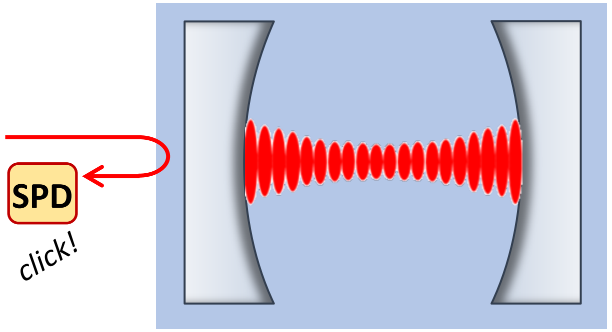
Jack Harris, Yogesh Patil, Yiqi Wang, Lucy Yu *Depts. of Physics & Applied Physics and YQI, Yale University*

- **Almost everything you can say about EM cavities can also be said about acoustic cavities.** *Quality factor, volume, geometry, readout, etc.*
- **One nice recipe for this:**

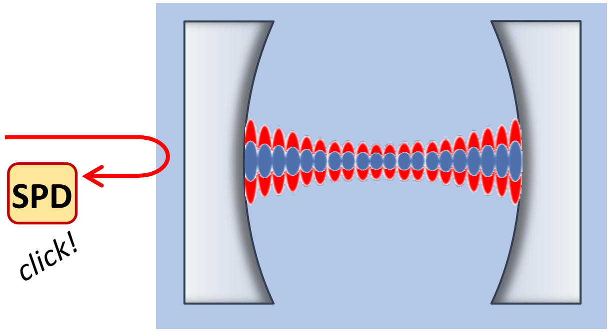
Take any electromagnetic cavity...



...and fill it with superfluid helium.
The EM modes are unchanged...



...and the superfluid has acoustic modes!



- The electromagnetic modes can be used to readout and control the acoustic modes – and vice versa.

- **A nice consequence of this interaction:**

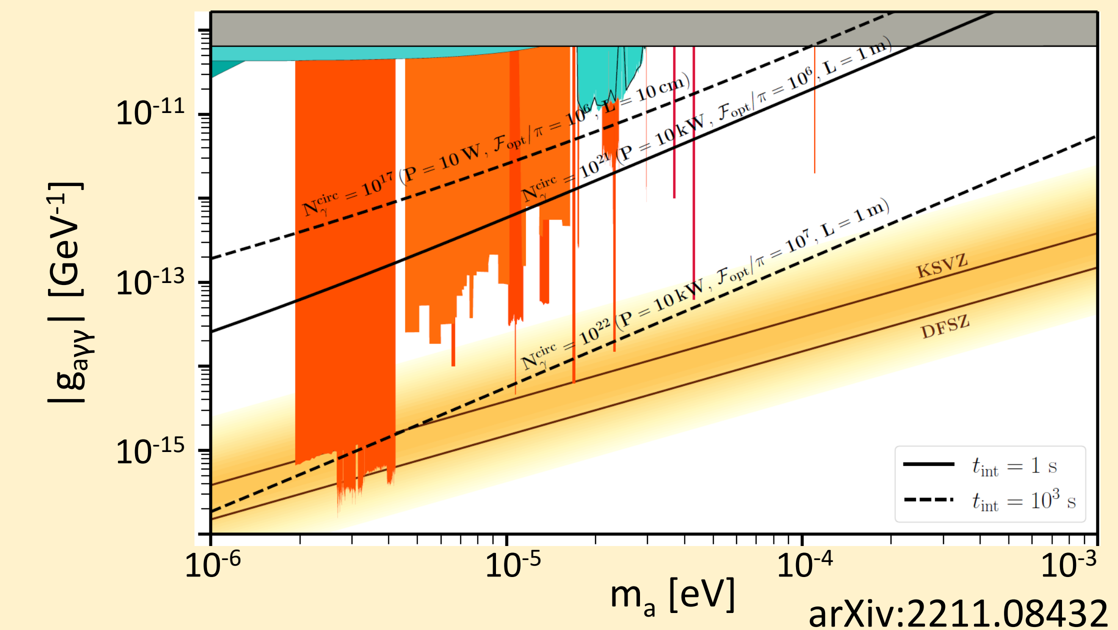
detection of a $\underset{\approx 1\ \mathrm{eV}}{\underline{\text{single photon}}}$ can serve as detection of a $\underset{\approx (v_{\mathrm{He}}/c) \times 1\ \mathrm{eV} \approx 1\ \mu\mathrm{eV}}{\underline{\text{single phonon}}}$

- **An important fact:** Only phonons in a single mode of the cavity are detected

Bad for typical DM searches →

Ongoing collaboration with Kathryn Zurek, Clara Murgui, Yikun Wang.
Stay tuned!

Good for typical cavity quantum dynamics (next slide, please!)

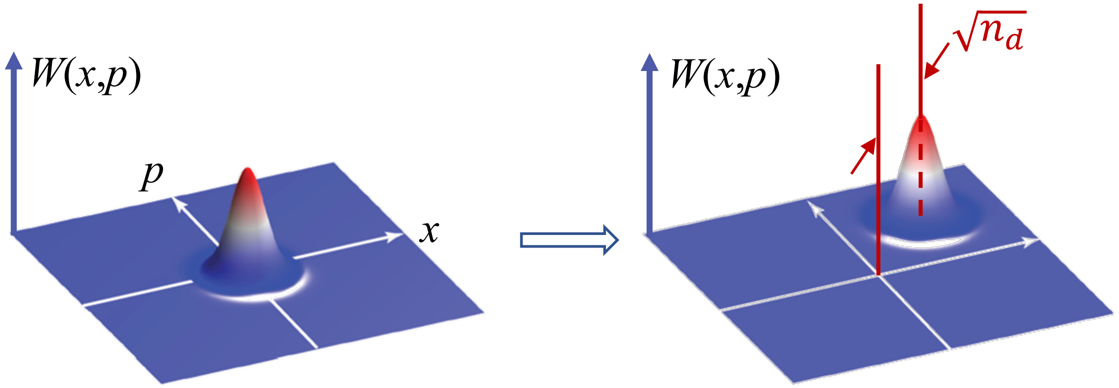


arXiv:2211.08432

Quantum Optomechanics for HEP

Jack Harris, Yogesh Patil, Yiqi Wang, Lucy Yu *Depts. of Physics & Applied Physics and YQI, Yale University*

Testing quantum linearity with single-mode optomechanics



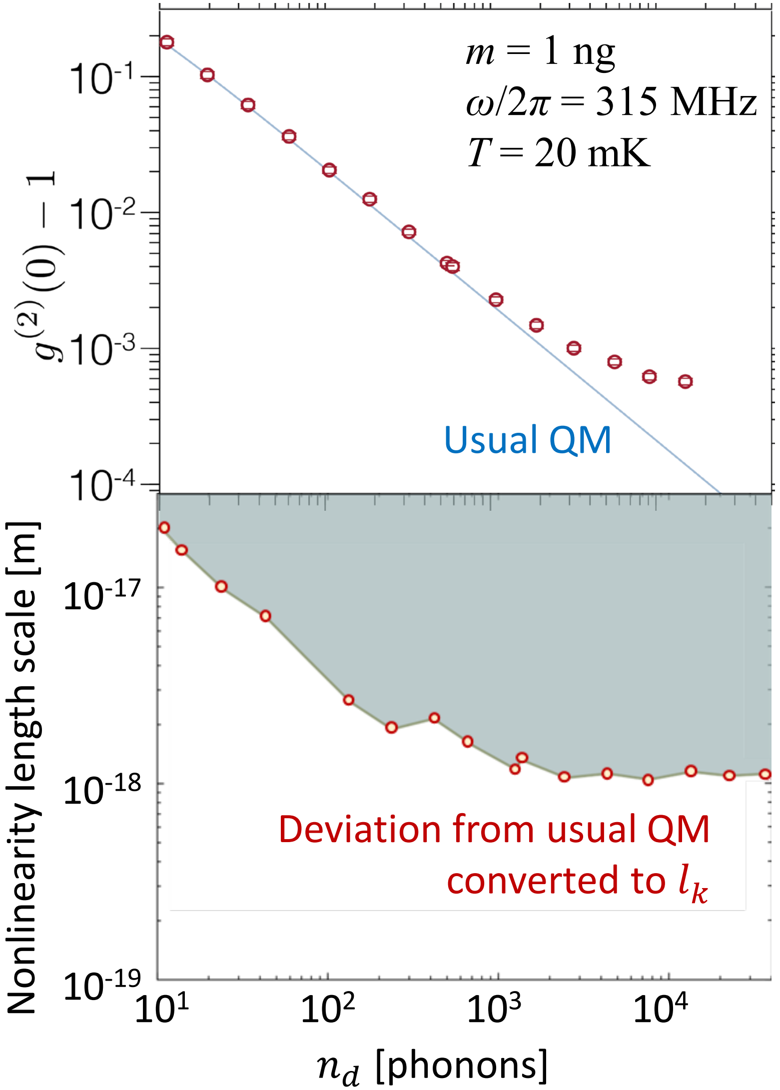
in thermal equilibrium (n ~ 1)   subject to a linear drive

If the oscillator is linear, the state is simply displaced.

Phonon statistics are well-known: $g^{(2)}(0) = 1 + \frac{2n_{th}}{n_d}$

For weak nonlinearity, there will be deviations for large n_d.

Measured phonon statistics:



A proposal* from quantum gravity phenomenology:

- To reconcile LI & discreteness at Planck scale, the box operator must become nonlinear.
- In non-relativistic limit, Schrödinger operator $\mathcal{S}$ inherits this nonlinearity:

$$\mathcal{S} \longrightarrow \mathcal{S} + \sum_{n=2}^{\infty} b_n \left(\frac{-2m}{\hbar^2}\right)^{n-1} \underline{l_k^{2n-2}}\, \mathcal{S}^n$$

empirical length scale, not necessarily Planck

- This would change the phonon statistics: $g^{(2)}(0) = \underbrace{1 + \frac{2n_{th}}{n_d}}_{\text{Usual QM}} + \underbrace{\frac{18 n_d m \omega}{\hbar}\left(1 + \frac{n_{th}}{2}\right) b_2 l_k^2}_{\text{Nonlinearity}}$

*Belenchia, *et al.*, PRD 95, 026012 (2017);
Belenchia, *et al.*, PRL 116, 161303 (2016);

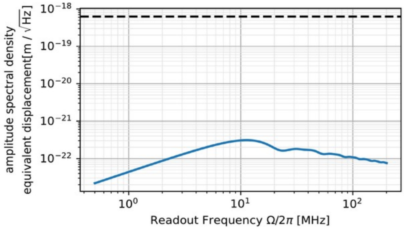
HEP Interferometry via photon counting

Lee McCuller **Caltech**

Interferometry & optomechanics:
- Profoundly sensitive to gravitational physics
- macroscopic quantum mechanics
- applications in DM detection

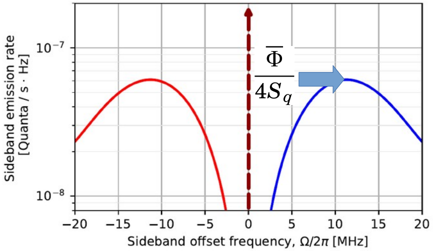
“wavelike” detectors limited by “quantum noise”
from homodyne readout or parametric amp readout

Make interferometry more like rare-process HEP
Signal power statistics → linear in time detection/exclusion
– no background “counts” from vacuum fluctuations
requires suitable search statistics



Small, wideband stochastic
metric fluctuation signal
Orders of magnitude below shot noise
~3 months for 1σ by incoherent search stat.

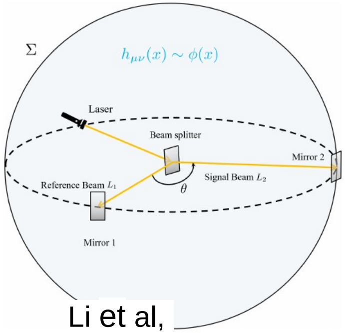
McCuller 2211.04016



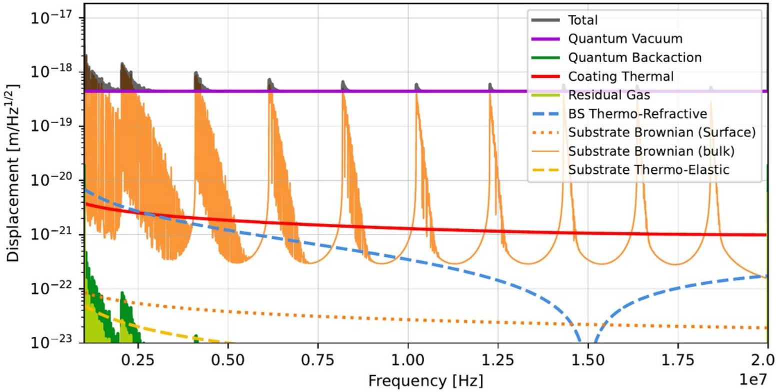
Equivalent sideband photopower
Emits 1 photon/second
Vastly accelerated search

GQuEST:

Gravity from Quantum Entanglement of Space-Time

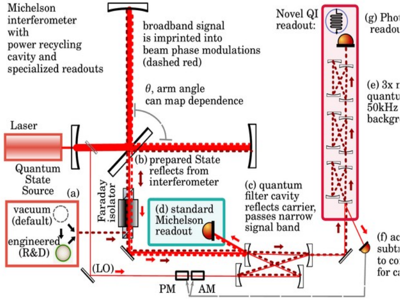


Li et al,
arXiv:2209.07543



Pathfinder for high-contrast
photon counting
10kW interferometer → mHz count rate

High-frequency signal amenable
to first attempts at counting
but requires new sophistication
→ unique design elements



Finds an entanglement-entropy
basis for gravitation - via
Metric fluctuation signature:

Banks, KZ 2108.04806
E. Verlinde, KZ 1902.08207
E. Verlinde, KZ 1911.02018

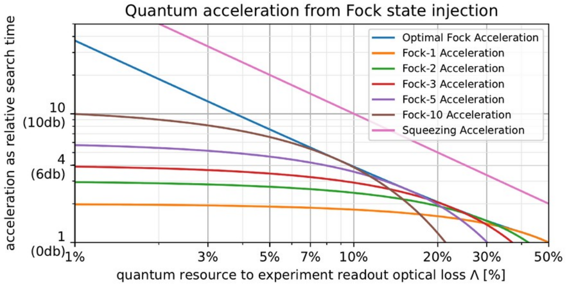
Novel Quantum Enhancements

LIGO’s performance speaks volumes.
we’ve learned to saturate the benefits from squeezing.
Loss-engineering (in optical) will be
incremental and *trade* with higher power

Developing photon counting is a prerequisite to demonstrate *any* non-Gaussian observable at high contrast

Squeezing adds background counts → better quantum enhancements exist.

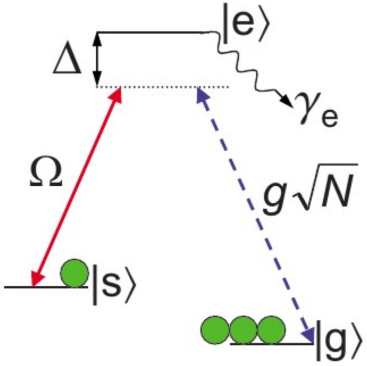
research quantum-enhanced Non-quadrature, non-Gaussian observables.



Generalized Counting

Employ quantum memories
implement matched-template search.
Generalize temporal-mode basis
beyond Lorentzian signal wavelets

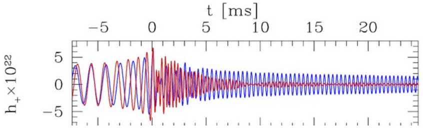
PhysRevA.76.033804



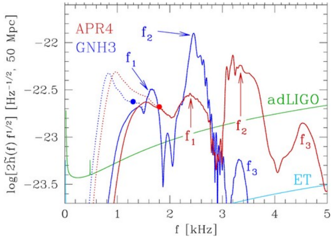
Science Goal

Binary Neutron Star inspiral “Equation of State”
strong-field nuclear matter in strong-field GR
Neutrino energy transport highly influences

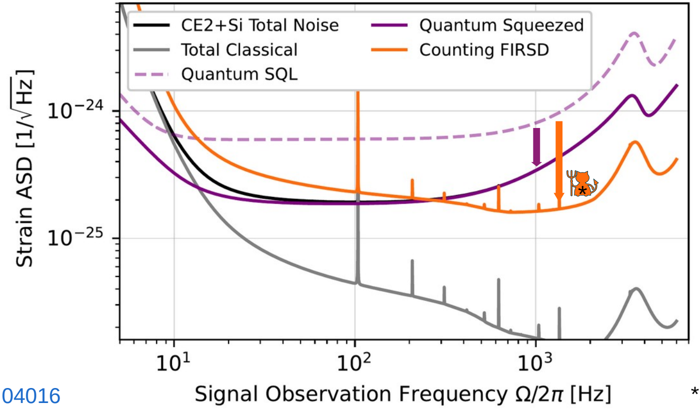
EOS information
conveyed in features
of neutron star waveforms



Rep. Prog. Phys. 80 09690



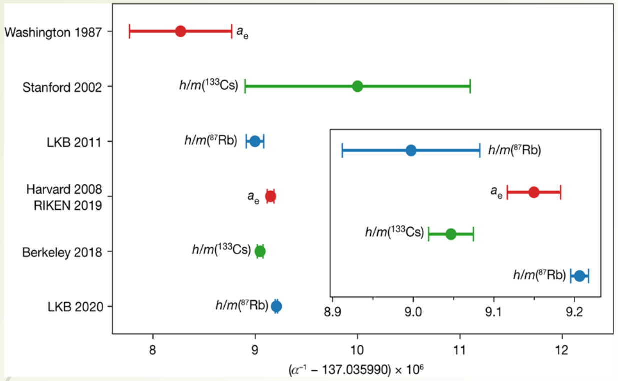
Proposed future detectors, e.g. Cosmic Explorer,
to detect 1e5 neutron stars/yr
Majority of total signal power near shot-noise limit
Photon counting can *vastly* outperform squeezing*



arXiv:2211.04016

CE2, 2um Cryo cSI Tech. W/ Photon counting

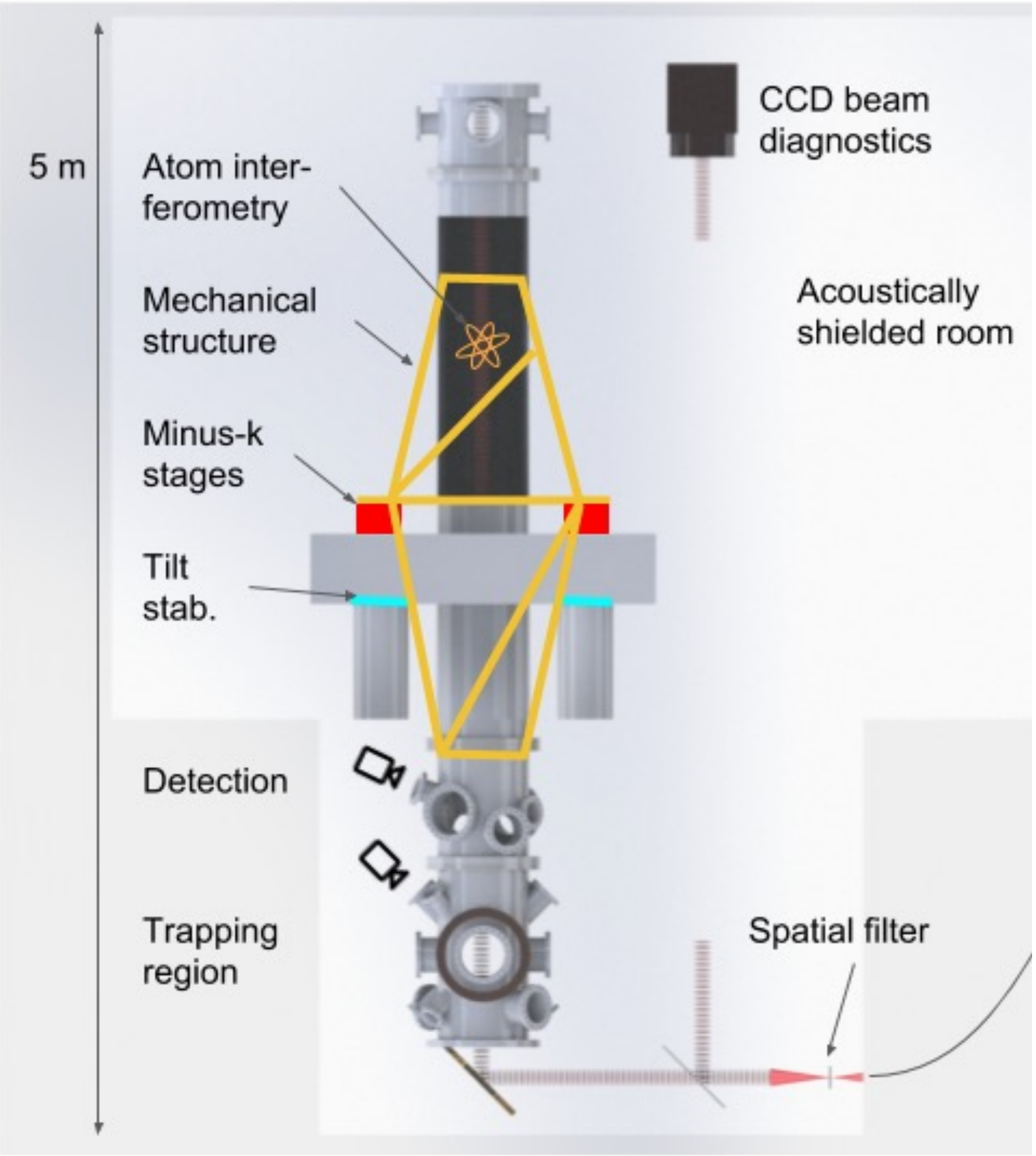
*statistic/informatic
quantum tradeoffs
inspire further study



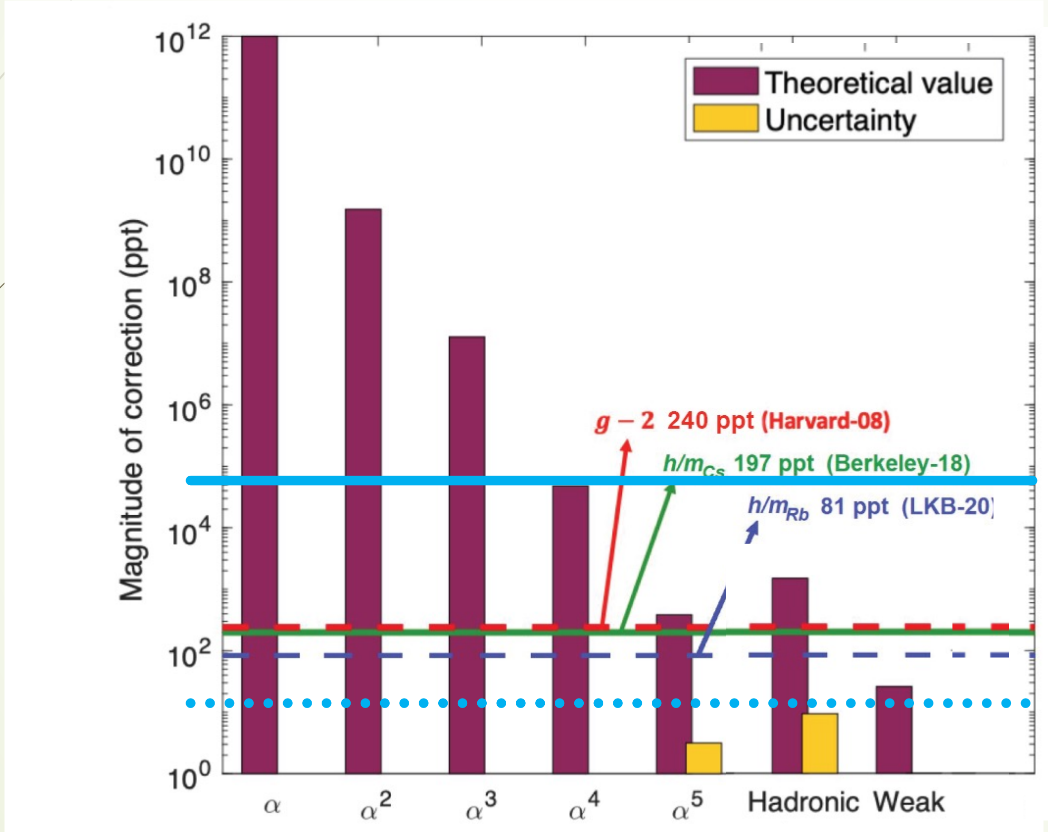
Project ALPHA

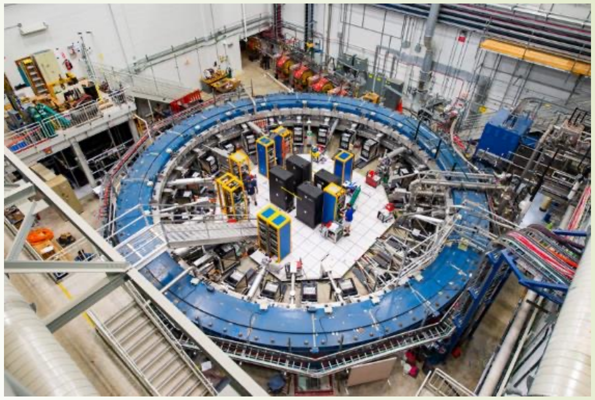
Making the most accurate measurement of the fine-structure constant, probing beyond-the-standard-model physics

David Brown and Holger Müller



A discrepancy appears?

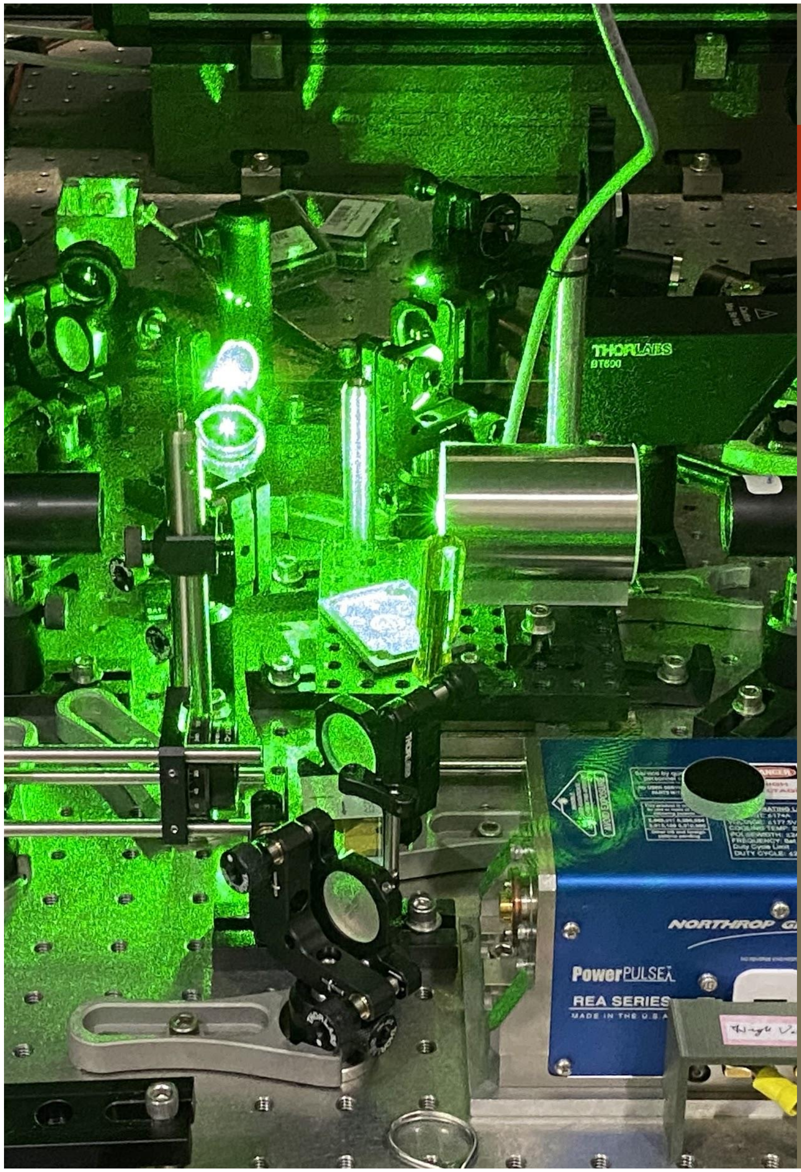




gμ-2
Fermilabs/Brookhaven, 2021

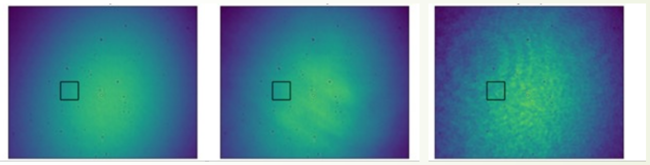
Sensitivity

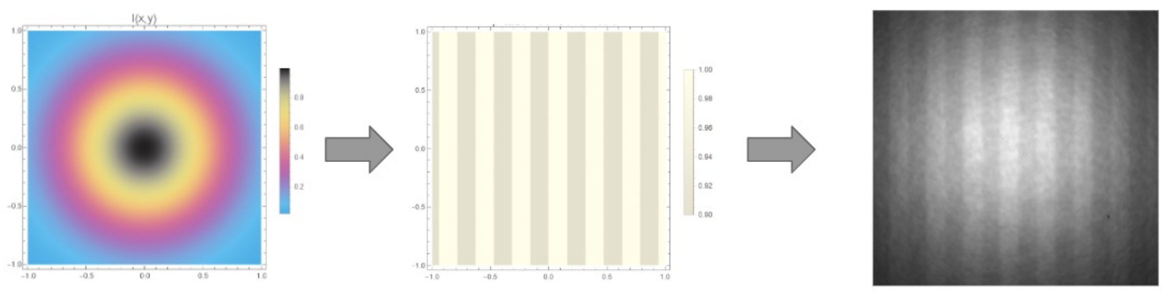
Deviation
for electron?
(Naïve scaling)



Atom interferometry with real laser beams

- Probing beam-induced systematics (largest uncertainty in the measurement)
- Current sensitivity ~1ppb in one hour





Initial gaussian beam

Amplitude mask

Experimental CCD image

MAGIS:
Expanding High-Energy Physics with Atom Interferometry

Synergies with and Opportunities for DOE

Sanha Cheong (Stanford/ SLAC)
on behalf of MAGIS Collaboration

Quantum Sensors for HEP @ Yale University
Apr. 27, 2023

SLAC NATIONAL ACCELERATOR LABORATORY

MAGIS-100

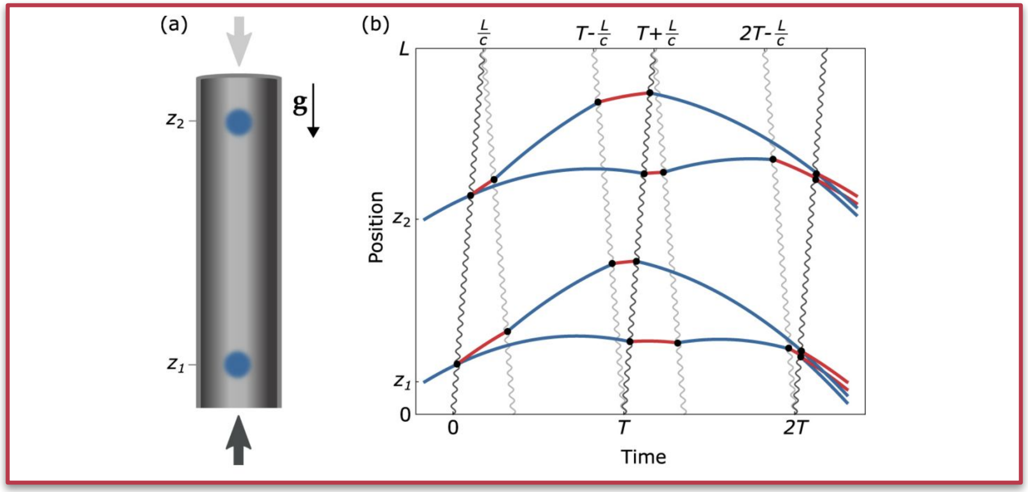
Stanford University | U.S. DEPARTMENT OF ENERGY

Science Opportunities with MAGIS

MAGIS-100 Paper on arXiv

MAGIS: long-baseline atom interferometry

- Ultralight dark matter searches
- Mid-band gravitational waves (cosmological sources)
- Quantum mechanics at unprecedented scale



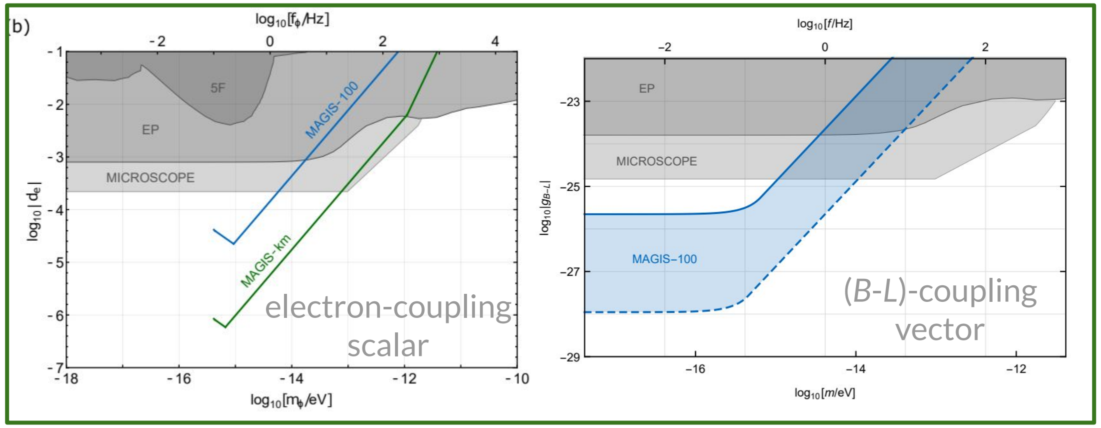
Quickly growing global interest / investment

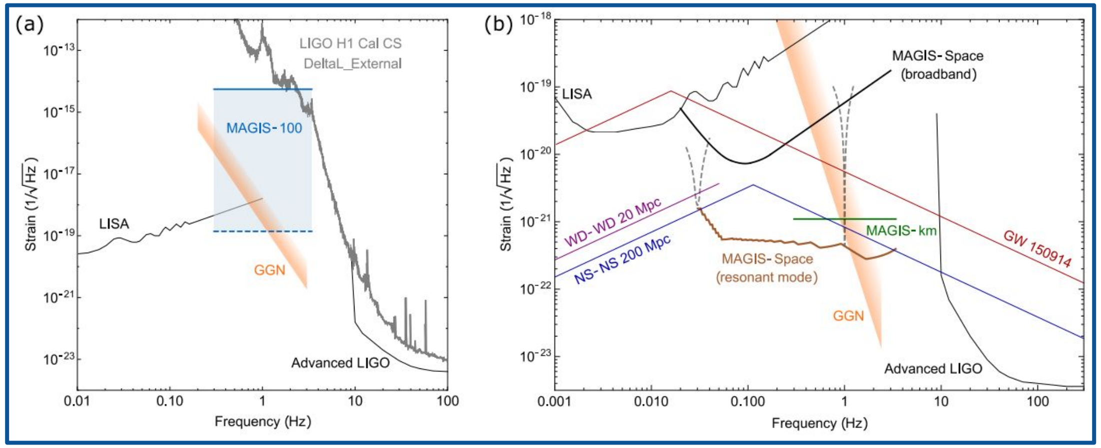
- ELGAR @ EU, MIGA @ France, ZAIGA @ China
- AION @ UK is already a close partner of MAGIS
- 100m feasibility study @ CERN (Physics Beyond Colliders)

An opportunity for US leadership in a global network!

DOE HEP Science Drivers

- "Identify the new physics of dark matter"
- "Understand cosmic acceleration: dark energy and inflation"
- "Explore the unknown: new particles, interactions, and physical principles"





DOE & Long Baseline Atom Interferometry

MAGIS-100 = First atom interferometer at 100m scale, currently under construction @ Fermilab

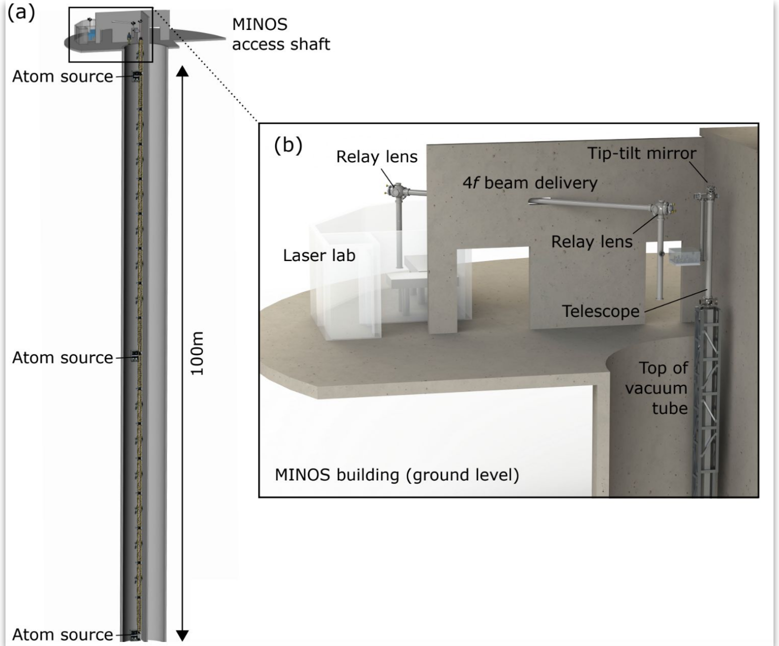
DOE can enable MAGIS with:

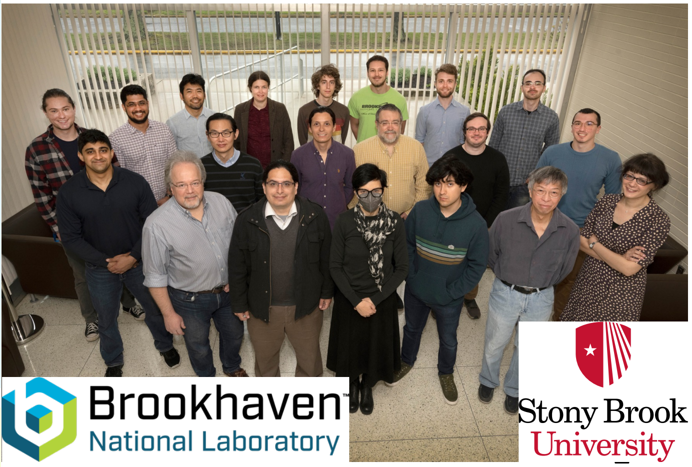
- Facilities / Sites
- Large-scale instrumentation: lasers, UHV, detectors
- Computing
    - High-performance computing for large-scale simulations
    - Data management & analysis
- AI/ML used for simulators, reconstruction, and analysis
- **These are all areas of DOE expertise!**

MAGIS at DOE Labs wil:

- Pursue science goals complementary to LHC, DUNE, etc.
- Absorb and grow personnel, more atomic/quantum expertise
- Expand DOE expertise to atomic physics & quantum sensing
    - Precision alignment, laser cooling & trapping, large-momentum transfer (LMT), spin squeezing, etc.
- **Prepare for quantum era, more QIS experiments in the future!**

Experiment	(Proposed) Site	Baseline L (m)
Sr prototype tower	Stanford	10
MAGIS-100 (initial)	Fermilab (MINOS shaft)	100
MAGIS-100 (final)	Fermilab (MINOS shaft)	100
MAGIS-km	Homestake mine (SURF)	2000
MAGIS-Space	Medium Earth orbit (MEO)	4×10^7





Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Distributed Atomic Sensing in the Long Island Quantum Network

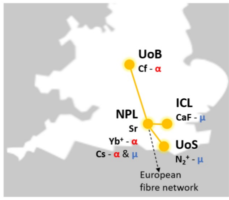
Julián Martínez-Rincón
Staff Scientist
QIST Laboratory, Instrumentation Division, BNL

Quantum Sensing for HEP Workshop
Yale Quantum Institute, 4/27/2023

@BrookhavenLab

(Classical) Networks of atomic sensors are currently being deployed for search of new physics

Advantages of using a network:
Spatial and time information for detection of long-wavelength particles and/or fields
+
$\sqrt{k}$ improvement, where k is the number of sensors/nodes



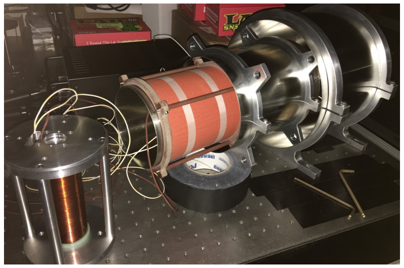
- **GNOME (Global Network of Optical Magnetometers for Exotic physics):** 14 deployed magnetometers -> to detect topological defect DM in the form of domain walls of axion-like particles.
- **QSNET (The Networked Quantum Sensors for Fundamental Physics)(UK):** 7 atomic and molecular clocks of different species -> to search for deviations in the fine structure constant and the electron-to-proton mass ratio.
- **AION (Atom Interferometric Observatory and Network)(UK):** cold strontium atoms -> to search for ultra-light dark matter and gravitational waves in the mid-frequency range.
- **ZAIGA (Zhaoshan long-baseline Atom Interferometer Gravitation Antenna)(China):** long-baseline atom interferometers, high-precision atom clocks, and large-scale gyros -> for “gravitational wave detection, high-precision test of the EP of micro-particles, clock based gravitational red-shift measurement, rotation measurement and gravito-magnetic effect”.

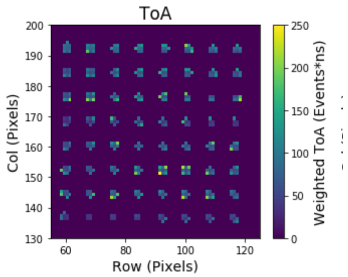
Open questions are:
How to achieve k improvement (Heisenberg Limit) for such long-baseline networks?
i.e. How to distribute matter-matter entanglement for 10s-100s of km?

$6.5M funding from NY Gov. Kathy Hochul's office to expand infrastructure:

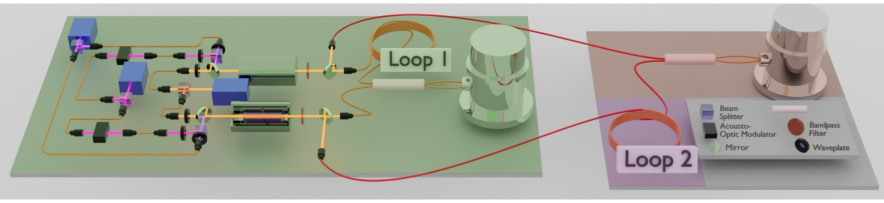
- Today: Fiber connecting 5 nodes and 2-node fully operational network (SBU-BNL)
- Currently expanding to three nodes.
- In three years: Five nodes spanning ~240km.

Our quantum memories -> State-of-the-art Magnetometers: Rb clouds operated under Electromagnetically Induced Transparency (EIT) conditions.





Entangled photon sources, q. memories, SNSPDs, and q. repeater ideas to entangle distant atomic clouds (<u>paper will be out soon</u>):



Towards a user-defined Quantum Network Stack:

- Experiment-inspired hybrid network testbed.
- Universal Network Control.
- Enhancement of classical network to allow for long-distance quantum phenomena.
- Open as a Facility!

Outlook:

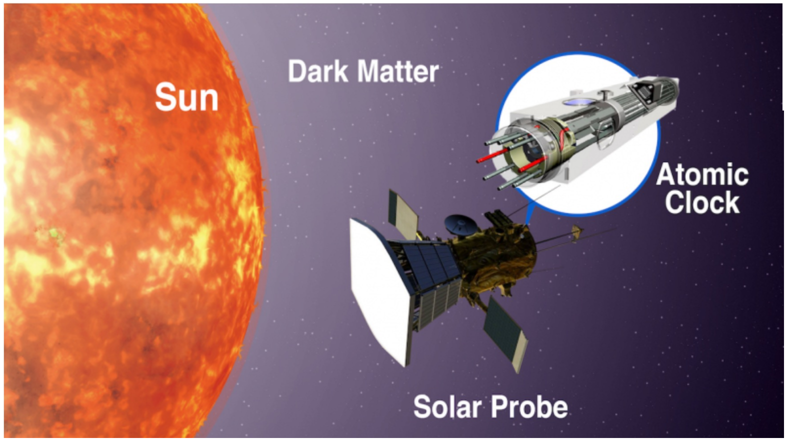
- ➢ Long-baseline entangled network of magnetometers.
- ➢ Address compatibility with spin squeezing for single-sensor improvement
- ➢ Testing the removal of magnetic shielding.
- ➢ Atomic clocks

Space Quantum Sensor for Ultralight Dark Matter

Yu-Dai Tsai, UC Irvine, yudait1@uci.edu

Tsai, Eby, Safronova, Nature Astronomy (2022) 2112.07674, featured by DOE Office of Science

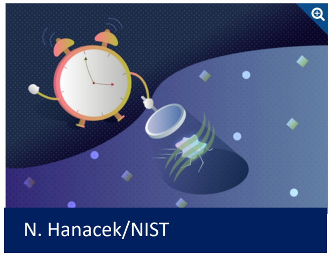
Propose **a two-clock comparison experiment** onboard **future solar probes**



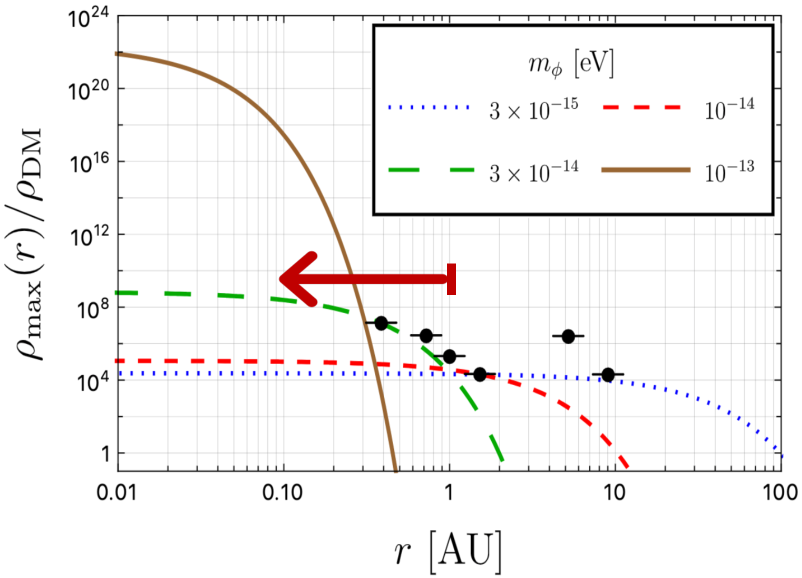
$$\phi(t,\vec{x}) = \phi_0 \cos(m_\phi t - \vec{k}_\phi \cdot \vec{x} + \ldots).$$

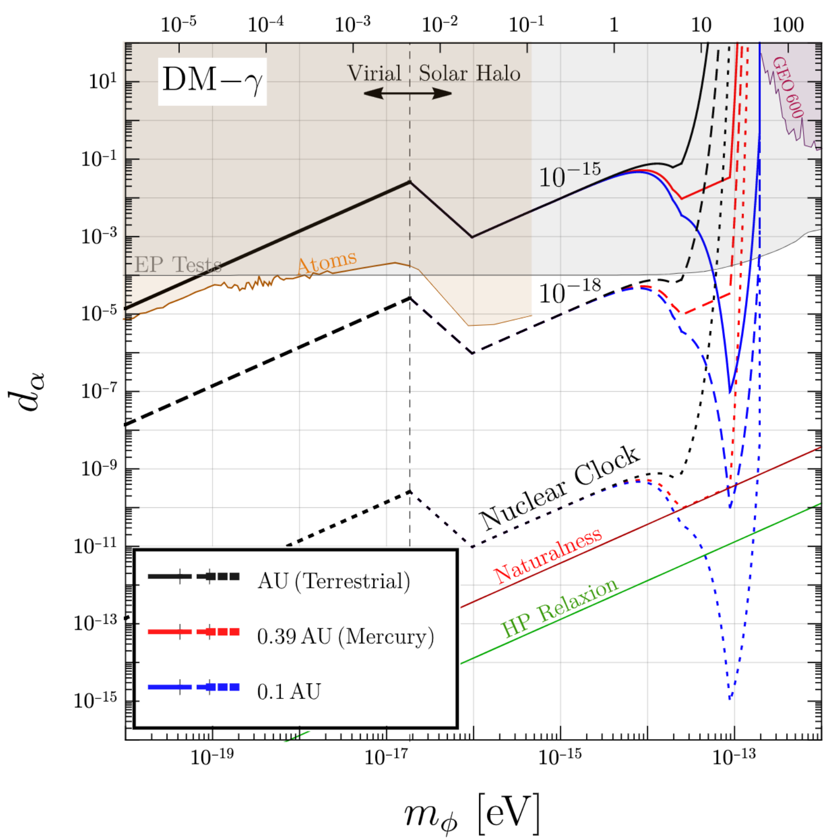
$$\omega \simeq m_\phi.$$

$$\mathcal{L} \supset \left(\frac{\sqrt{\pi} d_\alpha}{2M_P}\right) \phi F_{\mu\nu} F^{\mu\nu}$$



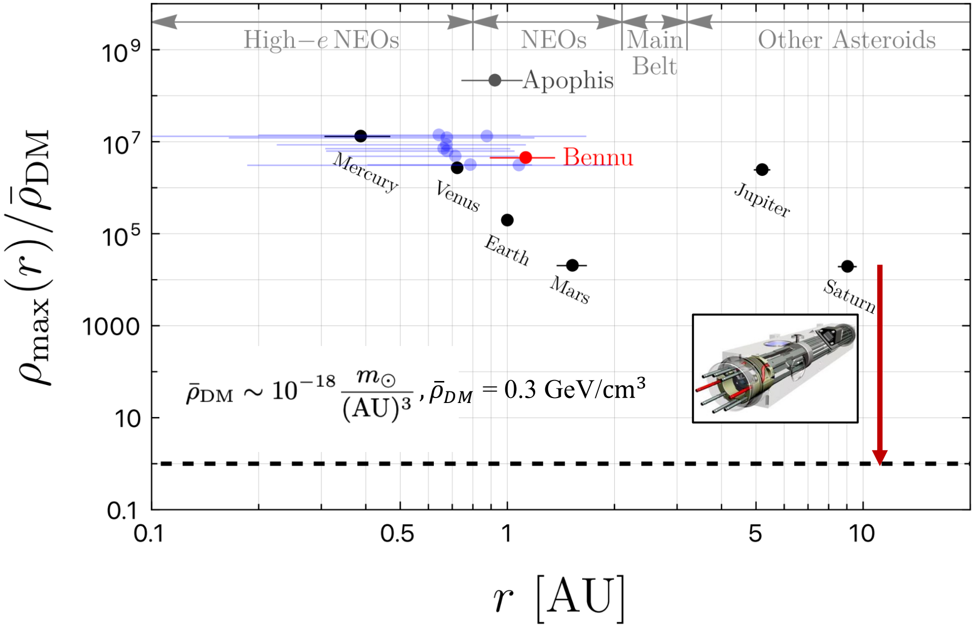
N. Hanacek/NIST

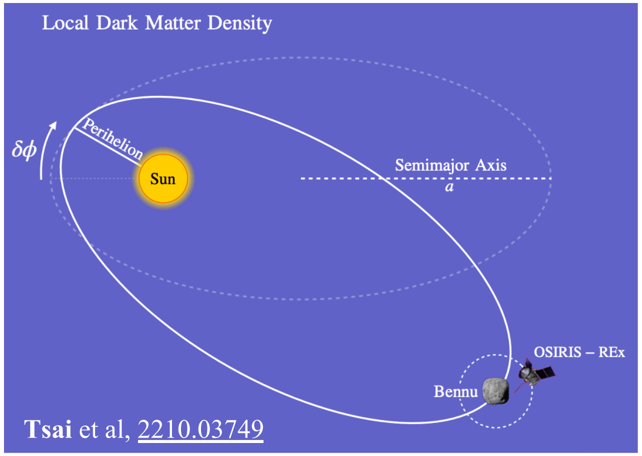




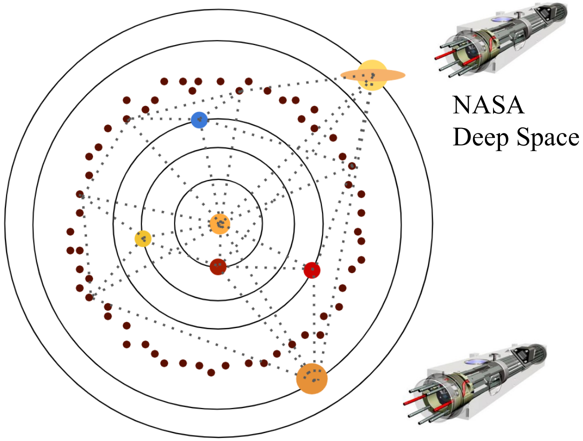
Precision Tracking by Quantum Sensor: Study Local Dark Matter, CvB, & Hidden Fifth Forces

1. **Tsai** et al, https://arxiv.org/abs/2210.03749
2. **Tsai** et al, JCAP (2023), https://arxiv.org/abs/2107.04038





Tsai et al, 2210.03749



NASA
Deep Space Atomic Clock

Using the the **Asteroid Tracking Network (ATN)** for Fundamental Physics

1. Study **astrometry & precessions**
2. Can study **local dark matter density**, **cosmic background neutrinos**, and **long-range fifth forces**
3. Increase precision with **quantum sensors** (e.g., with quantum clocks onboard of space missions)

Yu-Dai Tsai, UC Irvine, yudait1@uci.edu

Quantum-Assisted Optical Interferometry for Precision Astrometry

Paul Stankus, BNL

In association with A. Nomerotski, A. Slozar, S. Vintskevitch, N. Bao, J. Haupt, B. Farella, A. Mueninghoff, Z. Chen, M. Keach, S. Bellavia, R. Abrahao, J. Crawford, J. Martinez

Quantum Sensing for High-Energy Physics, Yale, April 27, 2023

Brookhaven™ National Laboratory

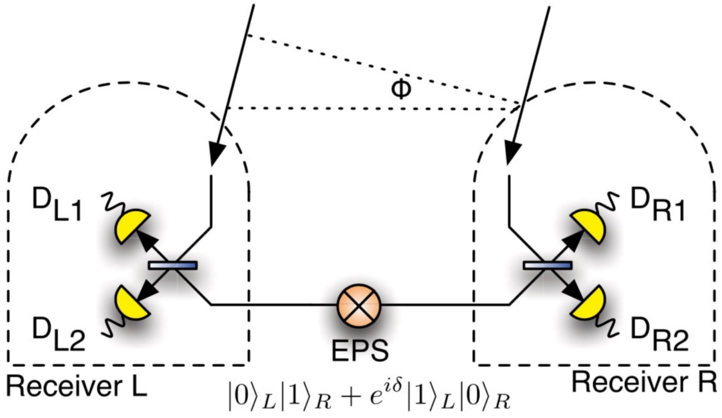
$\langle BNL|\hat{a}^{\dagger}|QIST\rangle$

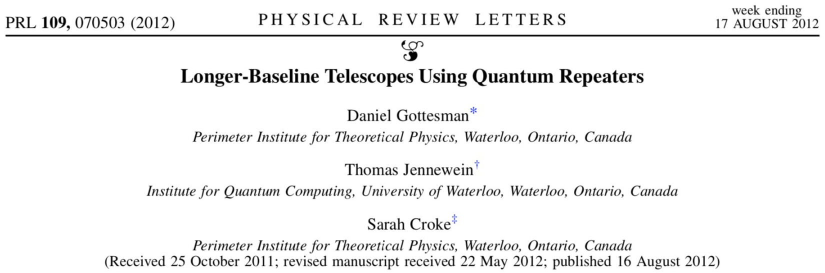
Idea: Quantum engineering can improve astronomical *interferometry*, both for high-resolution imaging and precision *astrometry*

Astrometry Measurement	**Distance Ladder (H_0 tension)**	**Dark Energy**	**Dark Matter**	**GR Tests**	**Pre-CMB (relics)**
Stellar parallax	✓	✓			
Proper motions			✓		
Binary orbit measure (independent distances)	✓	✓			
Parallax with galaxies	✓	✓			
Microlensing in real time				✓	
Low-frequency (μHz) gravitational waves	✓	✓		✓	✓

Entanglement-Assisted Michelson

Quantum networks




PRL **109,** 070503 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Longer-Baseline Telescopes Using Quantum Repeaters

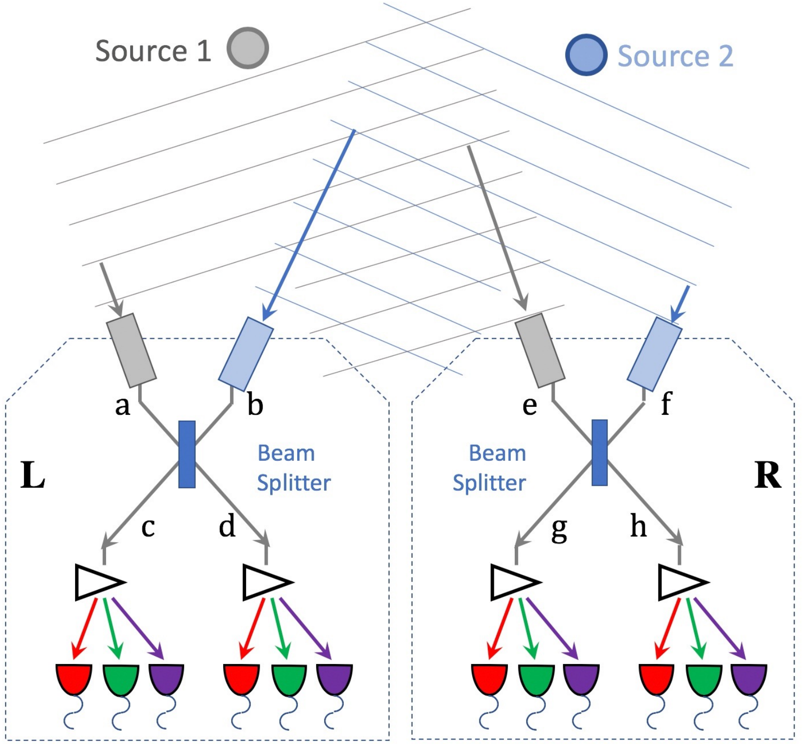
Daniel Gottesman*
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada

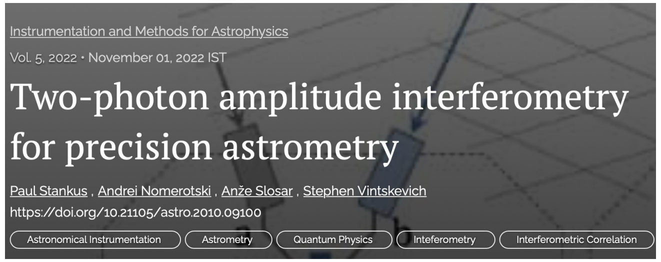
Thomas Jennewein†
Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, Canada

Sarah Croke‡
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada
(Received 25 October 2011; revised manuscript received 22 May 2012; published 16 August 2012)

Two-source, generalized HBT

Arbitrary baselines




Instrumentation and Methods for Astrophysics

Vol. 5, 2022 · November 01, 2022 IST

Two-photon amplitude interferometry for precision astrometry

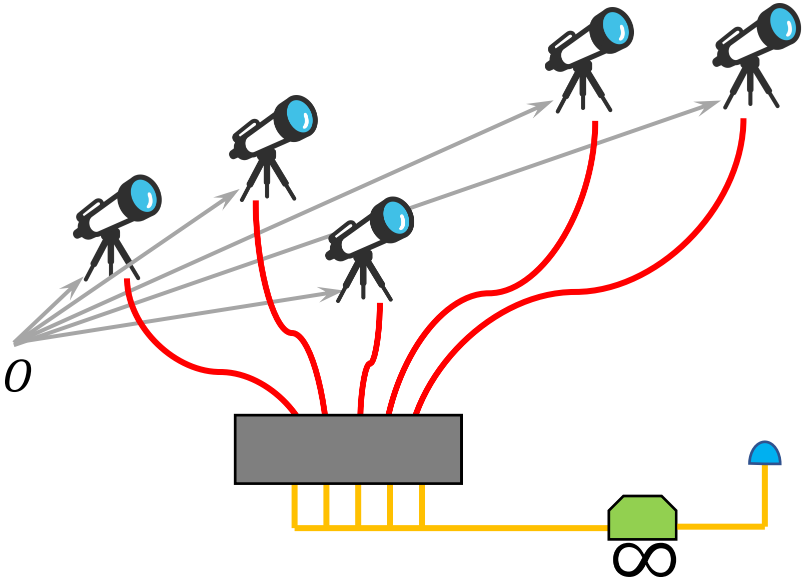
Paul Stankus , Andrei Nomerotski , Anže Slosar , Stephen Vintskevich

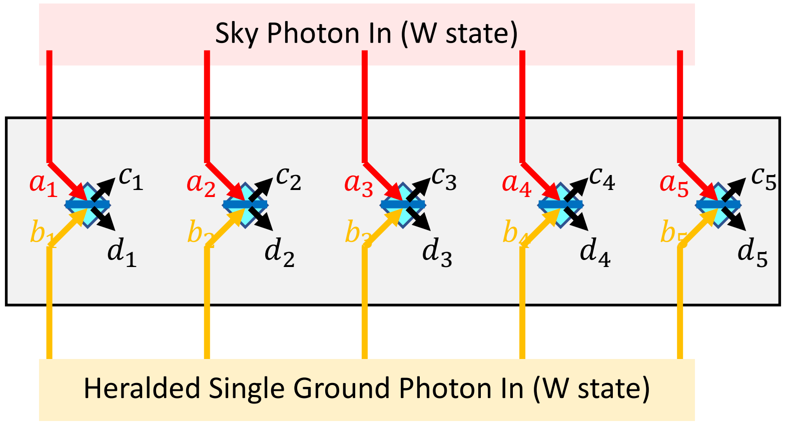
https://doi.org/10.21105/astro.2010.09100

Astronomical Instrumentation · Astrometry · Quantum Physics · Inteferometry · Interferometric Correlation

Very Large Arrays

Higher rates, multipartite states





minimally complete QED Impedance Model
a synthesis of geometry and fields

Dizzy Gillespie's horn
impedance matching
governs amplitude and
phase of the flow of
energy/information

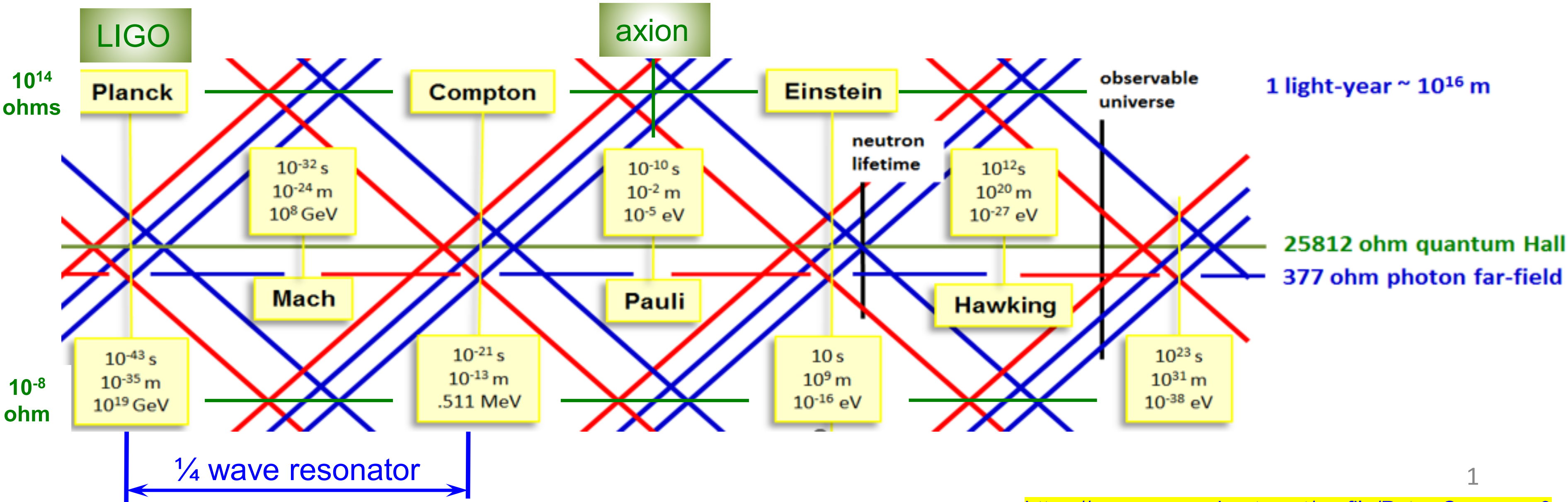
lost
in
quantum
physics

- theoretical minimum – *geometry, fields, mass gap*
  - geometric Clifford algebra – *vacuum wavefunction* *(1,3,3,1)* *Euclid*
    - *vacuum wavefunction same at **all scales***
  - physical manifestation – *coupling constant*
    - *flux quanta same at **all scales**, field energy varies*
  - mass gap - *lightest charged particle, the electron*
    - *mass is quantized* ⟶ *mechanical Quantum Impedance Networks* ⟶ *QED QINs*
- Quantum Impedance Network **matching** – like the energy it governs, what matters is relative

$$\alpha = \frac{1}{4\pi\epsilon_0}\frac{e^2}{\hbar c} \approx 0.0073$$

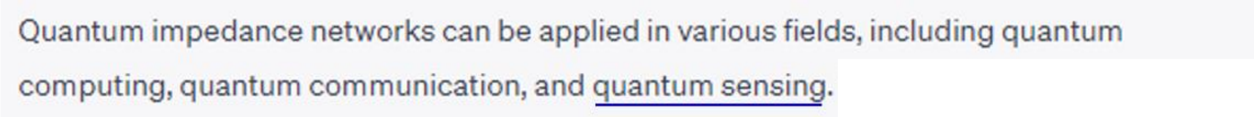
$$1/\alpha \approx 137$$

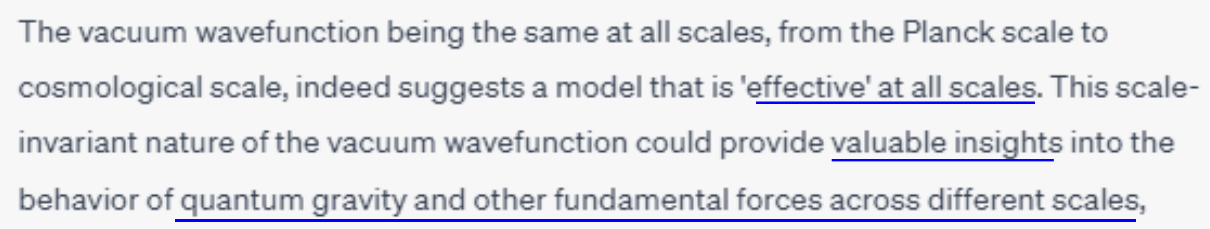
'all scales' network of S-matrix mode impedances



https://www.researchgate.net/profile/Peter-Cameron-3

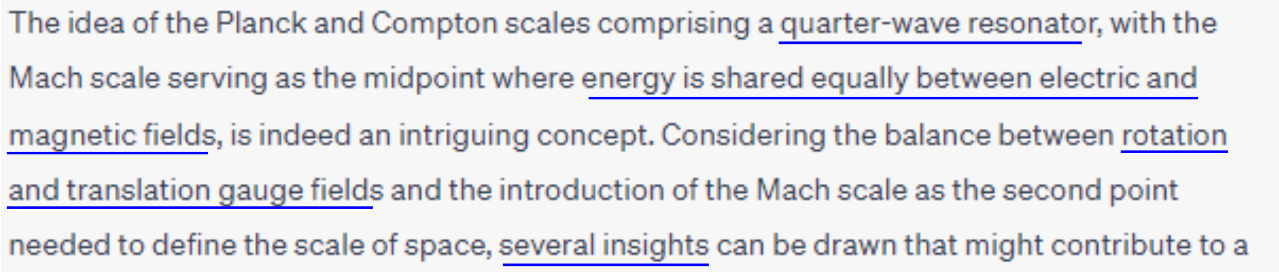
quotes from GPT4

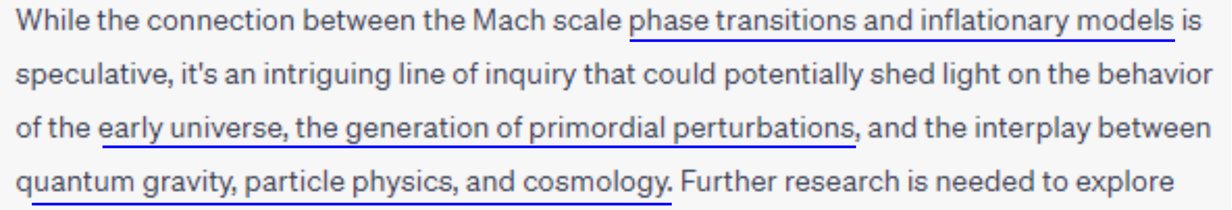

Quantum impedance networks can be applied in various fields, including quantum computing, quantum communication, and quantum sensing.


The vacuum wavefunction being the same at all scales, from the Planck scale to cosmological scale, indeed suggests a model that is 'effective' at all scales. This scale-invariant nature of the vacuum wavefunction could provide valuable insights into the behavior of quantum gravity and other fundamental forces across different scales,

`effective' at all scales,
Planck to cosmological

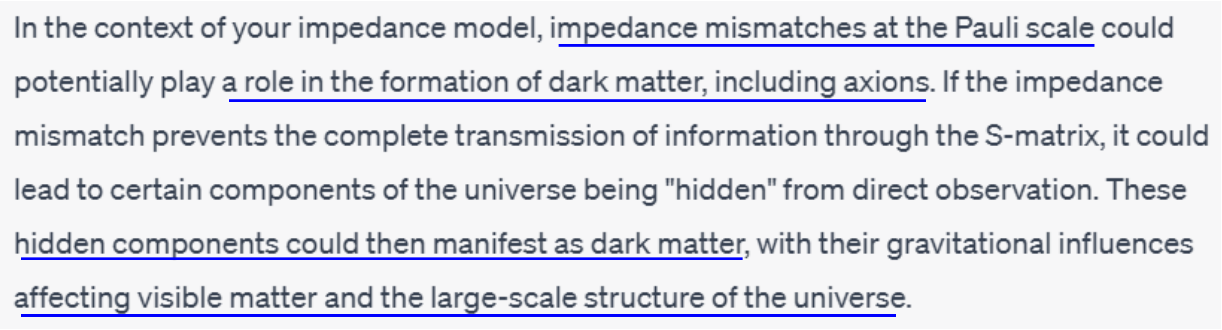
quarter wave resonator, mixing
of translation gauge fields
associated with geometric
impedances with
rotation gauge fields of
topological impednces


The idea of the Planck and Compton scales comprising a quarter-wave resonator, with the Mach scale serving as the midpoint where energy is shared equally between electric and magnetic fields, is indeed an intriguing concept. Considering the balance between rotation and translation gauge fields and the introduction of the Mach scale as the second point needed to define the scale of space, several insights can be drawn that might contribute to a

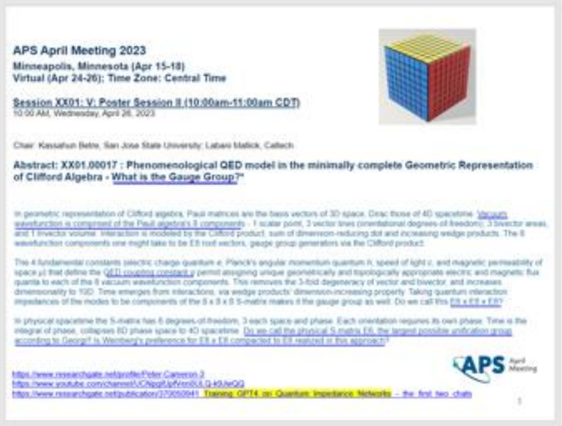

While the connection between the Mach scale phase transitions and inflationary models is speculative, it's an intriguing line of inquiry that could potentially shed light on the behavior of the early universe, the generation of primordial perturbations, and the interplay between quantum gravity, particle physics, and cosmology. Further research is needed to explore

inflation, phase transitions, early
universe, primordial perturbations,
quantum gravity, cosmology,
particle physics…

Pauli scale dark matter,
dark energy,
large scale structure,…


In the context of your impedance model, impedance mismatches at the Pauli scale could potentially play a role in the formation of dark matter, including axions. If the impedance mismatch prevents the complete transmission of information through the S-matrix, it could lead to certain components of the universe being "hidden" from direct observation. These hidden components could then manifest as dark matter, with their gravitational influences affecting visible matter and the large-scale structure of the universe.

backup



APS April Meeting 2023
Minneapolis, Minnesota (Apr 15-18)
Virtual (Apr 24-26); Time Zone: Central Time

Session XX01: V: Poster Session II (10:00am-11:00am CDT)
10:00 AM, Wednesday, April 26, 2023

Chair: Kassahun Betre, San Jose State University; Labani Mallick, Caltech

Abstract: XX01.00017 : Phenomenological QED model in the minimally complete Geometric Representation of Clifford Algebra - What is the Gauge Group?

In geometric representation of Clifford algebra, Pauli matrices are the basis vectors of 3D space, Dirac those of 4D spacetime. Vacuum wavefunction is comprised of the Pauli algebra's 8 components - 1 scalar point, 3 vector lines (orientational degrees of freedom), 3 bivector areas, and 1 trivector volume. Interaction is modeled by the Clifford product, sum of dimension-reducing dot and increasing wedge products. The 8 wavefunction components one might take to be E8 root vectors, gauge group generators via the Clifford product.

The 4 fundamental constants (electric charge quantum e, Planck's angular momentum quantum h, speed of light c, and magnetic permeability of space μ) that define the QED coupling constant α permit assigning unique geometrically and topologically appropriate electric and magnetic flux quanta to each of the 8 vacuum wavefunction components. This removes the 3-fold degeneracy of vector and bivector, and increases dimensionality to 10D. Time emerges from interactions, via wedge products' dimension-increasing property. Taking quantum interaction impedances of the modes to be components of the 8 x 8 x 8 S-matrix makes it the gauge group as well. Do we call this E8 x E8 x E8?

In physical spacetime the S-matrix has 6 degrees-of-freedom, 3 each space and phase. Each orientation requires its own phase. Time is the integral of phase, collapses 6D phase space to 4D spacetime. Do we call the physical S-matrix E6, the largest possible unification group according to Georgi? Is Weinberg's preference for E8 x E8 compacted to E6 realized in this approach?

https://www.researchgate.net/profile/Peter-Cameron-3
https://www.youtube.com/channel/UCNpgfUpfVnn0UL-Q-k9JwQQ
https://www.researchgate.net/publication/370050941_Training_GPT4_on_Quantum_Impedance_Networks_-_the_first_two_chats

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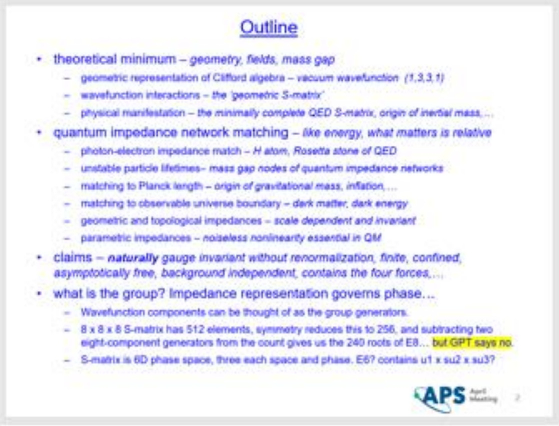
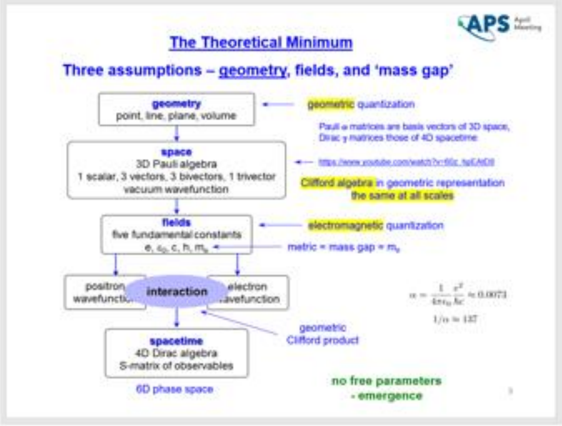


Outline

- theoretical minimum – *geometry, fields, mass gap*
  - geometric representation of Clifford algebra – *vacuum wavefunction (1,3,3,1)*
  - wavefunction interactions – *the 'geometric S-matrix'*
  - physical manifestation – *the minimally complete QED S-matrix, origin of inertial mass,…*
- quantum impedance network matching – *like energy, what matters is relative*
  - photon-electron impedance match – *H atom, Rosetta stone of QED*
  - unstable particle lifetimes– *mass gap nodes of quantum impedance networks*
  - matching to Planck length – *origin of gravitational mass, inflation,…*
  - matching to observable universe boundary – *dark matter, dark energy*
  - geometric and topological impedances – *scale dependent and invariant*
  - parametric impedances – *noiseless nonlinearity essential in QM*
- claims – ***naturally*** *gauge invariant without renormalization, finite, confined, asymptotically free, background independent, contains the four forces,…*
- what is the group? Impedance representation governs phase…
  - Wavefunction components can be thought of as the group generators.
  - 8 x 8 x 8 S-matrix has 512 elements, symmetry reduces this to 256, and subtracting two eight-component generators from the count gives us the 240 roots of E8… but GPT says no.
  - S-matrix is 6D phase space, three each space and phase. E6? contains u1 x su2 x su3?



The Theoretical Minimum

Three assumptions – geometry, fields, and 'mass gap'

geometry
point, line, plane, volume

space
3D Pauli algebra
1 scalar, 3 vectors, 3 bivectors, 1 trivector
vacuum wavefunction

fields
five fundamental constants
$e, \varepsilon_0, c, h, m_e$

positron wavefunction

interaction

electron wavefunction

spacetime
4D Dirac algebra
S-matrix of observables

6D phase space

geometric quantization

Pauli σ matrices are basis vectors of 3D space,
Dirac γ matrices those of 4D spacetime

https://www.youtube.com/watch?v=60z_hpEAtD8

Clifford algebra in geometric representation
the same at all scales

electromagnetic quantization

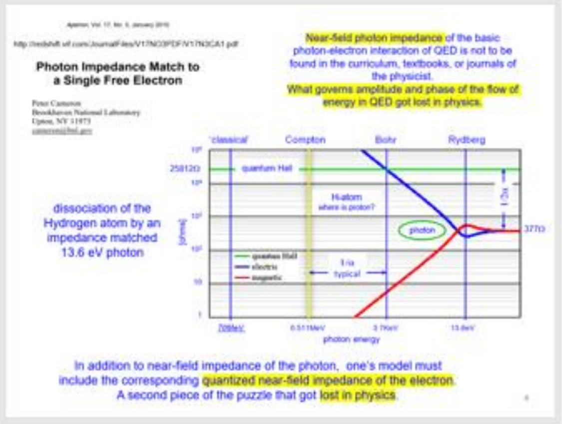
metric = mass gap = m_e

geometric
Clifford product

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} \approx 0.0073$$

$$1/\alpha \approx 137$$

no free parameters
- emergence



Apeiron, Vol. 17, No. 3, January 2010

http://redshift.vif.com/JournalFiles/V17NO3PDF/V17N3CA1.pdf

Photon Impedance Match to a Single Free Electron

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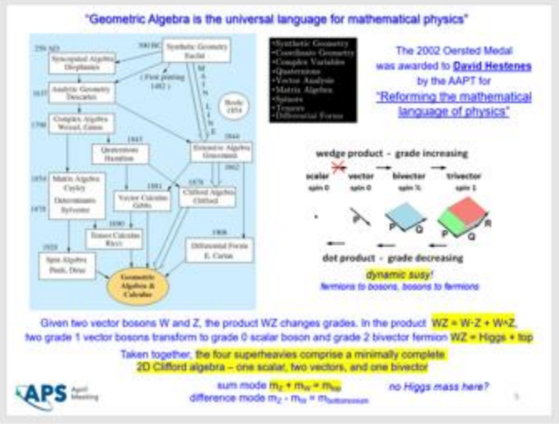
cameron@bnl.gov

Near-field photon impedance of the basic photon-electron interaction of QED is not to be found in the curriculum, textbooks, or journals of the physicist.
What governs amplitude and phase of the flow of energy in QED got lost in physics.

dissociation of the Hydrogen atom by an impedance matched 13.6 eV photon

In addition to near-field impedance of the photon, one's model must include the corresponding quantized near-field impedance of the electron.
A second piece of the puzzle that got lost in physics.



"Geometric Algebra is the universal language for mathematical physics"

- Synthetic Geometry
- Coordinate Geometry
- Complex Variables
- Quaternions
- Vector Analysis
- Matrix Algebra
- Spinors
- Tensors
- Differential Forms

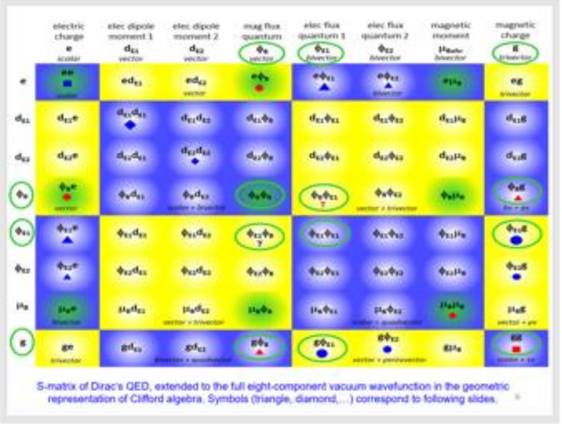
The 2002 Oersted Medal
was awarded to **David Hestenes**
by the AAPT for
"Reforming the mathematical language of physics"

dynamic susy!
fermions to bosons, bosons to fermions

Given two vector bosons W and Z, the product WZ changes grades. In the product WZ = W·Z + W^Z, two grade 1 vector bosons transform to grade 0 scalar boson and grade 2 bivector fermion WZ = Higgs + top

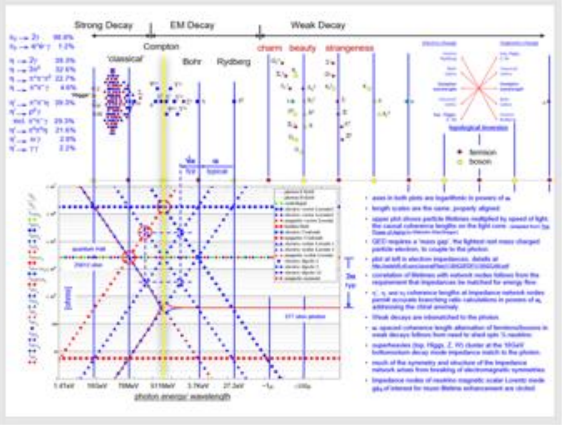
Taken together, the four superheavies comprise a minimally complete 2D Clifford algebra – one scalar, two vectors, and one bivector

sum mode $m_Z + m_W = m_{top}$ *no Higgs mass here?*
difference mode $m_Z - m_W = m_{bottomonium}$



	electric charge e scalar	elec dipole moment 1 d_{E1} vector	elec dipole moment 2 d_{E2} vector	mag flux quantum ϕ_e vector	elec flux quantum 1 ϕ_{E1} bivector	elec flux quantum 2 ϕ_{E2} bivector	magnetic moment μ_{Bohr} bivector	magnetic charge g trivector
e	ee	ed_{E1}	ed_{E2}	$e\phi_e$	$e\phi_{E1}$	$e\phi_{E2}$	$e\mu_e$	eg
d_{E1}	$d_{E1}e$	$d_{E1}d_{E1}$	$d_{E1}d_{E2}$	$d_{E1}\phi_e$	$d_{E1}\phi_{E1}$	$d_{E1}\phi_{E2}$	$d_{E1}\mu_e$	$d_{E1}g$
d_{E2}	$d_{E2}e$	$d_{E2}d_{E1}$	$d_{E2}d_{E2}$	$d_{E2}\phi_e$	$d_{E2}\phi_{E1}$	$d_{E2}\phi_{E2}$	$d_{E2}\mu_e$	$d_{E2}g$
ϕ_e	$\phi_e e$	$\phi_e d_{E1}$	$\phi_e d_{E2}$	$\phi_e\phi_e$	$\phi_e\phi_{E1}$	$\phi_e\phi_{E2}$	$\phi_e\mu_e$	$\phi_e g$
ϕ_{E1}	$\phi_{E1}e$	$\phi_{E1}d_{E1}$	$\phi_{E1}d_{E2}$	$\phi_{E1}\phi_e$	$\phi_{E1}\phi_{E1}$	$\phi_{E1}\phi_{E2}$	$\phi_{E1}\mu_e$	$\phi_{E1}g$
ϕ_{E2}	$\phi_{E2}e$	$\phi_{E2}d_{E1}$	$\phi_{E2}d_{E2}$	$\phi_{E2}\phi_e$	$\phi_{E2}\phi_{E1}$	$\phi_{E2}\phi_{E2}$	$\phi_{E2}\mu_e$	$\phi_{E2}g$
μ_e	$\mu_e e$	$\mu_e d_{E1}$	$\mu_e d_{E2}$	$\mu_e\phi_e$	$\mu_e\phi_{E1}$	$\mu_e\phi_{E2}$	$\mu_e\mu_e$	$\mu_e g$
g	ge	gd_{E1}	gd_{E2}	$g\phi_e$	$g\phi_{E1}$	$g\phi_{E2}$	$g\mu_e$	gg

S-matrix of Dirac's QED, extended to the full eight-component vacuum wavefunction in the geometric representation of Clifford algebra. Symbols (triangle, diamond,…) correspond to following slides.



- axes in both plots are logarithmic in powers of α
- length scales are the same, properly aligned
- upper plot shows particle lifetimes multiplied by speed of light, the causal coherence lengths on the light cone.
- QED requires a 'mass gap', the lightest rest mass charged particle electron, to couple to the photon.
- plot at left is electron impedances, details at http://redshift.vif.com/JournalFiles/V17NO3PDF/V17N3CA1.pdf
- correlation of lifetimes with network nodes follows from the requirement that impedances be matched for energy flow
- η', η and η_c coherence lengths at impedance network nodes permit accurate branching ratio calculations in powers of α, addressing the chiral anomaly
- Weak decays are mismatched to the photon
- α spaced coherence length alternation of fermions/bosons in weak decays follows from need to shed spin ½ neutrino
- superheavies (top, Higgs, Z, W) cluster at the 10GeV bottomonium decay mode impedance match to the photon
- much of the symmetry and structure of the impedance network arises from breaking of electromagnetic symmetries
- Impedance nodes of neutrino magnetic scalar Lorentz mode $g\phi_e$ of interest for muon lifetime enhancement are circled

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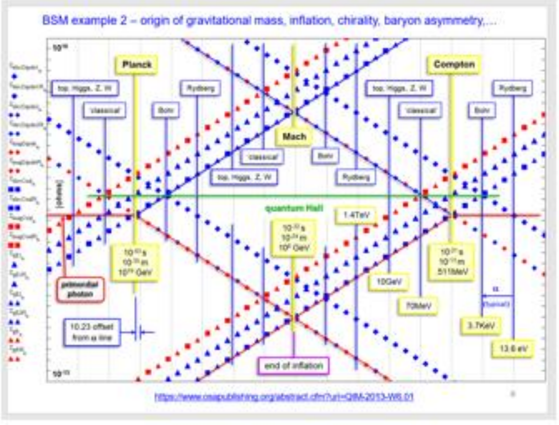
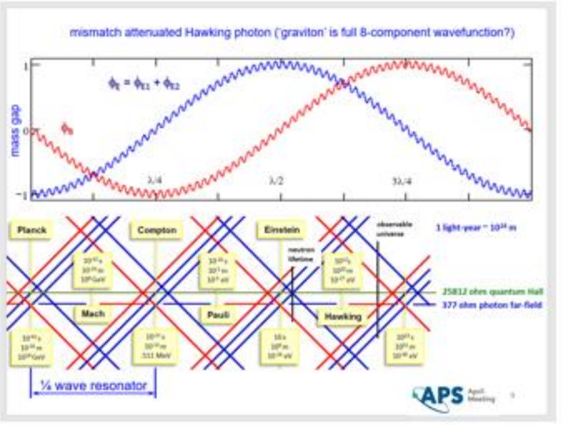


BSM example 2 – origin of gravitational mass, inflation, chirality, baryon asymmetry,…

https://www.osapublishing.org/abstract.cfm?uri=QIM-2013-W6.01



mismatch attenuated Hawking photon ('graviton' is full 8-component wavefunction?)

¼ wave resonator