Search for DPDM with Tunable SRF Cavities

Outline

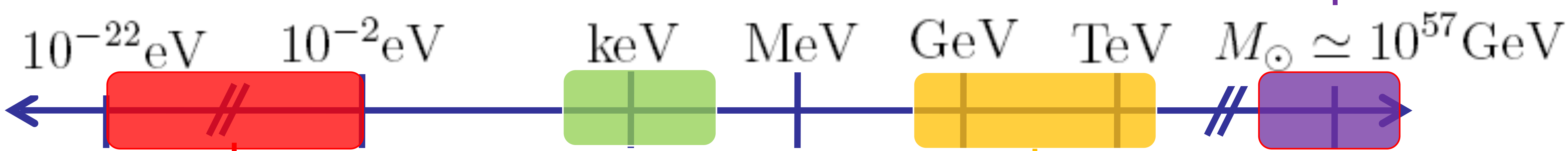
- Motivation of ultra-light dark matter search using Superconducting Radio Frequency (SRF) Cavity
- SRF Cavity Project for DPDM search
- SRF Cavity Project for cosmic DP? (preliminary)
- Experimental group
- Summary and Outlook

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

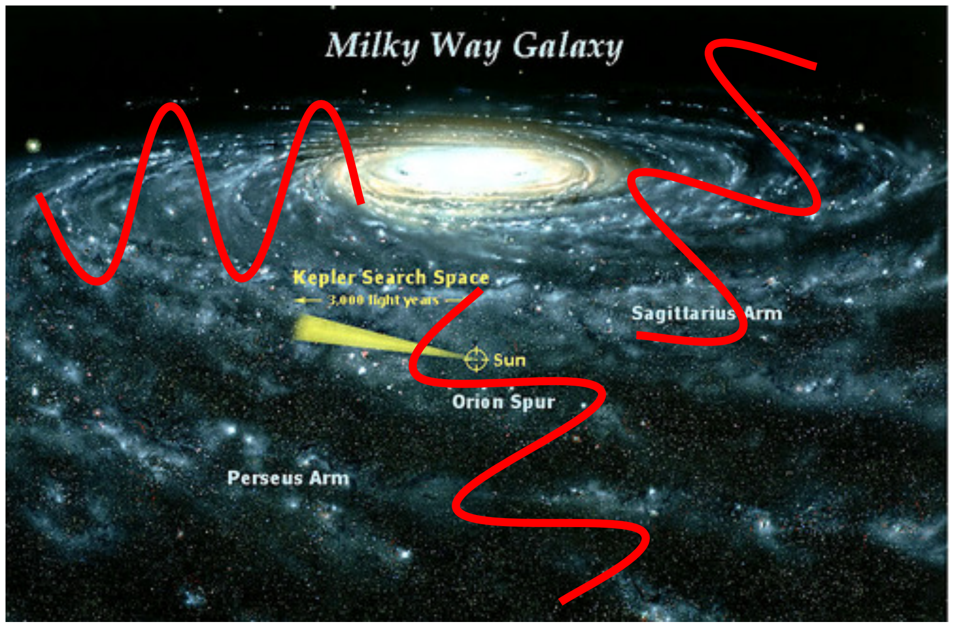
WIMPs: direct
(indirect)detection、
collider searches

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.



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

The de Broglie wavelength: galactic scales(kpc)

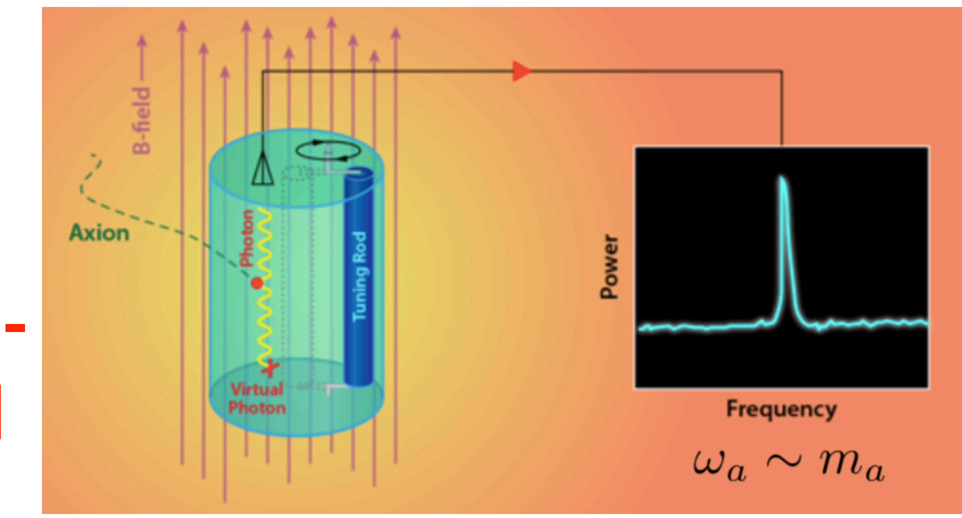
- Astronomical observation (time, position, velocity, polarization, etc)

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)

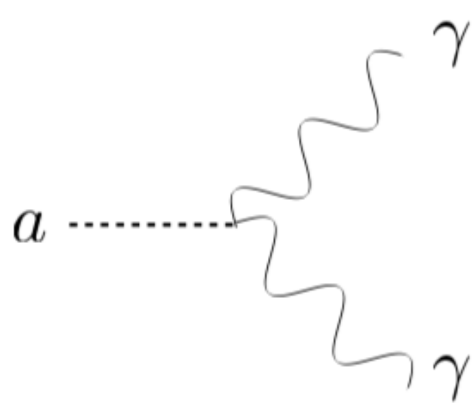
Haloscope, Quantum amplifier

New search methods!!!

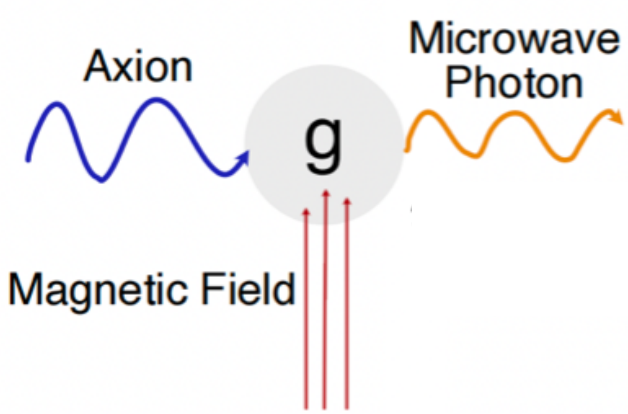
Quantum sensor

Ultra-light DM candidate

Axion (ALP): spin 0, CP odd



Inverse Primakoff effect



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

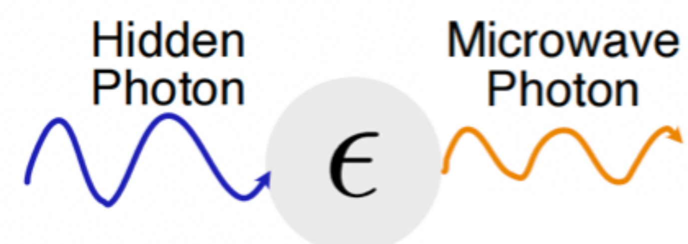
induces an effective current under strong magnetic field.

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

Dark photon: spin 1

mili-charge particles?

kinetic mixing

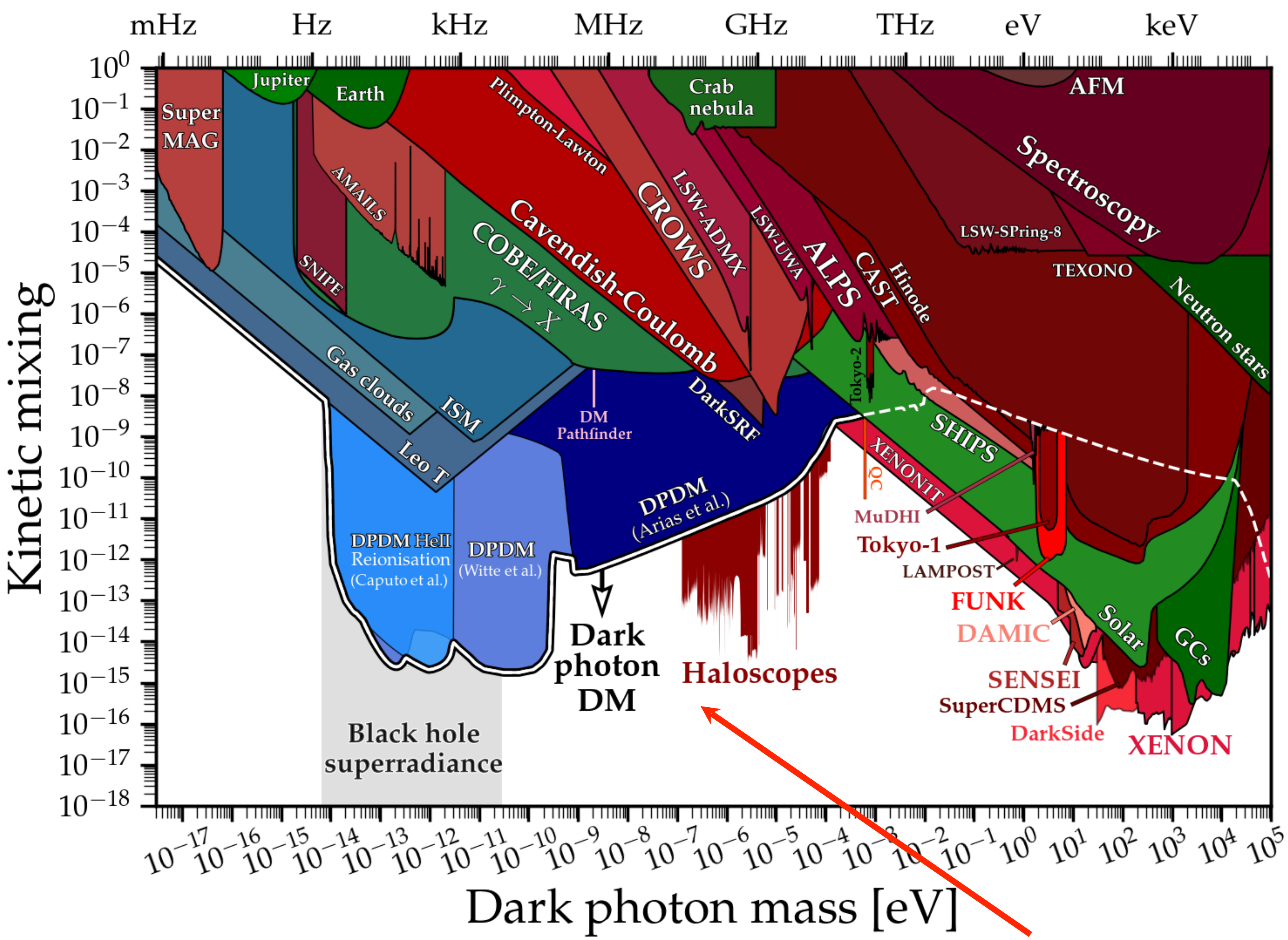


$$\mathscr{L} \supset -\tilde{A}_\mu \left(e J^\mu_{EM} - \varepsilon m^2_{A'} \tilde{A}'^\mu \right)$$

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

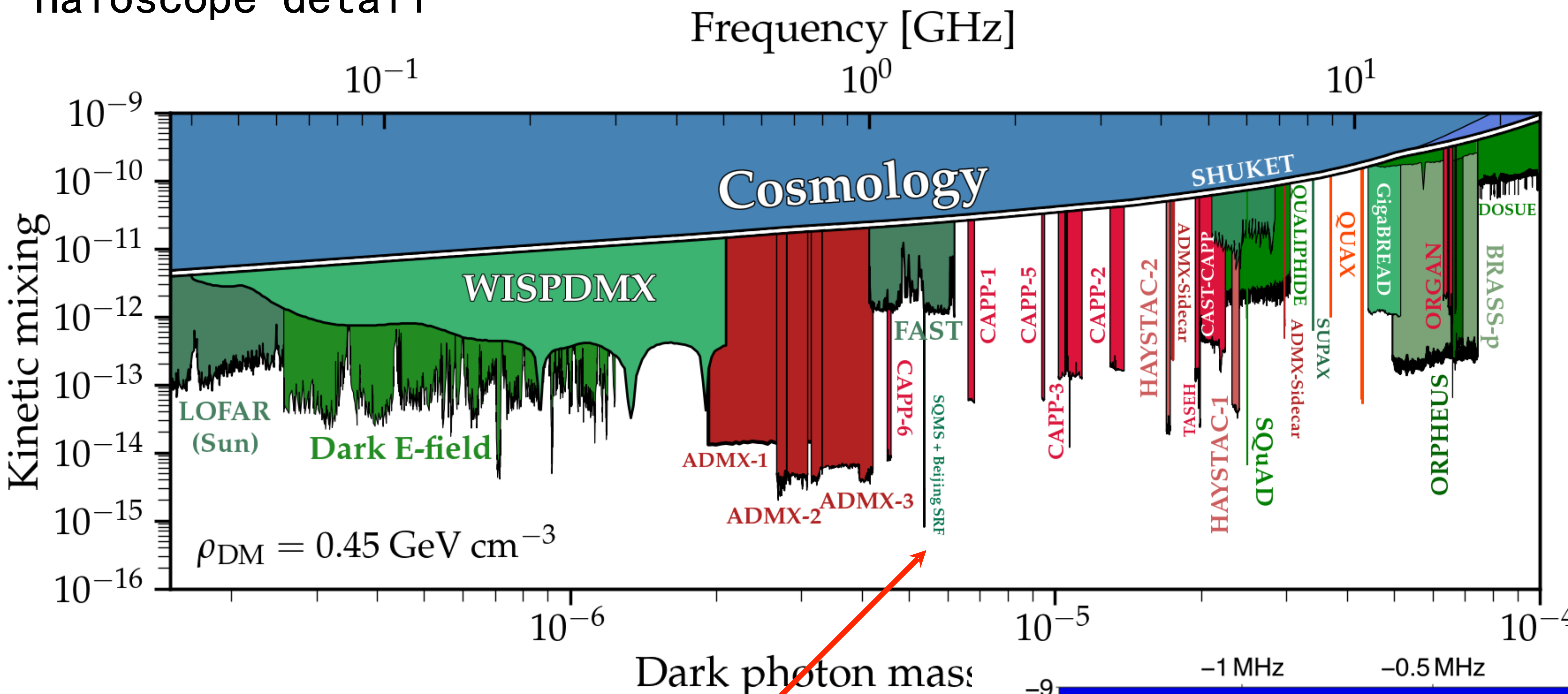
Haloscope sensitivity largely depends on Q: Superconducting cavity has Q~10^{10}

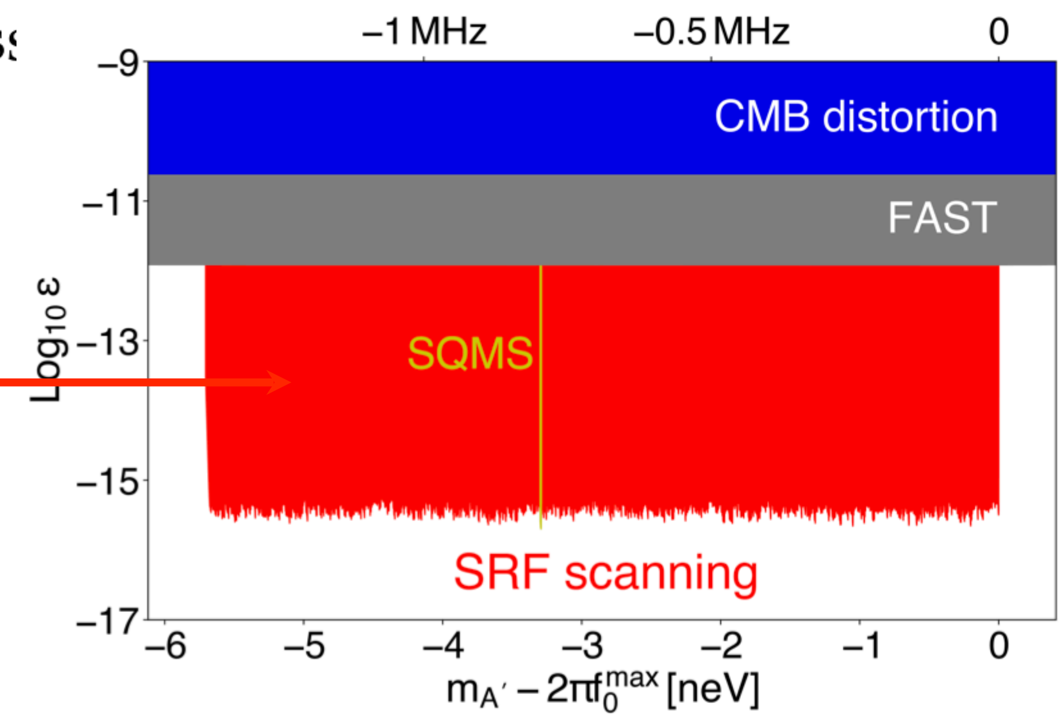
how to make use it? 5 orders more than traditional cavity.

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

DPDM search

Haloscope detail





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.

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

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)

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

Bandwidth of axion DM is 10^-6

Detector bandwidth < 10^-6 accelerate the scan rate

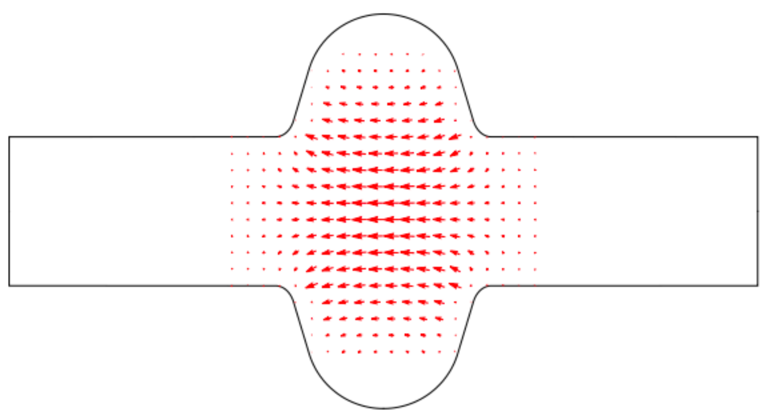
$$\lambda_a \sim 1/m_a\sqrt{\langle v_{\mathrm{DM}}^2\rangle} \sim 10^3/m_a$$

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,†]

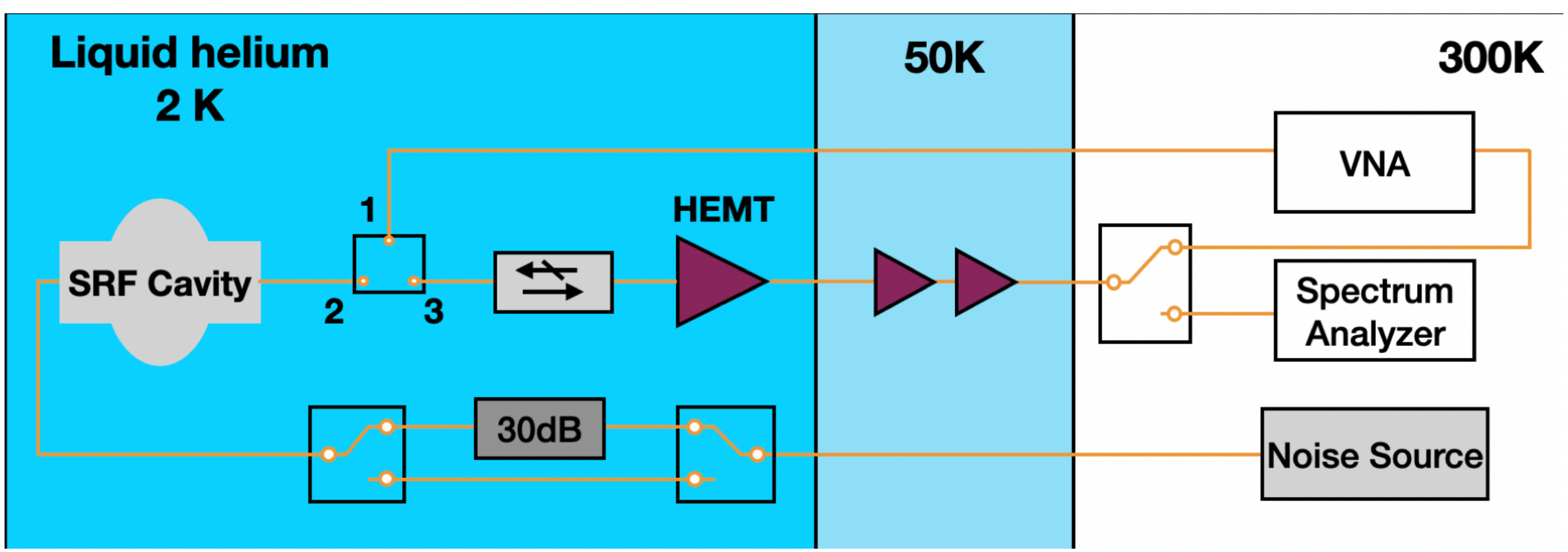
arxiv: 2305.09711

Experimental operation

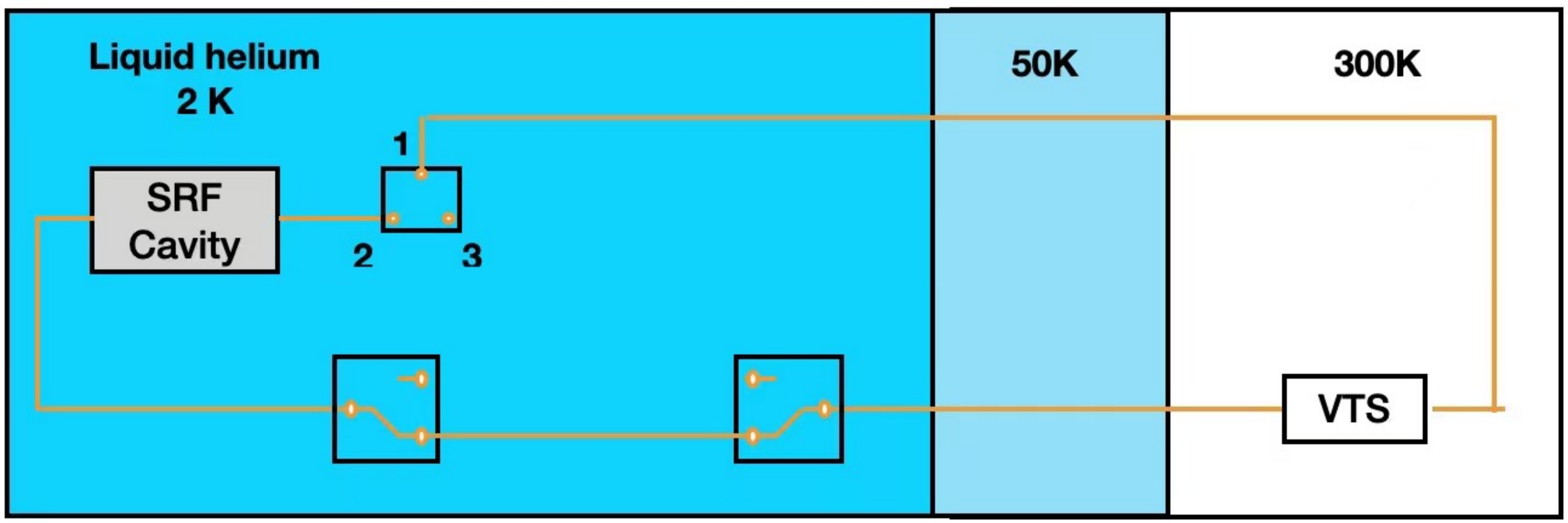
Parameters

	Value	Fractional Uncertainty
$V_{\text{eff}} \equiv V\,C/3$	$693\,\text{mL}$	$< 1\%$
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

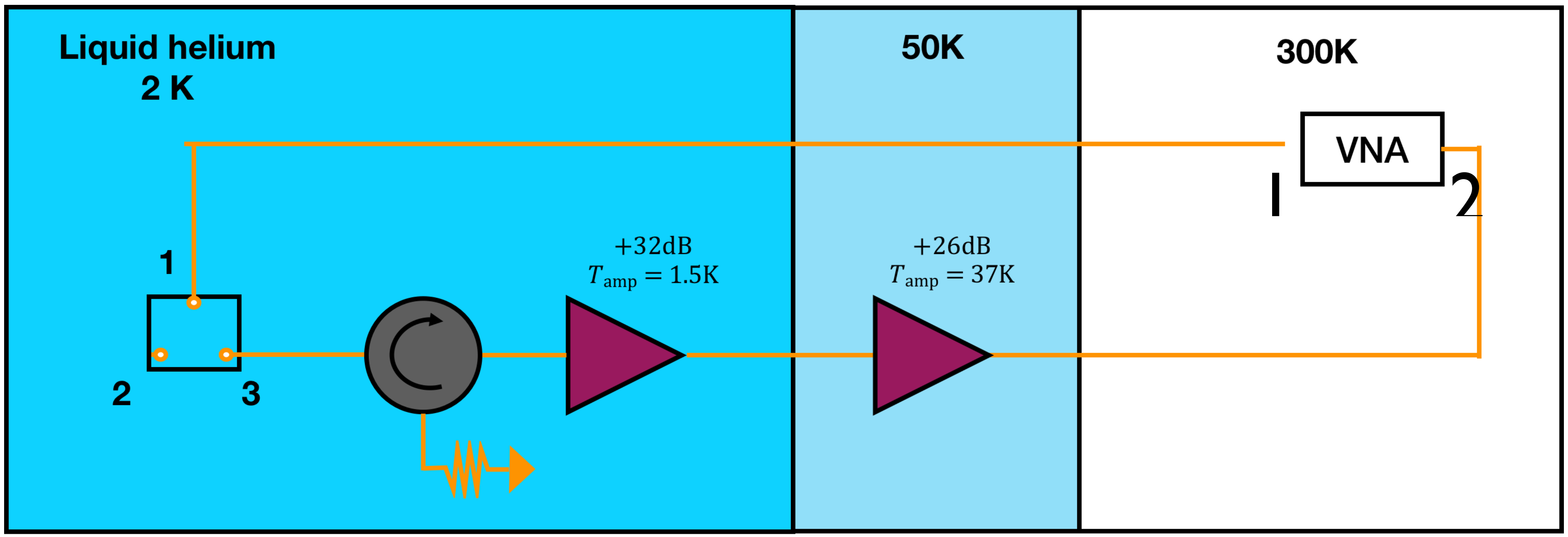


Step 1: Measure Cavity property



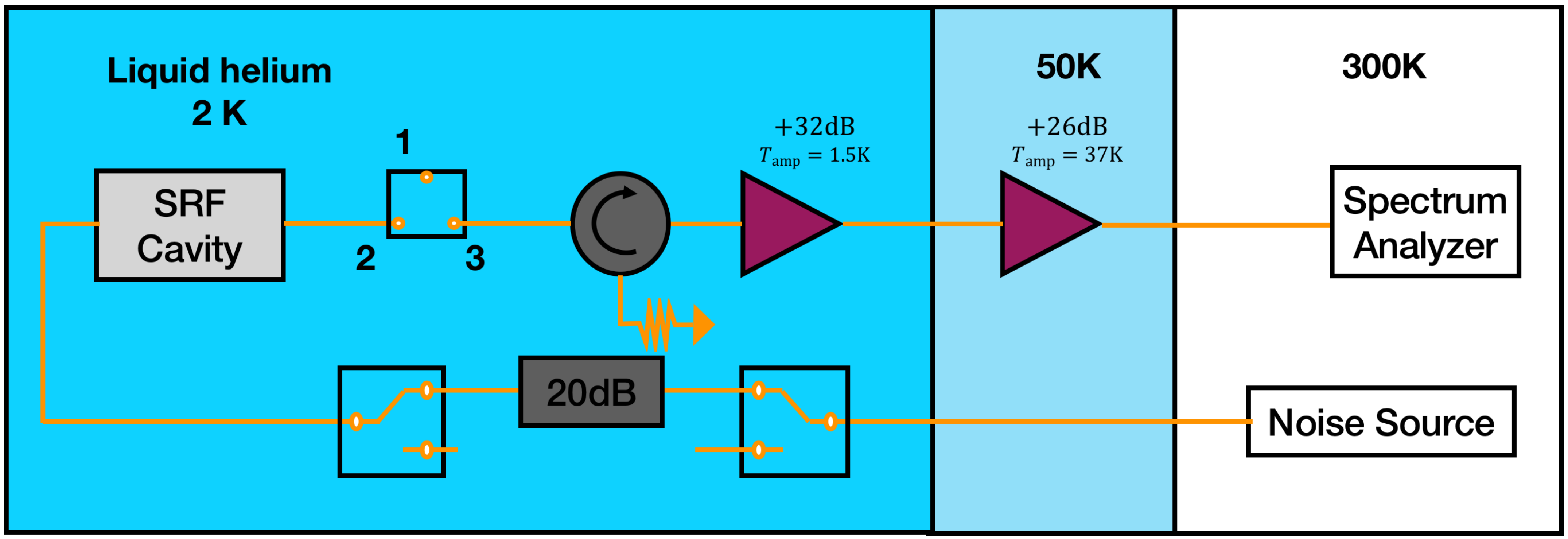
1-2 connection: VTS measurement for the cavity property.

Step 2: calibration



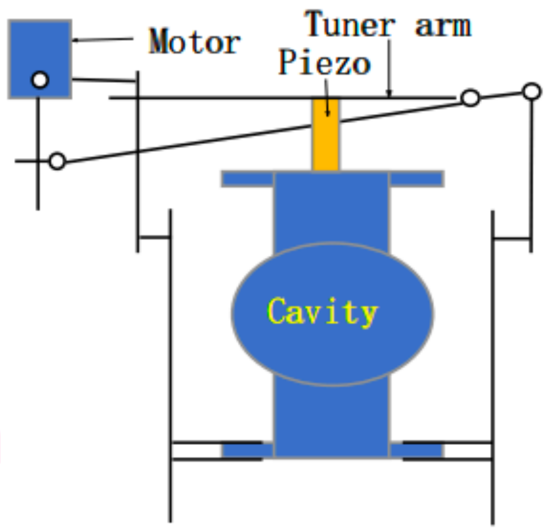
1-3 connection: calibration by subtracting the line loss to get the total gain G_net.

Step 3: Do experiment

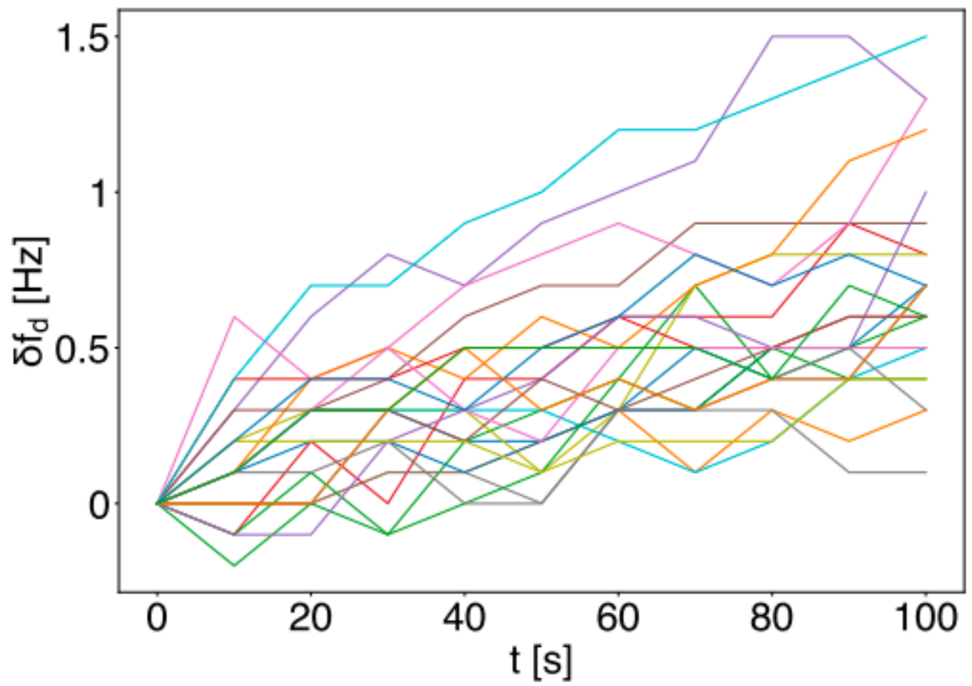


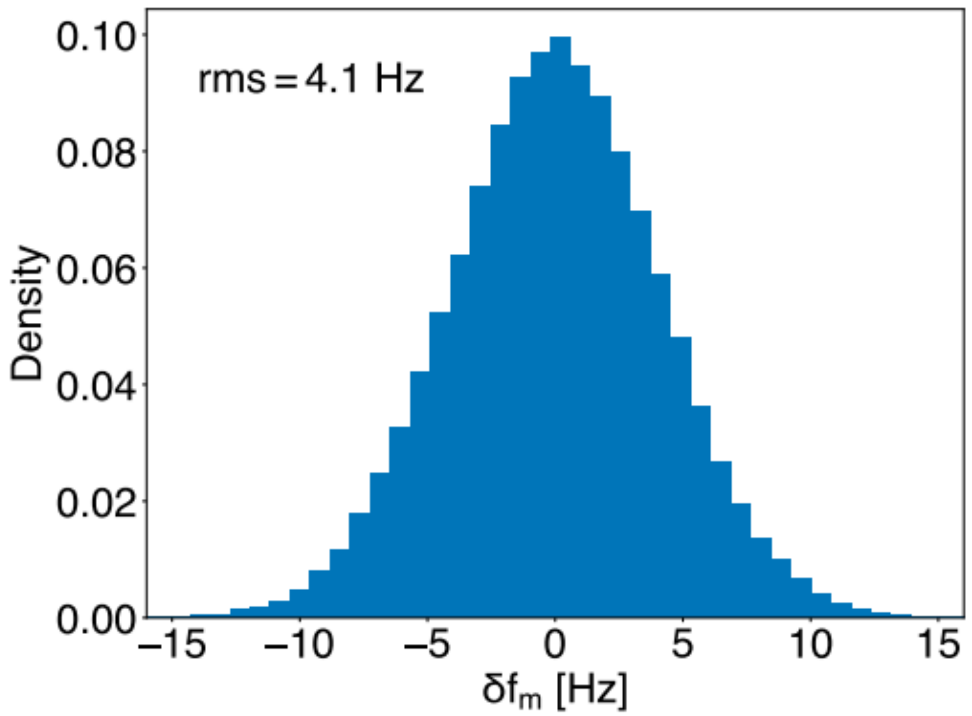
2-3 connection: tune the cavity resonant frequency to do the experiment

Scan Search with Mechanical Tuning



- **Mechanical 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 $\sigma_{f_0} \approx 4\rm Hz$

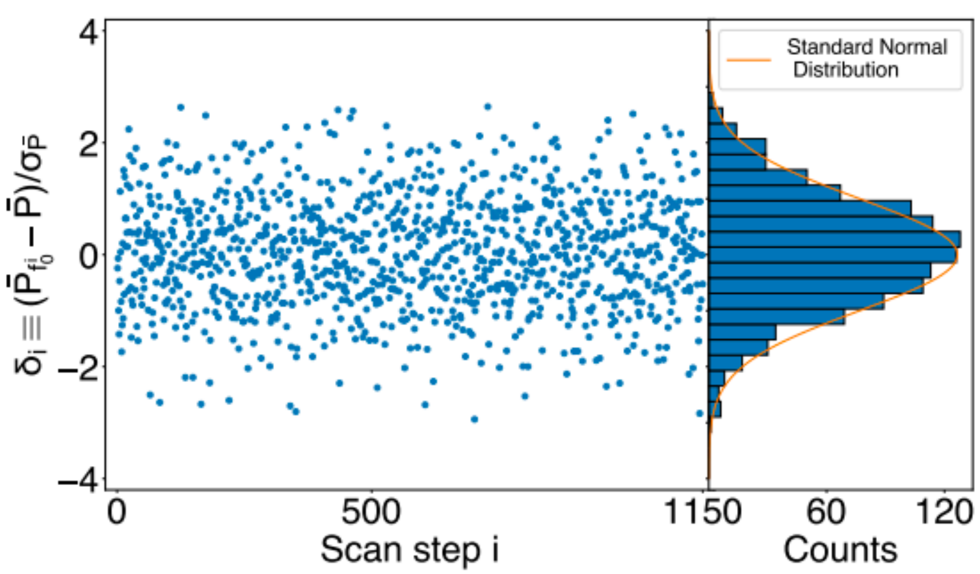


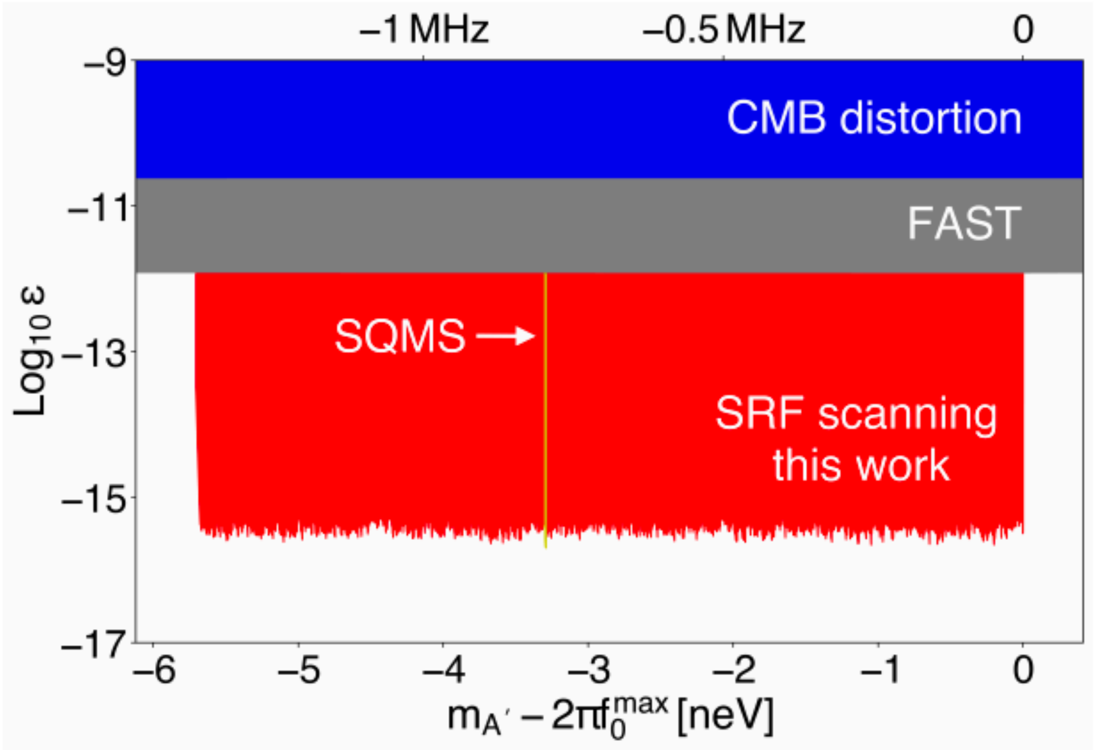


- **Conservatively** choose $\Delta f_0 \approx 10\rm Hz$

Data analysis and constraints

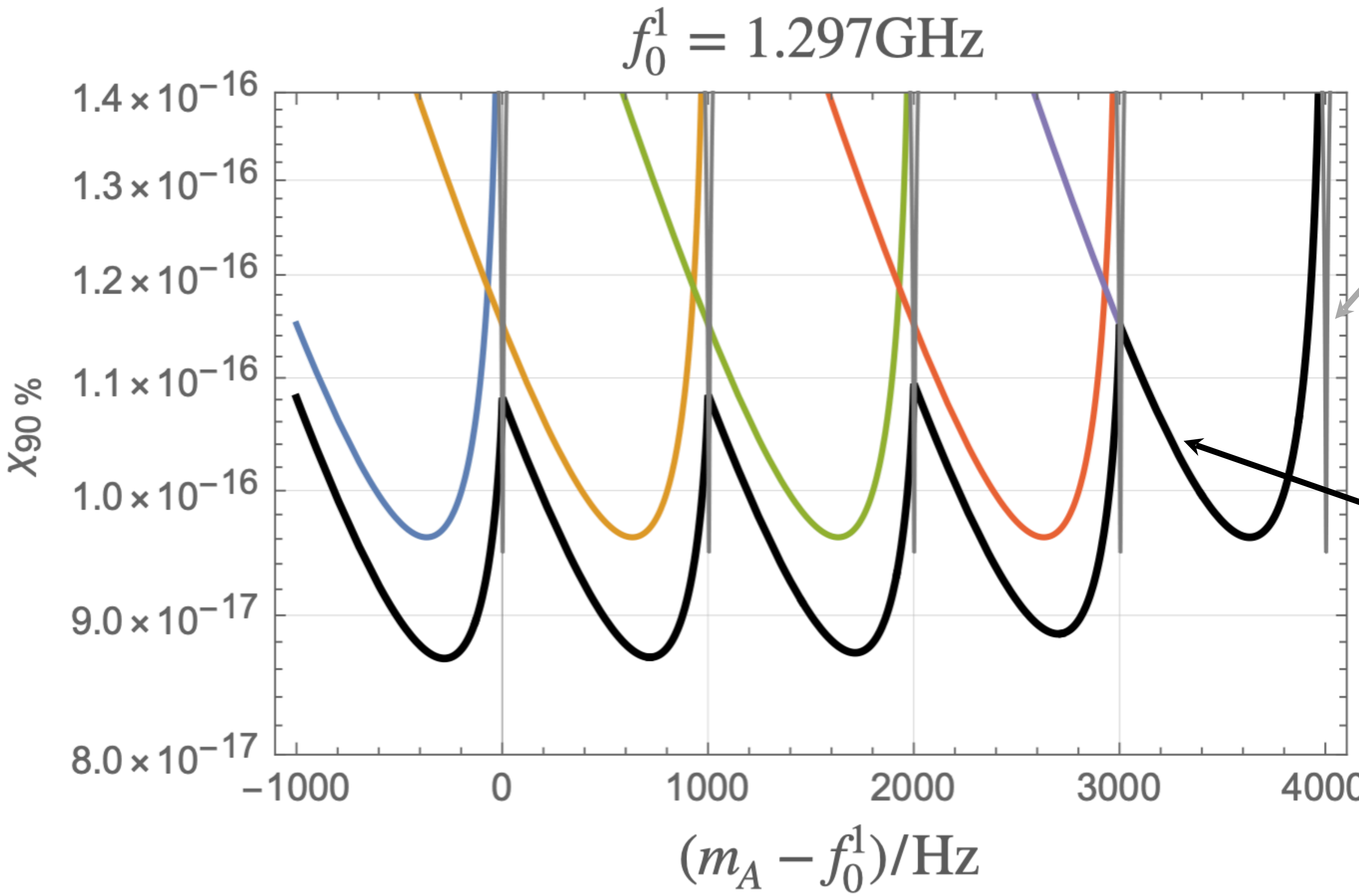
- Total 1150 scan steps with each 100 s integration time.
- **Group every 50 adjacent bins** and perform a constant fit to address small helium pressure fluctuation.
- Normal power excess shows **Gaussian distribution**:





- **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

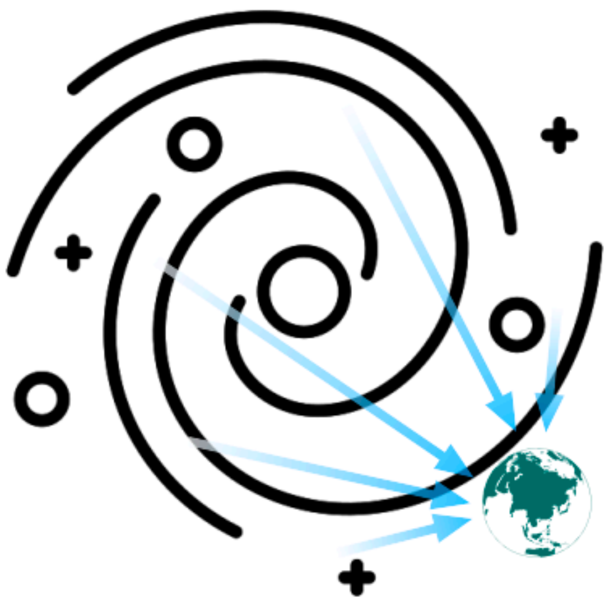
Scan step: f*Q_{DM}

simple fit function (constant): attenuation factor almost 1

different from ADMX

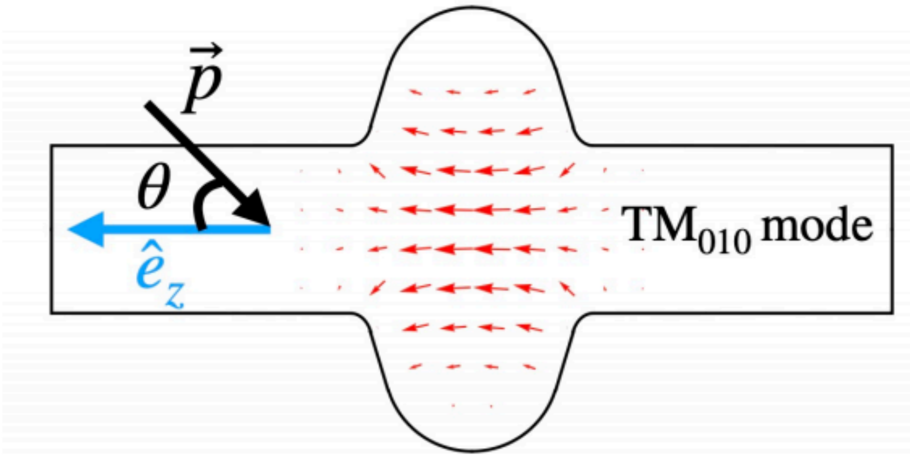
Modulated Signal from Galactic Dark Photons

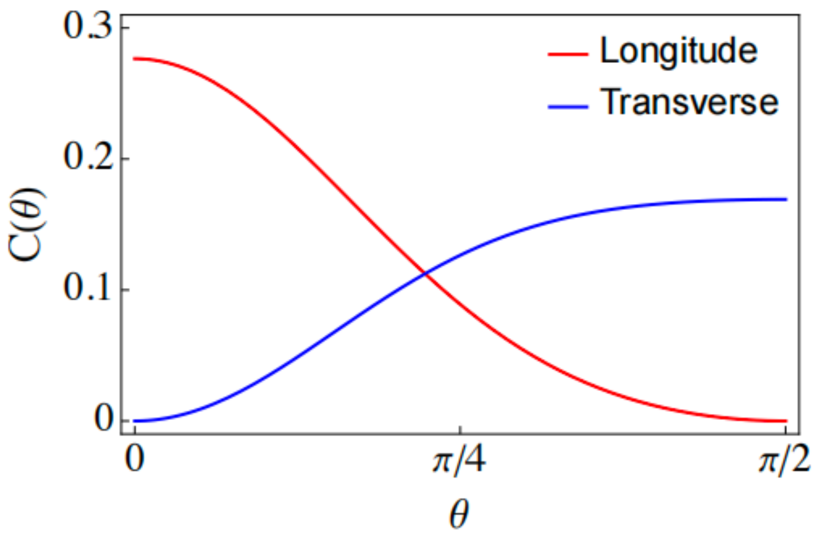
- Galactic dark photons from DM decay, e.g.: cascade decay from DM halo



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

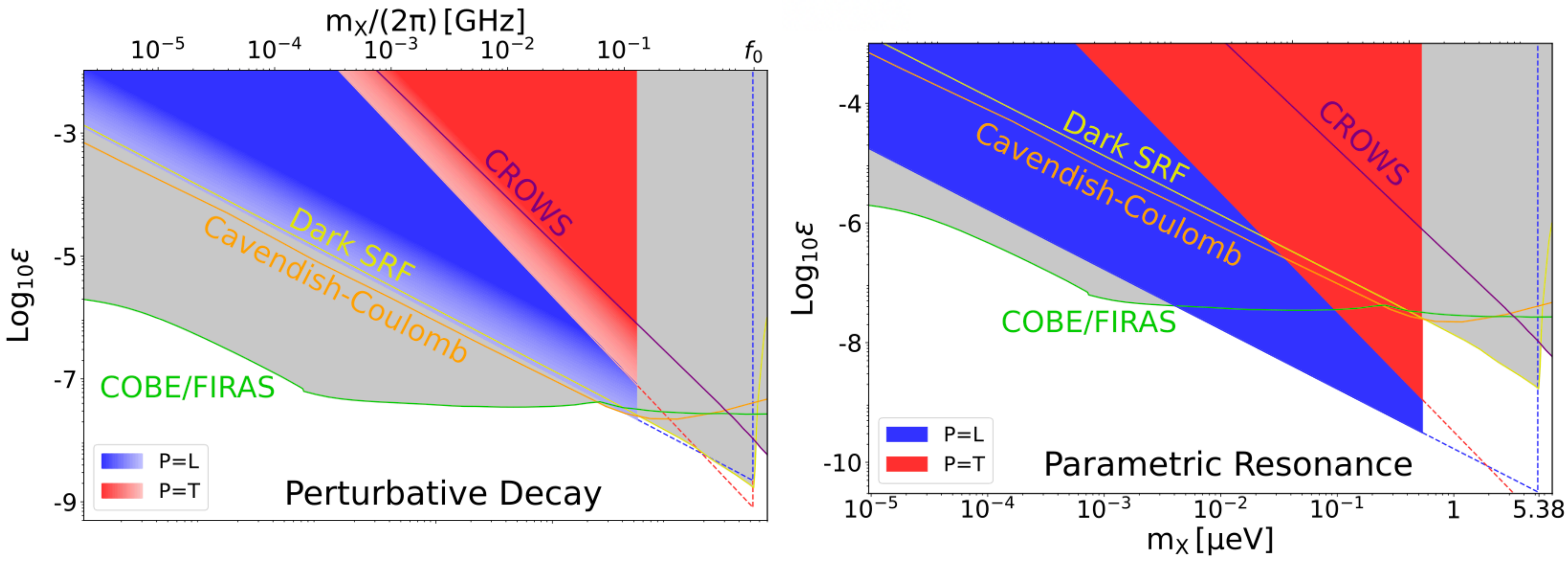
- Production is polarization-dependent, modulations for longitude and transverse modes are opposite





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

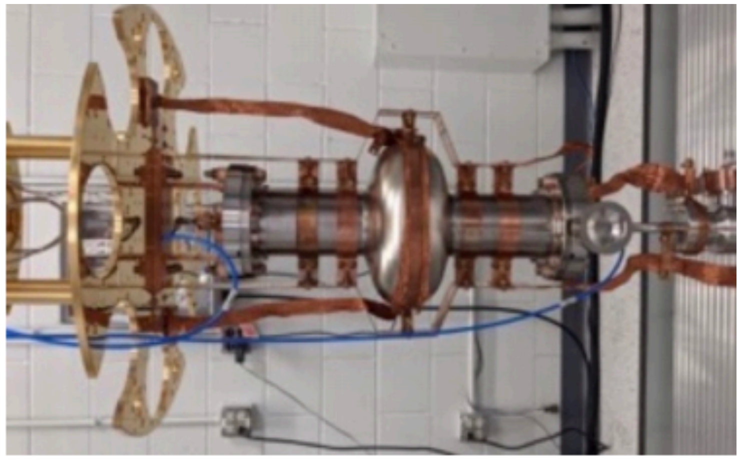


- Gradient color region represents exclusions for different DM mass

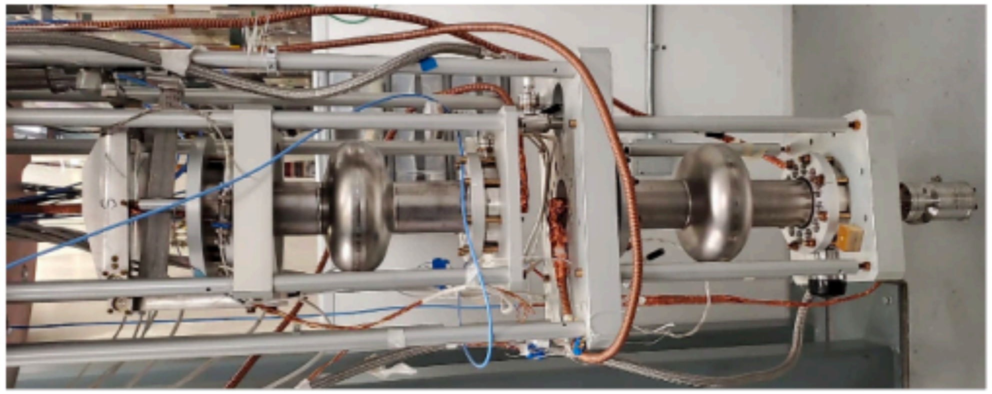
International SRF Campaigns

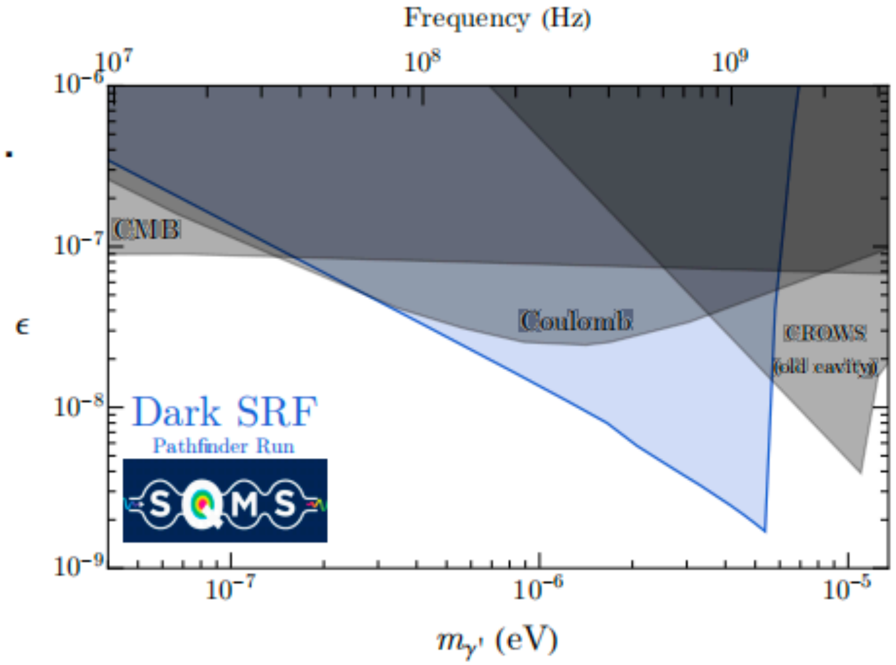
- **Fermilab SQMS**

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



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





- **DESY**:

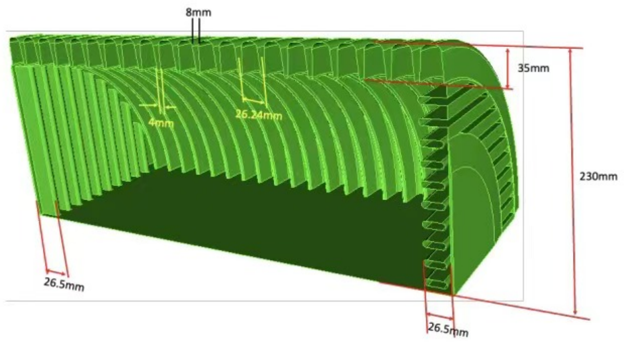
  •**MAGO 2.0**
  Mode transition from GW-induced cavity deformation.

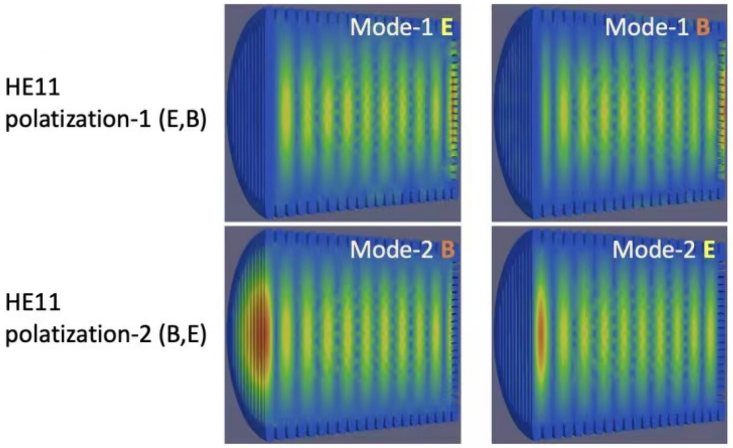
International SRF Campaigns

TWO PROTOTYPES [~ 1 YEAR]

SLAC NATIONAL ACCELERATOR LABORATORY

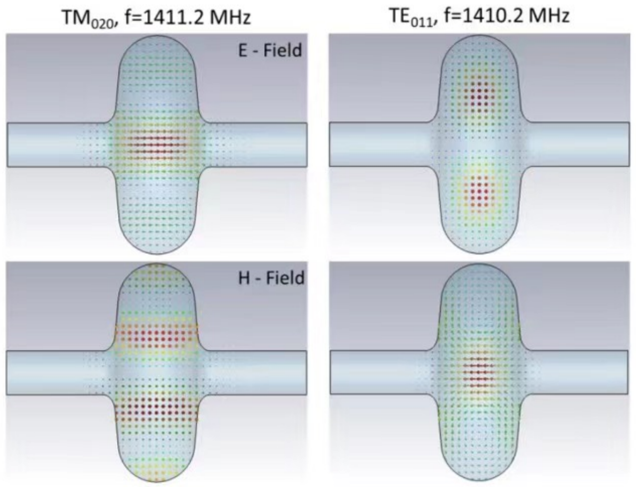
LDRD [only internal documents]

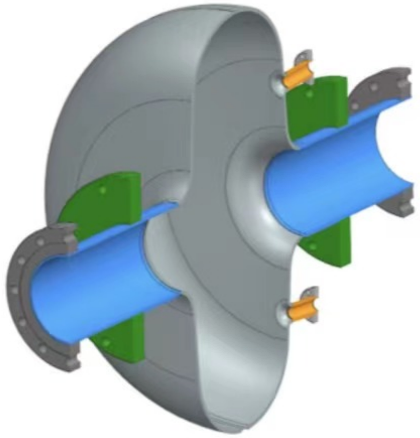




Fermilab

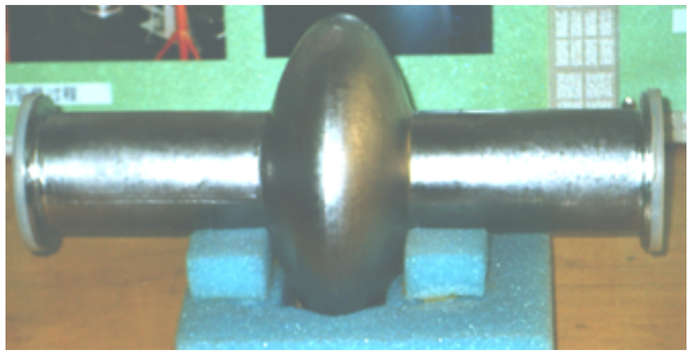
arXiv:2207.11346





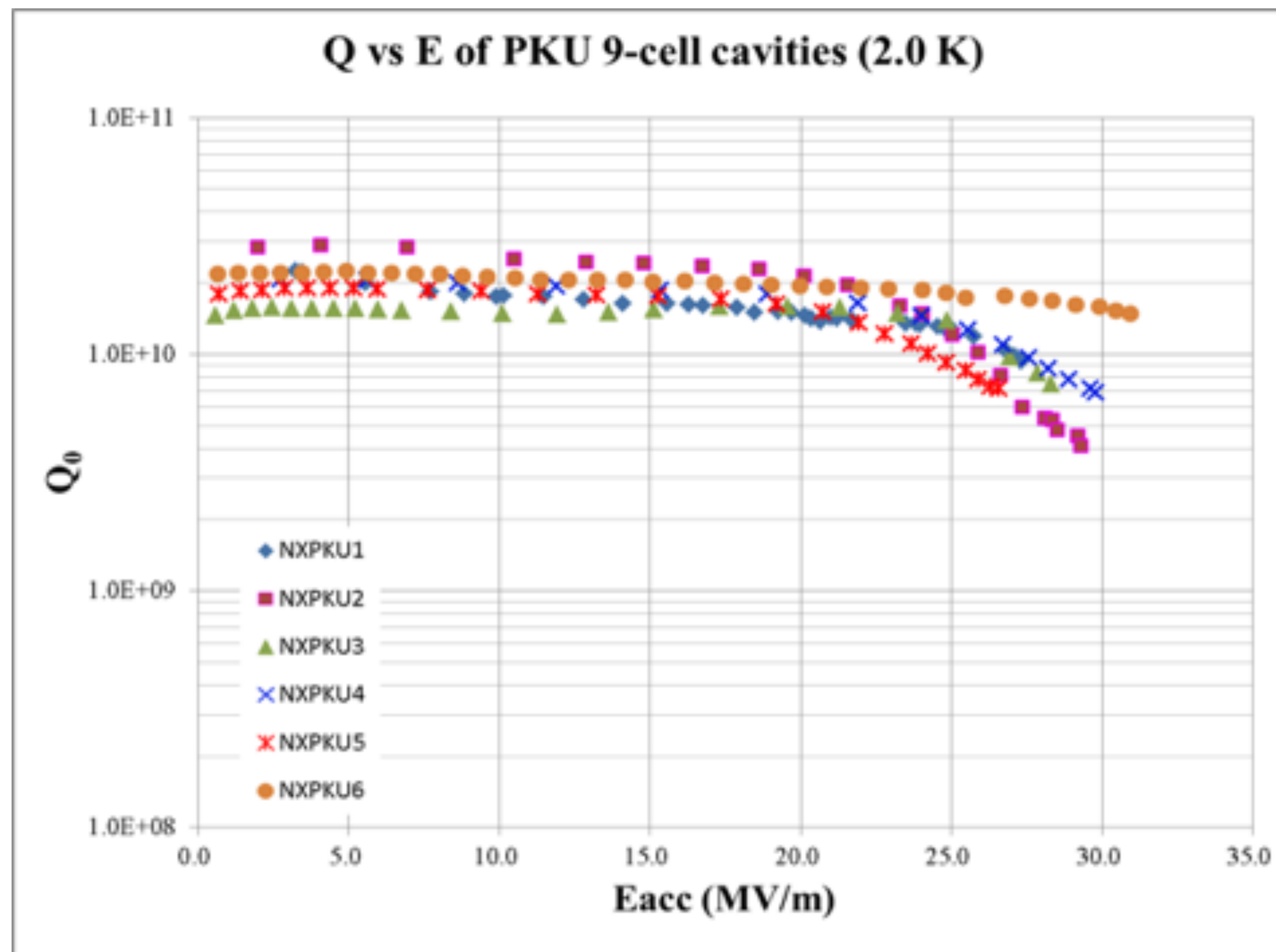
A brief introduction to the team member

SRF in Peking University



First 9-cell for ILC

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

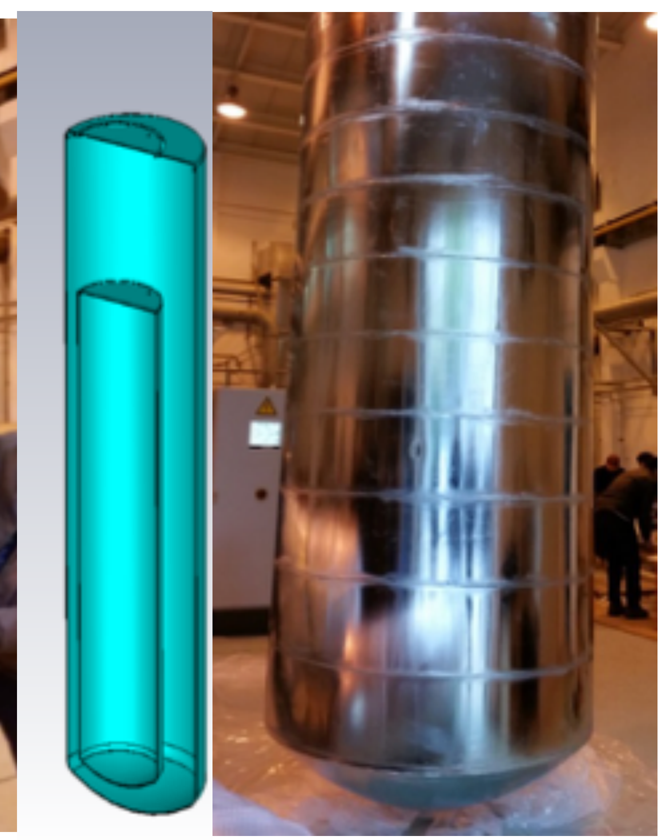


- Q ~ 1.6 -2.4 E^10 @ 16MV/m。
- equivalent level of international laboratories

Experimental facilities

Liquid helium system

2K pumping system



Vertical Dewar

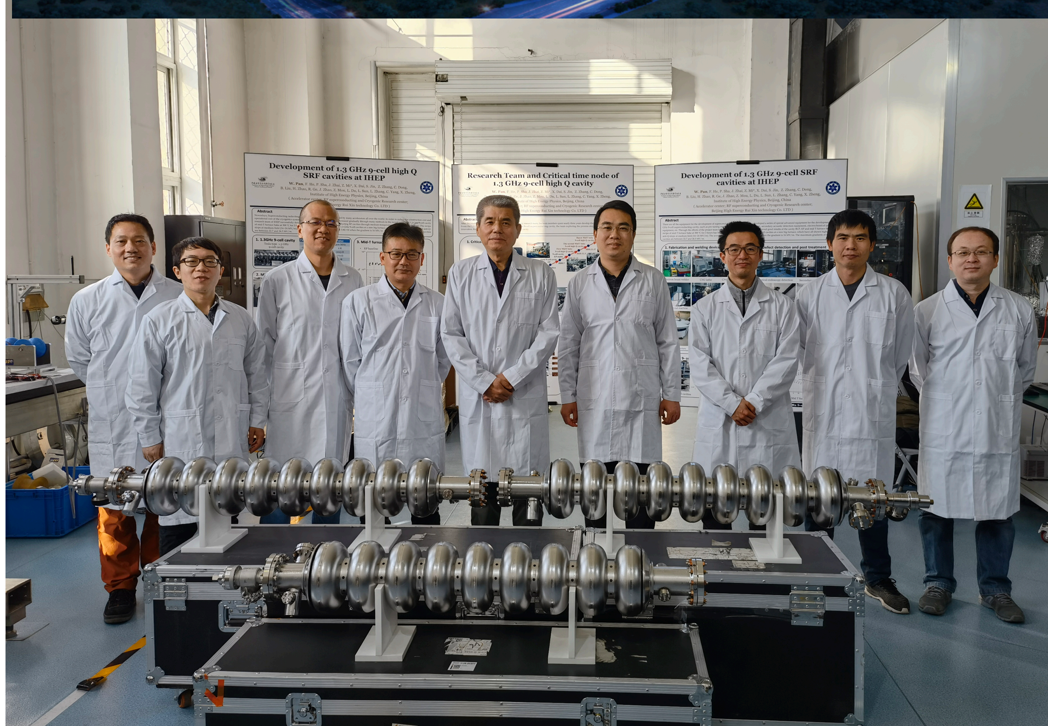
Cavity suspension

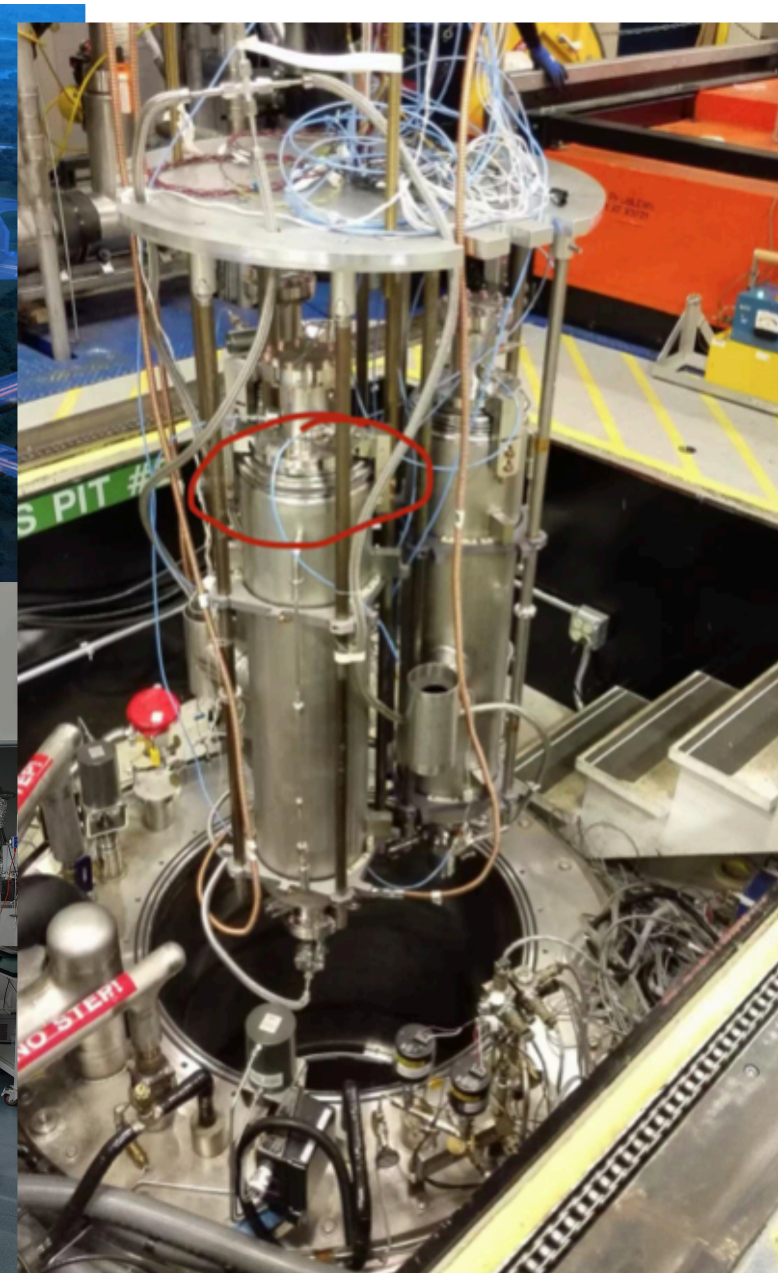
Magnetic shielding

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

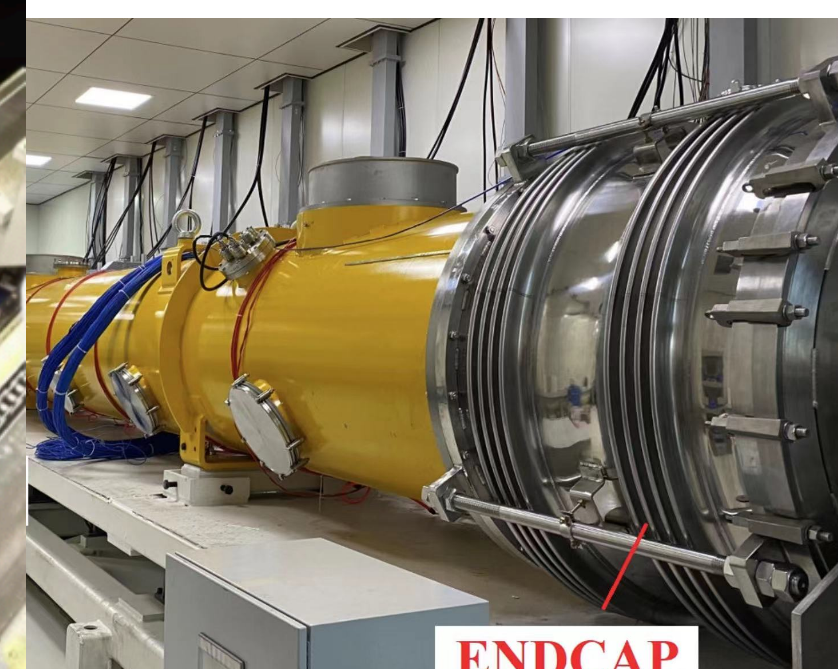
SRF in IHEP

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



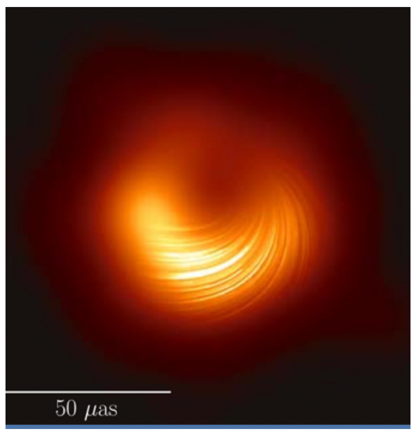


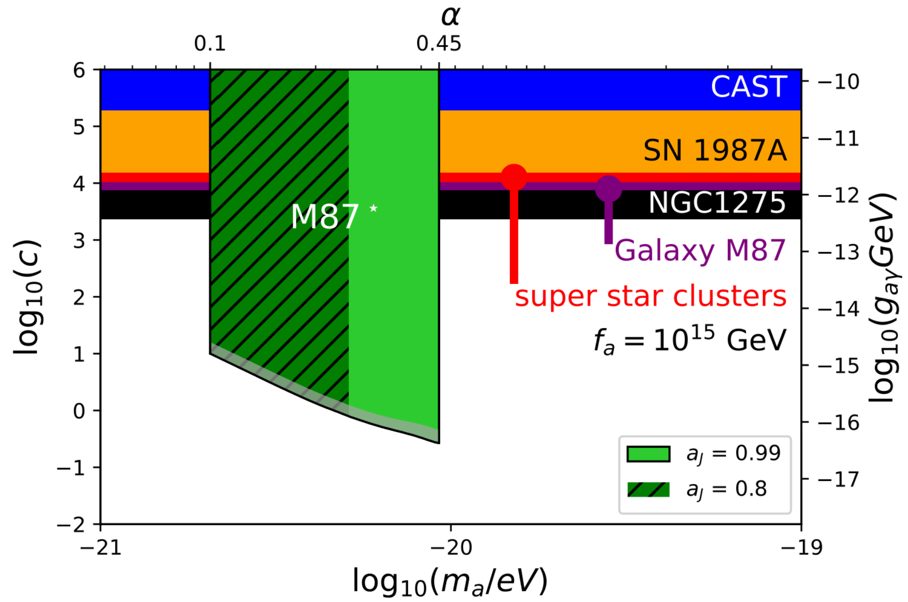
SRF used for Beijing & Shanghai Synchrotron Radiation Facility and future CEPC



Myself and other collaborations

EHT probe axion (birefringence)

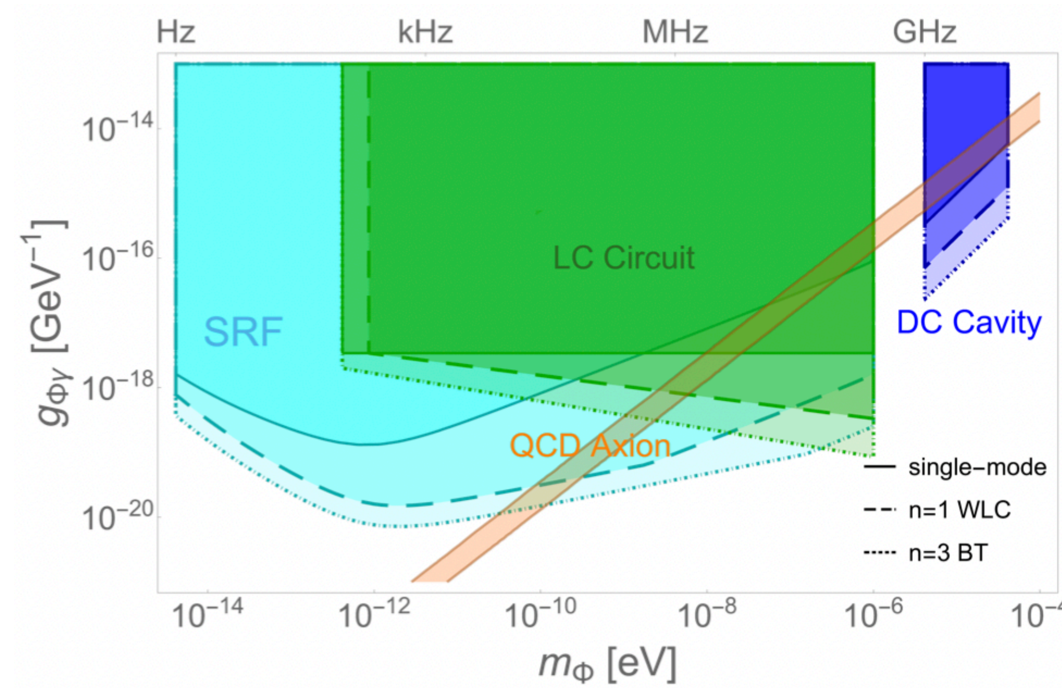




Y.F. Chen, J. Shu, X. Xue, Q. Yuan, Y. Zhao,
Phys. Rev. Lett. 124 (2020) no6, 061102

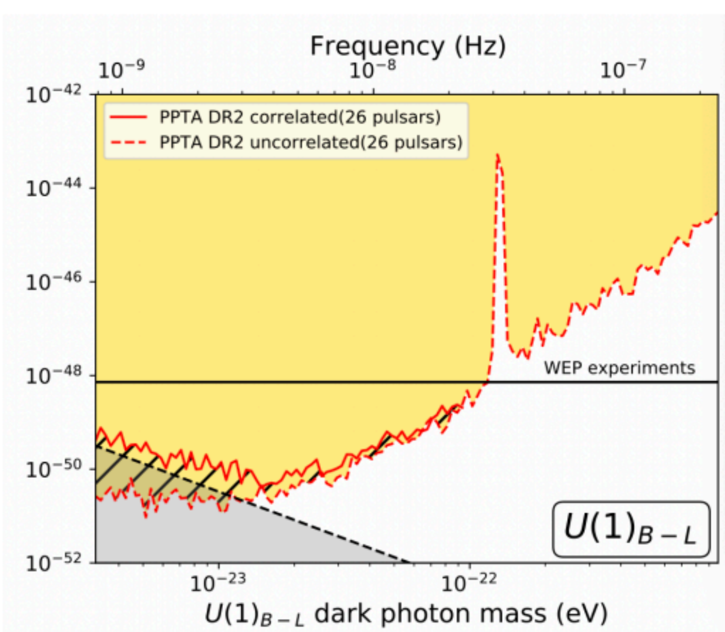
Y.F. Chen, .., J. Shu, .., Y. Zhao, Nature Astron. 6 (2022) 5, 592-598

Beyond SQL wave-like DM searches



Y-f. Chen, M-y. Jiang, J. Shu., Y-t. Yang,
Phys.Rev.Res. 4 (2022) 2, 023015
(arxiv time before Haystack)

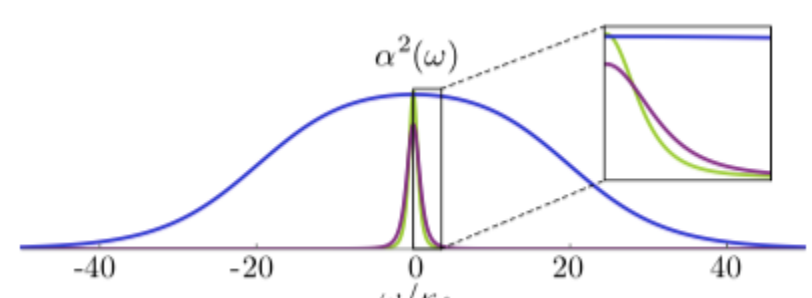
Y-f. Chen, C-L. Li, Y.X. Liu, J. Shu., Y-t. Yang, Y.-J. Zeng, arxiv: 2309.12387



PTA probe DPDM

X. Xiao, .., J. Shu, Y. Qiang, …,, Phys.Rev.Res. 4 (2022) 4, L012022

K. Wurtz, B. M. Brubaker, Y. Jiang, E. P. Ruddy, D. A. Palken and K. W. Lehnert, PRX Quantum 2 (2021) 4, 040350
Y. Jiang, K. O. Quinlan, M. Malnou, N.E. Frattini, and K. W. Lehnert, PRX Quantum 4 (2023) 4, 020302



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 . (opening, need more people)

Thank you!