# Dark photon dark matter search at the TASEH experiment

In Collaboration with: TASEH Collaboration

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# Dark Photon

One of the simplest possible SM extensions: add a new dark U(1) gauge symmetry.

The low-energy effective Lagrangian:

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F_{\varrho}^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\sin\alpha}{2}F^{\mu\nu}X_{\mu\nu} + eJ^{\mu}_{\mathrm{EM}}A_{\mu} - \frac{m_X^2\cos^2\alpha}{2}X^{\mu}X_{\mu}$$

It has kinetic mixing with the SM photon, the kinetic mixing $\epsilon = \tan\alpha$ is the mixing in the mass term in the interaction basis.

It can obtain mass via Higgs mechanism or Stueckelberg mechanism.

Light dark photons(sub-eV) are best described as a coherent wave oscillating at a frequency set by $m_X$, rather than a collection of distinct particles.

Like the axion, dark photon can also provide a natural DM candidate(DPDM).

# Dark Photon Relic Density

Gravitational particle production (inflationary fluctuations):

P.Graham, J.Mardon, S.Rajendran (2016); E. Kolb, A.Long (2021)

$$\Omega_{A'} = \Omega_{\text{CDM}} \times \sqrt{\frac{m_{A'}}{6 \times 10^{-6}\text{eV}}} \cdot \left(\frac{H_I}{10^{14}\text{GeV}}\right)^2$$

Axion oscillation:

P.Agrawal, N.Kitajima, M.Reece, T.Sekiguchi, F.Takahashi (2020)

$$\Omega_{A'} h^2 \simeq 0.2 \cdot \theta^2 \left(\frac{40}{\beta}\right) \left(\frac{m_{A'}}{10^{-9}\text{eV}}\right) \left(\frac{10^{-8}\text{eV}}{m_a}\right)^{1/2} \left(\frac{F_a}{10^{14}\text{GeV}}\right)^2$$

with $\frac{\beta}{4F_a} \cdot \phi F'_{\mu\nu} \tilde{F}'^{\mu\nu}$

Misalignment mechanism:

A.Nelson, J.Scholtz (2011); P.Arias et.al.(2012)

Requires non-minimal coupling to gravity $\frac{\kappa}{12} R A'_\mu A'^\mu$, otherwise $\rho \propto R^{-4}$ for $t \ll m_{A'}^{-1}$, giving too small relic density.

Decays of topological defects

A. J. Long and L. T. Wang (2019)

# Dark Photon Polarization

Misalignment mechanism naturally leads to relic DPDM with a fixed polarization within the cosmological horizon.

Axion oscillation dominantly produces a specific dark photon helicity.

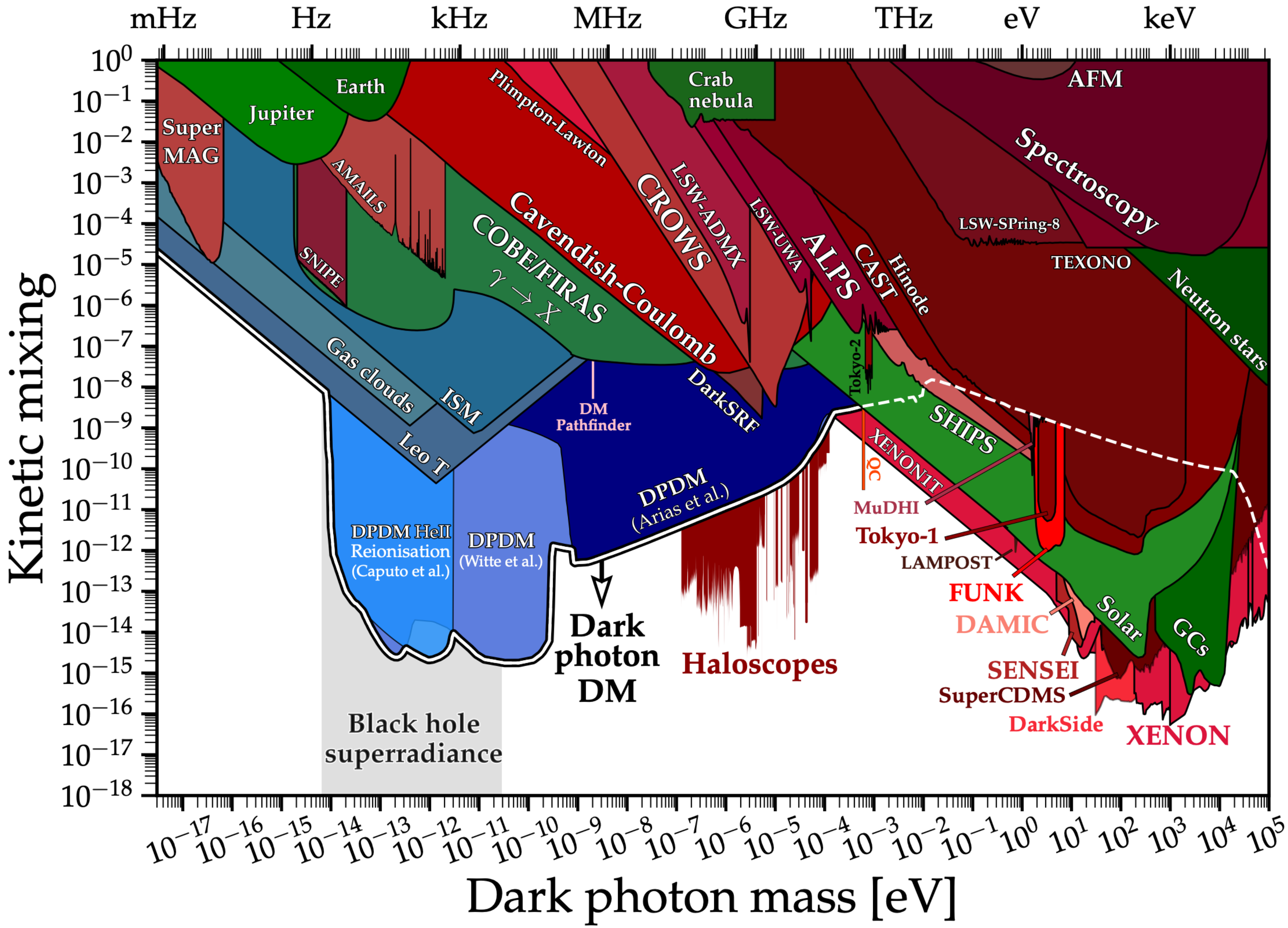
DPDM from the collapse of smaller closed cosmic string loops has no single polarization, which give us the random polarization scenario.

The direction of the DP field remains unchanged for most of the Universe history.

Two phenomenological extreme cases: fixed polarization and randomized polarization.

Any realistic scenario will presumably lie between these two extremes.

# Dark Photon Detection landscape




Cosmological bounds in blue

Astrophysical bounds in green

Experimental bounds in red

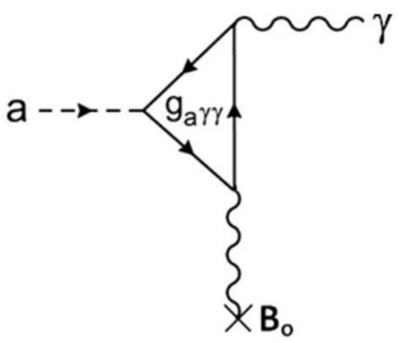
# Haloscope

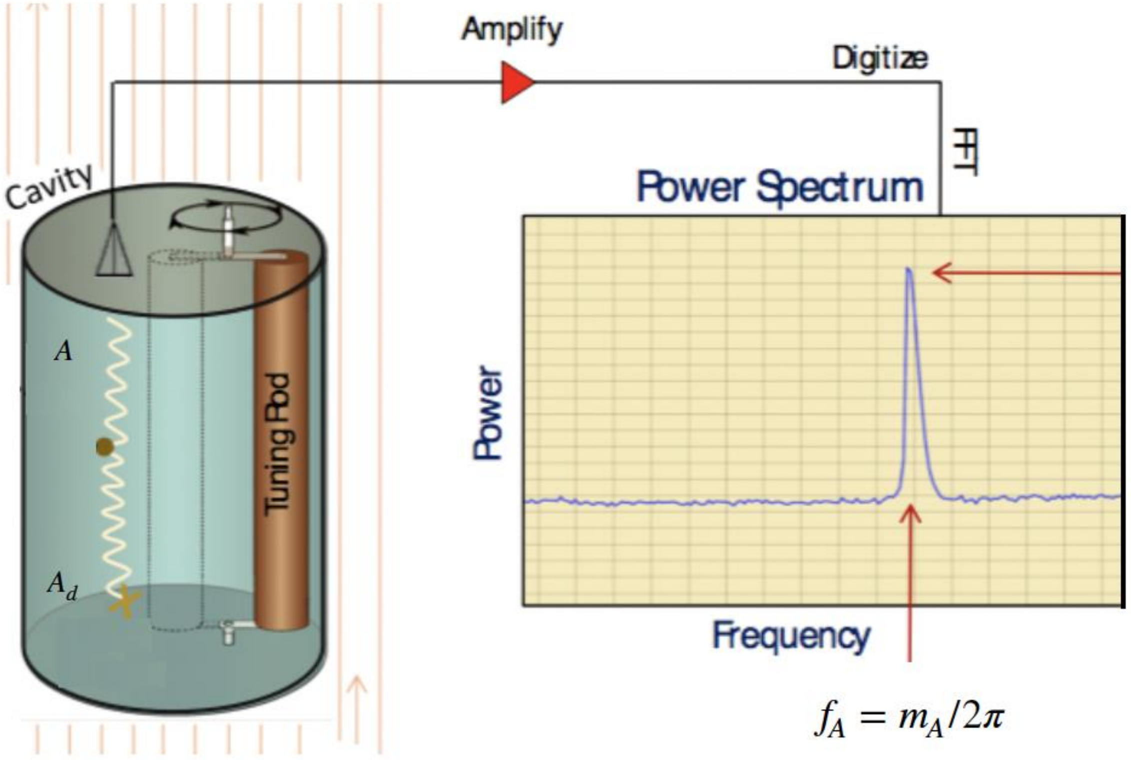
Dark photons/axions from the DM halo resonantly convert to photons when $m_X$ matches the resonance frequency of a microwave cavity.

Dark photons has kinetic mixing with the SM photon, and thus unlike axions we do not need magnetic fields in the Haloscope experiments.

We don't know $m_X$ , so we need to scan the parameter space.

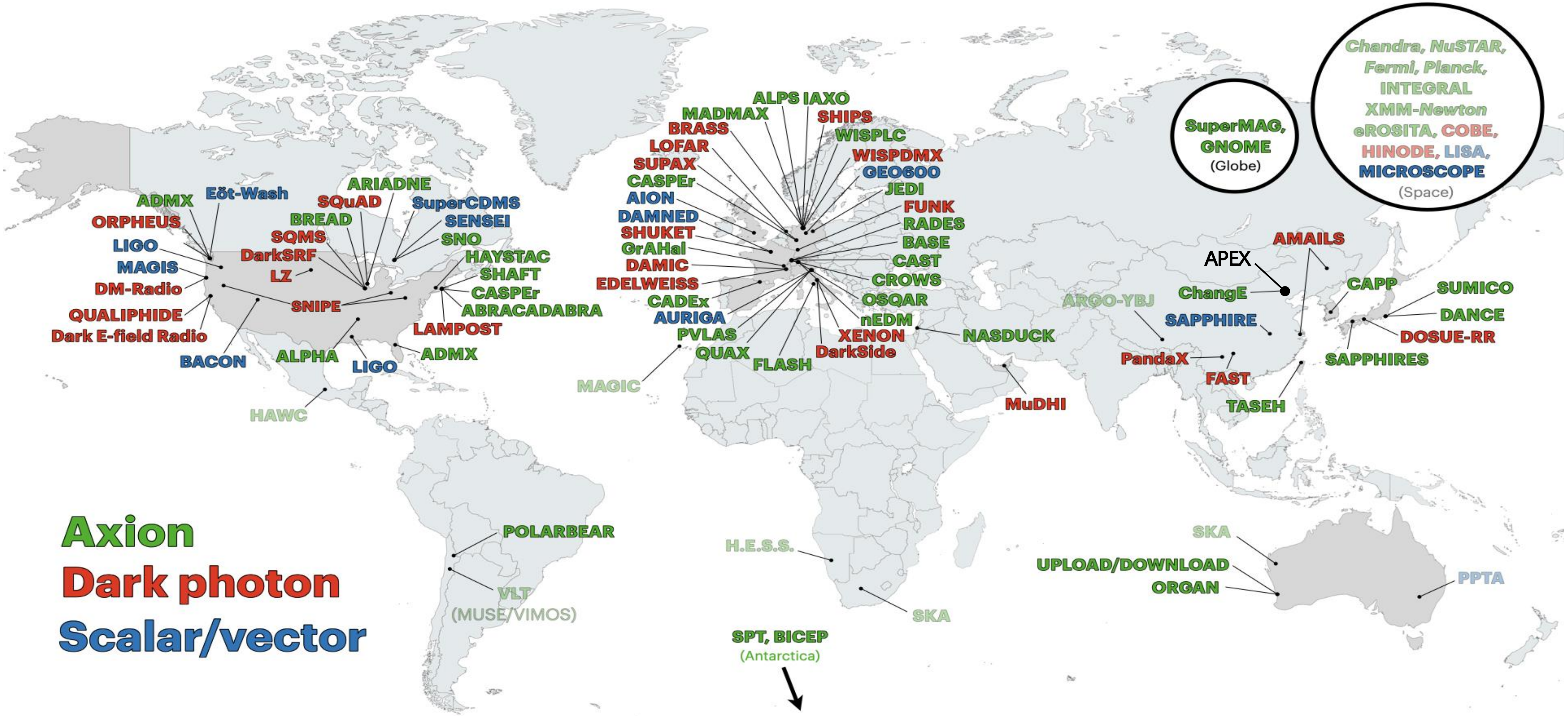
Sikivie,1983




Expected haloscope signal power is $\mathcal{O}\left(10^{-24}\ \mathrm{W}\right)$

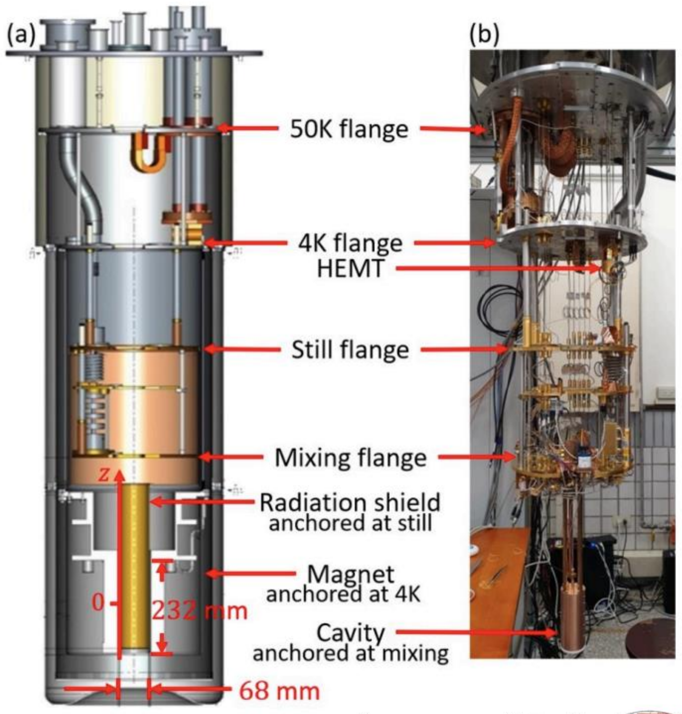
Noise floor from cavity blackbody radiation, plus added Johnson noise from the receiver chain

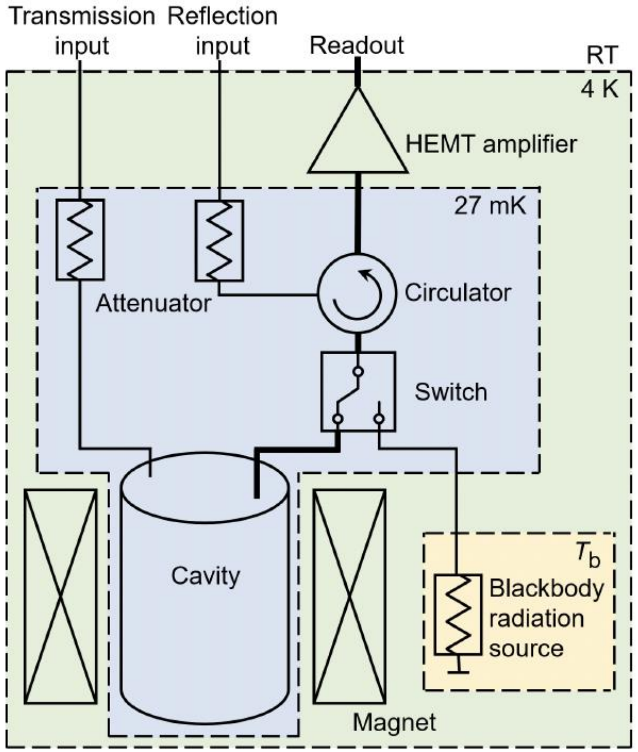


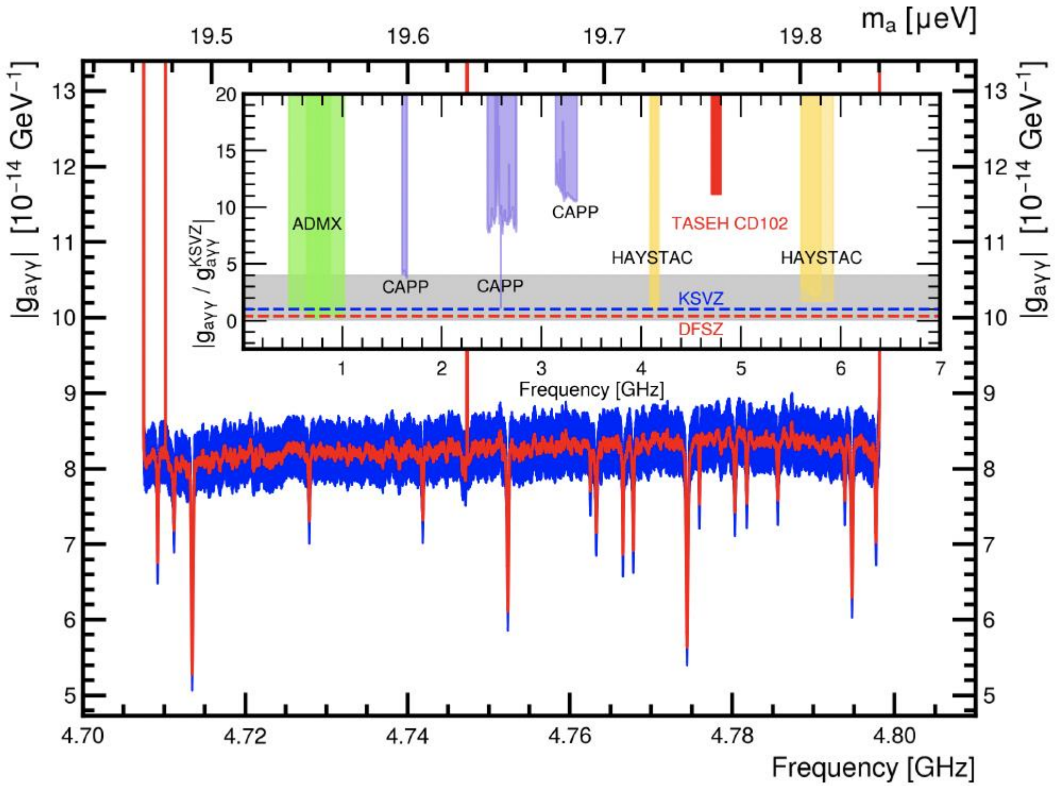

(Figure courtesy of Ciaran O'Hare)

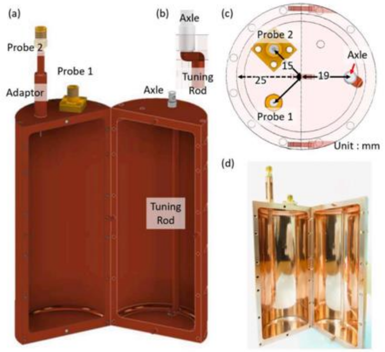
# Search for Axion/Dark photon DM with TASEH Haloscope

Axion cavity haloscope at National Central University, Taiwan. First experimental run completed in 2021. Ultimate goal to search 2.5-6 GHz band to QCD axion sensitivity



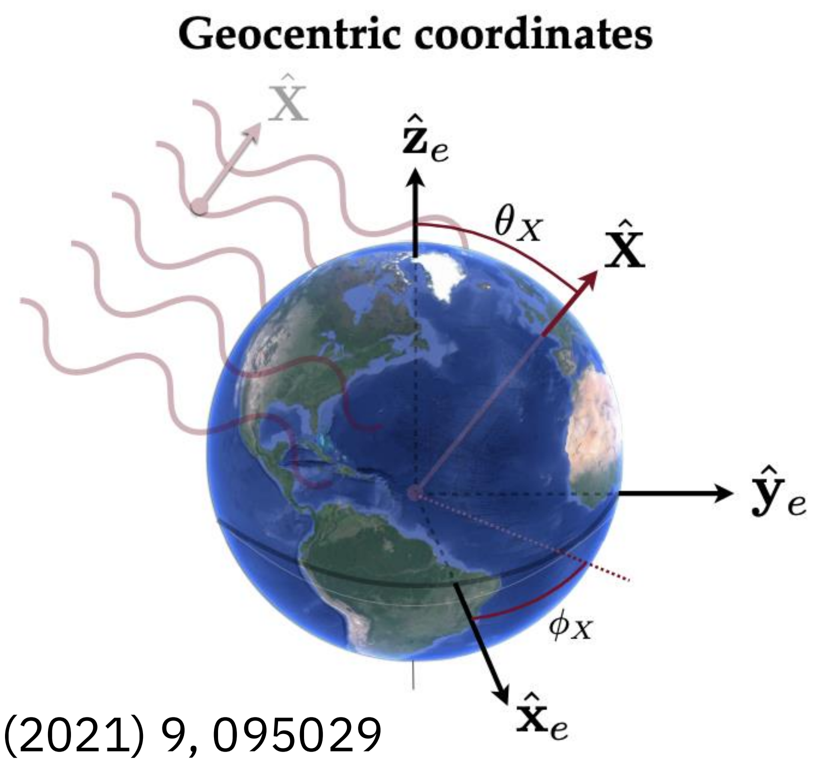



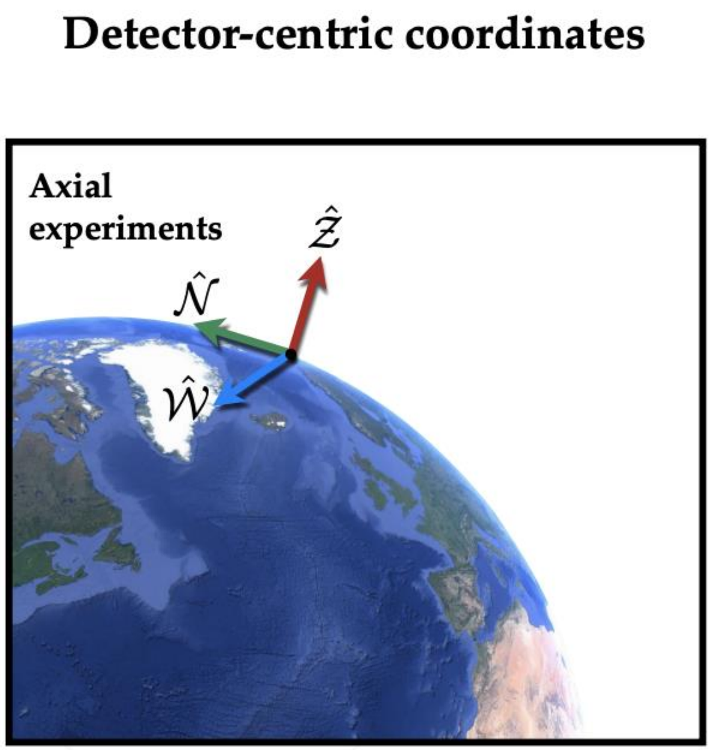




| $f_{low}$ | $f_{high}$ | $\Delta f_{step}$ | $B_0$ | $V$ | $C_{010}$ | $Q_0$ | $T_{sys}$ |
|---|---|---|---|---|---|---|---|
| 4.708 GHz | 4.798 GHz | $\sim$ 100 kHz | 8 Tesla | 0.234 L | 0.60-0.61 | $\sim$ 60000 | 2.2 K |

Phys.Rev.Lett. 129 (2022) 11, 111802; Phys.Rev.D 106 (2022) 5, 052002

# Dark photon cavity search with polarization




Phys.Rev.D 104 (2021) 9, 095029

$$\hat{X} = (\sin\theta_X \cos\phi_X, \sin\theta_X \sin\phi_X, \cos\theta_X)$$

$$\hat{\mathcal{Z}}(t) = (\cos\lambda_{\rm lab}\cos\omega t, \cos\lambda_{\rm lab}\sin\omega t, \sin\lambda_{\rm lab})$$

$\lambda_{\rm lab}$ is the latitude, $\omega = 2\pi/(1 \text{ sidereal day })$ angular frequency of the Earth's rotation

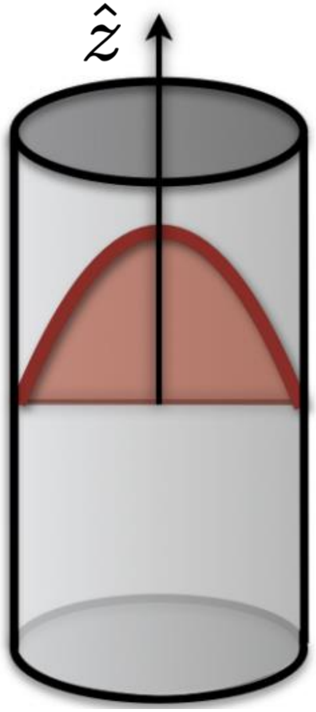
Angle between dark photon polarization and detector: $\cos\theta(t) = \hat{X}\cdot\hat{\mathcal{Z}}(t)$

# Axion cavity Haloscope is also a dark photon Haloscope

The DPDM power: $P = P_X + N \equiv P_X^0 \langle \cos^2\theta \rangle_T + N$

$$P_{\rm dp} = \epsilon^2 m_X \rho_{\rm DM} V C_{mnl} Q_L \frac{\rho}{1+\beta} L(f, f_c, Q_L), \quad \epsilon = \tan\alpha$$

$$C_{mnl} = \frac{\left(\int dV \mathbf{E}_{mnl}(\vec{x}) \cdot \hat{X}(\vec{x})\right)^2}{V \int dV \left|\mathbf{E}_{mnl}(\vec{x})\right|^2 |\hat{X}(\vec{x})|^2}, \quad L(f, f_c, Q_L) = \frac{1}{1 + 4Q_L^2 (f/f_c - 1)^2}$$




Compared with the axion power: $P = P_a + N$

$$P_{\rm a} = \left(\frac{g_{a\gamma}^2 B_0^2}{m_a}\right) \rho_{\rm DM} V C_{mnl} Q_L \frac{\beta}{1+\beta} L(f, f_c, Q_L), C_{mnl} = \frac{\left(\int dV \mathbf{E}_{mnl}(\vec{x}) \cdot \mathbf{B}(\vec{x})\right)^2}{V B_0^2 \int dV \left|\mathbf{E}_{mnl}(\vec{x})\right|^2}$$

Recast from $g_{a\gamma}$ to $\epsilon$ :

$$\epsilon = g_{a\gamma} \frac{B}{m_X |\cos\theta|}, \quad \cos\theta = \hat{z} \cdot \hat{X}$$

# Conversion factor with DP polarization

DP signal power accumulated over a measurement time T

$$\langle \cos^2\theta(t)\rangle_T = \frac{1}{T}\int_0^T \cos^2\theta(t)dt$$

over multi-measurement Ti

$$\langle \cos^2\theta(t)\rangle_T = \frac{1}{\sum P_i}\left(\frac{P_1}{T_1}\int_{T_1^{\text{start}}}^{T_1^{\text{start}}+T_1} \cos^2\theta(t)dt + \frac{P_2}{T_2}\int_{T_2^{\text{start}}}^{T_2^{\text{start}}+T_2} \cos^2\theta(t)dt + \cdots\right)$$

For randomized polarization (Independent of time):

$$\frac{1}{4\pi}\int \langle \cos^2\theta(t)\rangle_T d\cos\theta_X d\phi_X = \frac{1}{3}$$

For fixed polarization:

$$\int_{-\infty}^{+\infty} dP_X \int_{-\infty}^{-P_X} dN f(P_X) f(N) = \int_0^1 d\langle\cos^2\theta(t)\rangle_T \frac{f\left(\langle\cos^2\theta(t)\rangle_T\right)}{2}\left[1+\text{erf}\left(\frac{-P_X^0\langle\cos^2\theta(t)\rangle_T}{\sqrt{2}\sigma_N}\right)\right] = 0.05$$

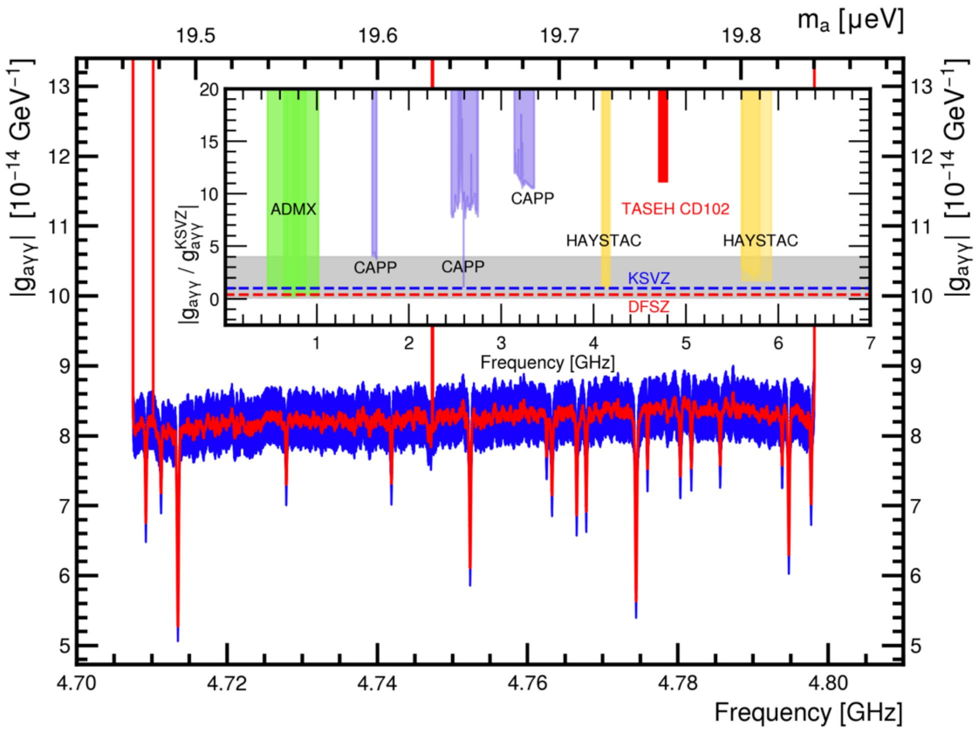
So:

$$\Phi\left(-\frac{P_X^0\langle\cos^2\theta\rangle_T^{\text{excl}}}{\sigma_N}\right) = 0.05, \quad \langle\cos^2\theta(t)\rangle_T^{\text{excl.}} = \frac{\Phi^{-1}[0.95]\sigma_N}{P_X^0} = \frac{1.64\sigma_N}{P_X^0}$$

# TASEH axion limits to dark photon limits

Measuring with periods T:

$$\frac{P_a}{\sigma_N} > \Phi^{-1}[0.95] = 1.64(\sim 95\%\ \text{C.L.}\ ) = \left(\frac{p_X^0 \epsilon^2 m_X \langle\cos^2\theta(t)\rangle_T^{\text{excl.}}}{\sigma_N}\right)_{\text{DP}} = \left(\frac{p_X^0 g_{a\gamma}^2 B^2}{\sigma_N}\right)_{\text{Axion}}$$




$$\epsilon = g_{a\gamma}\frac{B}{m_X\sqrt{\langle\cos^2\theta(t)\rangle_T^{\text{excl.}}}}$$

TASEH Axion limit

Phys.Rev.Lett. 129 (2022) 11, 111802
Phys.Rev.D 106 (2022) 5, 052002
Rev.Sci.Instrum. 93 (2022) 8, 084501

TASEH Dark Photon limit

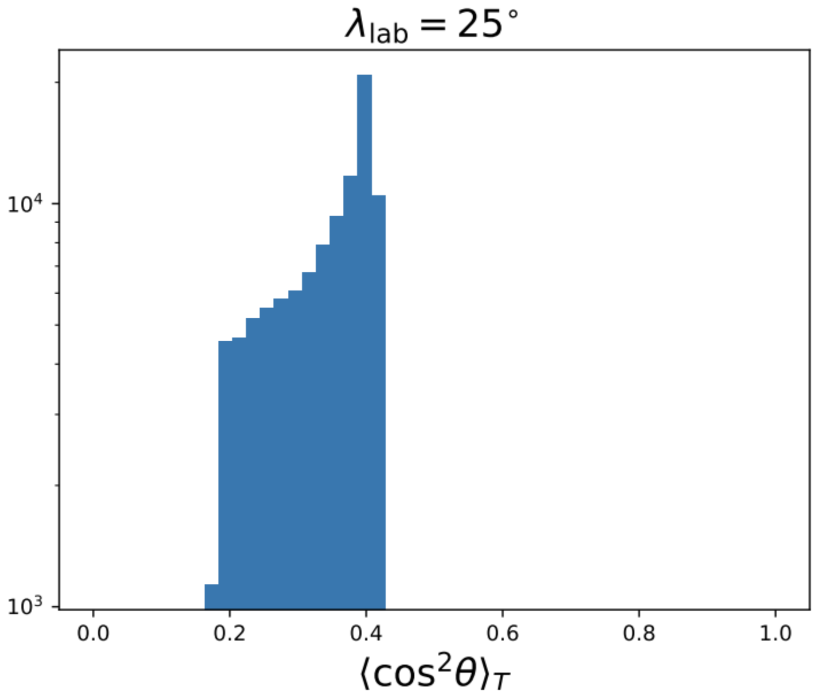
# Lattitude dependence for fixed polarization

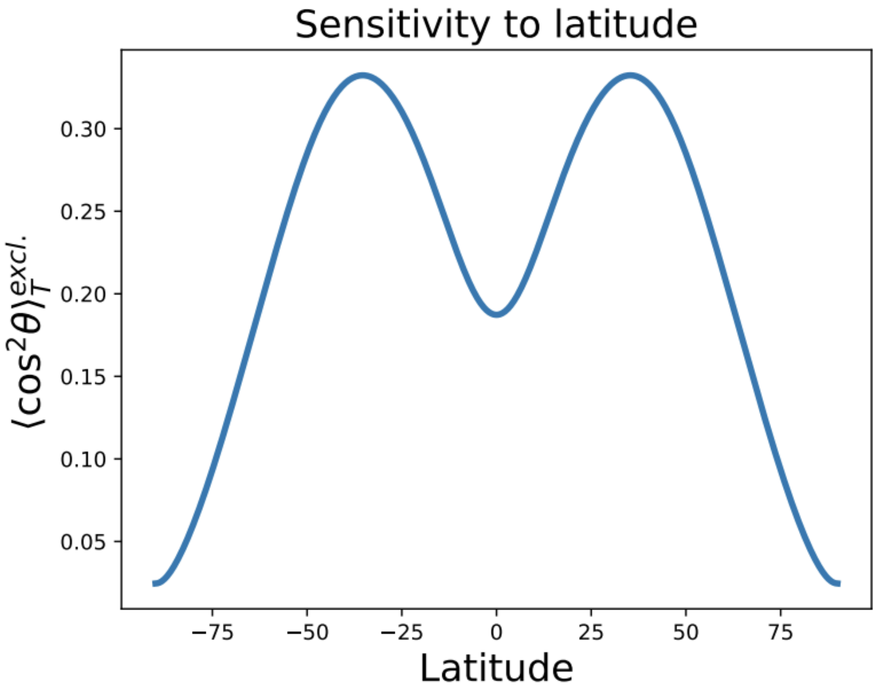
Measuring for a whole day:

$$\left\langle \cos^2\theta(t) \right\rangle_{1\text{ day}} = \frac{1}{8}\left(3 + \cos 2\theta_X - (1 + 3\cos 2\theta_X)\cos 2\lambda_{\text{lab}}\right)$$

Sampling spherical symmetric $\theta_X \rightarrow \left\langle \cos^2\theta(t) \right\rangle_{1}$ day

Calculate the conversion factor $\left\langle \cos^2\theta(t) \right\rangle_T^{\text{excl.}}$



# Measurement time dependence

Measuring a period T

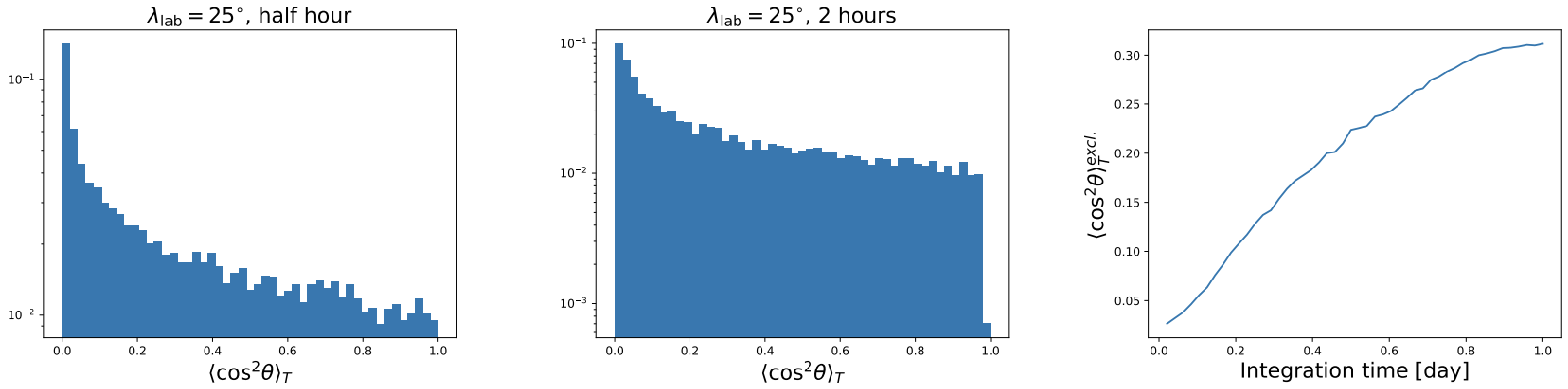
$$\cos\theta(t) = \sin\theta_X \cos\phi_X \cos\lambda_{\rm lab} \cos\omega t + \sin\theta_X \sin\phi_X \cos\lambda_{\rm lab} \sin\omega t + \cos\theta_X \sin\lambda_{\rm lab}$$

Taking $T = 1/48 \text{ day} \sim 0.5 \text{ hour}, \lambda_{\rm lab} = 25^\circ \to f\left(\langle\cos^2\theta(t)\rangle_T\right)$

$\to \langle\cos^2\theta(t)\rangle_T^{\rm excl} \sim 0.025$

Taking $T = 1/12 \text{ day} \sim 2 \text{ hour}, \lambda_{\rm lab} = 25^\circ \to f\left(\langle\cos^2\theta(t)\rangle_T\right)$

Changing the integration time

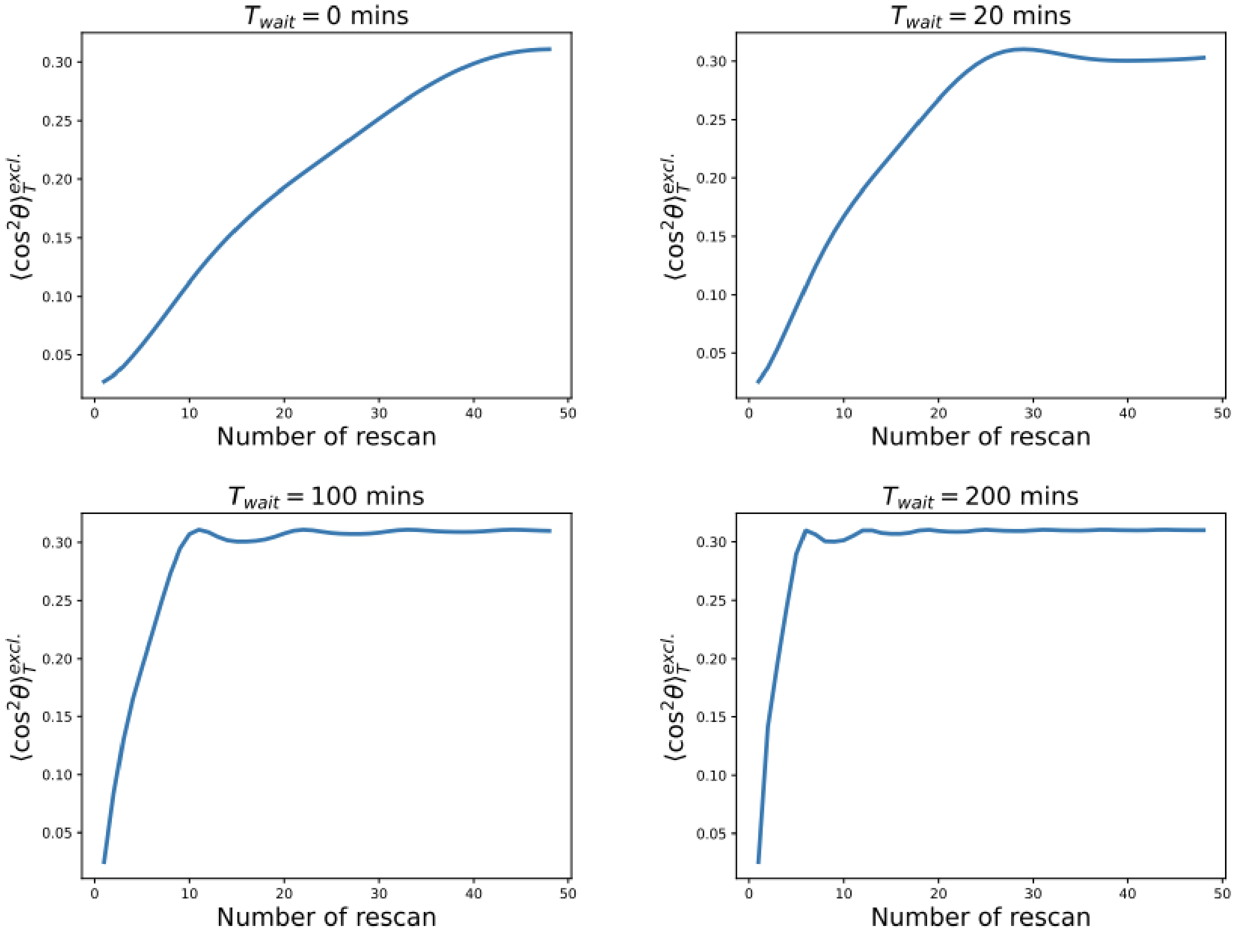


# Multiple measurement with time gaps

Repetitive measurement with $T_{\text{int}} = 30$ mins and $T_{\text{wait}} = 0, 20, 100, 200$ mins, $T_{\text{tot}} = T_{\text{int}} + T_{\text{wait}}$

(Assuming the same power for each measurement)

$$\langle \cos^2 \theta(t) \rangle_T = \frac{1}{T_{\text{int}}} \left( \int_0^{T_{\text{int}}} \cos^2 \theta(t) dt + \int_{T_{\text{tot}}}^{T_{\text{tot}}+T_{\text{int}}} \cos^2 \theta(t) dt + \int_{2T_{\text{tot}}}^{2T_{\text{tot}}+T_{\text{int}}} \cos^2 \theta(t) dt + \cdots \right)$$



# Scan strategy at TASEH

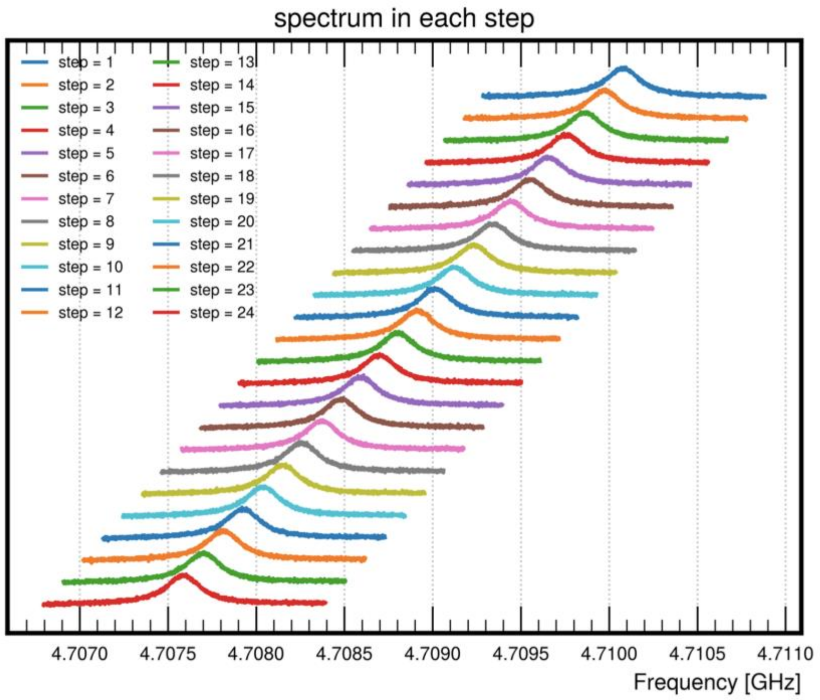
Total 839 scans

Scan step size ~ 100 kHz

Width of each scan 1600 kHz

Integration time ~ 40 mins

Waiting time ~ 2 mins




```
scan ibin frequency      power
783 102 [4.71270500e+00 2.76785695e-10]
784 212 [4.71270500e+00 2.76790478e-10]
785 317 [4.71270500e+00 2.77402236e-10]
786 426 [4.71270500e+00 2.77637399e-10]
787 530 [4.71270500e+00 2.77624467e-10]
788 631 [4.71270500e+00 2.79422577e-10]
789 733 [4.71270500e+00 2.82600761e-10]
790 841 [4.71270500e+00 2.83103894e-10]
791 944 [4.71270500e+00 2.79373589e-10]
792 1046 [4.71270500e+00 2.77746504e-10]
793 1152 [4.71270500e+00 2.77014806e-10]
794 1255 [4.71270500e+00 2.76267654e-10]
795 1364 [4.71270500e+00 2.76283169e-10]
796 1467 [4.7127050e+00 2.7579391e-10]
797 1567 [4.71270500e+00 2.76006453e-10]
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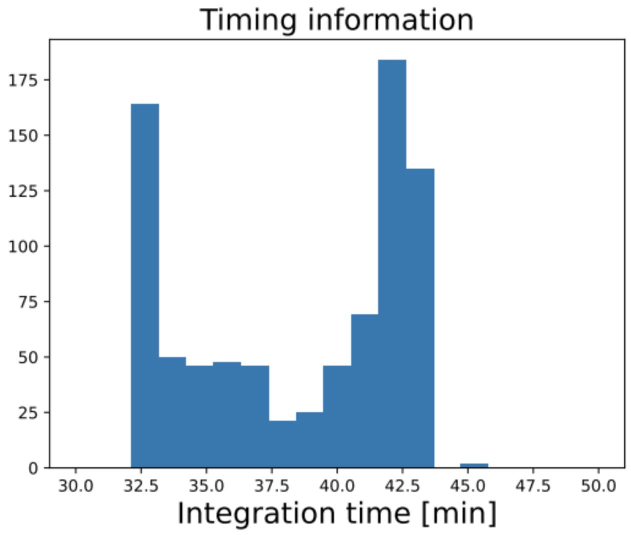
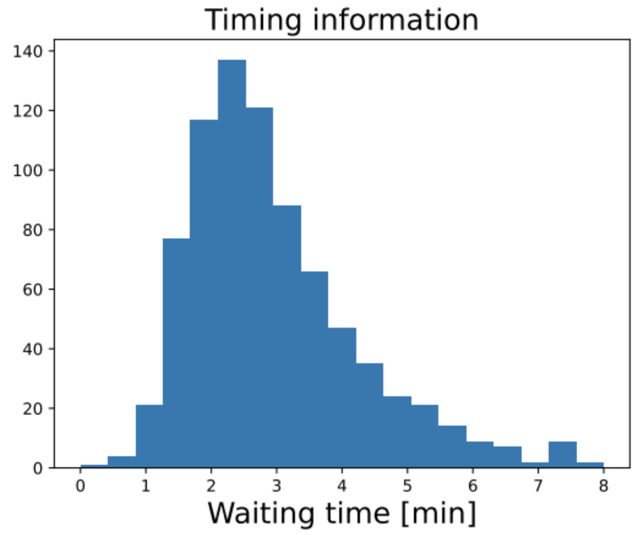


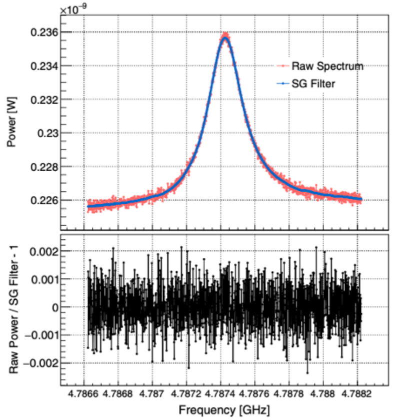
# TASEH data analysis procedure

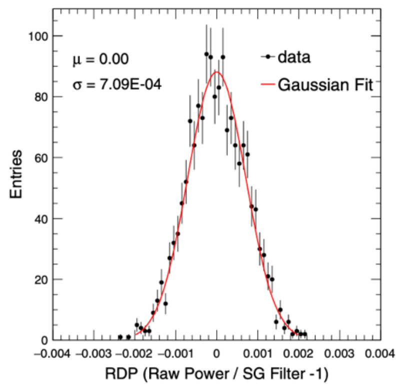
Perform FFT on the IQ time series data to obtain the frequency-domain power spectrum.

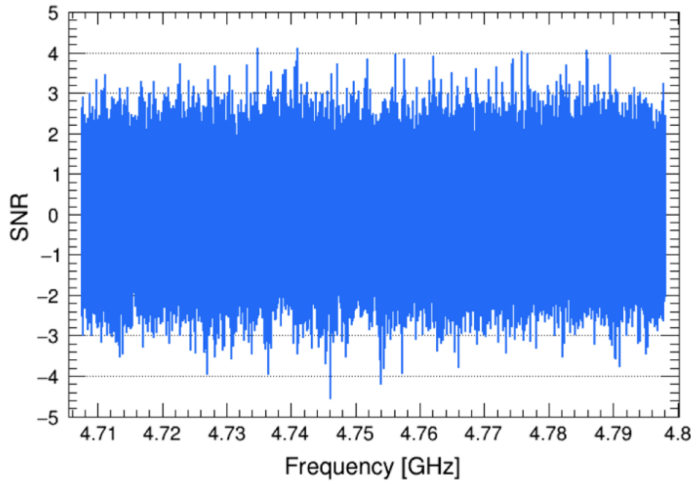
Apply the Savitzky-Golay (SG) filter to remove the structure of the background in the frequency-domain power spectrum.

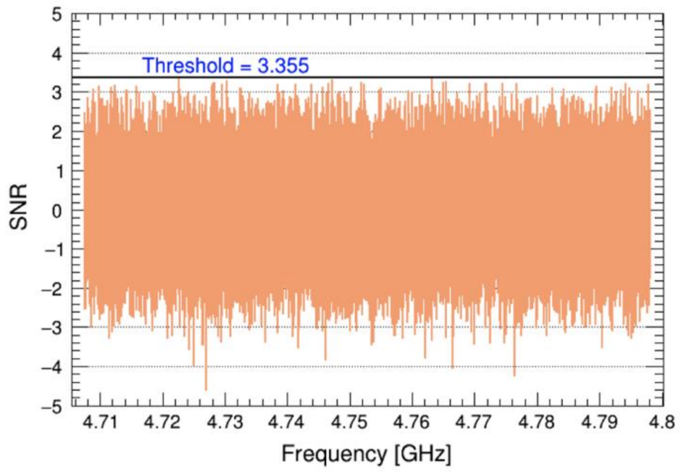
Combine all the spectra from different frequency scans with the weighting algorithm. Merge bins in the combined spectrum to maximize the SNR.

Rescan the frequency regions with candidates and set limits on coupling.



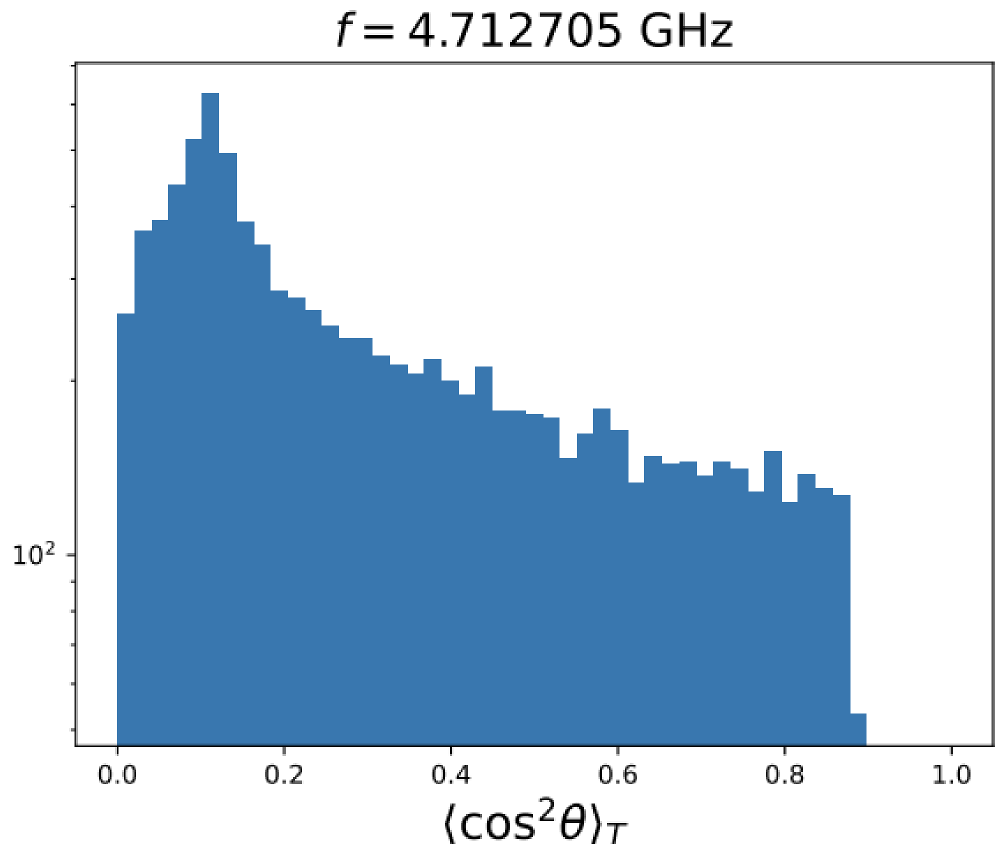



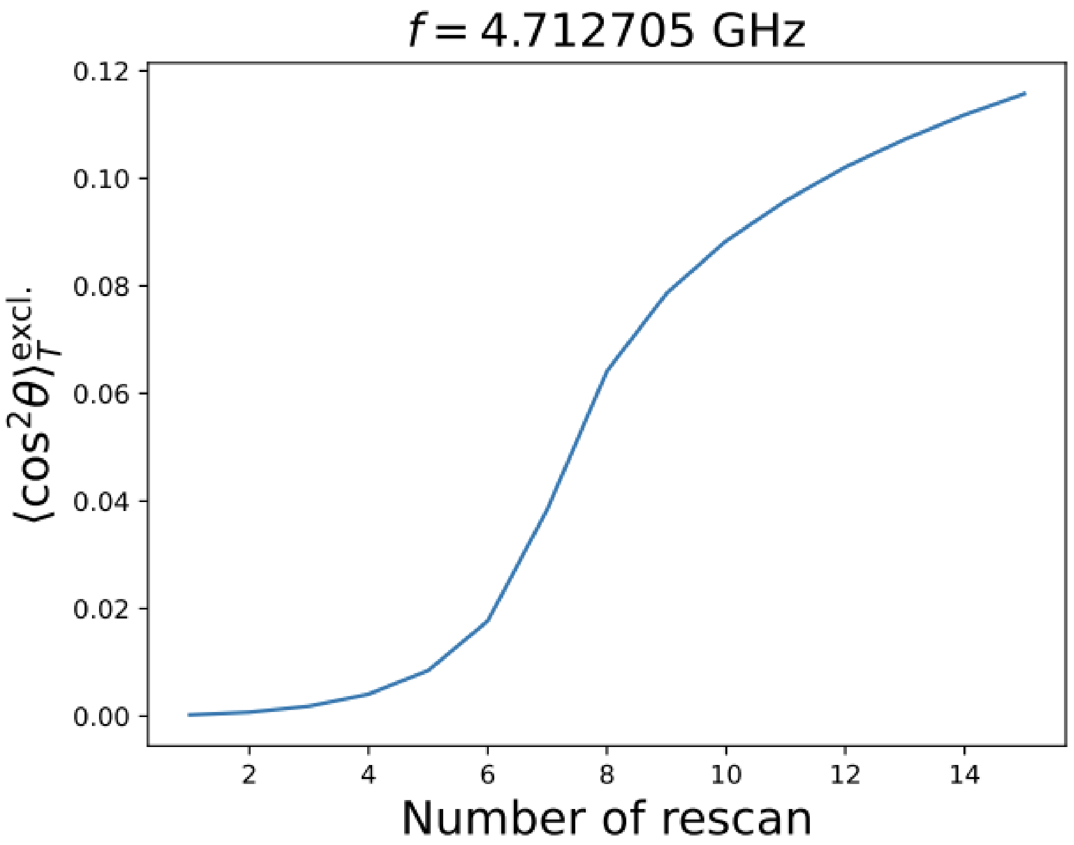



# An example: f = 4.712705 GHz

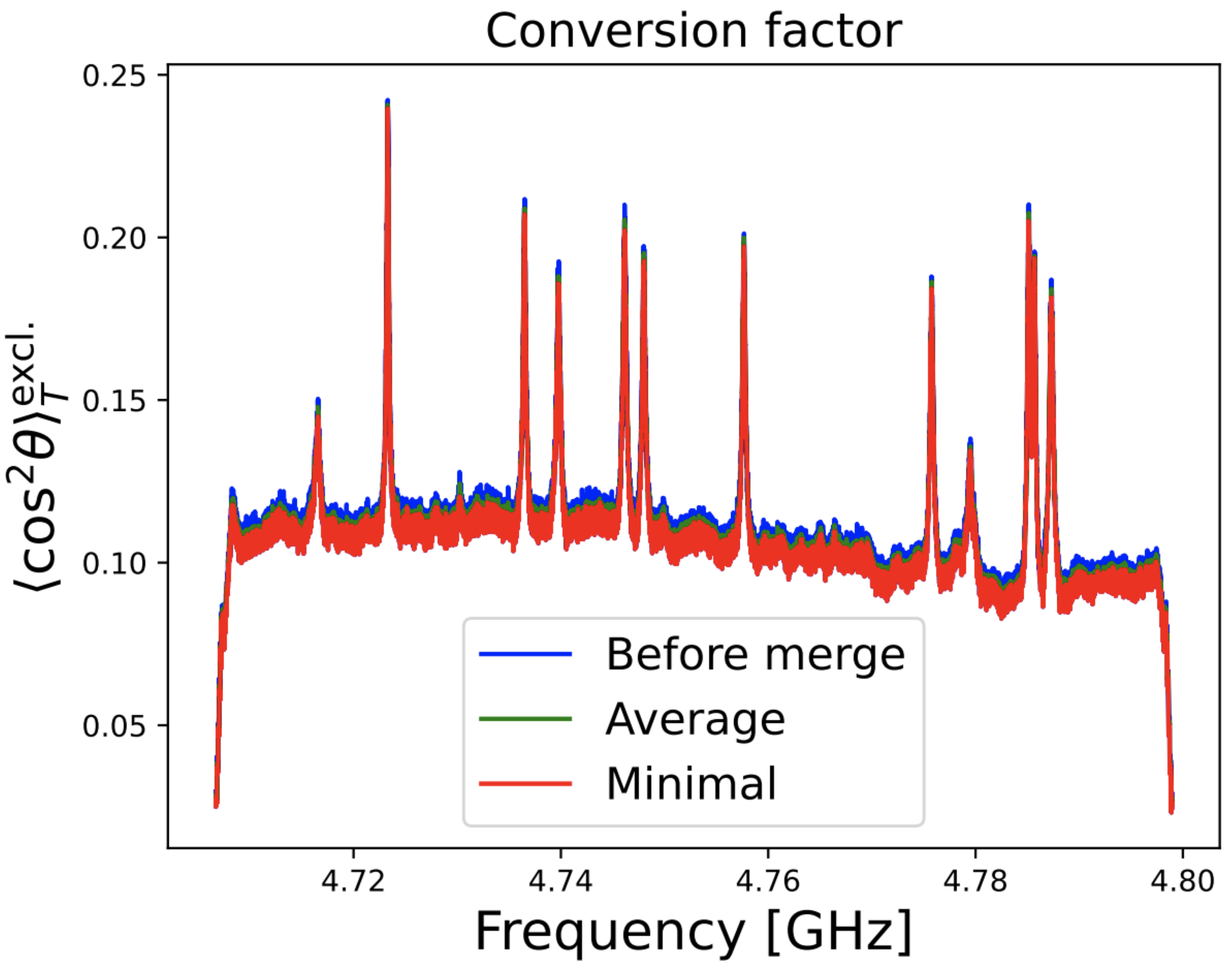
$$\langle \cos^2\theta(t)\rangle_T = \frac{1}{\sum P_i}\left(\frac{P_1}{T_1}\int_{T_1^{\text{start}}}^{T_1^{\text{start}}+T_1}\cos^2\theta(t)dt + \frac{P_2}{T_2}\int_{T_2^{\text{start}}}^{T_2^{\text{start}}+T_2}\cos^2\theta(t)dt + \cdots\right)$$

| | | | | |
|---|---|---|---|---|
| 2021.11.13 | 17:55.17 | 2021.11.13 | 18:37.26 | 4.713616 |
| 2021.11.13 | 18:40.11 | 2021.11.13 | 19:22.20 | 4.713508 |
| 2021.11.13 | 19:24.49 | 2021.11.13 | 20:06.58 | 4.713403 |
| 2021.11.13 | 20:10.45 | 2021.11.13 | 20:52.54 | 4.713293 |
| 2021.11.13 | 21:00.27 | 2021.11.13 | 21:42.37 | 4.713188 |
| 2021.11.13 | 21:45.38 | 2021.11.13 | 22:27.48 | 4.713079 |
| 2021.11.13 | 22:30.56 | 2021.11.13 | 23:13.06 | 4.712975 |
| 2021.11.13 | 23:17.56 | 2021.11.14 | 00:00.05 | 4.712874 |
| 2021.11.14 | 00:04.25 | 2021.11.14 | 00:46.36 | 4.712771 |
| 2021.11.14 | 00:49.28 | 2021.11.14 | 01:31.38 | 4.712664 |
| 2021.11.14 | 01:34.39 | 2021.11.14 | 02:16.48 | 4.712561 |
| 2021.11.14 | 02:19.19 | 2021.11.14 | 03:01.29 | 4.712459 |
| 2021.11.14 | 03:03.43 | 2021.11.14 | 03:45.53 | 4.712352 |
| 2021.11.14 | 03:48.02 | 2021.11.14 | 04:30.11 | 4.712249 |
| 2021.11.14 | 04:32.47 | 2021.11.14 | 05:14.57 | 4.712140 |
| 2021.11.14 | 05:18.40 | 2021.11.14 | 06:00.51 | 4.712038 |
| 2021.11.14 | 06:04.33 | 2021.11.14 | 06:46.43 | 4.711938 |
| 2021.11.14 | 06:50.42 | 2021.11.14 | 07:32.52 | 4.711829 |
| 2021.11.14 | 07:35.26 | 2021.11.14 | 08:17.37 | 4.711720 |



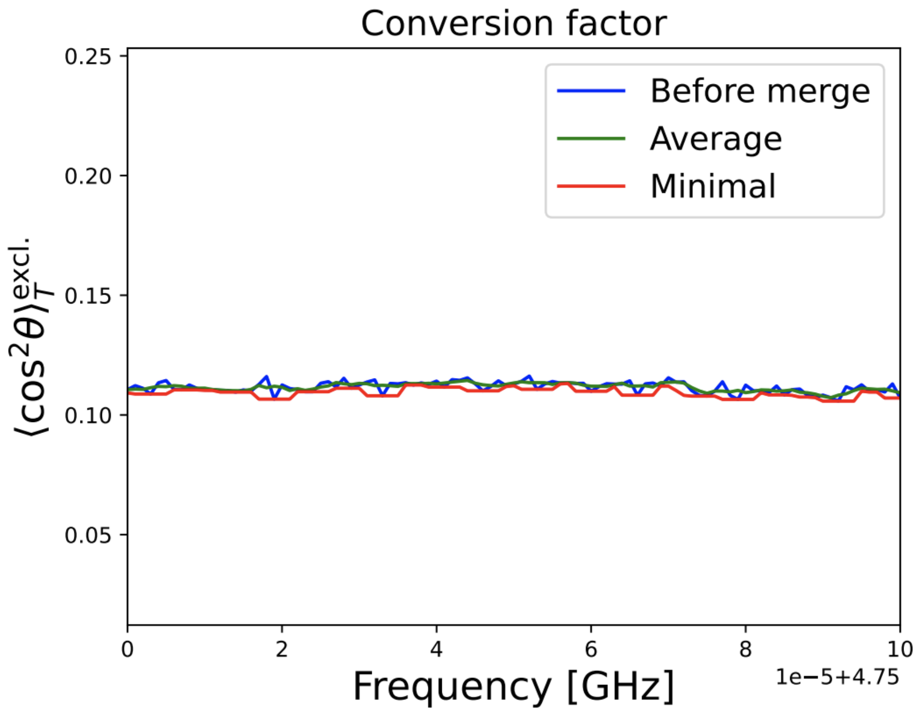
# Conversion factor for all frequencies



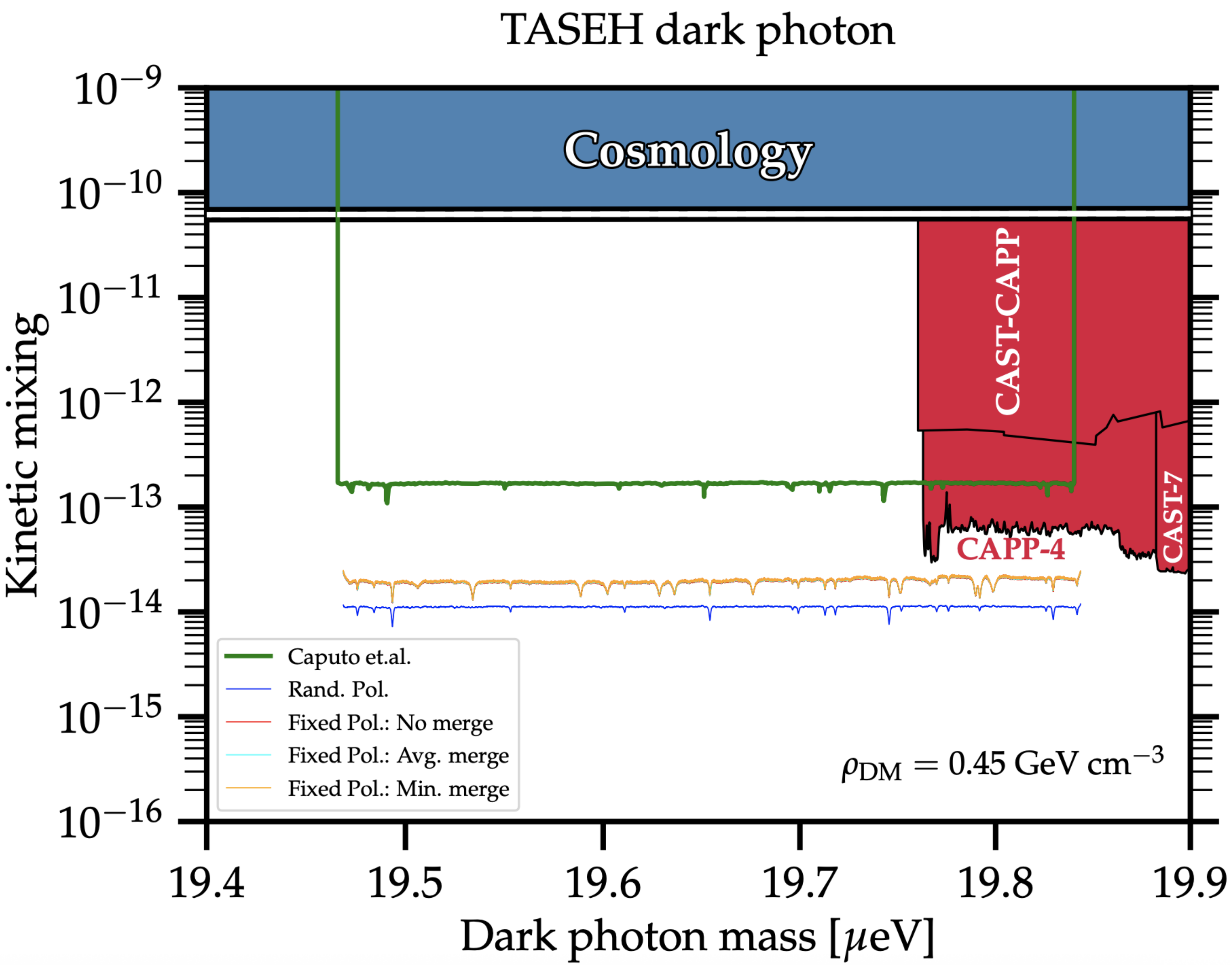

The expected axion bandwidth is about 5 kHz.

Five consecutive bins are merged to construct a final spectrum.

Zoom in [4.7500,4.7501] GHz:



# The dark photon bound from TASEH

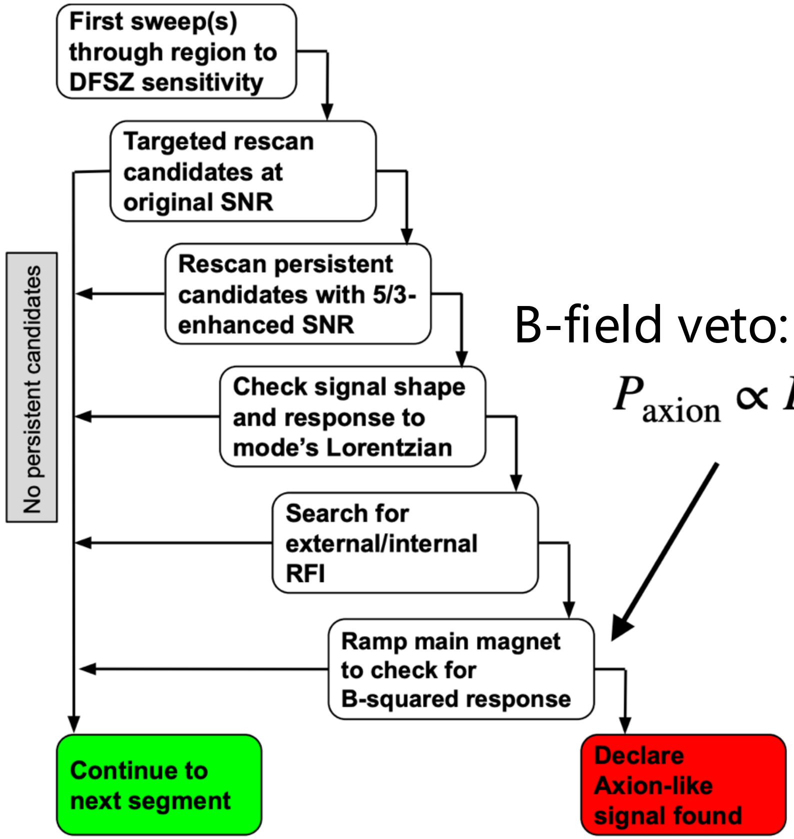



A very short measurement time was typically assumed for cavity haloscopes, which resulted in a value of ~ 0.0025 for the conversion factor.

The AxionLimits TASEH dark photon limit appeared to use a value of ~ 0.0016.

Since the true $\langle \cos^2 \theta(t) \rangle_T^{\rm excl.}$ ~ 0.1 at TASEH for the fixed polarization case, these assumptions weaken the bound on $|\epsilon|$.

# Confirming or Vetoing Candidate Signals




B-field veto:

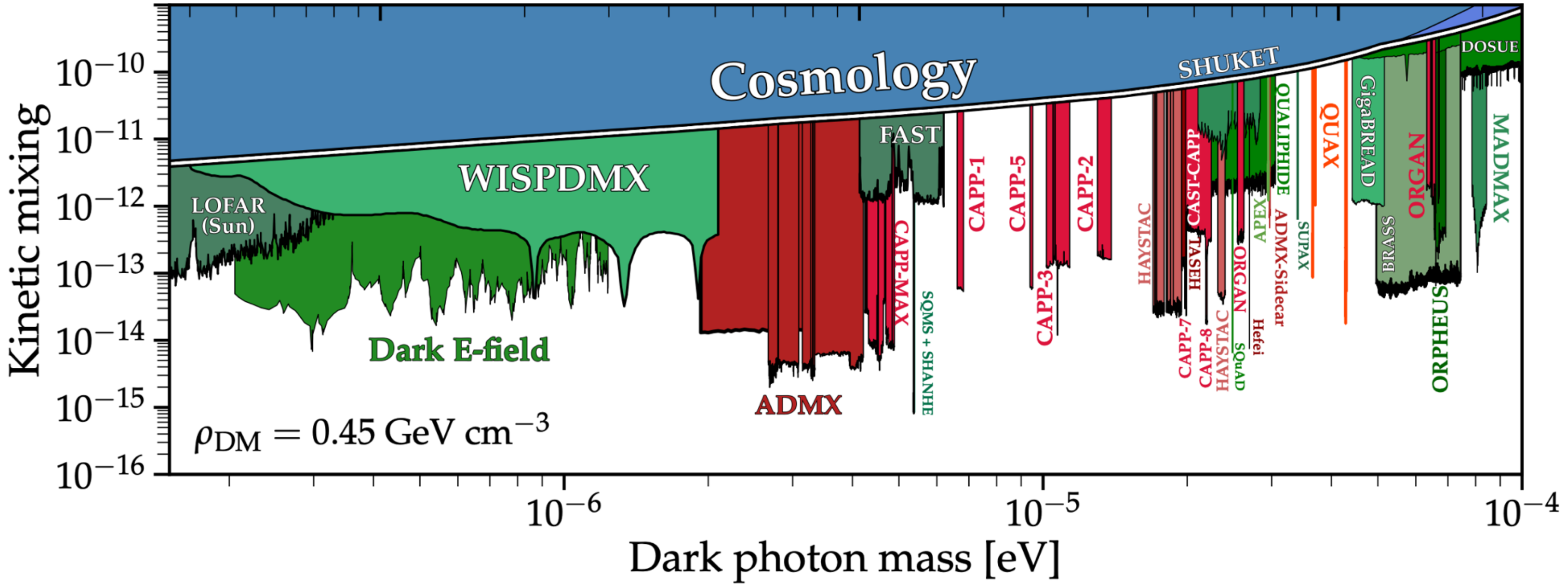
$P_{\text{axion}} \propto B^2$

Dark photons will fail the B-field veto

The corresponding axion parameter space will be excluded as normal

If this is then converted to a dark photon limit, we have a big problem

Is there a dark photon hiding somewhere in these 'excluded' regions?

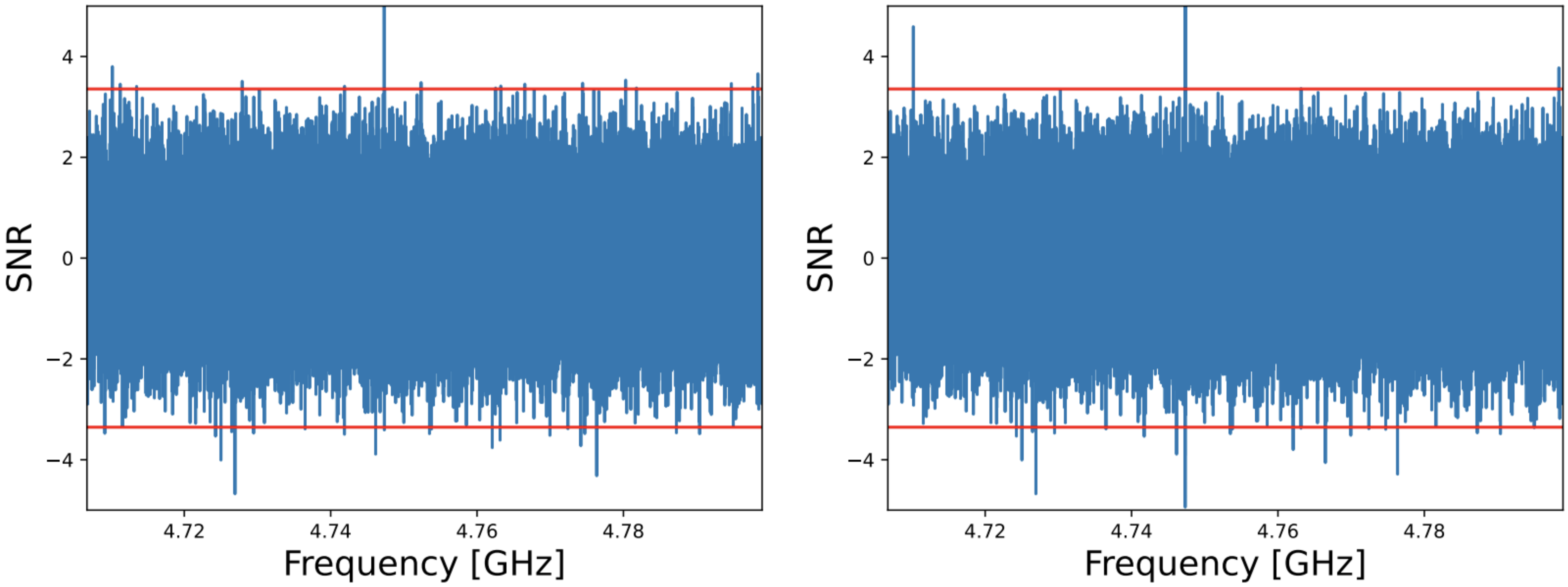



Candidates are always expected due to blind injections, noise fluctuations, RFI

Candidate veto procedure ensures reject non-axion signals

# A tentative signal

The merged spectrum before and after rescan:

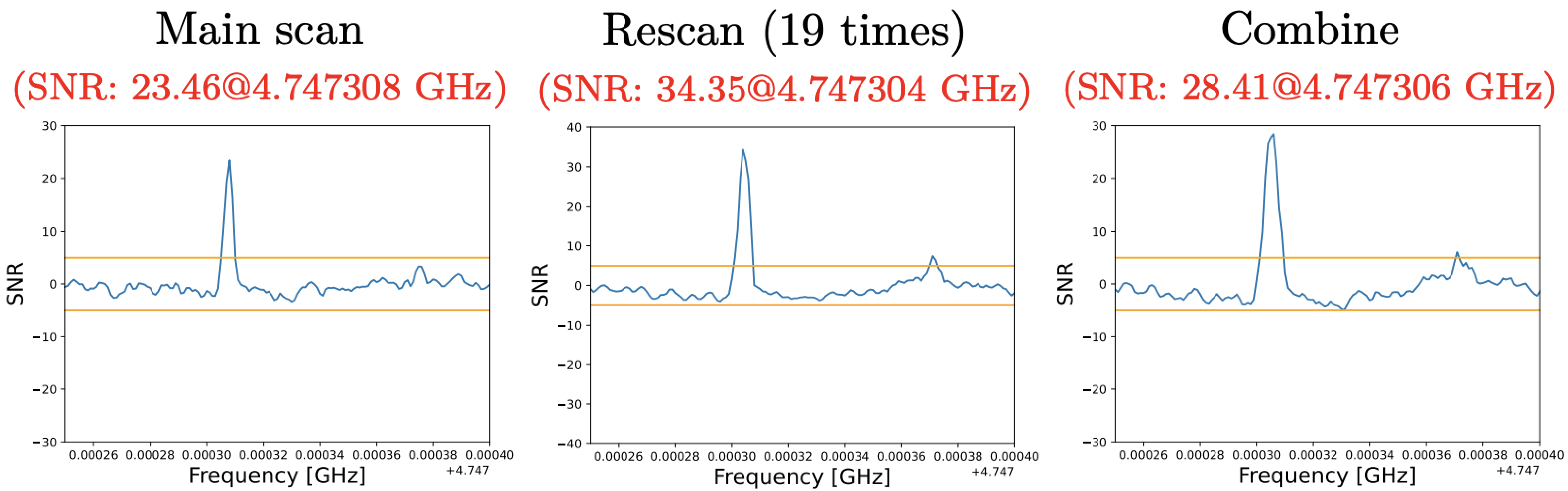



There are 22 candidates with an SNR greater than 3.355 → Rescan

Two candidates, in the frequency ranges of 4.71017 – 4.71019 GHz and 4.74730 – 4.74738 GHz

# The frequency 4.74730 – 4.74738 GHz

SNR before and after rescan



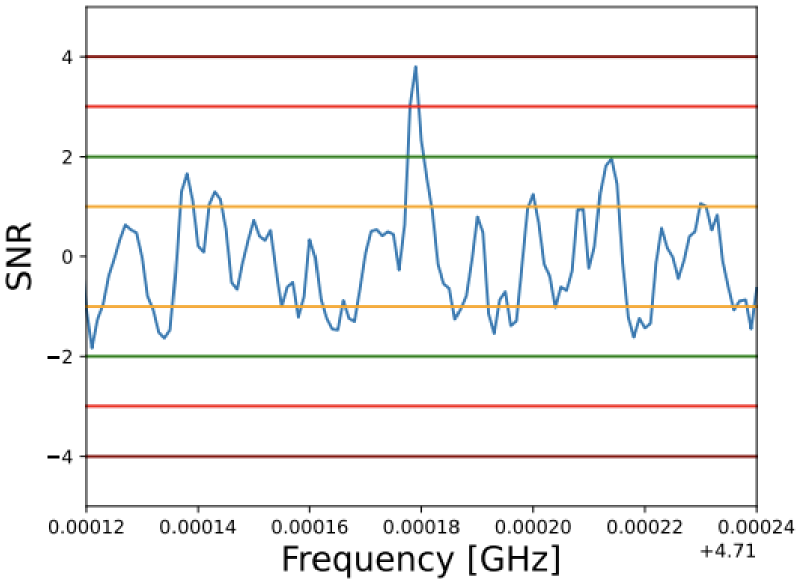

The signal was detected via a portable antenna outside the Dilute Refrigerate and found to come from the instrument control computer in the laboratory.

# The frequency 4.71017 – 4.71019 GHz

SNR before and after rescan (SNR: 3.801 → 4.593 at 4.710179 GHz)

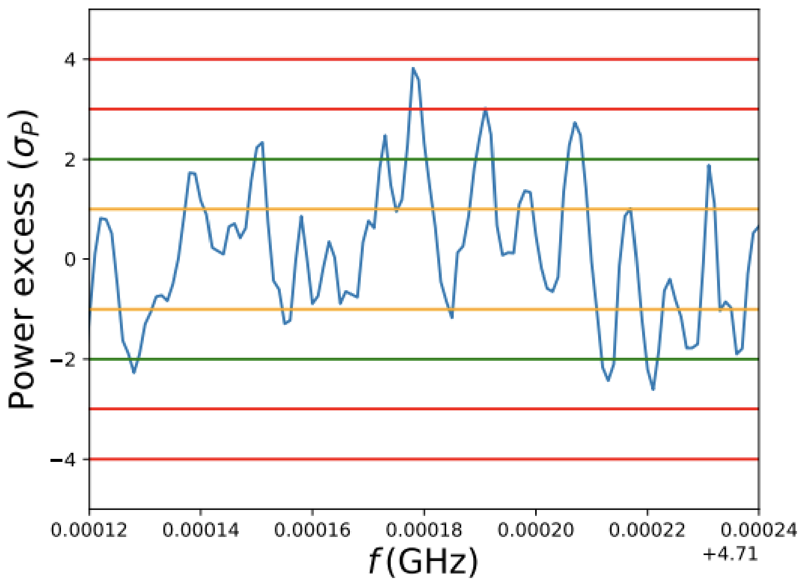
**Main scan**

(SNR: 3.801@4.710179 GHz)



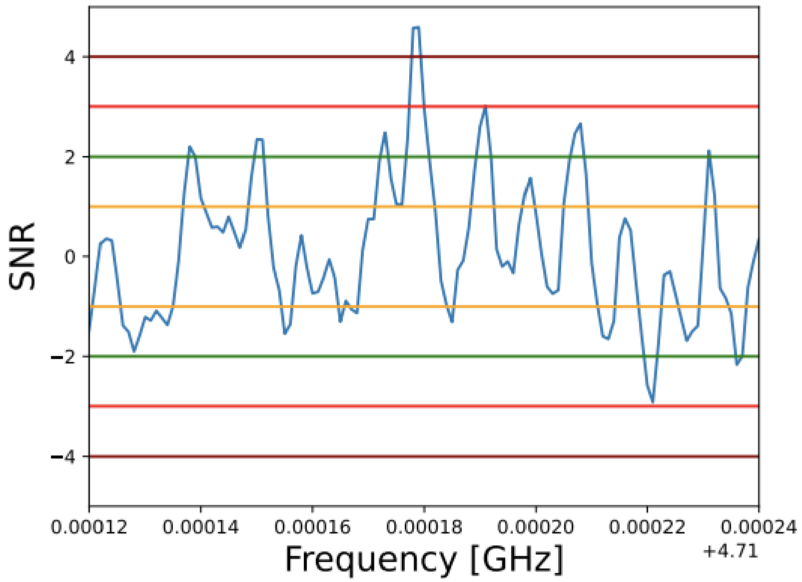

**Rescan (14 times)**

(SNR: 3.820 @4.710178 GHz)



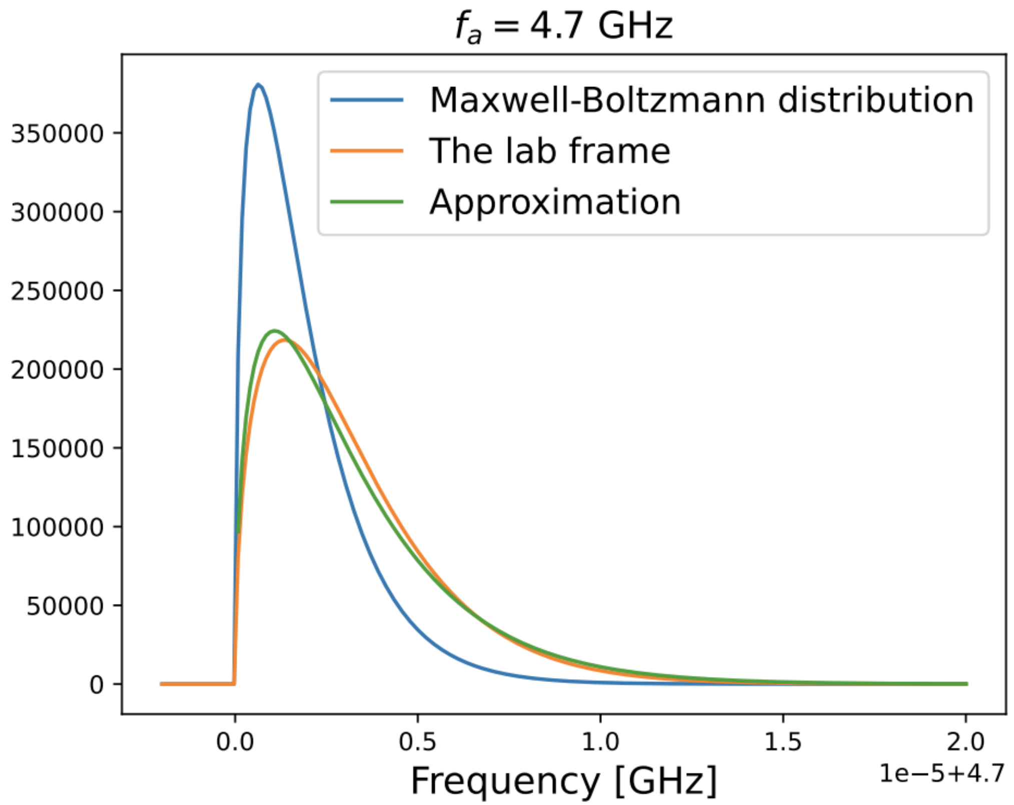

**Combine**

(SNR: 4.593 @4.710179 GHz)




The signal was not detected outside the Dilute Refrigerate but still present after turning off the external magnetic field.

# Fit rescaled RDP with DP line shape and power




Signal is Maxwell Boltzmann lineshape

$$F(f) \simeq 2\left(\frac{f-f_a}{\pi}\right)^{1/2}\left(\frac{3}{1.7 f_a v_{DM}^2}\right)^{3/2} \times \exp\left(-\frac{3\,(f-f_a)}{1.7 f_a v_{DM}^2}\right)$$

with $v_{DM} = 270\ \mathrm{km/s}$

Signal Power (assuming random polarization):

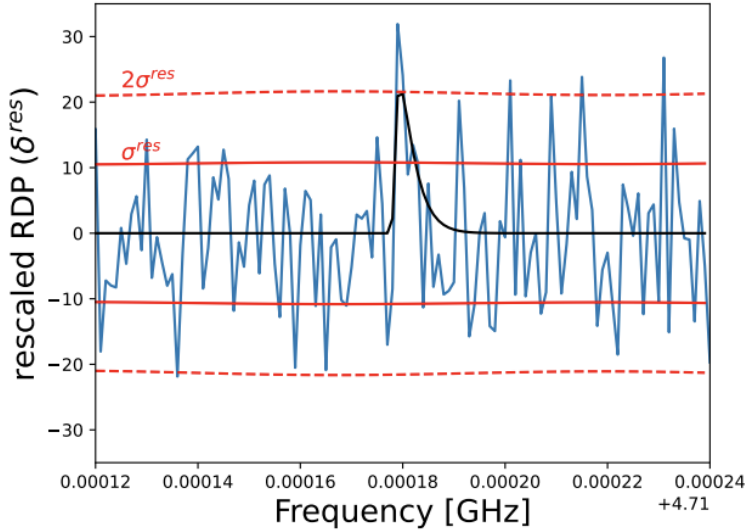
$$P_X = \left(\frac{\epsilon}{\epsilon_0}\right)^2 P_{\mathrm{KSVZ}} = \left(\frac{\epsilon}{\epsilon_0}\right)^2 \times \left(g_{a\gamma\gamma}\frac{\rho_a}{m_a^2}\omega_c B_0^2 V C_{mnl} Q_L \frac{\beta}{1+\beta}\right)$$

where the normalized kinetic mixing: $\epsilon_0 = \dfrac{g_{a\gamma\gamma}^{\mathrm{KSVZ}} B_0}{m_a \cos\theta} \sim 1.005 \times 10^{-15}$

# Fit Rescaled Relative Deviation of Power without Merge

Power rescaled to the KSVZ axion including Lorentzian cavity response.

## Main scan




$$\left(\frac{\epsilon}{\epsilon_0}\right)^2 = 101.68$$

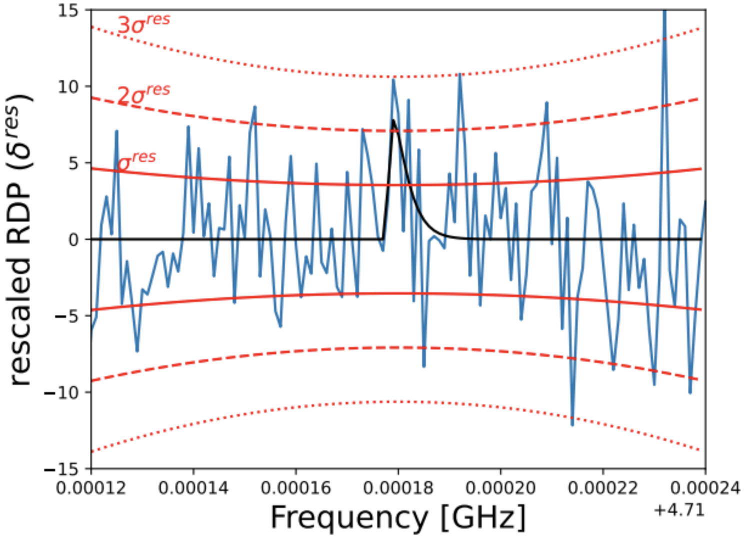
$$\epsilon = 1.013 \times 10^{-14}$$

$$f_X = 4.71017829\text{GHz}$$

$$\Delta\chi^2 = 12.82$$

Local significance 3.755

## Rescan




$$\left(\frac{\epsilon}{\epsilon_0}\right)^2 = 35.45$$

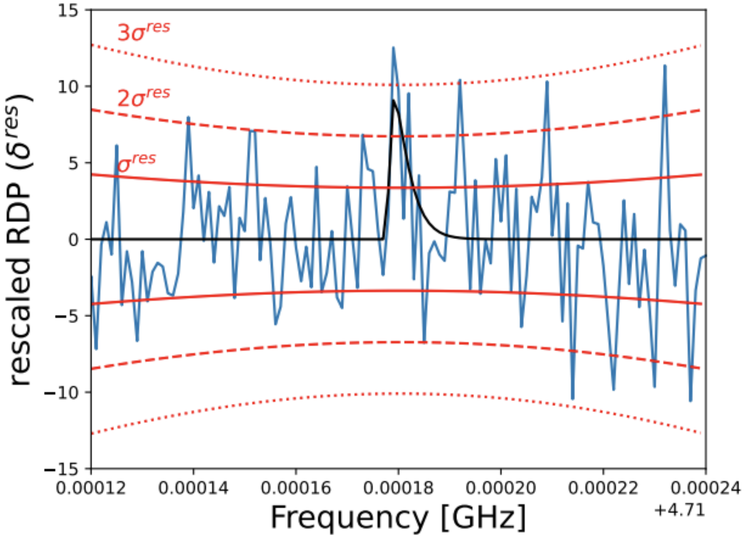
$$\epsilon = 5.984 \times 10^{-15}$$

$$f_X = 4.71017787\text{GHz}$$

$$\Delta\chi^2 = 13.96$$

Local significance 3.902

## Combine




$$\left(\frac{\epsilon}{\epsilon_0}\right)^2 = 41.59$$

$$\epsilon = 6.480 \times 10^{-15}$$

$$f_X = 4.710178\text{GHz}$$

$$\Delta\chi^2 = 21.40$$

Local significance 4.76

Trials Factor:44702

Global significance 1.73

# Conclusion

Dark photon is a viable DM, which can have random polarization or fixed polarization.

By re-examining data taken by the TASEH experiment, we derive a world-leading constraint on the dark photon parameter space, excluding kinetic mixing $|\epsilon| \gtrsim 2 \times 10^{-14}$ in the $19.46 - 19.84\mu\mathrm{eV}$ mass range, which exceeds the naive "rescaling limit" by roughly one order of magnitude.

We identify a tentative signal with a local significance of 4.7σ, corresponding to a dark photon with mass: $m_X \simeq 19.5\mu\mathrm{eV}$
and kinetic mixing: $\epsilon \simeq 6.5 \times 10^{-15} (f_X \simeq 4.71\mathrm{GHz})$