Winter Aspen 2023

Dark SRF pathfinder result and beyond

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Mainly based upon A. Romanenko et al, 2301.11512

Intro

Kinematically mixed dark photons are well-motivated.

There are many past, ongoing and future searches.

Today, I report the pathfinder results of one such efforts and discuss its future.

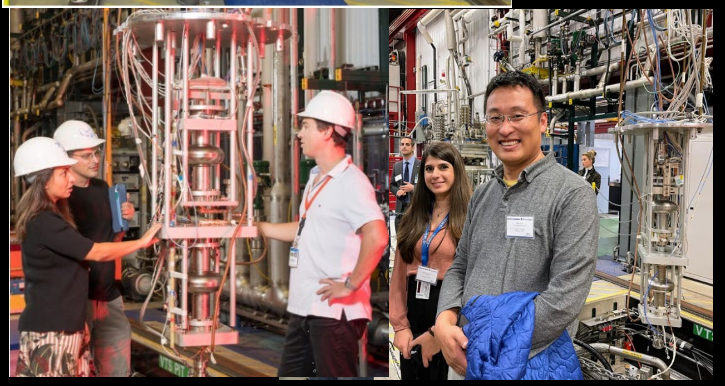
Graham et al, Phys.Rev. D90 (2014) no.7, 075017
S. R. Parker et al, Phys. Rev. D 88, 112004 (2013)
J. Hartnett et al, Phys. Lett. B 698 (2011) 346
J. Jaeckel and A. Ringwald, Phys. Lett. B 659, 509 (2008)

Pathfinder result

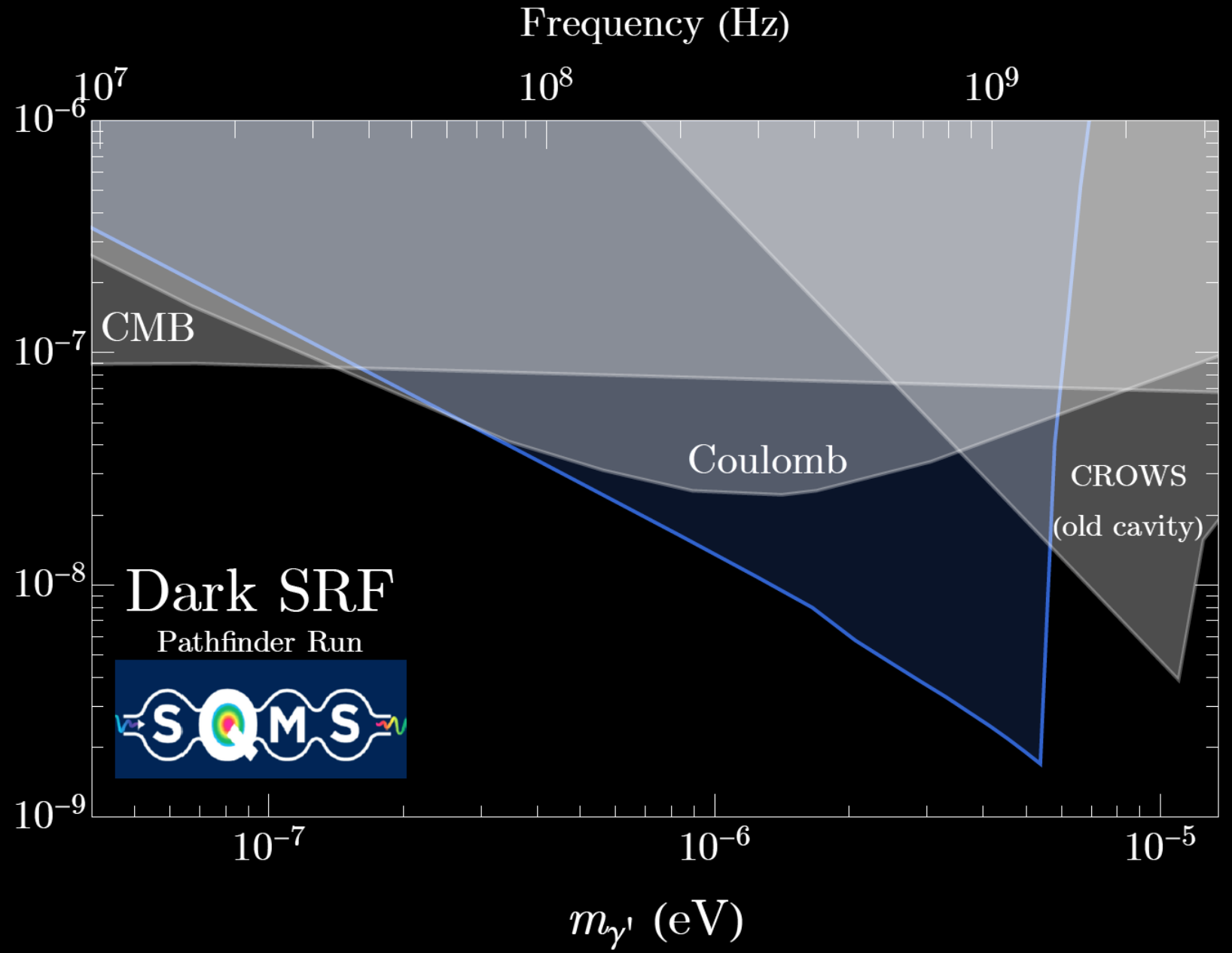
Our pathfinder run results already explore new territory!

Fermilab

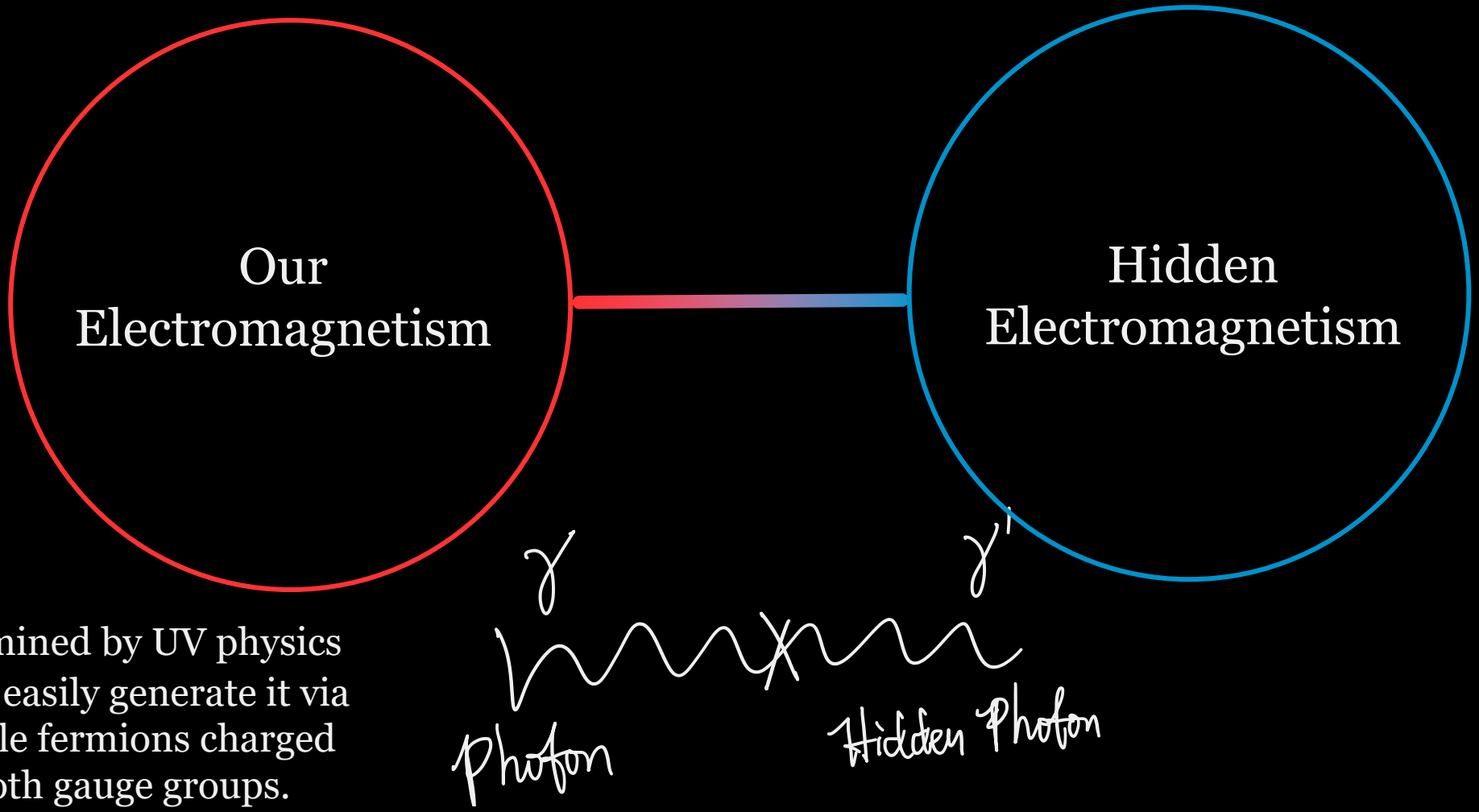
University of Minnesota



Work was performed at Fermilab and University of Minnesota



A generic light hidden photon

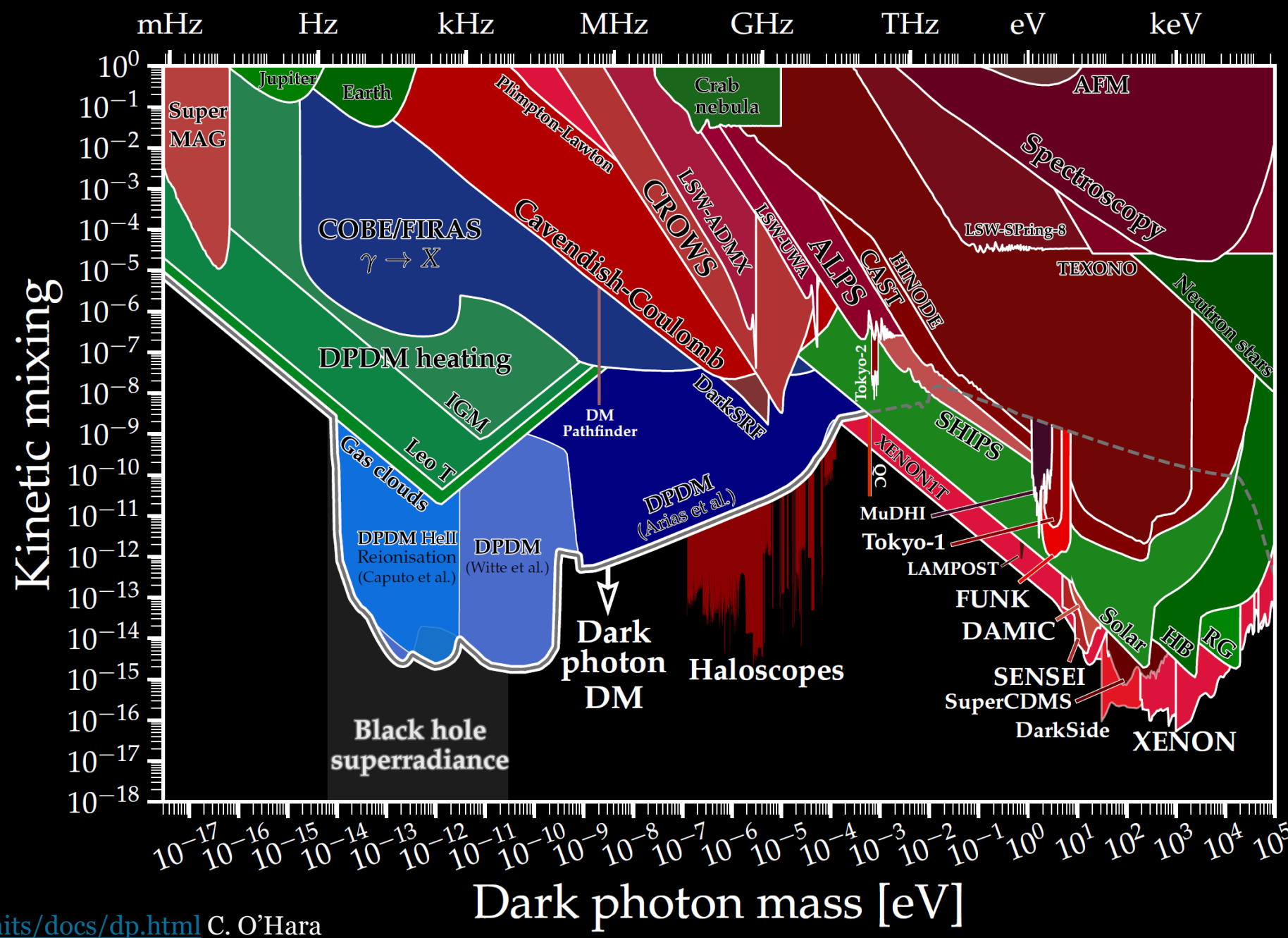


ϵ determined by UV physics
One can easily generate it via high-scale fermions charged under both gauge groups.

See the discussion on the ϵ size, e.g., Gherghetta, Kersten, Olive, Pospelov, 1909.00696

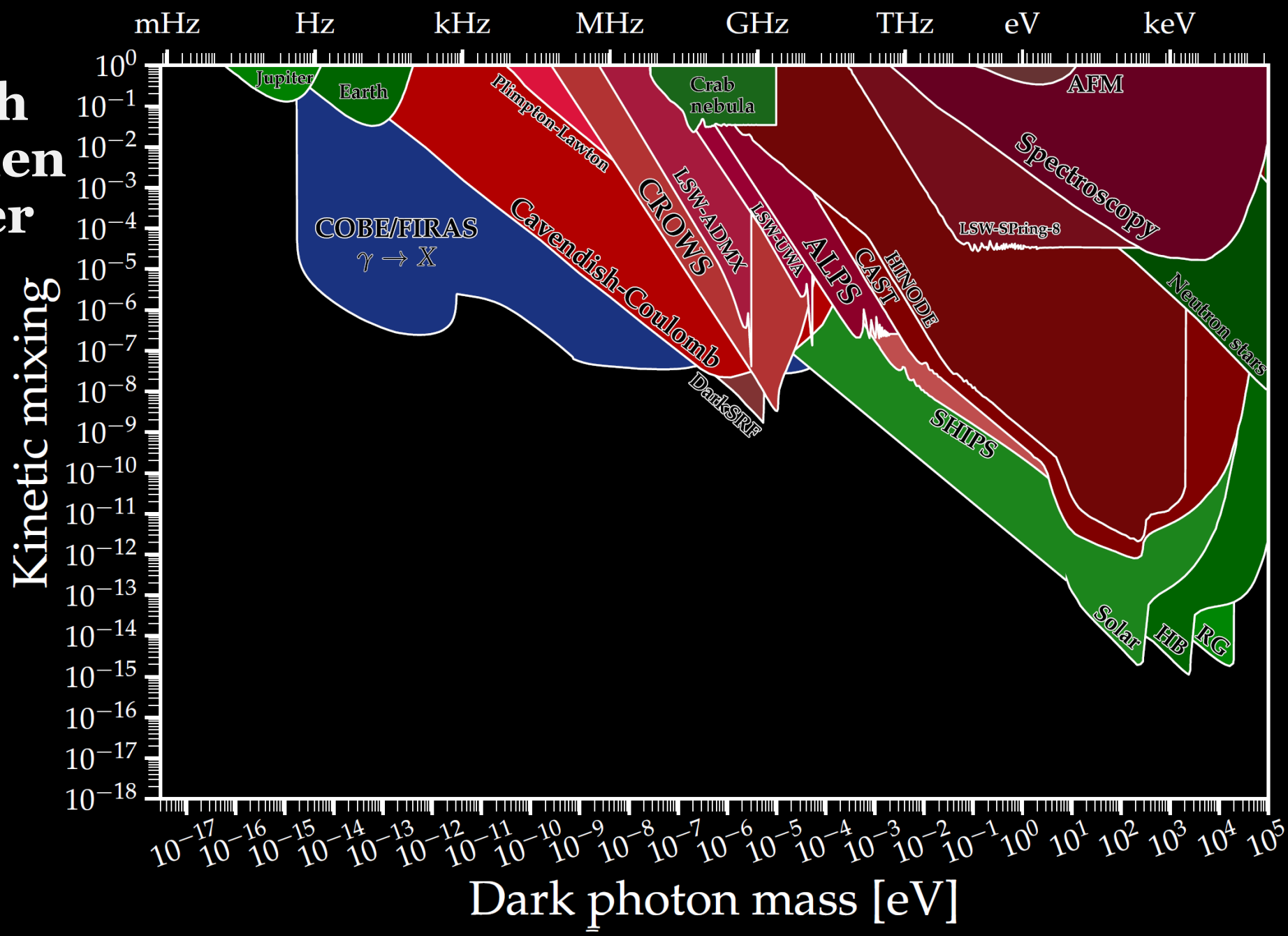
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m^2_{\gamma'} A'_\mu A'^\mu$$

An Active Program



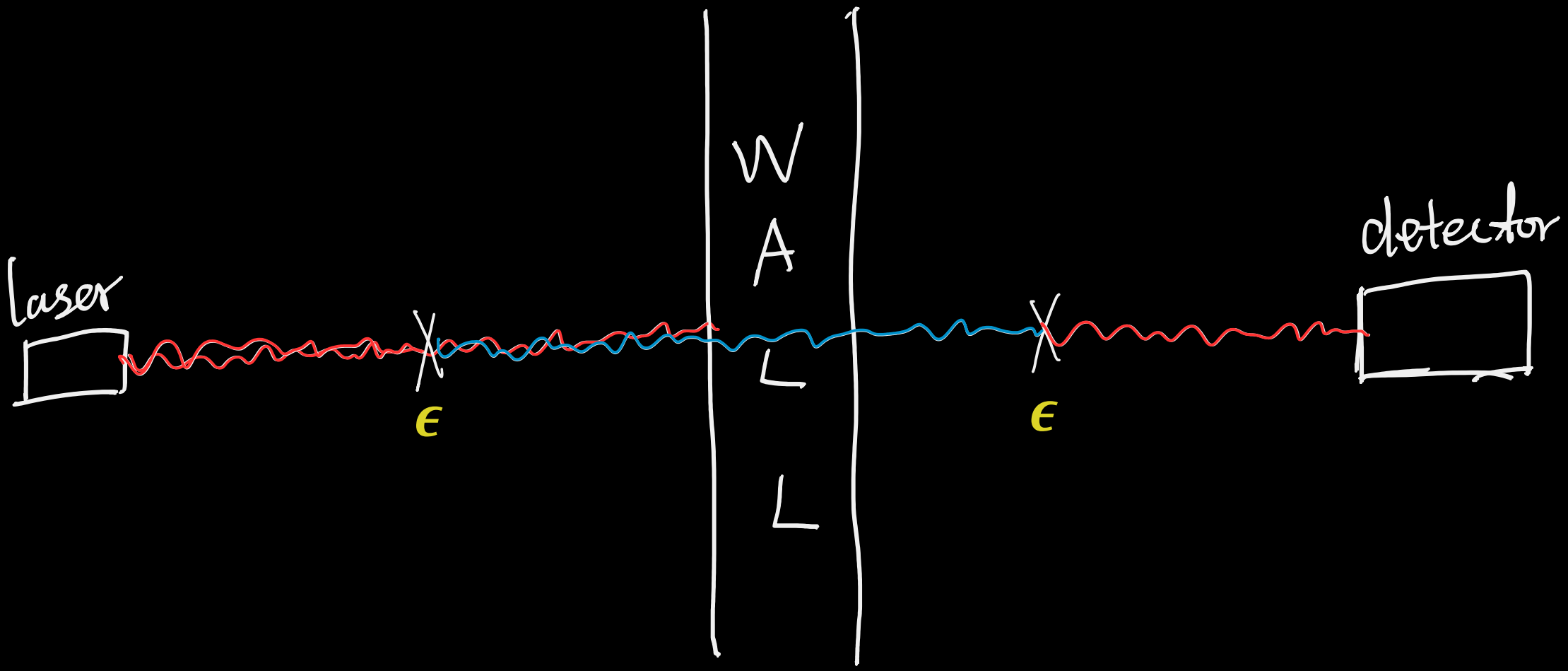
https://cajohare.github.io/AxionLimits/docs/dp.html C. O'Hara

An active program: much less known when not dark matter



What is Dark SRF?

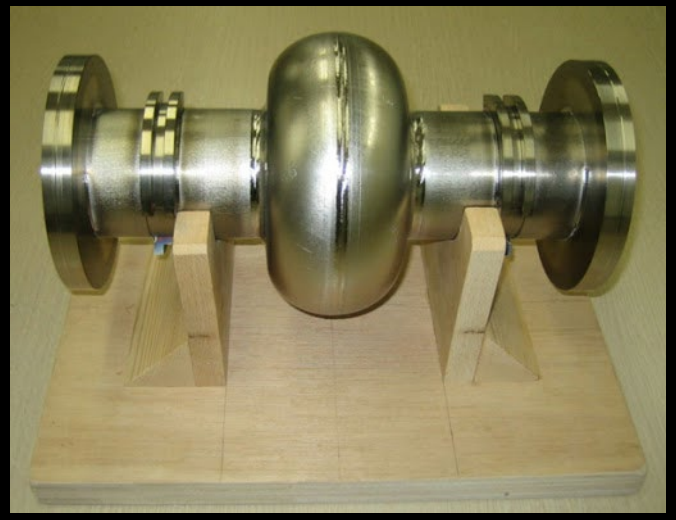
Light Shining through Wall (LSW)



We have the best SRF for High Energy Accelerators

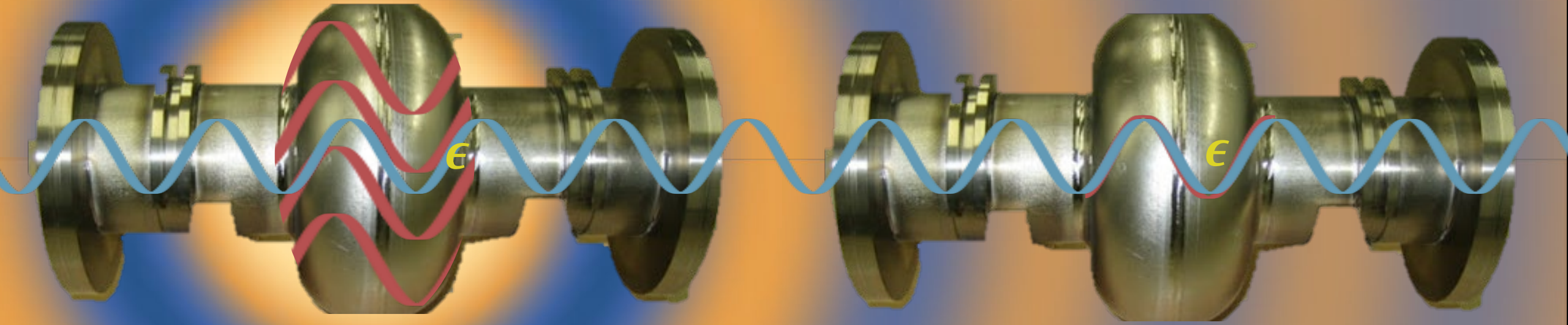
Superconducting RF Cavities:
- Large fields
- High Quality

Superconducting Radio Frequency (SRF) cavity



SRF for Dark Photon

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



$$\vec{E}'(\vec{r},t) \simeq -\epsilon\, m_{\gamma'}^2 \int_{V_{\text{emitter}}} d^3x\, \frac{\vec{E}_{\text{cav}}(\vec{x})}{4\pi|\vec{r}-\vec{x}|}\, e^{i(\omega t - k|\vec{r}-\vec{x}|)}$$

$$\vec{J}(\vec{r})e^{i\omega t} = -\frac{i\epsilon}{\omega}\left(m_{\gamma'}^2\vec{E}' - \vec{\nabla}(\vec{\nabla}\cdot\vec{E}')\right)$$

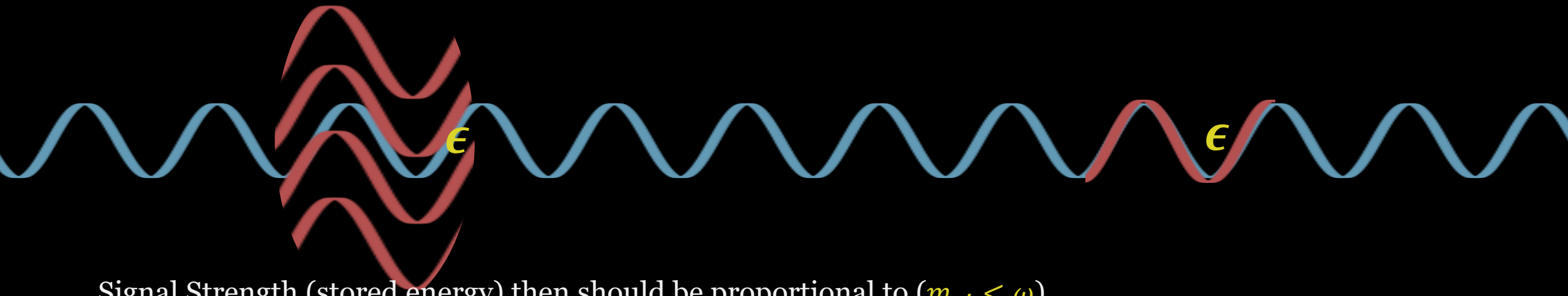
Power it up:

- 40 MV/m (26 J stored energy)
- ~10^{25} photons

SM photon does not penetrate the superconducting wall.
But dark photons can!

Isolated receiver
•High Q of 10^{10} (accumulate tiny signal power)

SRF for Dark Photon: naïve parametrics



Signal Strength (stored energy) then should be proportional to ($m_{\gamma'} < \omega$)

$$S \propto \frac{m_{\gamma'}^4}{\omega^4} \epsilon^4 Q_{receiver} Q_{emitter} P_{emitter} |G|^2$$

Background noise should be proportional to. e.g., thermal dominance

$$B \propto Temperature$$

Background fluctuation controlled at

$$\Delta B \propto Temperature \sqrt{\frac{t_{rungup}}{t_{integration}}}$$

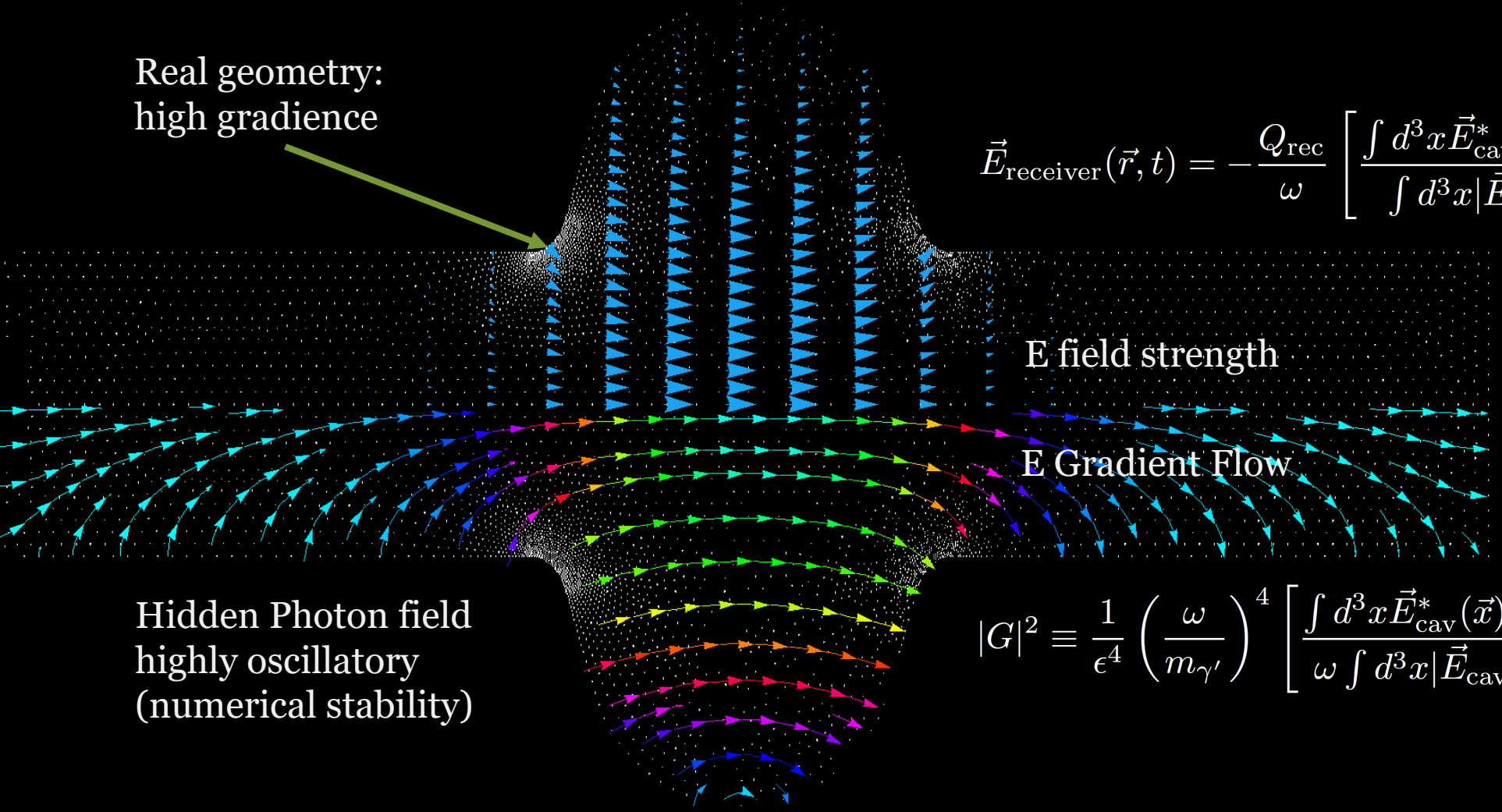
$$t_{rungup} = \frac{Q}{\omega} \sim 1\ sec$$

Background noise also received contribution from possible cross-talks:

$$B \propto P_{emitter}$$

Real Cavity Configuration

Real geometry:
high gradience



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

Hidden Photon field
highly oscillatory
(numerical stability)

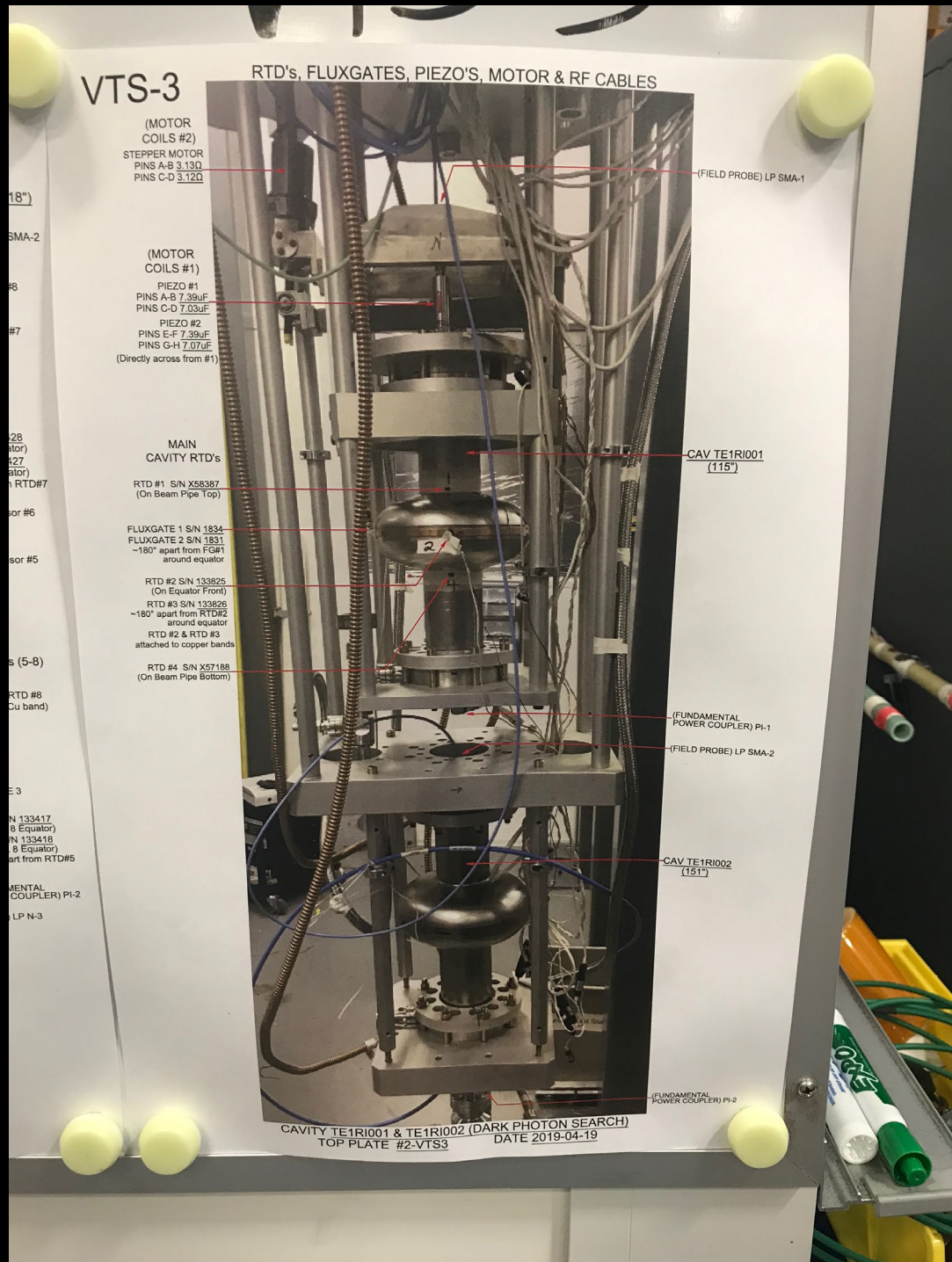
$$|G|^2 \equiv \frac{1}{\epsilon^4}\left(\frac{\omega}{m_{\gamma'}}\right)^4\left[\frac{\int d^3x \vec{E}^*_{\text{cav}}(\vec{x})\cdot\vec{j}(\vec{x})}{\omega\int d^3x |\vec{E}_{\text{cav}}(\vec{x})|^2}\right]^2$$

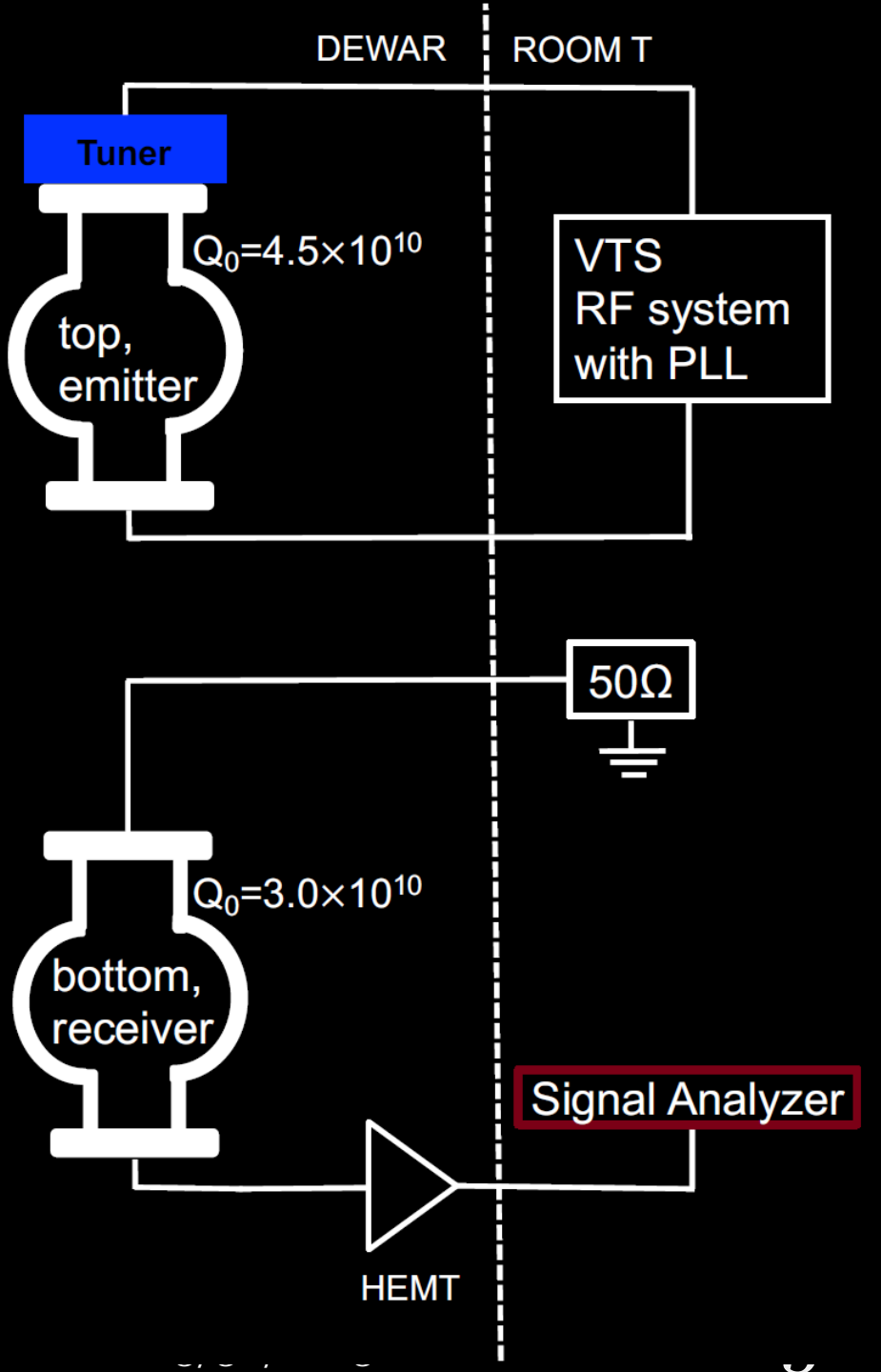
Dark SRF Pathfinder Runs

Pathfinder run(s) summary

It works!

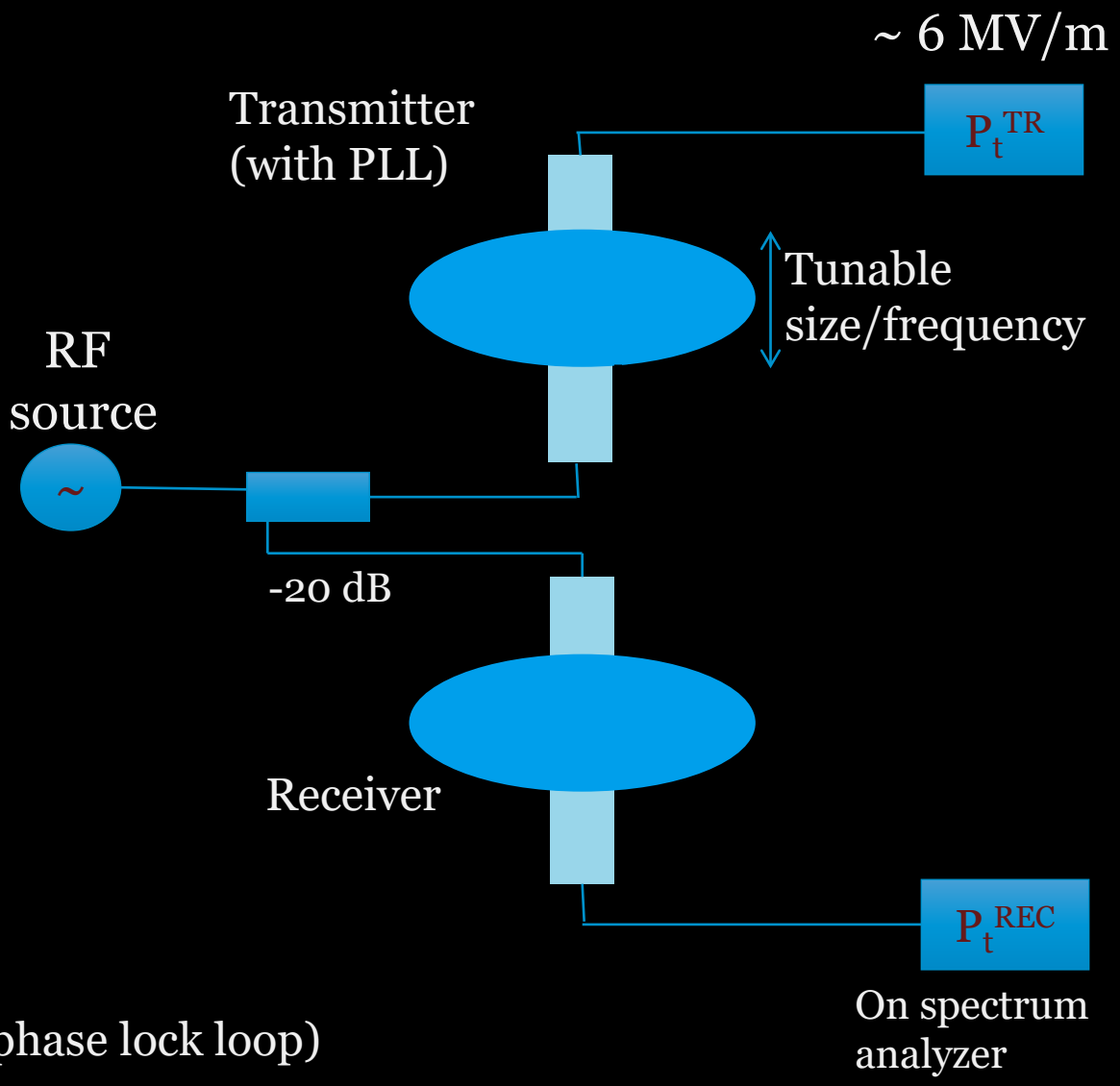
- ✓Design
- ✓Tuner operation
- ✓Microwave scheme for matching the frequencies
- ✓Actual data – first acquisition



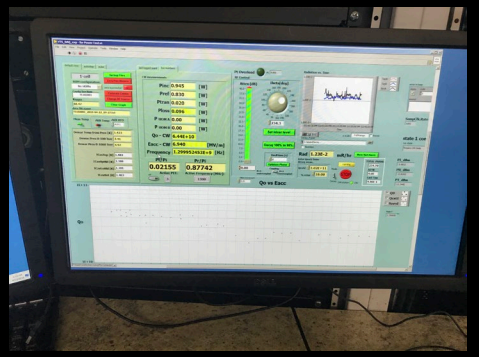

DEWAR
ROOM T
Tuner
Q_0=4.5×10^{10}
top,
emitter
VTS
RF system
with PLL
50Ω
Q_0=3.0×10^{10}
bottom,
receiver
Signal Analyzer
HEMT

2019 Run pictures

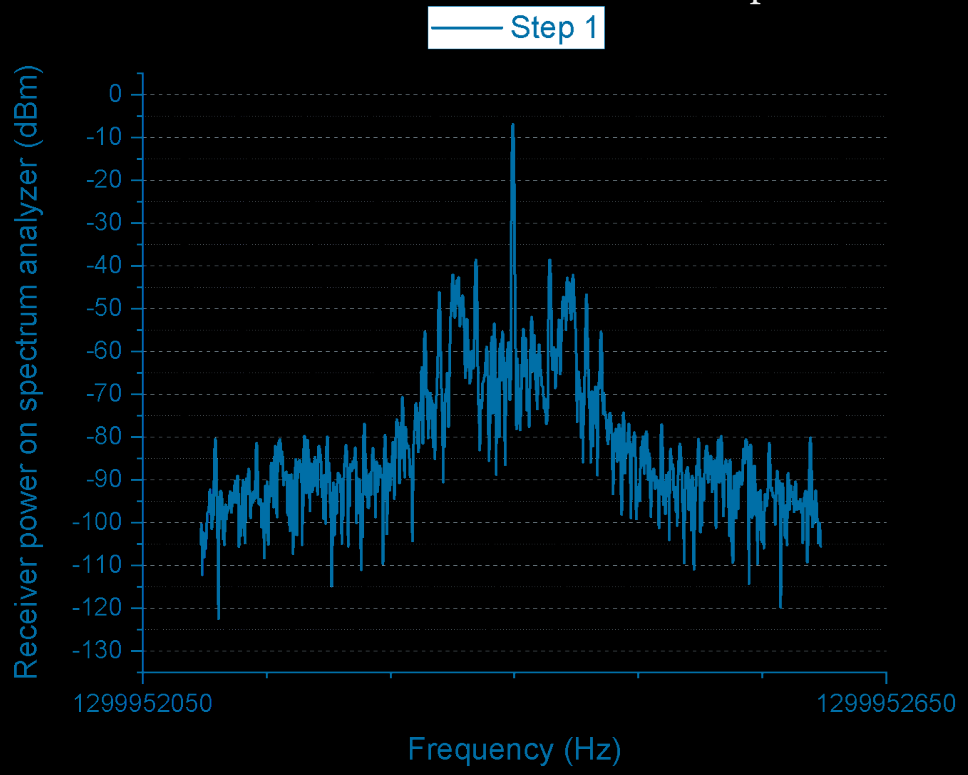
Cavity frequency matching – Step 1



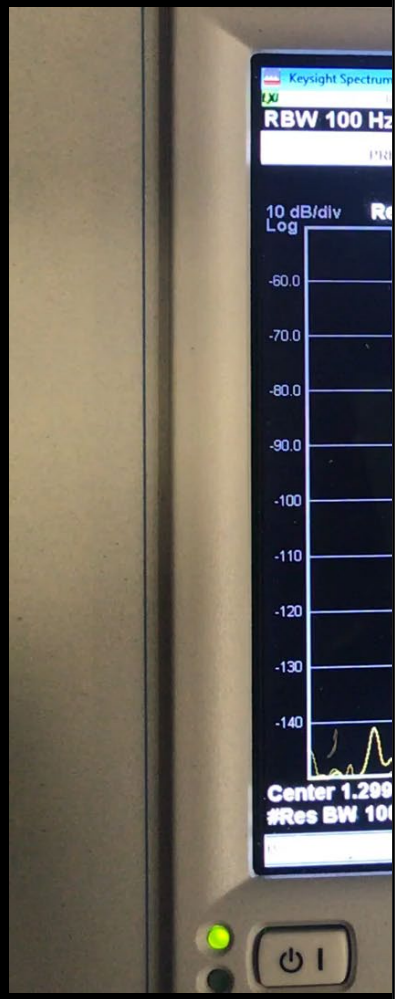
PLL (phase lock loop)



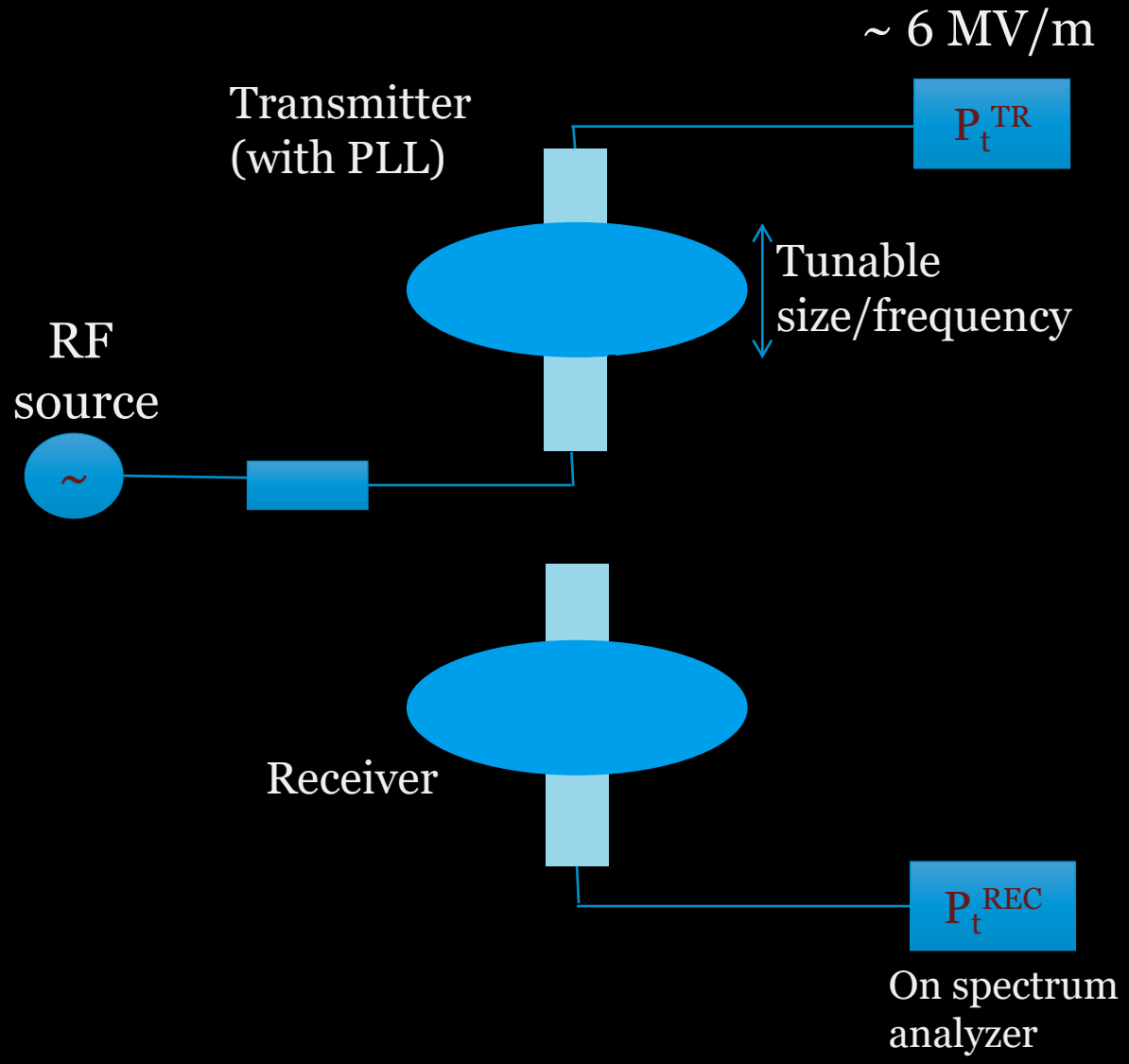
From now on, most measurement are shown in dBm (dB 10log(x), dBm=10log(x/mW).) Note that we are always in dB-space, 3dB = factor of 2 in linear space.

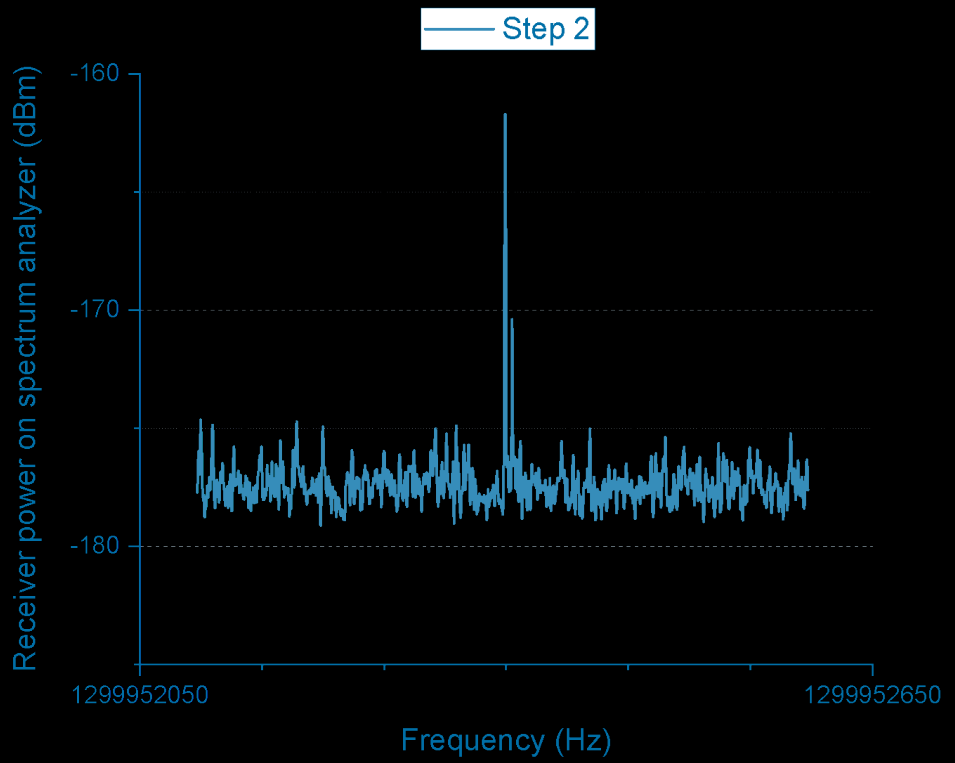


Frequency matchi

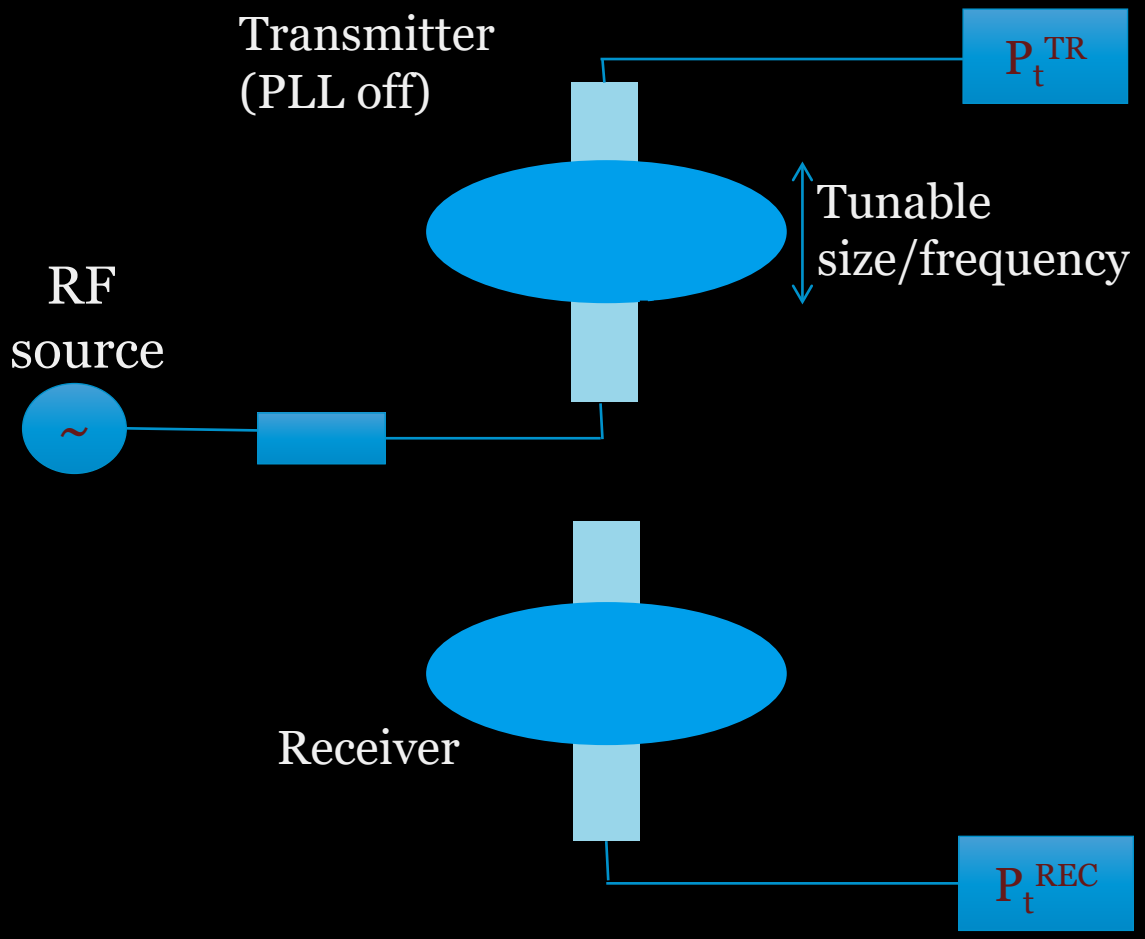


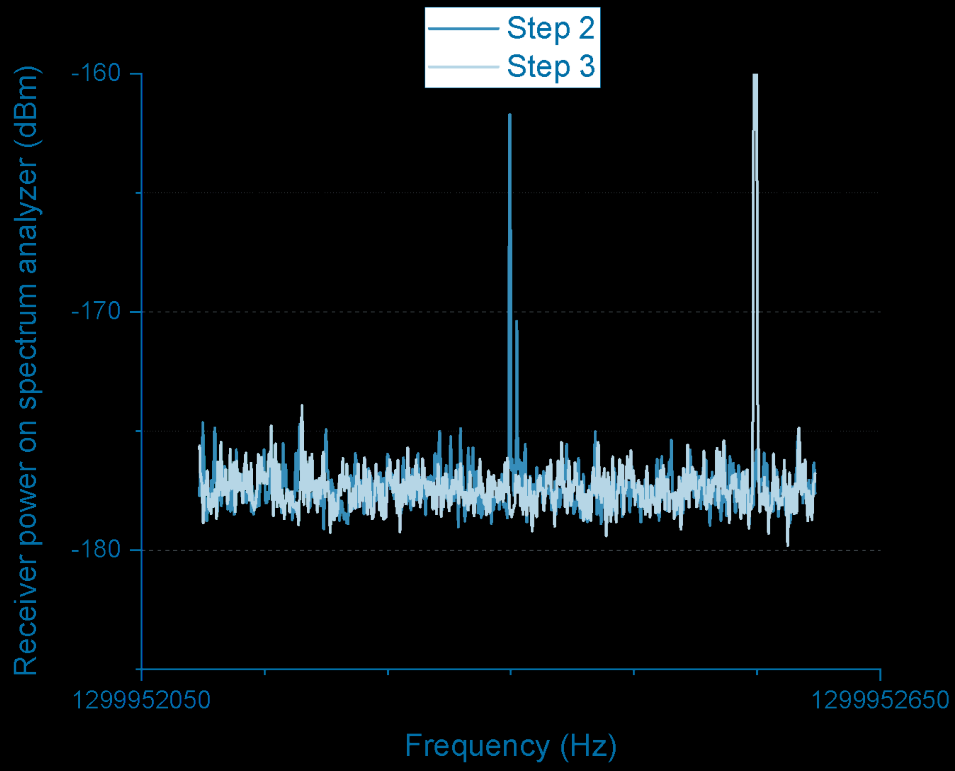
Dark Photon search! – (Step 2)





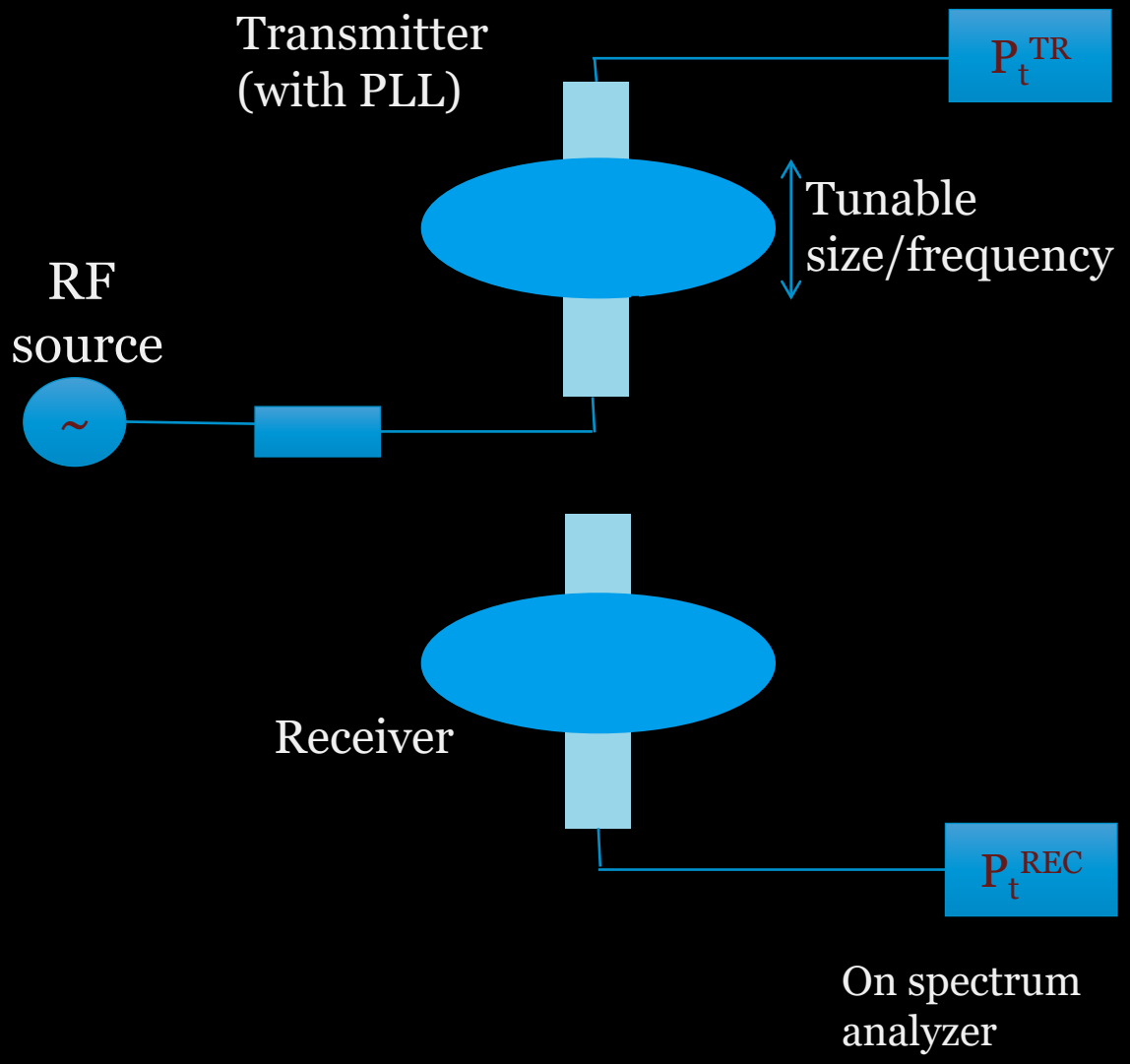
Cross-talk check - Step 3

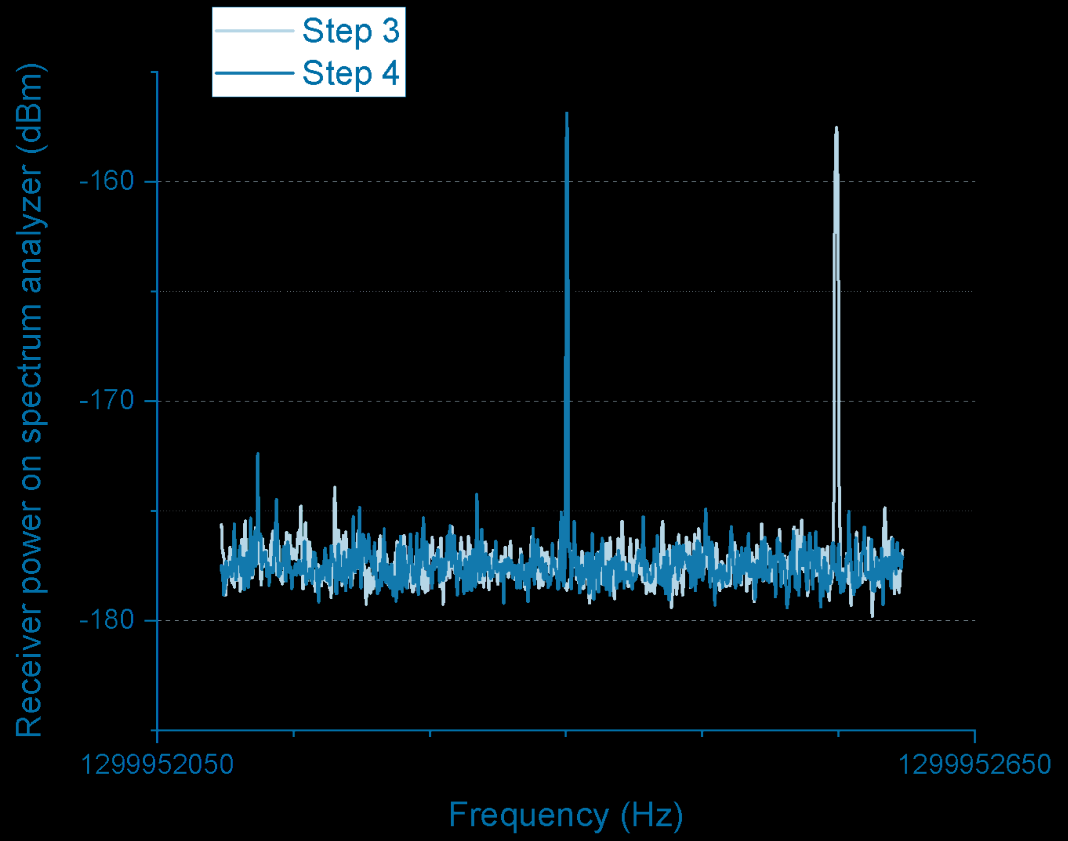




Back to dark photon search - Step 4 = Step 2

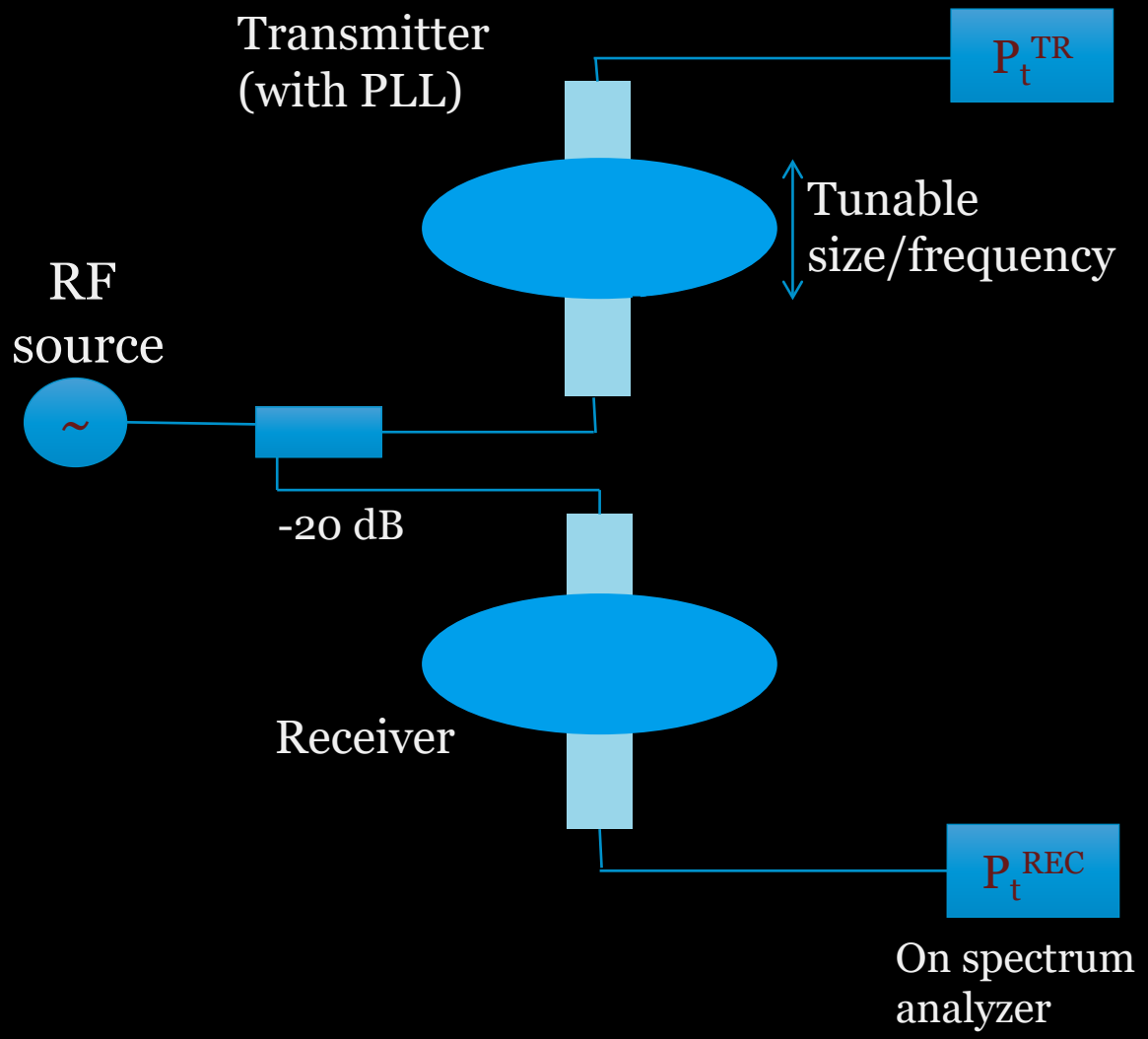
~ 6 MV/m

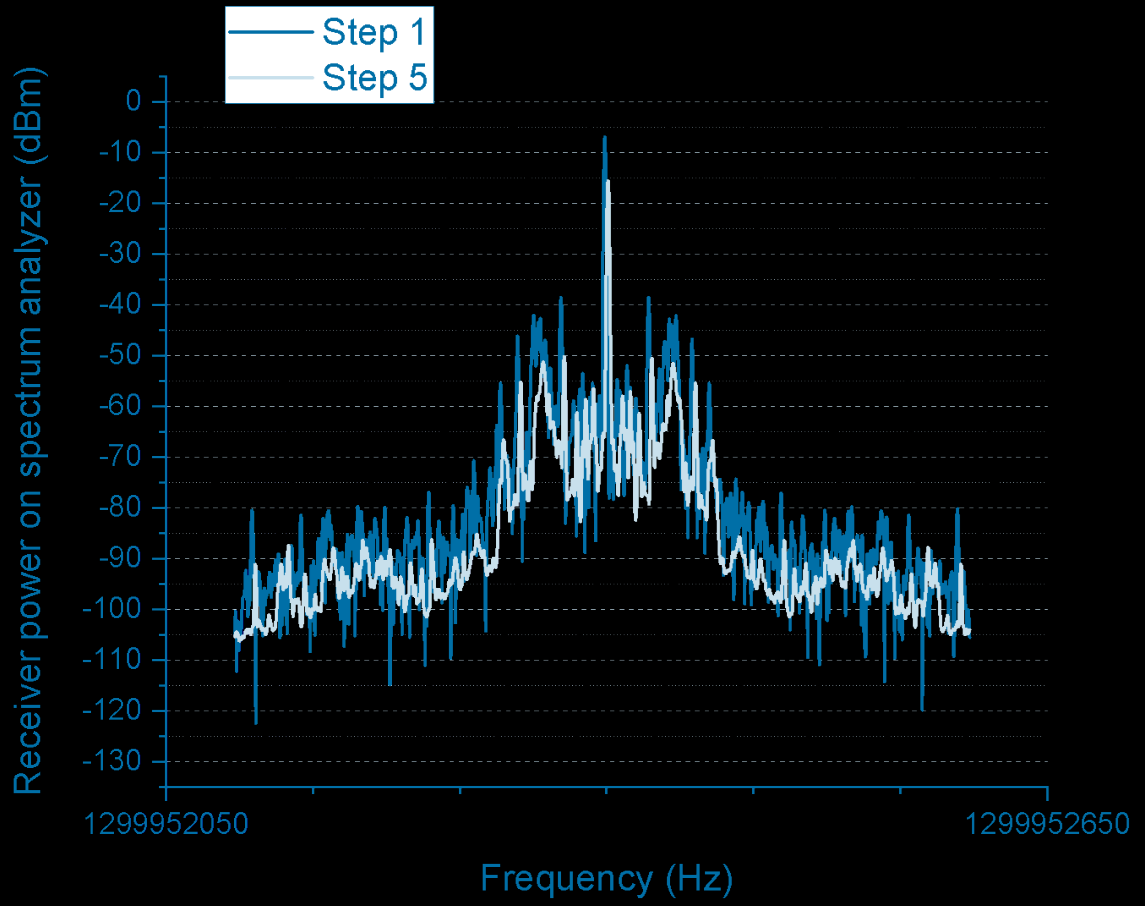




Back to Step 5 = Step 1 – all in tune

~ 6 MV/m



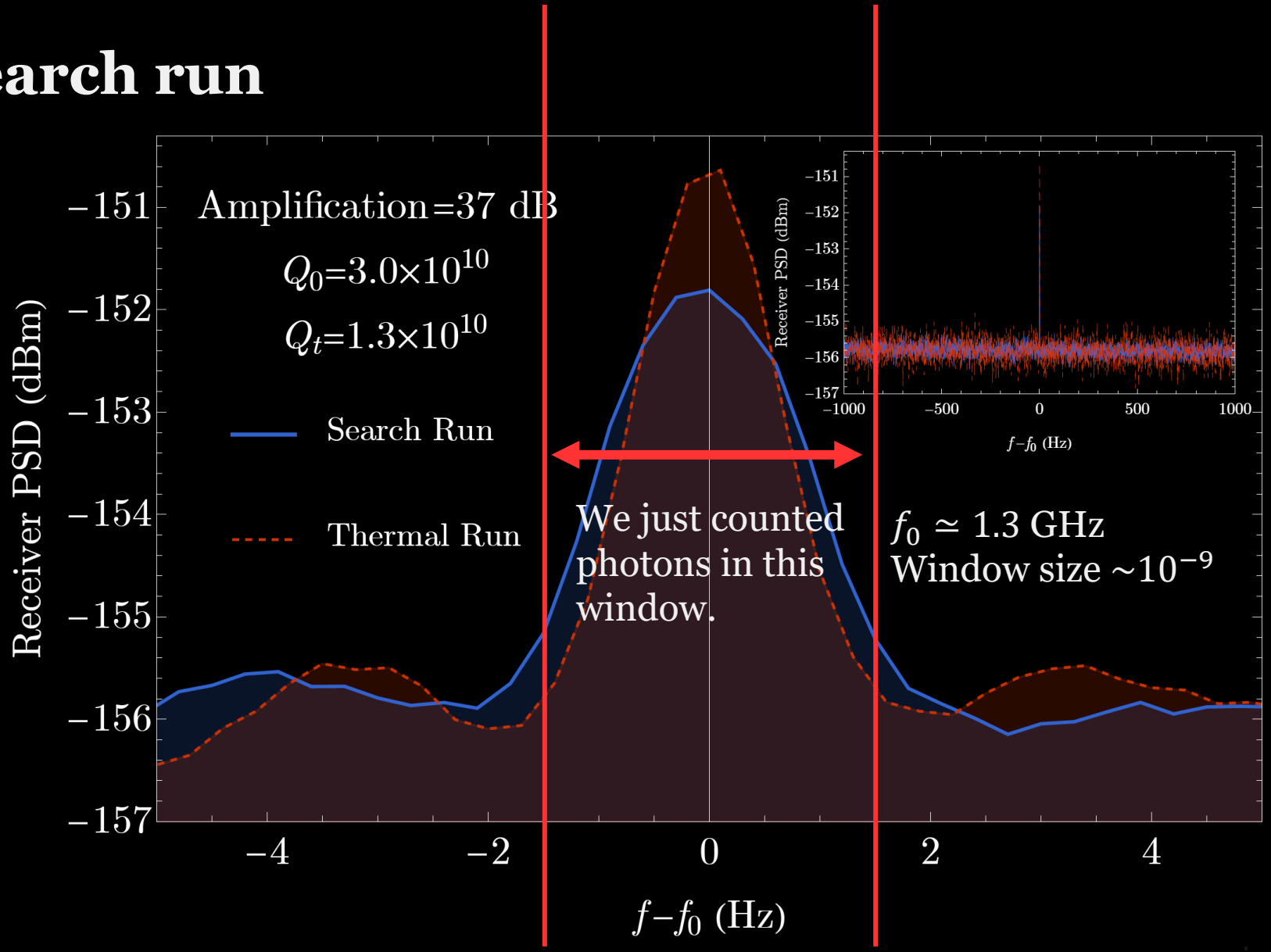


Measurements and Results

Thermal run v.s. Search run

- Blue: Search run
  - $-151.8^{+0.16}_{-0.17}$ dBm
- Red: Thermal run
  - $-151.6^{+0.23}_{-0.25}$ dBm

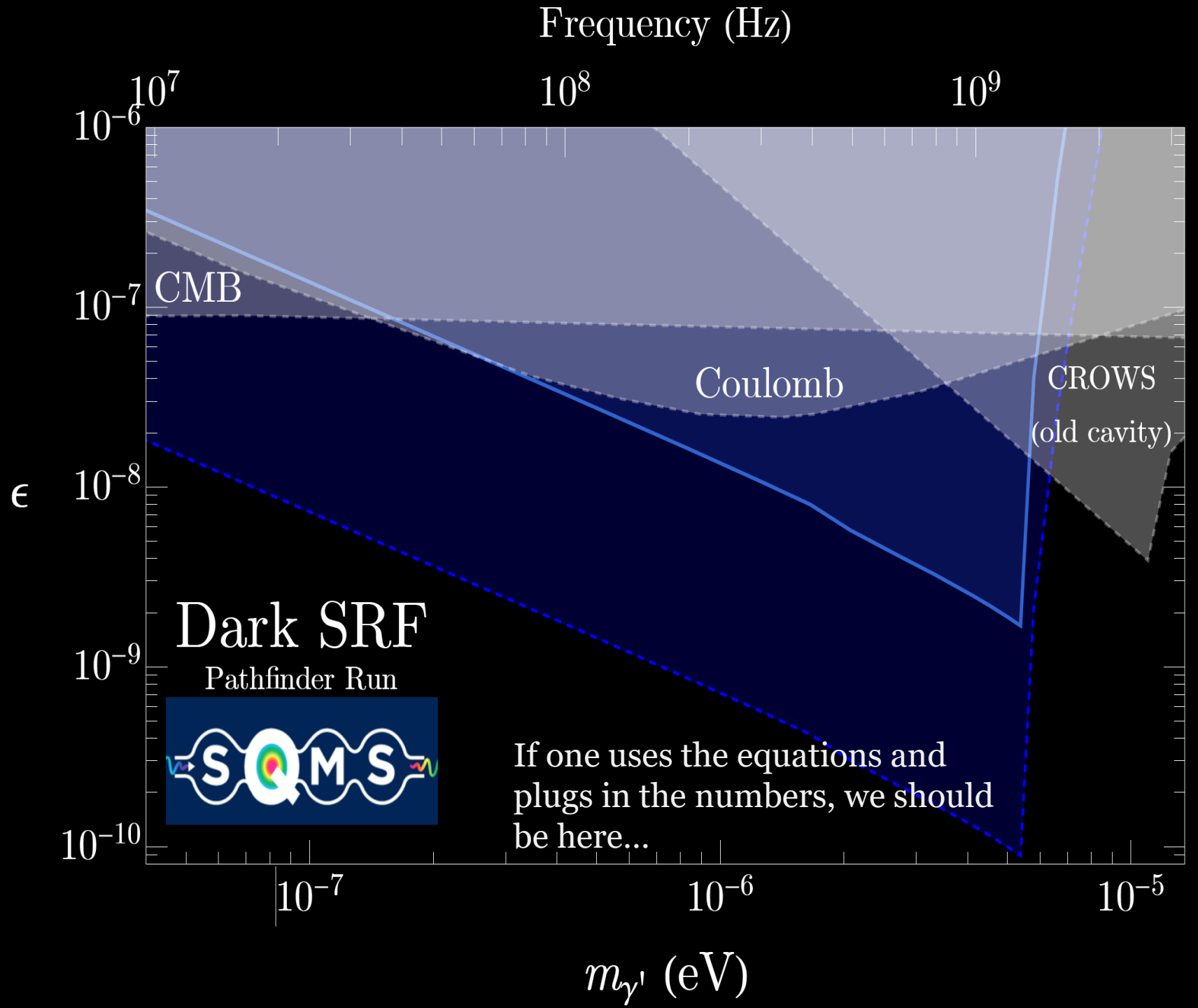
(uncertainty driven by the integration time)



Exciting New Coverage

Our pathfinder run results already explore new territory in such a log-log space!

We've learned a lot about the system and published our first results and been developing many new future directions (as planned).



High-Q not always a blessing

I lied (oversimplified) quite a bit:

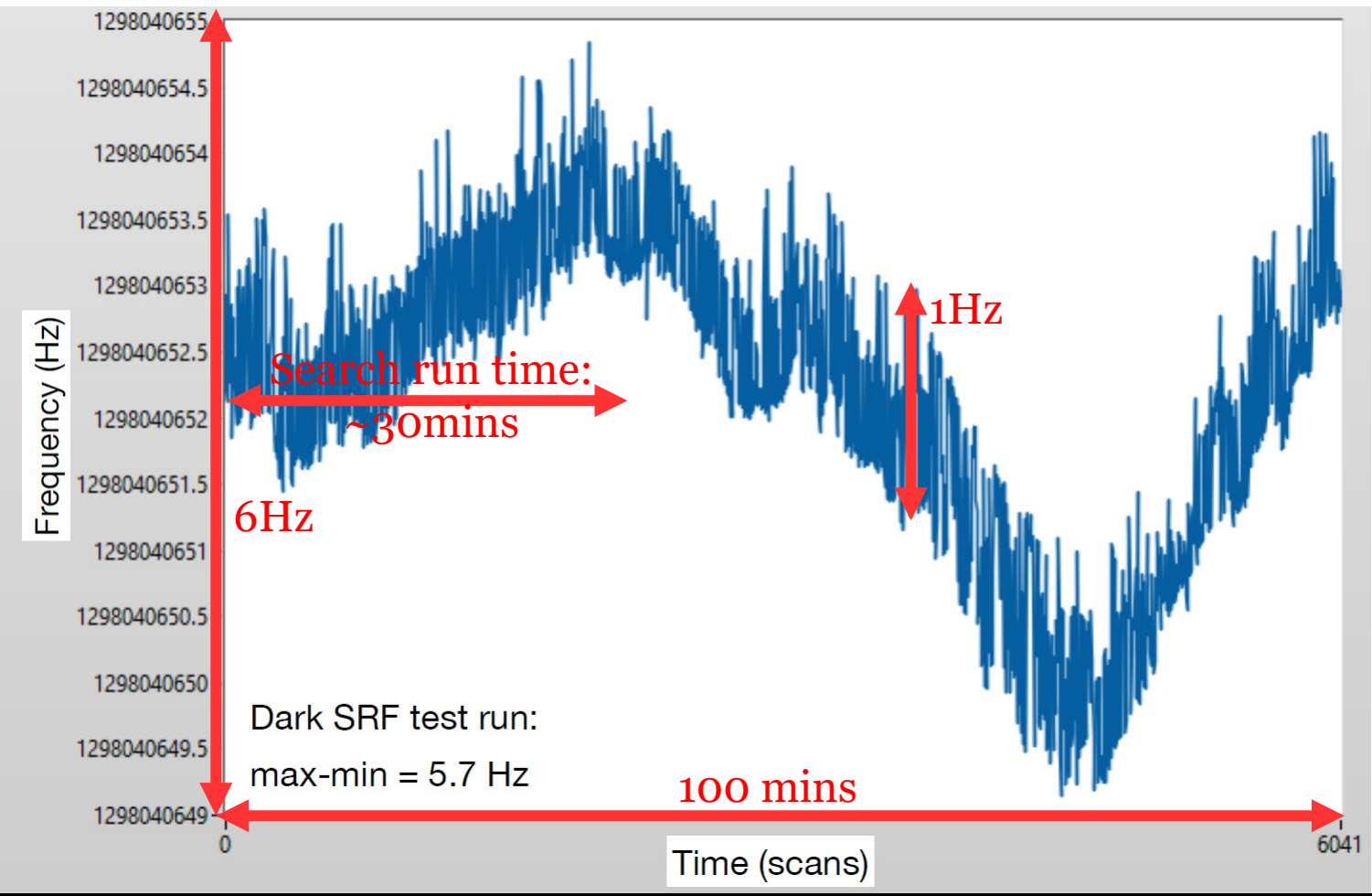
- High-Q is a double-sided sword
- Our pathfinder result did not benefit as Q^2 that we initially wanted
  - We are in a different limit that has not been explored before: $\frac{\omega}{Q} \ll \delta\omega$ (the sources I will highlight soon)
  - Post the end-of-2019 pathfinder search run, we had to perform many validations- and cross-check runs between 2020-2022

A GHz device can be stable in kHz-level ($Q = 10^6$), but many of its properties are not stable at subHz-level ($Q \geq 10^9$).

To get a physical sense,
Cavity size: ~20 cm
Quality factor: 10^{10}
Hence the line width: 0.13 Hz
For Hz-level stability, one needs to ensure the cavity size does not change at the sub-nanometer level.

Many sources contribute to instabilities: temperature, bubbles, pressure change at the surface, etc.

Emitter cavity frequency stability

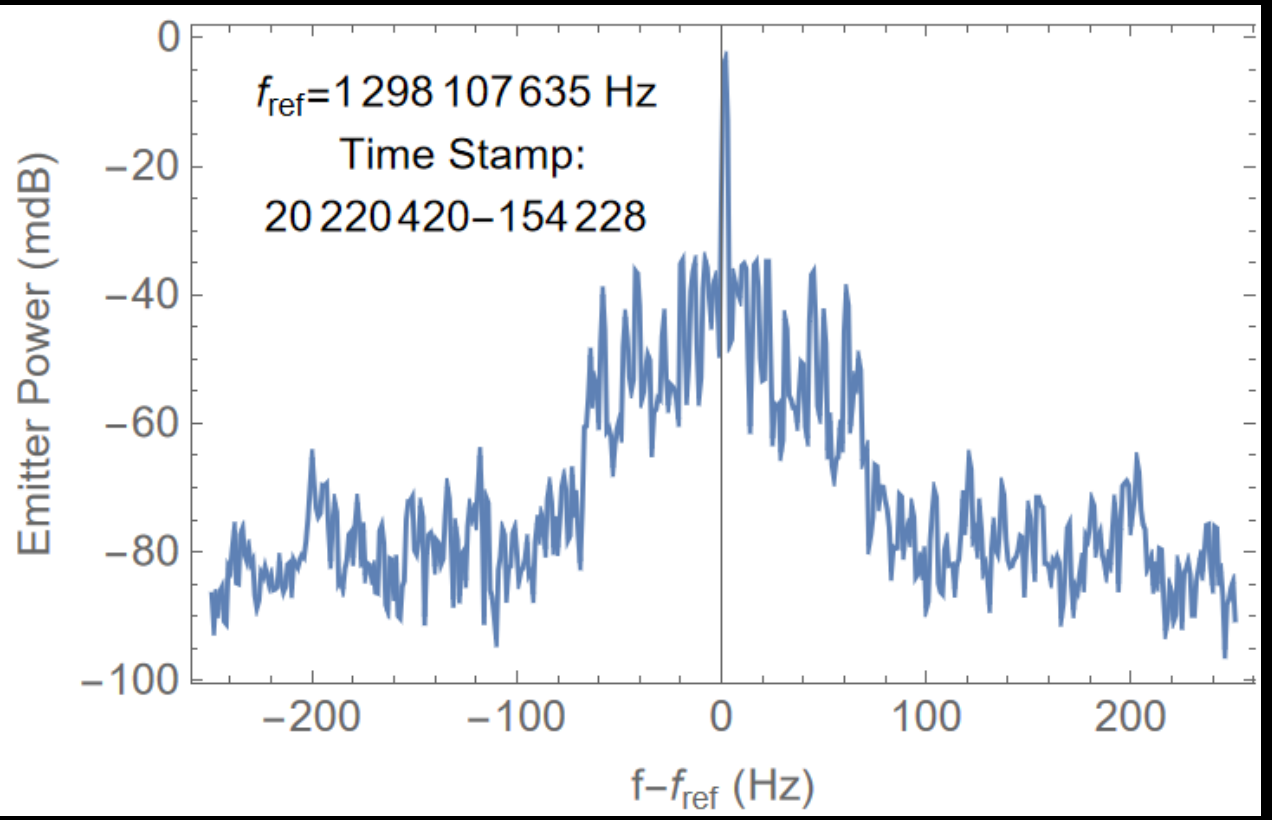


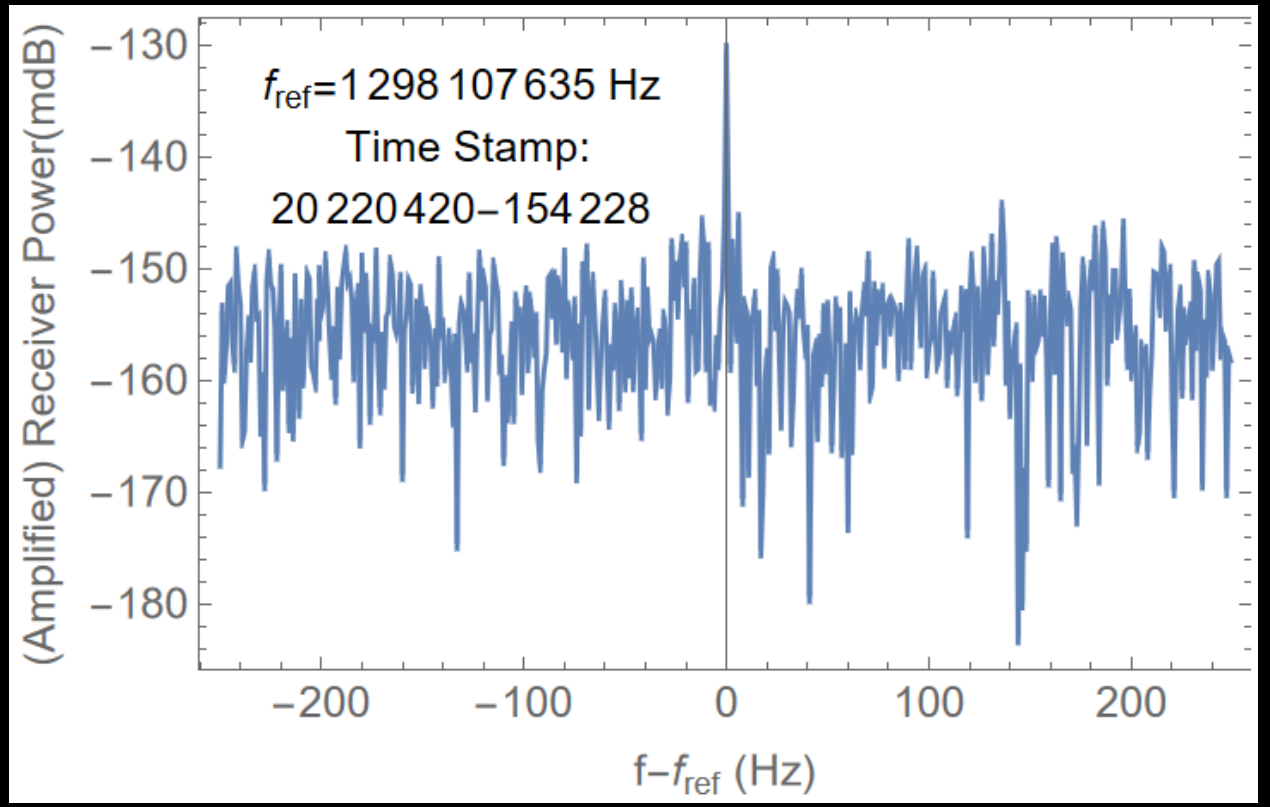
Dedicated frequency stability runs, two effects:

- Frequency drift
- Microphonics

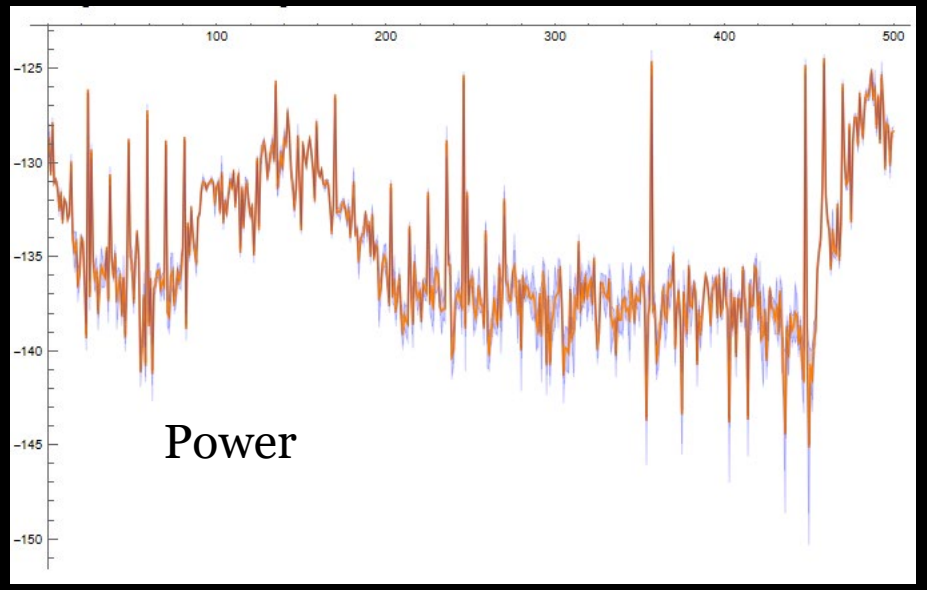
Parameter	Emitter	Receiver
Q_0	4.5×10^{10}	3.0×10^{10}
Q_{in}	1.8×10^{9}	4.5×10^{11}
Q_{t}	2.9×10^{11}	1.3×10^{10}
freq. drift	5.7 Hz	3.0 Hz
microphonics	3.1 Hz	3.1 Hz

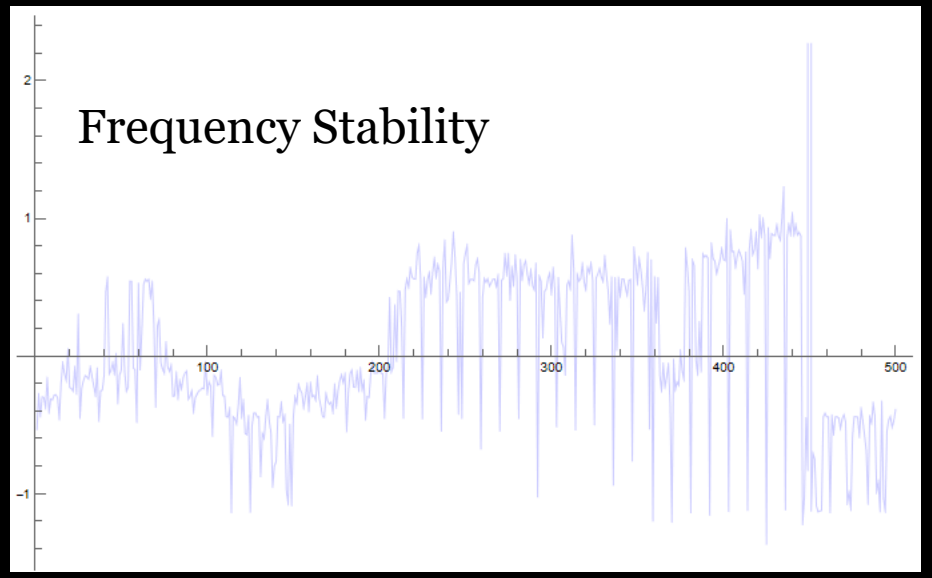
The PSD of the Emitter and Receiver at a given moment

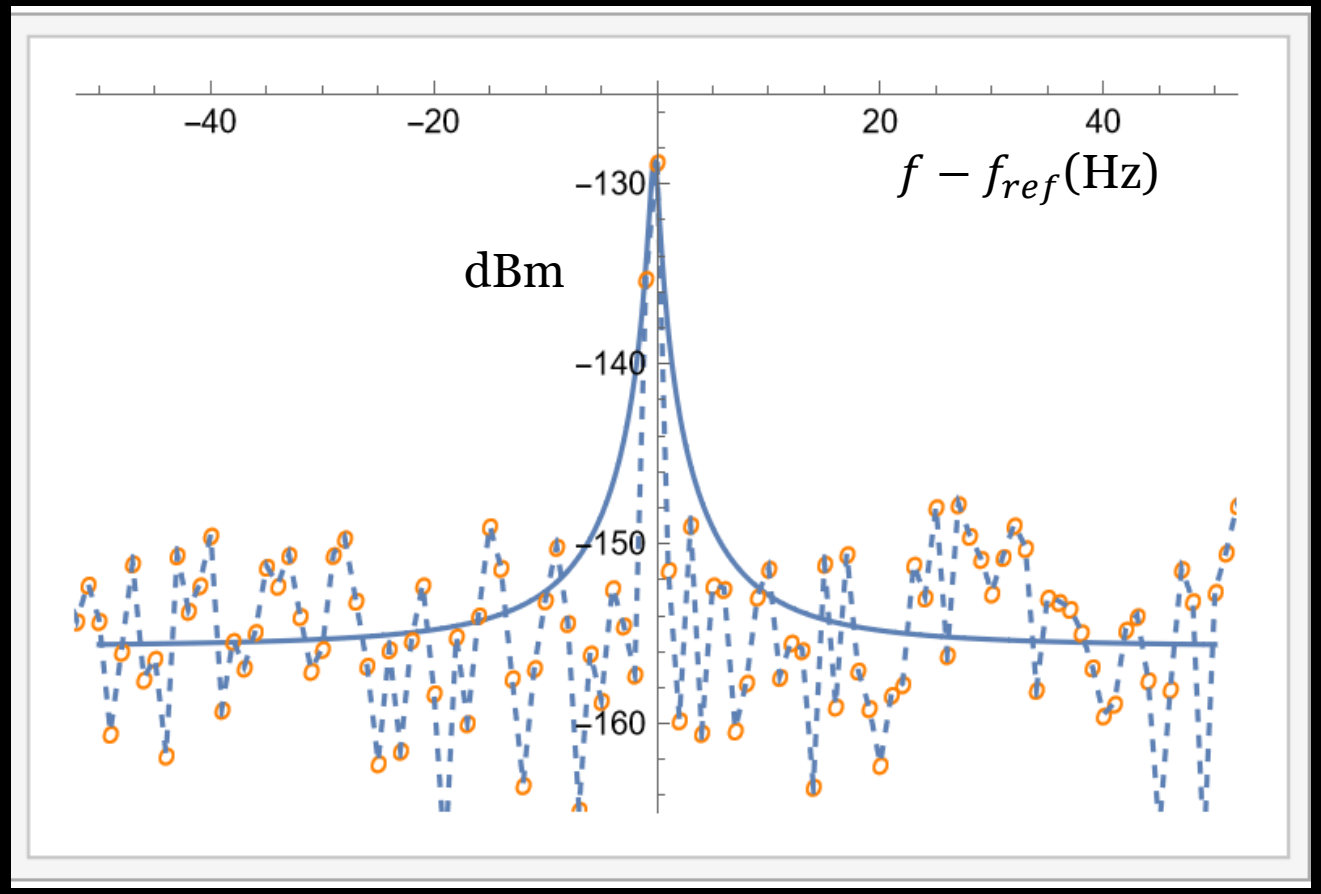




Data Visualization and checks (receiver fit; validation run 19, 2022)





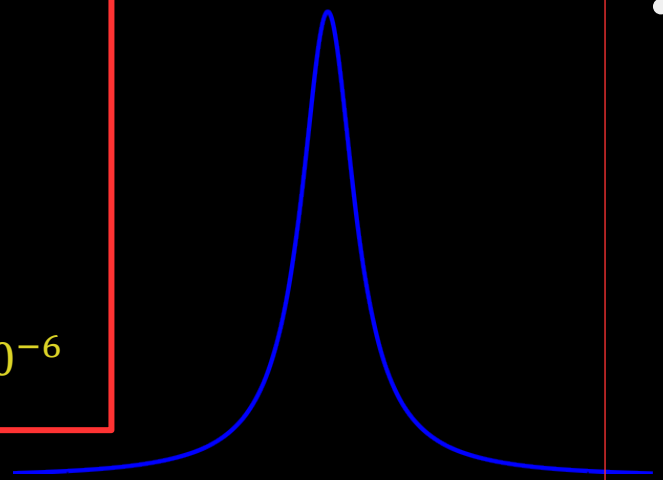


We presented a very conservative limit

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

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

$$\frac{\omega^2}{\omega^2+4\delta_\omega^2 Q_{rec}^2}$$
$$\to \frac{\left(\frac{\omega}{Q_{rec}}\right)^2}{\left(\frac{\omega}{Q_{rec}}\right)^2+4\delta_\omega^2}$$
$$\to \frac{(\sim 0.04\ Hz)^2}{(\sim 16\ Hz)^2} \to 7\times 10^{-6}$$

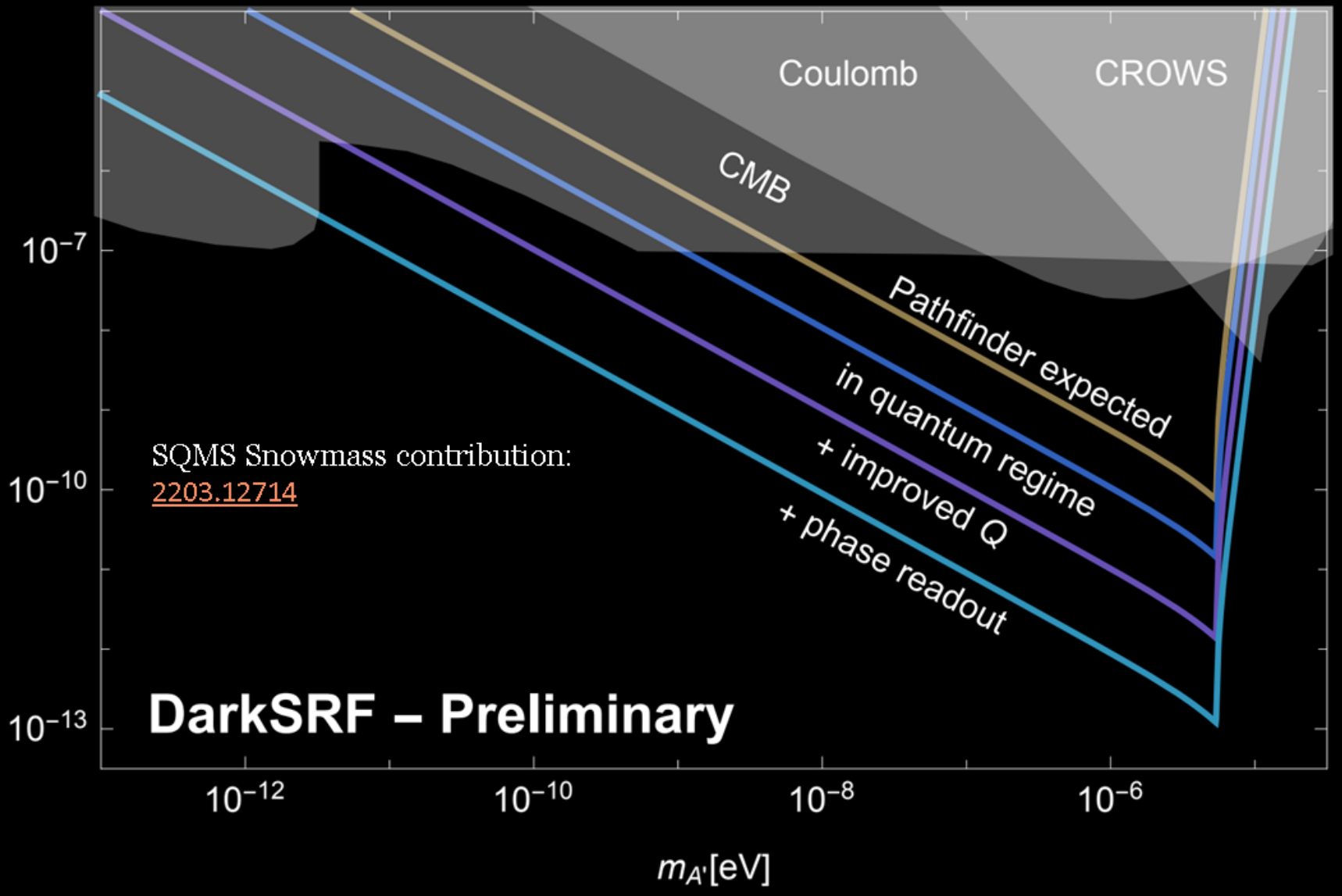


Essentially, modeled as searching off-resonance.

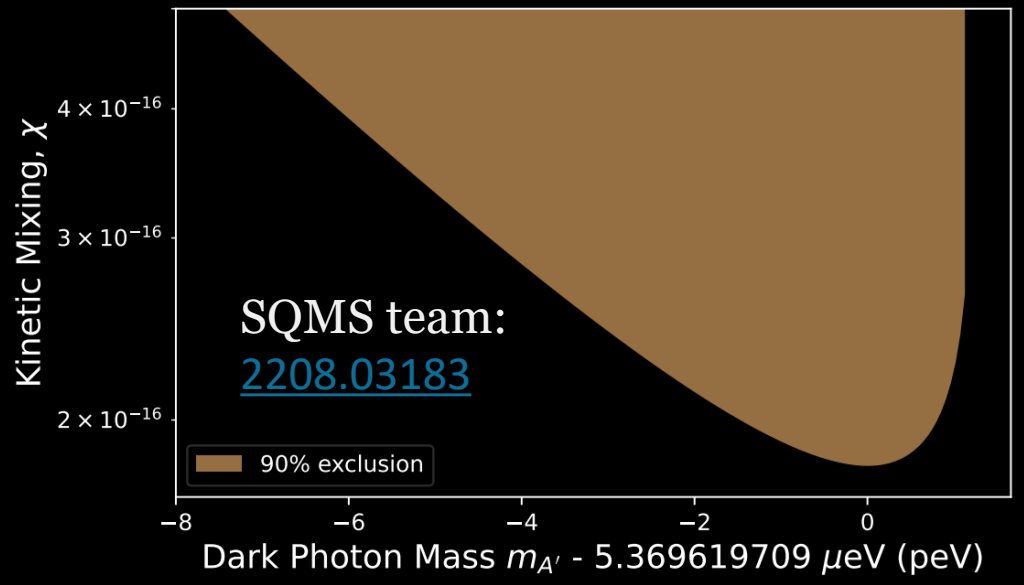
- Frequency drift took as a constant frequency **mismatch** at 5.7 $Hz \oplus$ 3.0 Hz
  - These are drifts at 100 mins scale, our search is 30 mins scale;
  - One can live-monitor and take the data with no drifts.
- Microphonics modeled as constant frequency **mismatch** at 3.1 $Hz \oplus$ 3.1 Hz
  - Theoretically, it is a much less suppression as it reduces effective integration time. (Working on proper modeling.)

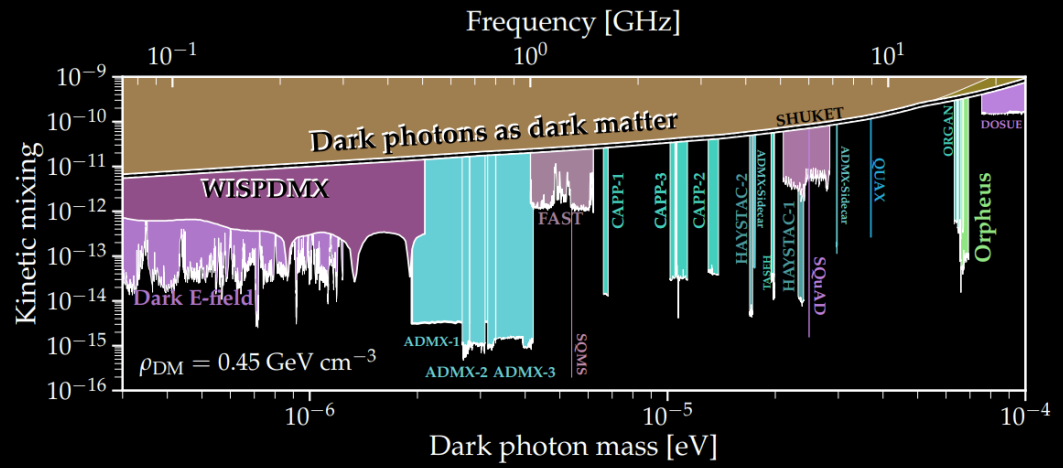
Near (or far?) Future

- Improving noise isolation and control into few photon limits;
- Improve Q (seems require careful discussion)
- Phase-sensitive readout
- Off-the-shelf cavities →better designed and treated ones
  - New design
  - New search protocol



Other and related activities





- Dark photon DM search;
- Axion LSW validation and search;
  - Single cavity design
  - Double cavity multi-mode design
  - Double cavity plus conversion region design
- Axion DM search;
- Gravity Wave validation and search;
- Millicharged particle search;
- Photon mass constraints;
- …

See many recent studies, and also partial summaries in SQMS SRF paper: 2203.12714

Outlook

- Fun journey to arrive at a first result using SRF cavities for HEP searches in the Dark SRF pathfinder run.
  - Covered new parameter regions in the log-log space;
  - Learnt & learning to handle ultrahigh Q opportunities;
  - Establishing and developing schemes for robust tests;
- An active program ahead:
  - Many planned steps improve the results significantly;
  - Many possible theory research directions to improve the results & treatments (interested parties highly welcome!);
  - Many “adjacent” exploration and searches possible;

Thank you!
& the fantastic Dark SRF team!