Detecting Dark Photons with Superconducting Radio-Frequency Cavities

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based on

arxiv: 2305.09711 with Tang, Wang, Chen, Li, Yang, Feng, Sha, Mi, Shu et al

arxiv: 2309.12387 with Chen, Li, Liu, Shu, Yang

ongoing work with Chen, Li, Liu, Liu, Shu

Dark Photons

- Dark photons: gauge boson of a hidden $U(1)$ symmetry
- Weak coupling with Standard model:

  kinetic mixing with photon: $\epsilon F^{\mu\nu} F'_{\mu\nu}$

  coupling with fermion, e.g.: $F'_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$, $F'_{\mu\nu}\bar{\psi}\sigma^{\mu\nu} i\gamma^5\psi$
- Various possible production mechanism

  candidates for wavelike dark matter

  relativistic background:

  e.g. decay from dark matter, thermal relics from the early universe, etc
- Polarization degree of freedom: more information to study

Detection methods of Dark Photons

Electromagnetic resonator:

- RF cavities, e.g.:

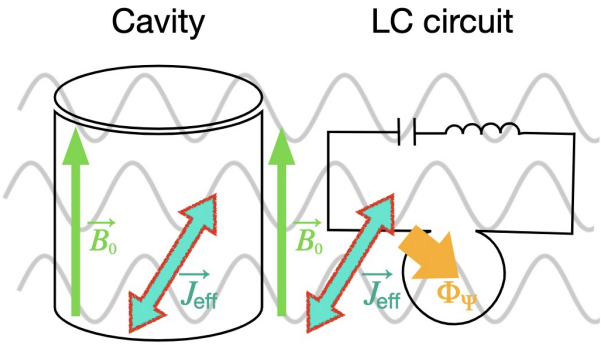
  SQMS [Cervantes et al 22']

  Dark SRF [Romanenko et al 23']

- LC circuit, e.g.:

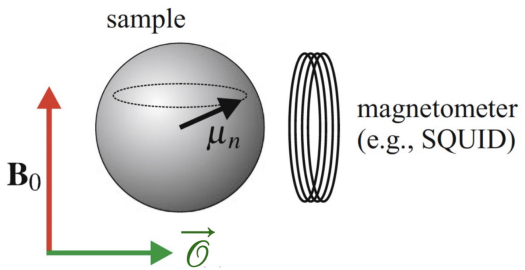
  DM Radio [Chaudhuri et al 15']

- Optomechanics [Graham et al 15']



Spin precession:

- CASPEr [Graham, Budker et al]



- Spin-based amplifier [Jiang, Peng, et al, USTC]

Cavities to Detect Dark Photons

- Modify Maxwell equations as an effective current $\vec{J}_{\text{eff}}$

  $\nabla \times \vec{B} = \partial_t \vec{E} + \vec{J} + \epsilon m_{A'}^2 \vec{A}'$

  No background $\vec{B}_0$ needed

- $H_{\text{int}} \propto \vec{E}_{\text{rf}} \cdot \vec{J}_{\text{eff}} \rightarrow$ **vector sensor**, sensitive to a specific direction

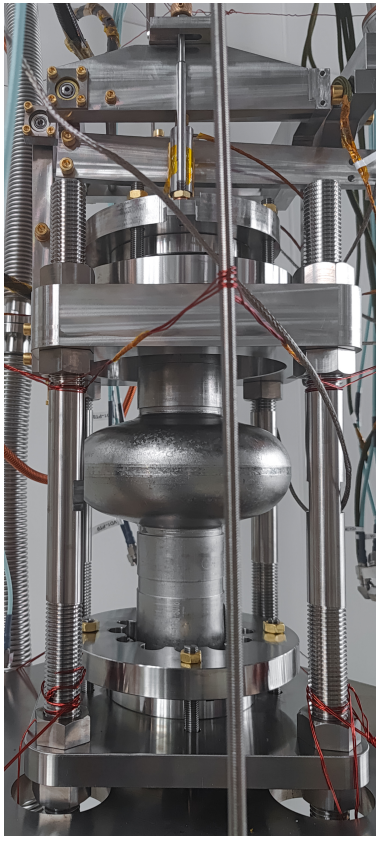
- $\vec{J}_{\text{eff}}$ excites cavity mode $\vec{E}_{\text{rf}}$:

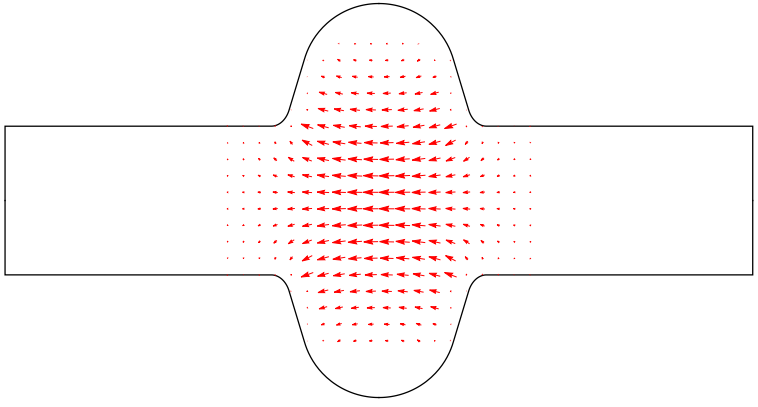
  Resonantly enhanced when $\omega_{\text{rf}} = \omega_{A'}$

  the signal characterized by **overlapping factor**

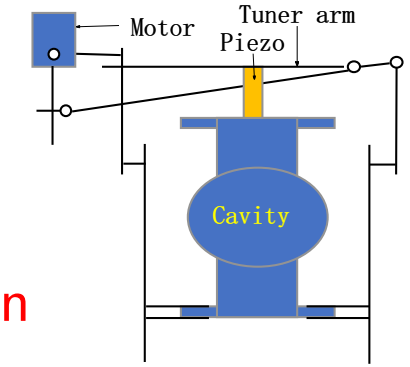
First Scan Search for DPDM with SRF cavities

- Superconducting Radio-Frequency (SRF) Cavities:
  extremely high $Q_0 \simeq 10^{10}$ $\rightarrow$ improve $\mathrm{SNR} \propto Q_0^{1/4}$
- 1-cell elliptical niobium cavity with mechanical tuner, immersed in liquid helium at $T \sim 2\,K$
- TM_{010} mode: z-aligned $\vec{E}$, **maximizes the overlap** for dark photon dark matter (DPDM)

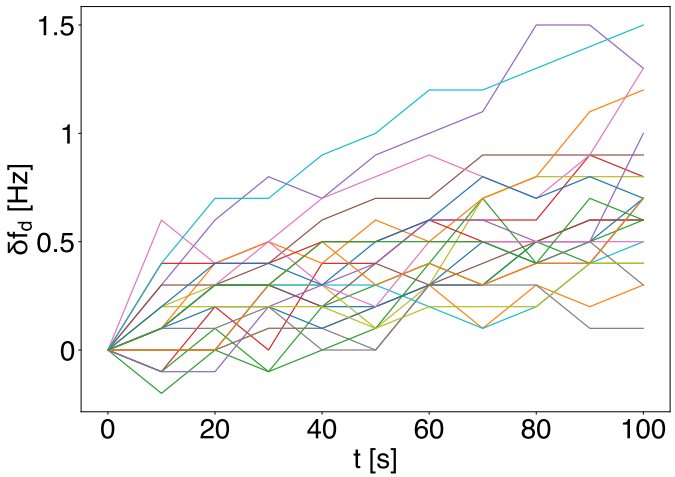


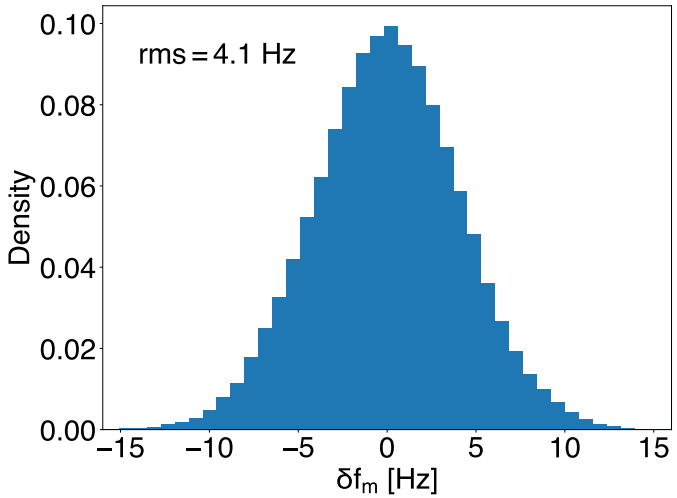


Experimental Operation



- Mechanical turner scans resonant frequency f_0 with the step $\sim f_0/Q_{\mathrm{DM}}$
- Calibrate f_0 and its stability range Δf_0 in each scan
- Frequency drift $\delta f_d \leq 1.5\mathrm{Hz}$ and microphonics effect $\sigma_{f_0} \approx 4\mathrm{Hz}$

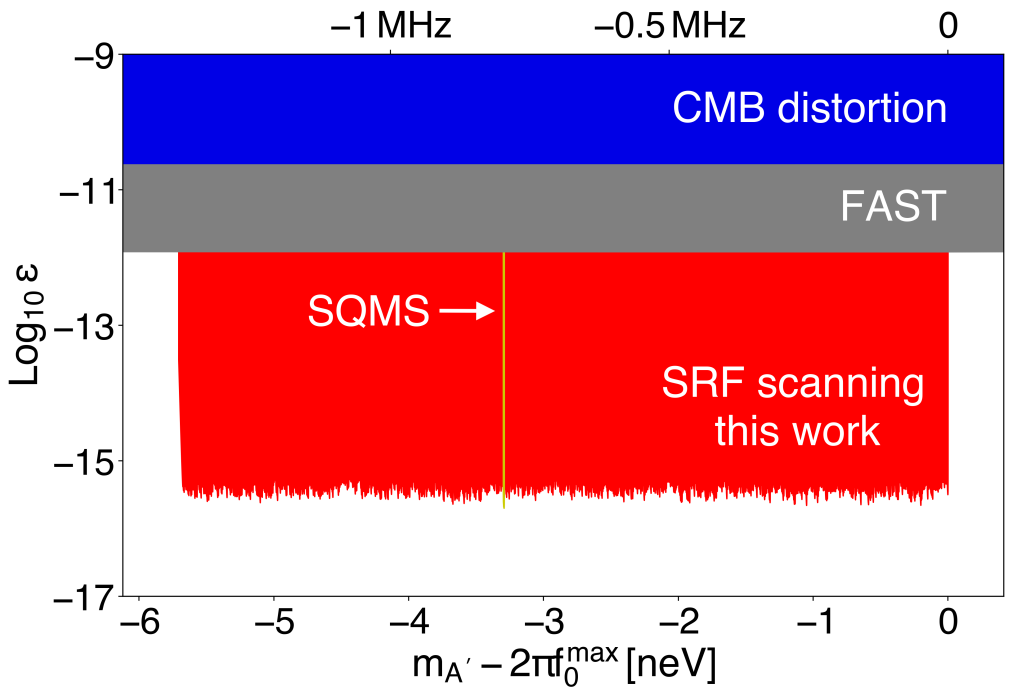




- **Conservatively** choose $\Delta f_0 \approx 10\mathrm{Hz}$ to maximize the sensitivity

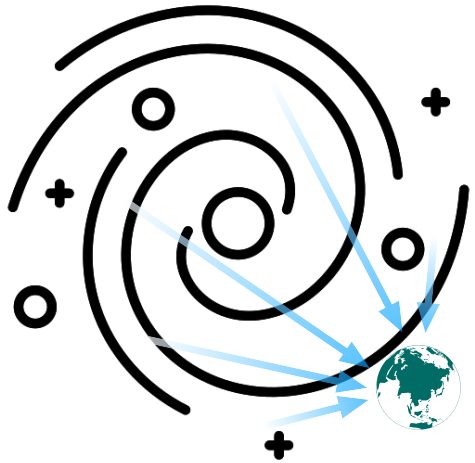
Constraints

- Scan covers $1.37\,\mathrm{MHz}$ of DPDM frequency around $1.3\,\mathrm{GHz}$
- Apply a constant fit to address small helium pressure fluctuation
- **First scan search** for DPDM and the **most stringent** constraints in most excluded regions.



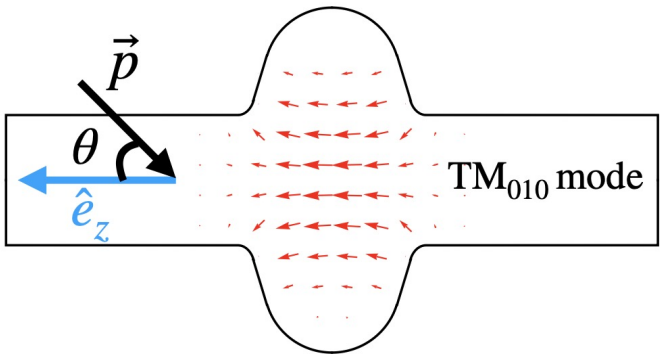
Modulated Signal from Galactic Dark Photons

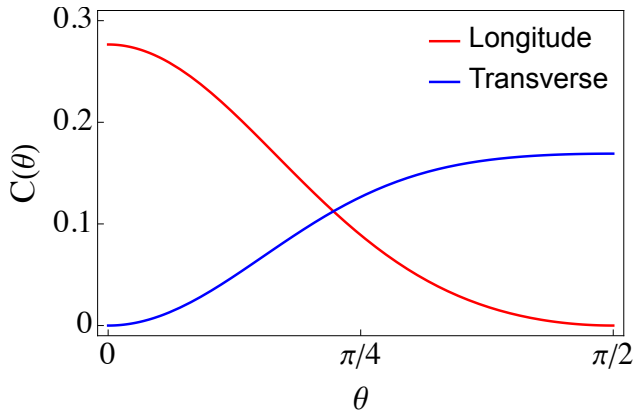
- Galactic dark photons from DM decay, e.g.:
  cascade decay from DM halo



- **Vectorial** observable $\propto \vec{A}'$
  $\rightarrow$ angular-dependent signal $\propto C(\theta)$
  $\rightarrow$ modulation as the Earth rotates

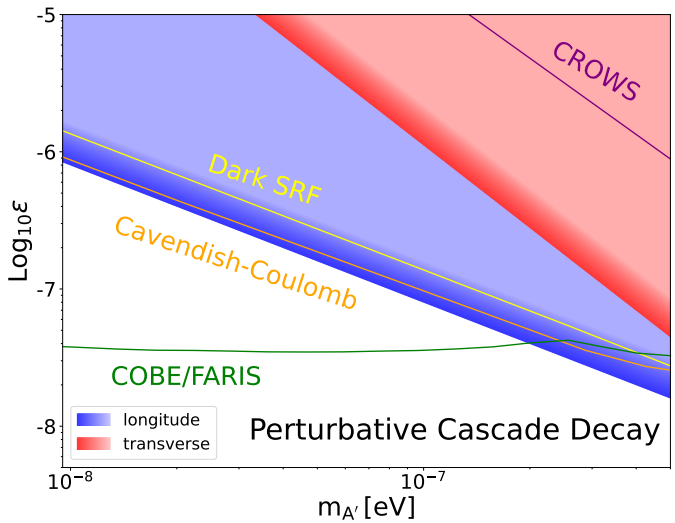
- Production is polarization-dependent, modulations for longitude and transverse modes are opposite





SRF Constraints for Galactic Dark Photons

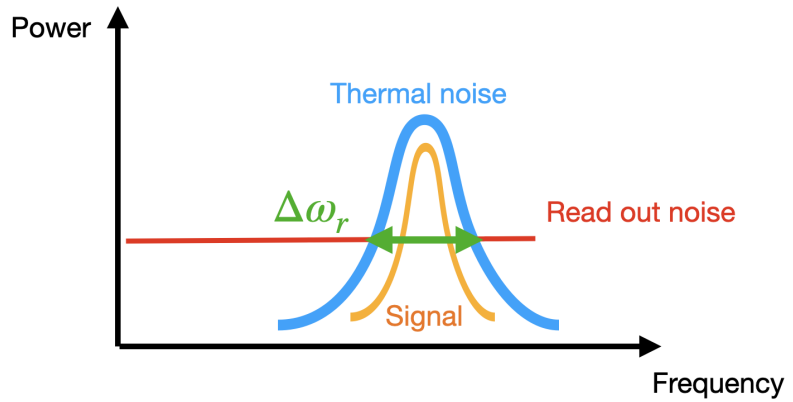
- Same dataset as DPDM search
- Scanned range within galactic dark photon bandwidth $\rightarrow$ combine all scan steps to analyze
- Longitude mode has better sensitivity because of the larger spatial wavefunction $\sim \omega_{A'}/m_{A'}$



- Gradient color region represents exclusions for different DM mass

Quantum Noise Limit in Scan Search

- Thermal noise is irreducible
- Read out part introduce extra noise
  $\rightarrow$ reduce sensitivity outside **response bandwidth** $\Delta\omega_r$



- $\Delta\omega_r$ determine the efficiency of a scan search
- How to overcome read-out noise:

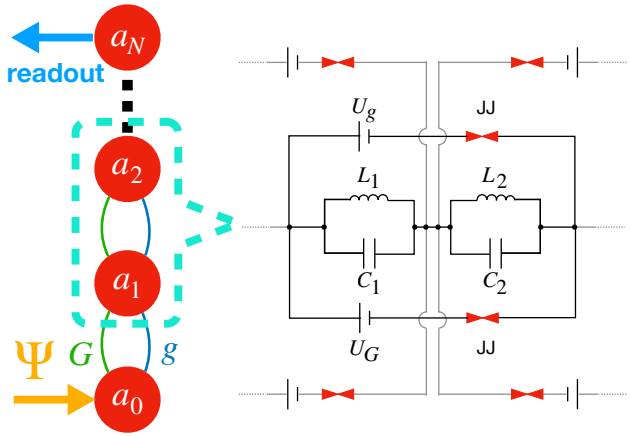
  squeezing [HAYSTAC 20']

  quantum non-demolition measurement [Dixit et al 20']

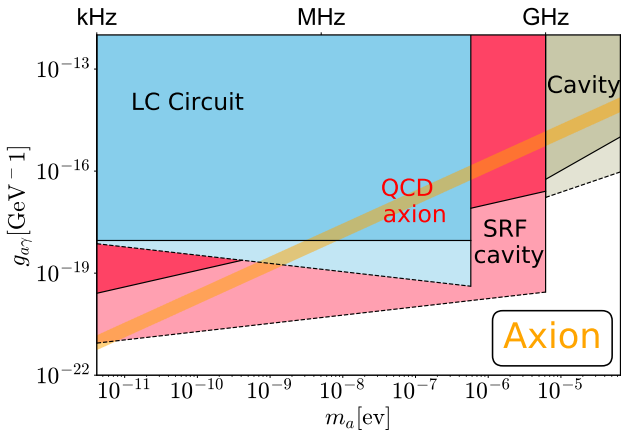
  PT-symmetric amplifiers [Li, Ma, Chen et al 20']

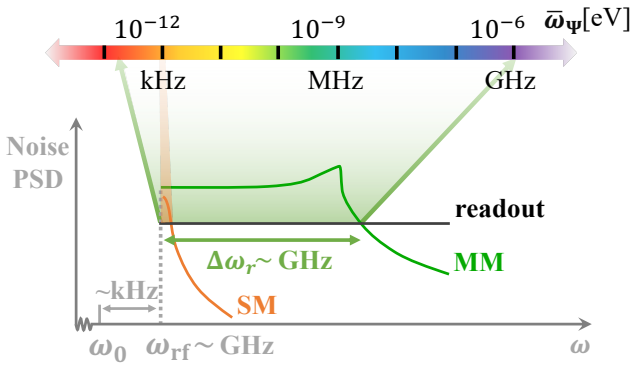
Simultaneous Resonant Broadband Detection

- A multi-mode system significantly enhances $\Delta\omega_r$
- Compatible with all EM resonators for ultralight bosons



- Scan several orders of frequency within one single step $\rightarrow$ remarkably boost scan search





Summary

- **SRF cavities** are powerful for dark photon detection.
- **The first scan search** for dark photon dark matter is conducted, which gives the **most stringent** limit in most excluded regions.
- Galactic dark photons with **rich information** can be studied by a **modulation** analysis with data in the DPDM search.
- **Connecting multiple resonators** can remarkably boost ultralight boson search.

Thank you!