More is Different in Resonant Electromagnetic Detectors

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Outlines

Electromagnetic Resonant Detection of Ultralight Bosons and HFGW

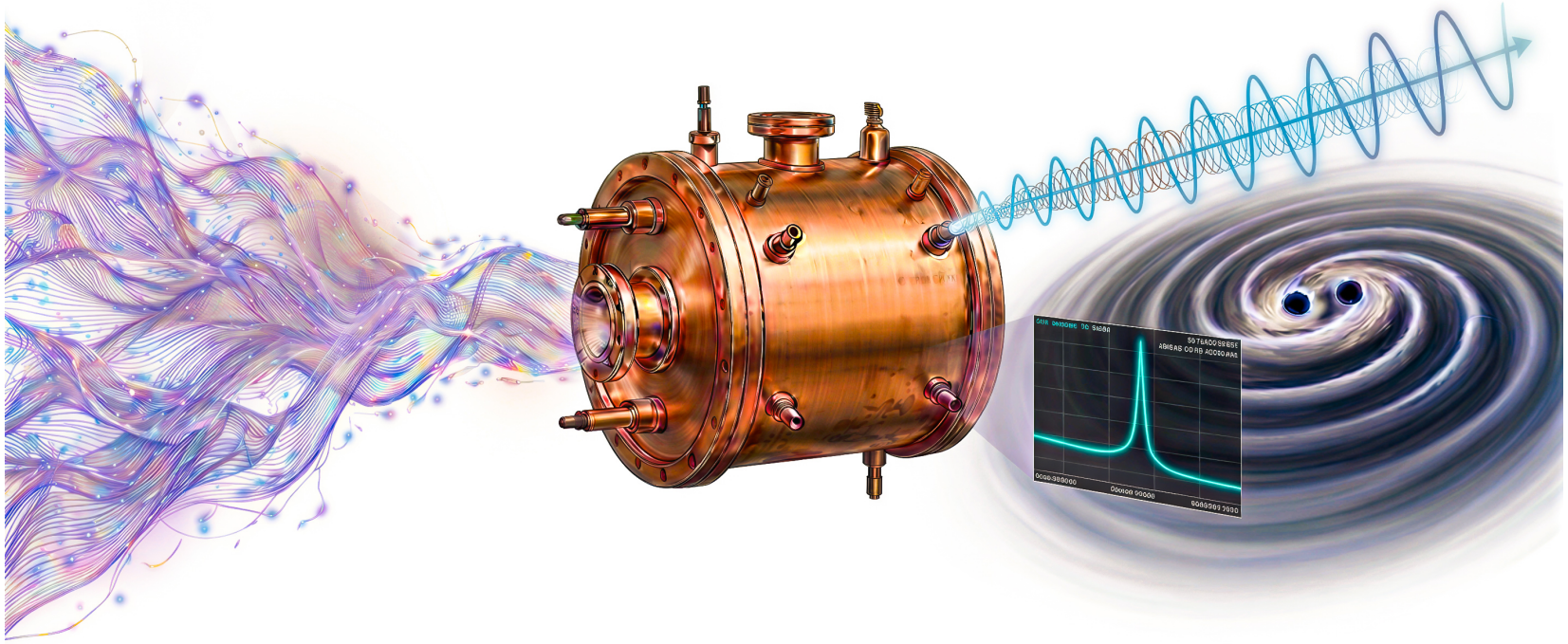
Simultaneous Resonant and Broadband Detection with Multi-mode Resonators

Cavity Multimodes as an Array

Electromagnetic Resonant Detection of Ultralight Bosons and HFGW

Ultralight Dark Matter and Gravitational Waves

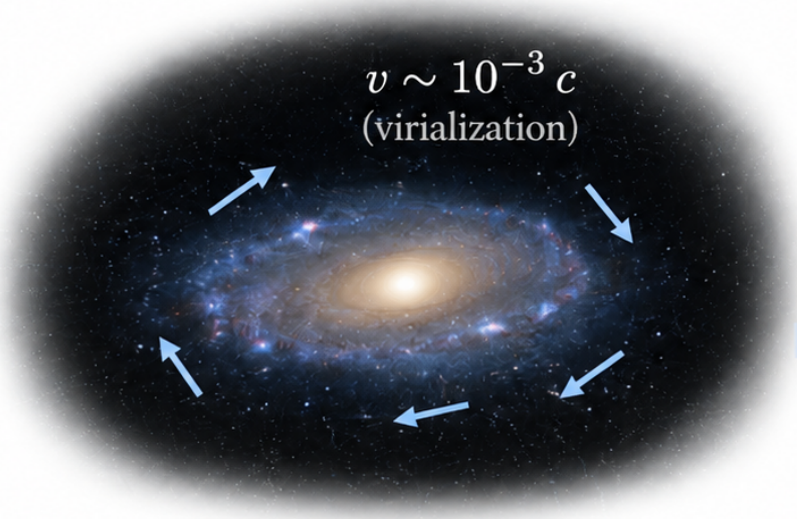
Resonant cavity or **circuit** for probing **fundamental physics**:



- **Ultralight bosons**: explaining neutron EDM and extra dimensions.
- **High-frequency gravitational wave**: >10 kHz window for new physics.

Ultralight Dark Matter: Frequency Distribution

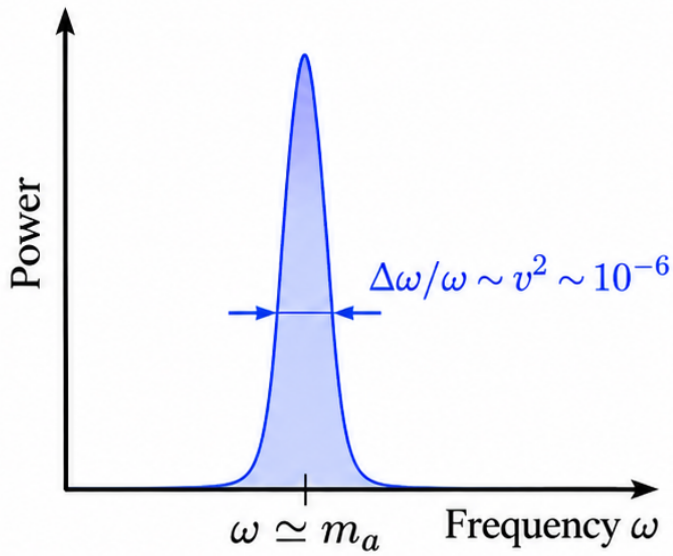
Galactic dark matter
(non-relativistic, virialized)



$$a(t, \boldsymbol{x}) \simeq a_0 \cos(m_a t + \boldsymbol{p} \cdot \boldsymbol{x})$$

$$|\boldsymbol{p}| \sim m_a v, \quad v \sim 10^{-3}\, c$$

Narrow frequency spread
$(\Delta\omega/\omega \sim v^2 \sim 10^{-6})$



- Ultralight dark matter: narrowband oscillating 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:

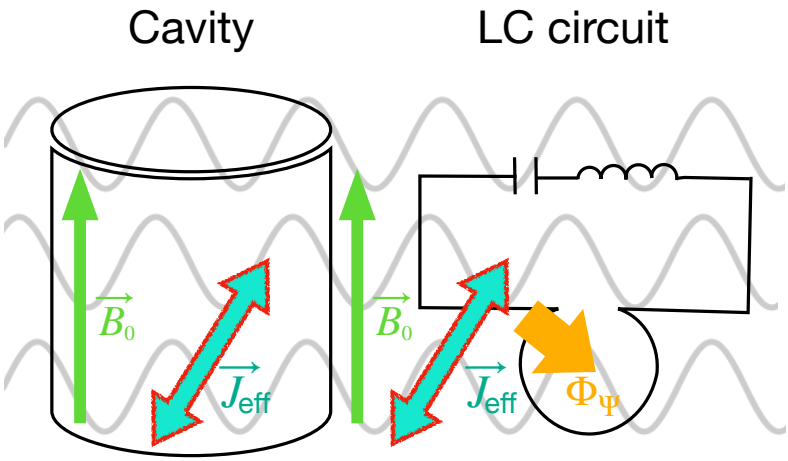
$\vec{J}_{\rm eff} = g_{a\gamma} \vec{B}_0 \partial_t a$;

Background $\vec{B}_0$.

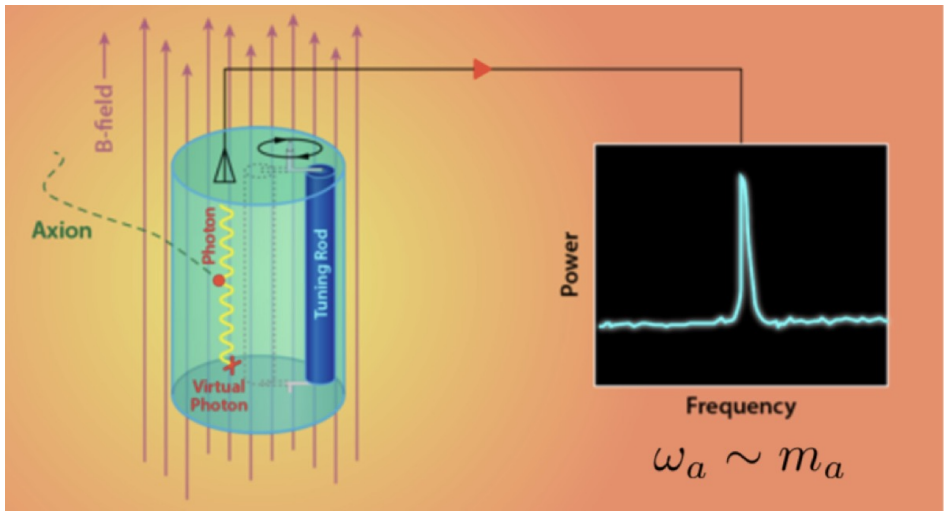
GW h:

$\vec{J}_{\rm eff} \propto \partial(h\, F_0)$;

Background $\vec{E}_0$ or $\vec{B}_0$.



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



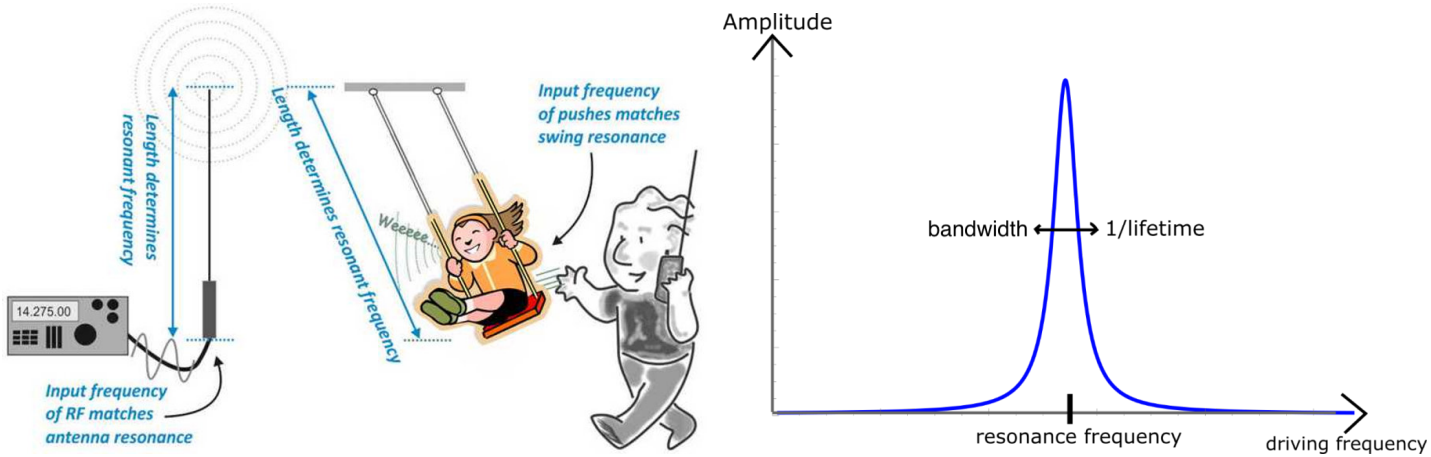
[ADMX]

Resonant EM detection for $\vec{J}_{\rm eff}$.

Electromagnetic Single-Mode Resonator

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

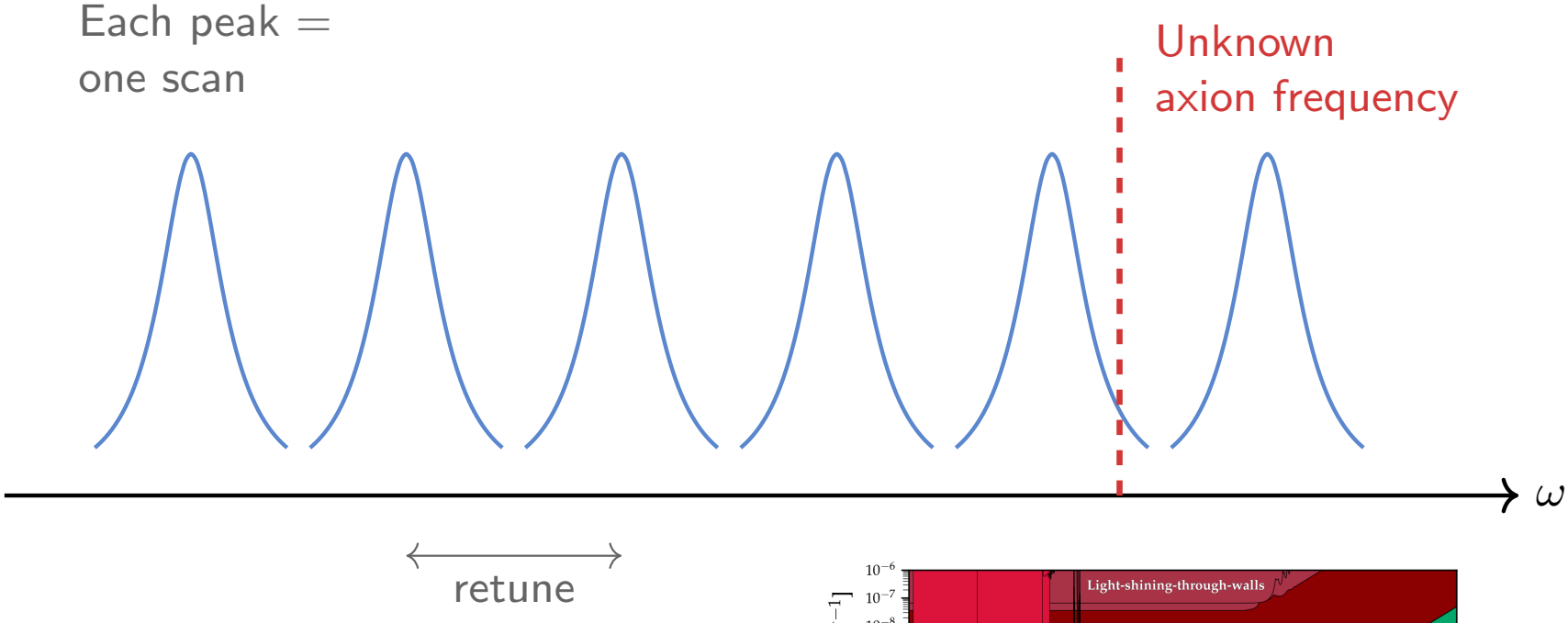
Trade-off between peak response and bandwidth.



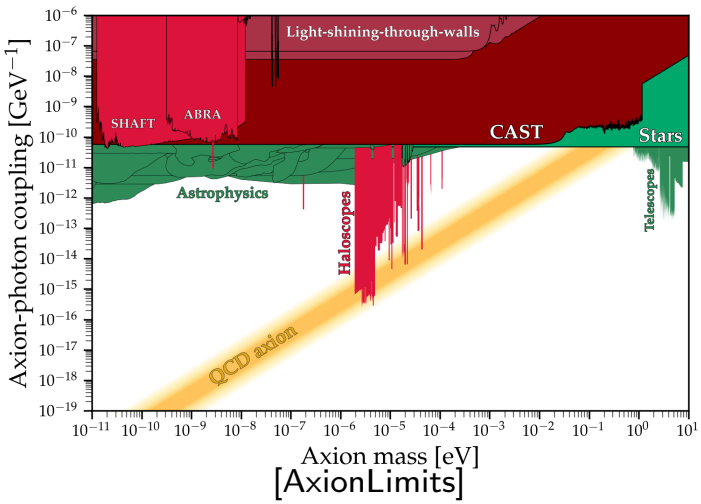
e.g. cavity or circuit for capturing $\vec{J}_{\text{eff}}$.

Electromagnetic Single-Mode Resonator

- **Resonantor**: requires **multiple scans** to cover unknown axion masses:

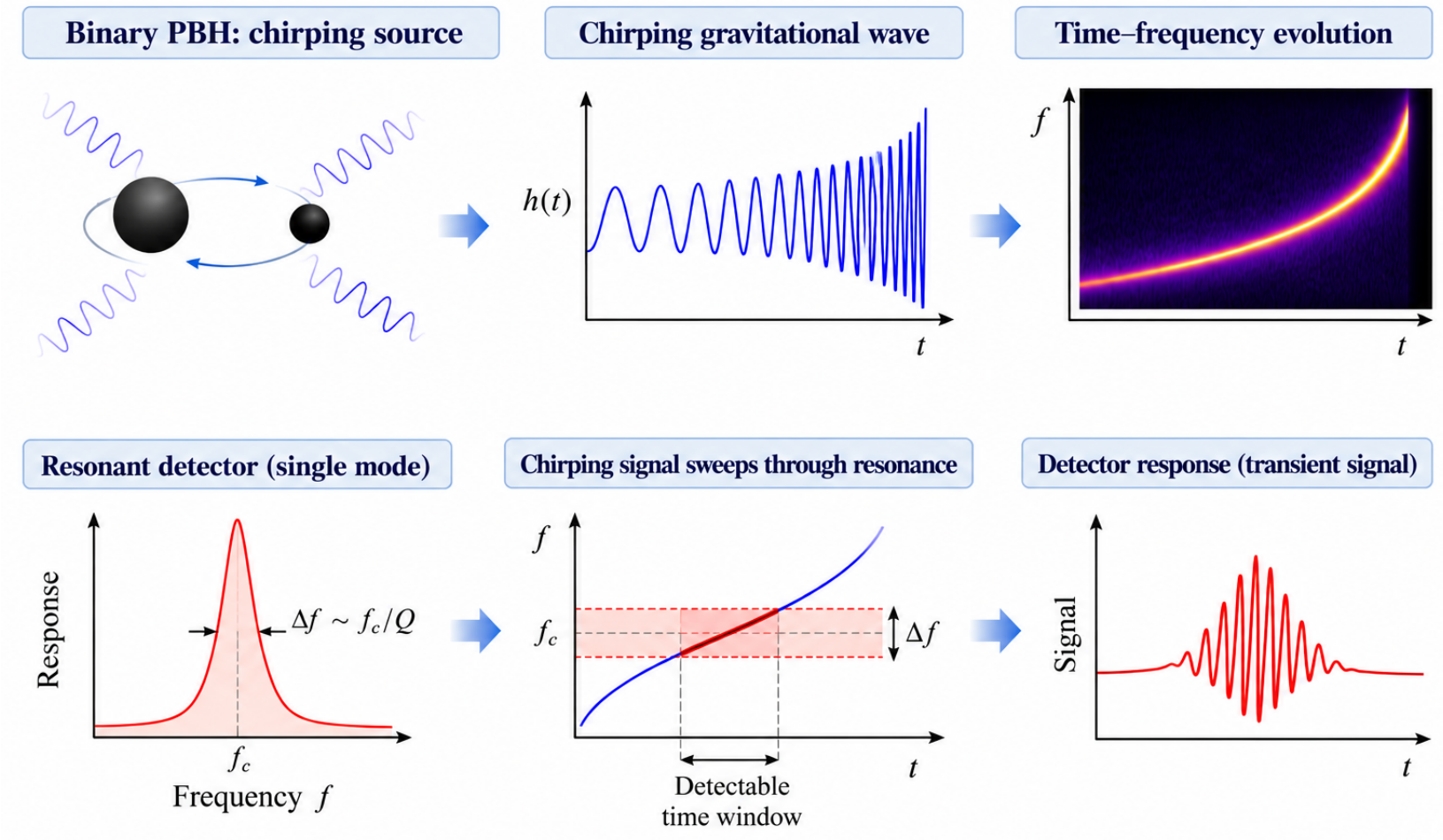


- Each cavity's frequency can be tuned by at most $\mathcal{O}(10\%)$.



Electromagnetic Single-Mode Resonator

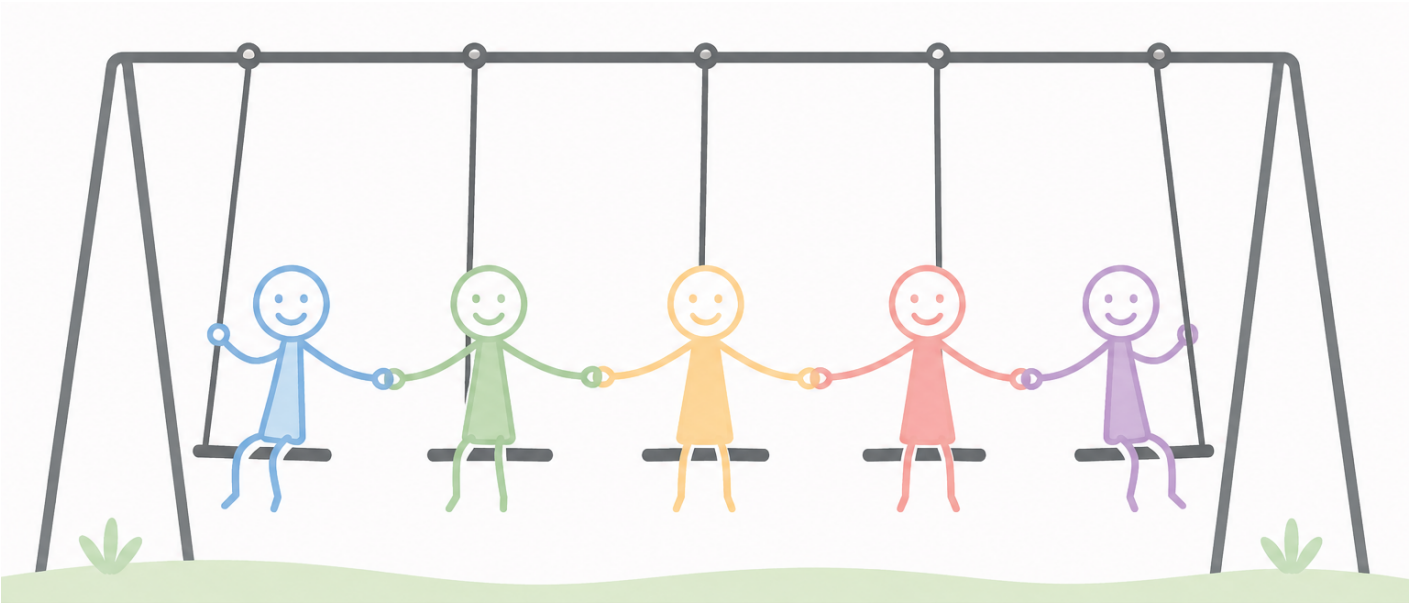
- **Resonator**: challenge for **transient** high-frequency GW sources.



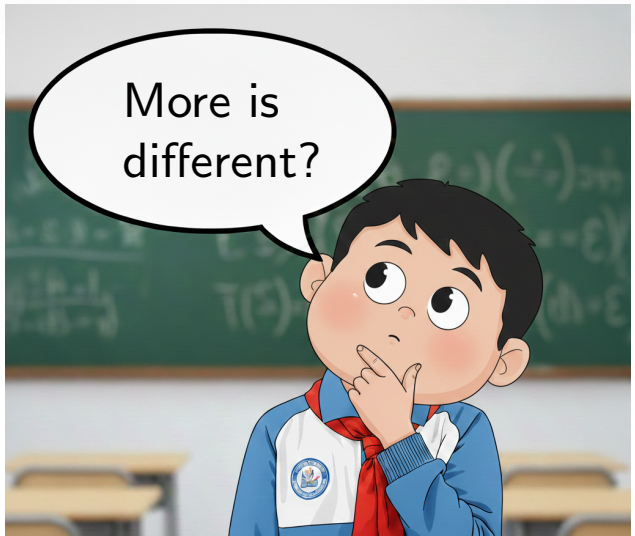
Simultaneous Resonant and Broadband Detection with Multi-mode Resonators

Multi-Mode Resonators

- **Beyond** single-mode resonators?

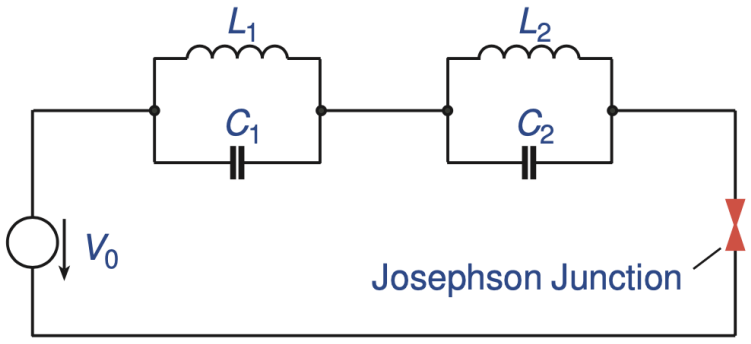


- How a **multi-mode resonator** respond differently?



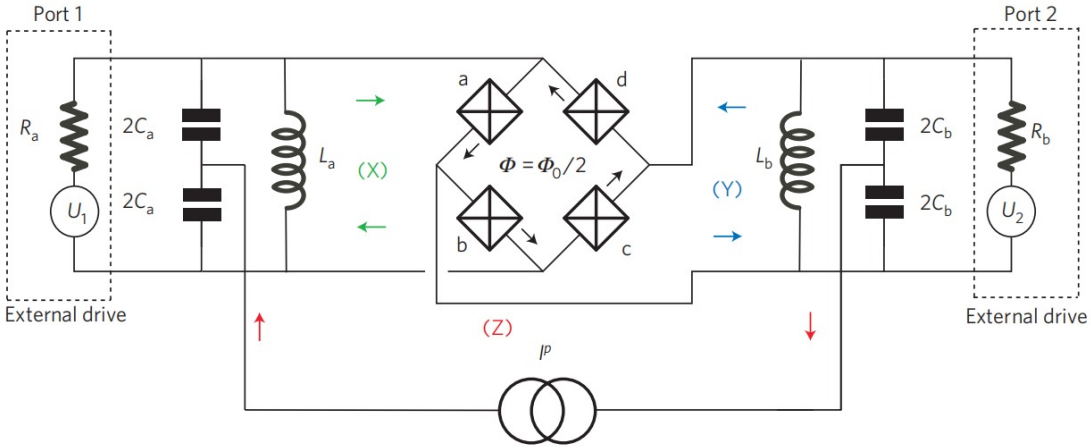
Multi-Mode Resonators

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



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

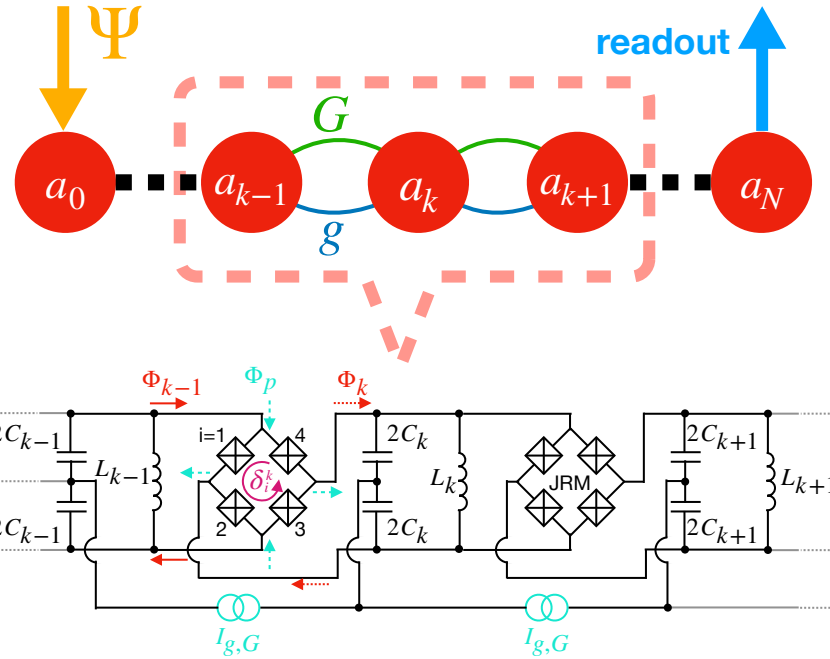
- Realization through **Josephson ring modulator** [Bergeal et al 10]:

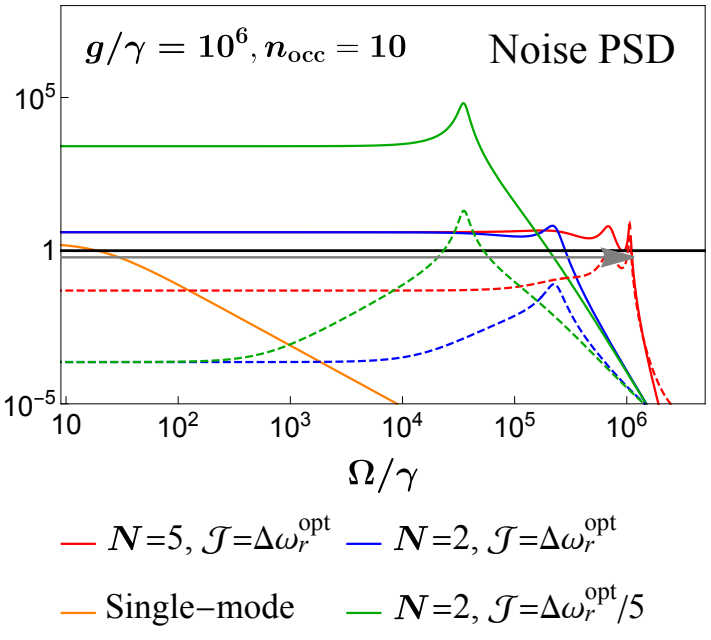


- $\omega_0 = |\omega_1 - \omega_2| \rightarrow$ **beam-splitting**: $\hbar g \hat{a}_1 \hat{a}_2^\dagger + h.c.$
- $\omega_0 = \omega_1 + \omega_2 \rightarrow$ **non-degenerate squeezing**: $\hbar G \hat{a}_1 \hat{a}_2 + h.c.$

Response Width for Multi-mode Resonators

A **chain** of multi-mode resonators:





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

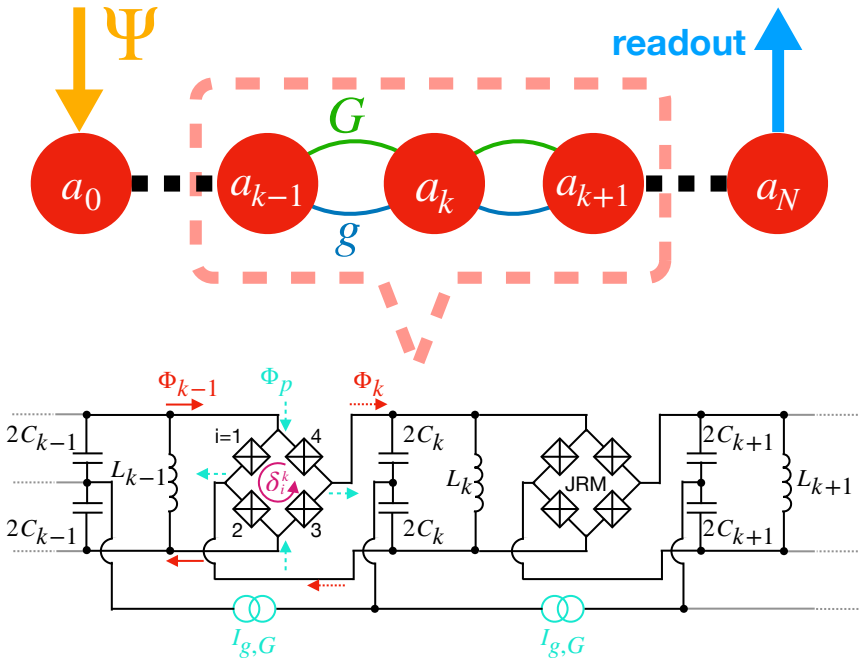
flatten **amplify**

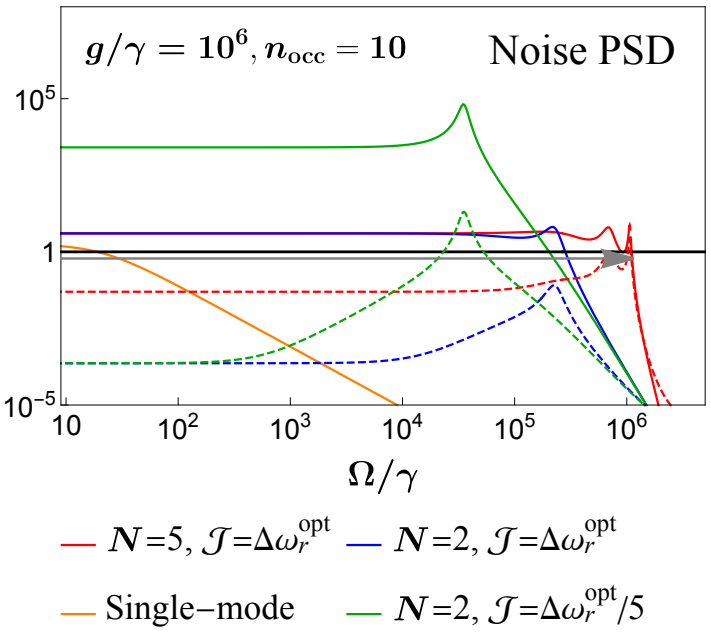
- $|g| = |G|$: **multiple resonance**.
- Large $\mathcal{J} \equiv \sqrt{|g|^2 - |G|^2}$ to **flatten** the response as required by dynamic range and robustness.

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

Response Width for Multi-mode Resonators

Broadened response in multi-mode resonators:



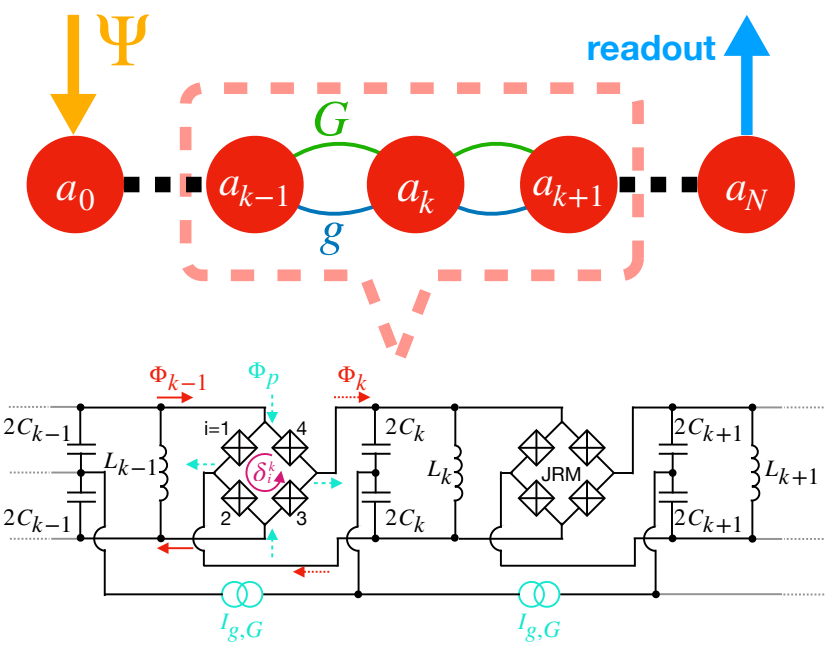


- Single-mode **bandwidth**: $\sim n_{\rm occ}\omega_{\rm rf}/Q_0$;
- Multi-mode **bandwidth limit**: $\sim \omega_{\rm rf}$ as $N \gg 1$.

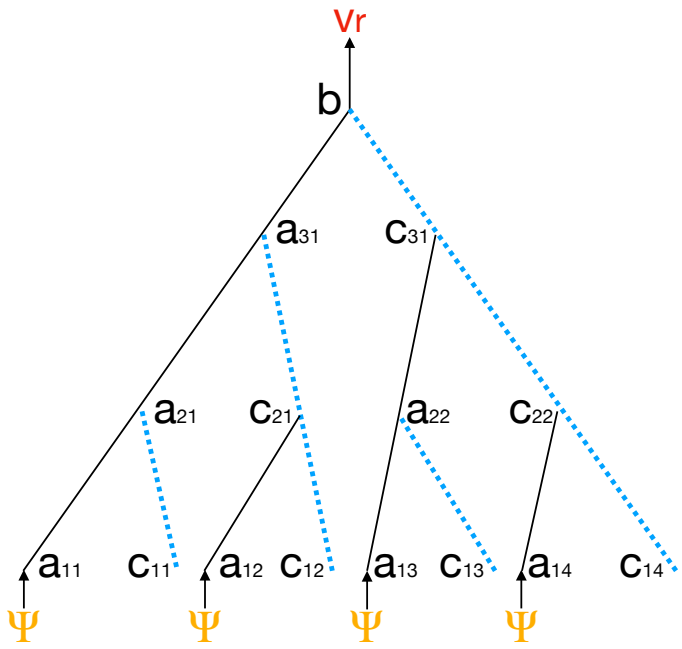
[YC et al, PRR 2103.12085, Rept.Prog.Phys. 2309.12387]

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]

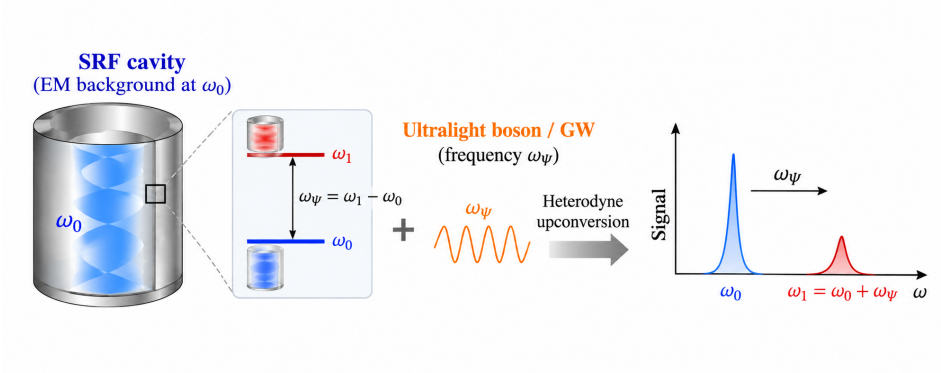


- **Single-quadrature** amplification
- Phase fluctuations & nonlinearities?
- **Both quadratures** experience gain
- Compatible with sensor networks

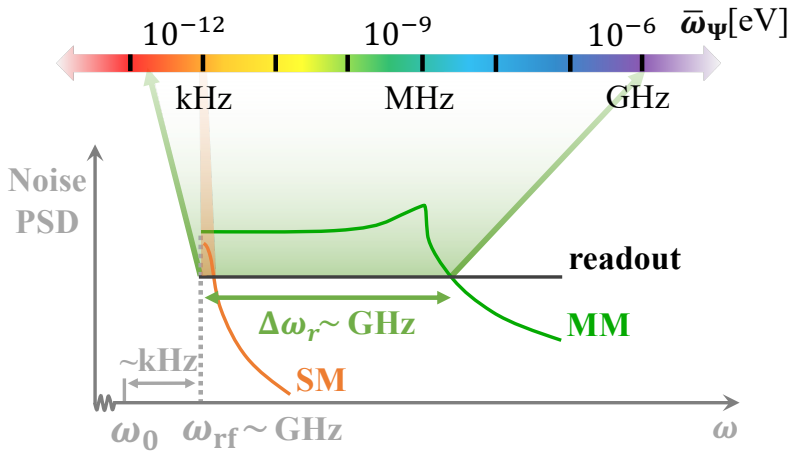
- **HAYSTAC Phase IV**, CEASEFIRE: prototype calibration for $N = 1$ **non-hermitian chain** with $g \sim$ MHz [Wurtz et al 21', Jiang et al 23'].

Simultaneous Resonant and Broadband Detection

- **SRF heterodyne upconversion** [Berlin et al 19]:

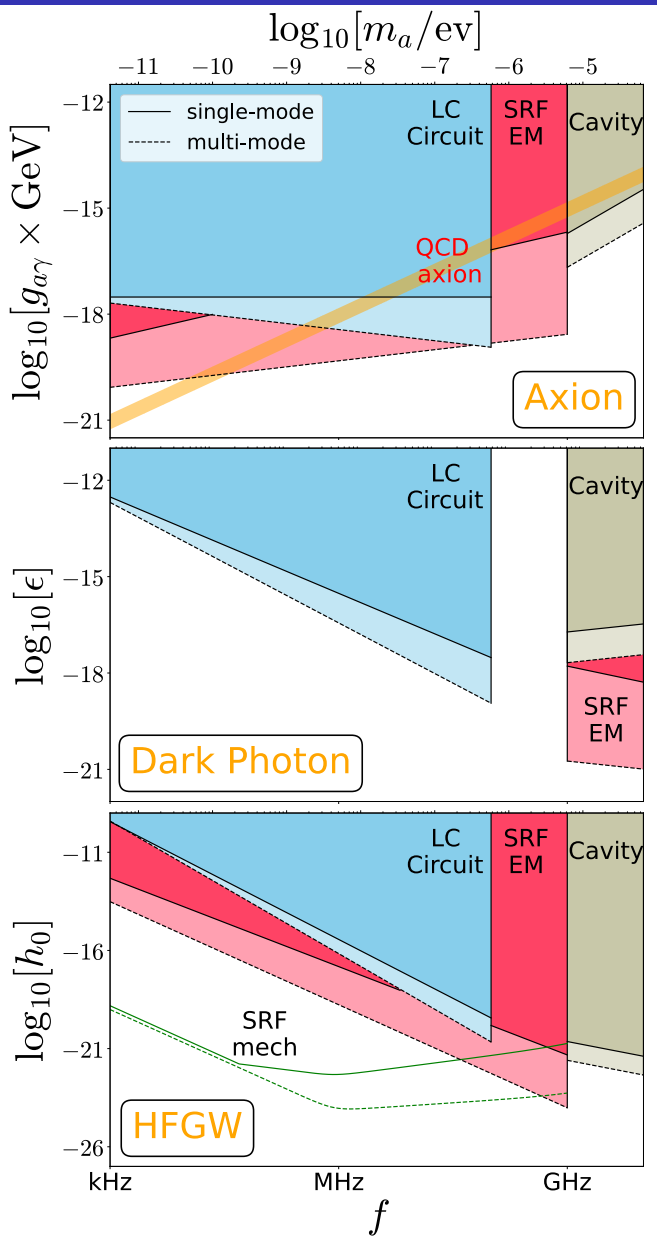


- **Multi-mode generalization**:



Simultaneous scan $N_e = 6$ orders of ω_Ψ

with **significant response**.

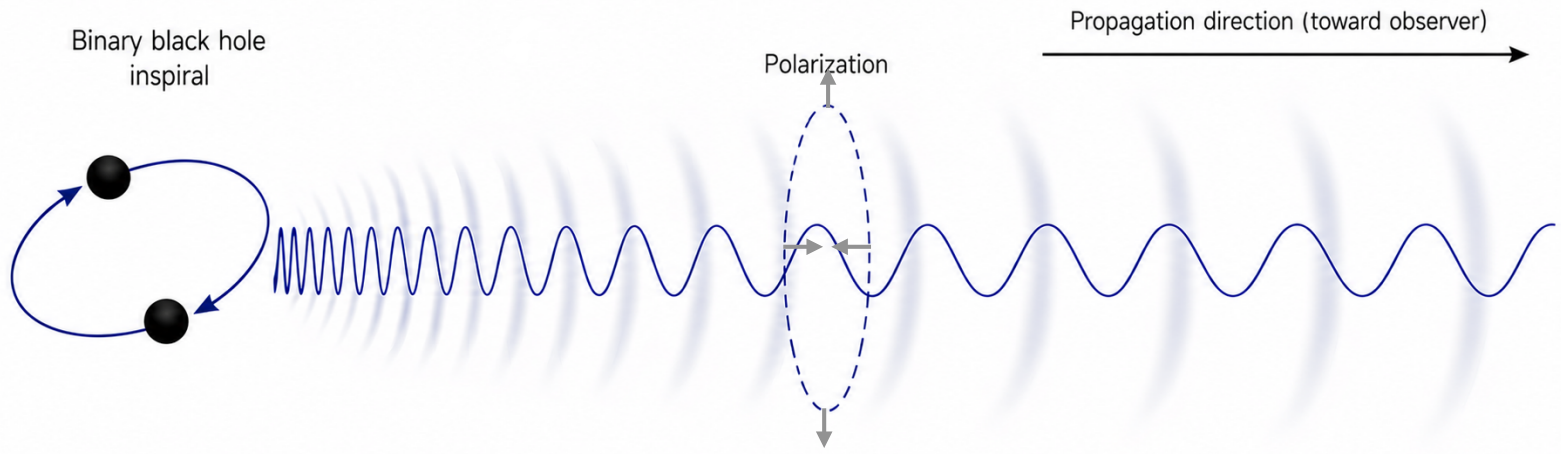


[YC et al, Rept.Prog.Phys. 2309.12387]

Cavity Multimodes as an Array for High-Frequency Gravitational Waves

Challenges for Identifying Target Gravitational Wave

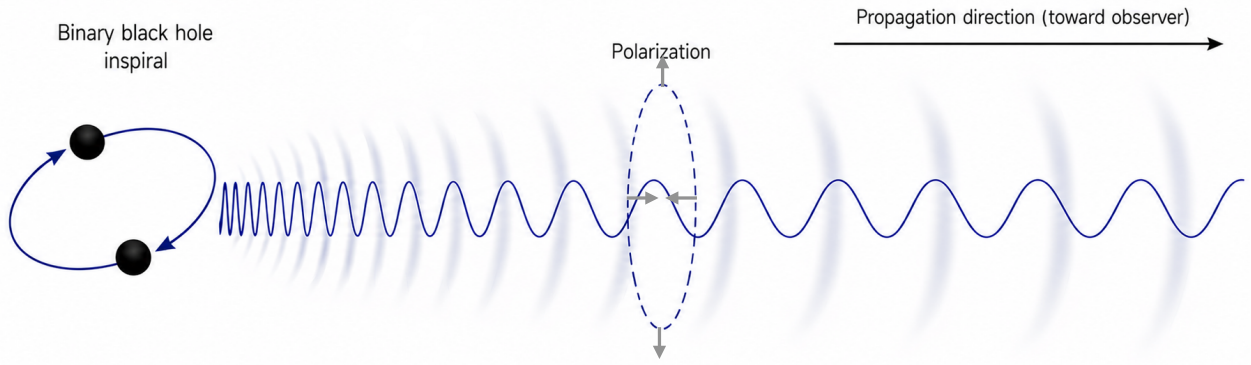
- **Coherent target gravitational wave**:
  - ✯ **Propagating direction**;
  - ✯ Polarization;
  - ✯ Waveform (frequency drift rate).



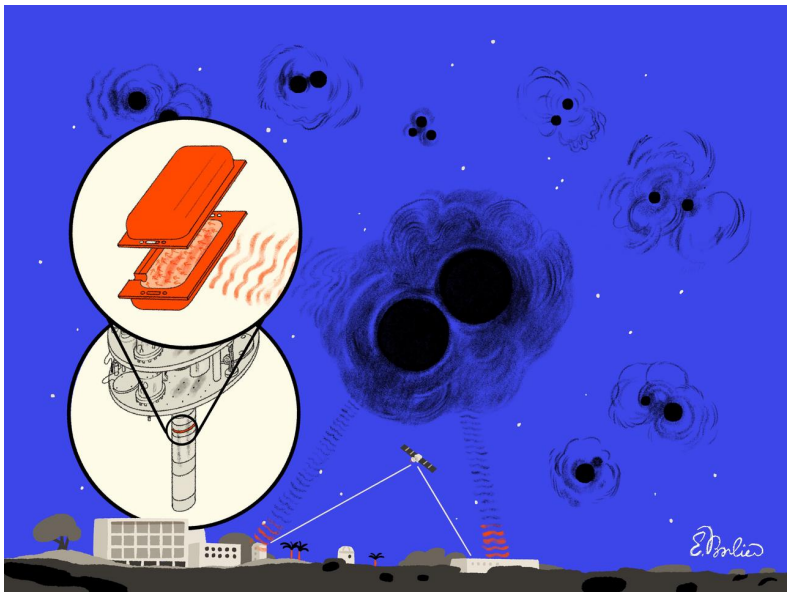
- **One cavity mode**: transient projection through cavity response.
- How to extract **full gravitational wave information**?

Cavity Network

- How to extract **full gravitational wave information**?



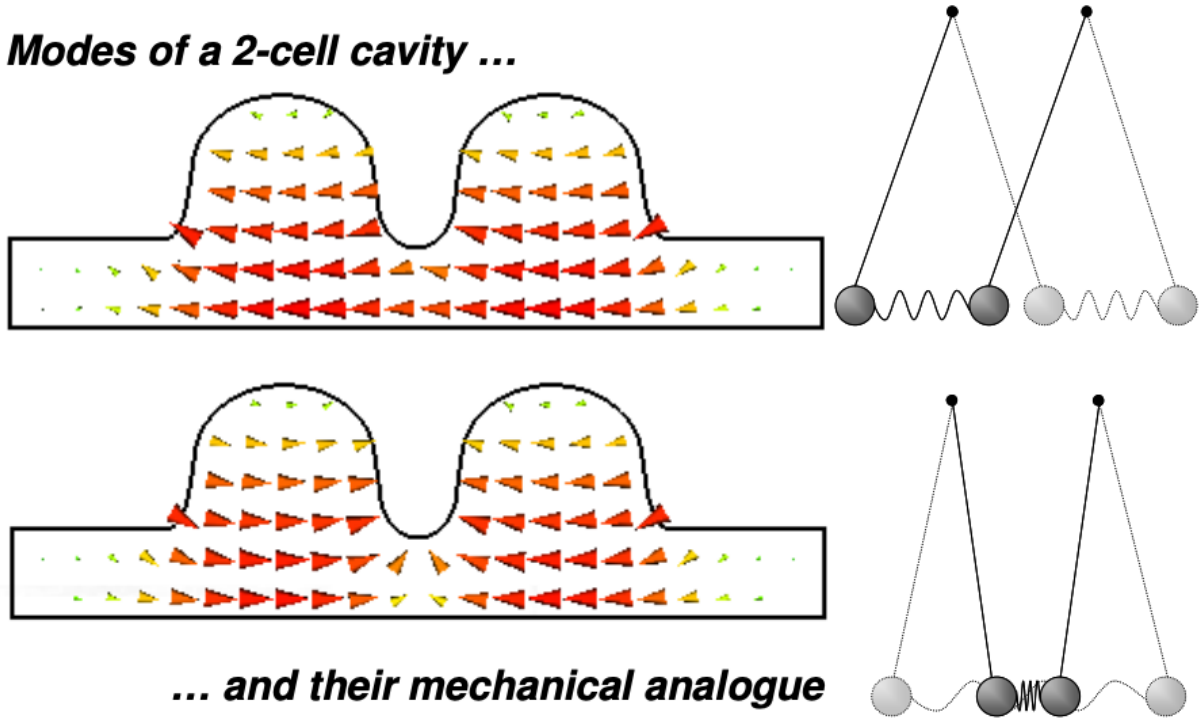
- **Cavity network**? Challenges for **synchronization**.



[Eve Barlier for GravNet]

Multi-mode Cavity as Network

- A cavity with **multiple modes**:

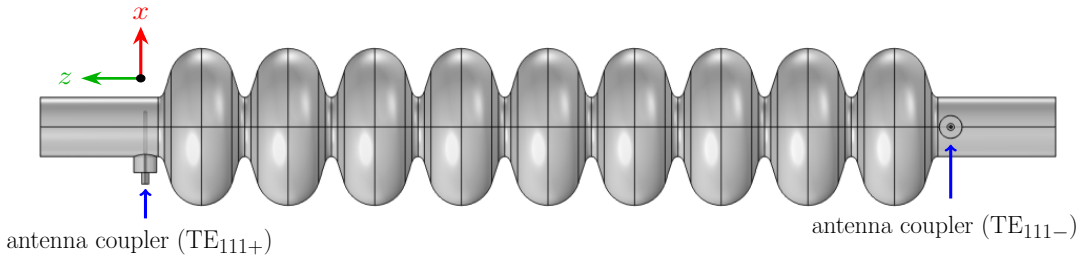


[Belomestnykh, Shemelin 05]

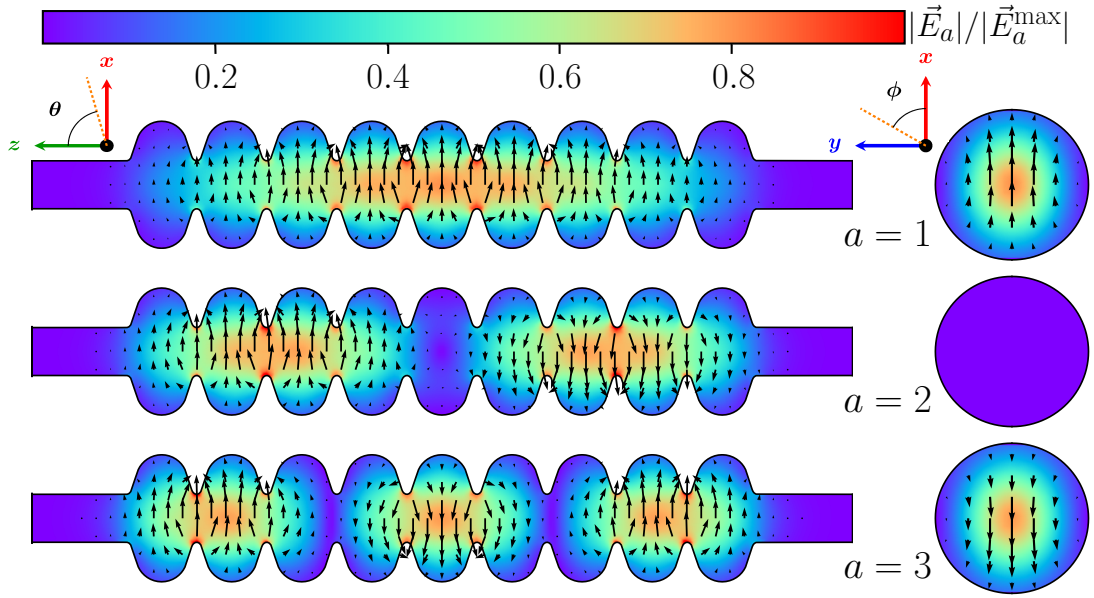
- E.g., **multi-cell cavity** with nearly degenerate modes.
- Intrinsicly a "**network**" with **automatic synchronization**.

9-cell Cavity

- **9-cell cavity** widely used in accelerators.



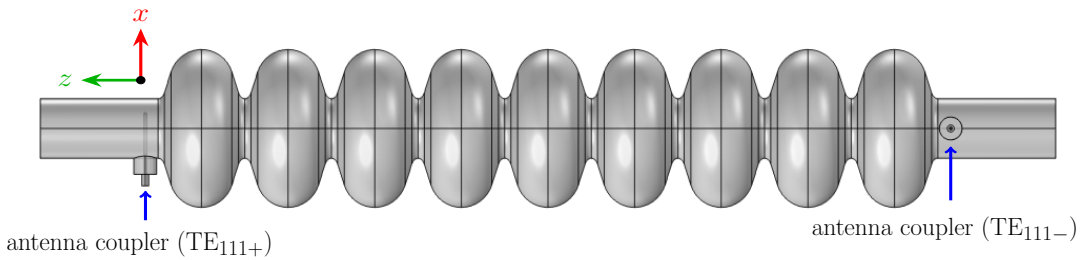
- $2 \times 9 = 18$ total **degenerate modes**.



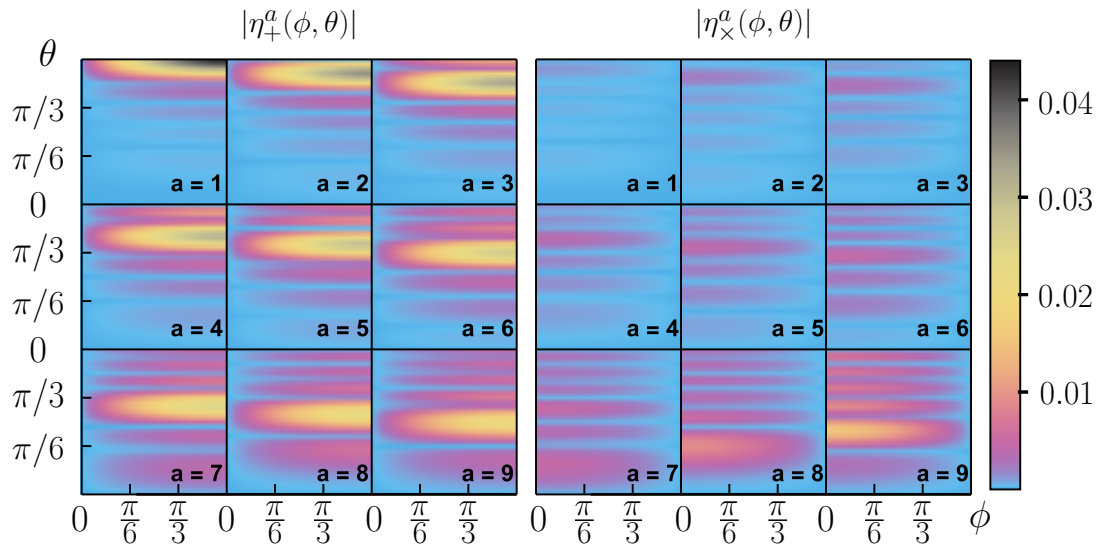
[Shang, Liu, Blas, YC, Shu, JCAP 2601.03341]

9-cell Cavity

- **9-cell cavity** widely used in accelerators.



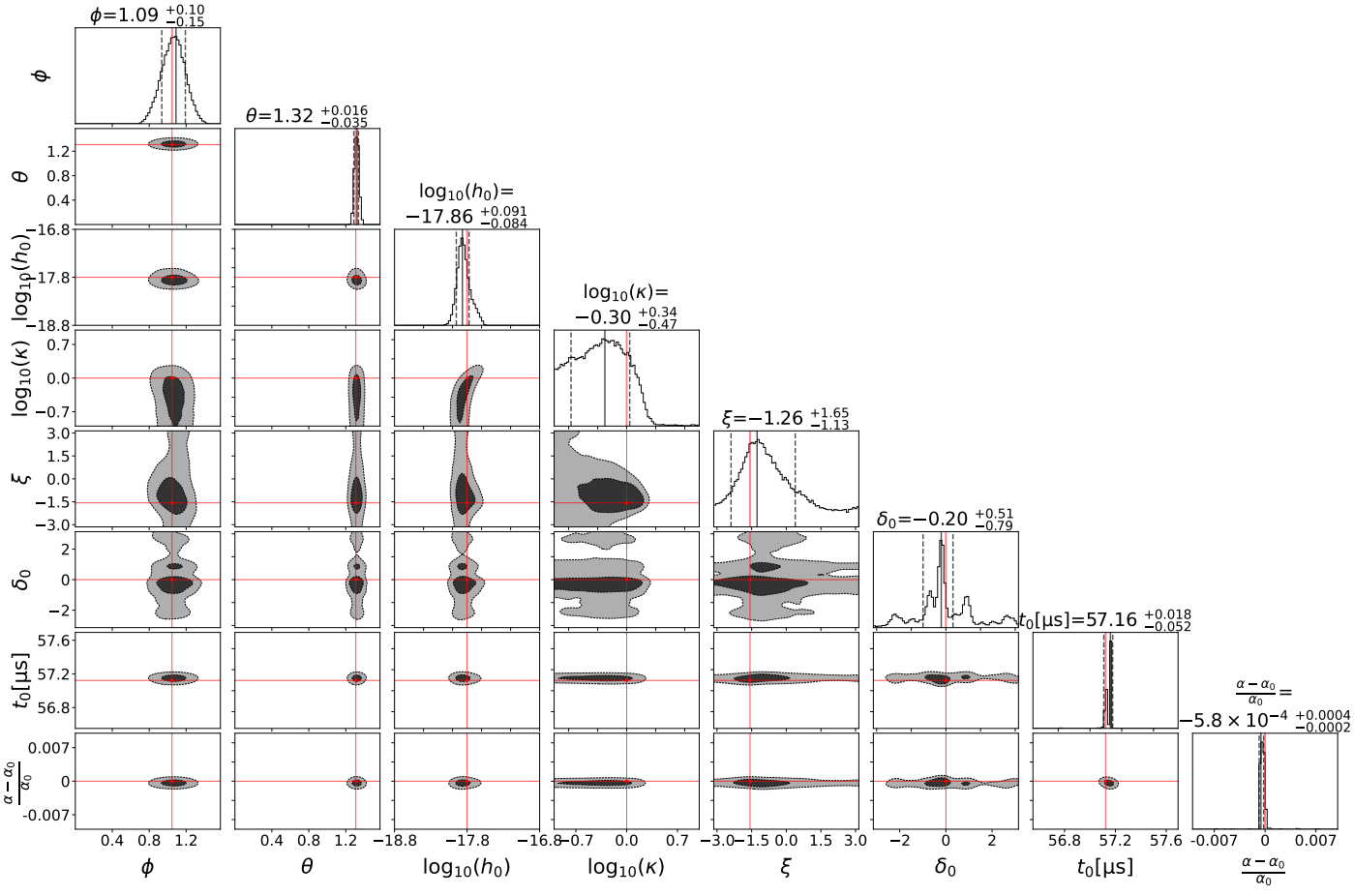
- $2 \times 9 = 18$ total **degenerate modes** with distinct **antenna patterns**:



[Shang, Liu, Blas, YC, Shu, JCAP 2601.03341]

9-cell Cavity

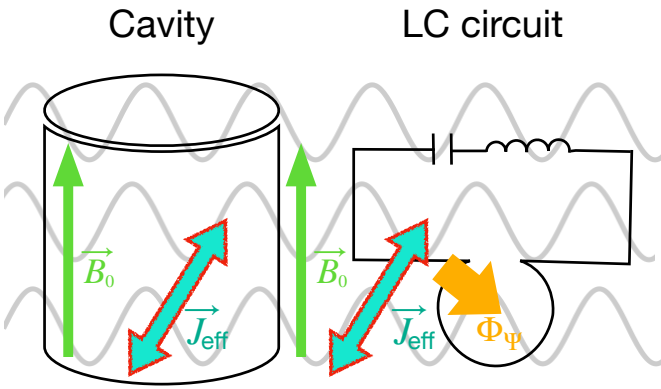
- A **9-cell cavity** enables full gravitational wave information extraction:



[Shang, Liu, Blas, YC, Shu, JCAP 2601.03341]

Summary

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



- Multi-mode resonantors have broadened response.

  $\rightarrow$ **Simultaneous resonant and broadband** detection for **SRF-based upconversion**.

- **Multi-cell cavity** with **degenerate modes** as an **intrinsic network**.

  $\rightarrow$ Enables full gravitational wave information extraction.

Thank you!

Appendix

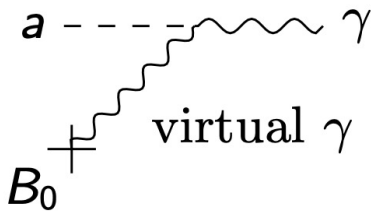
Axion Photon Coupling and Cavity Haloscope

- **Axion photon coupling**: $\propto g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$,

$$\rightarrow \nabla \times \mathbf{B} = \partial_t \mathbf{E} + \mathbf{J} - g_{a\gamma} \left(\mathbf{E} \times \nabla a - \mathbf{B} \partial_t a \right).$$

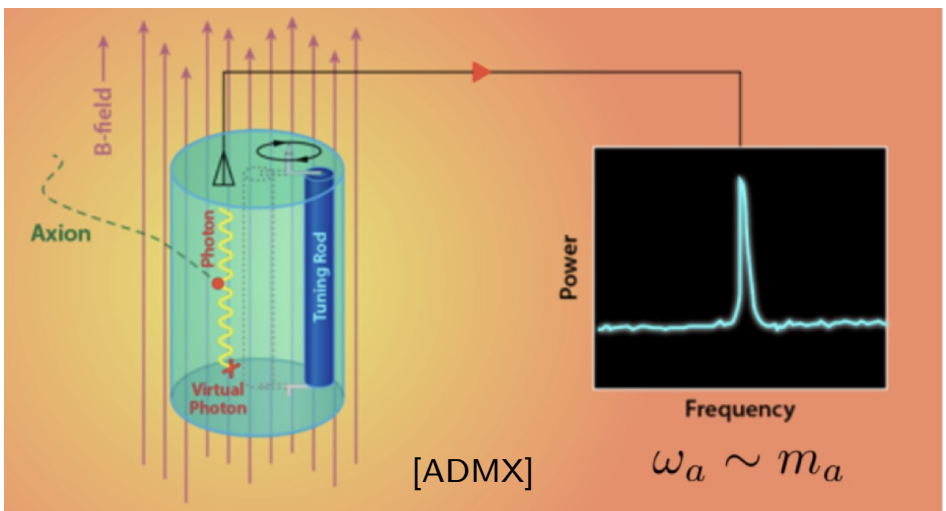
- **Resonant cavity haloscope** [Sikivie 83]:

$$\mathbf{J}_{\rm eff}(t) = g_{a\gamma} \mathbf{B}_0 \partial_t a \qquad \left(\partial_t^2 + \gamma \partial_t + \omega_{\rm rf}^2 \right) \mathbf{E}_{\rm rf} = \partial_t \mathbf{J}_{\rm eff}(t).$$



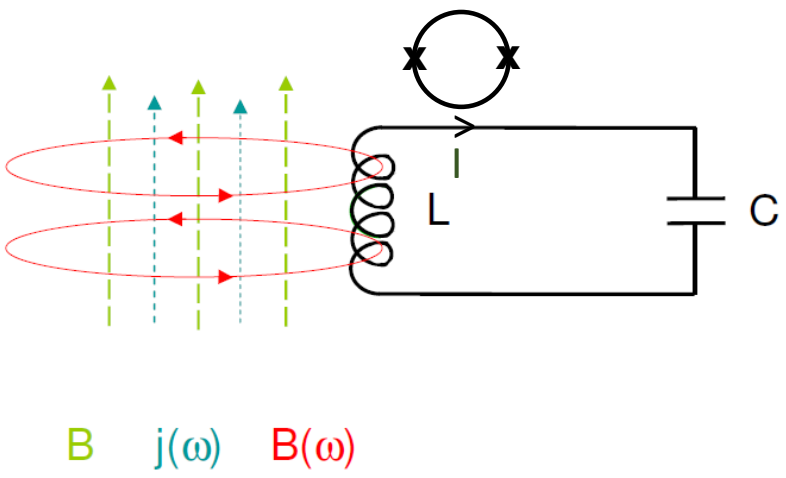
- Background static $\mathbf{B_0}$
  $\rightarrow$ resonant when
  $\omega_{\rm rf} = m_a \sim V^{-1/3} \sim \mathcal{O}(1)$ GHz.

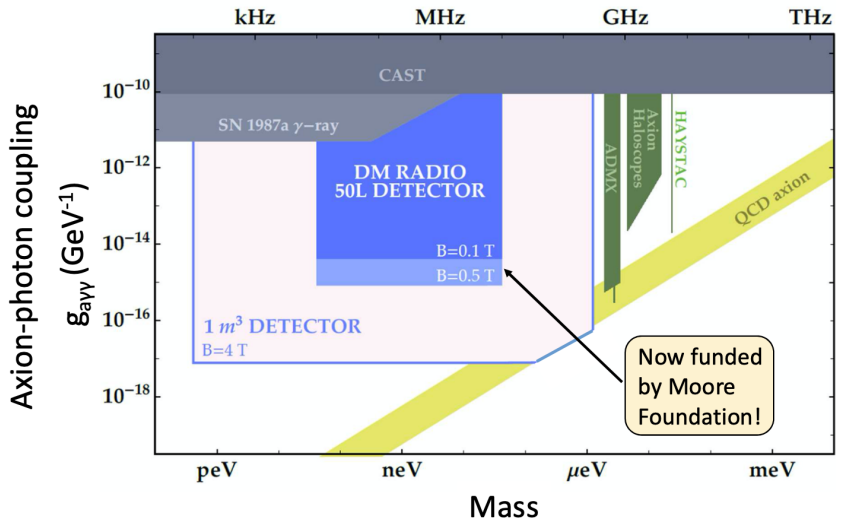
  e.g. ADMX, HAYSTAC, CAPP, ORGAN $\cdots$



Resonant LC circuit

- Resonant conversion happens when $m_a \simeq \omega_{\rm rf} = \frac{1}{\sqrt{LC}}$ [Sikivie et al 13].
- Scanning the mass from 100 Hz to 100 MHz by **tuning the capacitor C**.





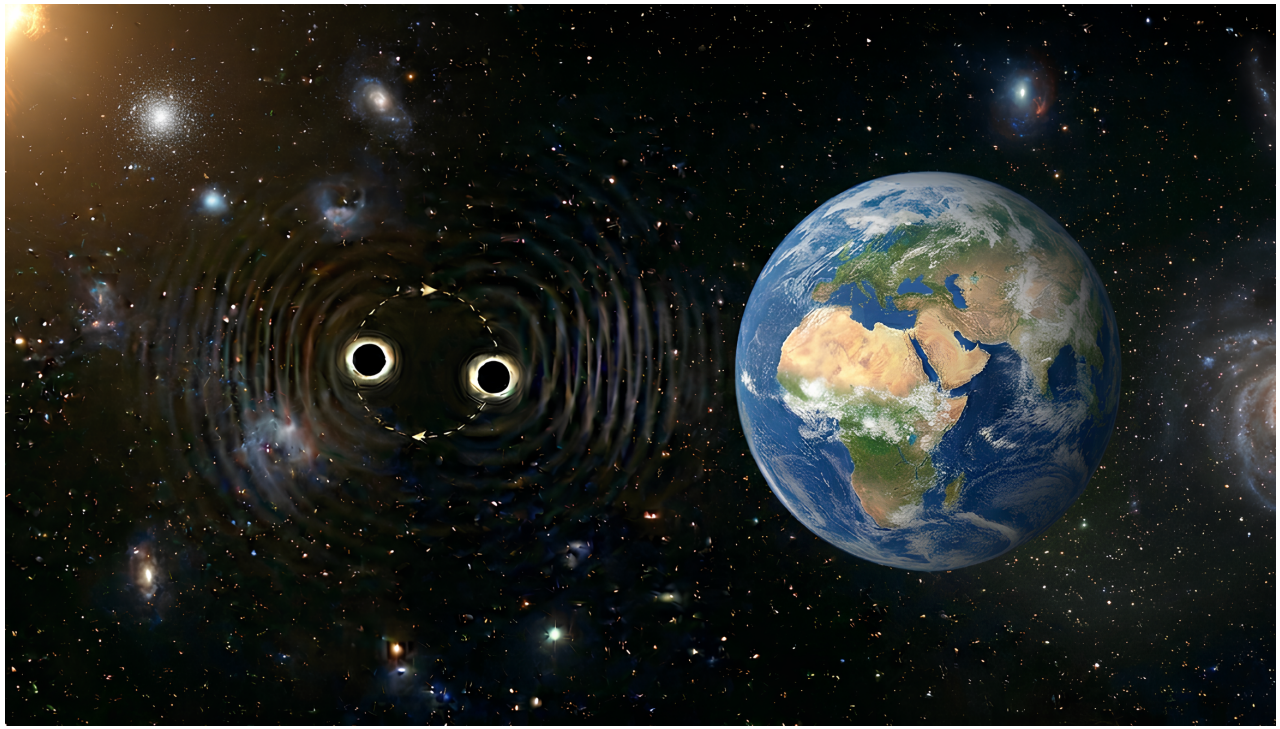
Assumptions: T=10 mK, Q=10^6, 3.5 year integration time, quantum-limited readout

[DM radio]

e.g. DM radio, ADMX-SLIC

High-Frequency Gravitational Waves

- Gravitational waves above 10 kHz: no known astrophysical origins.



- **Inverse Gertsenshtein effect**:

$$\frac{1}{2} h^{\mu\nu} T^{\mathrm{EM}}_{\mu\nu} \to J^{\mu}_{\mathrm{eff}} = \partial_{\nu} \left(\frac{1}{2} h F^{\mu\nu} + h^{\nu}{}_{\rho} F^{\rho\mu} - h^{\mu}{}_{\rho} F^{\rho\nu} \right).$$

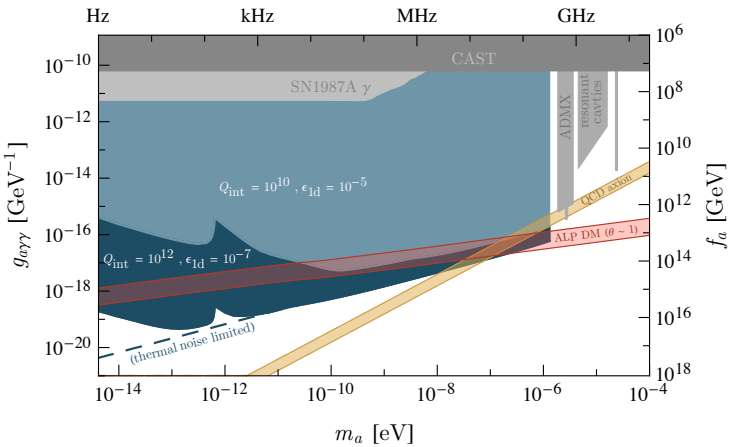
- **Mechanical resonance**: cavity deformation and mode transition, [MAGO 2.0].

Heterodyne Upconversion

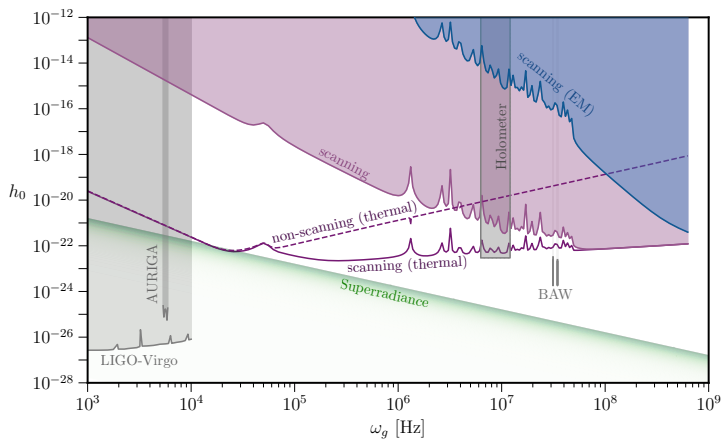
- **Heterodyne upconversion** [Goryachev et al 19', Berlin et al 19' 20', UPLOAD 19' 23']:

  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'].

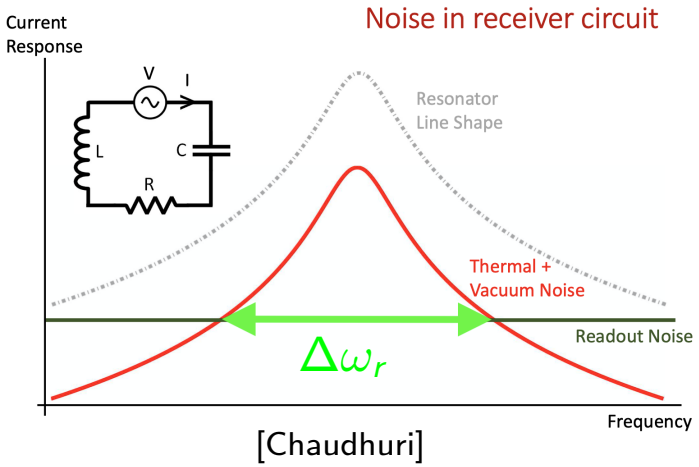
Standard Quantum Limit for Resonant Detection

- **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 $S_{\rm int} \gg S_{\rm r}$.



[Chaudhuri]

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

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

  Optimizing readout coupling $Q_{\rm cpl}$ to maximize $\Delta\omega_r$.

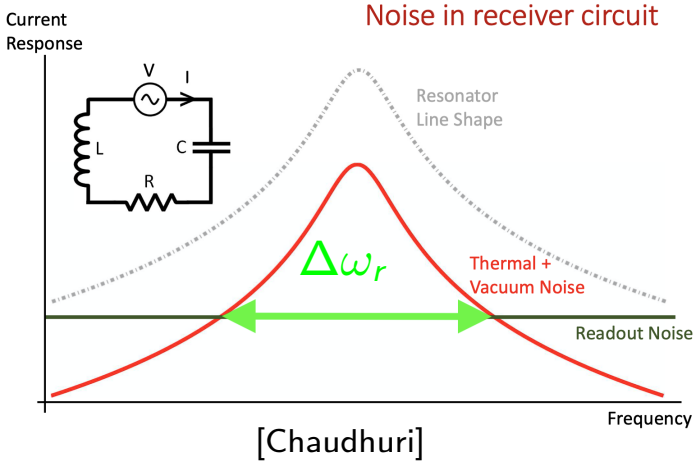
Beyond Standard Quantum Limit

- **Power law detection**:

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

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

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



[Chaudhuri]

$S_{\rm int} \propto$ 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.

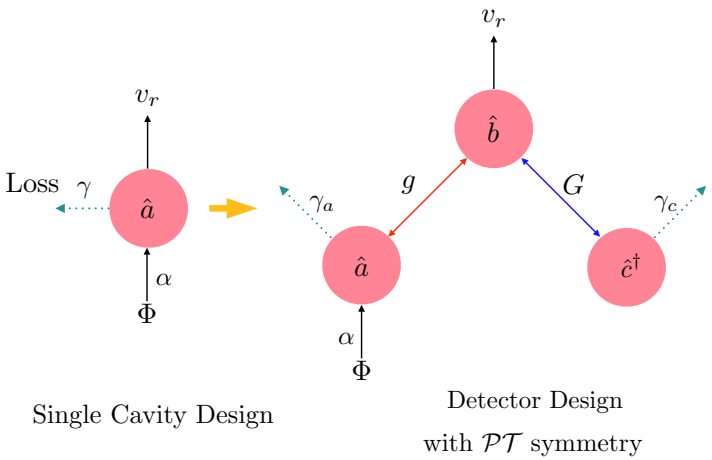
PACS: 07.60.Ly; 42.50.Ar; 95.30.SF
Keywords: Atomic phase coherence; Gravitational wave detector; White-light cavity; Negative dispersion; Vanishing absorption; Four-level system

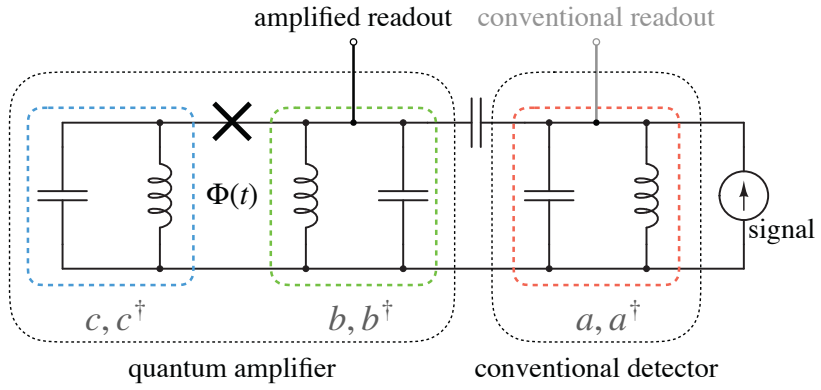
- Negative dispersion medium cancels the frequency-dependent **phase shift**:

  Achieves simultaneously large response and broad bandwidth.

- Microwave cavity?

White Light Haloscope [Li et al 20']





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

Simultaneous Resonant and Broadband Detection

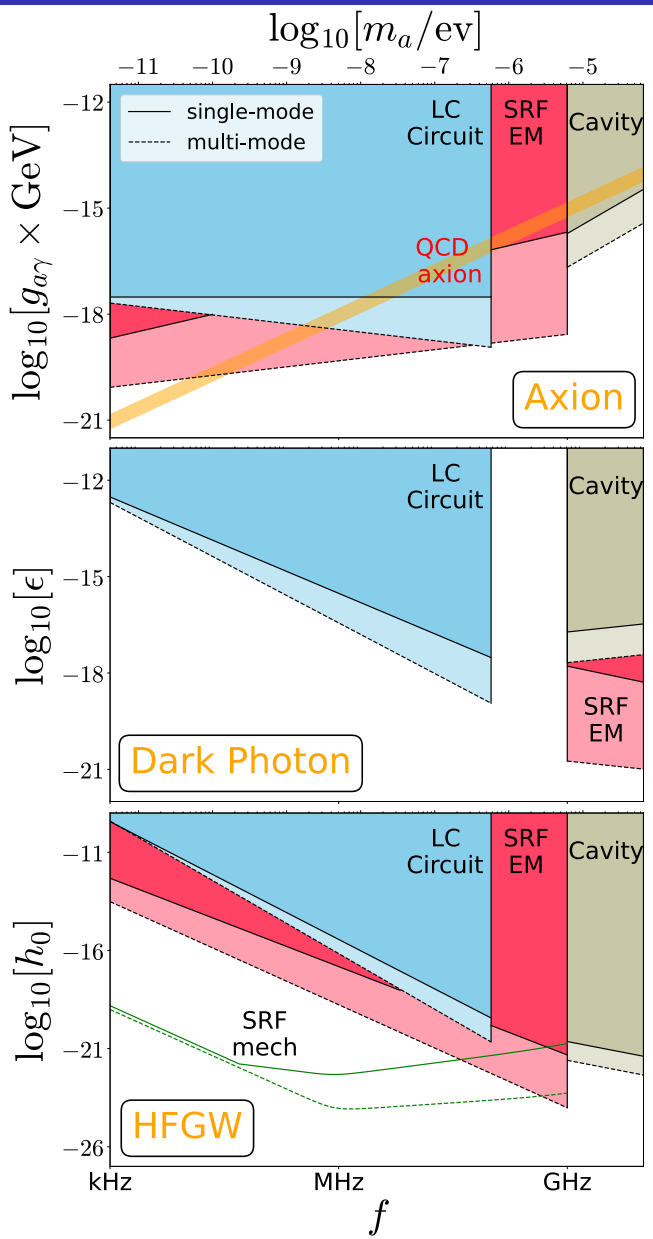
- ***e*-fold time:** 10^7 **s**.
- **Solid lines**: **single-mode resonators**

  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**:

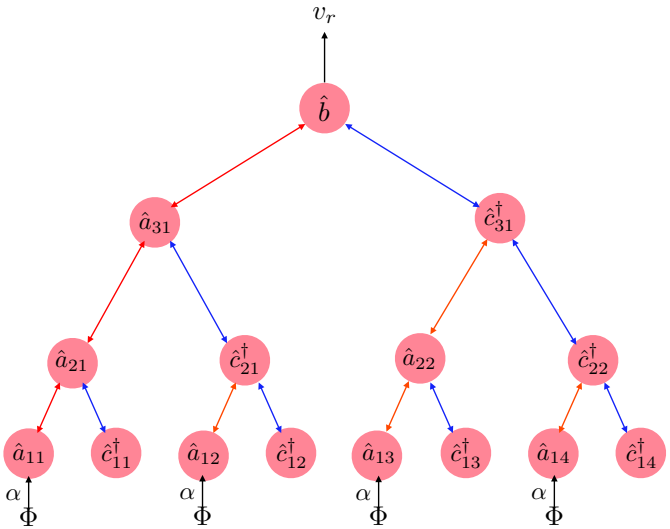
$$\frac{\mathrm{SNR}^2_{\rm MM}}{\mathrm{SNR}^2_{\rm SM}} \simeq \frac{Q_0}{n_{\rm occ}}.$$

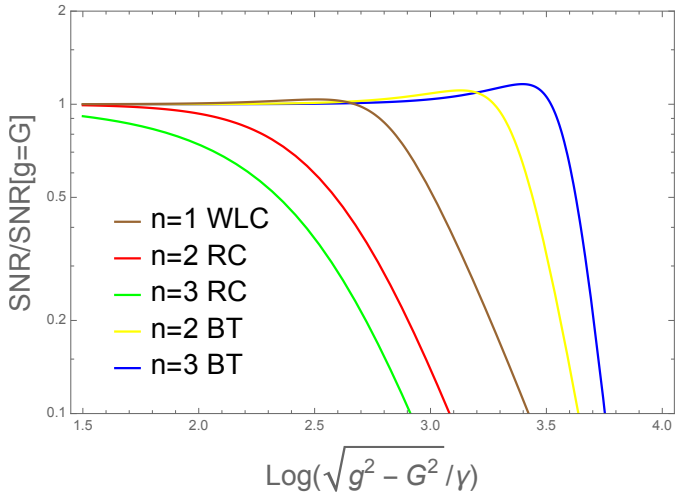
  High $n_{\rm occ}$ of LC circuits at low frequency made enhancement ineffective.



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

Binary Tree Haloscope





- **Fully $\mathcal{PT}$-symmetric setup** with $\hat{a}_{ij} \leftrightarrow \hat{c}^\dagger_{ij}$ brings strong **robustness**.

- Multi-probing sensors leads to **coherent enhancement**:

$$S^{\mathrm{BT}}_{\mathrm{sig}}(\Omega) = 2^{2n-2} S^{\mathrm{RC}}_{\mathrm{sig}}(\Omega).$$