The Dark Photon Searches at the APEX and TASEH Experiments

Tianjun Li

Institute of Theoretical Physics, Chinese Academy of Sciences
Henan Normal University

The 2024 Purple Mountain Dark Matter Workshop, Suzhou Campus, Nanjing University, October 11-15, 2024

APEX Collaboration, Phys. Rev. D **110**, no.2, L021101 (2024); Chin. Phys. C **48**, no.7, 073004 (2024); TASEH Collaboration, in preparation.

Axion and dark Photon EXperiment (APEX) collaboration

Dong He,[1] Jie Fan,[2] Xin Gao,[3] Yu Gao,[4] Nick Houston,[5] Zhongqing Ji,[5] Yirong Jin,[6] Chuang Li,[7] Jinmian Li,[3] Tianjun Li,[8,9] Shi-hang Liu,[1] Jia-Shu Niu,[10] Zhihui Peng,[1] Liang Sun,[2] Zheng Sun,[3] Jia Wang,[2] Puxian Wei,[11] Lina Wu,[12] Zhongchen Xiang,[2] Qiaoli Yang,[11] Chi Zhang,[2] Wenxing Zhang,[13] Xin Zhang,[14,15] Dongning Zheng,[2] Ruifeng Zheng,[11] and Jian-yong Zhou[1]

[1]*Key Laboratory of Low-Dimensional Quantum Structures and Quantum Control of Ministry of Education, Key Laboratory for Matter Microstructure and Function of Hunan Province, Department of Physics and Synergetic Innovation Center for Quantum Effects and Applications, Hunan Normal University, Changsha 410081, China*
[2]*Institute of Physics, Chinese Academy of Sciences, Beijing, 100190, China*
[3]*College of Physics, Sichuan University, Chengdu 610065, China*
[4]*Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[5]*Institute of Theoretical Physics, Faculty of Science, Beijing University of Technology, Beijing 100124, China*
[6]*Beijing Academy of Quantum Information Sciences, Beijing 100193, China*
[7]*College of Mechanical and Electrical Engineering, Wuyi University, Nanping 354300, China*
[8]*CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*
[9]*School of Physical Sciences, University of Chinese Academy of Sciences, No. 19A Yuquan Road, Beijing 100049, China*
[10]*Institute of Theoretical Physics, Shanxi University, Taiyuan, 030006, China*
[11]*College of Physics and Optoelectronic Engineering, Department of Physics, Jinan University, Guangzhou 510632, China*
[12]*School of Sciences, Xi'an Technological University, Xi'an 710021, P. R. China*
[13]*Tsung-Dao Lee Institute and School of Physics and Astronomy, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China*
[14]*National Astronomical Observatories, Chinese Academy of Sciences, 20A, Datun Road, Chaoyang District, Beijing 100101, China*
[15]*School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, China*

Motivation for New Physics beyond the Standard Model

- The convincing evidence

  Dark energy; dark matter; neutrino masses and mixing; baryon asymmetry; inflation; ...

- Fine-tuning problems

  Cosmological constant problem; gauge hierarchy problem; strong CP problem; SM fermion masses and mixings; ...

- Aesthetic problems

  Interaction and fermion unification; gauge coupling unification; charge quantization; too many parameters; ...

- The electroweak vacuum stability problem

  The stability problem can be easily solved in the new physics models.

- New Physics beyond the SM!

The Peccei-Quinn Mechanism and QCD Axion

- The Peccei-Quinn mechanism provides a natural solution to the strong CP problem, and predict the QCD axion
- The QCD axion can be a dark matter candidate if its mass is around 50 μeV.
- The resonant cavity experiment has been proved to be able to probe the QCD axion models!
- We plan to perform the resonant cavity experiment.

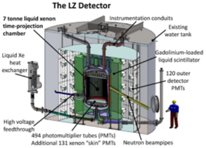
Axion Experiment

- We have gone through almost all the axion experiments and proposals in details, and thought it very carefully!!!
- The DOE Office of High Energy Physics and the NSF Physics Division have jointly selected a portfolio of projects for the second generation of direct detection dark matter experiments on July 11, 2014. The joint DOE/NSF second-generation program will include the LZ and SuperCDMS-SNOLAB experiments with their collective sensitivity to both low and high mass WIMPS, and ADMX-Gen2 to search for axions.
- In Summer 2016, we made the final decision to perform the resonant cavity experiment to search for QCD axion dark matter!

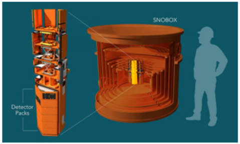
轴子暗物质实验的必要性

2014年7月11日，美国能源部（DOE）和美国国家自然科学基金（NSF）宣布支持3个第二代暗物质直接探测实验：

探测轴子暗物质的
ADMX-G2



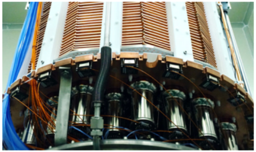
探测较重的WIMP暗物质的
LUX-ZEPLIN（LZ）



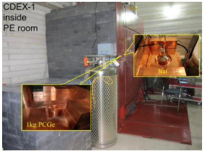
探测较轻的WIMP暗物质的
SuperCDMS

我国目前支持的暗物质实验直接探测实验主要有2个，均为探测WIMP暗物质，**在轴子暗物质探测领域尚属空白：**

暂无



PandaX（对应LZ）

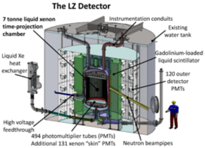


CDEX（对应SuperCDMS）

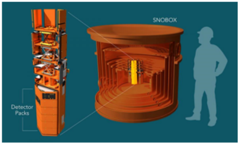
轴子暗物质实验的必要性

2014年7月11日，美国能源部（DOE）和美国国家自然科学基金（NSF）宣布支持3个第二代暗物质直接探测实验：

探测轴子暗物质的 ADMX-G2



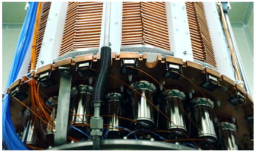
探测较重的WIMP暗物质的 LUX-ZEPLIN（LZ）



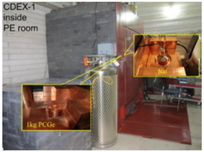
探测较轻的WIMP暗物质的 SuperCDMS

我国目前支持的暗物质实验直接探测实验主要有2个，均为探测WIMP暗物质，**在轴子暗物质探测领域尚属空白：**

2016年夏天，我们决定做轴子暗物质的共振腔探测实验。

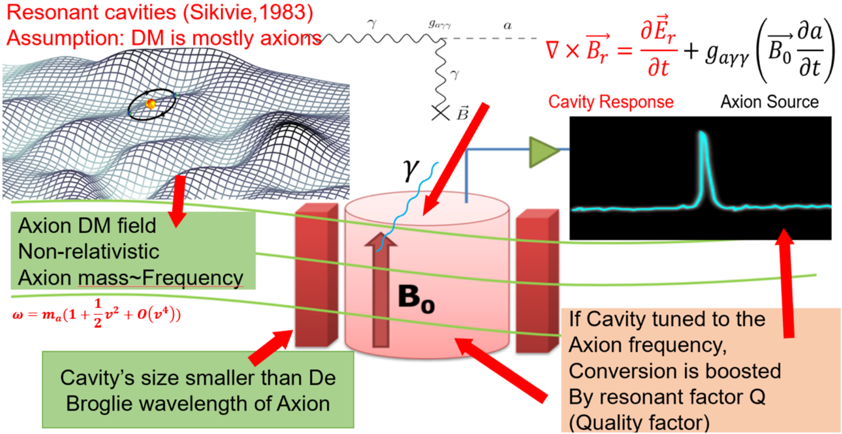


PandaX（对应LZ）

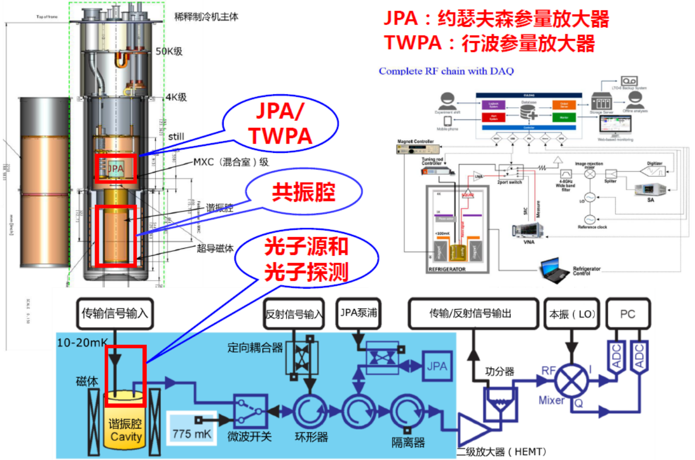


CDEX(对应SuperCDMS)

Resonant Cavity Detection (Haloscope) Basic principles



整体实验方案



稀释制冷机主体
50K级
4K级
still
MXC（混合室）级
谐振腔
超导磁体
JPA
JPA/
TWPA
共振腔
光子源和
光子探测
JPA：约瑟夫森参量放大器
TWPA：行波参量放大器
Complete RF chain with DAQ
Magnet Controller
2port switch
LNA
VNA
SA
Digitizer
Reference clock
REFRIGERATOR
Refrigerator Control
传输信号输入
反射信号输入
JPA泵浦
传输/反射信号输出
本振（LO）
PC
10-20mK
定向耦合器
JPA
功分器
RF
I
Q
Mixer
ADC
ADC
磁体
谐振腔
Cavity
775 mK
微波开关
环形器
隔离器
二级放大器（HEMT）

轴子实验团队

- 轴子理论与创新实验方案： 高宇，杨峤立, Nick Houston
- JPA/TWPA： 郑东宁，金贻荣, 相忠诚
- 共振腔： 孙亮，王佳，王旭
- 单光子源和探测： 彭智慧
- 稀释制冷机： 姬忠庆, 樊洁
- 总体协调负责： 李田军

实验进展

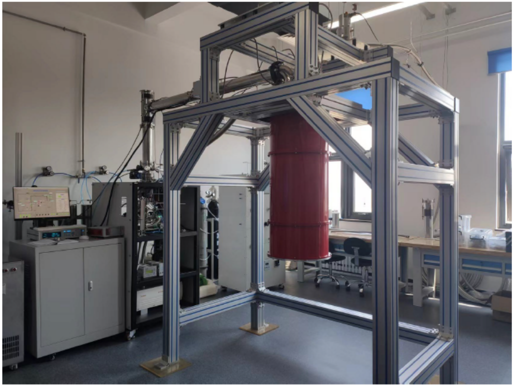
我们已获得了中国科学院科研仪器设备研制项目，“用于轴子探测的可调共振腔微波单光子探测系统”，**2020/1-2023/12**，**300**万元，并开展 **8-10 GHz** 的轴子可调共振腔微波单光子探测系统预研。

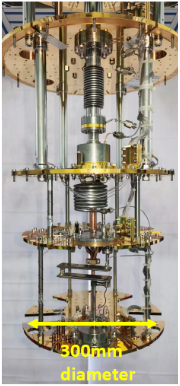
轴子实验相关预研已基本完成：

- 作为探测器工作在 **8-10GHz** 的可调频率共振腔；
- 在**8-10GHz**频率响应范围内的低噪声 **JPA**；
- 微波单光子源和探测。
- 并在湖南师范大学已经开展了 **8 GHz** 暗光子探测。

实验进展

- 轴子实验室：中国科学院物理研究所怀柔实验室；
- 极低温无液氦稀释制冷机，类似 Bluefors LD 400 或者 Oxford Triton 400.
- 预计2023年3月购买 9T超导磁体（冷孔90mm），超导磁体电源和电流引线.
- 预计2023年春季购买步进电机，用于共振腔调频。
- 预计2023年夏季实验集成并开始实验。

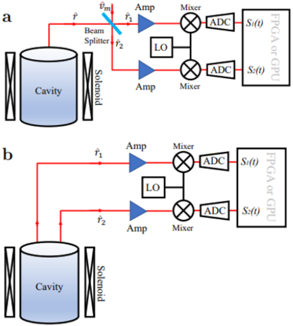




Specifications: Base T < 17mK, Cooling power 200uW. Similar size to Bluefors LD250/400 or Oxford Triton200/400.

Hope base T < 10mK, P>400uW@100mK by 2022/12

The dual-path scheme can enhance the signal-to noise ratio up to one-two order of magnitude compared with single-path scheme. Greatly increases scanning speed.



arxiv: 2201.08291

实验进展

我们已获得了中国科学院全球共性挑战专项项目，“质量范围在 50 μ eV 左右的 QCD 轴子暗物质探测研究”，2022/1-2024/12，260万元，与日本理化学研究所（RIKEN）的蔡兆申教授团队合作，开展 12.5 GHz 左右的轴子暗物质探测预研。

相关预研包括：

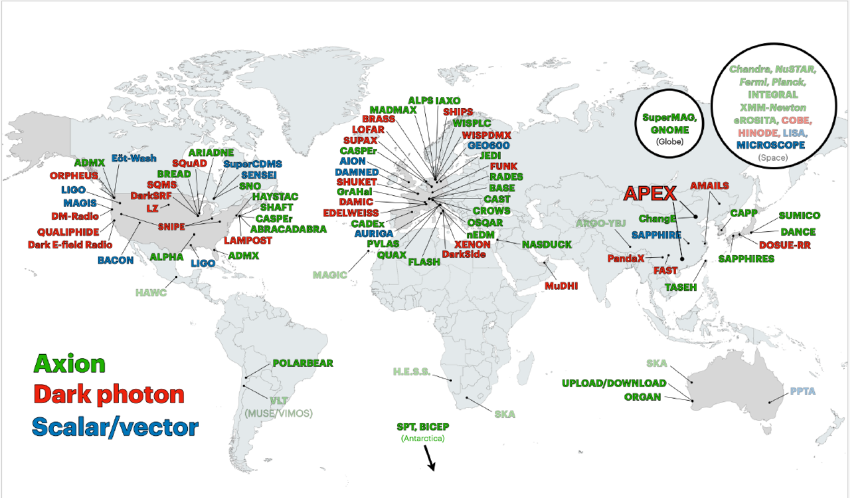
- 作为探测器工作在 12.5 GHz 的可调频率共振腔；
- 在 12.5 GHz频率响应范围内的低噪声 JPA；
- 微波单光子源和探测。

Dark photon dark matter theory

- One of the simplest possible SM extensions: add a new 'dark' $U(1)$

$$\mathscr{L} = -\frac{1}{4}(F^{\mu\nu}F_{\mu\nu} + F_d^{\mu\nu}F_{d\mu\nu} - 2\chi F^{\mu\nu}F_{d\mu\nu} - 2m_A^2 A_d^2),$$

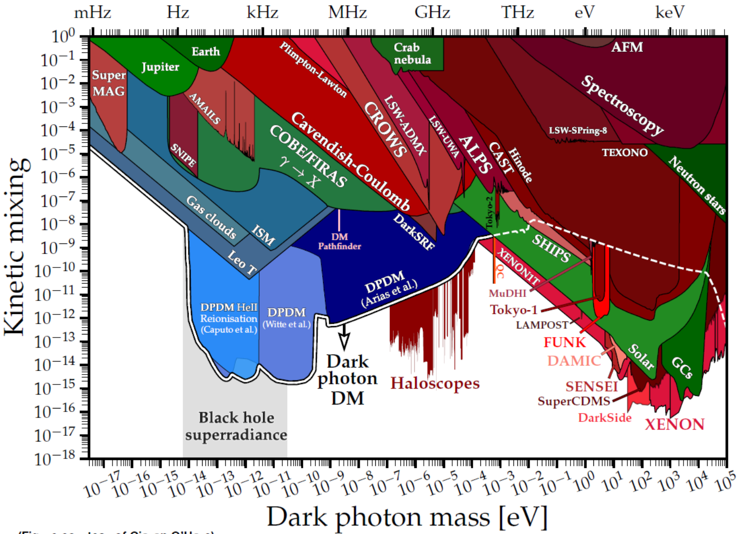
- A_d can mix directly with the SM photon, controlled via the parameter χ
- Light dark photons are best described as a coherent wave oscillating at a frequency set by m_A, rather than a collection of distinct particles.
- Just like the axion this can provide a natural DM candidate. Interesting phenomenology and experimental possibilities!
- Unlike the axion: no B-field needed, no specifically favoured m_A values



APEX was based at Hunan Normal University and the Institute of Physics, Chinese Academy of Sciences
From October APEX will run at Anhui University, whilst we prepare a dedicated laboratory at Henan Normal University

(Figure courtesy of Ciaran O'Hare)

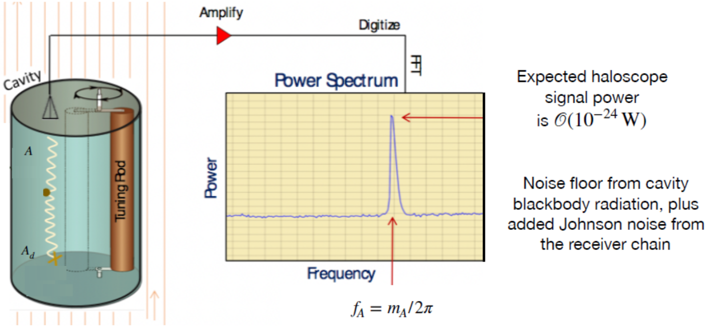
Dark Photon Experimental Constraints



(Figure courtesy of Ciaran O'Hare)

How do we search for this 'dark' wave?

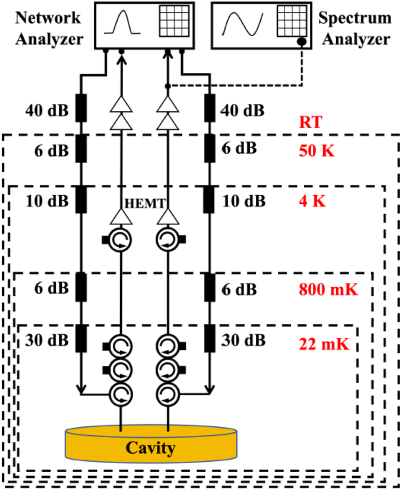
- Dark photons/axions from the DM halo resonantly convert to photons when m_A matches the resonance frequency of a microwave cavity



- Peak power is $P_0 = \dfrac{\beta}{\beta+1}\eta\chi^2 m_A \rho V_{\rm eff} Q_L$, $\quad V_{\rm eff} = \dfrac{\left(\int dV\,\mathbf{E}(\vec{x})\cdot\mathbf{A_d}(\vec{x})\right)^2}{\int dV\,|\mathbf{E}(\vec{x})|^2\,|\mathbf{A_d}(\vec{x})|^2}$

- We don't know m_A, so we need to scan the parameter space

APEX experimental details I

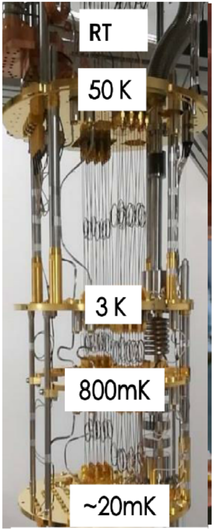


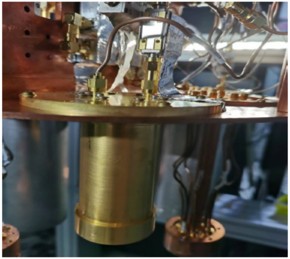
Key components

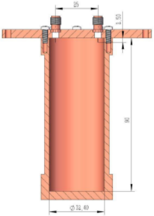
- Keysight N5231B network analyser
- Keysight N9020B spectrum analyser
- Bluefors LD 400 dilution refrigerator
- Cryogenic HEMT amplifiers, 36 dB gain
- Room temperature amplifiers, 36 dB gain
- Attenuators, circulators/isolators, cables

Total noise temperature: 7.5 K, gain: 108 dB, loss: 23 dB

APEX experimental details II

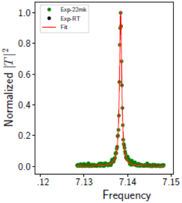


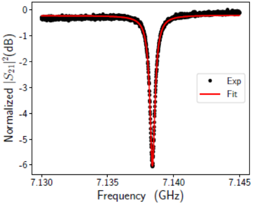




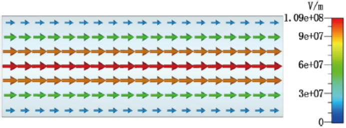
APEX experimental details III

- Transmission and reflection measurements allow us to find β, f_0, Q_L





- To find $V_{\rm eff}$ we simulate the TM010 mode in CST Microwave studio



Summary of key parameters

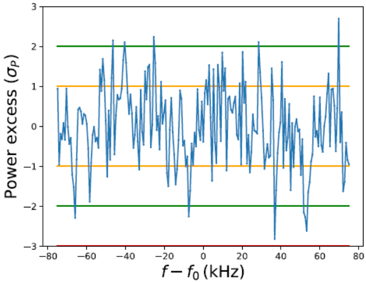
β	f_0	Q_L	$V_{\rm eff}$	G	η	b	$t_{\rm int}$
0.9539	7.139 GHz	11006	17.1 ml	88 dB	0.5	20 Hz	22.1 s

Data analysis

- Data arrive in the form of power spectra, measured by the spectrum analyzer

Each point here is the average of 10^8 measurements

No excess over 3σ: compatible with the null hypothesis



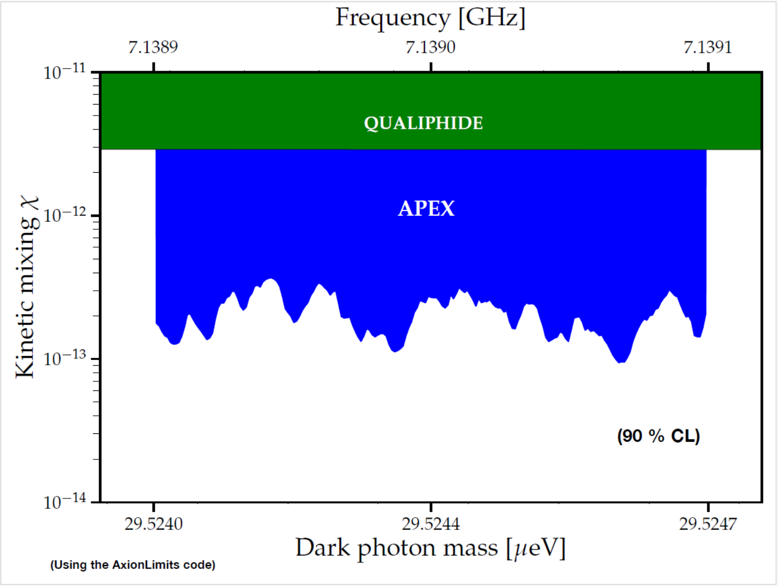
Mean power is $\mathcal{O}(10^{-23}\,\mathrm{W})$

Uncertainty is primarily statistical: 1.7% relative uncertainty in P_e, systematics are subleading

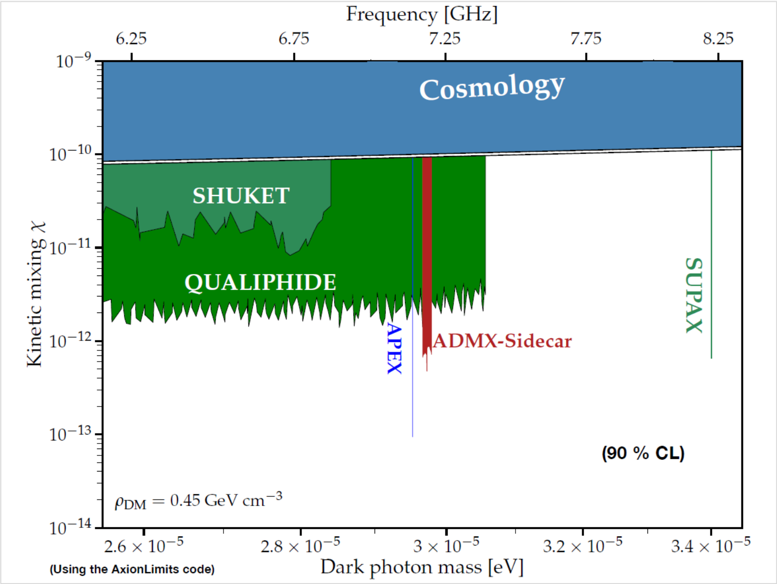
- We calculate the reference signal power P_{ref} in each bin and compare to the measured power excess P_e via the likelihood

$$p(P_e | m_A, \chi) = \prod_i \frac{1}{\sqrt{2\pi\sigma_P^2}} \exp\left(-\frac{(P_e - P_{\mathrm{ref}}\chi^2)^2}{2\sigma_P^2} \right)$$

APEX Experimental Constraint



APEX Experimental Constraint



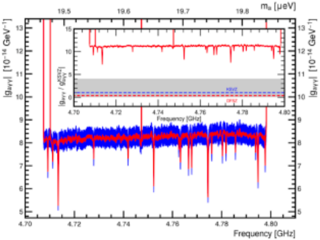
APEX Collaboration

- We have performed a cavity haloscope experiment, searching for dark photon DM
- Finding no statistically significant excess, we we place an upper limit $|\chi| < 3.7 \times 10^{-13}$ around $m_A \simeq 29.5\mu\text{eV}$ (90% CL)
- This exceeds other constraints on dark photon DM in this frequency range by roughly an order of magnitude

Dark Photon Search at the TASEH experiment

In Collaboration with: TASEH Collaboration
Cheng-Wei Chiang, Yuan-Hann Chang, Hien Doan, Nick Houston,
Tianjun Li, Lina Wu, Xin Zhang

The TASEH Axion Limits to Dark Photon Limits



TASEH Axion limit

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

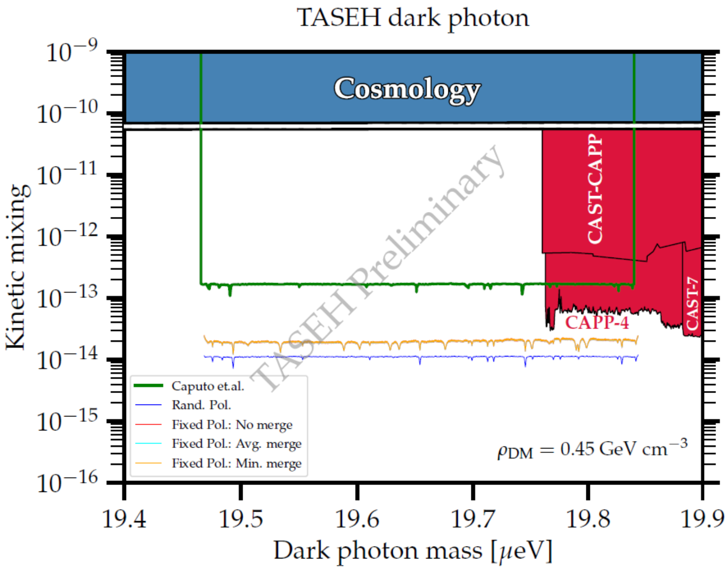
Phys.Rev.D 106 (2022) 5, 052002

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

→

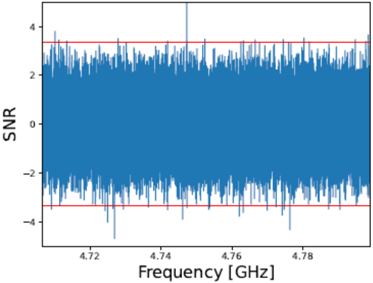
TASEH Dark Photon limit

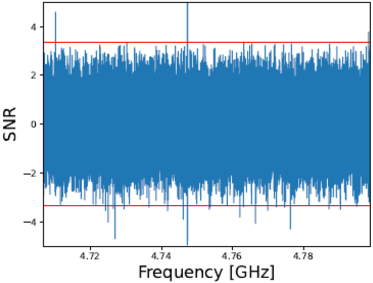
Dark Photon Search at the TASEH experiment



The Tentative Dark Photon Signals

The merged spectrum before and after rescan:





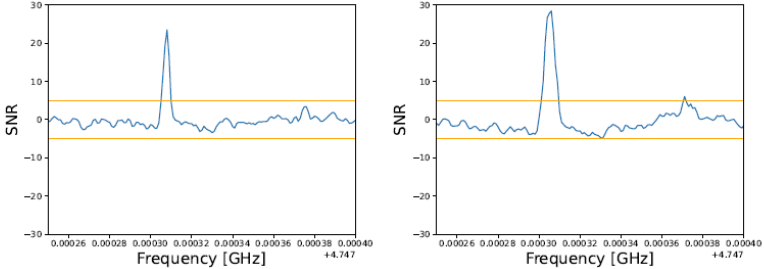
There are 22 candidates with an SNR greater than 3.355 → **Rescan**

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 Tentative Dark Photon Signal

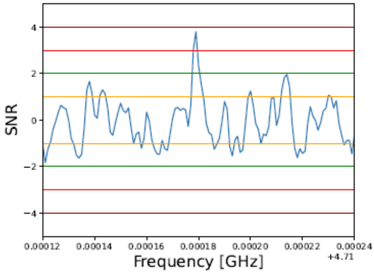
SNR before and after rescan

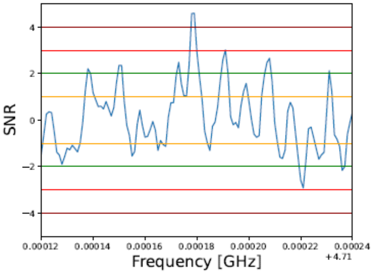


The signal was detected via a portable antenna outside the DR and found to come from the instrument control computer in the laboratory.

The Tentative Dark Photon Signal

SNR before and after rescan





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

The Prospects of the APEX Experiment

- Double check the tentative dark photon signal in the range 4.71017-4.71019 GHz via dual path read out system, Anhui University.
- The axion and dark photon searches at the Henan Normal University.
- The axion and dark photon searches at Chinese Academy of Sciences.

Summary

- The dark photon searches at the APEX and TASEH experiments.
- A tentative dark photon signal around in the range 4.71017-4.71019 GHz at the TASEH experiment.
- The Prospects of the APEX Experiment.

Thank You Very Much
for Your Attention!