Simultaneous Resonant and Broadband Detection via Cavities and Circuits

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Quantum Sensing meets
Ultra-high Frequency Gravitational Waves

Electromagnetic Detection of Ultralight Bosons and HFGW

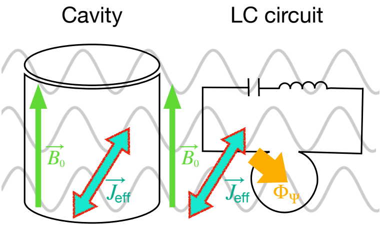
$\vec{J}_{\rm eff}$ in a cavity or shield room: $\Box \vec{A} = \vec{J}_{\rm eff}$.

Dark photon A':
$\vec{J}_{\rm eff} = \epsilon\, m_{A'}^2 \vec{A}'$;
No background field.

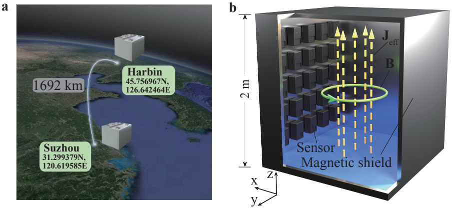
Axion a:
$\vec{J}_{\rm eff} = g_{a\gamma} \vec{B}_0 \partial_t a$;
Background $\vec{B}_0$.

GW h:
$\vec{J}_{\rm eff} \sim \partial (h\, F_0)$;
Background $\vec{E}_0$ or $\vec{B}_0$.

- **Resonant cavity**: $\omega_{\rm rf} \sim \omega_{J_{\rm eff}}$.
- **Circuit/magnetometer**: $B \sim |\vec{J}_{\rm eff} V^{1/3}|$ from $\vec{J}_{\rm eff}$ where $1/\omega_{J_{\rm eff}} \gg V^{1/3}$.



e.g. ADMX, HAYSTAC, CAPP, ORGAN, DM radio...

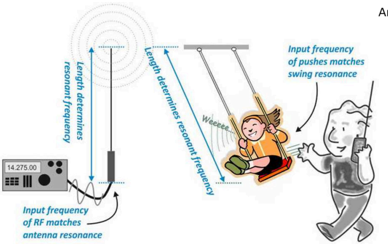


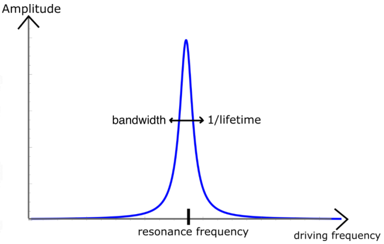
[Jiang et al, Nature Commun, 2305.00890]

Electromagnetic Single-Mode Resonator

- **Resonator**: significant response to signal at narrow bandwidth.

  Trade-off between peak response and bandwidth.





  e.g. cavity or circuit for capturing $\vec{J}_{\rm eff}$.

- Require **multiple scans** to cover ultralight dark matter mass window;
- Challenge for **transient** high-frequency gravitational wave sources.

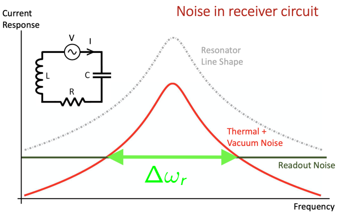
Standard Quantum Limit for Resonant Detection

- **Power law detection**:

Noise PSD: resonant intrinsic noise $S_{\rm int} \propto kT$ + flat readout noise $S_{\rm r} \sim \hbar\omega$.

- Responses to $S_{\rm sig}$ and $S_{\rm int}$ are the same.

  Scan rate $\propto \Delta\omega_r$ within which $S_{\rm int} \gg S_{\rm r}$.



$S_{\rm int} \propto$ Cauchy distribution

- **Standard quantum limit**: [Chaudhuri et al 18']

  Optimizing readout coupling $Q_{\rm cpl}$:

  $\beta \equiv Q_0/Q_{\rm cpl} = 2$ for quantum-noise limited $kT \ll \hbar\omega$ [Krauss et al 85'].

  $\beta \approx 2n_{\rm occ}$ for $n_{\rm occ} \approx kT/(\hbar\omega) \gg 1$ and $\Delta\omega_r \propto n_{\rm occ}$ [e.g., Chaudhuri et al 18', Berlin et al 19'].

Beyond Standard Quantum Limit

- **Power law detection**:

Noise PSD: resonant intrinsic noise $S_{\rm int} \propto kT$ + flat readout noise $S_{\rm r} \sim \hbar\omega$.

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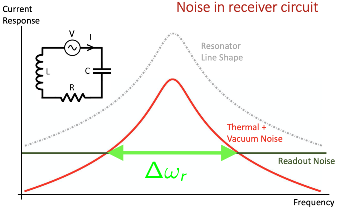

$S_{\rm int} \propto$ Cauchy distribution

- **Beyond standard quantum limit**:

  Squeezing $S_{\rm r}$, e.g., HAYSTAC Phase II.

  Increasing the sensitivity to $S_{\rm sig}$, e.g., white light cavity in optomechanics/GW detection [Miao et al 15'].

  Qubit.

White Light Optical-Cavity [Wicht et al 97']

Full length article

White-light cavities, atomic phase coherence, and gravitational wave detectors

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Abstract

We propose a new concept to realize optical cavities with large buildup but broadband response (*white-light cavities*) using atomic phase coherence. We demonstrate that strongly driven double-Λ systems can show negative dispersion without absorption, which is needed in order to compensate for the variation of the wavelength with frequency. Internal buildup profiles and the cavity bandwidth of standard devices and *white-light cavities* will be briefly compared. These devices may be useful to improve the bandwidth and sensitivity of future generations of laser interferometric gravitational wave detectors.

PACS: 07.60.Ly; 42.50.Ar; 95.30.SF
Keywords: Atomic phase coherence; Gravitational wave detector; White-light cavity; Negative dispersion; Vanishing absorption; Four-level system

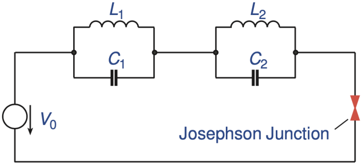
- Negative dispersion medium cancels the frequency-dependent **phase shift**:

  Achieves simultaneously large response and broad bandwidth.

- Microwave cavity?

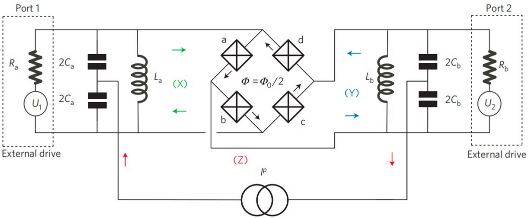
Multi-Mode Resonators

- Toy model: DC-Josephson effects to couple 2 circuit modes:



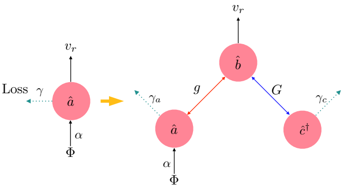
$$H = -I_0\varphi_0 \cos\left[\omega_0 t + (\Phi_1 + \Phi_2)/\varphi_0\right] = \frac{I_0}{\varphi_0}\cos[\omega_0 t]\Phi_1\Phi_2 + \cdots$$

- Realization through **Josephson ring modulator** [Bergeal et al 10]:



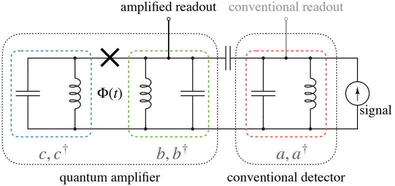
- $\omega_0 = |\omega_1 - \omega_2| \to$ **beam-splitting**: $\hbar g \hat{a}_1 \hat{a}_2^\dagger + h.c.$
- $\omega_0 = \omega_1 + \omega_2 \to$ **non-degenerate squeezing**: $\hbar G \hat{a}_1 \hat{a}_2 + h.c.$

White Light Haloscope [Li et al 20']



Single Cavity Design

Detector Design with $\mathcal{PT}$ symmetry



Probing mode: $\hbar\alpha(\hat{a} + \hat{a}^\dagger)\Psi$

- **Beam-splitting**: $\hbar g(\hat{a}\hat{b}^\dagger + \hat{a}^\dagger \hat{b})$.
- **Non-degenerate parametric interaction**: $\hbar G(\hat{b}\hat{c} + \hat{b}^\dagger \hat{c}^\dagger)$.
- **$\mathcal{PT}$-symmetry ($\hat{a} \leftrightarrow \hat{c}^\dagger$) emerges** when $g = G$.

$$
\begin{aligned}
(\dot{\hat{a}} + \dot{\hat{c}}^\dagger) &= -i(g - G)\hat{b} - i\alpha\Psi + \cdots ; \\
\dot{\hat{b}} &= -\gamma_r \hat{b} - ig(\hat{a} + \hat{c}^\dagger) + \cdots .
\end{aligned}
$$

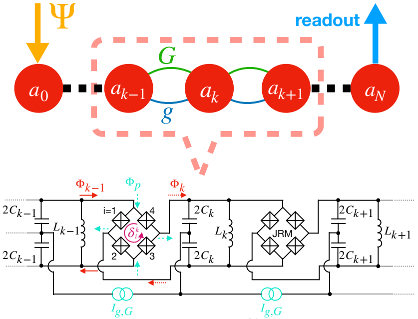
- **Double resonance** when $g \gg$ **intrinsic dissipation** γ:

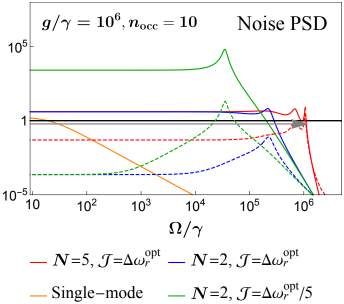
$$
S_{\rm sig}^{\rm WLC}(\Omega) = \frac{2\gamma_r \alpha^2 S_\Psi(\Omega)}{(\gamma + \gamma_r)^2 + \Omega^2} \left(\frac{g^2}{\gamma^2 + \Omega^2} \right).
$$

Readout coupling γ_r

Response Width for Multi-mode Resonators

Broadened response in multi-mode resonators:





$$H_{\rm ch} = \sum_{k=0}^{N-1} \left(\mathrm{i} g\, \hat{a}_k \hat{a}_{k+1}^\dagger + \mathrm{i} G\, \hat{a}_k \hat{a}_{k+1} + h.c. \right) .$$

flatten **amplify**

- $|g| > |G|$ to make the system stable.
- Large $\mathcal{J} \equiv \sqrt{|g|^2 - |G|^2}$ to **flatten** the response as required by dynamic range and robustness.

[YC et al, PRR 2103.12085, Rept.Prog.Phys. 2309.12387]

Response Width for Multi-mode Resonators

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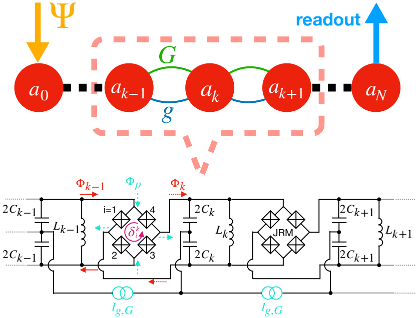
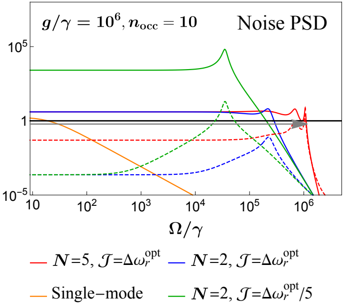




$$H_{\rm ch} = \sum_{k=0}^{N-1} \left(\mathrm{i} g \hat{a}_k \hat{a}_{k+1}^\dagger + \mathrm{i} G \hat{a}_k \hat{a}_{k+1} + h.c. \right) .$$

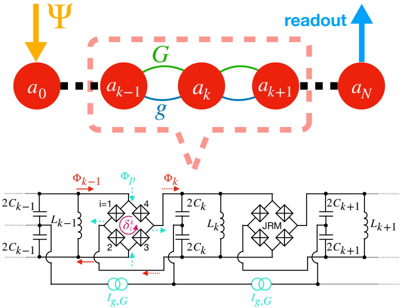
- New sensitivity limit for multi-mode resonators, optimal for SRF cavity:

$$\frac{\Delta\omega_r^{\rm MM}}{\Delta\omega_r^{\rm SM}} \propto \left(\frac{g Q_0}{\omega_{\rm rf}\, n_{\rm occ}} \right)^{\frac{2N}{2N+1}} \to \frac{Q_0}{n_{\rm occ}} \text{ as } N \gg 1, \; g \to \omega_{\rm rf}, \; \Delta\omega_r^{\rm MM} \to \omega_{\rm rf}.$$

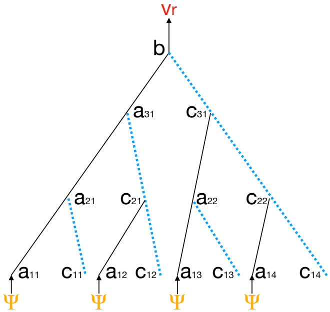
[YC et al, PRR 2103.12085, Rept.Prog.Phys. 2309.12387]

Chain and Binary Tree

Non-hermitian chain [McDonald et al 18', YC et al Rept.Prog.Phys. 2309.12387]



Binary tree [YC et al, PRR 2103.12085, Rept.Prog.Phys. 2309.12387]



- **Single-quadrature** amplification
- Phase fluctuations & nonlinearities?

- **Both quadratures** experience gain
- Compatible with sensor networks

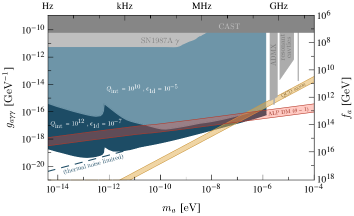
▶ **HAYSTAC Phase IV**, CEASEFIRE: prototype calibration for $N = 1$ **non-hermitian chain** with $g \sim$ MHz [Wurtz et al 21', Jiang et al 23'].

Heterodyne Upconversion

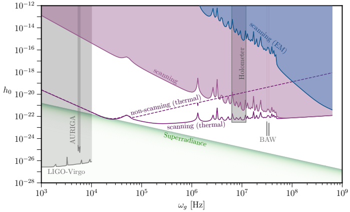
- **Heterodyne upconversion** [Goryachev et al 19', Berlin et al 19', UPLOAD 19' 23']:

  injecting AC pump mode: $\omega_{\rm rf} - \omega_0 \approx \omega_a$ or ω_h.

- Resonant scan: tune $\omega_{\rm rf} - \omega_0$ from Hz to GHz:



[Berlin et al 19']



[Berlin et al 23']

- Both **EM** and **mechanical** coupling from GW [Berlin et al 21' 23'].

- **Jing Shu**'s talk for **SHANHE collaboration**'s experimental progress.

Simultaneous Resonant and Broadband Detection

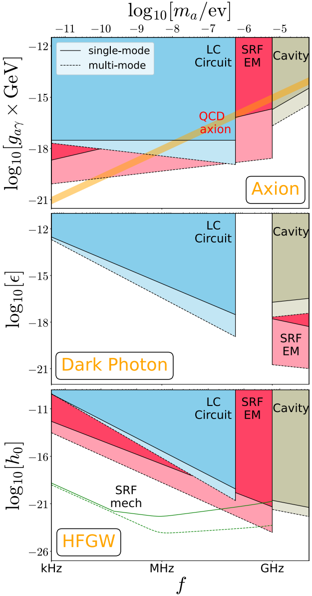
- *e*-fold time: 10^7 s.
- **Solid lines**: **single-mode resonators**

  with $\Delta\omega_r \sim n_{\rm occ}\omega_{\rm rf}/Q_0$.
- **Dashed lines**: **multi-mode resonators**

  with $\Delta\omega_r \to \omega_{\rm rf}$.
- **DC cavity and LC circuits**:

  $$\frac{\rm SNR^2_{MM}}{\rm SNR^2_{SM}} \simeq \frac{Q_0}{n_{\rm occ}}.$$

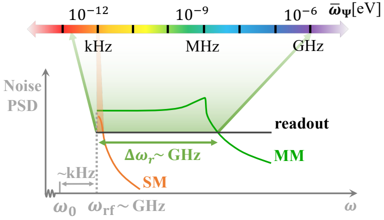
  High $n_{\rm occ}$ of LC circuits at low frequency made enhancement ineffective.



[YC et al, Rept.Prog.Phys. 2309.12387]

Simultaneous Resonant and Broadband Detection

- **SRF heterodyne upconversion**:

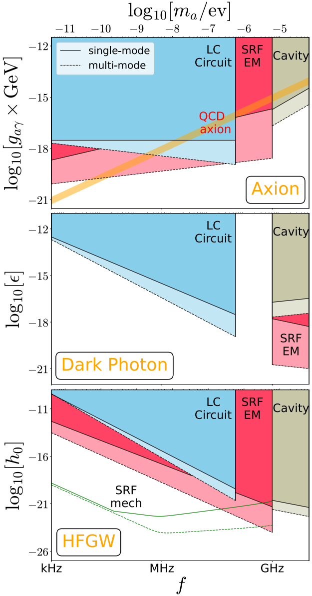


Simultaneous scan $N_e = 6$ orders of ω_Ψ

with **significant response**:

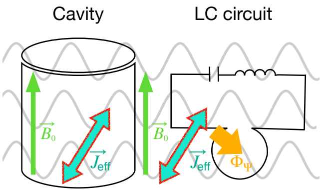
$$\frac{\mathrm{SNR}^2_{\mathrm{MM}}}{\mathrm{SNR}^2_{\mathrm{SM}}} \simeq N_e \frac{\bar{\omega}_\Psi \, Q_0}{\omega_{\rm rf} \, n^{\rm eff}_{\rm occ}}$$

- Ineffective enhancement for **GW mechanical resonance** near kHz due to high $n^{\rm eff}_{\rm occ}$.



[YC et al, Rept.Prog.Phys. 2309.12387]

Summary



- **Resonant cavities or circuits** are powerful detectors for ultralight bosons and HFGW.

- Multi-mode resonantors have broadened response.

  → **Simultaneous resonant and broadband** detection for **SRF-based upconversion**.

Thank you!