SRF Cavity Search for Dark Photon

Jing Shu (Peking University, Beijing)

Outline

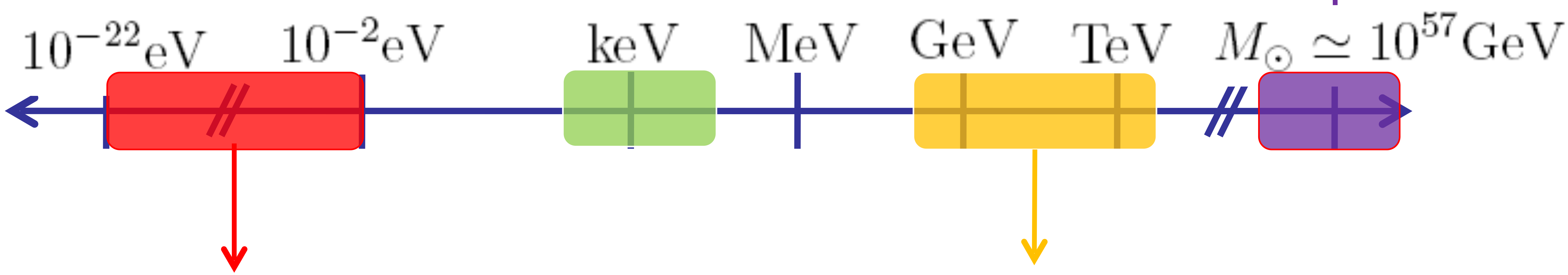
- Motivation of ultra-light dark matter search using Superconducting Radio Frequency (SRF) Cavity
- SRF Cavity Project for DPDM search
- SRF Cavity Project for cosmic DP
- Experimental group
- SRF with quantum quits
- Arrays to eliminate all the background noises
- Summary and Outlook

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

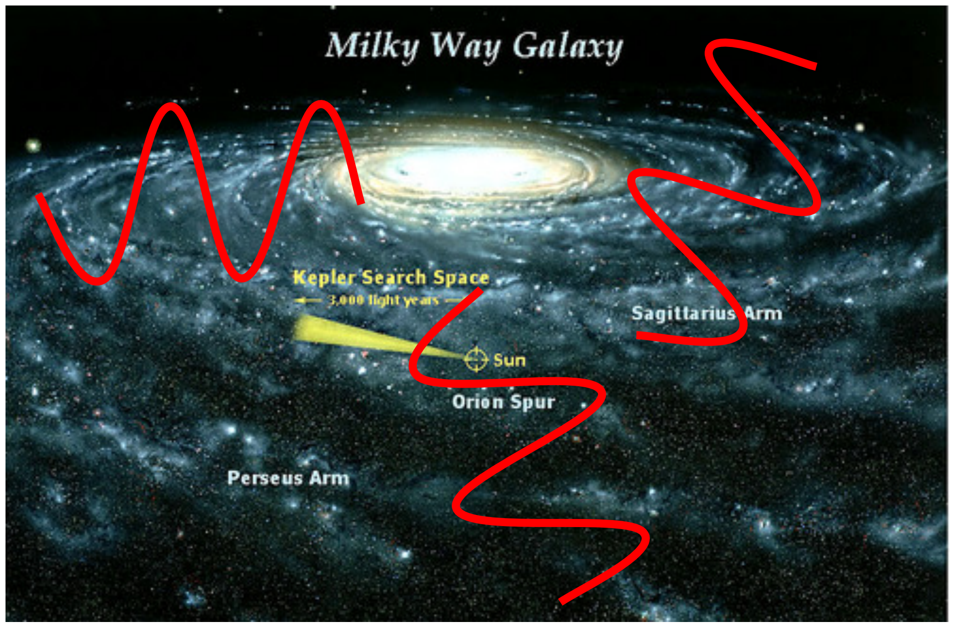
WIMPs: direct
(indirect)detection、
collider searches

particle-like DM

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

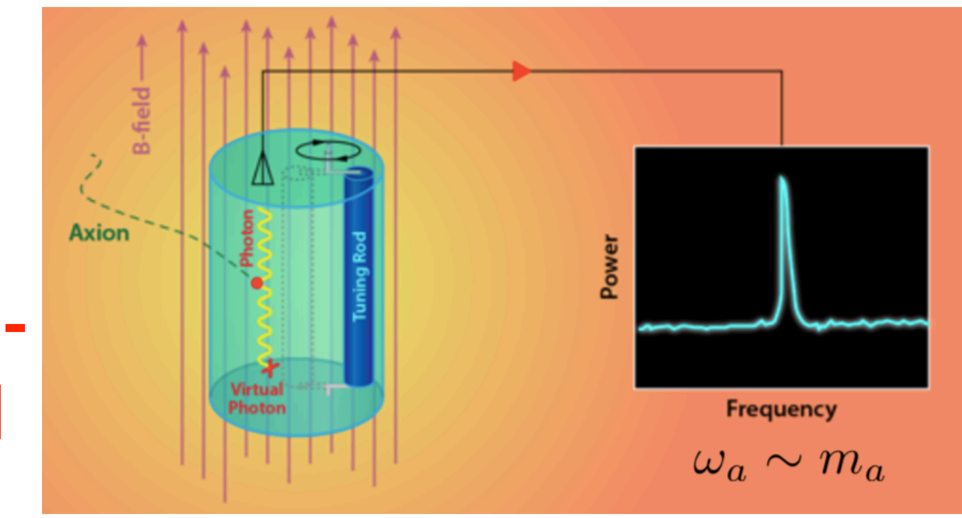
The ultra-light DM

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)

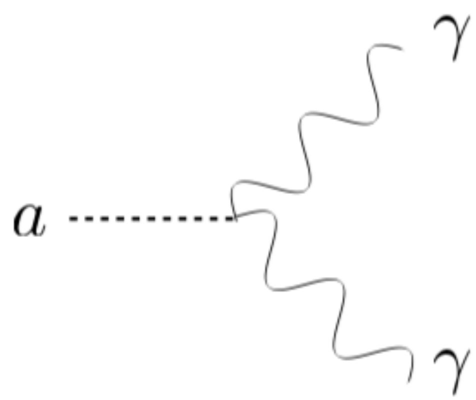
Haloscope, Quantum amplifier

New search methods!!!

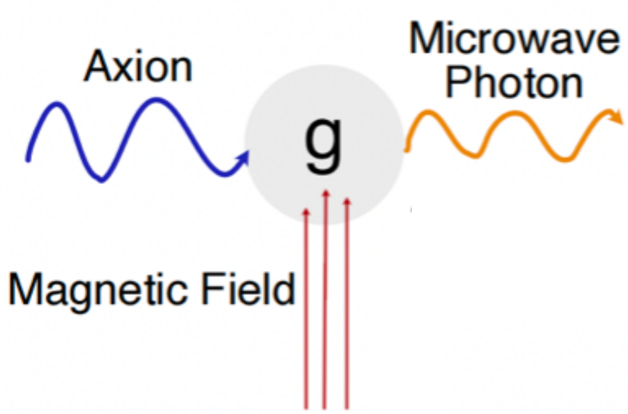
Quantum sensor

Ultra-light DM candidate

Axion (ALP): spin 0, CP odd



Inverse Primakoff effect



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

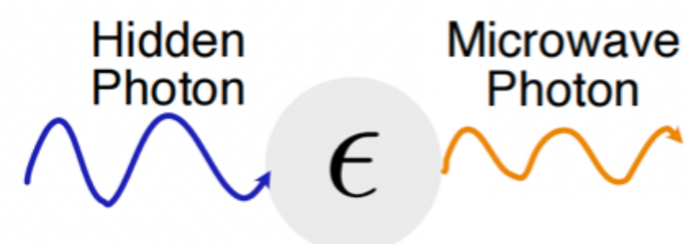
induces an effective current under strong magnetic field.

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

Dark photon: spin 1

mili-charge particles?

kinetic mixing

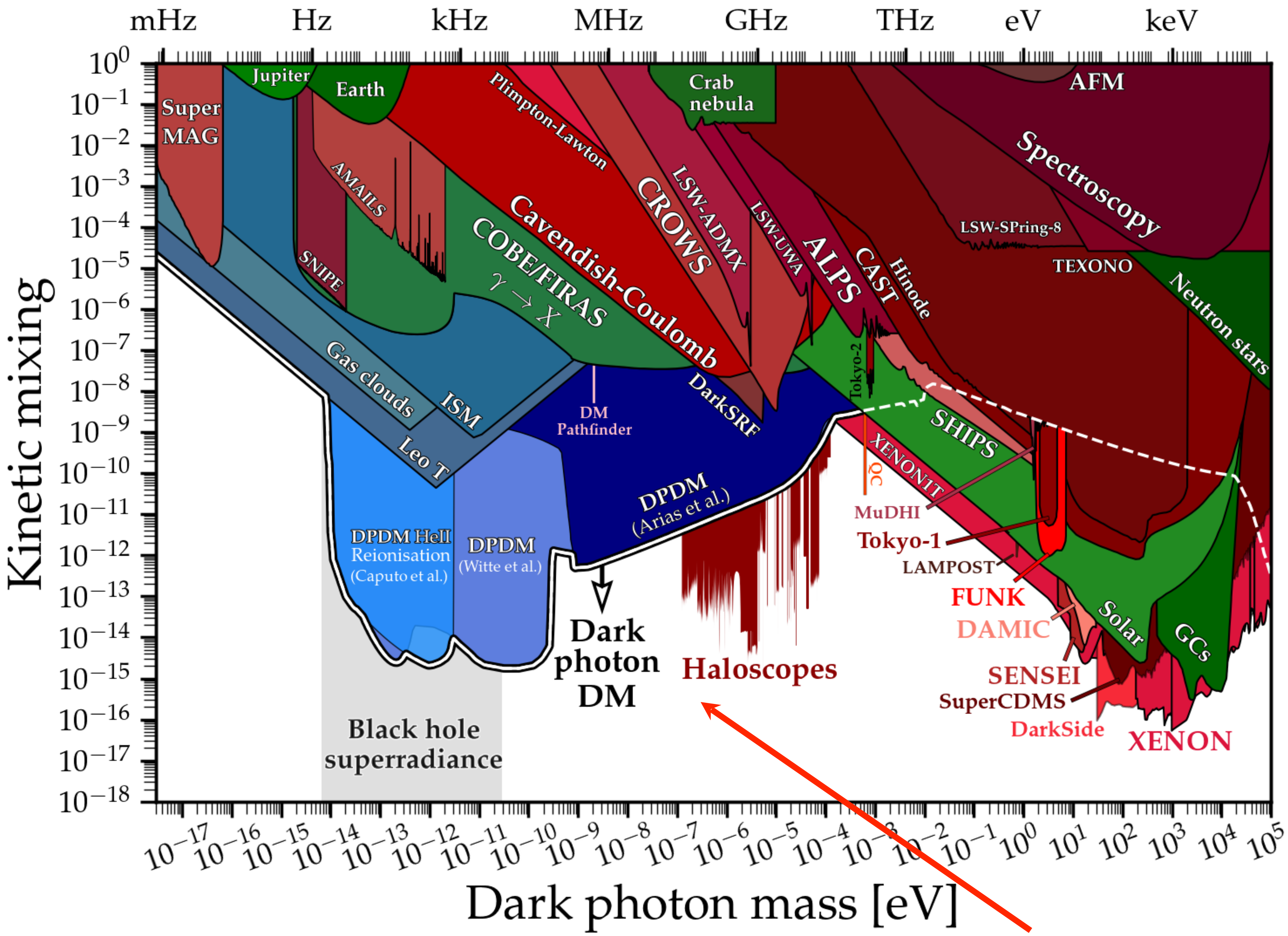


$$\mathscr{L} \supset -\tilde{A}_\mu \left(e J^\mu_{EM} - \varepsilon m^2_{A'} \tilde{A}'^\mu \right)$$

induces an effective current anyway.

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

Current DPDM search

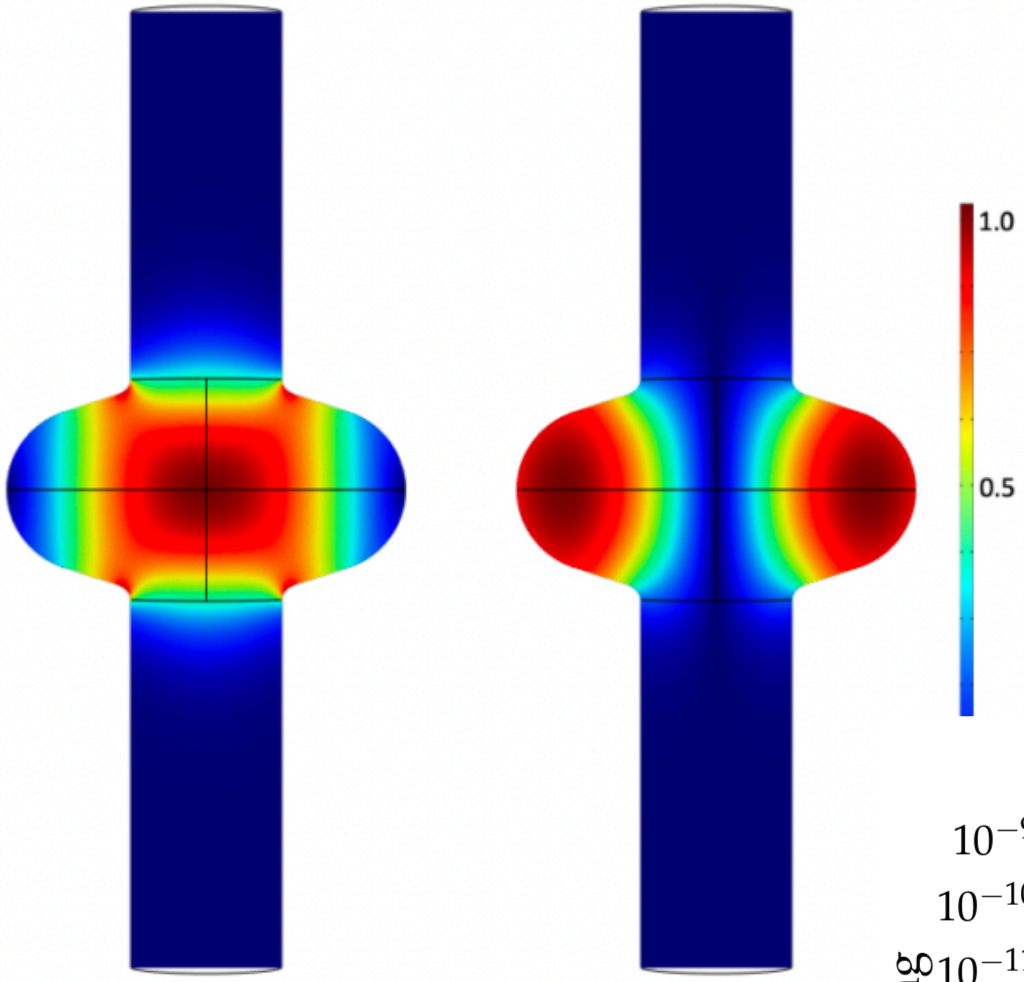


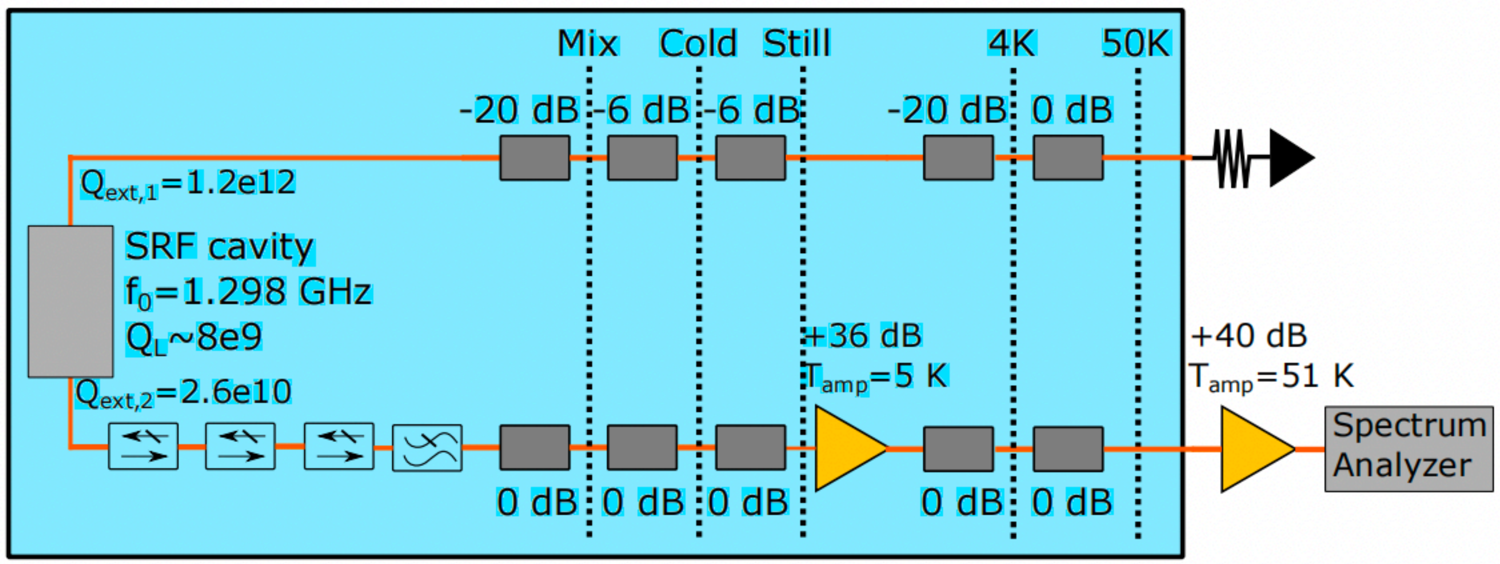
Haloscope sensitivity largely depends on Q: Superconducting cavity has Q~10^{10}

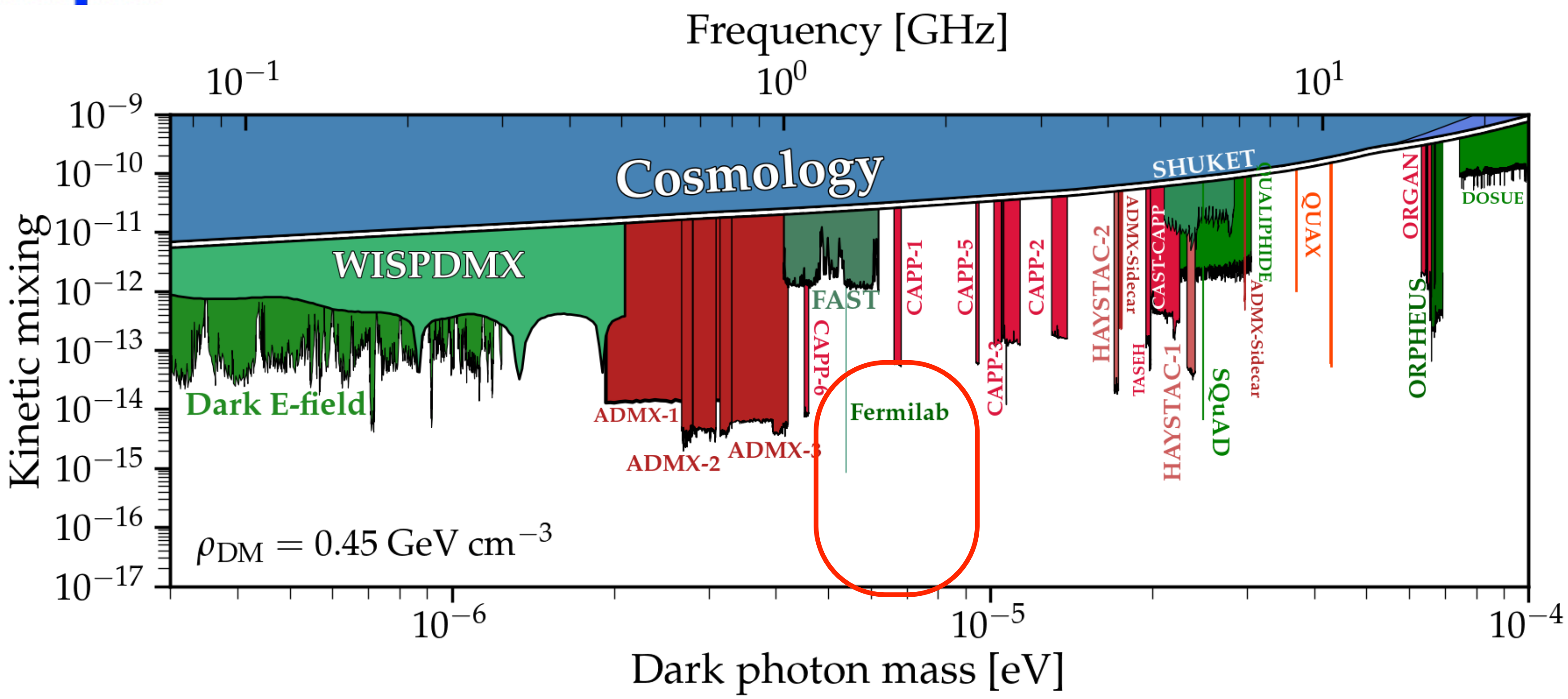
how to make use it? 5 orders more than traditional cavity.

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

Result from Fermilab







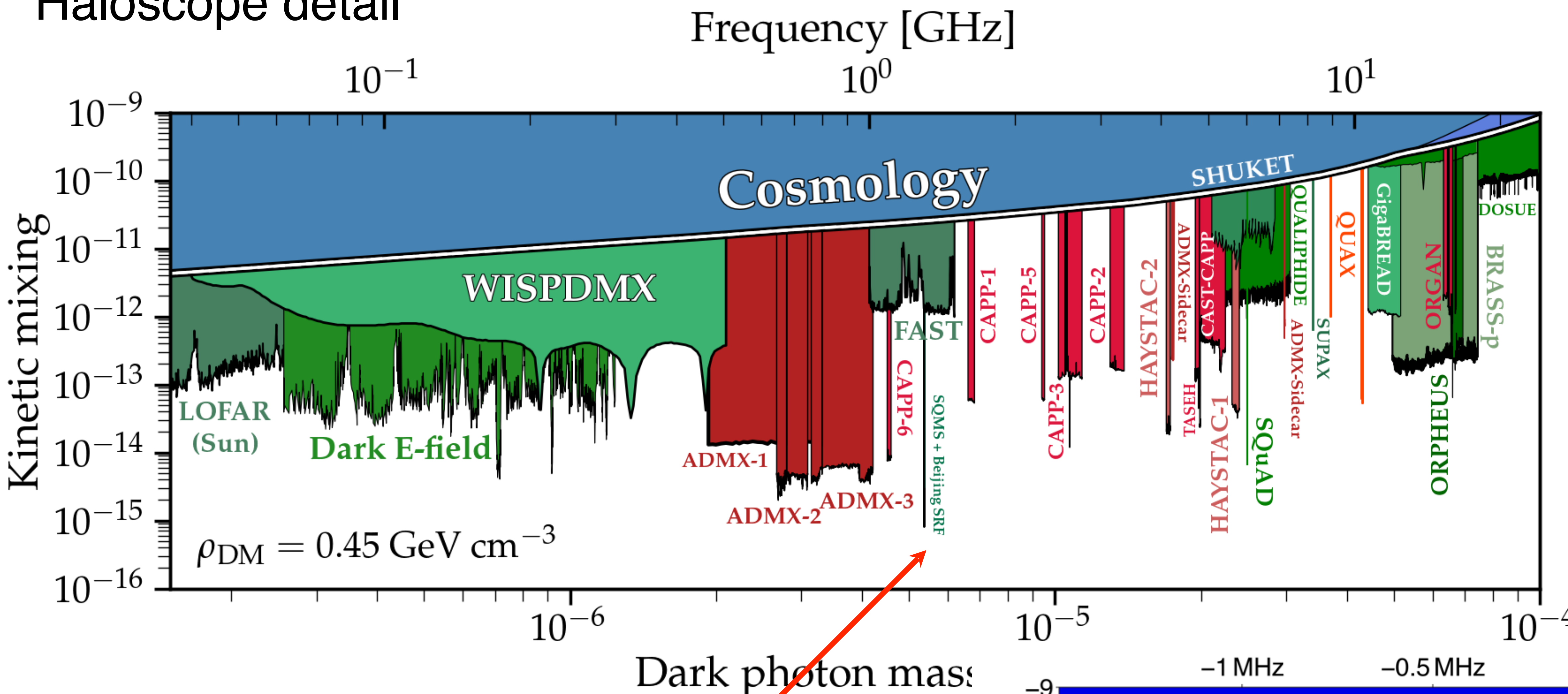
Deepest constrain

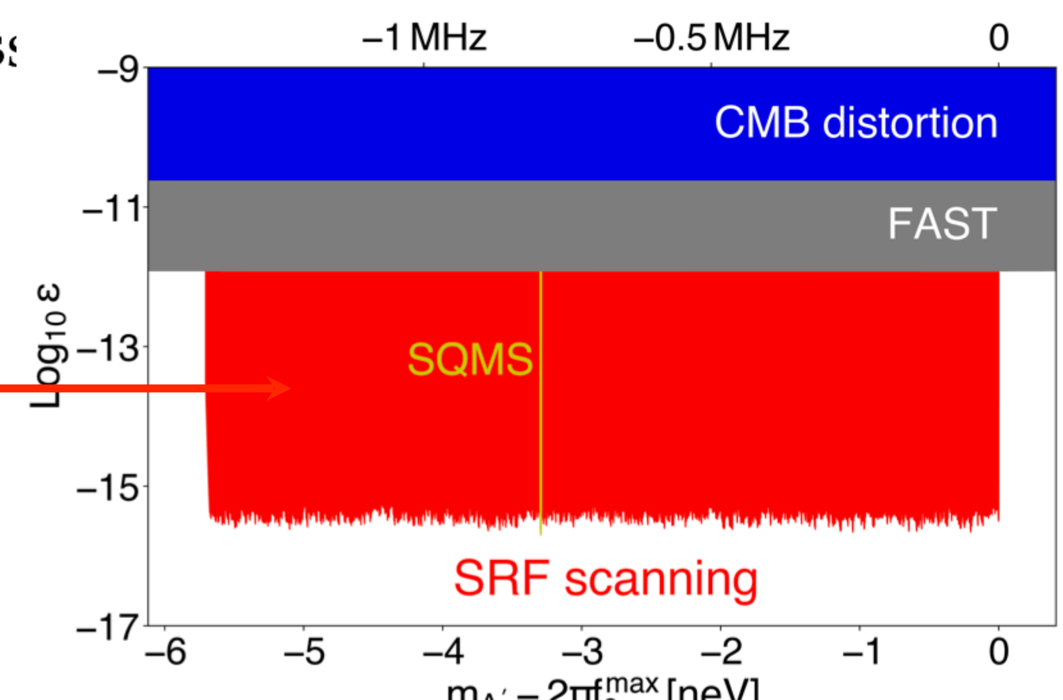
$Q \sim 4.7 \times 10^9$

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

DPDM search

Haloscope detail





First tunable results with deepest exclusion limit

SHANHE Collaboration, Zhenxing Tang,… Jing Shu, 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: $\omega_a \simeq \text{GHz}\,\frac{m_a}{10^{-6}\text{ eV}}$

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

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

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

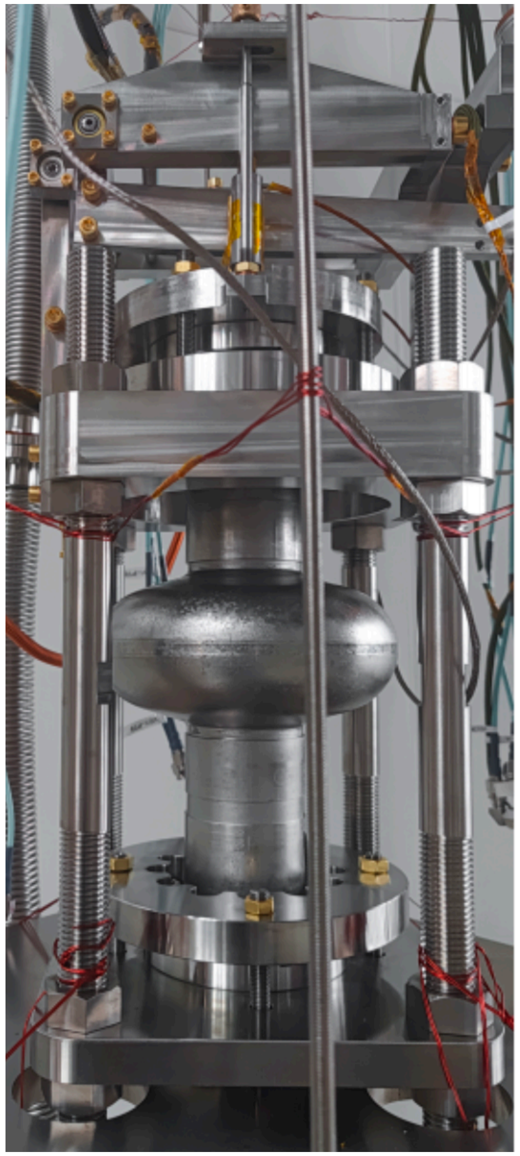
$$\lambda_a \sim 1/m_a\sqrt{\langle v_{\rm DM}^2\rangle} \sim 10^3/m_a$$

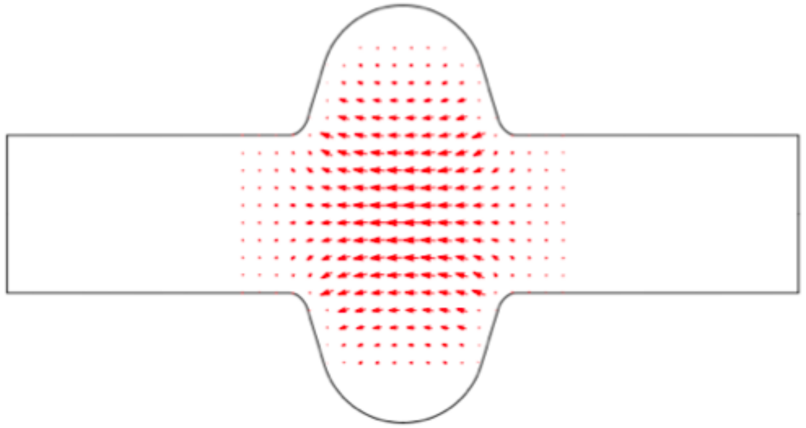
Momentum width10^-3

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 $Q_0 \approx 10^{10} \rightarrow$ 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)





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

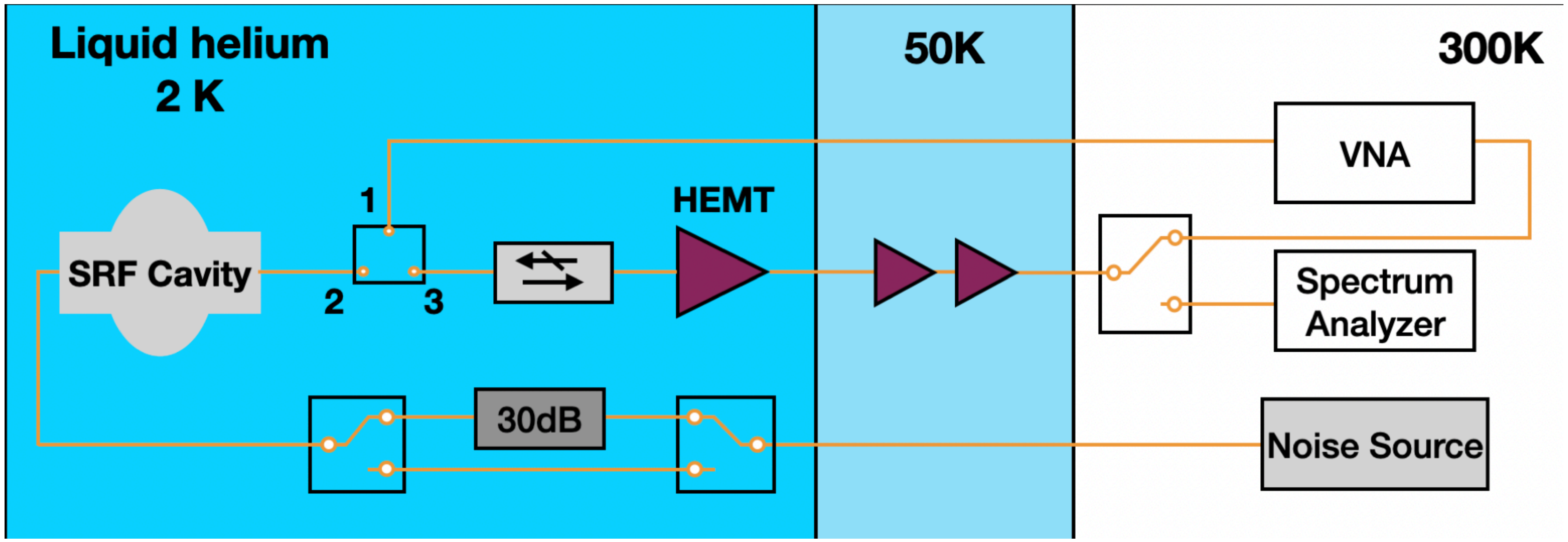
SHANHE Collaboration, Zhenxing Tang,… Jing Shu, Phys.Rev.Lett. 133 (2024) 2, 021005

Experimental operation

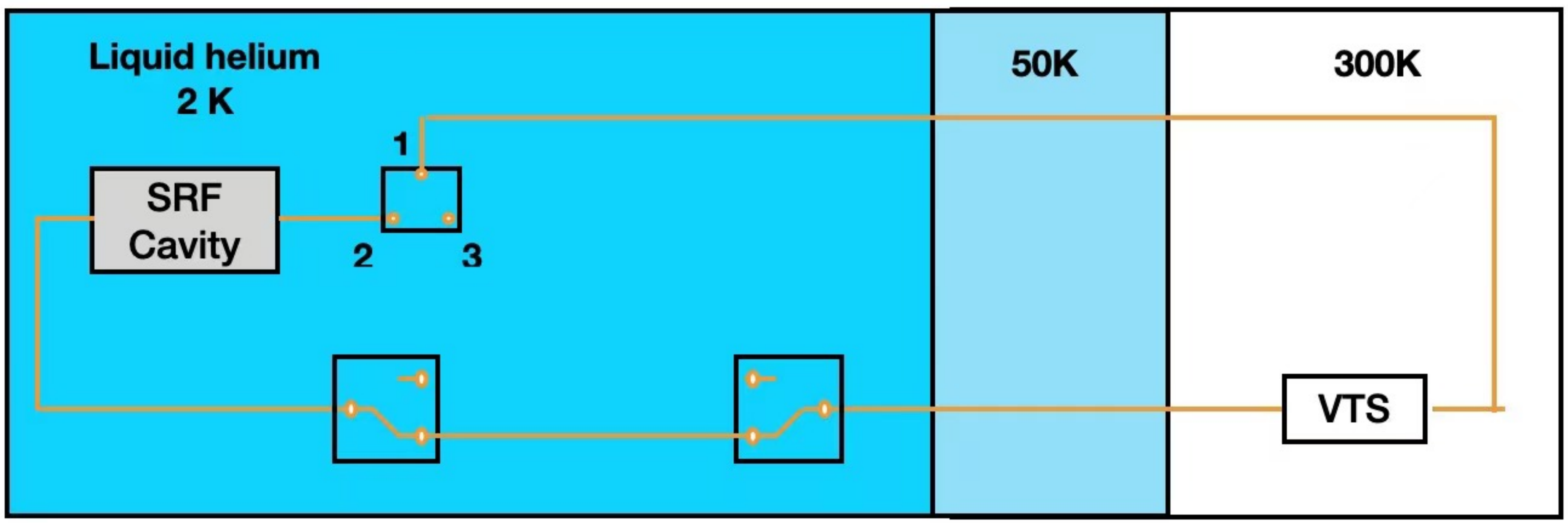
Parameters

	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

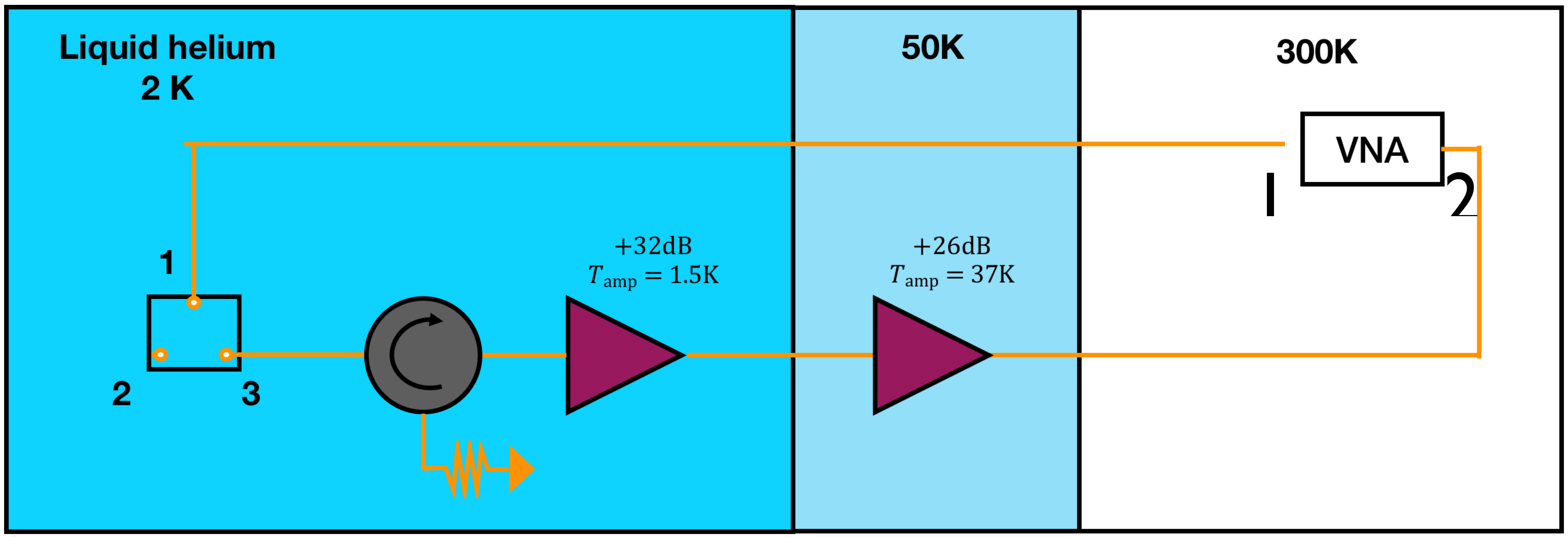


Step 1: Measure Cavity property



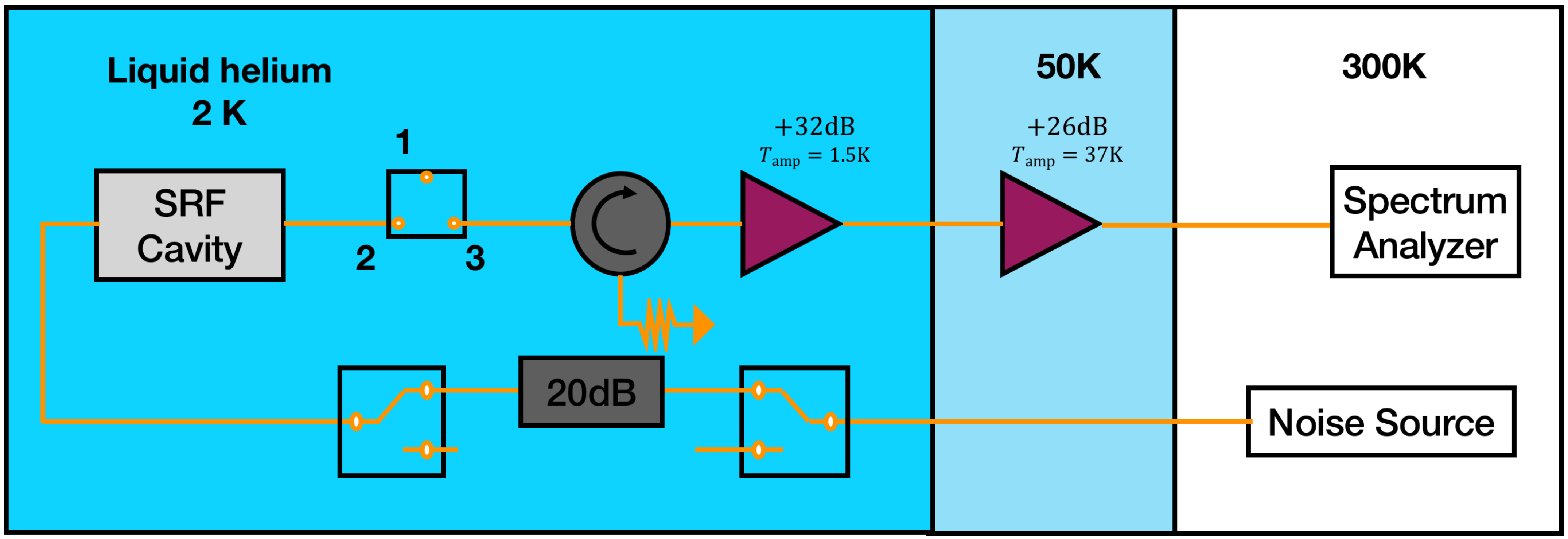
1-2 connection: VTS measurement for the cavity property.

Step 2: calibration



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

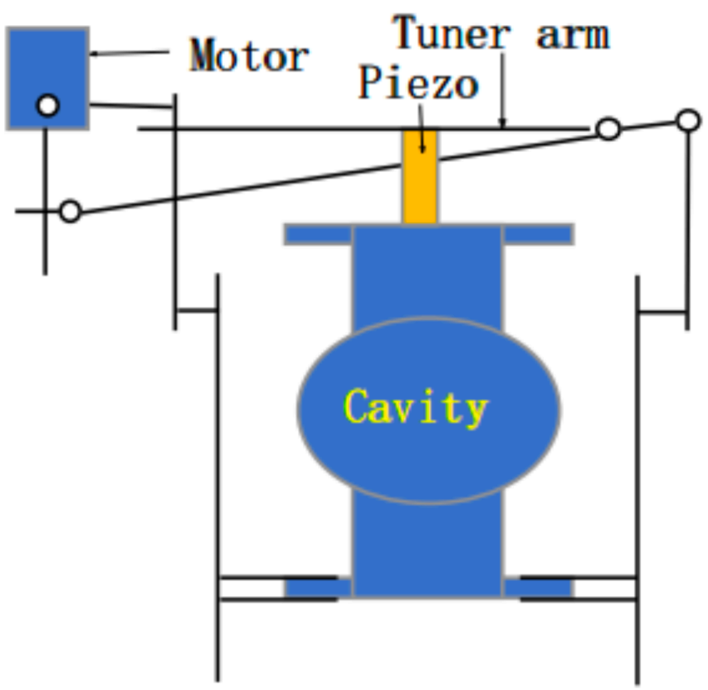
Step 3: Do experiment

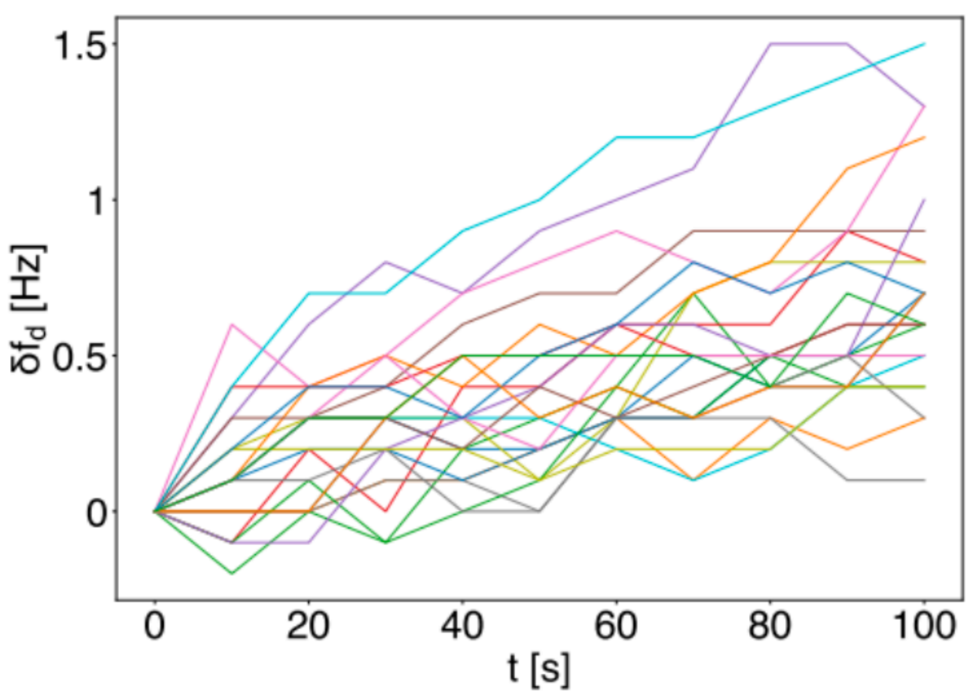


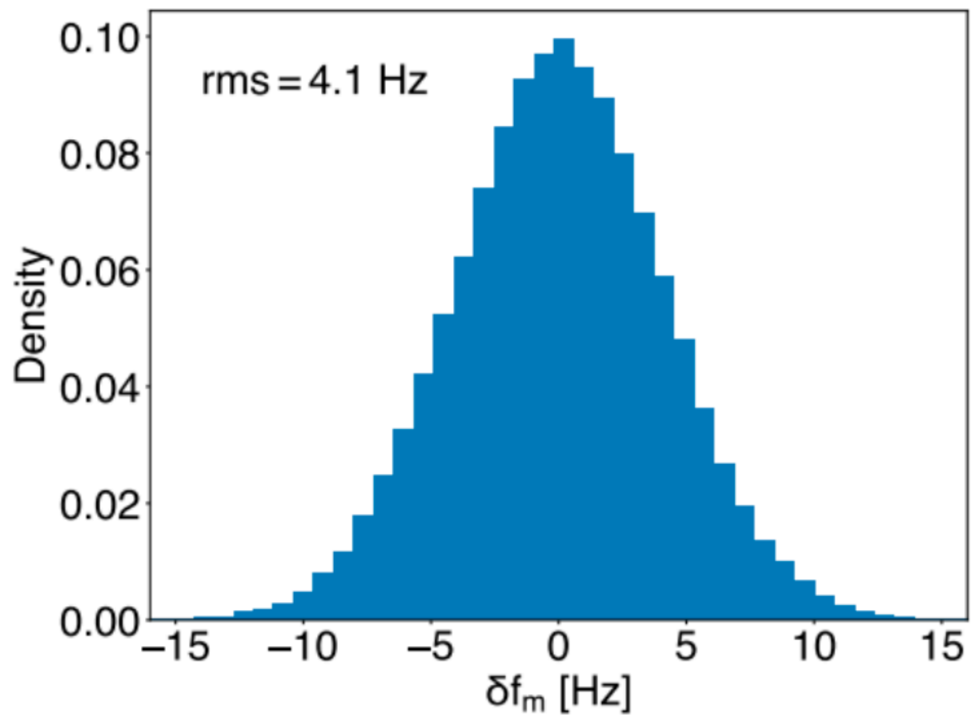
2-3 connection: tune the cavity resonant frequency to do the experiment

Scan Search with Mechanical Tuning

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





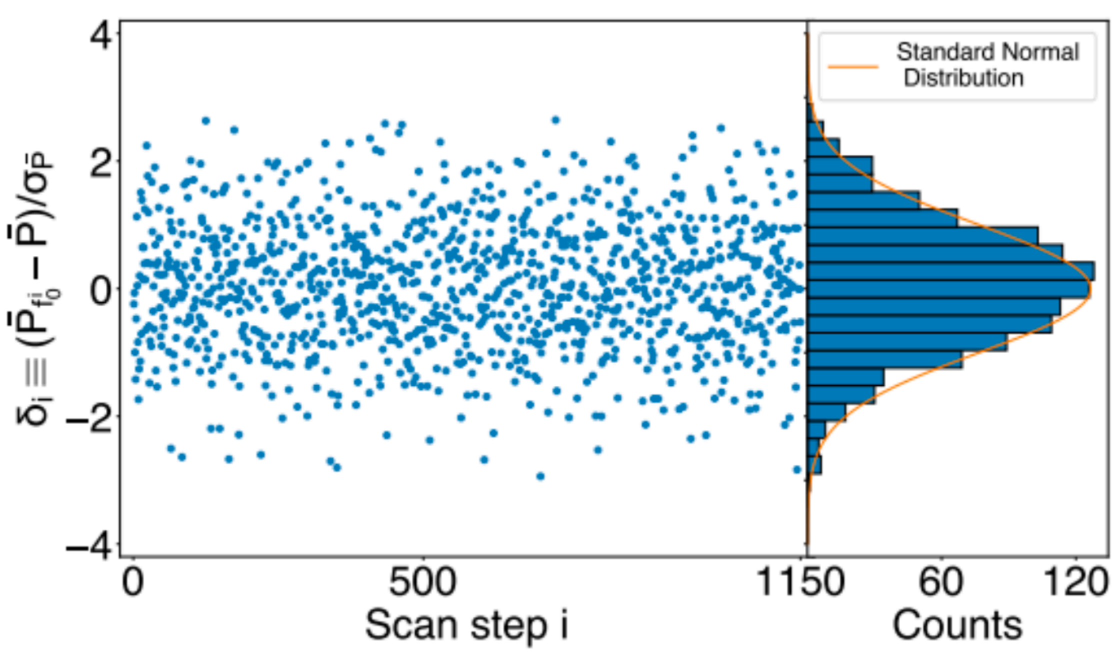


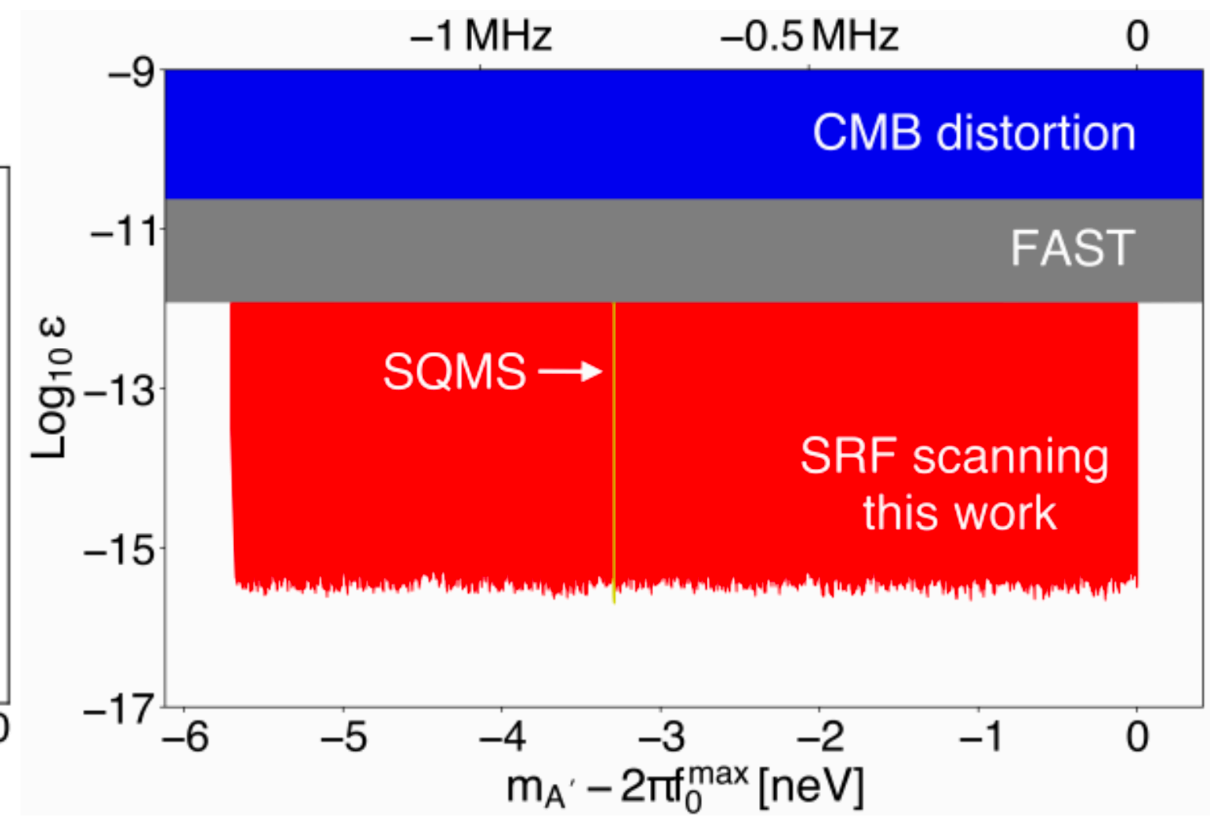
- **Conservatively** choose $\Delta f_0 \approx 10{\rm Hz}$

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**:

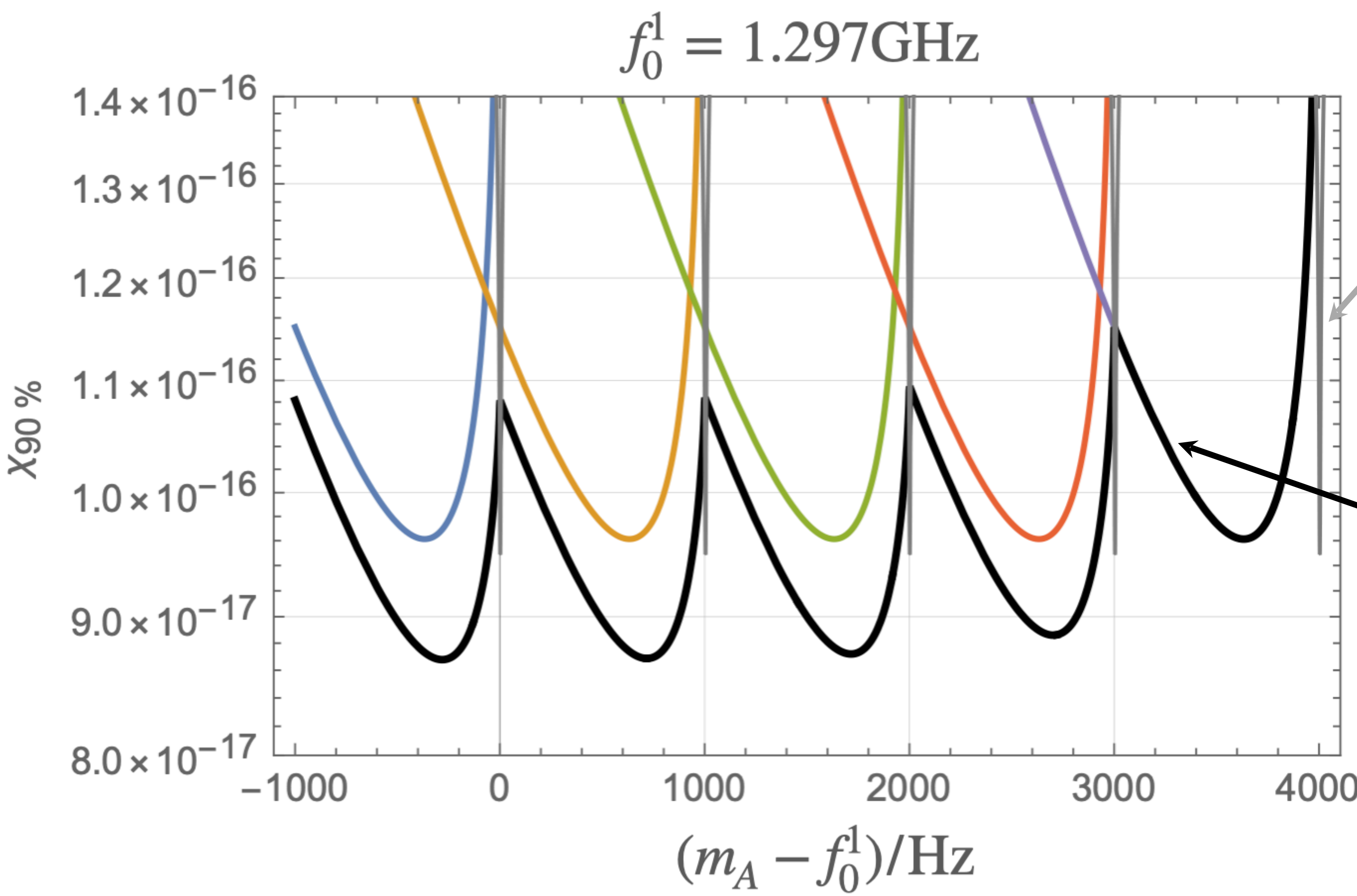
SHANHE Collaboration, Zhenxing Tang,… Jing Shu, Phys.Rev.Lett. 133 (2024) 2, 021005





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

Few comment on $Q \gg Q_{\rm DM}$



Direct Exclusion from the cavity

Noise power reduce with Q

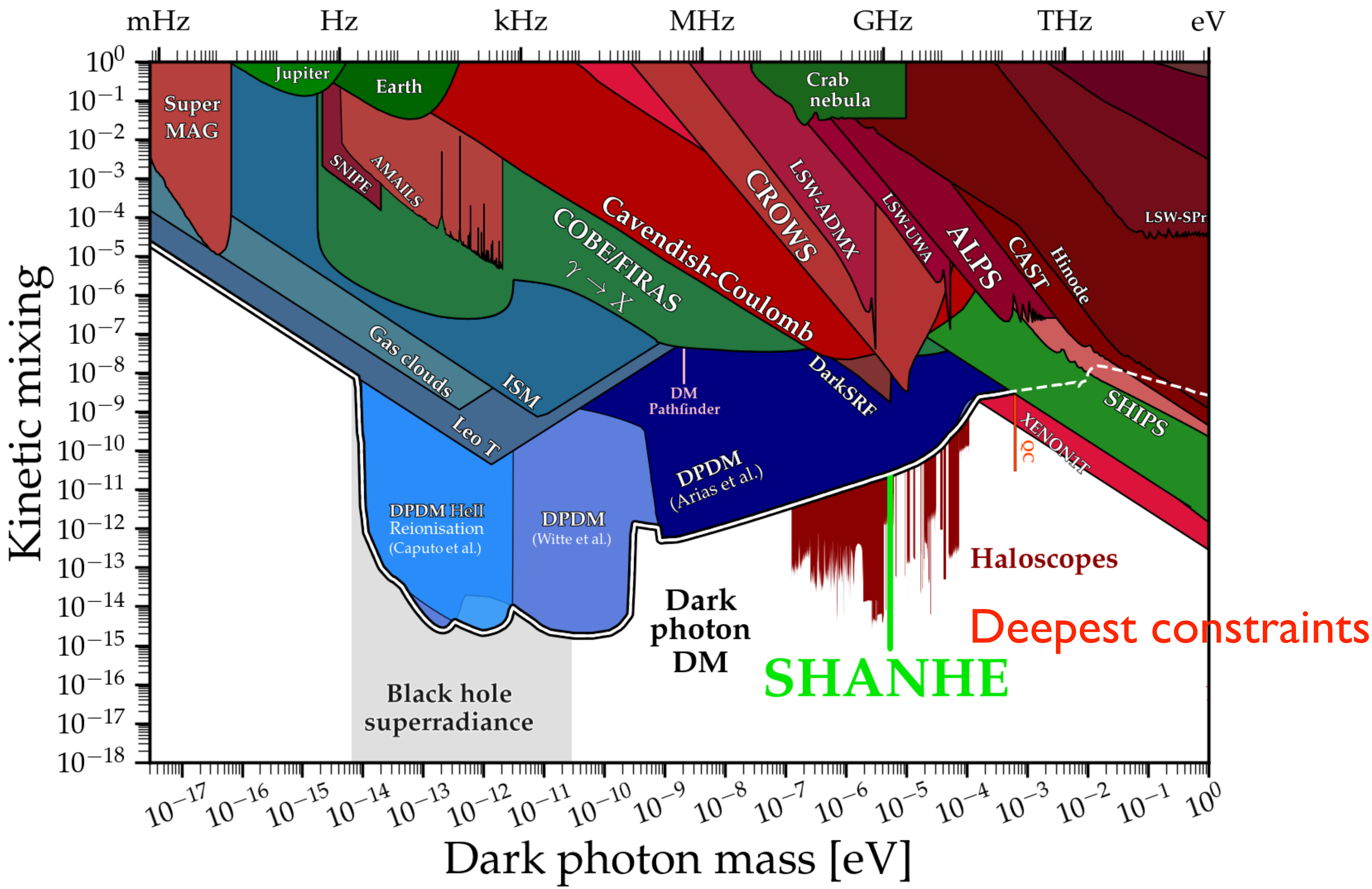
Virialized DM Exclusion

Scan step: $f \times Q_{\rm DM}$

simple fit function (constant): attenuation factor almost 1

different from ADMX

Data analysis and constraints



SHANHE Collaboration, Zhenxing Tang,… Jing Shu, 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*

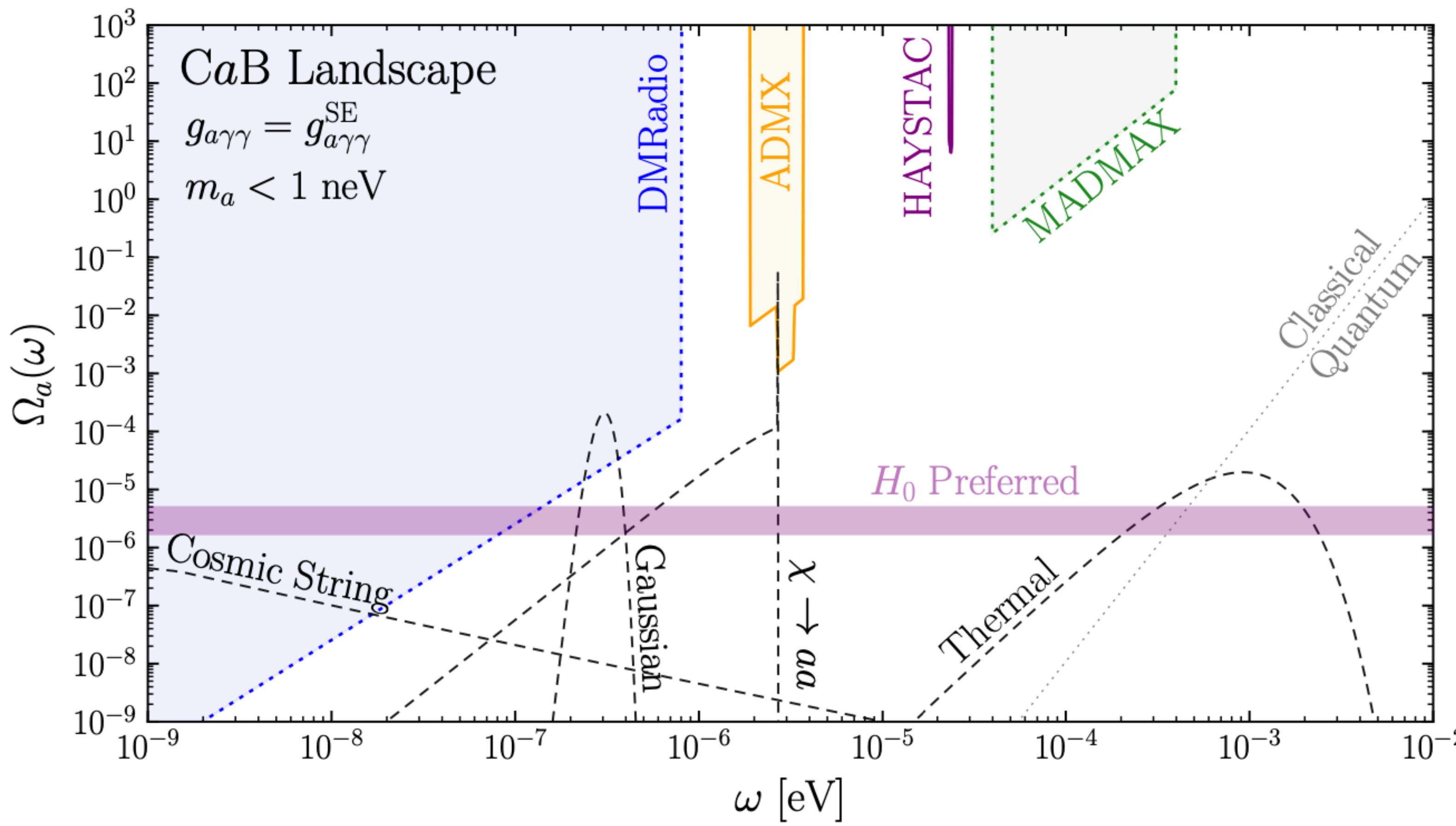
[2] *Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720, USA*

[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

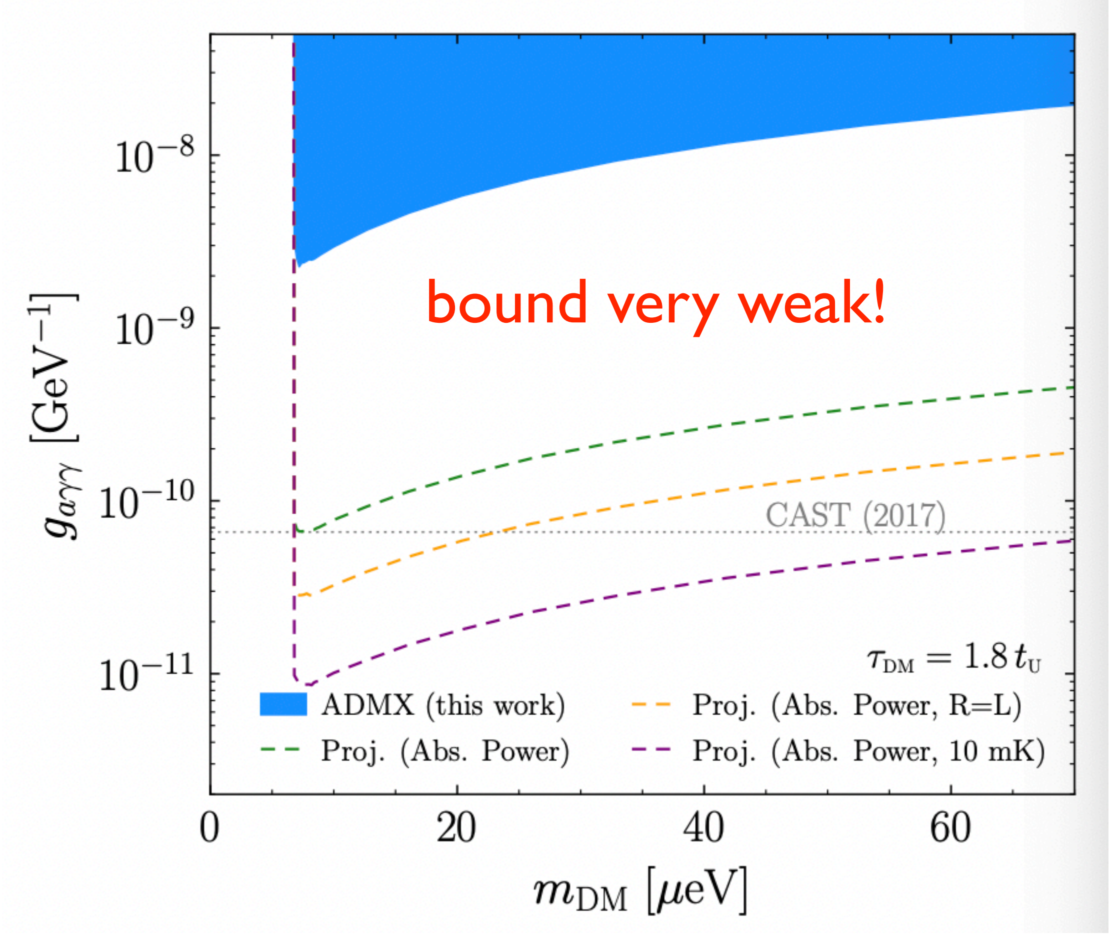
- How about galactic DP backgrounds? (Anisotropic backgrounds, from annihilation or decay?)

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



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

- Polarization

Longitudinal: from a heavy dark Higgs decay

Transverse: axion-DP coupling

Modulated Signal from Galactic Dark Photons

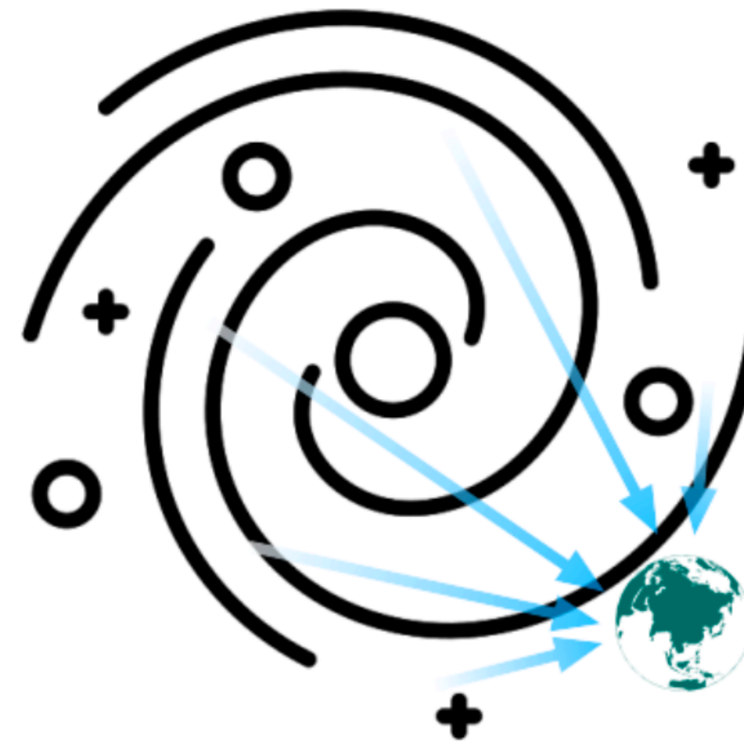
▶Galactic dark photons from DM decay, e.g.: cascade decay from DM halo

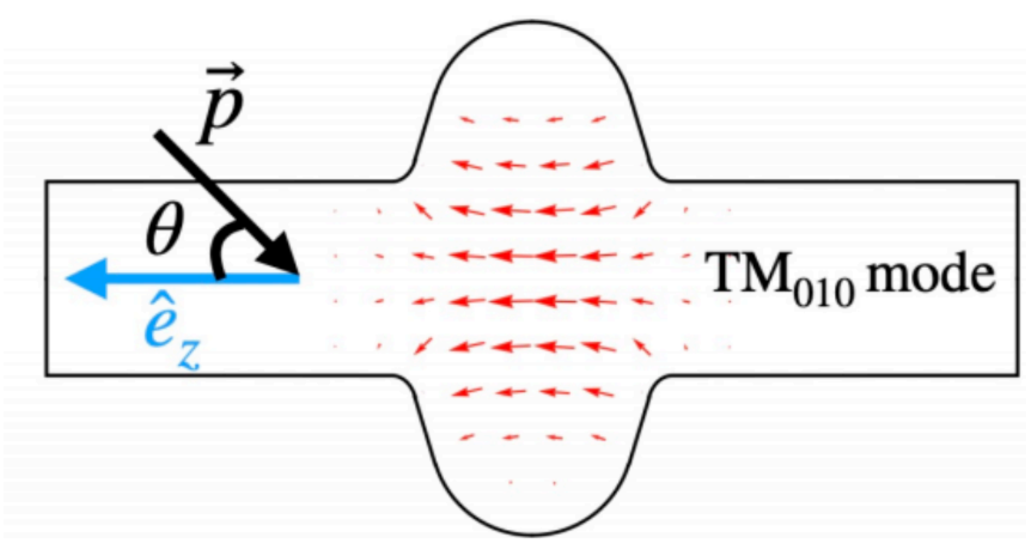
▶Vectorial observable $\propto \vec{A}'$

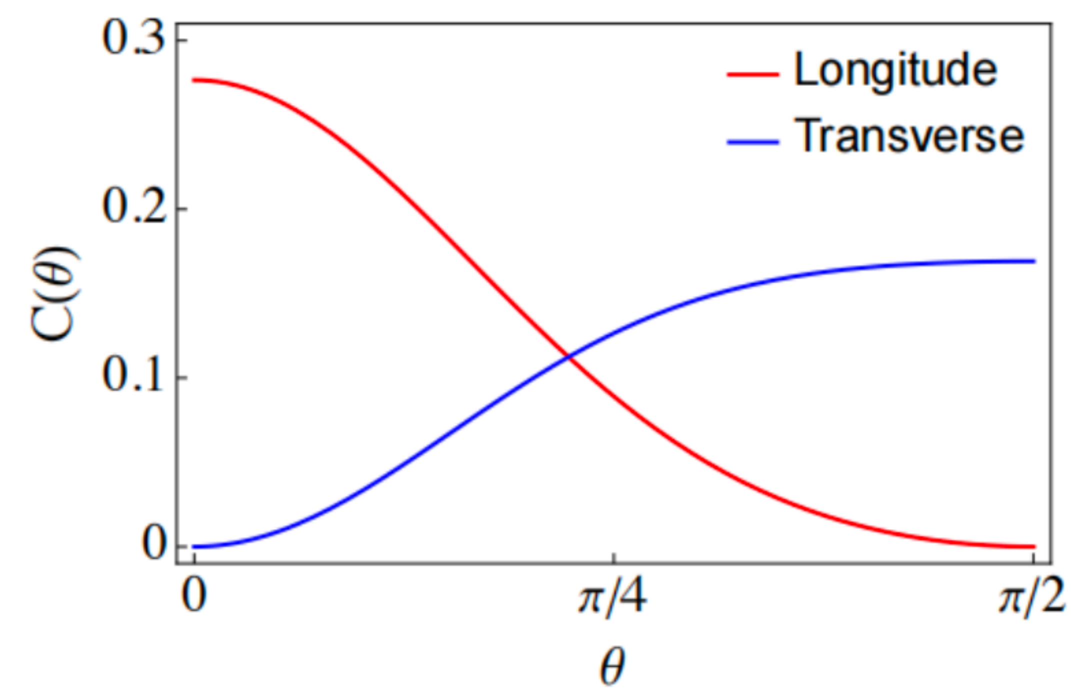
→ angular-dependent signal $\propto C(\theta)$

→ modulation as the Earth rotates

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



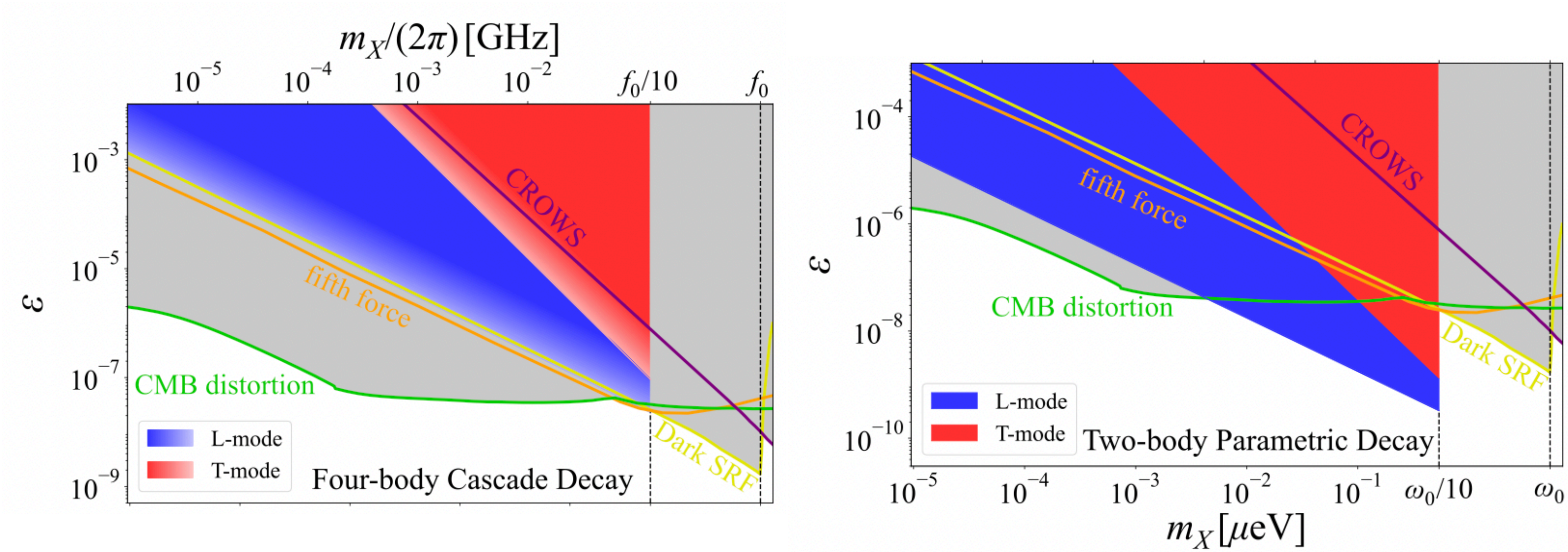




Yifan Chen, Chunlong Li, Yuxiang Liu, Yuxin Liu, Jing Shu, Yanjie Zeng, e-Print: 2402.03432 [hep-ph].

SRF Constraints for Galactic Dark Photons

- ▶Same dataset as DPDM search
- ▶Scanned range within galactic dark photon bandwidth → 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

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

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

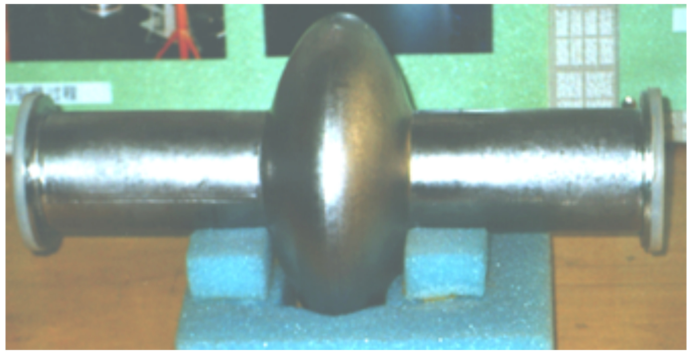
Supportive collaboration

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

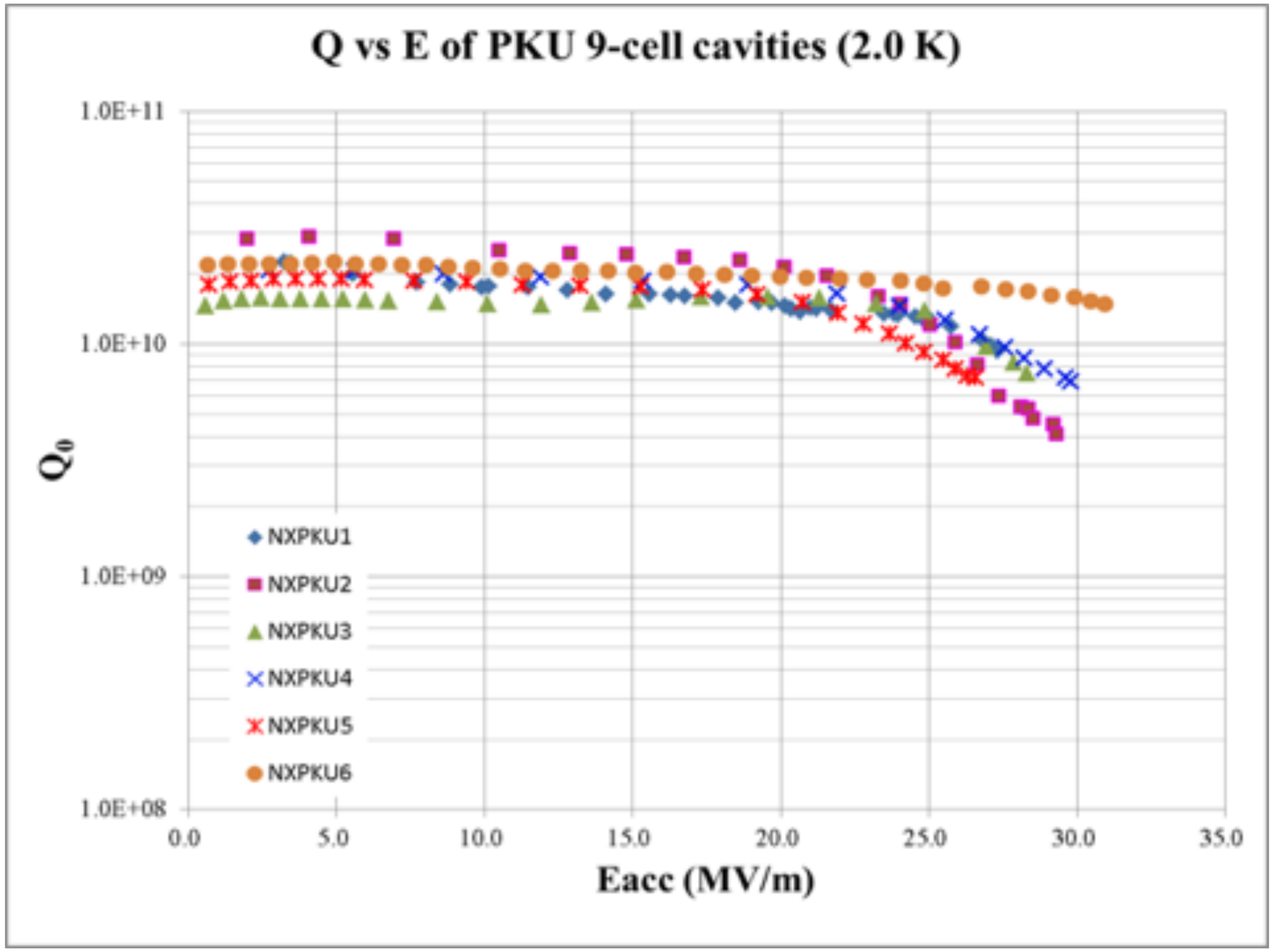
量子科学与工程研究院
Institute for Quantum Science and Engineering

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

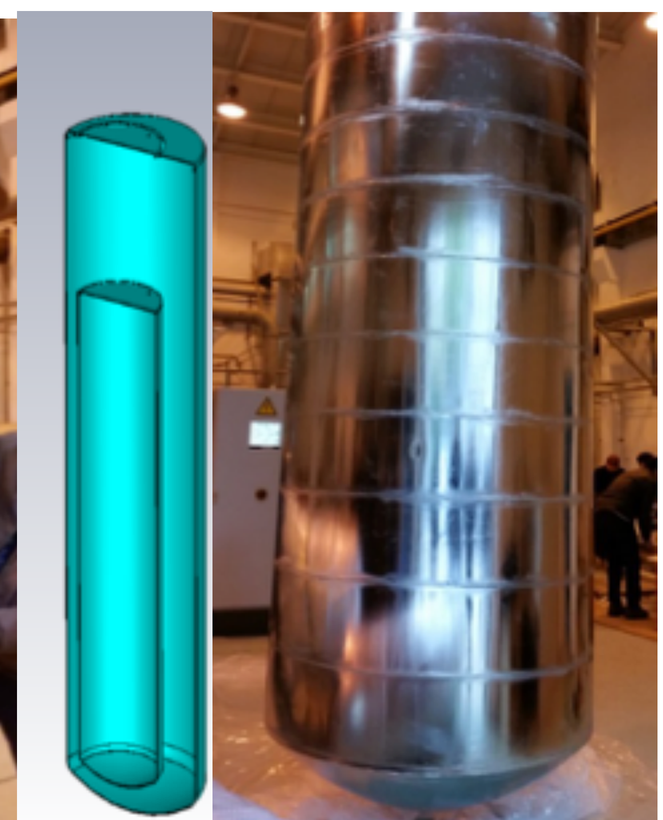
Experimental facilities

Liquid helium system

2K pumping system

Vertical Dewar

Cavity suspension



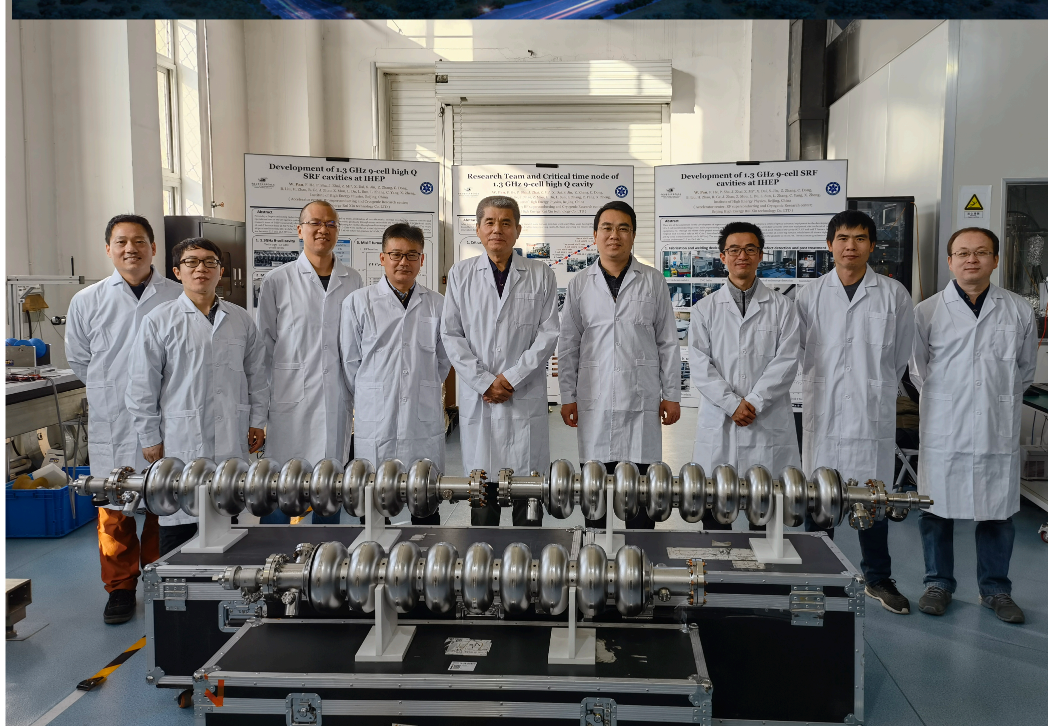
Magnetic shielding

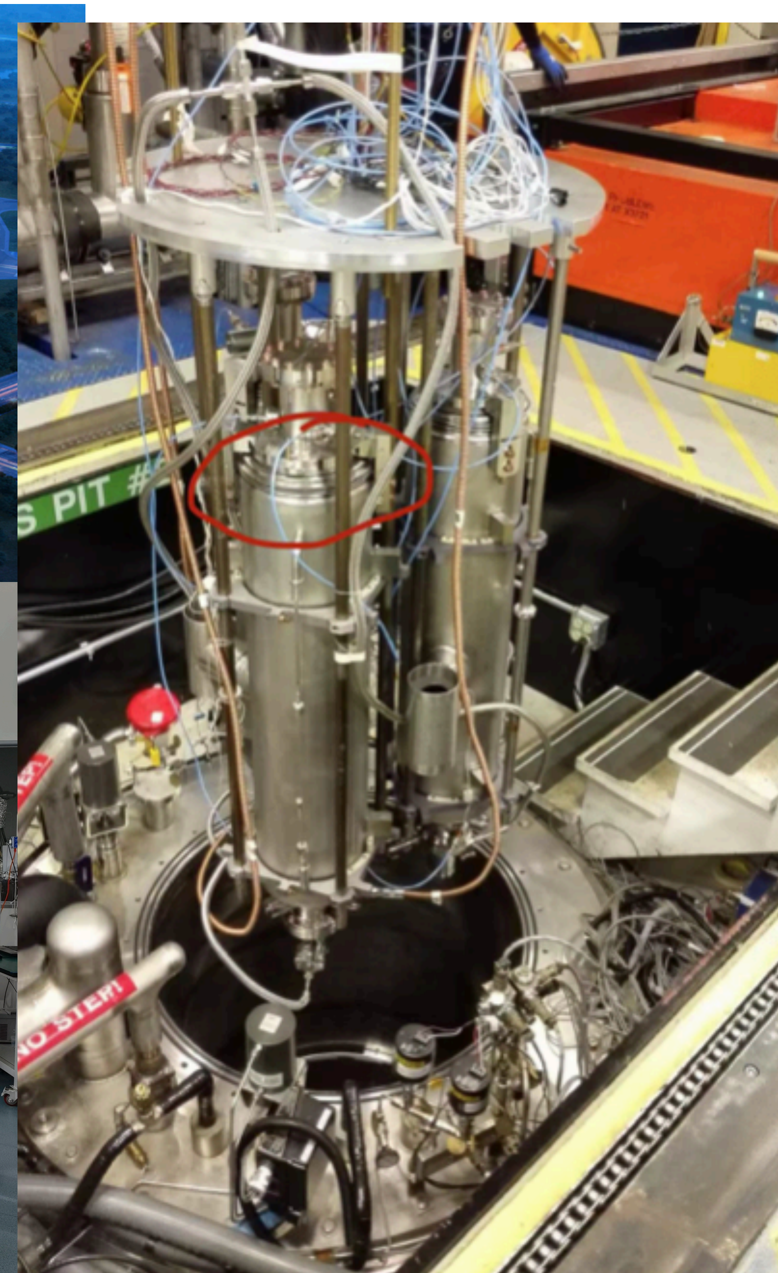
- residual magnetism<10 mGs
- Static heat leak: < 1 W
- Cooling power: >200W@2K

SRF in IHEP

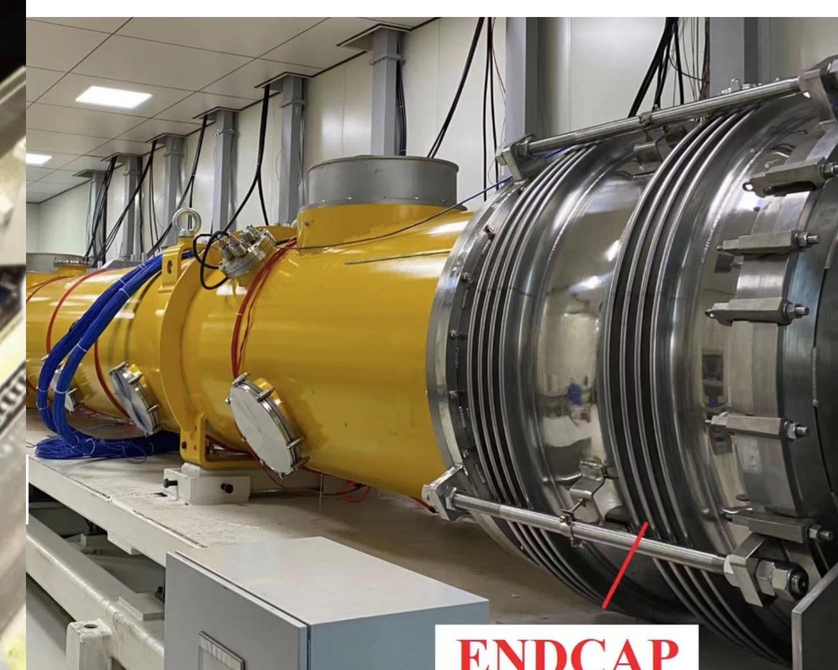
中国科学院高能物理研究所

Institute of High Energy Physics Chinese Academy of Sciences





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



International SRF Campaigns

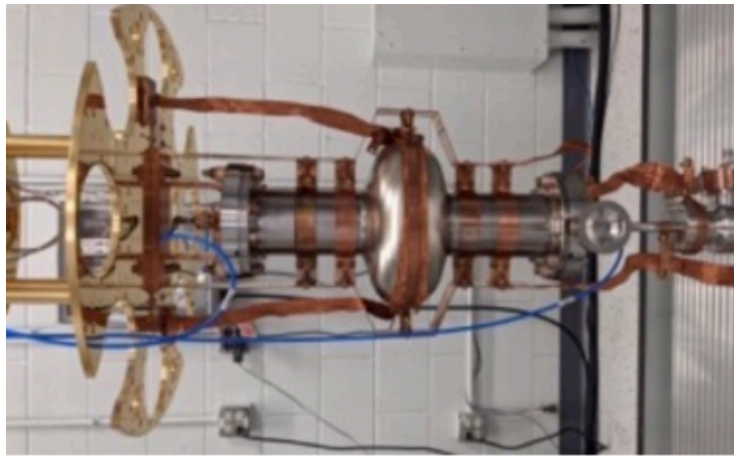
- Fermi-Lab SQMS

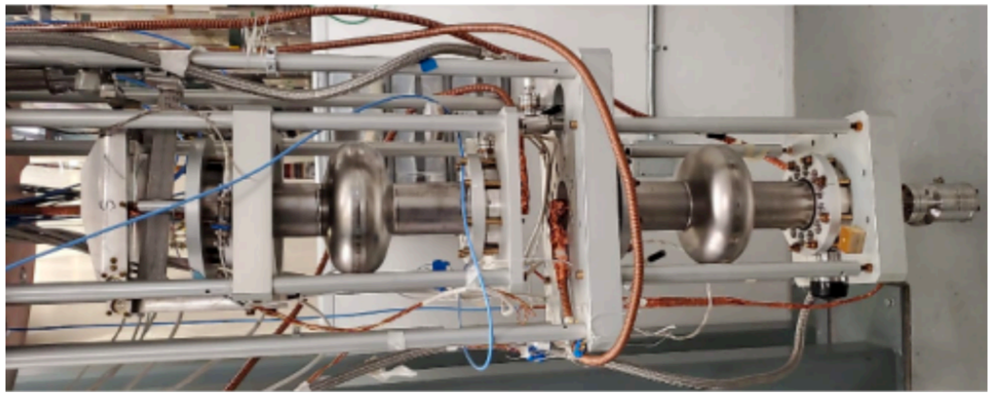
  •SERAPH:

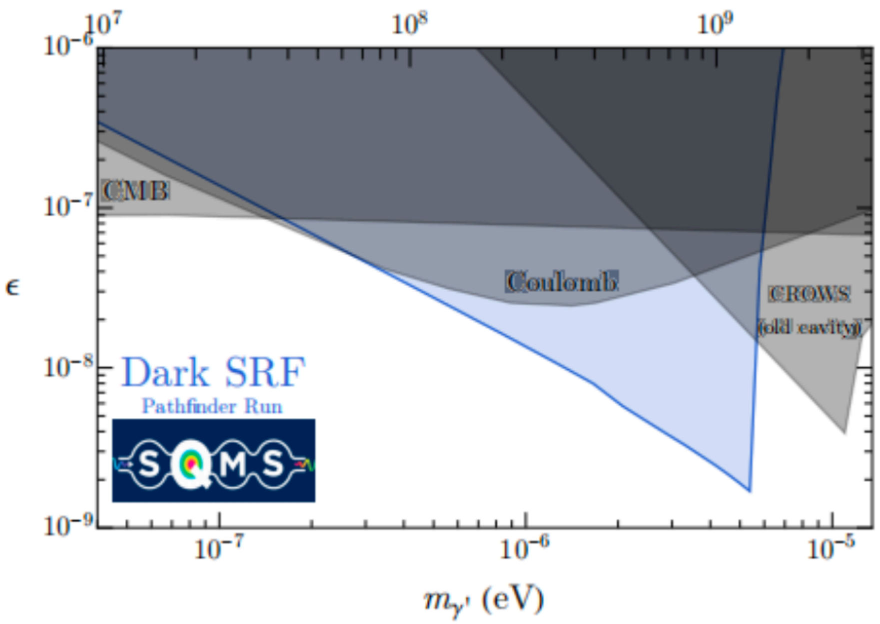
  Single-bin search and ongoing scan searches

  •Dark SRF:

  Light-shining-wall search for dark photon







- DESY:

  •MAGO 2.0

  Mode transition from GW-induced cavity deformation

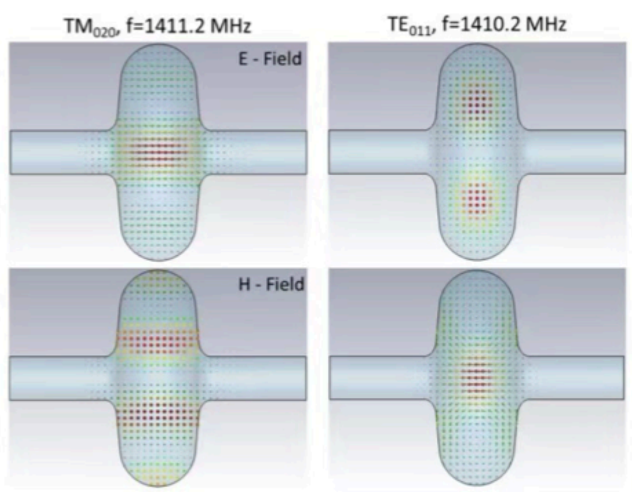
Axion search

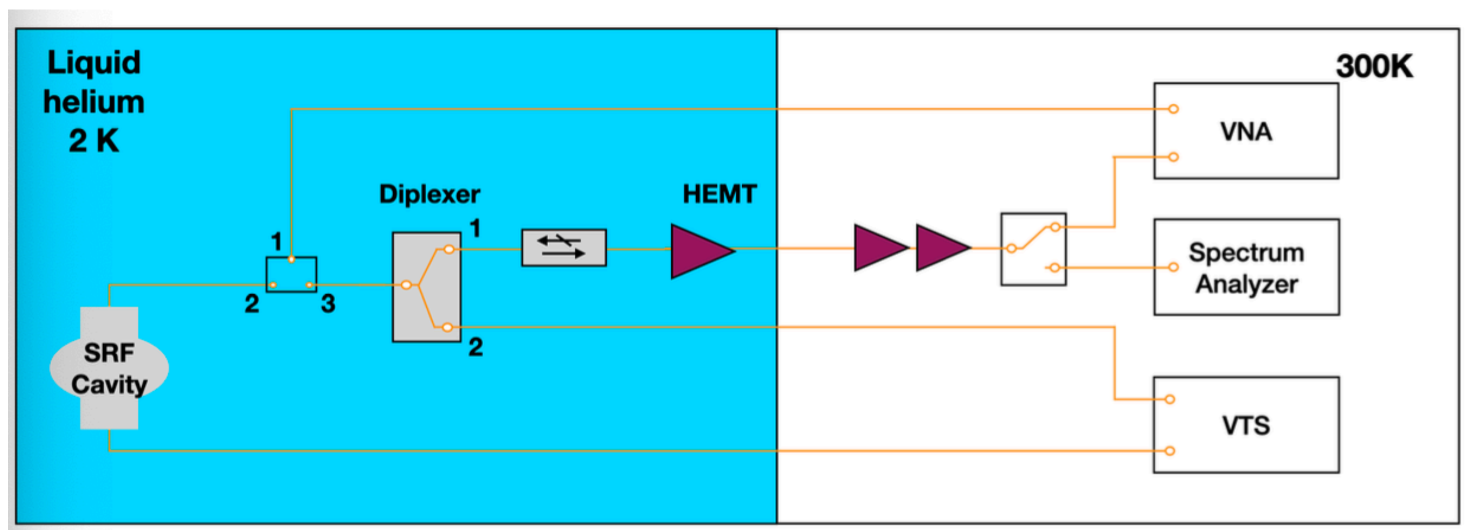
TDR like

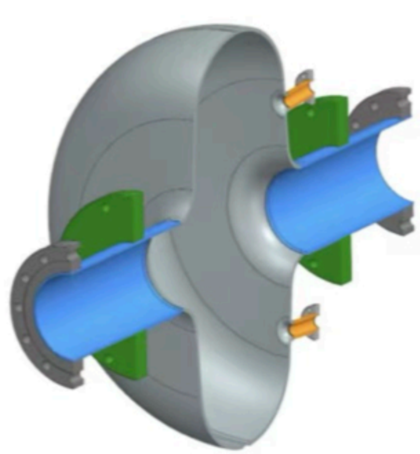
SHANHE collaboration

arXiv:2207.11346

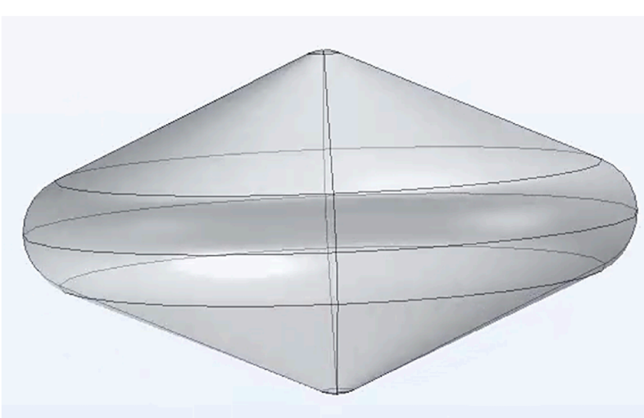
Using the existing 1.3G cavity as a pathfinder



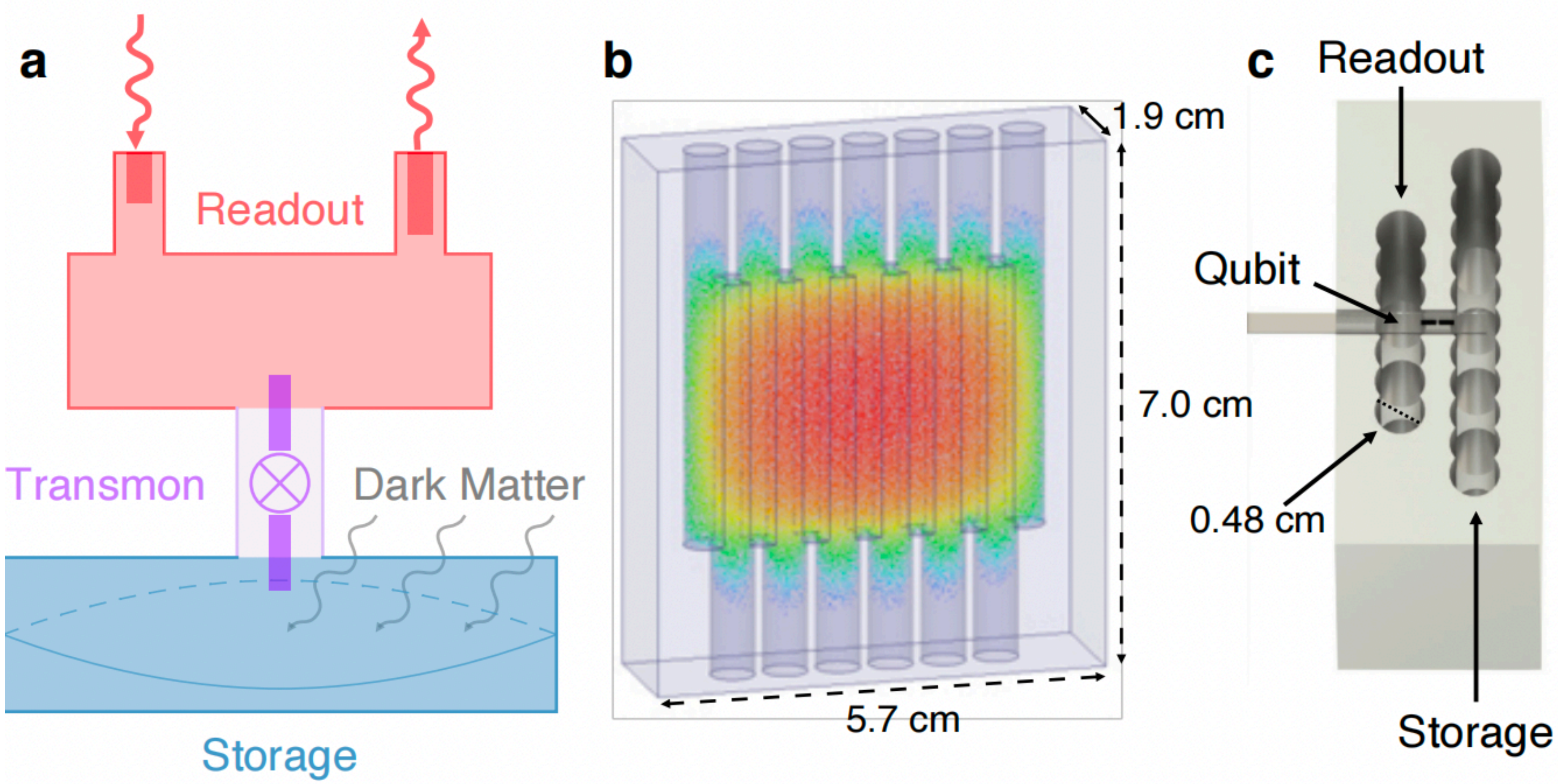




New designed cavity will be operated in the future.



Quantum qubits measure DPDM



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

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

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

Measuring only the photon number while completely ignore the phase (quantum non-demolition measurements).

Quantum qubit (two level system) as a single photon detector

Using Ramsey interferometry to measure the photon number parity

Quantum qubits measure DPDM

- Wave-like dark matter background field will change the time evolution operator. For a coherent state, can be modeled as a displacement operator.

$$\hat{D}(\beta) = e^{\beta a^\dagger - \beta^* a}, \text{ where } |\beta| = \sqrt{\rho_{DM} m_{DM} G V} \epsilon \tau$$

- Acting on the cavity prepared in the vacuum state

$$\left| \langle 1 | \hat{D}(\beta) | 0 \rangle \right|^2 \approx \left| \langle 1 | \beta a^\dagger | 0 \rangle \right|^2 = |\beta|^2$$

- For a large n Fock state, signal enhanced by (n+1).

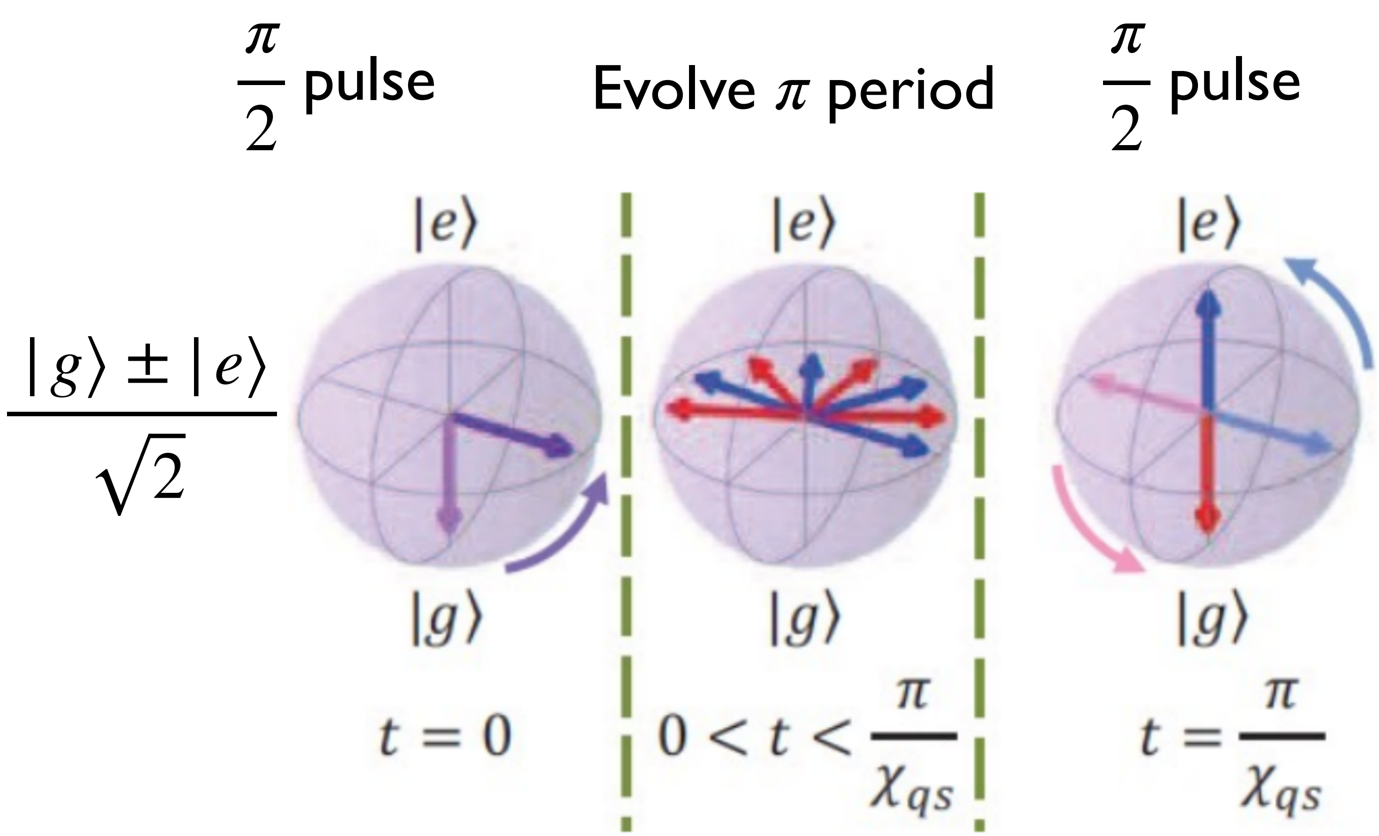
$$\left| \langle n+1 | \hat{D}(\beta) | n \rangle \right|^2 \approx \left| \langle n+1 | \beta a^\dagger | n \rangle \right|^2 = |\beta|^2 (n+1)$$

- Shorter coherence time $T_n = T^1_{cavity}/n$, More difficult to prepare

- Sensitivity mainly given by the background photon number $\bar{n}_c$

Quantum parity measurement

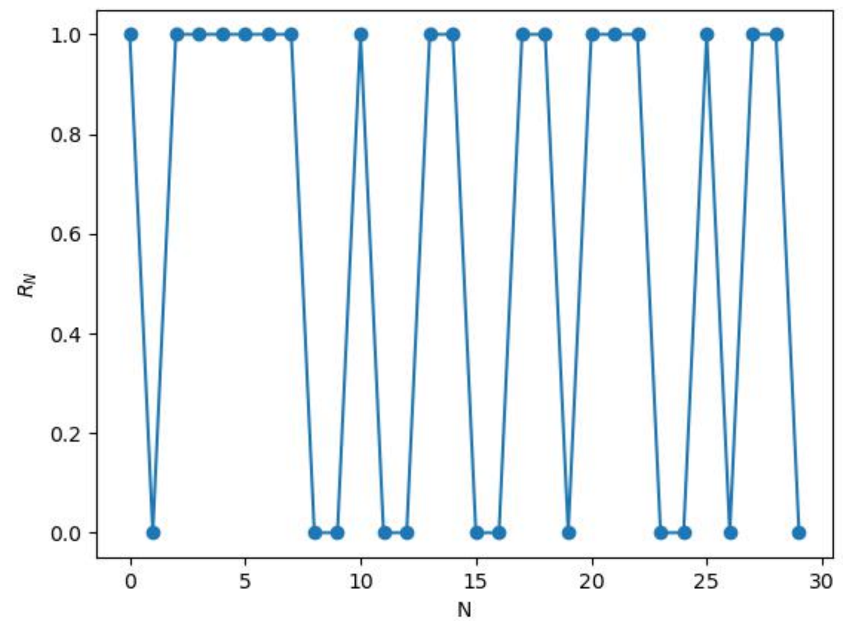
Ramsey interferometry in Bloach sphere



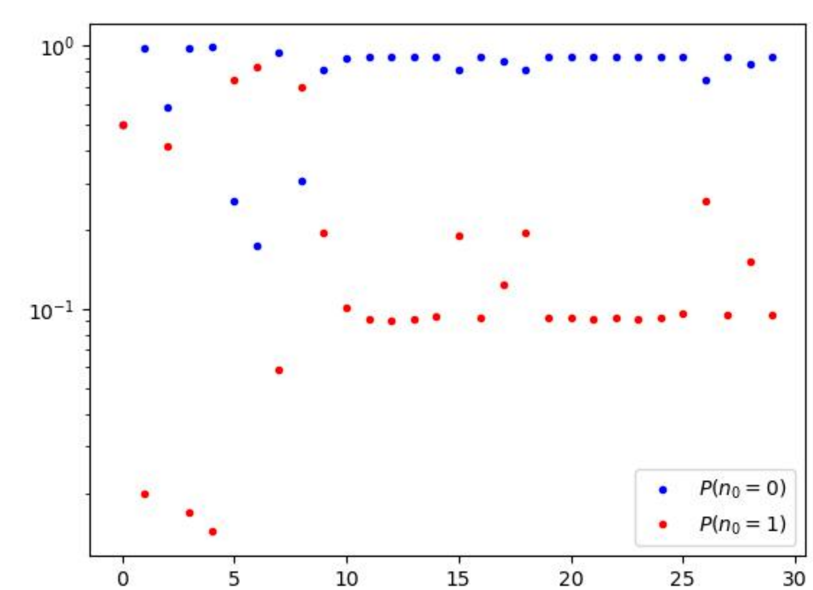
$$H_{int} = 2\chi a^\dagger a \frac{\sigma_z}{2}, \quad t = \frac{\pi}{\chi}$$

The qubit state is flipped if there is odd number of photons in the cavity.

Excited state probability



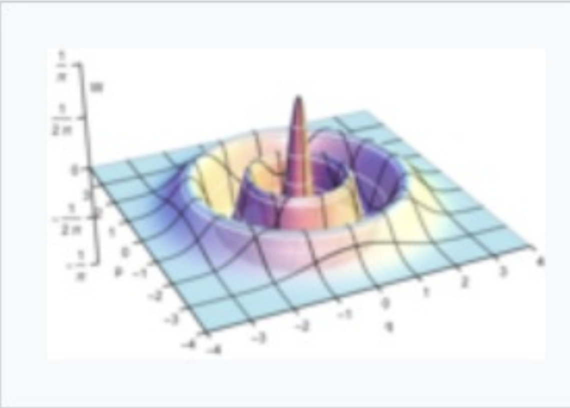
hidden Markov model to specify the probability



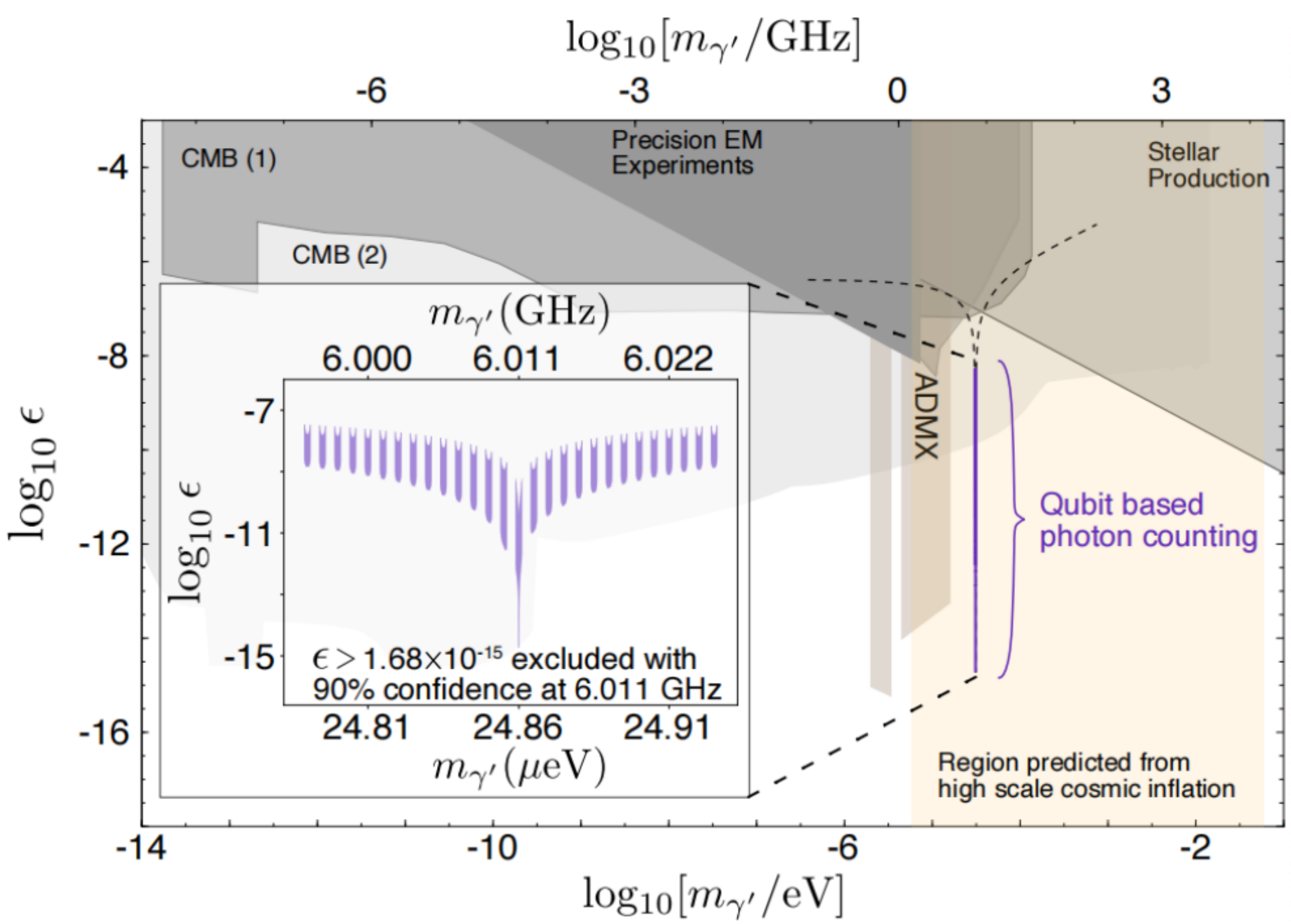
Quantum qubits measure DPDM

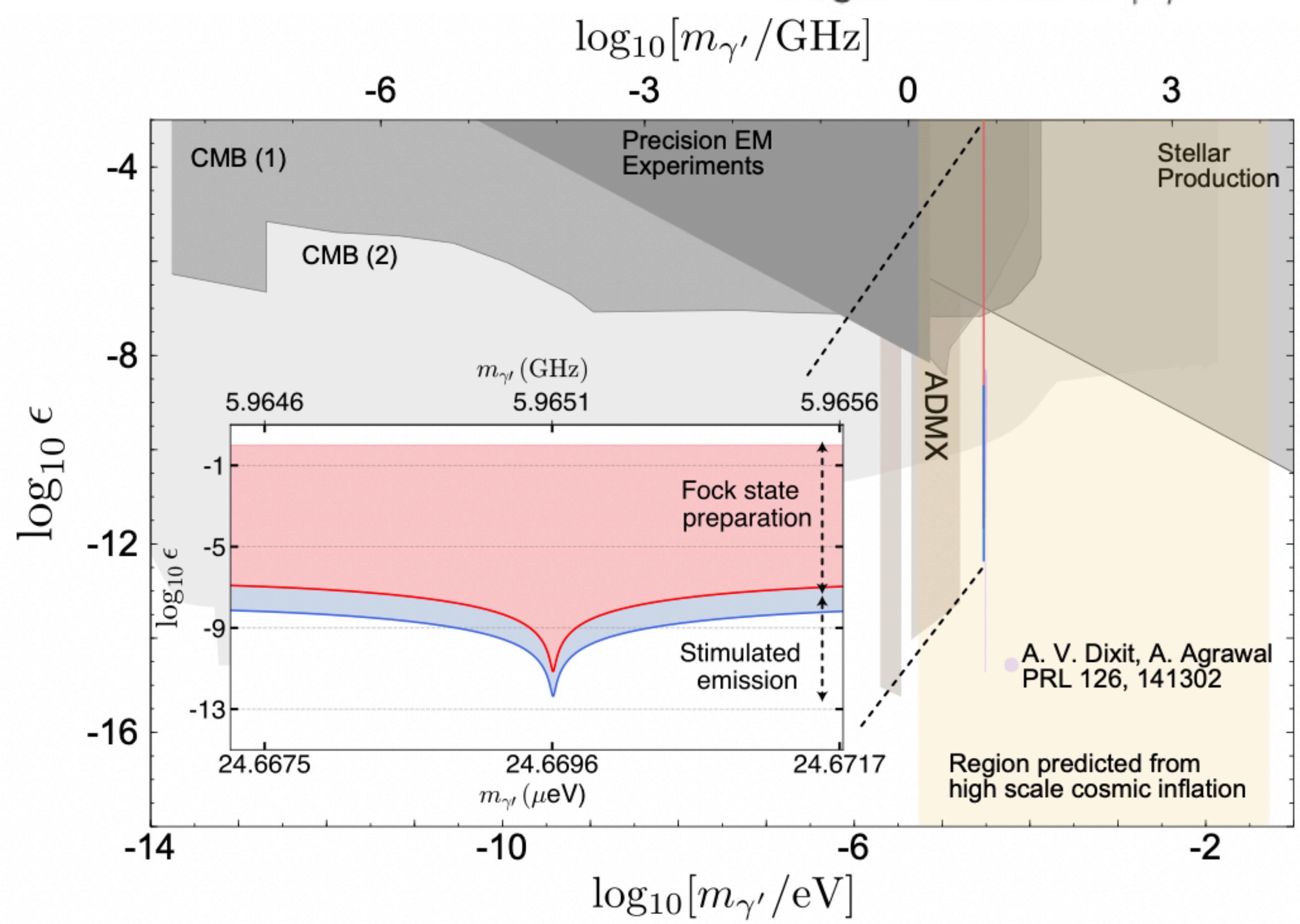
DPDM： Using the Vacuum state to measure

DPDM： Using the Fock state (N=4) to measure



Wigner function of $|4\rangle$





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

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

A.V.. Dixit et al. Phys. Rev. Lett. 126, 141302 (2021)

A. Agrawal et al. Phys. Rev. Lett. 132, 140801 (2024)

How to eliminate the noise?

Even we use various clever ways to background noises, even beyond standard quantum limit, can we really to further suppress them?

One observation is that when using multiple sensors, the DM signals can be coherent among multiple sensors, while most backgrounds are not!

Consider the 2-level systems readout

Can generalize

- The displacement operator

$$\hat{D}(\beta) = e^{\beta a^\dagger - \beta^* a} \text{ where } \beta = \frac{1}{2}\eta_{DM} e^{i\phi_{DM} t}$$

- Restricting to the two-level subspace

$$D(\beta)\,|\,g\rangle \simeq |\,g\rangle + \beta\,|\,e\rangle$$

- Dark matter signal

$$\left|\langle e\,|\,\hat{D}(\beta)\,|\,g\rangle\right|^2 \approx \left|\langle e\,|\,\beta a^\dagger\,|\,g\rangle\right|^2 = |\beta|^2$$

- Sensitivity mainly given by the background occupation number $\bar{n}_c$

Can apply to various systems

- SRF cavity

$$\eta_{DM} = \epsilon_{DM}\sqrt{\rho_{DM}\omega G V}$$

- Transmon qubits

$$\eta_{DM} = \frac{1}{2}\epsilon_{DM}\kappa d\sqrt{C\omega\rho_{DM}}$$

- Trapped ions

$$\eta_{DM} = e\epsilon_{DM}\sqrt{\frac{\rho_{DM}}{m_{ION}\omega}}$$

How to eliminate the noise?

Density matrix

$$\rho = |\beta\rangle\langle\beta| \simeq \begin{pmatrix} 1-|\beta|^2 & \beta^* \\ \beta & |\beta|^2 \end{pmatrix}$$

Density matrix with error

What you can measure is the population measurements (diagonal term) ?

$$\rho \to \mathcal{E}(\rho) = \begin{pmatrix} p_{T_1}\rho_{gg} + p_{\text{reset}}p_0 & p_{T_2}\rho_{ge} \\ p_{T_2}\rho_{eg} & p_{T_1}\rho_{ee} + p_{\text{reset}}p_1 \end{pmatrix}$$

Relax and dephasing

$$p_{T_1} = e^{-\tau/T_1} \text{ and } p_{T_2} = e^{-\tau/T_2}$$

Thermal population

$$p_0 \text{ and } p_1 = 1 - p_0$$

$$SNR = \frac{S}{B} = \frac{p_{T_1}|\beta|^2}{p_{\text{reset}}p_1}$$

$$\frac{S}{\sqrt{B}} = \frac{p_{T_1}|\beta|^2}{\sqrt{p_{\text{reset}}p_1}}.$$

J. Shu, B. Xu, … arXiv:2410.22413

How to eliminate the noise?

Two detectors

$$|\Psi\rangle = \hat{D}(\beta)|gg\rangle \simeq |gg\rangle + \beta|ge\rangle + \beta|eg\rangle$$

- Density matrix

$$\rho^{(2)} = |\Psi\rangle\langle\Psi| = \begin{pmatrix} 1-2\beta^2 & \beta & \beta & 0 \\ \beta & \beta^2 & \beta^2 & 0 \\ \beta & \beta^2 & \beta^2 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} + O(\beta^3) + \begin{pmatrix} 1-\epsilon_A-\epsilon_B & 0 & 0 & 0 \\ 0 & \epsilon_B & 0 & 0 \\ 0 & 0 & \epsilon_A & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

- Dark matter signal

$$\langle eg|\rho^{(2)}|eg\rangle + \langle ge|\rho^{(2)}|ge\rangle = \rho^{(2)}_{11} + \rho^{(2)}_{22} \sim 2\beta^2 + \epsilon_A + \epsilon_B$$

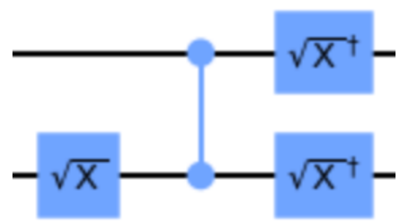
increases with N_q

How to eliminate the noise?

Coherent signals are off-diagonal, how to measure them?

- Define

$$\mathcal{U}_c = \left(\sqrt{X}^\dagger \otimes \sqrt{X}^\dagger\right) ZZ \left(\sqrt{X} \otimes I\right) =$$



Where $\sqrt{X} = \frac{1}{2}\begin{pmatrix} 1+i & 1-i \\ 1-i & 1+i \end{pmatrix}$, $ZZ = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$

Use an unitary transformation realized by quantum gates

- Applying $\mathcal{U}_c$

$$\mathcal{U}_c \rho^{(2)} \mathcal{U}_c^\dagger = \begin{pmatrix} \frac{1}{2} & -\frac{i}{2} + i\beta^2 & 0 & -i\beta \\ \frac{i}{2} - i\beta^2 & \frac{1}{2} - 2\beta^2 & 0 & \beta \\ 0 & 0 & 0 & 0 \\ i\beta & \beta & 0 & 2\beta^2 \end{pmatrix} + O(\beta^3) + \begin{pmatrix} \frac{1}{2}\left(1-\epsilon_A-\epsilon_B\right) & \frac{i}{2}\left(\epsilon_A+\epsilon_B-1\right) & 0 & 0 \\ -\frac{i}{2}\left(\epsilon_A+\epsilon_B-1\right) & \frac{1}{2}\left(1-\epsilon_A-\epsilon_B\right) & 0 & 0 \\ 0 & 0 & \frac{1}{2}\left(\epsilon_A+\epsilon_B\right) & \frac{i}{2}\left(\epsilon_A-\epsilon_B\right) \\ 0 & 0 & -\frac{i}{2}\left(\epsilon_A-\epsilon_B\right) & \frac{1}{2}\left(\epsilon_A+\epsilon_B\right) \end{pmatrix}$$

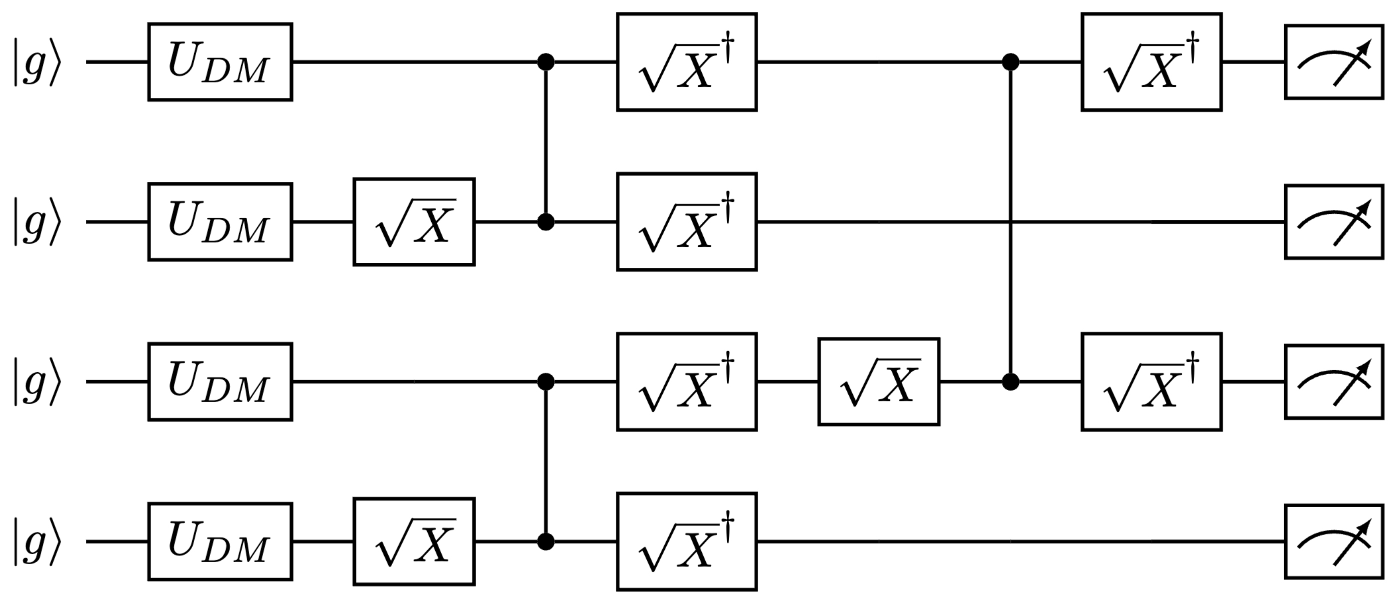
- Pure signal given by

$$\rho'_{44} - \rho'_{33} = \left(2\beta^2 + \frac{\epsilon_A+\epsilon_B}{2}\right) - \frac{\epsilon_A+\epsilon_B}{2} = 2\beta^2$$

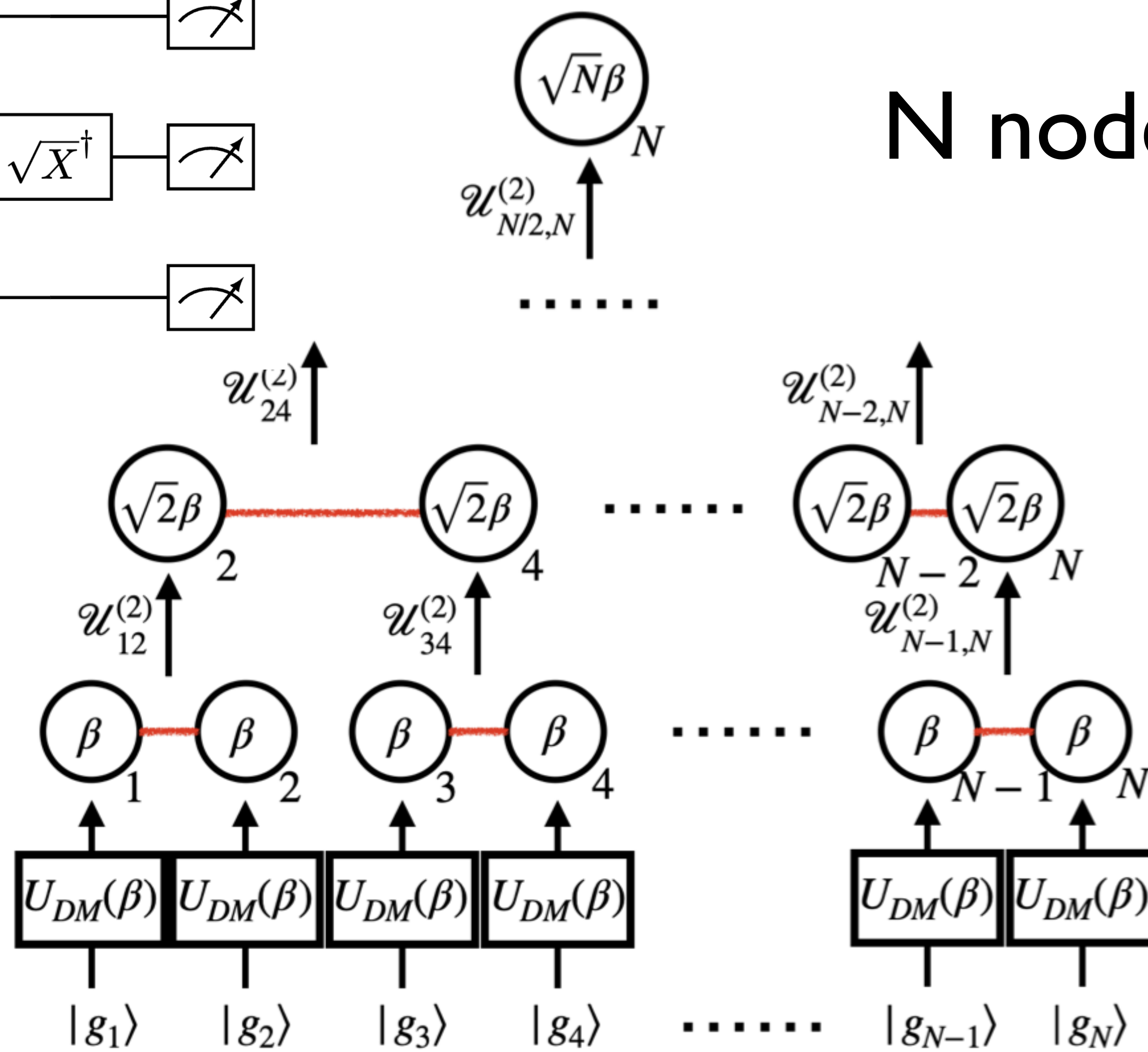
No incoherent noise!!!

Generalize to N nodes

Four nodes



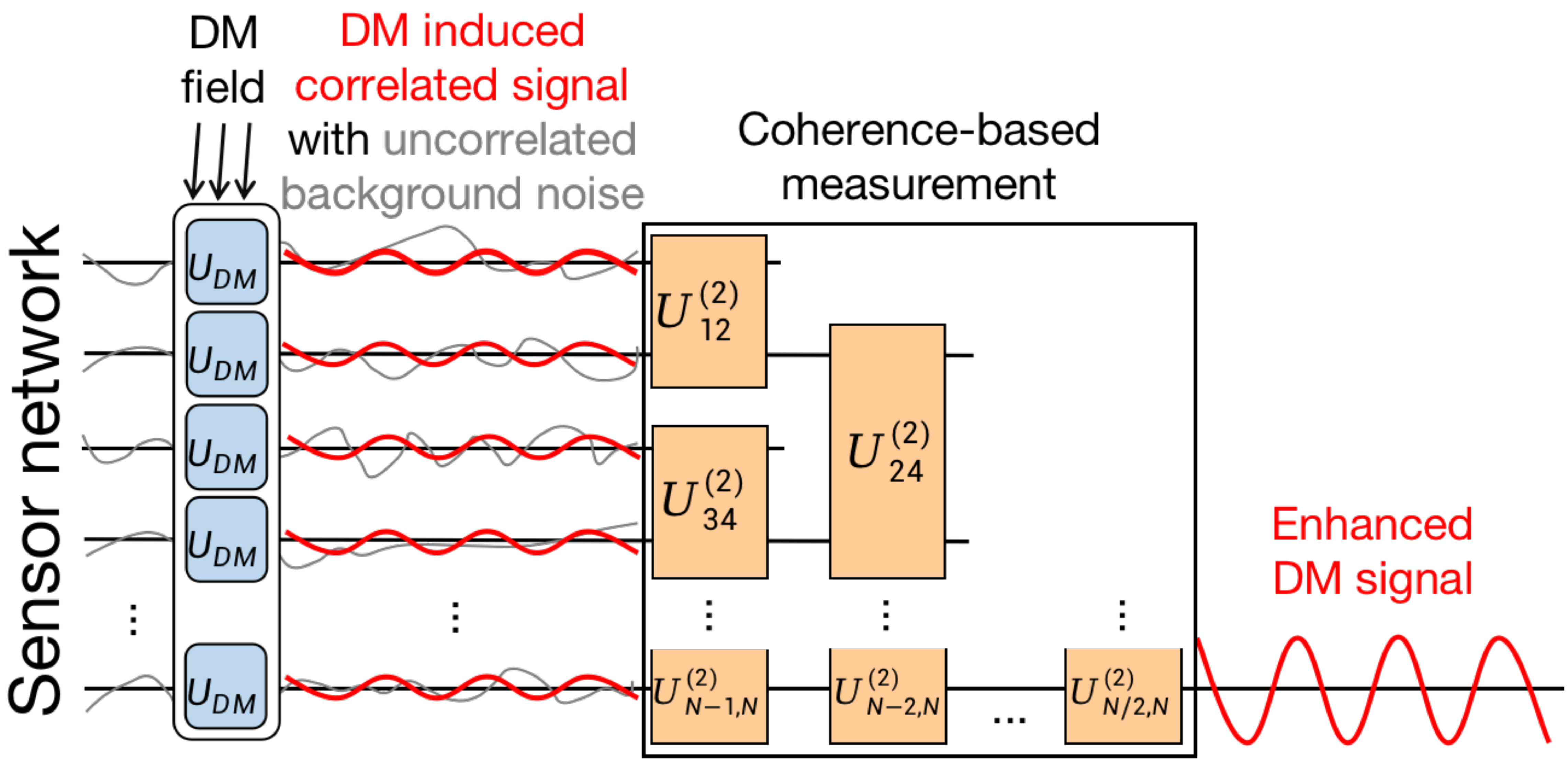
N nodes



Signal (off-diagonal) goes like N^2

Backgrounds go like N

How to eliminate the noise?

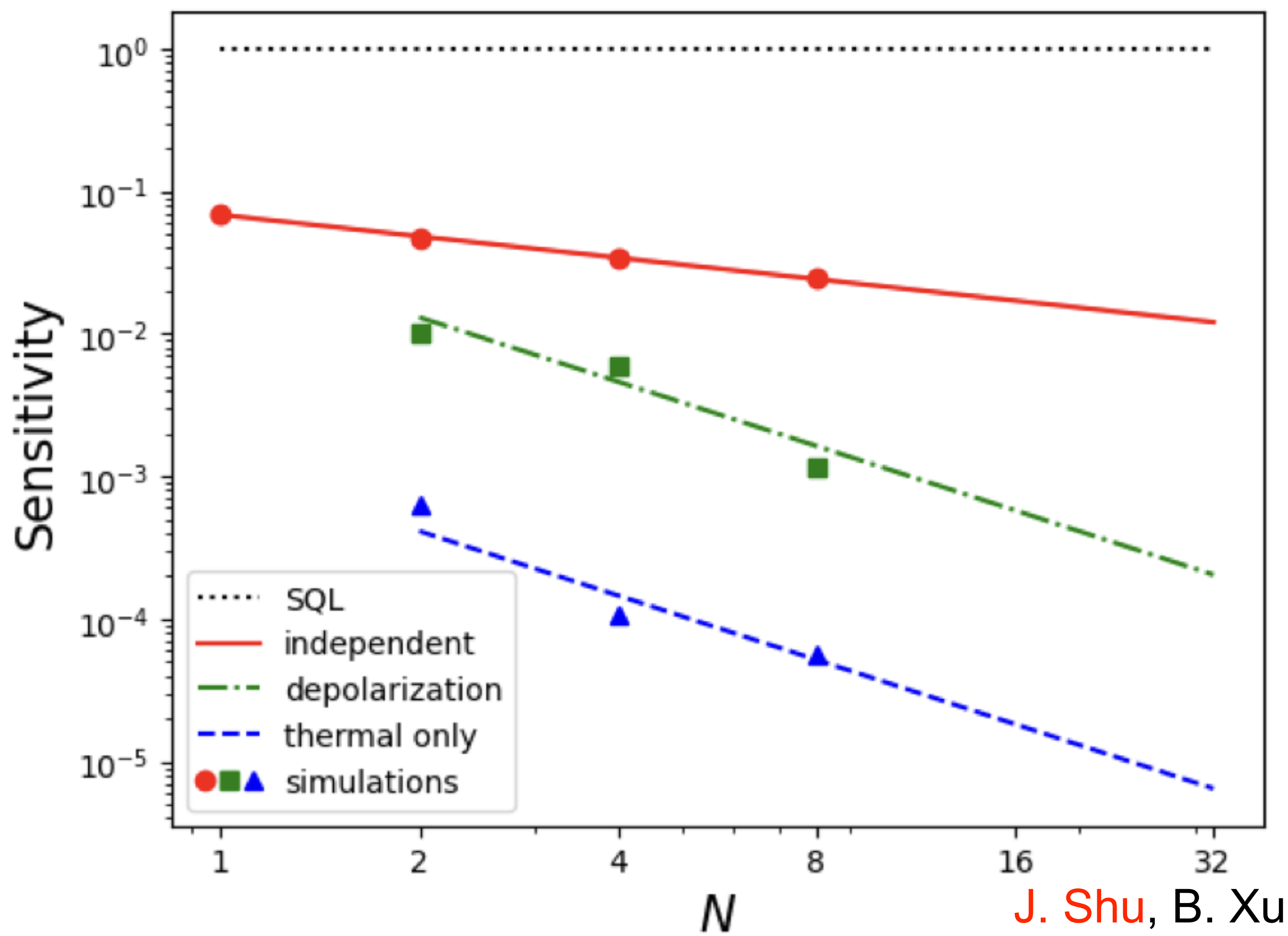


J. Shu, B. Xu, … arXiv:2410.22413

How to eliminate the noise?

The gates have infidelities, can be much smaller

Sensor type	$\bar{n}_{r0}$	Two-qubit gate infidelity $\bar{\mathcal{F}}$
Cavity	10^{-3} [46]	10^{-4} [47]
Transmon	10^{-3} [48, 49]	10^{-3} [50, 51]
Ions	10^{-2} [52]	10^{-3} [53, 54]



J. Shu, B. Xu, … arXiv:2410.22413

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).
- When combined with QND methods, very powerful
- Can be extended to sensors arrays (quantum 2.0)
- In the future (axion, GWs, quantum qubit, etc), much more can be done .

Thank you!

Backup slides

Myself and other collaborations

Ph.D.: UChicago

Boya distinguished professor: PKU

Both theory and experimentalist

Top quark, Composite Higgs, EFT, DM, baryon asymmetry, PT, etc.

Wave-like DM & GWs

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

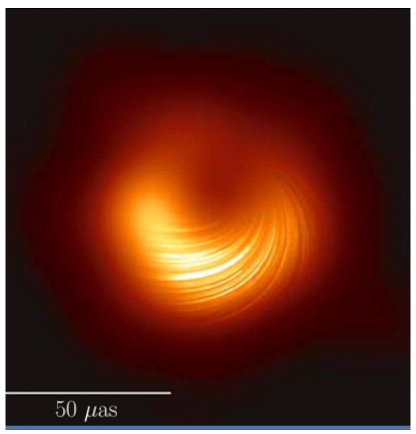
supportive collaborations

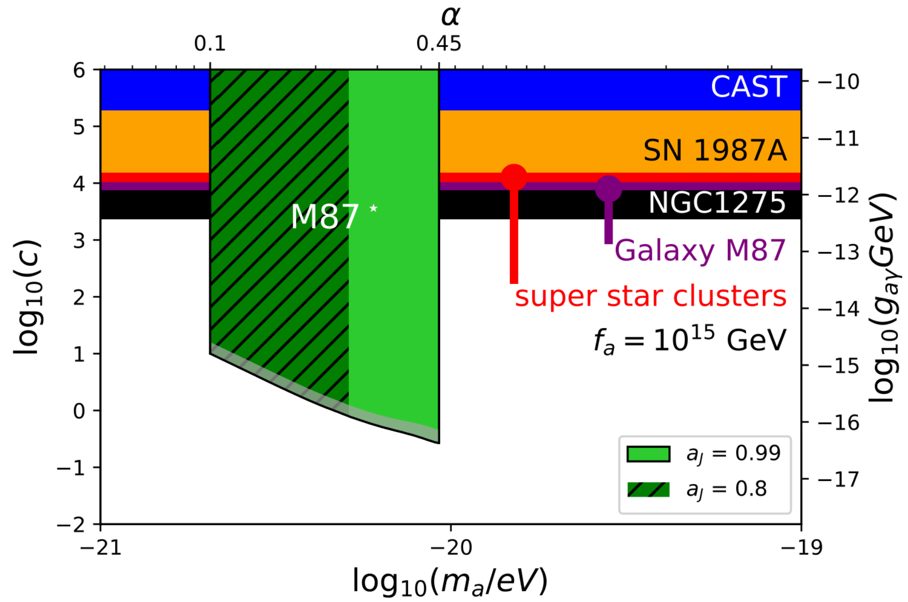
中國科學院物理研究所
Institute of Physics, Chinese Academy of Sciences

Job opening for people how has experience in axion DM searches (electronics like JPA, quantum qubit, etc)

Myself and other collaborations

EHT probe axion (birefringence)

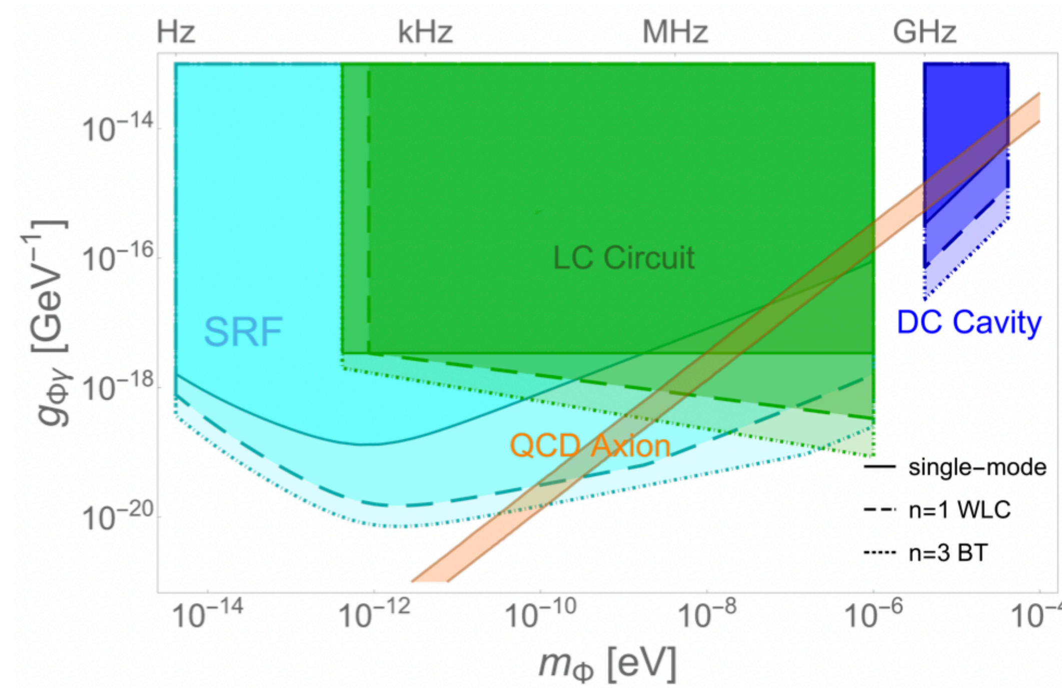




Y.F. Chen, J. Shu, X. Xue, Q. Yuan, Y. Zhao,
Phys. Rev. Lett. 124 (2020) no6, 061102

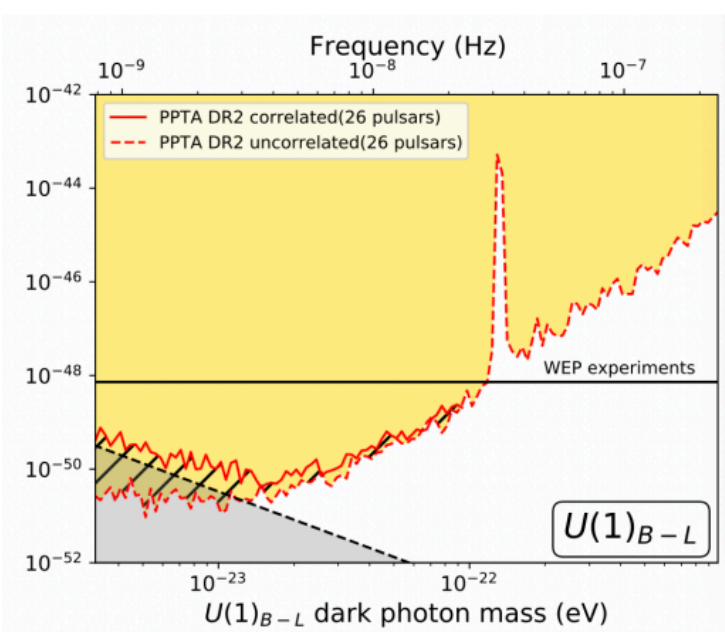
Y.F. Chen, .., J. Shu, .., Y. Zhao, Nature Astron. 6 (2022) 5, 592-598

Beyond SQL wave-like DM searches



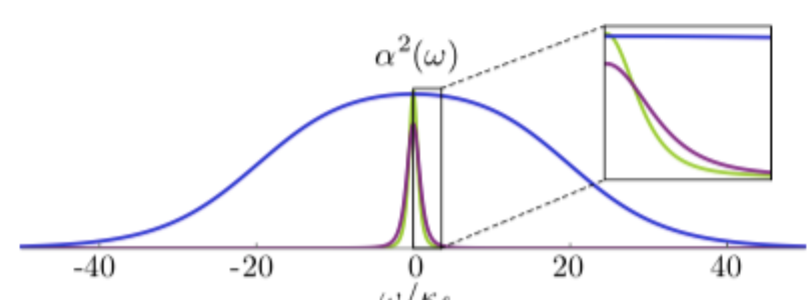
Y-f. Chen, M-y. Jiang, J. Shu., Y-t. Yang,
Phys.Rev.Res. 4 (2022) 2, 023015
(arxiv time before Haystack)

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



PTA probe DPDM

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



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