Axion and Microwave Photon

2^{nd} School for Particle Detector and Application at KNU
Jan. 22 2021

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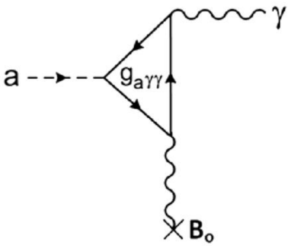
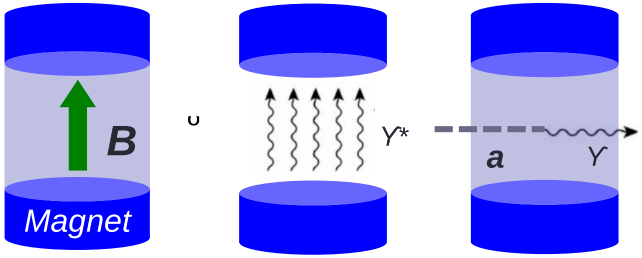
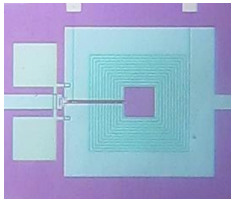
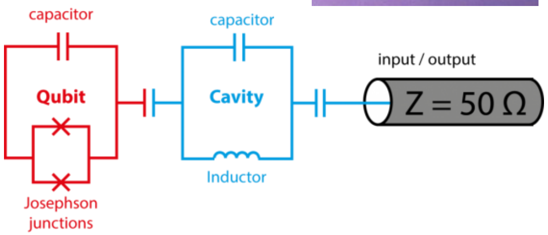
Outline

- *Axion and dark matter*
  - *Strong CP problem*
  - *Dark matter*
- *Axion detection*
  - *Detection principle*
  - *Searching strategies*
- *Microwave detection*
  - *Power amplifiers*
  - *Single photon detectors*
  - *Thermal detectors*
- *Summary*









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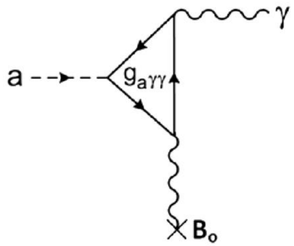
  - ***Strong CP problem***
  - ***Dark matter***



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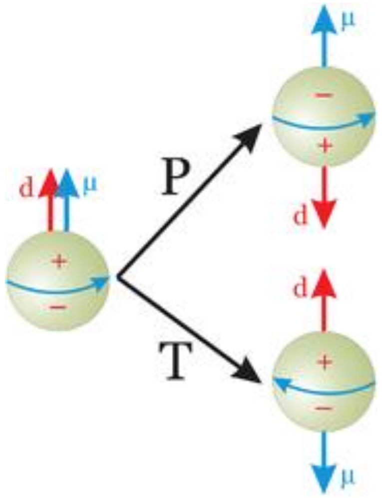
Strong CP problem

- *QCD vacuum structure adds an extra terms to L_{QCD}*

$$L_\theta = \theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

  - *Violates CP symmetry proportionally to θ*
  - *Not predictable by theory, must be measured*

- *CP-violation term induces charge separation*
  - *Neutron electric dipole moment (nEDM)*
  - *Experimental value is very tiny*
    - *$d_n < 10^{-26}$ ecm => $\theta < 10^{-10}$*
  - *Theoretically, θ = 0 if a quark is massless (X)*



- *Strong CP problem*
  - *Naturalness problem ($0 < \theta_{the} < 2\pi$ vs. $\theta_{exp} \sim 0$)*

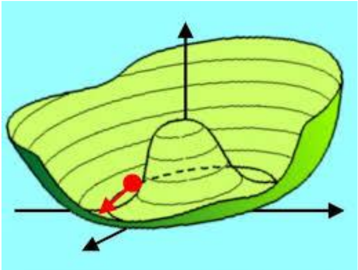
PQ mechanism and axion

- *Peccei & Quinn (1977)*
  - *New global $U_{PQ}(1)$ symmetry w/ scalar field a(x)*

$$L_\theta = \left(\theta - \frac{a(x)}{f_a}\right)\frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

  - *Spontaneously broken at energy scale f_a*
  - *Induces a potential with minimum at $a(x) = \theta \times f_a$*
  - *Dynamic solution to the strong CP problem*

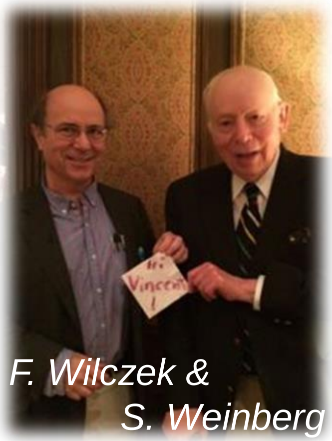

R. Peccei & H. Quinn



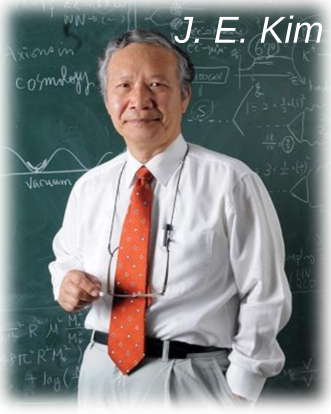
- *Wilczek & Weinberg (1978)*
  - *(pseudoscalar) Goldstone boson => Axion*
  - *Axion mass depends on energy scale f_a*

$$m_a = m_\pi \frac{f_\pi}{f_a} \approx 6\,eV \frac{10^6\,GeV}{f_a}$$

  - *For f_a ~ EW scale => m_a ~ 100 keV => PQWW axion excluded by collider experiments*


F. Wilczek & S. Weinberg

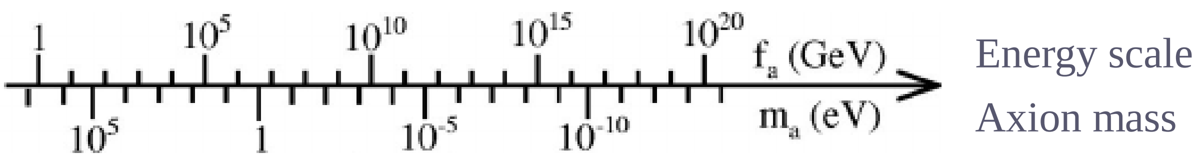
Invisible axion



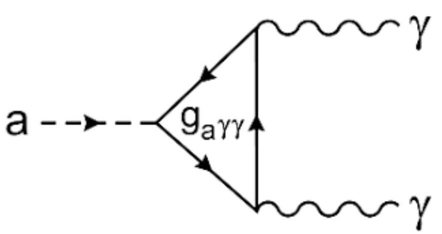
- *J.E. Kim (1979)*
  - *Proposed very light axions with a very large f_a (in early universe)*

$$m_a \approx 6\ \mu eV \frac{10^{12}\ GeV}{f_a}$$

  - *Spanned axion mass by many orders of magnitude*



- *Axion interactions*
  - *Quarks, gluons, photons, leptons,…*
  - *Model dependent on PQ charge assignment*
    - *KSVZ – Heavy quark (ex. $g_\gamma = -0.97$)*
    - *DFSZ – Higgs doublet (ex. $g_\gamma = 0.36$)*



$$L_{a\gamma\gamma} = -\left(\frac{\alpha}{\pi}\frac{g_\gamma}{f_a}\right) a\vec{E}\cdot\vec{B}$$

$$= -g_{a\gamma\gamma}\, a\vec{E}\cdot\vec{B}$$

Axion dark matter

- *Cosmic axion (1983)*
  - *May account for dark matter*
    - *Neutral, stable, and feeble integrations*
  - *Cosmological constraint: $f_a < 10^{12}$ GeV*
    - *Too light axions would be overproduced in early universe*
  - *Astronomical observation: SN1987A*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COSMOLOGY OF THE INVISIBLE AXION

John PRESKILL [1], Mark B. WISE [2]
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and

Frank ...

Volume 120B, number 1,2,3 PHYSICS LETTERS 6 January 1983

A COSMOLOGICAL BOUND ON THE INVISIBLE AXION

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Volume 120B, number 1,2,3 PHYSICS LETTERS 6 January 1983

THE NOT-SO-HARMLESS AXION

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and

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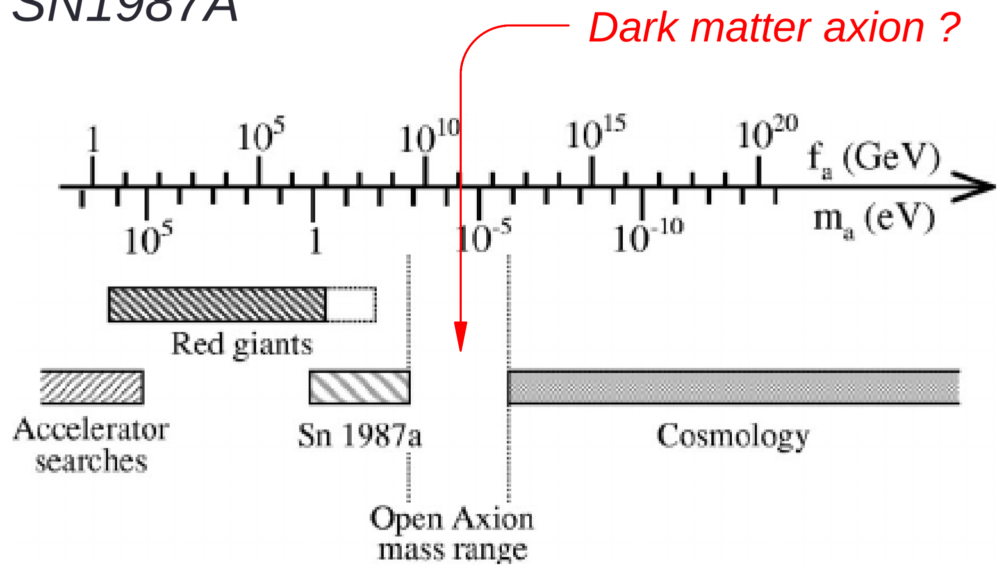
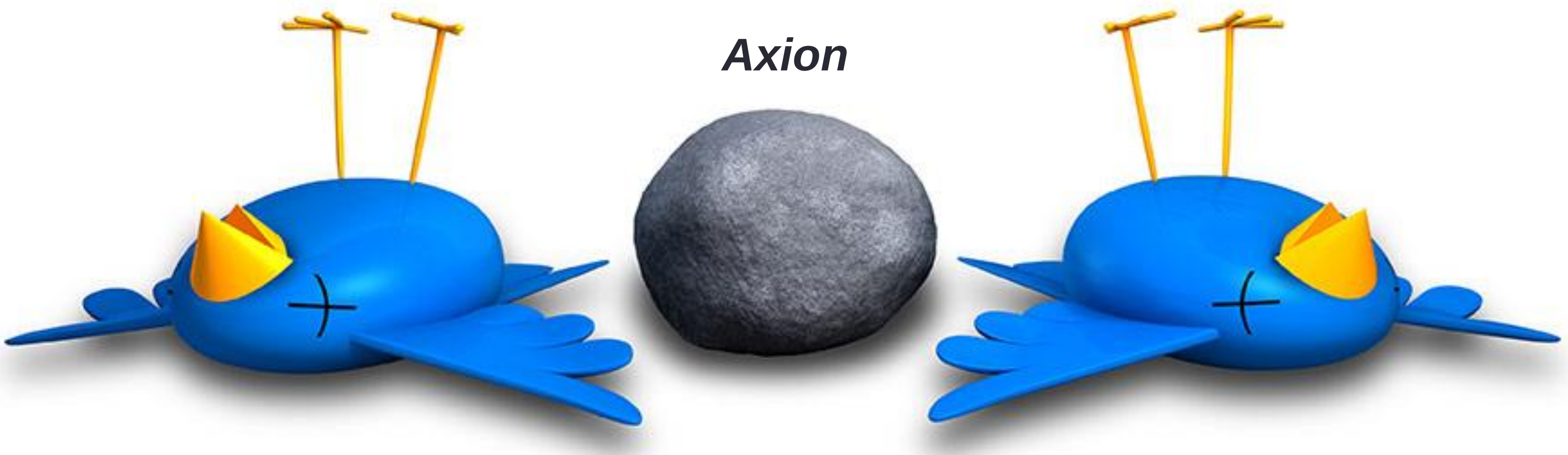
Received 17 September 1982
Received manuscript received 14 October 1982



10^{-6} eV < m_a < 10^{-3} eV

Axion dark matter

KILLING TWO BIRDS WITH ONE STONE



Strong CP problem

Dark matter

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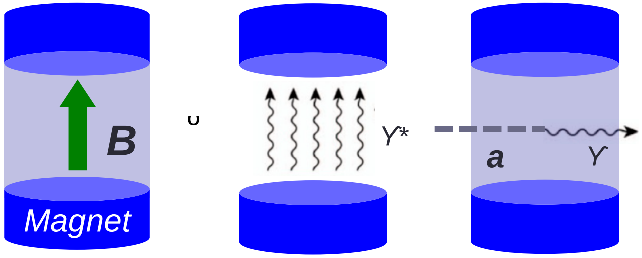
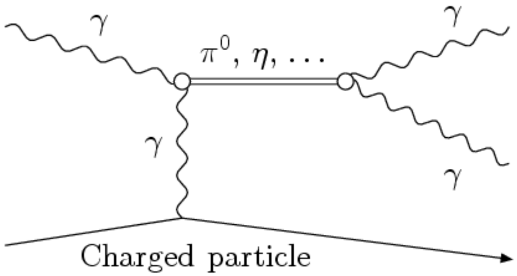


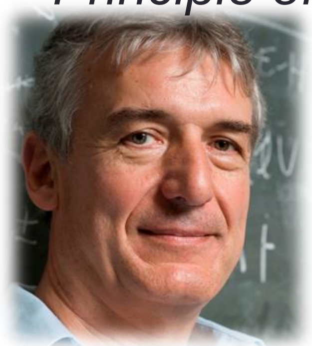
Detection principle

- *Coupling with photons*
  - *Primakoff effect*
  - *Energetic photons + EM of nuclei*
    => pseudoscalar particles

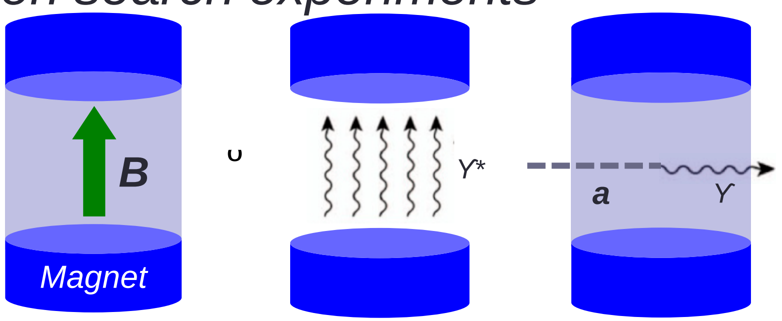


- *Conversion of axions to photons in a magnetic field (1983)*
  - *Axions "borrow" virtual photons from the magnetic field to turn into real photons*
  - *Principle of axion search experiments*

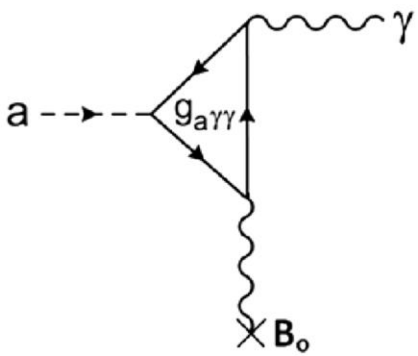
$$L_{a\gamma\gamma} = -g_{a\gamma\gamma}\, a\vec{E}\cdot\vec{B}$$



P. Sikivie

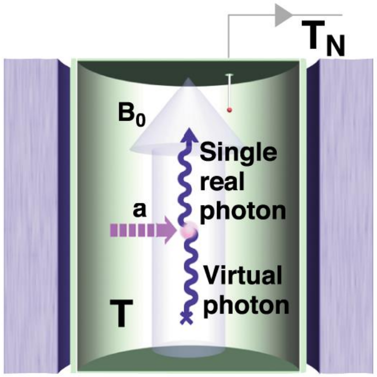


Classical EM field *Sea of virtual photons* *Primakoff effect*

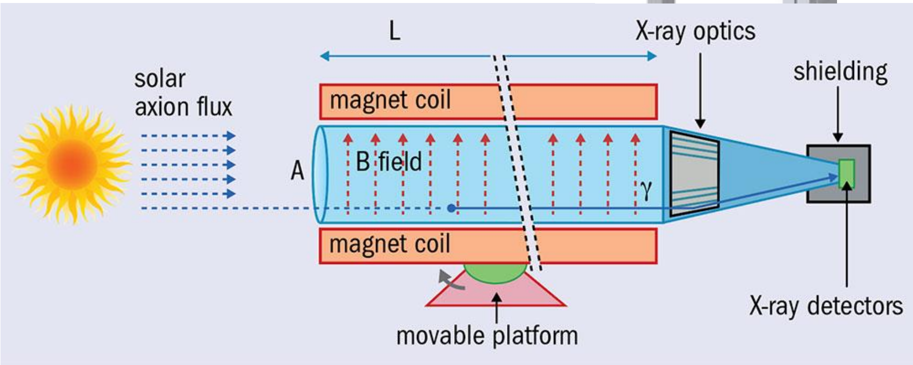


Main approaches

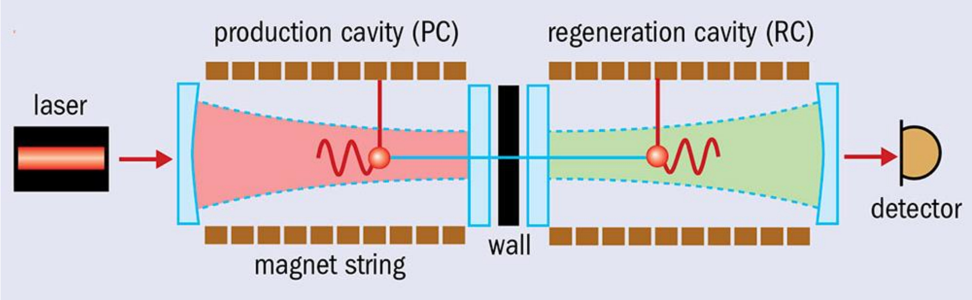
- *Haloscope*
  - *DM axions in our galactic halo*
  - *Microwave resonators*
  - *ADMX, HASTAC, CAPP,…*



- *Helioscope*
  - *Solar axions*
  - *Emitted by the solar core*
  - *CAST, IAXO,…*

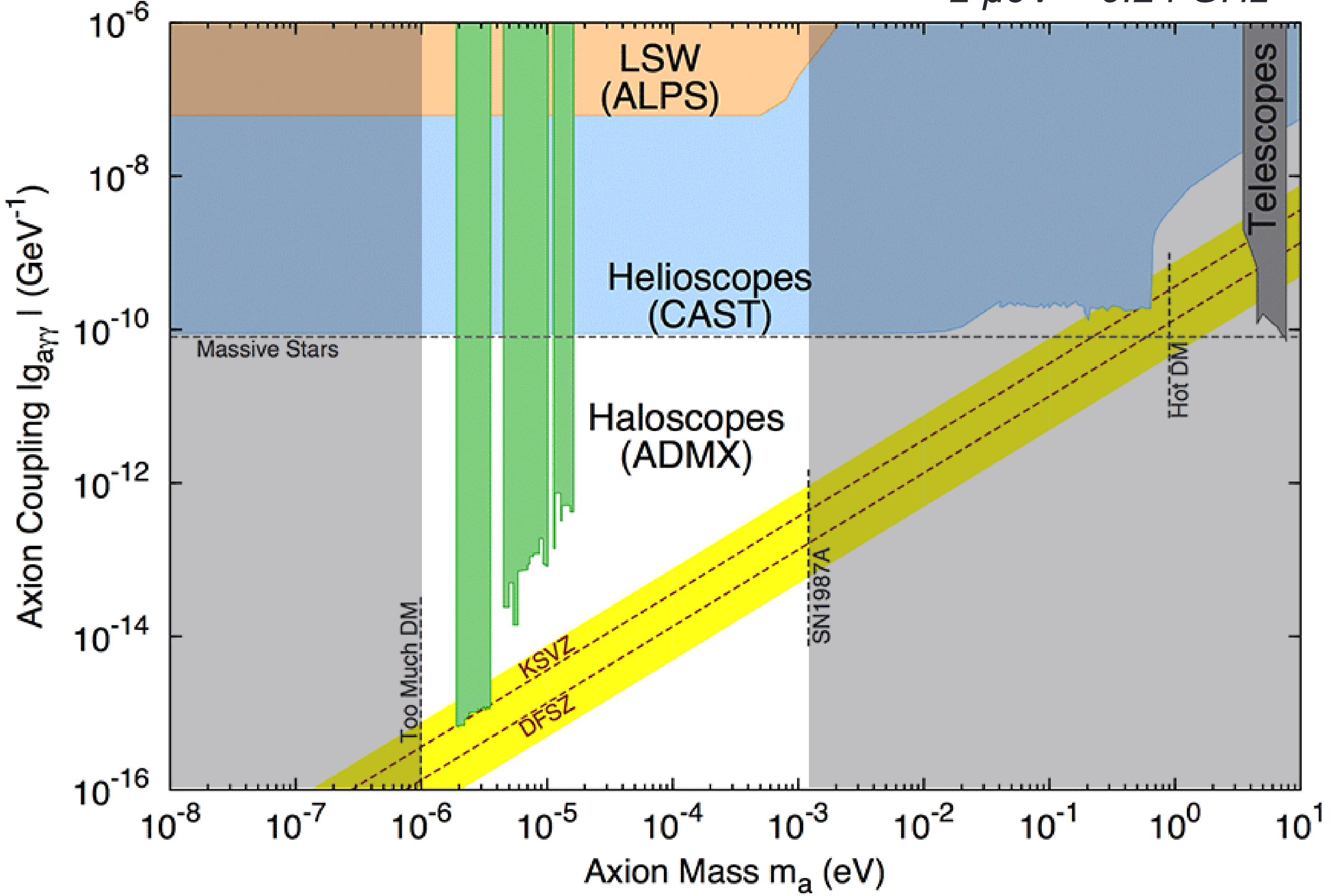


- *Photon regeneration*
  - *Light Shining through Wall*
  - *Axion generation at the lab*
  - *ALPS,…*



Axion Parameter Space

1 μeV = 0.24 GHz



Frequency range: 1 GHz ~ 1 THz (microwave region)

Physical Quantities

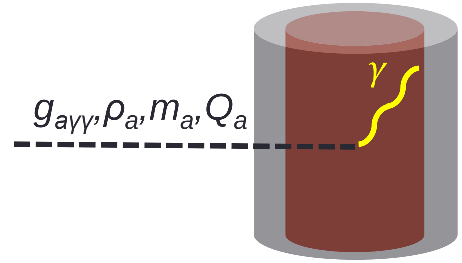
- theoretical parameters
- experimental parameters

- ## Conversion power

$$P_{a\to\gamma\gamma} = g^2_{a\gamma\gamma}\frac{\rho_a}{m_a}B^2VC_{mnp}\min(Q_L,Q_a) \sim 10^{-23}W$$

Coupling constant; Axion number density; Magnetic field; Effective volume; Cavity Q factor; Axion Q factor

Cavity Q_L,V,C



Strong B_0

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

$$SNR \equiv \frac{P_{signal}}{P_{noise}} = \frac{P_{a\to\gamma\gamma}}{k_B T_{syst}}\sqrt{\frac{t_{\rm int}}{\Delta f_a}}$$

Integration time; Axion bandwidth ($\sim 10^{-6} f$); System noise temperature

$$T_{syst} = T_{phy} + T_{add}$$

Noise = equivalent temperature

- ## Scan rate (F.O.M.)

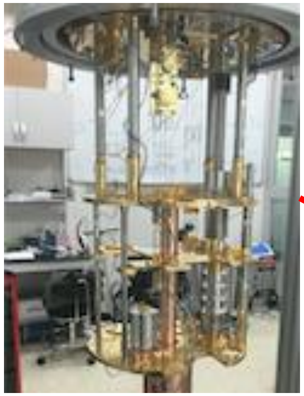
$$\frac{df}{dt} = \left(\frac{1}{SNR}\right)^2\left(\frac{P(f)}{k_B T_{syst}}\right)^2\cdot\frac{Q_a}{Q_L} \propto B^4V^2C^2Q_L T_{syst}^{-2}$$

Haloscope in a Nutshell

- *Enhancing the scan rate*

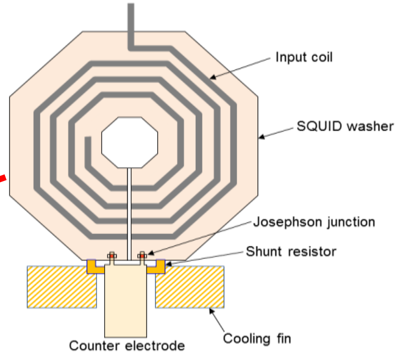
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

Cryogenics T



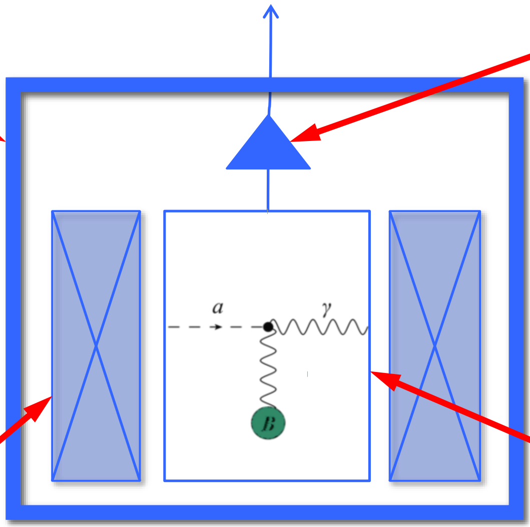
Lowering thermal noise

Quantum noise limited amplifier T



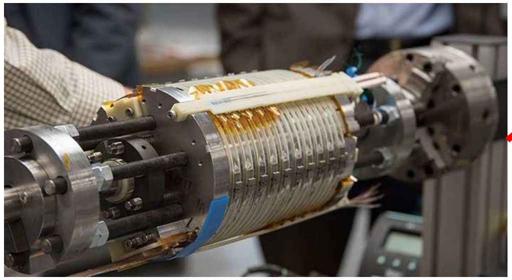
Signal amplification w/ minimal noise added

RF readout chain



Axion-photon conversion (Primakoff effect)

High field HTS Magnet B



Boosting a→γγ conversion rate

High Q resonator VCQ

Resonant frequency tuning

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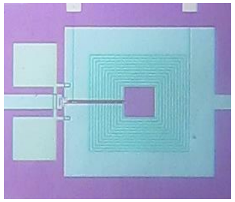
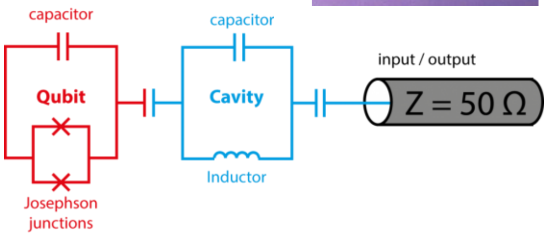
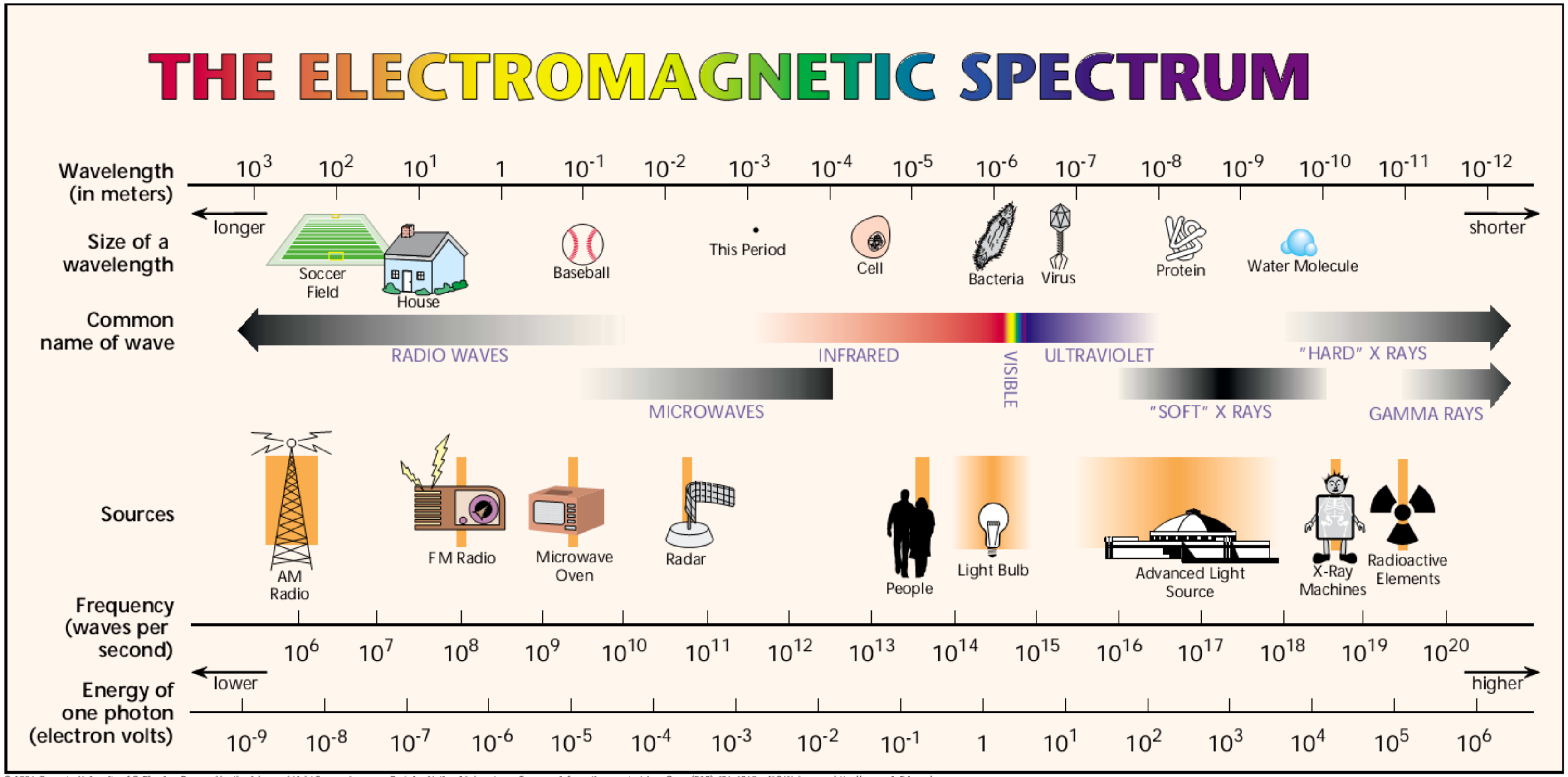




- *Summary*

Electromagnetic spectrum



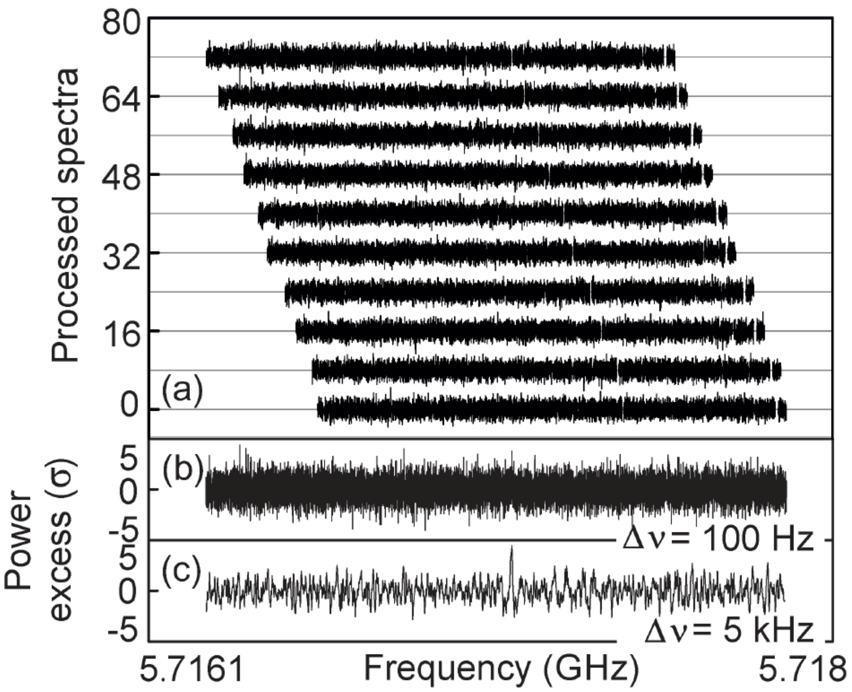
Axions
(wave-like)

Colliders
(particle-like)

Power detection

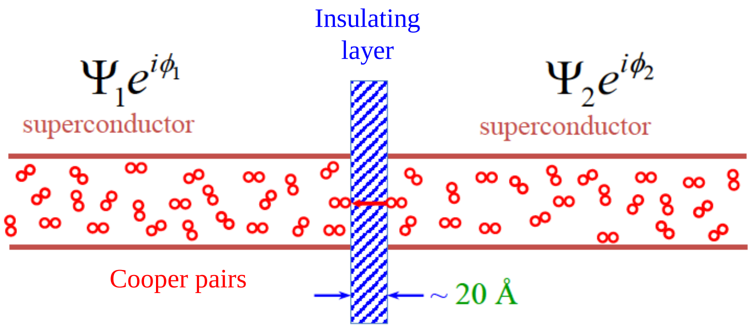
- *Typical detection scheme for axion search experiments*
  - *w/ transistor-based amplifiers*
  - *Significant electrical shot noise is added*
  - *Typical power ~10^{-23} W*
    - *~1 photon/s at 10 GHz*
    - *T_{add} ~ 5 K (~10 photons)*
- *Quantum technology*
  - *Josephson effects*
  - *Subject to the quantum limit*
    - *Amplitude ν & phase φ*
    - *Δν × Δφ > hbar*
    - *Standard quantum limit (SQL)*
      - *T_{SQL} ≈ 50 mK × f [GHz]*

High-electron-mobility transistor (HEMT)



Josephson effect

- *Josephson junction (JJ)*
  - *Two superconductors separated by a thin insulator*
  - *Building block of microwave quantum electronics*
- *DC Josephson effect*
  - *δ => potential across the insulator*
  - *DC current w/o external field*
- *AC Josephson effect*
  - *V_{DC} across the junction, ϕ varies with t*
  - *Oscillating current*
  - *Voltage-to-frequency converter*
- *A broad range of application*
  - *Non-dissipative and non-linear*
  - *SQUID (magnetometer)*
  - *Superconducting qubit (quantum computation and information)*
  - *Standard representation of voltage*

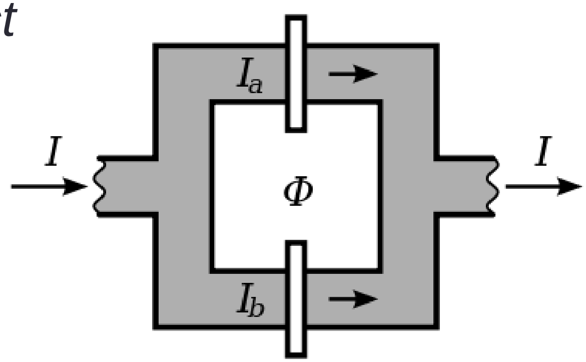


$$\delta = \phi_1 - \phi_2$$

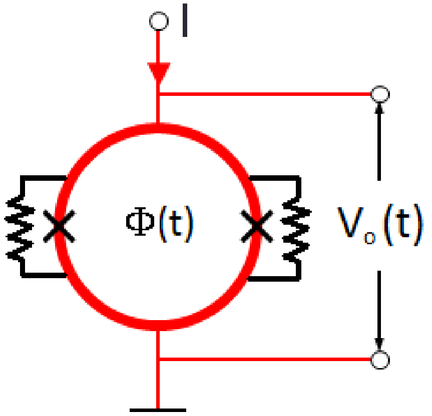
Supercurrent

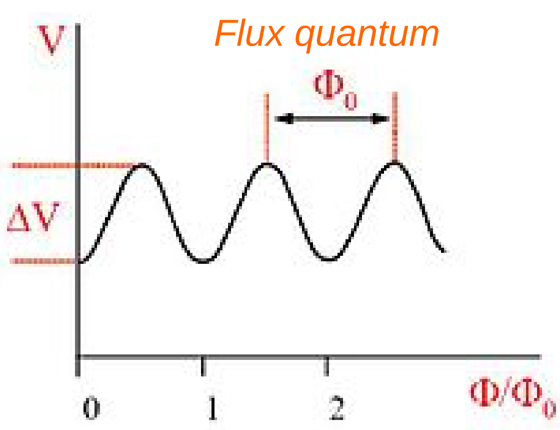
SQUID

- *Superconducting Quantum Interference Device*
  - *Two JJs in a loop*
  - *Sensitive magnetometer via Josephson effect*

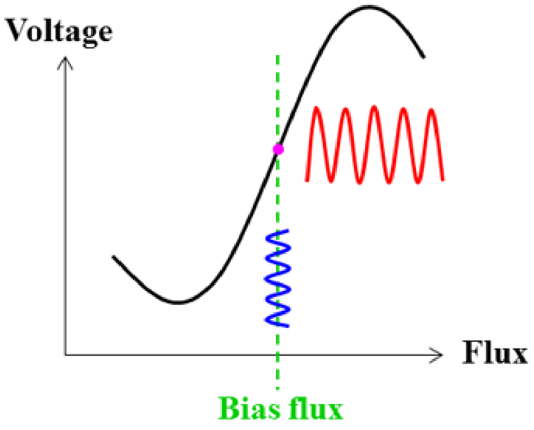


- *Principle*
  - $\Phi = 0$, $I_a = I_b = I/2$
  - $\Phi \neq 0$, $I_a \neq I_b$ => V (to cancel Φ)
- *Quantum noise limited amplifiers*
  - *Standard Quantum Limit:* $T_{SQL} \approx 50$ *mK* $\times f$ *[GHz]*



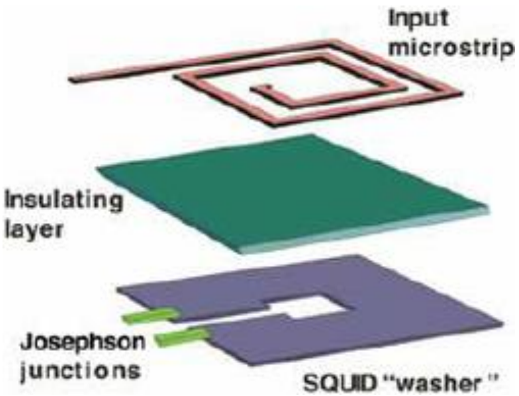


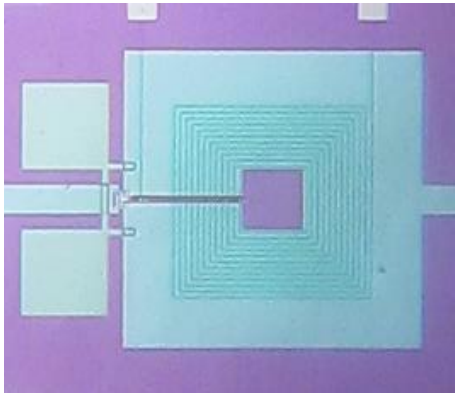
$\Phi_0 = h/2e = 2.0\times10^{-15}$ *Wb*

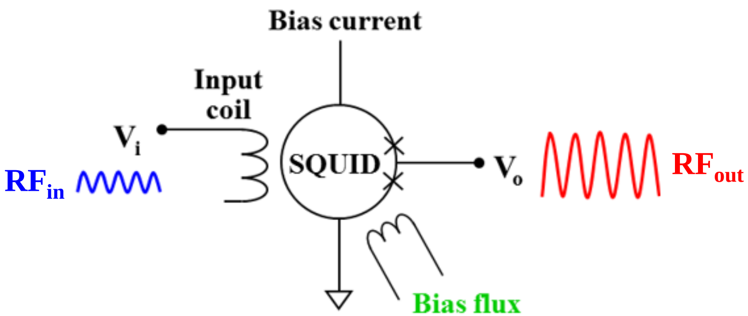


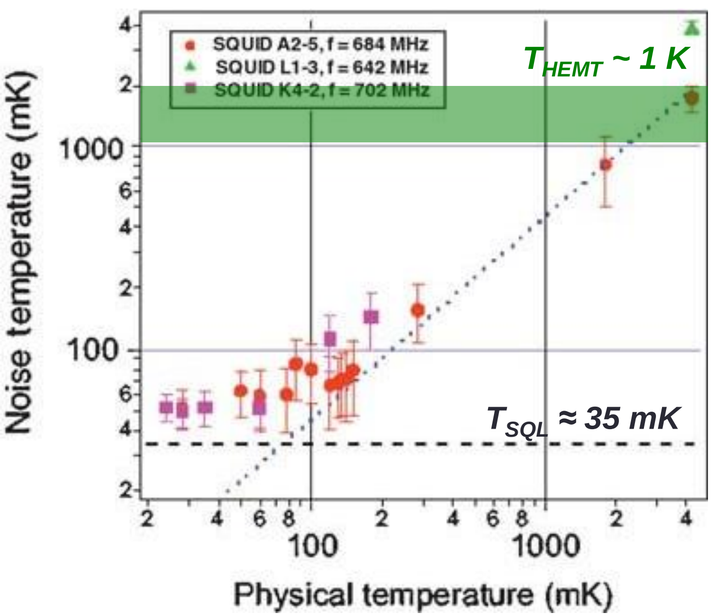
MSA

- *Microstrip SQUID Amplifier*
  - *SQUID washer + insulating layer + SC microstrip coil*
    - *L and C between washer and coil determines the resonant frequency*
  - *RF input signal couples with a SQUID via a mutual inductance*



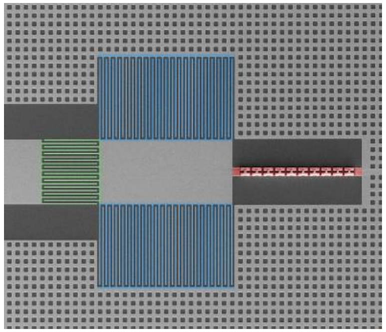


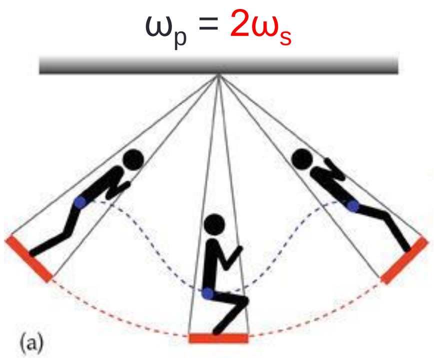


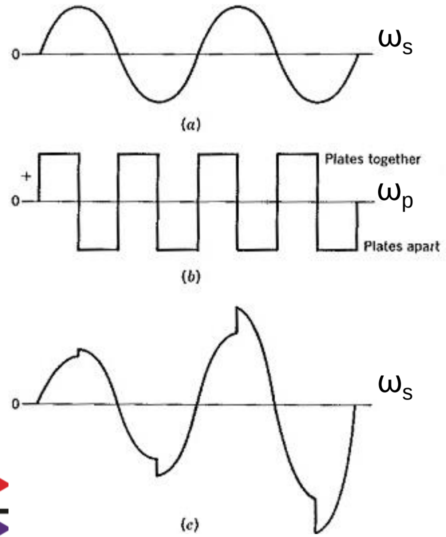


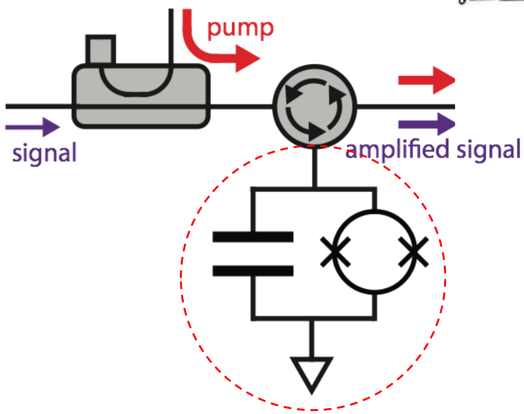
JPA

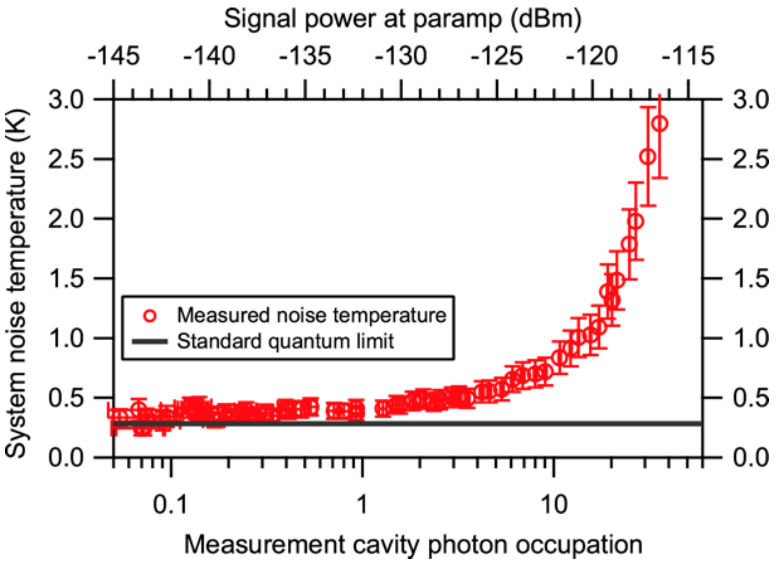
- *Josephson Parametric Amplifier*
  - *LC resonator with an array of SQUIDs*
  - *Parametric (inductance) gain from a pump tone*





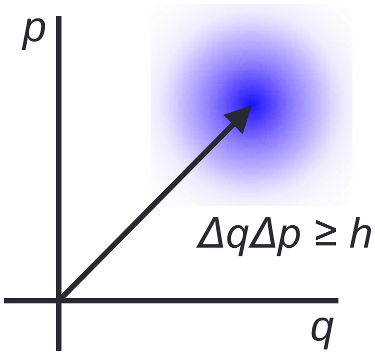






Linear amp. vs. SPD

- *Linear amplifiers are subject to the fundamental limit*
  - *Standard quantum limit (SQL)*
  - $T_{SQL} \approx 50\ mK \times f\ [GHz]$)
    - *Linear dependence on frequency*
    - *cf.* T_{phy} *(< 100 mK) is fixed by experimental setup*
  - *At high frequencies,* T_{SQL} *is predominant*

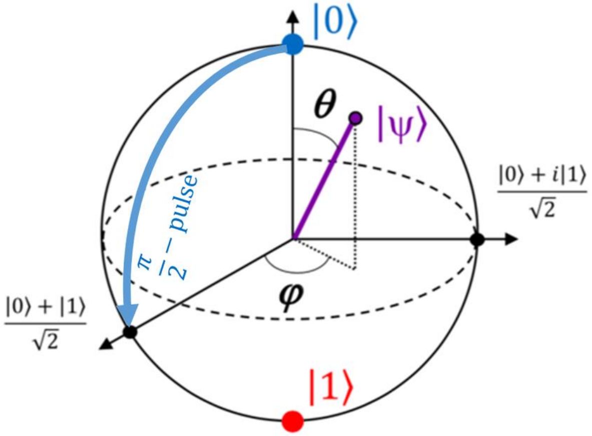


- *Single photon detectors count photon numbers*
  - *Not subject to the SQL*
  - *Well developed in optics*
  - *Very challenging in microwave regime* ($E_{mw} \sim 10^{-6} E_{opt}$)
  - *Recently actively being developed for Qubit in the GHz range (quantum information processing)*

Qubit

- *Quantum bit*
  - *Basic units of quantum information*
  - *Two-state (two-level) quantum mechanical systems*
    - *Analogous to classical bits: |0) and |1)*
  - *Superposition and entanglement*
  - *Represented by the Bloch sphere*

- *Examples*
  - *Electron spin: up & down*
  - *Photon polarization: horizontal & vertical*
  - *Atom energy state: |g) & |e)*
  - *…*

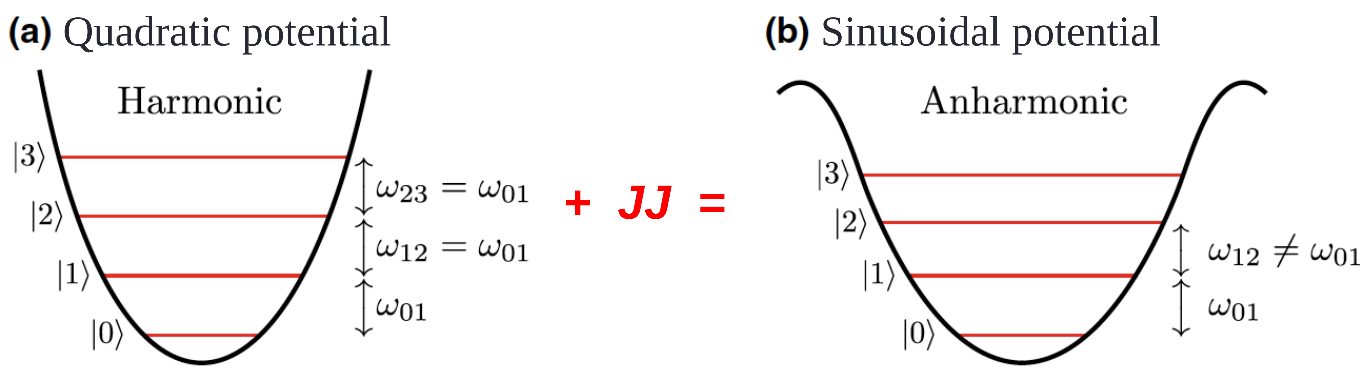


$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle$$

A state is represented by a point on the surface of the Bloch sphere

Josephson-junction qubit

- *Single atoms or ions*
  - *Well know qubit systems*
  - *Parameters are fixed by nature and hard to control*
- *Superconducting circuits on a chip (artificial atoms)*
  - *Analogous to processors in classical computers*
  - *Very flexible in design and tunable parameters*
  - *For nonlinearity, JJs are integrated*

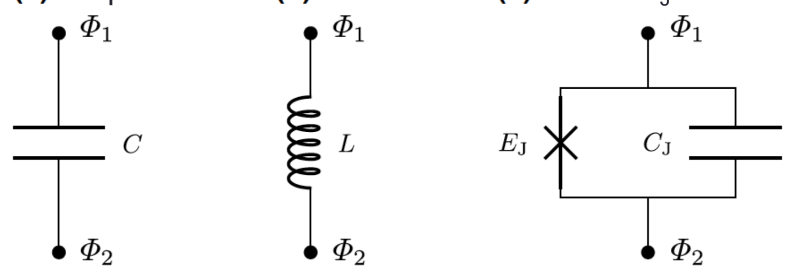


Energy levels are equally spaced (not suitable for qubit)

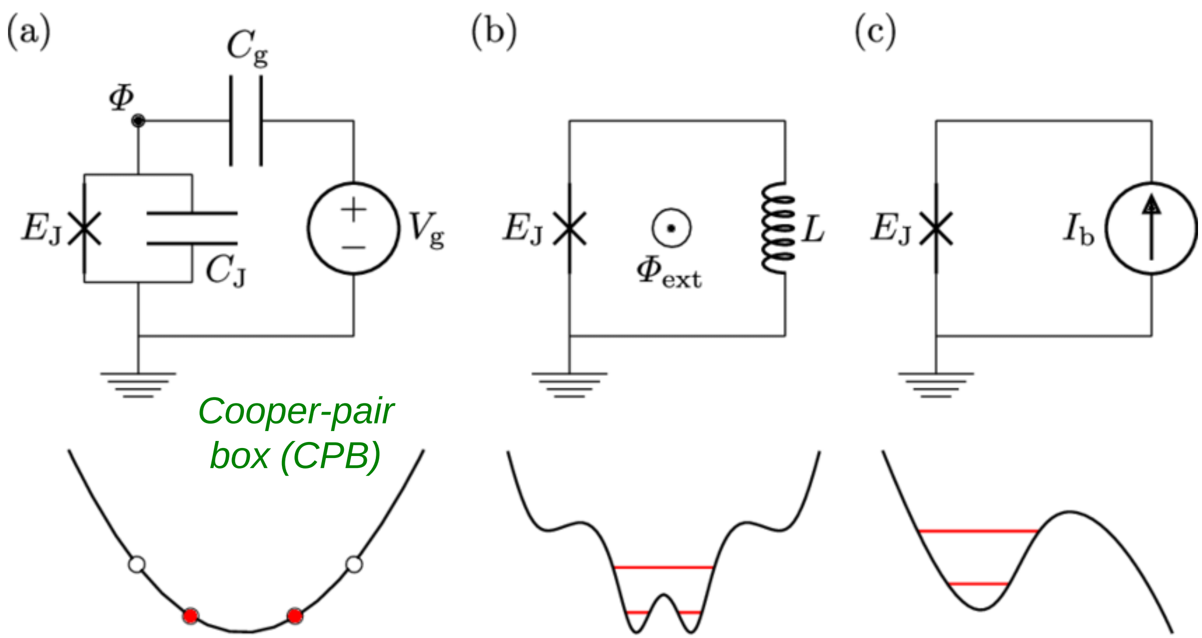
Energy levels are not equally spaced (suitable for qubit)

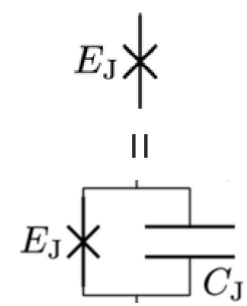
Superconducting JJ circuits

- *Basic circuit elements*



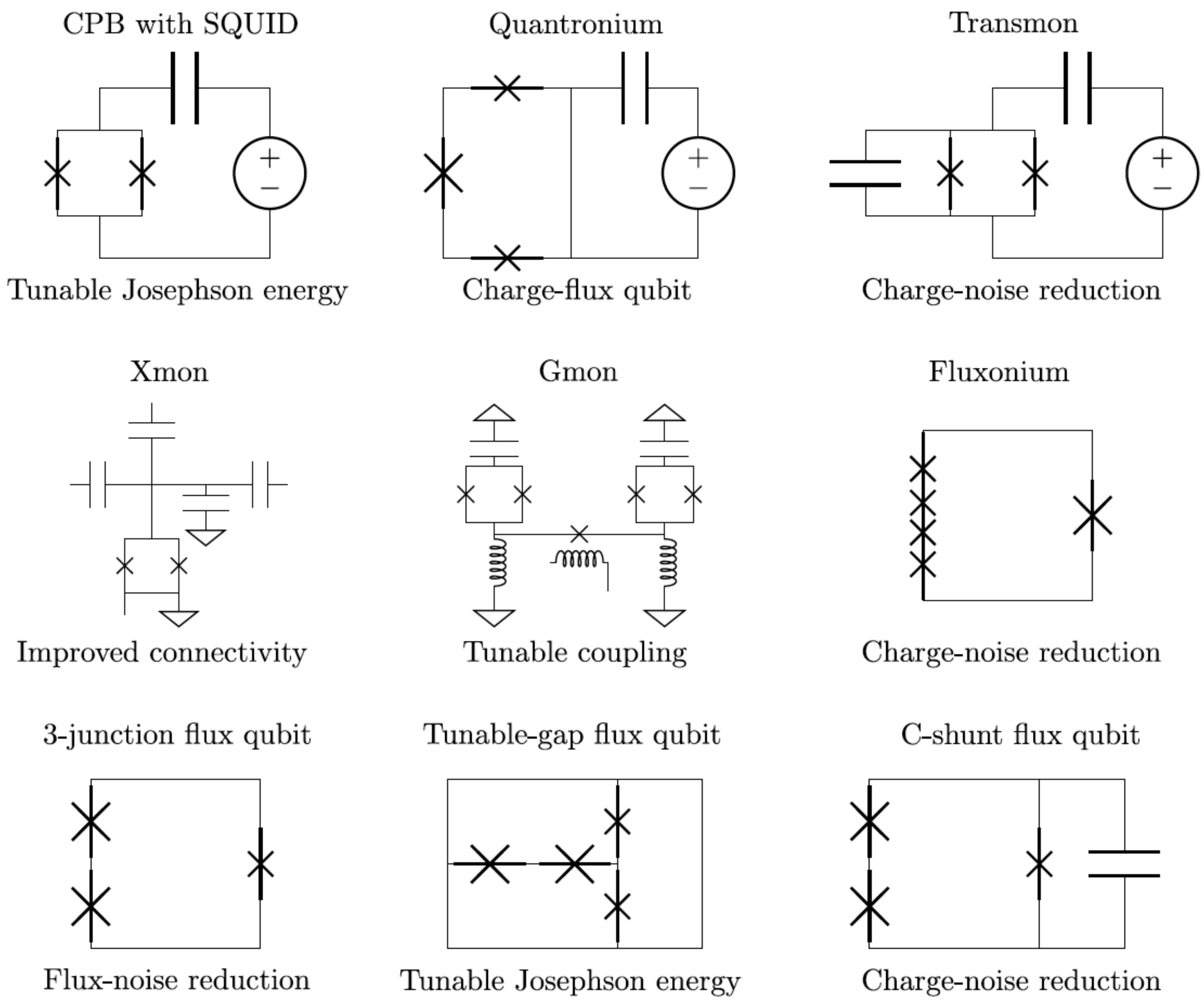
- *Basic JJ qubits*





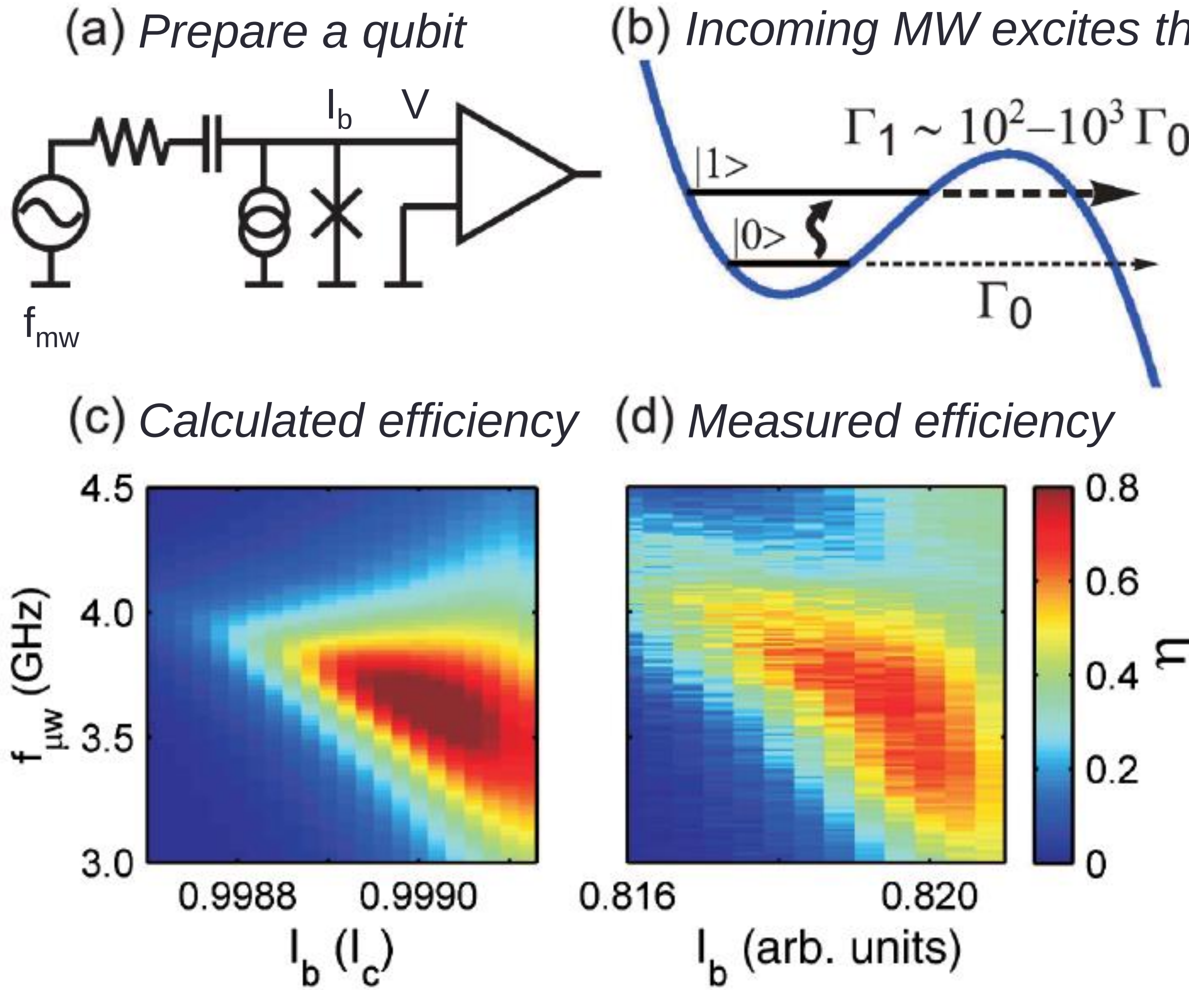
Charge-driven Flux-driven Current-driven

Qubit refinements



SPD – Current-biased JJ

Phys. Rev. Lett. ***107****, 217401 (2011)*

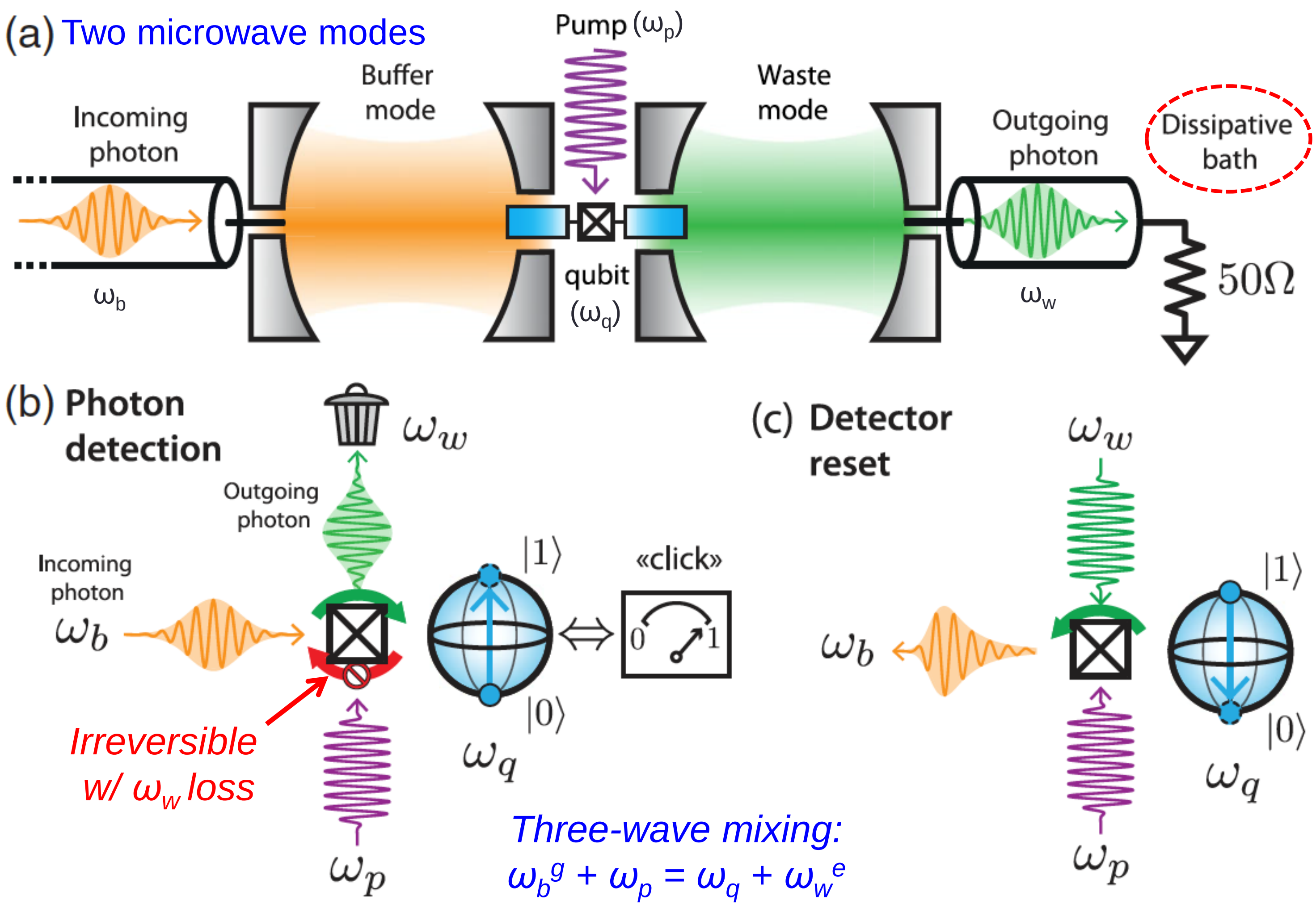


$\Gamma_{0,1}$: tunneling rate

SPD – Irreversible qubit counting

- *Repeated measurement !*

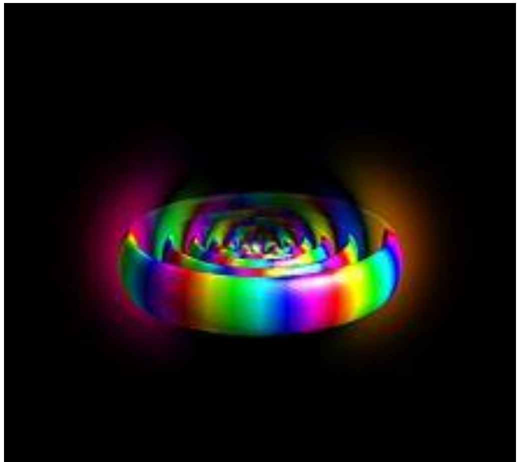
Phys. Rev. X ***10,*** *021038 (2020)*



Three-wave mixing:
$\omega_b^g + \omega_p = \omega_q + \omega_w^e$

Rydberg atoms

- *General properties*
  - *Alkali (hydrogen-like) atoms*
  - *Large principle quantum number, n*
    - $10 < n < 150$
  - *Classical size r*
    - $r = n^2 a_0$ (a_0: Bohr radius)
  - *Tunable transition frequency between |g) and |e)*
    - *Via stark effect*

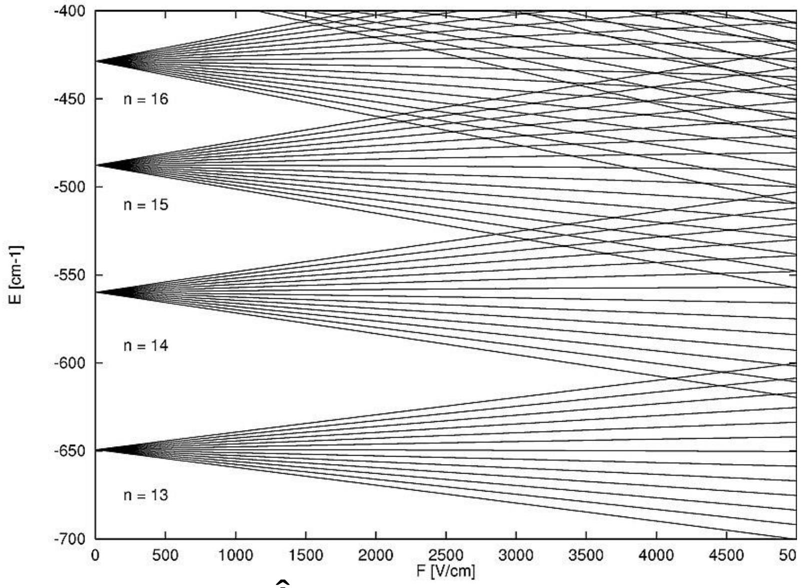


Electron orbital of Rb with n=12

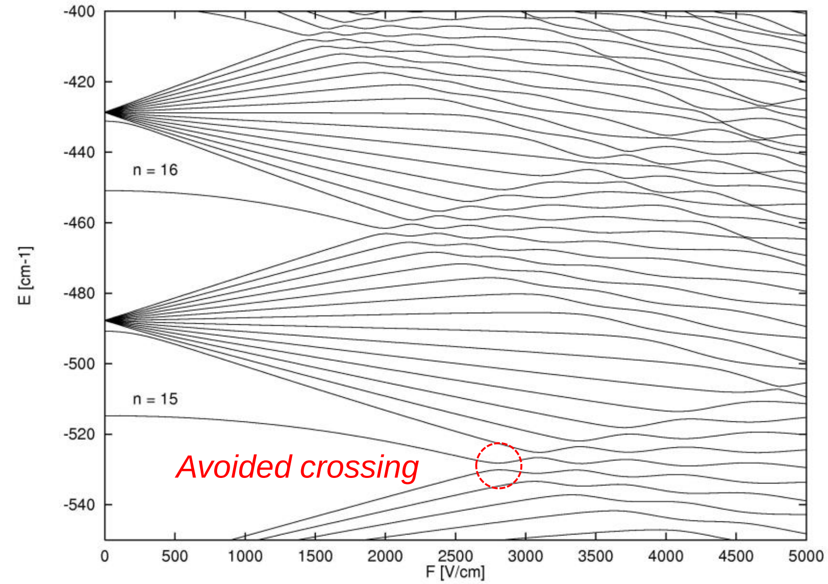
- *Peculiar properties*
  - *Large transition dipole moment*
    - *Strong coupling with EM field*
  - $\Delta E_n = E_{n+1} - E_n \sim$ GHz (ex. $\Delta E_{100} \approx 7$ GHz)
  - *Long life time:* $\tau \sim$ msec (ex. $\tau_{100} \approx 1$ msec)
- *Good for MW photon detection*

Stark Effect

Energy level of hydrogen near n = 15



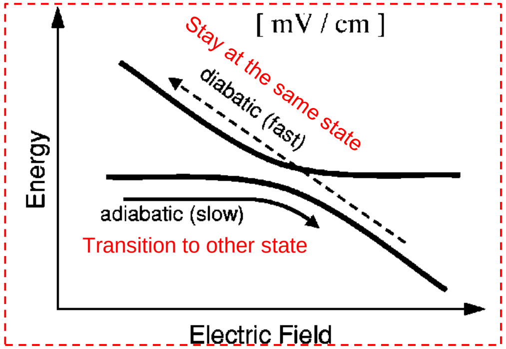
Energy level of lithium near n = 15



$$E_n = \frac{\hat{A}}{n^2} \quad (\hat{A} : Rydberg\ const.)$$

Bohr model

$$E_{n,l} = \frac{\Re}{(n-\delta_l)^2} = \frac{\Re}{\tilde{n}^2}$$

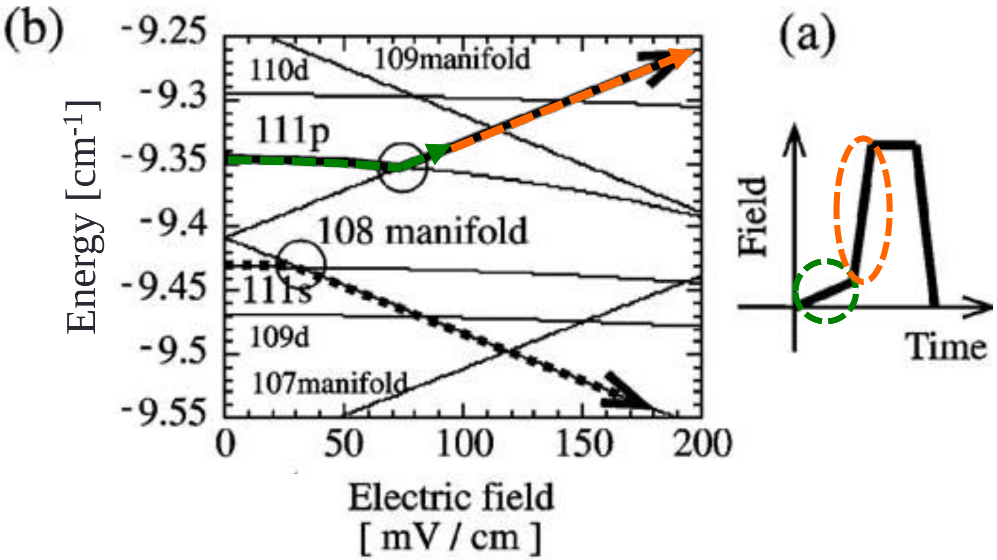


Manifold (n-degenerated) state
=> Stark map

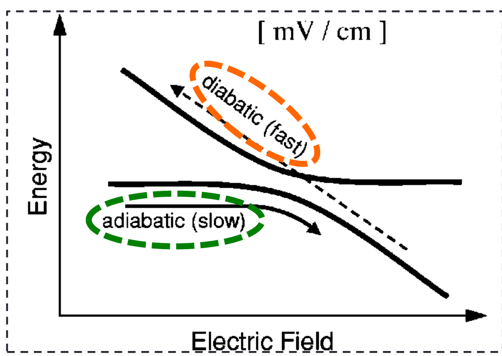
Detection principle

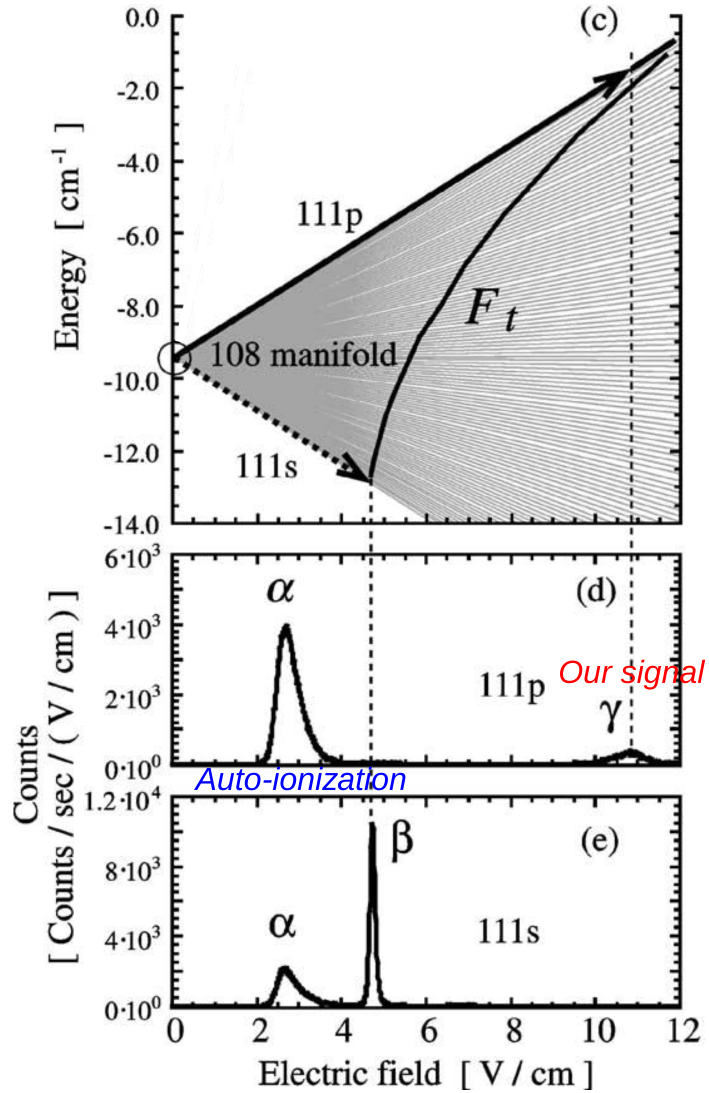
Phys. Lett. A **303**, 285 (2002)

- *Manifold state b/w s and p states*



108 manifold
b/w
111s and 111p

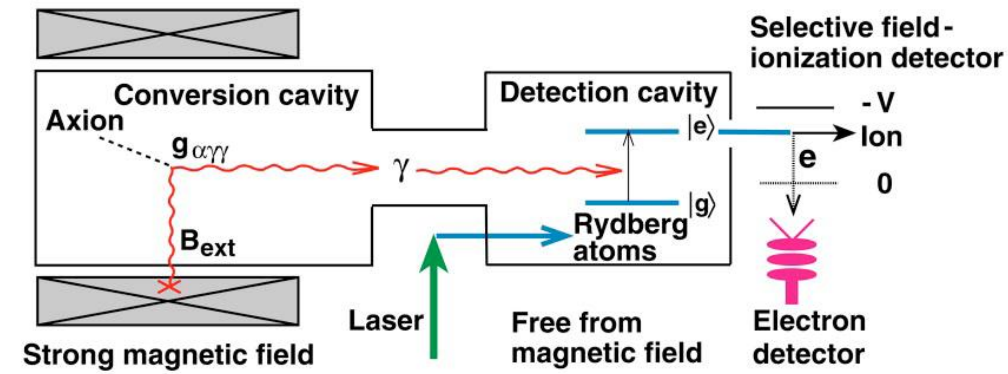


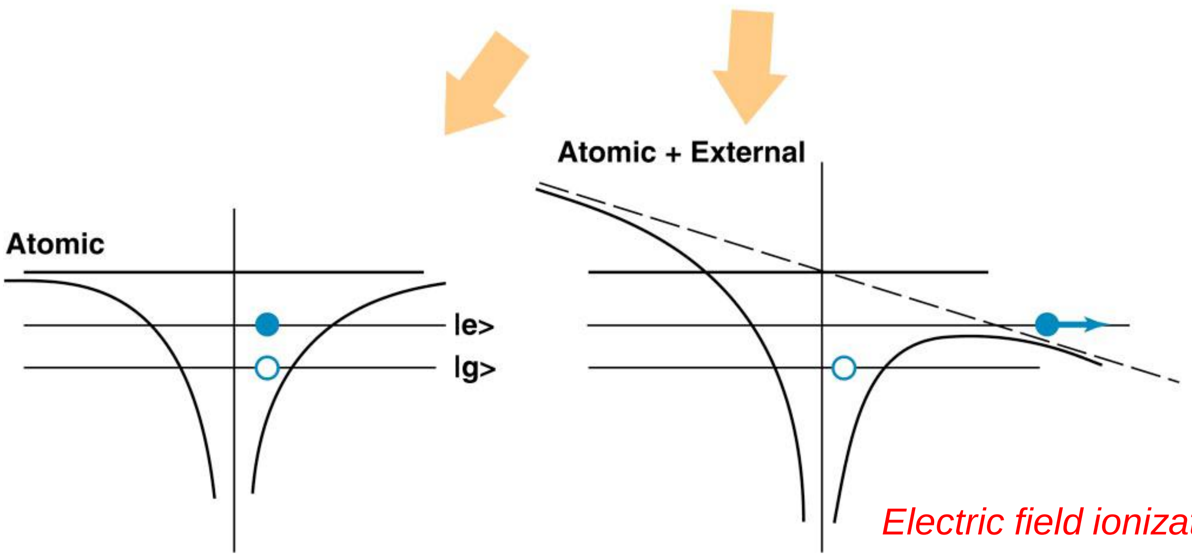


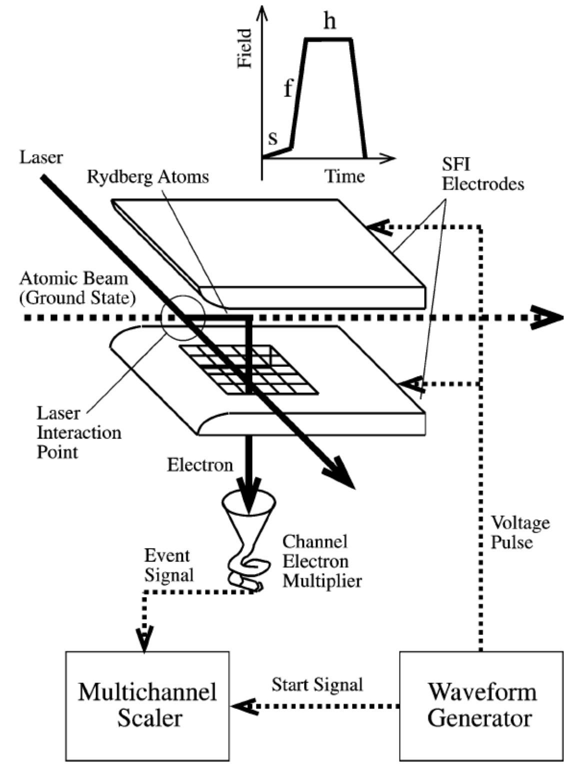
Rydberg atom cavity detector

- *CARRACK experiment*

Rev. Mod. Phys. ***75****, 777 (2003)*





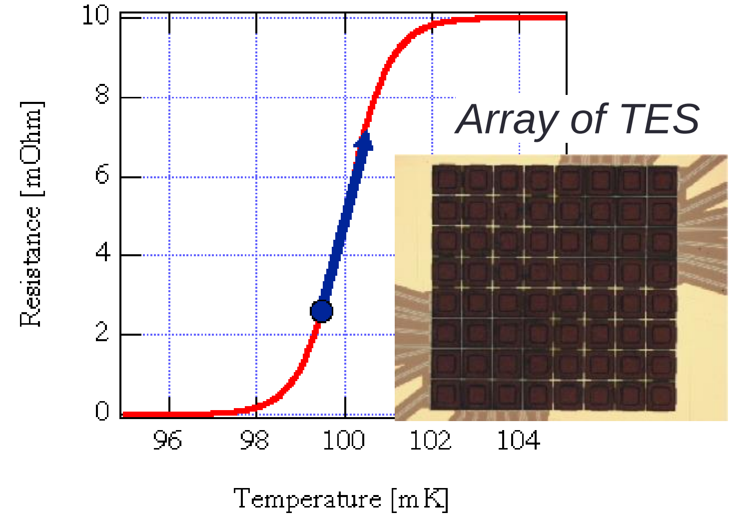


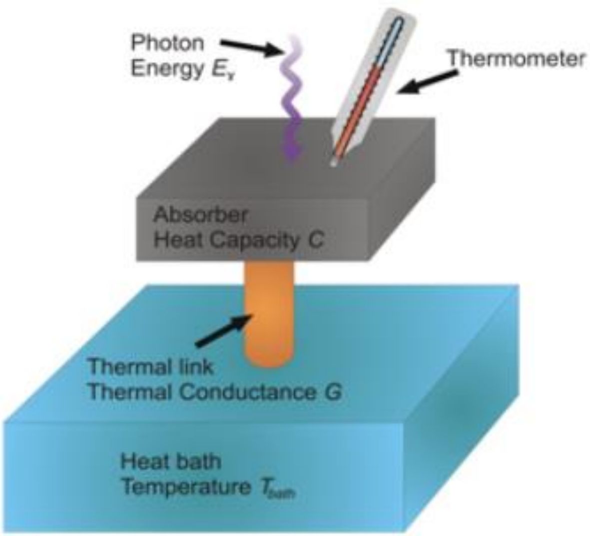
Electric field ionization

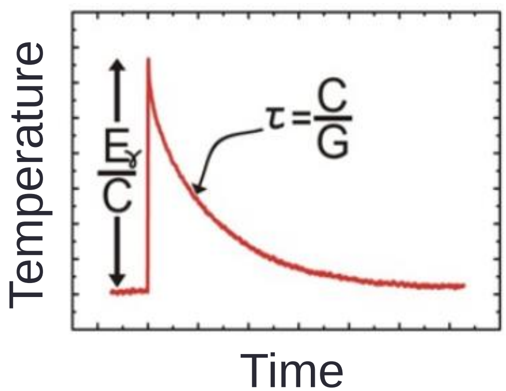
Bolometer

- *Thermal detector*
  - *No need to collect electron*
  - *Material with small heat capacity (C)*
  - *Large thermal conductance (G)*
  - *Fundamental limit by thermodynamics*

Transition Edge Sensor (TES)

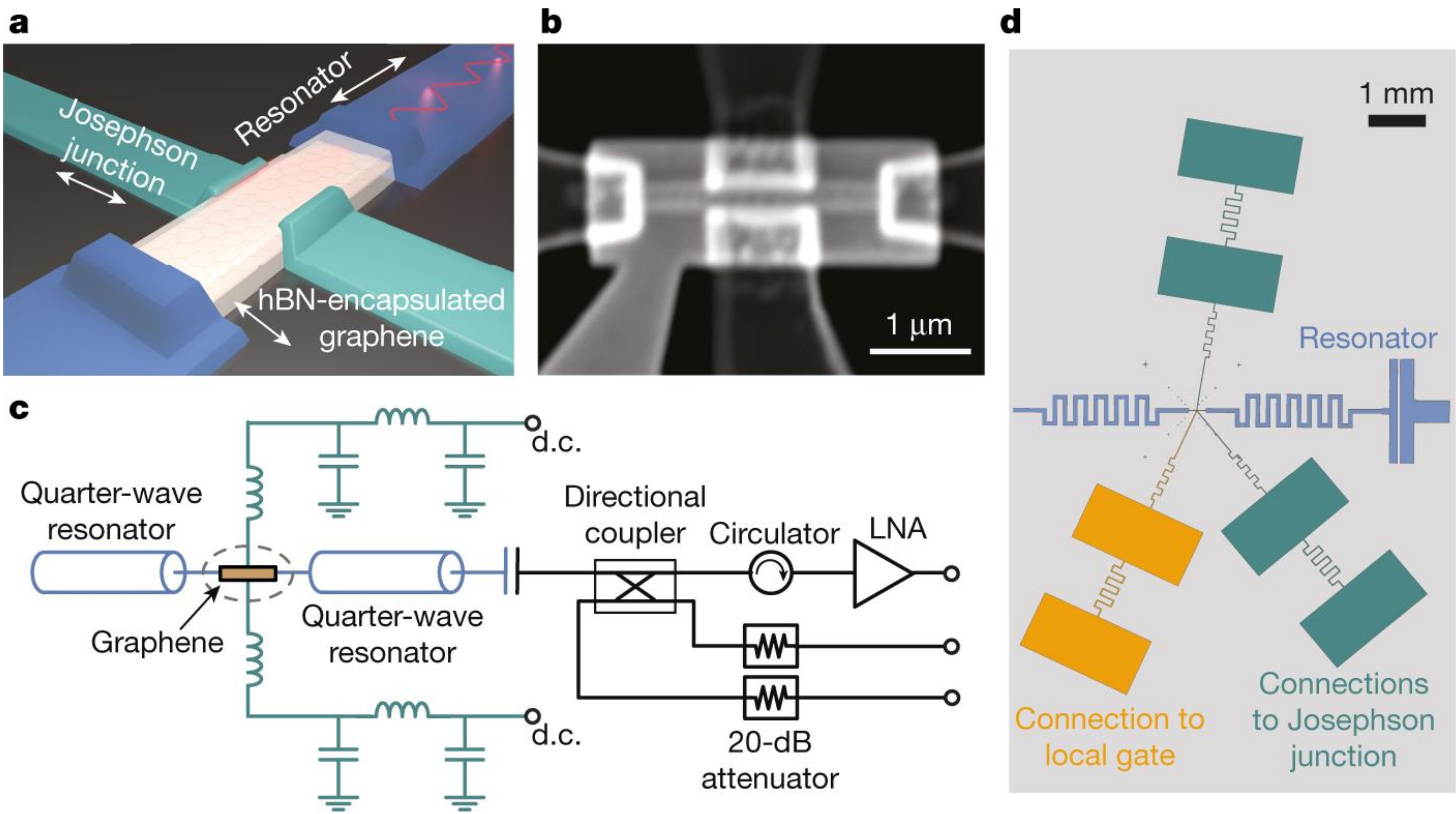






Graphene-based bolometer

Nature ***586***, *42 (2020)*



Summary

- *Axion is a hypothetical particle to address fundamental questions in physics*
  - *Strong CP problem & dark matter*
- *Axion is detectable in the form of microwave photons under strong magnetic field*
- *Various principles have been developed*
  - *Power detection*
    - *Linear amplifier, SQUID, JPA*
  - *Single photon detection*
    - *Qubit excitation / Rydberg atom*
  - *Thermal detection*
    - *Bolometer*
- *Photon detection in the microwave domain has a wide range of applications*

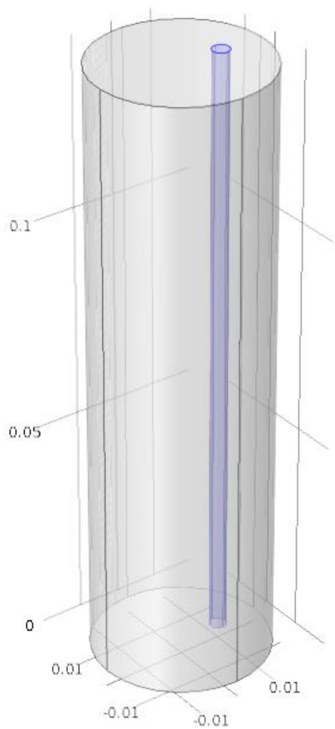
Thank you for your attention!

Frequency tuning

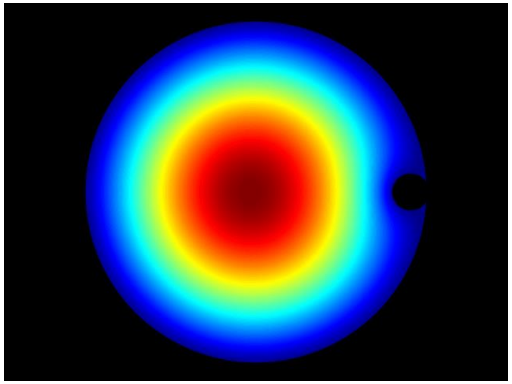
Cylindrical cavity

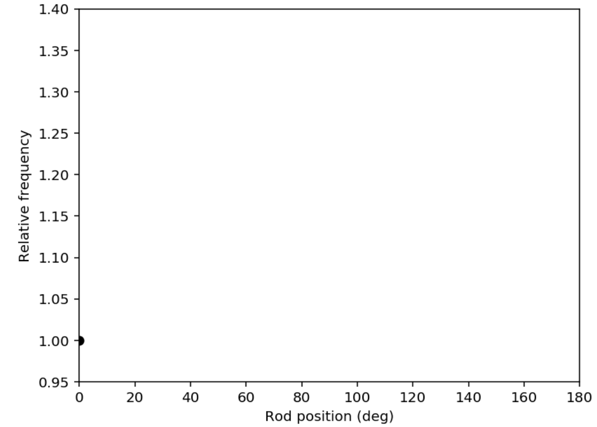
↓

Tuning rod(s)

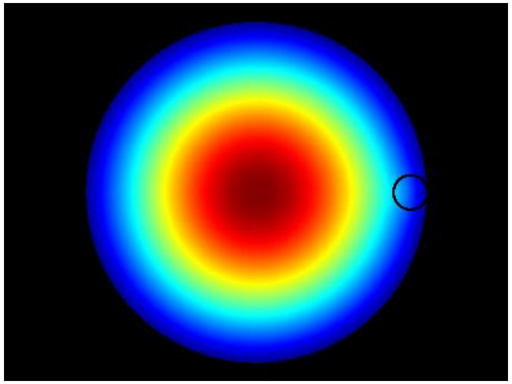


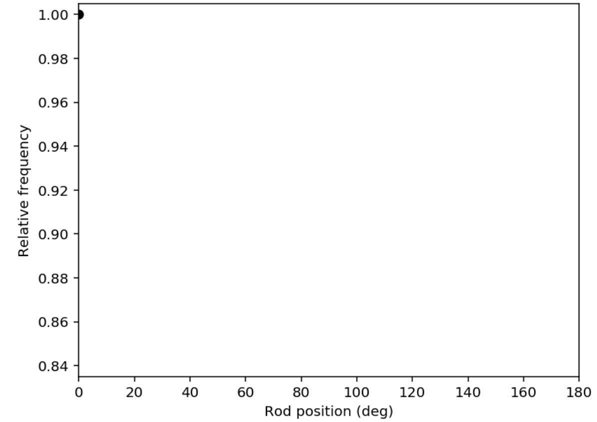
Conductor rod (TM_{010})





Dielectric rod (TM_{010})





Form factor

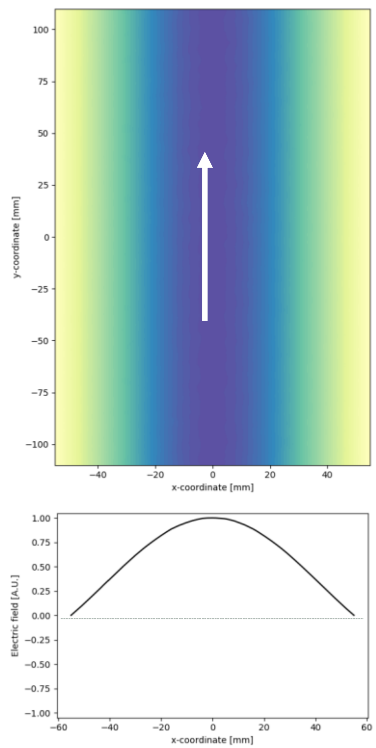
- *Geometry and mode dependent*
  - *Cavity mode and external field*

$$C_{mnp} = \frac{\left| \int \vec{E}_c \cdot \vec{B}_0 \, dV \right|^2}{\int \varepsilon \left| \vec{E}_c \right|^2 dV \int \left| \vec{B}_0 \right|^2 dV}$$

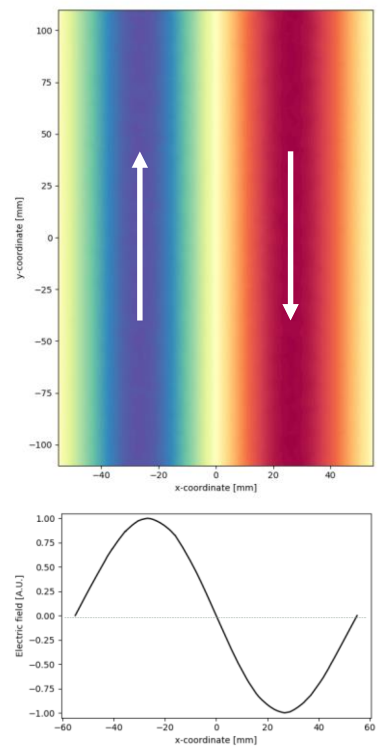
TM_{010} *TM_{110}*

E_c field

E_c profile



B_0



$C_{010} = 0.69$ $C_{110} = 0$

For cylindrical cavities
- *z-direction for TM modes*
- *φ-direction for TE modes*

TM_{010} mode
- *Maximum form factor*
- *Typical cavity mode for axion haloscopes*