SRF Cavity Physics

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? (preliminary)
- Experimental group
- Summary and Outlook

Motivation of ultra-light dark matter

Various DM candidate

stereo
neutrino、X
ray astronomy

PBH,MACHOs, etc

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

Wave-like DM

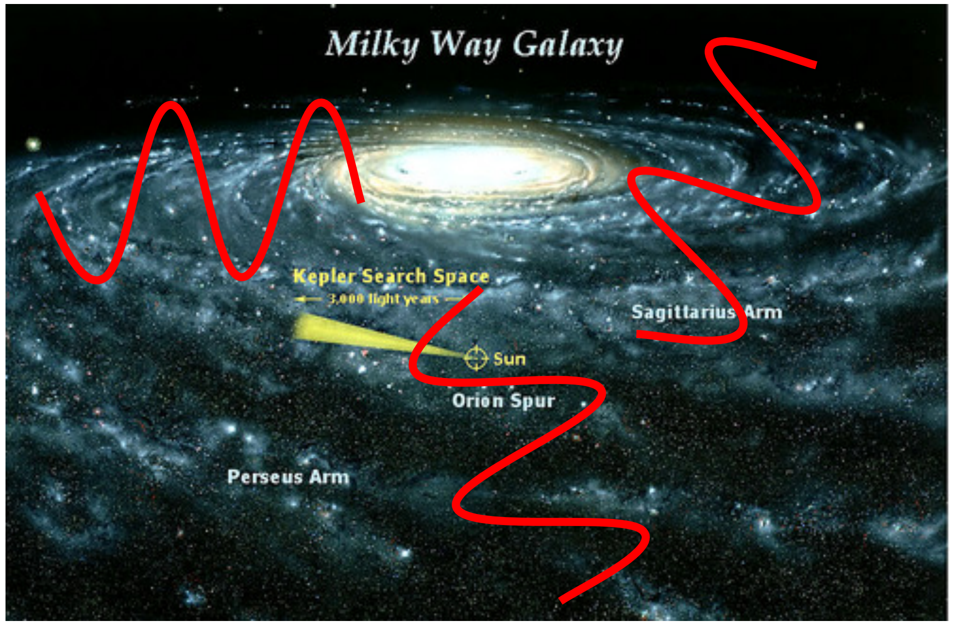
WIMPs: direct (indirect)detection、collider searches

particle-like DM

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

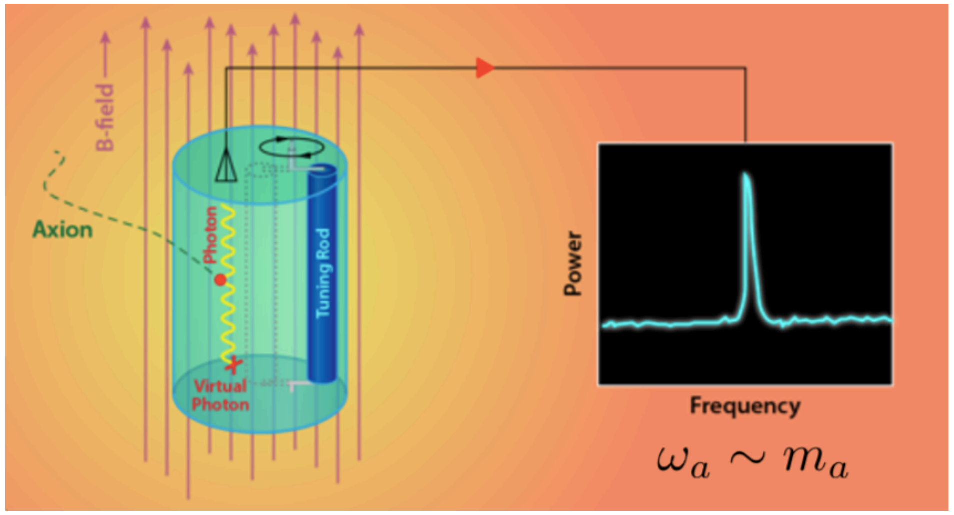
The ultra-light DM

QM： All matter exhibits both particle and wave properties.



(m~10^{-22} eV)

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



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

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)

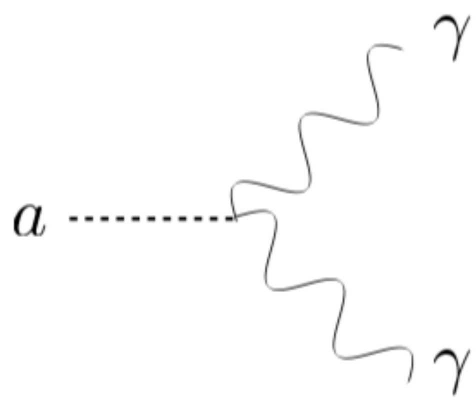
Haloscope, Quantum amplifier

New search methods!!!

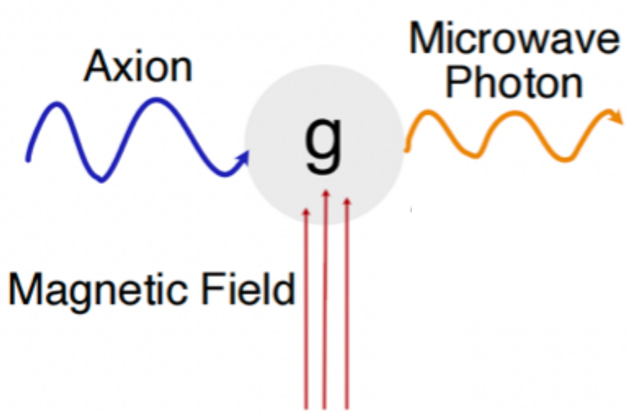
Quantum sensor

Ultra-light DM candidate

Axion (ALP)： spin 0， CP odd



Inverse Primakoff effect



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

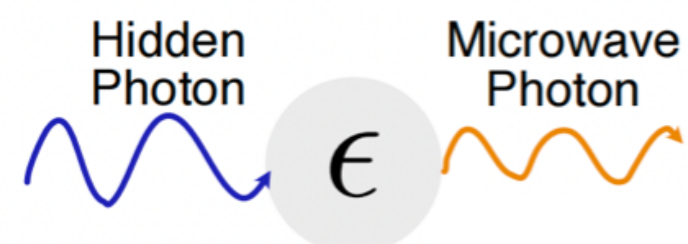
induces an effective current
under strong magnetic field.

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

Dark photon： spin 1

mili-charge particles?

kinetic mixing

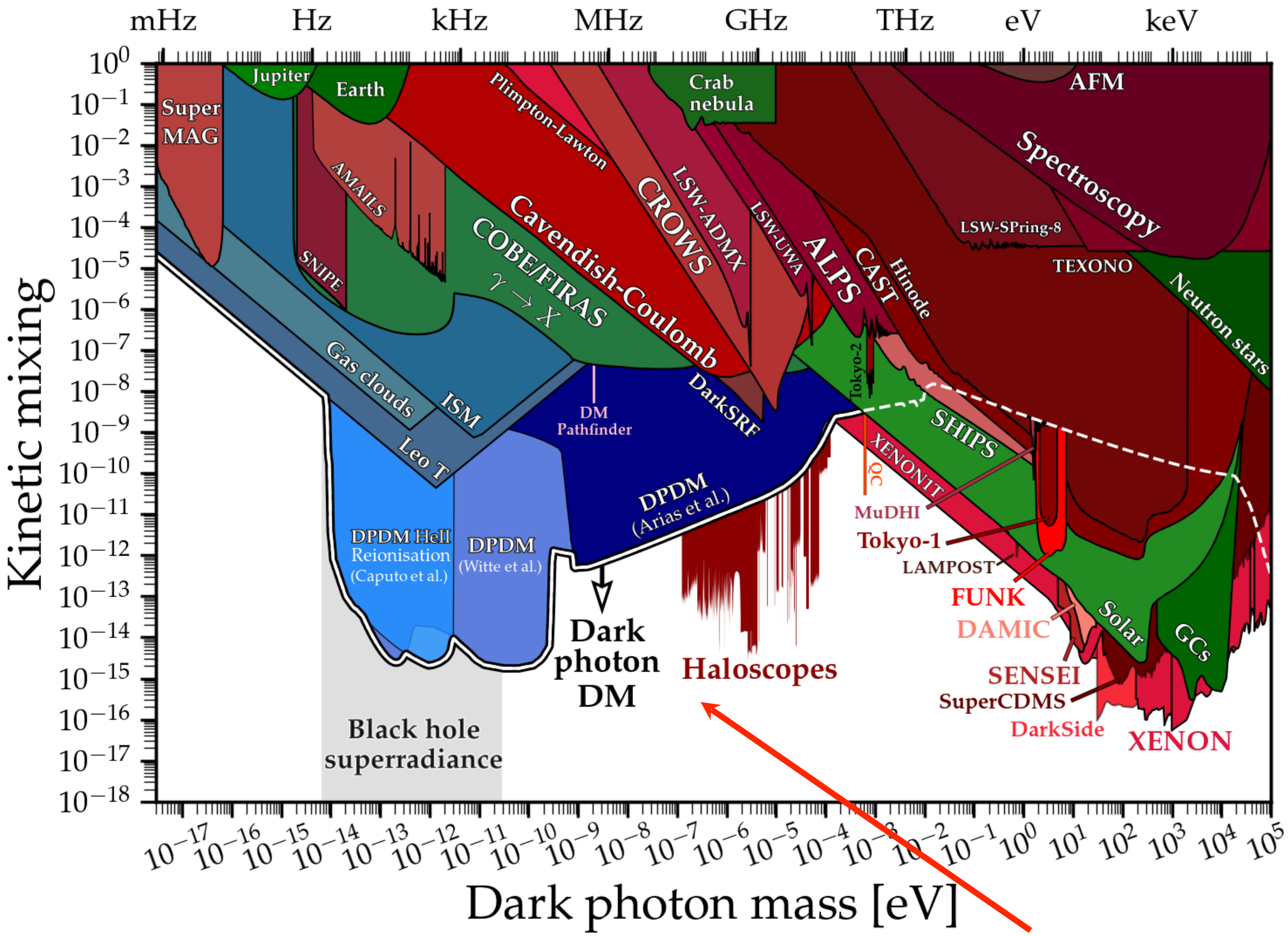


$$\mathscr{L} \supset -\tilde{A}_\mu \left(e J^\mu_{EM} - \varepsilon m^2_{A'} \tilde{A}'^\mu \right)$$

induces an effective current
anyway.

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

Current DPDM search



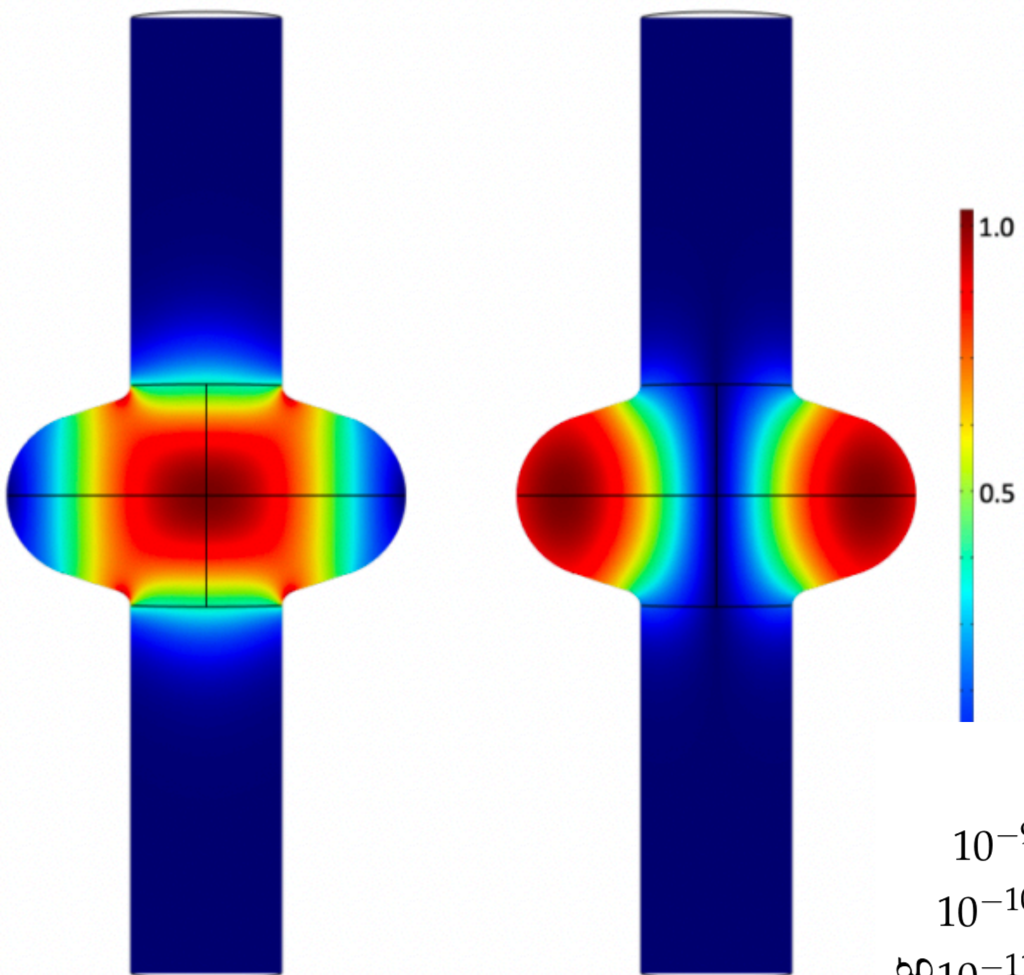
Still a lot of room to detect

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

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

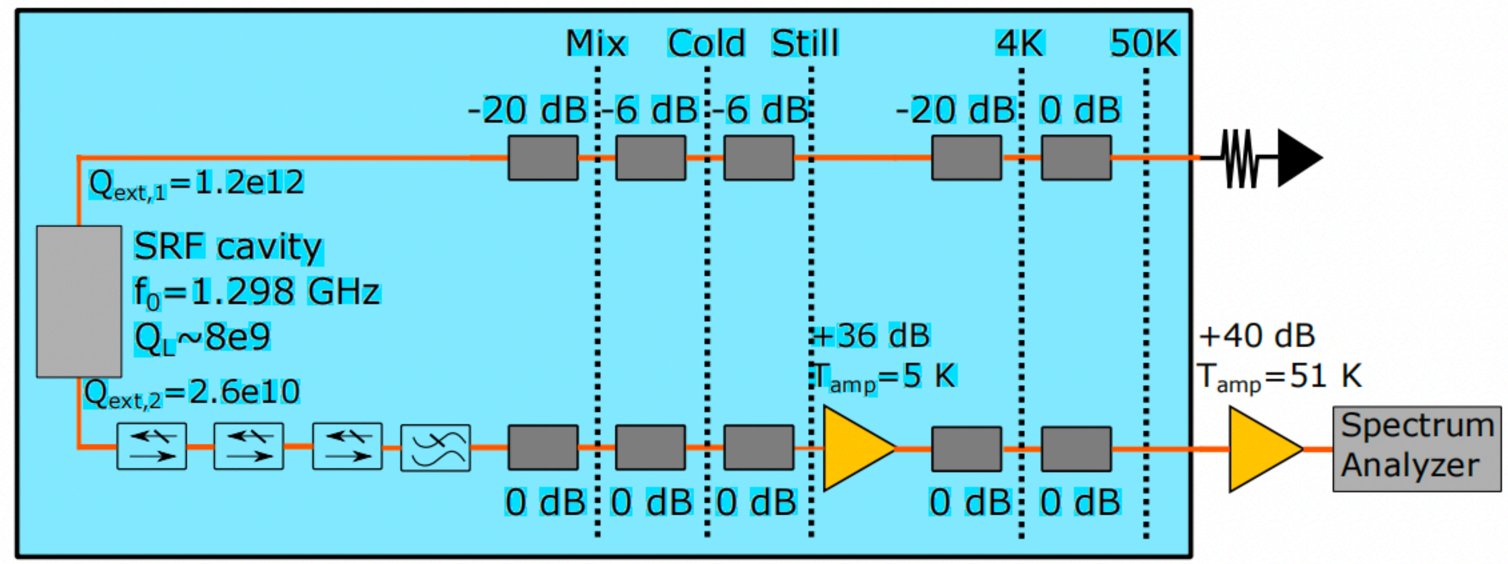
Axion limit webpage: https://github.com/cajohare/AxionLimits/blob/master/docs/dp.md

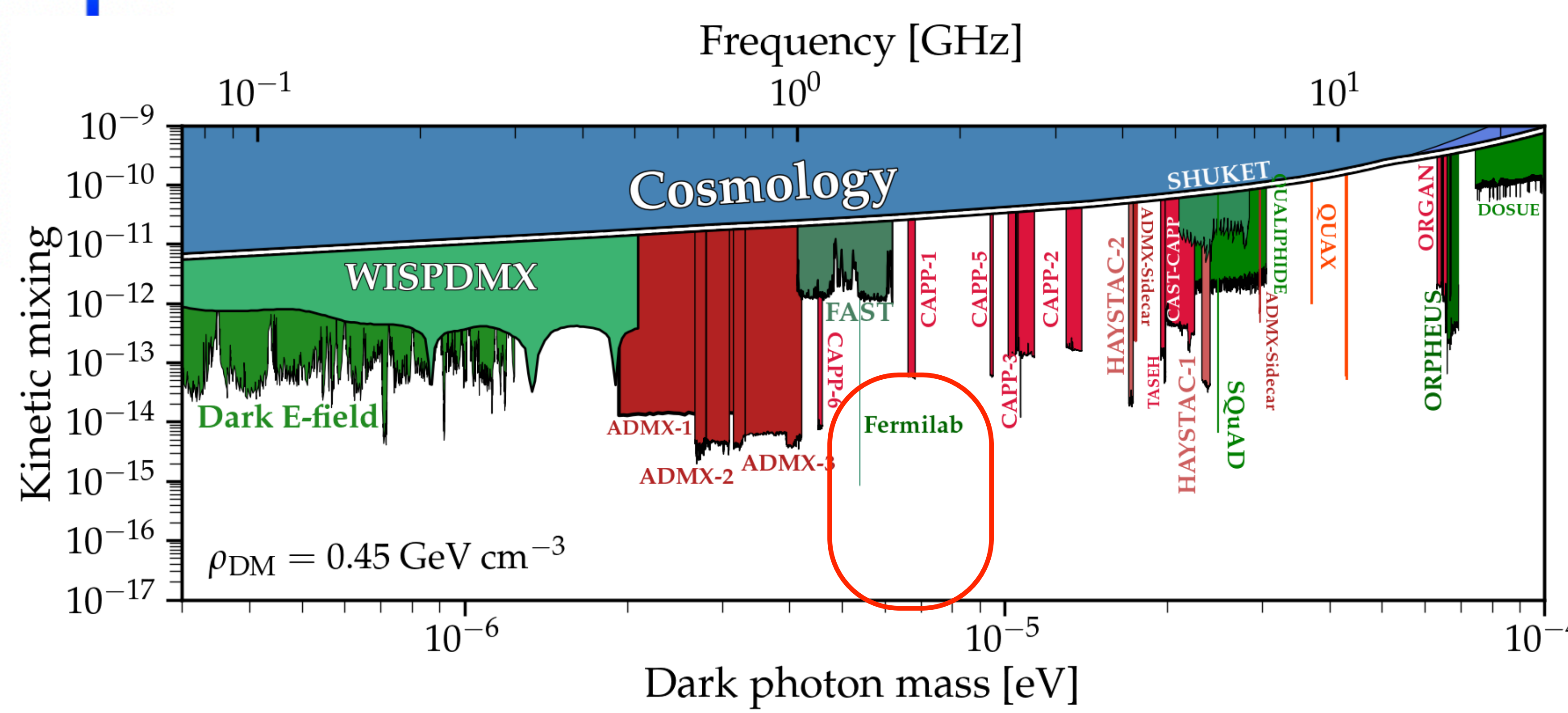
美国费米实验室 (2022)



最高的探测灵敏度(22s)

Q~8.7*10^9



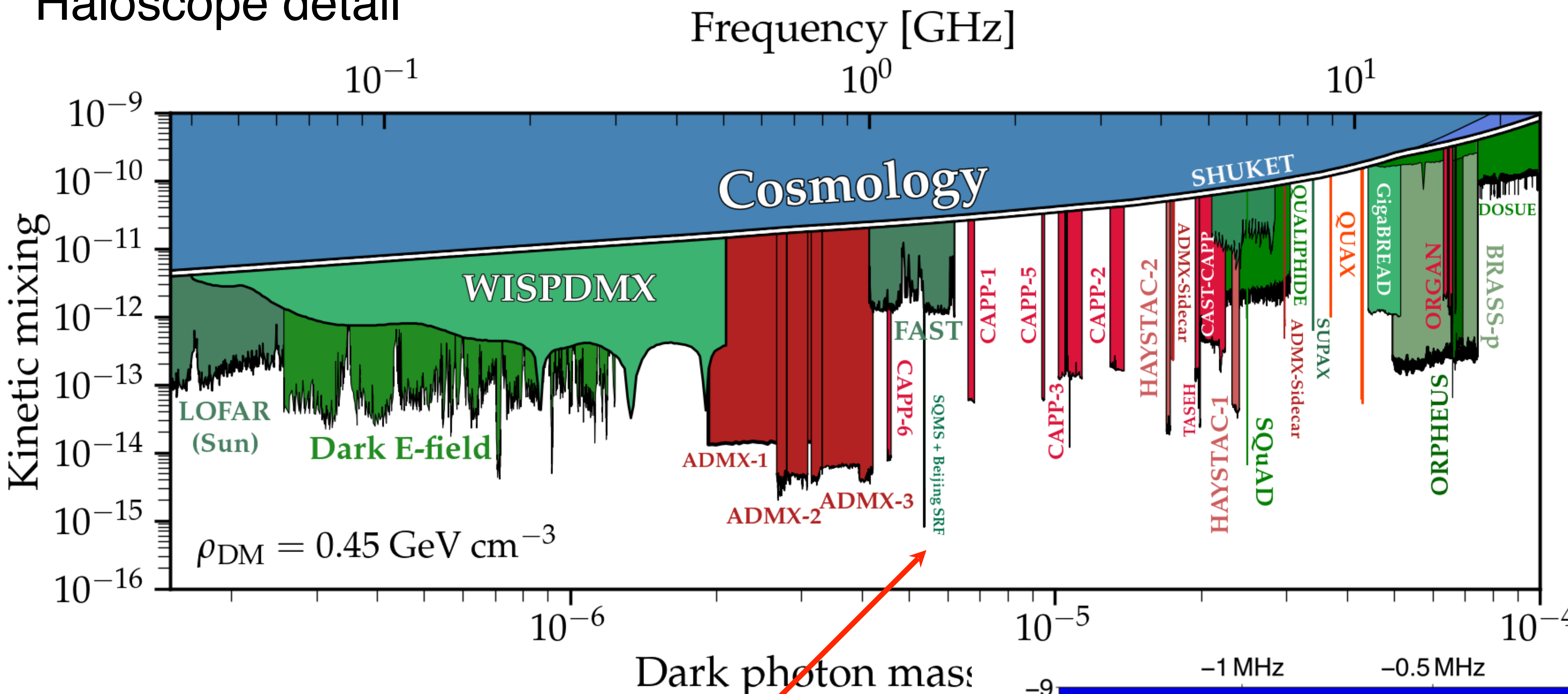


R. Cervantes,[1,*] C. Braggio,[2,3] B. Giaccone,[1] D. Frolov,[1] A. Grasselino,[1] R. Harnik,[1] O. Melnychuk,[1] R. Pilipenko,[1] S. Posen,[1] and A. Romanenko[1]

2203.03183

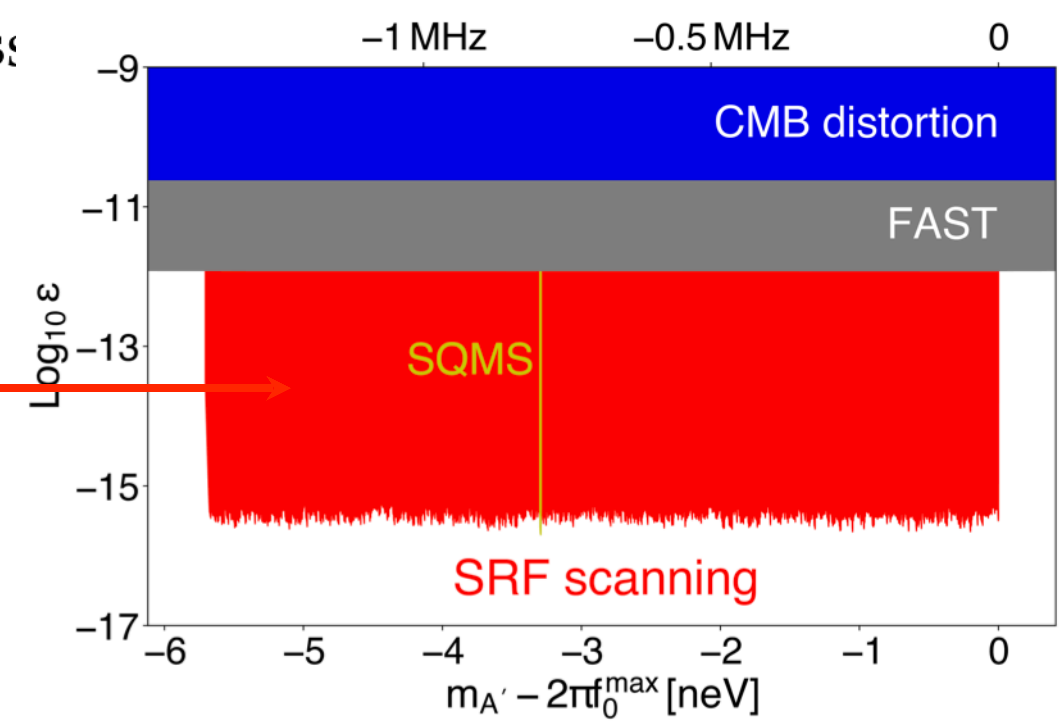
DPDM search

Haloscope detail



arxiv: 2305.09711

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

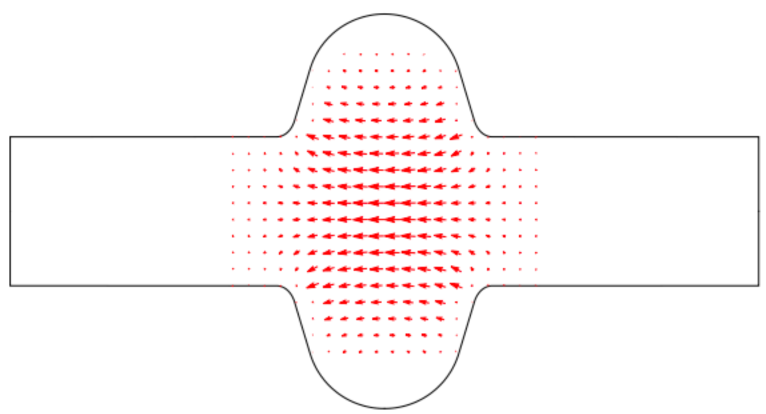
$$\lambda_a \sim 1/m_a\sqrt{\langle v_{\rm DM}^2\rangle} \sim 10^3/m_a$$

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)



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

SRF Cavity Searches for Dark Photon Dark Matter: First Scan Results

Zhenxing Tang,[1,2,*] Bo Wang,[3,*] Yifan Chen,[4] Yanjie Zeng,[5,6] Chunlong Li,[5] Yuting Yang,[5,6] Liwen Feng,[1,7] Peng Sha,[8,9,10] Zhenghui Mi,[8,9,10] Weimin Pan,[8,9,10] Tianzong Zhang,[1] Yirong Jin,[11] Jiankui Hao,[1,7] Lin Lin,[1,7] Fang Wang,[1,7] Huamu Xie,[1,7] Senlin Huang,[1,7] and Jing Shu[1,2,12,†]

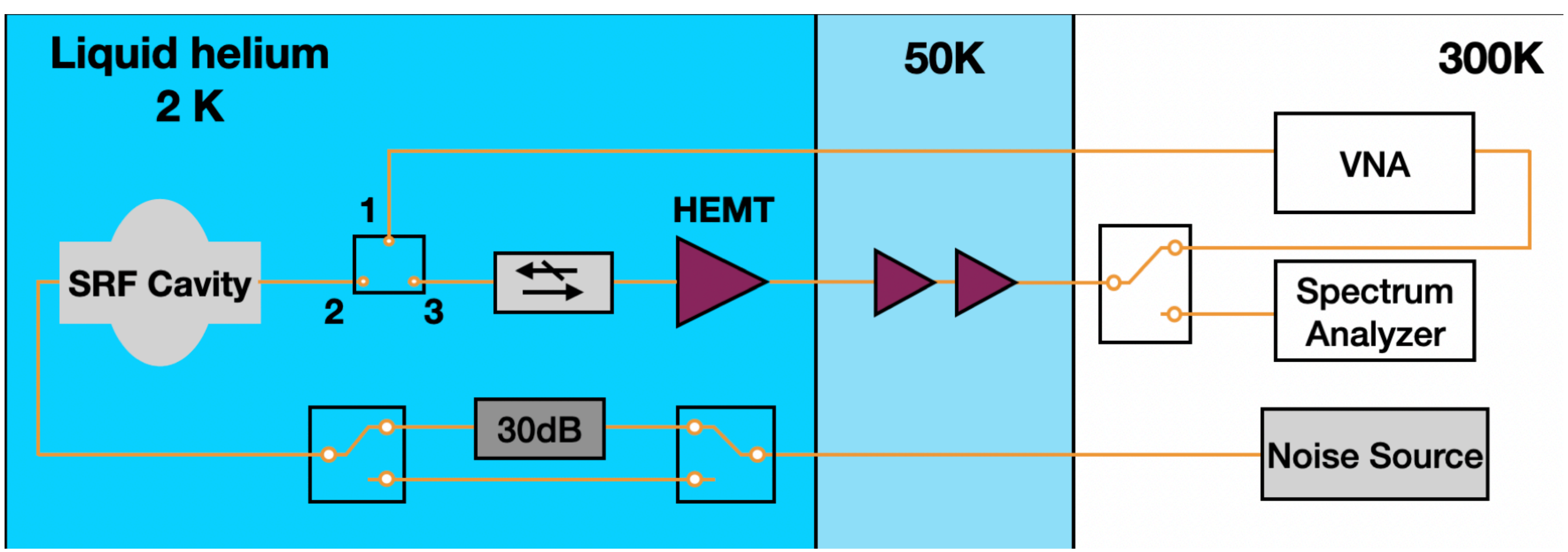
arxiv: 2305.09711

Experimental operation

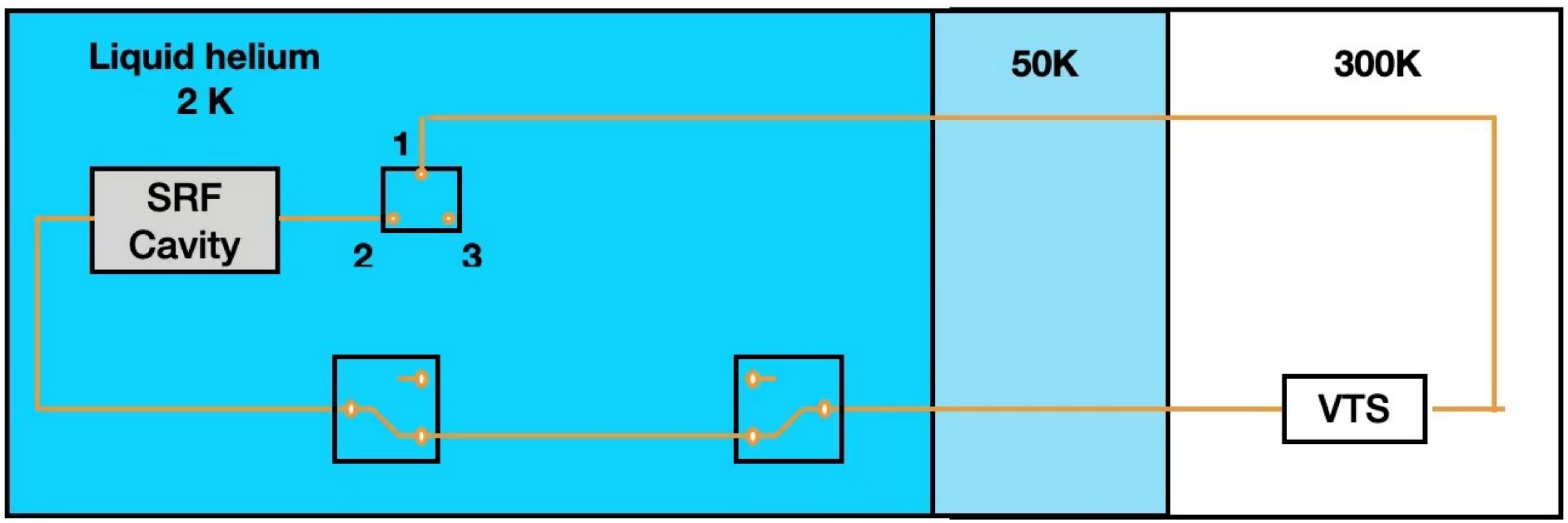
Parameters

	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

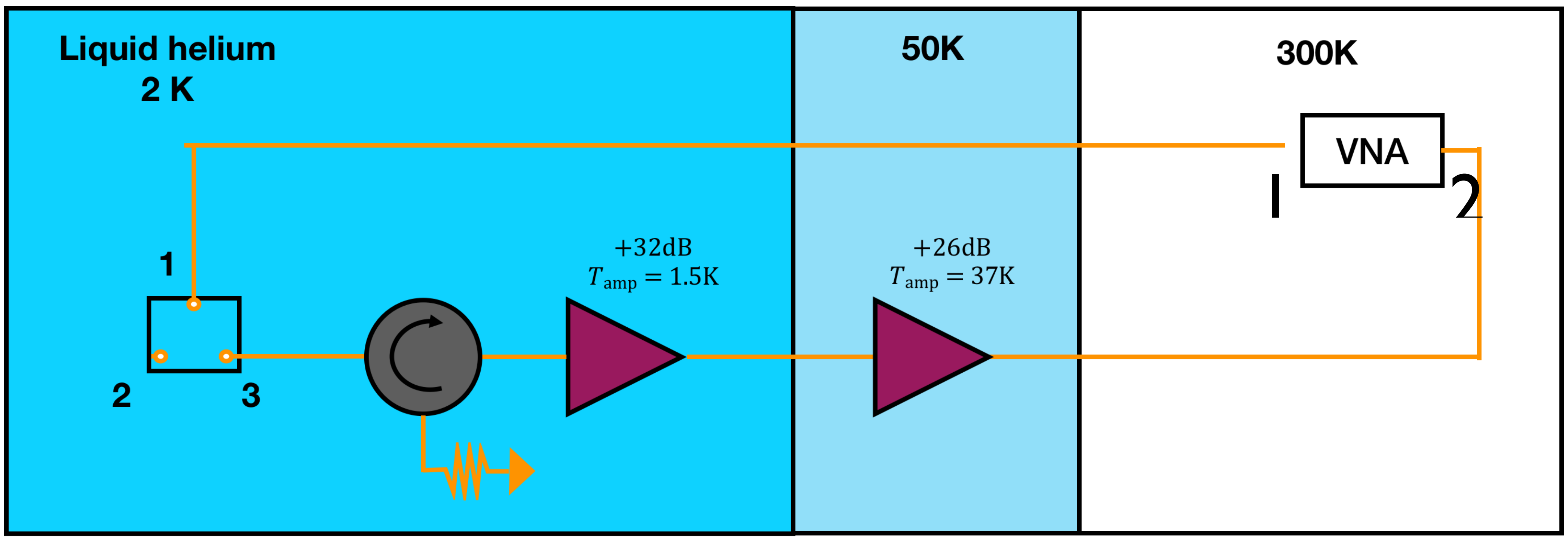


Step 1: Measure Cavity property



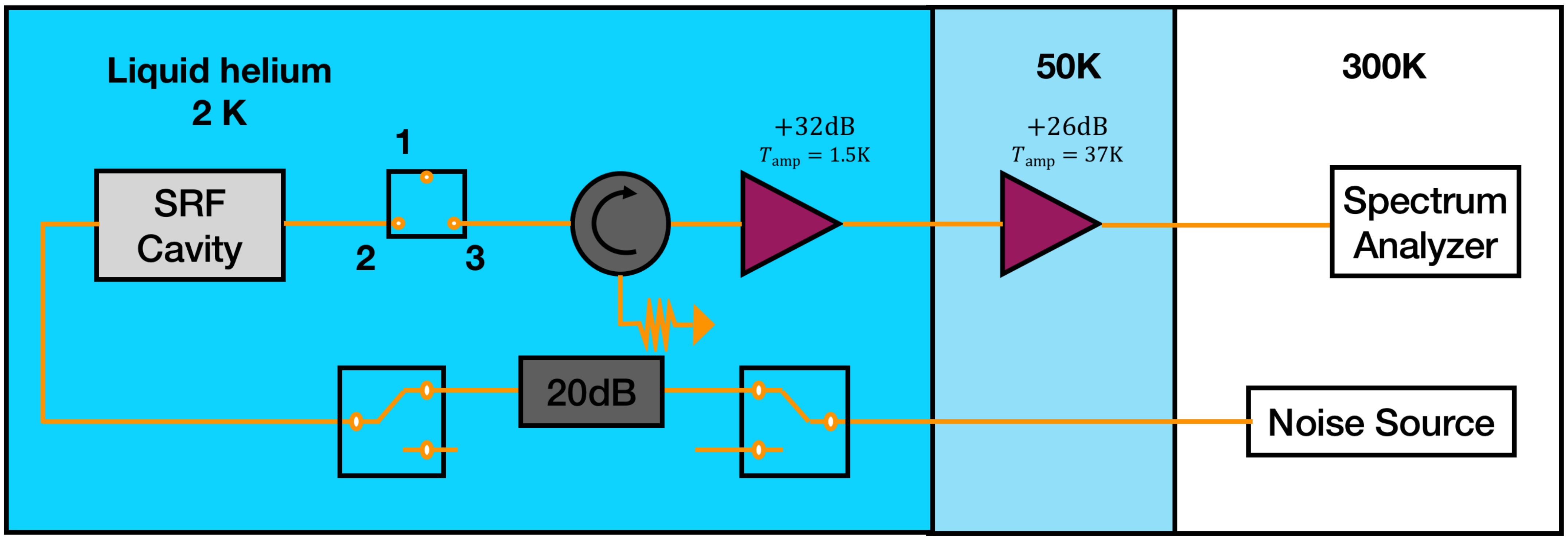
1-2 connection: VTS measurement for the cavity property.

Step 2: calibration



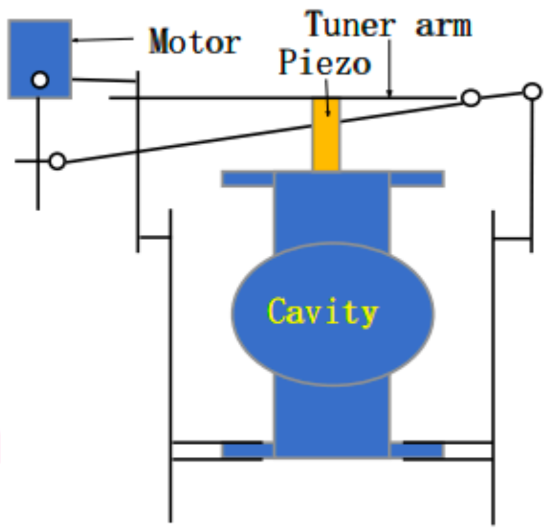
1-3 connection: calibration by subtracting the line loss to get the total gain G_net.

Step 3: Do experiment

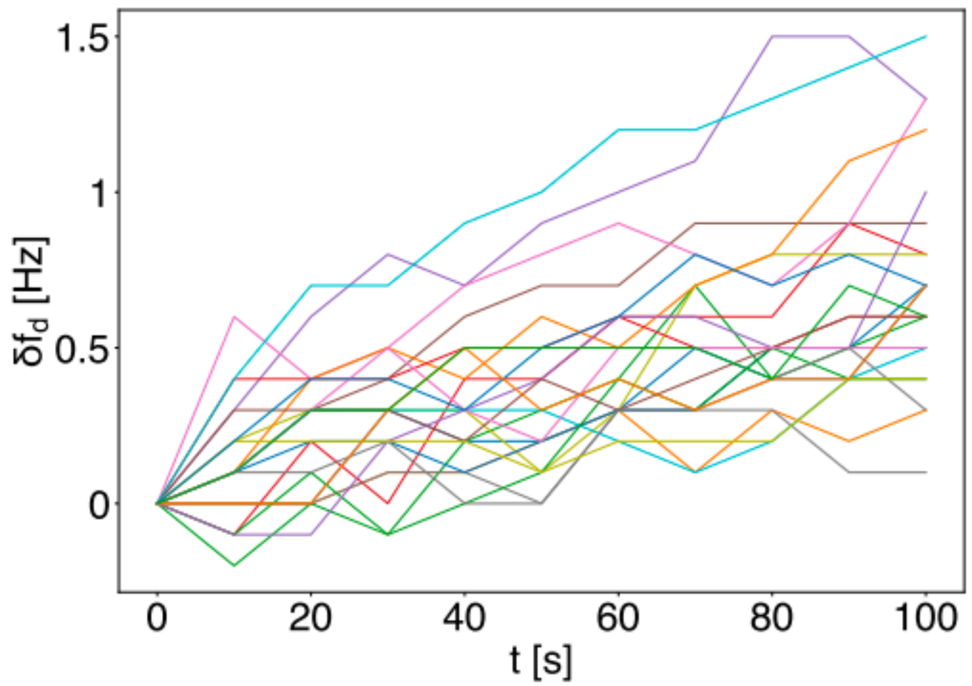


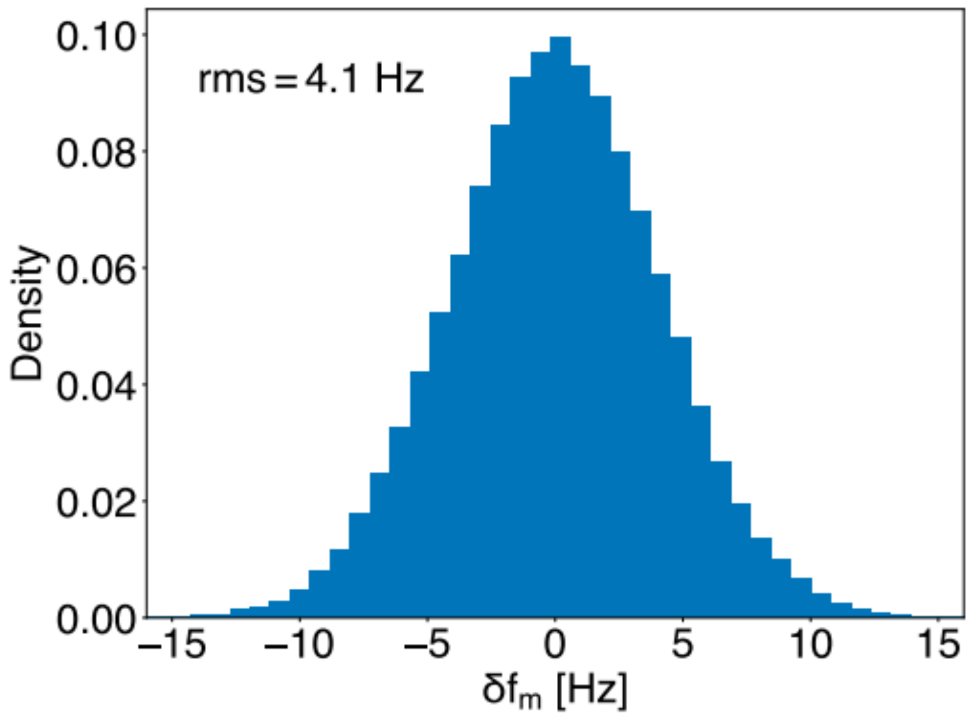
2-3 connection: tune the cavity resonant frequency to do the experiment

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 $\delta f_d \leq 1.5\rm Hz$ and microphonics effect $\sigma_{f_0} \approx 4\rm Hz$

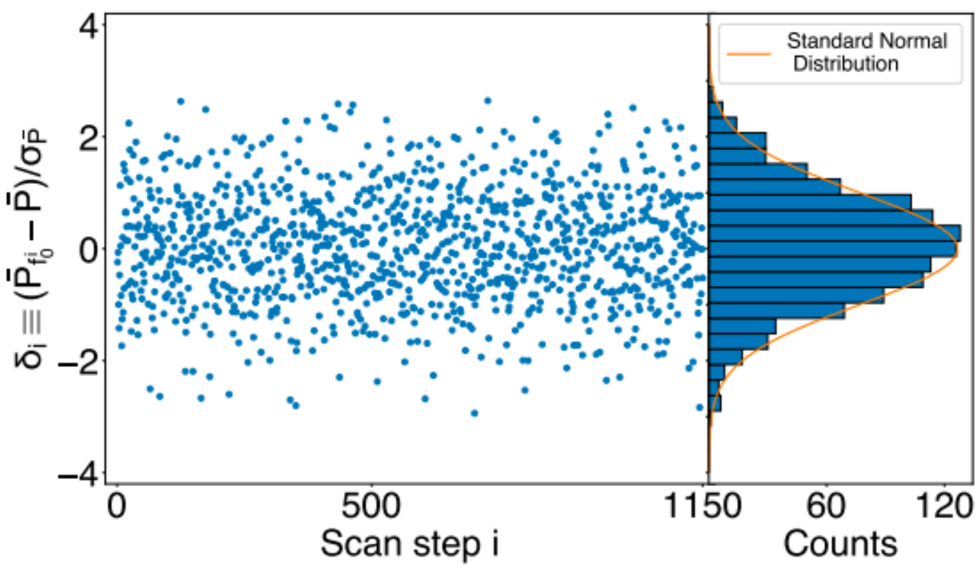


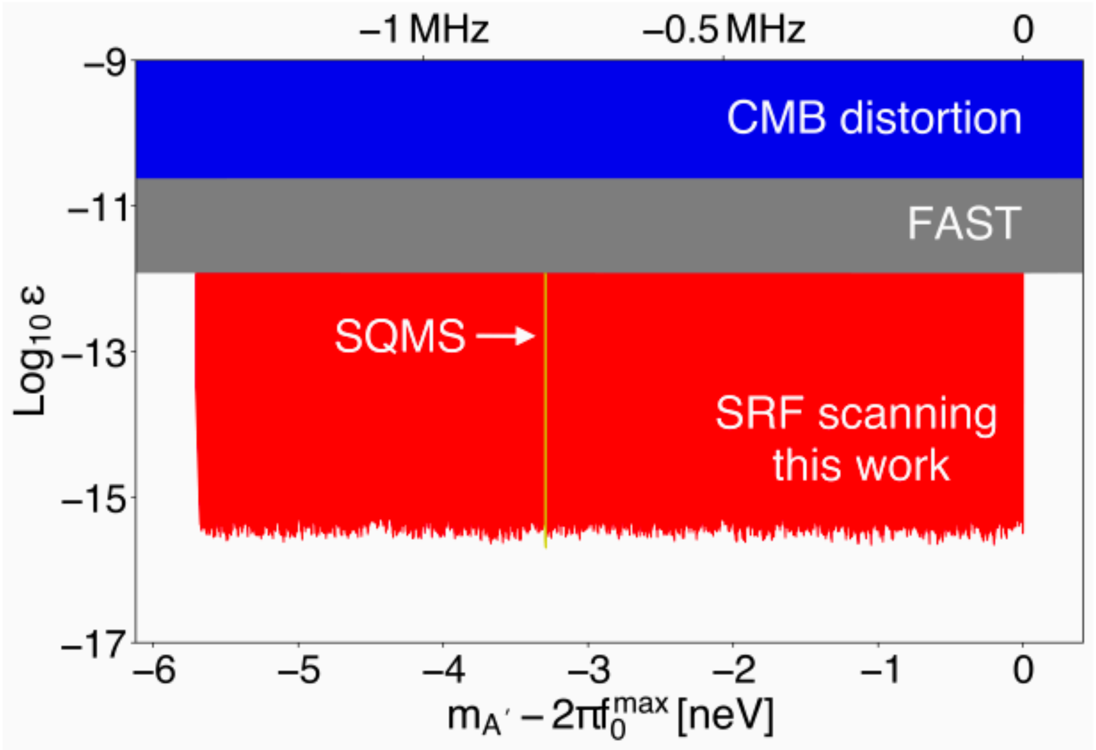


- **Conservatively** choose $\Delta f_0 \approx 10\rm Hz$

Data analysis and constraints

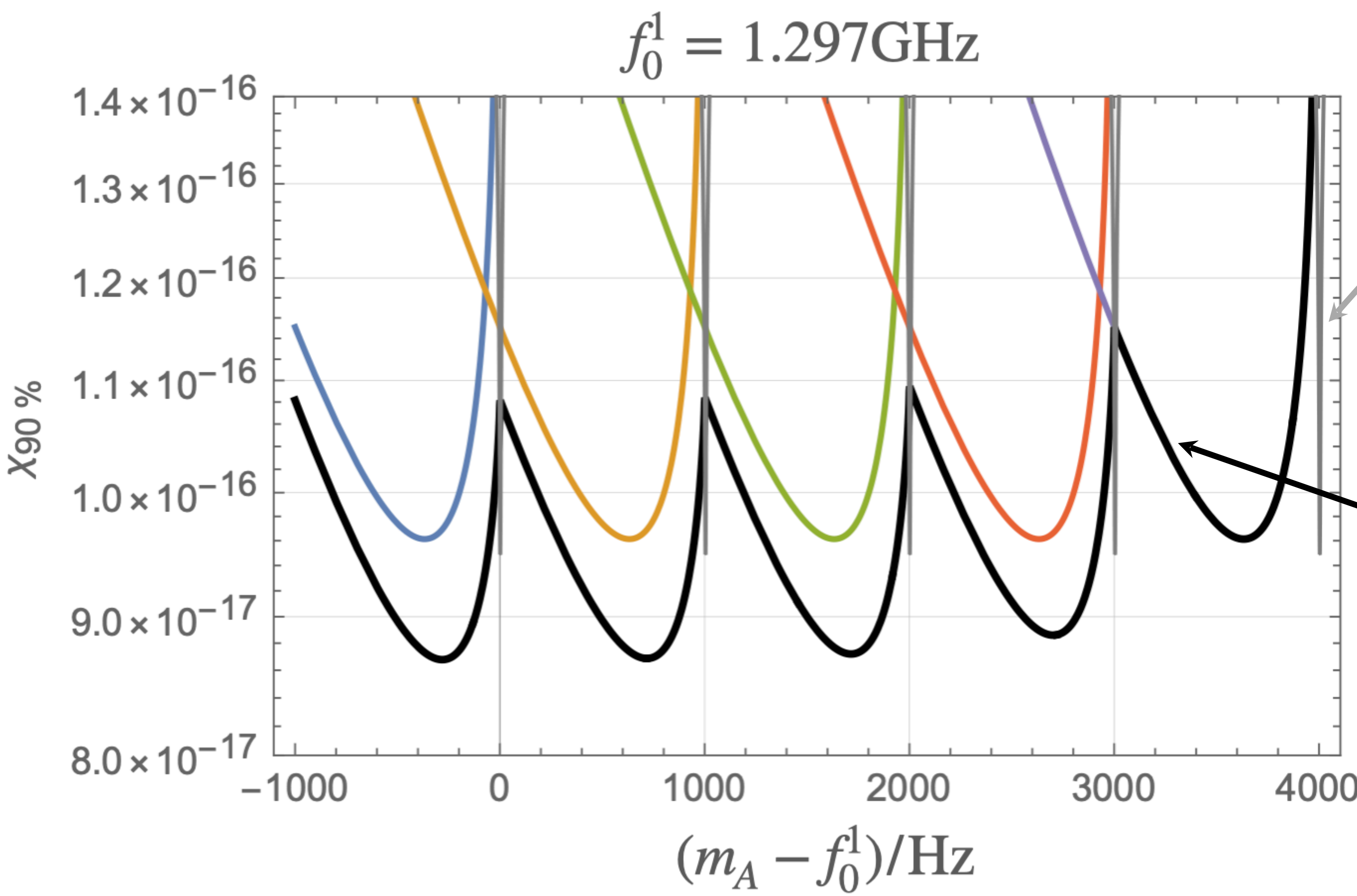
- Total 1150 scan steps with each 100 s integration time.
- **Group every 50 adjacent bins** and perform a constant fit to address small helium pressure fluctuation.
- Normal power excess shows **Gaussian distribution**:





- **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

Modulated Signal from Galactic Dark Photons

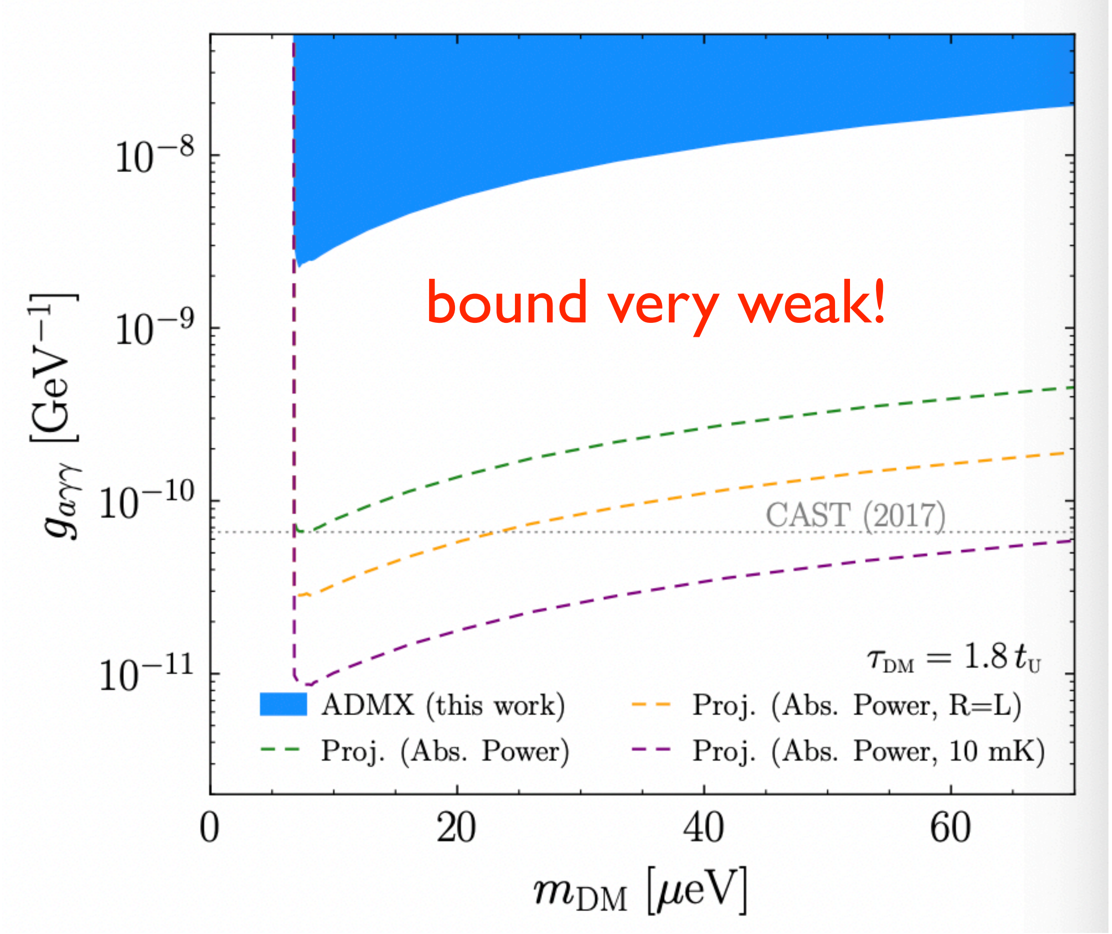
- How about galactic DP backgrounds? (Anisotropic backgrounds, from annihilation or decay?)

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



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

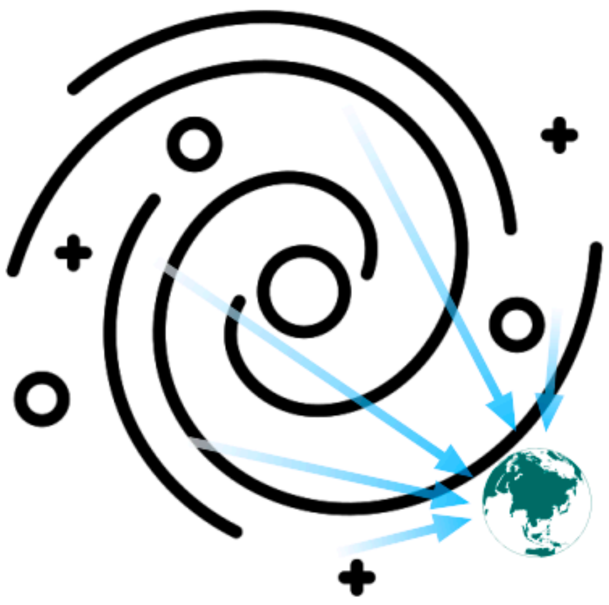
- Polarization

Longitudinal: from a dark Higgs

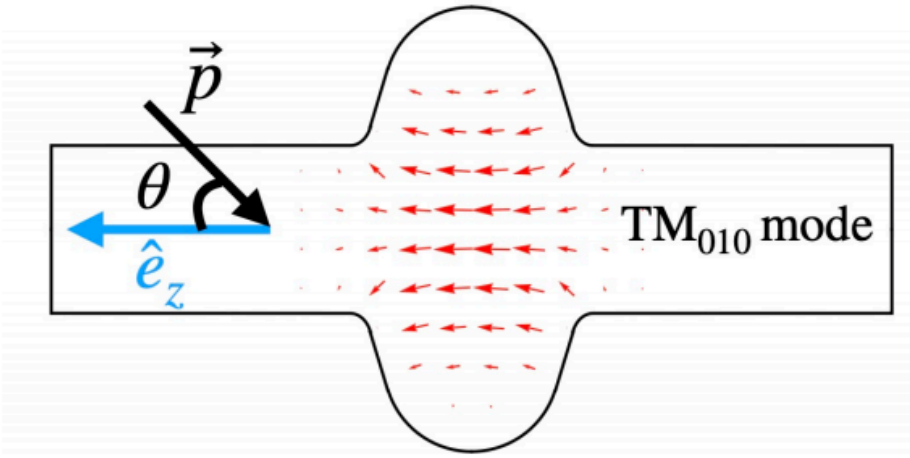
Transverse: axion-DP coupling

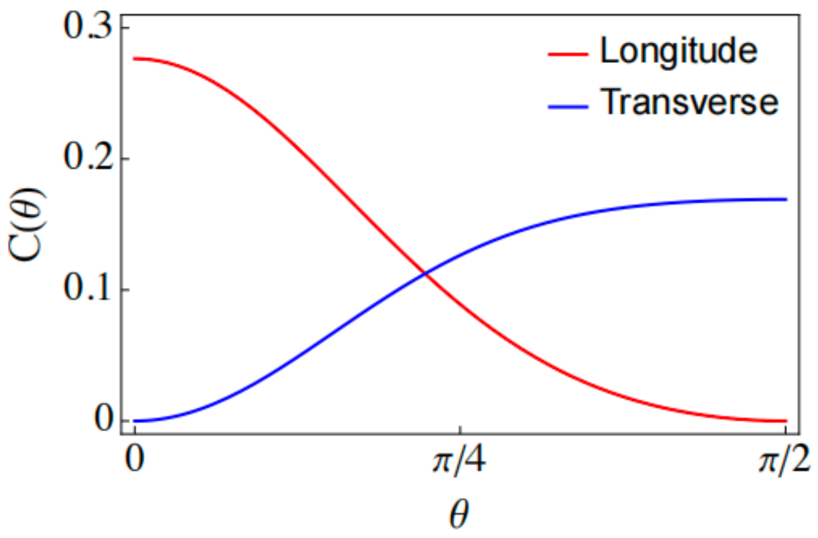
Modulated Signal from Galactic Dark Photons

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



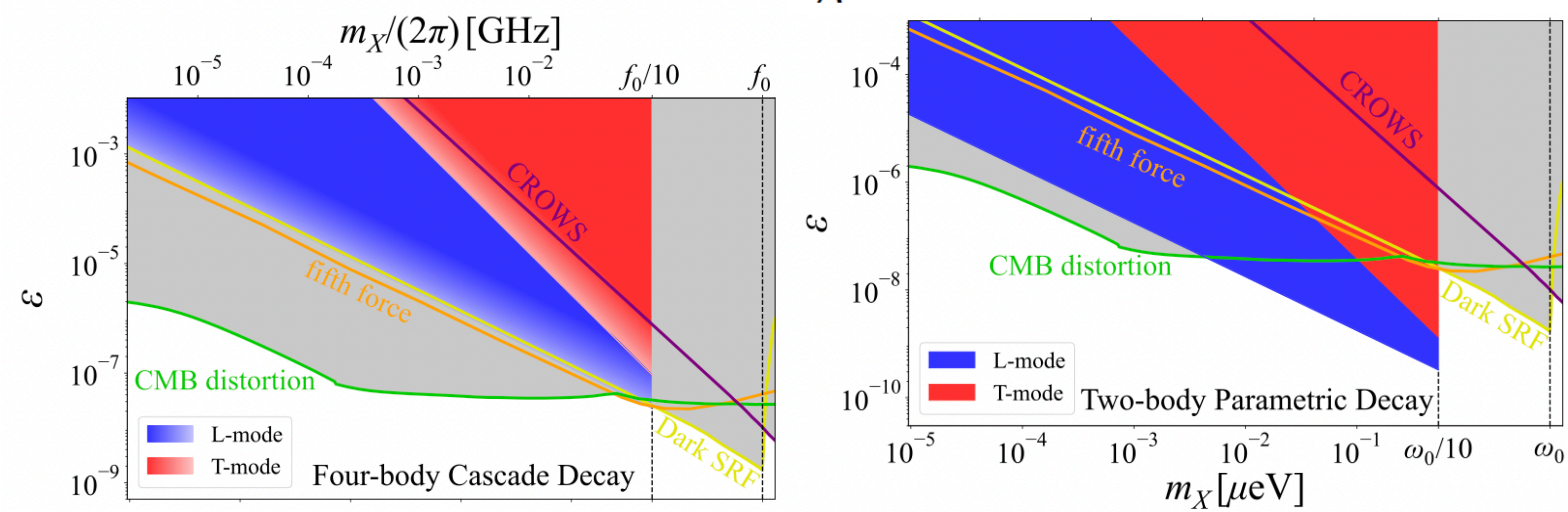
- **Vectorial** observable $\propto \vec{A}'$
  $\rightarrow$ angular-dependent signal $\propto C(\theta)$
  $\rightarrow$ modulation as the Earth rotates
- Production is polarization-dependent, modulations for longitude and transverse modes are opposite





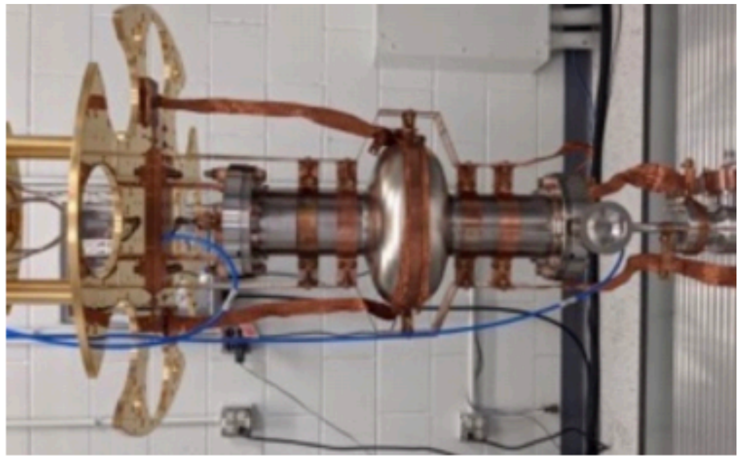
SRF Constraints for Galactic Dark Photons

- 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 $\sim \omega_{A'}/m_{A'}$



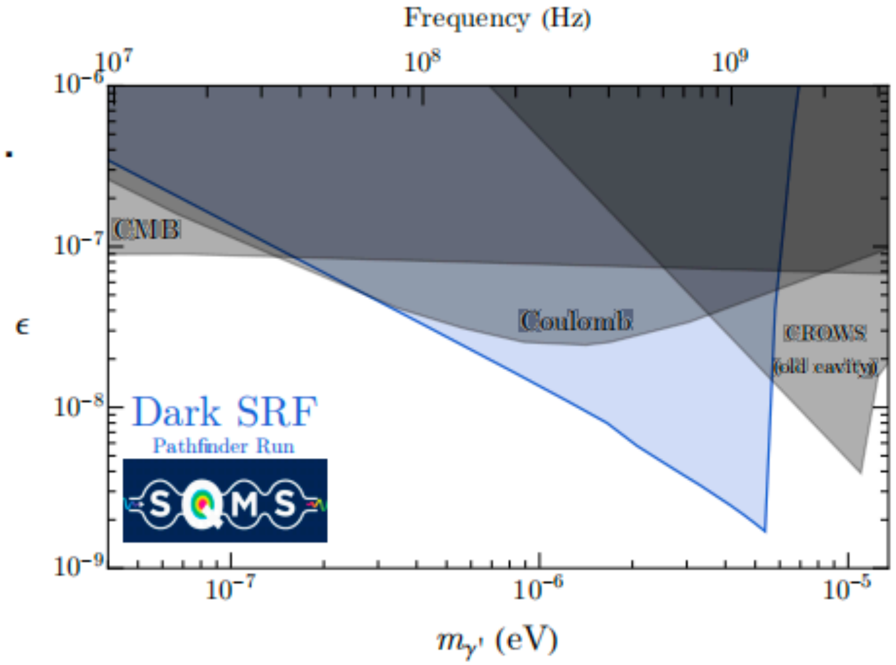
- Gradient color region represents exclusions for different DM mass

International SRF Campaigns

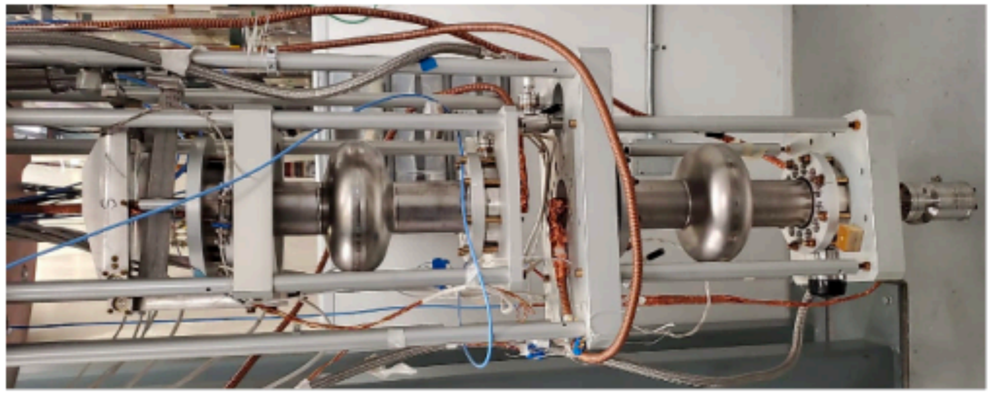


- **Fermilab SQMS**

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



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



- **DESY**:

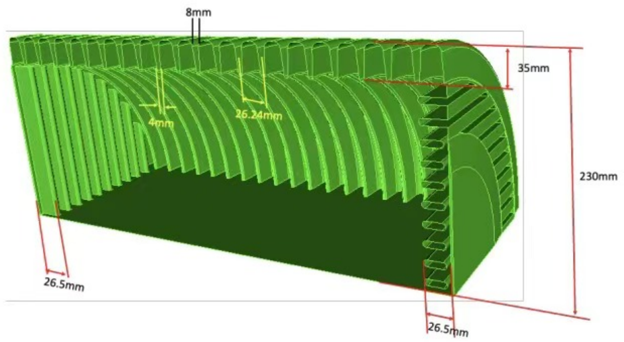
  •MAGO 2.0
  Mode transition from GW-induced cavity deformation.

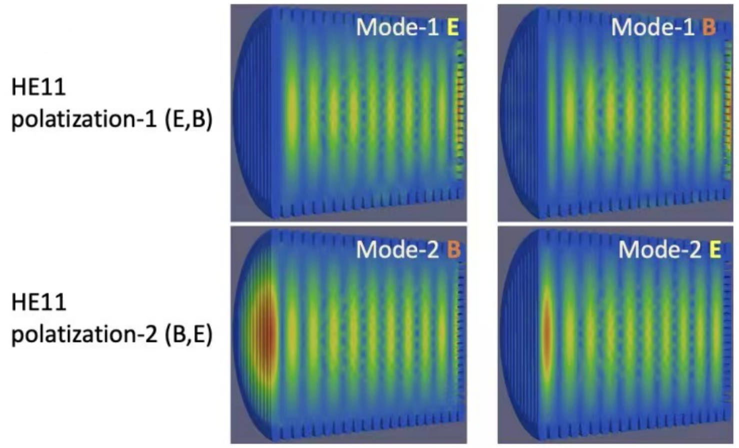
International SRF Campaigns

TWO PROTOTYPES [~ 1 YEAR]

SLAC NATIONAL ACCELERATOR LABORATORY

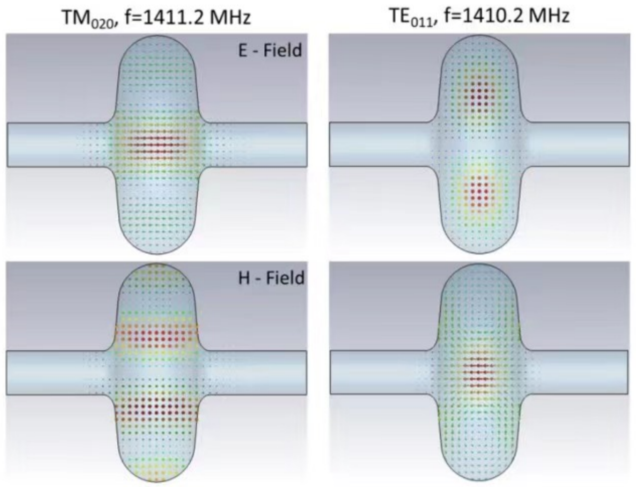
LDRD [only internal documents]

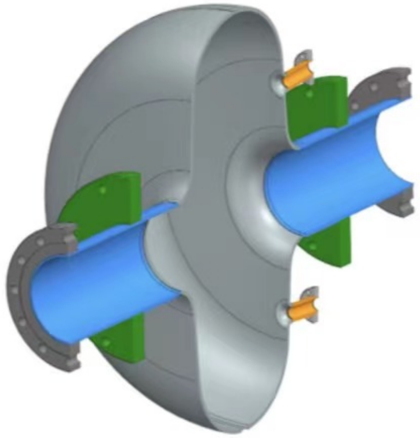




Fermilab

arXiv:2207.11346





SRF for axion search

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

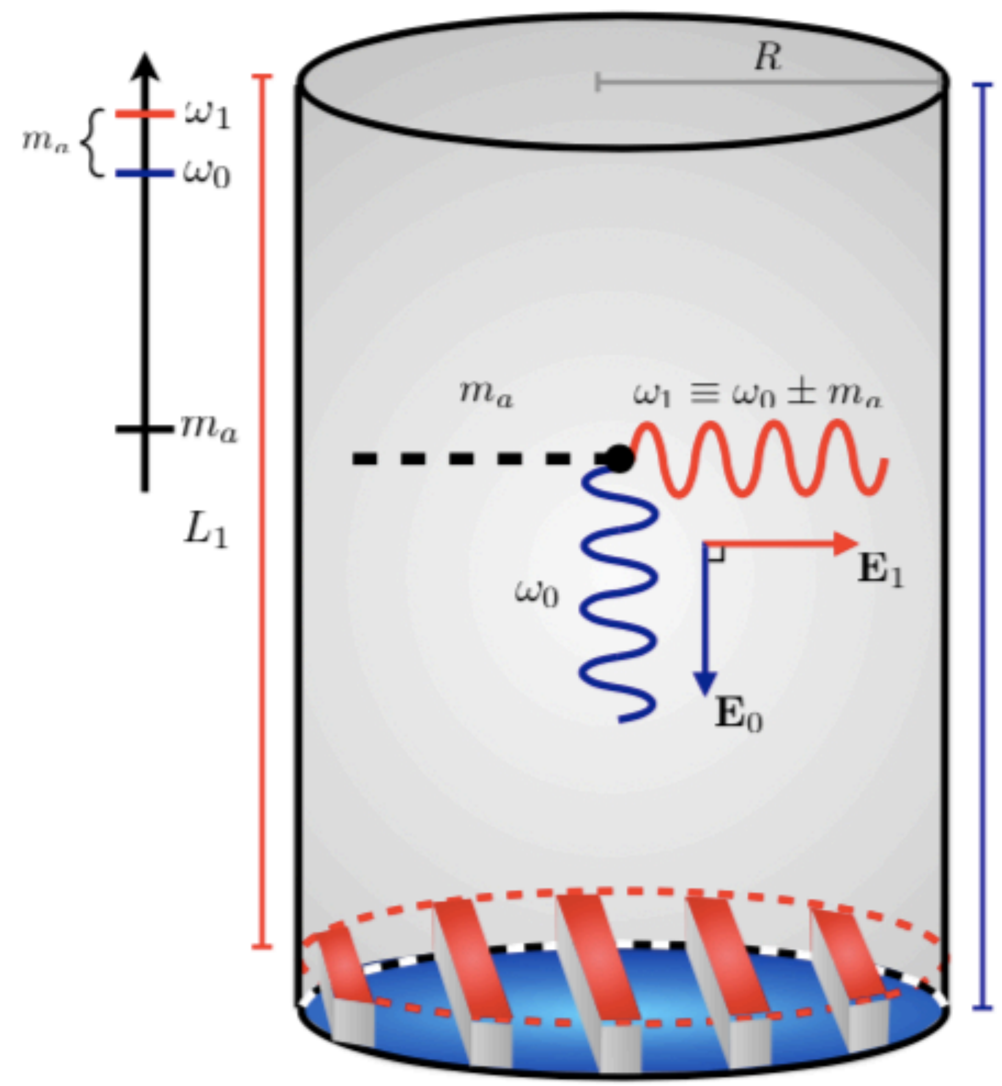
The AC magnetic field $\mathbf{B}$ inside SRF

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

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)

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

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

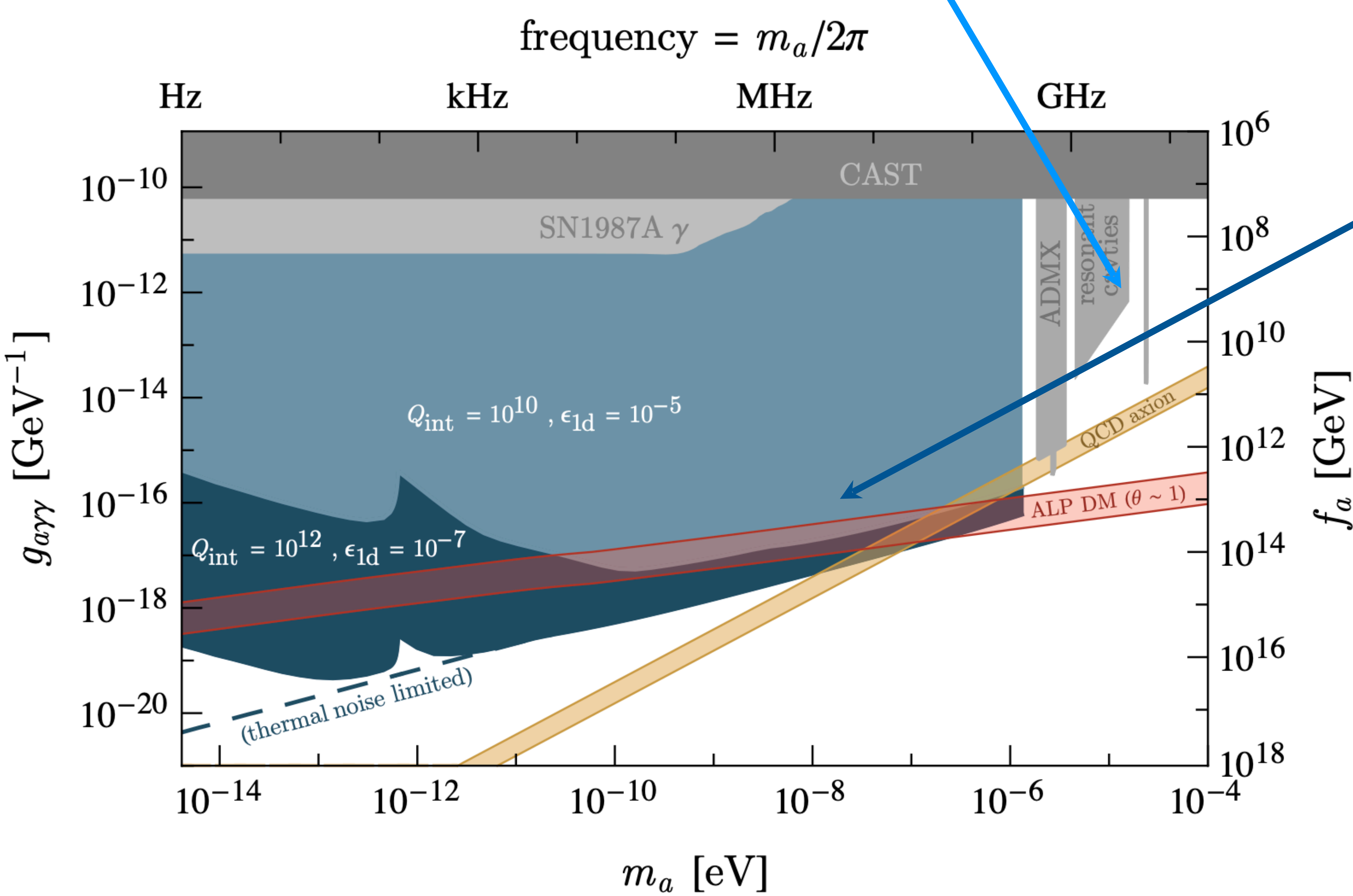


超导谐振腔搜寻轴子暗物质

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

Normal cavity detection frequency is limited by the cavity size.

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



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。

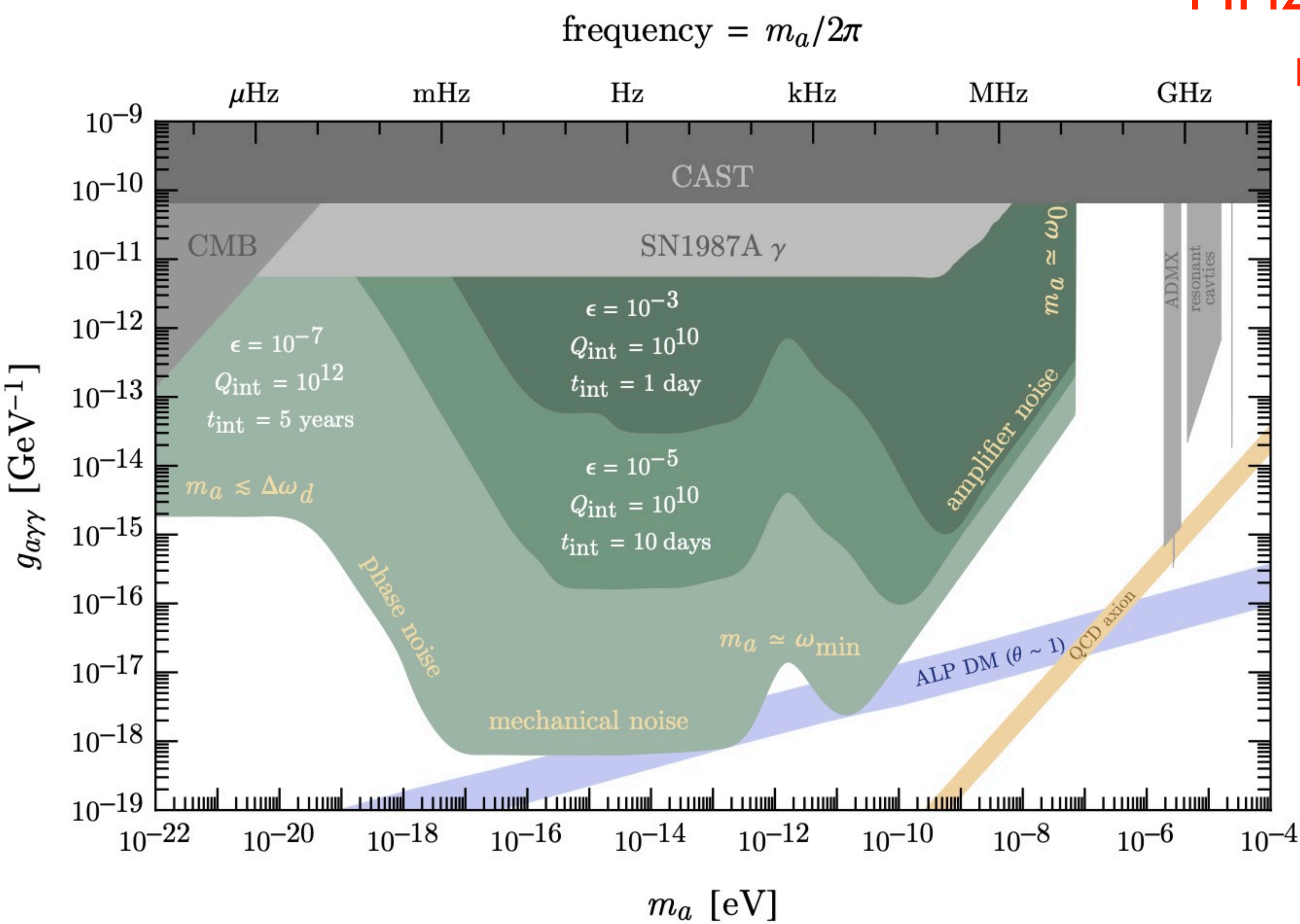
Large unexplored parameter space!

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]].

Pathfinder & New design

SRF with resonant frequency ~2.7 GHz;
searching for axion dark matter mass around 200 MHz.

Cavity operating temperature: 2K. Higher cooling power is required due to injection of AC magnetic field.

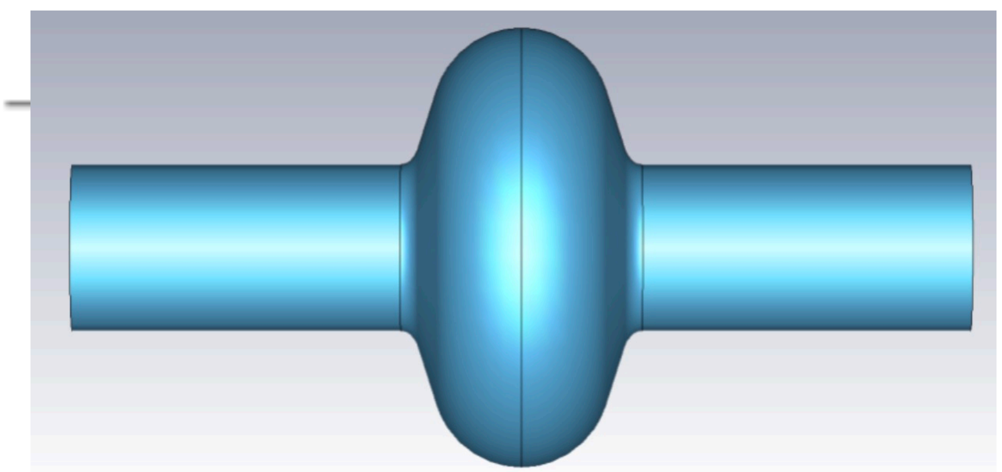
Pathfinder 非调谐腔: 1.3 GHz 1-cell

$B_0 = 34$ mT, $\eta_{10} = 0.46$，体积 $V = 3.188 \times 10$

TE011 与 TM020 的频率差：$\delta f = 0.2$ GHz.

探测模式 TM020 频率：$f_1 = 2.7$ GHz.

$Q_1 = 10^{10}$

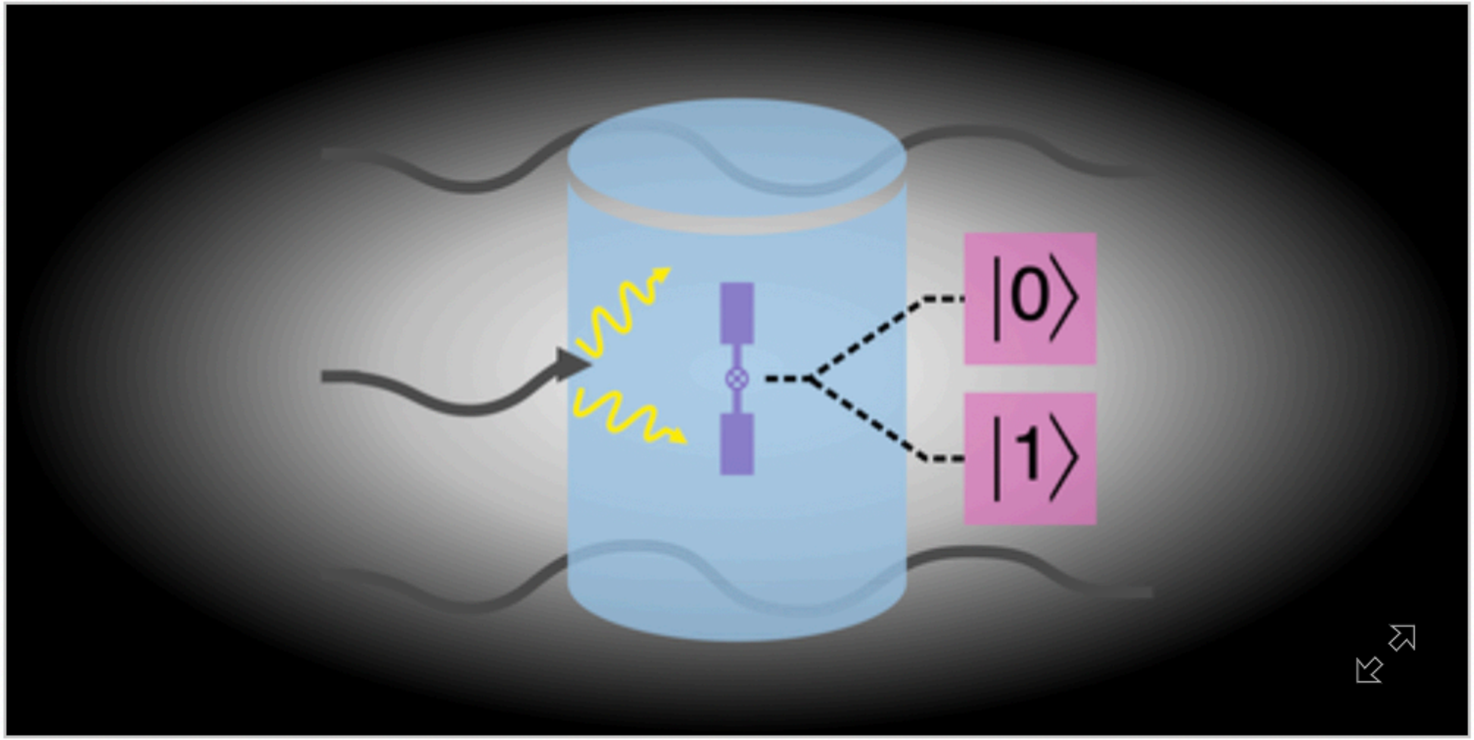


Quantum qubits measure DPDM

Qubits Could Act as Sensitive Dark Matter Detectors

April 8, 2021 • *Physics* 14, s45

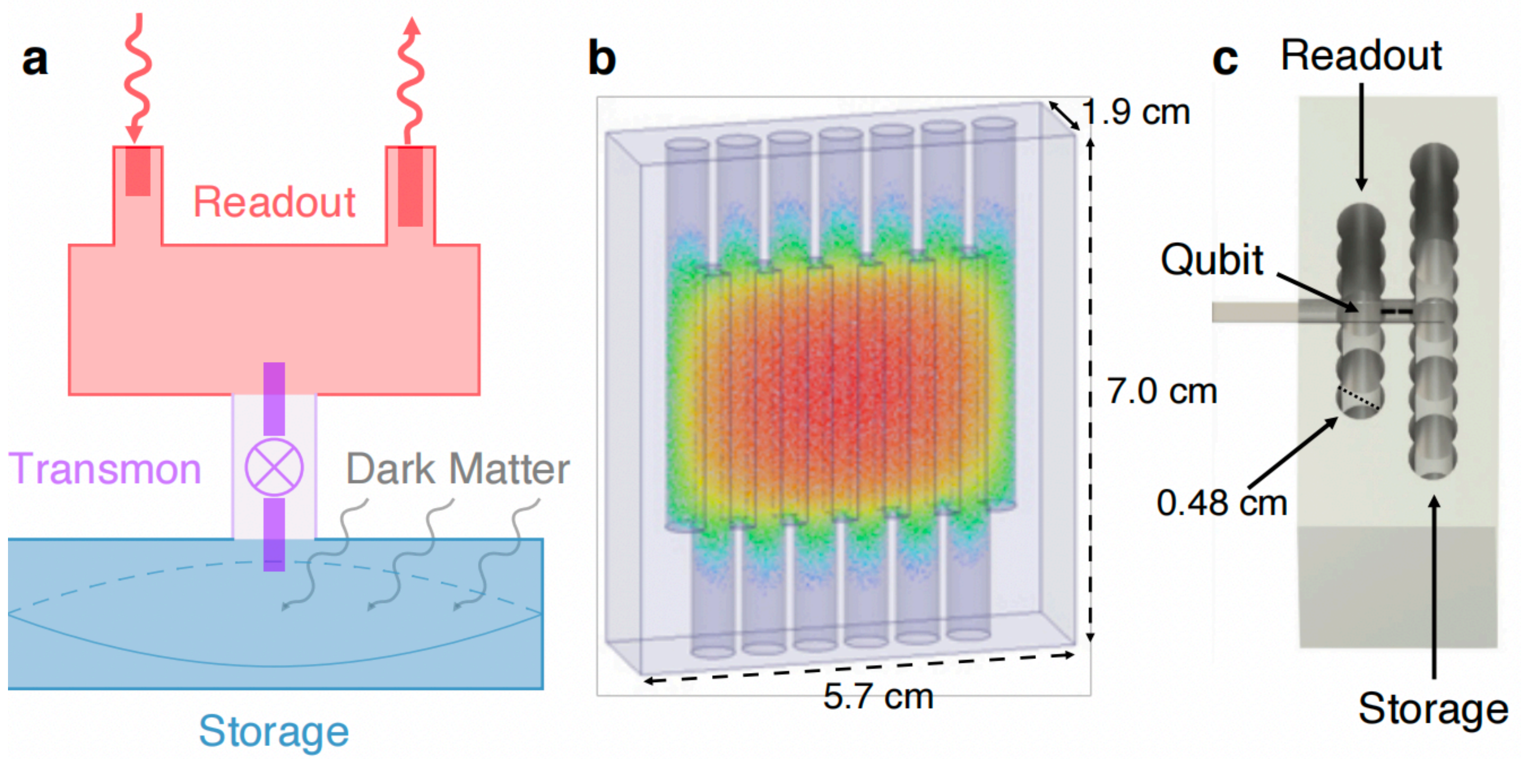
A detector made from superconducting qubits could allow researchers to search for dark matter particles 1000 times faster than other techniques can.



A. Dixit/University of Chicago

Quantum qubits measure DPDM

Al 3D SRF Q~2*10^7



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

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

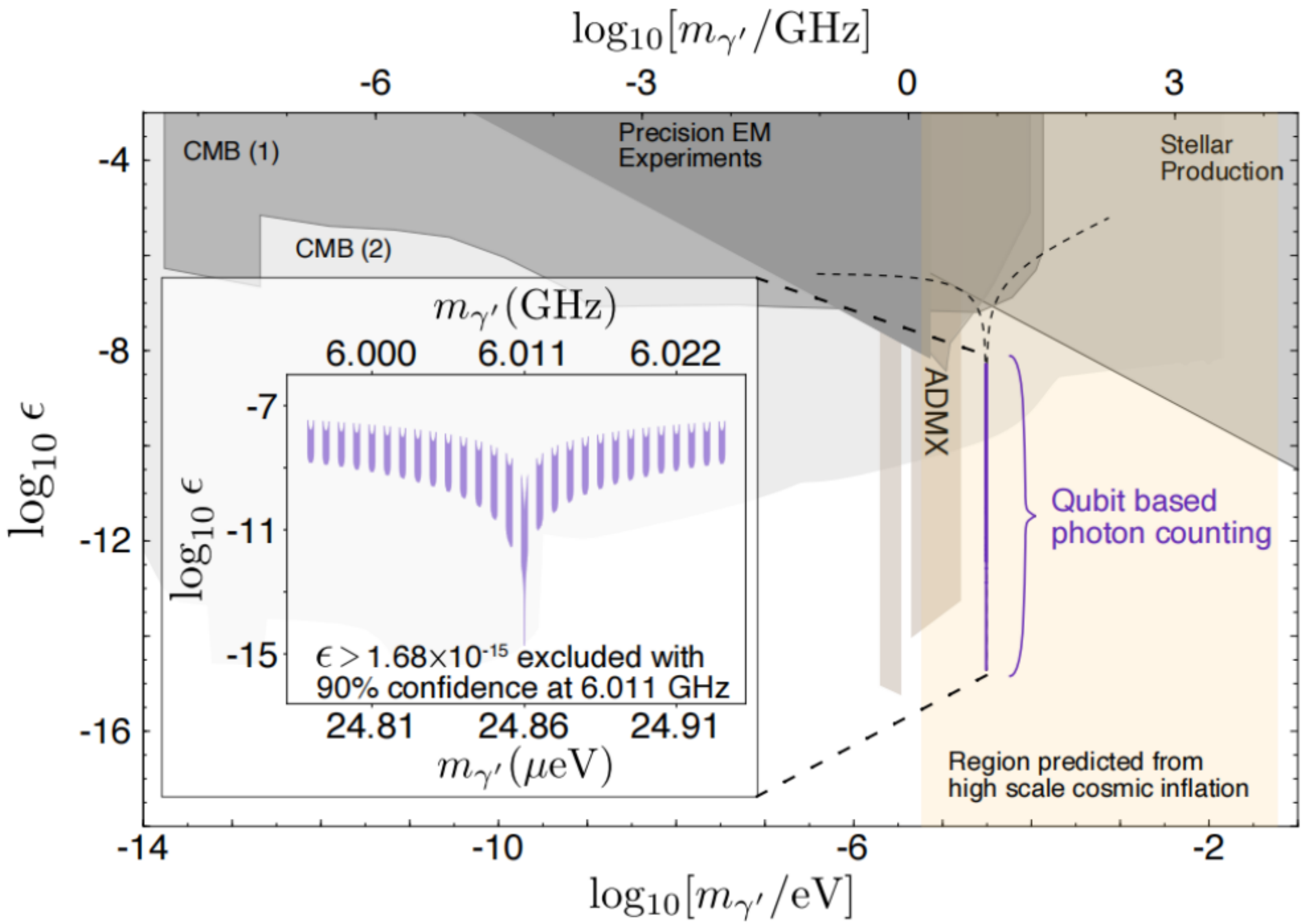
Qubit： two energy level system, induce non-demolition measurements (spectroscopy)

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

DPDM signal： count the photon number by f shift

Ramsey interferometry, etc

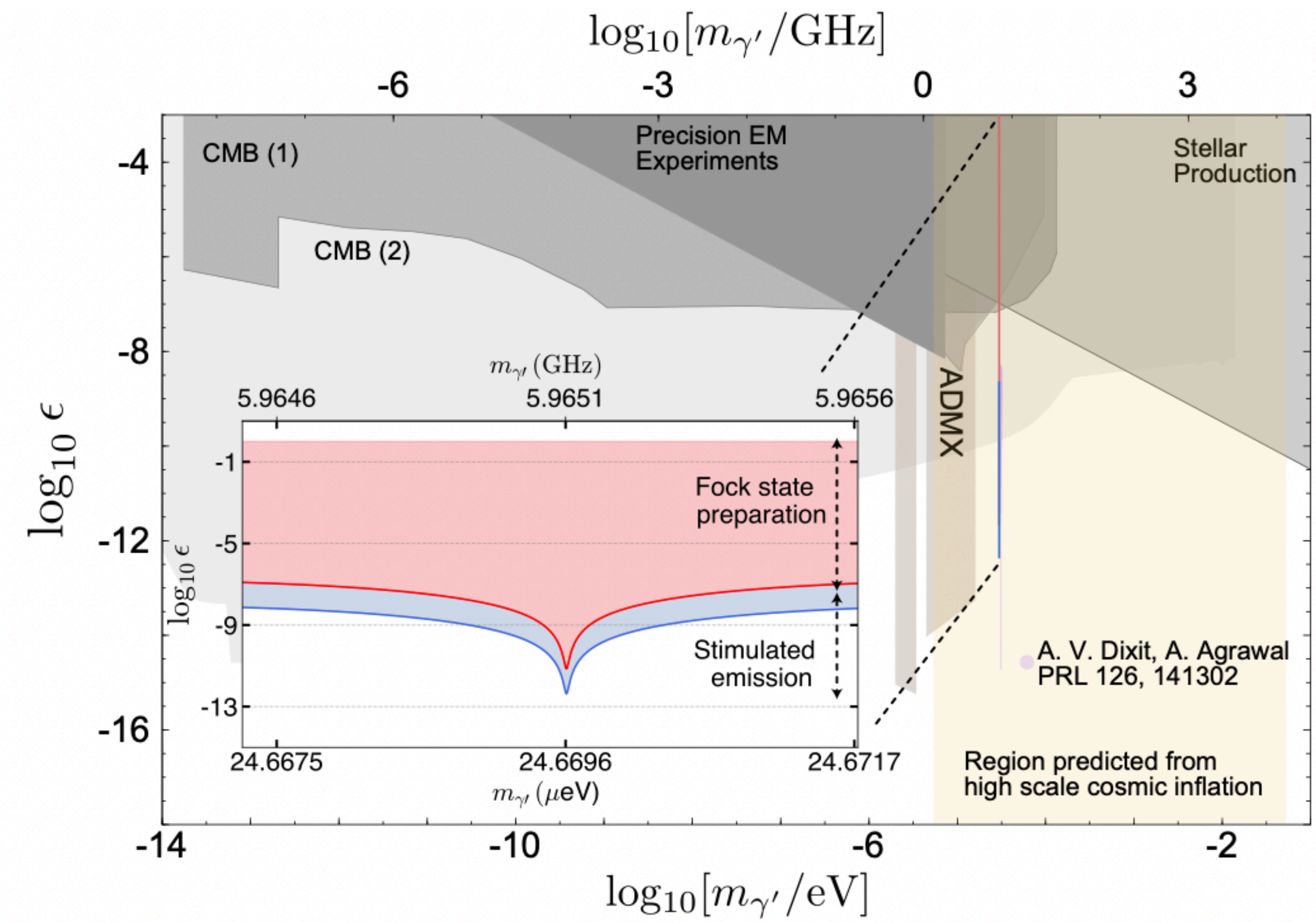
Quantum qubits measure DPDM



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

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

Quantum qubits measure DPDM



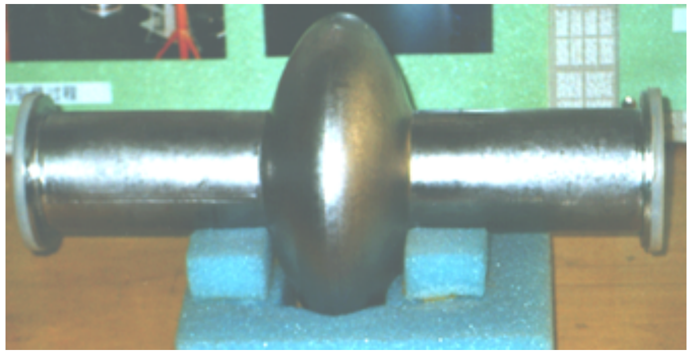
DPDM： Using the Fock state to measure

$\epsilon \geq 4.35 \times 10^{-13}$

2305.03700

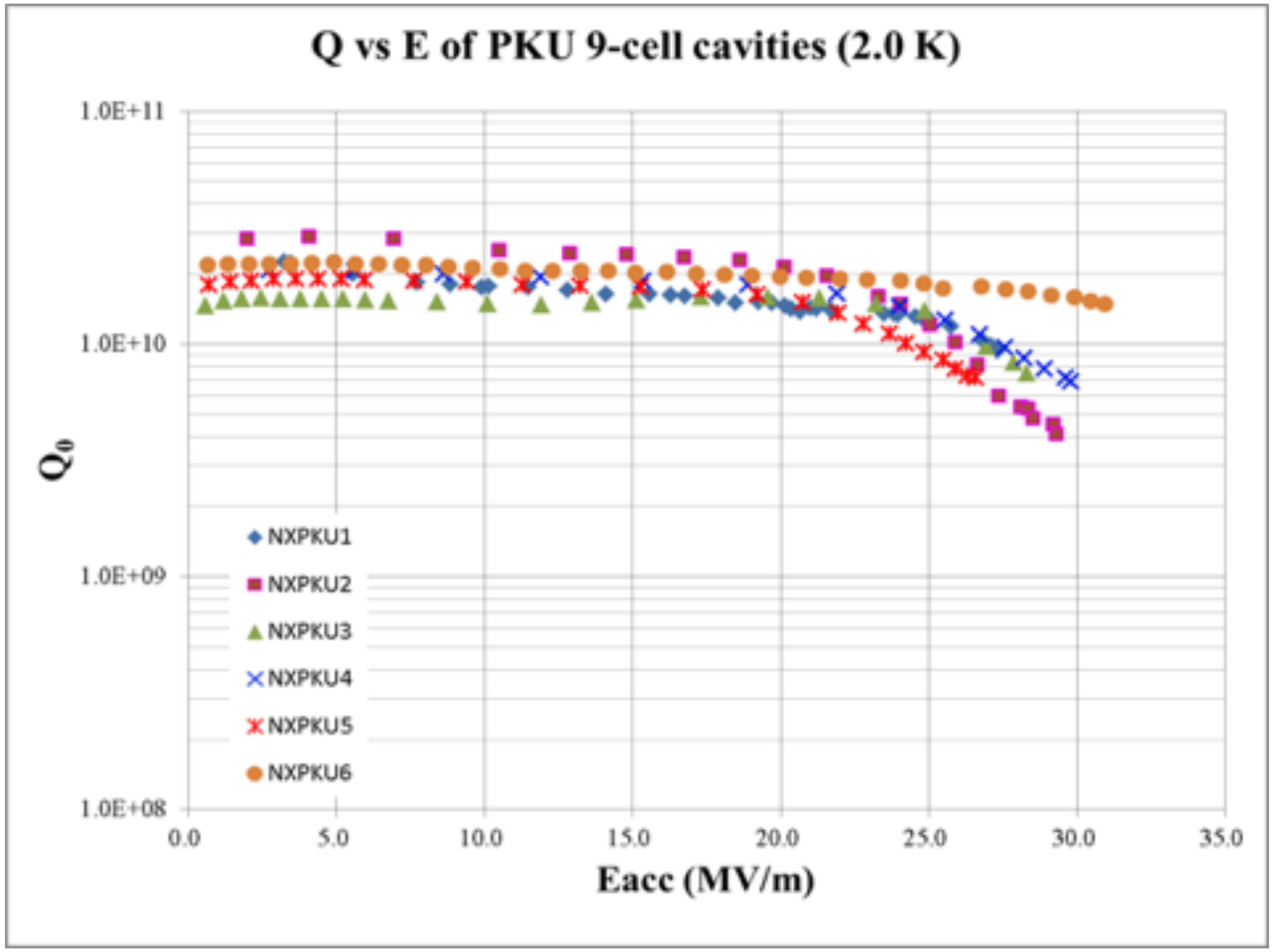
A brief introduction to the team member

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

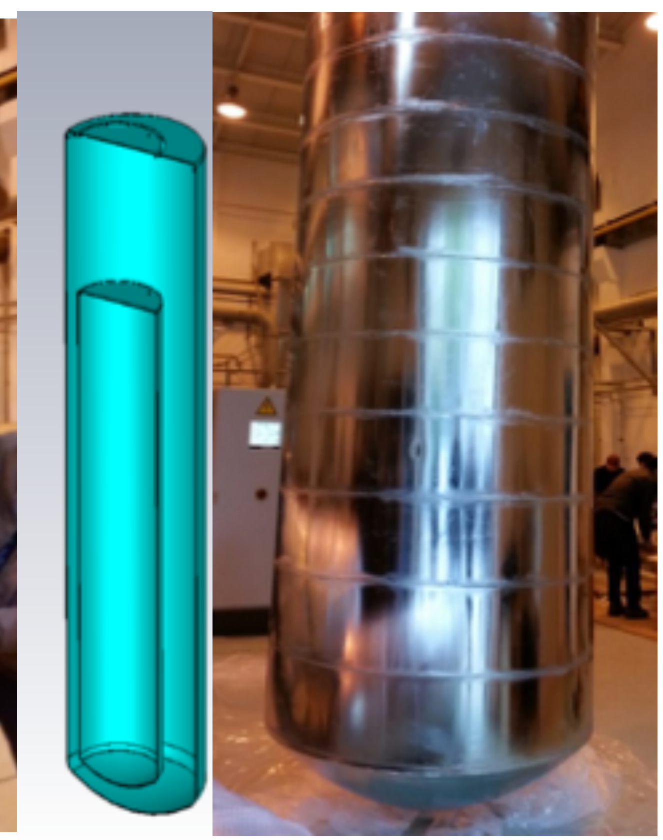
Experimental facilities

Liquid helium system

2K pumping system

Vertical Dewar

Cavity suspension

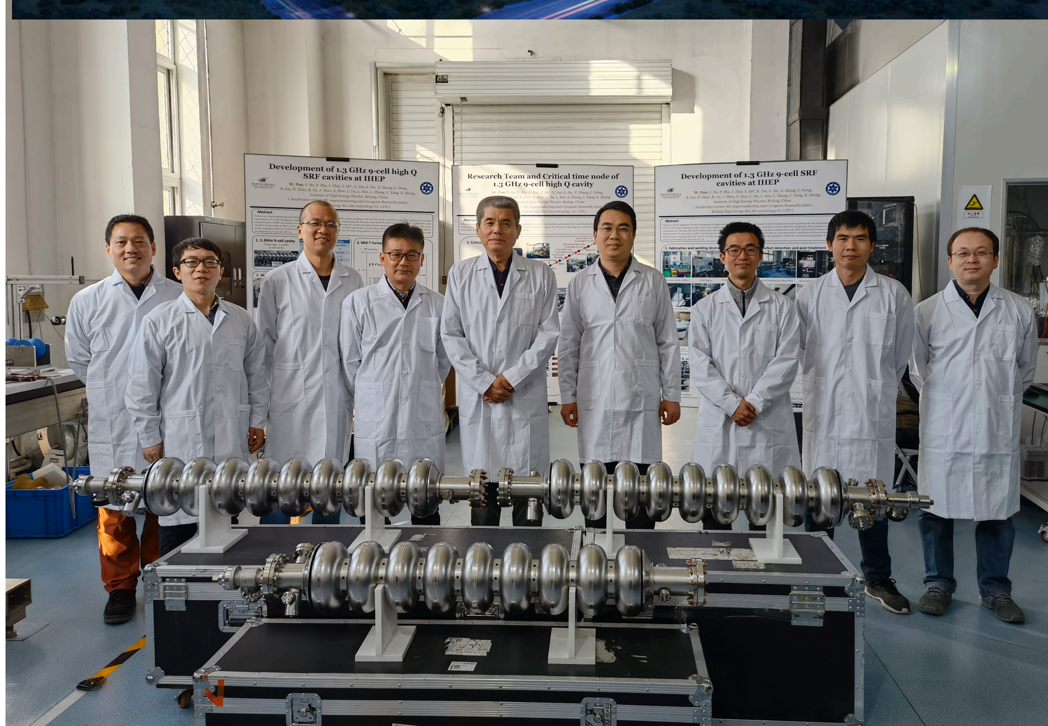


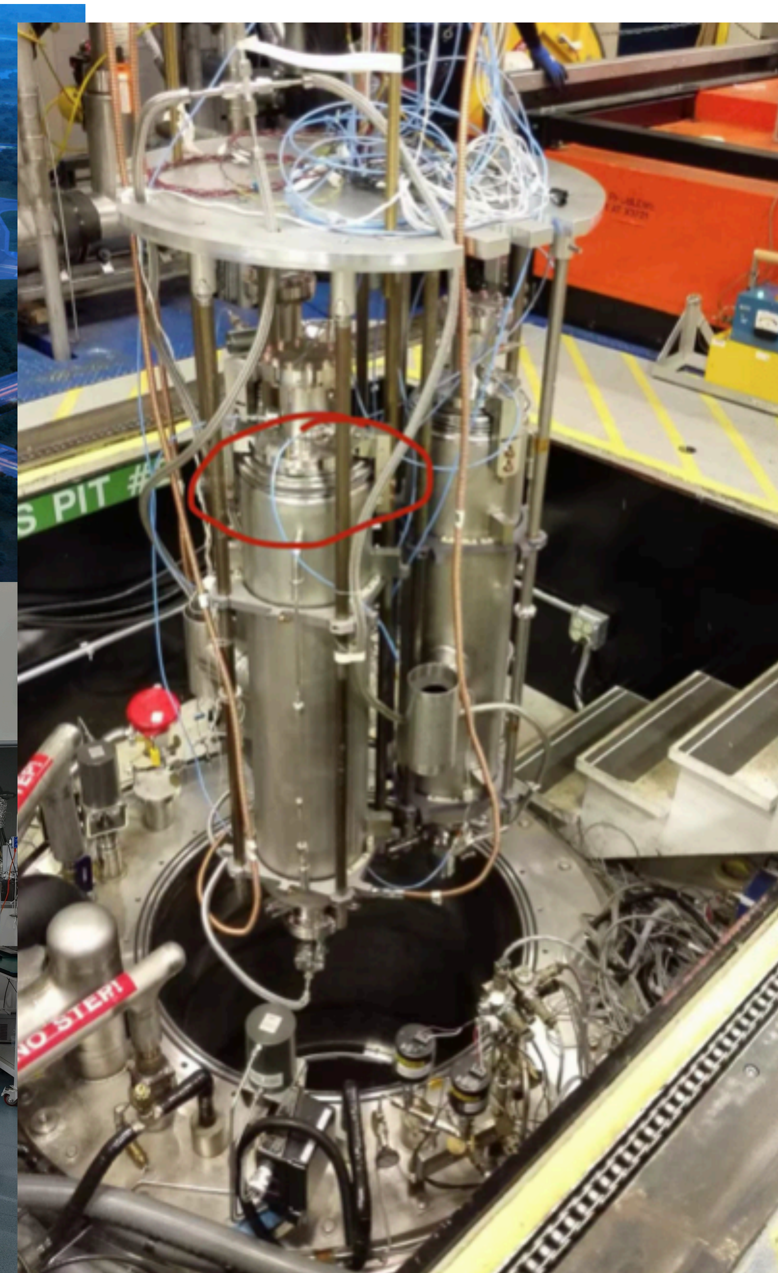
Magnetic shielding

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

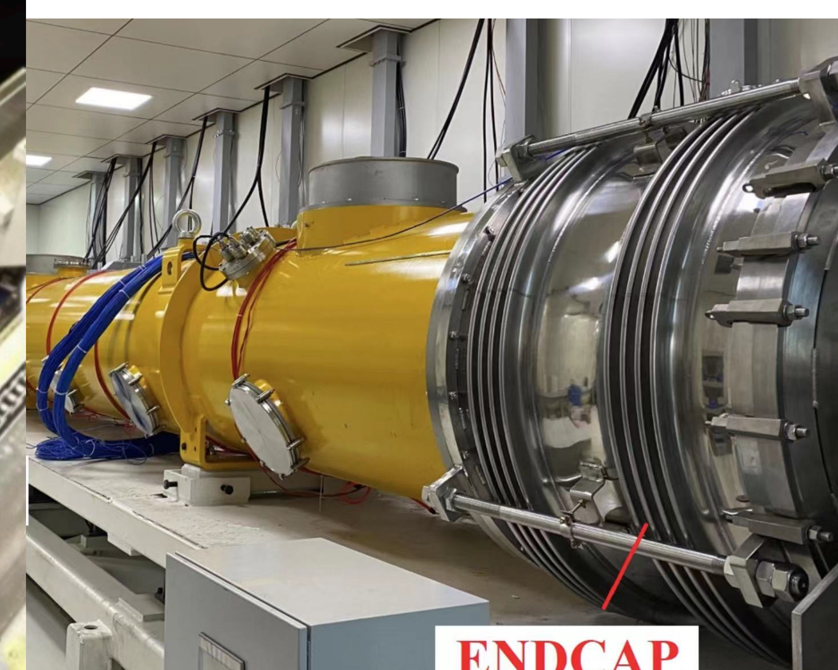
SRF in IHEP

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



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!