Searching for dark photon dark matter at the TASEH experiment

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In Collaboration with: TASEH Collaboration
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Outline

1. Dark Photon dark matter at early universe
2. Dark Photon Detection
   - Cavity experiments
   - DP polarization
3. The TASEH experiment
4. The dark photon bound at TASEH
   - A signal candidate?

Dark Photon production

- Gravitational particle production (inflationary fluctuations)

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

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

- Axion oscillation *P.Agrawal, N.Kitajima, M.Reece, T.Sekiguchi, F.Takahashi(2020)*

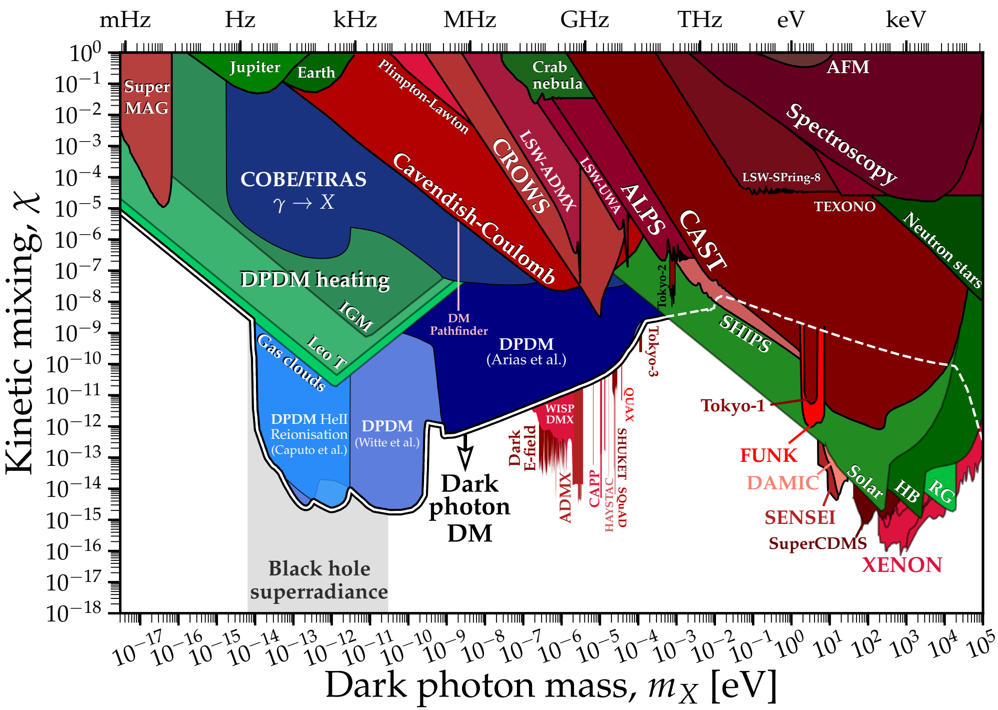
$$\Omega_{A'} h^2 \simeq 0.2 \cdot \theta^2 \left(\frac{40}{\beta}\right) \left(\frac{m_{A'}}{10^{-9}\ {\rm eV}}\right) \left(\frac{10^{-8}\ {\rm eV}}{m_a}\right)^{1/2} \left(\frac{F_a}{10^{14}\ {\rm GeV}}\right)^2$$

  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

Dark Photon Polarization

- Axion oscillation dominantly produces a specific dark photon helicity.
- Mis-alignment mechanism naturally leads to relic DPDM with a fixed polarization within the cosmological horizon.
- The direction of the DP field remains unchanged for most of the universe history.
- Two phenomenological extreme cases: fixed polarization and randomised polarization. Any real scenarios will be bounded within these two limits.



Cosmological

viable DPDM

CMB distortions from $\gamma \to X$

Astrophysical

stellar cooling

DPDM heating

gamma rays from Crab Nebula

Laboratory:

Coulomb $1/r^2$ force law

light-shining-through-walls

direct detection of DPDM

haloscope limits

Dark photon cavity haloscope

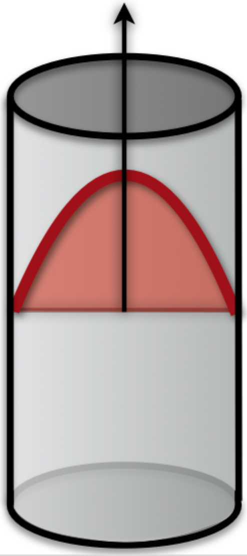
The low-energy effective Lagrangian

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

The cavity power

$$P_{\mathrm{dp}} = \epsilon^2 m_X \rho_{\mathrm{DM}} V C_{mnl} Q_L \frac{\beta}{1+\beta} L(f, f_c, Q_L), \quad C_{mnl} = \frac{(\int dV \mathbf{E}_{mnl}(\vec{x}) \cdot \hat{X}(\vec{x}))^2}{V \int dV |\mathbf{E}_{mnl}(\vec{x})|^2 |\hat{X}(\vec{x})|^2}$$

coupling strength $\epsilon = \tan\alpha$, volumn V, $\hat{X}$ is the DM polarization direction, loaded quality factor Q_L, cavity coupling coefficient β.



Compared with the Axion power:

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

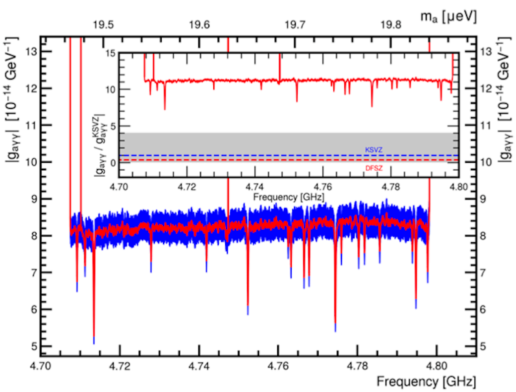
Recast from $g_{a\gamma}$ to ϵ: $\epsilon = g_{a\gamma}\frac{B}{m_X|\cos\theta|}$, $\cos\theta = \hat{z}\cdot\hat{X}$, $\hat{z}$ is sensitive direction

TASEH axion limits to dark photon limits

Measuring with periods T

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

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



TASEH Axion limit

Phys.Rev.Lett. 129 (2022) 11, 111802

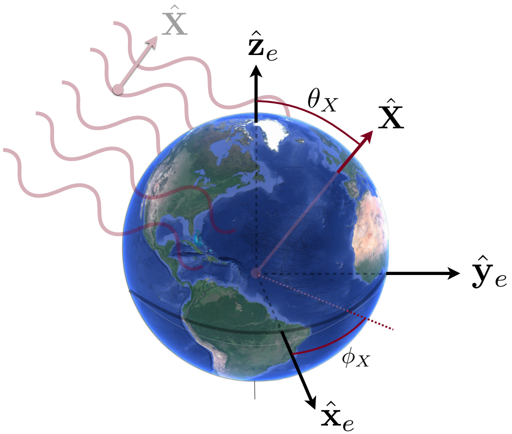
Phys.Rev.D 106 (2022) 5, 052002

Rev.Sci.Instrum. 93 (2022) 8, 084501

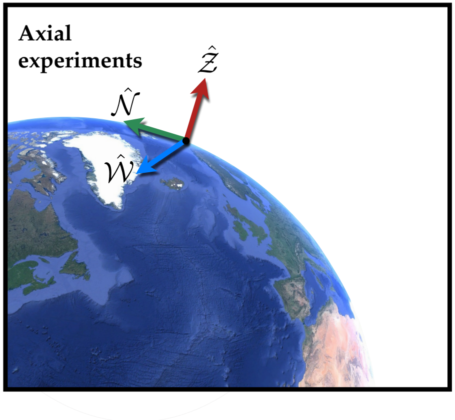
TASEH Dark Photon limit

Dark photon cavity search with polarization

Geocentric coordinates



Detector-centric coordinates



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

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

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

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

$$\cos\theta(t) = \hat{X} \cdot \hat{Z}(t)$$

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 T_i

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

- 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[see 2105.04565]:

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

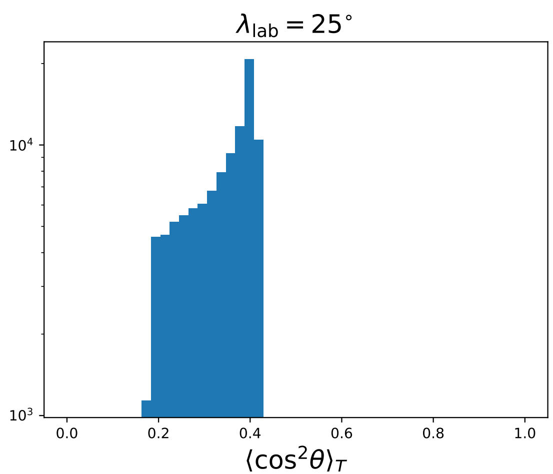
$$\langle \cos^2\theta(t)\rangle_T^{\rm excl.} = \frac{1.64\sigma_N}{P_X^0}$$

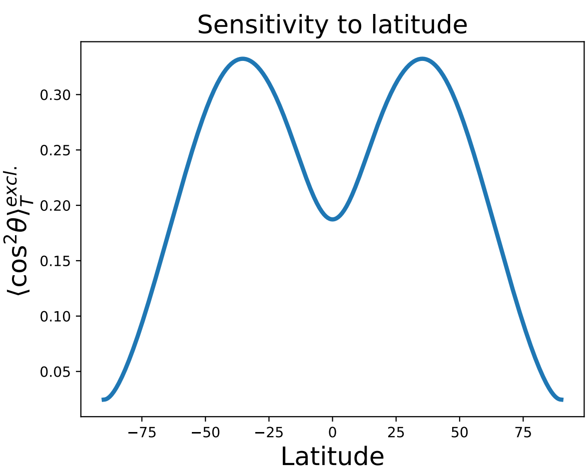
Lattitude dependence for fixed polarization

- Measuring for a whole day:

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

- Sampling spherical symmetric $\theta_X \rightarrow \langle \cos^2\theta(t)\rangle_{1\ \text{day}}$ distribution.
- Calcualate the conversion factor $\langle \cos^2\theta(t)\rangle_T^{\text{excl.}}$



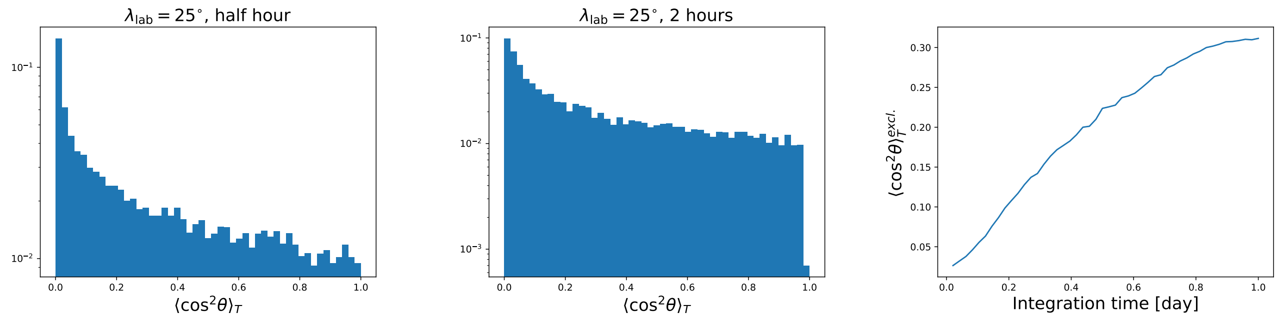


Measurement time dependence

- Measuring a period T

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

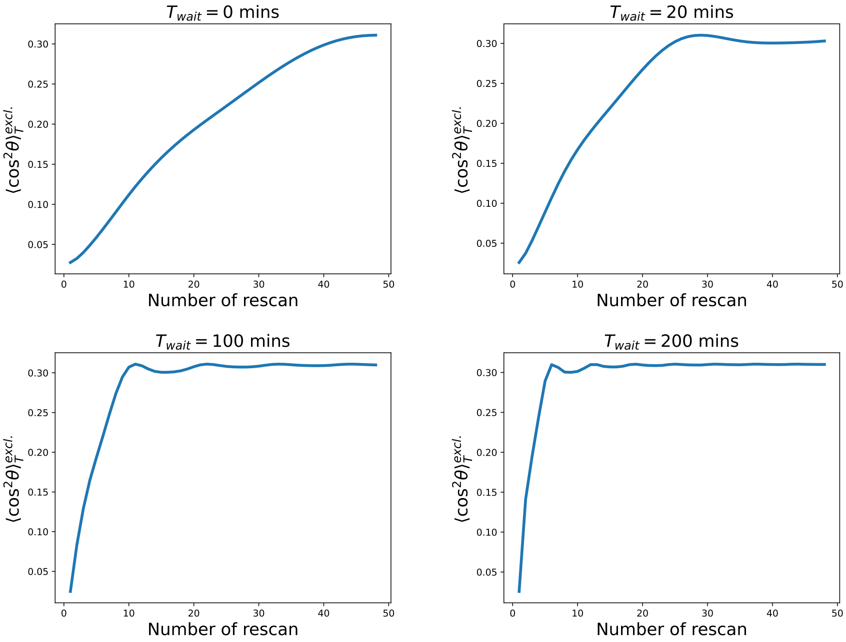
- Taking $T = 1/48$ day ~ 0.5 hour, $\lambda_{\rm lab} = 25^\circ \to f(\langle \cos^2\theta(t)\rangle_T)$ $\to \langle \cos^2\theta(t)\rangle_T^{\rm excl.} \sim 0.025$
- Taking $T = 1/12$ day ~ 2 hour, $\lambda_{\rm lab} = 25^\circ \to f(\langle \cos^2\theta(t)\rangle_T)$ $\to \langle \cos^2\theta(t)\rangle_T^{\rm excl.} \sim 0.048$
- Changing the integration time



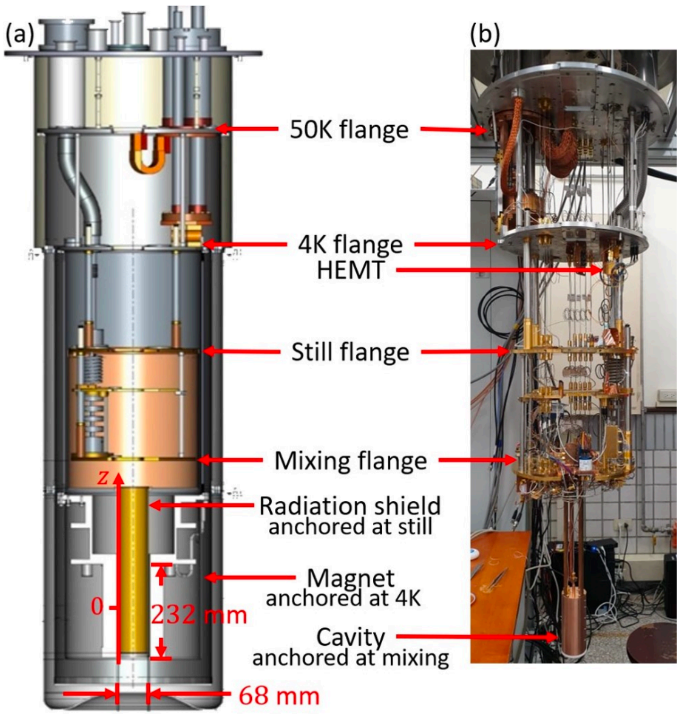
Multiple measurement with time gaps

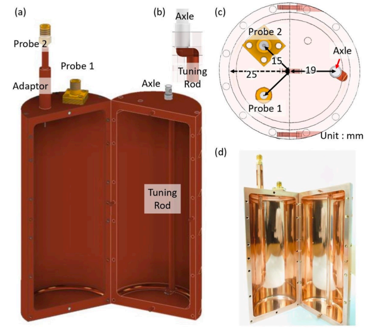
- Repetitive measurement with $T_{\text{int}} = 30$ mins and $T_{\text{wait}} = 0, 20, 100, 200$ mins, $T_{\text{tot}} = T_{\text{int}} + T_{\text{wait}}$ (assuming the same power for each measurement)

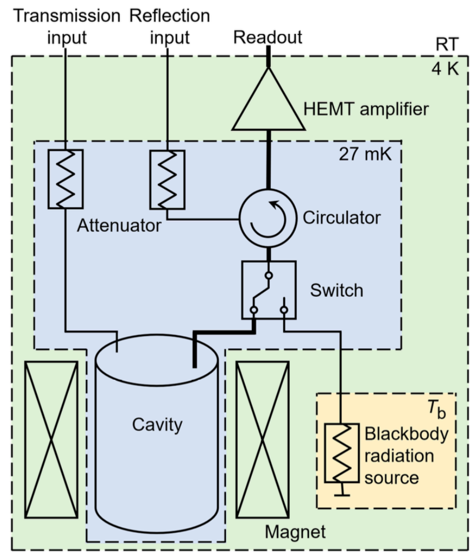
$$\langle \cos^2 \theta(t) \rangle_T = \frac{1}{T_{\text{int}}} \left(\int_0^{T_{\text{int}}} \cos^2 \theta(t)\, dt + \int_{T_{\text{tot}}}^{T_{\text{tot}}+T_{\text{int}}} \cos^2 \theta(t)\, dt + \int_{2T_{\text{tot}}}^{2T_{\text{tot}}+T_{\text{int}}} \cos^2 \theta(t)\, dt + \cdots \right)$$



The TASEH experiment







The detector configuration and the measurements

f_{lo}	4.70750 GHz
f_{hi}	4.79815 GHz
N_{step}	837
Δf_{s}	95 – 115 kHz
B_0	8 Tesla
V	0.234 L
C_{010}	0.60 – 0.61
Q_0	58000 – 65000
β	1.9 – 2.3
T_{mx}	27–28 mK
T_{c}	155 mK
T_{a}	1.9–2.2 K
Δf_a	5 kHz

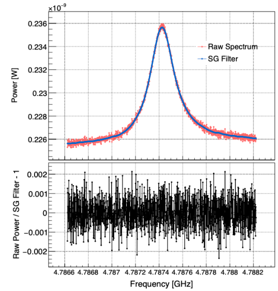
Latitude: $\lambda_{\text{TASEH}} = 25^\circ$

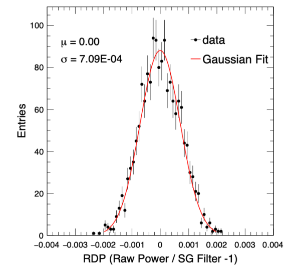
Rescanning strategy:

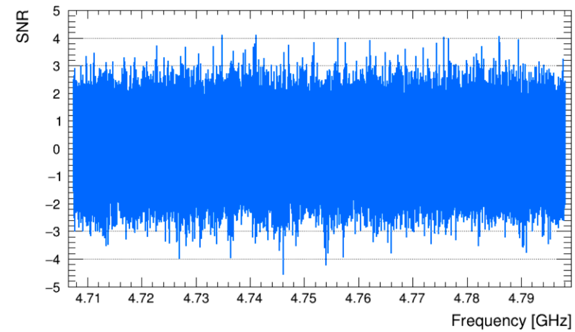
Start YYYY.MM.DD	hh:mm:ss	Stop YYYY.MM.DD	hh:mm:ss	Frequency [GHz]	Q0
2021.10.13	18:22.10	2021.10.13	18:55.09	4.798147	61469
2021.10.13	19:08.22	2021.10.13	19:41.23	4.798036	61540
2021.10.13	19:48.41	2021.10.13	20:28.08	4.797927	61623
2021.10.13	20:40.55	2021.10.13	21:13.55	4.797813	61612
2021.10.13	21:22.33	2021.10.13	21:55.34	4.797705	61426
2021.10.13	22:00.46	2021.10.13	22:33.46	4.797596	61500
2021.10.13	22:41.50	2021.10.13	23:14.50	4.797483	61485
2021.10.13	23:19.55	2021.10.13	23:52.55	4.797375	61639
2021.10.13	23:56.47	2021.10.14	00:29.47	4.797263	61671
2021.10.14	00:33.18	2021.10.14	01:06.19	4.797164	61595
2021.10.14	01:11.26	2021.10.14	01:44.26	4.797067	61743
2021.10.14	01:47.20	2021.10.14	02:20.21	4.796959	61700
2021.10.14	02:23.24	2021.10.14	02:56.24	4.796860	61729
2021.10.14	03:00.29	2021.10.14	03:33.29	4.796754	61858
2021.10.14	03:38.17	2021.10.14	04:11.19	4.796654	61540
2021.10.14	04:13.47	2021.10.14	04:46.46	4.796546	61741
2021.10.14	04:50.51	2021.10.14	05:23.52	4.796436	61546
2021.10.14	05:27.59	2021.10.14	06:00.59	4.796326	61758
2021.10.14	06:04.49	2021.10.14	06:38.18	4.796223	61755
2021.10.14	06:43.24	2021.10.14	07:16.24	4.796120	61680

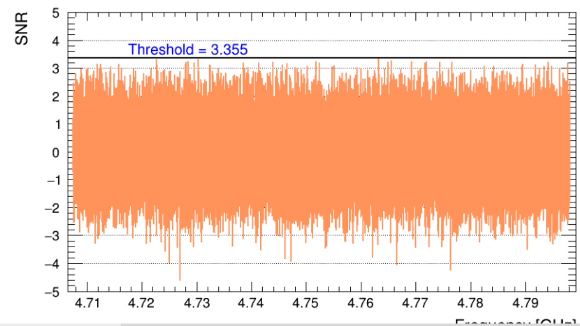
The data analysis procedure

- Perform fast Fourier transform (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 the axion-two-photon coupling.

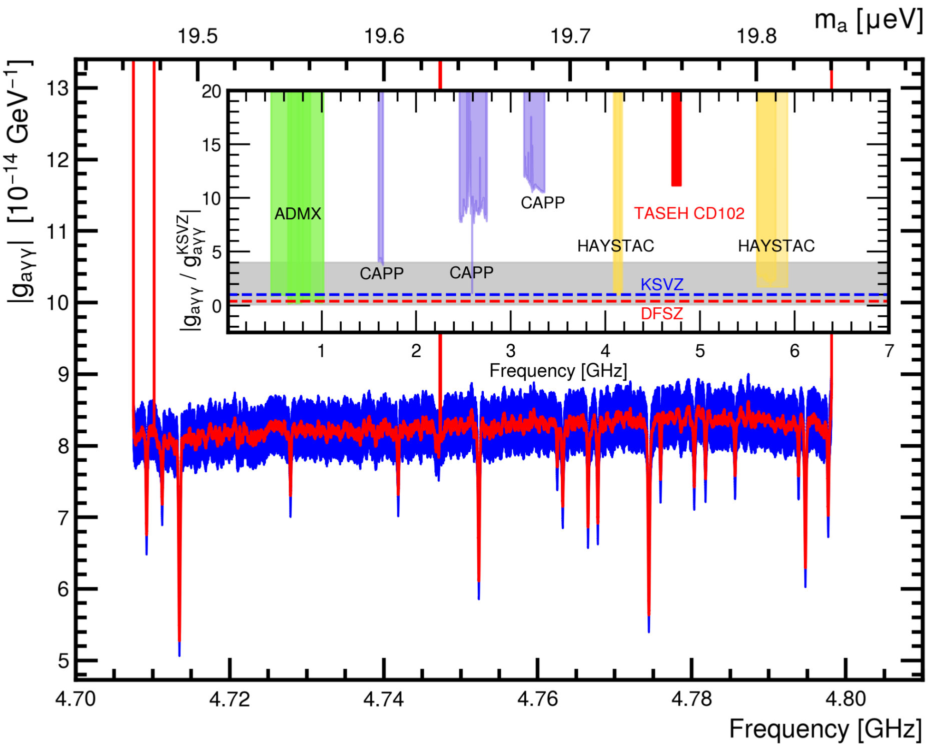








The bounds obtained for axion



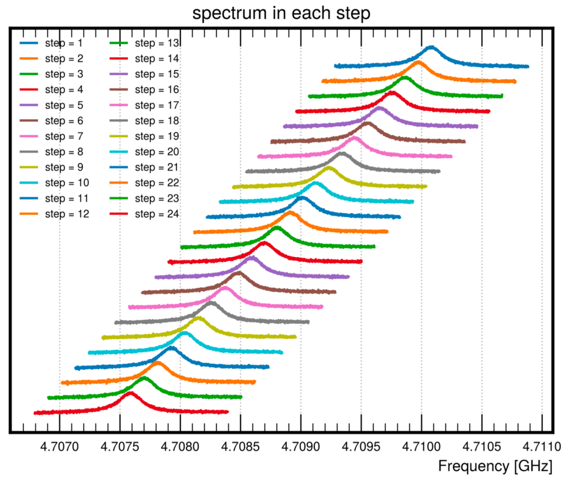
Blue error band indicates the systematic uncertainties

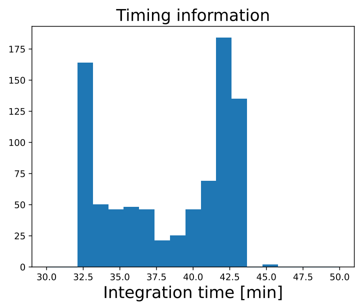
Gray band shows the allowed region of various QCD axion models

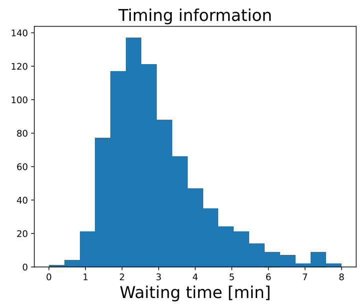
Dashed lines are the values predicted by the KSVZ and DFSZ benchmark models

Rescan 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





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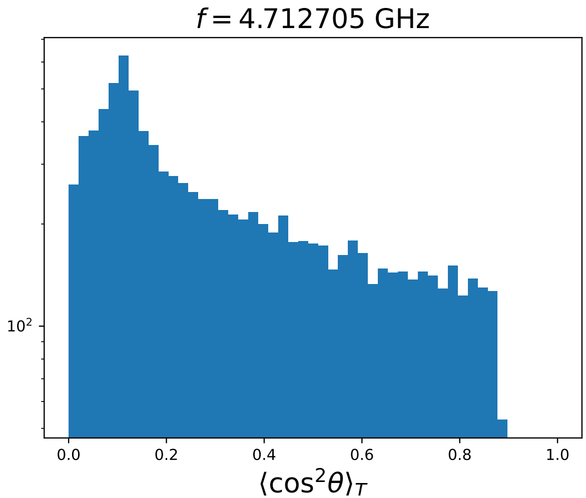
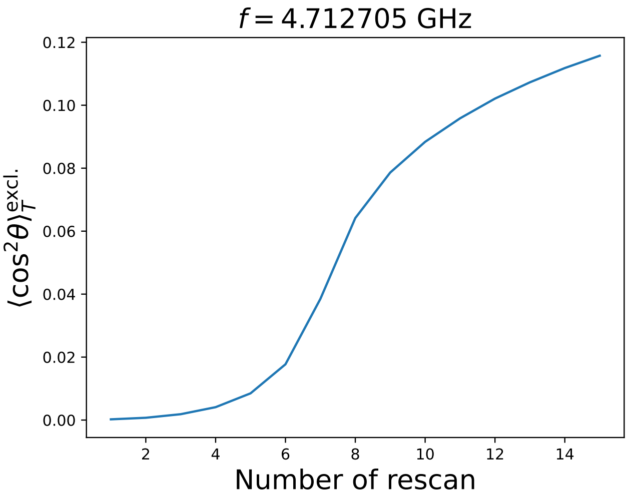
scan ibin frequency      power
783 102 [4.71270500e+00 2.76785695e-10]
784 212 [4.71270500e+00 2.76790478e-10]
785 317 [4.71270500e+00 2.77402236e-10]
786 426 [4.71270500e+00 2.77637399e-10]
787 530 [4.71270500e+00 2.77624467e-10]
788 631 [4.71270500e+00 2.79422577e-10]
789 733 [4.71270500e+00 2.82600761e-10]
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]
```

An example: $f = 4.712705$ GHz

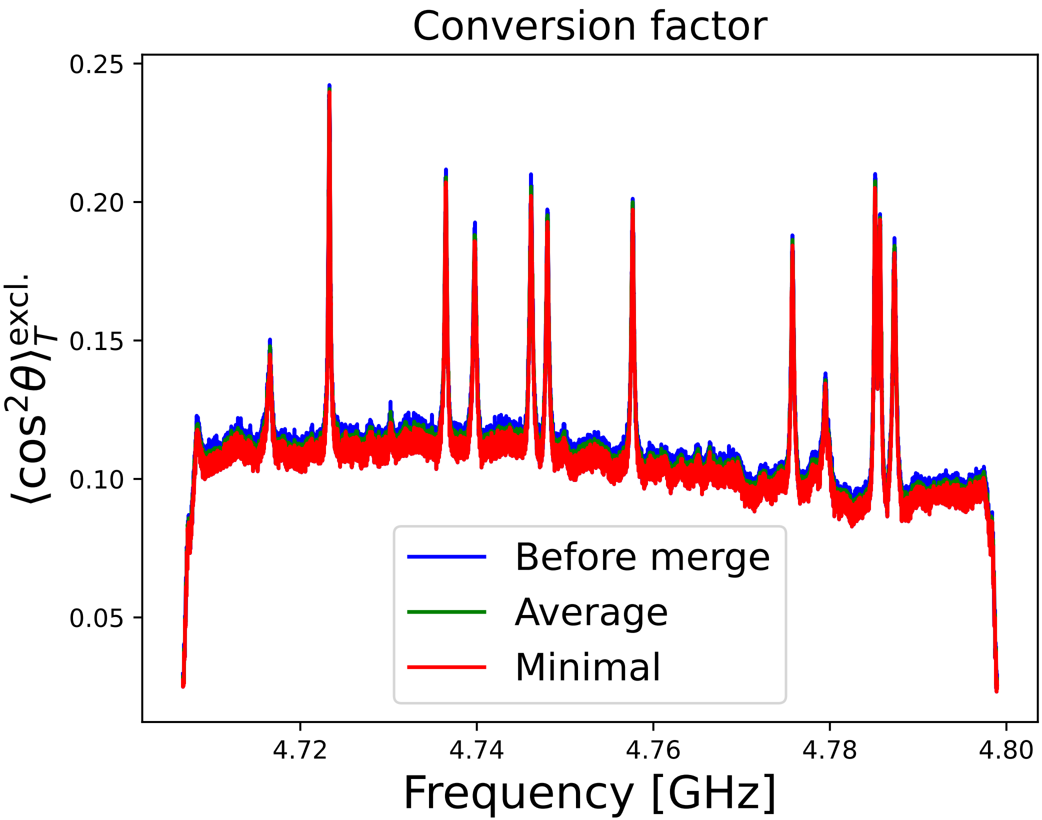
$$\langle \cos^2\theta(t)\rangle_T = \frac{1}{\sum P_i}\Big(\frac{P_1}{T_1}\int_{T_1^{\rm start}}^{T_1^{\rm start}+T_1}\cos^2\theta(t)\,dt + \frac{P_2}{T_2}\int_{T_2^{\rm start}}^{T_2^{\rm start}+T_2}\cos^2\theta(t)\,dt + \cdots\Big)$$

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





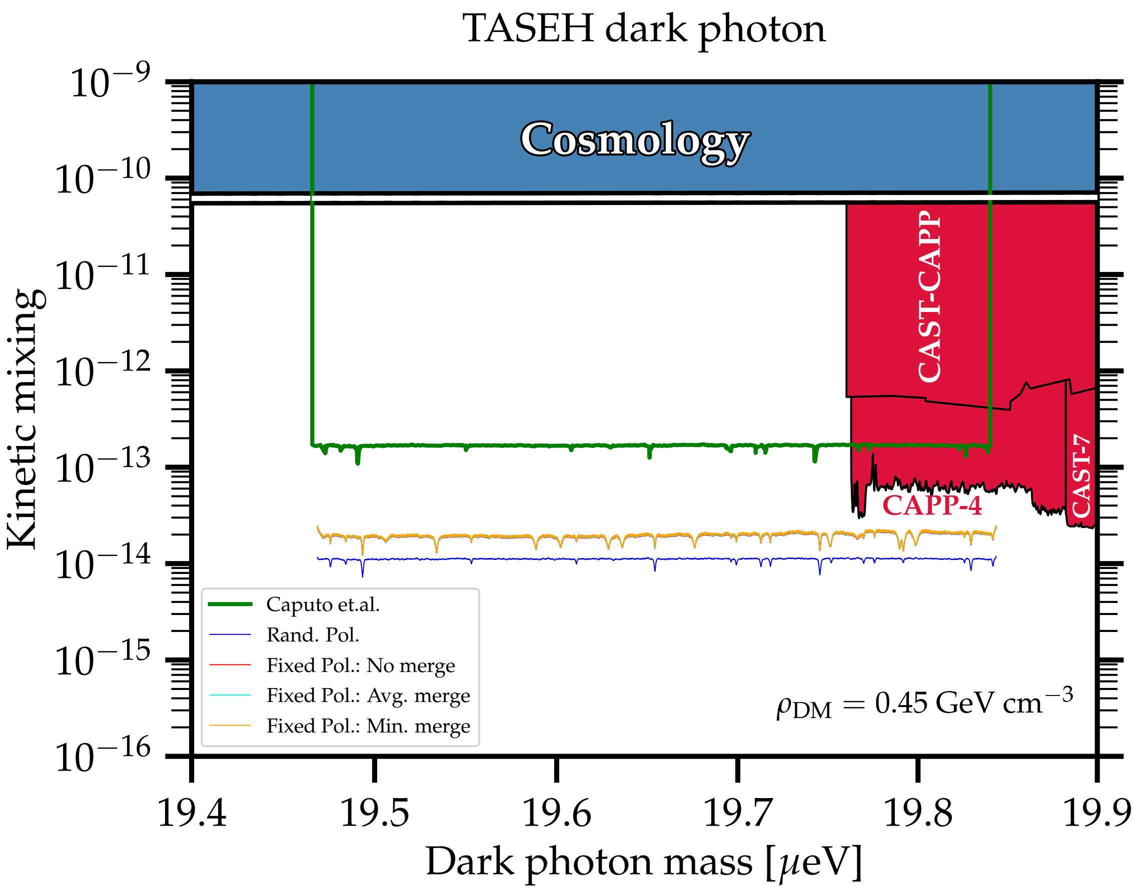
Conversion factor



. The expected axion bandwidth is about 5 kHz.

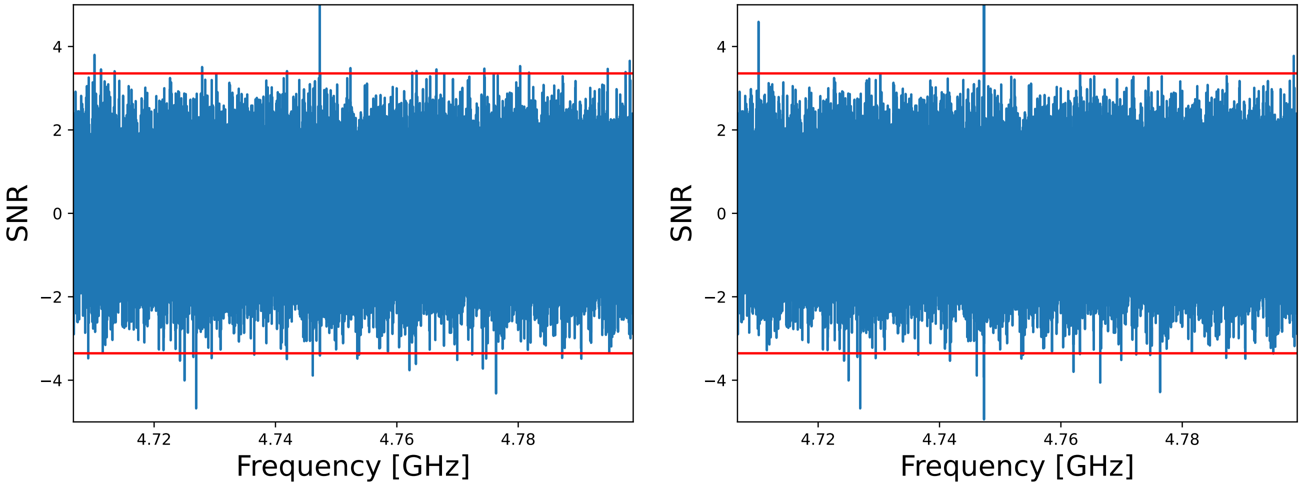
. Five consecutive bins are merged to construct a final spectrum.

The dark photon bound from TASEH



Dark photon signal candidates?

The merged spectrum before and after rescan:



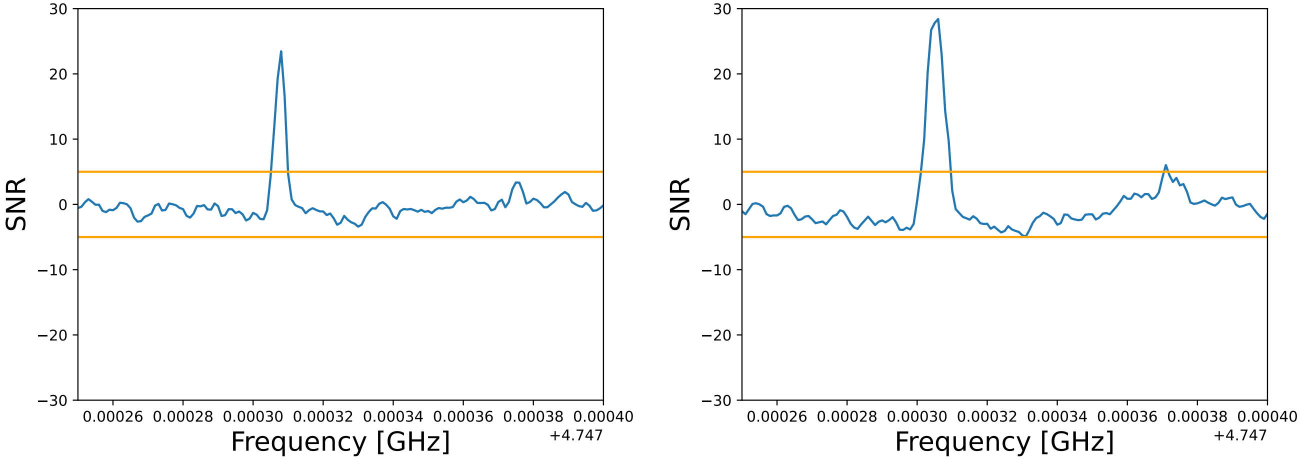
There are 22 candidates with an SNR greater than 3.355 → **Rescan**

Start YYYY.MM.DD	hh:mm:ss	Stop YYYY.MM.DD	hh:mm:ss	Frequency [GHz]	Q0
2021.11.15	15:28.35	2021.11.15	16:10.44	4.710179	65291
2021.11.15	16:14.06	2021.11.15	16:56.16	4.710180	65437
2021.11.15	16:58.30	2021.11.15	17:40.41	4.710180	64777
2021.11.15	17:43.47	2021.11.15	18:25.56	4.710179	65561
2021.11.15	18:28.47	2021.11.15	19:10.57	4.710179	65347
2021.11.15	19:12.53	2021.11.15	19:55.03	4.710179	65322
2021.11.16	06:51.46	2021.11.16	07:33.54	4.710180	65382
2021.11.16	07:37.26	2021.11.16	08:19.35	4.710180	65403
2021.11.16	08:23.20	2021.11.16	09:05.30	4.710180	65454
2021.11.16	09:11.44	2021.11.16	09:57.40	4.710181	65389
2021.11.16	10:01.12	2021.11.16	10:43.22	4.710180	65454
2021.11.16	10:47.05	2021.11.16	11:29.15	4.710180	65517
2021.11.16	11:35.18	2021.11.16	12:17.28	4.710181	65456
2021.11.16	12:20.38	2021.11.16	13:02.47	4.710181	65423

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

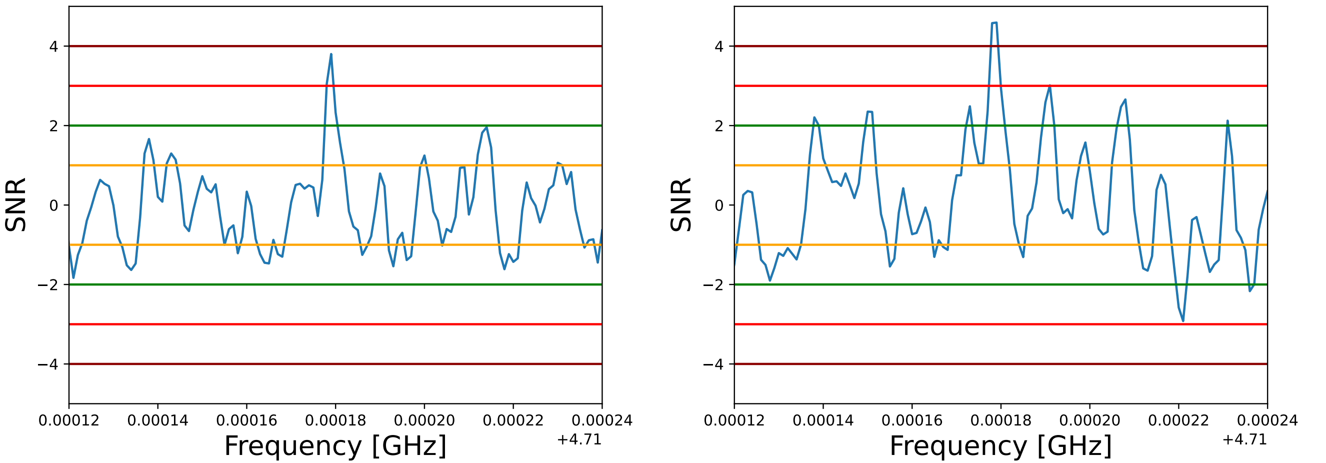
SNR before and after rescan



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

The frequency 4.71017 –4.71019 GHz

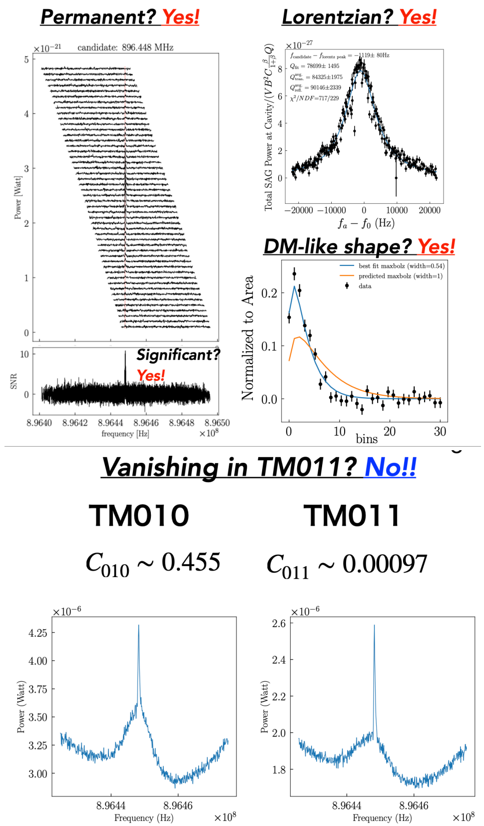
SNR before and after rescan (SNR: 3.801 → 4.593 @ 4.710179 GHz)



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

Confirming singal

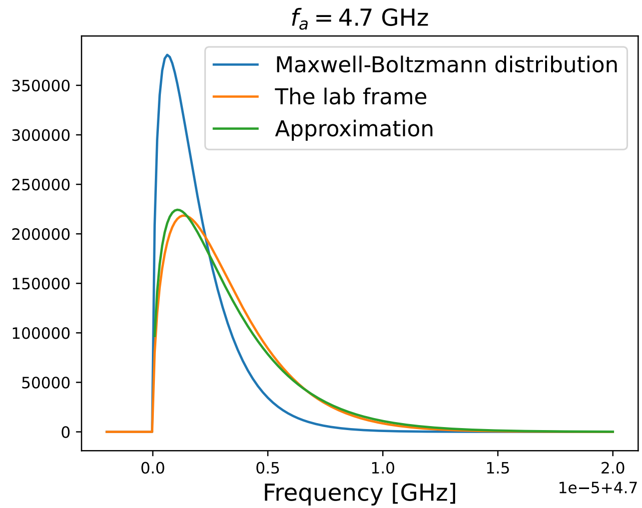
Axion? ADMX-G2 Run1C



Not the real axions!

- Maxwell Boltzmann lineshape
- Signal is Lorentzian. i.e. when the signal appears in different scans, the power should be modified according to the Lorentzian shape of the cavity response. The signal is coming from the cavity itself, and not being added in the receiver chain.
- The same signal doesn't appear in other cavity modes (which should be strongly suppressed due to smaller effective volume).

Fit rescaled RDP with DP line shape and power



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

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

Signal Power (assuming random polarization):

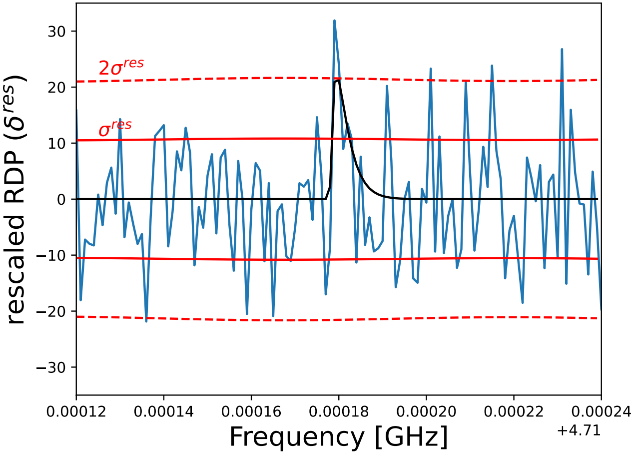
$$P_X = \left(\frac{\epsilon}{\epsilon_0}\right)^2 P_{\mathrm{KSVZ}} = \left(\frac{\epsilon}{\epsilon_0}\right)^2 \times \left(g_{a\gamma\gamma}\frac{\rho_a}{m_a^2}\omega_c B_0^2 V C_{mnl} Q_L \frac{\beta}{1+\beta}\right)$$

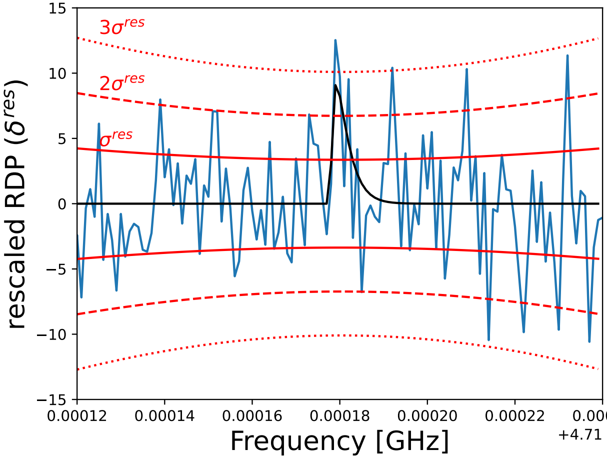
where kinetic mixing

$$\epsilon_0 = \frac{g_{a\gamma\gamma}^{\mathrm{KSVZ}} B_0}{m_a \cos\theta} \sim 3.350 \times 10^{-16}$$

Fit to rescaled relative deviation of power (w/o merge)

Before and after rescan





$$\left(\frac{\epsilon}{\epsilon_0}\right)^2 = 101.68,\ \epsilon = 3.378 \times 10^{-15}$$
$$f_X = 4.71017829\text{ GHz},\ \Delta\chi^2 = 12.82,$$

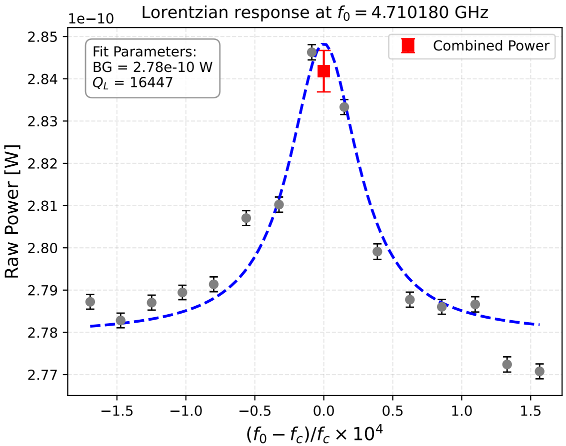
Local significance **3.755**

$$\left(\frac{\epsilon}{\epsilon_0}\right)^2 = 41.59,\ \epsilon = 2.160 \times 10^{-15},$$
$$f_X = 4.710178\text{ GHz},\ \Delta\chi^2 = 21.40,$$

Local significance **4.762**

Power rescaled to the KSVZ axion including Lorentzian cavity response.

Lorentzian response

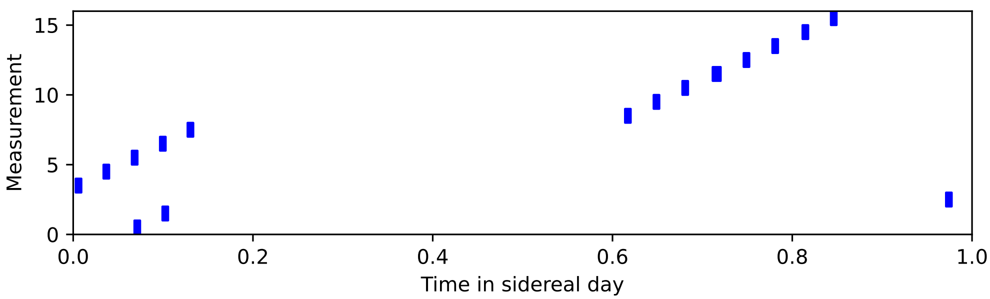


$$P = P_{\mathrm{BG}} + \frac{P_S}{1 + 4Q_L^2(f_0/f_c - 1)^2}$$

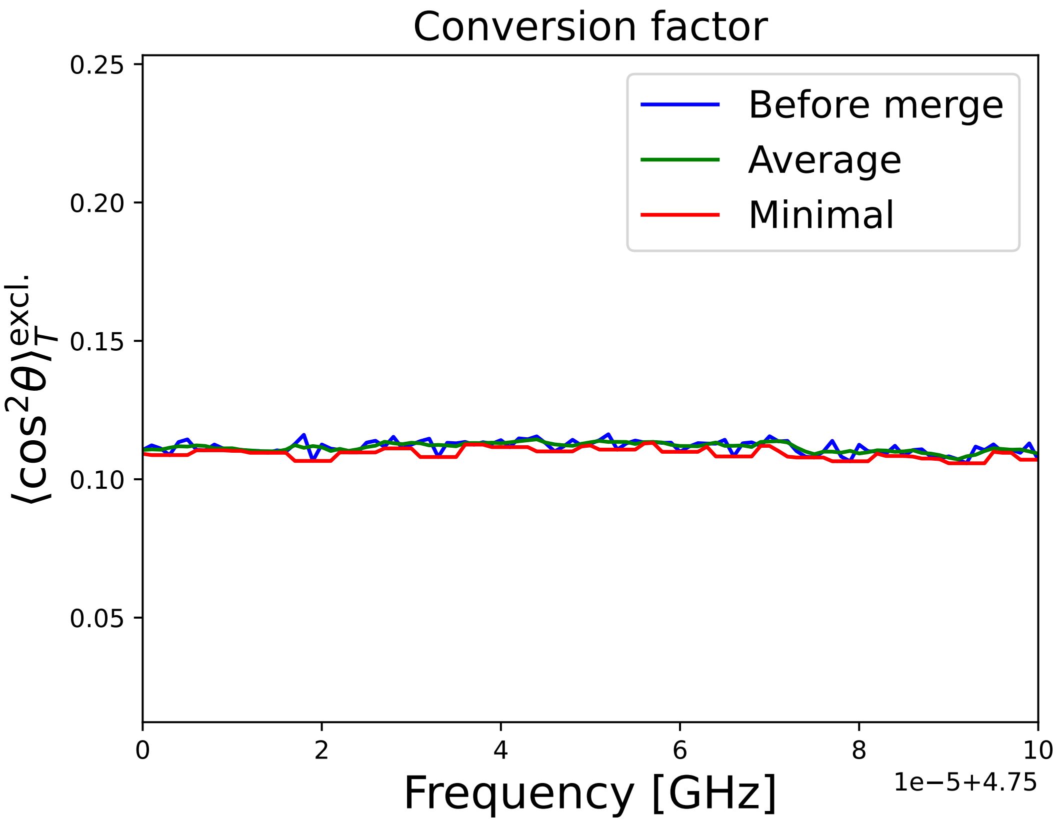
- Uncertainty for the central point is largest due to it being the average of multiple rescans with varying power levels, whilst other data points away from $f_c = f_0$ were not rescanned.
- The signal power has a Lorentzian response to cavity tuning, as is expected from a real signal originating within the haloscope itself.

Conclusion

- Dark photon is viable DM, can be produced with polarization and remains polarized during the evolution of the universe.
- TASEH experiment provides a unique chance to investigate the DP in the mass range $\sim$[19.4,19.9] μeV.
- The rescanning strategy at TASEH helps improve constraints on ϵ for the polarized DP scenario. A more precise DP bound is obtained for the fixed polarization scenario (one order of magnitude stronger then previous estimation).
- A measured signal is explained by a random polarized DP, given mass and coupling ϵ.
- Polarization measurement needs longer integration time.



Backup: Conversion factor in [4.7500,4.7501]



Weighting algorithm in combination

Rescale the relative deviation of power: an axion signal is equal to unity if the signal power is distributed in only one frequency bin.

$$\delta_{ij}^{\text{res}} = R_{ij}\delta_{ij},\ \sigma_{ij}^{\text{res}} = R_{ij}\sigma_i \text{ for } i\text{th scan, } j\text{th bin}$$

$$R_{ij} = \frac{k_B T_{\text{sys}} \Delta f_{\text{bin}}}{P_{ij}^{\text{KSVZ}} h_{ij}},\ h_{ij} = \frac{1}{1 + 4Q_{Li}^2 (f_{ij}/f_{ci} - 1)^2}$$

For given frequency f_n, combine all related scans with weight $\omega_n = \frac{1}{(\sigma_{ij}^{\text{res}})^2}$

$$\delta_n^{\text{com}} = \frac{\sum(\delta_{ij}^{\text{res}} \cdot \omega_n)}{\sum \omega_n},\ \sigma_n^{\text{com}} = \frac{\sqrt{\sum(\sigma_{ij}^{\text{res}} \cdot \omega_n)^2}}{\sum \omega_n}$$

Merging five consecutive bins

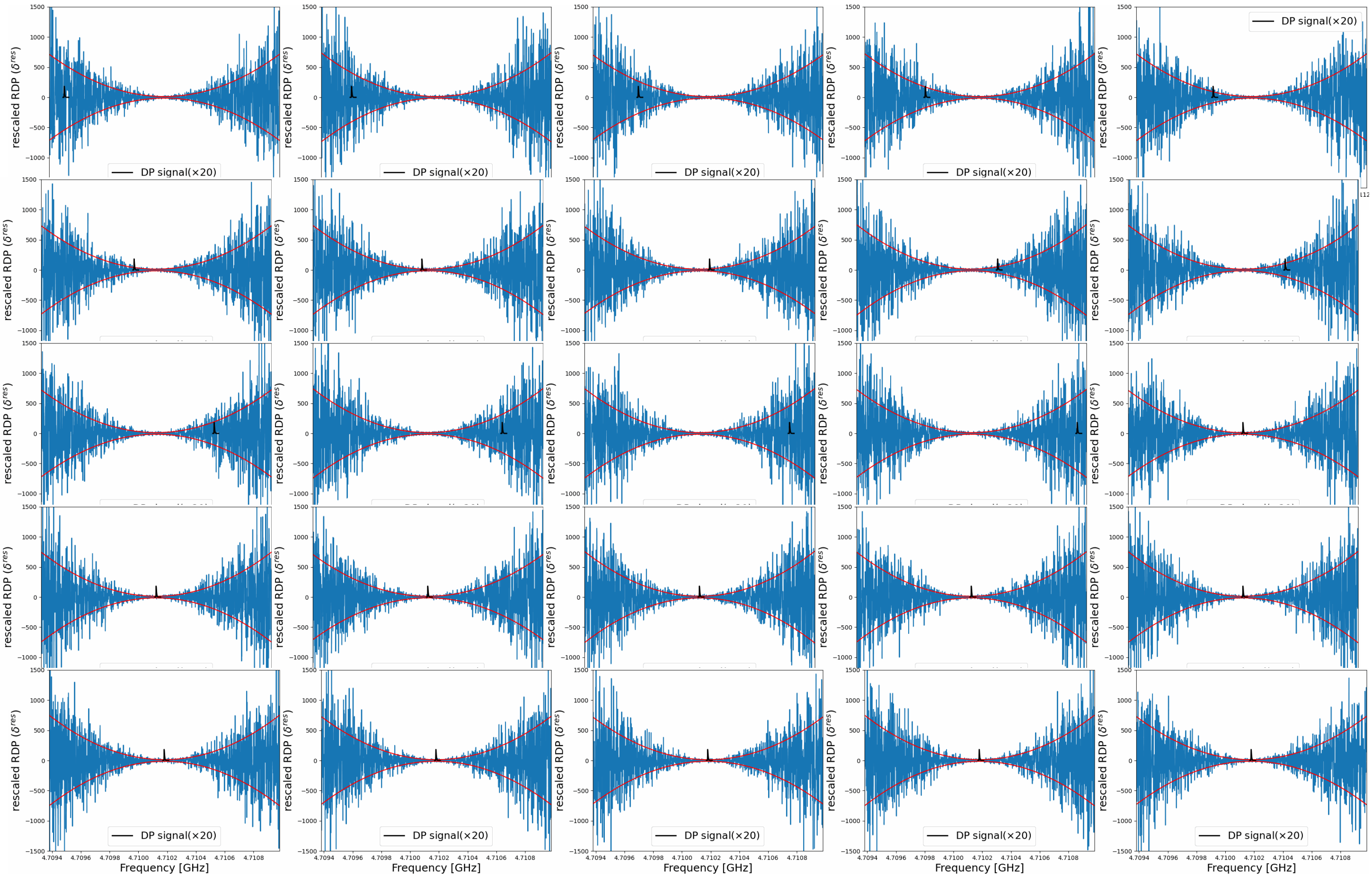
Given the signal shape $\mathcal{F}(f, f_a)$, the rescaling for kth bin, $k = 1, \cdots, 5$

$$L_k = \int_{f_a+\delta f_{\rm mis}+(k-1)\Delta f_{\rm bin}}^{f_a+\delta f_{\rm mis}+k\Delta f_{\rm bin}} \mathcal{F}(f, f_a)\, df$$

The average ($\bar{L}_k$) over the ranges of f_a and $\delta f_{\rm mis}$: 0.23, 0.33, 0.21, 0.11, 0.06.

$$\delta_g^{\rm merge} = \frac{\sum_k \frac{\delta^{\rm com}_{g+k-1}}{\bar{L}_k} \cdot \left(\frac{\bar{L}_k}{\sigma^{\rm com}_{g+k-1}}\right)^2}{\sum_k \left(\frac{\bar{L}_k}{\sigma^{\rm com}_{g+k-1}}\right)^2}, \;\; \sigma_g^{\rm merge} = \frac{1}{\sqrt{\sum_k \left(\frac{\bar{L}_k}{\sigma^{\rm com}_{g+k-1}}\right)^2}}$$

The time dependent information for resolving DP polarization (overview)



The time dependent information for resolving DP polarization (zoom-in)