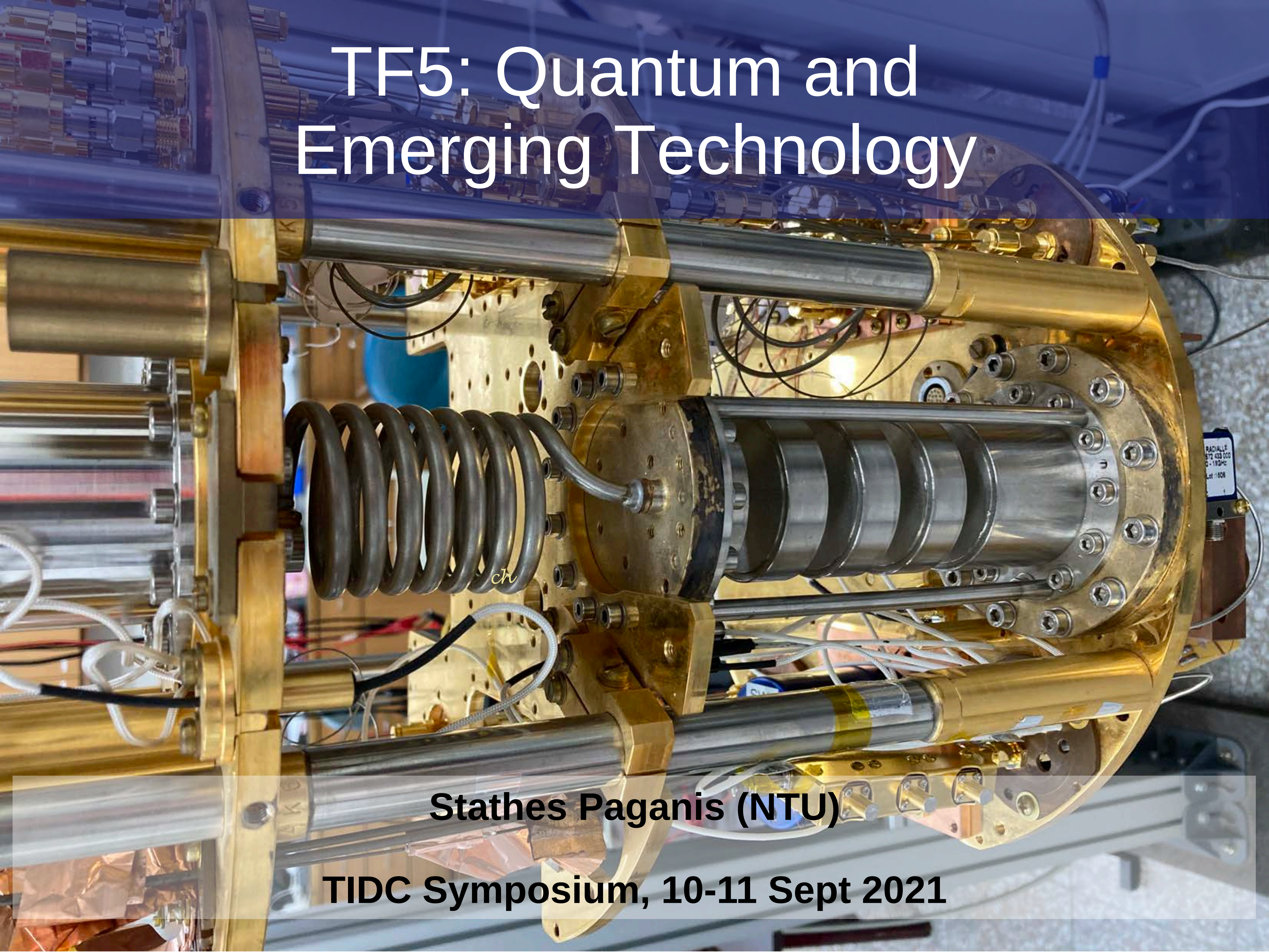
TF5: Quantum and Emerging Technology



Stathes Paganis (NTU)

TIDC Symposium, 10-11 Sept 2021

Status of TF5

Anna Grassellino, Marcel Demarteau, Michael Doser, Caterina Braggio, Stafford Withington, Peter Graham, John March-Russel, Andrew Geraci

Symposium: April 12

14 presentations

first block covering physics landscape

following blocks focusing on technologies

discussion of three important points

ECFA Detector R&D Roadmap Symposium of Task Force 5: Quantum and emerging technologies

Monday 12 Apr 2021, 09:00 → 18:30 Europe/Zurich

09:00 → 09:15 Introduction

09:15 → 11:00 science targets – Overview and Landscape

9:15 EDM searches & tests of fundamental symmetries Peter Fierlinger / TU Munich

9:45 Tests of QM [wavefunction collapse, size effects, temporal separation, decoherence]

10:15 Multimessenger detection [including atom interferometer or magnetometer networks] Giovanni Barontoni / Birmingham

10:45 Axion and other DM (as well as non-DM Ultra-light) particle searches Mina Arvanitaki / Perimeter Institute

11:15 → 11:30 Coffee break

11:30 → 12:30 Experimental methods and techniques - Overview and Landscape

11:30 Precision spectroscopy and clocks, networks of sensors and of entangled systems [optical atomic clocks] David Hume / NIST

12:00 Novel ionic, atomic and molecular systems [RaF, multiatomic molecules, exotic atoms] Marianna Safranova / U. Delaware

12:30 → 13:30 Lunch break

13:30 → 16:00 Experimental and technological challenges, New Developments

13:30 Superconducting platforms [detectors: TES, SNSPD, Haloscopes, including single photon detection]

14:00 High sensitivity superconducting cryogenic electronics, low noise amplifiers Stafford Withington / Cambridge

14:30 Broadband axion detection Kent Irwin / Stanford

15:00 Mechanical / optomechanical detectors Andrew Geraci / Northwestern

15:30 Spin-based techniques, NV-diamonds, Magnetometry Dima Budker / Mainz

16:00 → 16:15 Coffee break

16:15 → 18:30 Experimental and technological challenges, New Developments

16:15 Calorimetric techniques for neutrinos and axions potential speaker identified

16:35 Quantum techniques for scintillators potential speaker identified

16:55 Atom interferometry at large scales (ground based, space based) Jason Hogan / Stanford

17:25 → 18:15 Discussion session : discussion points
- Scaling up from table-top systems
- Networking – identifying commonalities with neighboring communities
- Applying quantum technologies to high energy detectors

18:15 → 18:30 Wrap-up

Topics

Experimental methods and techniques – Overview

- Spin-based techniques, NV-diamonds, Magnetometry: Dima Budker (Mainz).
- Novel ionic, atomic and molecular systems [RaF, tests in multiatomic molecules, exotic atoms]: Marianna Safronova (Univ. Delaware)
- Quantum-limited Metrology with Optical Clocks: David Hume (NIST).

Experimental methods and techniques – New Developments

- High sensitivity superconducting cryogenic electronics, low noise amplifiers, TES: Withington
- Superconducting Cavities for DM search: Alexander Romanenko
- Quantum Acceleration of Axion Detection: Kent Irwin (Stanford)
- Optomechanical detectors for DM: A. Geraci (Northwestern U.)

Technological Challenges

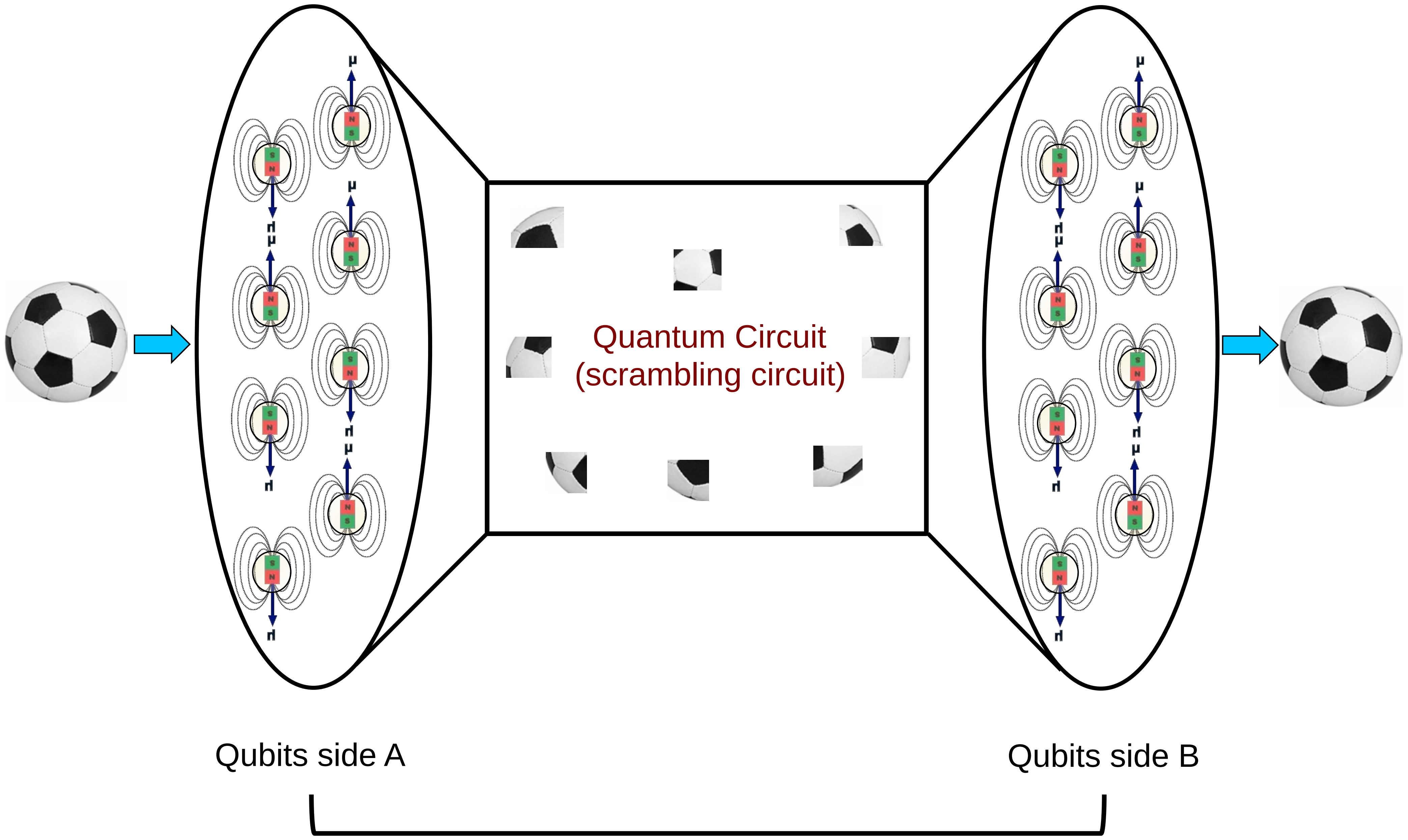
- Low energy techniques for neutrino and axions: L. Castaldo (Heidelberg)
- Quantum scintillation materials: Etiennette Auffray Hillemans (CERN)
- Atom interferometry at large scales (ground based, space based): Jason Hogan (Stanford)

Why we care about Q-Technology

Some unexpected connection to Cool Physics

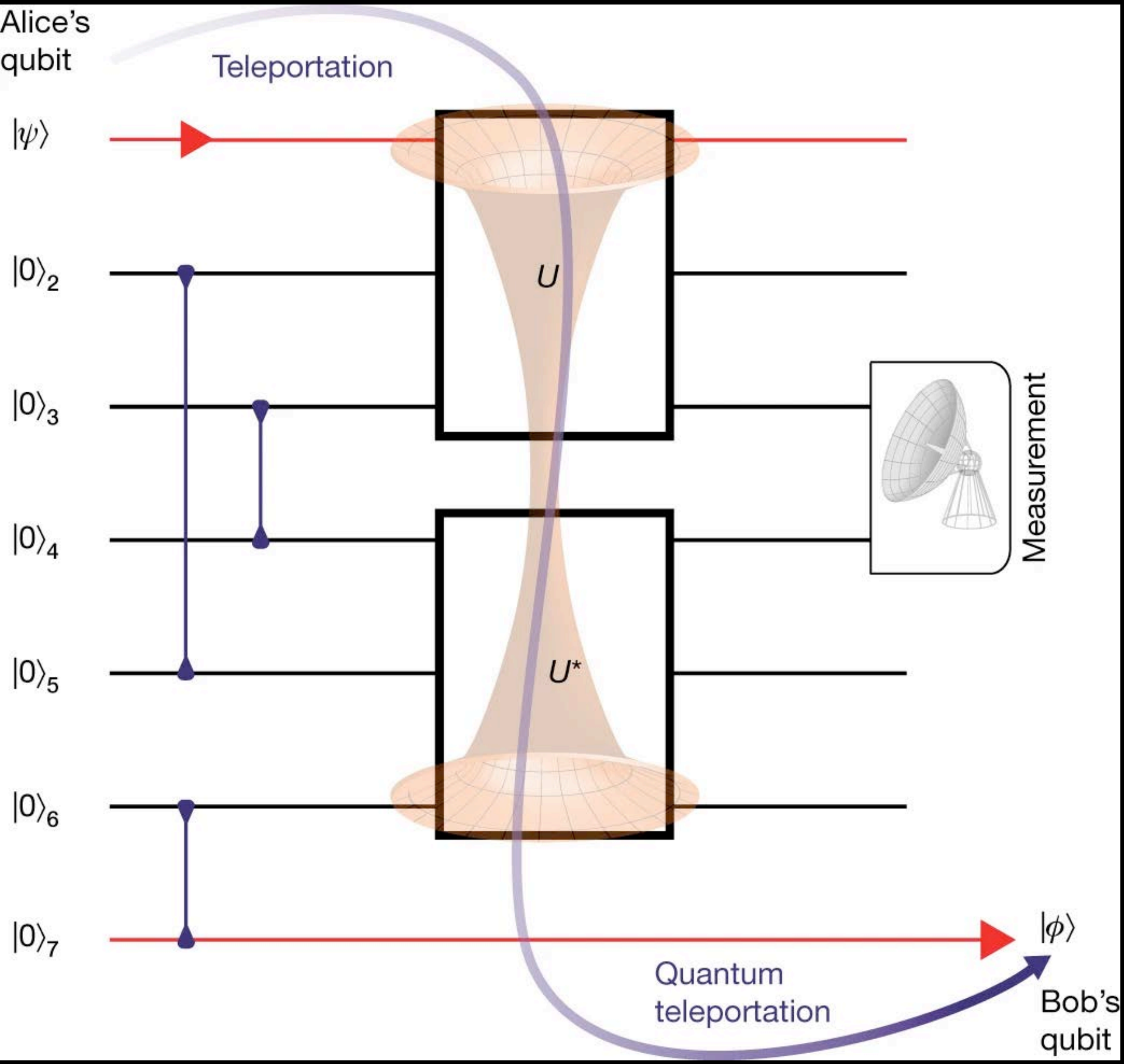
My talk is at 31minute below:
https://www.youtube.com/watch?v=5w1HDaM4dHg

Teleportation without decoding



Classical channel still present

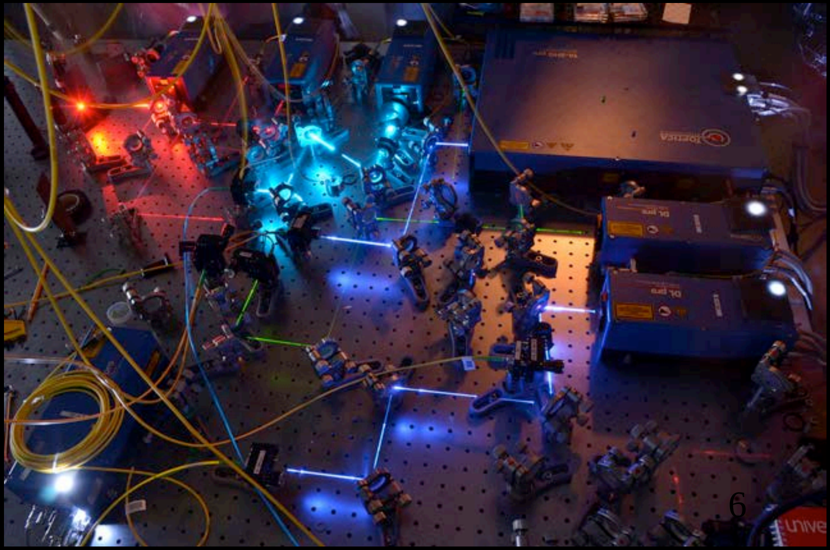
Experiment proves scrambling!



Verified quantum information scrambling
Landsman, Figgatt, T. Schuster, Linke, Yoshida, Yao & Monroe, Nature 567, 61–65 (2019)

Used a quantum teleportation algorithm encoded in a circuit made from seven coupled ytterbium ions held in a row, each acting as a single qubit. This quantum computation process teleported a single qubit from one end of the row to the other.

The goal was to verify quantum information scrambling



Examples and benefits of this approach:
(2021/2) arXiv:2102.0106
(2021/3) arXiv:2103.14996

ECFA Detector R&D Roadmap Symposium of Task Force 5
Quantum and Emerging Technologies

Novel ionic, atomic and molecular systems

Marianna Safronova

Department of Physics and Astronomy,
University of Delaware, Delaware, USA

thorium nuclear clock

https://thoriumclock.eu/

Q-SEnSE
An NSF Quantum Leap Challenge Institute

https://www.colorado.edu/research/qsense/

NSF

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Office of Naval Research
ONR
Science & Technology

erc
European Research Council

ECFA Detector R&D Roadmap Symposium of Task Force 5
Quantum and Emerging Technologies

Which quantum technologies are likely to lead to disruptive discoveries in fundamental physics in the next 10-20 years?

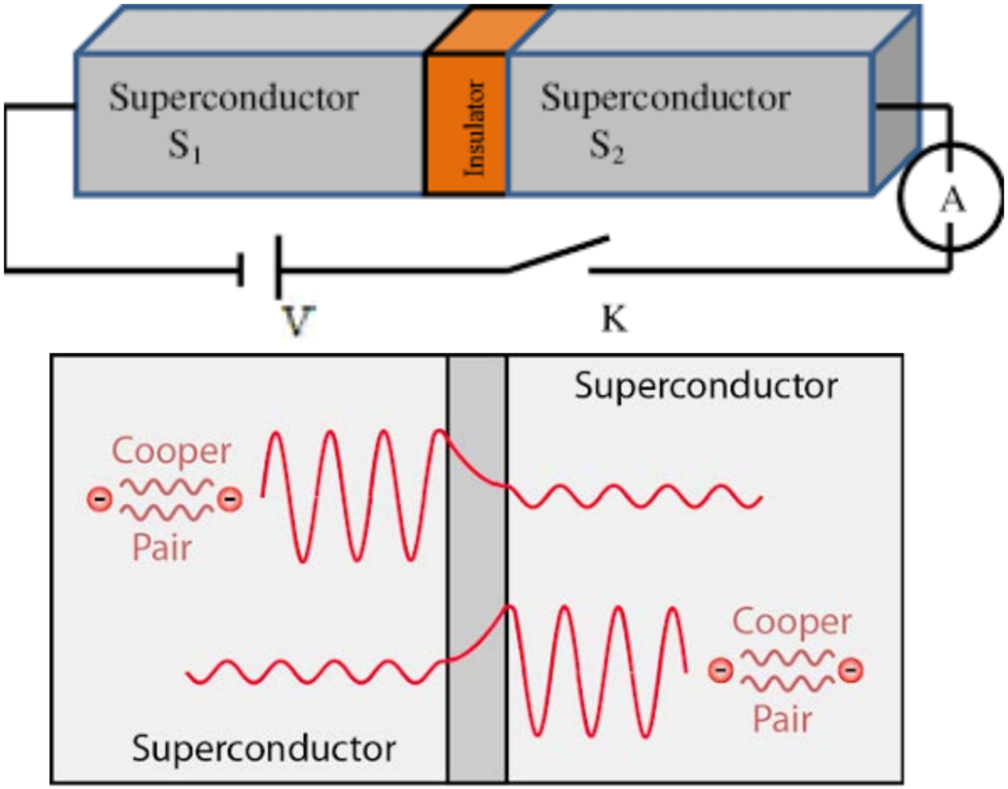
How do we define "quantum technology" and "quantum sensor"?

A technology or device that is naturally described by quantum mechanics is considered ``quantum''.

Then, ***a "quantum sensor" is a device, the measurement (sensing) capabilities of which are enabled by our ability to manipulate and read out its quantum states***.

Quantum Technology and the Elephants
Quantum Science and Technology Editorial
Marianna Safronova & Dmitry Budker

Josephson Junction



$$\Psi_1 = n_s e^{i\varphi_1} \qquad \Psi_2 = n_s e^{i\varphi_2}$$

Josephson Junction:
SIS sandwich

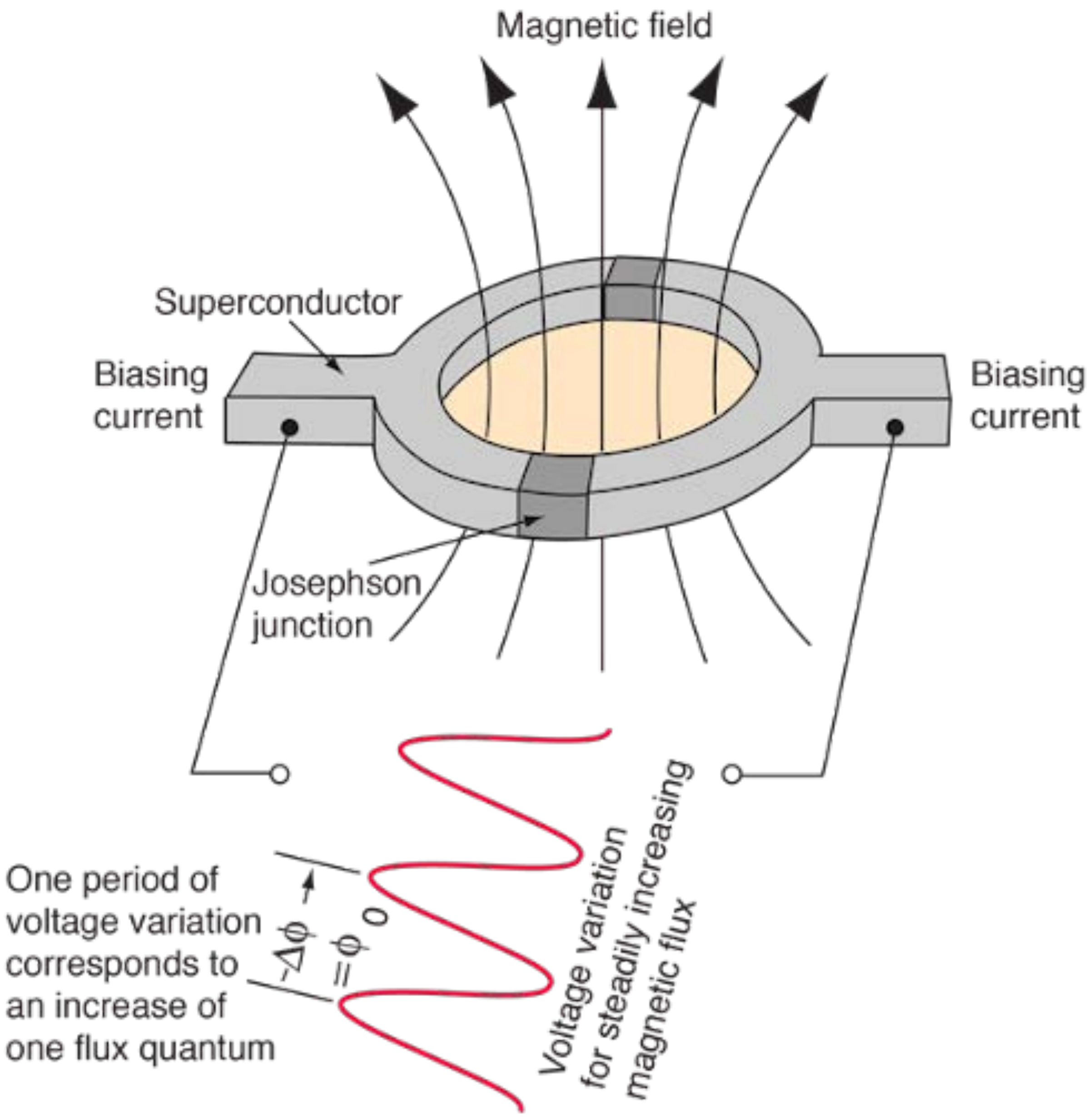
Cooper pairs can tunnel and produce current

$$I_s = I_c \sin\left(\Delta\varphi\right)$$ 1st J relation

$$V = \frac{\hbar}{2e}\frac{\partial}{\partial t}\left(\Delta\varphi\right)$$ 2nd J relation

$$f_J = \frac{e}{\pi\hbar}V$$

SQUID: two JJ in a loop



SC devices: some history

Stafford Withington

1910-1970 First half of the 20th century, the physics of the superconducting state first became a rich area of study.

Superconducting materials support a wealth of physical processes, some of which are highly desirable and can be used to create devices, and others cause endless problems.

1970s Superconducting device physics started to emerge following the discovery of pair tunnelling, and the invention of the SQUID. Josephson junction parametric amplifiers (JJPA) started to appear.

1980s Refinement of superconducting device physics as an enabling technology for fundamental physics began in the context of devising low-noise first-stage mixers (SIS) for submillimetre-wave astronomy (200 GHz -1 THz) .

Ground-based spectroscopy and interferometry (JCMT, CSO, IRAM, KOSMA, ALMA), and space-based platforms (Herschel) were enabled through major technological refinement of mixers.

Opening up the submillimetre-wave Universe led to major discoveries in star and galaxy formation, and the evolution of large scale structure in the Universe.

Stafford Withington (Cambridge)

1990s. Demonstration of superconducting bolometers in the form of a transition edge sensor (TES).

Large arrays of bolometers (100-600 GHz) have revolutionised ground-based observations of the intensity and polarimetric anisotropies of the CMB, leading to numerous detailed observations of the early Universe.

Search for B-modes in the early inflationary phase of the Big Bang is a major challenge, which will be enabled by large superconducting polarimetric imaging arrays (CMB-S4, LightBIRD).

Considerable innovation and success in the development of ultra-low-noise superconducting readout electronics for large arrays – time domain and frequency domain multiplexing.

↓

2000s saw the invention of kinetic inductance detectors (KID) for large format imaging arrays across the whole of the spectrum – more elegant way of achieving multiplexing - SDR

↓

2010 saw the introduction of the travelling wave parametric amplifier (TWPA) for quantum noise limited coherent amplification of large bandwidths.

↓

2020 Superconducting qubits for quantum computing, superconductor/spin-system quantum memory elements.

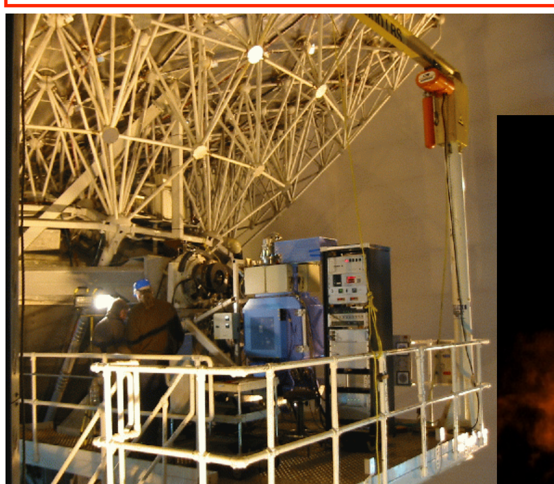
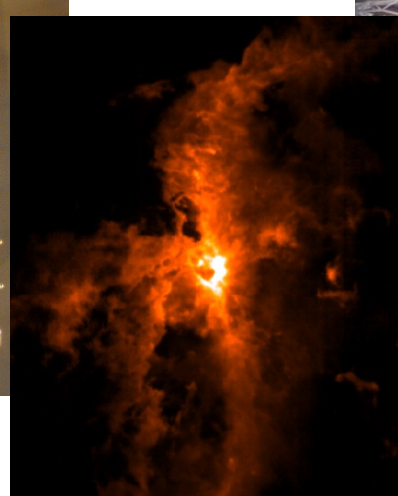
- Submillimetre-wave wave and FIR astronomy would not exist, and its numerous discoveries would not have happened, if it were not for superconducting electronics.

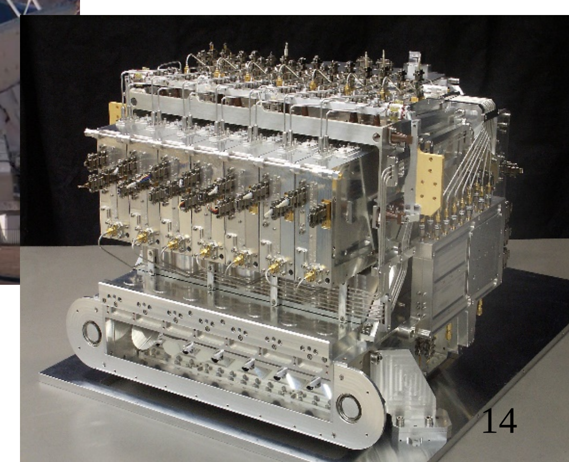
  Recently, the direct imaging of the event horizon of the black hole in M87 – Event Horizon Telescope (VLBI) – was performed using superconducting mixers

- Many future ground-based and space observatories (including x-ray) are entirely reliant on the existence and further development of superconducting electronics – cannot be uninvented!

- Many future space-based astronomy platforms will be launched with superconducting electronics (Athena, SPICA, LightBIRD, Earth Observation).

- None of this technology was provided by industry – all of it comes out of university and government laboratories – responsibility for continuity of supply.



2020 (50 years later)…

Massive opportunities for quantum-limited performance and *enhanced functionality* in astronomy.

The application of superconducting sensors/electronics to further advance fundamental physics.

2020-2024

Quantum Technology for Fundamental Physics - £31M investment by UKRI (STFC)
(Coordinated by Ian Shipsey, Oxford)

3 out of the 7 projects funded are enabled by superconducting electronics:

- Quantum Sensors for the Hidden Sector – vacuum state of activity radiation (QSHS)
  (JJPA's, QUBITs, Bolometers)
- Quantum Technology for measurement of Neutrino Mass through CRES (QTNM)
  (SQUID amplifiers, and TWPA for quantum noise limited spectroscopy)
- Quantum Enhanced Interferometry for New Physics
  (SNSPD as optical photon counters to enable new advances in laser interferometry)

Stafford Withington (Cambridge)

Devices

	Microwave	Submillimetre	Far infrared	Optical	High energy
	10 – 100 GHz 3 cm- 3 mm	100 GHz – 1 THz 3 mm – 300 µm	1 – 10 THz 300 – 30 µm	2 µm – 300 nm	UV, Ɣray and Xray
SIS mixers		🟢			
HEB			🟢		
CEB		🟢			
TES	🔴	🟢	🟢	🟢	🟢
KID	🔴	🟢	🟢	🟢	
SNSPD			🔴 TIDC	🟢	
SQUID	🟢				
JJPA	🟢				
TWPA	🟢	🔴			

Stafford Withington (Cambridge)

S-I-S (JPL Caltech)

Herschel Space Observatory’s image reveals great turmoil in the W3/W4/W5 complex of molecular clouds and star-forming regions. MDL-produced SIS mixers on Herschel HIFI discovered many terahertz spectral lines from molecules in interstellar space.

Superconducting Materials

	Ti	Nb	Al	Mo	Ta (bcc)	Ta (β)
T_c (K)	0.55	9.2	1.2	1.1	4.5	0.47 - 0.57
f_c (GHz)	40	676	88	81	327	35-42
σ_N (MS/m)	5.88	11.4	132	10.9	24.4	0.5
ξ (nm)	57	30	189	100	11 – 60	17 (?)
j_c (GA/m^2)	6.5	400	100	14	200-1100	1.7
j_* (GA/m^2)	19	1200	280	40	600-3300	5

UNIVERSITY OF CAMBRIDGE

Elemental BCS superconductors (courtesy Songyuan Zhao):

Tc critical temperature – cool to about 10% of Tc
fc gap frequency calculate from Tc using BCS – pair breaking, not pair breaking
σ_N – normal state conductance
ξ – coherence length
jc – critical current
j* - calculate from jc

Alloys – the nitrides (reactive deposition)

	TiN	NbTiN	NbN
T_c (K)	4	14	10
f_c (GHz)	300	1000	750
σ_N (MS/m)	1	1 - 2.5	
ξ (nm)			
j_c (GA/m^2)	4	4	20
j_* (GA/m^2)	11	11	143 (expt) 56 (theory)

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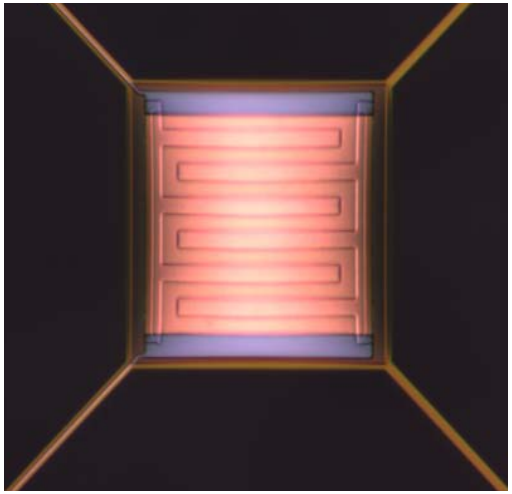
Also silicides, such as WSi

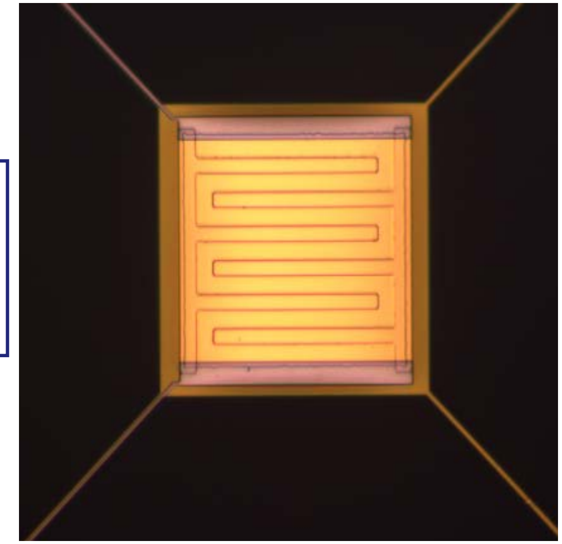
Bilayers and multilayers used extensively for `tuning' the Tc and gap:

MoAu, TiAu, TiAl, MoCu

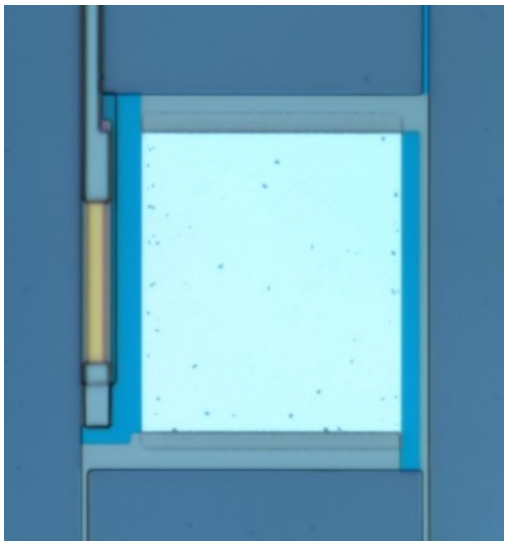
Driven by proximity effect, including lateral proximity effect



Cambridge MoCu – 120 mK (40/106 nm)
Difficult to manufacture
SiO_2 passivation layer to protect Cu



Cambridge MoAu – 150 mK (40/170 nm)
Self passivating - low C
Good inter-diffusion stability



Cambridge TiAl – 550- 650mK (150/40 nm)
Metallurgically stable
Good for Tc ~ 700 mK

SRON TiAu – 120 mK (16/85)
Self passivating
Good inter-diffusion stability

Exploring the performance of thin-film superconducting multilayers as kinetic inductance detectors for low-frequency detection

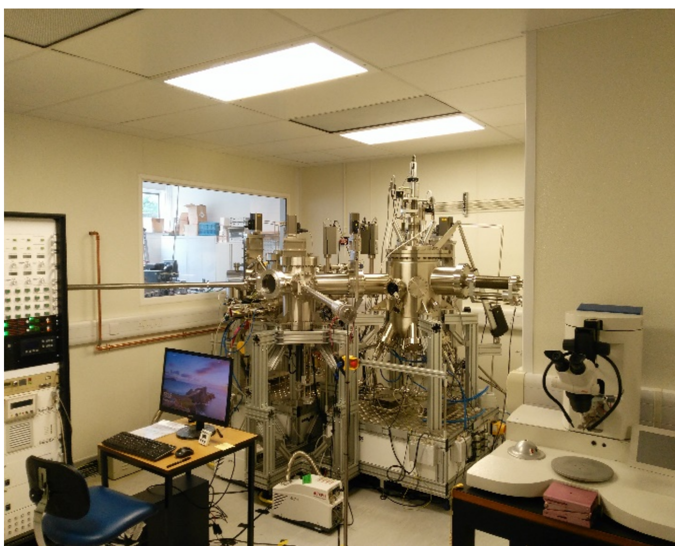
To cite this article: Songyuan Zhao *et al* 2018 *Supercond. Sci. Technol.* **31** 015007

- Device processing repertoire across a wide range of devices and materials:

Nb, Ta, β-Ta, Al, NbN, TiN, NbTiN, Mo, Hf, Ir, Cu, Au, AuCu, AuPd, SiO_2 SiO AlOx

- All on SIN and SoI membranes – 4 UHV deposition systems – sputtering and e-beam

- Bilayers based on proximity effect, and lateral proximity effect, can be used to `engineer' properties of films: MoAu, MoCu, TiAu, TiAl multilayers



TES: Transition Edge Sensors

Spectroscopy of massive particles using TES:
Xray Photoelectron Spectroscopy (XPS)

(Kunal Patel Univ. Cambridge, Alex Shard NPL)

spectroscopy of low energy electrons (200eV-1keV)

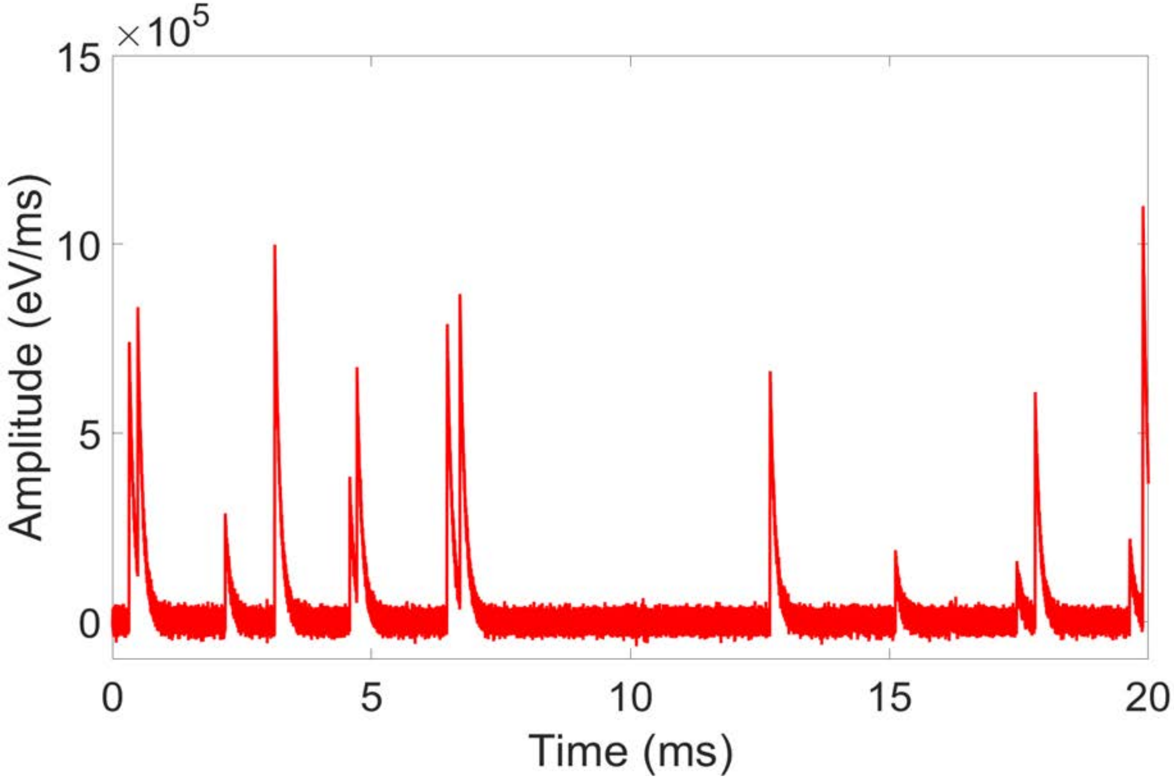
Existing electron spectrometers only measure a narrow electron energy band at a time.

- swept across some total range to build the spectrum.
- energy filtering process discards over 99% of electrons at a time, large and bulky

A TES spectrometer would not discard electrons allowing for a far greater count rate: typical spectrum has ~ 1million events

Comprehensive simulation pipline has been developed (Kunal)

- electrothermal behavior of TES, including phonon and Johnson noise
- stream of pulse on top of the noise floor
- recovery using Bayesian methods
- fundamental limit of energy resolution through Fisher analysis



Simulated TES electron measurement data

⇩

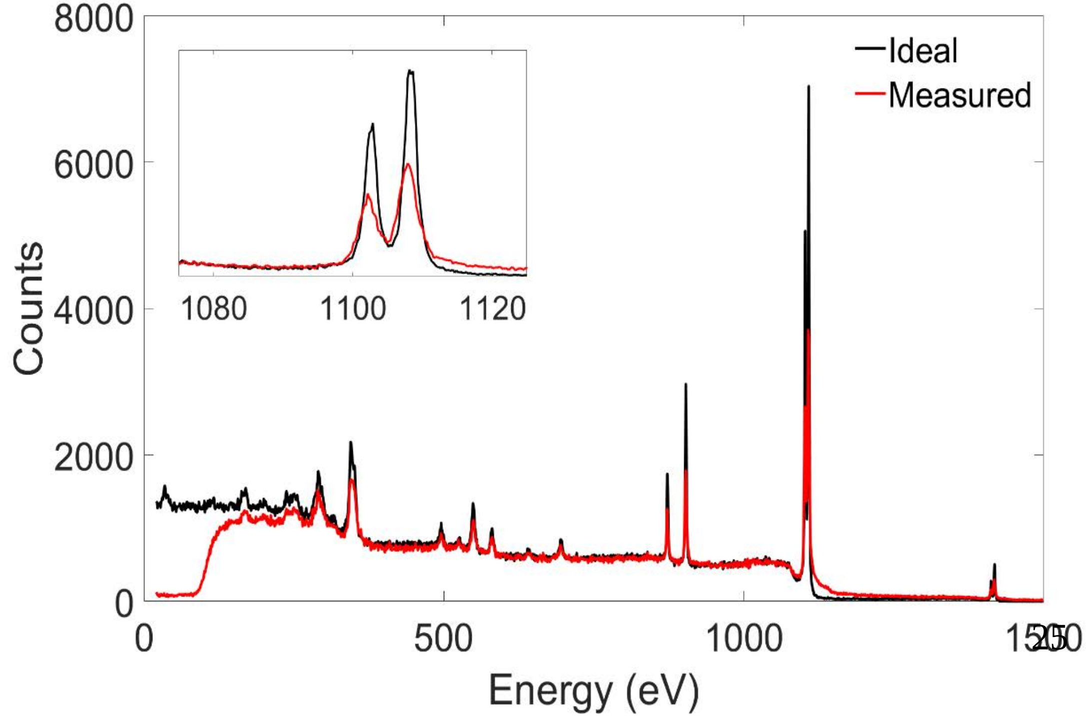
Reconstructed electron spectrum from simulated data

Resolution comparable with current electron spectrometers

~0.5 eV @ 1keV

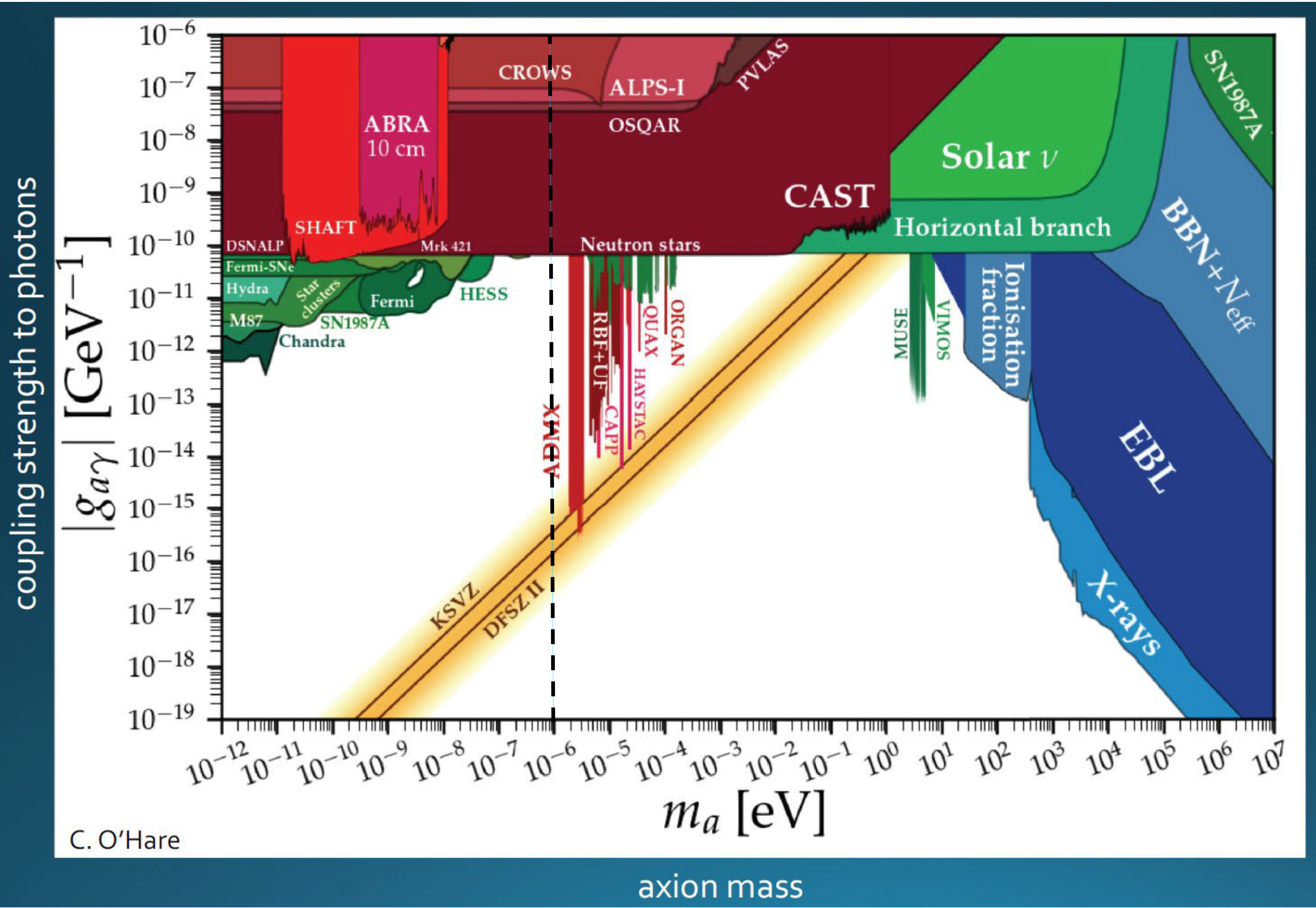
Array of 100 TESs would improve typical x-ray photoelectron spectroscopy considerably

cf Cyclotron Resonance Emission Spectroscopy



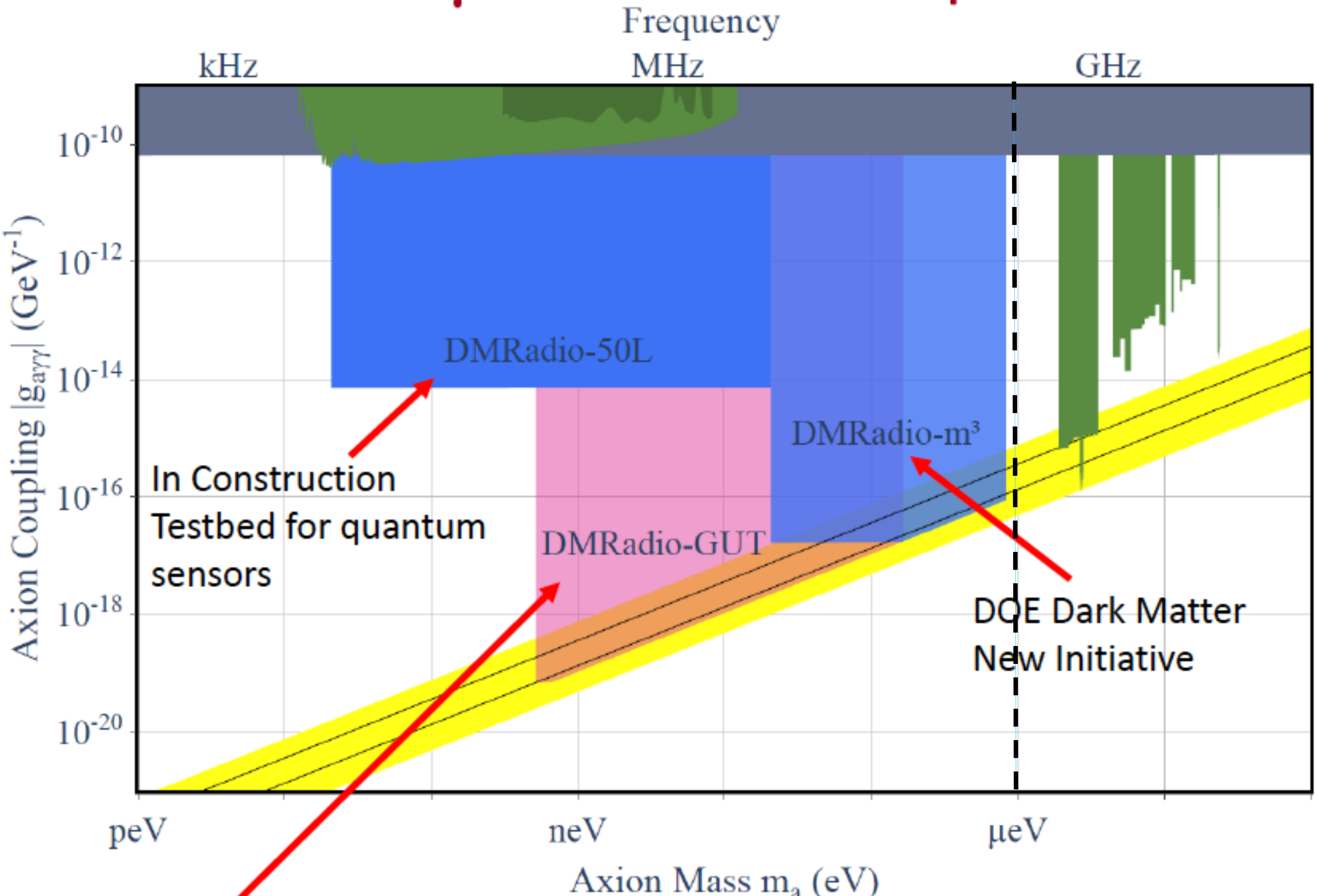
Quantum Acceleration of EM Axion discovery

Kent Irwin



coupling strength to photons
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
CROWS
ALPS-I
PVLAS
OSQAR
ABRA
10 cm
SHAFT
Mrk 421
DSNALP
Neutron stars
CAST
Solar ν
Horizontal branch
SN1987A
BBN+$N_{\rm eff}$
Fermi-SNe
Hydra
Star clusters
Fermi
HESS
M87
SN1987A
Chandra
ADMX
RBF+UF
CAPP
QUAX
HAYSTAC
ORGAN
MUSE
VIMOS
Ionisation fraction
EBL
X-rays
KSVZ
DFSZ II
C. O'Hare
axion mass

< 1 μeV: DM Radio Experiment Family



In Construction
Testbed for quantum sensors

DOE Dark Matter New Initiative

DMRadio-GUT is a long way off!

Chaudhuri, Saptarshi. Snowmass2021-Letter of Interest "DMRadio-GUT: Probing GUT-scale QCD Axion Dark Matter."

‘Listening’ for axions in cavities

Bibber, Lehnet, Chou, Physics Today 72, 6, 48, 2019

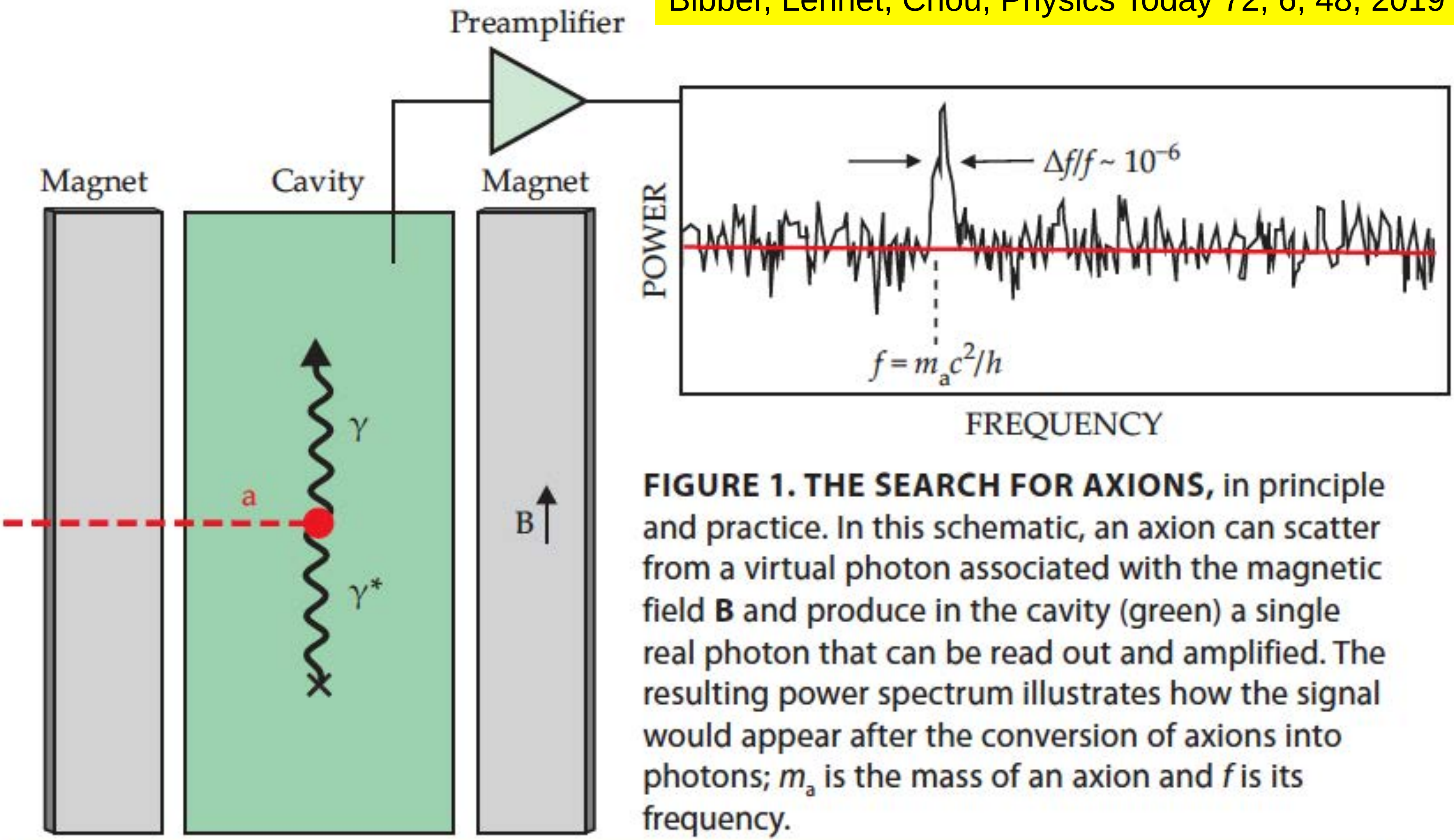


FIGURE 1. THE SEARCH FOR AXIONS, in principle and practice. In this schematic, an axion can scatter from a virtual photon associated with the magnetic field **B** and produce in the cavity (green) a single real photon that can be read out and amplified. The resulting power spectrum illustrates how the signal would appear after the conversion of axions into photons; m_a is the mass of an axion and f is its frequency.

Noise and Std Quantum Limit

System noise has three components:

$$k_B T_N = h\nu \left(\frac{1}{e^{h\nu / k_B T} - 1} + \frac{1}{2} \right) + k_B T_A$$

Amplifier

Black body
(T=temperature)

Vacuum fluctuations
(present even at T=0)

$$k_B T_{SQL} = h\nu$$

System noise measured in units of ‘Std Quantum Limit’.

Beauty of QM: we can push beyond the SQL

Beyond SQL: Quantum Squeezing

Bibber, Lehnet, Chou, Physics Today 72, 6, 48, 2019

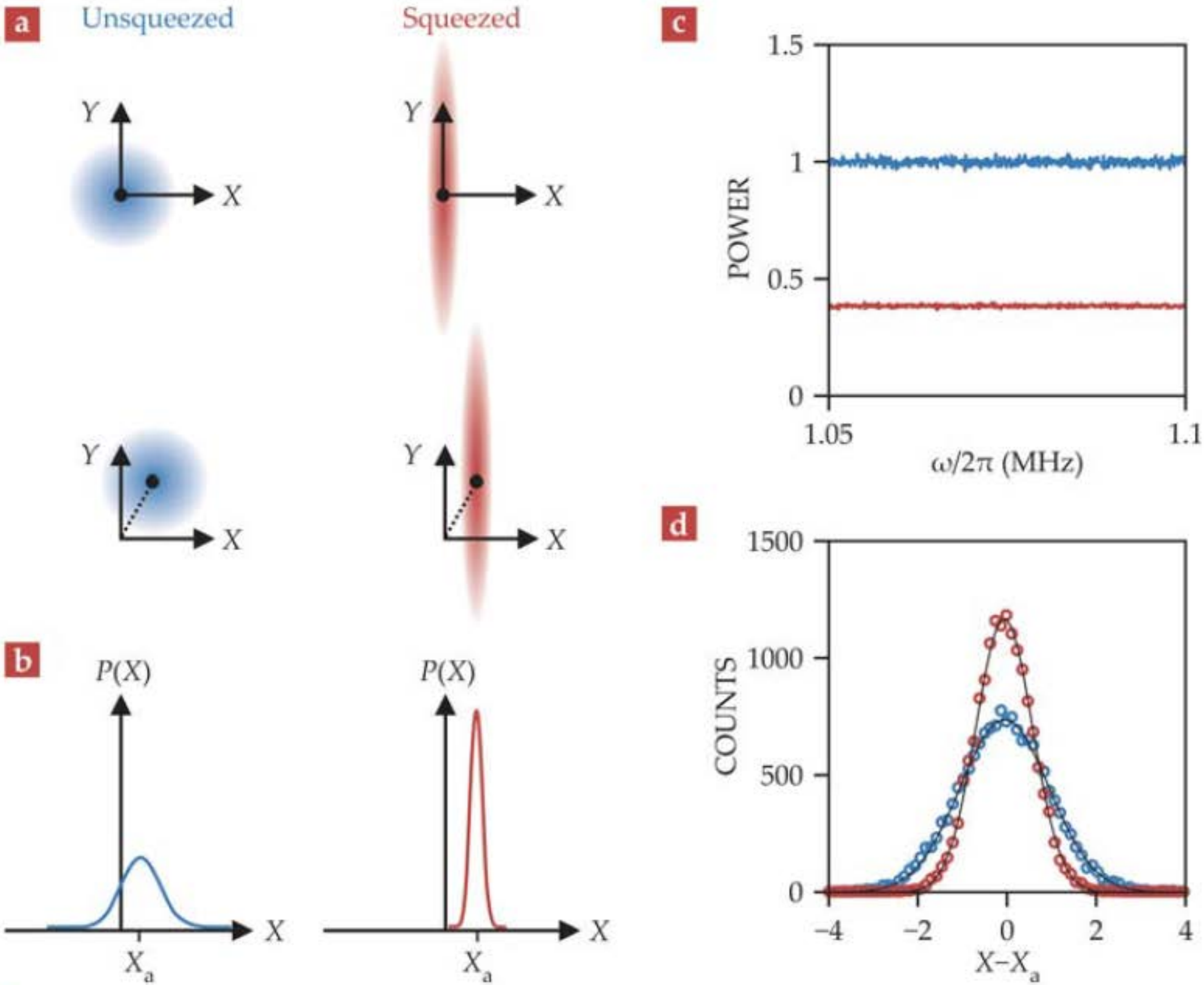
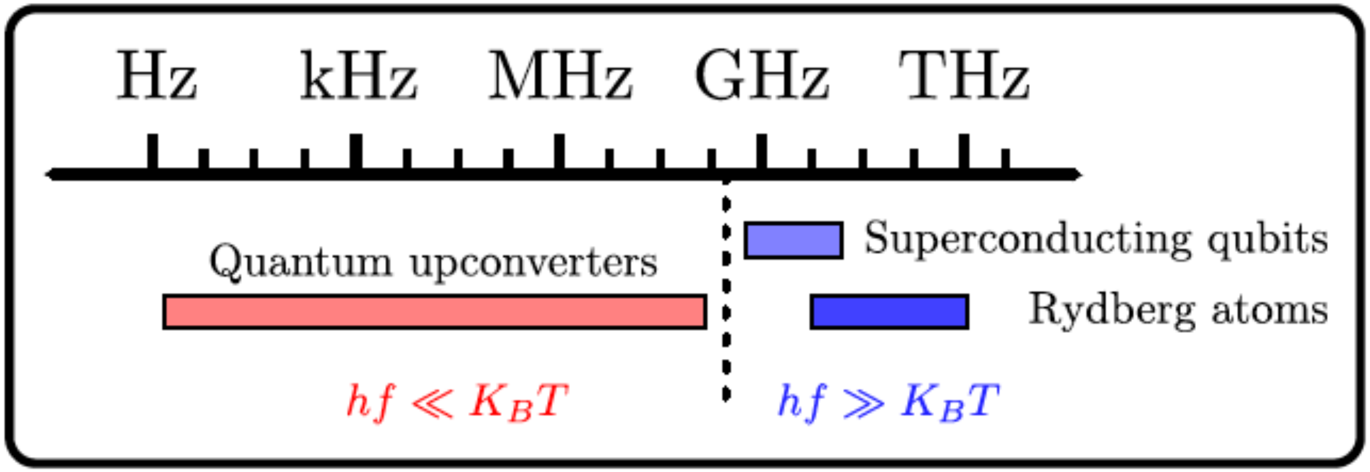


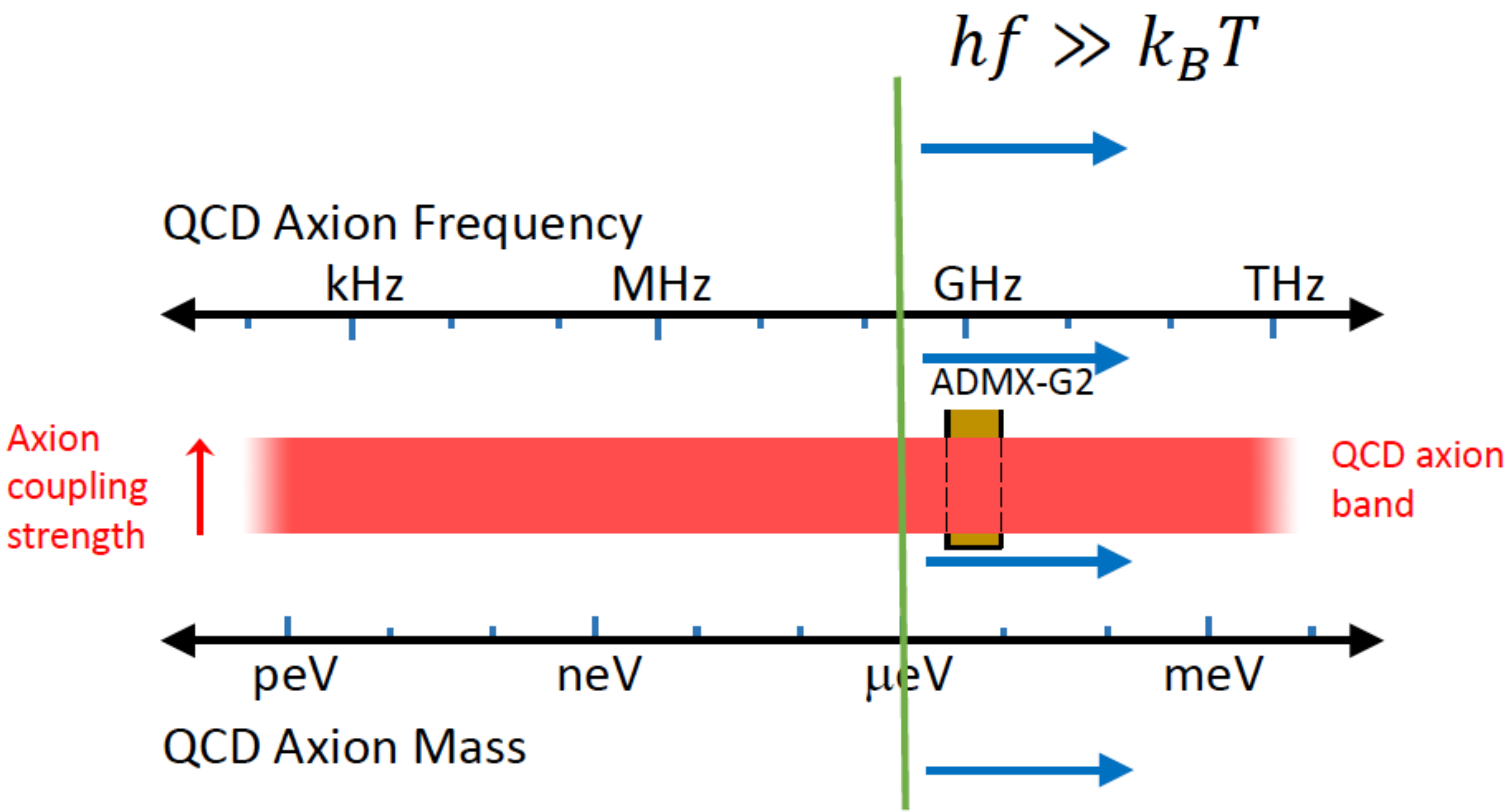
FIGURE 4. AN AXION SEARCH MEASUREMENT. In this illustration **(a)** of phase-space variables *X* and *Y*, the variables' noncommutation imply that the phase space cannot be localized to an area smaller than a Heisenberg uncertainty region. The cavity state is initially prepared in either its ground state (blue) or a squeezed state (red). But once an axion has entered the cavity, the state is displaced (the dotted line) by the axion field. **(b)** A noiseless measurement of the *X* component yields a probability density *P*(*X*). Because noise has been squeezed from the *X* to the *Y* variable, the displacement in *X* by the actual axion signal is more easily detected. **(c)** Noise power from a squeezed-state receiver prototype is plotted versus frequency *ω*. **(d)** A histogram of measured values of *X* with (red) and without (blue) squeezing match the theoretical plot of panel b, in units of the vacuum noise.

Electromagnetic Quantum Sensing Regimes



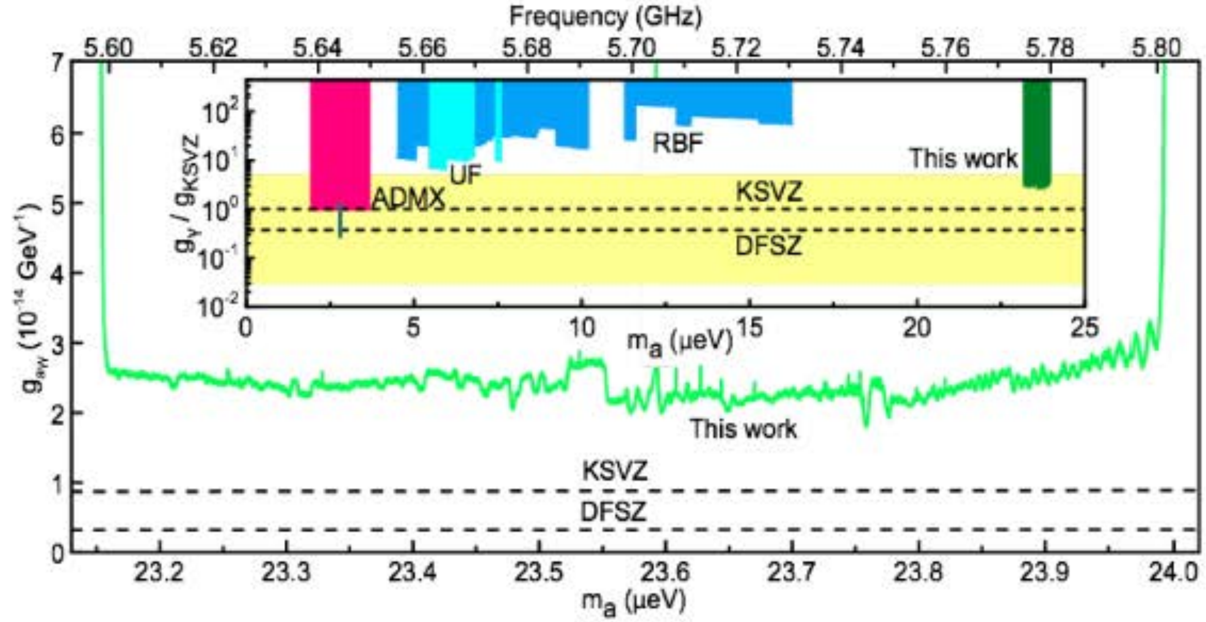
- Approaching the Standard Quantum Limit
- Squeezing
- QND photon counting
- Backaction evasion
- High-N Fock state preparation, entangled cavities…
- Also: pair-breaking detectors (TES, MKID, CEB, magcal) going to lower frequency… 100 GHz?

>~ μeV: Ground State

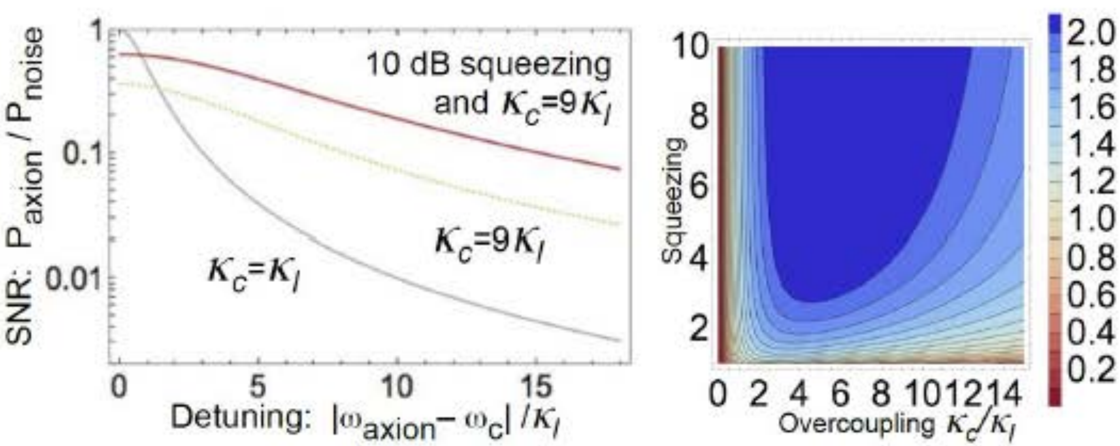


- Ground state
- Cavity resonators (experimental scale of order of Compton wavelength)
- Scattering-mode amplifiers

HAYSTAC: Acceleration through squeezing



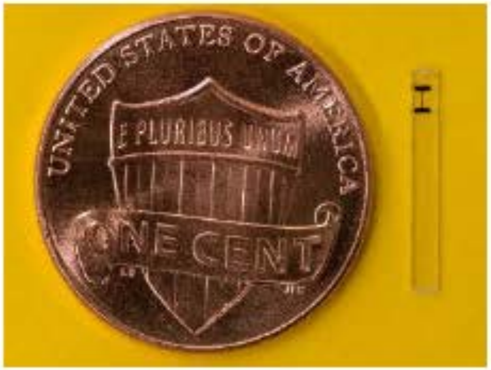
HAYSTAC run 1 & 2 combined exclusion plot



HAYSTAC Phase II squeezed state receiver projected acceleration

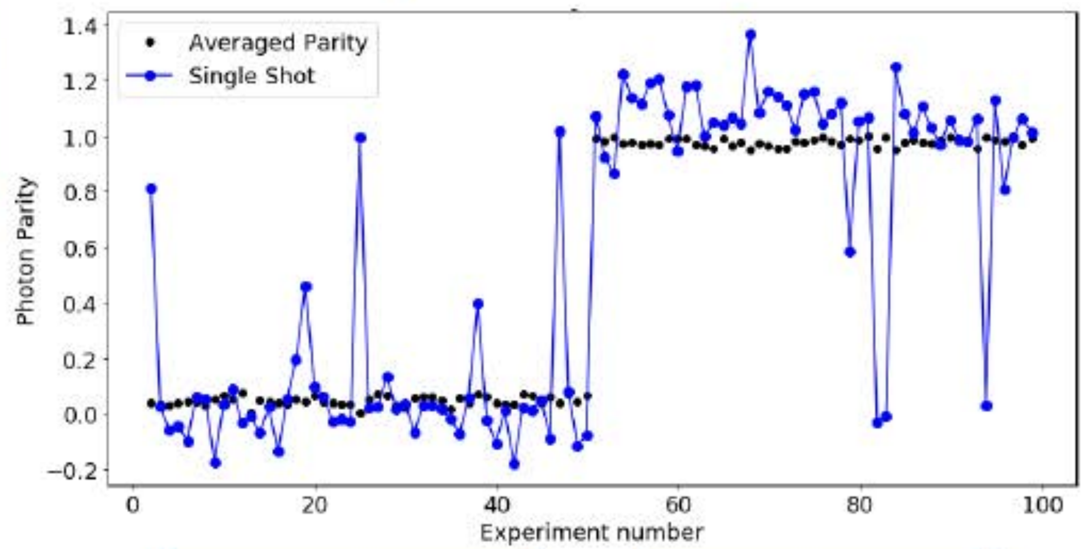
Droster, Alex G., and Karl van Bibber. "HAYSTAC Status, Results, and Plans." *arXiv preprint arXiv:1901.01668* (2019).

Ground state measurement: QND photon counting

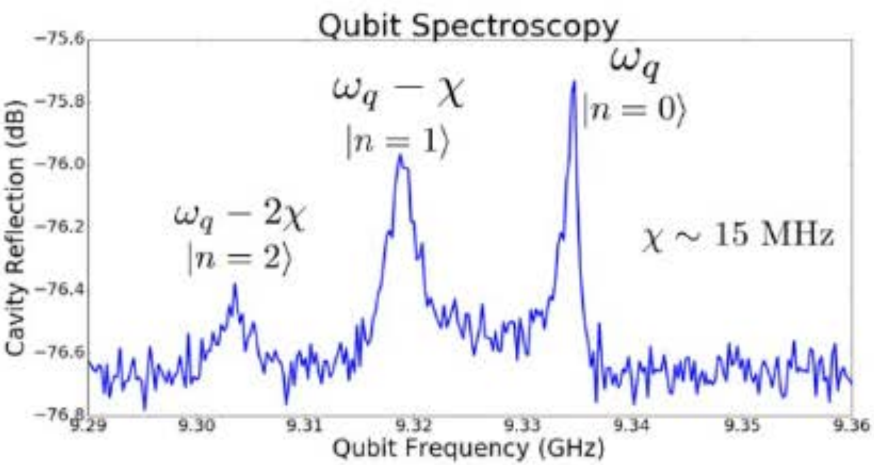


Akash Dixit, Aaron Chou, David Schuster

Repeatedly measure the clock frequency to determine whether the cavity contains 0 or 1 photon:



Use qubit as an atomic clock whose frequency depends on the number of photons in the cavity. The electric field of even a **single photon** will exercise the non-linearity of the qubit oscillator and shift its frequency.



Many QND measurements agree that the cold cavity contains 0 photons

Inject 1 photon

Many QND measurements of the single photon **without absorbing it.**

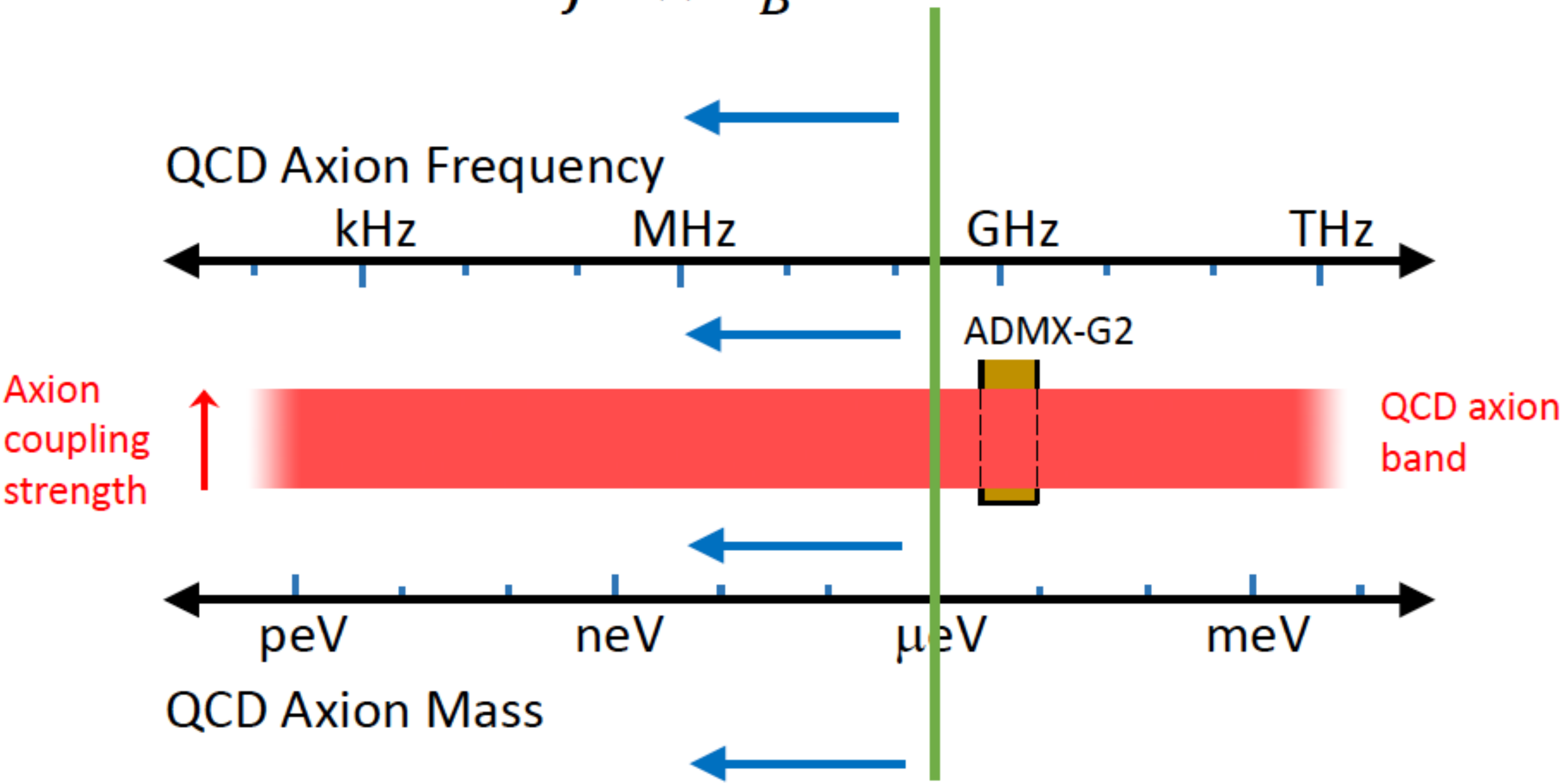
Count # of photons by measuring the quantized frequency shift of the qubit.

Figure Credit: Aaron Chou, FNAL

Fermilab THE UNIVERSITY OF CHICAGO HEISING-SIMONS FOUNDATION

<~ µeV : High Occupation

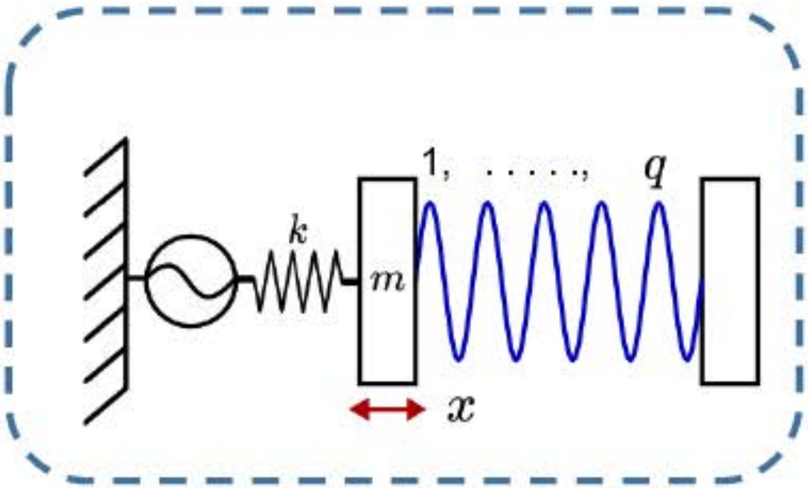
$$hf \ll k_B T$$



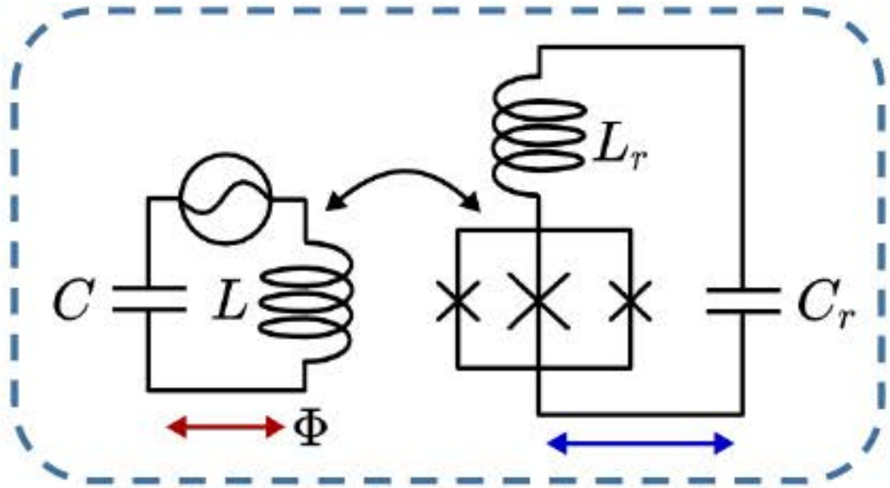
- Thermal state
- Lumped LC resonators (experimental scale << Compton wavelength)
- Op amp-mode amplifiers

Radio-Frequency Quantum Upconverters: Analagous to Optomechanical Systems

LIGO:



Axion detector with RQU:



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

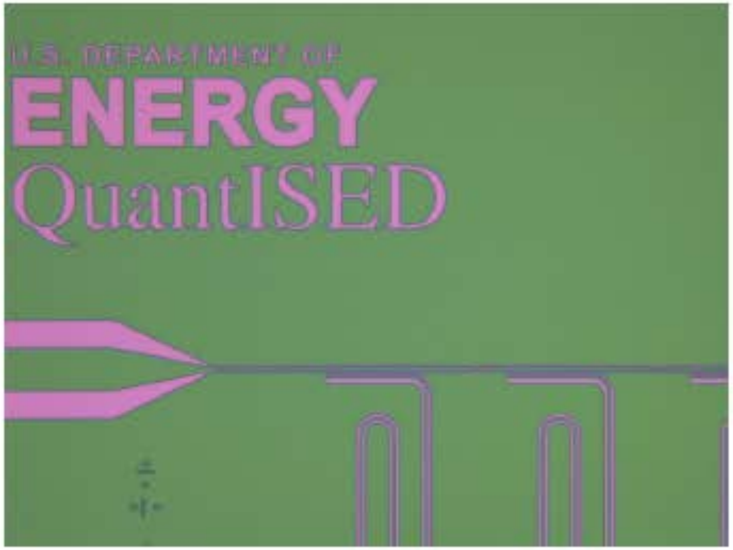
$$\omega_a = \sqrt{\frac{1}{LC}} \quad \omega_b = \sqrt{\frac{1}{L_r(\Phi)C_r}}$$

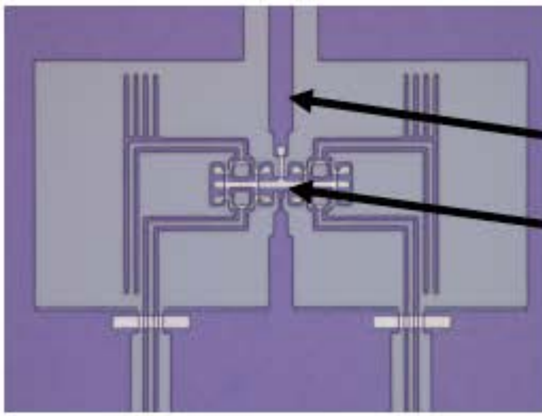
Same Hamiltonian for both systems (to first order in coupling)

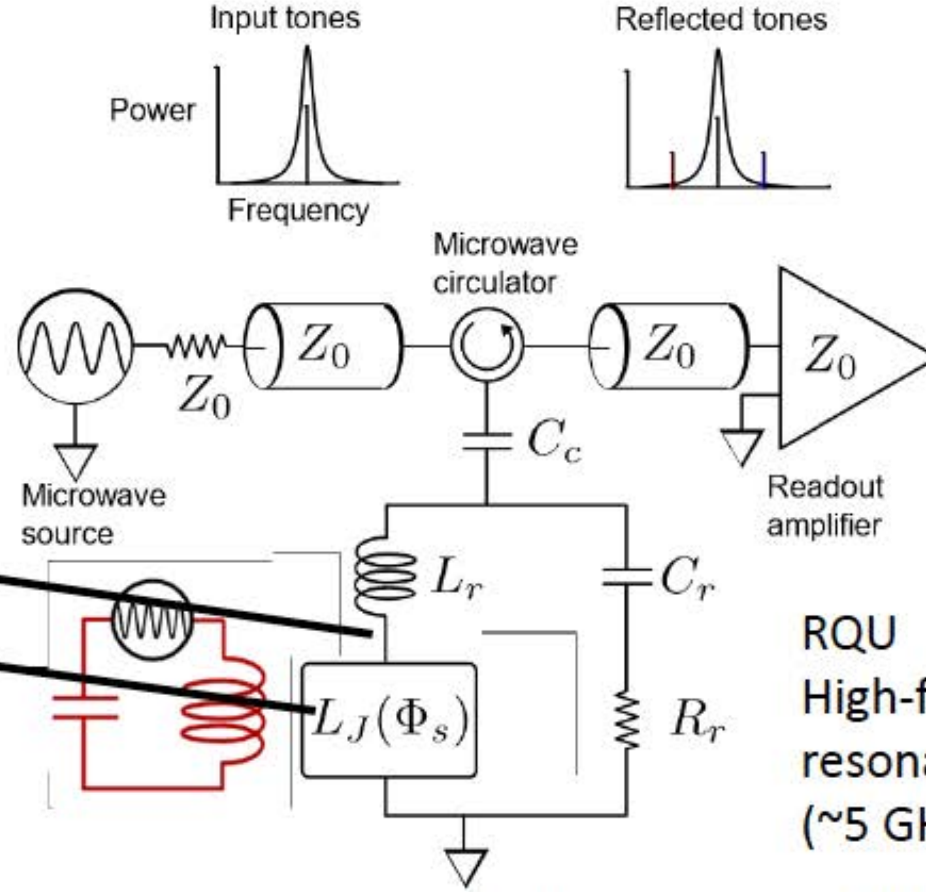
$$\widehat{\mathrm{H}} = \hbar\omega_a\left(\hat{a}^\dagger\hat{a} + 1/2\right) + \hbar\omega_b\left(\hat{b}^\dagger\hat{b} + 1/2\right) + \widehat{\mathrm{H}}_{\mathrm{INT}}$$

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

RF Quantum Upconverters



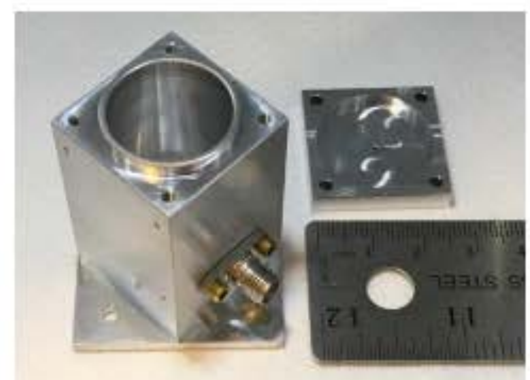




RQU
High-frequency
resonator
(~5 GHz)

RQUs:
3-junction RQU 1-junction RQU

Cavity resonator RQUs:



Snowmass2021 - Letter of Interest

Radio Frequency Quantum Upconverters: Precision Metrology for Fundamental Physics

Thematic Areas: (check all that apply □/■)
□ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics
■ (Other) IF1 Quantum Sensors
□ (Other) AF7 Accelerator Technology R&D

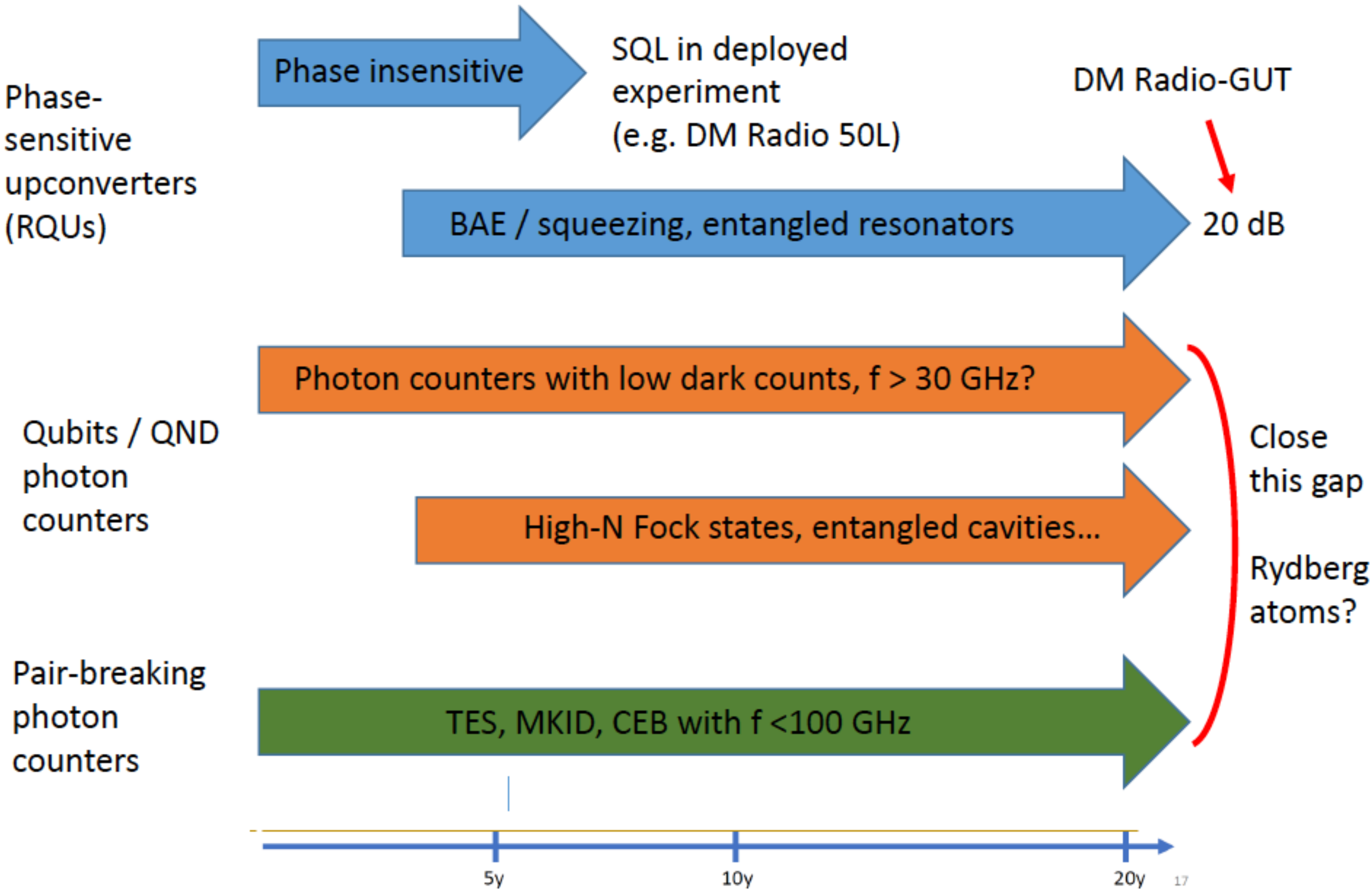
Contact Information:
Name: S. E. Kuenstner (kuenstns@stanford.edu)
Collaboration: DMRadio

Authors: J. Adam (Boston University), D. Aybas (Boston University), S. Chaudhuri (Princeton), H.-M. Cho (SLAC), C. S. Dawson (Stanford), P. W. Graham (Stanford), A. V. Gramolin (Boston University) S. P. Ho (Stanford), K. D. Irwin (Stanford/SLAC), F. Kadribasic (Stanford), R. Kolevatov (Princeton), S. E. Kuenstner (Stanford), D. Li (SLAC), A. Phipps (CSU East Bay), S. Rajendran (JHU), N. M. Rapidis (Stanford), M. Simanovskaia (Stanford), J. Singh (Stanford), A. O. Sushkov (Boston University), E. C. van Assendelft (Stanford), K. Wells (Stanford), B. A. Young (Santa Clara), C. Yu (Stanford).

Abstract:

We propose a comprehensive program to investigate the advantages of quantum metrology techniques in the frequency range between DC and 300MHz. The work will be based on the Radio Frequency Upconverter (RQU), which is a flexible and adaptable platform for precision metrology of a variety of quantum systems including electromagnetic circuits and polarized nuclear spin ensembles. The immediate application of the RQU to fundamental physics is in searches for the QCD axion via interactions with electromagnetism and nuclear spin. These experiments are poised to search for the QCD axion over approximately 6 orders of magnitude in mass, spanning from approximately 1 peV to 1μeV.

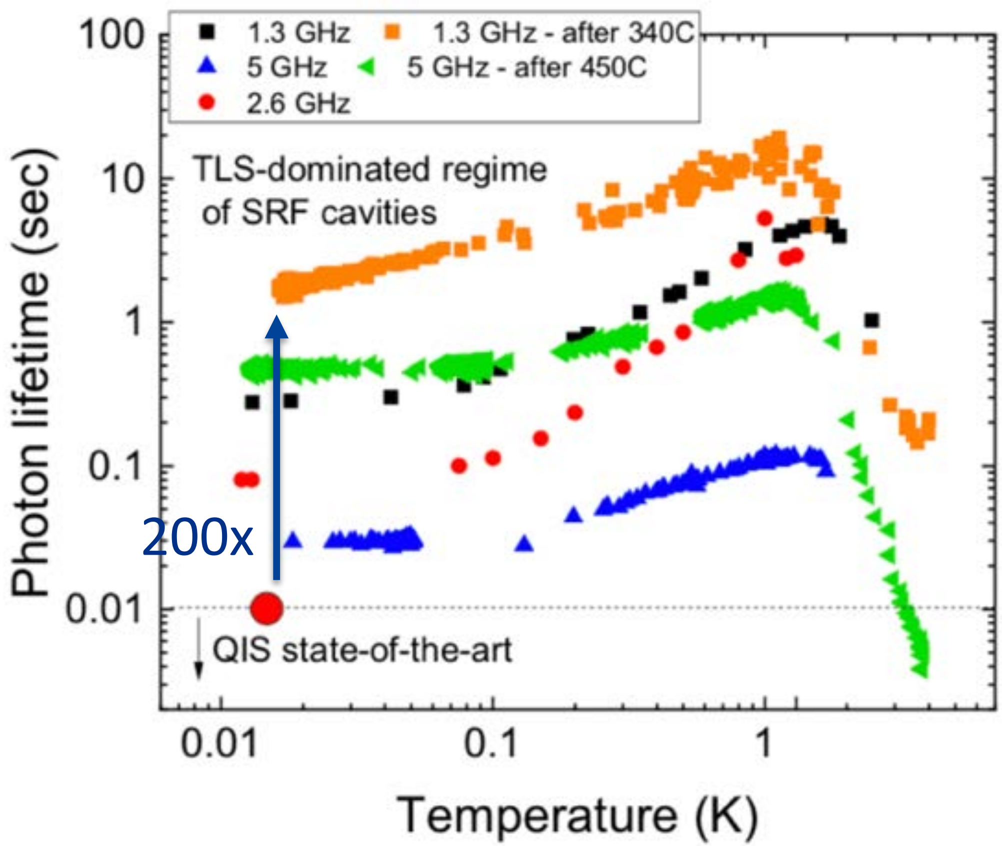
Conclusion: notional development timeline

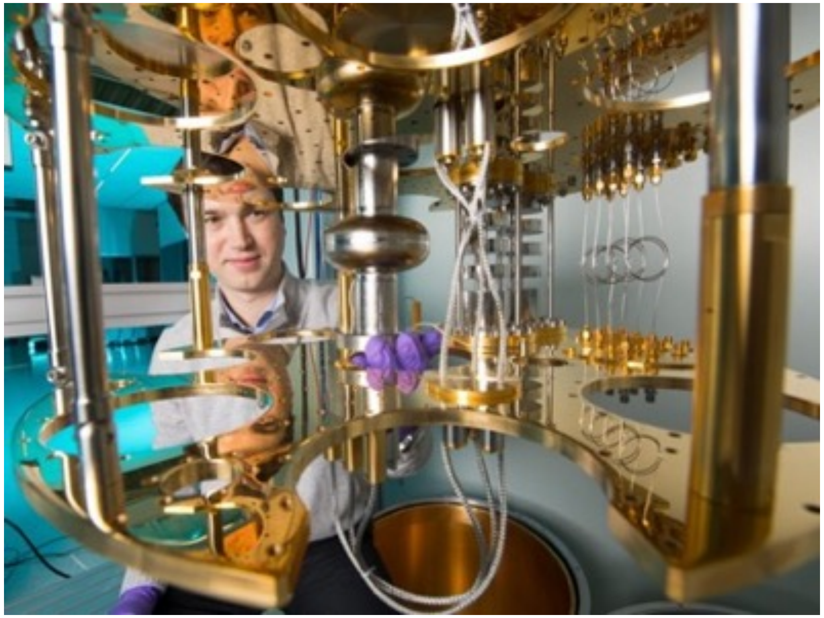


Superconducting RF Cavities and DM

Alexander Romanenko

Fermilab superconducting cavities: highest coherence (high Q) quantum microwave resonators



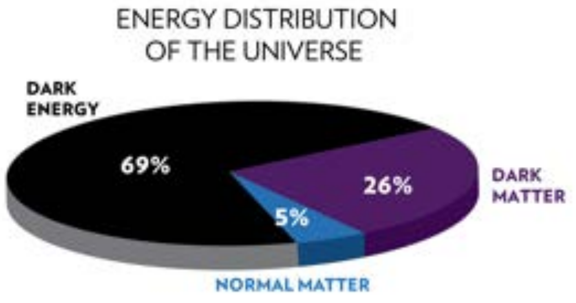


- Demonstrated record values of 2 seconds of coherence in quantum regime

A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Belomestnykh, S. Posen, and A. Grassellino
Phys. Rev. Applied **13**, 034032, 2020

Applications: Longer Range Interactions and Wave-like Dark Matter

- New light particles are theoretically well motivated. e.g.
  - Axion like particles (including the QCD axion)
  - Dark photons



- For such light particles two hypotheses can be tested:

New particle:

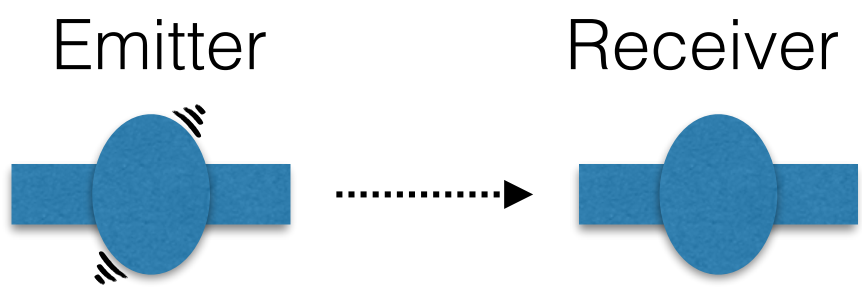
$\mathcal{L} \supset$ dark photons?
axions?
long range force?

Dark matter (and new particle):

$\supset$ dark photons?
axions?

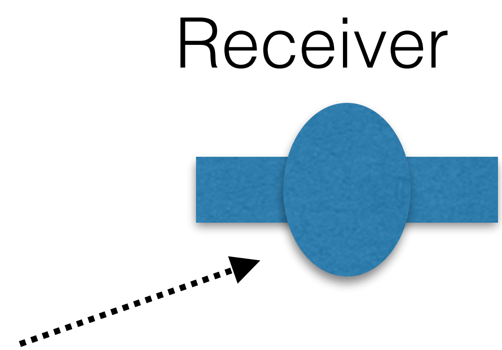
Basic search schemes

Light Shining through wall:



a search for a mediator.

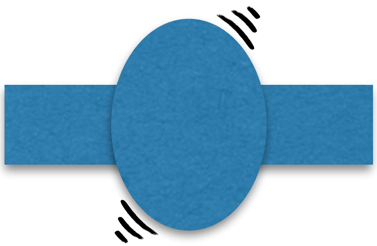
A dark matter search:



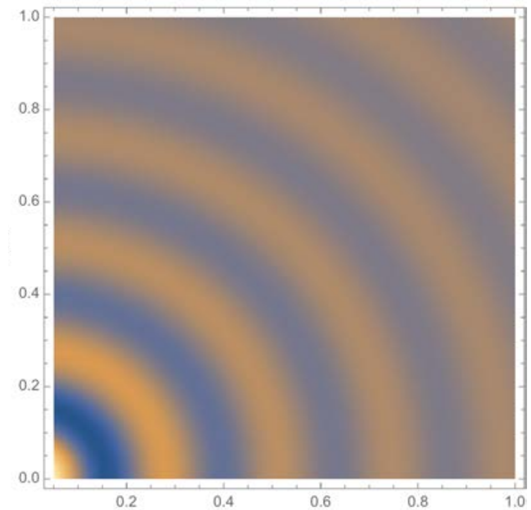
the DM filled Universe
is the emitter

Dark Photon Search

Q> 1e9

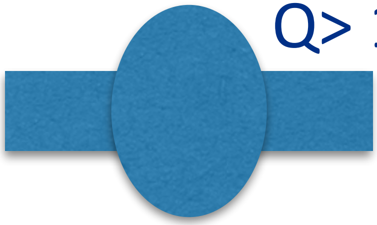


Emitter Cavity



a dark photon field is radiated at 1.3 GHz.

Q> 1e10



Receiver Cavity

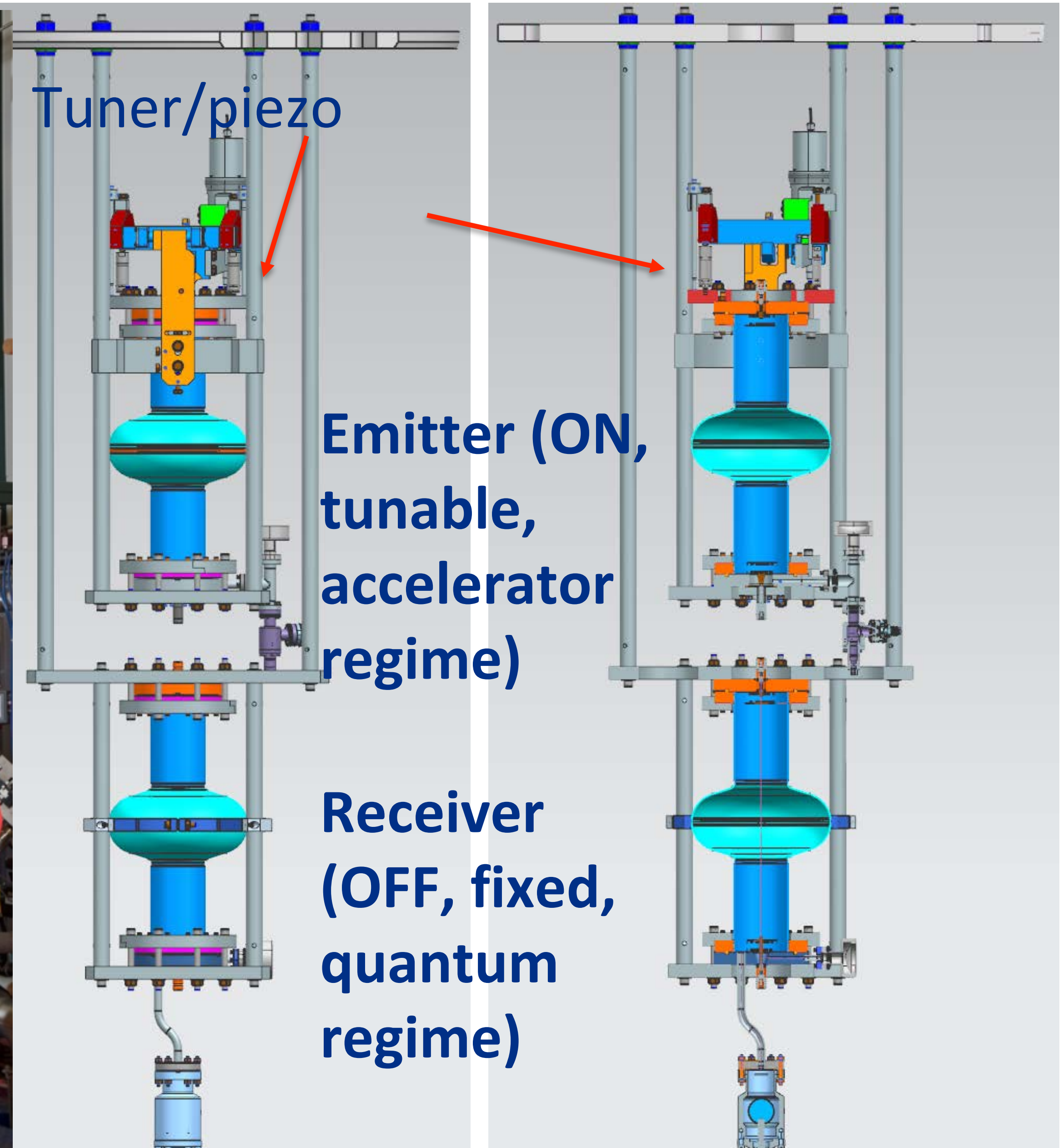
Frequency of 1.3 GHz, excited to ~ 35 MV/m. Thats ~ 10^{25} Photons!

Tuned to 1.3 GHz. Responds to dark field. Contains only thermal noise (T=1.4 K).

For correct cavity positioning $P_{\rm rec} \sim G^2 \, \epsilon^4 \left(\frac{m_{\gamma'}}{\omega}\right)^4 Q_{\rm rec} Q_{\rm em} P_{\rm em}$

Fermilab

DarkSRF experiment @ Fermilab



Low energy techniques: neutrino & axions

L. Gastaldo

Table of contents

Cutting edge detectors for:

Low energy neutrino physics

- direct neutrino mass determination (β- and EC kinematic)
- searches for neutrinoless double beta decay
- measurement of coherent elastic neutrino nucleus scattering

- Long baseline neutrino oscillation
- Neutrino telescopes

Covered by F. Resnati in TF8 Symposium

Search for axions

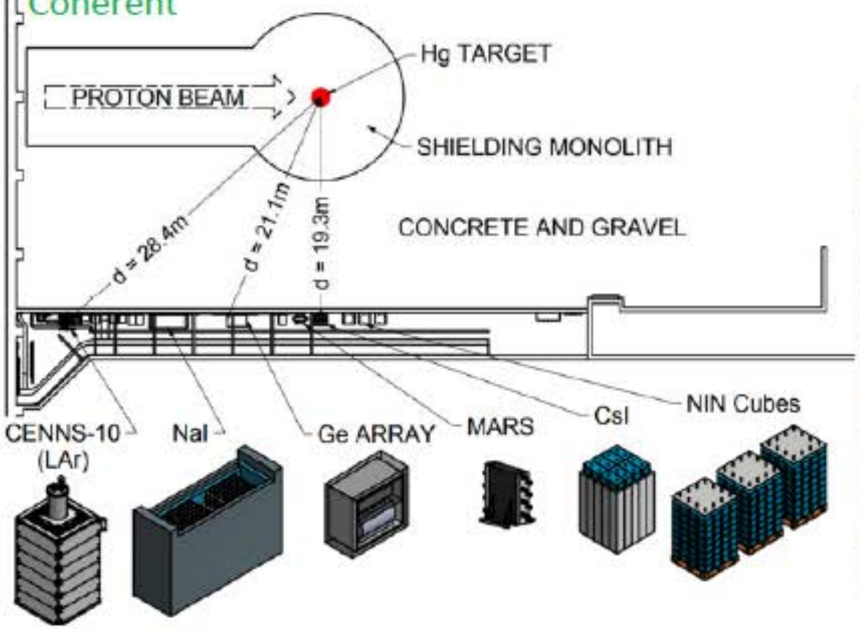
- light shining through a wall
- helioscope

Haloscope just discussed in K. Irwin's talk

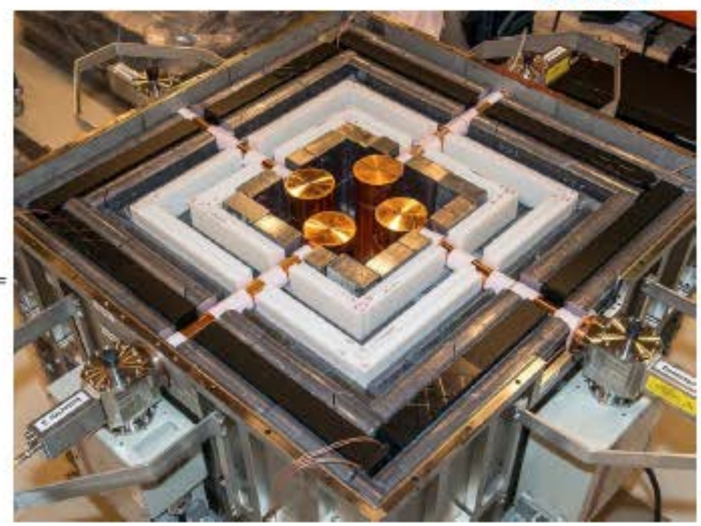
Coherent elastic neutrino nucleus scattering

Neutrino sources	Detectors	Experiments
Pion decay at rest @SNS ORNL	Room temperature scintillators (CsI - NaI)	Coherent
Reactor	Ar scintillation detector	MINER
EC sources	Low temperature calorimeters/bolometers	Ricochet
Pion decay at rest @ESS	Ge semiconductor – ionization detectors	NuCLEUS
	CCD	CONUS
		TEXONO
		CONNIE

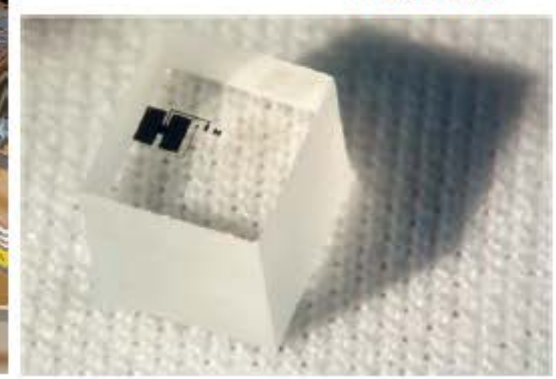
Coherent



CONUS



NuCLEUS



Axion searches

ECFA
European Committee for Future Accelerators

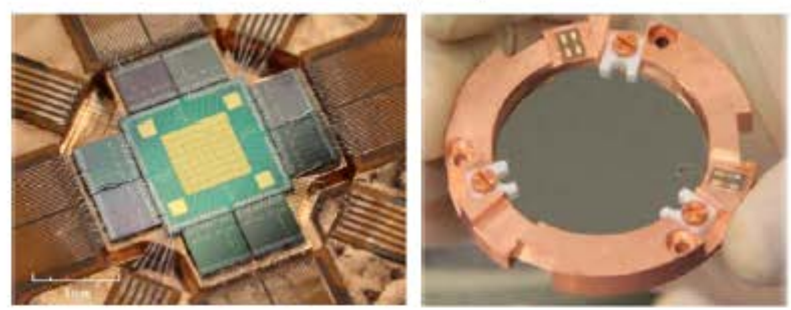
Axion source	Detectors	Experiments
Sun	Helioscopes - low background x-ray det.	(baby-)IAXO
Photon conversion in a lab (Laser source)	low background single photon detector (eV)	ALPS-II(I) /JURA
	Heterodyne	OSQAR
	CCD	

In baby-IAXO 2 70 cm bores will be available
In IAXO 8 70 cm bores will be available
→ different detector technology with equivalent background to reduce systematics

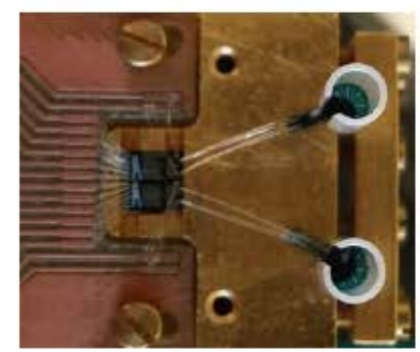
In ALPS II both TES and heterodyne are considered – on-goind R&D to define background

RT detector for IAXO: Micromegas, gridpix, SDD

LT detector for IAXO: MMC, TES, NTD-Ge



Single eV-photon detector for ALPS-II

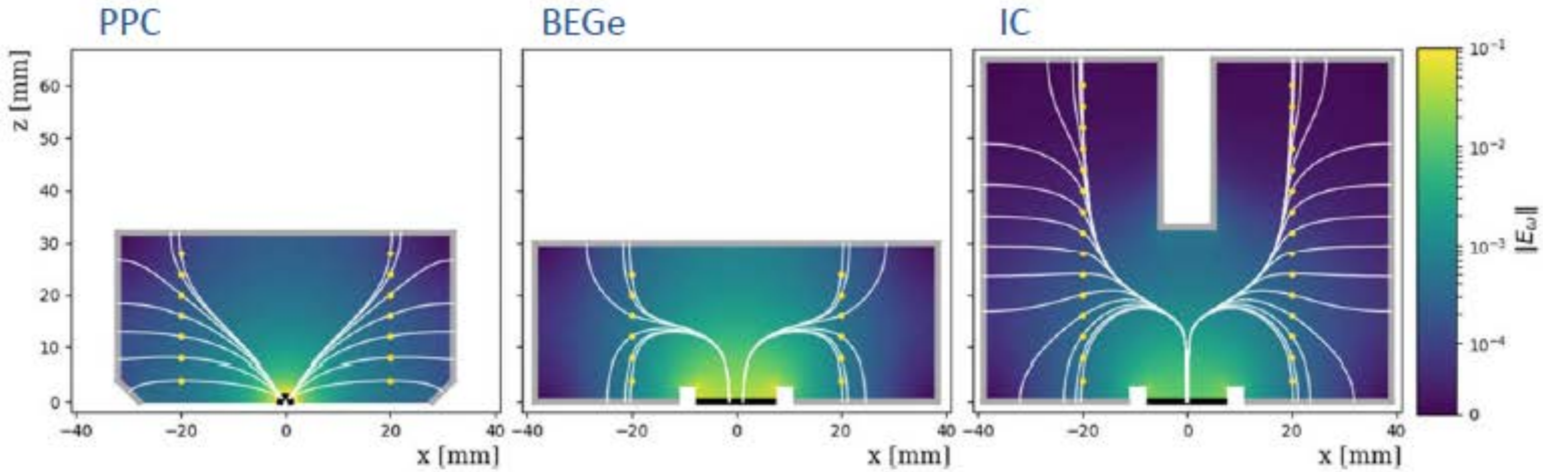


HP germanium detectors

ECFA
European Committee for Future Accelerators

Major R&D topics

- Lower threshold
- improving energy resolution while increasing mass
- lower background while increasing mass
- develop low noise readout electronics
- Optimize geometry for improved pulse shape discrimination



p-type point contact Germanium detectors ~ 1 kg

CONUS
energy threshold < 300 eV_{ee}

Majorana
2.5 keV FWHM @ ~ 2.4 MeV

Gerda/Legend

Broad Energy Germanium detector BEGe	~ 0.8 kg
Inverted coaxial Germanium detectors	~ 2-3 kg

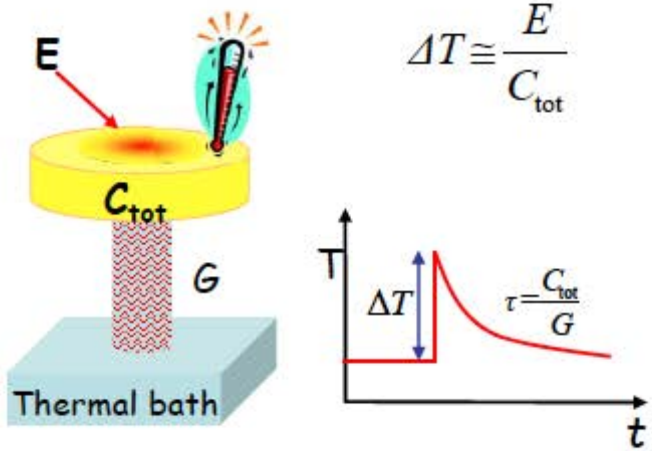
→ 3 keV FWHM @ ~ 2.4 MeV
→ pulse shape discrimination

Comellato et al., Eur. Phys. J. C (2021) 81:76

R&D performed by research centers partially with companies

Low temperature microcalorimeters

Calorimetric concept ... at mK



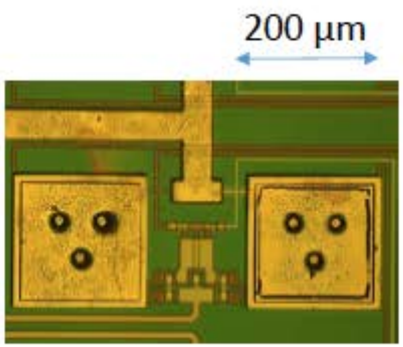
$$\Delta T \cong \frac{E}{C_{tot}}$$

High precision thermometers:

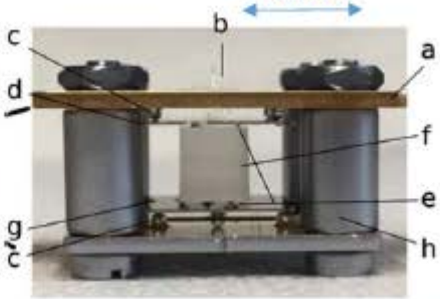
Resistance of highly doped semiconductors
NTD-Ge, Si thermistor

Resistance at superconducting transition
Transition Edge Sensors, TES

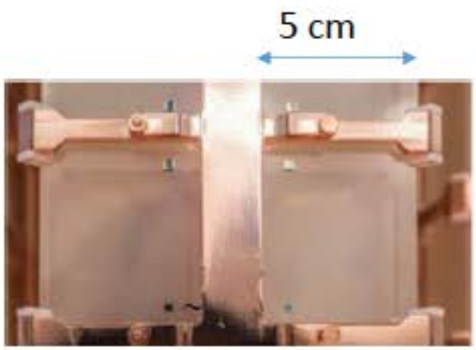
Magnetization of paramagnetic material
Metallic Magnetic Calorimeters, MMC

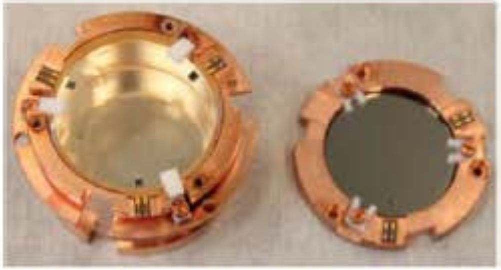


MMC enclosing ^{163}Ho for ECHo – 3 eV FWHM



Detector module for Nucleus, Al_2O_3 with TES <20 eV threshold





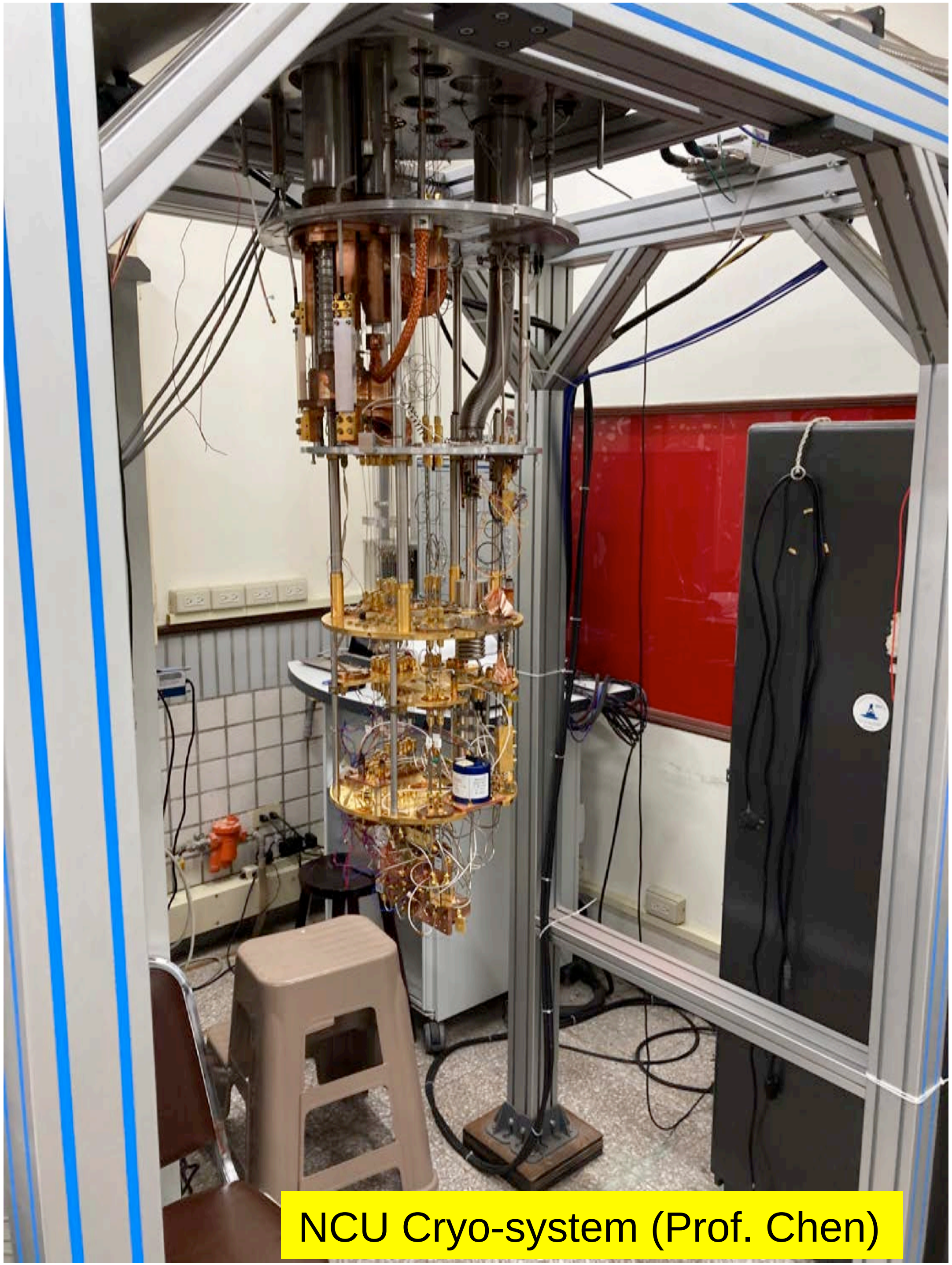
Detector module for CUORE (top) and CUPID-Mo (bottom) with NTD-Ge – 5 -7 keV FWHM

- Very flexible detectors, suitable for different absorbers
- R&D for different applications

- Major challenges
  - Continuous improvement of energy resolution for small and large detectors
  - Upgrade multiplexing

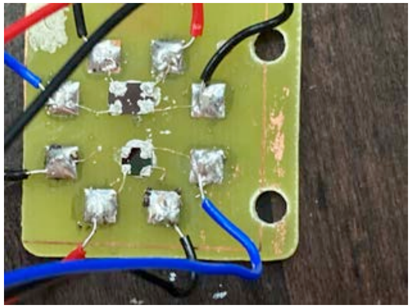
R&D performed by research centers

Niobium films produced for TIDC



NCU Cryo-system (Prof. Chen)

Wu Hsin-Yeh, SP et al, August 2021



- Nb film on SiO using NTU ME Sputter.
- Film Tc measurements also performed with an NTU physics SQUID equipment.
- Physics to buy a dedicated high Vacuum sputter to be installed in Mechanical Engineering Labs and shared. (SP et al organizing the purchase and cost nothing to TIDC!).

Additional Slides

CEB: Cold Electron Bolometers

L.Kuzmin et.al.: Nature Communications Physics vol 2, 104 (2019)

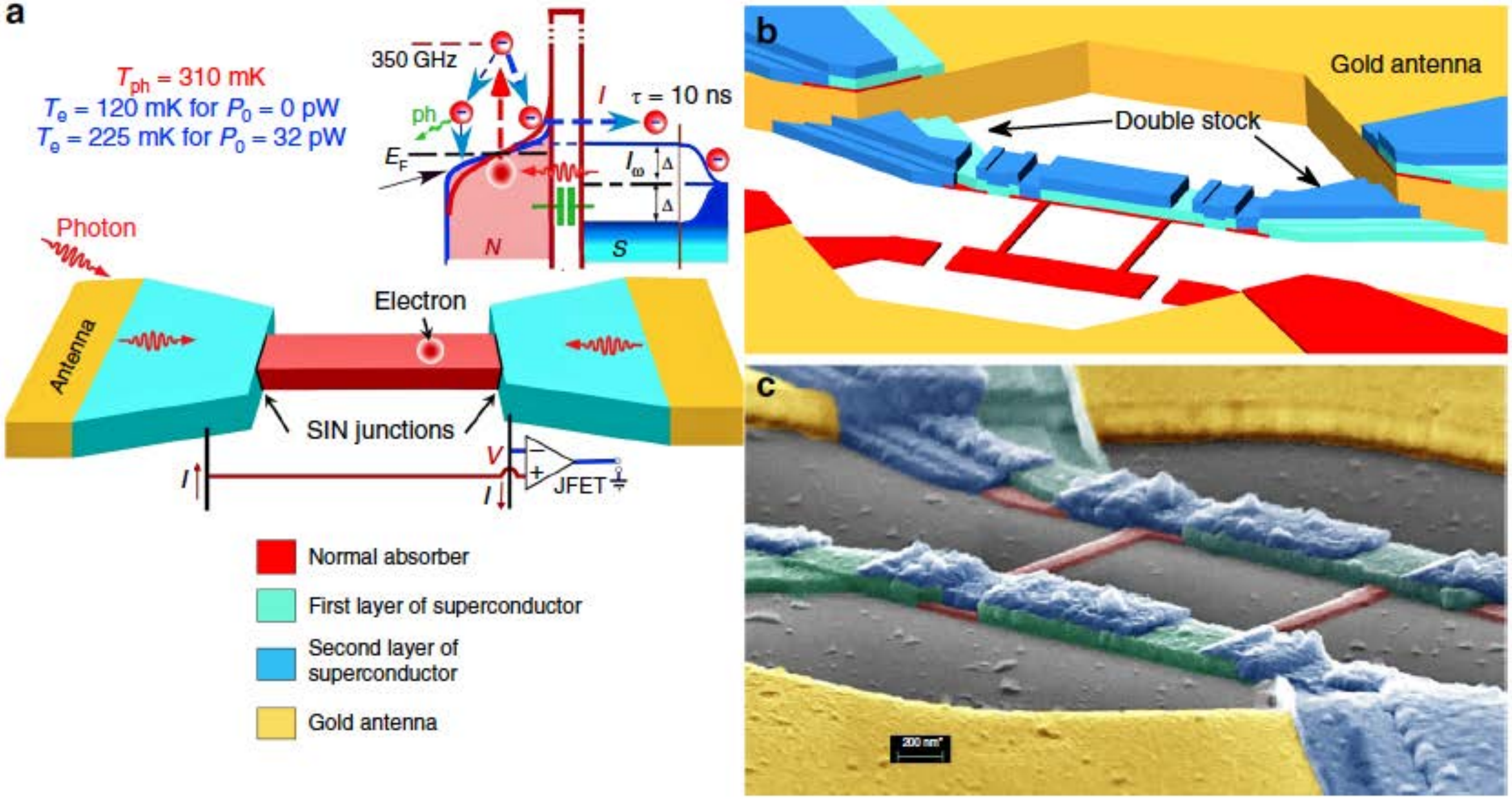


Fig. 1 A single cold-electron-bolometer (CEB). **a** Simplified scheme showing a CEB in current-bias mode and an energy diagram that shows the main heat flow processes: absorption of a photon by an electron in a normal absorber, thermalization of electrons, tunneling of hot electrons, and dissipation of heat in the phonon system. The read-out scheme is shown in current-bias mode. **b** 3D-model of a CEB, fabricated by the shadow evaporation technique. Superconducting electrods are shown for the top junction only. **c** A scanning electron microscope image of fabricated CEB integrated into a gold antenna. The color legend applies to the entire figure

HAYSTAC: Acceleration by Squeezing

K. M. Backes et. al., Nature, Vol 590, 11 Feb 2021

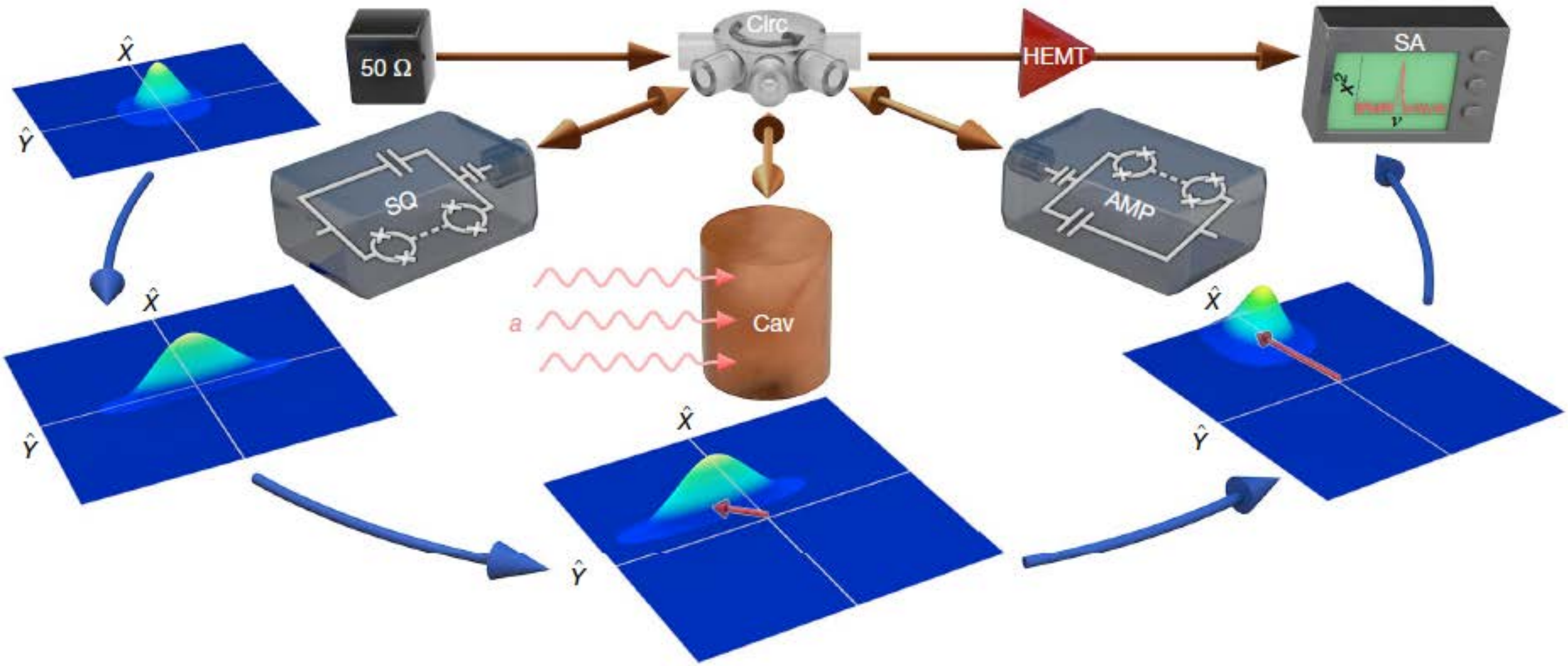
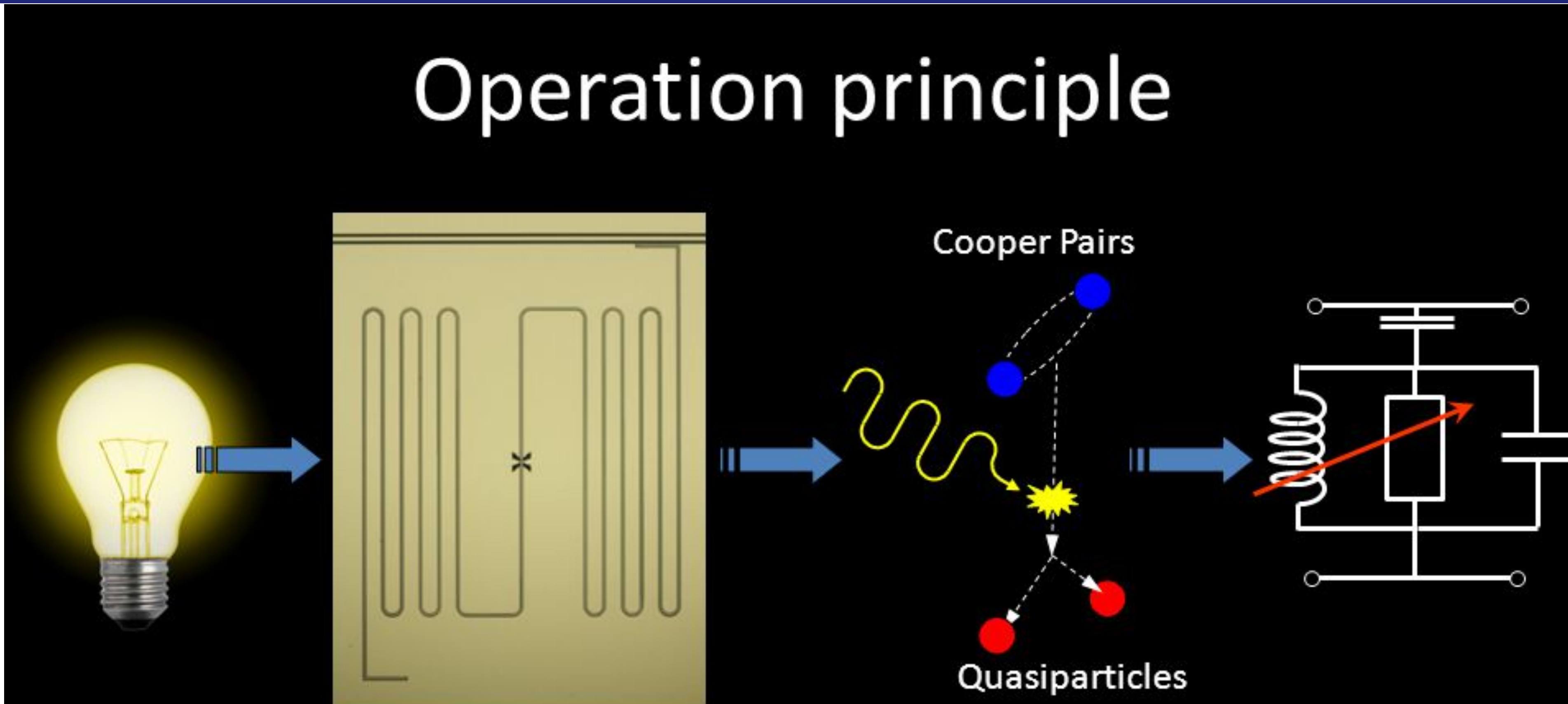
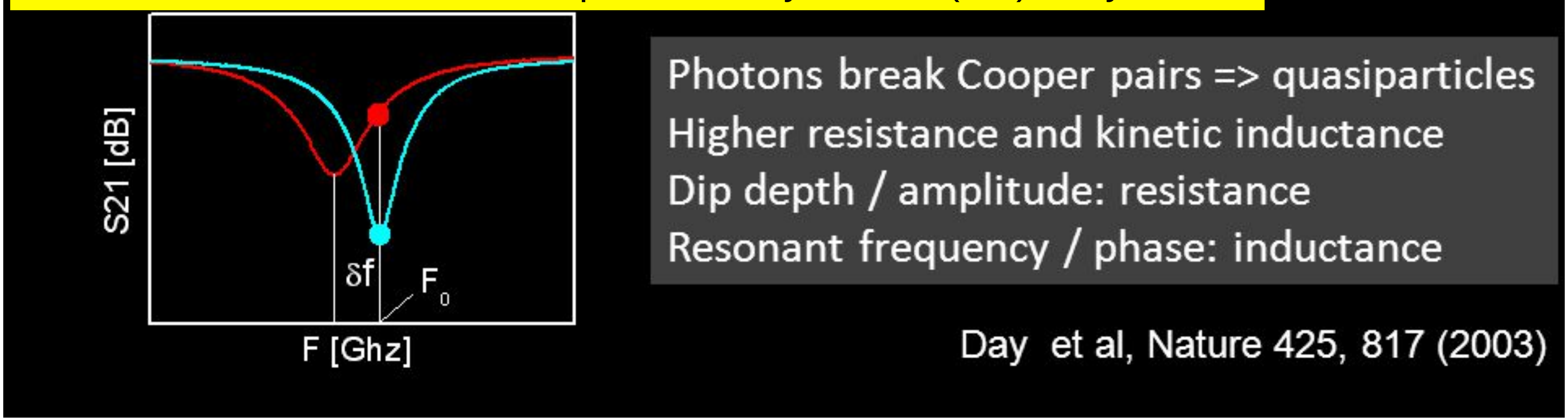


Fig. 1 | Illustration of the SSR-equipped haloscope, showing the transformation of the vacuum state in quadrature space. A vacuum state, the Wigner function (colour surface)[34] of which is symmetric in quadratures $\hat{X}$ and $\hat{Y}$, is sourced as Johnson–Nyquist noise from a 50-Ω microwave termination (black box) at 61 mK. It is routed by a nonreciprocal element (Circ) to the SQ JPA, which squeezes the $\hat{X}$ quadrature. The squeezed state may then be displaced by a hypothetical axion field a in the axion cavity (Cav). It is subsequently unsqueezed by the AMP JPA, which in the process amplifies the axion-induced displacement along $\hat{X}$. The resulting state is measured by a conventional microwave receiver led by a high-electron-mobility transistor (HEMT) amplifier. The time record of many realizations of this process is Fourier-transformed for subsequent spectral analysis (SA).

Kinetic Inductance Detectors



Visser et.al, Journal of Low Temperature Physics 167(3-4), May 2012.



KID: Principle of operation

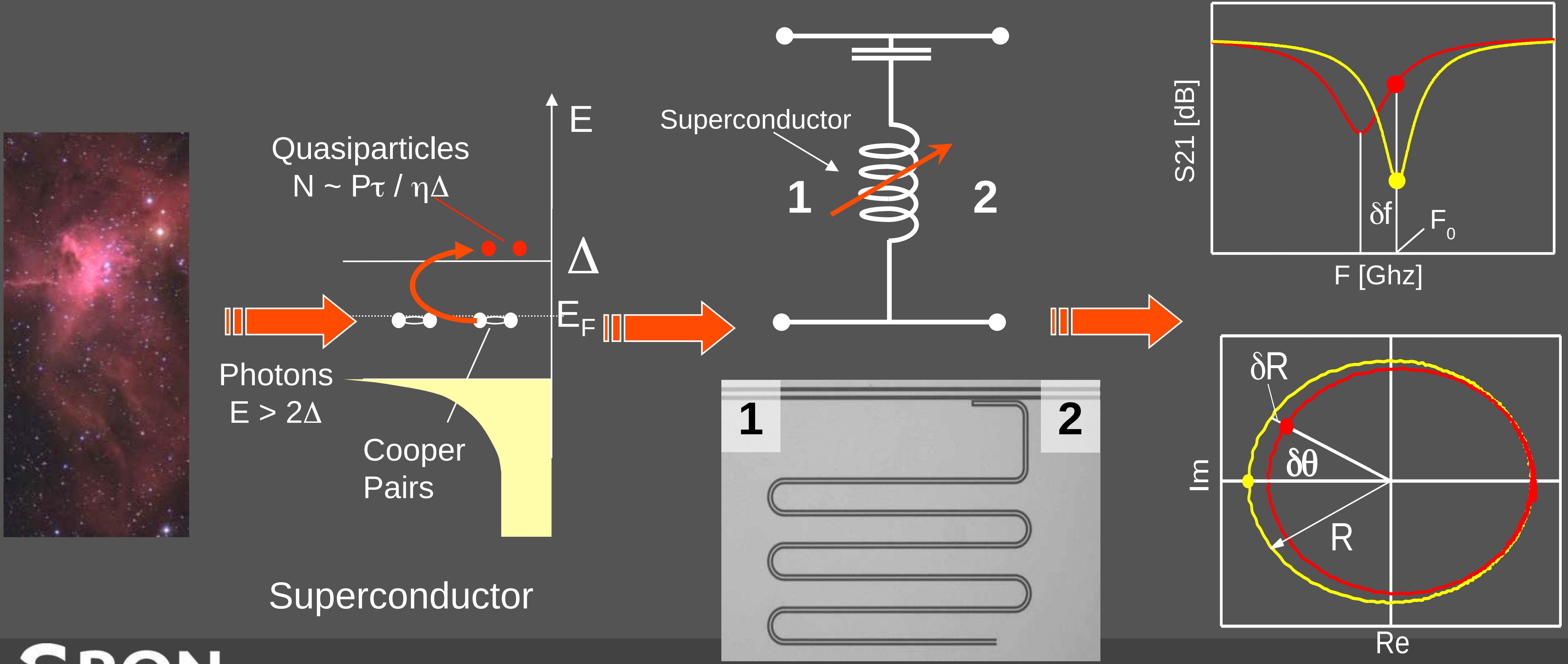
Stephen Yates et. al.

P. Day, et al., Nature 425, 817 (2003).

- Superconducting pair breaking detector
- Measure broken Cooper pairs by measuring the Kinetic Inductance
- At T<<Tc Superconductor impedance

$$Z_s \sim -i\omega L_K$$

- Read out Z_s by resonant circuit @ F=2-8 GHz
- Combine superconductor in series with C
- Read-out using phase or amplitude!



Antenna coupled KID

¼ λ resonator @$F_{readout}$

Most sensitive @ end

Printed antenna @ F_{RF}

$F_{RF} >> F_{readout}$

Antenna does not influence resonator

Needs lens!