Searching for Wavelike Dark Matter with SRF Cavities

APS April Meeting 4/12/2022

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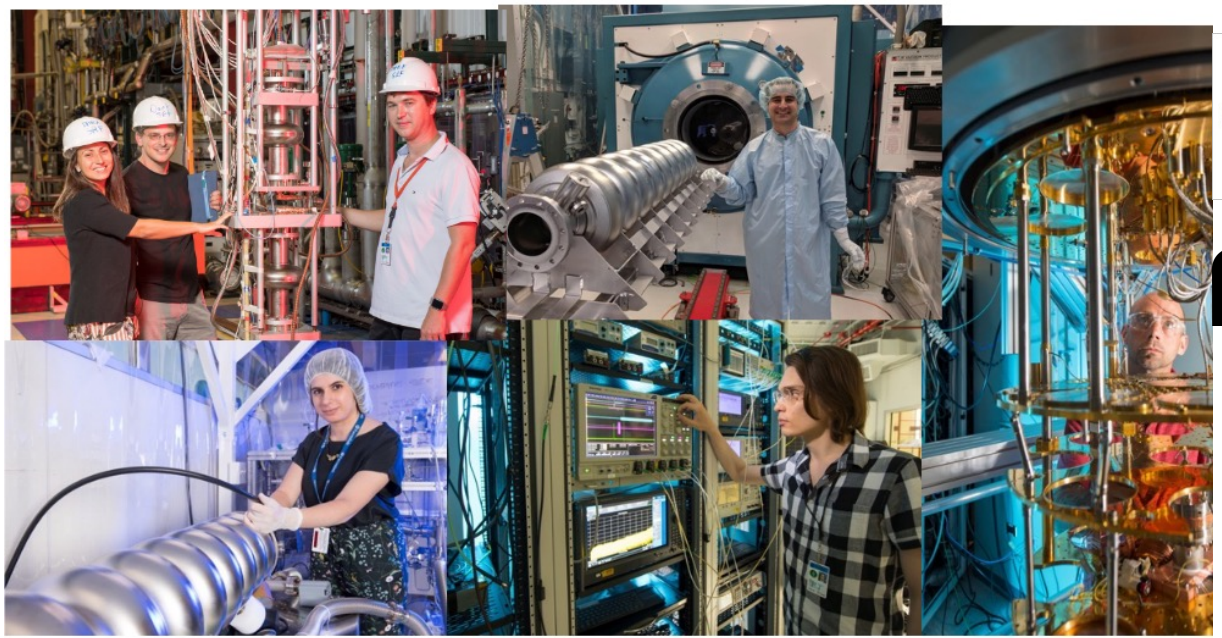
arXiv:2208.03183

SQMS and Fermilab



Credit: A. Grassellino

Partners include:

Northwestern University

RUTGERS

NIST

INFN

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

rigetti

We have $Q \sim 10^9 - 10^{10}$ cavities!

How far can we push SRF technology for BSM physics searches?

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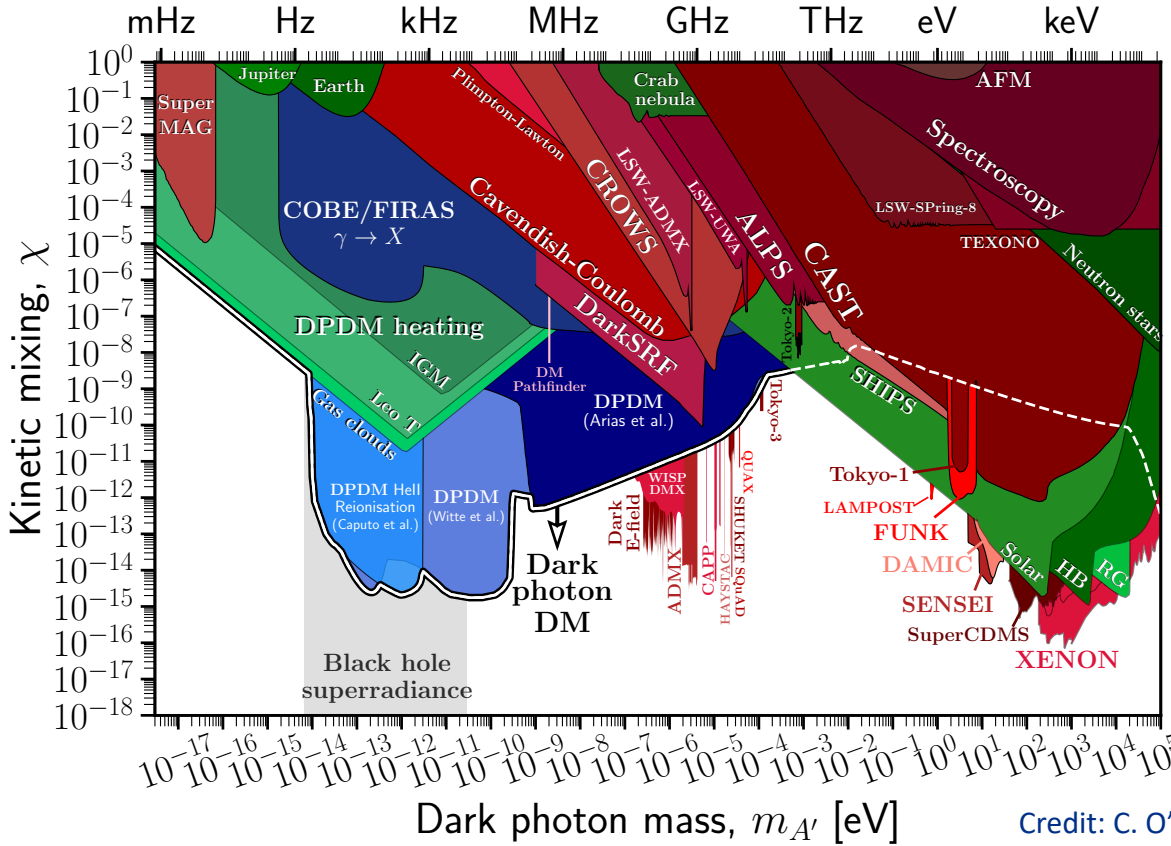
Dark Matter and Dark Photons



Credit: C. O'Hare

$$-4\mathcal{L}_{gauge} = F_1^{\mu\nu}F_{1\mu\nu} + F_2^{\mu\nu}F_{2\mu\nu} + 2\chi F_1^{\mu\nu}F_{2\mu\nu}$$

Credit: S. Ghosh

Can try to create our own (DarkSRF LSW) or detect it as dark matter.

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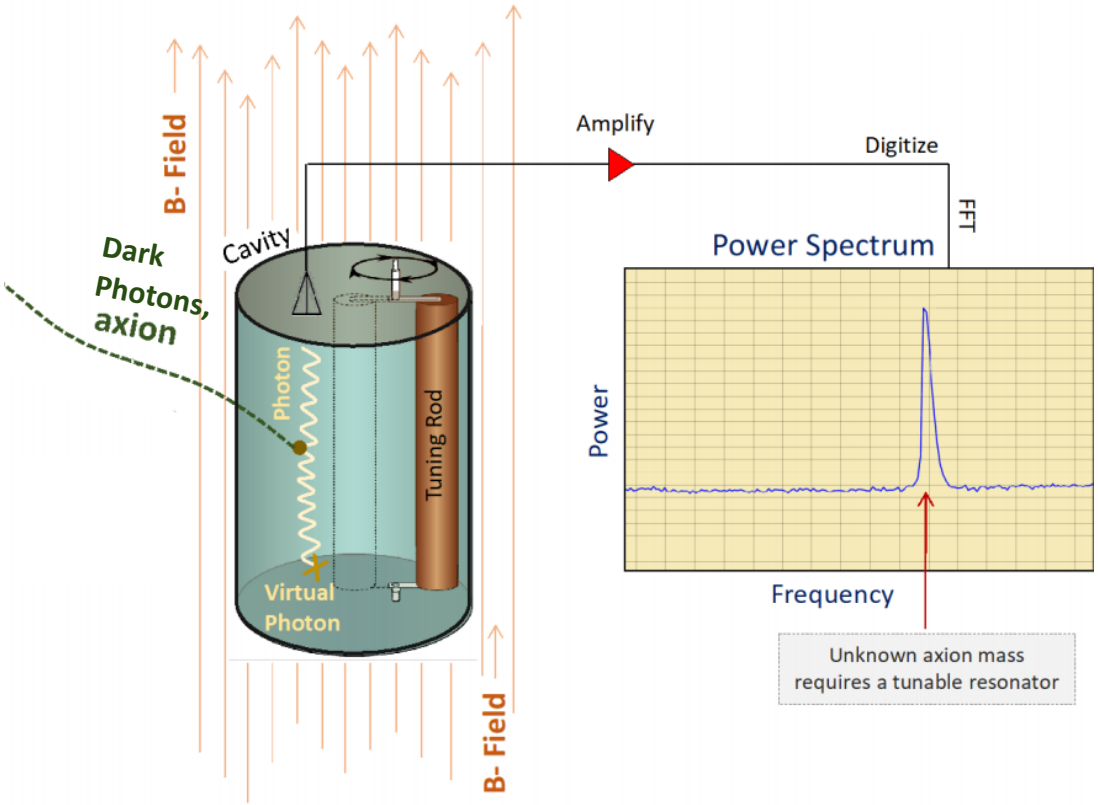
Haloscope Search for Dark Matter



Credit: C. Boutan

Microwave cavities and quantum sensors can detect dark photons and axions.

Dark photon searches don't need B-field.

Looking for $< 10^{-24}$ W signal over wide range of frequencies.

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SRF Cavity Search for Dark Photons

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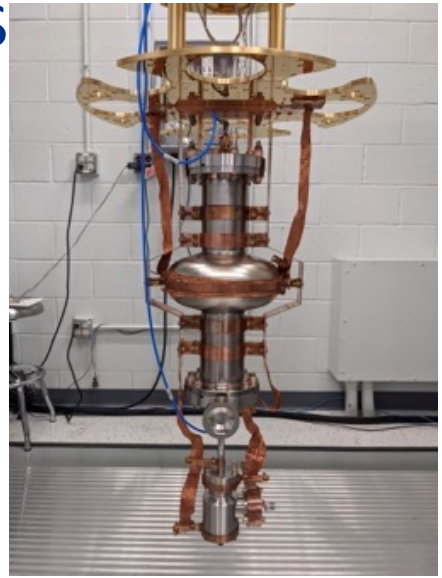


$Q \sim 10^{10}$

ADMX

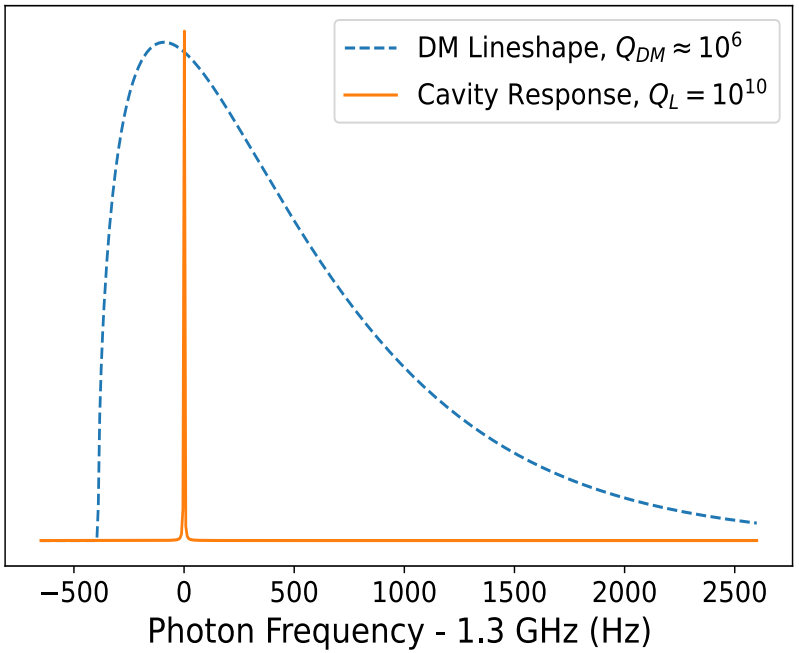
Credit: N. Du

$Q \approx 8 \times 10^{4}$

High Q allows for larger signal and lower noise floor.

Possibly factor 10^5 increase in scan rate.

Scan rate is proportional to Q_L



$$\frac{\mathrm{d}f}{\mathrm{d}t} \sim Q_L Q_{DM} \left(\frac{\eta \chi^2 m_{A'} \rho_{A'} V_{eff} \beta}{\mathrm{SNR} T_n (\beta + 1)} \right)^2$$

Even if $Q_L \gg Q_{DM}$

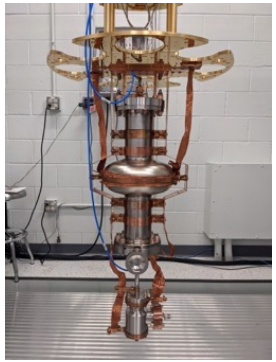
- Signal power $P_s \propto \min(Q_L, Q_{DM})$
- Noise power reduces with Q_L.
- Tuning steps $\Delta f \propto \Delta f_{DM}$. Cavity sensitive to distribution of possible DM rest masses.

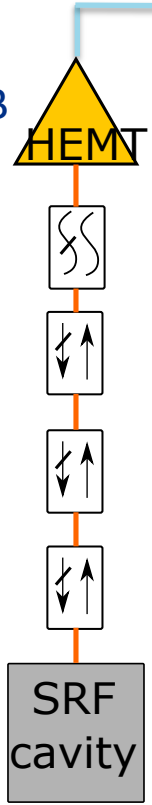
This tuning scheme would miss non-virialized DM.

Skeptical? arXiv:2208.03183

Parasitic Search for Dark Photons

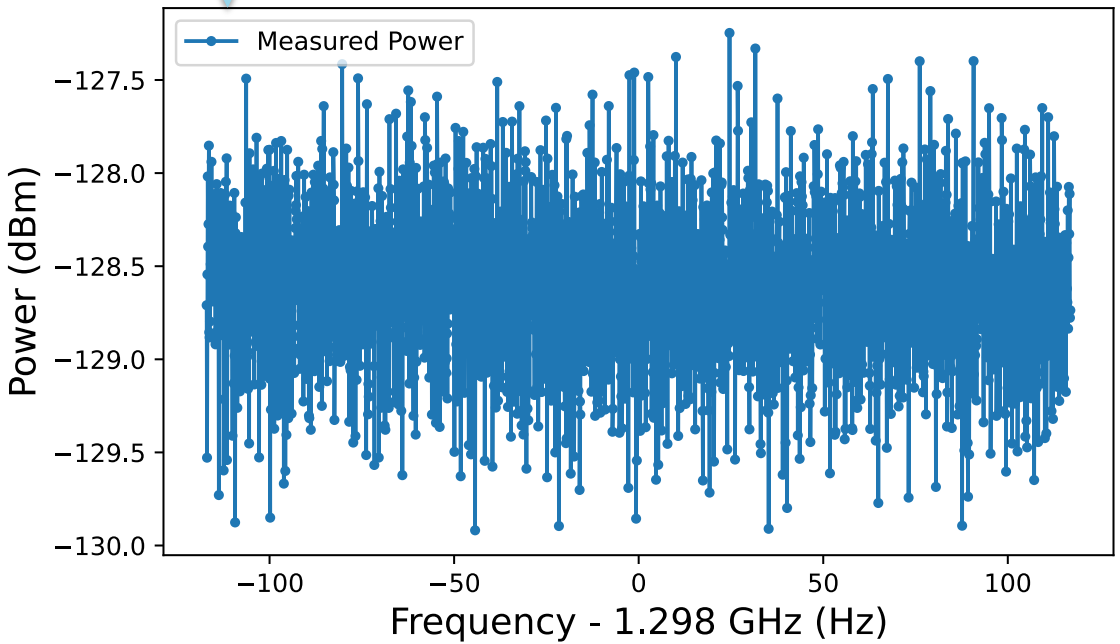
$T_a \approx 4.9$ K
G $\approx +37$ dB





$T_c \approx 45$ mK
$Q_L > 8\times10^9$
$f_0 = 1.298$ GHz

No DP signal. Just noise.



1000 seconds integration time

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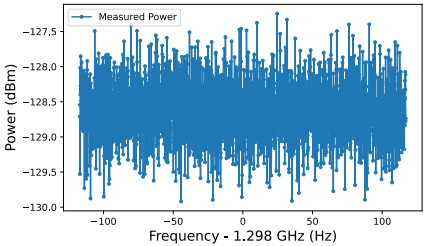
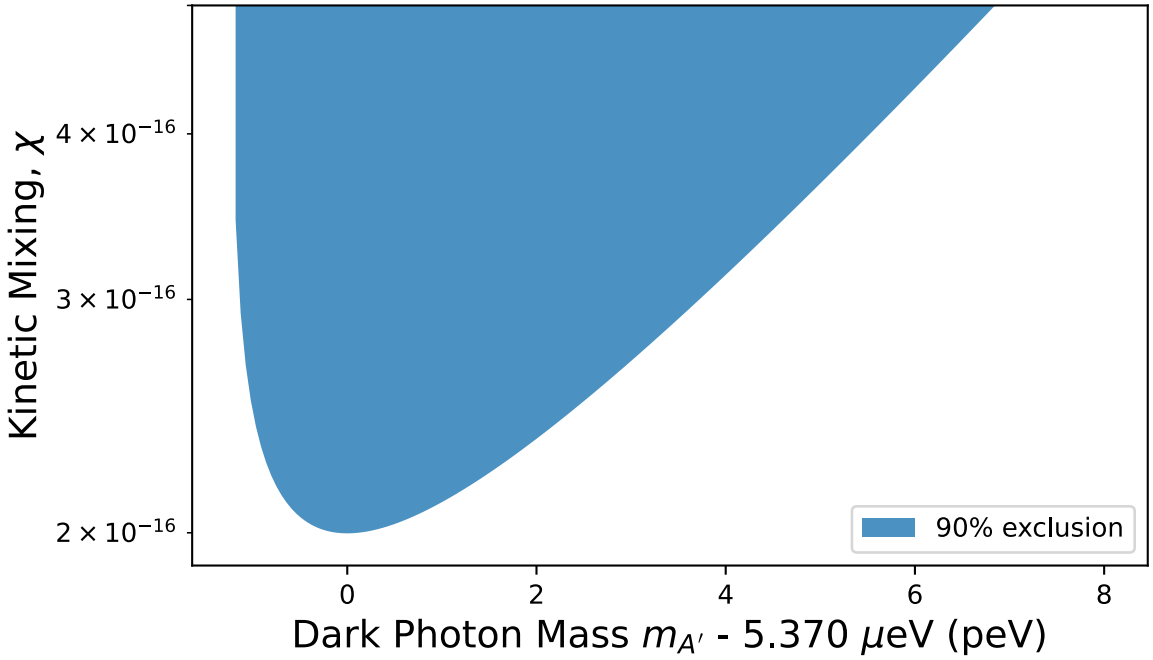
Excluded Dark Photon Parameter Space



haloscope analysis



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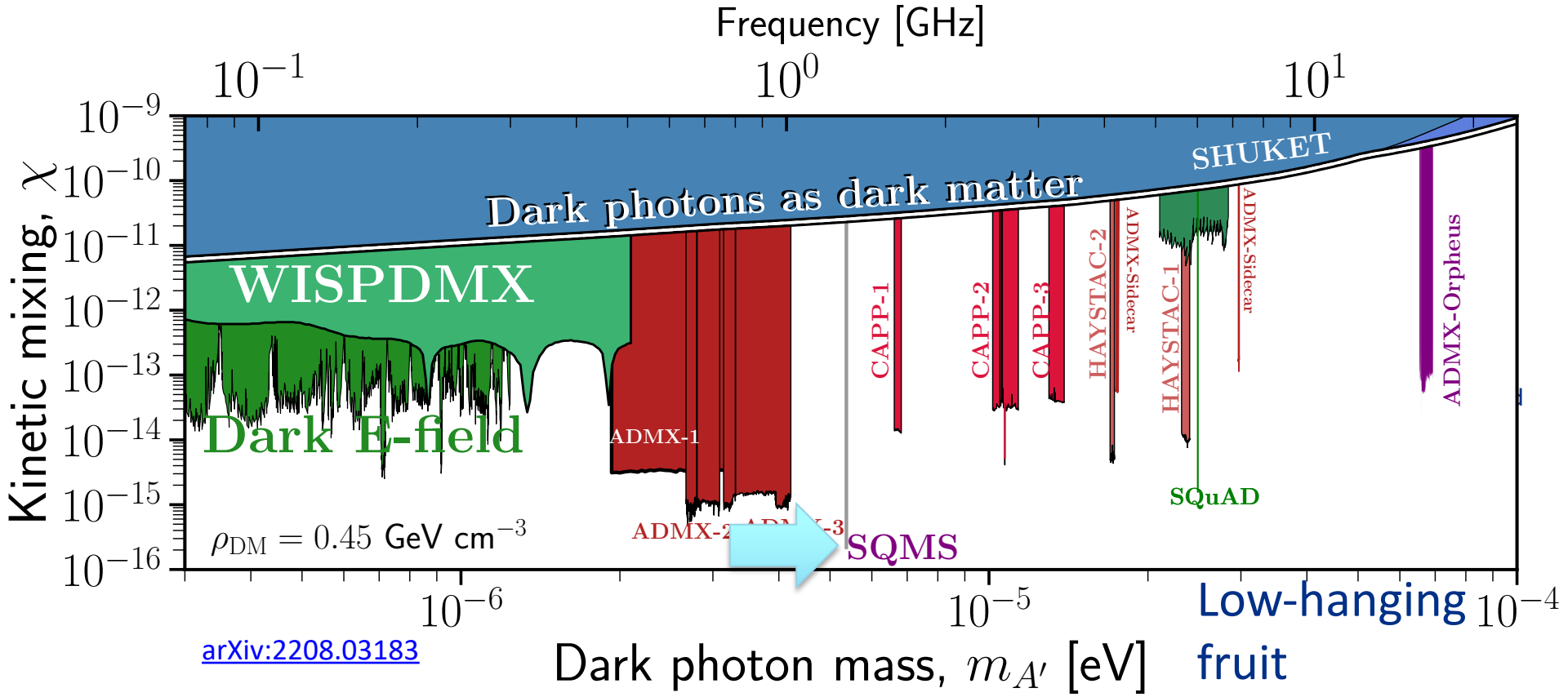
Deepest Exclusion to Wavelike DPDM



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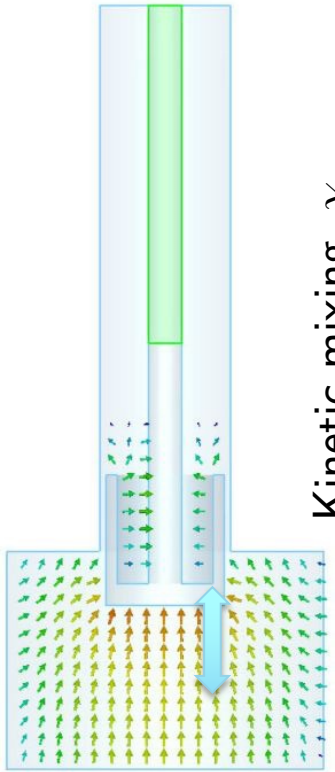
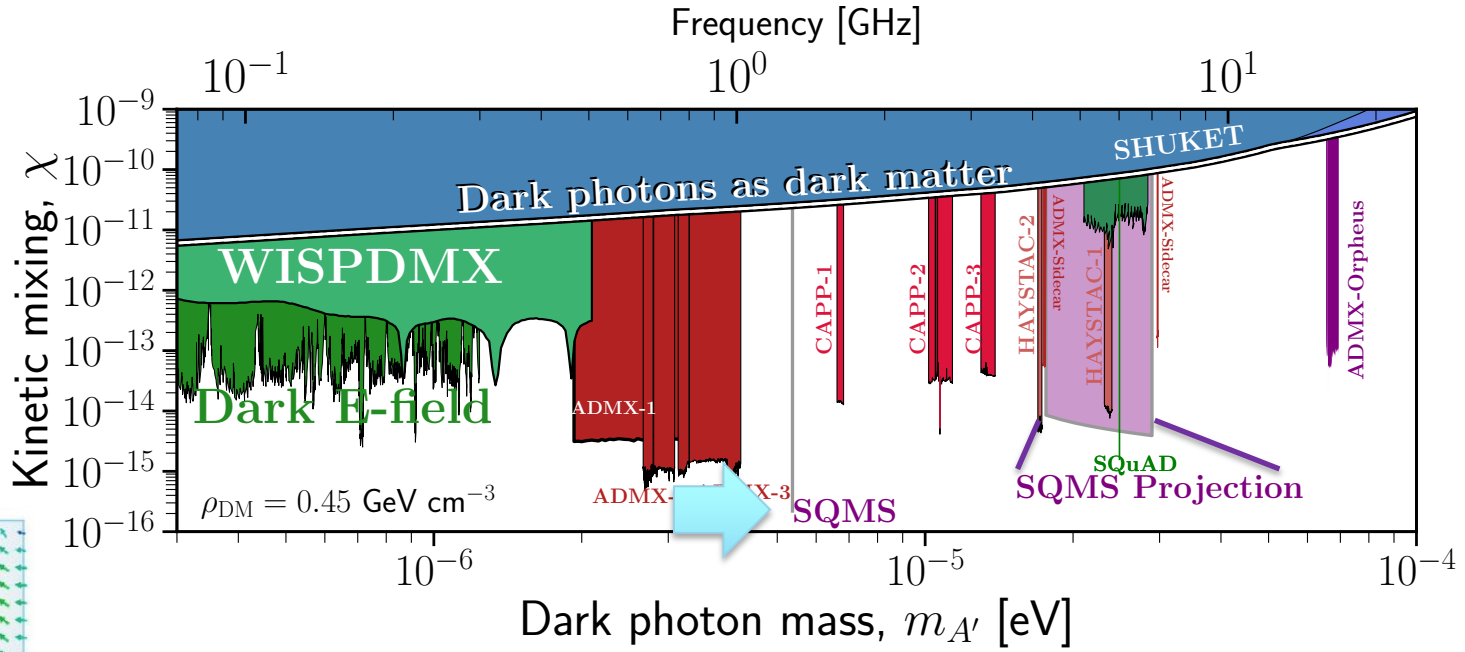
Developing Widely Tunable SRF Cavity



"plunger" cavity



Future: sub-SQL metrology with transmon qubit.

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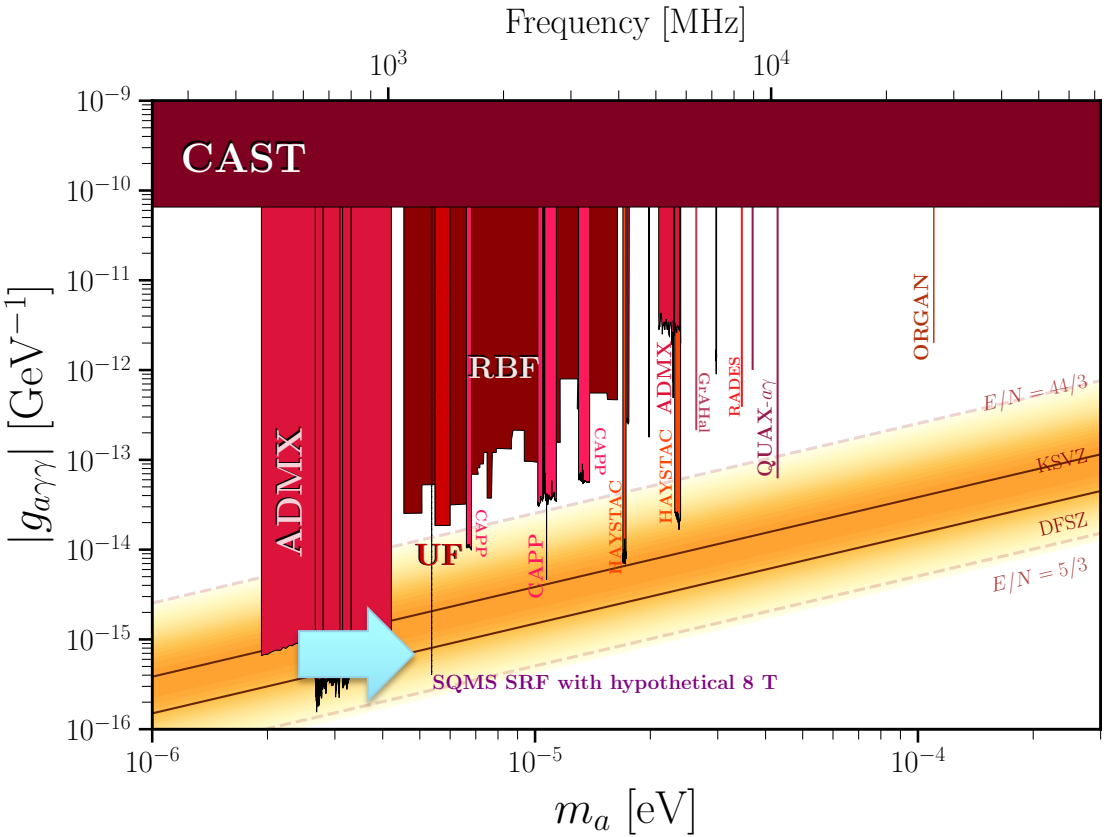
If this would work in an 8T field



Sensitivity to **QCD axion** with single cavity and HEMT.

Just make $Q \sim 10^{10}$ cavities work in magnetic fields!

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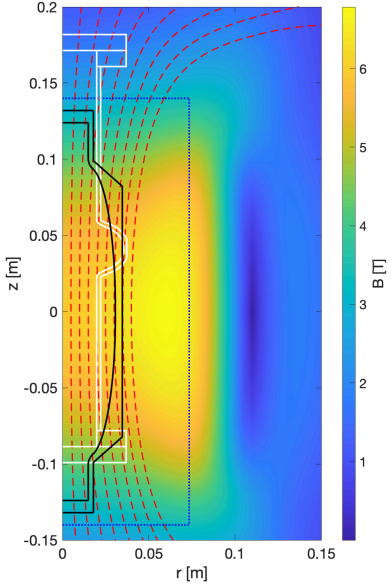
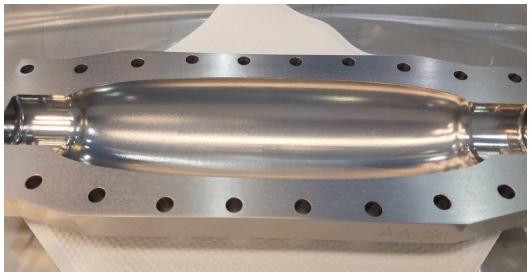
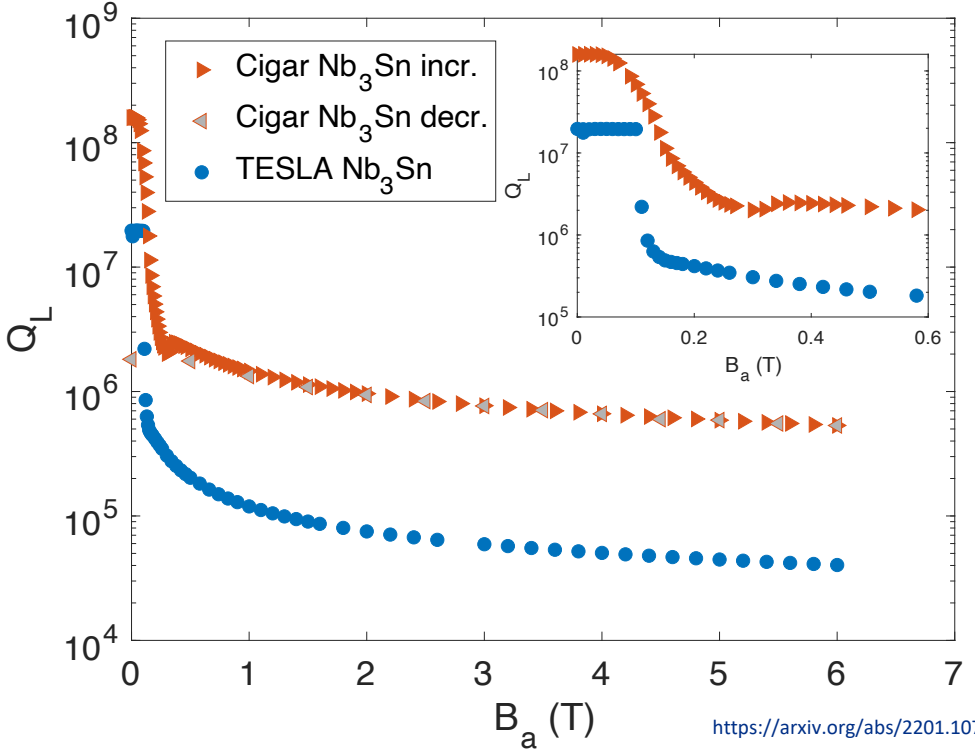
Progress towards high Q cavities for Axion Searches







https://arxiv.org/abs/2201.10733v2

Also advances by ADMX, CAPP, INFN, LLNL, and U. Chicago

With room for improvement

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Practical considerations for SRF haloscopes

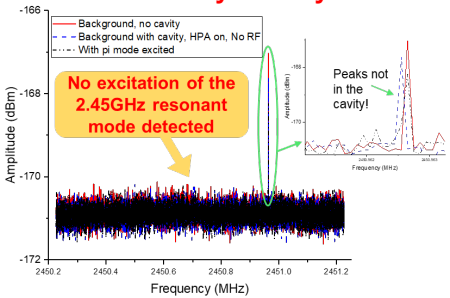
- Achieving higher Q despite TLS dissipation.
- Microphonics can introduce modulation effect that spreads signal over greater bandwidth.
- Ring down/ring up time may be $\tau > 10$ s. Harder to operate and characterize.
- Tuning strategy may not capture non-virialized dark matter.

Other SRF Axion Searches at SQMS

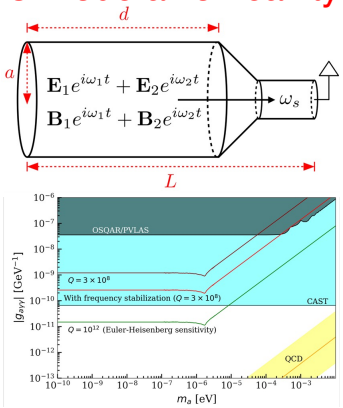
SQMS Physics & Sensing researchers are working on developing searches for axions, ALPs and axions DM with SRF cavities:

- Conducting feasibility study on 1.3GHz 9-cell cavities in preparation for axion searches development:
  - Measure noise background in SRF cavity
  - Study possible energy leak from excited mode(s) to other resonant modes or to linear combinations of pump modes (Non-linear Meissner effect)
- Working on the **design of the high Q SRF cavities for axion and axion DM searches**

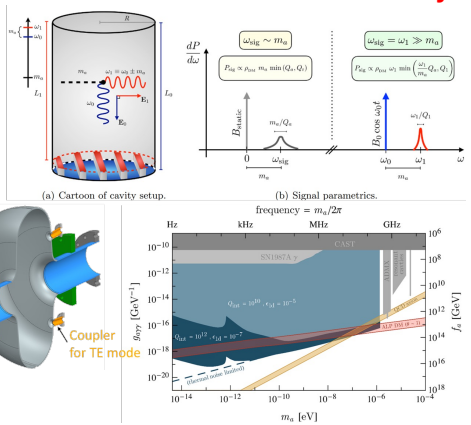
Feasibility study



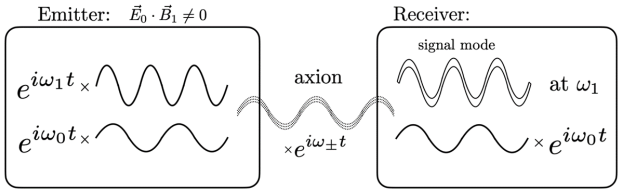
3-mode axion cavity



2-mode axion DM cavity



LSW axion search



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Berlin, *et al.*, JHEP, DOI:10.1007/JHEP07(2020)088
Bogorad, *et al.*, PRL, DOI:10.1103/PhysRevLett.123.021801
Gao & Harnik, JHEP, DOI:10.1007/JHEP07(2021)053
Sauls, PTEP, DOI:10.1093/ptep/ptac034
Giaccone, *et al.*, *arXiv:2207.11346* (2022)

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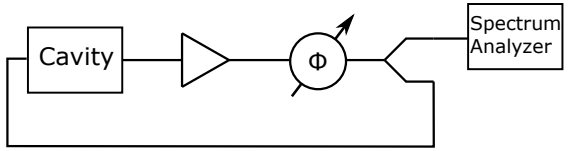
Summary

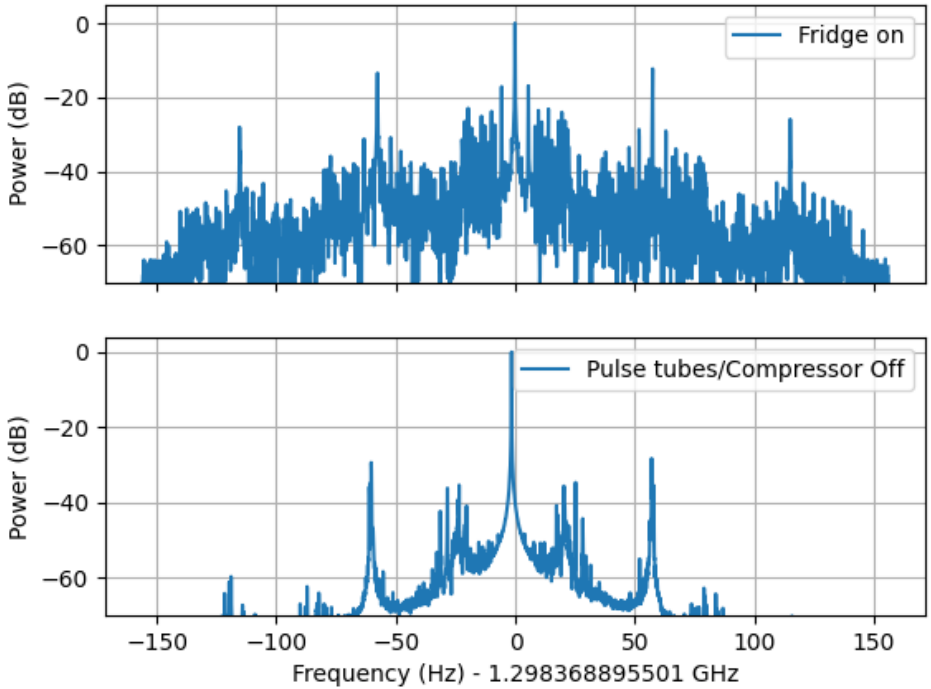
- Scan rate proportional to $Q_L$even if $Q_L \gg Q_{DM}$.
- Deepest sensitivity to wavelike dark photon dark matter with $Q_L = 10^{10}$
- Great progress developing SRF cavities for axion searches.

Backup

Debugging Microphonics



- Measured with self-excitation loop.
- Creates modulation of dark matter signal. Power gets spread into sidebands.
- Mitigated by turning off DR pulse tubes.
- Quantifiable systematic



Not expected to be a problem in future runs.

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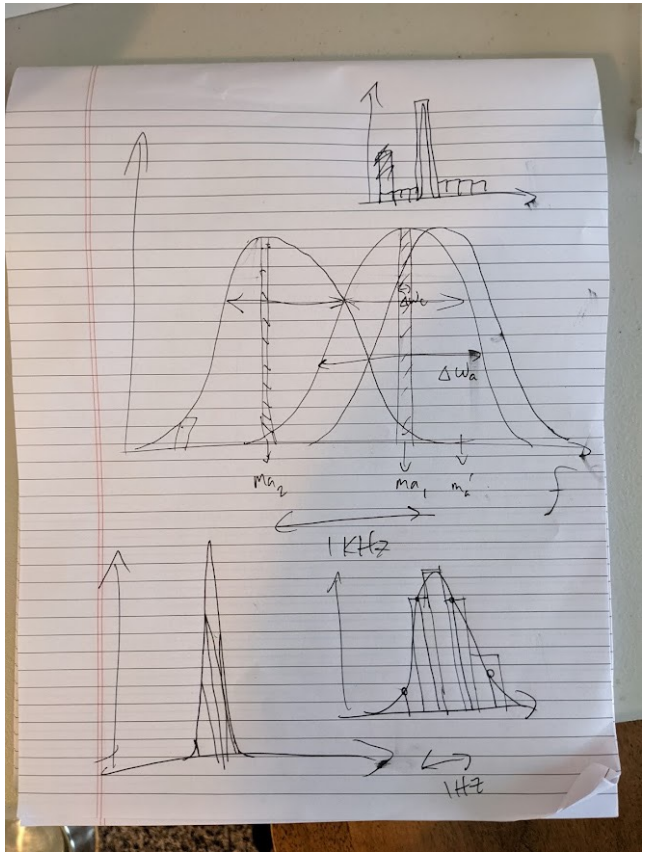
Scan Rate for Narrow Cavity Bandwidths



$$\mathrm{SNR} = \frac{P_s}{P_n}\sqrt{b\Delta t}$$

$$P_n \propto b$$

$$\text{for } Q_L >> Q_{DM}$$

$$\Delta f \propto 1/Q_{DM}$$

$$b \propto Q_L$$

$$P_s \propto Q^0$$

$$\Delta t \propto 1/Q_L$$

$$\frac{df}{dt} \propto Q_L$$