SRF Cavity Searches for DP

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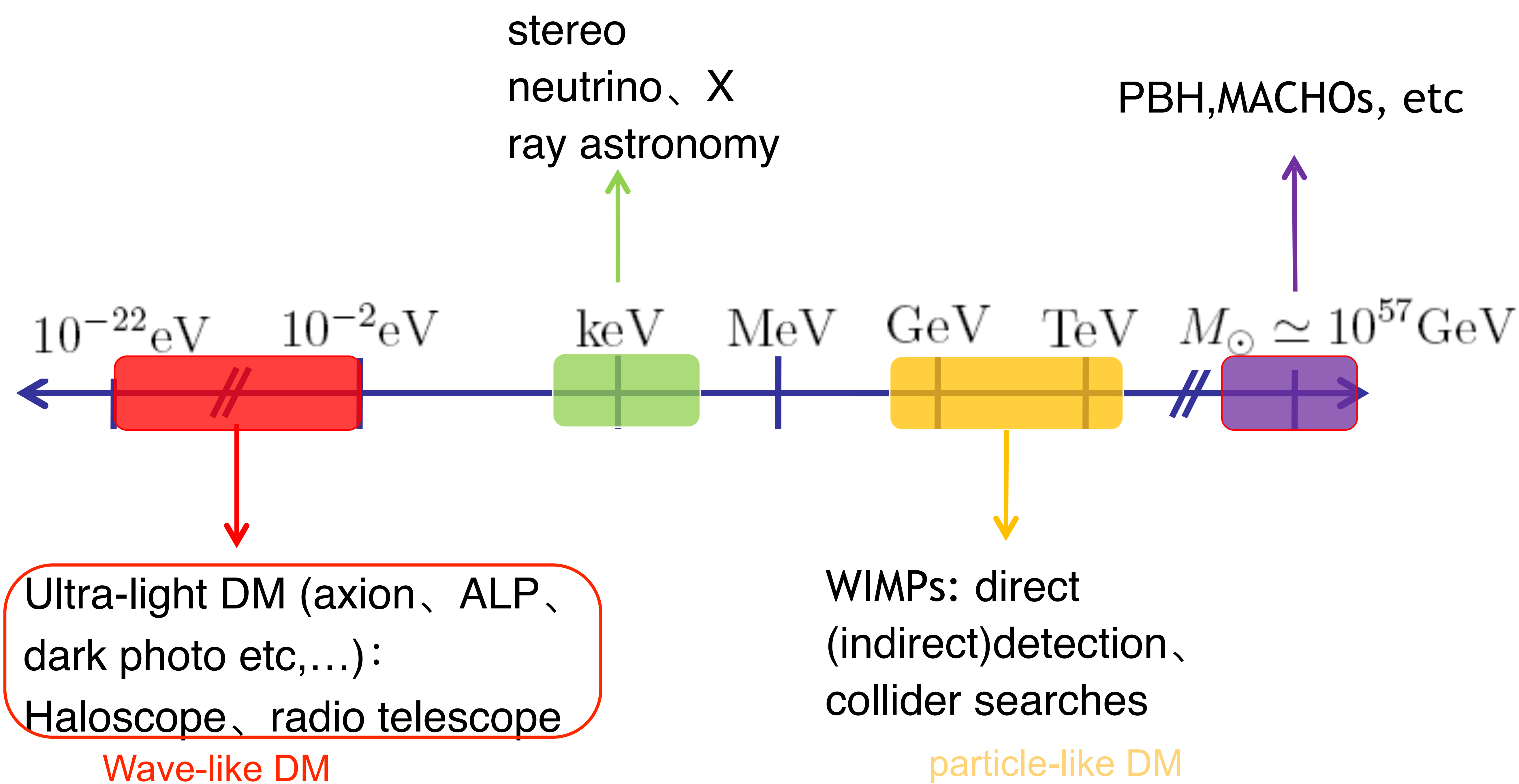
Peking University

Outline

- Motivation of ultra-light dark matter search using Superconducting Radio Frequency (SRF) Cavity
- SRF Cavity Project for DPDM search
- SRF Cavity Project for cosmic DP
- Other projects
- Experimental group (SHANHE collaboration)
- Summary and Outlook

Motivation of ultra-light dark matter

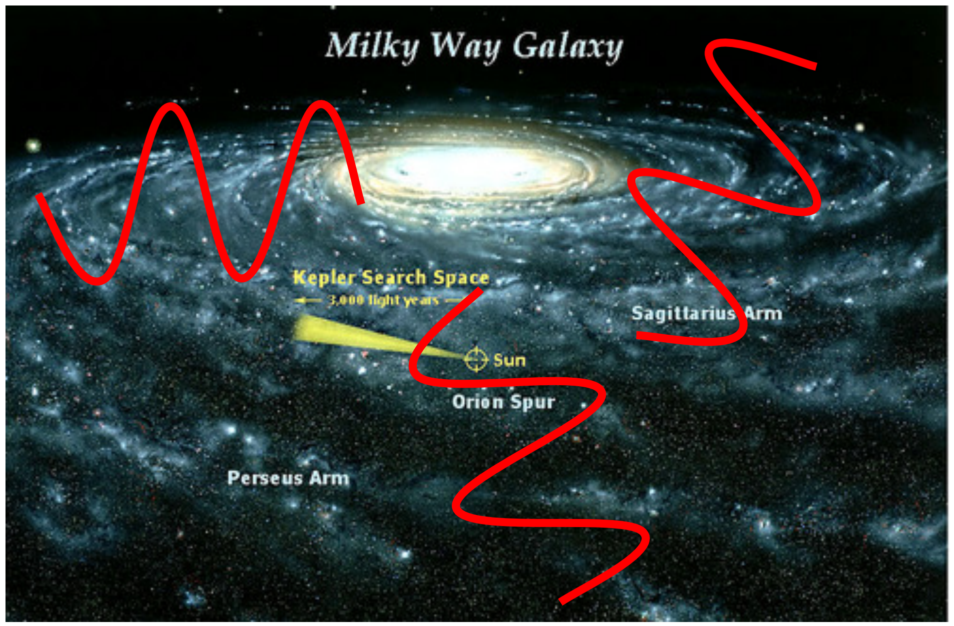
Various DM candidate



There's a broad spectrum of possible particles with varied masses and interaction strengths, making experimental searches challenging.

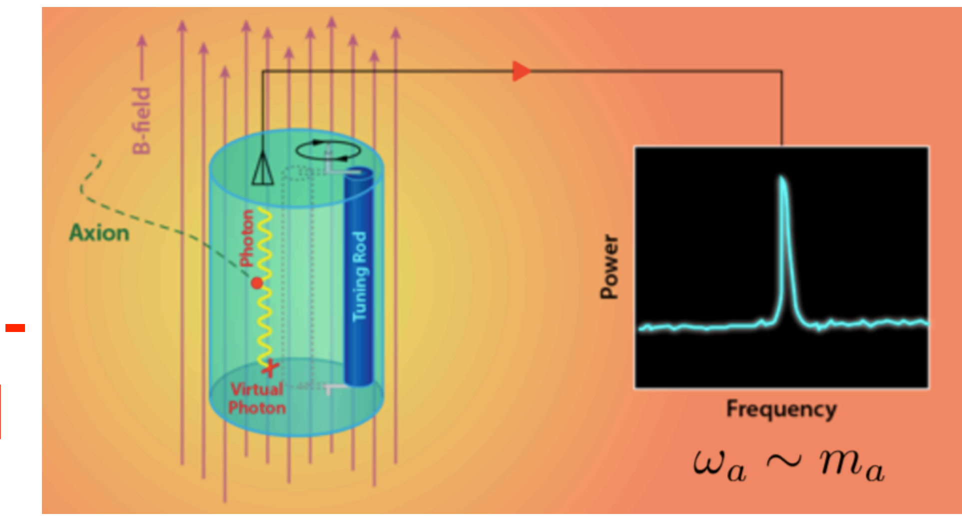
The ultra-light DM

QM： All matter exhibits both particle and wave properties.



($m \sim 10^{-22}$ eV)

Wavelengths at macroscopic scales, manifesting as a wave-like background field



$$m_a \sim \text{GHz} \sim 10^{-6}\ \text{eV}$$

The de Broglie wavelength: galactic scales(kpc)

- Astronomical observation (time, position, velocity, polarization, etc)

Distinct from traditional dark matter detection (particle scattering)

enormous potential for development in this field

similar as the GWs detection

Compton wave length (m)

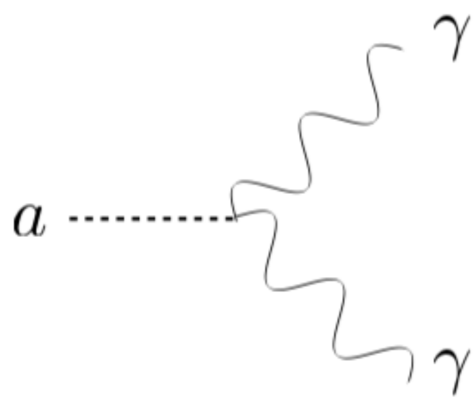
Haloscope, Quantum amplifier

New search methods!!!

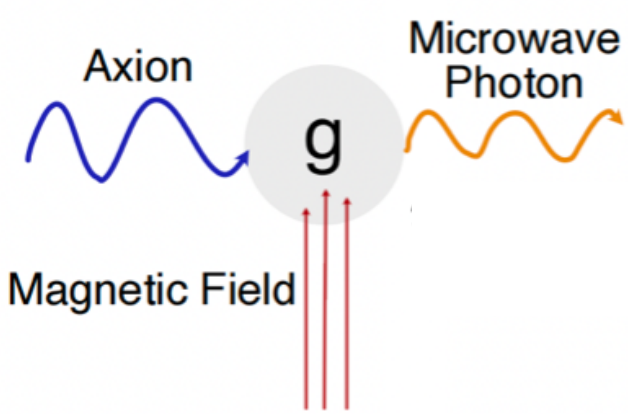
Quantum sensor

Ultra-light DM candidate

Axion (ALP): spin 0, CP odd



Inverse Primakoff effect



$$\nabla \times \mathbf{B} \simeq \partial_t \mathbf{E} + \mathbf{J} + g_{a\gamma\gamma} \mathbf{B}\, \partial_t a$$

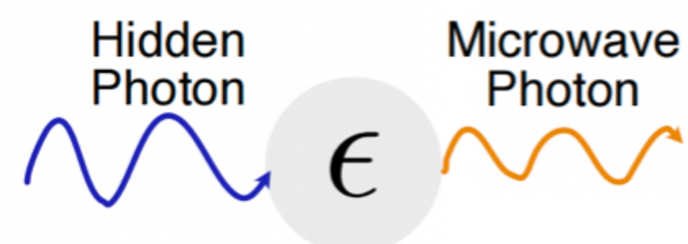
induces an effective current under strong magnetic field.

$$\vec{J}^a_{\rm eff} = g_{a\gamma}\omega_a a \vec{B}_0.$$

Dark photon: spin 1

mili-charge particles?

kinetic mixing

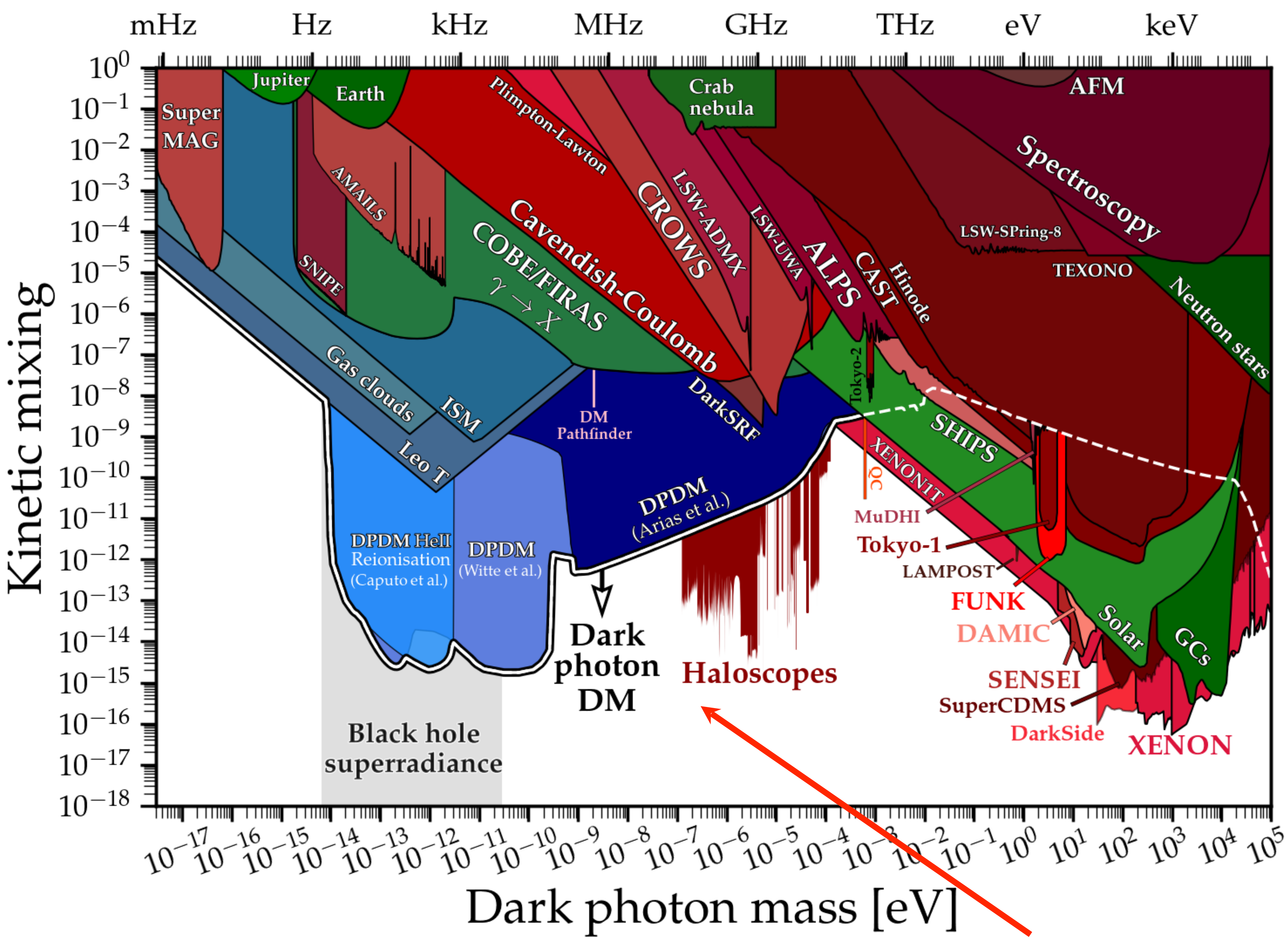


$$\mathcal{L} \supset -\tilde{A}_\mu \left(eJ^\mu_{EM} - \varepsilon m^2_{A'} \tilde{A}'^\mu\right)$$

induces an effective current anyway.

$$J^{A'\,\mu}_{\rm eff} = \epsilon m^2_{A'} A'^\mu,$$

Current DPDM search



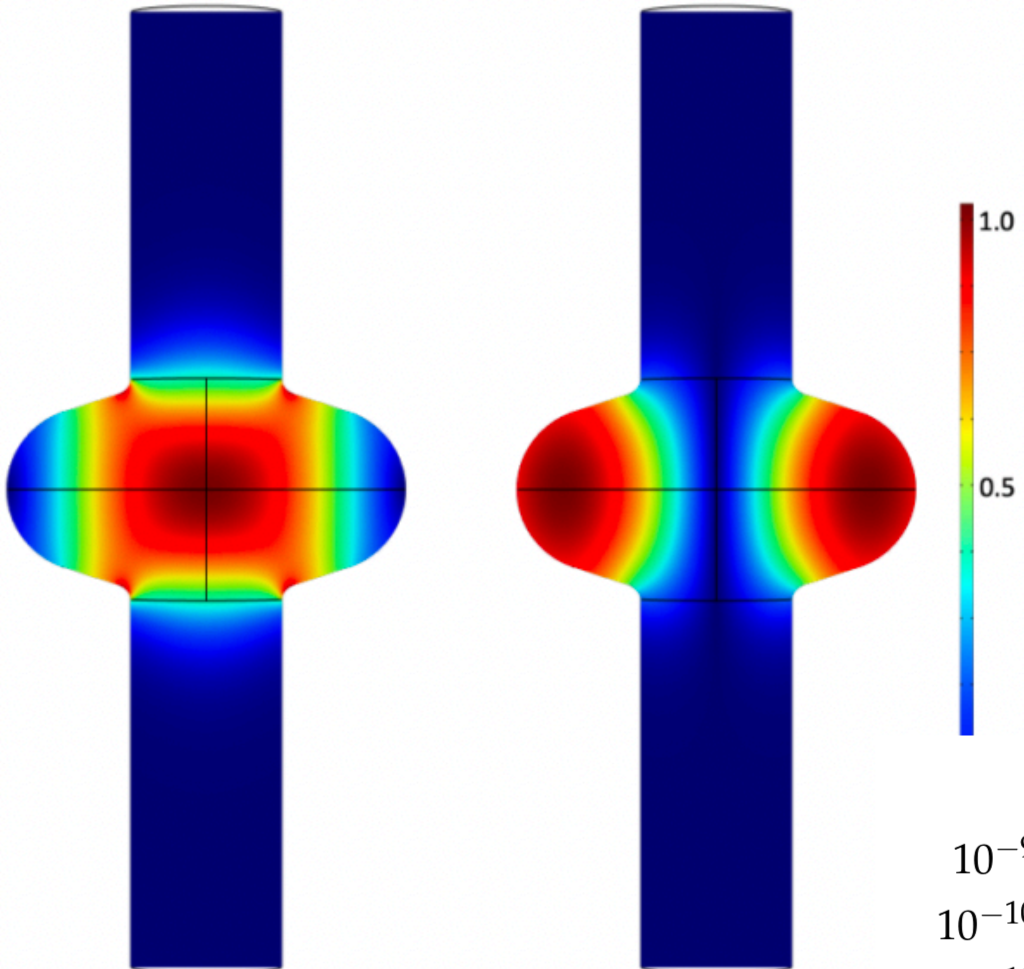
Still a lot of room to detect

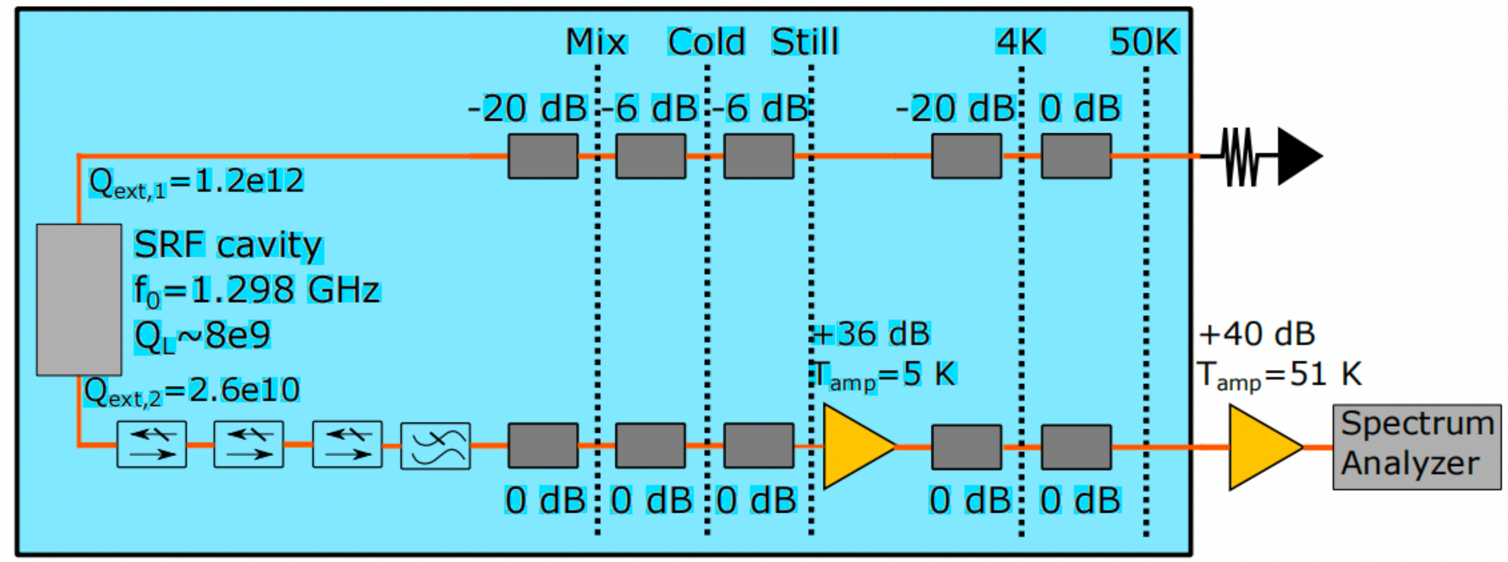
Haloscope sensitivity largely depends on Q: Superconducting cavity has Q~10^{10}

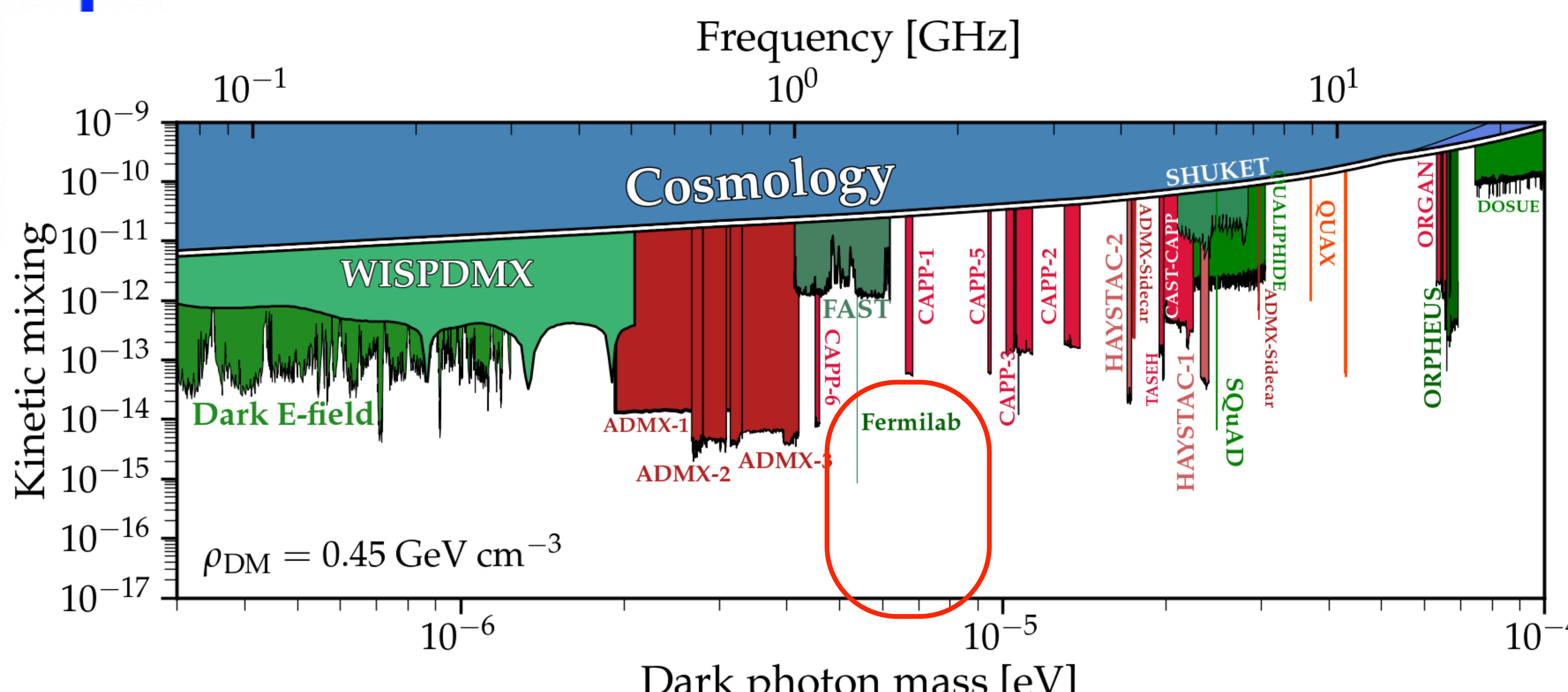
how to make use it? 5 orders more than traditional cavity.

Axion limit webpage: https://github.com/cajohare/AxionLimits/blob/master/docs/dp.md

Fermilab (2022)







Highest sensitivity

Q~8.7*10^9

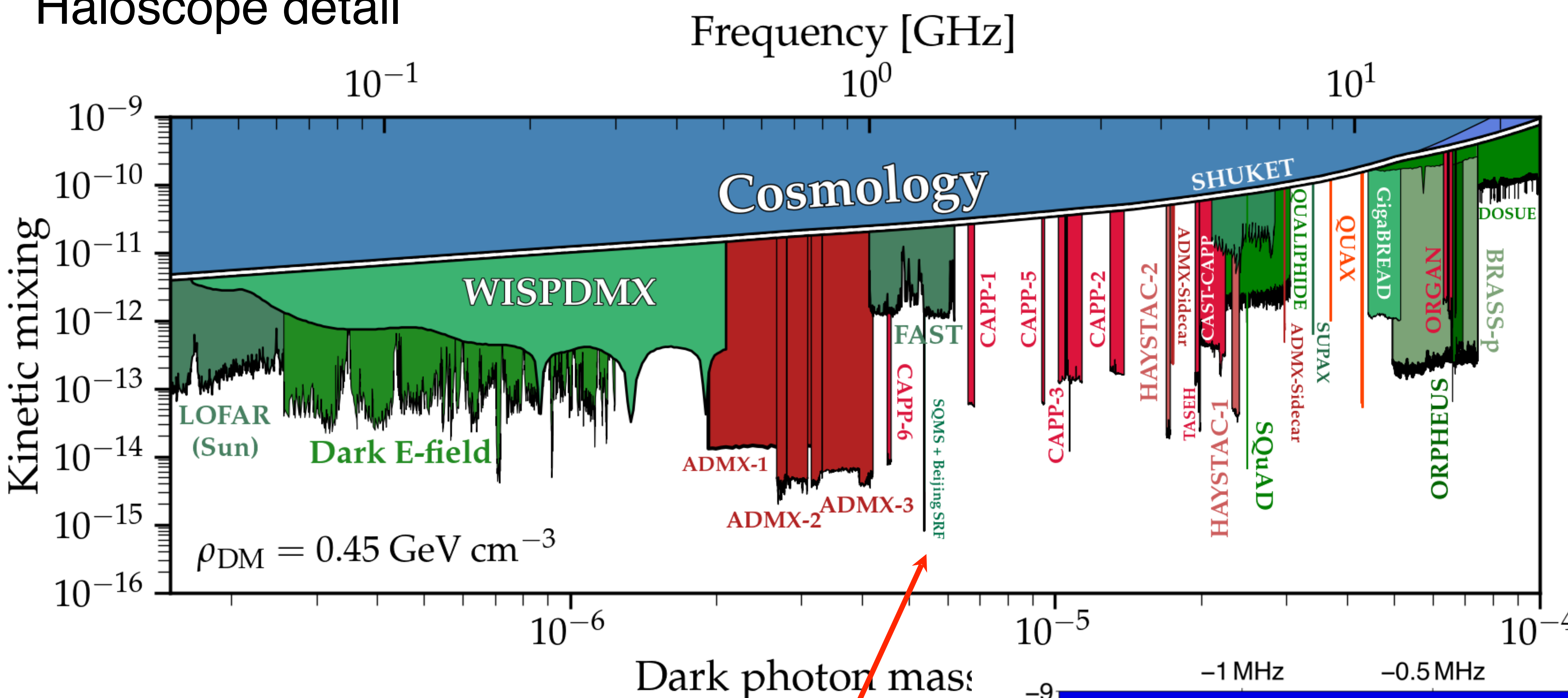
Operated in the dilution fridge

R. Cervantes,[1,*] C. Braggio,[2,3] B. Giaccone,[1] D. Frolov,[1] A. Grasselino,[1]
R. Harnik,[1] O. Melnychuk,[1] R. Pilipenko,[1] S. Posen,[1] and A. Romanenko[1]

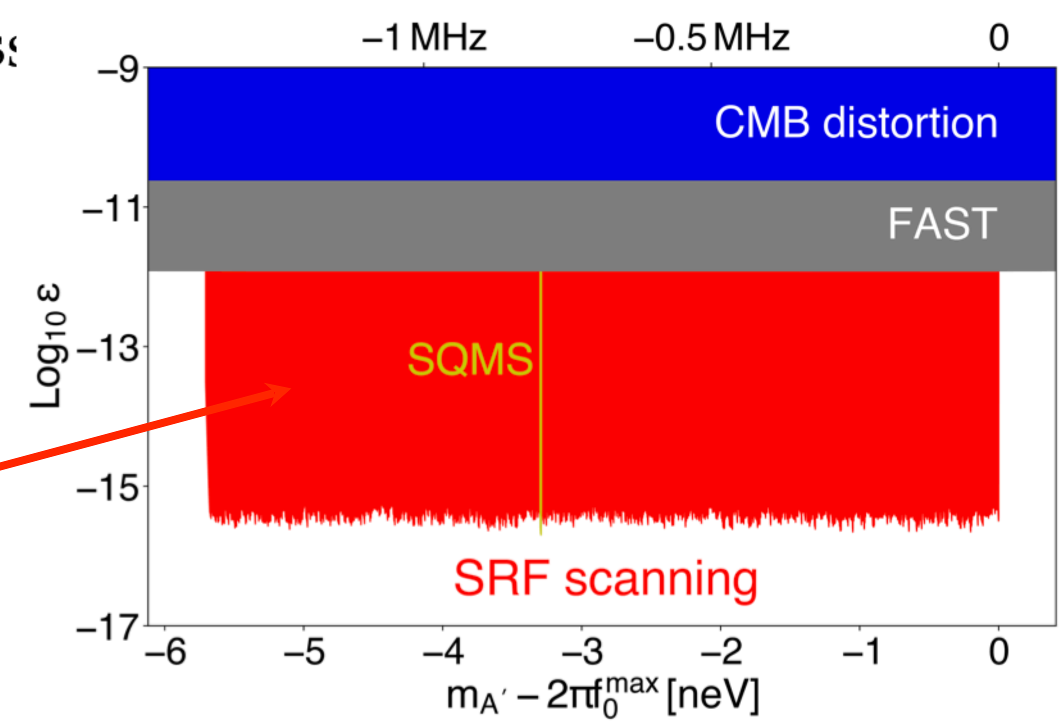
2203.03183

DPDM search

Haloscope detail



SHANHE Collaboration, Zhenxing Tang, Bo Wang, Yifan Chen,… Jing Shu, e-Print: 2305.09711 [hep-ph], Phys.Rev.Lett. 133 (2024) 2, 021005



First tunable results with deepest exclusion limit

Spectrum of Ultra-light Dark Matter

The Virial Theorem: the velocity of dark matter near Earth is approximately 10^-3 boosted by gravity.

$$a(t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_a}\cos(m_a t + \phi)$$

Frequency: $\omega_a \simeq \mathrm{GHz}\,\frac{m_a}{10^{-6}\ \mathrm{eV}}$

Coherence: $\tau_a \simeq \mathrm{ms}\,\frac{10^{-6}\ \mathrm{eV}}{m_a}$

Max Exp. Size: $\lambda_a \simeq 200\ \mathrm{m}\,\frac{10^{-6}\ \mathrm{eV}}{m_a}$

Axion DM as an example, same for other kinds (DPDM, etc)

$$\tau_a \sim 1/m_a\langle v_{\rm DM}^2\rangle \sim Q_a/m_a \sim 10^6/m_a$$

Bandwidth of axion DM is 10^-6

Detector bandwidth < 10^-6 accelerate the scan rate

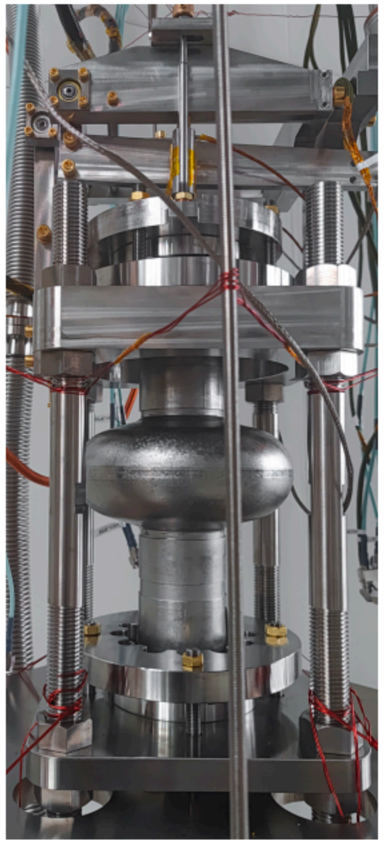
$$\lambda_a \sim 1/m_a\sqrt{\langle v_{\rm DM}^2\rangle} \sim 10^3/m_a$$

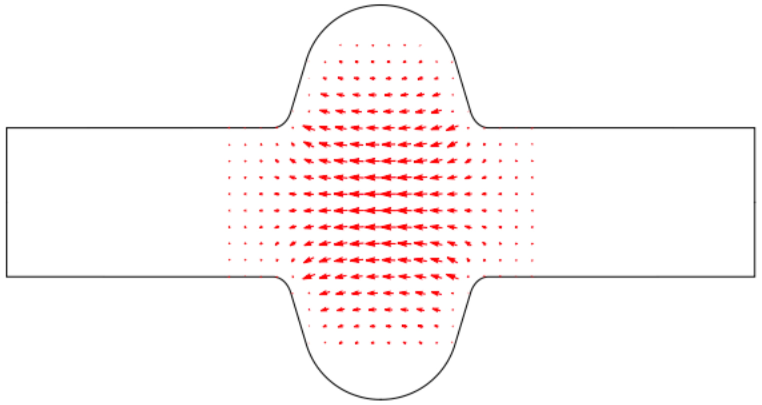
Momentum width10^-3

SRF Cavity Project for DPDM

SRF Cavity

- Significant $Q_0 > 10^{10}$ compared to copper cavity with $Q_0 \leq 10^6$.
- Superconducting Radio-Frequency (SRF) Cavities: extremely high $Q_0 \simeq 10^{10}$ $\rightarrow$ improve $\mathrm{SNR} \propto Q_0^{1/4}$
- 1-cell elliptical niobium cavity with mechanical tuner, immersed in liquid helium at $T \sim 2\,K$
- TM_{010} mode: z-aligned $\vec{E}$, **maximizes the overlap** for dark photon dark matter (DPDM)





$$\epsilon \approx 10^{-16} \left(\frac{10^{10}}{Q_0}\right)^{\frac{1}{4}} \left(\frac{4\,\mathrm{L}}{V}\right)^{\frac{1}{2}} \left(\frac{0.5}{C}\right)^{\frac{1}{2}} \left(\frac{100\,\mathrm{s}}{t_{\mathrm{int}}}\right)^{\frac{1}{4}} \left(\frac{1.3\,\mathrm{GHz}}{f_0}\right)^{\frac{1}{4}} \left(\frac{T_{\mathrm{amp}}}{3\,\mathrm{K}}\right)^{\frac{1}{2}},$$

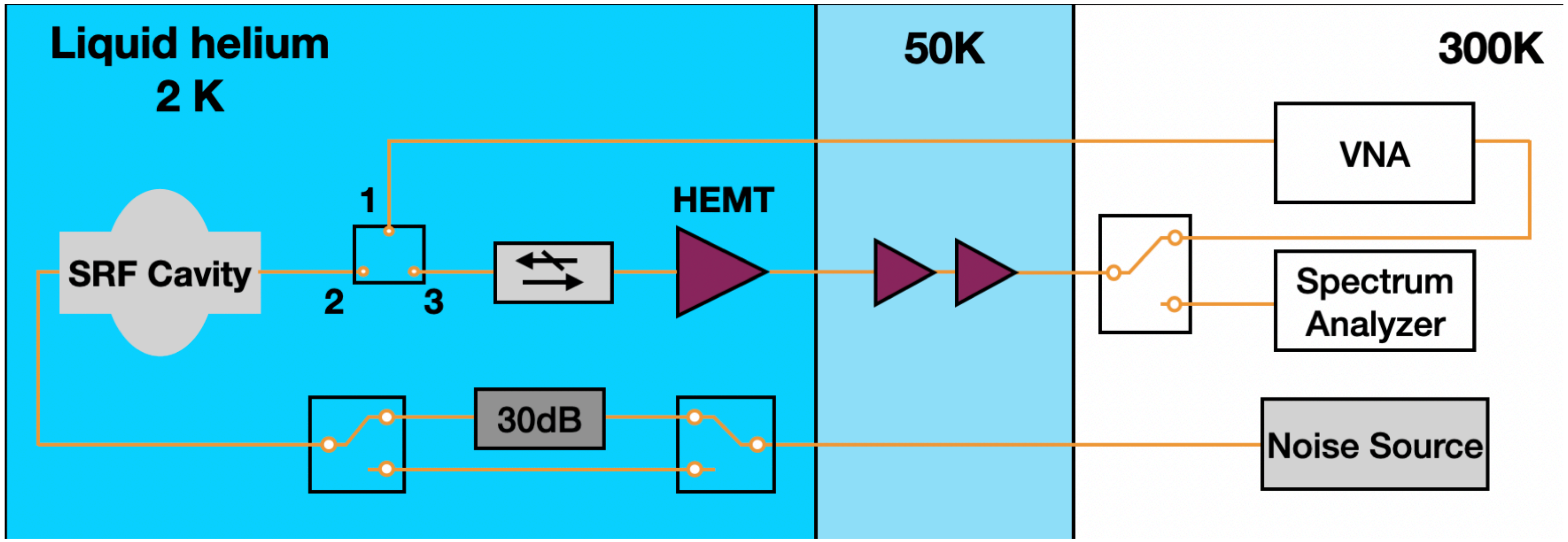
SHANHE Collaboration, Zhenxing Tang, Bo Wang, Yifan Chen,… Jing Shu,
e-Print: 2305.09711 [hep-ph], Phys.Rev.Lett. 133 (2024) 2, 021005

Experimental operation

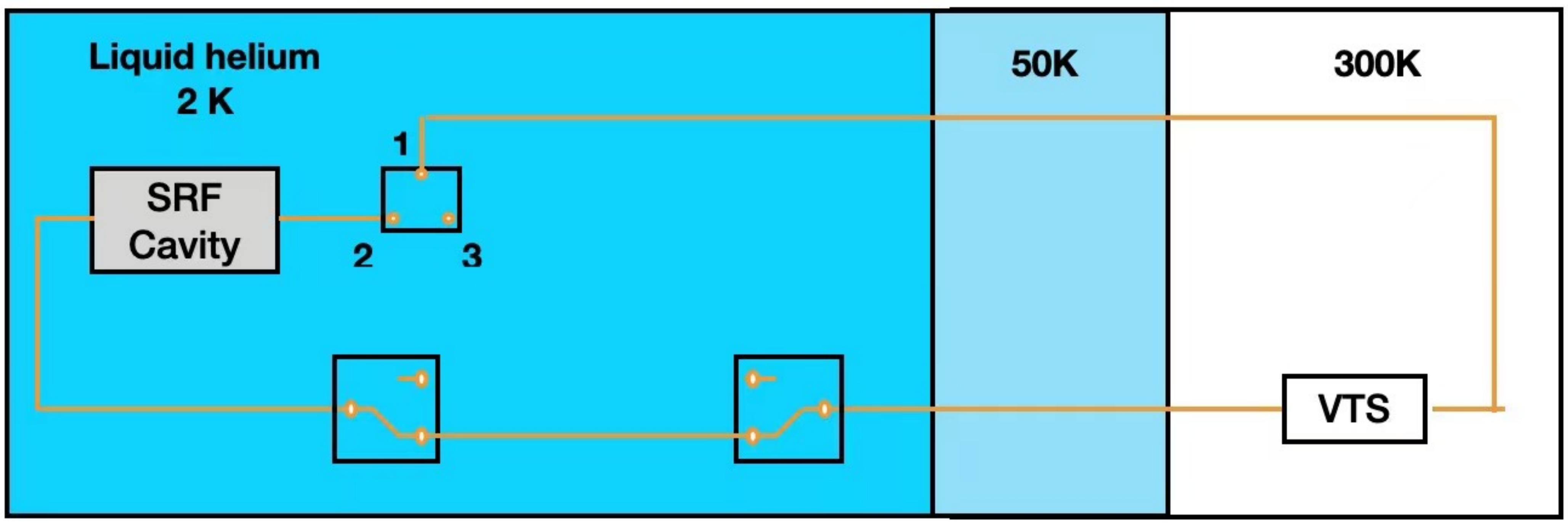
Parameters

	Value	Fractional Uncertainty
$V_{\rm eff} \equiv V\, C/3$	$693\,\mathrm{mL}$	$< 1\%$
β	0.634 ± 0.014	1.4%
$G_{\rm net}$	$(57.30 \pm 0.14)\,\mathrm{dB}$	3.1%
Q_L	$(9.092 \pm 0.081) \times 10^9$	/
$f_0^{\rm max}$	$1.2991643795\,\mathrm{GHz}$	/
Δf_0	$11.5\,\mathrm{Hz}$	/
$t_{\rm int}$	$100\,\mathrm{s}$	/

microwave electronics for DPDM searches

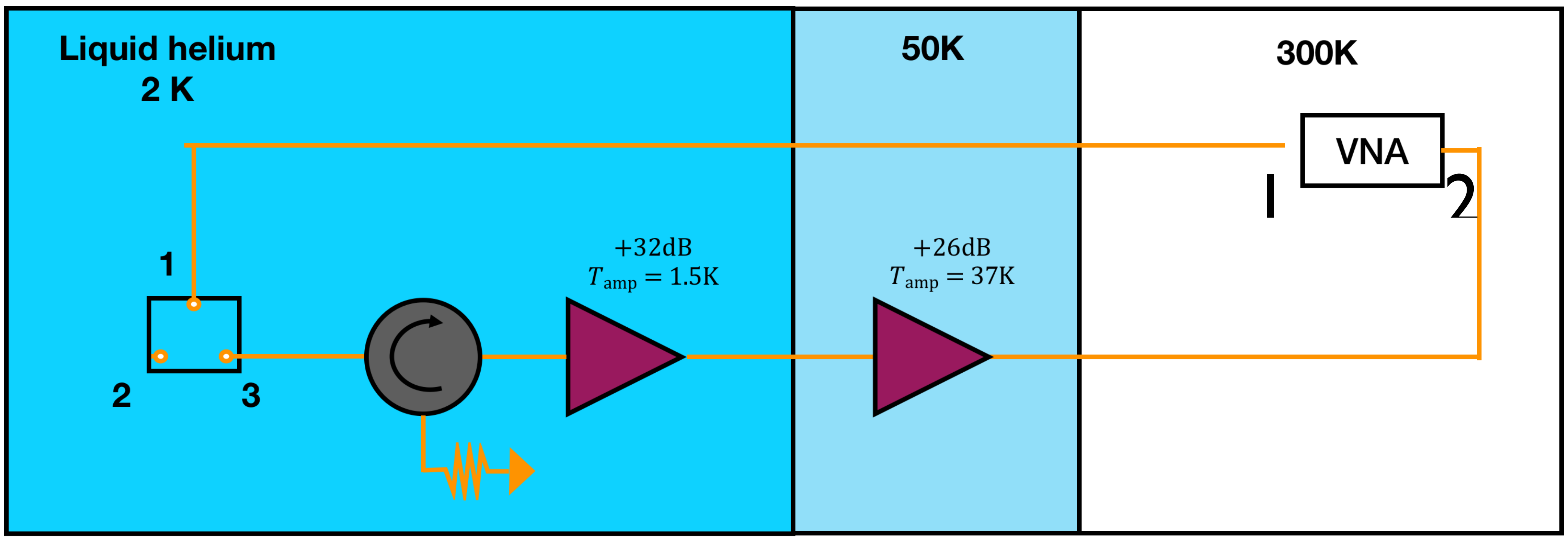


Step 1: Measure Cavity property



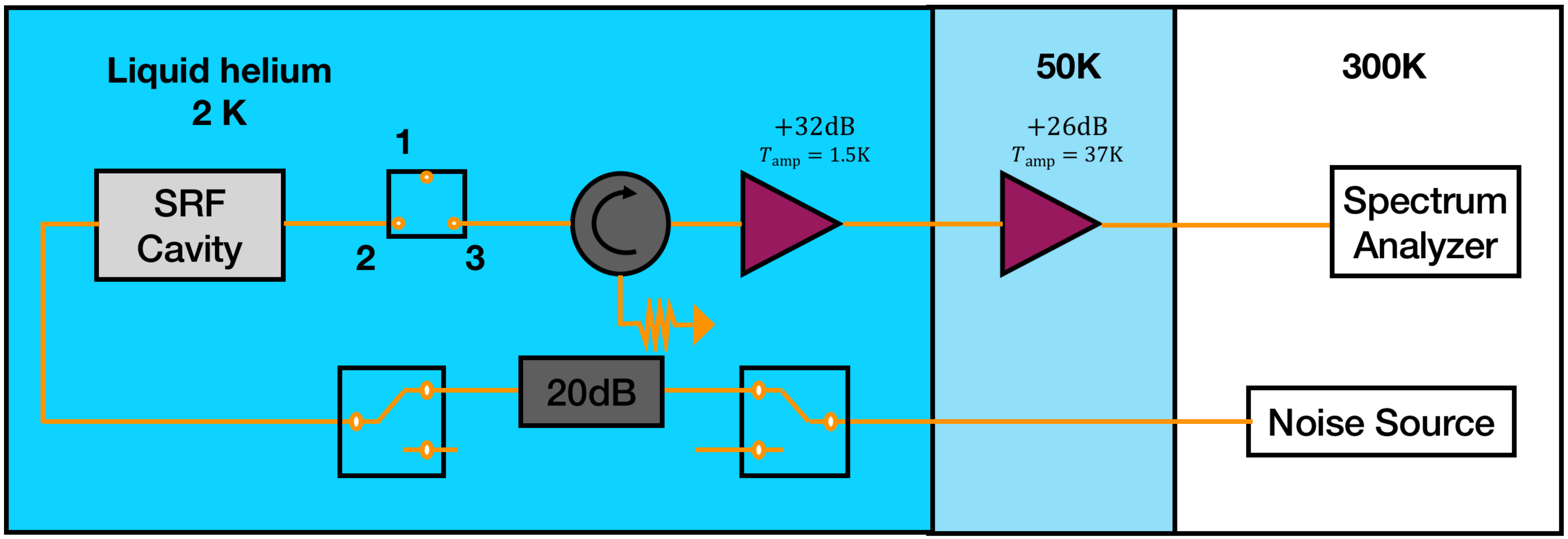
1-2 connection: VTS measurement for the cavity property.

Step 2: calibration



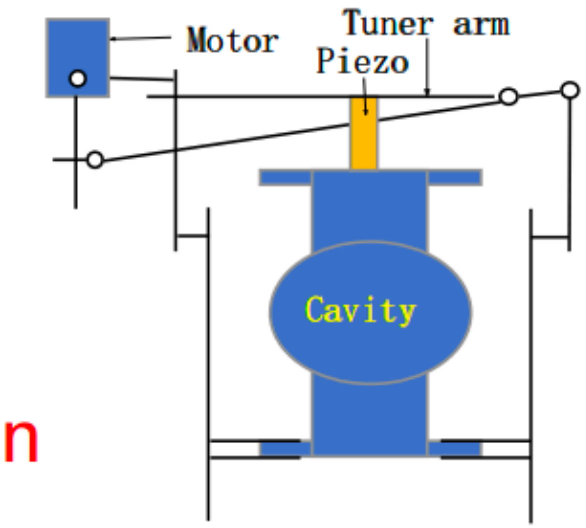
1-3 connection: calibration by subtracting the line loss to get the total gain G_net.

Step 3: Do experiment

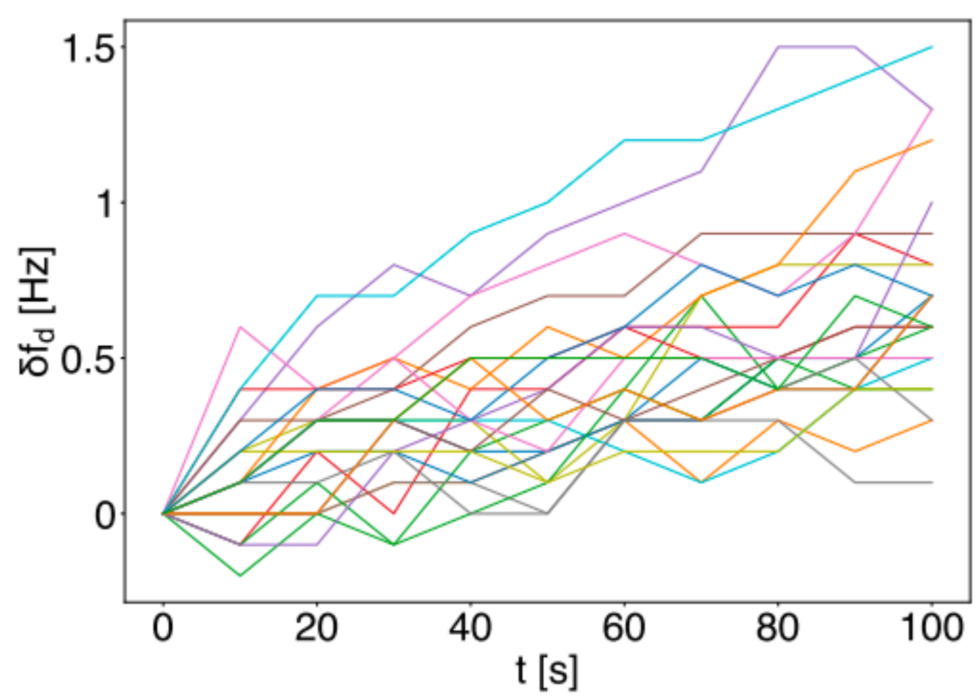


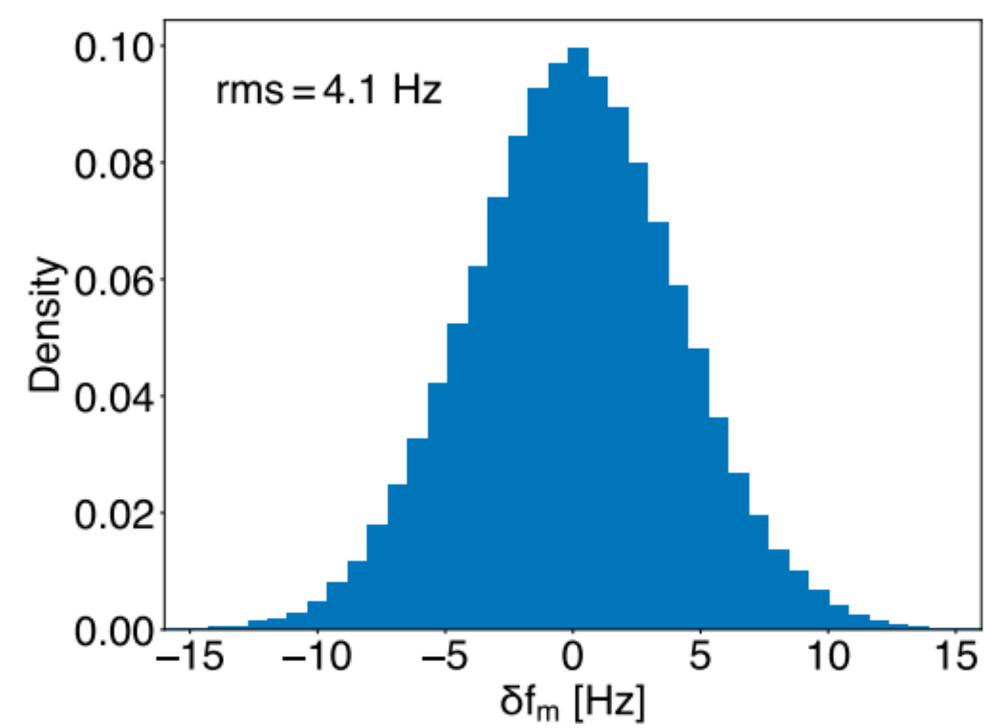
2-3 connection: tune the cavity resonant frequency to do the experiment

Scan Search with Mechanical Tuning



- Mechanical turner scans resonant frequency f_0 with the step $\sim f_0/Q_{\rm DM}$
- Calibrate f_0 and its stability range Δf_0 in each scan
- Frequency drift $\delta f_d \leq 1.5\mathrm{Hz}$ and microphonics effect $\sigma_{f_0} \approx 4\mathrm{Hz}$



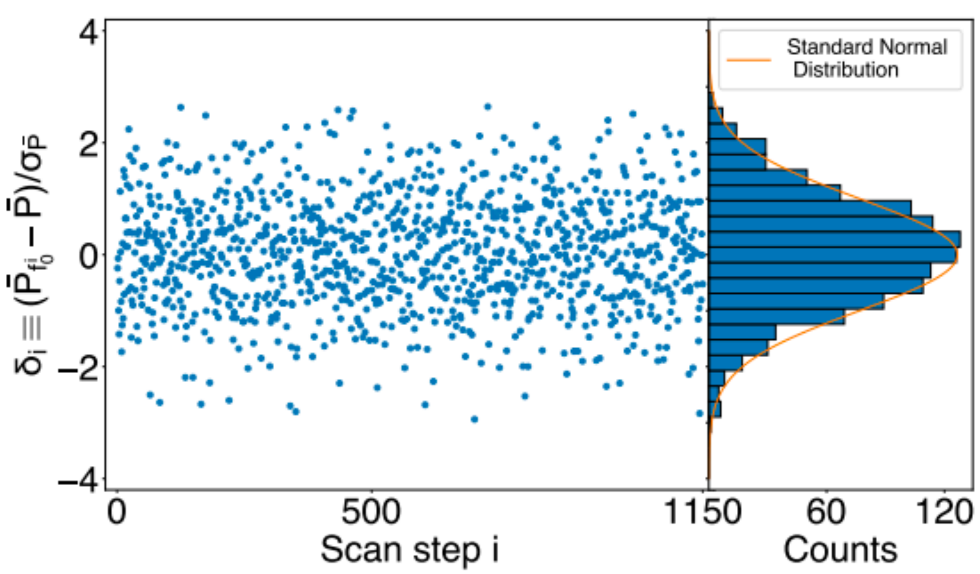


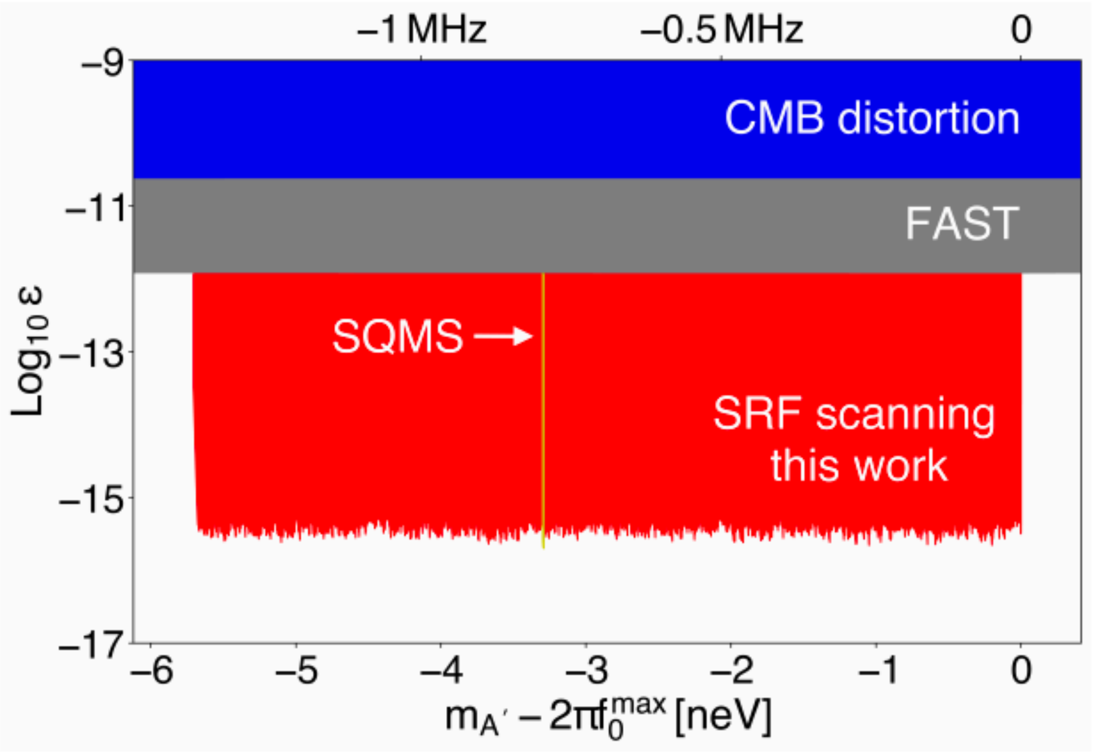
- **Conservatively** choose $\Delta f_0 \approx 10\mathrm{Hz}$

New results: Microphnoics effect do not enters into the noise control (bounds can be deeper)

Data analysis and constraints

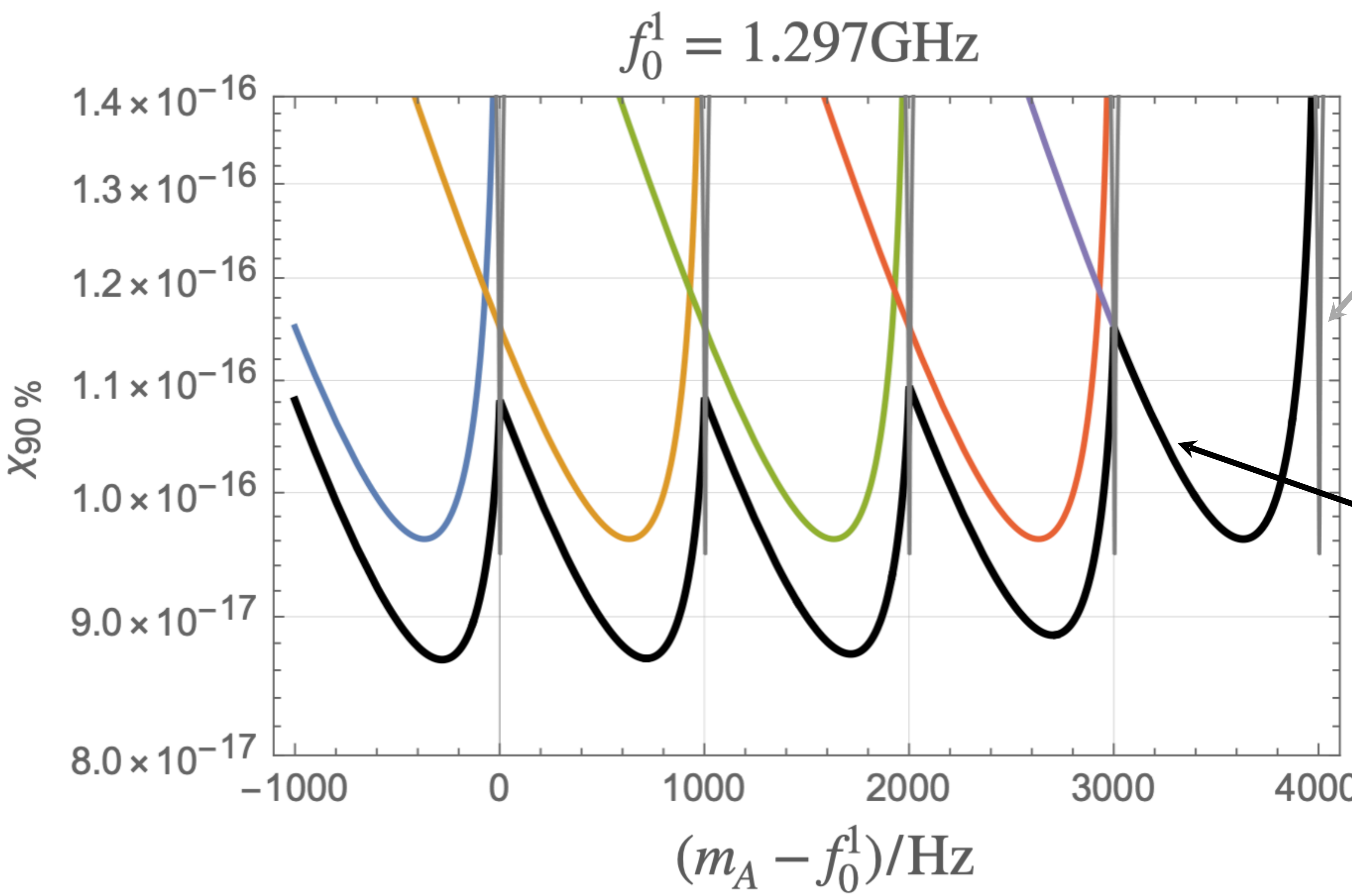
- Total 1150 scan steps with each 100 s integration time.
- **Group every 50 adjacent bins** and perform a constant fit to address small helium pressure fluctuation.
- Normal power excess shows **Gaussian distribution**:





- **First scan search with SRF and most stringent constraints in most exclusion space**.

Few comment on Q >> Q_{DM}



Direct Exclusion from the cavity

Noise power reduce with Q

Virialized DM Exclusion

Scan step: f*Q_{DM}

simple fit function (constant):
attenuation factor almost 1

different from ADMX

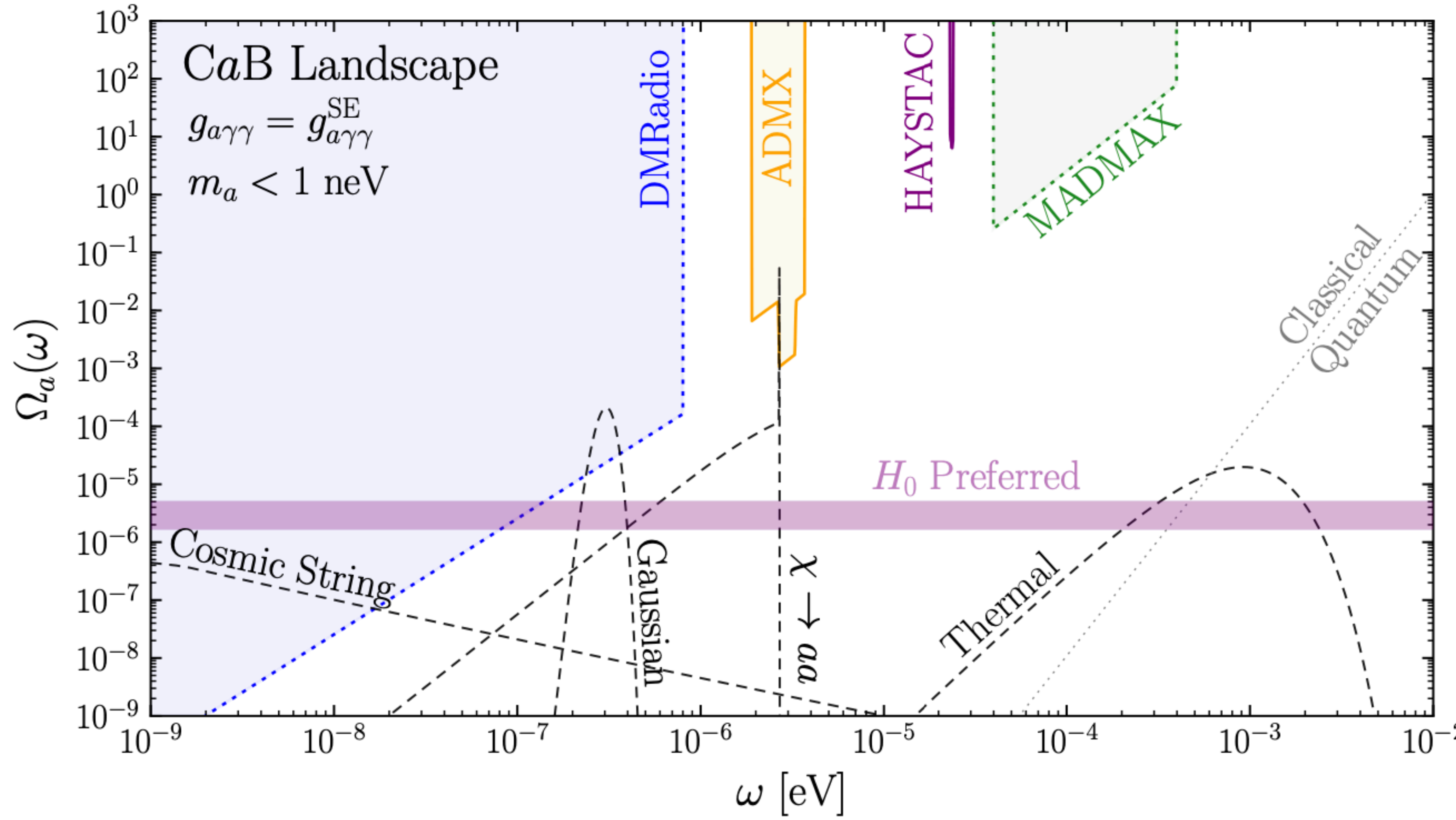
Cosmic DP backgrounds

The Cosmic Axion Background

Jeff A. Dror,[1,2,3,*] Hitoshi Murayama,[2,3,4,†] and Nicholas L. Rodd[2,3,‡]
[1] *Department of Physics and Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064, USA*
[2] *Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720, USA*
[3] *Theory Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[4] *Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa 277-8583, Japan*

Besides the DM searches, new particles can be served as the cosmic backgrounds.

- Relativistic
- Anisotropic



Modulated Signal from Galactic Dark Photons

- How about galactic DP backgrounds? (Anisotropic backgrounds, from annihilation or decay?)

Perturbative cascade decay (broad 4-body spectrum)

Parametric resonance decay (relative sharp 2-body spectrum)

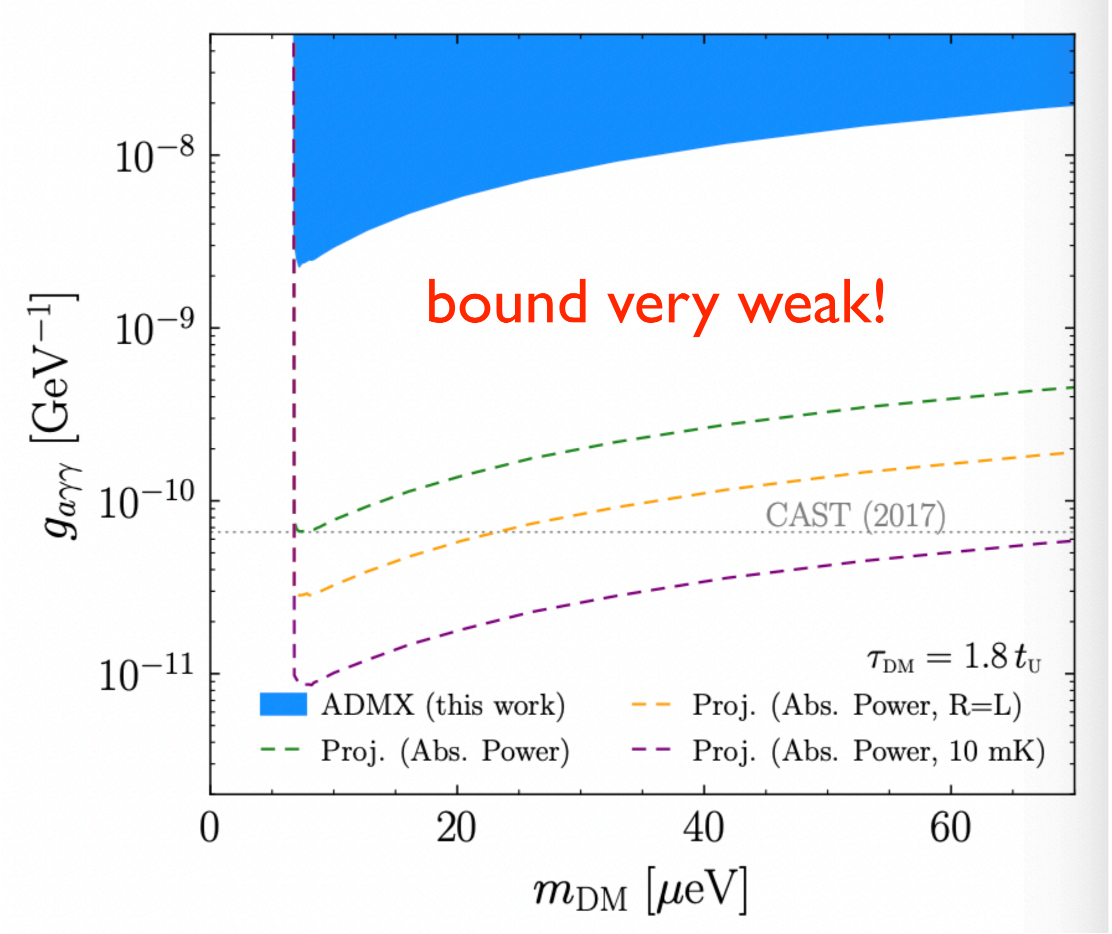
- ADMX experiment (axion)

The very deep constrains for DP would give us much stringent constrains

- Polarization

Longitudinal: from a heavy dark Higgs decay

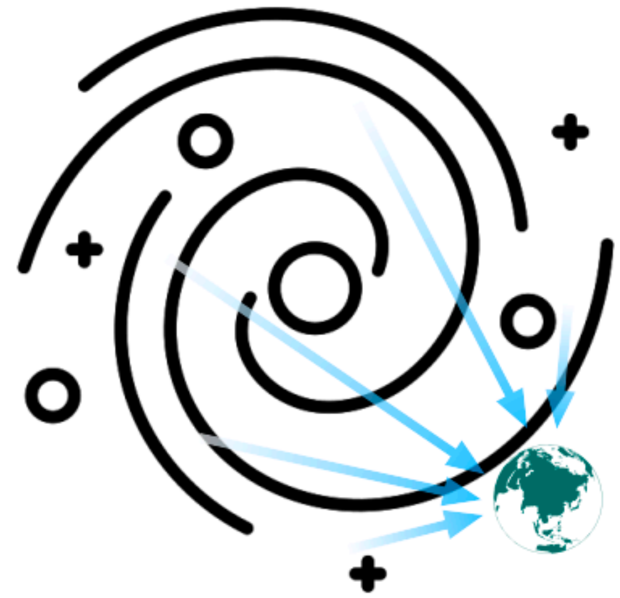
Transverse: axion-DP coupling



T. Nitta et al. (ADMX), Phys. Rev. Lett. 131, 101002 (2023)

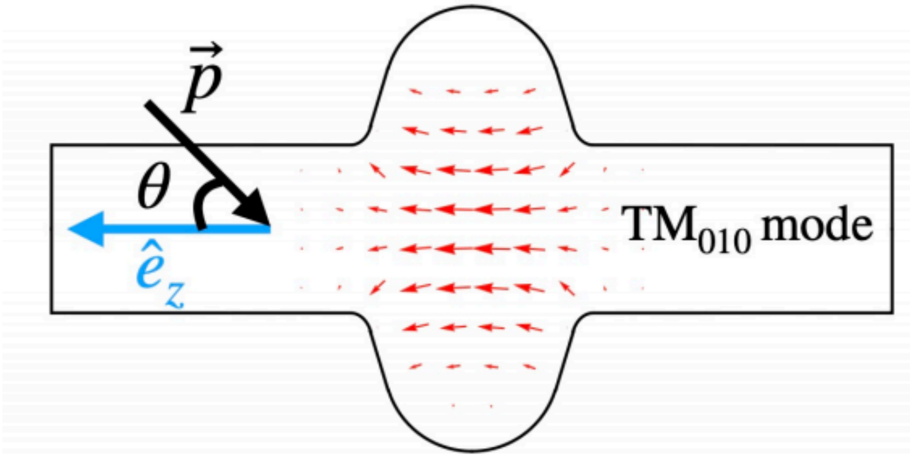
Modulated Signal from Galactic Dark Photons

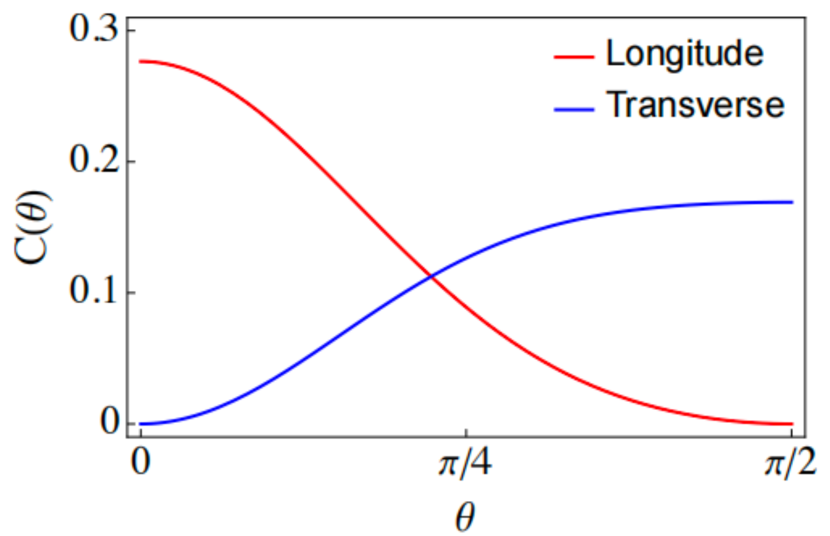
- Galactic dark photons from DM decay, e.g.: cascade decay from DM halo



- **Vectorial** observable $\propto \vec{A}'$
  $\rightarrow$ angular-dependent signal $\propto C(\theta)$
  $\rightarrow$ modulation as the Earth rotates

- Production is polarization-dependent, modulations for longitude and transverse modes are opposite

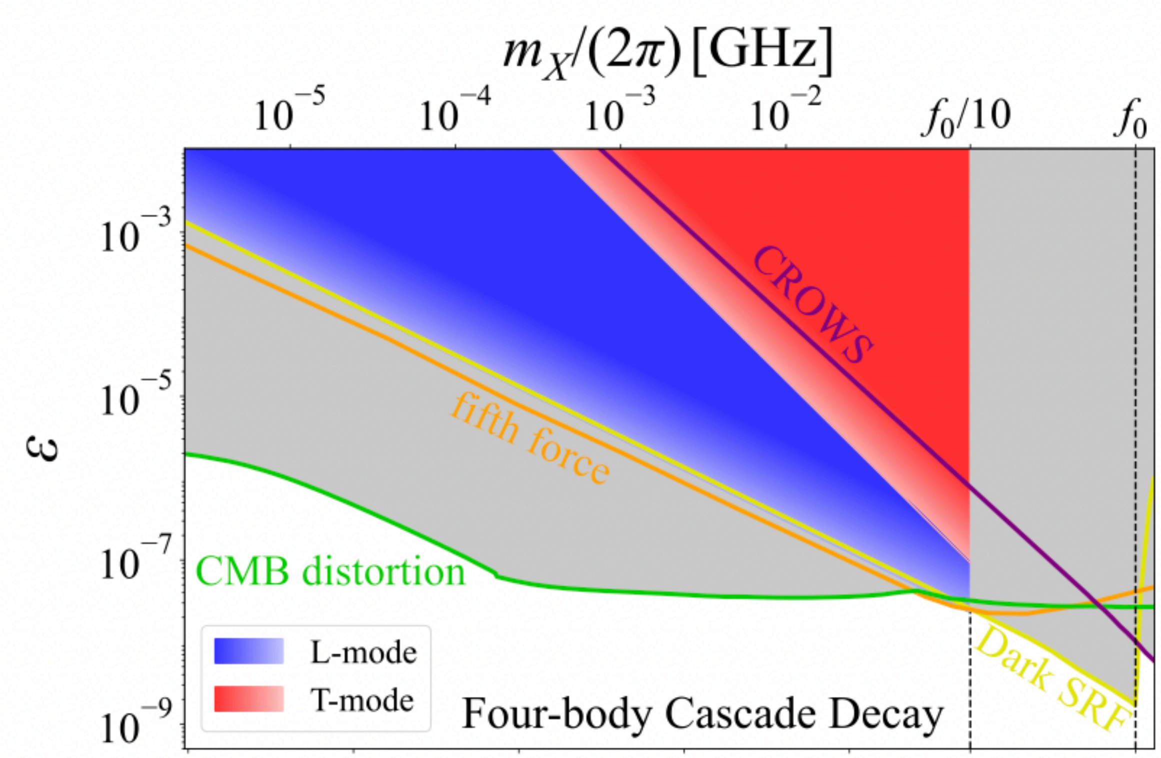


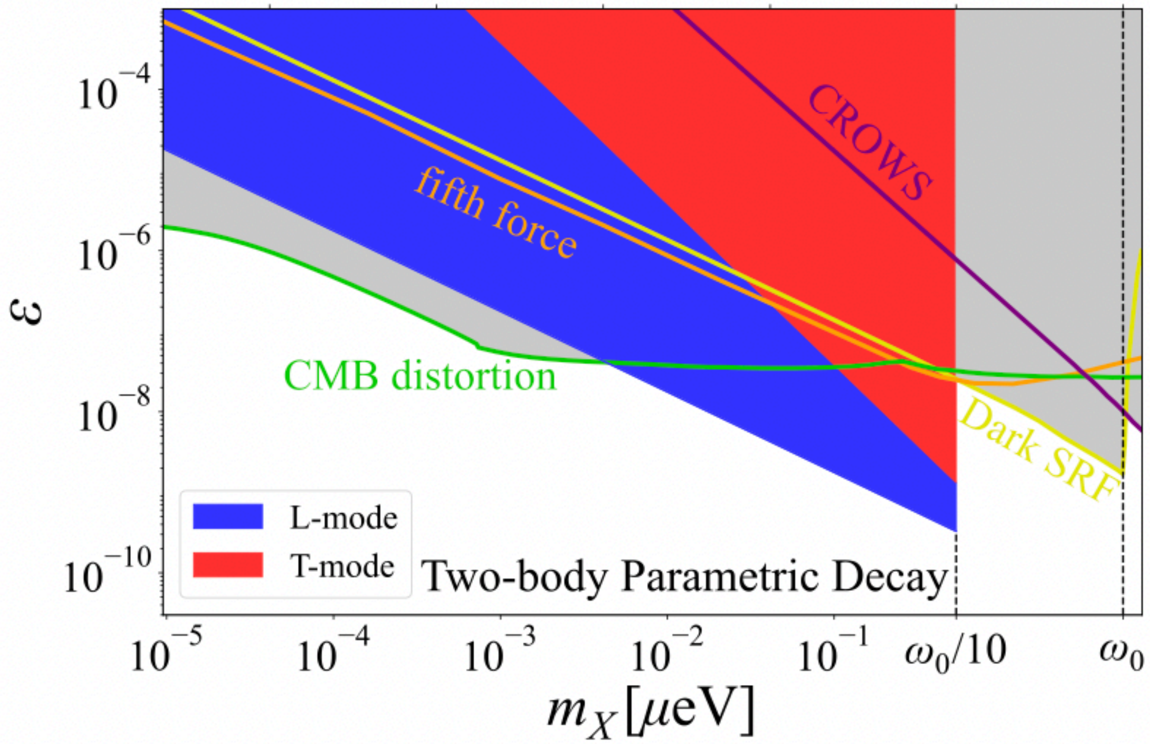


Yifan Chen, Chunlong Li, Yuxiang Liu, Yuxin Liu, Jing Shu, Yanjie Zeng, e-Print: 2402.03432 [hep-ph].

SRF Constraints for Galactic Dark Photons

- Same dataset as DPDM search
- Scanned range within galactic dark photon bandwidth $\rightarrow$ combine all scan steps to analyze
- Longitude mode has better sensitivity because of the larger spatial wavefunction $\sim \omega_{A'}/m_{A'}$

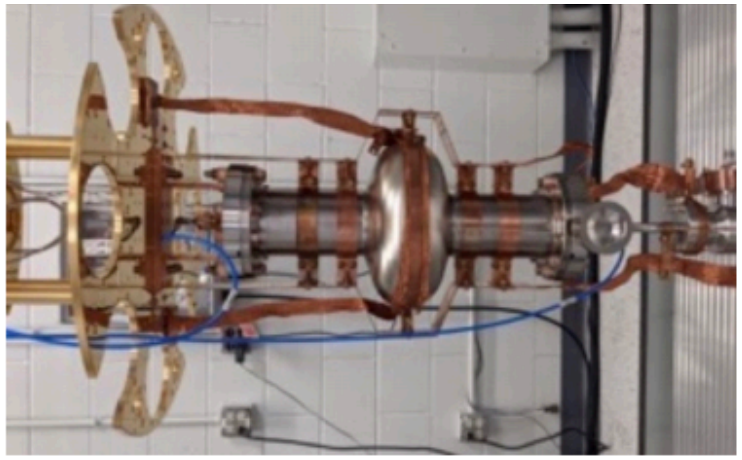




- Gradient color region represents exclusions for different DM mass

Yifan Chen, Chunlong Li, Yuxiang Liu, Yuxin Liu, Jing Shu, Yanjie Zeng, e-Print: 2402.03432 [hep-ph].

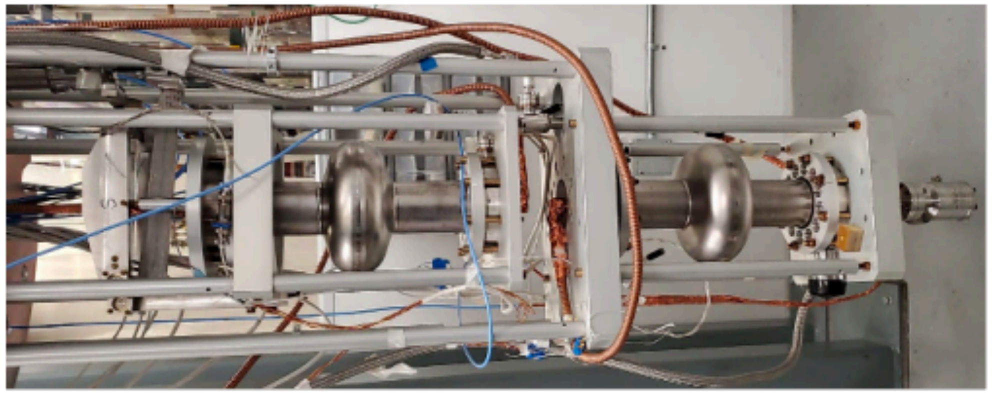
International SRF Campaigns

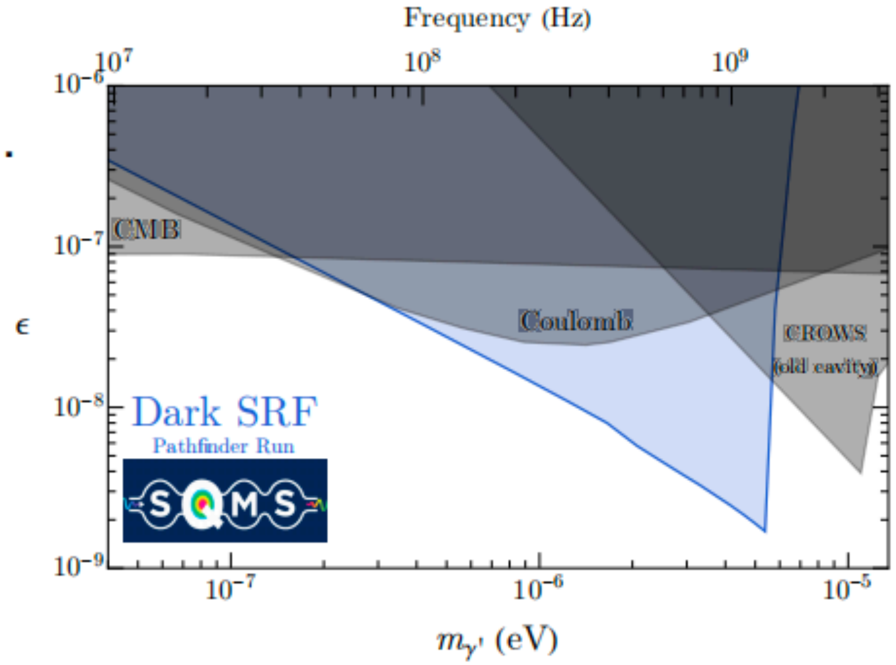


- **Fermilab SQMS**

  •**SERAPH**:
  Single-bin search and ongoing scan searches.

  •**Dark SRF**:
  Light-shining-wall search for dark photon.





- **DESY**:

  •**MAGO 2.0**
  Mode transition from GW-induced cavity deformation.

SRF for axion search

$$\sum_n \left(\partial_t^2 + \frac{\omega_n}{Q_n}\partial_t + \omega_n^2 \right) \mathbf{E}_n = g_{a\gamma\gamma}\partial_t(\mathbf{B}\partial_t a)$$

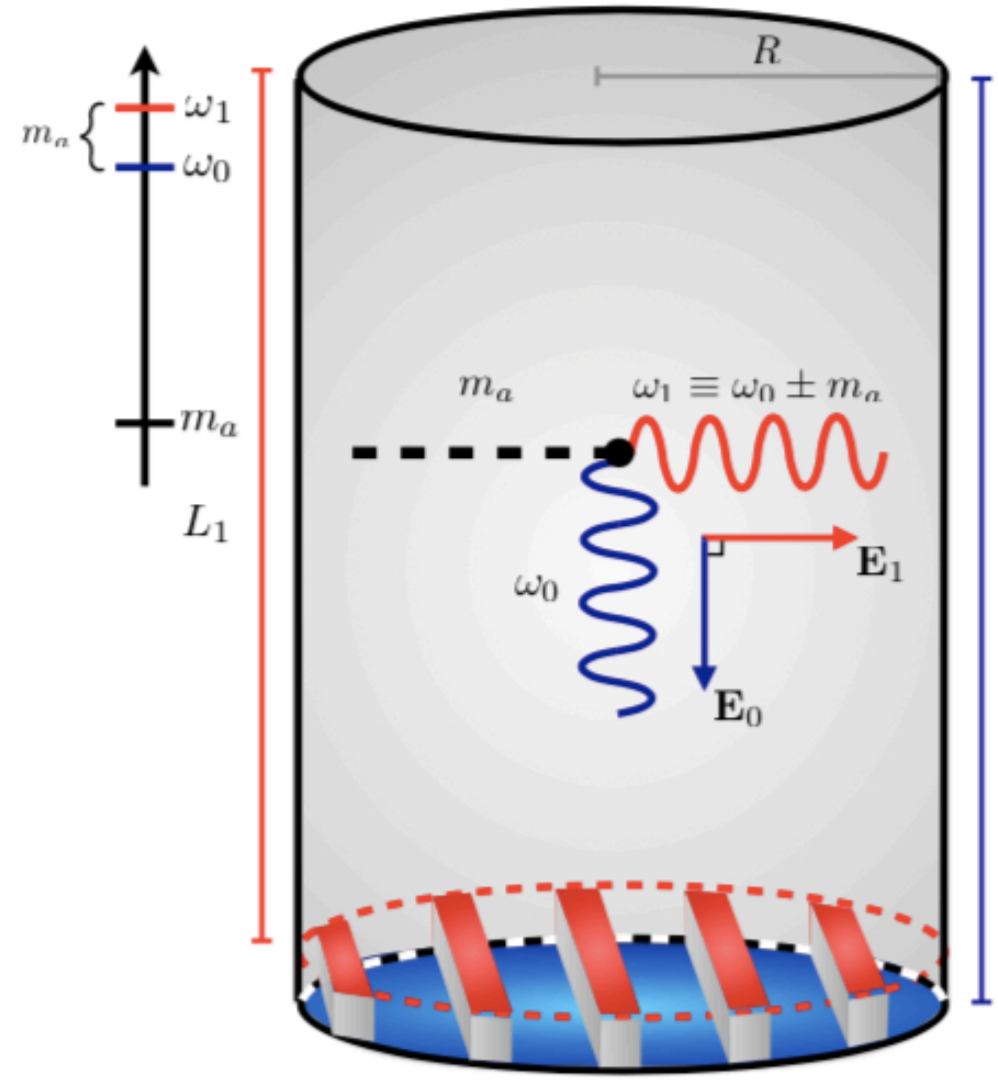
The AC magnetic field $\mathbf{B}$ inside SRF

$$\omega_1 \simeq \omega_0 + m_a \qquad \partial_t(\mathbf{B}) \simeq i\omega_0 \mathbf{B}$$

The axion mass corresponds to the energy level difference, so one can make the axion mass much smaller than the size of the cavity! (Scan over a wide range)

$$P_{\rm sig} \simeq \frac{1}{4}(g_{a\gamma\gamma}\eta_{10}B_0)^2 \rho_{\rm DM} V \times \pi Q_a/m_a$$

A.Berlin, R.T. D'Agnolo, et al, JHEP07(2020)no.07, 088.

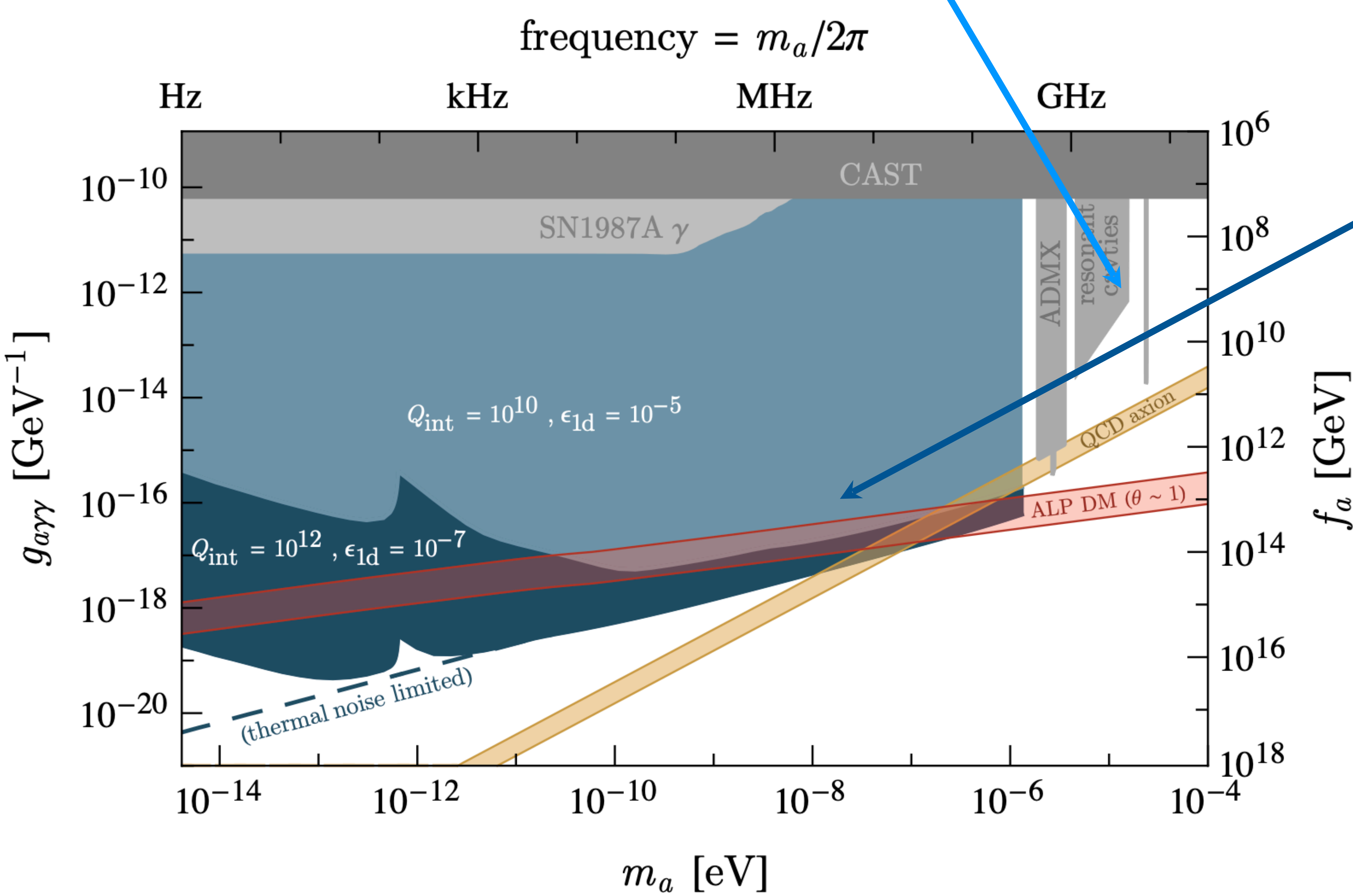


超导谐振腔搜寻轴子暗物质

Normal cavity: $\omega_1 \simeq m_a$ $\quad \partial_t(\mathbf{B}) \simeq 0$

Normal cavity detection frequency is limited by the cavity size.

$\omega_1 \simeq \omega_0 + m_a$ $\quad \partial_t(\mathbf{B}) \simeq i\omega_0 \mathbf{B}$



A.Berlin, R.T. D'Agnolo, et al, JHEP07(2020)no.07, 088.

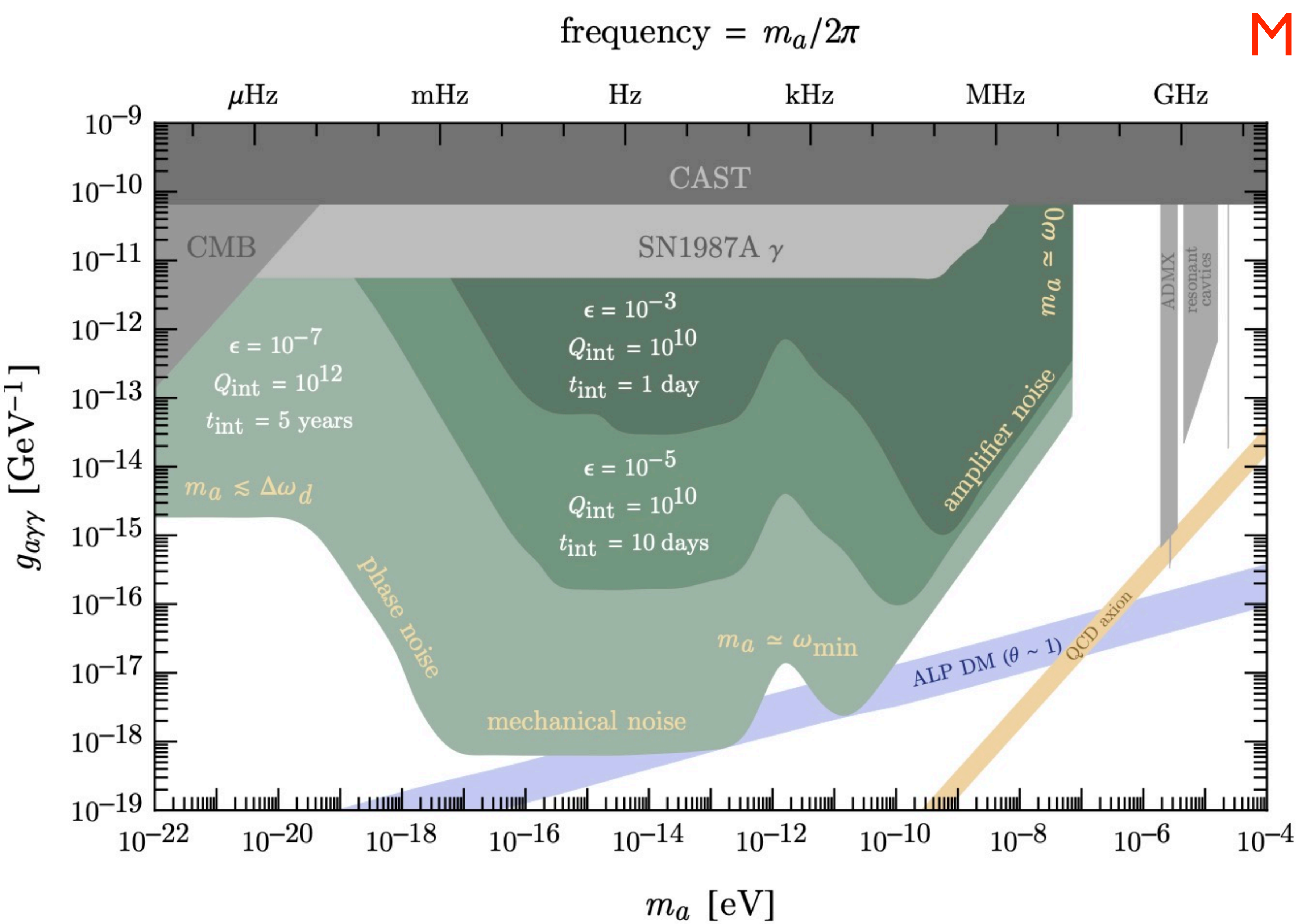
The quasi-degenerate mode can help detect the light mass region, probe a much wider range。

Large unexplored parameter space!

Broadband search

For ultra-light axion, $\omega_1 = \omega_0 + m_a \simeq \omega_0$

Two degenerate and transverse modes can reach the ultra-light region!



MHz: readout, thermal noise dominate

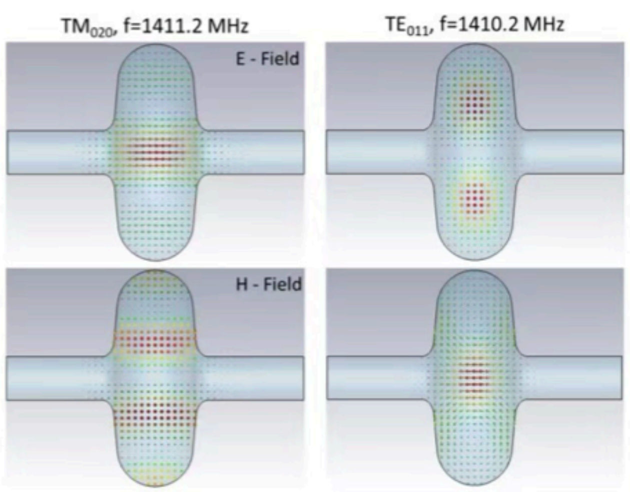
A.Berlin, R.T. D'Agnolo, et al, [arXiv:2007.15656 [hep-ph]].

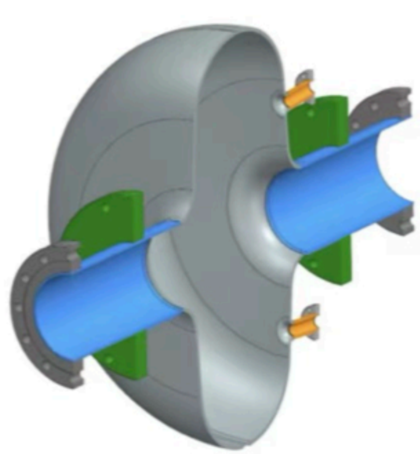
Axion search

TDR like

Fermilab

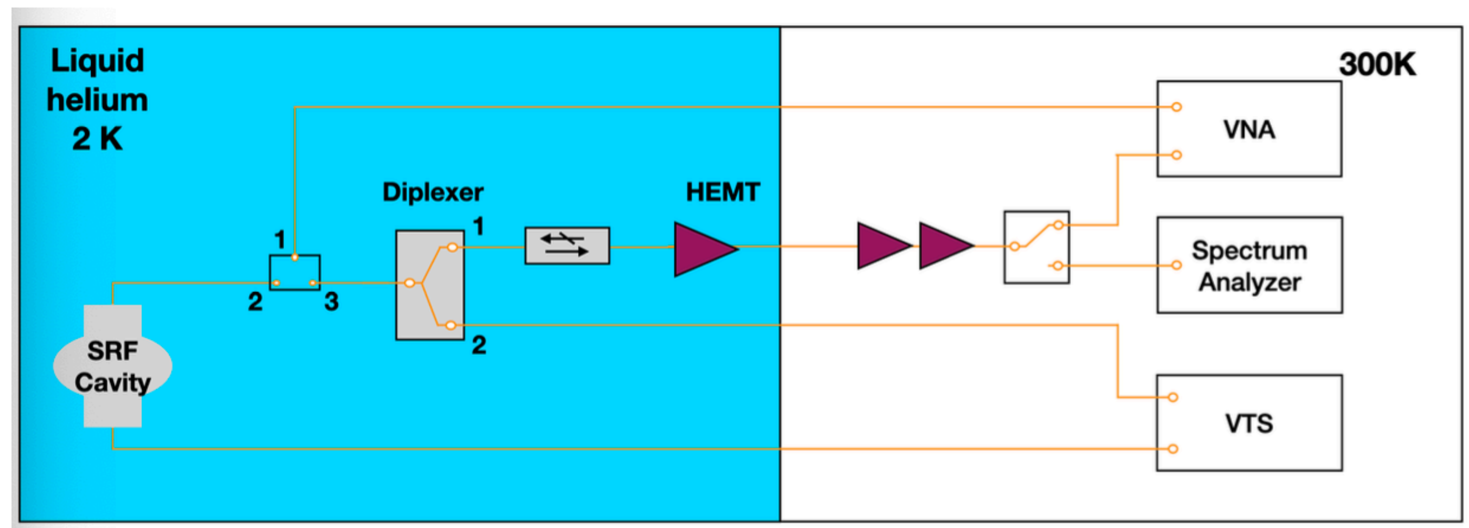
arXiv:2207.11346



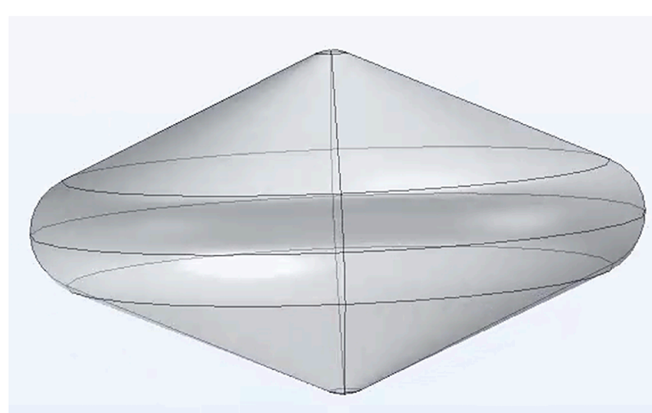


SHANHE collaboration

Using the existing 1.3G cavity as a pathfinder



New designed cavity will be operated in the future.

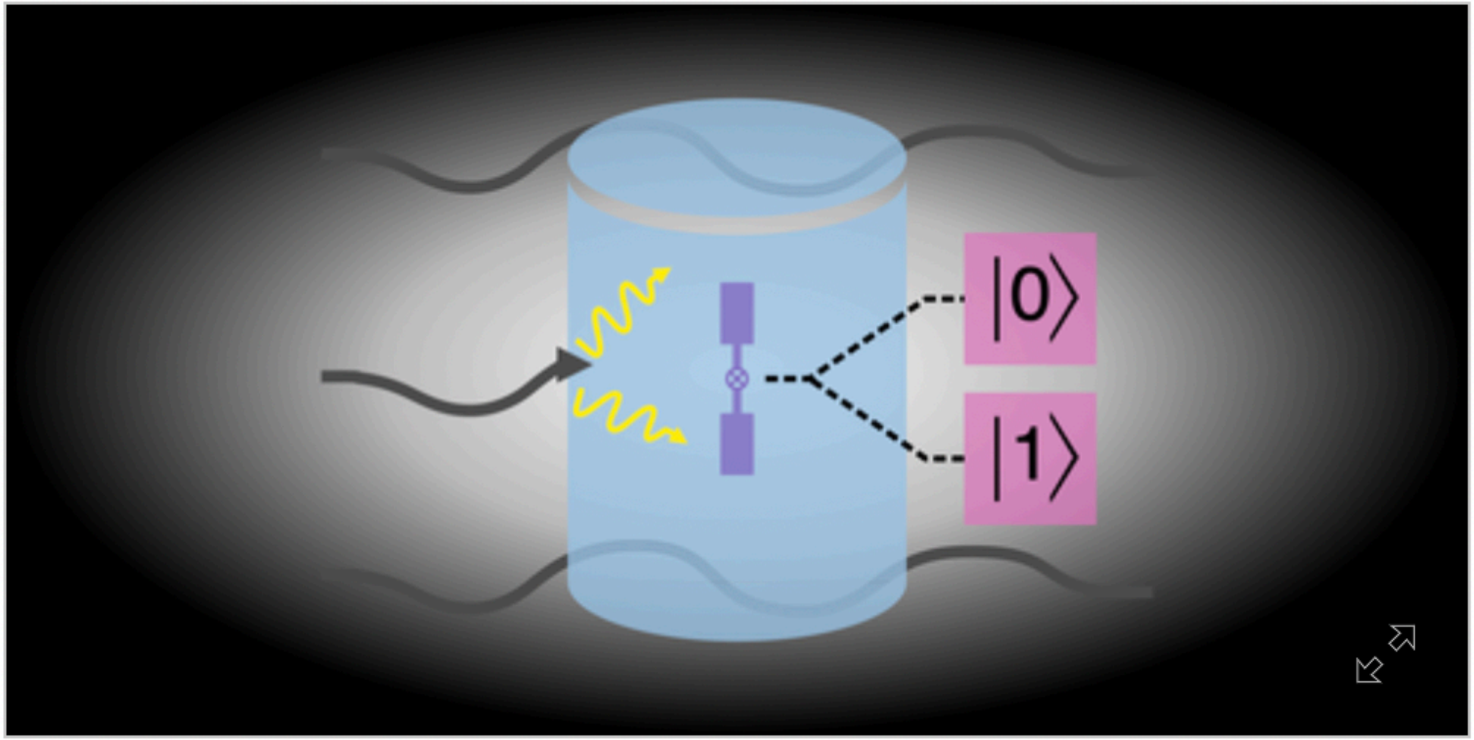


Quantum qubits measure DPDM

Qubits Could Act as Sensitive Dark Matter Detectors

April 8, 2021 • *Physics* 14, s45

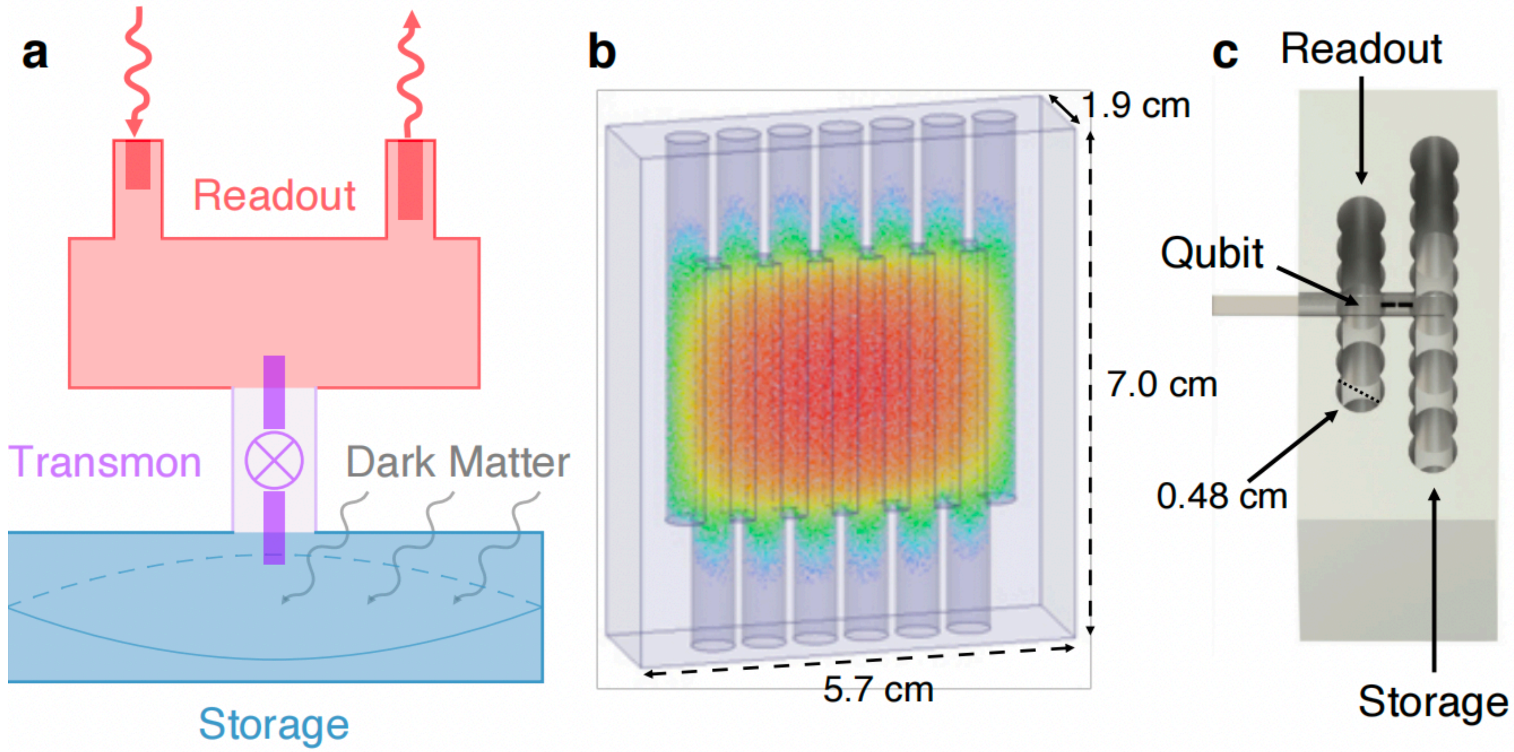
A detector made from superconducting qubits could allow researchers to search for dark matter particles 1000 times faster than other techniques can.



A. Dixit/University of Chicago

Quantum qubits measure DPDM

Al 3D SRF Q~2*10^7



Storage 6.011 GHz

Readout 8.052 GHz

Qubit 4.749 GHz

$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}\omega_q \sigma_z + 2\chi a^\dagger a \frac{1}{2}\sigma_z$$

$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}\omega_q \sigma_z + 2\chi a^\dagger a \frac{1}{2}\sigma_z$$

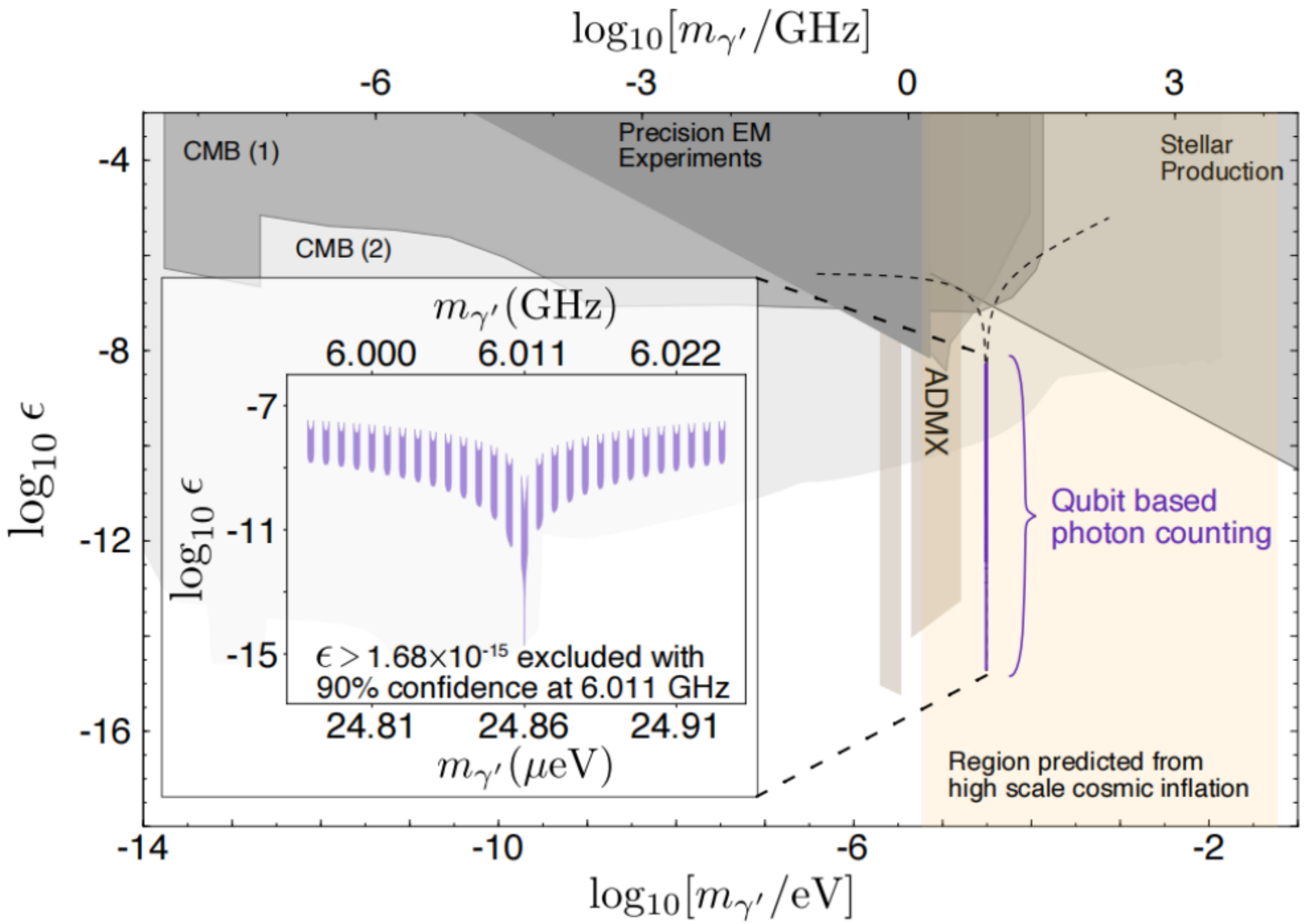
Qubit： two energy level system, induce non-demolition measurements (spectroscopy)

$$\begin{aligned}\mathcal{H}_{int} &= \vec{d} \cdot \vec{E} \\ &= g(\sigma_+ + \sigma_-)(a + a^\dagger) \\ &\sim 2\chi a^\dagger a \frac{1}{2}\sigma_z\end{aligned}$$

DPDM signal： count the photon number by f shift

Ramsey interferometry, etc

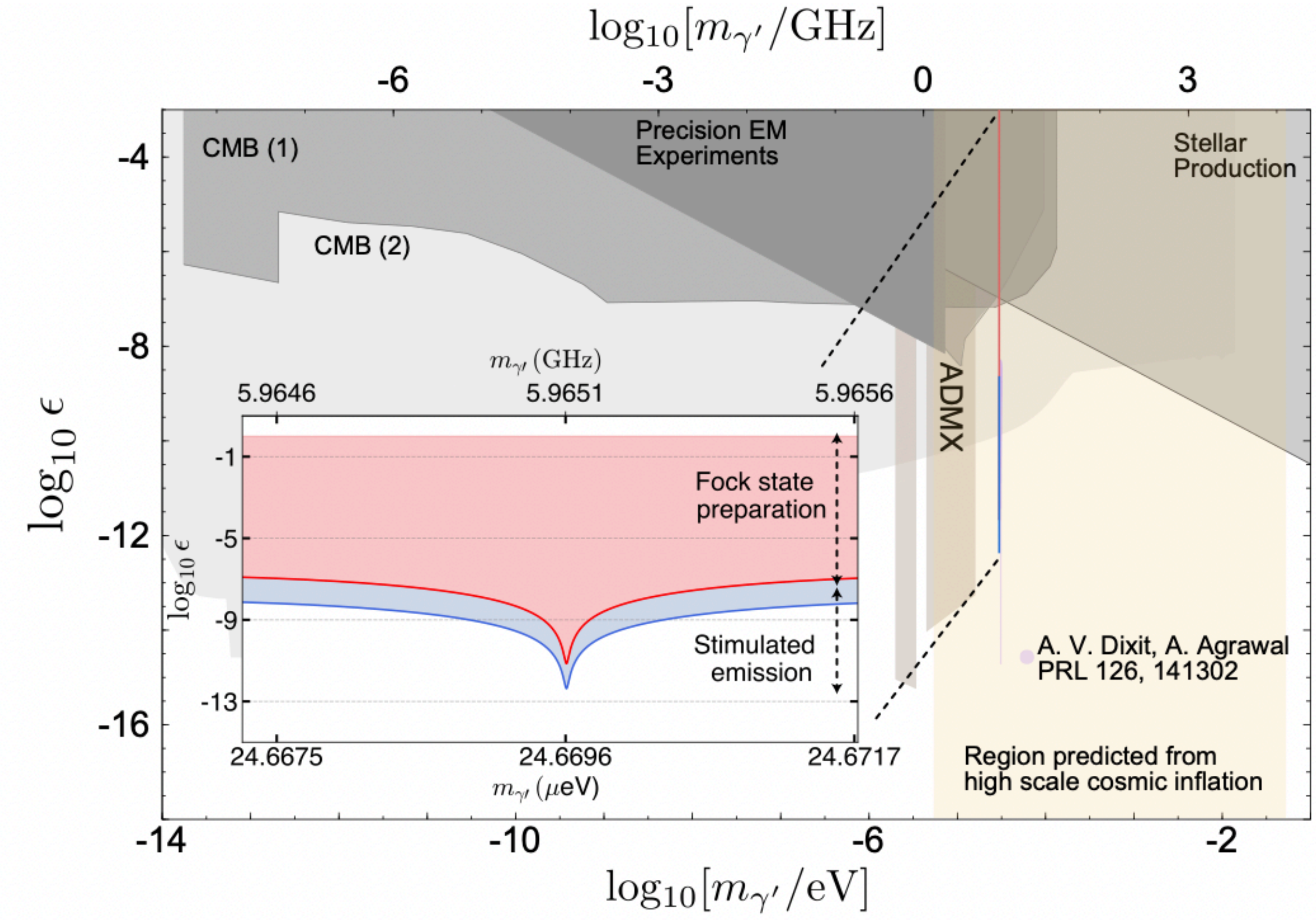
Quantum qubits measure DPDM



$$\epsilon > 1.68 \times 10^{-15}$$

A. V. Dixit *et al.*, "Searching for dark matter with a superconducting qubit," **Phys. Rev. Lett. 126, 141302 (2021)**.

Quantum qubits measure DPDM

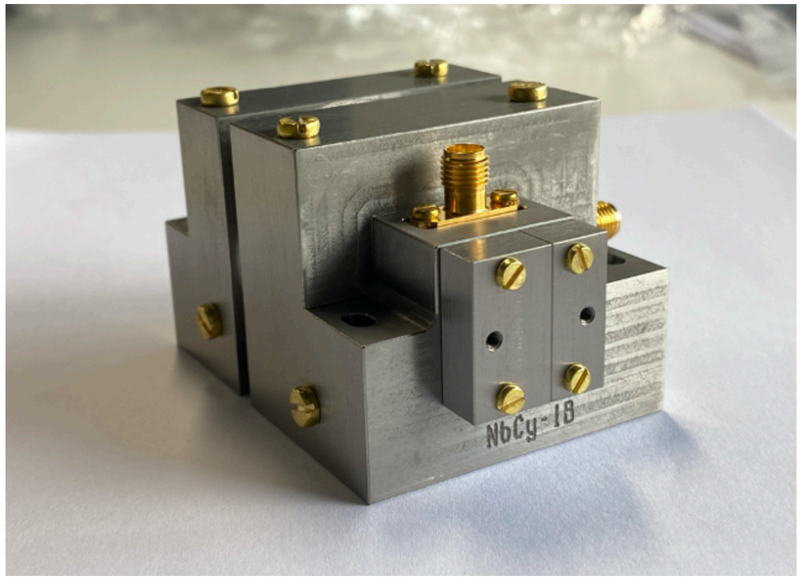


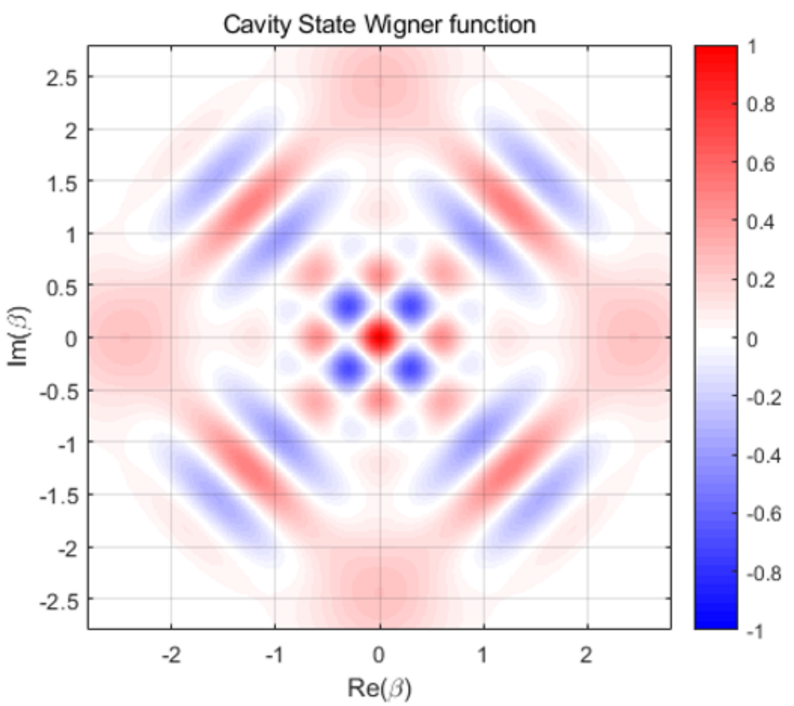
$\epsilon \geq 4.35 \times 10^{-13}$ DPDM： Using the Fock state to measure

A. Agrawal, Akash V. Dixit, Tanay Roy, Srivatsan Chakram, Kevin He, Ravi K. Naik, David I. Schuster, Aaron Chou, Phys.Rev.Lett. 132 (2024) 14, 140801 • e-Print: 2305.03700 [quant-ph]

Quantum qubits measure DPDM

Improved SRF Q by 1 order by using Nb instead of Al





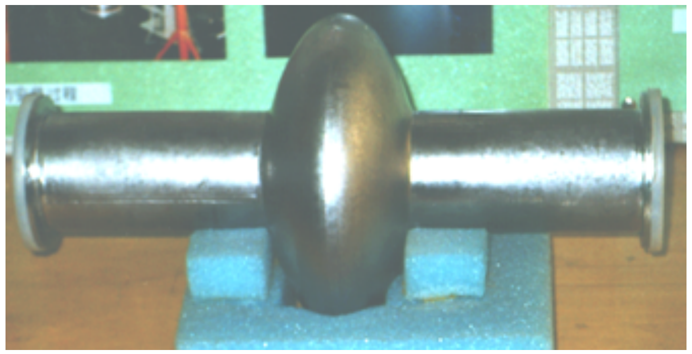
	Fermi Lab	CC-2B	NbCy-1B (1)	NbCy-1B (3)
Qubit (GHz)	4.749	4.962	5.205	5.134
T_{1q} (μs)	108	114	73.8	58.9
T_{2q} (μs)	61	189	40.0	55.6
t_π (ns)	σ = 6	20	200	30
n_q ($\times 10^{-2}$)	5.1	2.49	1.31	0.52
T_q (mK)	78	64.9	57.8	46.9
Storage (GHz)	6.011	6.532	6.439	6.439
T_{1s} (μs)	546	639.6	3573	2783
T_{2s} (μs)	774	~900	5079	~4300
Q_s ($\times 10^7$)	2.06	2.63	14.5	11.3
χ_{qs} (MHz)	1.13	2.59	0.6	0.56
t_p (ns)	380	172	569	877

Better measurements by using the cat-like states

Our new results ~ 10^{-15}

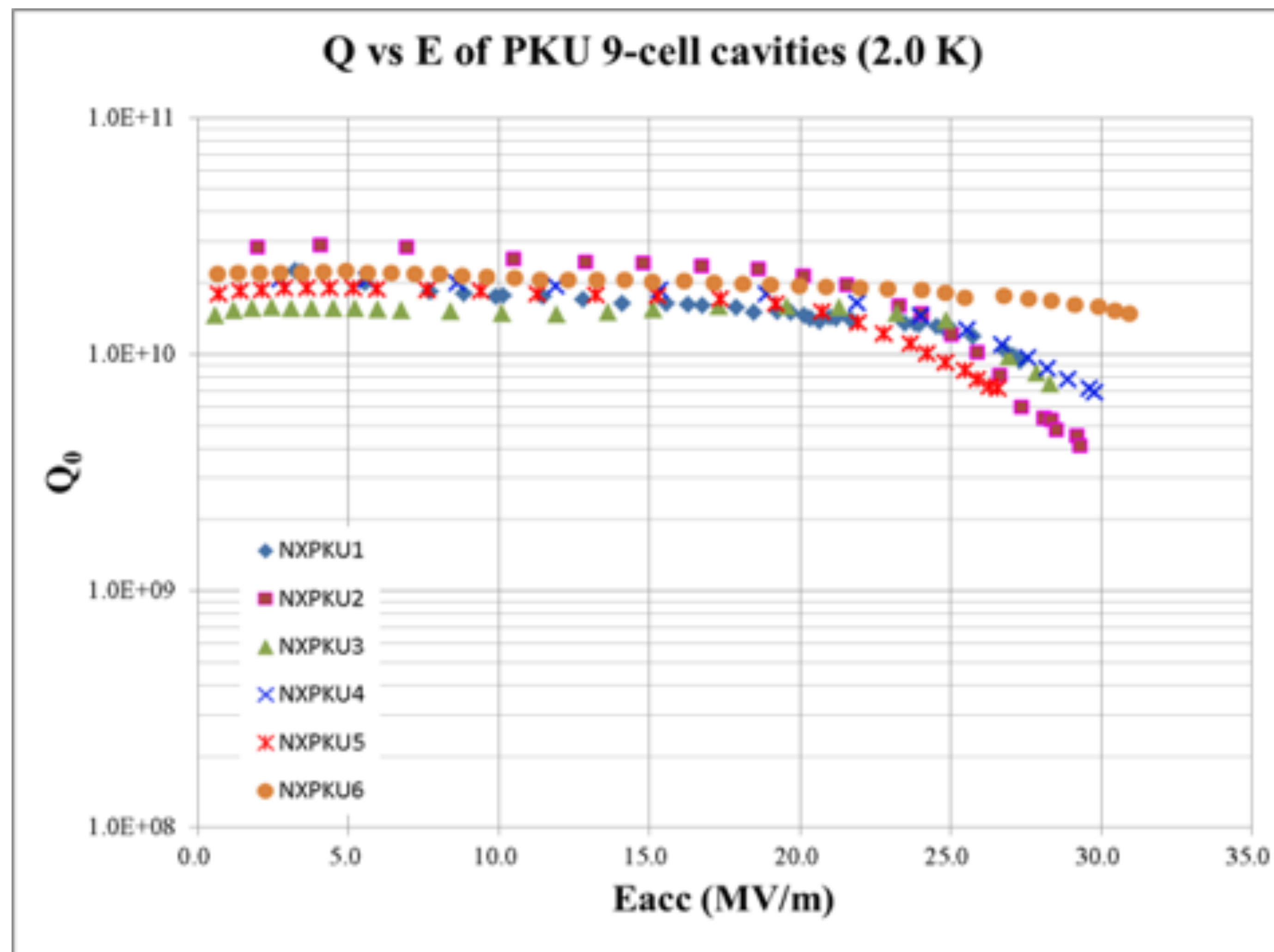
A brief introduction to the team member

SRF in Peking University



Peking University developed China's first superconducting radio frequency (SRF) accelerator cavity. (1994)

First 9-cell for ILC



- Q ~ 1.6 -2.4 E^10 @ 16MV/m。
- equivalent level of international laboratories

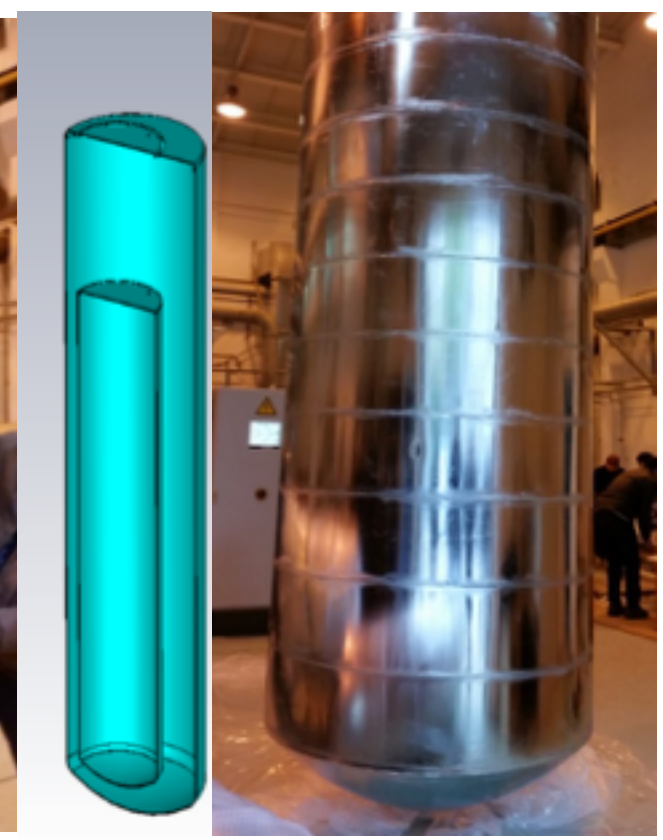
Experimental facilities

Liquid helium system

2K pumping system

Vertical Dewar

Cavity suspension

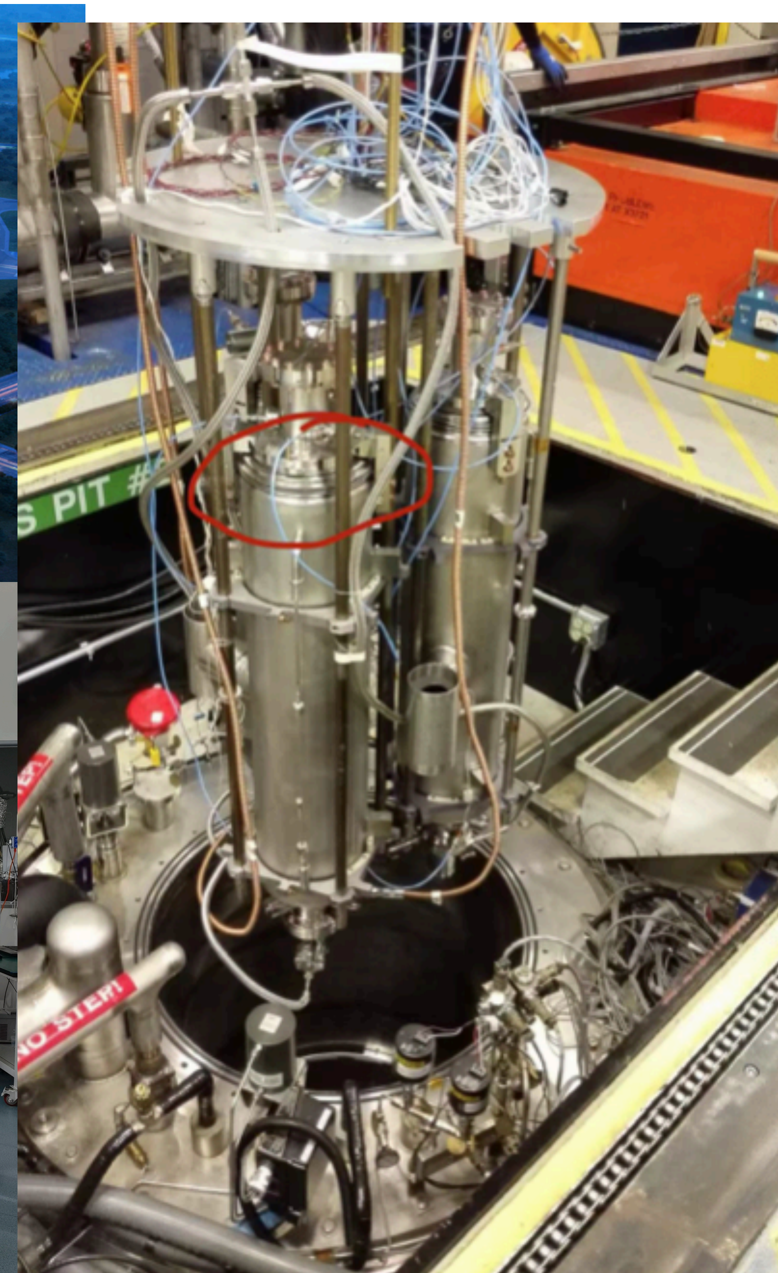


Magnetic shielding

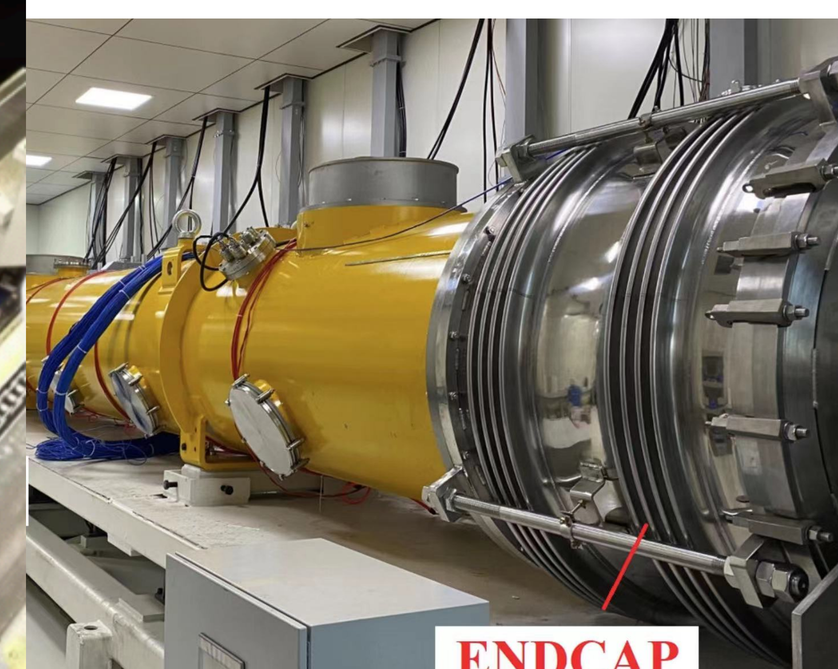
- residual magnetism<10 mGs
- Static heat leak: < 1 W
- Cooling power: >200W@2K

SRF in IHEP

中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences



SRF used for Beijing & Shanghai Synchrotron Radiation Facility and future CEPC



SHANHE collaboration

Superconducting cavity for High-frequency gravitational wave, Axion, and other New particles in High Energy physics

Main collaboration

中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Supportive collaboration

中國科學院物理研究所
Institute of Physics, Chinese Academy of Sciences

北京量子信息科学研究院
Beijing Academy of Quantum Information Sciences

量子科学与工程研究院
Institute for Quantum Science and Engineering

PEKING UNIVERSITY 1898

Boya distinguished professor in Peking university

Summary and outlook

Summary and outlook

- High-Q SRF is extremely interesting in Haloscope wave-like DM searches (get deepest constraints).
- DP backgrounds has rich information (polarization & angular distribution).
- In the future (axion, GWs, quantum qubit, etc), much more can be done .

Thank you!