SRF cavities and Superconducting qubits for Gravitational Waves and Dark Photons detection

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04/10/2022

OUTLINE

- **Gravitational Waves**
    - Theory
    - Gertsenshtein effect
    - Heterodyne experiment
    - Noise and Sensitivity

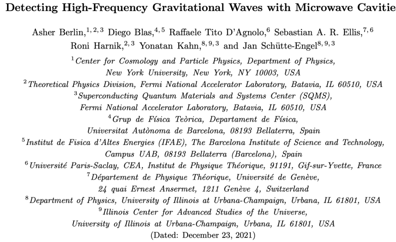
- **Dark Photons**
    - Theory
    - Dixit et al.'s experiment
    - Experiments of photons parity measurements at SQMS?

Preface

- This talk is mainly based on :

Sebastian Ellis, *Revisiting Gravitational Wave Detection in a SRF Cavity* (DESY-Talk, March 11, 2021)
Asher Berlin et al., *Detecting High-Frequency Gravitational Waves with Microwave Cavities* (2021)
Asher Berlin et al., *Axion Dark Matter Detection by Superconducting Resonant Frequency Conversion* (2019)
Asher Berlin et al., *Searches for New Particles, Dark Matter, and Gravitational Waves with SRF cavities* (2022)
Akash Dixit et al., *Searching for Dark Matter with a Superconducting Qubit* (2020)

… and ideas developed on the road in this two months



Detecting High-Frequency Gravitational Waves with Microwave Cavities

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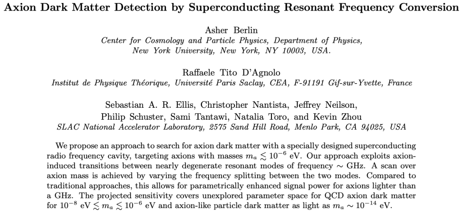
(Dated: December 23, 2021)



Axion Dark Matter Detection by Superconducting Resonant Frequency Conversion

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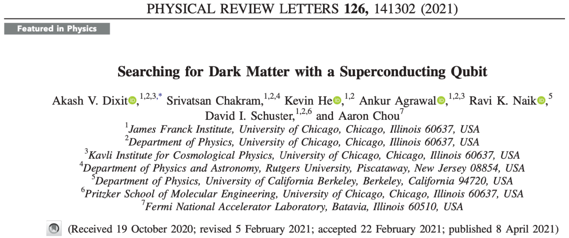
We propose an approach to search for axion dark matter with a specially designed superconducting radio frequency cavity, targeting axions with masses $m_a \lesssim 10^{-6}$ eV. Our approach exploits axion-induced transitions between nearly degenerate resonant modes of frequency $\sim$ GHz. A scan over axion mass is achieved by varying the frequency splitting between the two modes. Compared to traditional approaches, this allows for parametrically enhanced signal power for axions lighter than a GHz. The projected sensitivity covers unexplored parameter space for QCD axion dark matter for 10^{-8} eV $\lesssim m_a \lesssim 10^{-6}$ eV and axion-like particle dark matter as light as $m_a \sim 10^{-14}$ eV.



PHYSICAL REVIEW LETTERS **126,** 141302 (2021)

Featured in Physics

Searching for Dark Matter with a Superconducting Qubit

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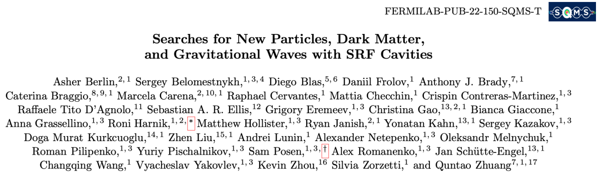
(Received 19 October 2020; revised 5 February 2021; accepted 22 February 2021; published 8 April 2021)



FERMILAB-PUB-22-150-SQMS-T

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

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Caterina Braggio,[8,9,1] Marcela Carena,[2,10,1] Raphael Cervantes,[1] Mattia Checchin,[1] Crispin Contreras-Martinez,[1,3]
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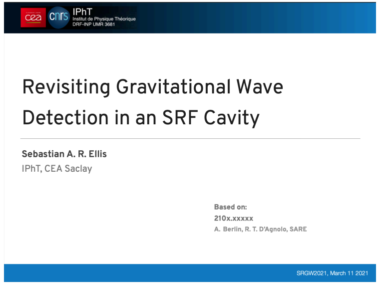


Revisiting Gravitational Wave
Detection in an SRF Cavity

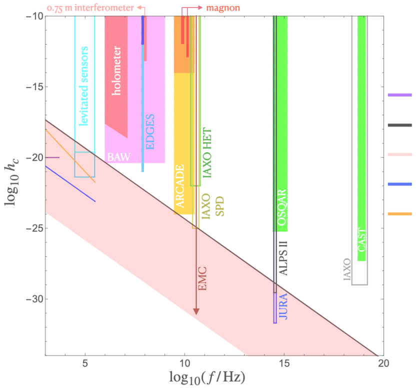
Sebastian A. R. Ellis
IPhT, CEA Saclay

Based on:
210x.xxxxx
A. Berlin, R. T. D'Agnolo, SARE

SRGW2021, March 11 2021

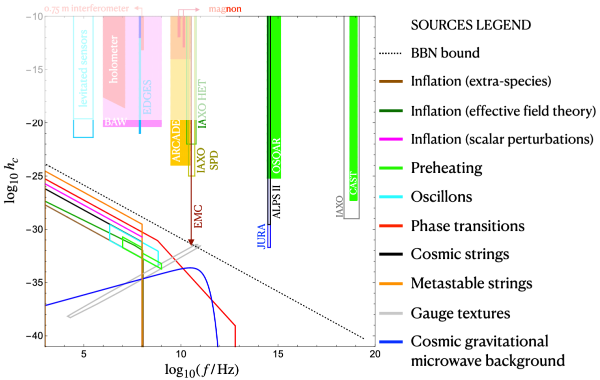
Gravitational Waves, a long story…

- Theorized by A. Einstein in the Theory of General Relativity, 1915.
- First observation by LIGO and Virgo in the regime of Hz-kHz, 2016.



Coherent

Stocastic



- The Universe is expected to be populated by GW over decades in frequency.

➡ Development of RF cavities for GW detection to explore a larger regime of frequencies. *Pegorato et al. (1978)*.

- In the last few years, Superconducting RF cavities for GW and Dark Matter detection. *Berlin et al.*

Gravitational Waves - Theory

The *linearized theory* of GR is invariant under the Poincaré group

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad\qquad |h_{\mu\nu}| \ll 1$$

Einstein equations :

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

➡

GW equation of motion :

$$\begin{cases} \Box \bar{h}_{\mu\nu} = -\dfrac{16\pi G}{c^4} T_{\mu\nu} \\ \partial^\nu \bar{h}_{\mu\nu} = 0 \quad \text{(Lorentz gauge)} \end{cases}$$

A GW can most easily described in the TT-gauge :

$$\partial_\mu h^{\mu\nu} = 0, \quad h_\mu^{\ \mu} = 0, \quad h_{00} = h_{0i} = 0$$

$$R_{0i0j} = -\frac{1}{2} \ddot{h}_{ij}^{TT}$$

$$h_{\mu\nu}^{TT} = H_{\mu\nu} e^{i\omega(t-z)}, \qquad H_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Monochromatic
GW in z-direction

Gravitational Waves - Theory

Electromagnetism in presence of gravity : $\partial_\mu \rightarrow \nabla_\mu$

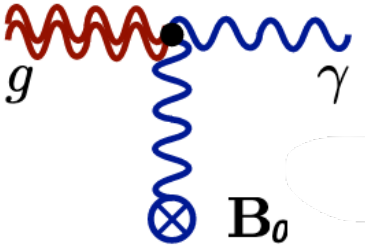
$$\begin{cases}\nabla_\mu F^{\mu\nu} = -\dfrac{4\pi}{c}J^\nu \\ \nabla_{[\mu}F_{\nu\rho]} = 0\end{cases} \longrightarrow \partial_\mu F^{\mu\nu} \simeq J^\nu\left(1+\frac{h_\alpha^{\ \alpha}}{2}\right) - h^{\nu\alpha}J_\alpha + \frac{\partial_\mu\left(h_\alpha^{\ \alpha}F^{\mu\nu}\right)}{2} +$$

$$+\partial_\mu(h^{\mu\alpha}F^\nu_{\ \alpha} + h^{\nu\alpha}F_\alpha^{\ \mu})$$

A variation of metric (GWs) acts as EM sources

- GR-EM interaction is encapsulated in the Einstein-Hilbert action :

$$\mathcal{S} = -\frac{1}{4}\int d^4x\sqrt{-g}\,g^{\mu\alpha}g^{\nu\beta}F_{\mu\nu}F_{\alpha\beta} \propto \int hF^2 \xrightarrow[\text{Inverse-Gertsenshtein effect}]{}$$



$$\sim h\vec{B}\cdot\vec{B}_0$$

Gertsenshtein effect, a classical interpretation

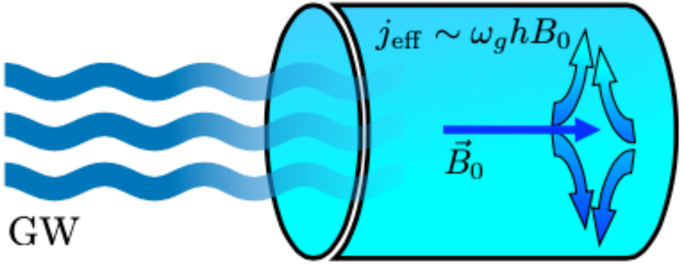
- Formalism of *effective* current

$$\mathcal{S}[\mathcal{O}(h)] = -\frac{1}{2}\int d^4x\, j^\mu_{\rm eff} A_\mu$$

$$j^\mu_{\rm eff} \equiv \partial_\nu \left(\frac{1}{2} h F^{\mu\nu} + h^\nu{}_\alpha F^{\alpha\mu} - h^\mu{}_\alpha F^{\alpha\nu}\right)$$

(not invariant under gauge transf.)

$$\boxed{L_{det} \sim 1/\omega_g}$$



GW - cavity interaction

- Direct interaction : inverse-Gertsenshtein effect
- Indirect or mechanical interaction : GW perturbs the cavity wall, $\omega_0 \sim \mathcal{O}(1)/L_{det}$

- GW is on-resonant with an eigenmode of the cavity and couples to a static B-field
- Good method to detect high-frequency GW, $f \sim \mathcal{O}(GHz)$
- Method already established in ADMX

Gertsenshtein effect - electromagnetic interaction

- Coupling of GW to electromagnetic field can be described in weak field limit by

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}j^{\mu}_{\text{eff}}A_{\mu}$$

- The GW inducted current was given by $j^{\mu}_{\text{eff}} \equiv \partial_{\nu}\left(\frac{1}{2}hF^{\mu\nu} + h^{\nu}{}_{\alpha}F^{\alpha\mu} - h^{\mu}{}_{\alpha}F^{\alpha\nu}\right)$

- We define a normalized current $\vec{j}_{+,\times}$ as $\vec{j}_{\text{eff}}(\vec{x}) := B_0\omega_g^2V_{cav}^{1/3}\left(h_+\vec{j}_+(\vec{x}) + h_\times\vec{j}_\times(\vec{x})\right)$

- A GW on resonant with a cavity mode $\vec{E}_n$ induces a signal

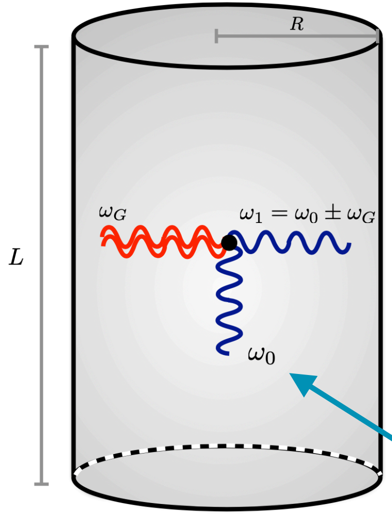
$$\boxed{P_{sig} = \frac{1}{2}Q\omega_g^3V_{cav}^{5/3}(\eta_n h_0 B_0)^2}$$

$$h_0 = h_+ \text{ or } h_\times$$

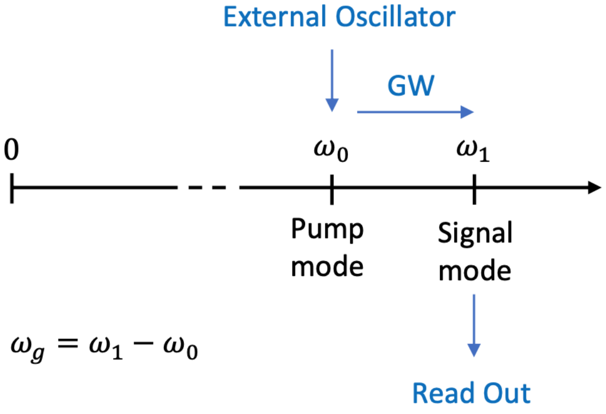
$$\eta_n \equiv \frac{\left|\int_V d^3\mathbf{x}\mathbf{E}_n^* \cdot \hat{\mathbf{j}}_{+,\times}\right|}{V^{1/2}(\int_V d^3\mathbf{x}\,|\,\mathbf{E}_n\,|^2)^{1/2}}$$

Heterodyne experiments

- The GW is on-resonant with the frequency difference of two cavity modes and couples to both E- and B- field.



Cylinder for illustrative purposes only!



$\omega_g = \omega_1 - \omega_0$

Resonant B-field in the cavity

- $\omega_0 \sim \mathcal{O}(\mathrm{GHz})$
- $Q_{int} \simeq 10^9 \div 10^{12}$
- Tunability $\delta\omega \sim$ MHz

The effect of $\overrightarrow{B}_{sig}$ are different depending on the $\overrightarrow{B}_0$:

$$\Delta B_{\mathrm{sig}} \sim h B_0 \sqrt{Q} \min\left[\frac{\omega_g^2}{\omega_0^2}, 1\right] \quad \text{(oscill)}$$

$$\Delta B_{\mathrm{sig}} \sim h B_0 \sqrt{Q} \min\left[\frac{\omega_g^2}{\omega_0^2}\frac{\omega_g}{\omega_0}, 1\right] \quad \text{(static)}$$

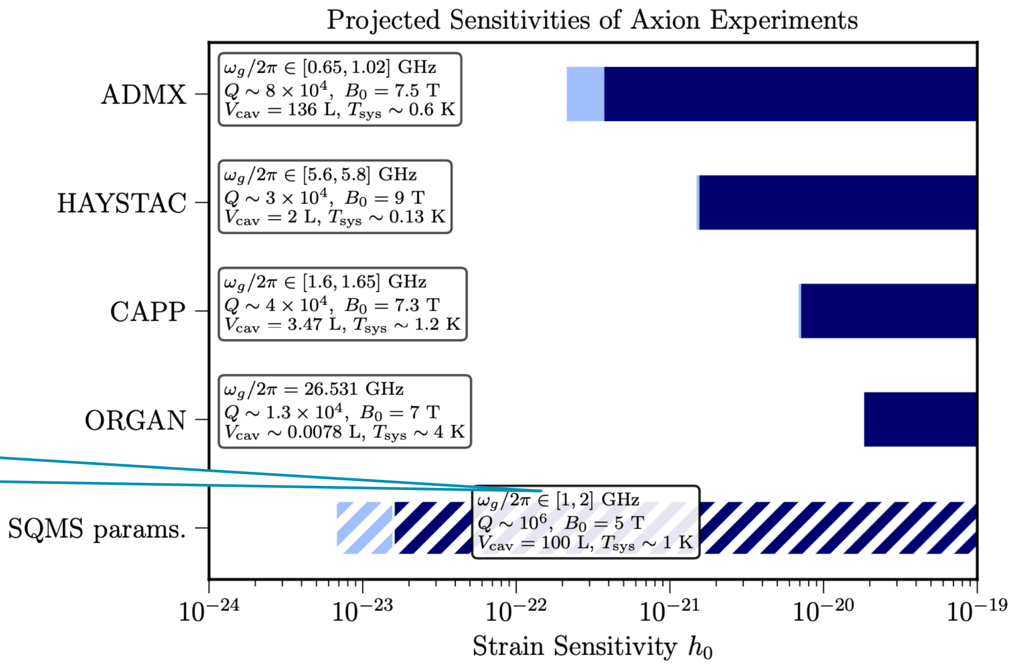
High Frequency Sensitivity

- Estimation of the the projected sensitivity of axion cavity haloscope experiments to high-frequency coherent gravitational waves.

$$\omega_g/2\pi \in [1, 2]\ \text{GHz}$$

$$Q \sim 10^6 \qquad B_0 = 5\ \text{T}$$

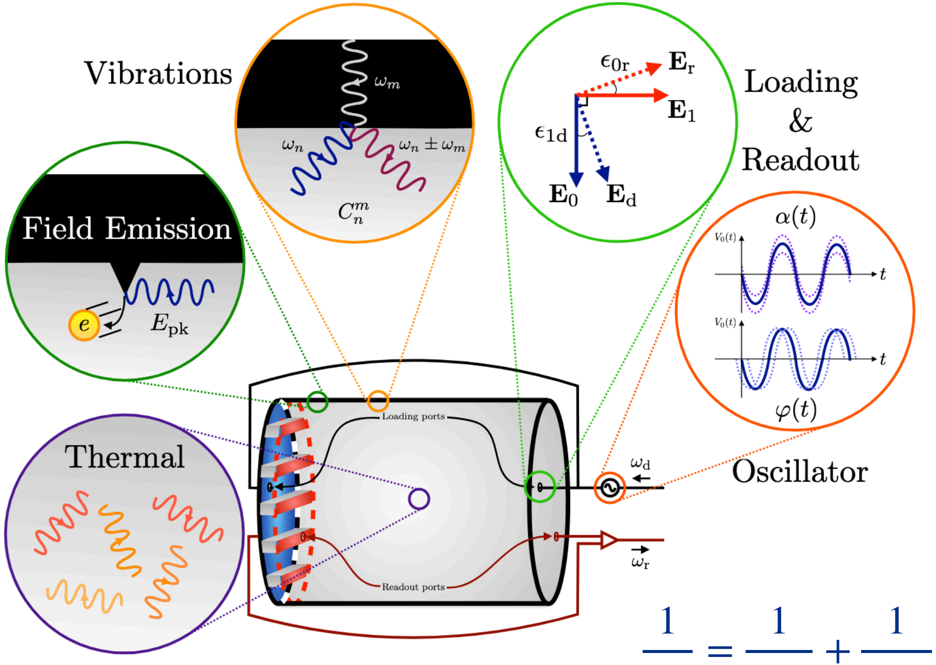
$$V_{cav} = 100\ \text{L} \quad T_{sys} \sim 1\ \text{K}$$



A.Berlin et al.

Noise sources

- Advantage of heterodyne setup: noise sources are well investigated



$$\frac{1}{Q_1} = \frac{1}{Q_{int}} + \frac{1}{Q_{cpl}}$$

- Every noise sources drives additional power into the signal mode described by PSD.

- Thermal Noise (cavity walls):

$$S_{th}(\omega) = \frac{Q_1}{Q_{int}} \frac{4\pi T k_B (\omega\omega_1/Q_1)^2}{(\omega^2 - \omega_1^2)^2 + (\omega\omega_1/Q_1)^2}$$

- Amplifier Noise:

$$S_{ql}(\omega) = 4\pi\hbar\omega_1$$

Noise sources

- Phase Noise (Oscillator):

$$S_{\text{phase}}(\omega) \simeq \frac{1}{2}\epsilon_{\text{1d}}^2 \underbrace{S_\phi(\omega-\omega_0)}_{\text{Input Oscillator}} \underbrace{\frac{(\omega\omega_1/Q_1)^2}{(\omega^2-\omega_1^2)^2+(\omega\omega_1/Q_1)^2}}_{\text{Cavity response (B-W)}} \underbrace{\frac{\omega_0 Q_1}{\omega_0 Q_0}P_{\text{in}}}_{\text{Overall Normalization}}$$

- Mechanical Noise :

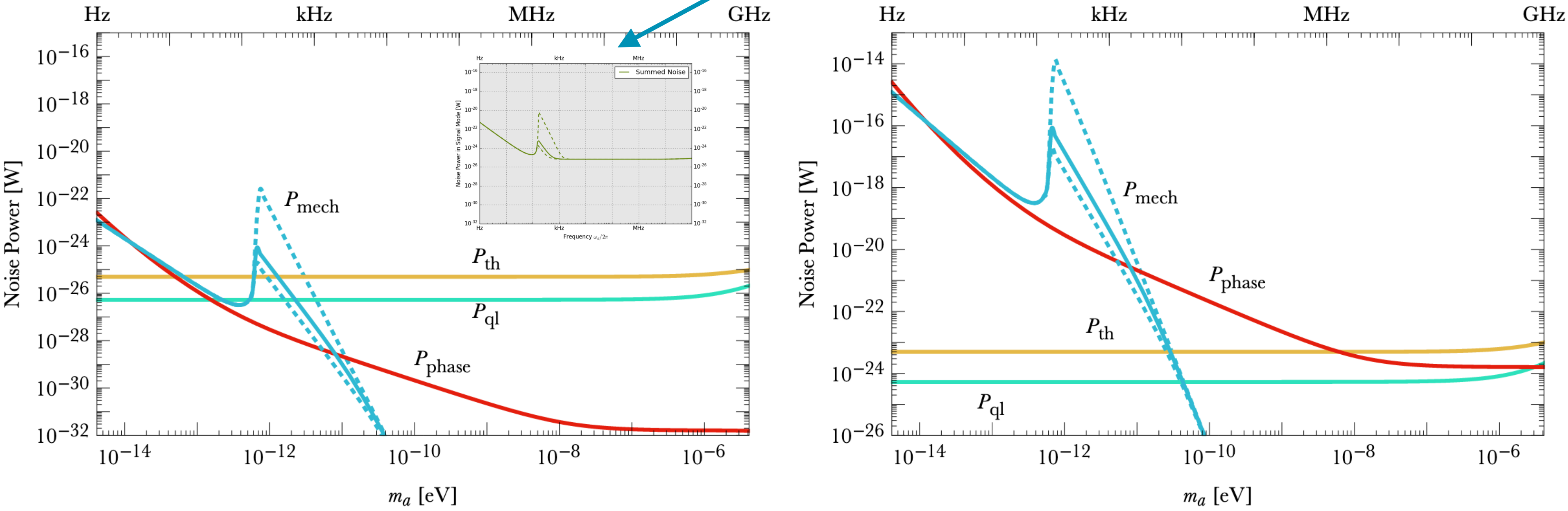
$$S_{\text{mech}}(\omega) = \sum_{n=0,1} S^{(n)}_{\text{mech}}(\omega) \simeq \frac{\epsilon_{\text{1d}}^2}{4}\frac{\omega_0}{Q_0}P_{\text{in}} \sum_{n=0,1} \underbrace{\frac{(\overbrace{S_{q_m}(\omega-\omega_0)}^{\text{Wall Displacement}}/V^{2/3})(\omega_n/Q_n)\omega_n^4\omega^2}{\left[(\omega^2-\omega_n^2)^2+(\omega\omega_n/Q_n)^2\right]\left[(\omega_0^2-\omega_n^2)^2+(\omega_0\omega_n/Q_n)^2\right]}}_{\text{CavityResponse}}$$

- All PSDs can be summed up

$$\boxed{S_{noise}(\omega) = S_{ql}(\omega) + \frac{Q_1}{Q_{cpl}}\left(S_{th}(\omega) + S_{phase}(\omega) + S^{(1)}_{mech}(\omega)\right) + \frac{Q_0}{Q_{cpl}}S^{(0)}_{mech}(\omega)}$$

Plot of different noises

Summed PSDs of noises



(a) $\epsilon_{\rm 1d} = 10^{-7}$, $Q_{\rm int} = 10^{12}$

(b) $\epsilon_{\rm 1d} = 10^{-5}$, $Q_{\rm int} = 10^{10}$

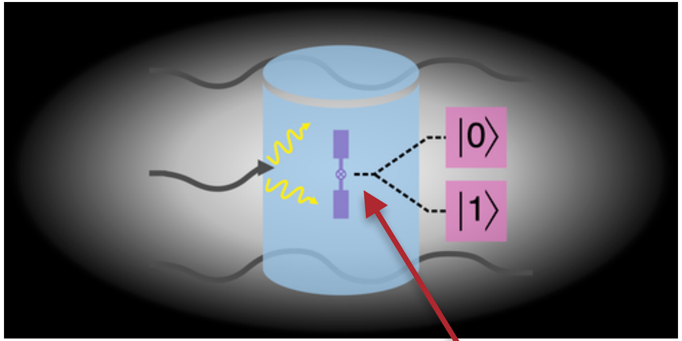
Quantum Sensors for GW: Cavity-qubit system and Squbit ††

- **Cavity-qubit system** : the suggestion is that

$$\mathrm{SNR} \rightarrow \mathrm{SNR} \times \sqrt{\frac{T_{cav}}{T_R}}$$

$$|\psi\rangle = |g\rangle|1\rangle + |e\rangle|0\rangle$$

Problem : not enough sensitivity in phase's measurements



readout on qubit

- **Squbit - GW** : draft idea is to to find a mapping between the spinor field of the QED in the chiral representation and the two level states of the qubit.

$$\psi = \begin{pmatrix} \psi_R \\ \psi_L \end{pmatrix} \qquad \psi_R \mapsto |0\rangle, \psi_L \mapsto |1\rangle$$

†† ultra-preliminary

Quantum Sensors for GW: Cavity-qubit system and Squbit ††

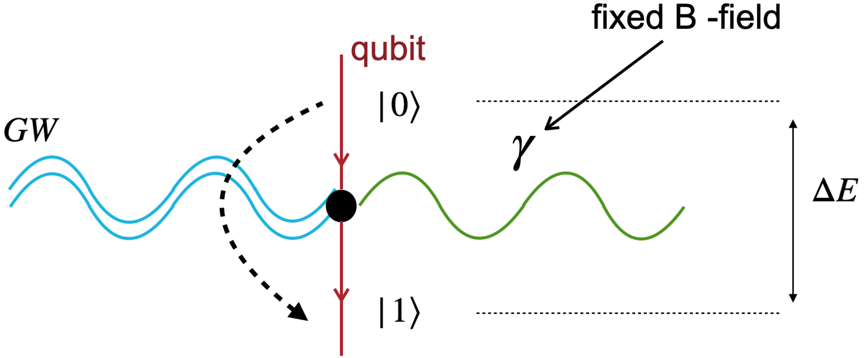
- **Squbit - GW**

$$\mathcal{L}^{QED}_{dip,int} = \Lambda\bar{\psi}\sigma^{\mu\nu}\gamma^5\psi F_{\mu\nu} = \Lambda(\psi_R^\dagger,\psi_L^\dagger)\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}\sigma^{\mu\nu}\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}\begin{pmatrix}\psi_R\\ \psi_L\end{pmatrix}F_{\mu\nu}$$

$$= \Lambda(\psi_L^\dagger,\psi_R^\dagger)\sigma^{\mu\nu}\begin{pmatrix}\psi_R\\ -\psi_L\end{pmatrix}\eta_{\mu\alpha}h_{\nu\beta}F^{\alpha\beta} + \ldots \propto \Lambda(\psi_L^\dagger\psi_R - \psi_R^\dagger\psi_L)\eta_{\mu\alpha}h_{\nu\beta}F^{\alpha\beta}$$

$$\sigma^\mu = (1,\sigma^i)$$

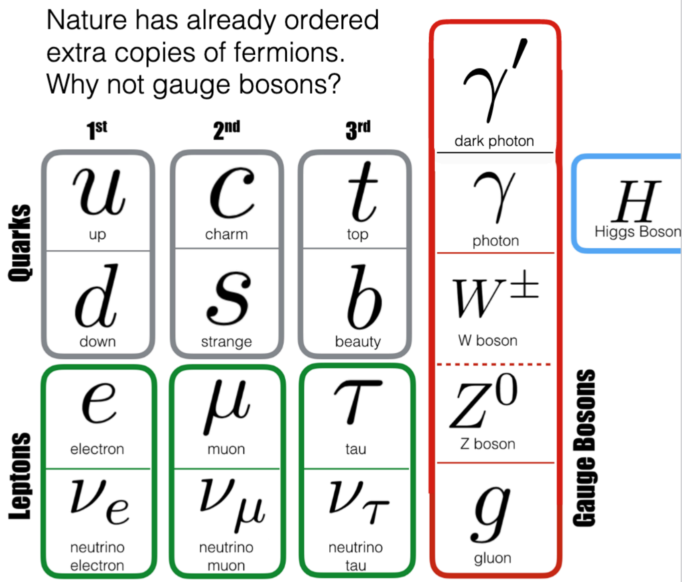
$$\sigma^{\mu\nu} = \frac{i}{2}(\bar{\sigma}^\mu\sigma^\nu - \bar{\sigma}^\nu\sigma^\mu)$$



†† ultra-preliminary

Dark Photons

- It is a *massive* photon m_{df}, a gauge boson of $\mathbf{U(1)}$ symmetry.
- Group symmetry of extended SM : $SU(3) \times SU(2) \times U(1) \times \mathbf{U(1)}$
- Any heavy particle that is charged, both photons will generate mixing.


Nature has already ordered extra copies of fermions. Why not gauge bosons?


$\supset$ **dark photons?**

$\rho_{DM} \simeq 0.4\ \text{GeV/cm}^3$

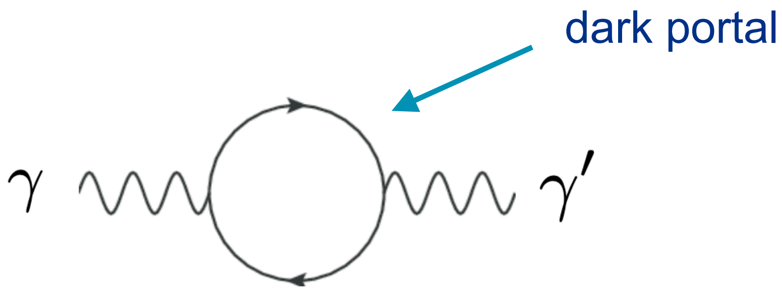
- The only renormalizable interaction between the dark and visible photons that we can construct is the *kinetic mixing* term.

Dark Photons

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu + \epsilon F^{\mu\nu}F'_{\mu\nu} \supset \epsilon(\vec{E}\cdot\vec{E}' + \vec{B}\cdot\vec{B}')$$

$$\mathcal{L}_{int} \propto -e\epsilon J^{EM}_\mu A'^\mu$$

(kinetic mixing)

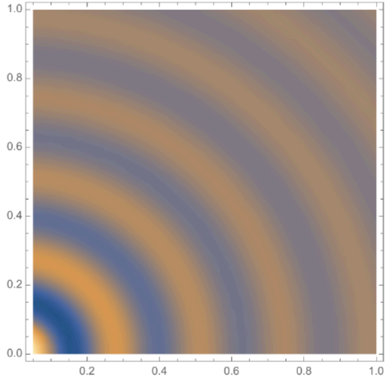


An oscillating EM field is a source of dark photons, and vice versa.

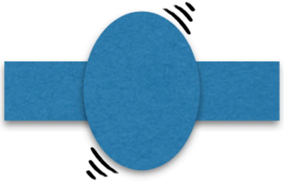
There are two different kind of experiment for dark photon search

- Light-shining-through a wall: Dark SRF
- Parity measurement of photons number in a SRF cavity : Dixit Experiment

Dark SRF : the first simple setup

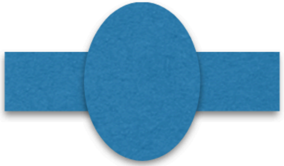


a dark photon field is radiated at 1.3 GHz.



Emitter Cavity

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



Receiver Cavity

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

Dixit et al.’s experiment

- **Setup**: cavity-quibit system for parity measurements of photons number.
- **Qubit-based photon counter** : QND techniques.

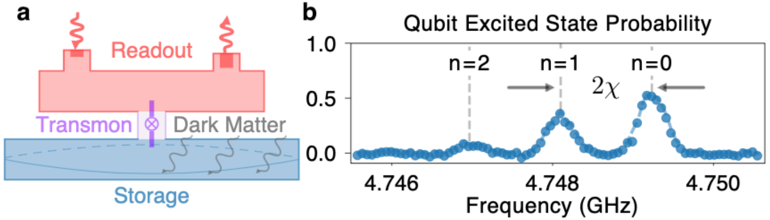
$$H/\hbar \overset{g \ll \Delta}{\simeq} \omega_c a^\dagger a + \frac{1}{2}(\omega_q + 2\chi a^\dagger a)\sigma_z$$

Frequency qubit shift

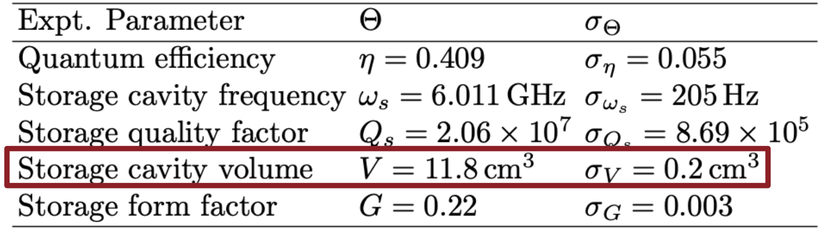
$$\hat{n} = a^\dagger a$$

$$\bar{n} \ll 1 \quad \Rightarrow \quad n = 0, 1$$

Ramsey measurements



$$\hbar\omega_c = m_{df} c^2$$



Expt. Parameter	Θ	σ_Θ
Quantum efficiency	$\eta = 0.409$	$\sigma_\eta = 0.055$
Storage cavity frequency	$\omega_s = 6.011\,\mathrm{GHz}$	$\sigma_{\omega_s} = 205\,\mathrm{Hz}$
Storage quality factor	$Q_s = 2.06 \times 10^7$	$\sigma_{Q_s} = 8.69 \times 10^5$
Storage cavity volume	$V = 11.8\,\mathrm{cm}^3$	$\sigma_V = 0.2\,\mathrm{cm}^3$
Storage form factor	$G = 0.22$	$\sigma_G = 0.003$

(1) We go to the *rotating* ω_q*- frame*

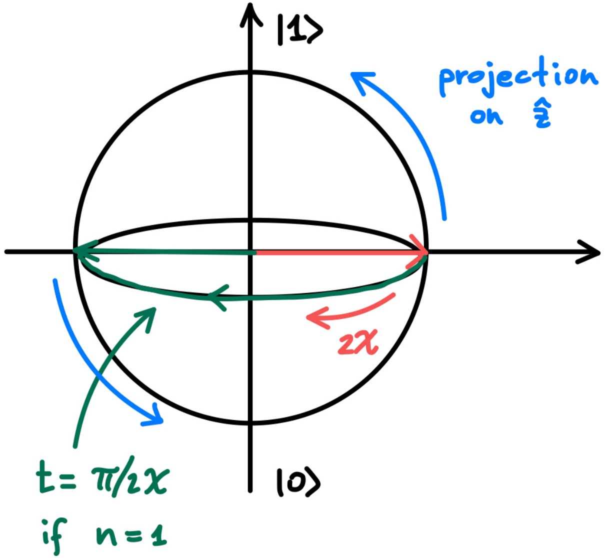
$$|g\rangle \; or \; |e\rangle \xrightarrow[\pi/2 - pulse]{} \frac{|g\rangle + |e\rangle}{\sqrt{2}}$$

precedes with a frequency $|2\chi|$ if there is one photon.

Dixit et al.'s experiment

(2) if there is the photon, after a time $t = \pi/2\chi$ the state was flipped in the plane.

(3) we make a projection on $\hat{z}$ axis, with a $-\pi/2$ pulse.



If there are zero photons in the cavity, the qubit remains in its initial state. If there is one photon in the cavity, the qubit state is flipped ($|g\rangle \leftrightarrow |e\rangle$).

$$V = 11.8\ cm^3$$

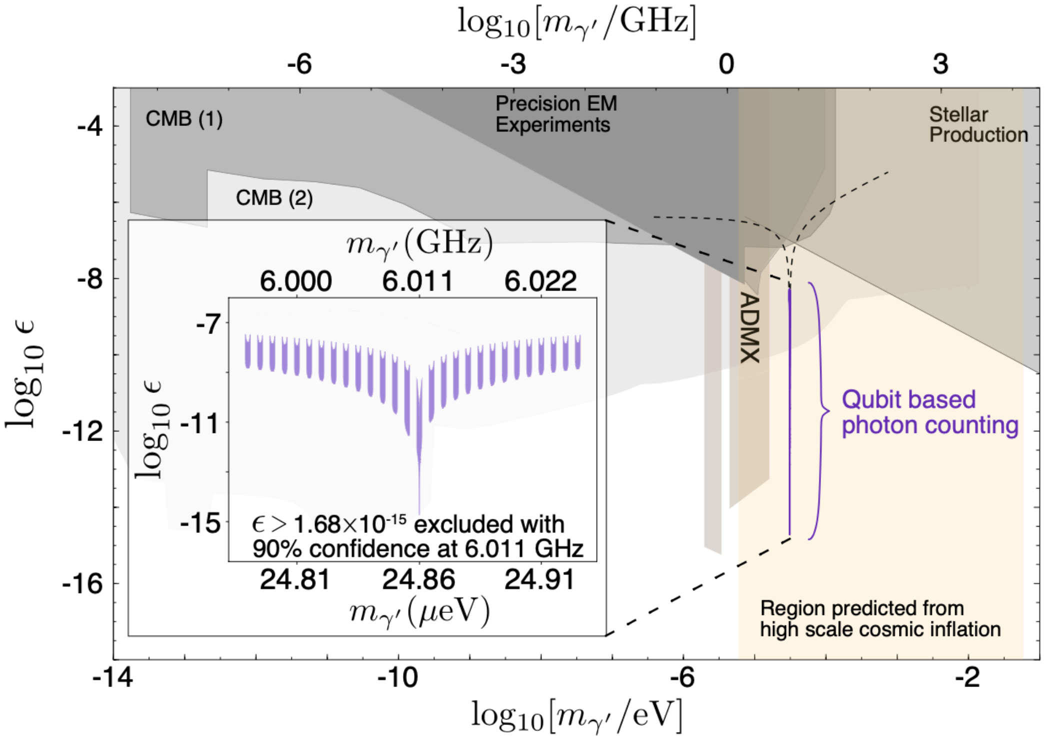
$$\rho_{DM} \simeq 0.4\ GeV/cm^3$$

$$n_{df} \simeq \rho_{DM}/m_{df} \ \Rightarrow\ N_{df} \simeq n_{df} \cdot V \simeq \left(\frac{0.4\ GeV}{cm^3}\right) \times \left(\frac{1}{\mu eV}\right) \times 11.8\ cm^3 \simeq 10^{15}$$

Dixit et al.’s experiment

The experiment has excluded dark photon candidates with mass centred around $m_{df} \sim 24.86\ \mu eV\ (6.011\ \mathrm{GHz})$ and $\epsilon \geq 1.68 \times 10^{-15}$ by using a superconducting qubit to repeatedly measure the same photon.

Integration time : $T_1^s = 8.33\ s$



What about using Fock states of photons?

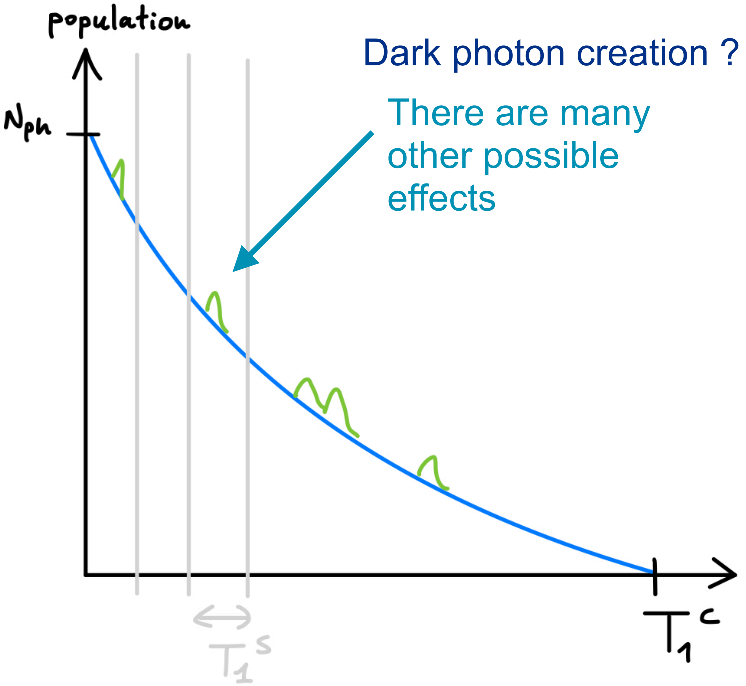
- We prepare the cavity with a N_{ph} photons (Fock state).
- After an amount of time T_1^c the photons population is expected to go to zero.
- We can do $\simeq T_1^c / T_1^s$ parity measurements.

Hold on…is there an advantage using this protocol?

$$\frac{df_\gamma}{dt} = \Gamma_{\gamma' \to \gamma}(1 + f_\gamma) - \Gamma_{\gamma \to \gamma'}(1 + f_{\gamma'})$$

$$\propto f_{\gamma'}(1 + f_\gamma) - f_\gamma(1 + f_{\gamma'})$$

$$= f_{\gamma'} - f_\gamma \simeq f_{\gamma'}$$



Dark photon creation ?

There are many other possible effects

$N_{df} \gg N_{ph}$ $\Longrightarrow$ **Answer: NO**

Conclusion and next steps…

Gravitational Waves

- More studies to understand is the cavity-quibit system can have an advantage in the sensitivity
- Theoretical work: understand the qubit-GW interaction. It means to unify linearized GR with quantum formalism of qubit.

Dark Photons

- No advantage in using Multiphotons Fock states.
- Reproduce the Dixit experiment : use SQMS cavities of different sizes to explore a larger regime of m_{df}. The biggest cavity has a volume of $209.367\ cm^3$, i.e. a resonant frequency of $\simeq 3\ GHz \ \Rightarrow \ N_{df} \simeq 10^{17}$.

Thank you for listening !

Special thanks to S. Zorzetti, A. Grassellino, R. Harnik, A. Berlin and especially to 5 SAUK ◎

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