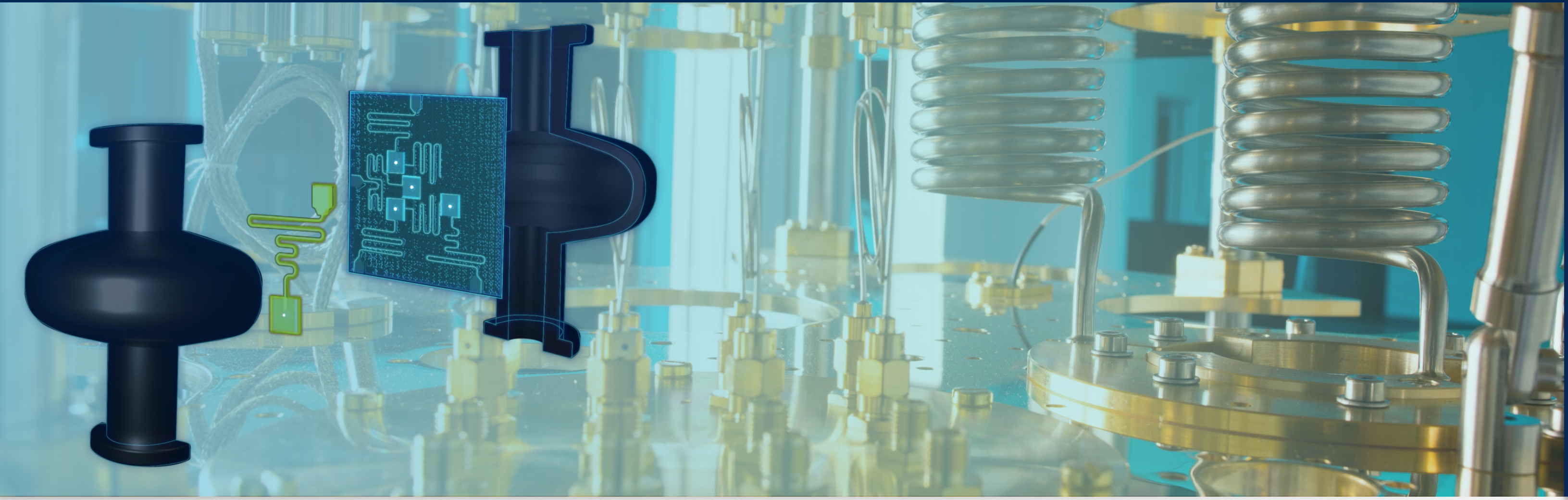
FERMILAB-SLIDES-23-173-SQMS



This material is based upon work supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Superconducting Quantum Materials and Systems Center (SQMS) under contract number DE-AC02-07CH11359

Ultra-high Q cavity-based search for the Dark Photon: new exclusion limit from Dark SRF phase 1 and step forward for phase 2

PATRAS 2023, 7/7/2023

Bianca Giaccone (Superconducting Quantum Materials and Systems Center, Fermilab)

Romanenko et al., Phys. Rev. Lett. 130, 261801 (2023)

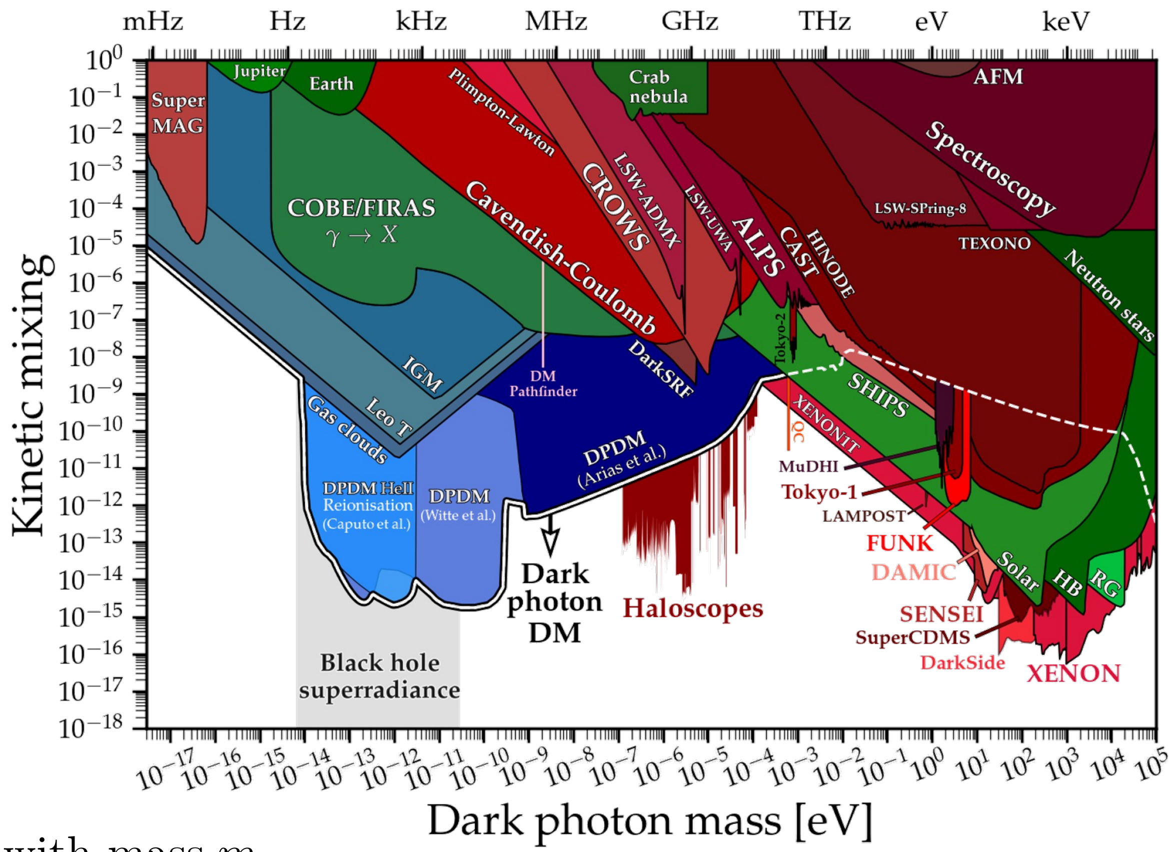
Dark Photon

Massive vector boson that interacts through kinetic mixing with the SM photon

$$\mathcal{L} \supset \text{dark photon?}$$

$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu}F^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}) + \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2_{\gamma'}A'_\mu A'^\mu + -eA_\mu j^\mu_{EM}$$

with $\begin{cases} A_\mu, F_{\mu\nu} \longrightarrow \text{SM photon} \\ A'_\mu, F'_{\mu\nu} \longrightarrow \text{hidden photon with mass } m_{\gamma'} \\ j^\mu_{EM} \longrightarrow \text{EM current} \end{cases}$



https://cajohare.github.io/AxionLimits/docs/dp.html

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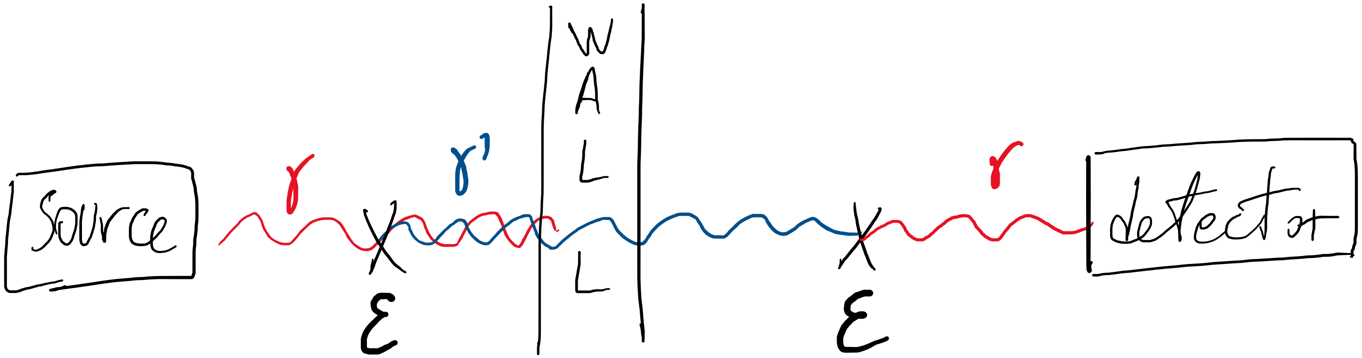
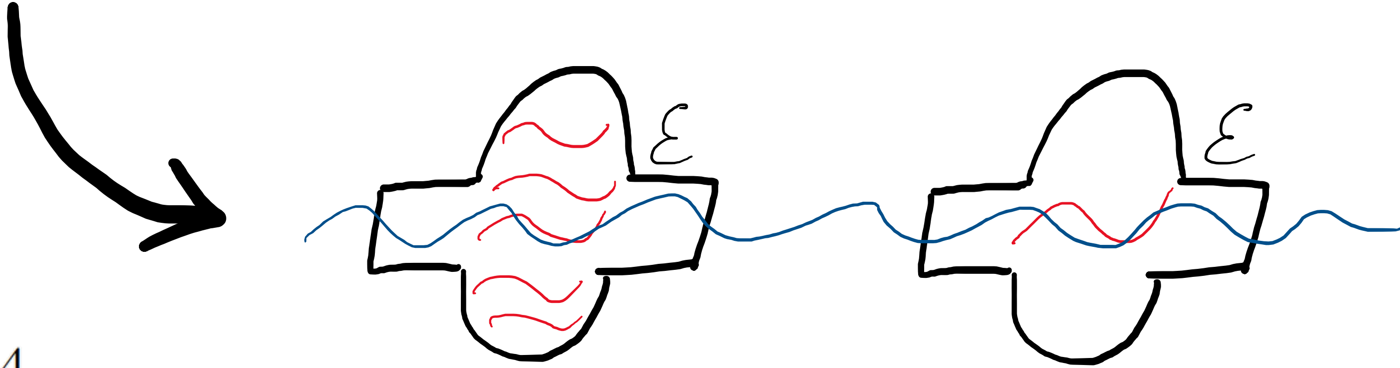
Light-Shining-through-Wall searches

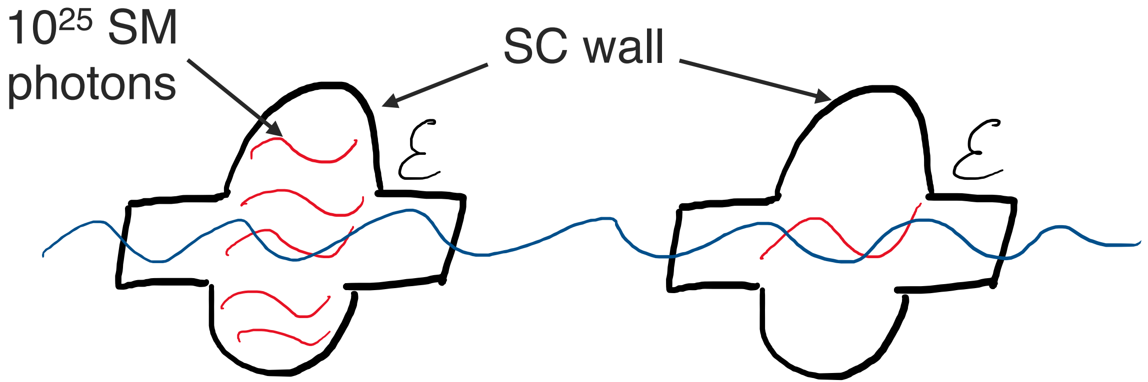




$$P_{\text{rec}} = \epsilon^4 \left(\frac{m_{\gamma'}}{\omega}\right)^4 |G|^2 \, \omega \, Q_{\text{rec}} \, U_{\text{em}}$$

Graham et al., Phys Rev D90, 075017 (2014)
Romanenko et al., Phys. Rev. Lett. 130, 261801 (2023)

Advantage of using high Q cavities



Emitter cavity,
in the accelerator regime, high field

Receiver cavity,
in the low field regime

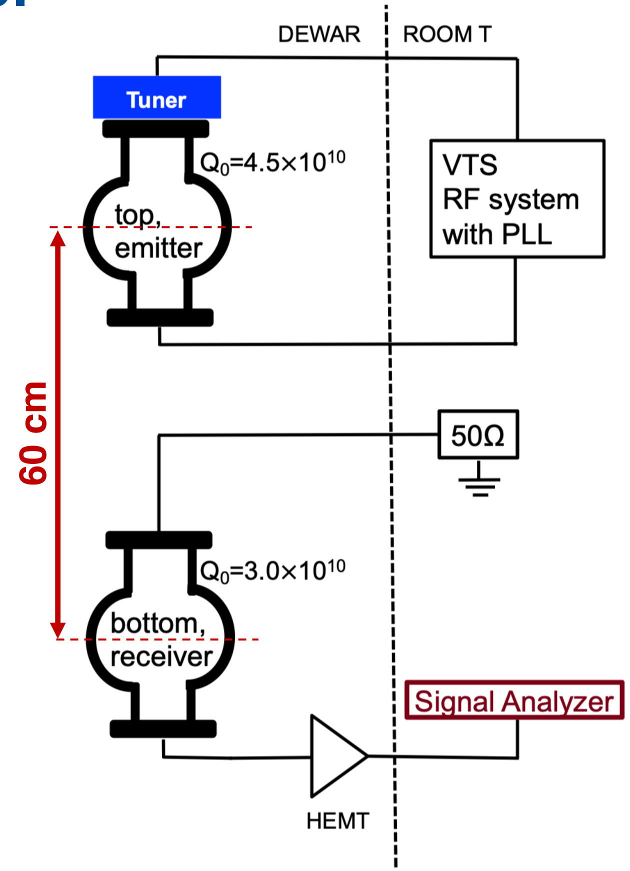
bility
ss

Necessary to match cavities frequency!

LHe vertical test stand facility at Fermilab

Dark SRF: phase 1 → measurement protocol

- 1.3GHz single cell cavities sitting in LHe at 1.3-2 K
- Cavities were characterized using accelerator style measurements and calibration
- Want to match the cavities frequency to sub-Hz level using tuner on emitter
- Many tests of frequency monitoring were conducted for both cavities to assess their stability
- HEMT on receiver P_t line → cryo amplifier to raise signal above Room Temp background



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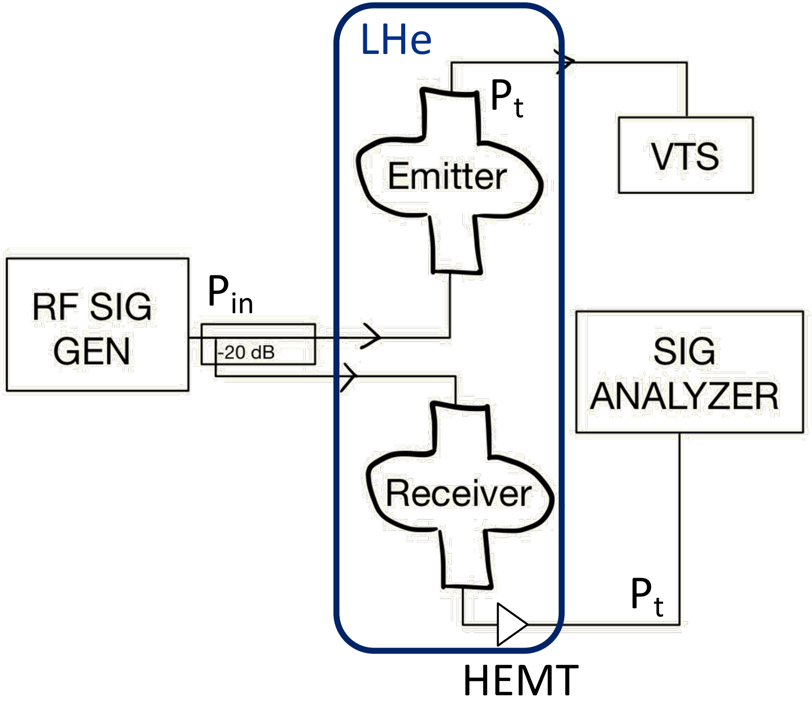
Dark SRF: phase 1 → measurement protocol

1. Excite emitter to desired field and match its frequency to receiver
2. Search for Dark photon for ~30min
3. Verify frequency matching
4. Cross-talk check
5. Thermal background check

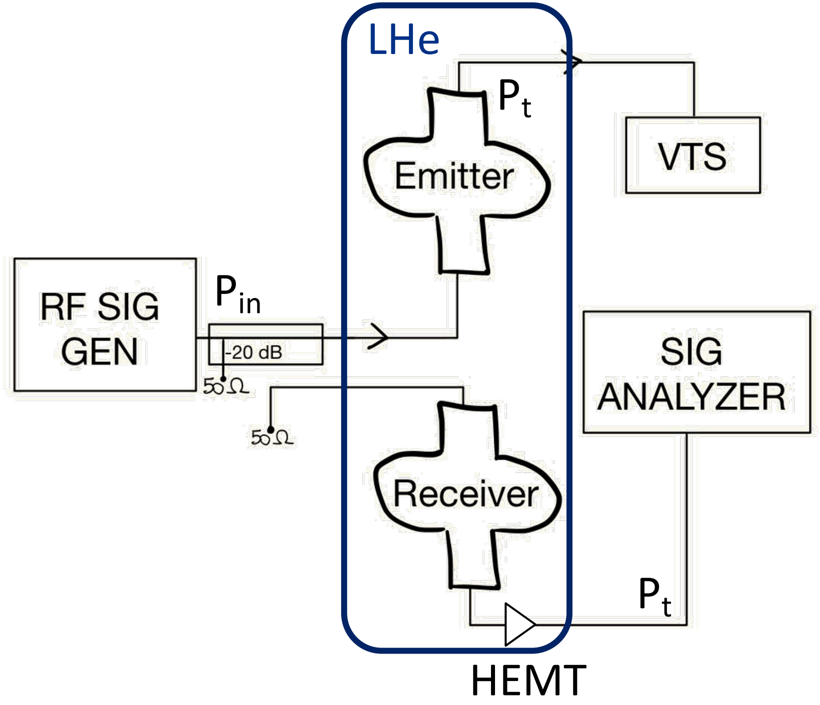
Step 1 & 3



Dark SRF: phase 1 → measurement protocol

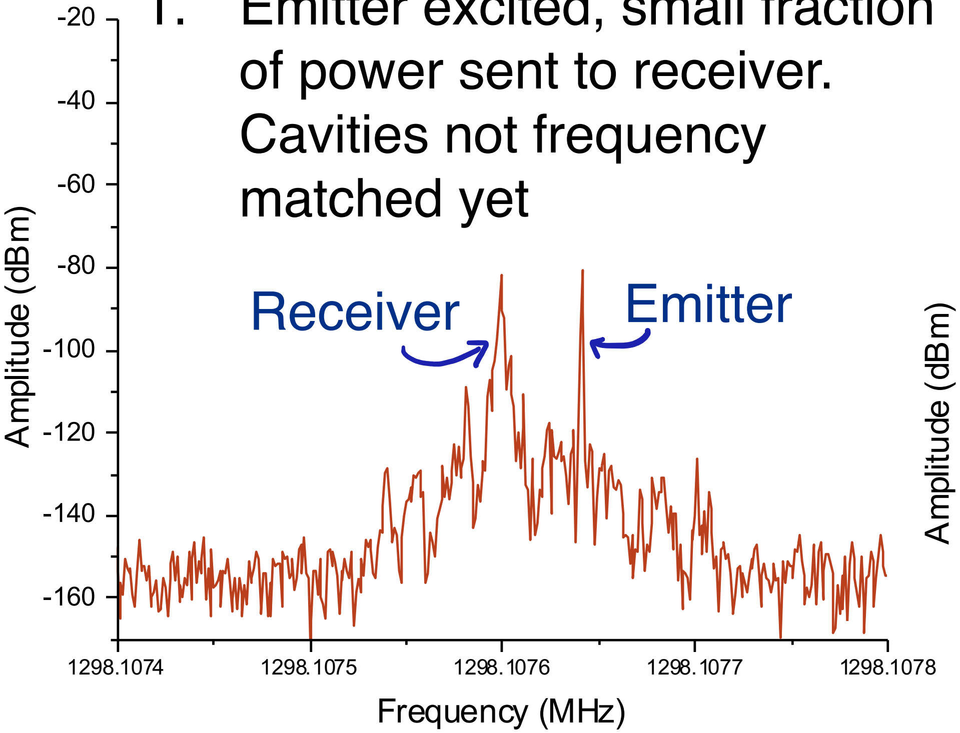
1. Excite emitter to desired field and match its frequency to receiver
2. Search for Dark photon for ~30min
3. Verify frequency matching
4. Cross-talk check
5. Thermal background check

Step 2, 4, 5

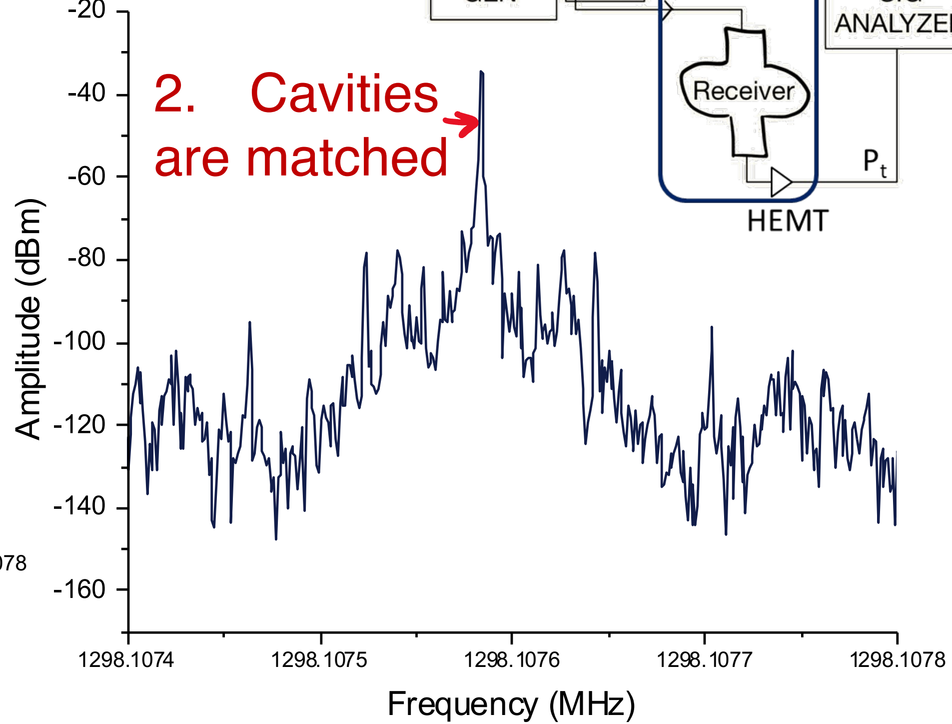


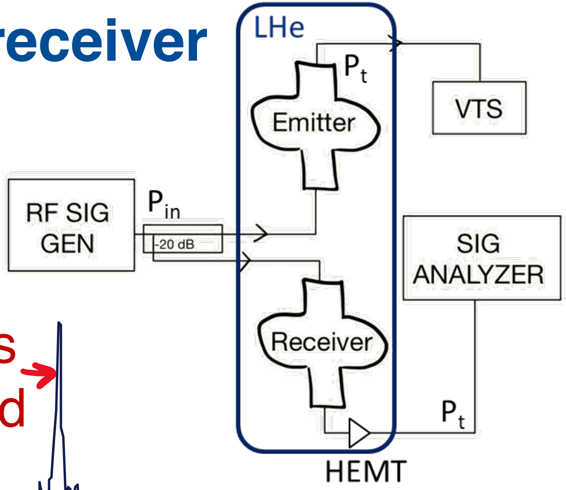
Step 1: excite emitter and match frequency to receiver

1. Emitter excited, small fraction of power sent to receiver. Cavities not frequency matched yet



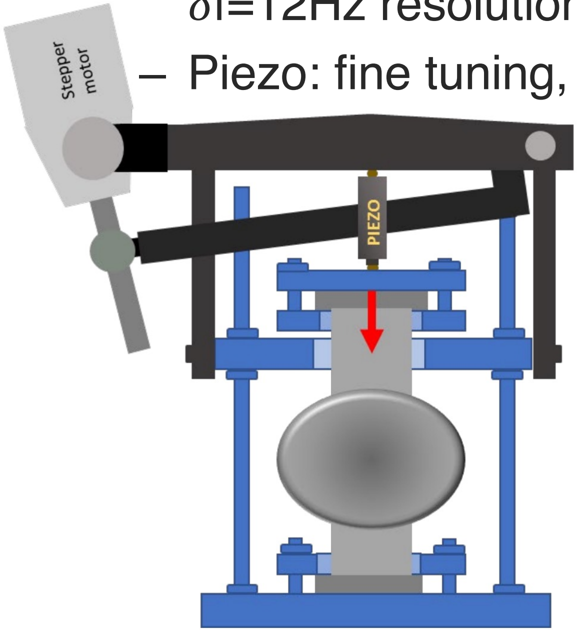
2. Cavities are matched

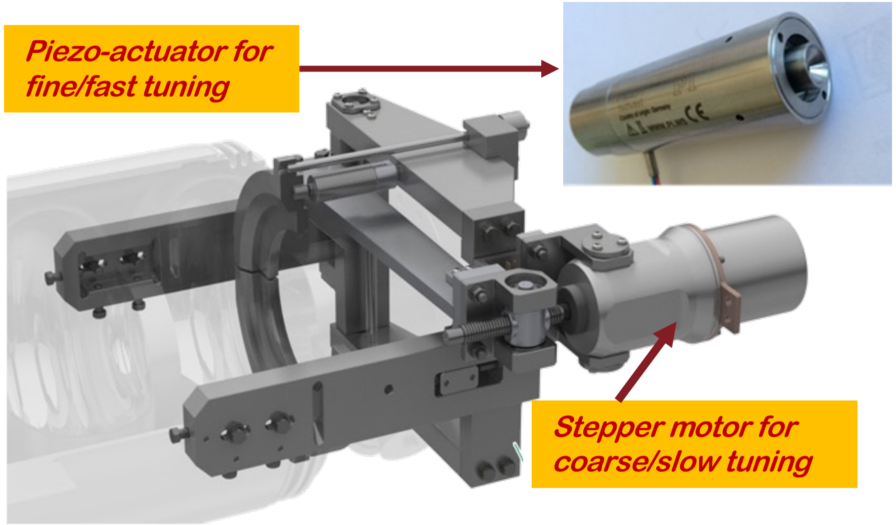




Cavity tuning

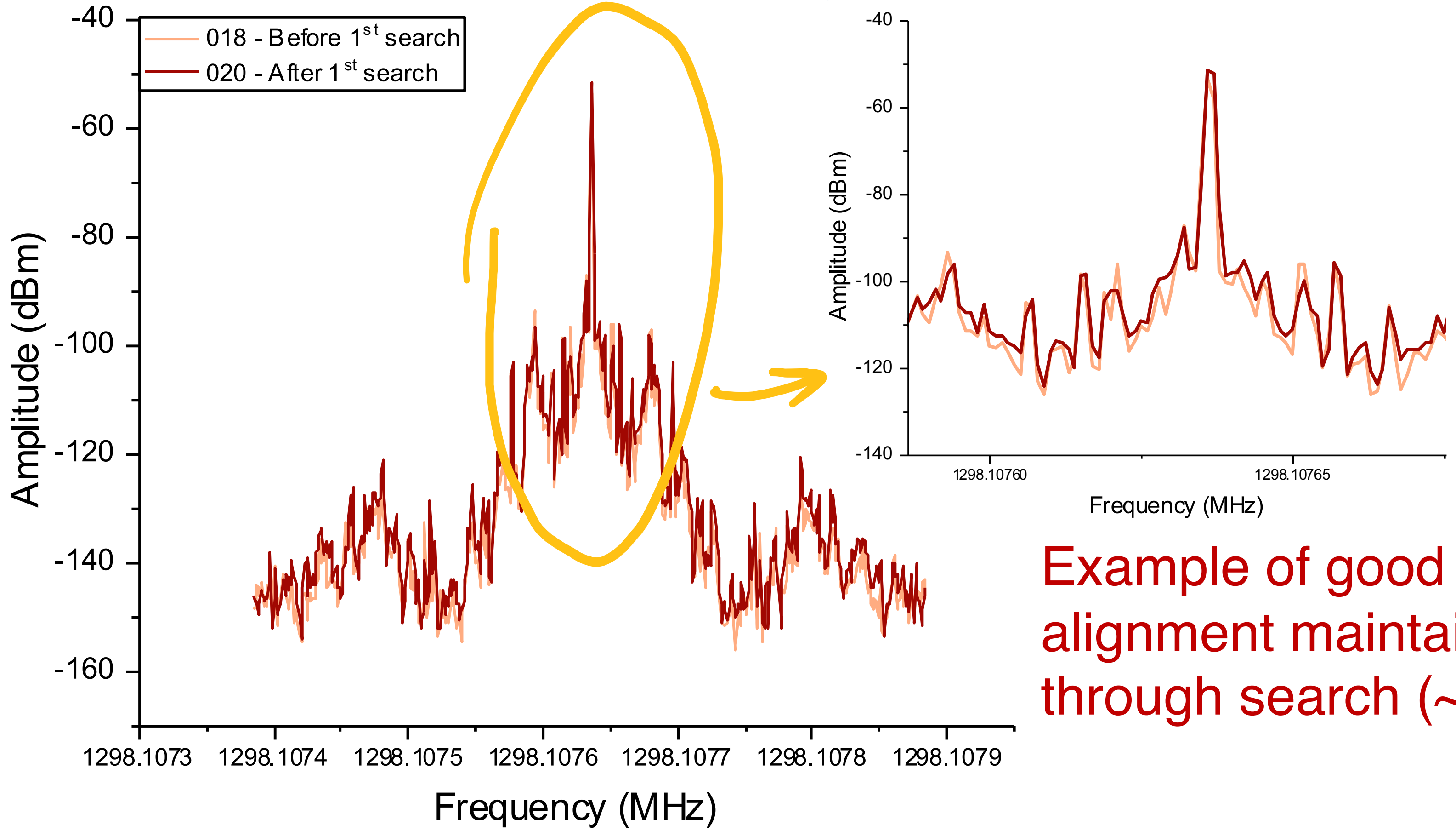
- LCLS II double lever tuner to tune "transmitter" cavity
- Tuner mounted on emitter cavity and preloaded
  - Stepper motor: coarse tuning with Δx=2mm or Δf=5MHz, and δx=5nm or δf=12Hz resolution
  - Piezo: fine tuning, Δx=3um or Δf=8KHz, and δx=0.05nm or δf=0.1Hz resolution





Pischalnikov et al., doi:10.18429/JACoW-SRF2019-TUP085

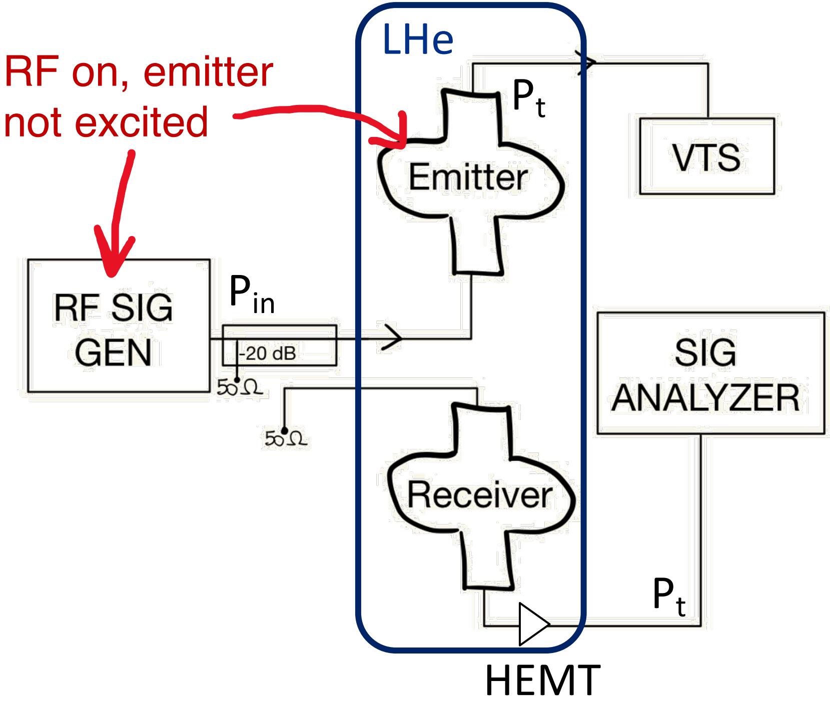
Step 1 & 3: check frequency alignment before and after search



Example of good frequency alignment maintained through search (~35min).

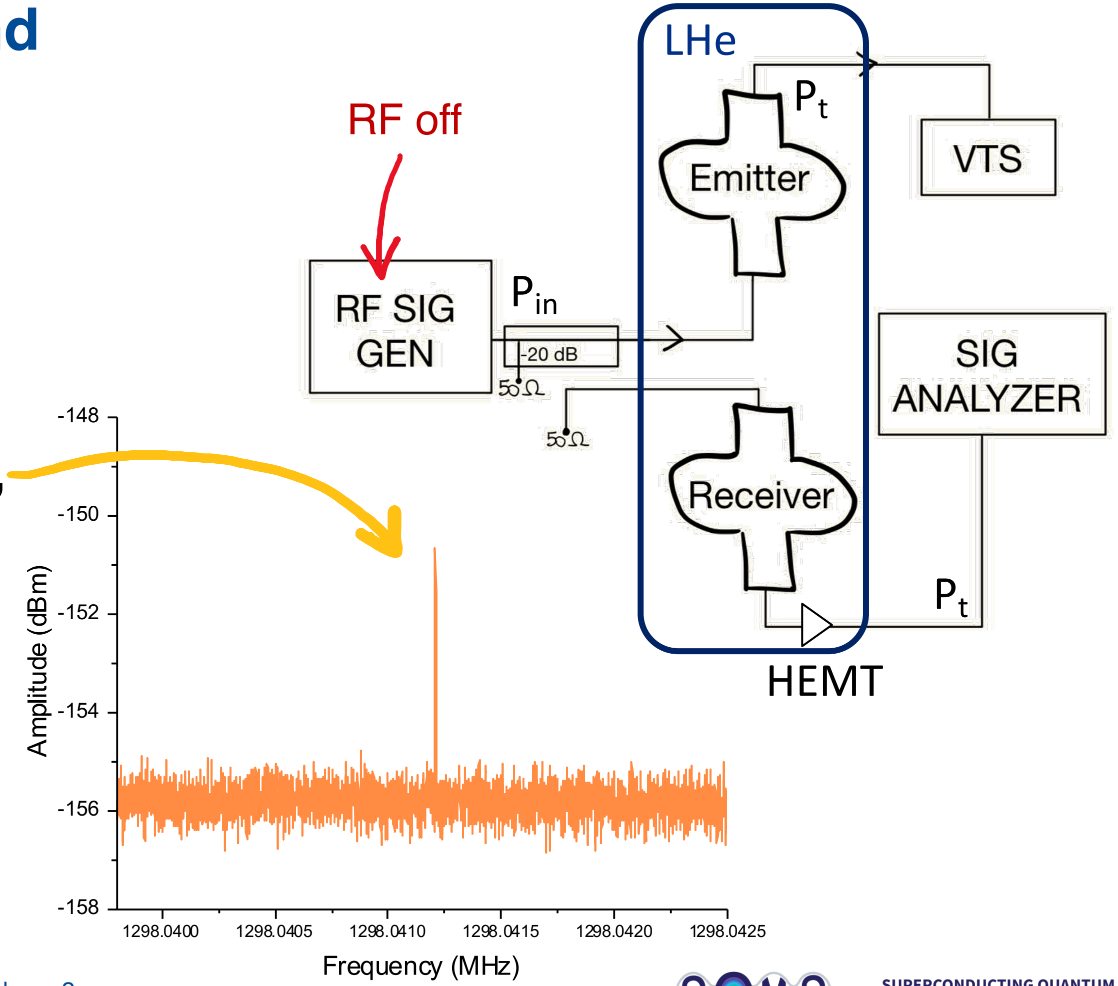
Step 4: cross-talk check

- If peak of excess power found in the receiver cavity: what is its origin?
- Send RF power without exciting emitter (phase locked loop open)
- Does peak in receiver follows frequency of RF signal generator?
  - If yes → peak due to cross-talk
  - If no → more investigation needed



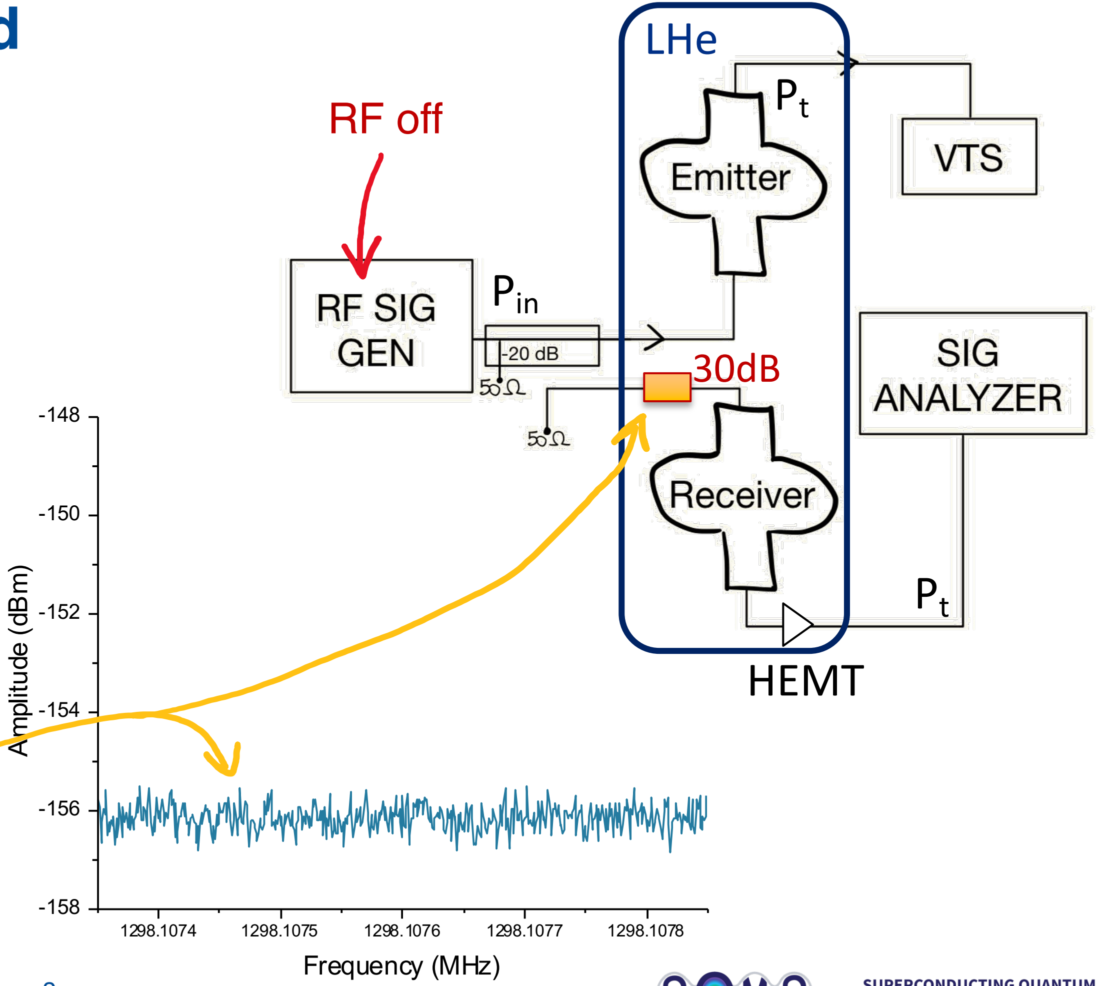
Step 5: thermal background

- RF signal generator is turned off
- Measure receiver power spectrum
- Any peak measured?
  - During 2019 run: yes, due to RT photons leaking from receiver input line



Step 5: thermal background

- RF signal generator is turned off
- Measure receiver power spectrum
- Any peak measured?
  - During 2019 run: yes, due to RT photons leaking from receiver input line
  - Later: no, we added 30dB attenuation on input line



Limit derived from Dark photon search in LHe with 1.3GHz high Q cavities

Expected signals

Dark photon fields radiated from emitter cavity deposits power in receiver:

$$P_{\text{rec}} = \epsilon^4 \boxed{\left(\frac{m_{\gamma'}}{\omega}\right)^{4}} |G|^2 \, \omega \, Q_{\text{rec}} \, U_{\text{em}}$$

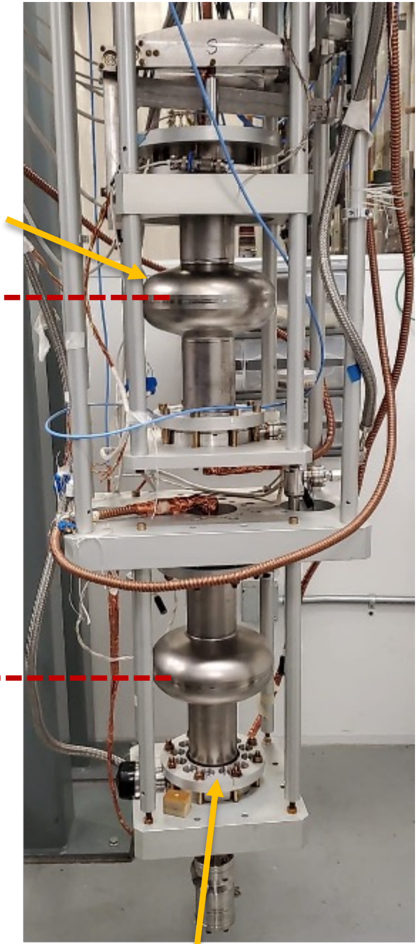
with G form factor.

Advantage of using Longitudinal mode!

Dominant noise is thermal:

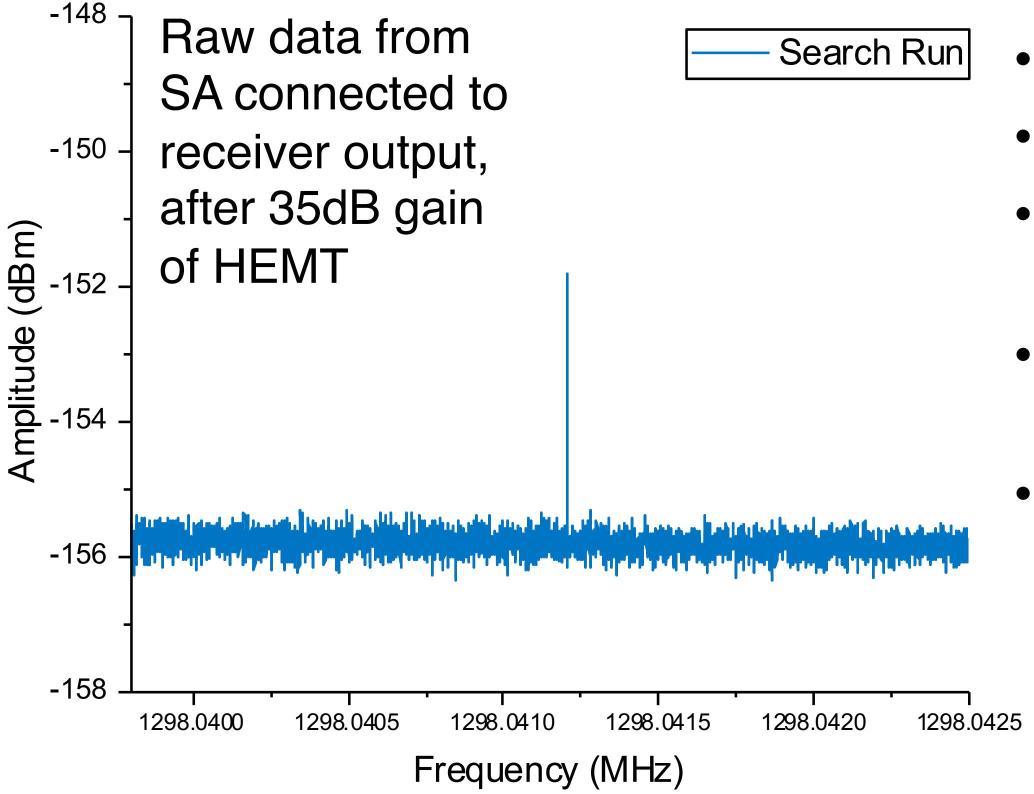
$$\text{SNR} = \frac{P_{\text{rec}}}{P_{\text{th}}} \sqrt{\boxed{\delta\nu \, t_{\text{int}}}} = \frac{P_{\text{rec}}}{k_B T_{\text{eff}}} \sqrt{\frac{t_{\text{int}}}{\delta\nu}}$$

number of independent measurements



Romanenko et al., Phys. Rev. Lett. 130, 261801 (2023)

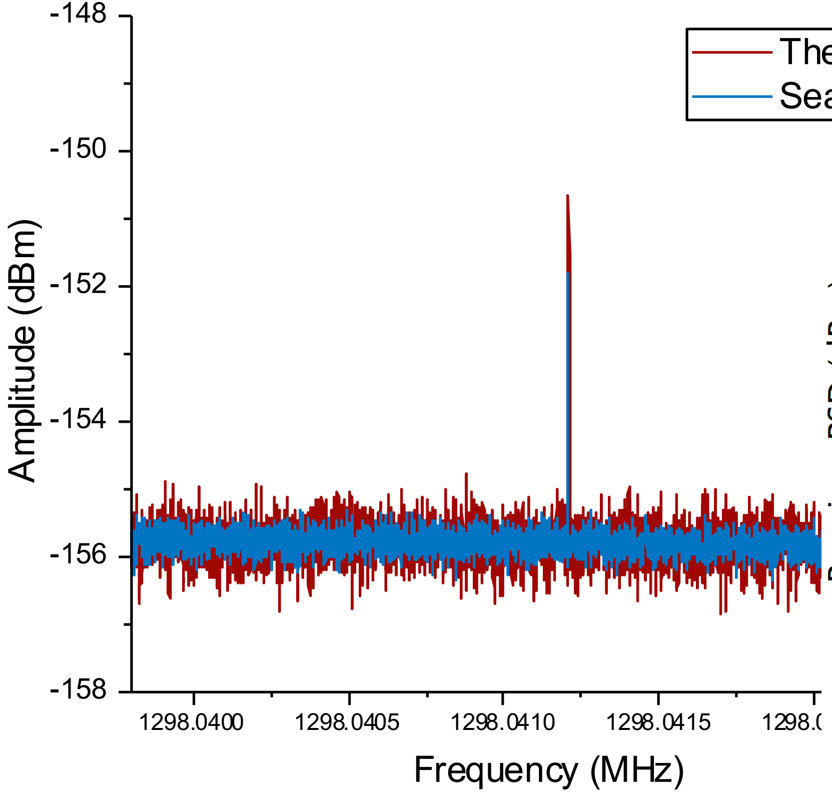
Dark photon search at 6.2 MV/m (=0.6 J stored energy)

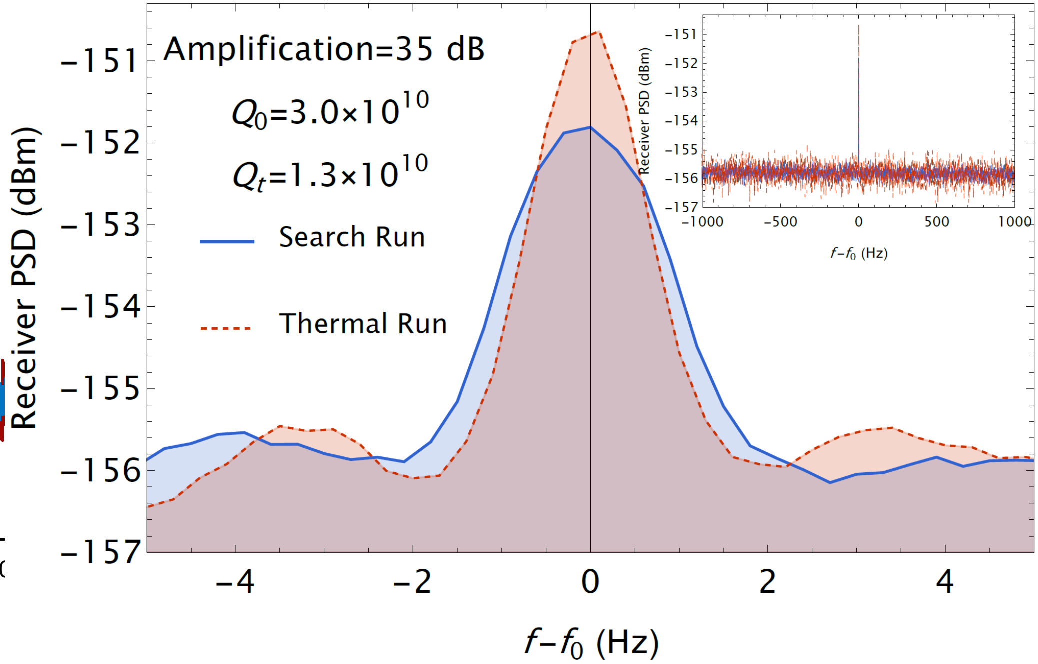


- $Q_{0,rec}=3.0\times10^{10}$
- $T\approx1.4K$
- Emitter $E_{acc}=6.2MV/m$
- Collected data for about 40 min, ~1300 scans
- We see a peak in receiver power spectrum!
- But let's check the thermal background…

Dark photon search at 6.2 MV/m (=0.6 J stored energy)

- $Q_{0,rec}$=3.0x10^{10}
- T≈1.4K





Dark SRF: phase 1 → results

$$\vec{E}_{\mathrm{receiver}}(\vec{r},t) = -\frac{Q_{\mathrm{rec}}}{\omega}\left[\frac{\int d^3x \vec{E}^*_{\mathrm{cav}}(\vec{x})\cdot\vec{j}(\vec{x})}{\int d^3x |\vec{E}_{\mathrm{cav}}(\vec{x})|^2}\right]\vec{E}_{\mathrm{cav}}(\vec{r})e^{i\omega t}$$

$$|G|^2 \equiv \frac{1}{\epsilon^4}\left(\frac{\omega}{m_{\gamma'}}\right)^4\left[\frac{\int d^3x \vec{E}^*_{\mathrm{cav}}(\vec{x})\cdot\vec{j}(\vec{x})}{\omega\int d^3x |\vec{E}_{\mathrm{cav}}(\vec{x})|^2}\right]^2$$

Cavities in LHe: need to consider effects of non perfect frequency matching, drift and jittering. Conservatively modeled as:

$$|G|^2 \to \frac{\omega^2}{\omega^2 + 4\delta_\omega^2 Q_{\mathrm{rec}}^2}|G|^2$$

(more on next slides)

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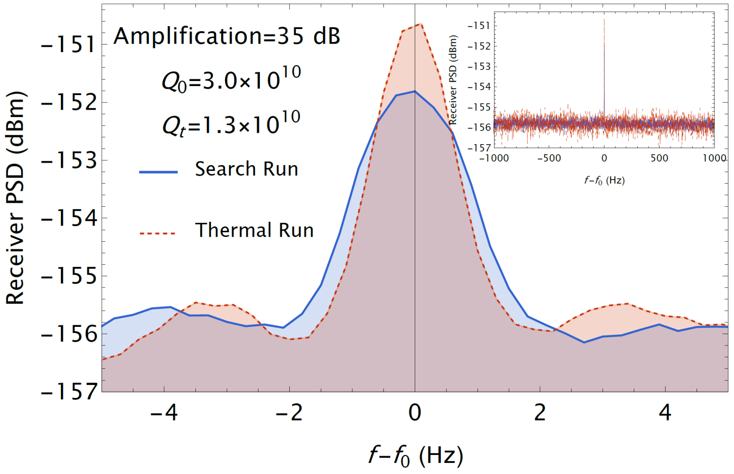
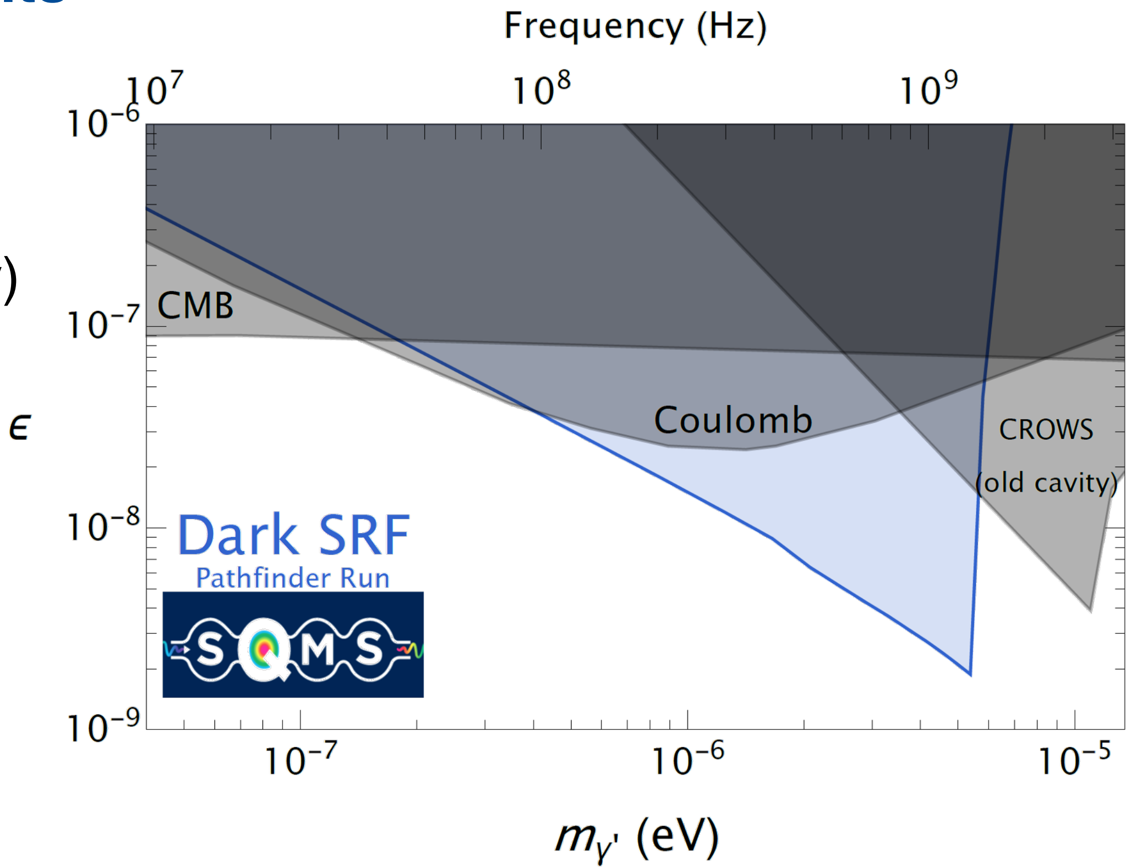
Dark SRF: phase 1 → results

Thermal run vs Search run

Search run conducted at
6.2 MV/m (= 0.6 J stored energy)





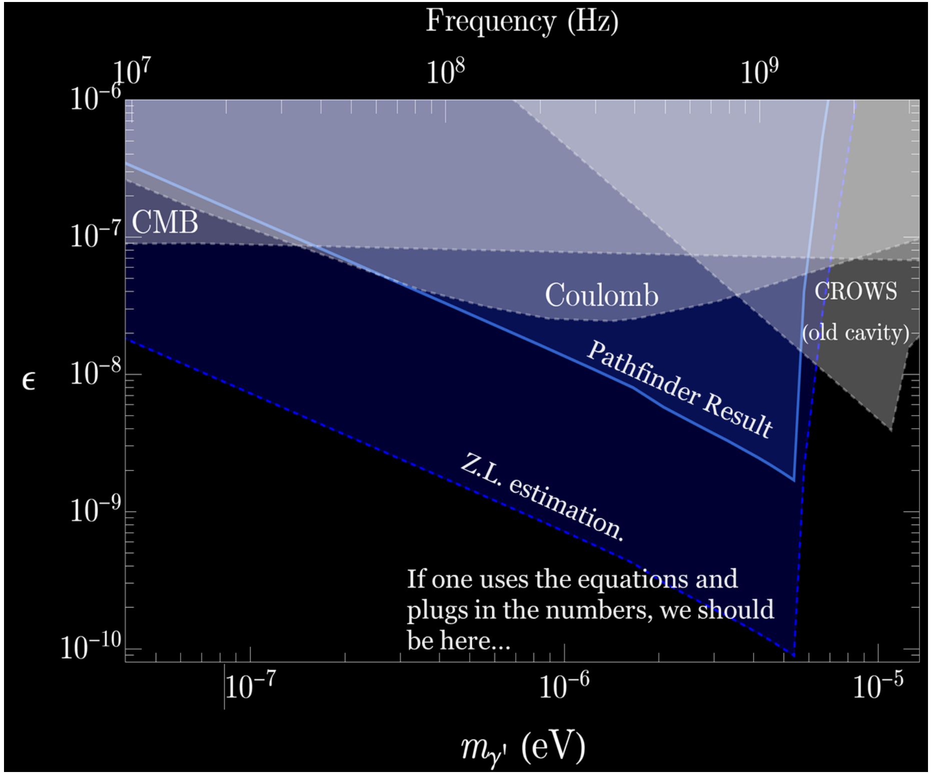
Romanenko et al., Phys. Rev. Lett. 130, 261801 (2023)

Dark SRF: phase 1 → limits to expected sensitivity

Ultra-high Q → ultra narrow bandwidth!

- $Q_{0,emitter}=4.5\text{x}10^{10}$, $Q_{0,receiver}=3.0\text{x}10^{10}$
- To account for frequency drifts and microphonics → derived **very conservative limit!**
- **Drifts** → accounted as constant frequency mismatch at 5.7Hz and 3.0Hz
- **Microphonics** → modeled as constant mismatch at 3.1Hz for each cavity

We are working on improving frequency stability and live monitoring, and on proper microphonics modeling

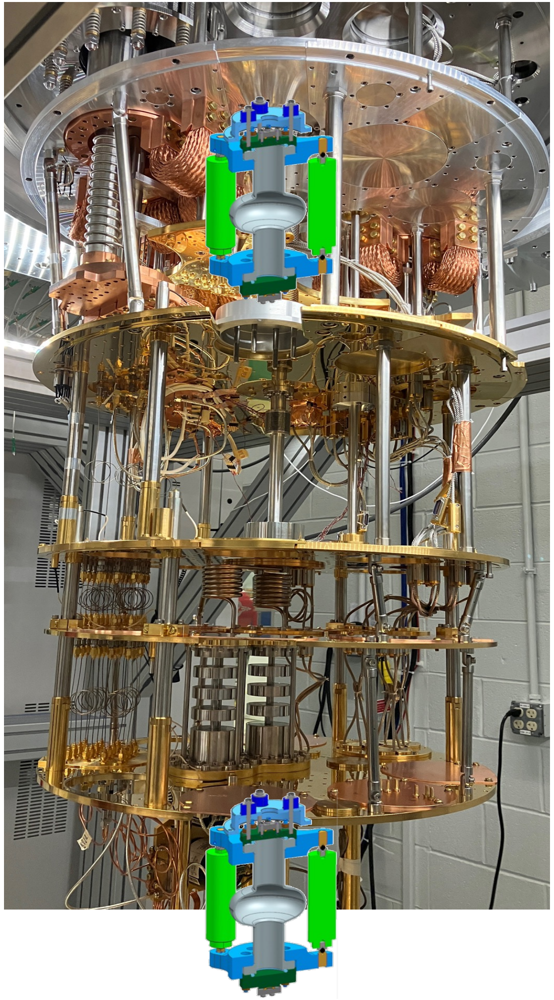


Plot from Z. Liu, presented at "Prospecting for New Physics through Flavor, Dark Matter, and Machine Learning", Aspen Center for Physics, March 2023

Dark SRF phase 2

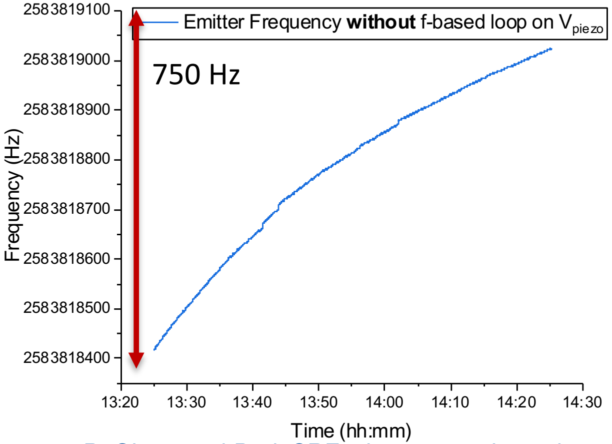
Dark SRF: phase 2 → 2.6GHz cavities in DR

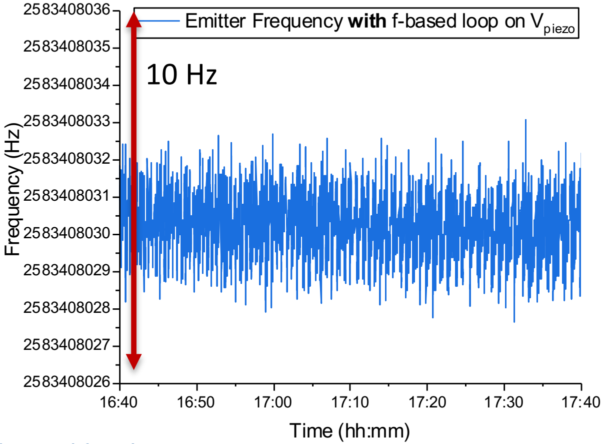
- Deploy Dark SRF in dilution refrigerator (DR) to reduce thermal background
- Emitter cavity on additional 4K plate, receiver on mK plate with JPA on P_t
- Modifications of experimental setup for DR:
  - ✓ Change cavity frequency to 2.6GHz due to size limitation
  - ✓ Modify tuner system (piezo only!)
  - ✓ Verify frequency matching and stability with new tuner
  - ❑ Reduce crosstalk
  - ❑ Move entire setup to dilution refrigerator

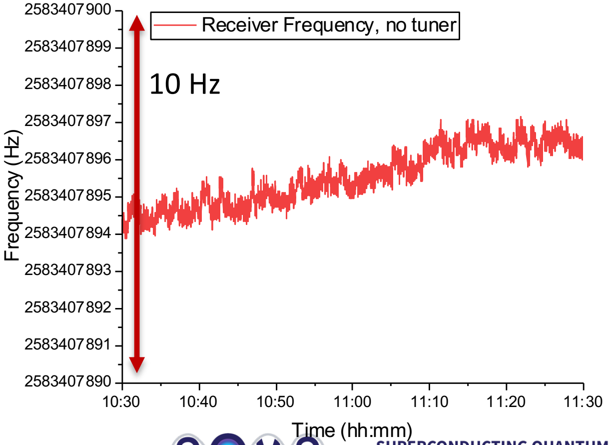


Dark SRF: phase 2 → current status and steps forward

- New piezo-based tuner system, troubleshooted through LHe runs
  - Initially measured without feedback loop: huge drifts on both cavities (emitter at 15MV/m: 650Hz in 1 hour!)
  - **<u>Emitter</u>**: implemented f-based loop to control piezo voltage → removed slow drift: frequency AVG stable at 0.1Hz/hr, with 1.5Hz RMS
  - **<u>Receiver</u>**: frequency signal not constantly available (silent cavity!) → removed piezo stacks, made cavity more rigid to minimize frequency shifts: 1.7Hz/hr

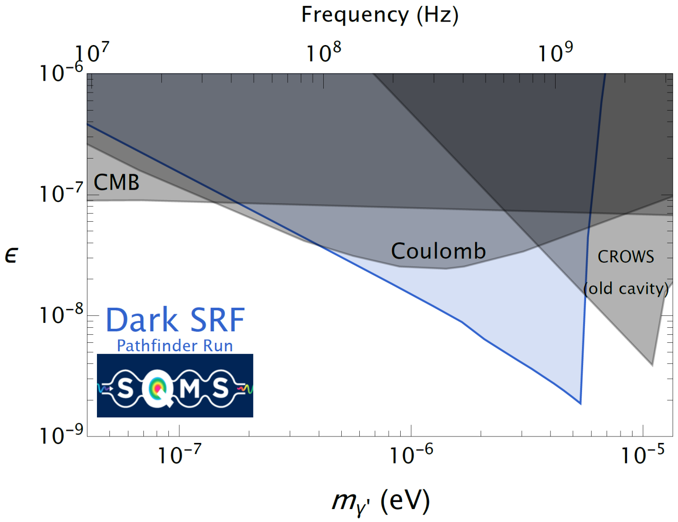


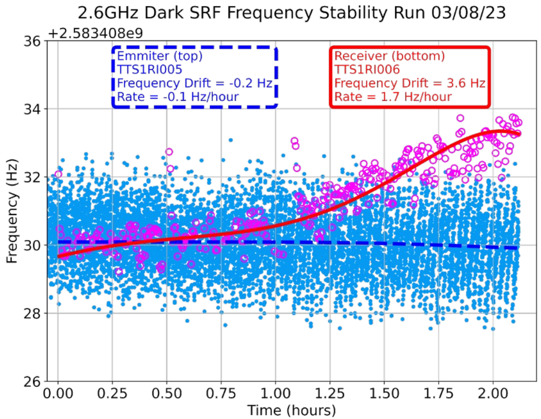




Conclusions

- Realized 1st proof of concept SC cavity-based LSW experiment
- Addressed many challenges to operate ultra-high Q cavities in this regime!
- **Pathfinder Dark SRF 1.3GHz run → extended dark photon exclusion limit in broad range of $m_{\gamma'}$ and ε**
- Working on Dark SRF 2.6GHz to run in dilution refrigerator
  - Reduce receiver thermal background
  - Improve on frequency matching, stability
  - Improve microphonics modeling
  - Implement phase sensitivity and much more





Romanenko et al., Phys. Rev. Lett. 130, 261801 (2023)
Contreras-Martinez et al., WEPWB109, Presented at SRF2023

THANK YOU!

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Search for Dark Photons with Superconducting Radio Frequency Cavities

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