SRF Cavity Search for Dark Photon

Yanjie Zeng
Institute of Theoretical Physics,
Chinese Academy of Sciences

Advisor: Prof. Jing Shu

Outline

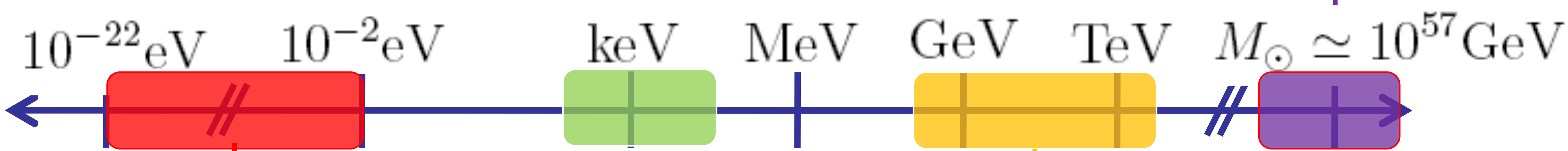
- Motivation of ultra-light dark matter search using Superconducting Radio Frequency (SRF) Cavity
- SRF Cavity Project for DPDM search
- SRF Cavity Project for cosmic DP
- Experimental group
- Summary and Outlook

Motivation of ultra-light dark matter

Various DM candidate

sterile neutrino:
X ray astronomy

PBH,MACHOs, etc



Ultra-light DM (axion、ALP、dark photon etc,…)：Haloscope、radio telescope

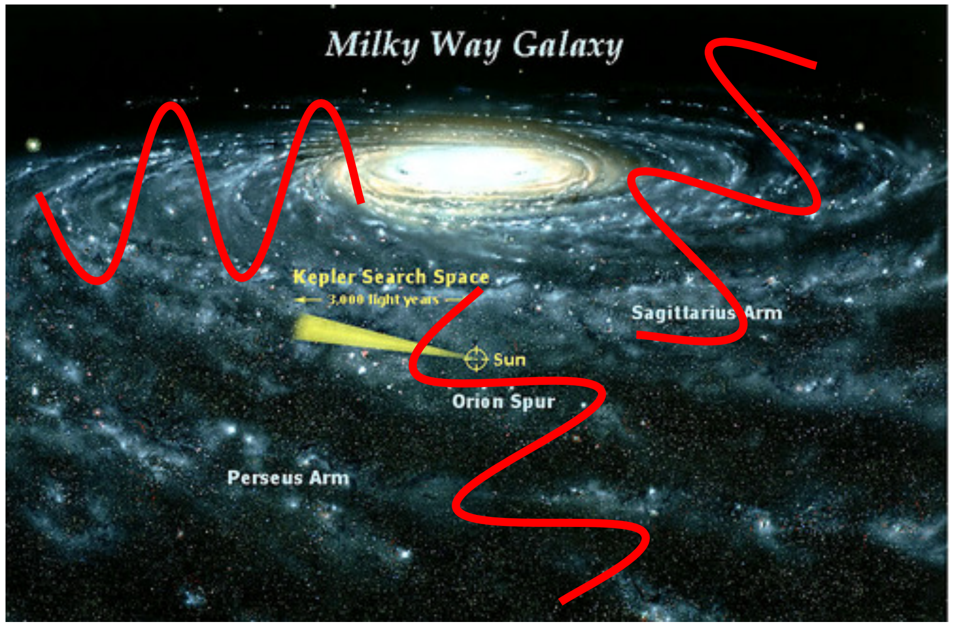
Wave-like DM

WIMPs: direct (indirect)detection、collider searches

particle-like DM

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

The ultra-light DM



(m~10^{-22} eV)

The de Broglie wavelength: galactic scales(kpc)

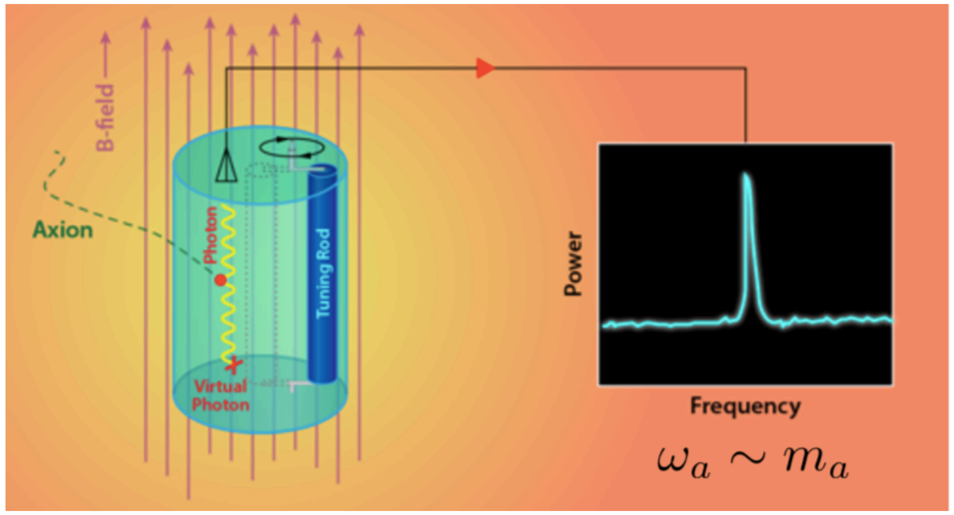
- Astronomical observation (time, position, velocity, polarization, etc)

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

Distinct from traditional dark matter detection (particle scattering)

enormous potential for development in this field

similar as the GWs detection



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

Compton wave length (m)

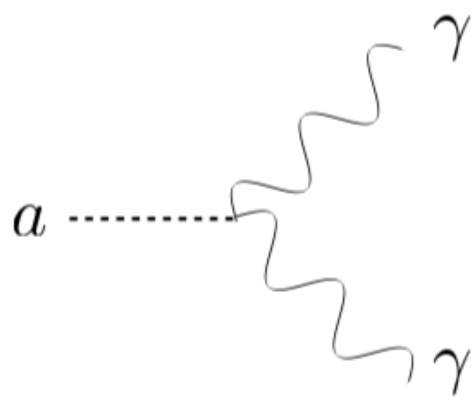
Haloscope, Quantum amplifier

New search methods!!!

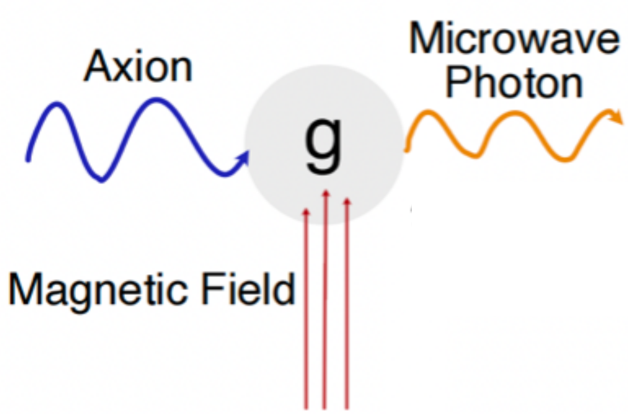
Quantum sensor

Ultra-light DM candidate

Axion (ALP): spin 0, CP odd



Inverse Primakoff effect



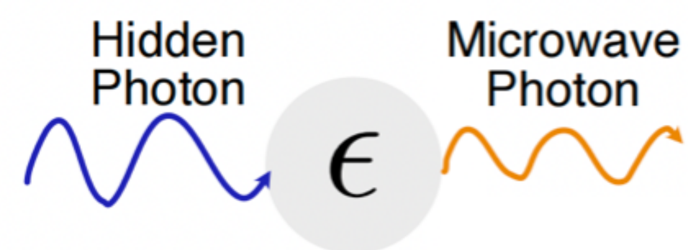
$$\nabla \times \mathbf{B} \simeq \partial_t \mathbf{E} + \mathbf{J} + \underline{g_{a\gamma\gamma} \mathbf{B}\, \partial_t a}$$

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

kinetic mixing

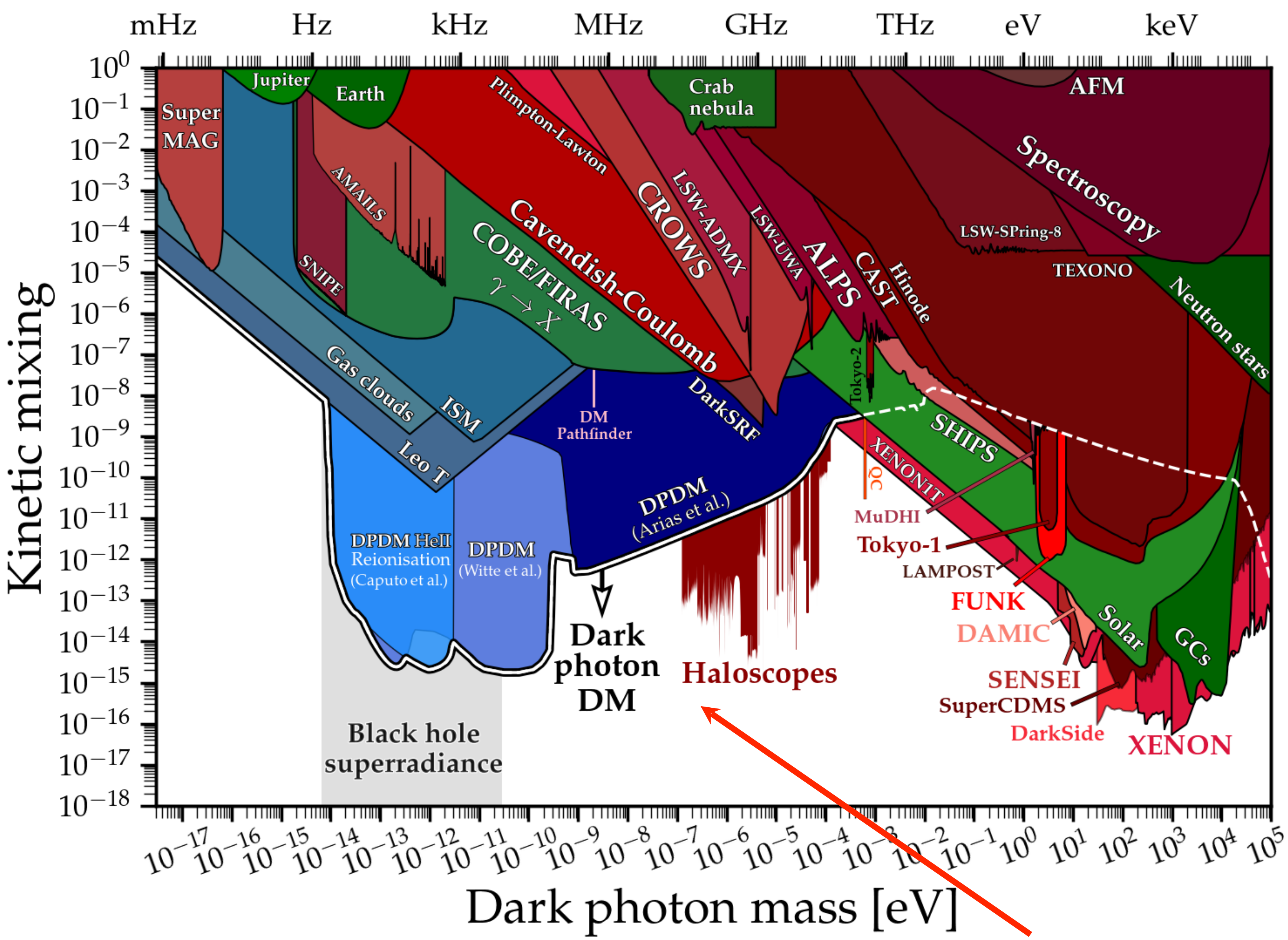


$$\mathscr{L} \supset -\tilde{A}_\mu \left(eJ^\mu_{EM} - \varepsilon m^2_{A'} \tilde{A}'^\mu \right)$$

induces an effective current anyway.

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

Current DPDM search



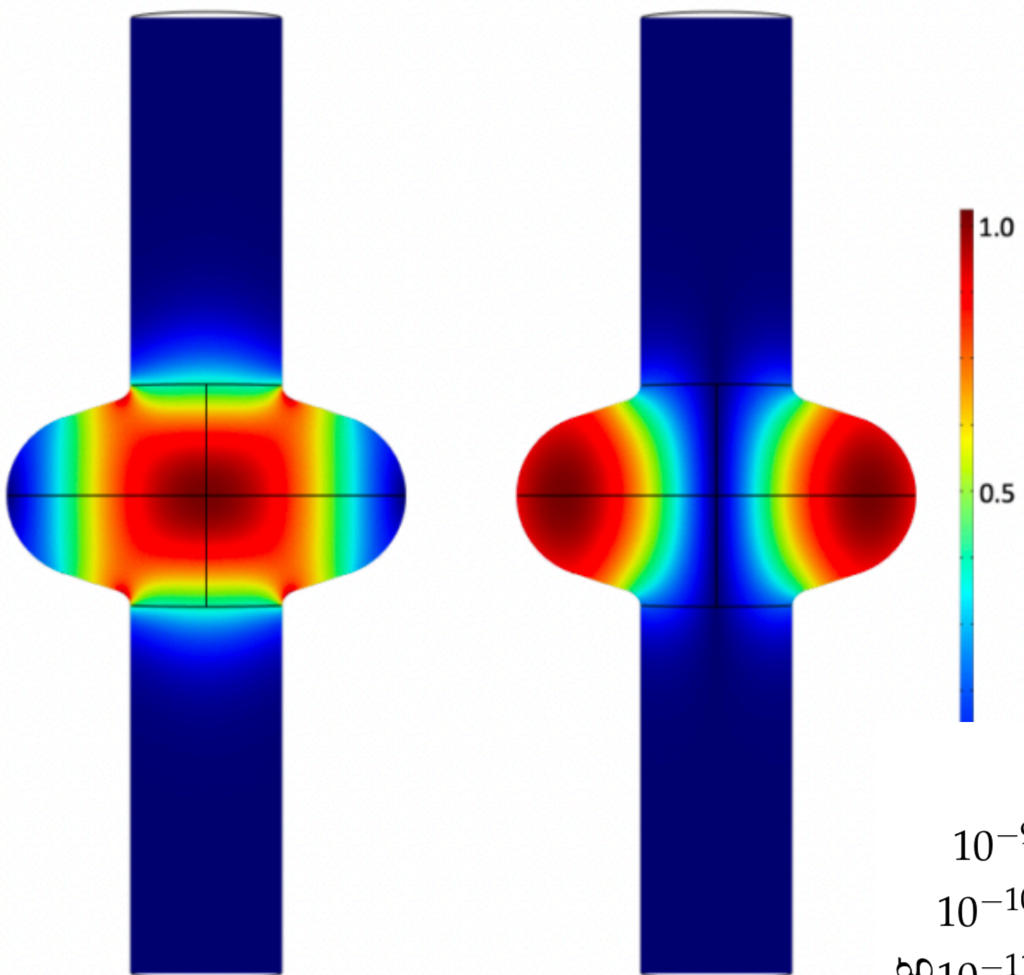
Haloscope sensitivity largely depends on Q: Superconducting cavity has Q~10^{10}

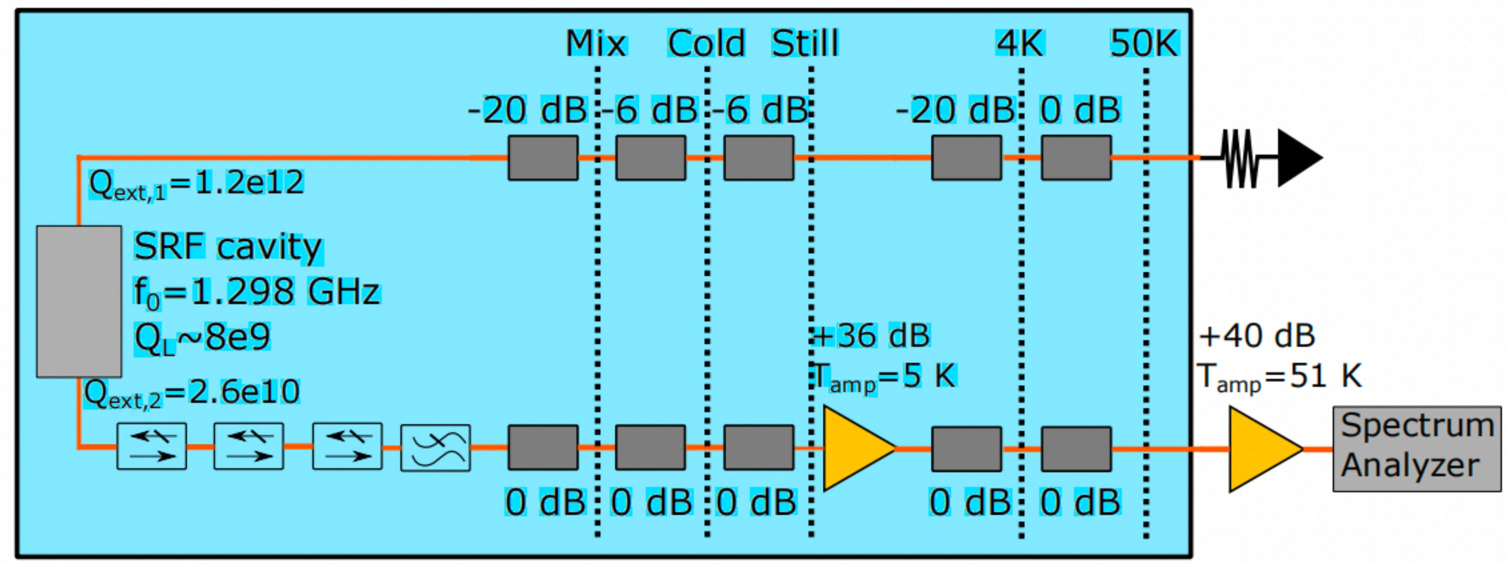
Still a lot of parameter space to detect

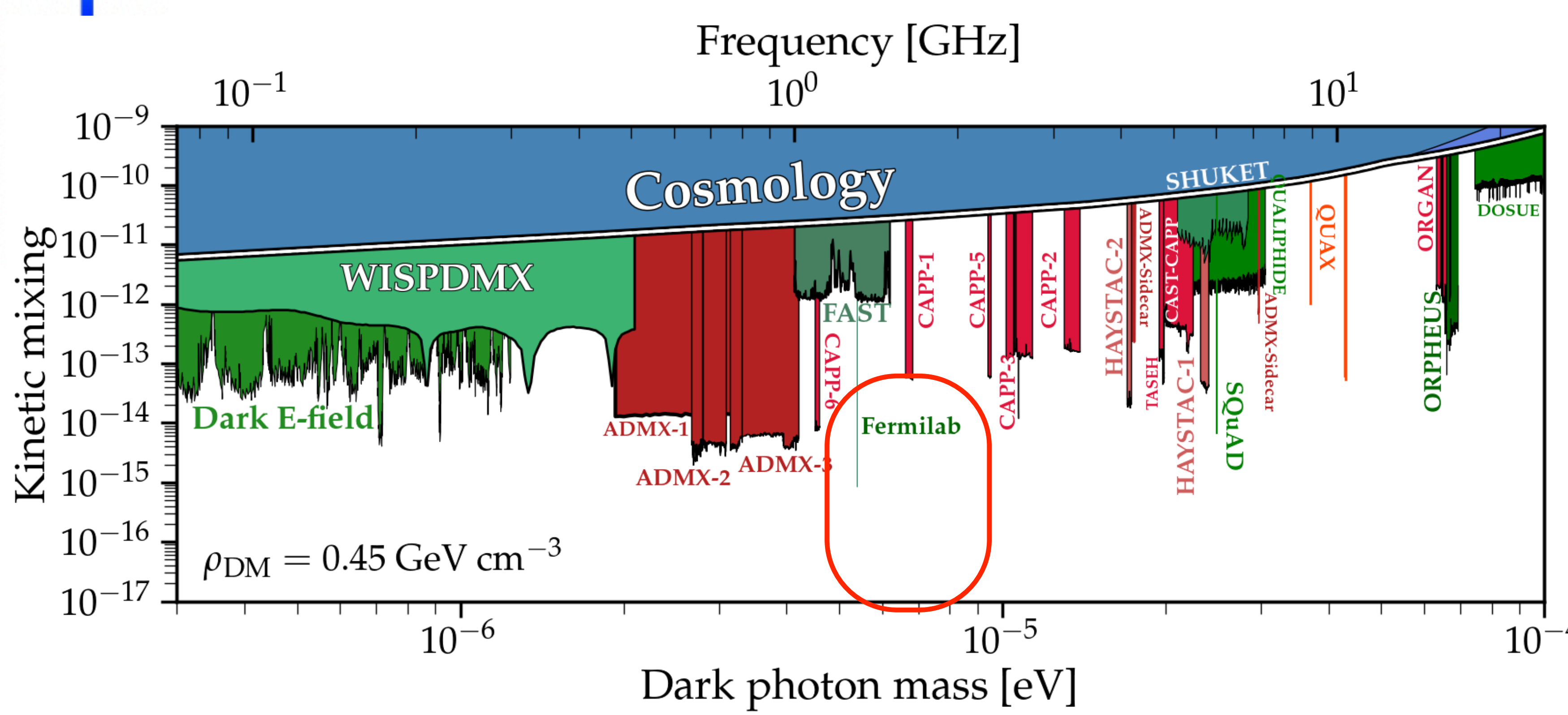
how to make use it? 5 orders more than traditional cavity.

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

Result from Fermilab







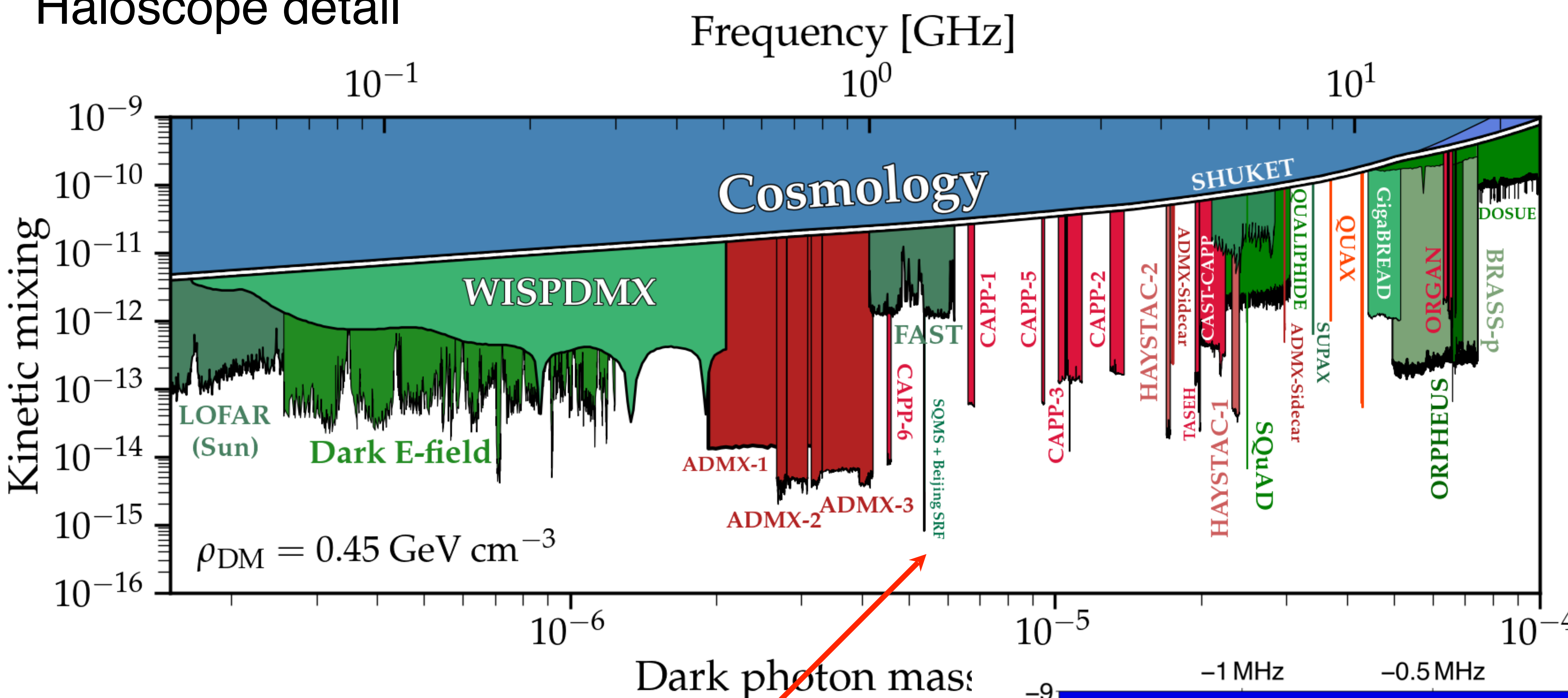
Deepest constrain

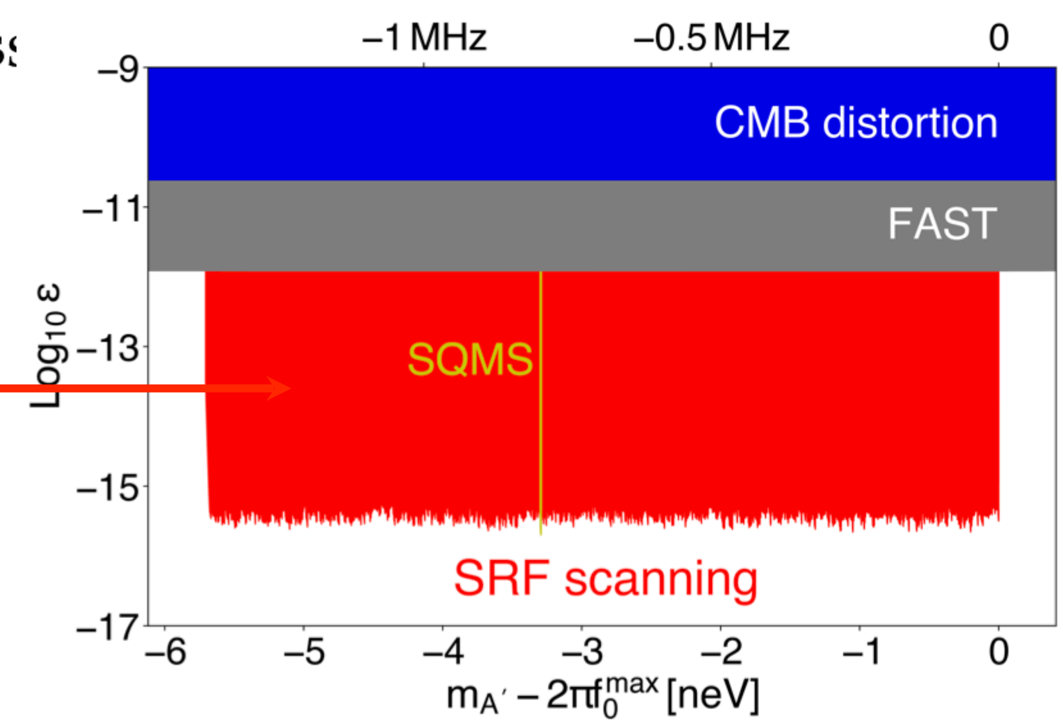
$Q \sim 4.7 \times 10^9$

R. Cervantes et al. (SQMS), Phys. Rev. D 110, 043022 (2024)

DPDM search

Haloscope detail





First tunable results with deepest exclusion limit

SHANHE Collaboration, Z. Tang et al, Phys.Rev.Lett. 133 (2024) 2, 021005

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: $\omega_a \simeq \text{GHz}\,\dfrac{m_a}{10^{-6}\ \text{eV}}$

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

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

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

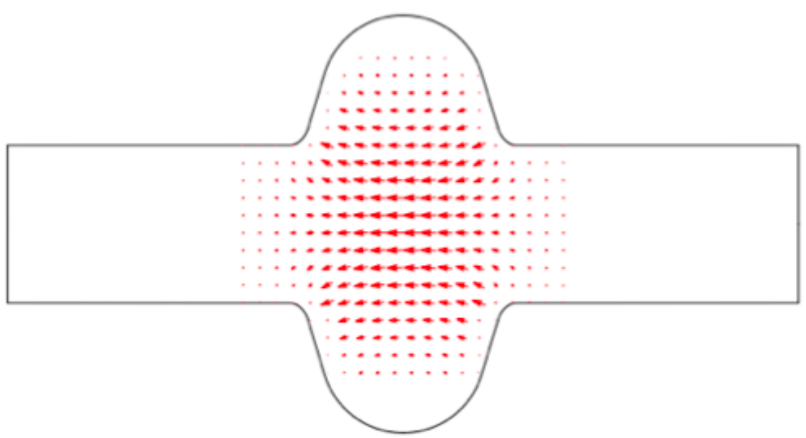
$$\lambda_a \sim 1/m_a\sqrt{\langle v_{\rm DM}^2\rangle} \sim 10^3/m_a$$

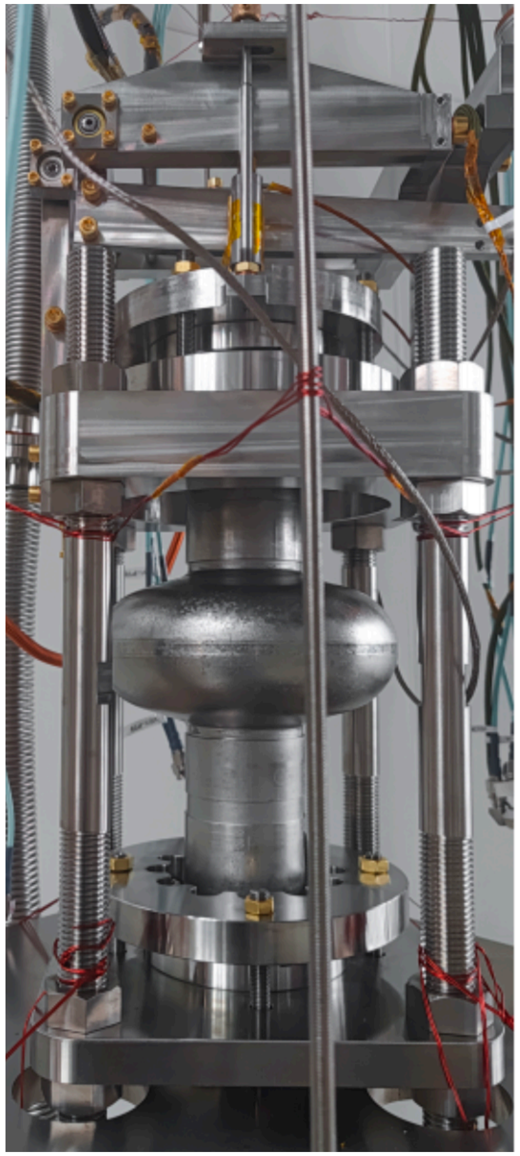
Momentum width10^-3

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 $Q_0 \approx 10^{10}$ → improve SNR $\propto Q_0^{1/4}$
- ▶ 1-cell elliptical niobium cavity with mechanical tuner, immersed in liquid helium at $T \sim 2\,\mathrm{K}$
- ▶TM_{010} mode: z-aligned $\vec{E}$, maximizes the overlap for dark photon dark matter (DPDM)





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

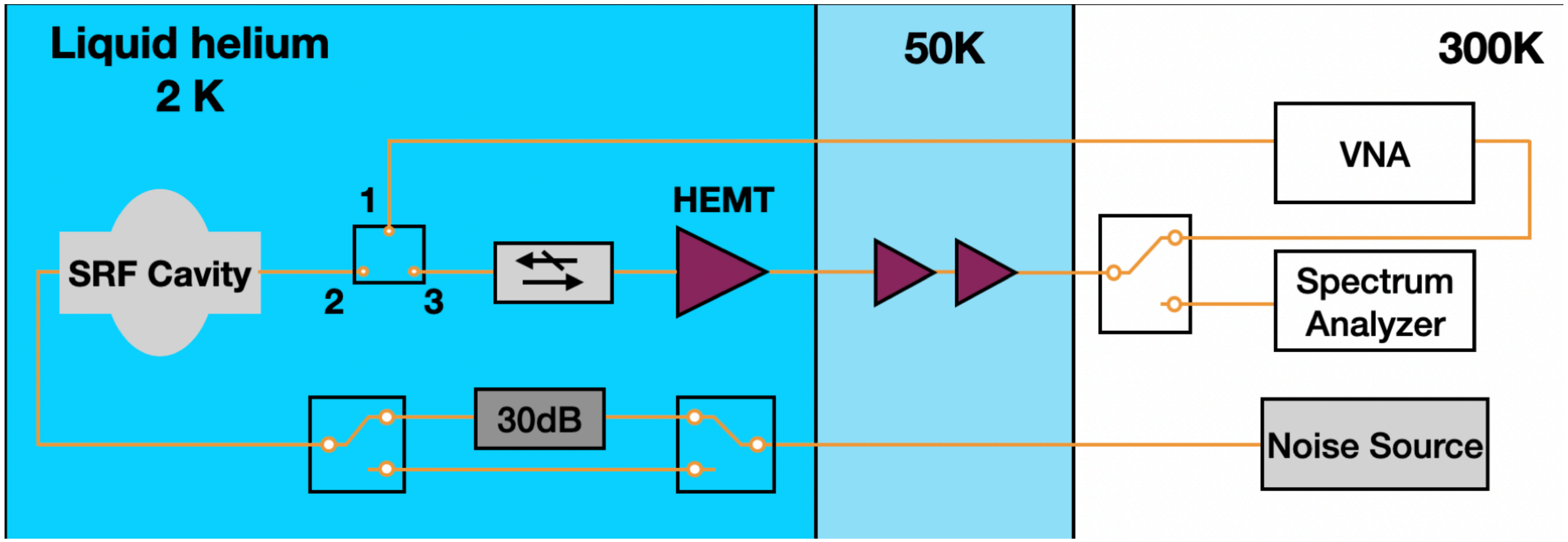
SHANHE Collaboration, Z. Tang et al, Phys.Rev.Lett. 133 (2024) 2, 021005

Experimental operation

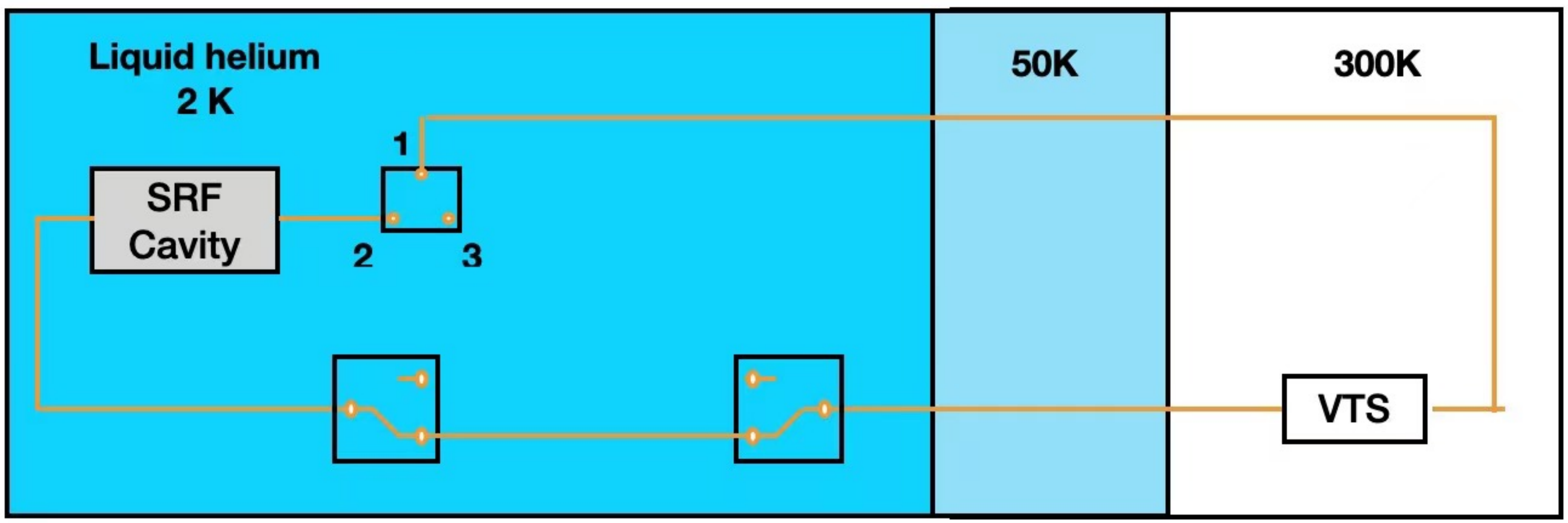
Parameters

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

microwave electronics for DPDM searches

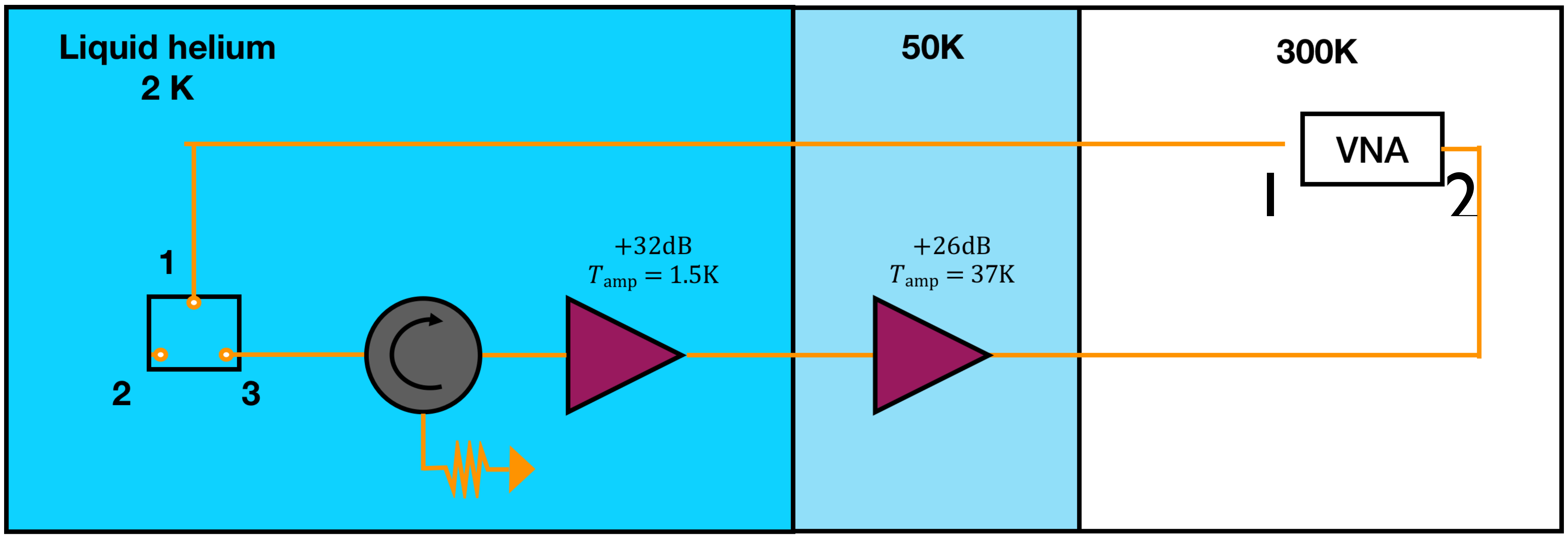


Step 1: Measure Cavity property



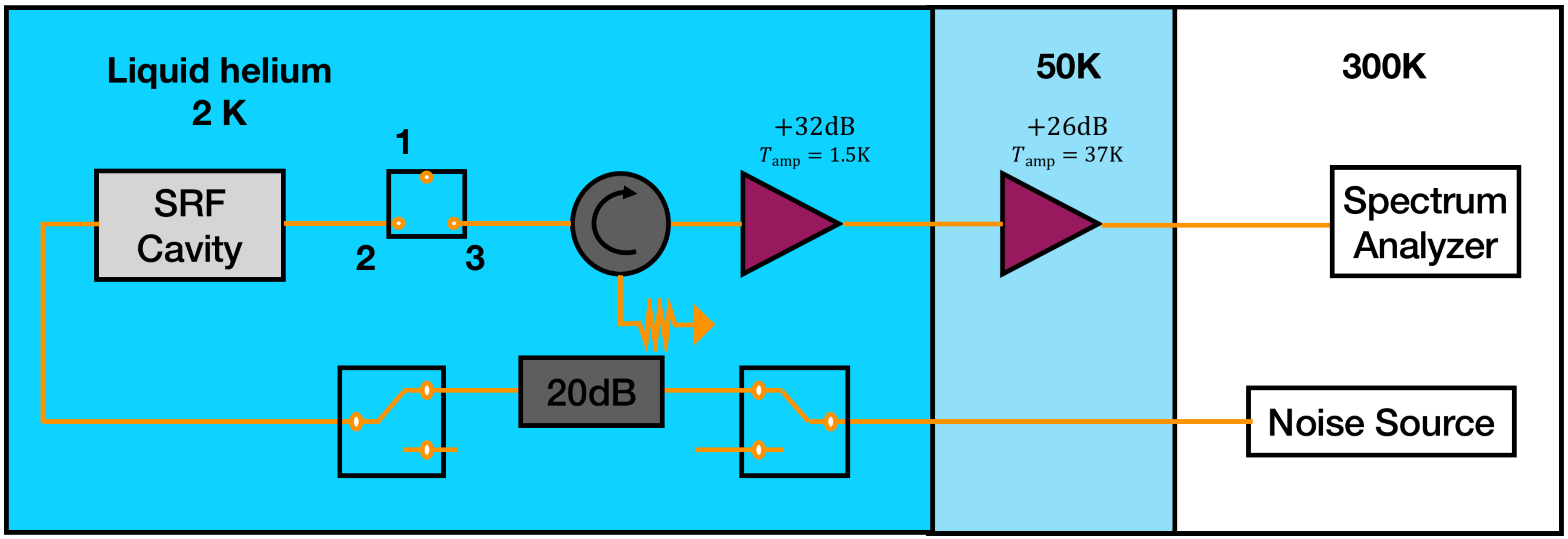
1-2 connection: VTS measurement for the cavity property.

Step 2: calibration



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

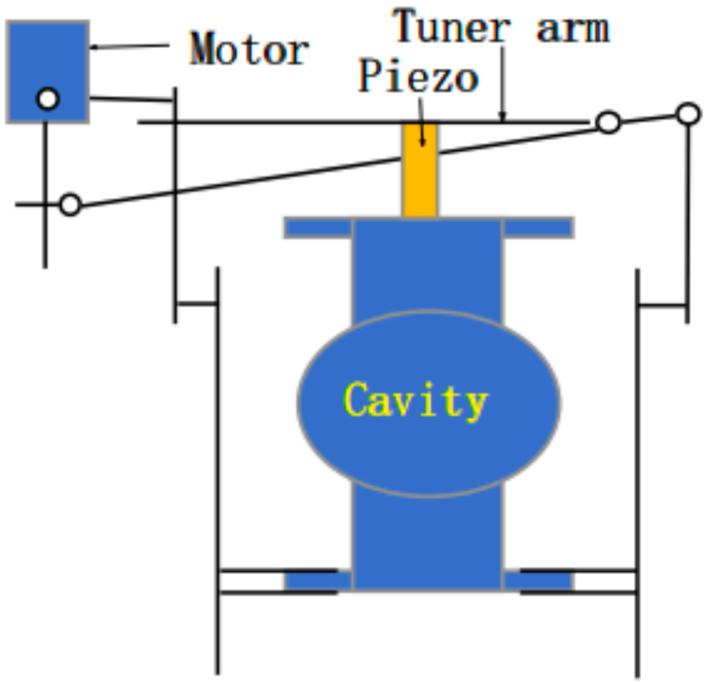
Step 3: Do experiment

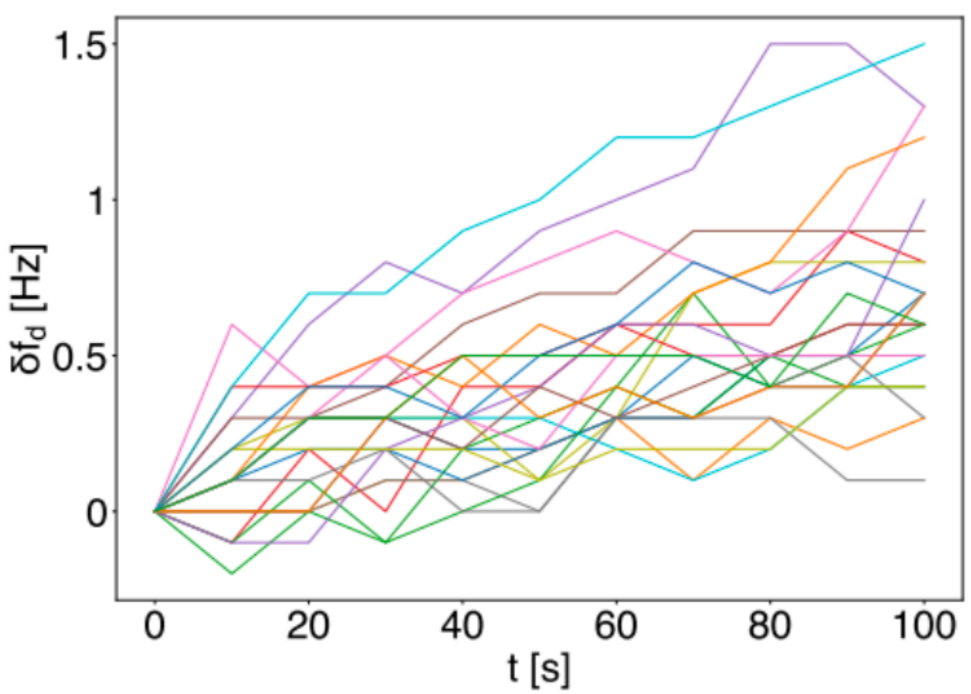


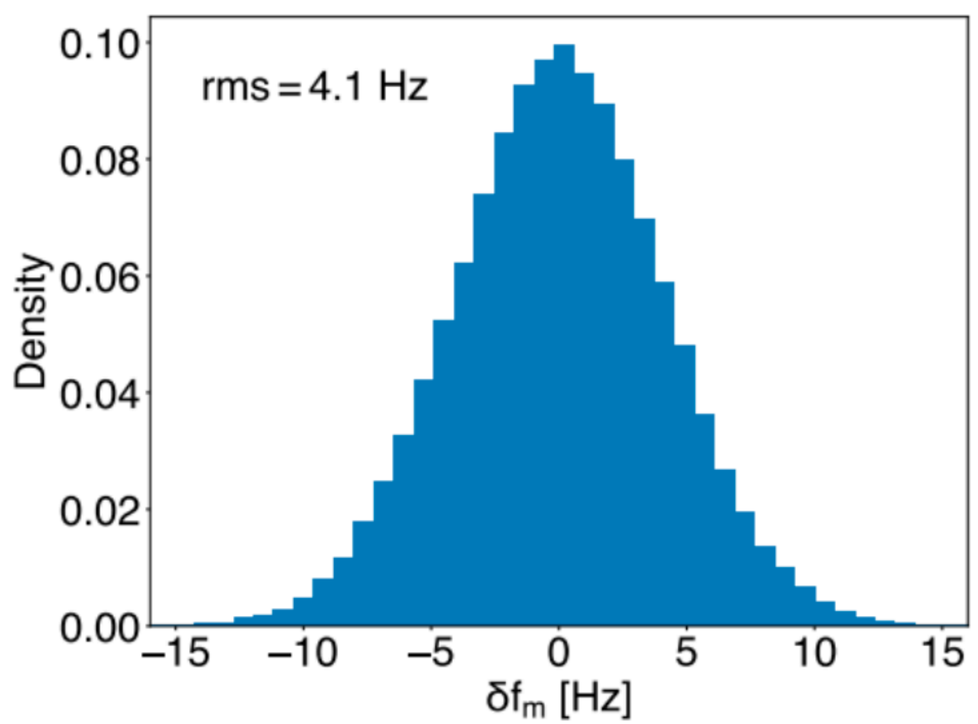
2-3 connection: tune the cavity resonant frequency to do the experiment

Scan Search with Mechanical Tuning

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





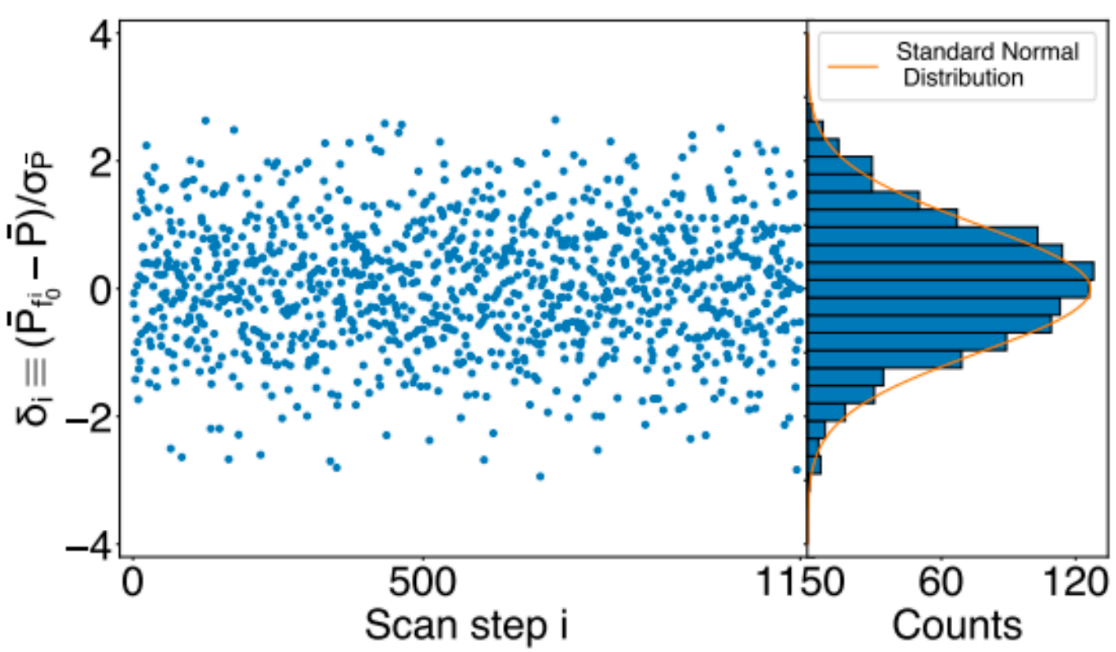


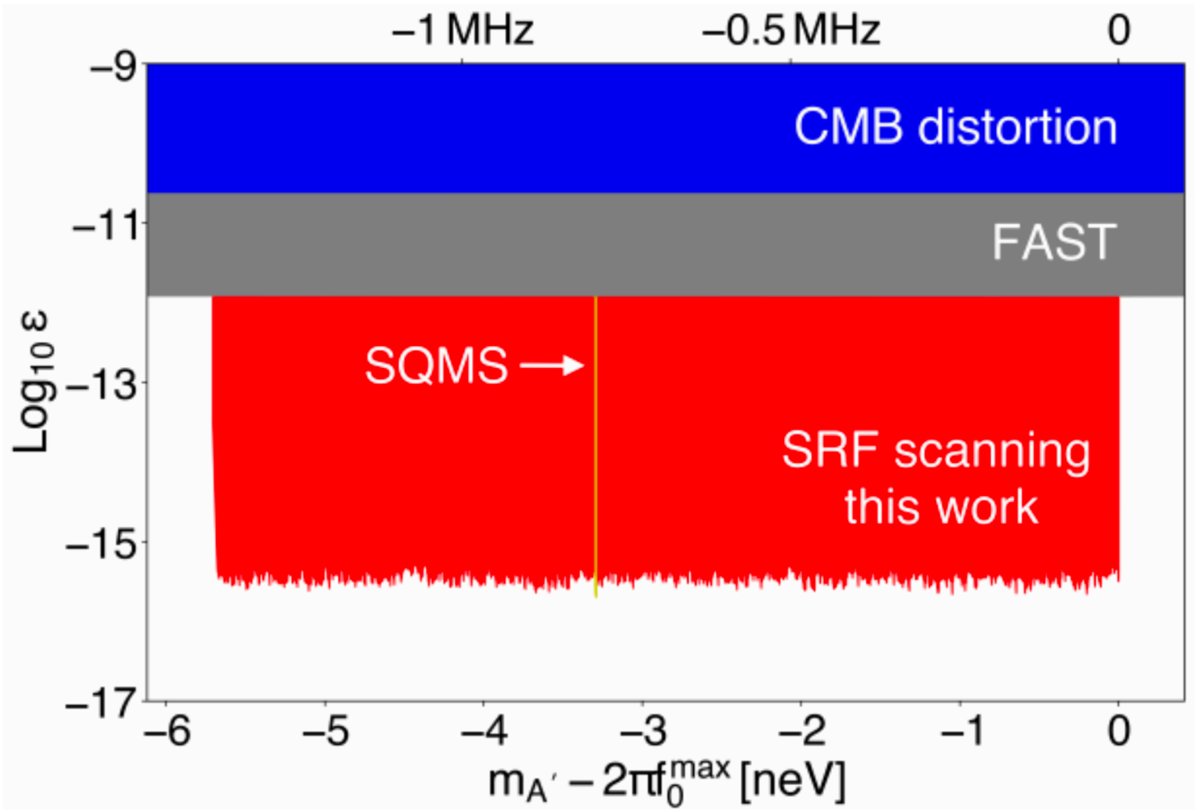
- **Conservatively** choose $\Delta f_0 \approx 10\mathrm{Hz}$

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**:

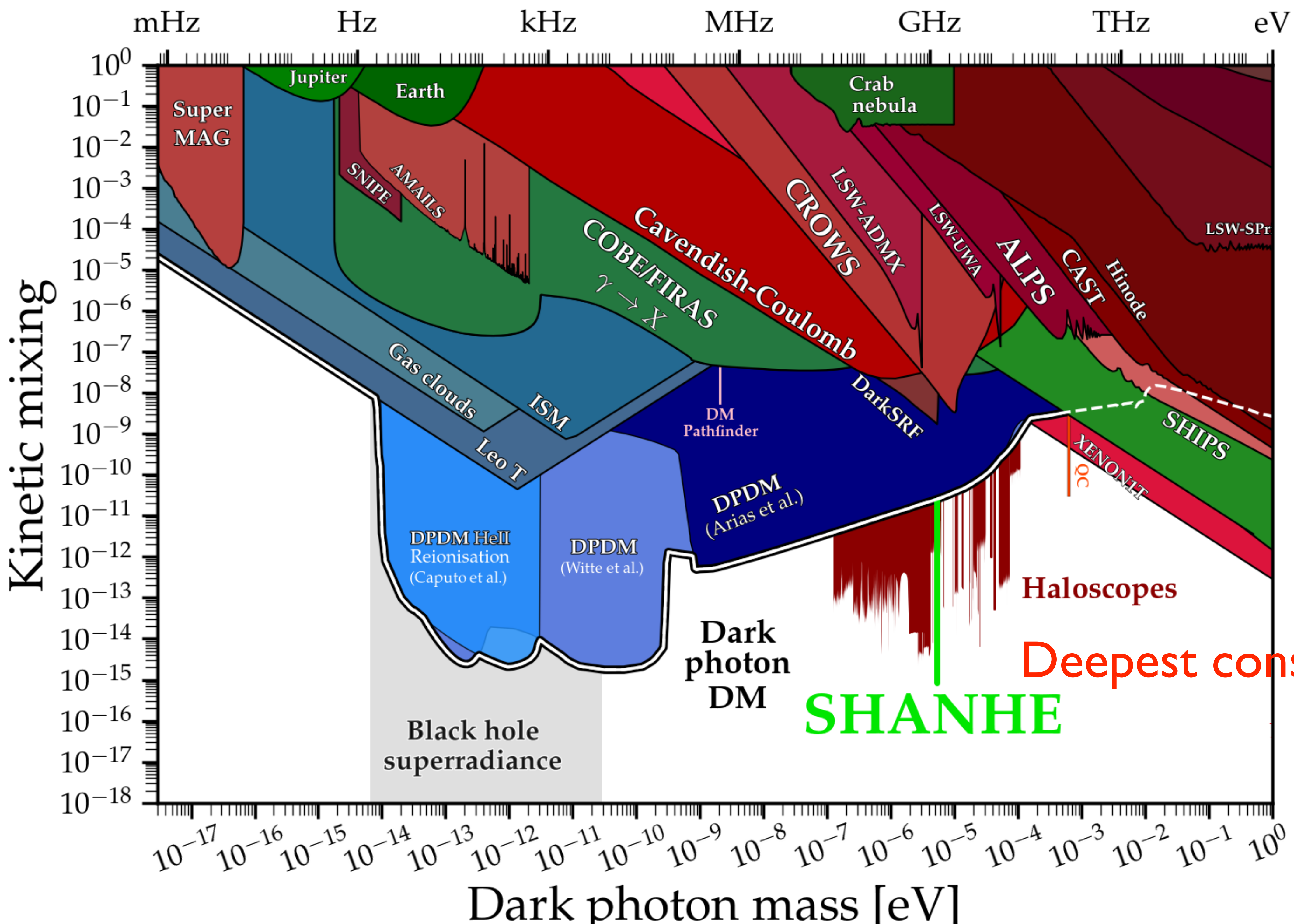
SHANHE Collaboration, Zhenxing Tang,… Jing Shu, Phys.Rev.Lett. 133 (2024) 2, 021005





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

Data analysis and constraints



Deepest constraints

SHANHE

SHANHE Collaboration, Z. Tang et al, Phys.Rev.Lett. 133 (2024) 2, 021005

SRF Cavity Project for cosmic DP

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*

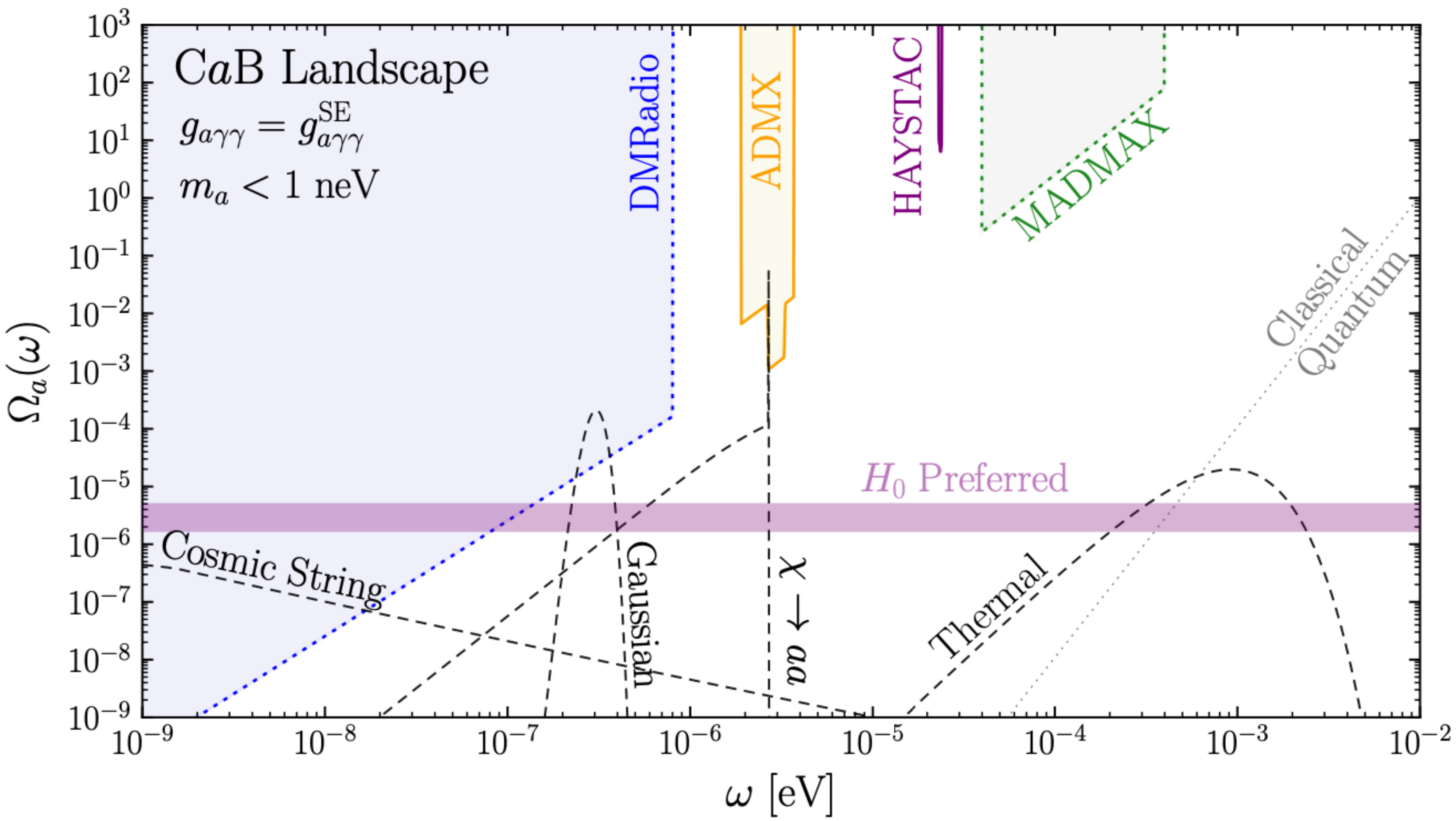
[2] *Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720, USA*

[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*

New particles can also be served as the cosmic backgrounds.

- Relativistic
- Anisotropic



Modulated Signal from Galactic Dark Photons

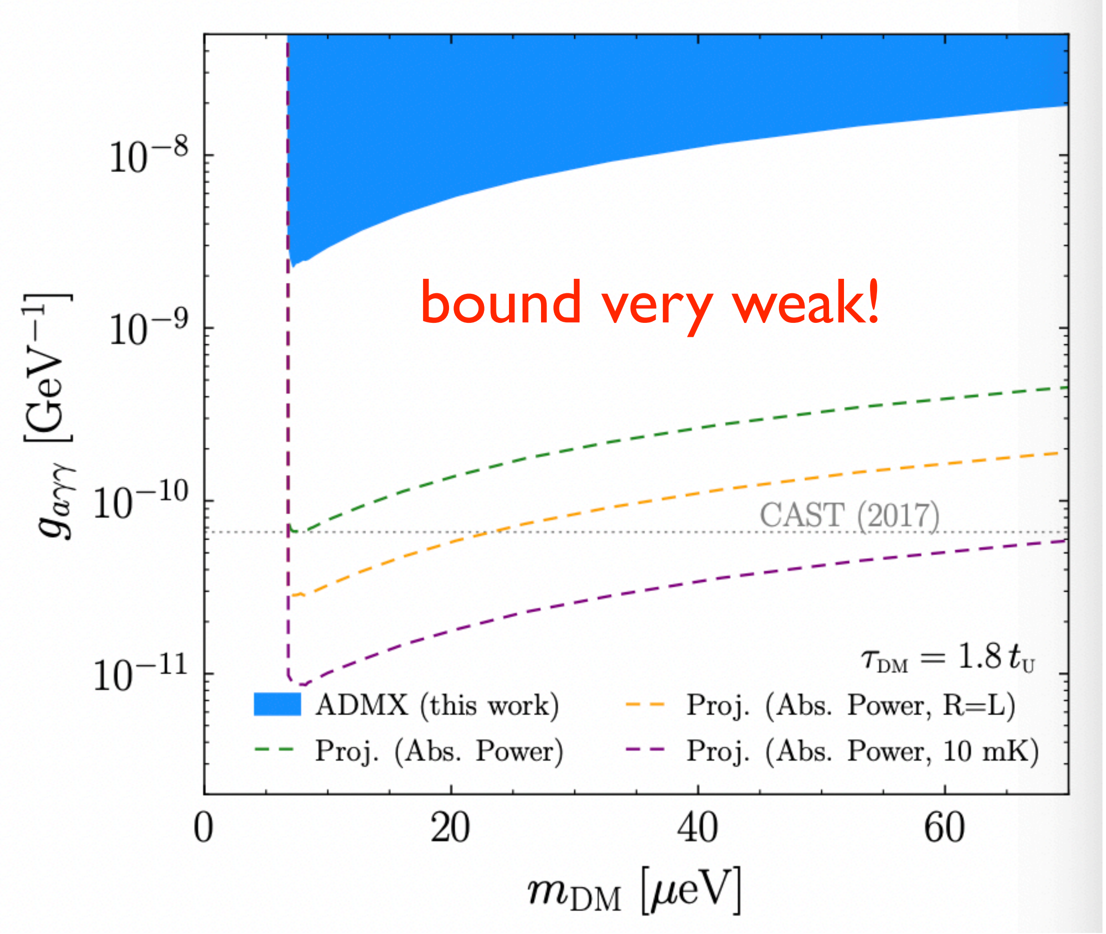
- How about galactic DP backgrounds? (Anisotropic backgrounds, from annihilation or decay?)

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

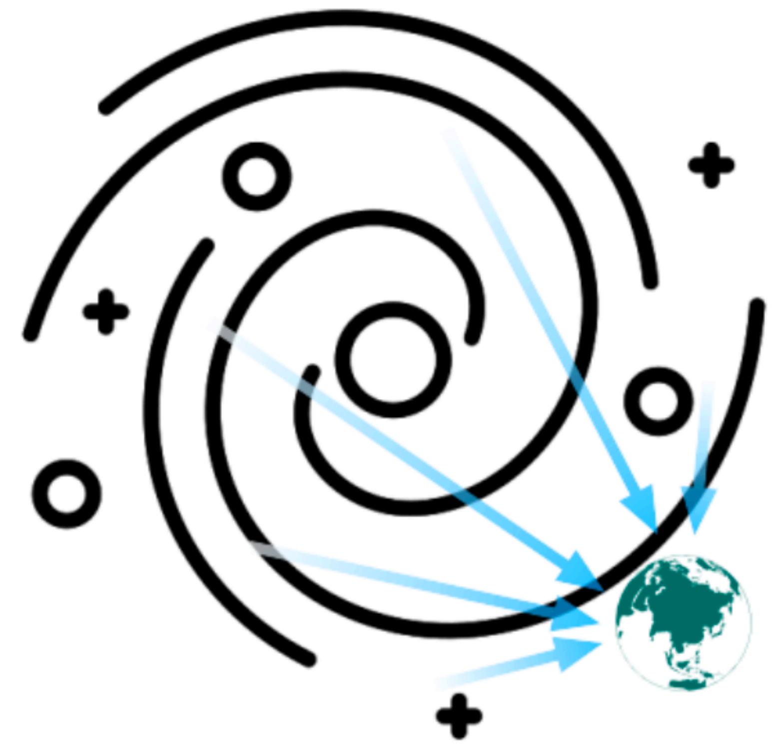
▶ Galactic dark photons from DM decay, e.g.: cascade decay from DM halo

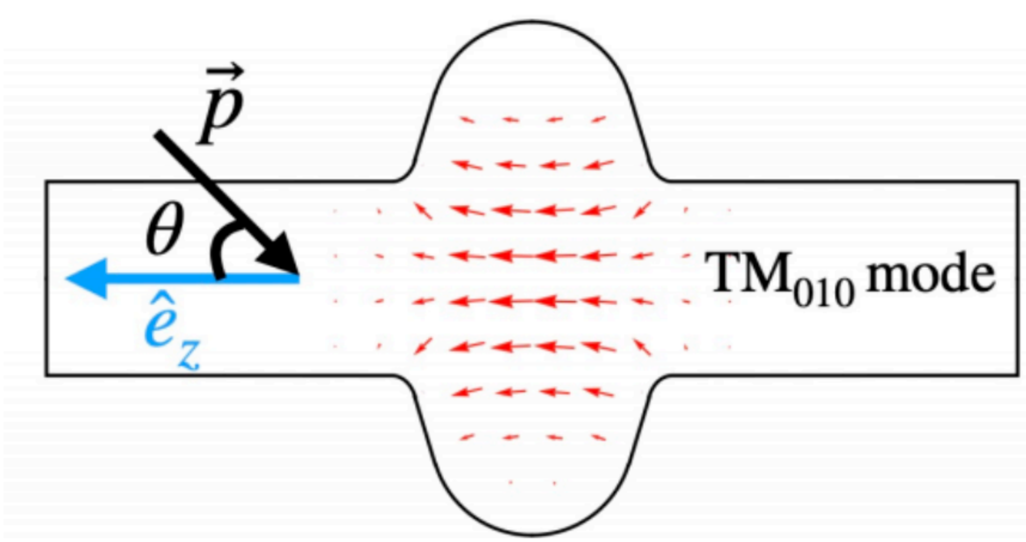
▶ Vectorial observable $\propto \overrightarrow{A}'$

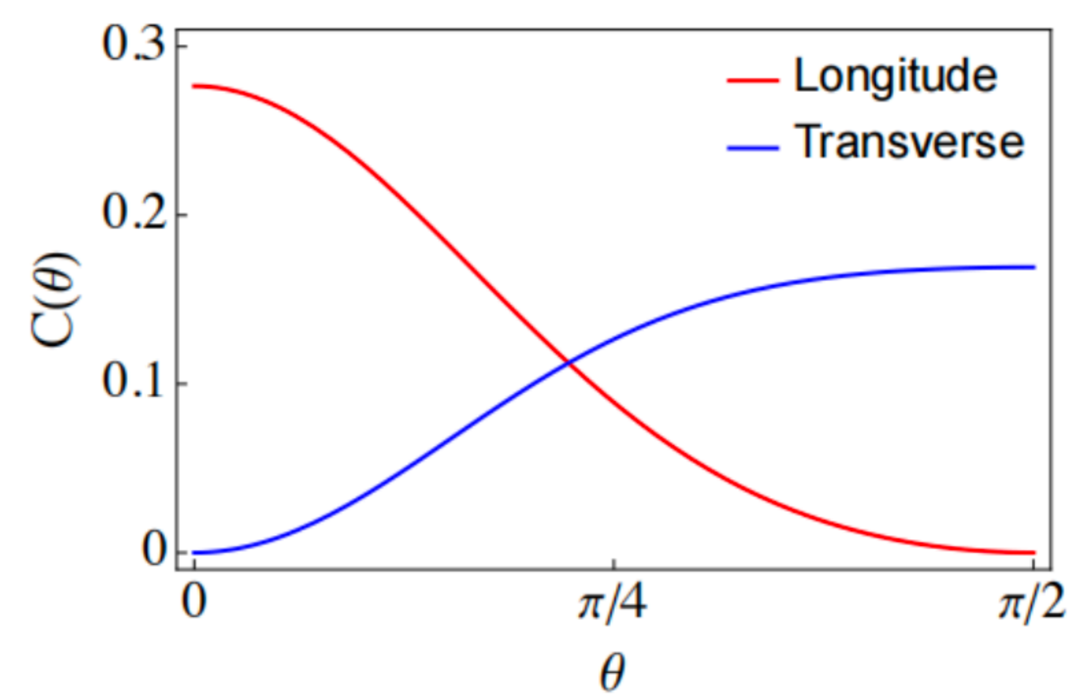
→ angular-dependent signal $\propto C(\theta)$

→ modulation as the Earth rotates

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



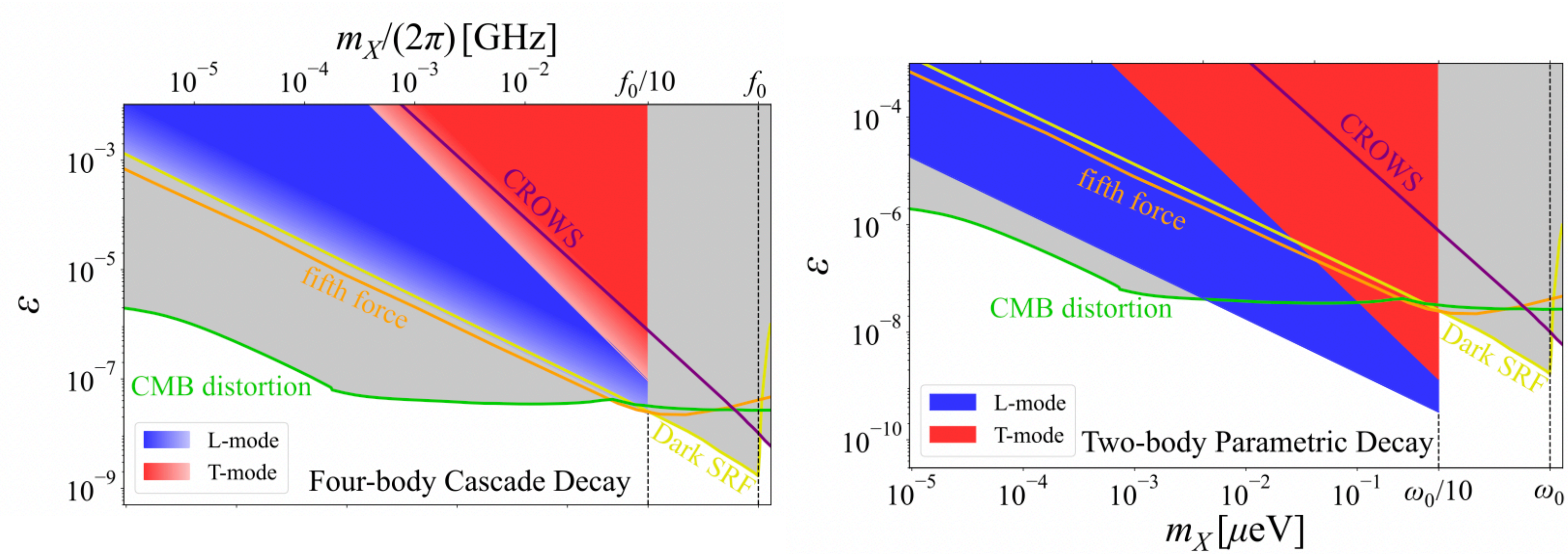




Y. Zeng et al, *Sci.Bull.* 70 (2025) 661-666.

SRF Constraints for Galactic Dark Photons

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



- Gradient color region represents exclusion for different DM mass

Y. Zeng et al, *Sci.Bull.* 70 (2025) 661-666.

A brief introduction to the team member

SHANHE collaboration

SHANHE
(mountains and rivers)

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

SHANHE collaboration

Research Group Members

Full-time Staff: 1 Professor, 1Associate Research Fellow, 1 Postdoctoral Researchers, 1 Lecturer, 3 Ph.D. Students

Prof. Jing Shu

- **B.S.** Peking University
  Ph.D. University of Chicago
- Returned to China under the Youth Thousand Talents Program in 2012
- Achievement in Asia Award by International Organization of Chinese Physicists and Astronomers in 2019
- National Science Fund for Distinguished Young Scholars, 2020
- Current BOYA Distinguished Professor, Peking University
- Overall team development

Assoc. R. F. Zhenxing Tang

- **B.S.** Lanzhou University
  Ph.D. University of Science and Technology of China
- Postdoc. Dalian Institute of Chemical Physics, 2015
- Senior Microwave Engineer, Neusoft Medical Systems, Shenyang, 2016
- Assoc. R. F., USTC, 2017 – specializing in accelerator physics design and project engineering
- Current Assoc. R. F., Peking University
- Project engineering for the team

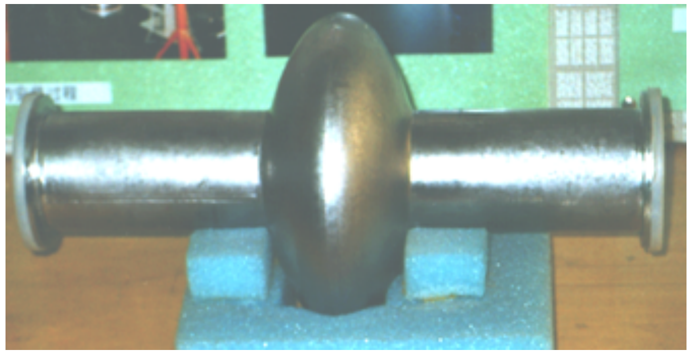
Postdoc. Yifan Chen

- **B.S.** University of Science and Technology of China
  M.S. École Polytechnique, Paris
  Ph.D. Sorbonne University, France
- Postdoc., Institute of Theoretical Physics, Chinese Academy of Sciences, 2019
- Currently Postdoc. at the Niels Bohr Institute, University of Copenhagen, focusing on particle physics, black hole gravity, and quantum precision measurement.
- Fundamental Theory for the team

Lecturer Bo Wang

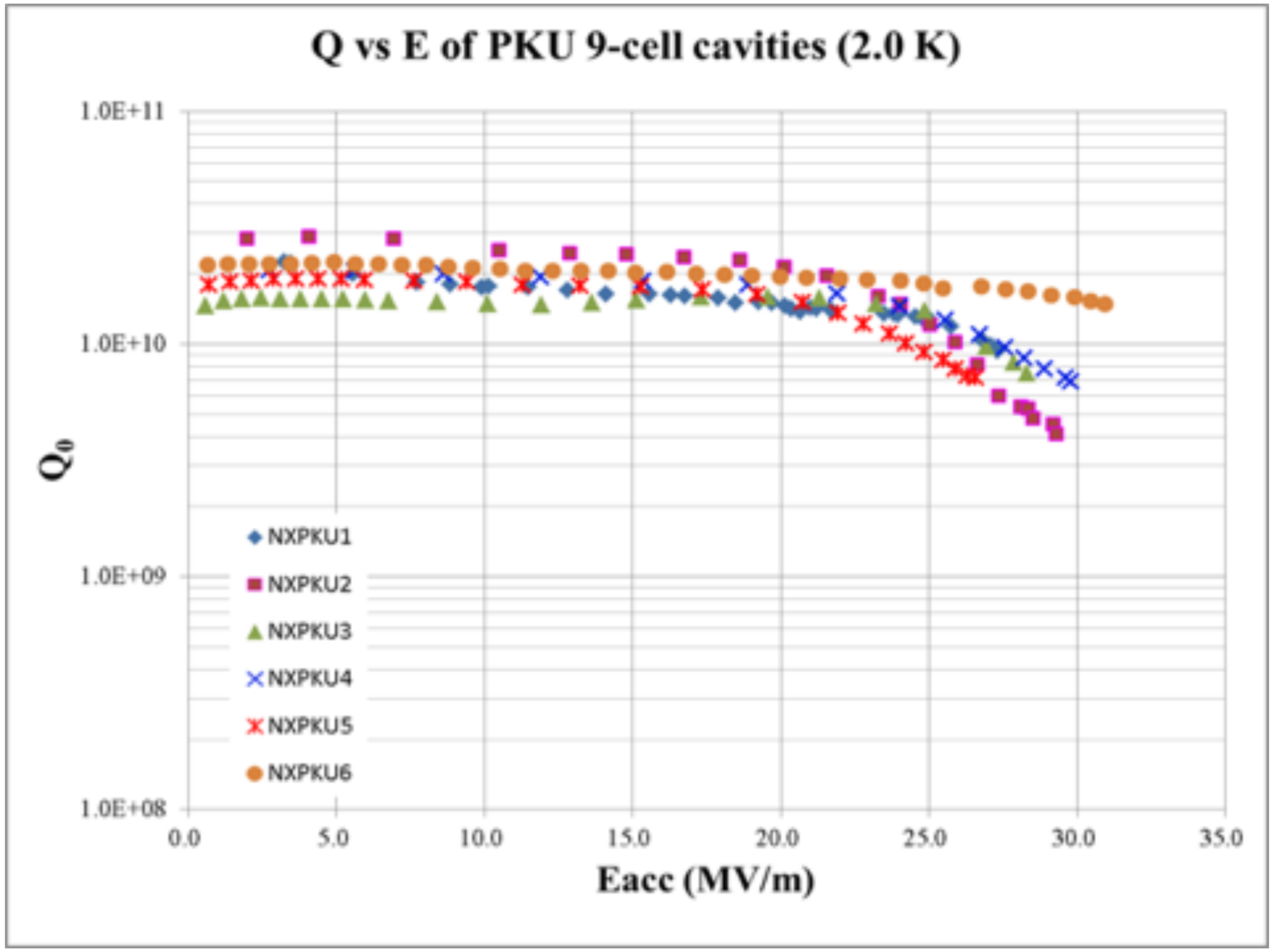
- **B.S.** Southeast University
  M.S. Northeastern University
  Ph.D. University of Chinese Academy of Sciences
- Currently Lecturer at Ningxia University.
- Under Ph.D. advisor Shu Jing, researching dark matter, high-frequency gravitational waves, astrophysics and quantum precision measurements
- Theoretical and experimental research on detecting ultralight dark matter using superconducting cavities

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

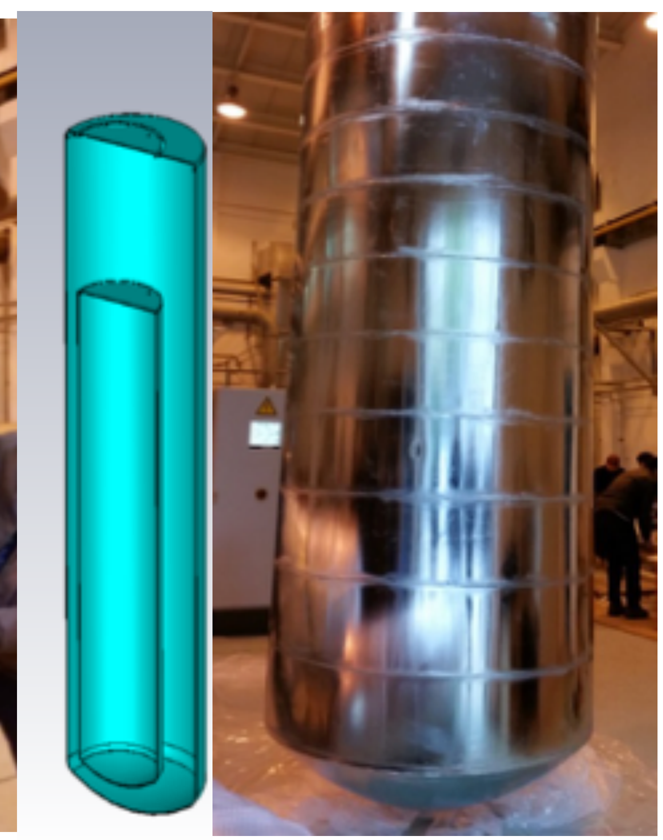
Experimental facilities

Liquid helium system

2K pumping system

Vertical Dewar

Cavity suspension

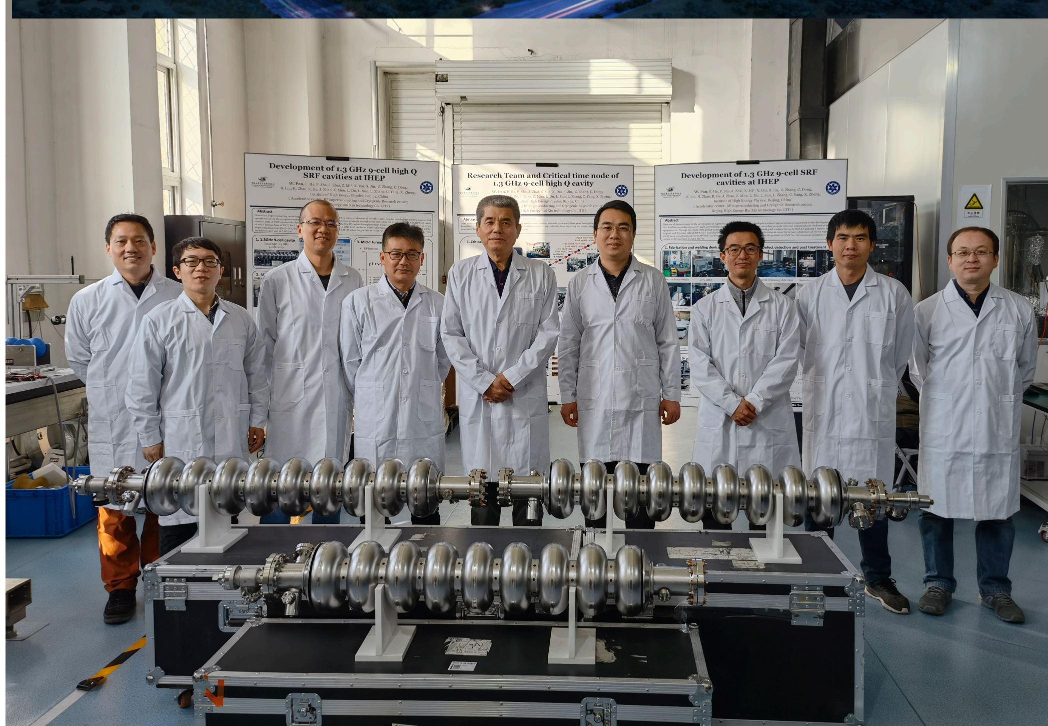


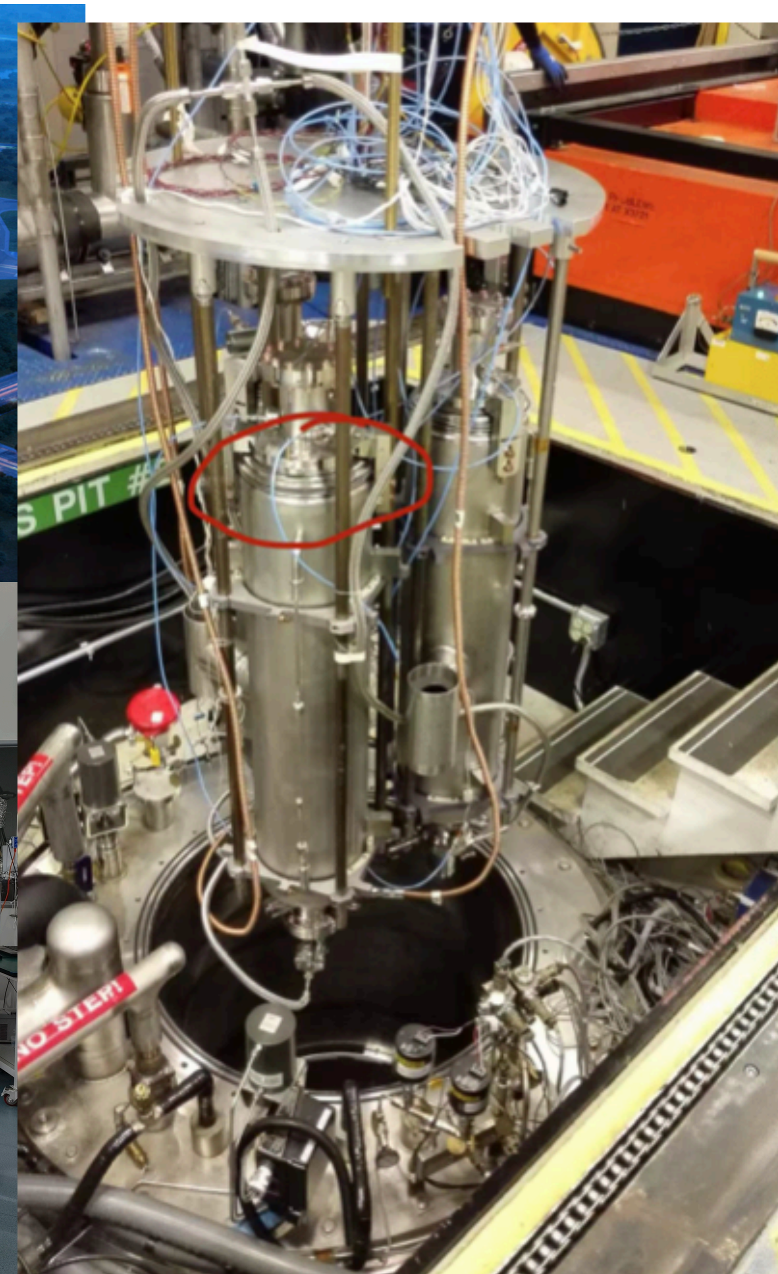
Magnetic shielding

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

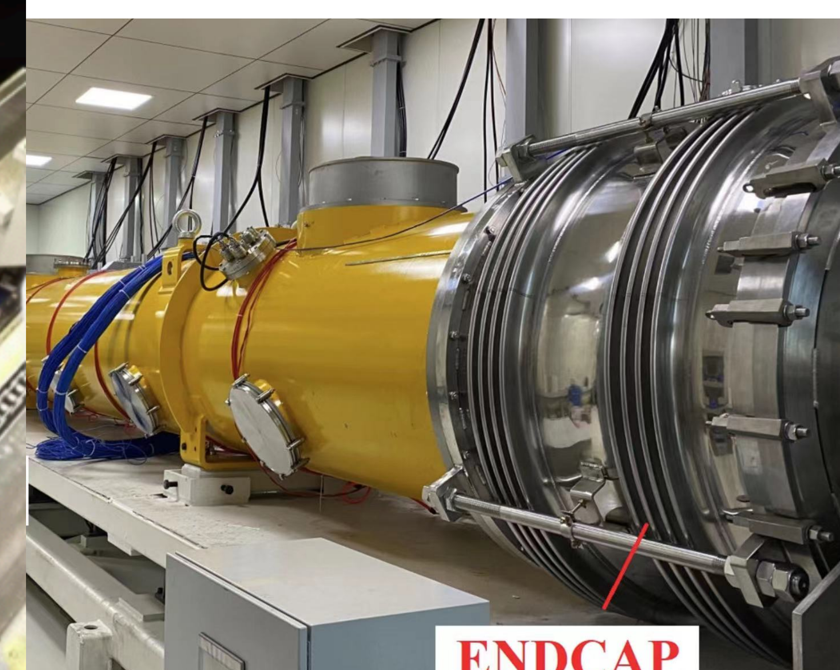
SRF in IHEP

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



International SRF Campaigns

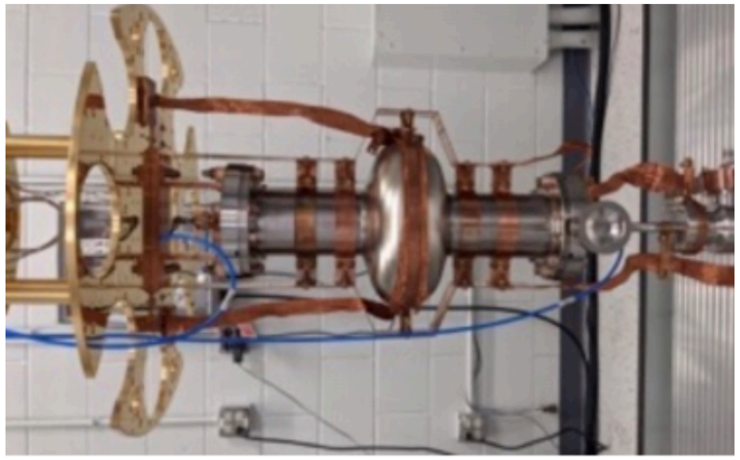
▶ Fermi-Lab SQMS

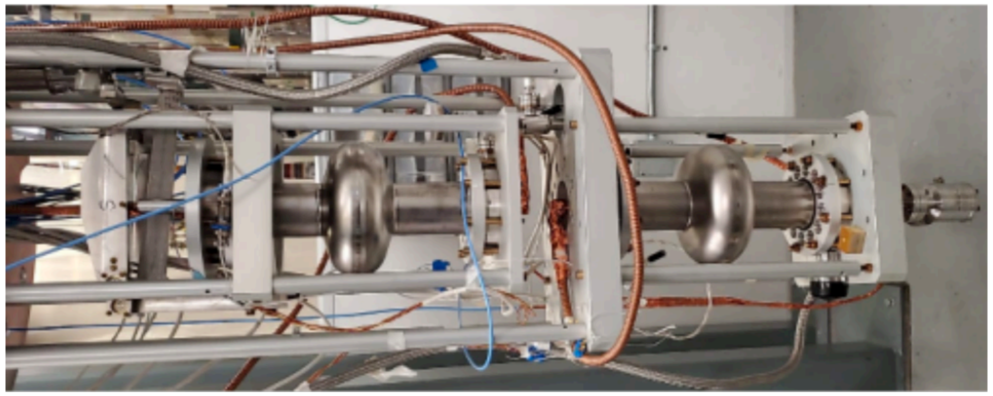
•SERAPH:

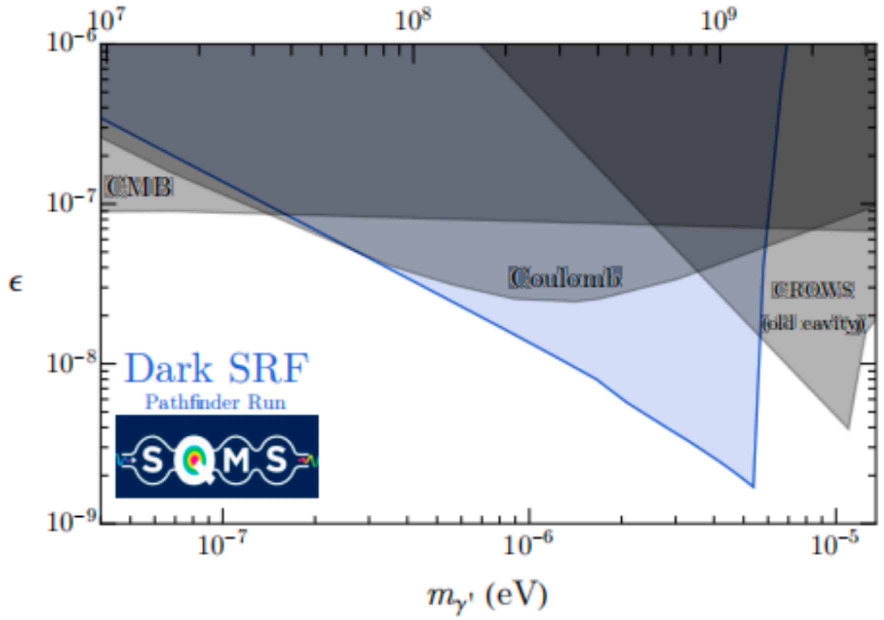
Single-bin search and ongoing scan searches

•Dark SRF:

Light-shining-wall search for dark photon







▶ DESY:

•MAGO 2.0

Mode transition from GW-induced cavity deformation

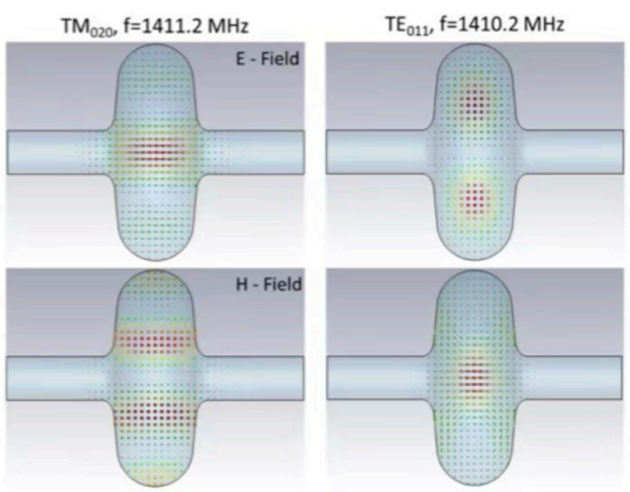
Axion search

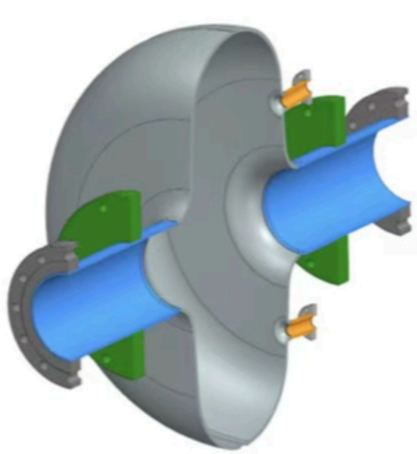
TDR like

SHANHE collaboration

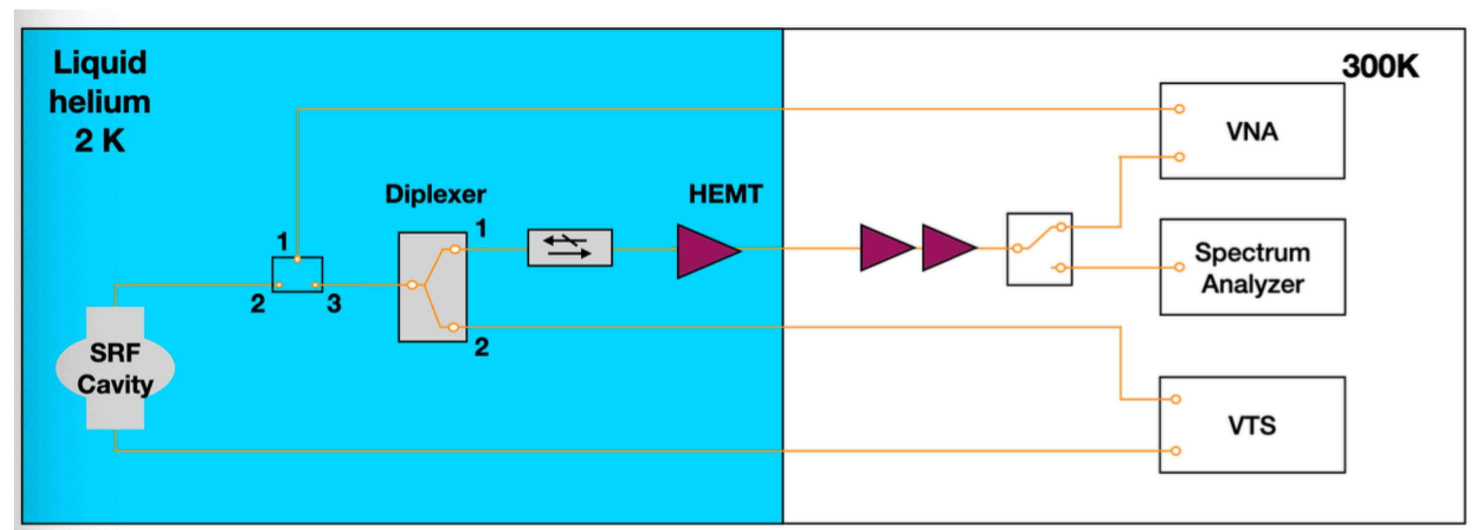
Fermilab

arXiv:2207.11346

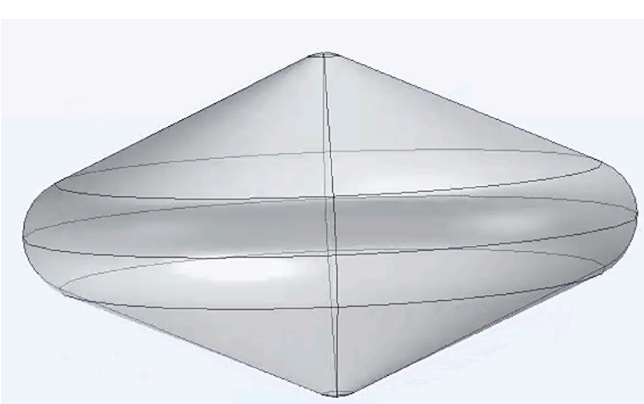




Using the existing 1.3G cavity as a pathfinder



New designed cavity will be operated in the future.



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, etc), much more can be done .

Thank you!