Quantum Probes of Axion Dark Matter

Workshop on
Particle Physics, Quantum Information And Machine Learning

Jul 13 – 17, 2026
Daejeon, IBS

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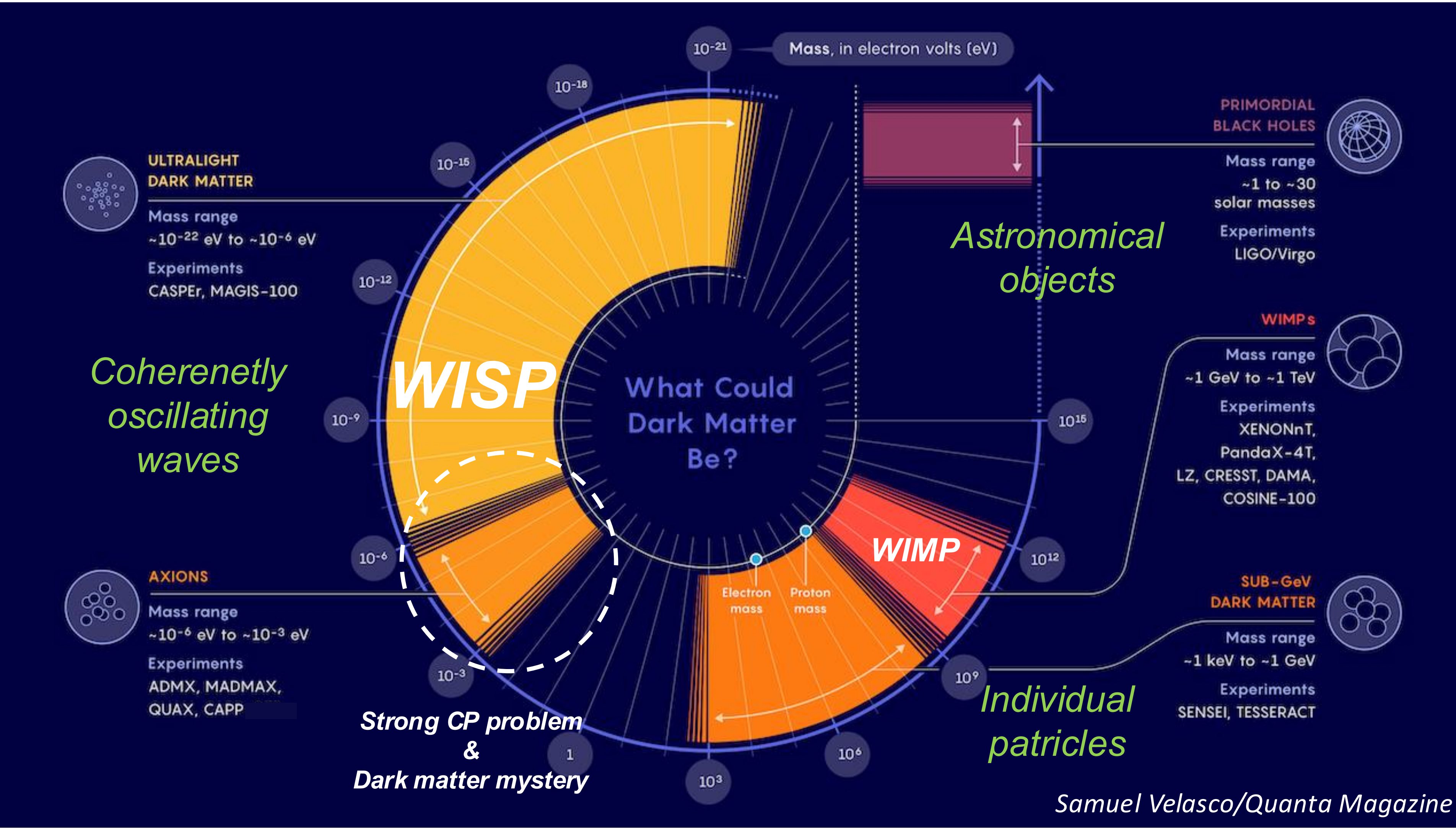
Institute for Basic Science (IBS)

ibs Institute for Basic Science

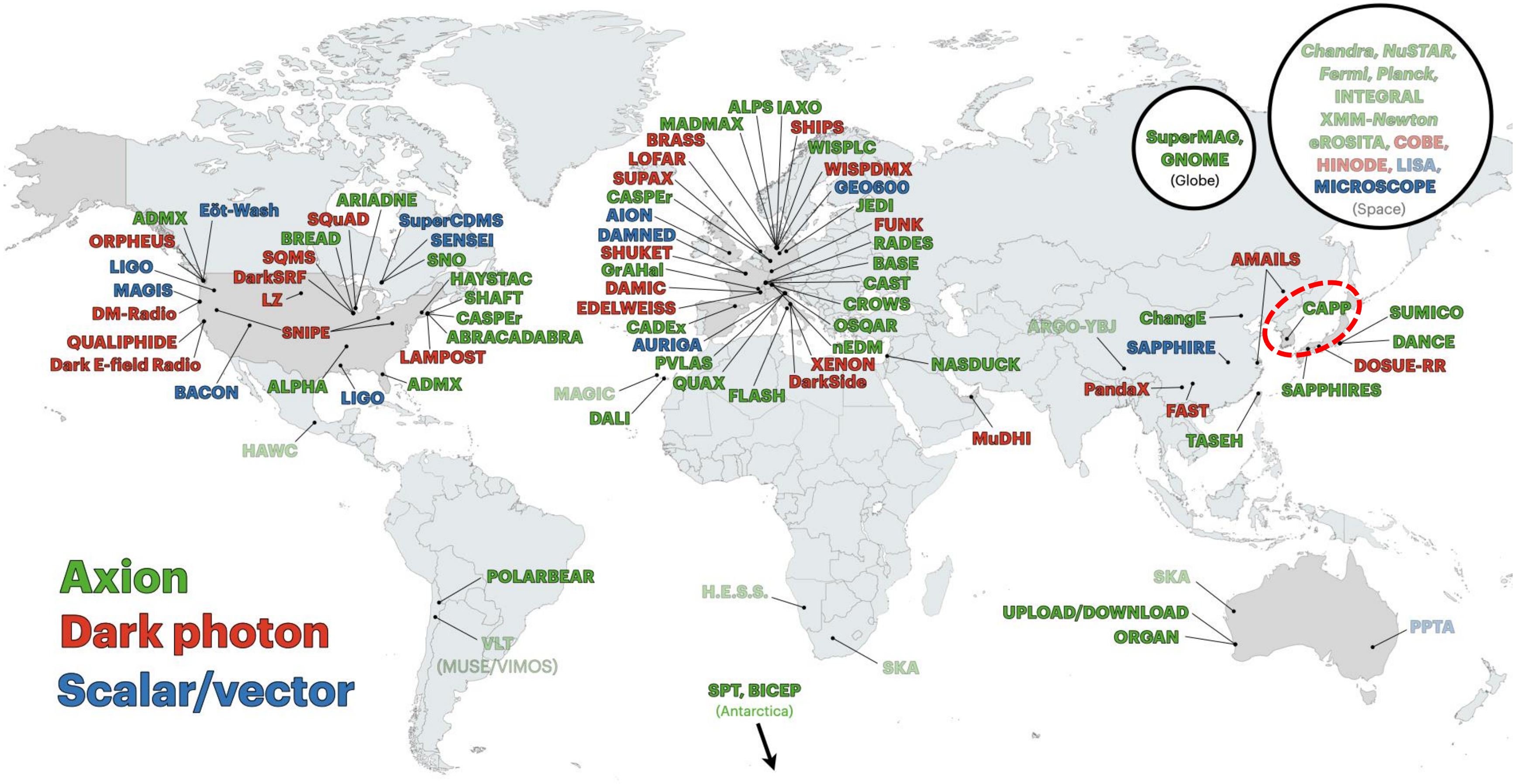
Dark matter candidates



Samuel Velasco/Quanta Magazine

Experiment map

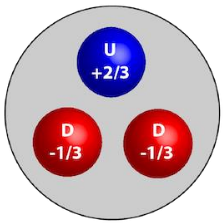
C. O'Hare (2020)

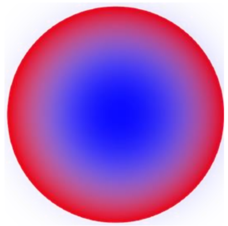


Why Axions?

Strong CP problem

QCD vs. EXP

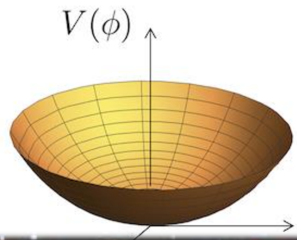




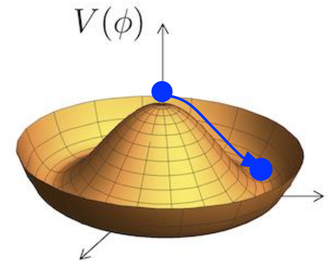
Neutron

Peccei-Quinn solution (1977)

Unbroken symmetry $(T \sim \infty)$



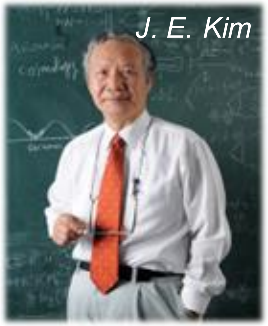
Spontaneously Broken Symmetry $(T \sim f_a)$



"Mexican hat"

Invisible axion (1979)

- *Very light (sub-eV)*
- *Extremely weakly interacting*
- *Produced in early Universe*

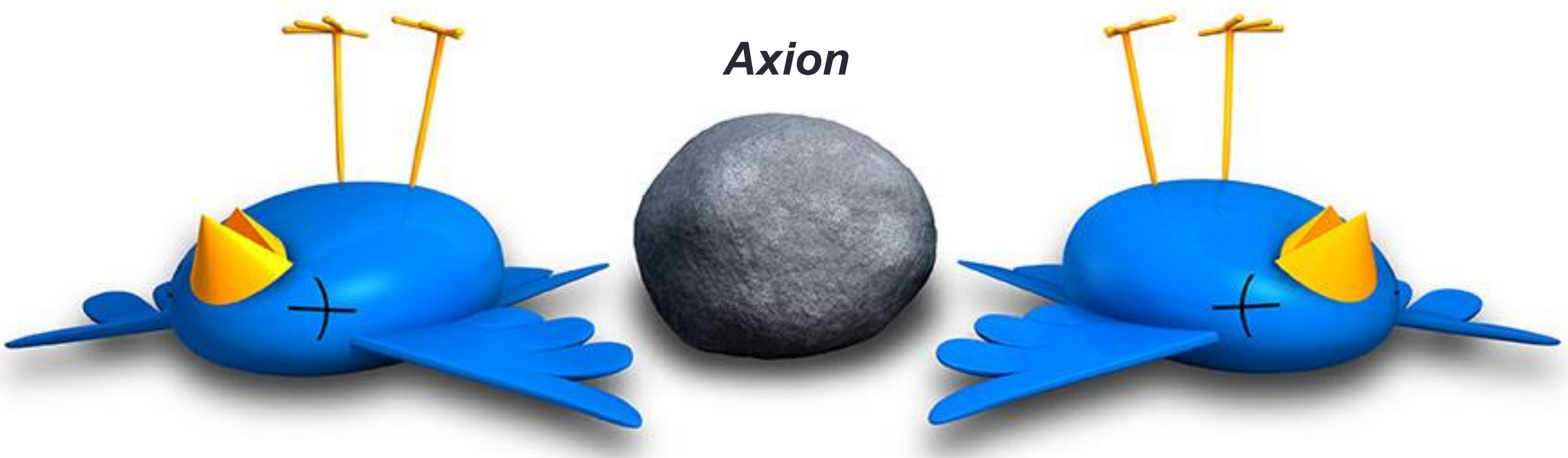


A new particle:
Axion (1978)

Axion dark matter

KILLING TWO BIRDS WITH ONE STONE

Axion



Strong CP problem *Dark matter*

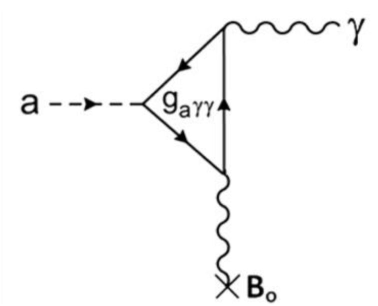
Axion models and detection

- *Axion interactions with SM*

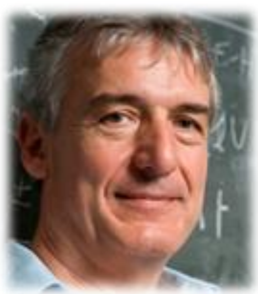
	Photons	Fermions	nEDMs
Hamiltonian	$g_{a\gamma\gamma} a\boldsymbol{E}\cdot\boldsymbol{B}$	$g_{aff}\nabla a\cdot\hat{\boldsymbol{S}}$	$g_{EDM}\, a\hat{\boldsymbol{S}}\cdot\boldsymbol{E}$
Observable	*Photon*	*Spin precession*	*Oscillating EDM*
Detection	*Power spectrum, photon counter, …*	*Magnetometer, NMR, …*	*NMR, polarimeter, …*

- *Axion models*

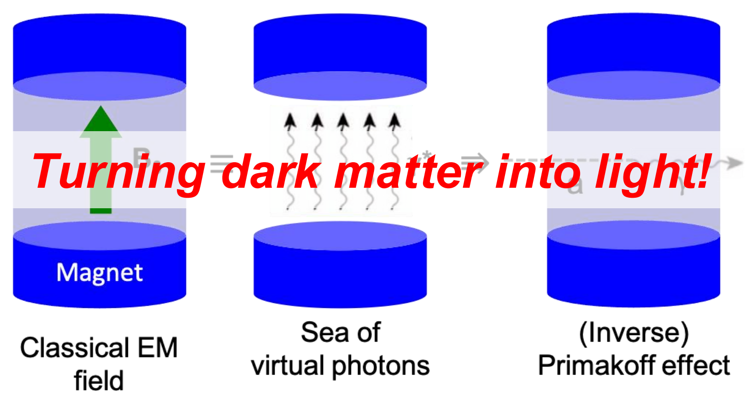
PQWW	DFSZ	KSVZ
SM ferminons		*BSM fermions*
Standard ($f_a \sim v_{EW}$)	*Invisible ($\boldsymbol{f_a \gg v_{EW}}$)*	
Ruled out	*Benchmark*	



- *Detection principle*
  - *Sikivie effect (1983)*

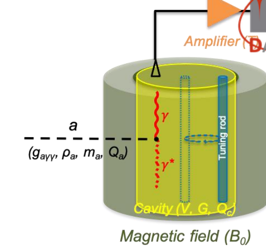


P. Sikivie



Search strategies

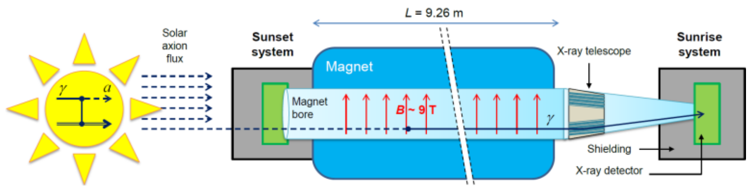
- *Haloscope*
  - *Dark matter halo in our galaxy (cavity resonance)*



  - $P_{a\gamma\gamma} \approx 9\times10^{-23}\,W\left(\frac{g_{a\gamma\gamma}}{0.36}\right)^2\left(\frac{\rho_a}{0.45\frac{GeV}{cc}}\right)\left(\frac{f_a}{1.1\,GHz}\right)\left(\frac{B_0}{10.5\,T}\right)^2\left(\frac{V}{37\,L}\right)\left(\frac{C}{0.6}\right)\left(\frac{Q_c}{10^5}\right)$

    ~100 photons/sec

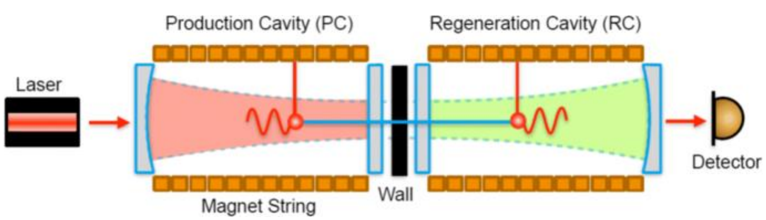
- *Helioscope*
  - *Solar axion*



  - $\mathcal{P}_{a\to\gamma} \approx 2.6\times10^{-17}\left(\frac{g_{a\gamma\gamma}}{10^{-10}\,GeV^{-1}}\right)^2\left(\frac{B_0}{10\,T}\right)^2\left(\frac{L}{10\,m}\right)^2\mathcal{F}, \quad \mathcal{F} = \frac{2(1-\cos qL)}{(qL)^2}$

    ~10 photons/day

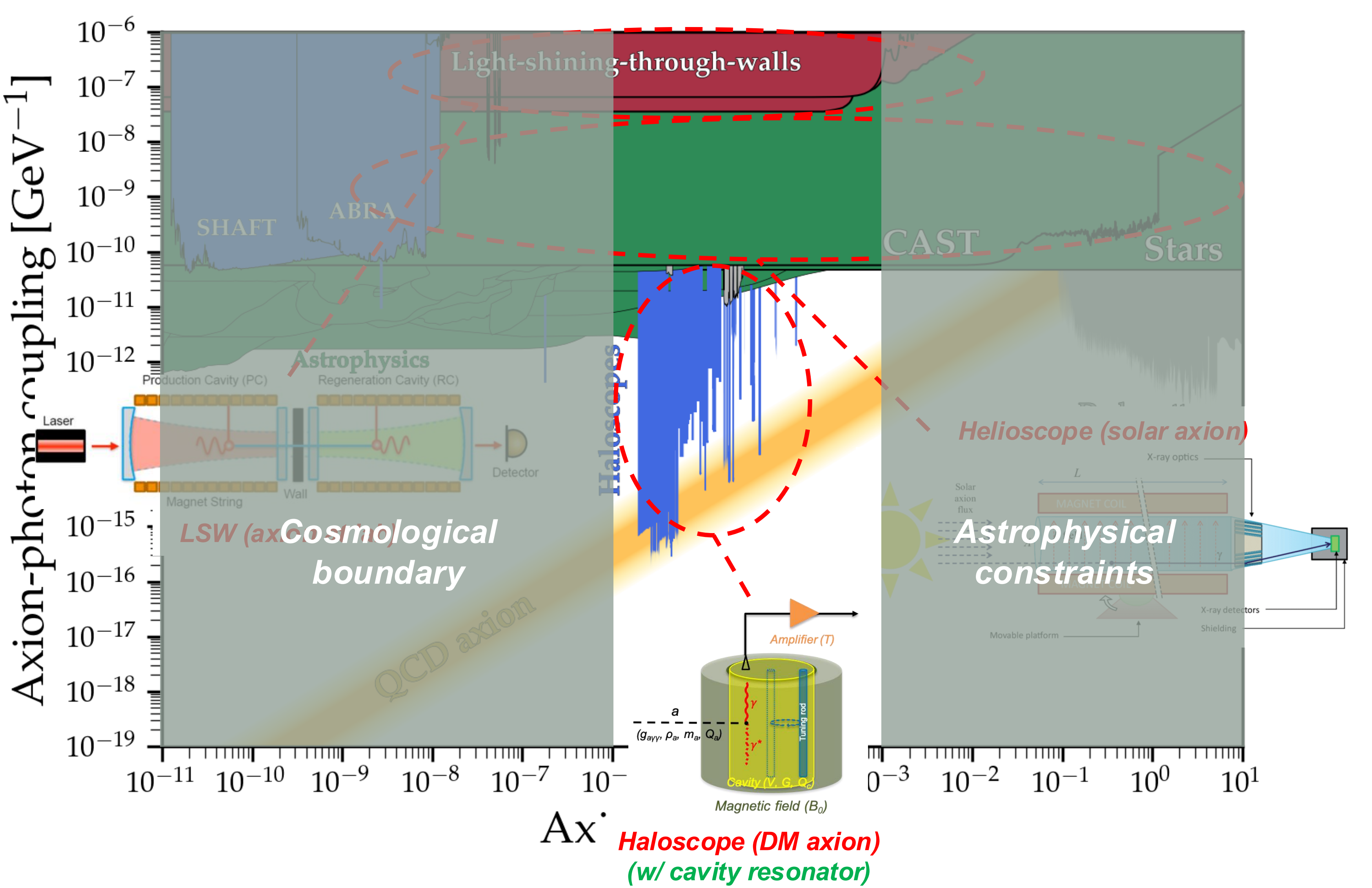
- *Light shinning through a wall*
  - *Axion production at lab*



  - $\dot{N}_\gamma \approx 4\times10^{-5}Hz\left(\frac{g_{a\gamma\gamma}}{10^{-10}\,GeV^{-1}}\right)^4\left(\frac{P_{laser}}{40\,W}\right)\left(\frac{BL}{560\,Tm}\right)\left(\frac{\beta_{PC}}{5000}\right)\left(\frac{\beta_{RC}}{40000}\right)$

    ~1 photon/day

Axion search – current status



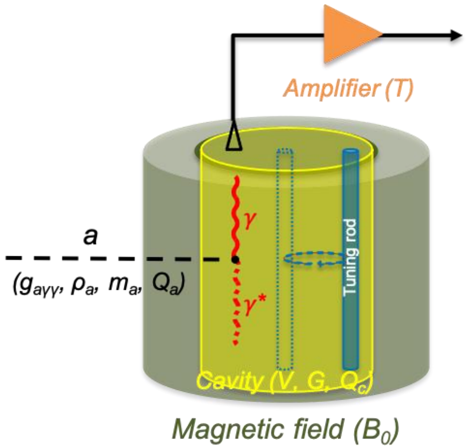
Cavity haloscope

- *Resonant conversion when $f_{axi} = f_{cav}$*
  - *Most sensitive in μeV (GHz) region*

- *Axion-photon conversion power (a→γγ)*

$$P_{a\gamma\gamma} \approx 9\times10^{-23}\,W\left(\frac{g_{a\gamma\gamma}}{0.36}\right)^2\left(\frac{\rho_a}{0.45\frac{GeV}{cc}}\right)\left(\frac{f_a}{1.1\,GHz}\right)\times\left(\frac{B_0}{10.5\,T}\right)^2\left(\frac{V}{37\,L}\right)\left(\frac{C}{0.6}\right)\left(\frac{Q_c}{10^5}\right)$$

(~100 photons/sec)



- *Signal-to-noise ratio (SNR)*

$$SNR = \frac{P_{signal}}{P_{noise}} = \frac{1}{4}\frac{P_{a\gamma\gamma}}{k_B(T_{sys}/0.2\,K)}\sqrt{\frac{\Delta t}{Q_a/10^6}}$$

System noise ($P = k_B T \Delta f$)

$T_{sys} = T_{thr} + T_{add}$

ex) $0.2\,K \sim 3\times10^{-22}\,W$

(~4000 photons/sec)

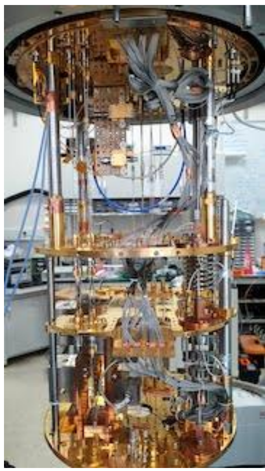
- *Unknown mass => scan rate (F.O.M.)*

$$\frac{df}{dt} \approx 2\frac{GHz}{year}\left(\frac{5}{SNR}\right)^2\left(\frac{0.2\,K}{T_{sys}}\right)^2\left(\frac{P_{a\gamma\gamma}}{1x10^{-22}\,W}\right)^2\left(\frac{10^5}{Q_c}\right) \sim \boldsymbol{B_0^4V^2C^2Q_cT_{sys}^{-2}}$$

Cavity haloscope – in a nutshell

- *Leading sensitivity in the μeV mass range*

Cryogenics T



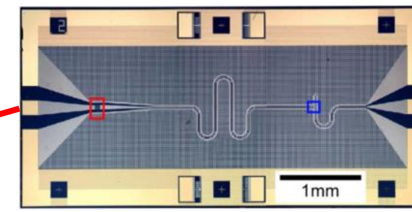
Thermal noise reduction

$$\frac{df}{dt} \sim B_0^4 V^2 C^2 Q_c T_{sys}^{-2}$$

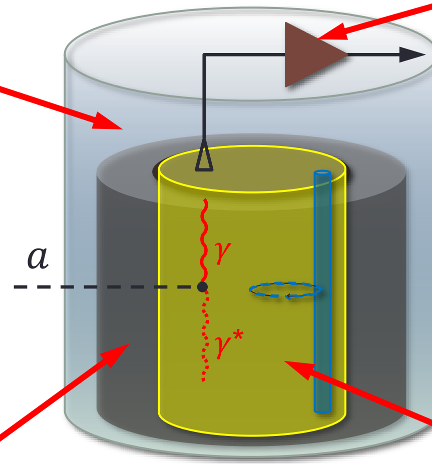
P_{sig} ~ 10^{-23} W

(~100 photons/s)

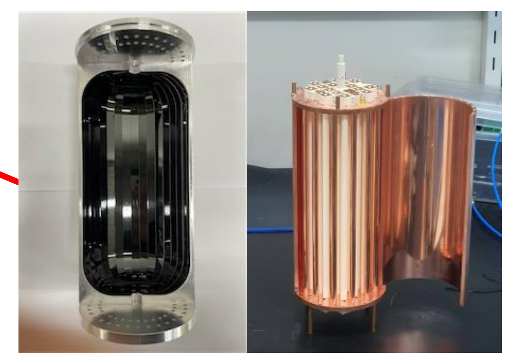
Quantum noise limited amplifier T



Signal amplification w/ minimal noise

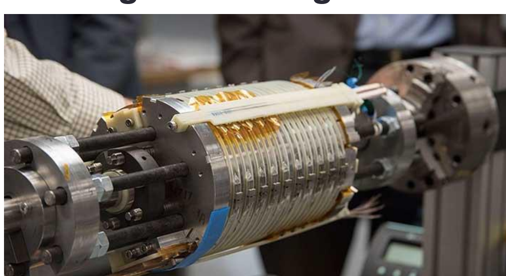


Tunable High-Q resonator
V, Q, C, Δf



Signal enhancement

High field Magnet B

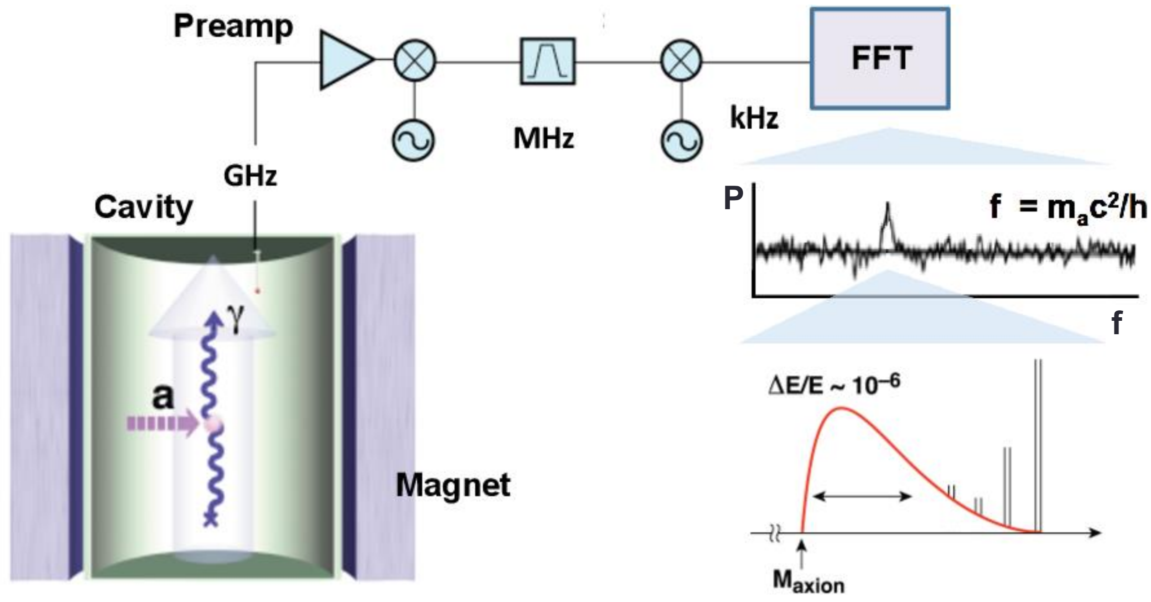


Boosting a→γγ conversion

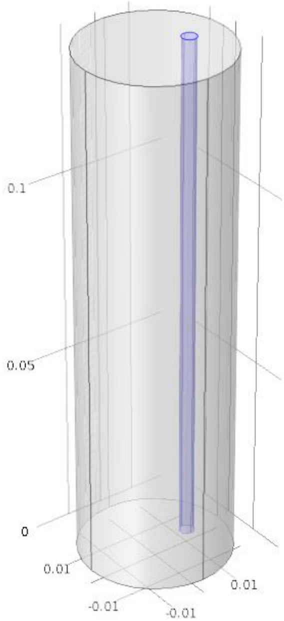
Resonant enhancement
$f_{axion} = f_{cavity}$

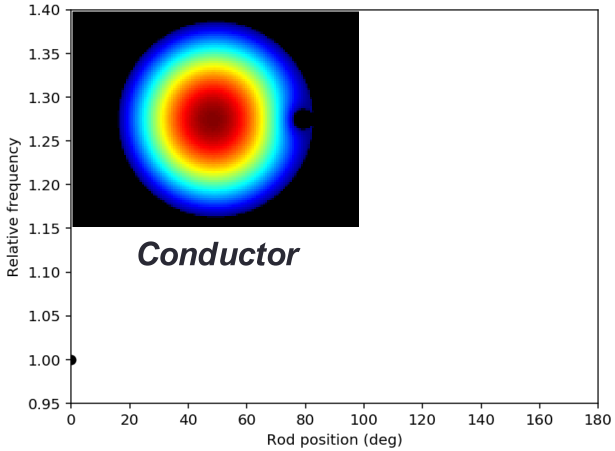
Extreme conditions!

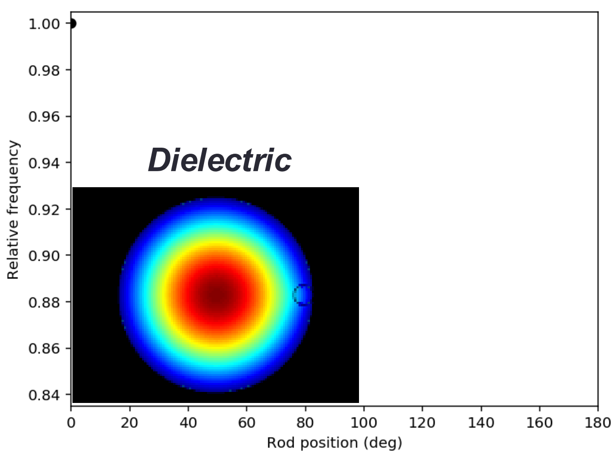
Cavity haloscope = Axion radio

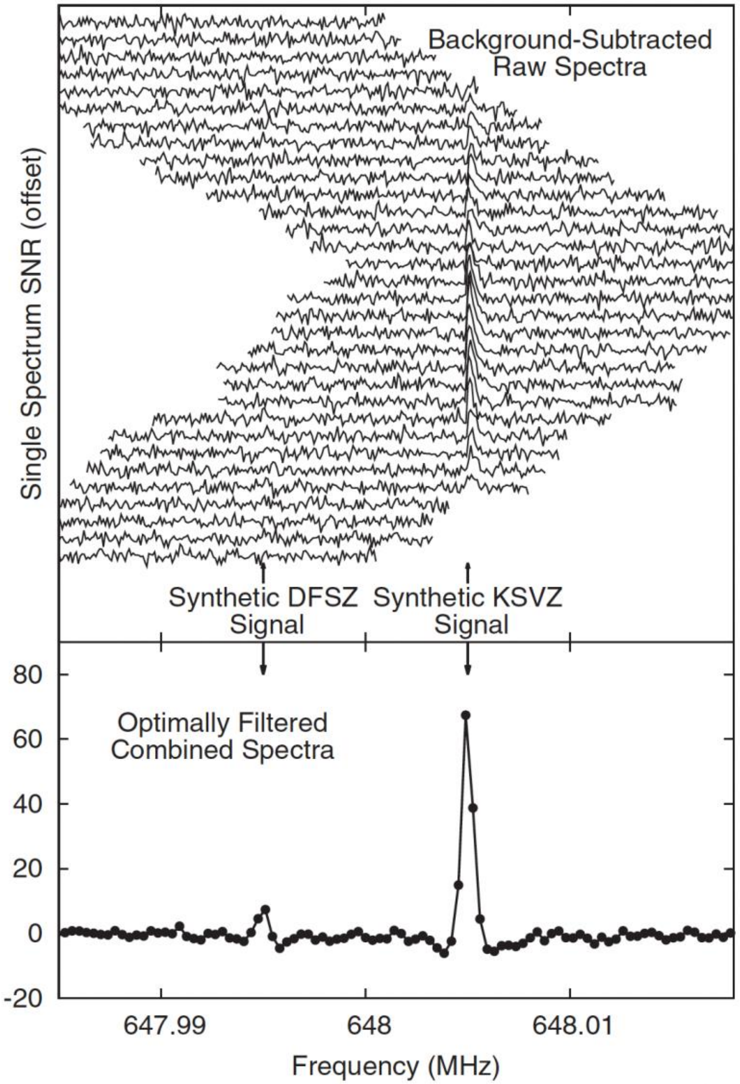


Frequency tuning and signal

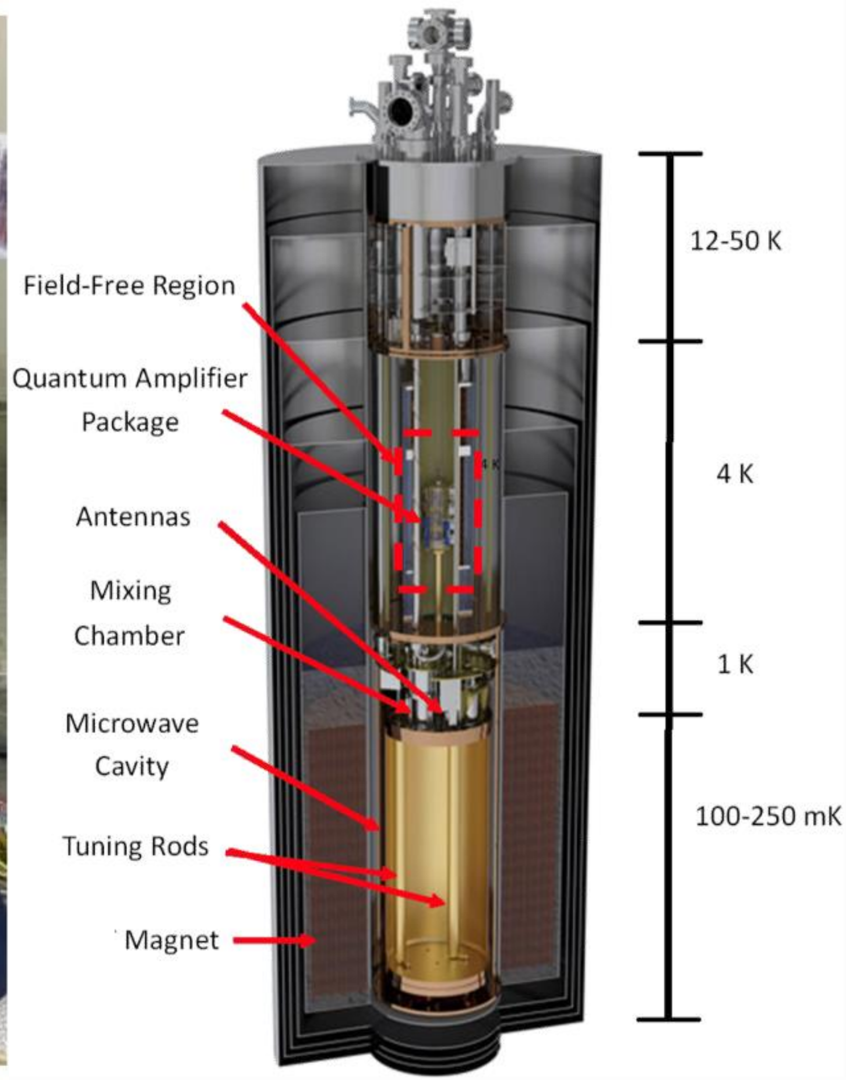








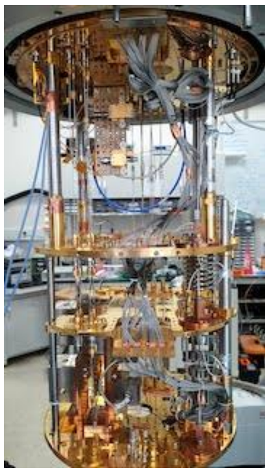
A cavity haloscope



Cavity haloscope – in a nutshell

- *Leading sensitivity in the μeV mass range*

Cryogenics *T*

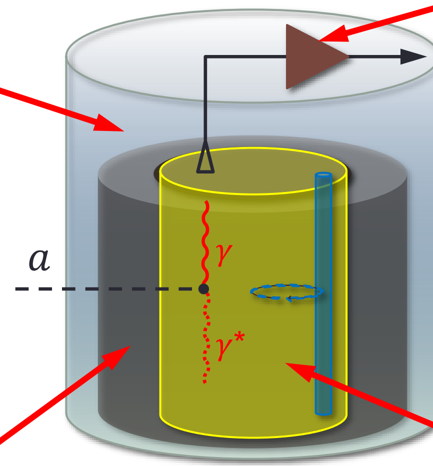


Thermal noise reduction

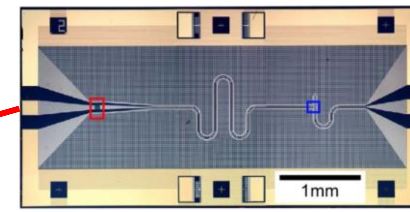
$$\frac{df}{dt} \sim B_0^4 V^2 C^2 Q_c T_{sys}^{-2}$$

$P_{sig} \sim 10^{-23}$ W

(~100 photons/s)

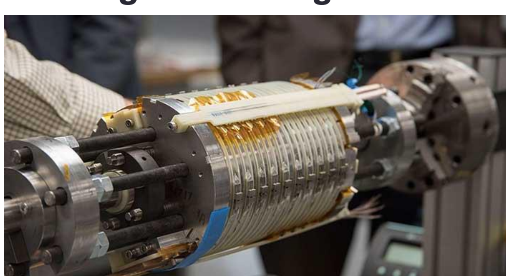


Quantum noise limited amplifier *T*



Signal amplification w/ minimal noise

High field Magnet *B*



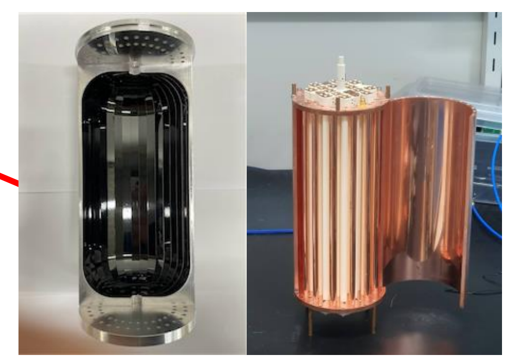
Boosting a→γγ conversion

Resonant enhancement

$f_{axion} = f_{cavity}$

Tunable High-Q resonator

V, Q, C, Δf



Signal enhancement

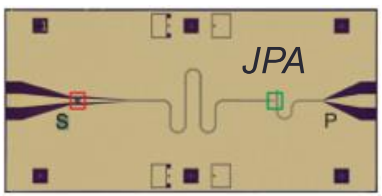
Extreme conditions!

Microwave signal detection

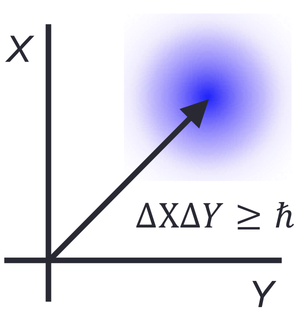
Power detection vs. *photon counting*

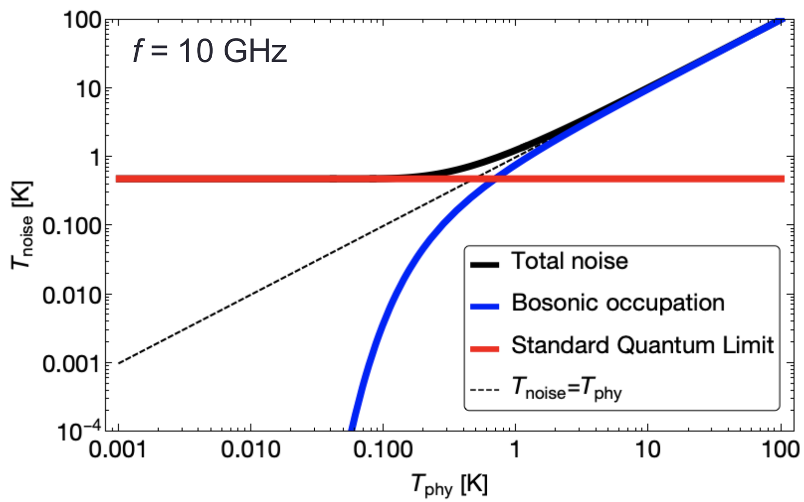
(w/ amplifiers) *(w/ single photon detector)*

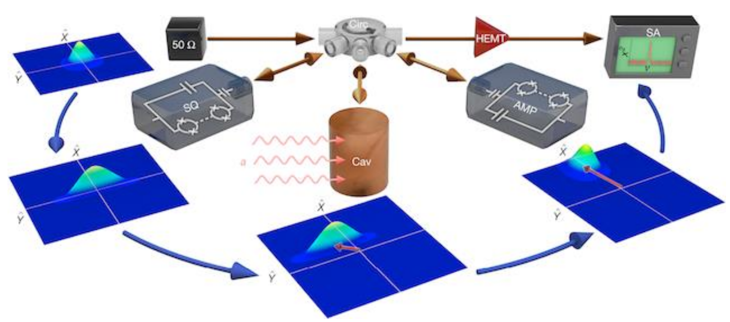
Transistor-based
Heat dissipation
(T_N ~ K)



JJ non-linearity
Quantum limited
T_{SQL} ~ 50 mK x f [GHz]





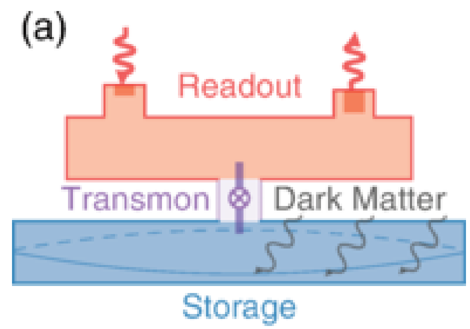


Quantum squeezing ($T_N < T_{SQL}$)

Single photon detector (SPD)

↓

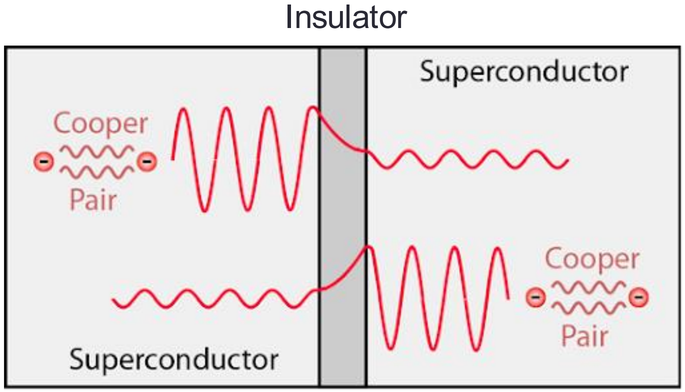
Game changer at high frequencies and low temperatures



Single photon counting
Not subject to SQL
(T_N << T_{SQL})

Josephson junction

- *SC-IN-SC (SIS)*



$|\Psi_1|e^{i\phi_1}$ *Cooper-pair Tunneling* $|\Psi_2|e^{i\phi_2}$

Superconducting weak link:

Phase difference ($\phi = \phi_1 - \phi_2$)

⇓

Governing dynamics

JJ symbol

- *Josephson effects*
  - *DC effect*
    - $I_s = I_c \sin\phi$
    - *Supercurrent at V=0*
  - *AC effect*
    - $\frac{d\phi}{dt} = 2eV/\hbar \Rightarrow I_s(t) = I_c \sin\left(\frac{2eV(t)}{\hbar}\right)$
    - *Voltage sets MW oscillation*
  - *Josephson inductance*
    - $L(\phi) = \frac{L_J}{\cos\phi}$, $L_J = \frac{\Phi_0}{2\pi I_c}$
    - *Lossless, nonlinear, flux-tunable*

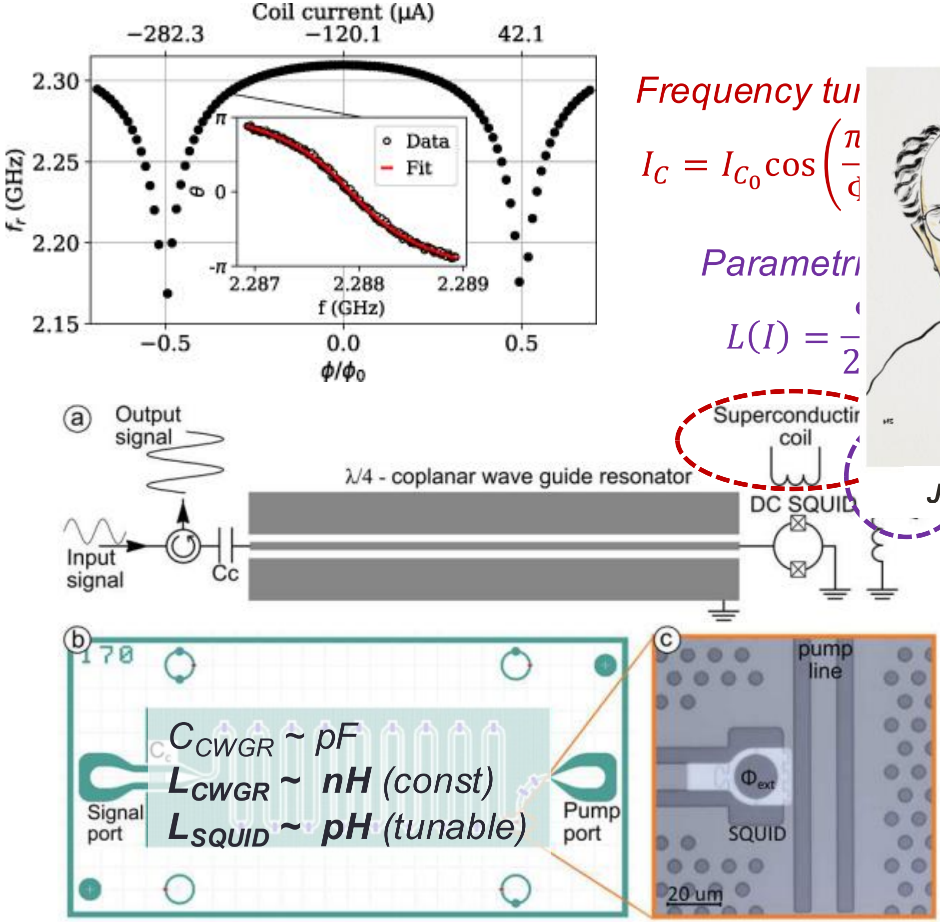
Core element of quantum devices

SQUID ⟶ ***JPA*** ⟶ ***Qubit***

flux-tunable — *quantum-limited amplification* — *artificial atom*

QNL amplification

- *Flux-driven Josephson parametric amplifiers (JPAs)*



C_{CWGR} ~ pF
L_{CWGR} ~ **nH** *(const)*
L_{SQUID} ~ **pH** *(tunable)*

$$I_C = I_{C_0}\cos\left(\frac{\pi}{\Phi}\right.$$

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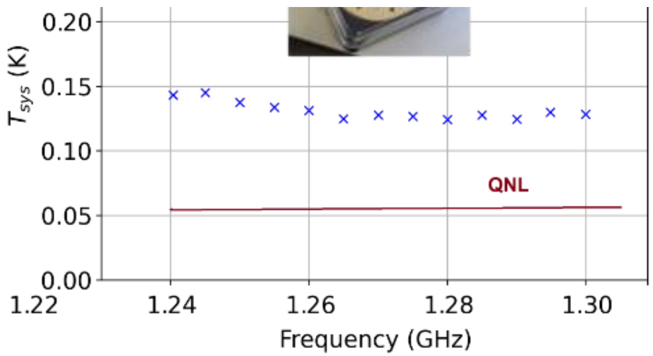
Nobel Prize in Phyiscs 2025

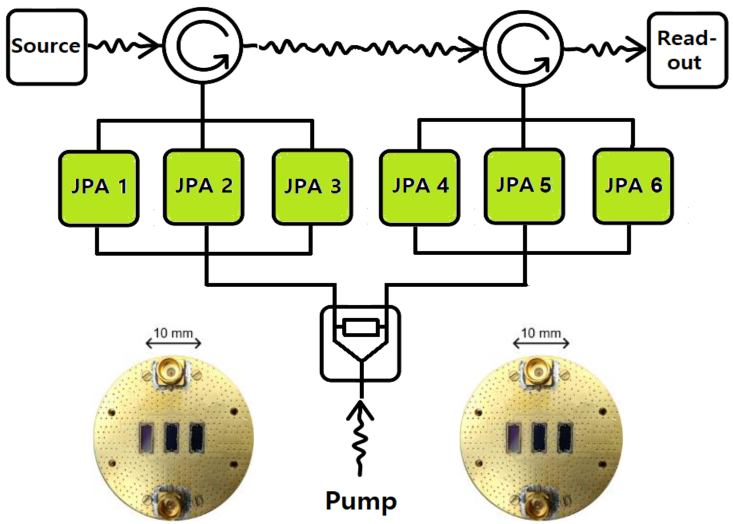
John Clarke ***Michel H. Devoret*** ***John M. Martinis***

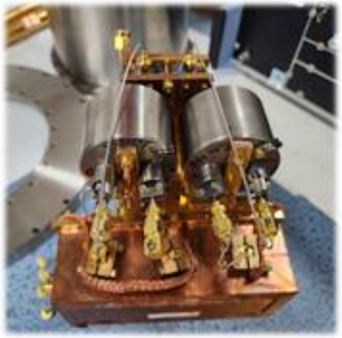


- *High gain / low noise*
- *Narrow bandwidth (~50 MHz)*

Multi-JPA system

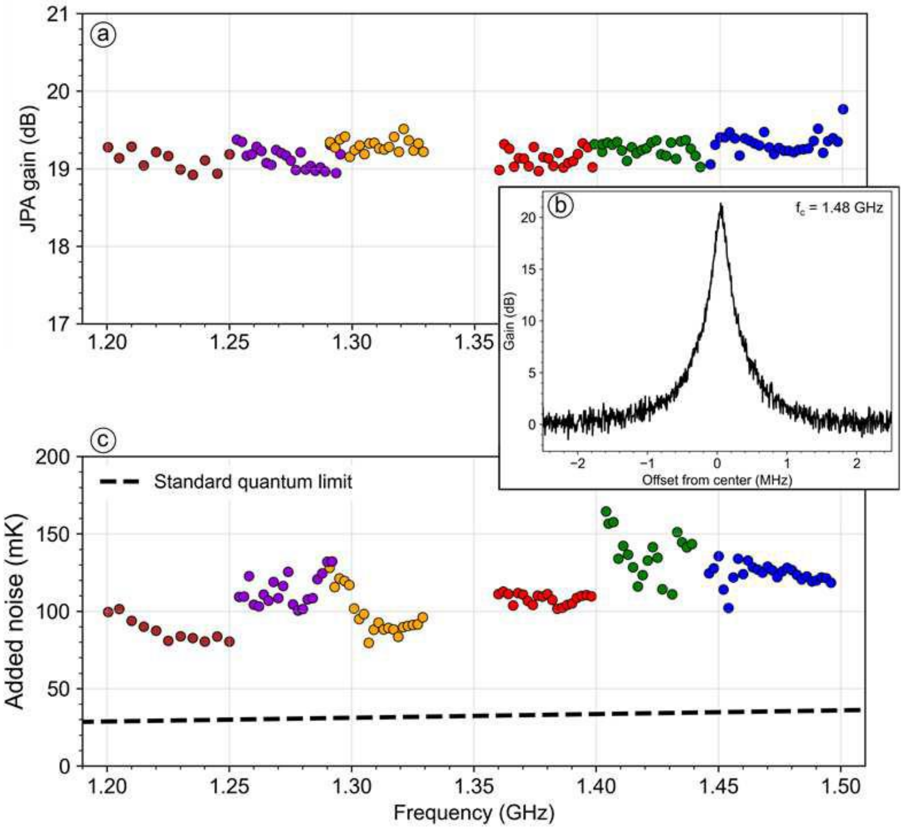
- *Parallel-series configuration*





3-layer shield (Al–μ– Nb)

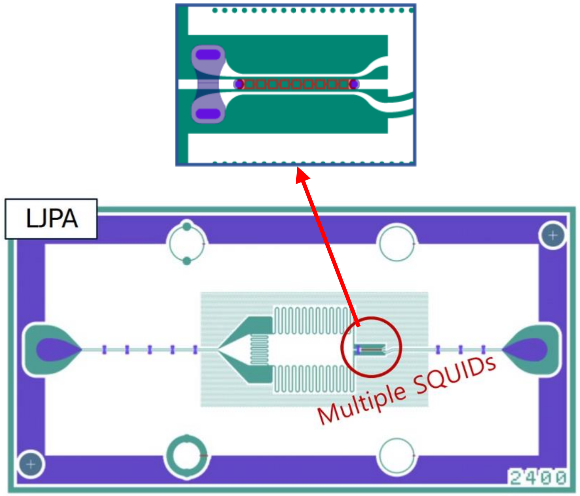
$f_{JPA_i} \neq f_{JPA_j}$ ⇒ *frequency multiplexing*

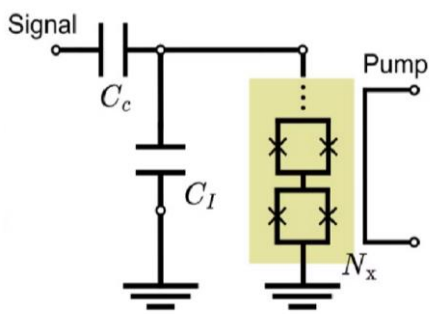


- *High gain / low noise*
- *Broad bandwidth (~300 MHz)*

Lumped-element JPA

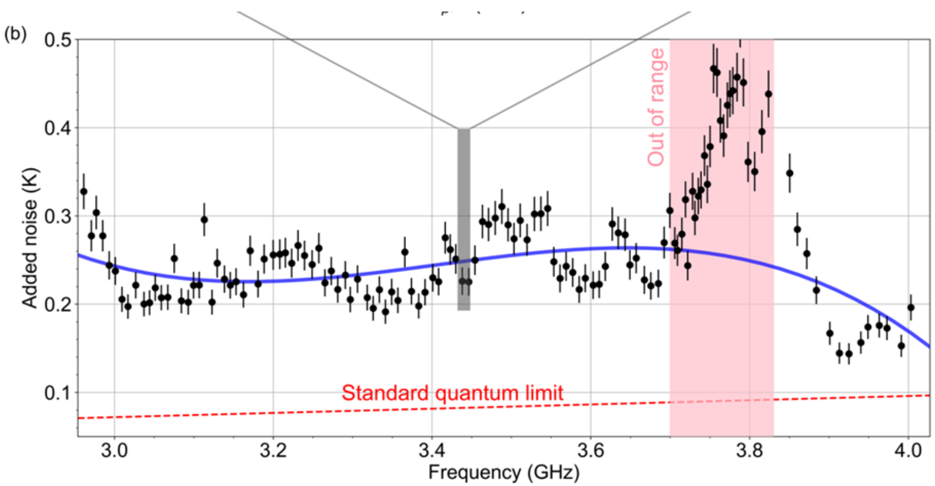
- *SQUID array ⇒ large (tunable) inductance*

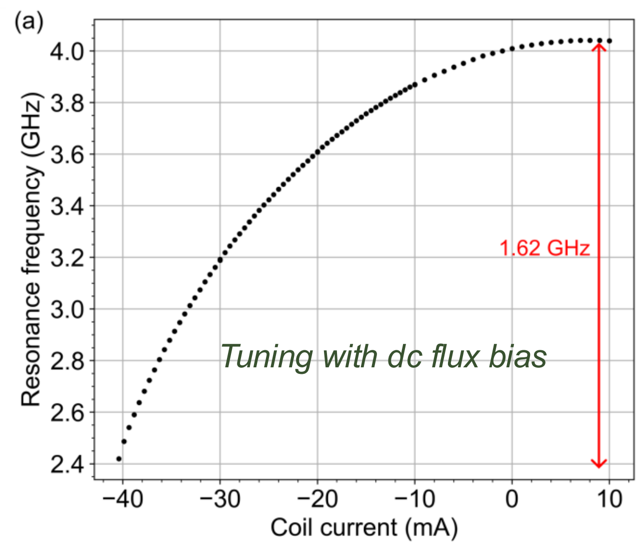




- *No wave guide resonator*
- ***Multiple SQUIDs***
- *Interdigital capacitor*

- *Wide tuning range*





6 JPA assembly: 300 MHz

A single JPA: 50 MHz

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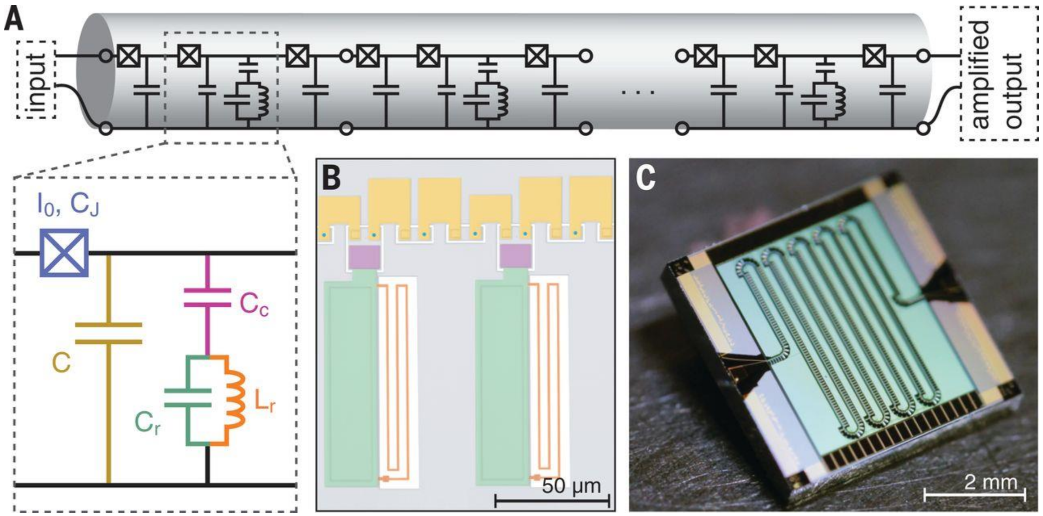
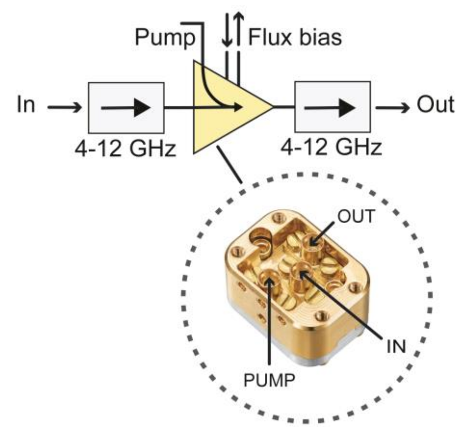
Traveling-Wave Parametric Amp.

- *Nonlinear lumped-element transmission line*



Commercially available



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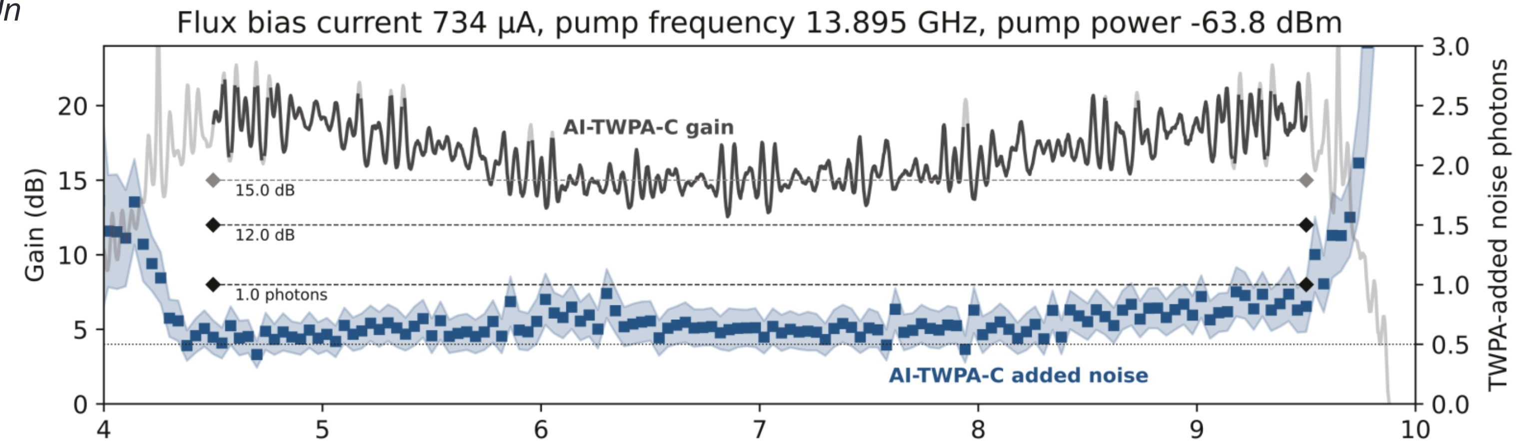
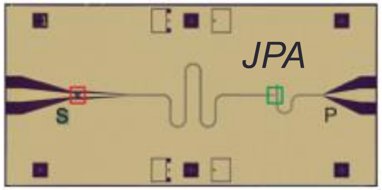


Signal detection

$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

Power detection
(w/ amplifiers)

Transistor-based
Heat dissipation
(T_N ~ K)



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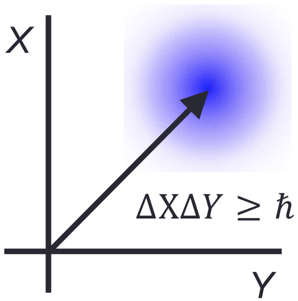
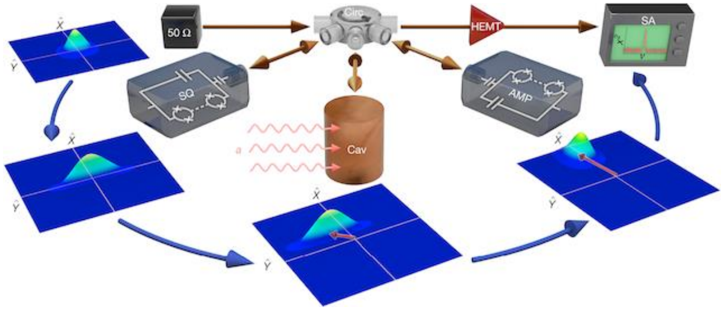
T_{SQL} ~ 50 mK x f [GHz]



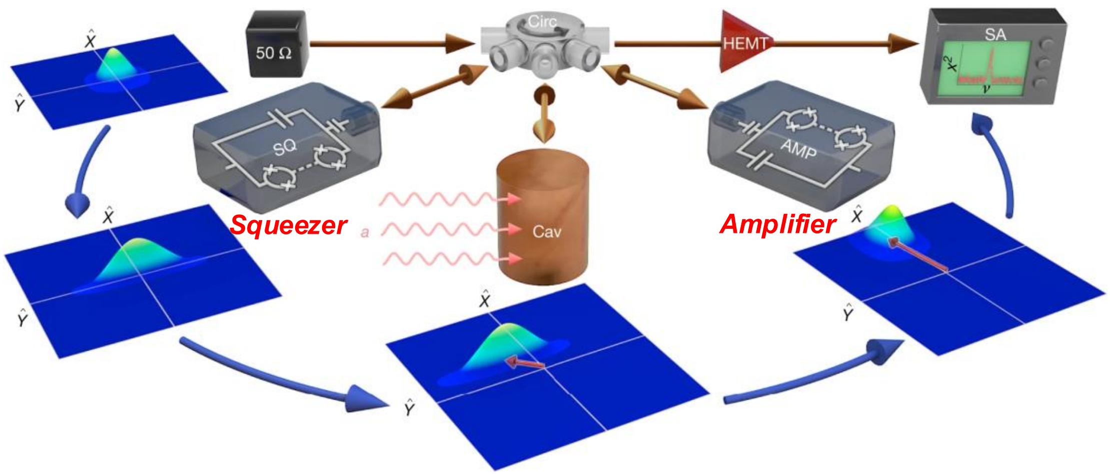


Quantum squeezing (T_N < T_{SQL})

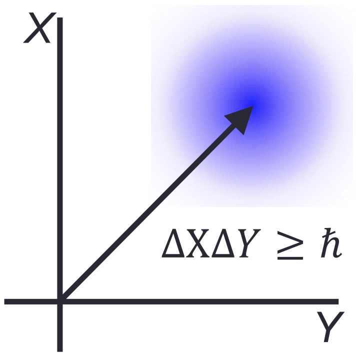
Quantum squeezing

- *JPAs in phase-sensitive mode*
  - *Squeezed-state receiver (SSR)*

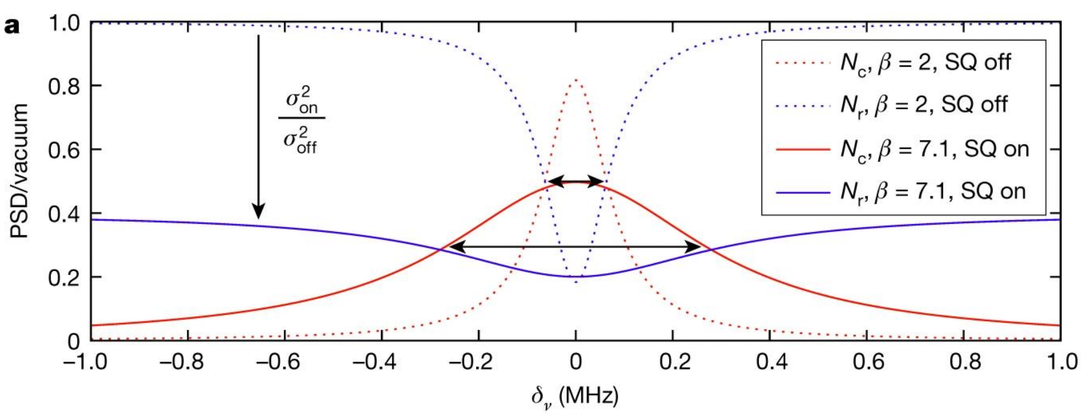
*Nature **590** 238 (2021)*



Phase-insensitive mode



T_{SQL} ~ 50 mK x f [GHz]

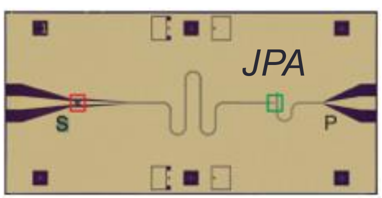


- *N_r: reflected noise*
- *N_c: cavity noise*
- *N_t: Total noise noise*

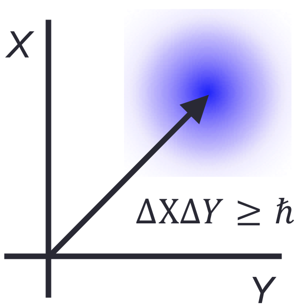
SSR:
- *Reduces N_r*
- *Increases δ_ν*
- *Increases df/dt*

Microwave signal detection

Transistor-based
Heat dissipation
(T_N ~ K)

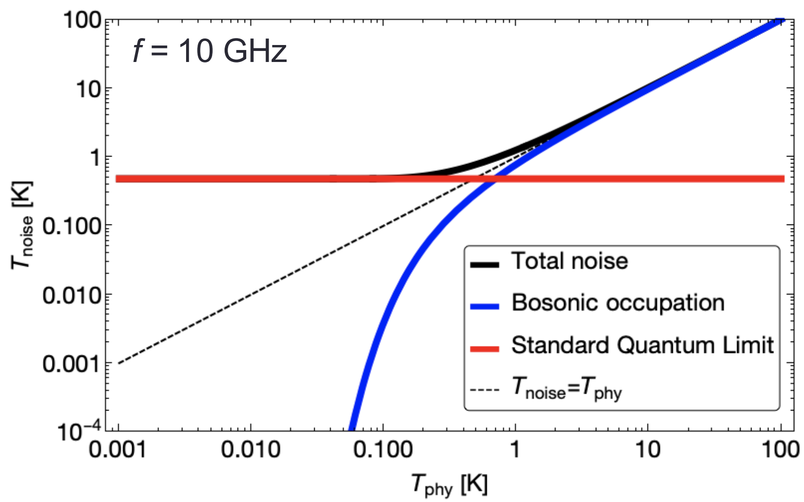


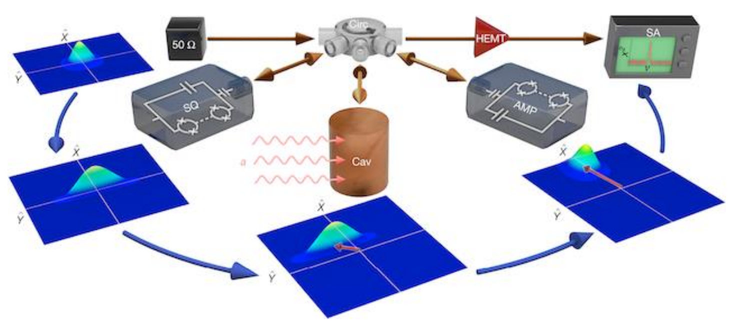
JJ non-linearity
Quantum limited
T_{SQL} ~ 50 mK x f [GHz]



Power detection vs. photon counting

(w/ amplifiers) *(w/ single photon detector)*



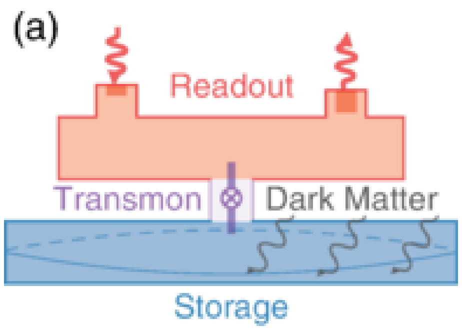


Quantum squeezing (T_N < T_{SQL})

Single photon detector (SPD)

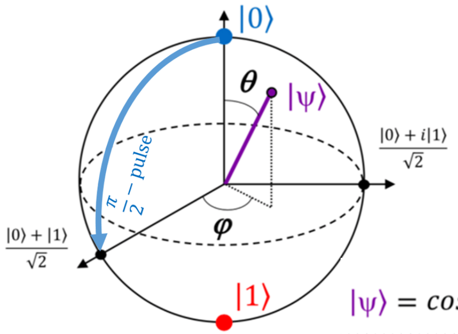
↓

Game changer at high frequencies and low temperatures



Single photon counting
Not subject to SQL
(T_N << T_{SQL})

Qubit

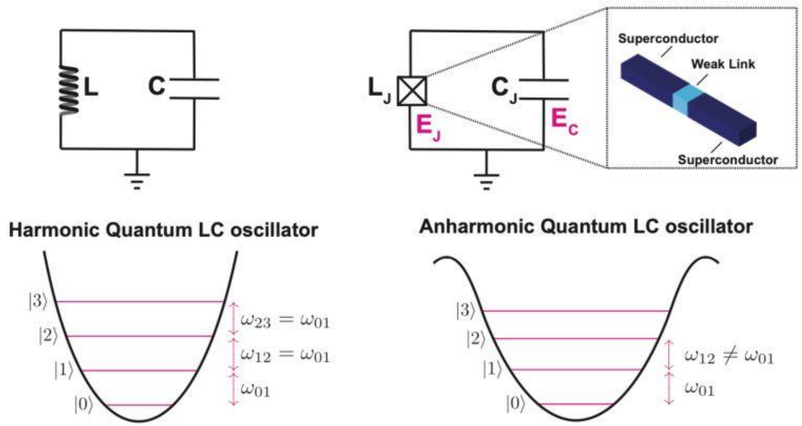


$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle$$

Qubit

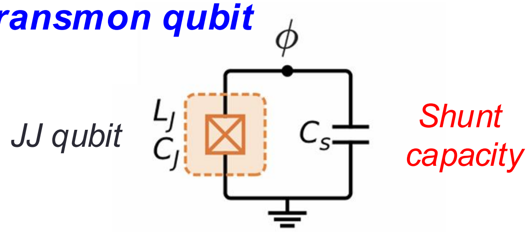
- *Two-level quantum system: |0⟩ and |1⟩*
- *Quantum information*
  - *Superposition + entanglement*
- *ex) Spin-1/2, photon polarization, atom energy state*

JJ qubit: SC LC circuits + JJs



- *Nonlinearity provides unequal energy space*
- *"Artificial atoms"*
- *Flexible, tunable, scalable*

Transmon qubit



$$\hbar w_{01} = E_1 - E_0 \approx \sqrt{8E_J E_c} - E_c$$

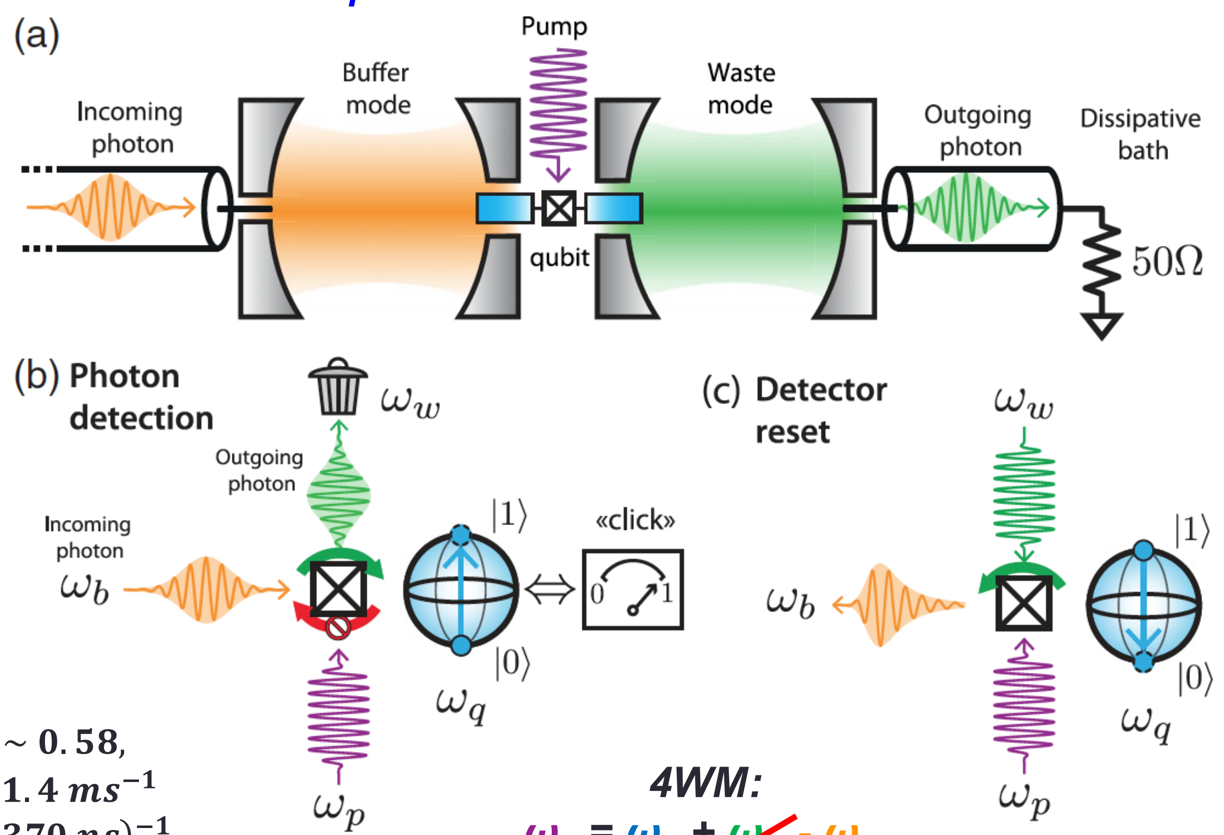
$$\left(E_J = \frac{\Phi_0 I_c}{2\pi}, \Phi_0 = \frac{h}{2e}, E_c = \frac{e^2}{2C}\right)$$

- *JJ qubit in E_J/E_C >> 1 regime*
- *Charge-noise reduction*
- *Long coherence (~100 us)*
- *Stable operation*

Dissipation-Engineered SMPD

- *Qubit-resonator dissipator*

*Phys. Rev. X **10**, 021038 (2020)*



$\eta_{max} \sim 0.58,$
$\Gamma_{dc}^{min} \sim 1.4\ ms^{-1}$
$\gamma_{reset} \sim (370\ ns)^{-1}$

4WM:
$\omega_p = \omega_q + \omega_w - \omega_b$

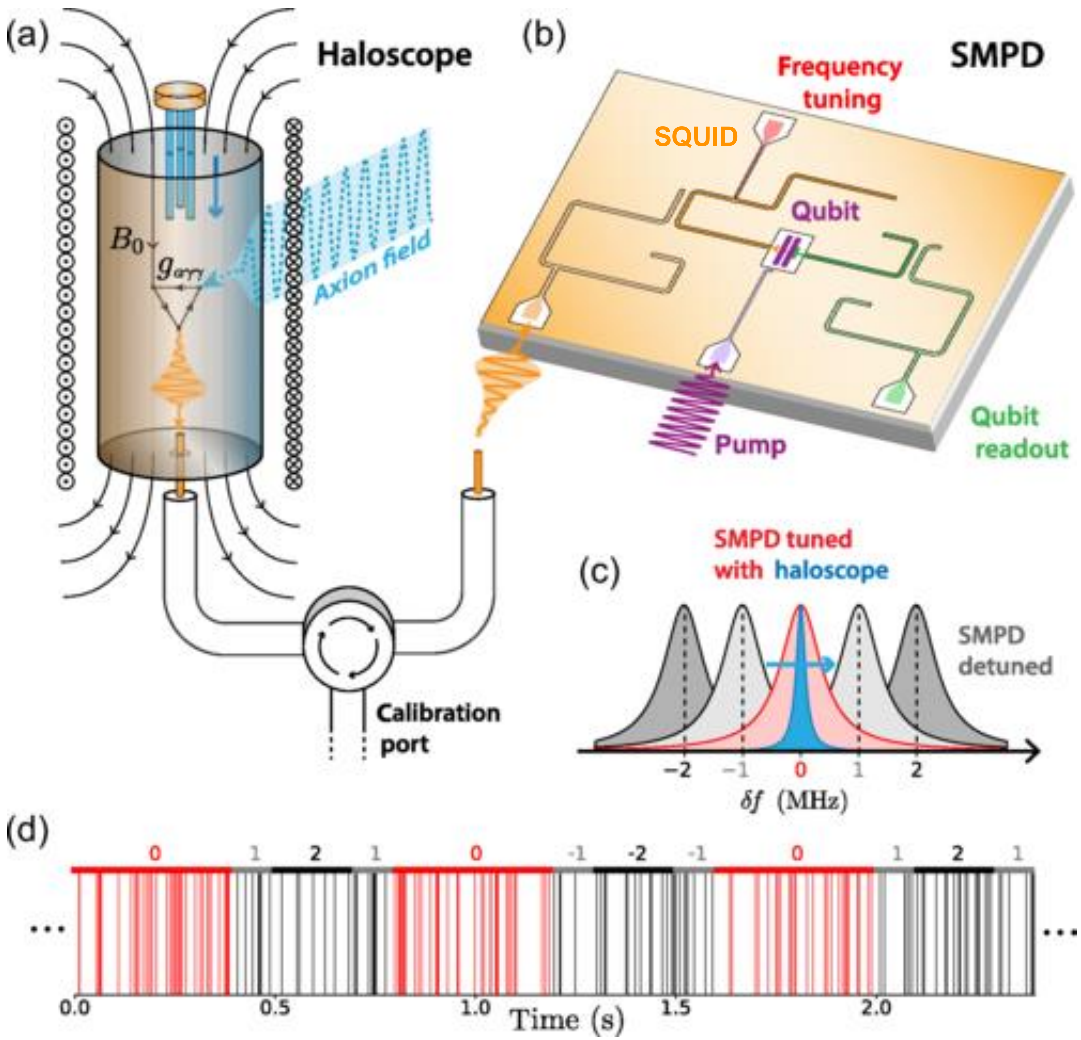
Small bandwidth!

Irreversible process (Quantum Nondemolition detection)

Tunable SMPD

- *SQUID-based tunability*
  - *Buffer + SQUID*
- *Four-wave mixing*
  - $\nu_p + \nu_b = \nu_q + \nu_w$
  - $\eta \sim 0.5$
  - $\Gamma_{dc} \sim 100\ s^{-1}$
- *Axion search*
  - *7.3 GHz*
  - *High-Q cavity*
  - *2T magnetic field*
  - *20x scan rate*
- *Cyclical operation*
  - $\nu_b \neq \nu_c$: *bkg only*
  - $\nu_b = \nu_c$: *sgl + bkg*
  - *In situ calibration*

PRX ***15****, 021031 (2025)*



Microwave signal detection

Power detection vs. photon counting

(w/ amplifiers) *(w/ single photon detector)*

Transistor-based
Heat dissipation
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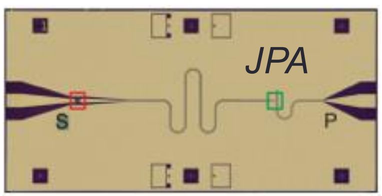
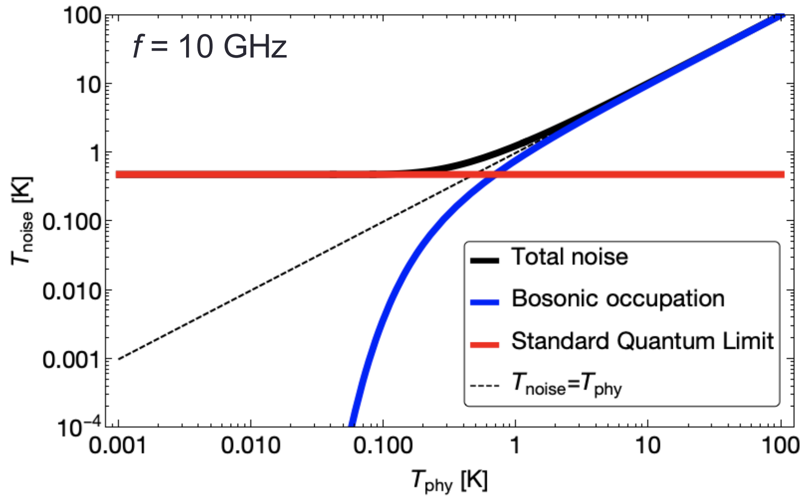
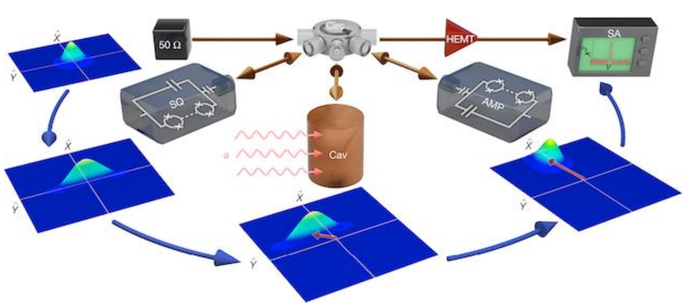


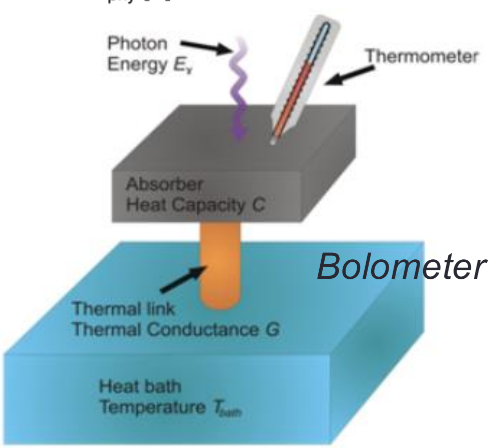
JJ nonlinearity
Quantum limited
(T_{SQL} ~ 50 mK x f [GHz])

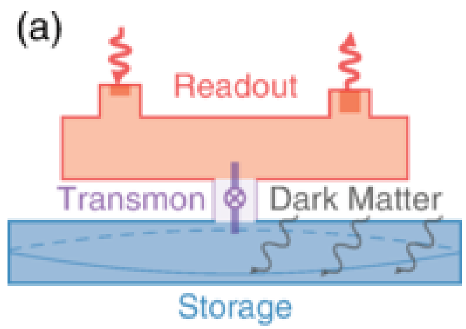


Single photon detector (SPD)
↓
Game changer at high frequencies and low temperatures



Quantum squeezing (T_N < T_{SQL})





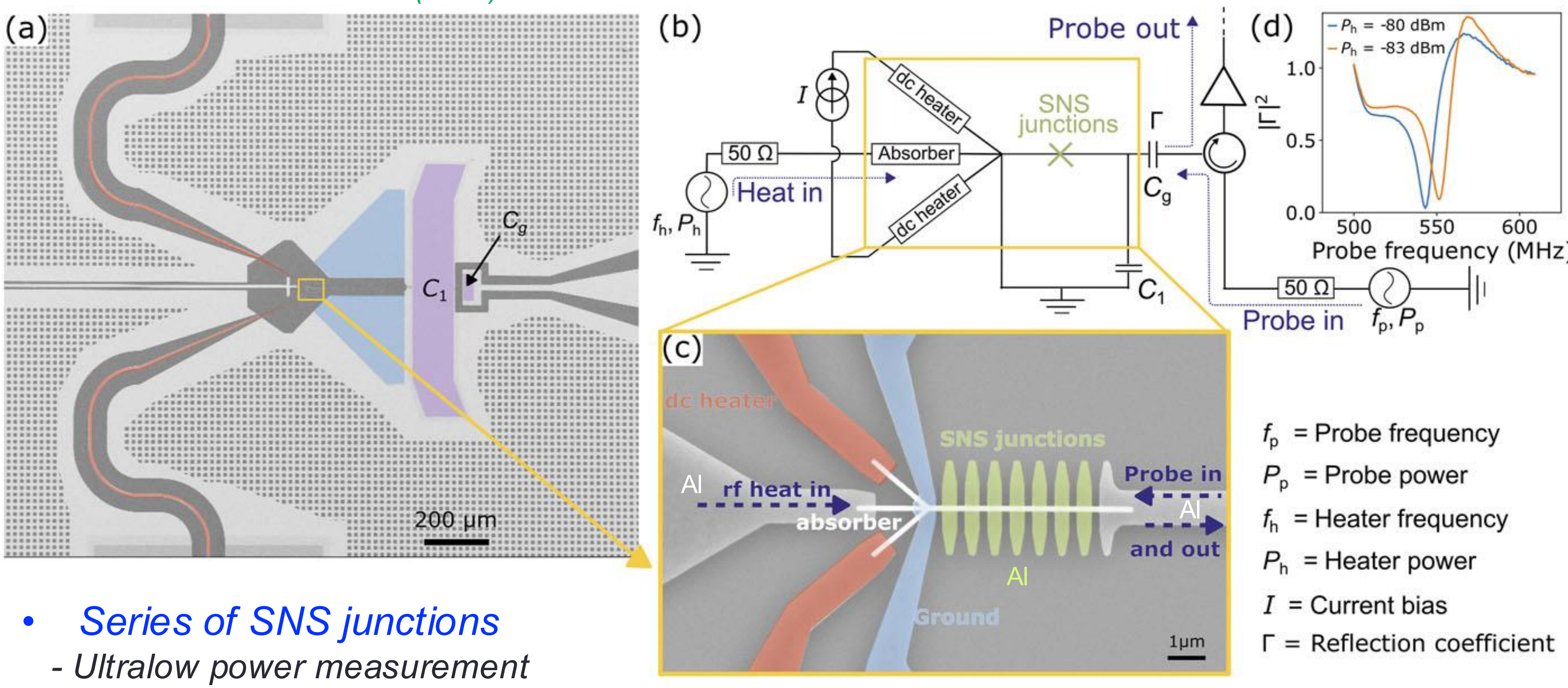
Single photon counting
Not subject to SQL
(T_N << T_{SQL})

Nanobolometer

- *Nanowire bolometer with SNS-JJ resonator readout*

Rev. Sci. Instrum. ***94*** *054710 (2023)*

Redshift upon heating



Normal metal (Au_xPd_{1-x}) nanowire

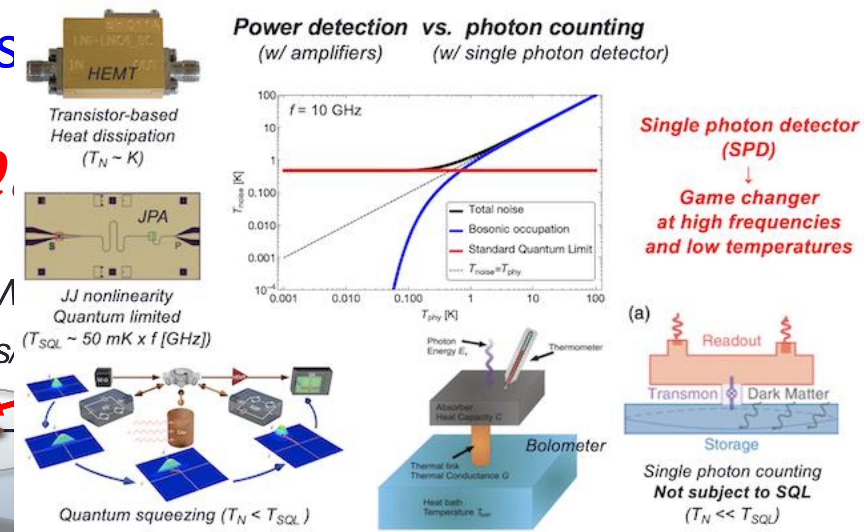
- *Series of SNS junctions*
  - *- Ultralow power measurement*
  - *- Broadband: 100 MHz ~ 20 GHz*
  - *- Low noise: NEP_{min} ~ 2 aW/√Hz*
- *dc heater*
  - *- In situ traceable calibration*

Graphene (SGS)

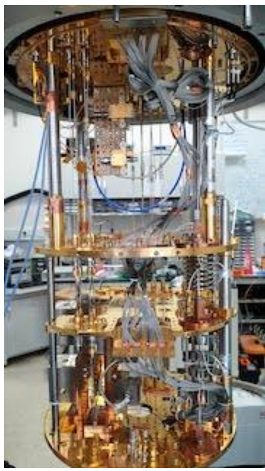
Low C & small V => fast detector speed

Cavity haloscope – in a nutshell

- *Leading sensitivity in the μeV mass*



Cryogenics *T*

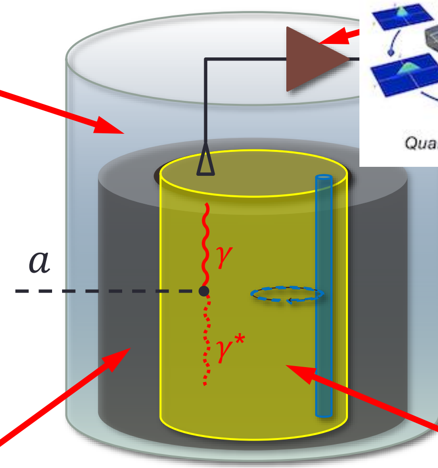


Thermal noise reduction

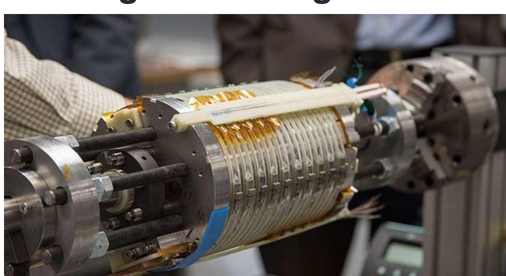
$$\frac{df}{dt} \sim B_0^4 V^2 C^2 Q$$

P_{sig} ~ 10^{-23} W

(~100 photons



High field Magnet *B*



Boosting a→γγ conversion

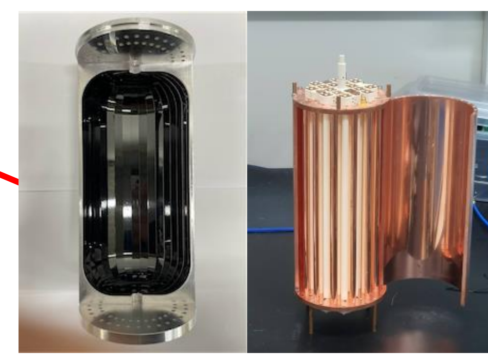
Resonant enhancement

$f_{axion} = f_{cavity}$

Extreme conditions!

Tunable High-Q resonator

V, Q, C, Δf



Signal enhancement

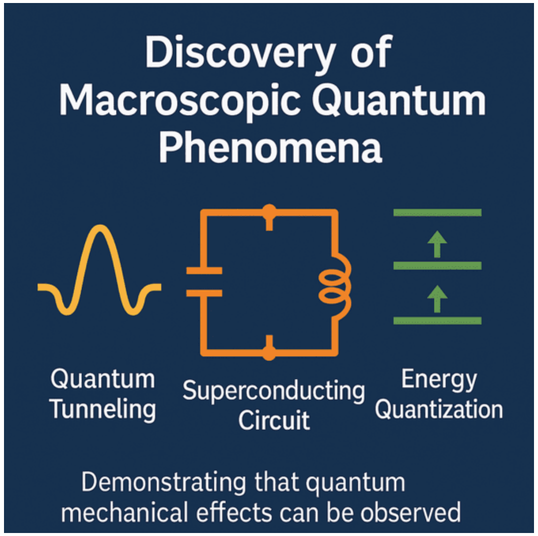
Quantum vs. Axion

Nobel Prize in Phyiscs 2025

John Clarke

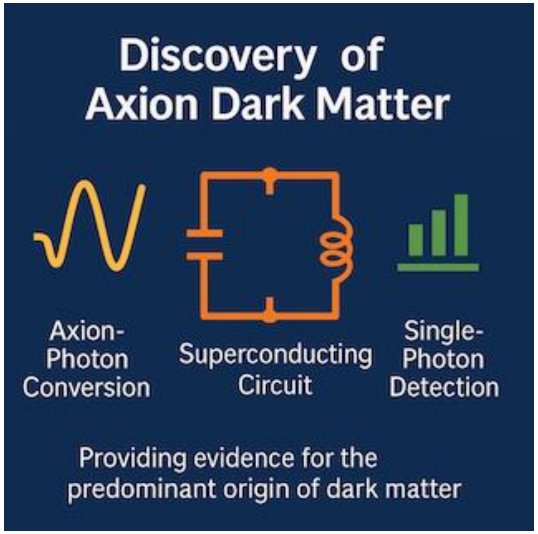
Michel H. Devoret

John M. Martinis



Nobel Prize in Phyiscs 20XX

Xxxx Xxxx *Yyyy Yyyyy* *Zzzz Zzzzz*




AXION EXPERIMENTS
Listening for Dark Matter
QUANTUM TECH
SQUID / Sensors
Qubits
Quantum Amplifier
JPA
Turn up the quantum gain!
Low-Noise Readout
Frequency
a
AI / ML
Neural Networks
Training on cosmic whispers.
Pattern Recognition
Frequency
Peek-a-axion!
Anomaly Detection
Hmm... someone's hiding here.
ENHANCED SENSITIVITY
Still looking... still excited!
Let's catch that axion!
PARTICLE PHYSICS
DATA SCIENCE & ML
COLLABORATION FOR HIGH-SENSITIVITY SEARCHES