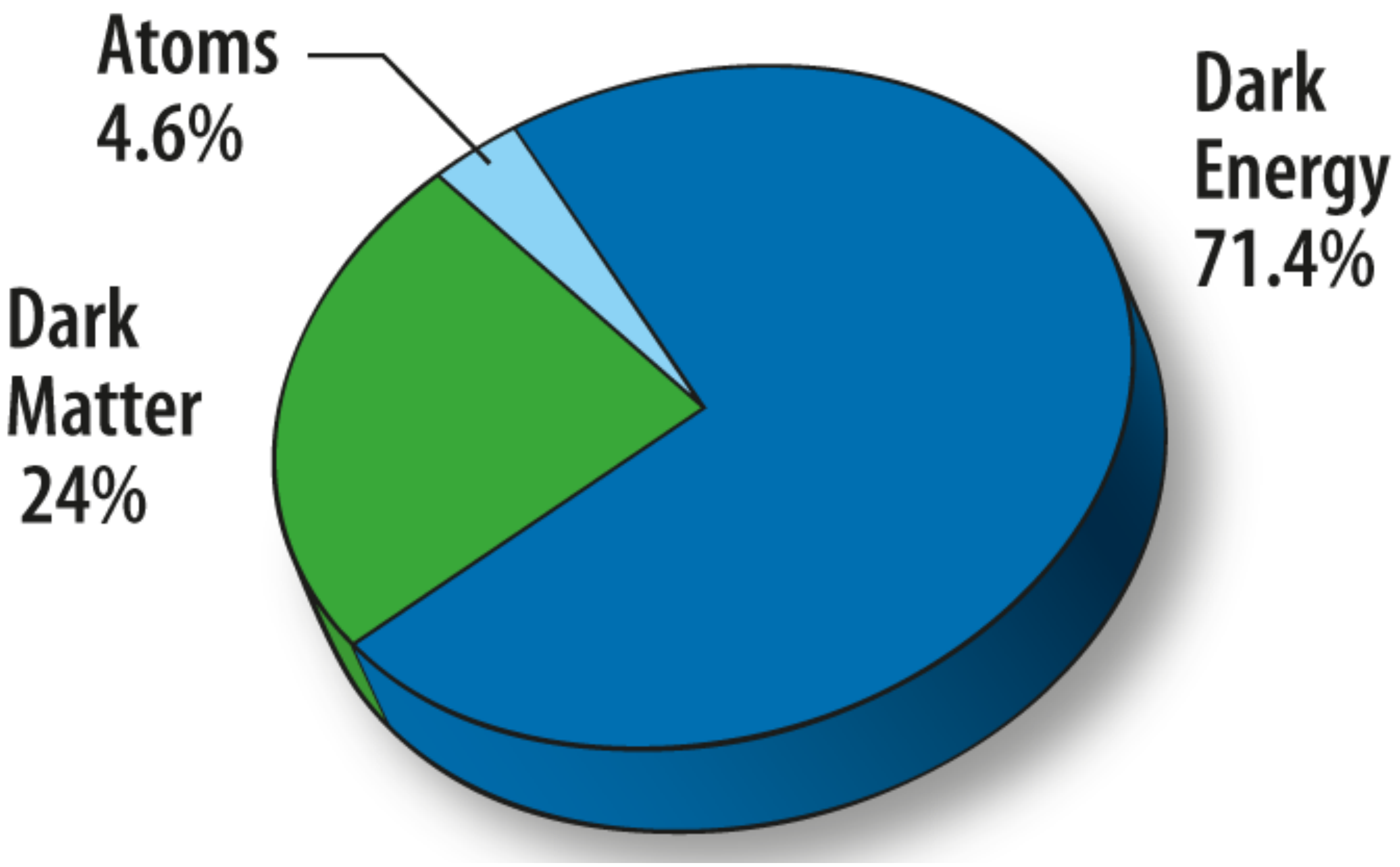
Dark photon constraints from the APEX cavity haloscope experiment

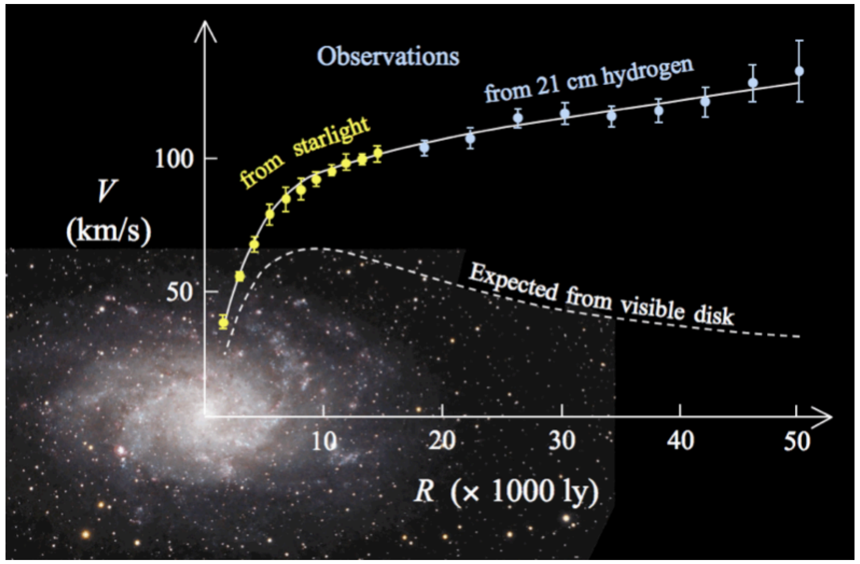


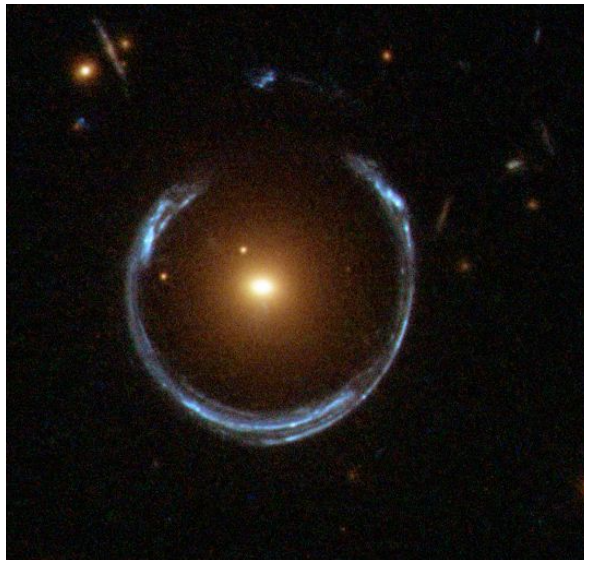
Nick Houston, 北京工业大学, on behalf of the APEX collaboration

Based on 2404.00908 (Phys. Rev. D) and 2404.10264 (Chin. Phys. C)

MEPA 2024, nhouston@bjut.edu.cn

The big picture





- Very good indirect evidence exists for dark matter, so why hasn't it been detected?

- This talk is about using a resonant microwave cavity - a haloscope, to search for a particular dark matter candidate - the dark photon

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.

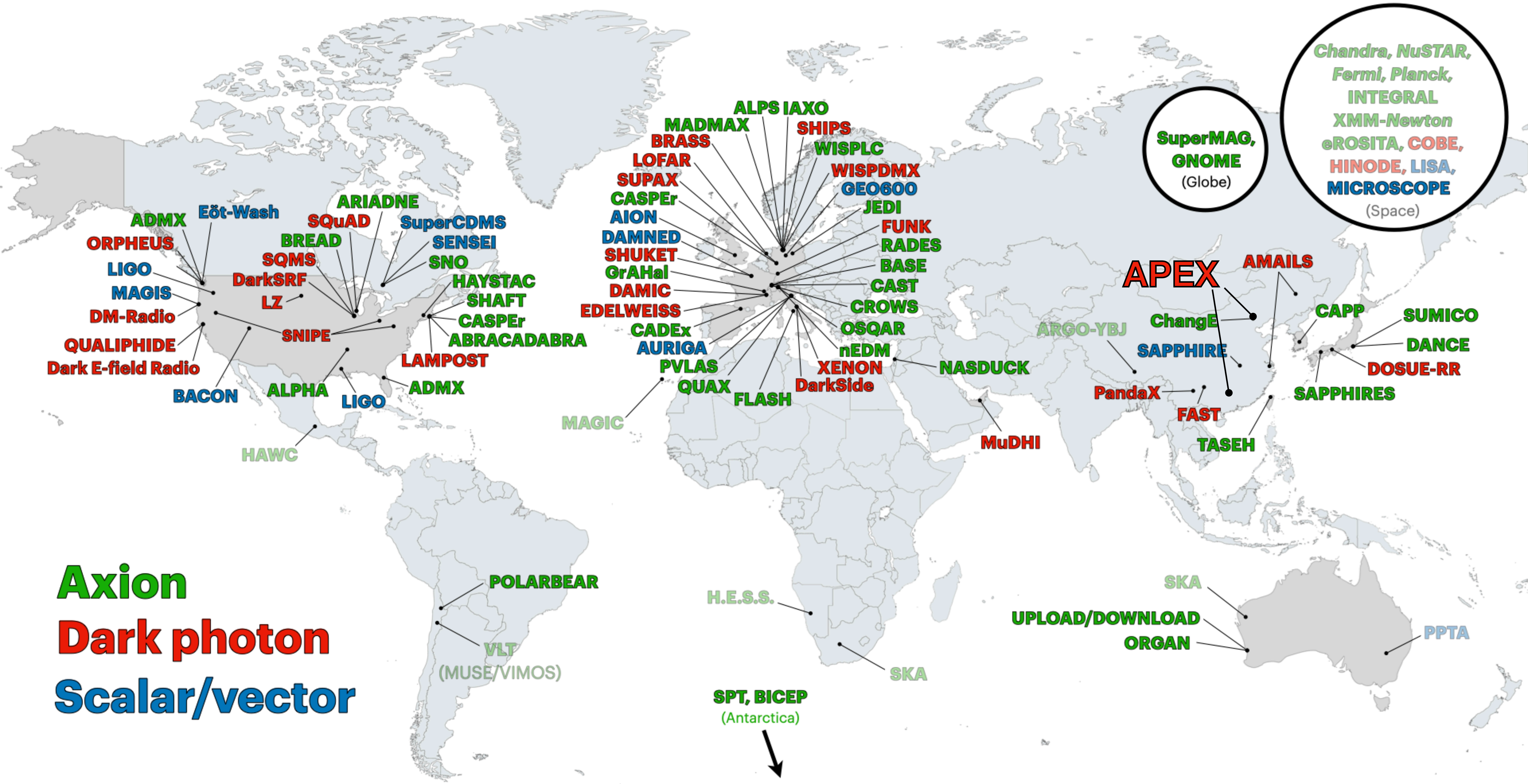
- Just like the axion this can provide a natural DM candidate. Interesting phenomenology and experimental possibilities!

- Unlike the axion: no B-field needed, no specifically favoured m_A values

Axion and dark Photon EXperiment (APEX) collaboration

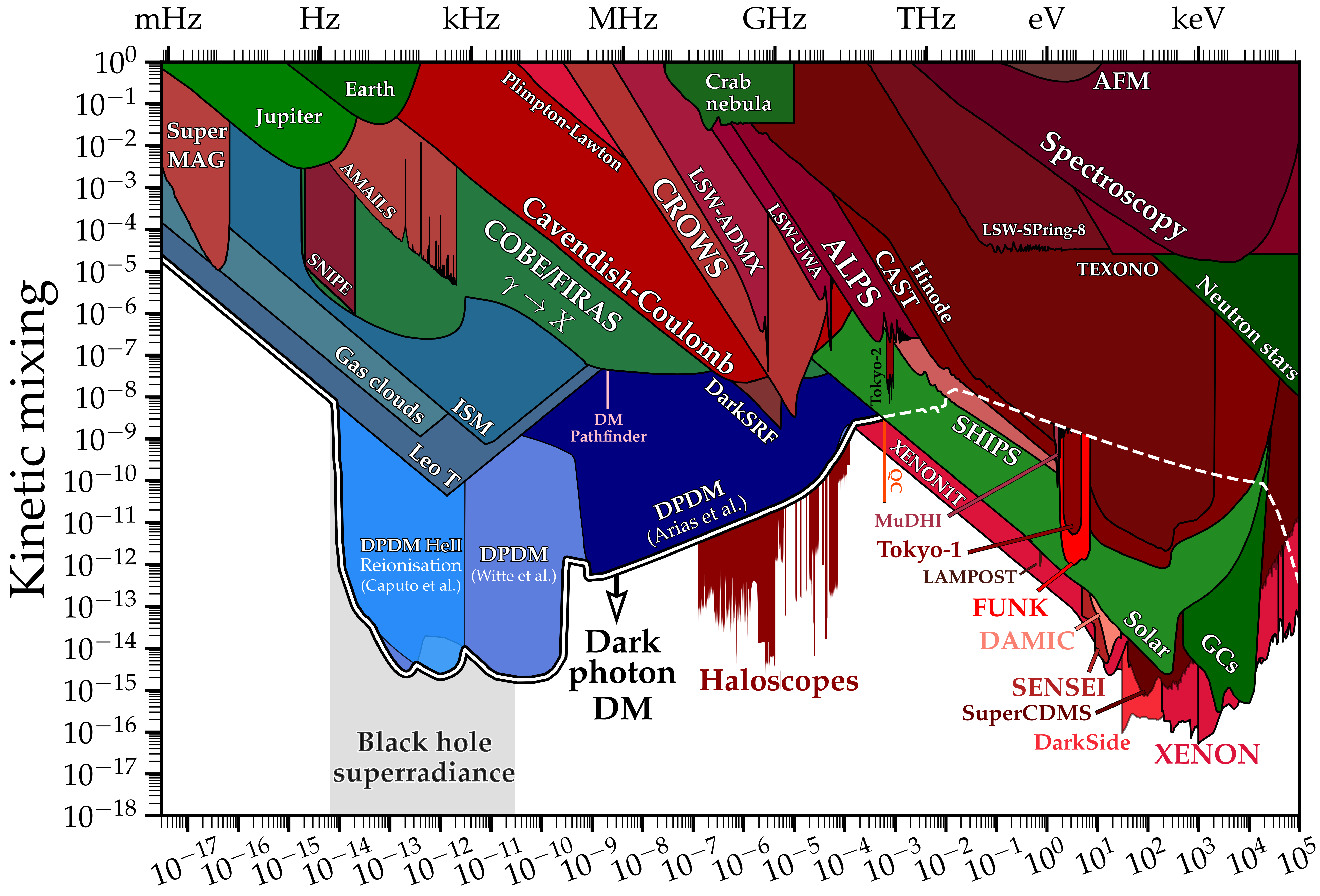
Dong He,[1] Jie Fan,[2] Xin Gao,[3] Yu Gao,[4] Nick Houston,[5] Zhongqing Ji,[5] Yirong Jin,[6] Chuang Li,[7] Jinmian Li,[3] Tianjun Li,[8,9] Shi-hang Liu,[1] Jia-Shu Niu,[10] Zhihui Peng,[1] Liang Sun,[2] Zheng Sun,[3] Jia Wang,[2] Puxian Wei,[11] Lina Wu,[12] Zhongchen Xiang,[2] Qiaoli Yang,[11] Chi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



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

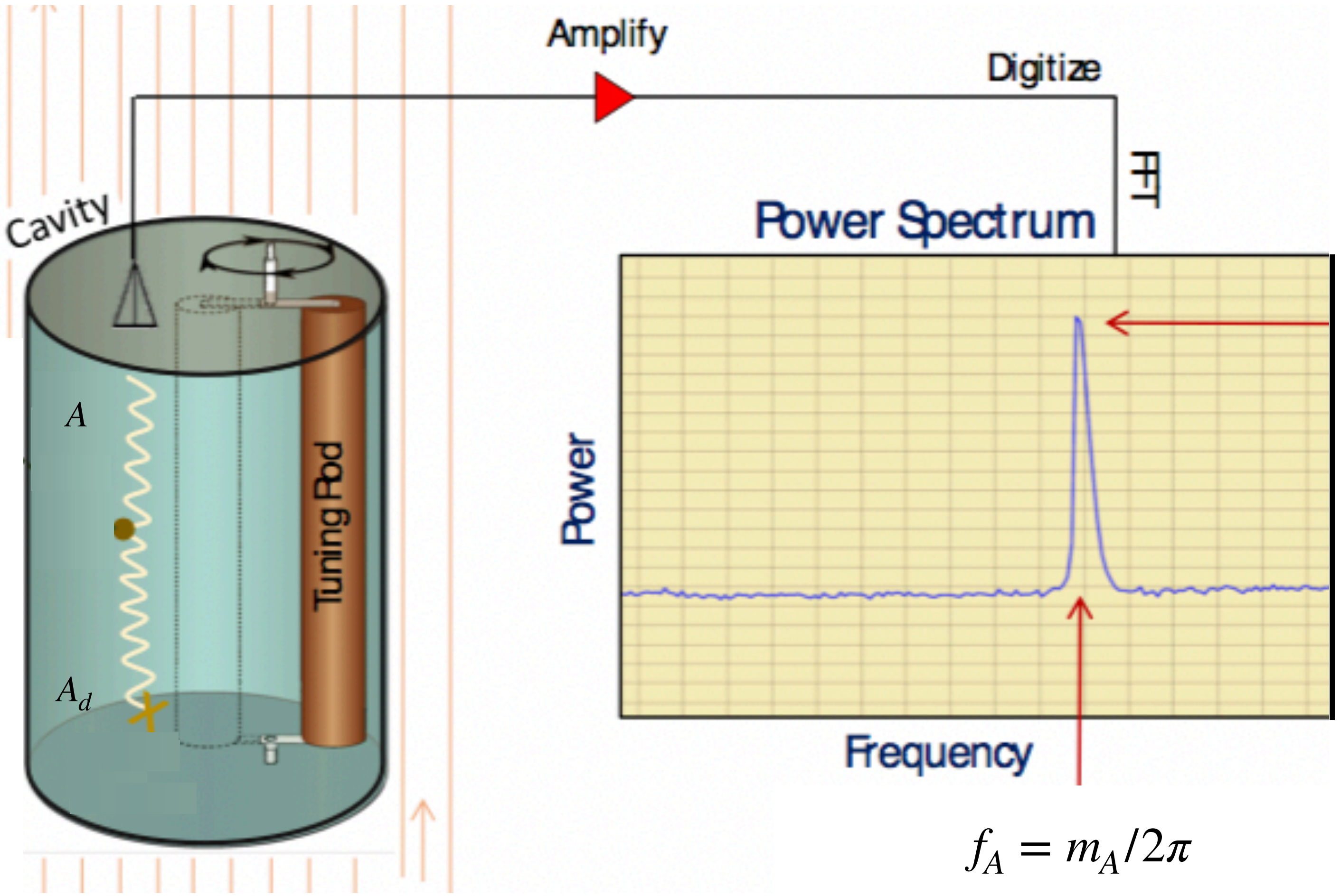
(Figure courtesy of Ciaran O'Hare)



(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



$f_A = m_A/2\pi$

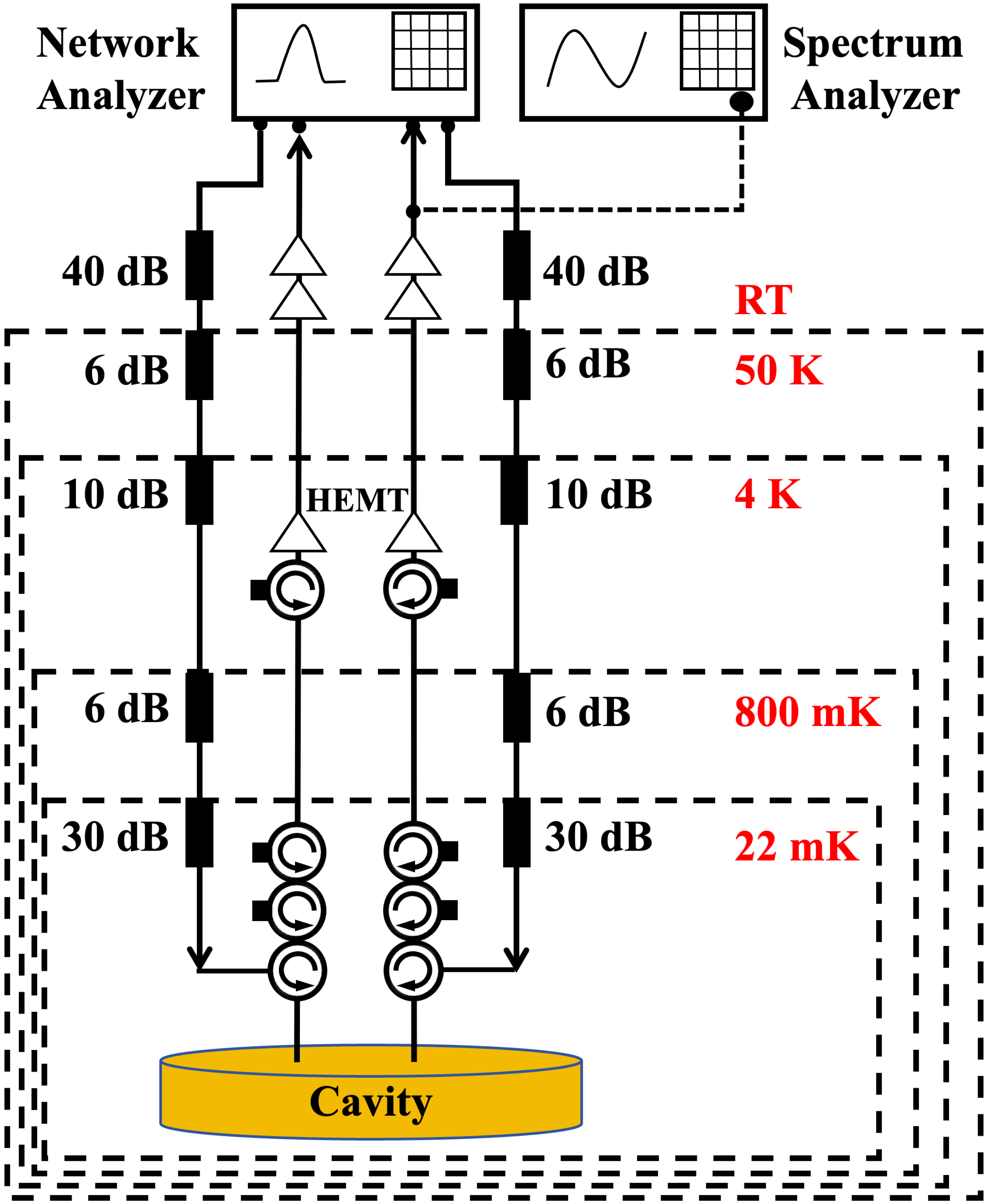
Expected haloscope signal power is $\mathcal{O}(10^{-24}\,\mathrm{W})$

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

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

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

APEX experimental details I

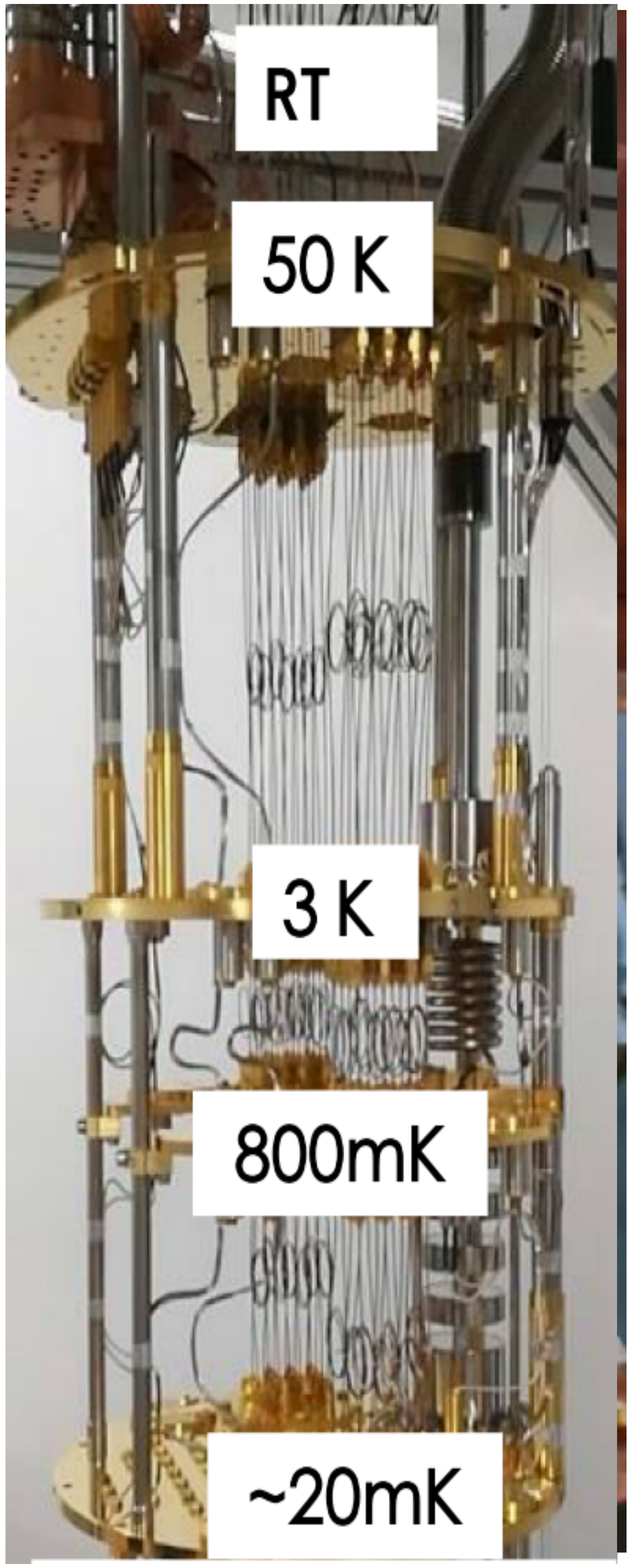


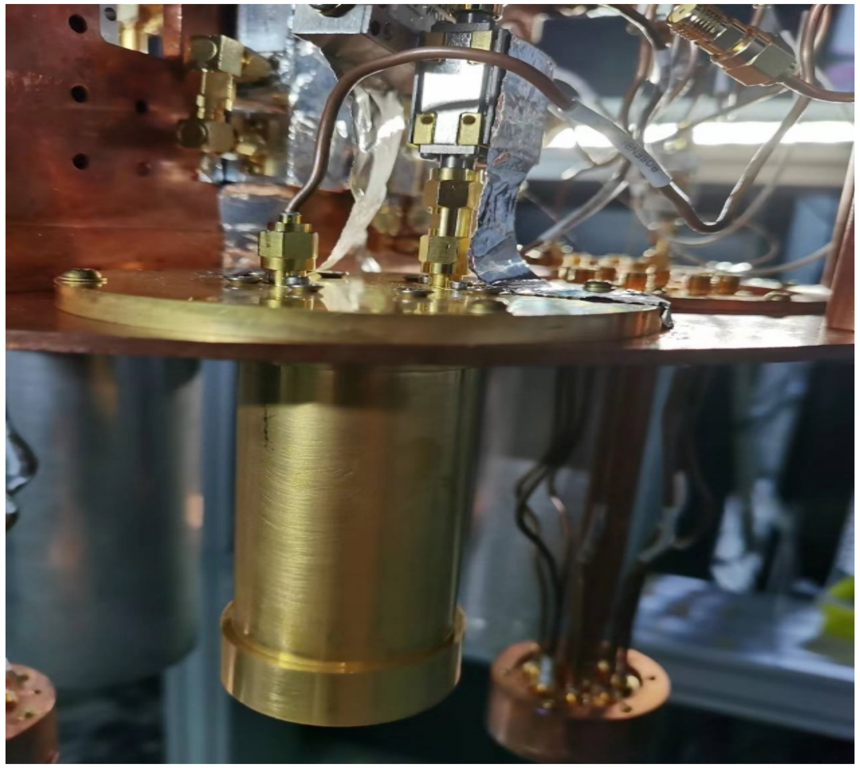
Key components

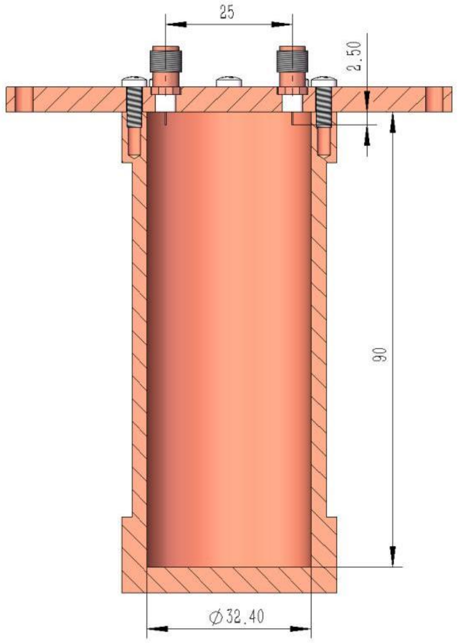
- Keysight N5231B network analyser
- Keysight N9020B spectrum analyser
- Bluefors LD 400 dilution refrigerator
- Cryogenic HEMT amplifiers, 36 dB gain
- Room temperature amplifiers, 36 dB gain
- Attenuators, circulators/isolators, cables

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

APEX experimental details II

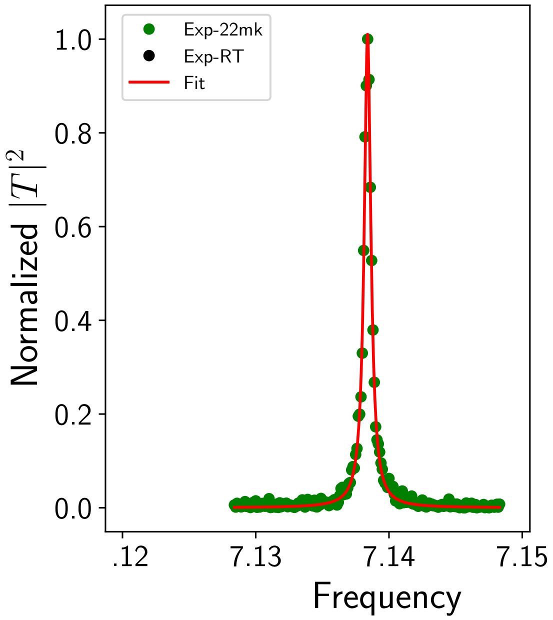


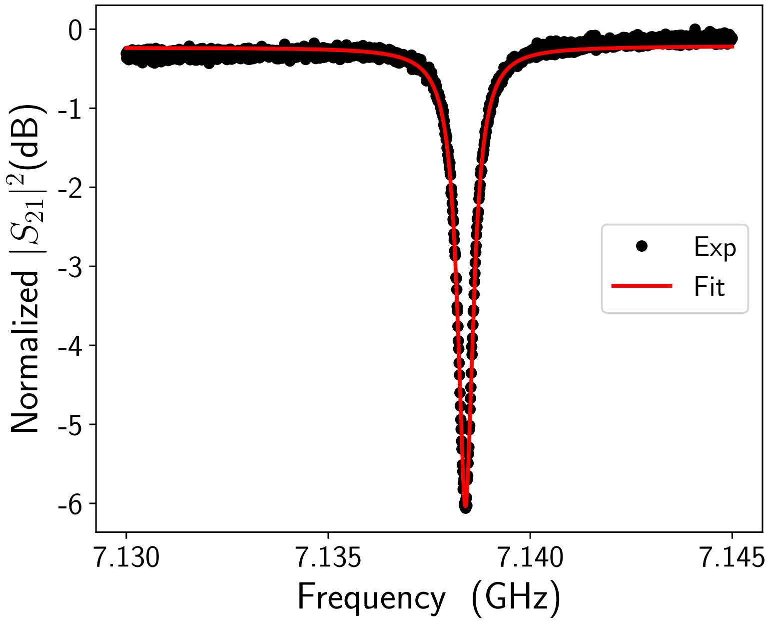




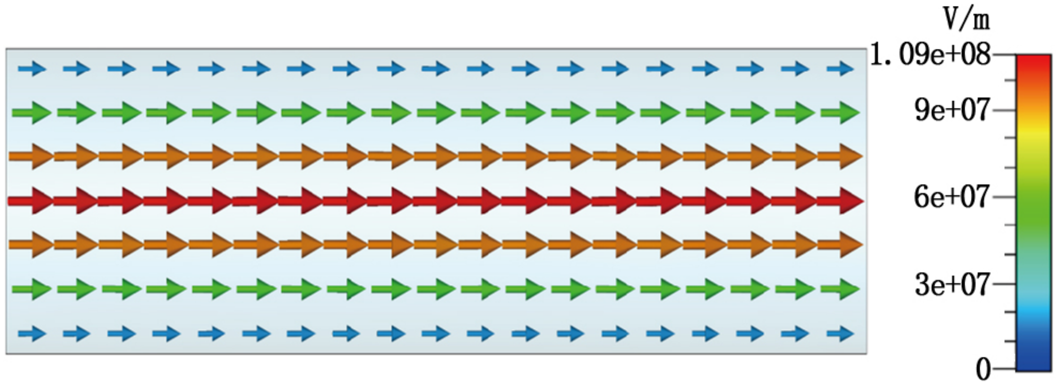
APEX experimental details III

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





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



Summary of key parameters

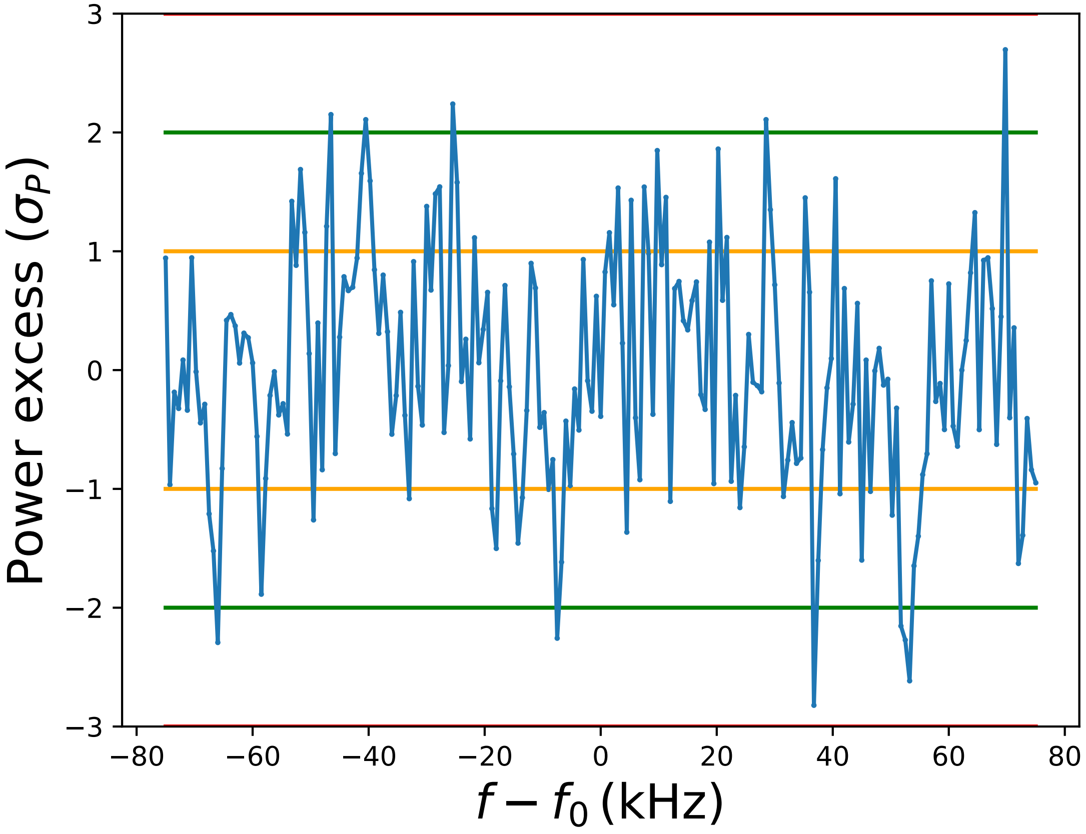
β	f_0	Q_L	V_{eff}	G	η	b	t_{int}
0.9539	7.139 GHz	11006	17.1 ml	88 dB	0.5	20 Hz	22.1 s

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

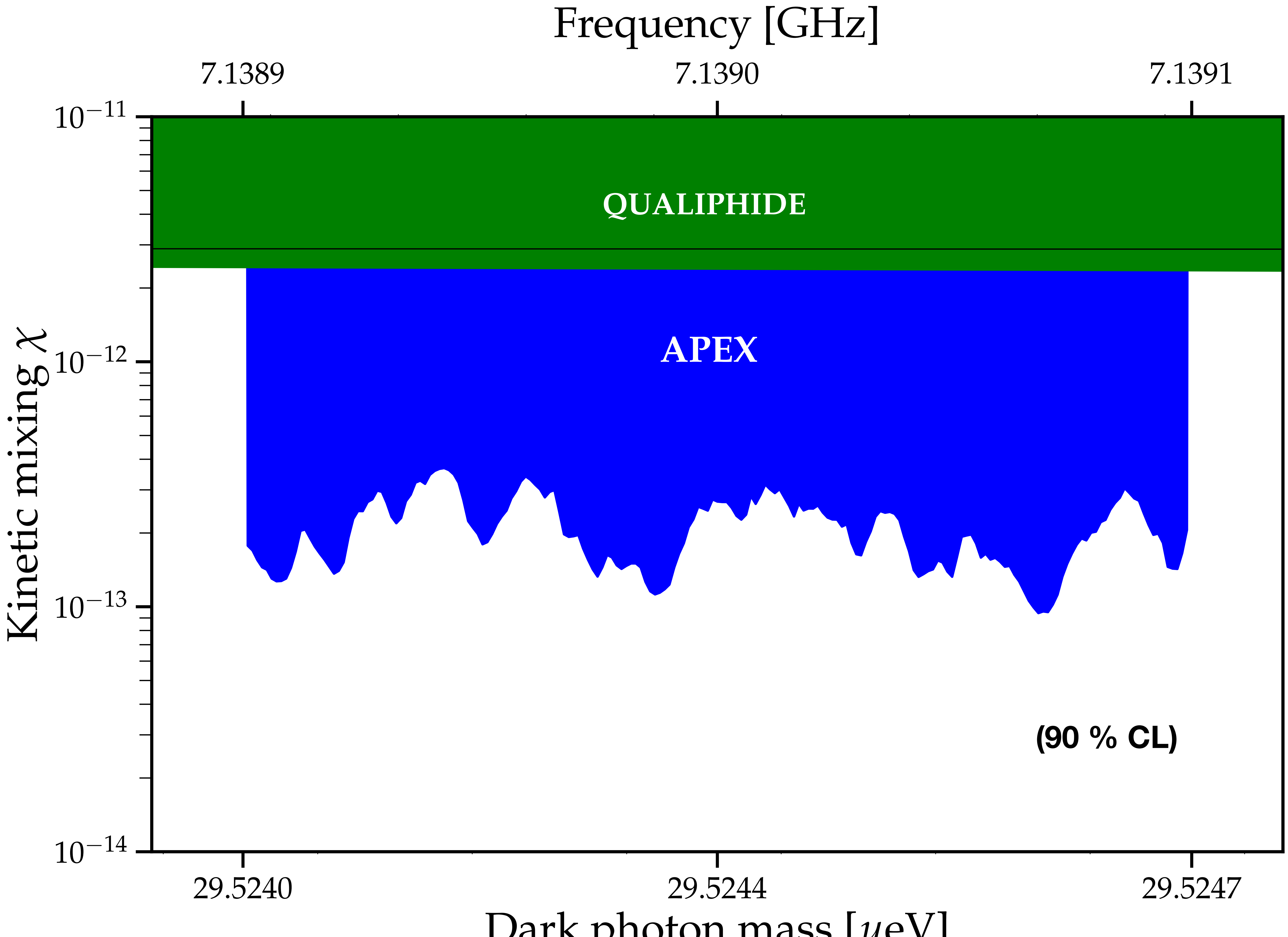


Mean power is $\mathcal{O}(10^{-23}\,\mathrm{W})$

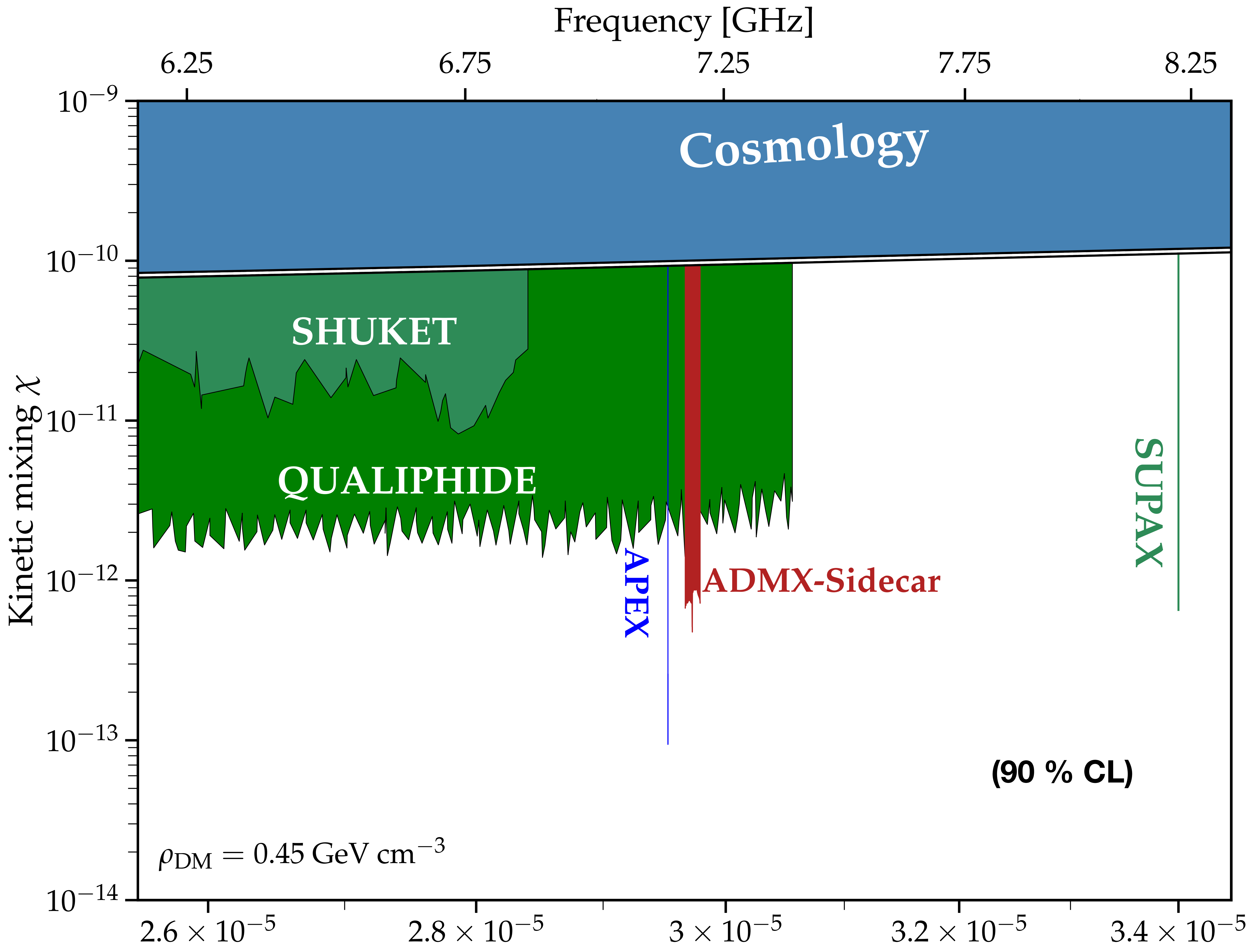
Uncertainty is primarily statistical: 1.7% relative uncertainty in P_e, systematics are subleading

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

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



(Using the AxionLimits code)



(Using the AxionLimits code)

Discussion and conclusions

- 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 $m_A \simeq 29.5\mu\mathrm{eV}$ (90% CL)

- This exceeds other constraints on dark photon DM in this frequency range by roughly an order of magnitude

- From Oct 2024 (Anhui University): implement cavity scanning, with addition of 9 T magnetic field and 'dual-path' interferometric readout for axion searches with quantum enhanced sensitivity

- From Oct 2025: move to a dedicated lab at Henan Normal University, to search for axions, dark photons and even gravitational waves

More details in 2404.00908 and 2404.10264

Discussion and conclusions

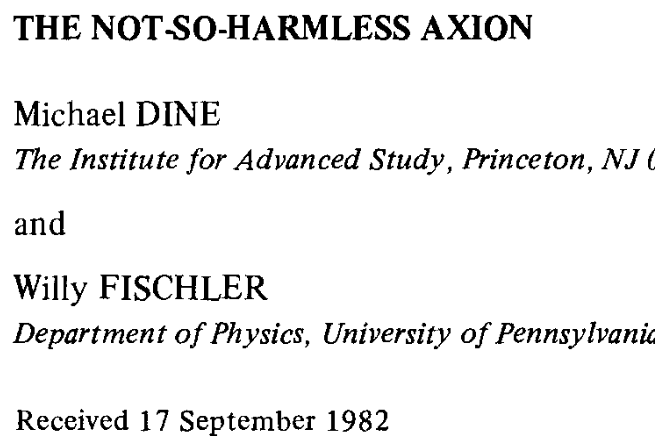
- We have performed a cavity haloscope experiment, searching for dark photon DM
- Finding no statistically significant excess, we we place an upper limit $|\chi| < 3.7 \times 10^{-13}$ around $m_A \simeq 29.5\mu\mathrm{eV}$ (90% CL)
- This exceeds other constraints on dark photon DM in this frequency range by roughly an order of magnitude
- From Oct 2024 (Anhui University): implement cavity scanning, with addition of 9 T magnetic field and ‘dual-path’ interferometric readout for axion searches with quantum enhanced sensitivity
- From Oct 2025: move to a dedicated lab at Henan Normal University, to search for axions, dark photons and even gravitational waves

More details in 2404.00908 and 2404.10264

Thanks for listening!

Extra: axion/dark photon cosmology

- Not long after the first axion papers, people realised that this wonderful new light particle could be dangerous….
- Solving $\ddot{\phi} + 3H\dot{\phi} + m_a^2\phi = 0$ gives



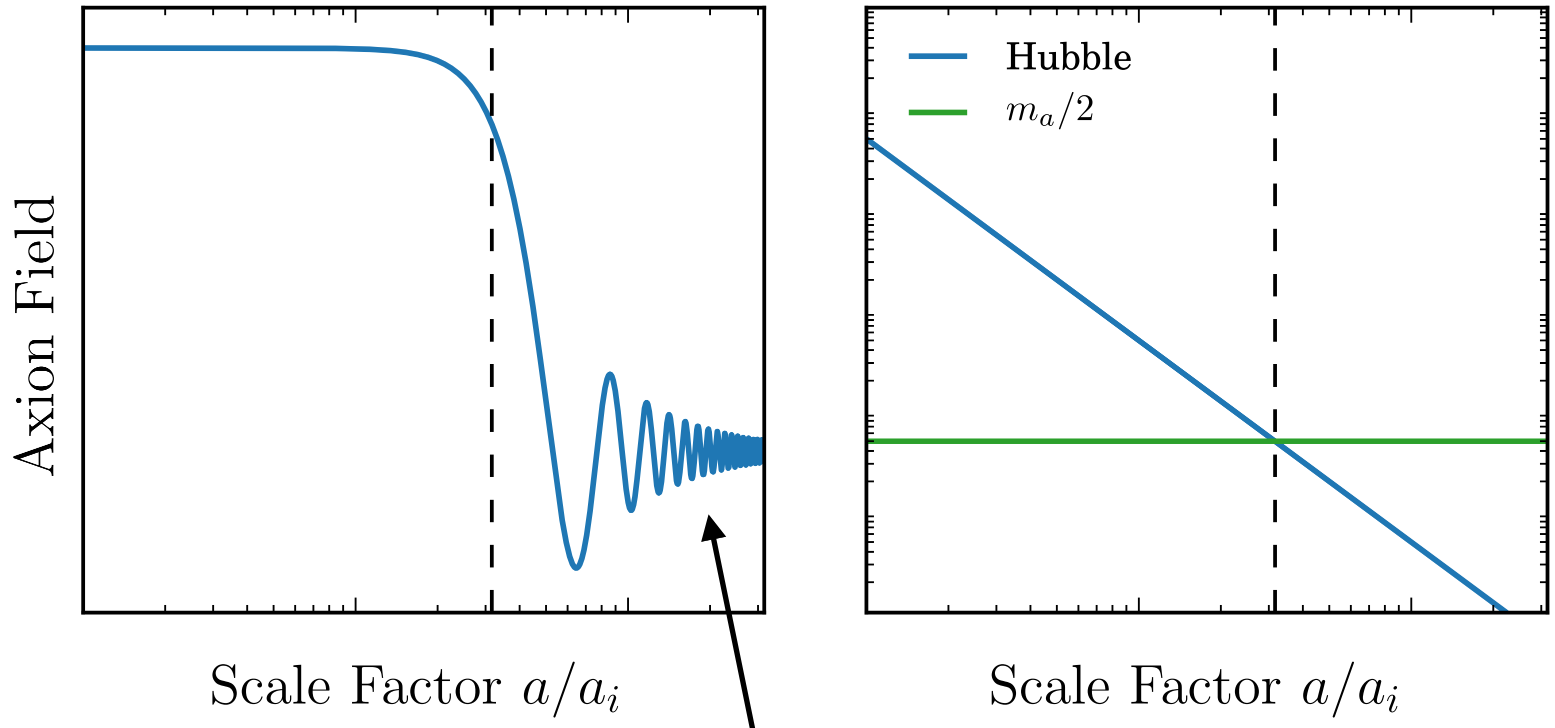
THE NOT-SO-HARMLESS AXION

Michael DINE
The Institute for Advanced Study, Princeton, NJ

and

Willy FISCHLER
Department of Physics, University of Pennsylvani

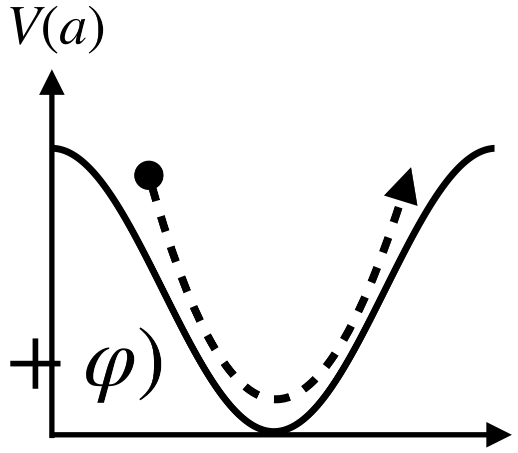
Received 17 September 1982



What happens here?

Figure courtesy of ‘Axion Cosmology’, D. J. E. Marsh, 1510.07633

Extra: The misalignment mechanism



- When axion/dark photon begins oscillate, $\phi \simeq \phi_0 \cos(m_a t + \varphi)$
- Inserting into the EOM gives $\phi_0 \propto a^{-3/2}$, $\rho_a \propto |\phi_0|^2 \propto a^{-3}$
- At the top of the potential we have $\omega_a = -1$ (dark energy), at the bottom $\omega_a = 1$ (free scalar field). Therefore $\langle \omega_a \rangle = 0$
- **Just like ordinary non-relativistic matter: the coherent oscillations of the axion field function as a natural cold dark matter candidate**
- For QCD axions, with initial misalignment angle $\theta_{a,i}$ we typically have

$$\Omega_a h^2 \sim 2 \times 10^4 \left(\frac{f_a}{10^{16}\ \mathrm{GeV}} \right)^{7/6} \langle \theta_{a,i}^2 \rangle$$