Probing the ultra-light dark matter with Quantum Sensors

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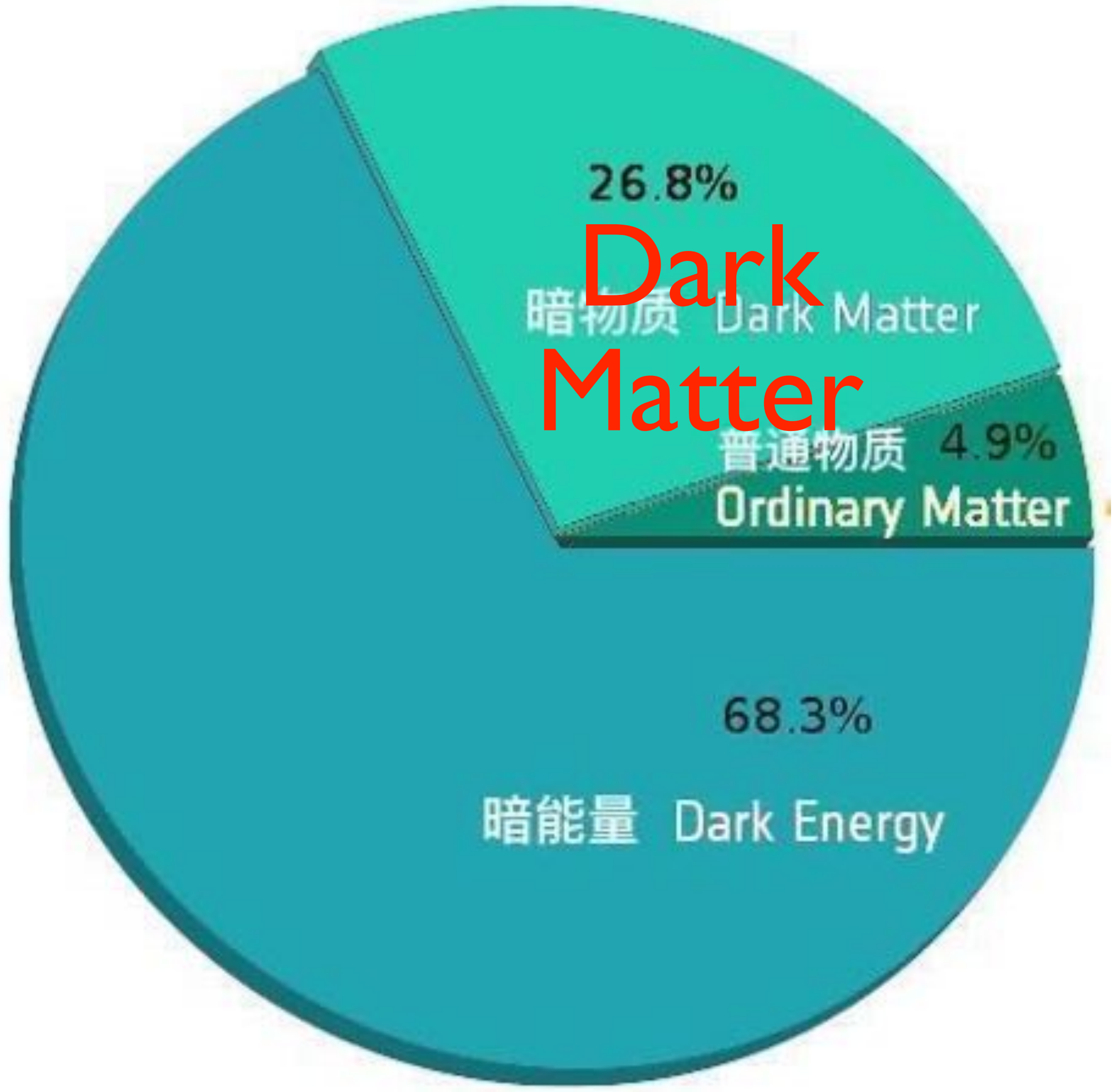
Outline

- Motivation of ultra-light dark matter
- SRF Cavity Search for wave-like DM
- SRF Cavity with qubits （Quantum Non-demolition Detection）
- “Simultaneous resonant and broadband” detection
- Large sensor-array to eliminate the noise
- Summary and Outlook

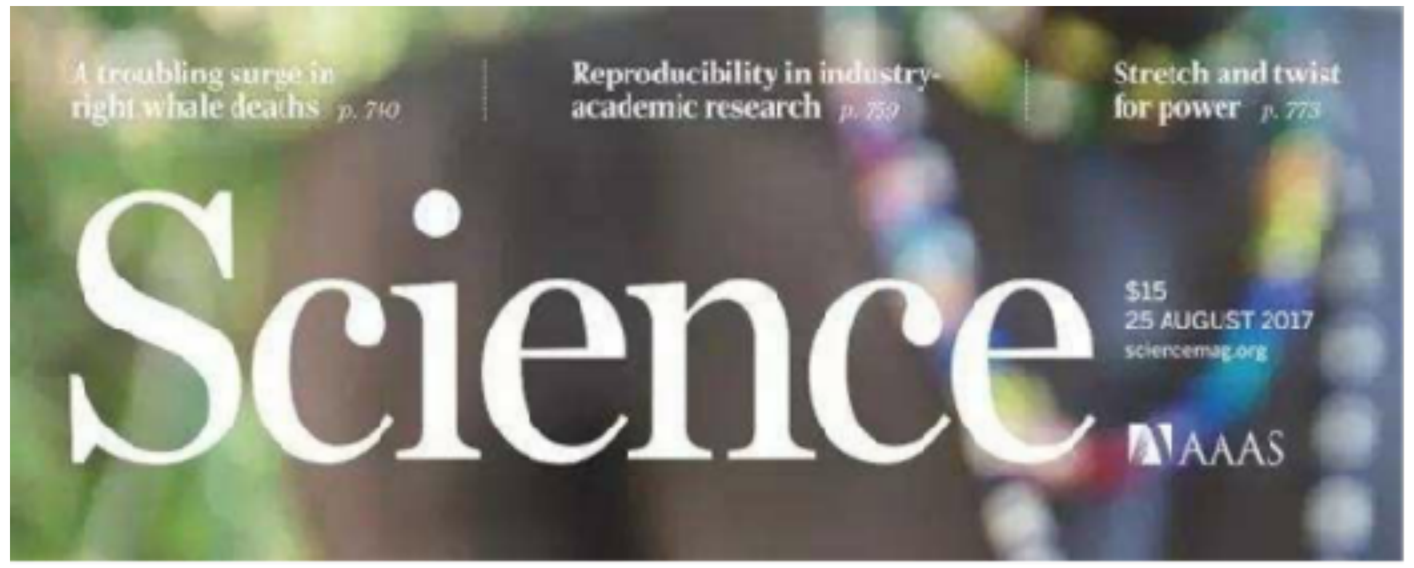
Motivation of ultra-light dark matter

Background: Dark Matter

$U(1)$



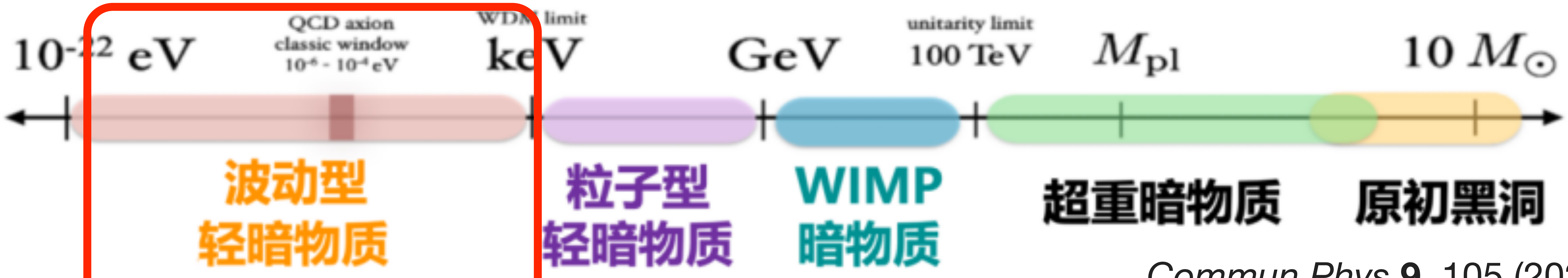
Dark Matter



2021年科学杂志+交大:
125个科学问题

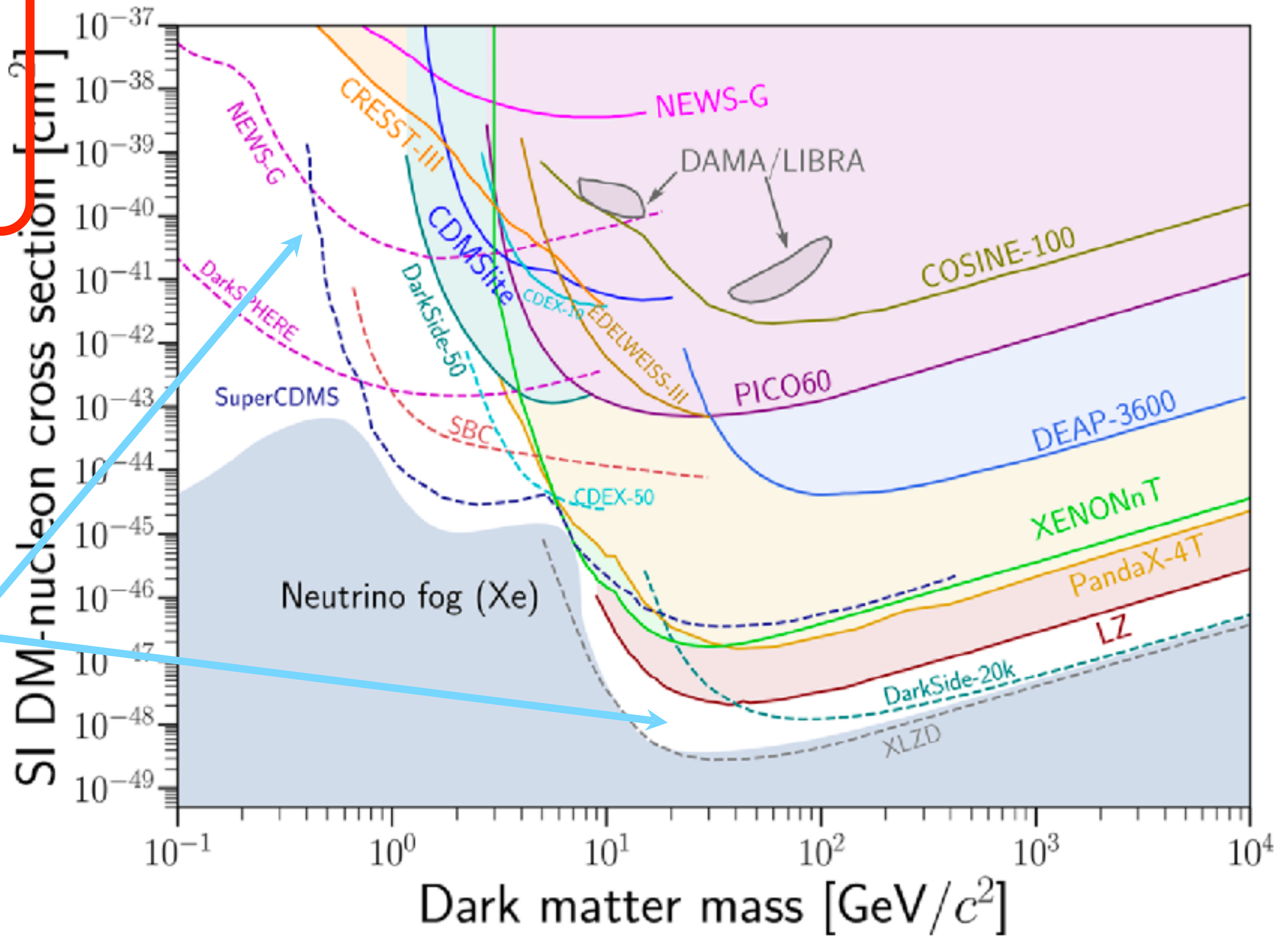
什么是暗物质?

Unknown composition; vast mass/frequency range



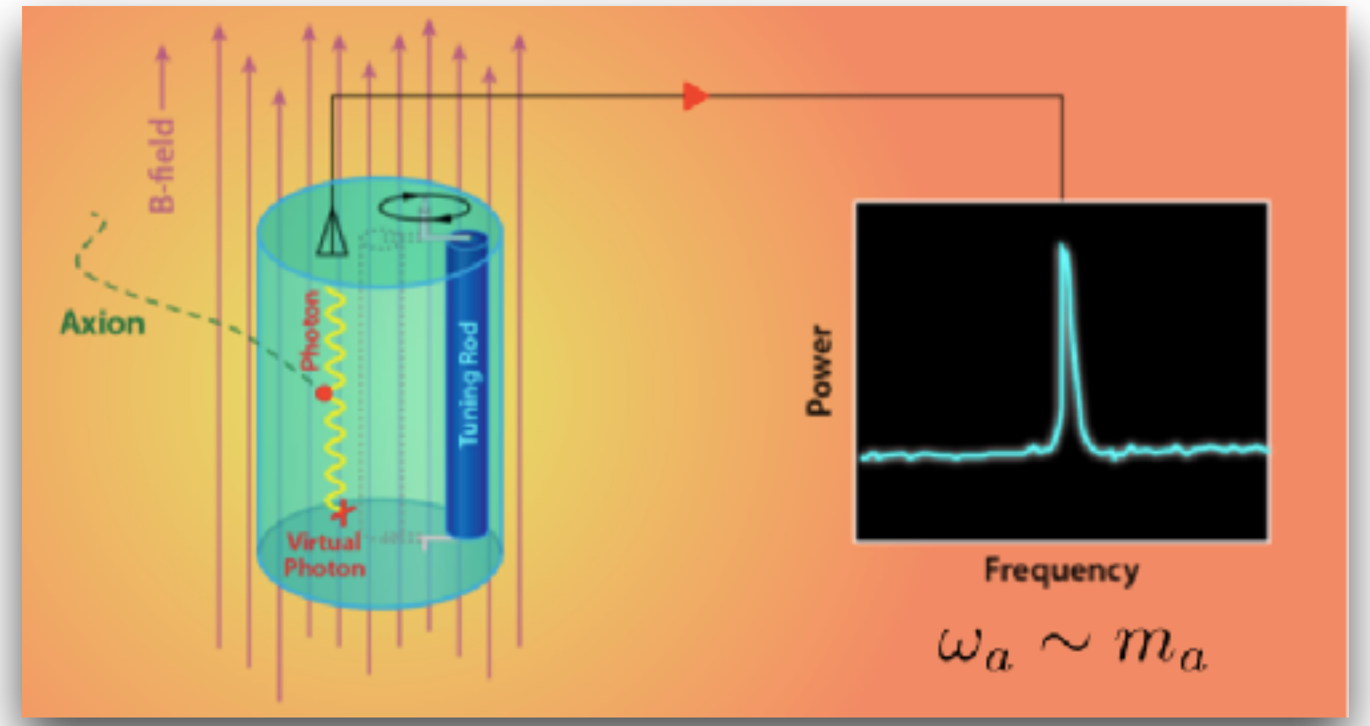
New detection methods needed!

Commun Phys **9**, 105 (2026)



WIMP DM: tight bounds, little space remained

Background: Wave-like DM Search



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

Compton wavelength reaches lab scale (m)

Resonant cavity (antenna) + quantum amplifier

Quantum Experiments

$SU(2)_W \times U(1)_Y$

Quantum mechanics: matter behaves both like particle and wave

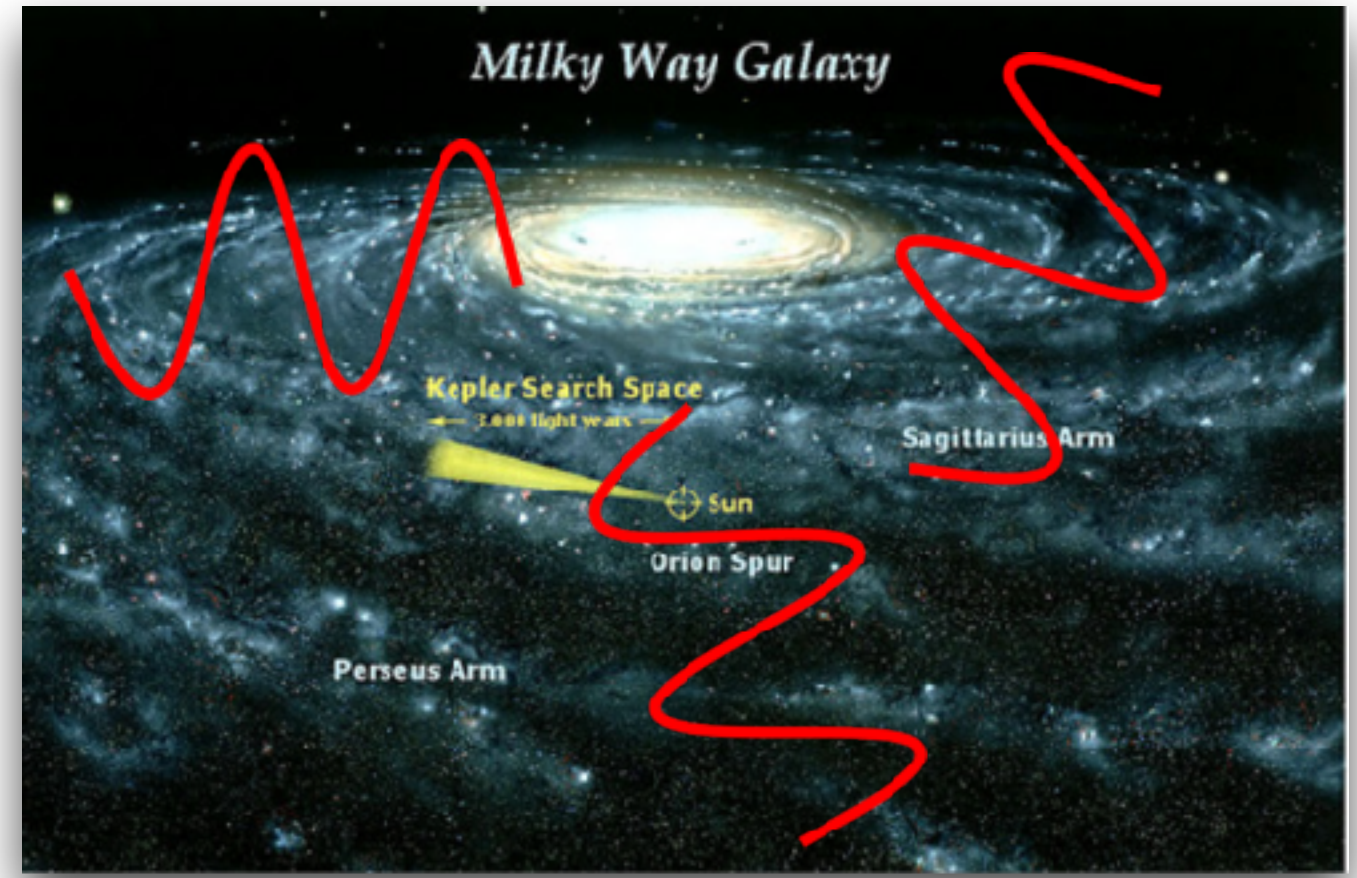
Ultralight dark matter

macro-scale wavelength

wave background field

Beyond particle-scattering DM searches

Large potential for wave detection



$m \sim 10^{-22}\text{eV}$

de Broglie wavelength reaches galactic scale (kpc)

Astronomical observations (time, position, polarization)

Astronomical Observations

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

Wave-like DM: axion, DPDM, milli-charge particle etc

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

Almost monochromatic!

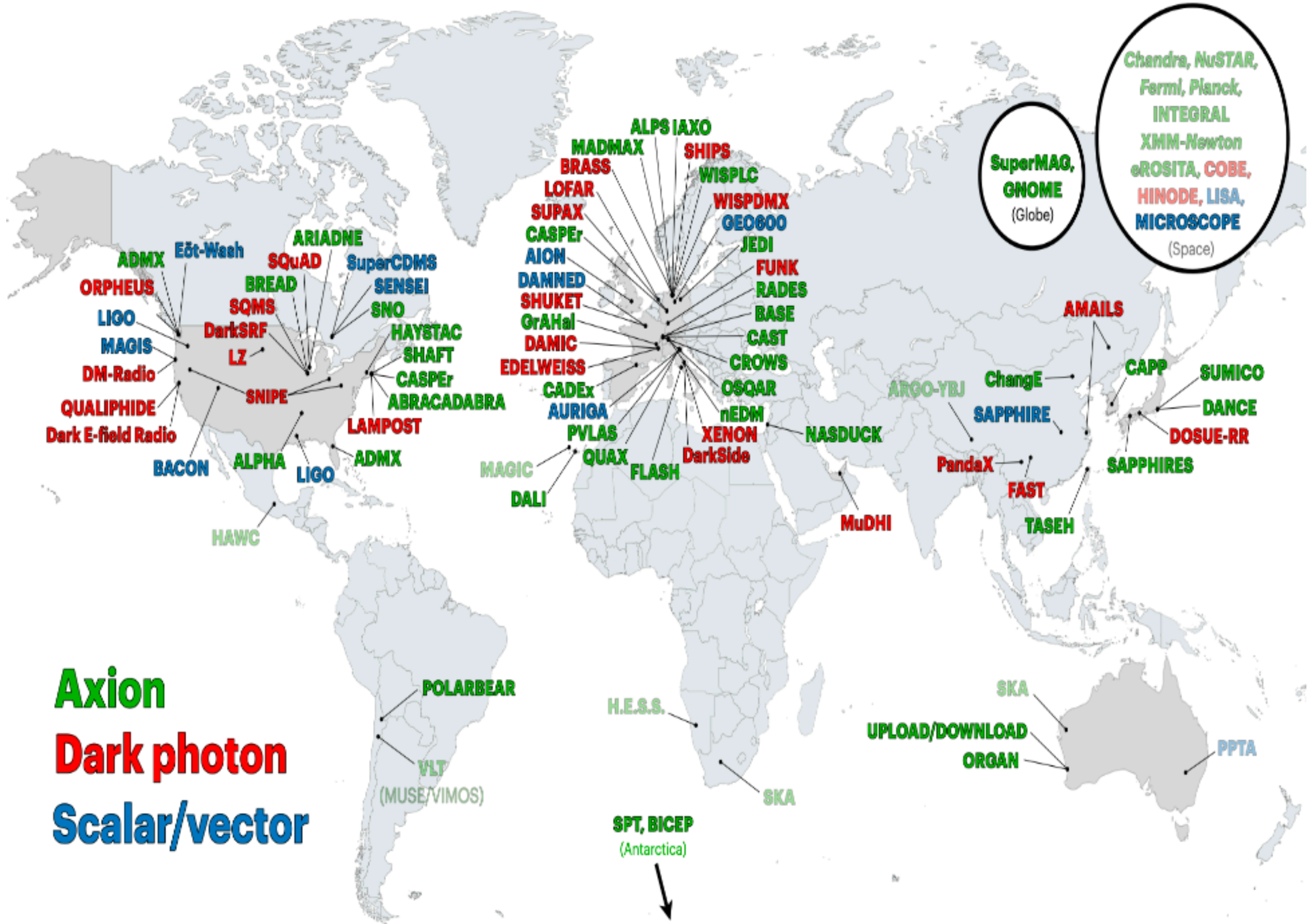
Bandwidth of axion DM is 10^{-6}

Detector bandwidth 10^{-6} accelerate the scan rate

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

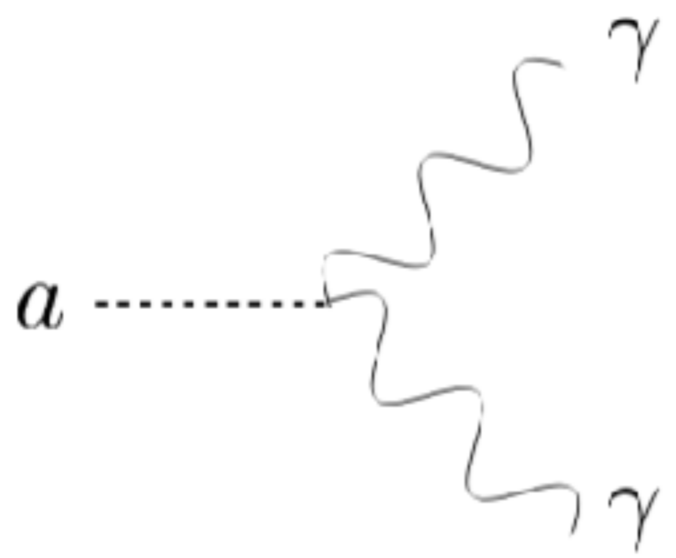
Momentum width 10^{-3}

Various wave-like DM search

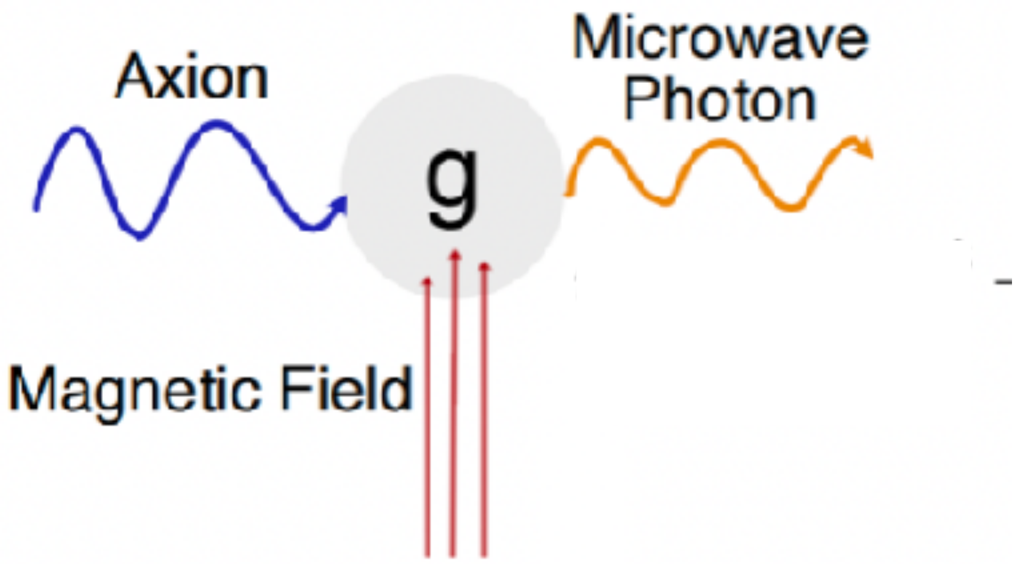


Background: Wave-like DM Search

Axion (ALP)： spin 0, CP odd



Inverse Primakoff effect



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

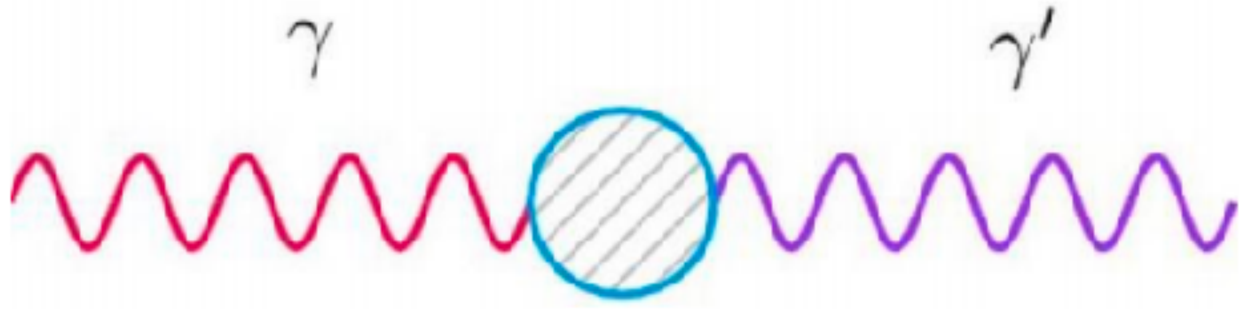
induces an effective current
under strong magnetic field.

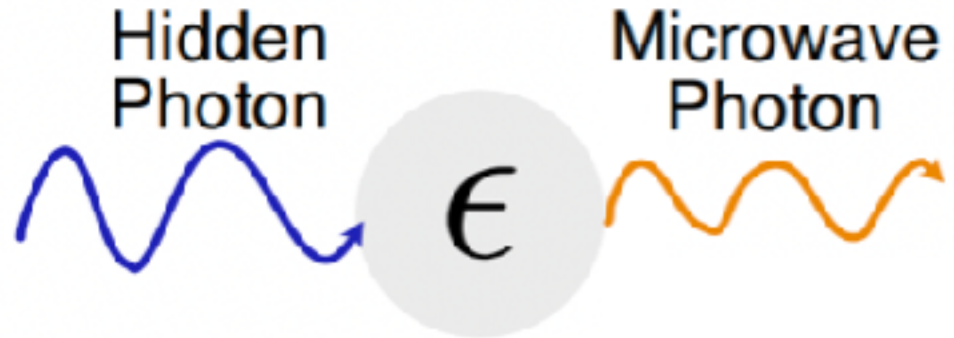
$$\vec{J}^{a}_{\rm eff} = g_{a\gamma} \omega_a a \vec{B}_0.$$

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.

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

SRF Cavity Search for wave-like DM

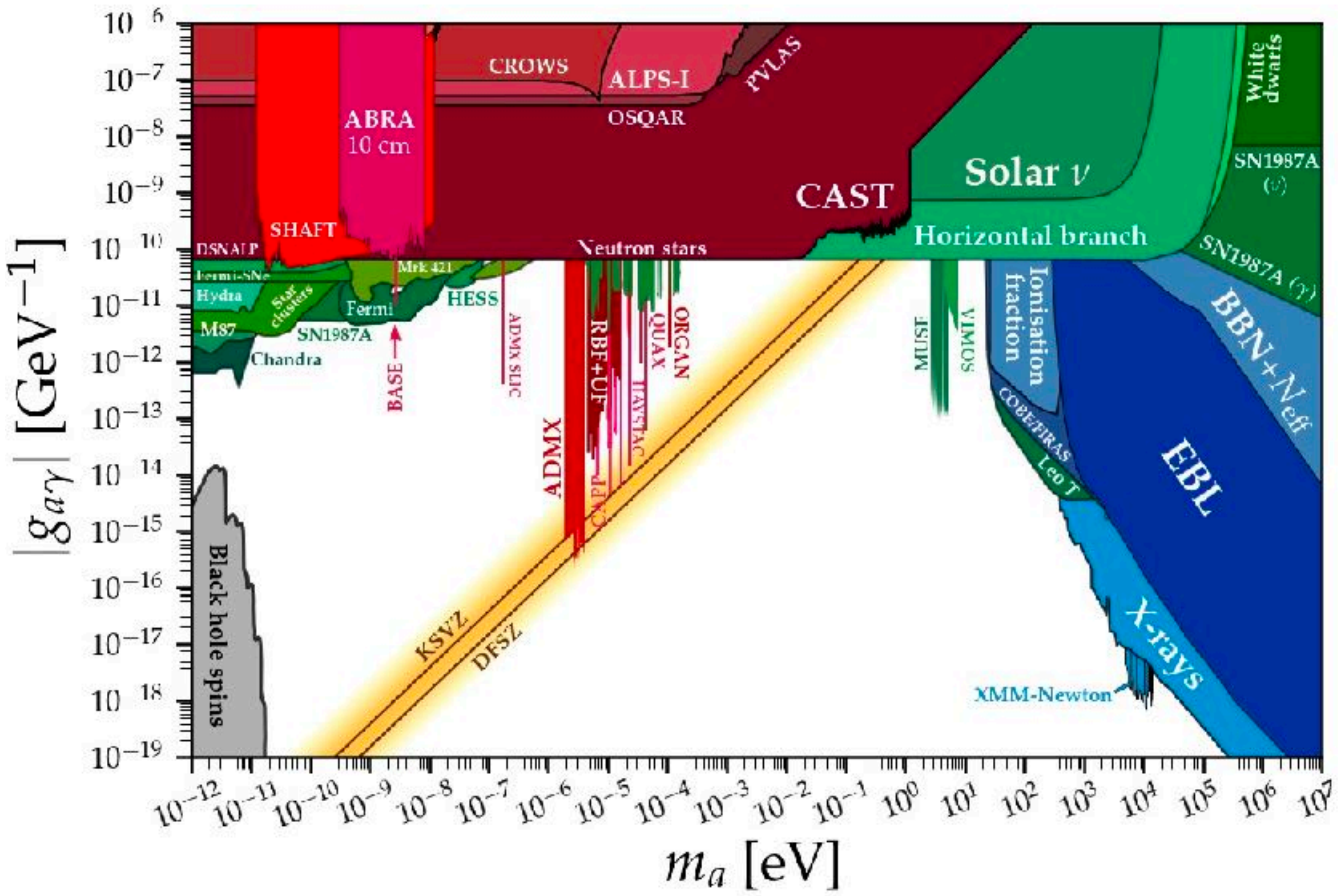
Current status

- Axon dark matter detection competition :
  - Traditional resonant cavity: ADMX, CAPP, HAYSTACK
  - LC circuit: DM Radio, ABRACADABRA
  - Nuclear Magnetic Resonance: CASPER, Spin amplifier (USTC)

  …

- The main experimental limits come from the resonant cavity, CAST, and stellar cooling.

A huge parameter space to be explored!



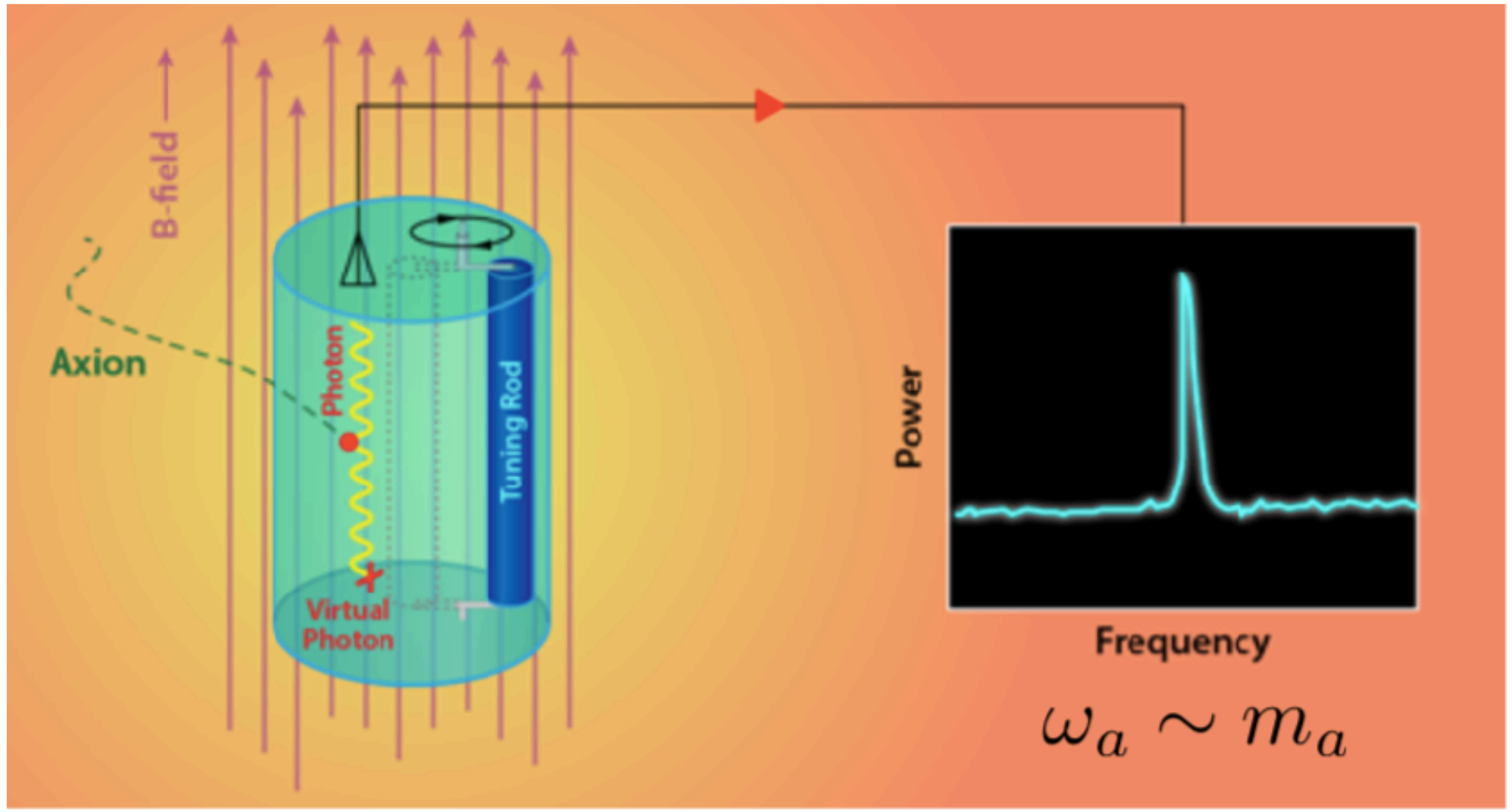
Cavity with static B field

$$\left(\partial_t^2 + \frac{m_a}{Q_1}\partial_t + m_a^2\right)\mathbf{E}_1 \sim m_a \cos m_a t$$

$$Q_a \sim 10^6$$

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

Quantum amplifier to readout the signal.



e.g. ADMX, HAYSTACK

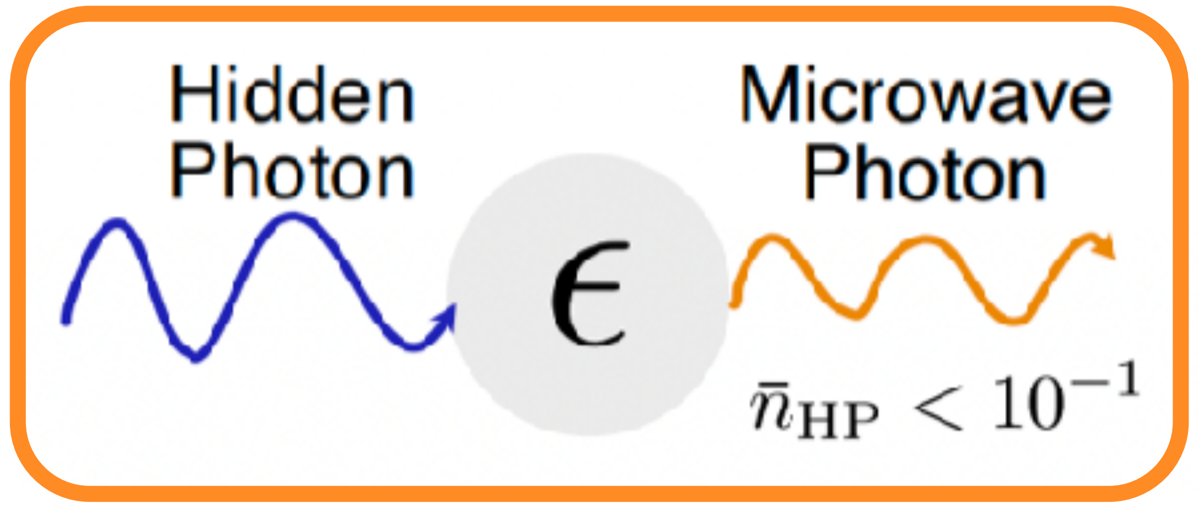
Cavity size ~ (axion mass)^-1

Signal power decreases with axion mass

Ground-Based Wave-DM Search

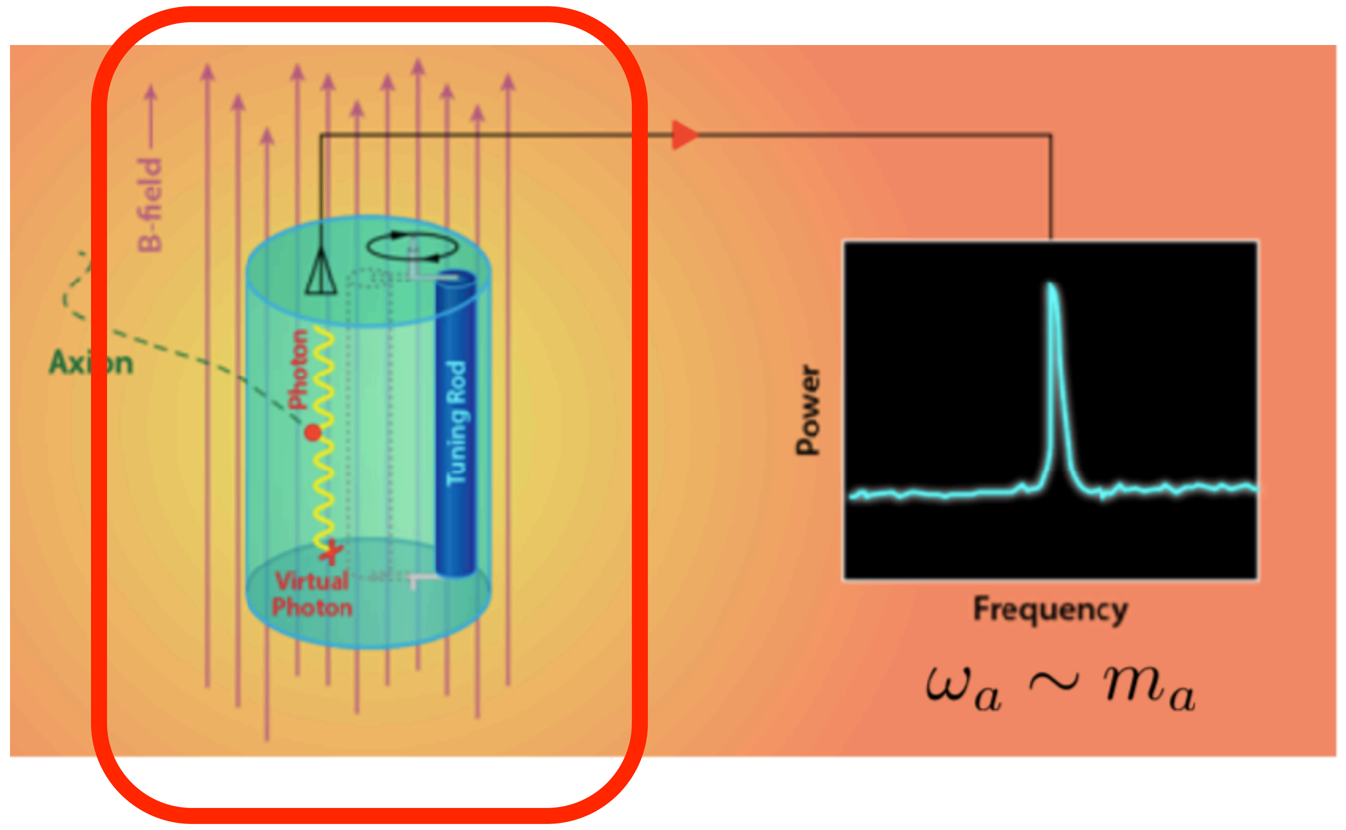
$U(1)_Y$

Wave-like DM-photon coupling produces microwave signals

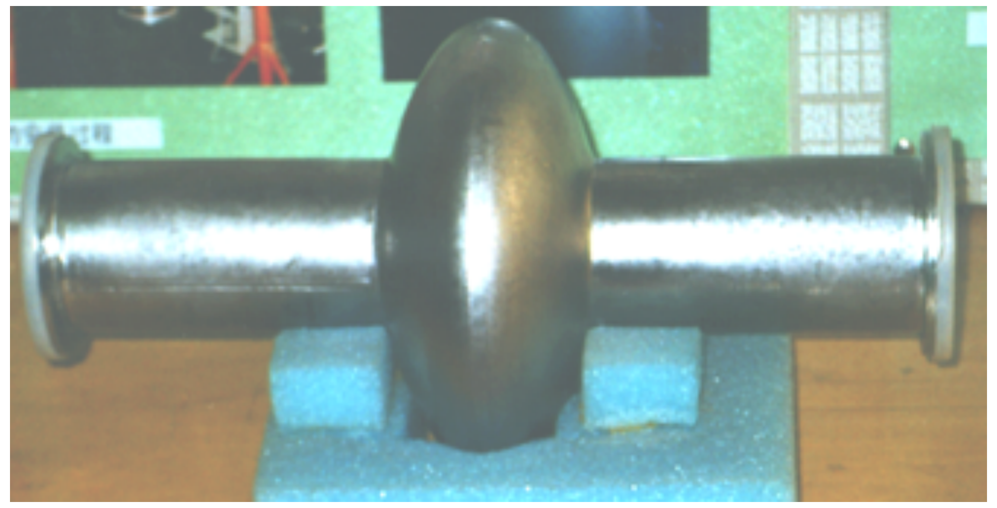


Microwave resonant cavity: high-sensitivity (high-Q) receiver

Accelerator SC cavities have ultra-high Q



Upgrade to SC cavity



Q: ~5 orders higher than conventional cavities

Superconducting (SC) cavity: Q ~ 10^{10}

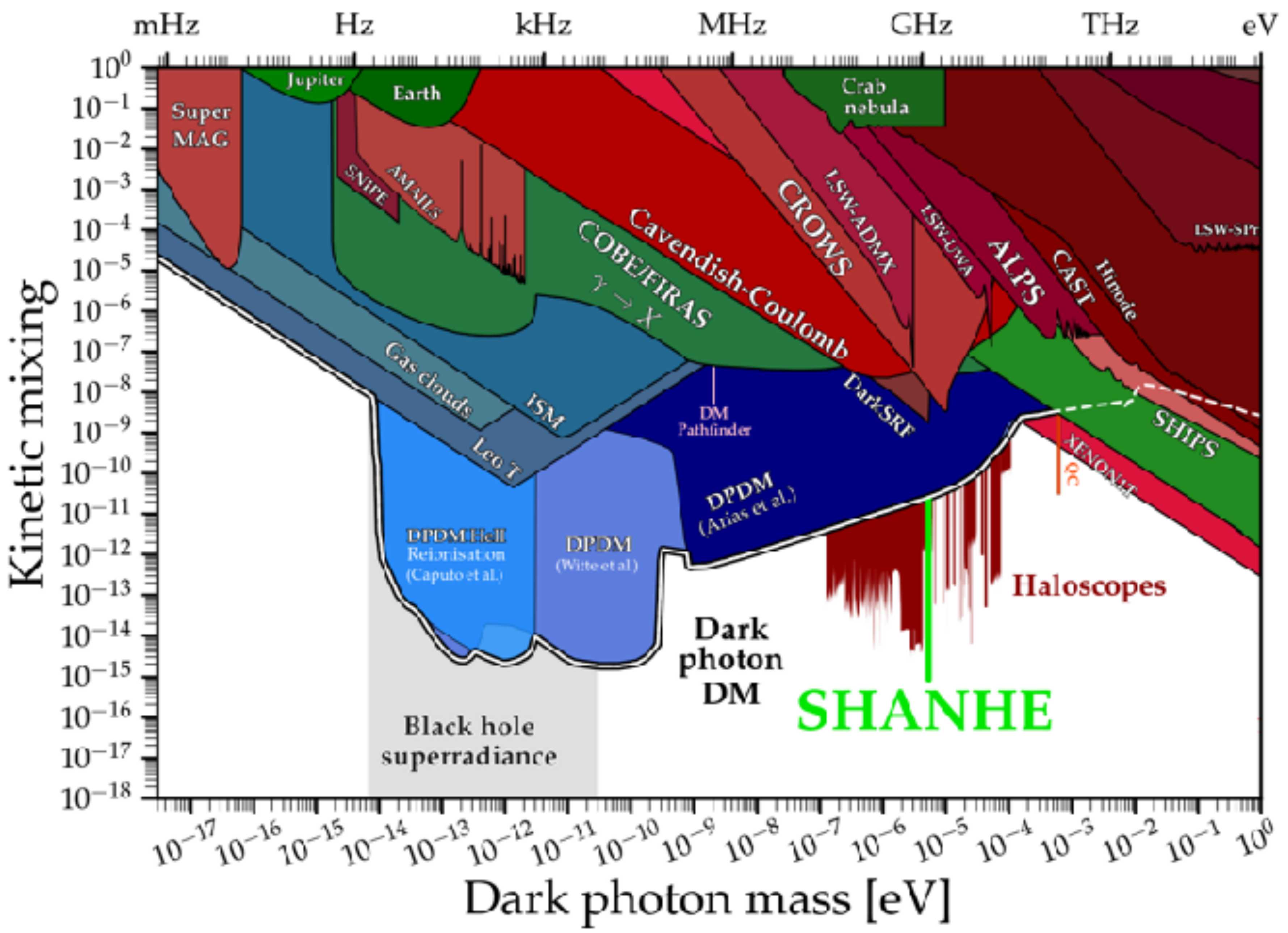
$$\epsilon \approx 2.8 \times 10^{-16} \boxed{\left(\frac{10^{10}}{Q_0}\right)^{\frac{1}{4}}} \left(\frac{\xi}{100}\right)^{\frac{1}{4}} \left(\frac{4\,\mathrm{L}}{V}\right)^{\frac{1}{2}} \left(\frac{0.5}{C}\right)^{\frac{1}{2}} \left(\frac{100\,\mathrm{s}}{t_{\mathrm{int}}}\right)^{\frac{1}{4}} \left(\frac{1.3\,\mathrm{GHz}}{f_0}\right)^{\frac{1}{4}} \left(\frac{T_{\mathrm{amp}}}{3\,\mathrm{K}}\right)^{\frac{1}{2}},$$

Higher Q, higher sensitivity

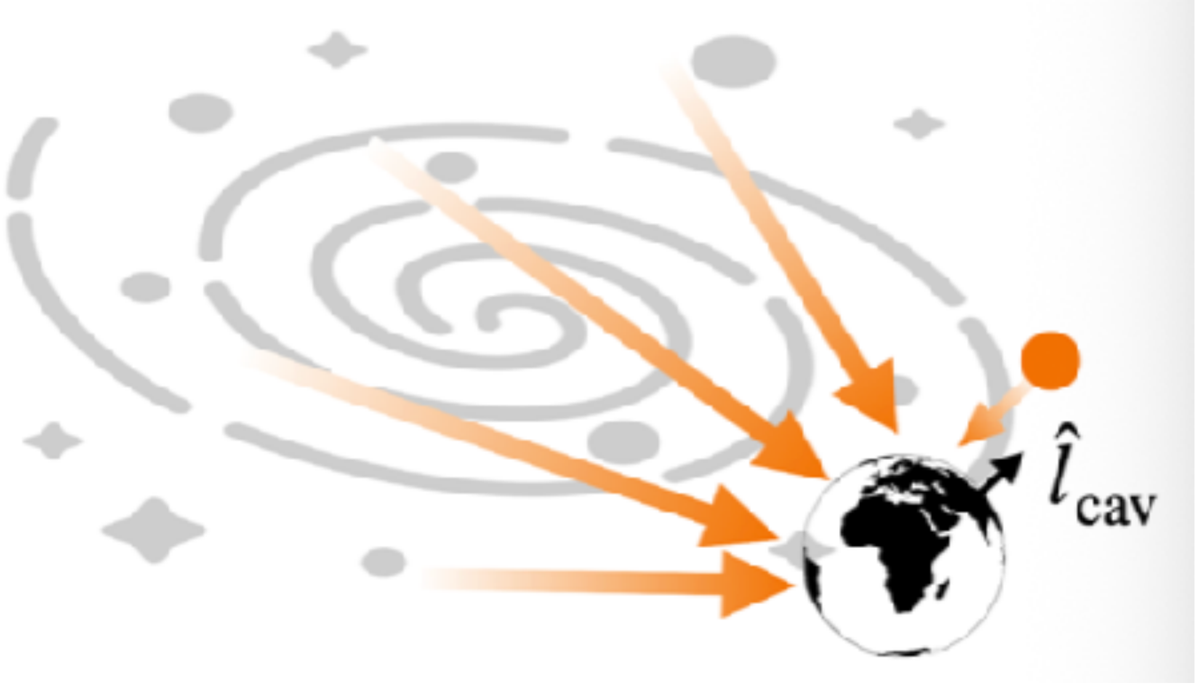
Key Result: Tunable Superconducting-Cavity Wave-DM Search

Peking University established the SHANHE dark-matter search collaboration

First successful tunable superconducting-cavity search for dark-photon DM, reaching the best sensitivity $\epsilon < 2.2 \times 10^{-16}$

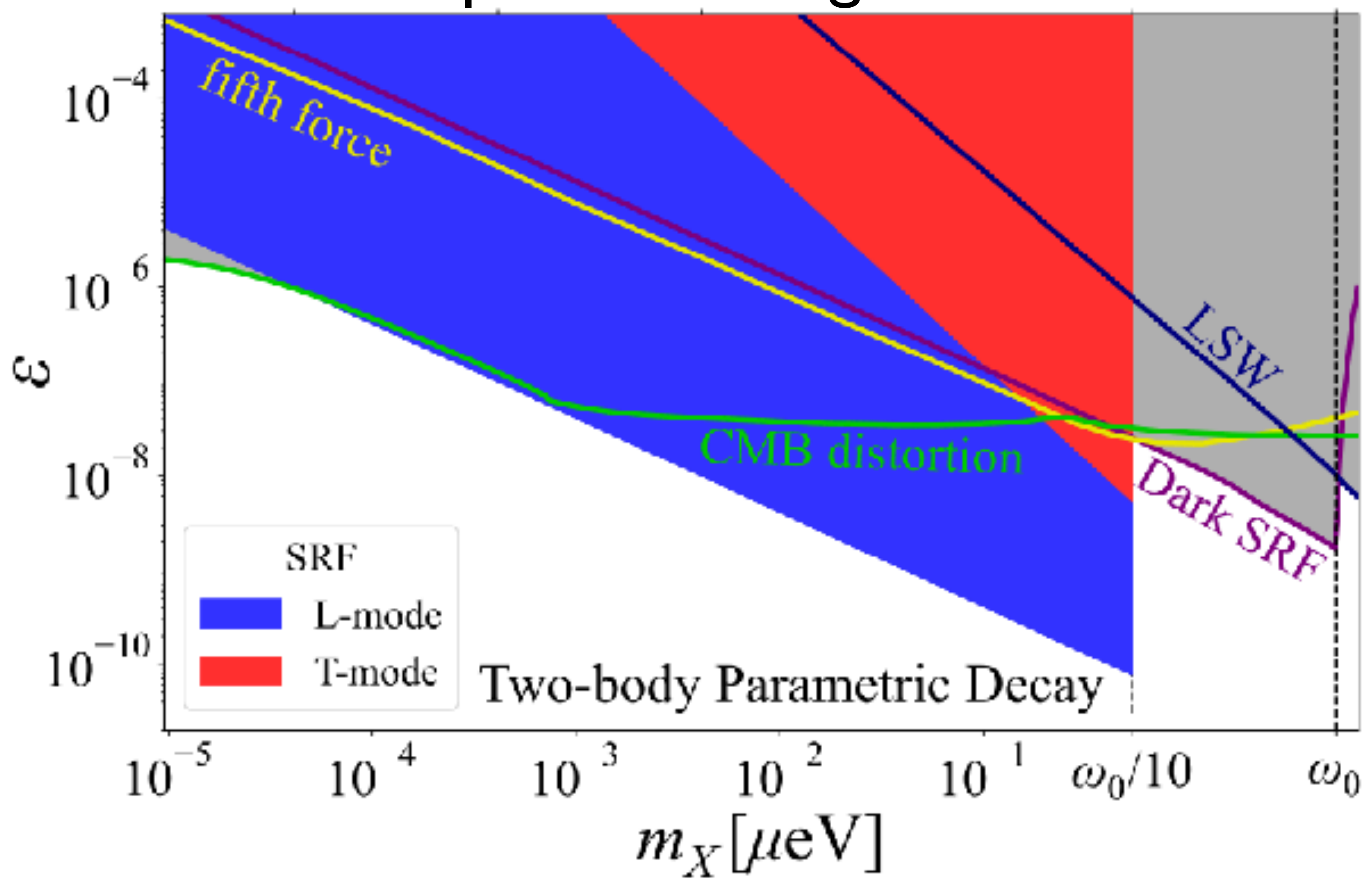


SHANHE Collaboration, Phys. Rev. Lett. 133 (2024) 2, 021005



An anisotropic dark photon background gives a signal modulated by Earth's rotation.

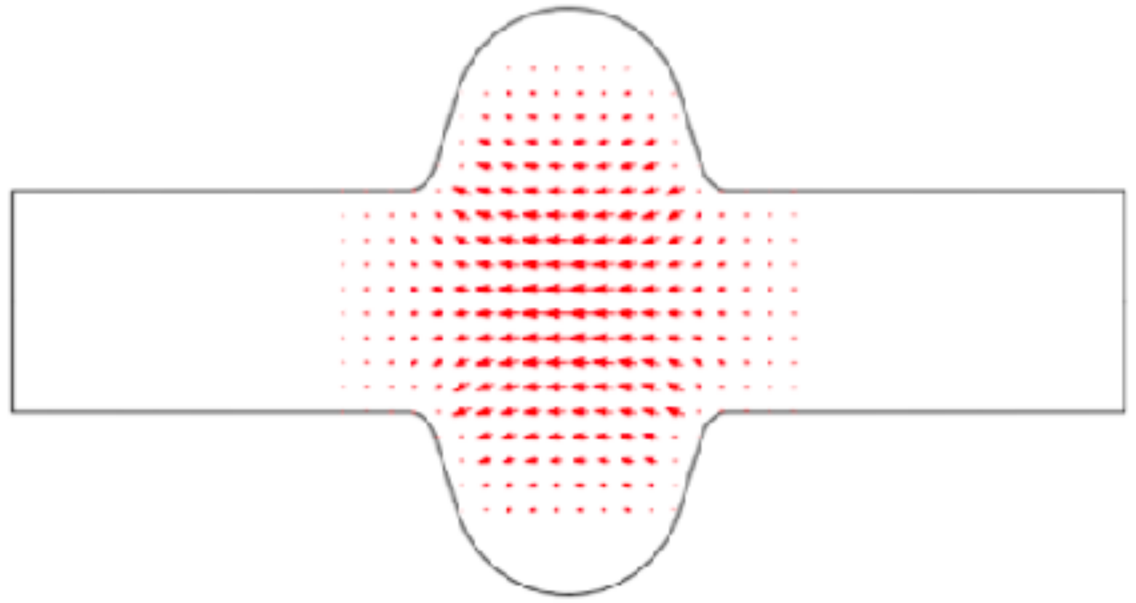
Constraints on DM annihilation into a dark-photon background



SHANHE Collaboration, Sci. Bull. 70 (2025) 661

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)



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

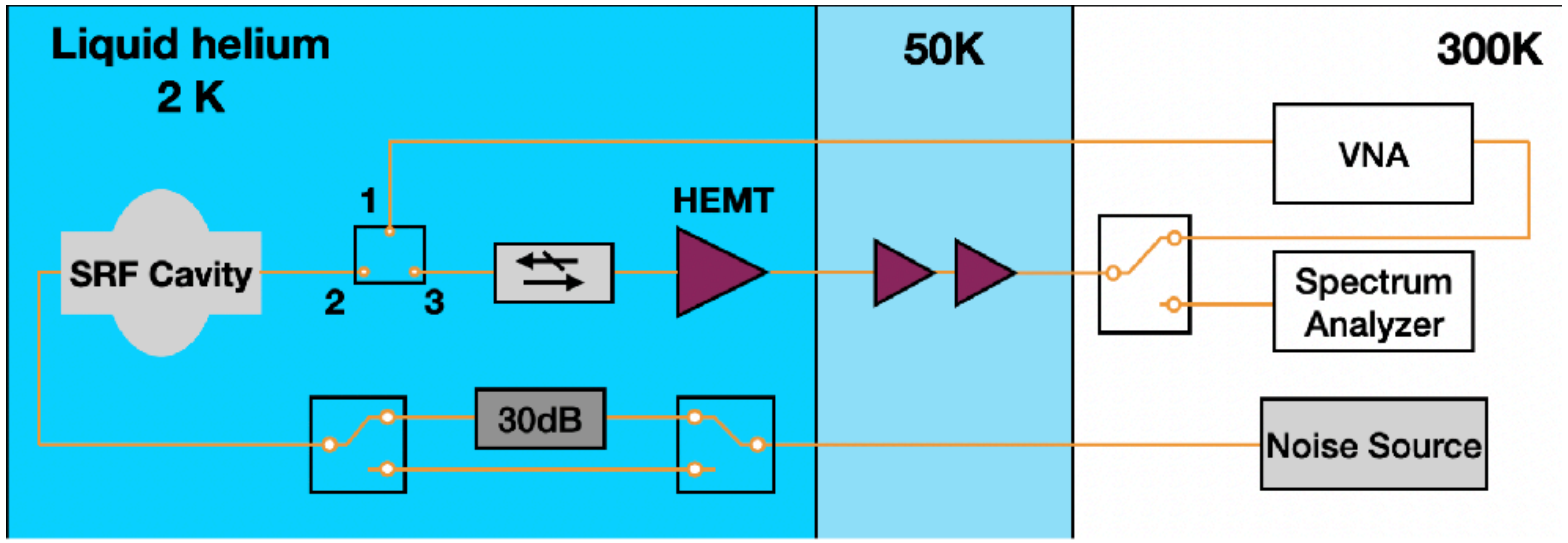
SHANHE Collaboration, Phys.Rev.Lett. 133 (2024) 2, 021005

Experimental operation

Parameters

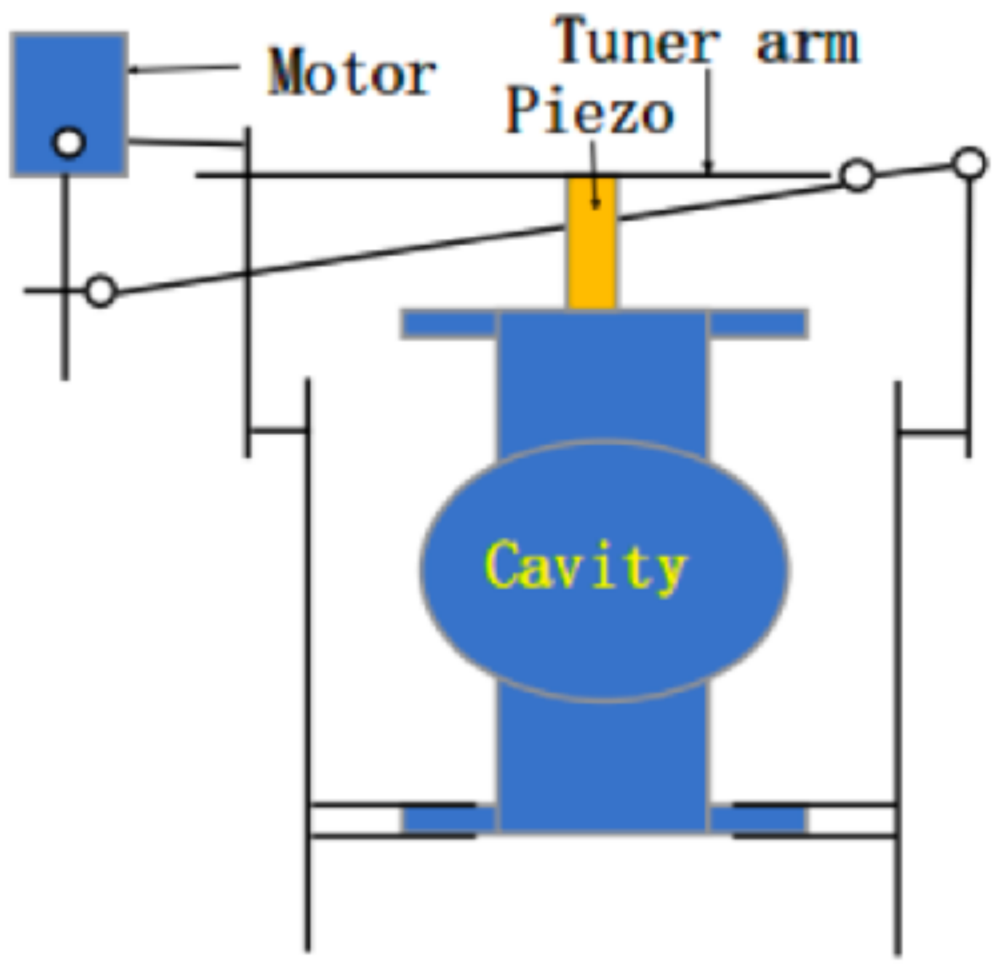
	Value	Fractional Uncertainty
$V_{\text{eff}} \equiv V\,C/3$	$693\,\text{mL}$	$< 1\%$
β	0.634 ± 0.014	1.4%
G_{net}	$(57.30 \pm 0.14)\,\text{dB}$	3.1%
Q_L	$(9.092 \pm 0.081) \times 10^9$	/
f_0^{max}	$1.2991643795\,\text{GHz}$	/
Δf_0	$11.5\,\text{Hz}$	/
t_{int}	$100\,\text{s}$	/

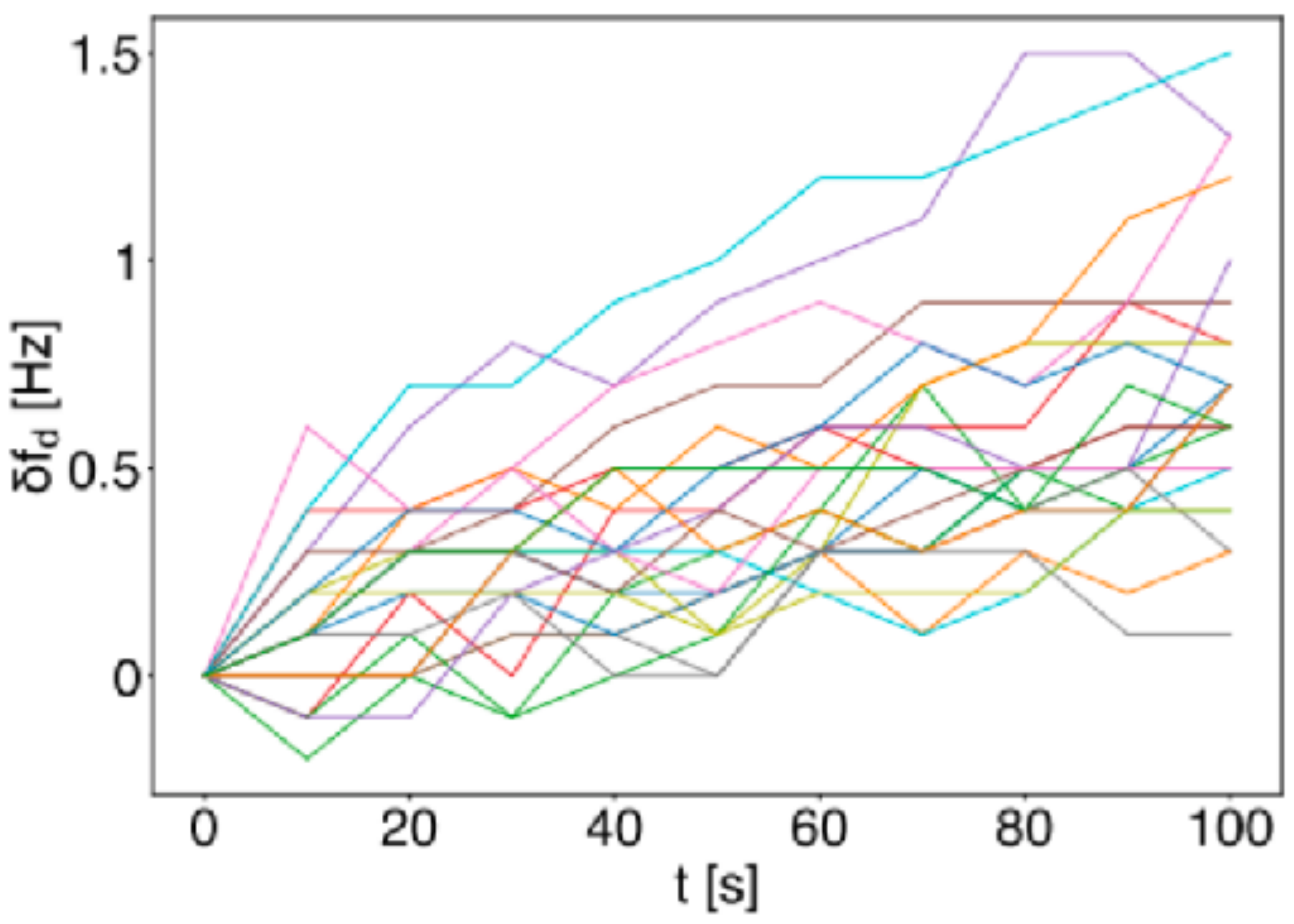
microwave electronics for DPDM searches

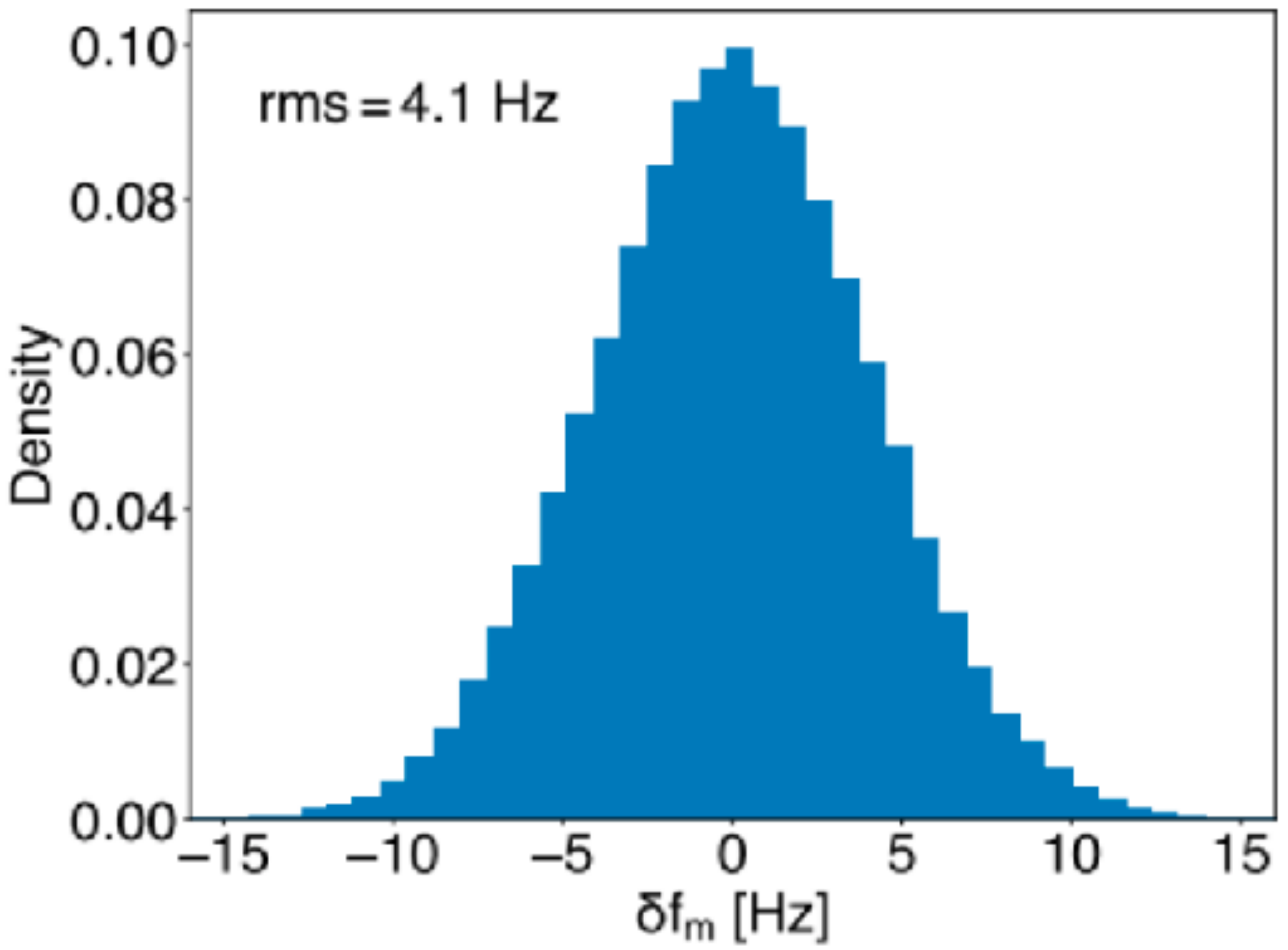


Scan Search with Mechanical Tuning

- Mechanical tuner 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 $\delta f_{\rm d} \leq 1.5{\rm Hz}$ and microphonics effect $\sigma_{f_0} \approx 4{\rm Hz}$





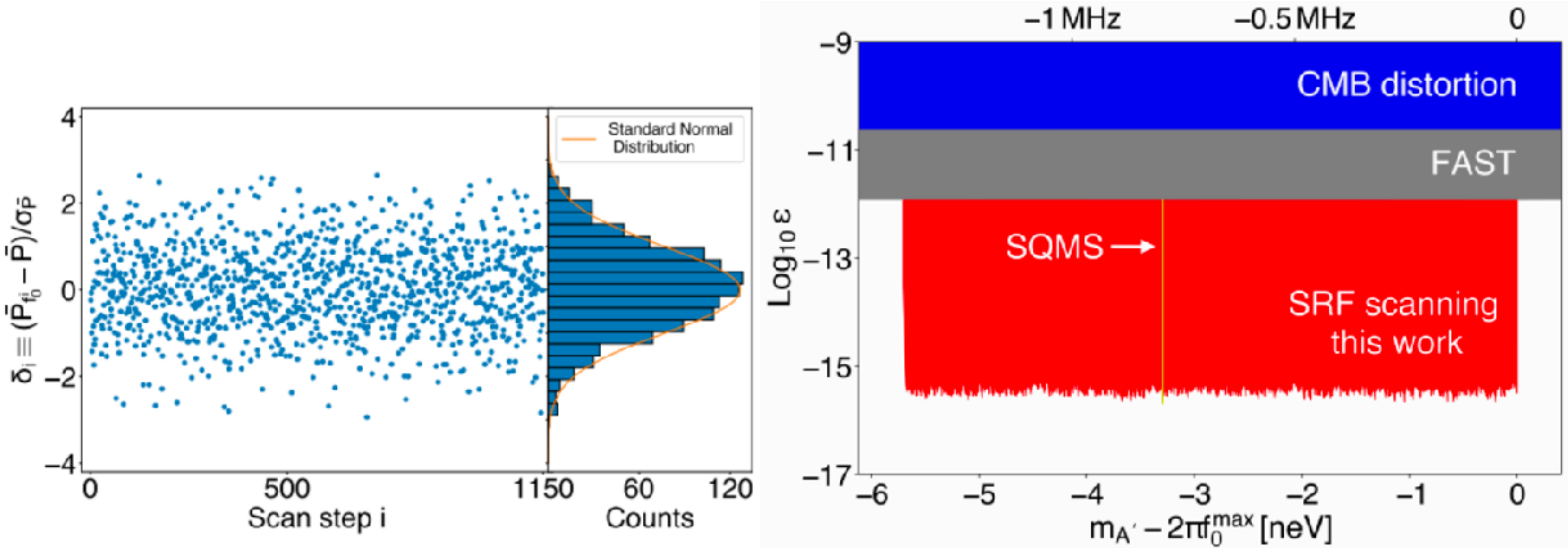


- **Conservatively** choose $\Delta f_0 \approx 10{\rm Hz}$

Data analysis and constraints

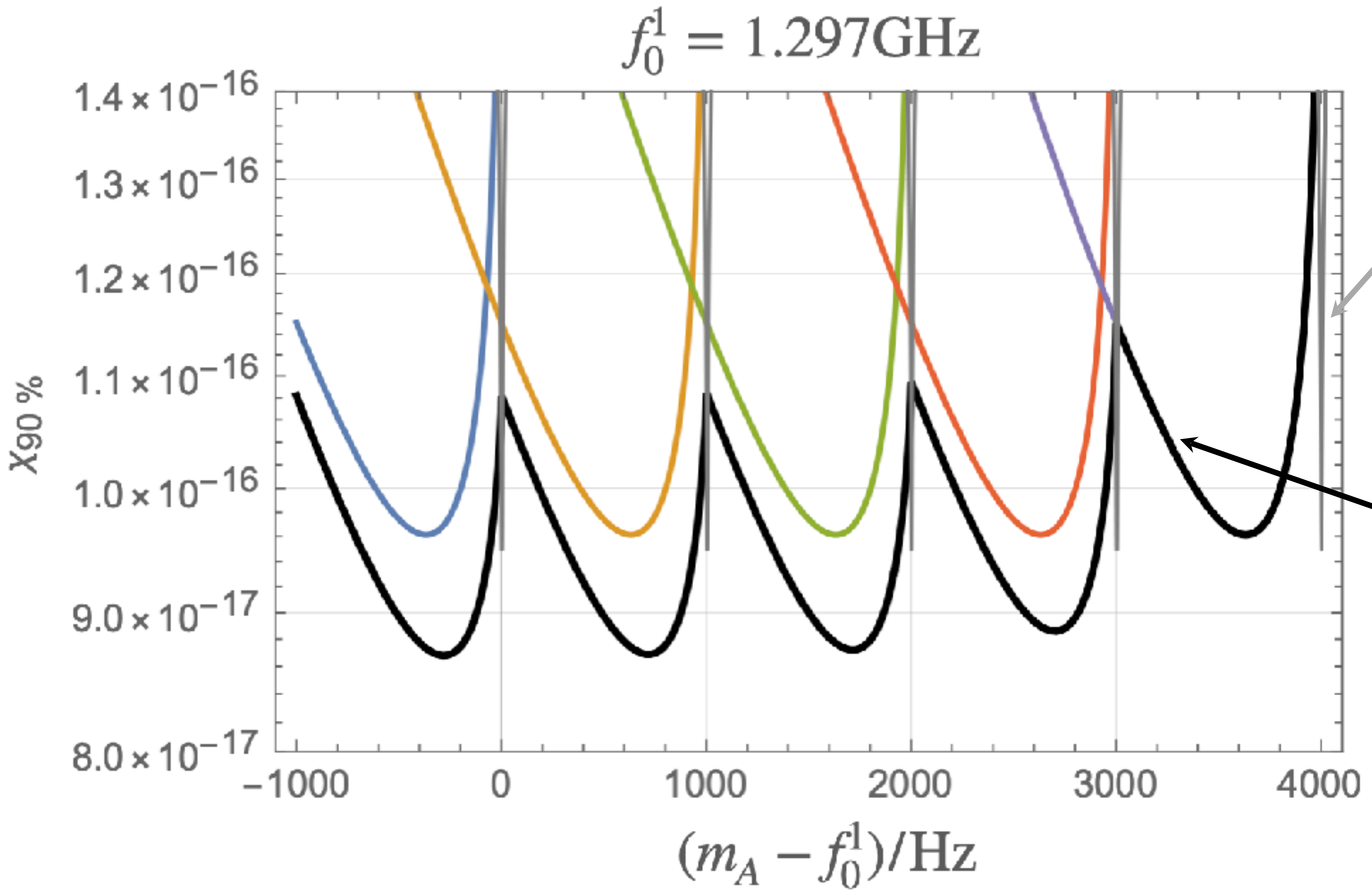
- Total 1150 scan steps with each 100 s integration time
- **Group** every 50 adjacent bins and perform a constant fit to address small helium pressure fluctuation.
- Normal power excess shows **Gaussian distribution**:

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

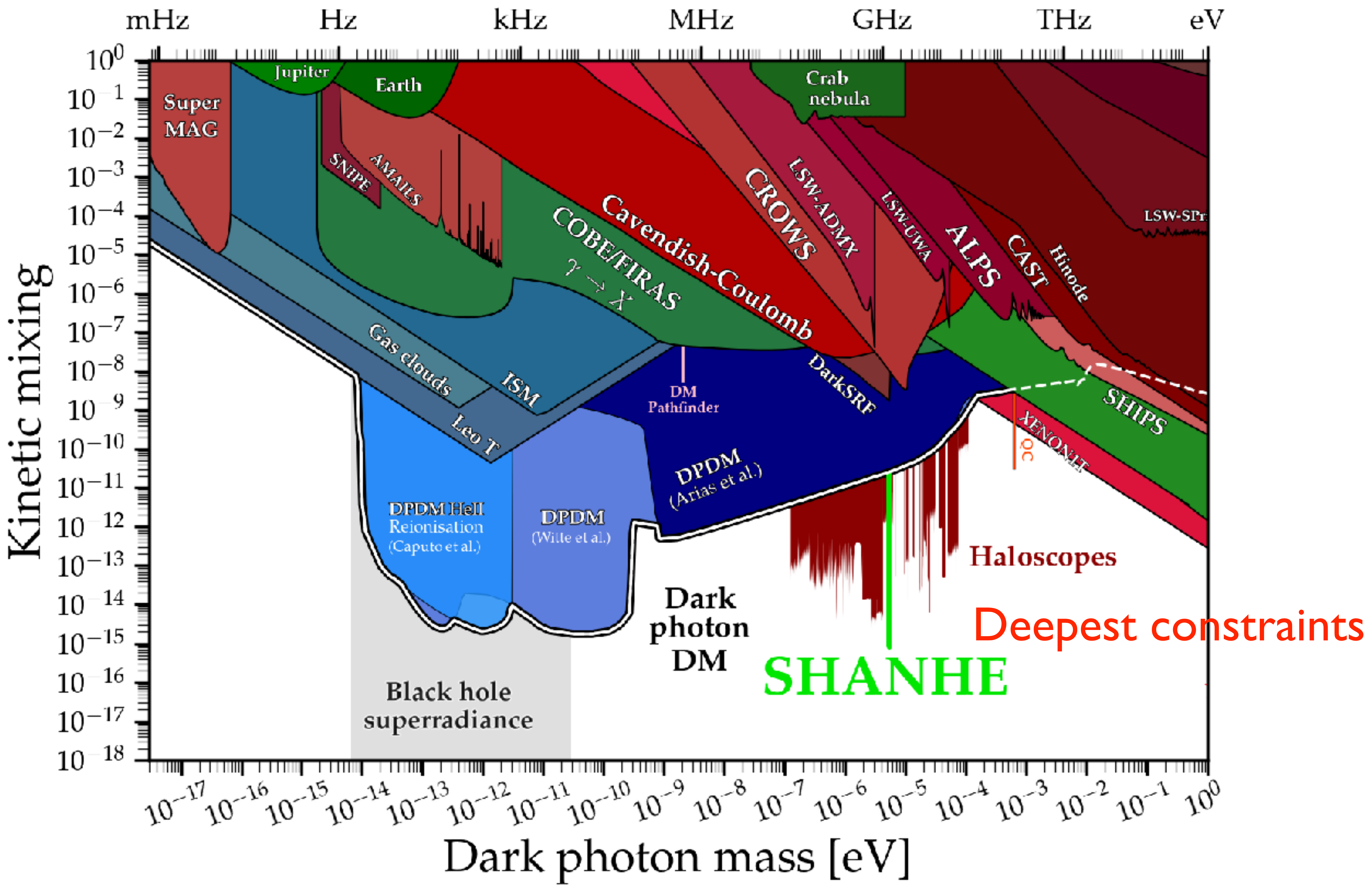
Virialized DM Exclusion

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

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*

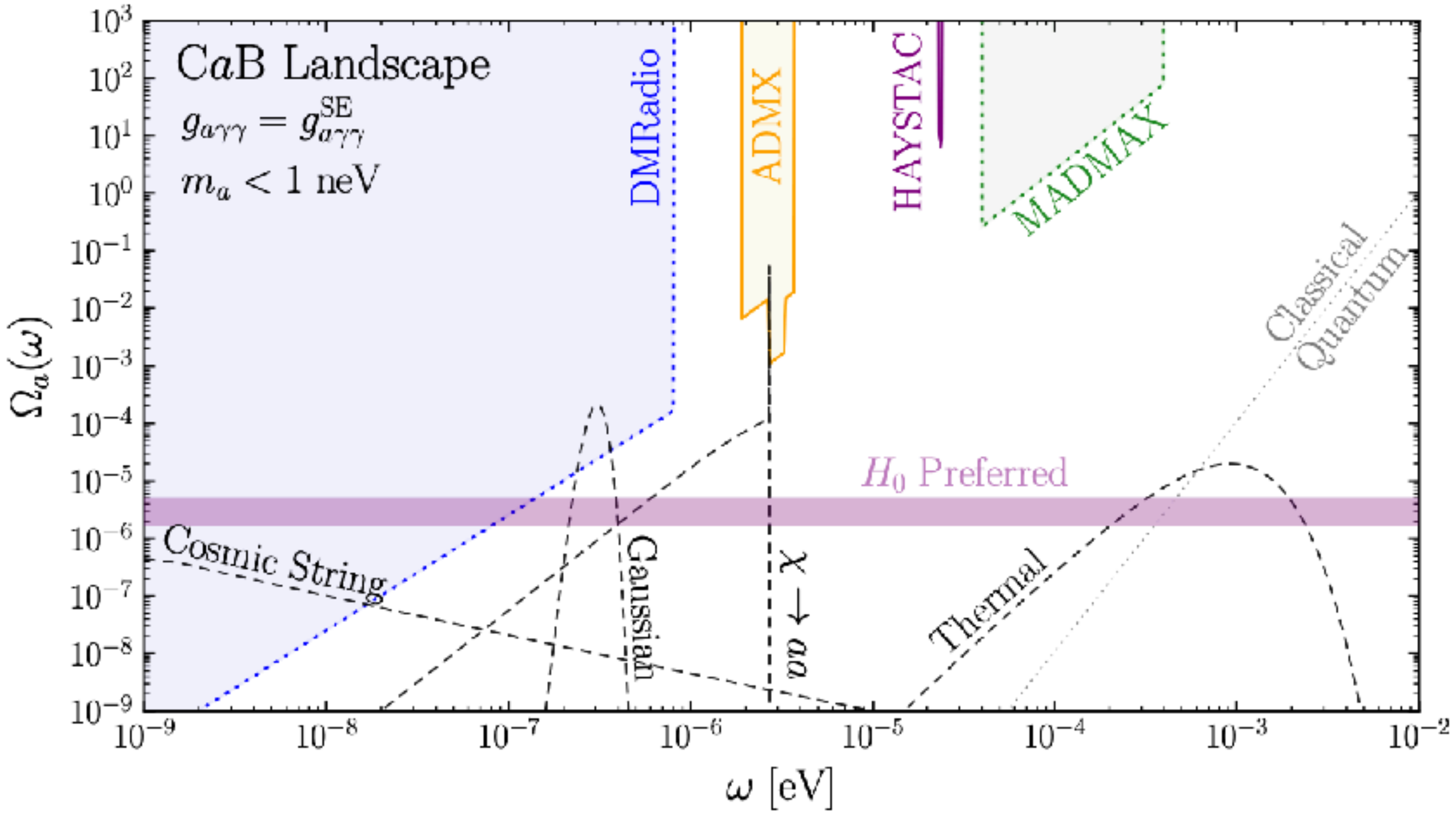
[2] *Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720, USA*

[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

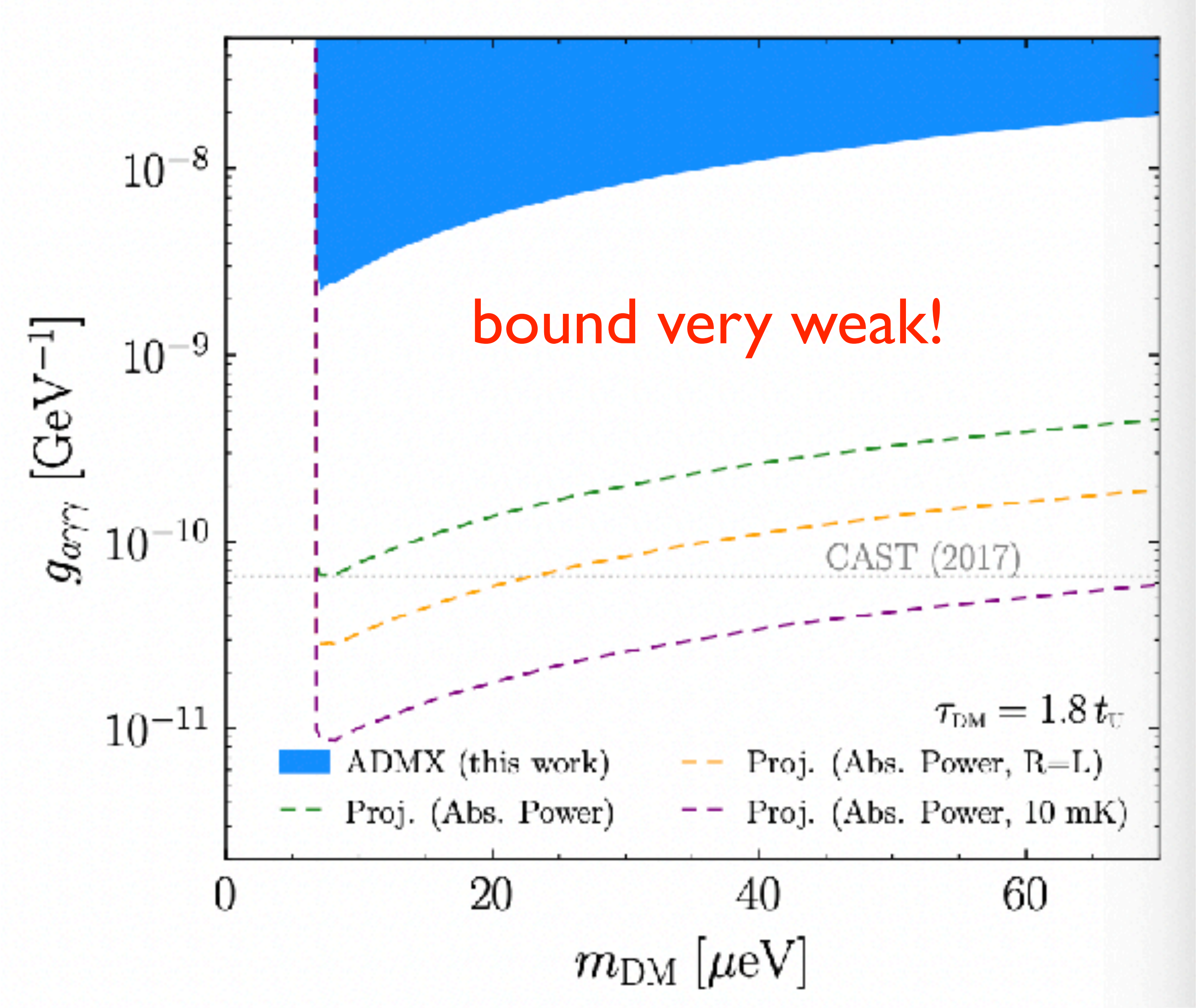
- How about galactic DP backgrounds? (Anisotropic backgrounds, from annihilation or decay?)

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

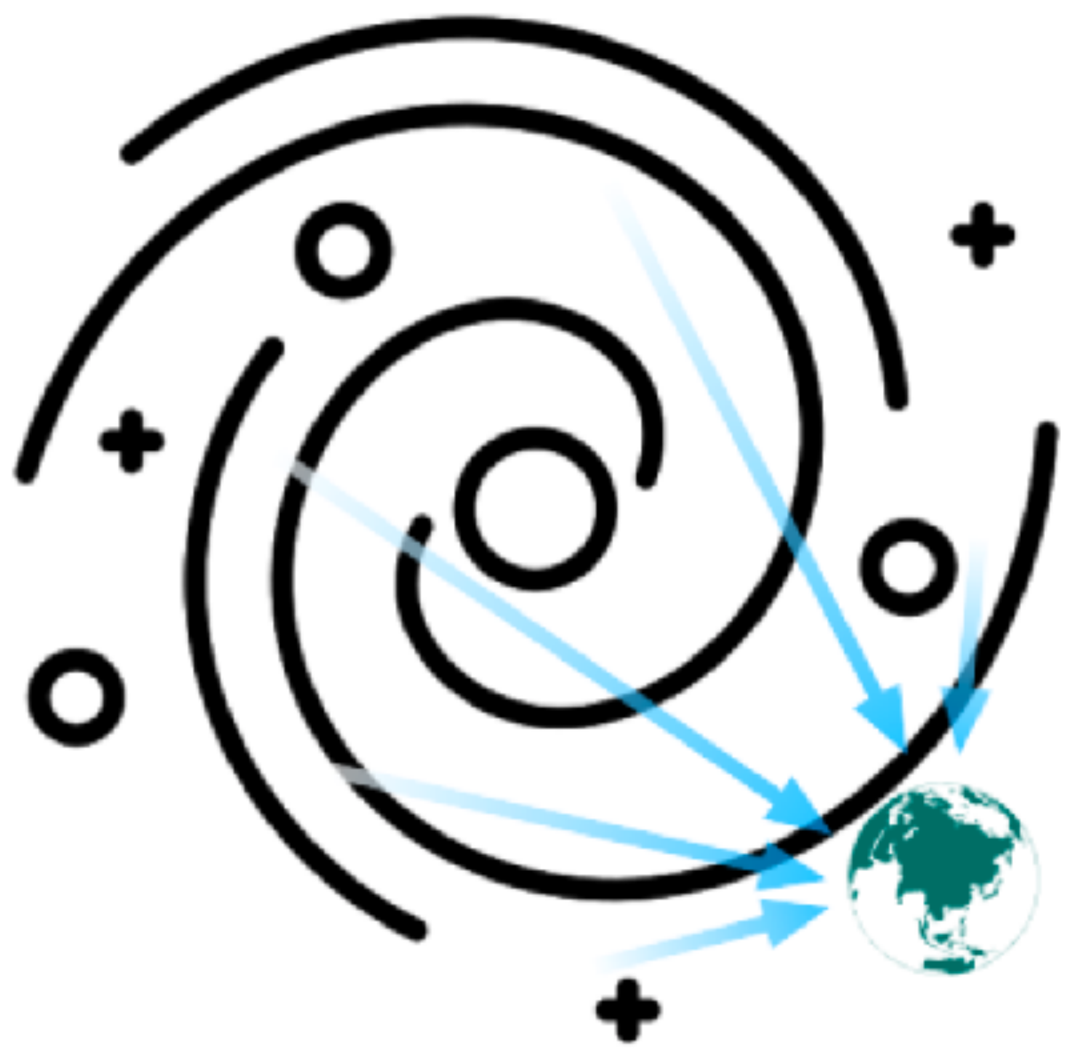
- Galactic dark photons from DM decay, e.g.: cascade decay from DM halo

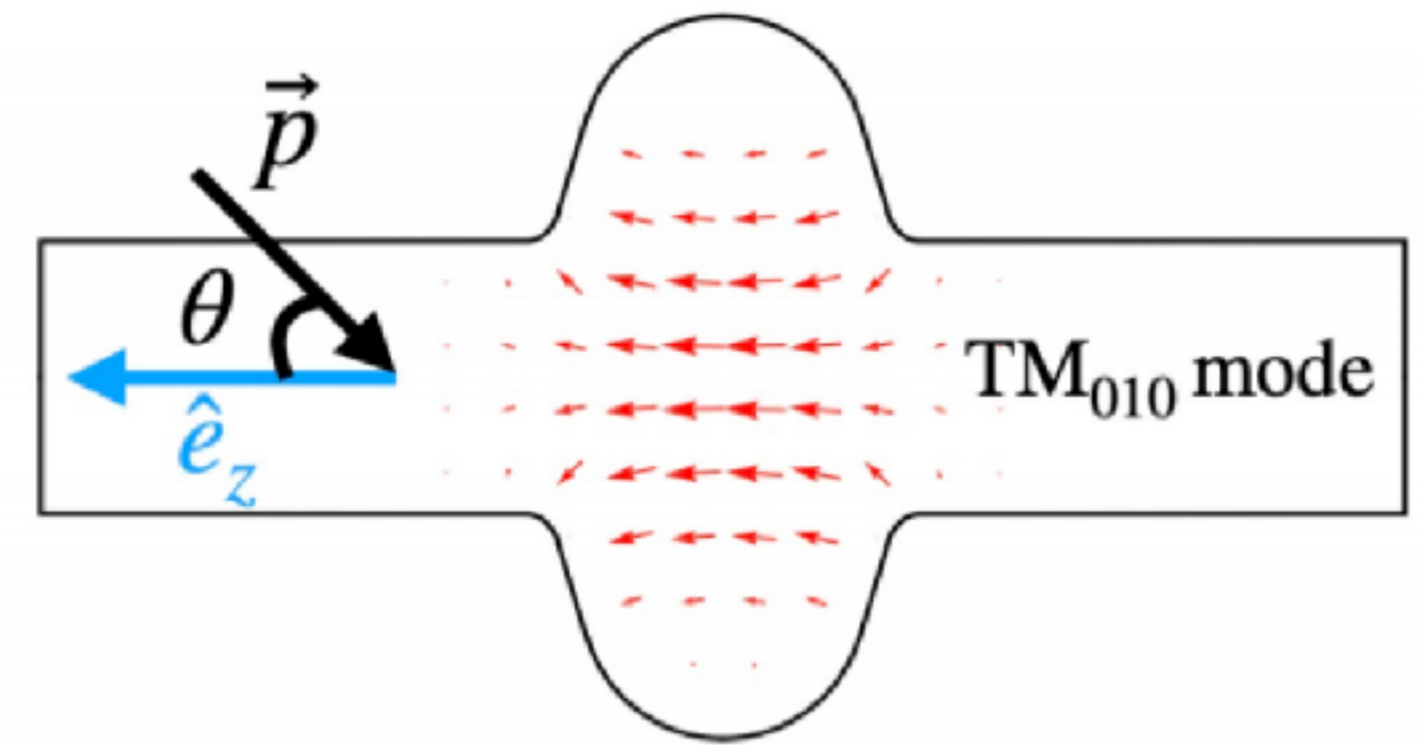
- Vectorial observable $\propto \vec{A}'$

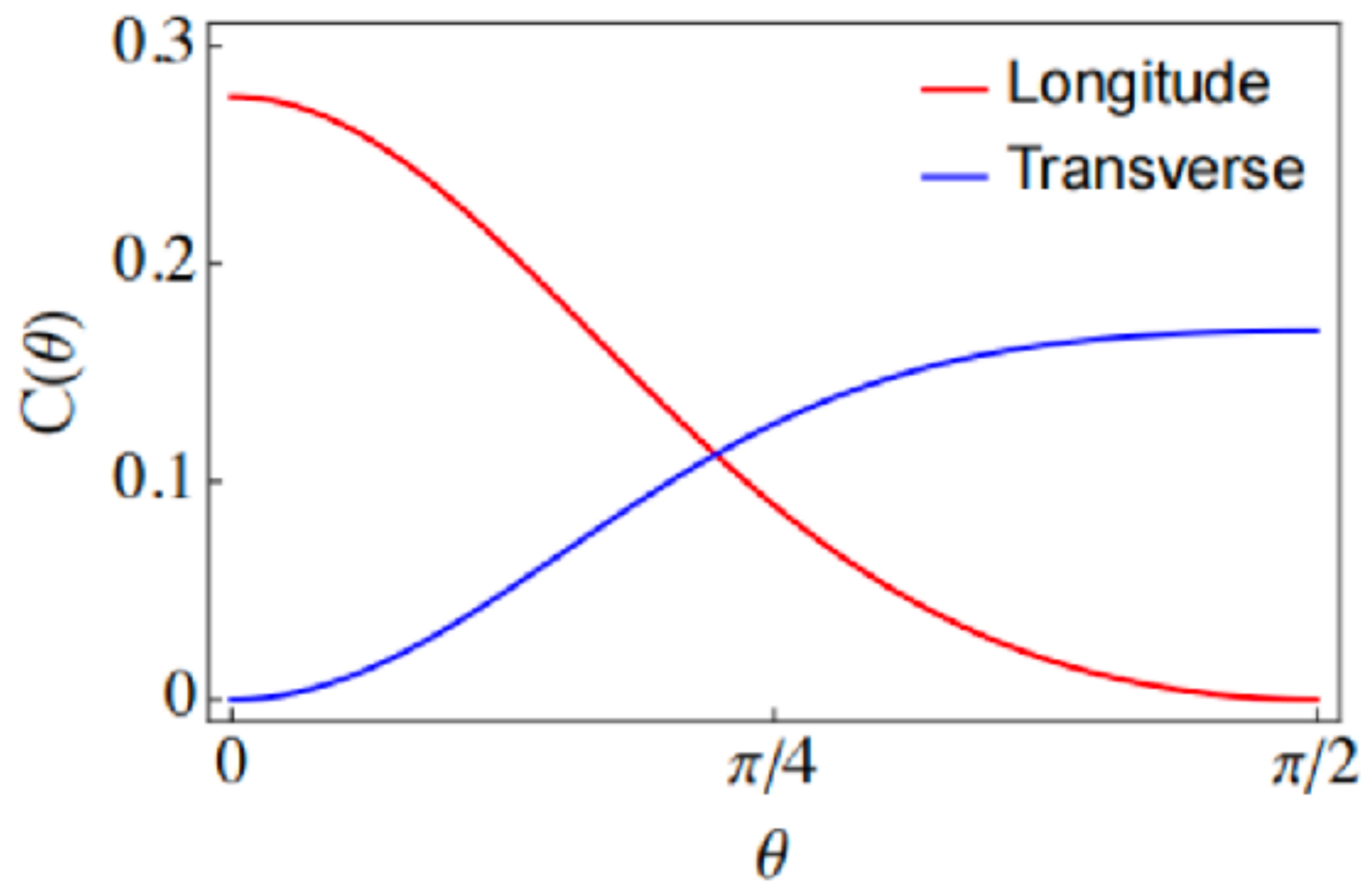
→ angular-dependent signal $\propto C(\theta)$

→ modulation as the Earth rotates

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



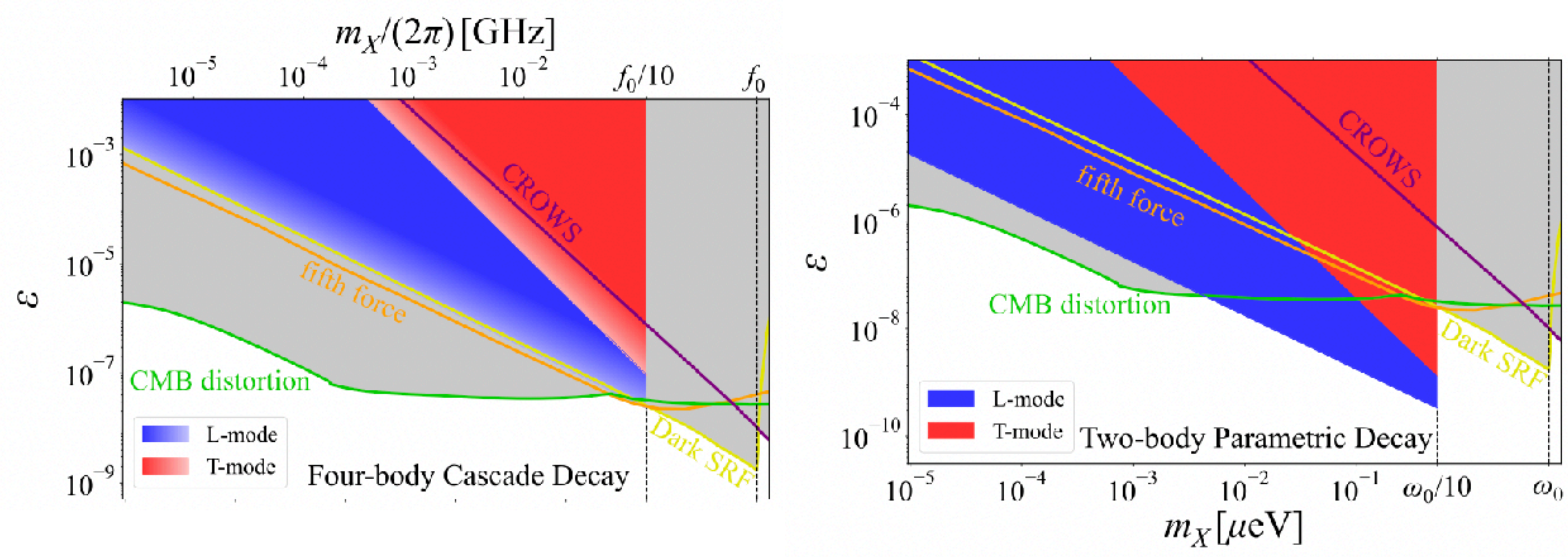




Yifan Chen, Chunlong Li, Yuxiang Liu, Yuxin Liu, Jing Shu, Yanjie Zeng, e-Print: 2402.03432 [hep-ph].

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

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SRF Heterodyne Axion Detection

- Key challenge: axion detection with SRF cavities in strong magnetic fields.

Strong fields break superconductivity; axion searches require magnetic fields.

Inject high-power microwaves to generate a strong AC magnetic field inside the SRF cavity.

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

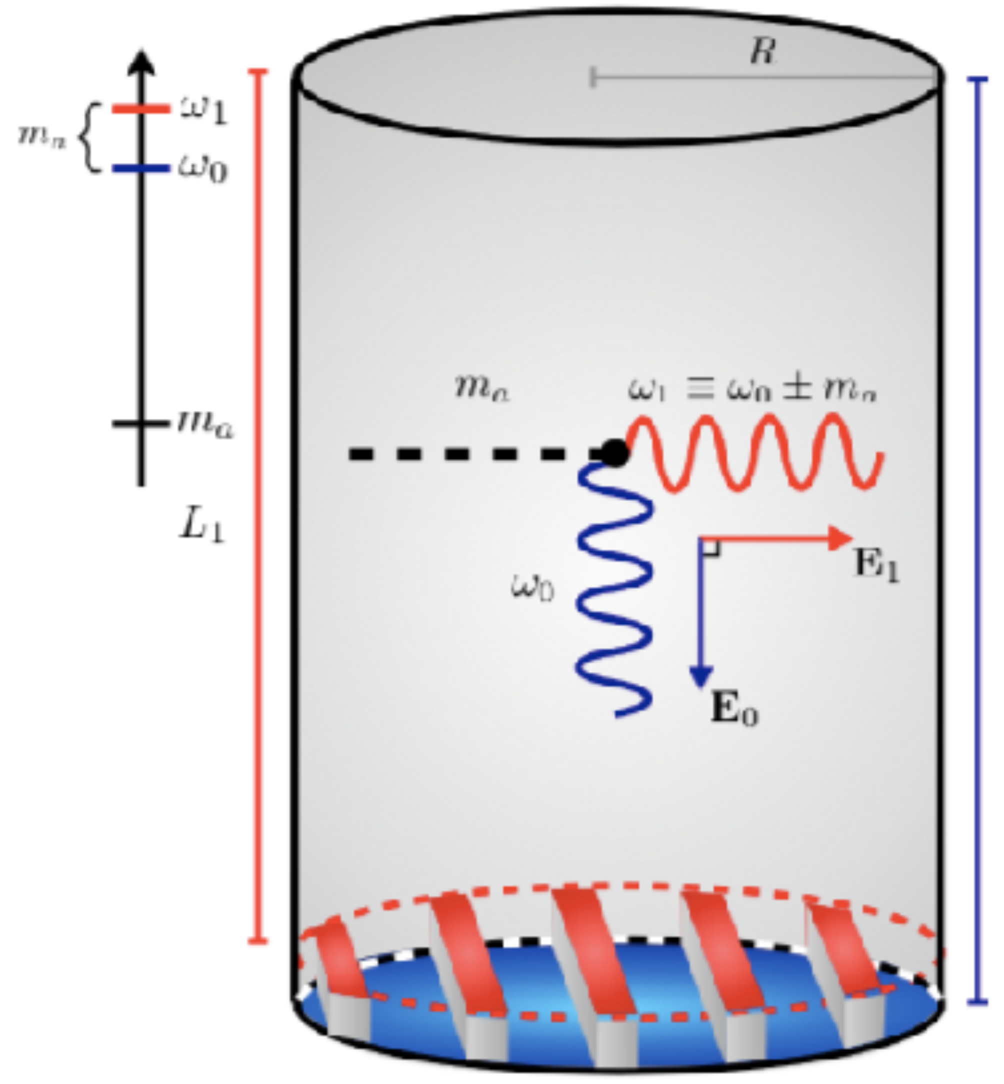
Mode: $\mathbf{E_1}$ Axion DM: $\mathbf{a}$

Dynamic field $\mathbf{B_0}$:

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

Tune mode splitting between near-degenerate levels to match axion mass, enabling smaller axion mass scans.

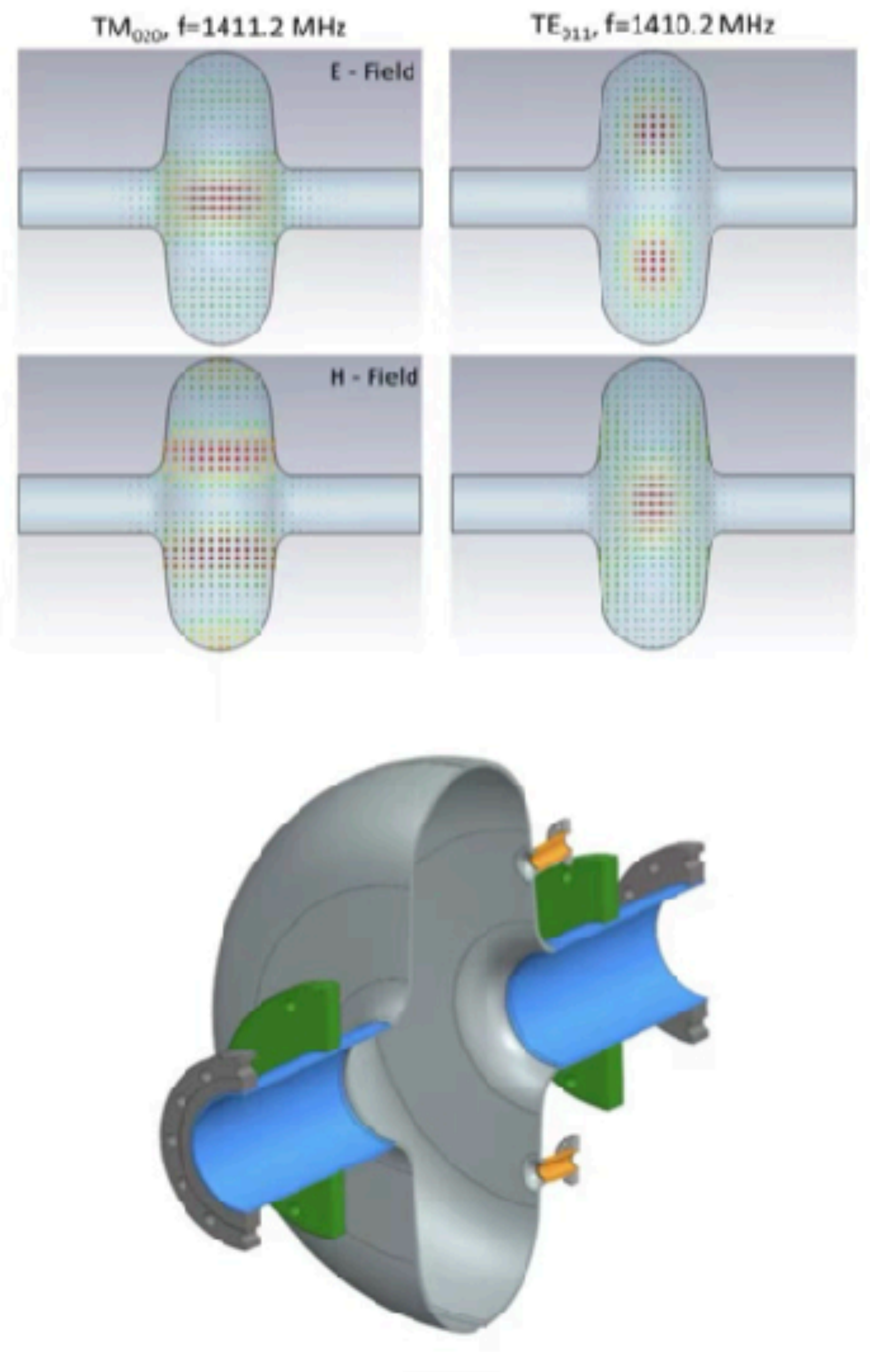
A. Berlin, R. T. D'Agnolo, et al., JHEP 07 (2020) 088.



Fermilab design complete

Fermilab

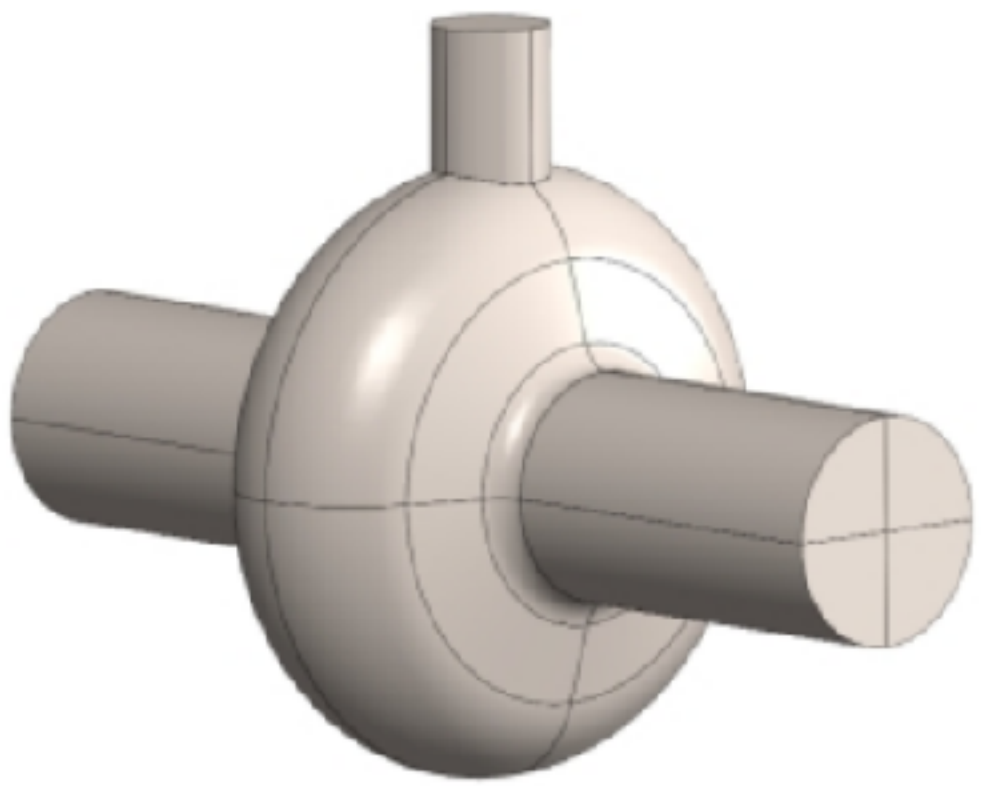
arXiv:2207.11346



SRF Heterodyne Axion Detection

$$f_0 \approx \mathrm{GHz}\left(\frac{30\mathrm{cm}}{L}\right)$$

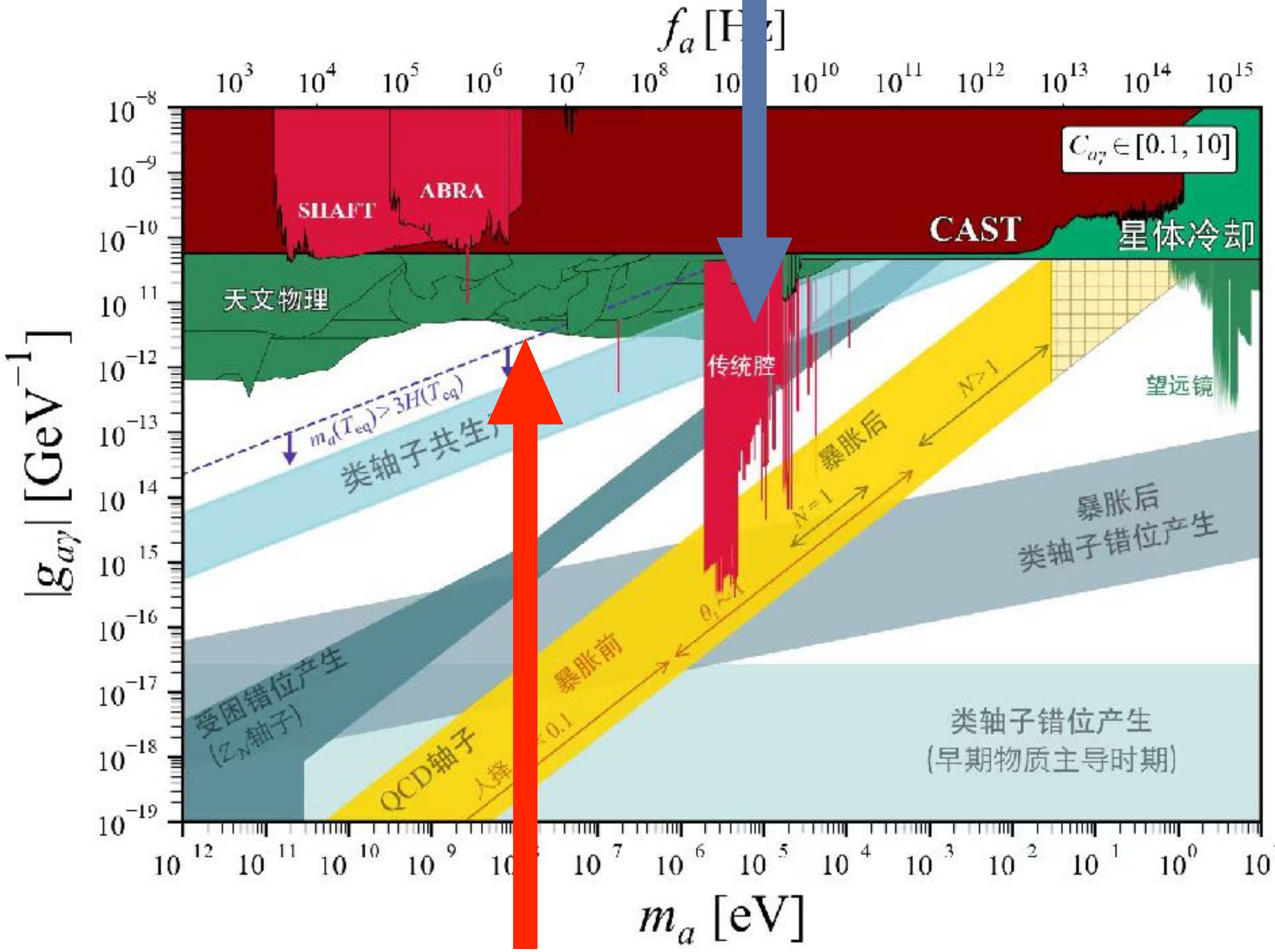
- Superconducting-cavity level transitions probe axion dark matter and high-frequency GWs



Use energy-level splittings to probe lower-frequency axions and GWs

$$\boxed{\mathrm{MHz} \sim \mathrm{GHz}}$$

Conventional cavities: GHz



Optimized for DM-induced transition measurements: new cavity geometry, mode selection, antenna design

No group has yet demonstrated this; Fermilab, CERN, etc. are actively competing.

MHz-GHz: almost no terrestrial coverage!

Research Plan and Methods

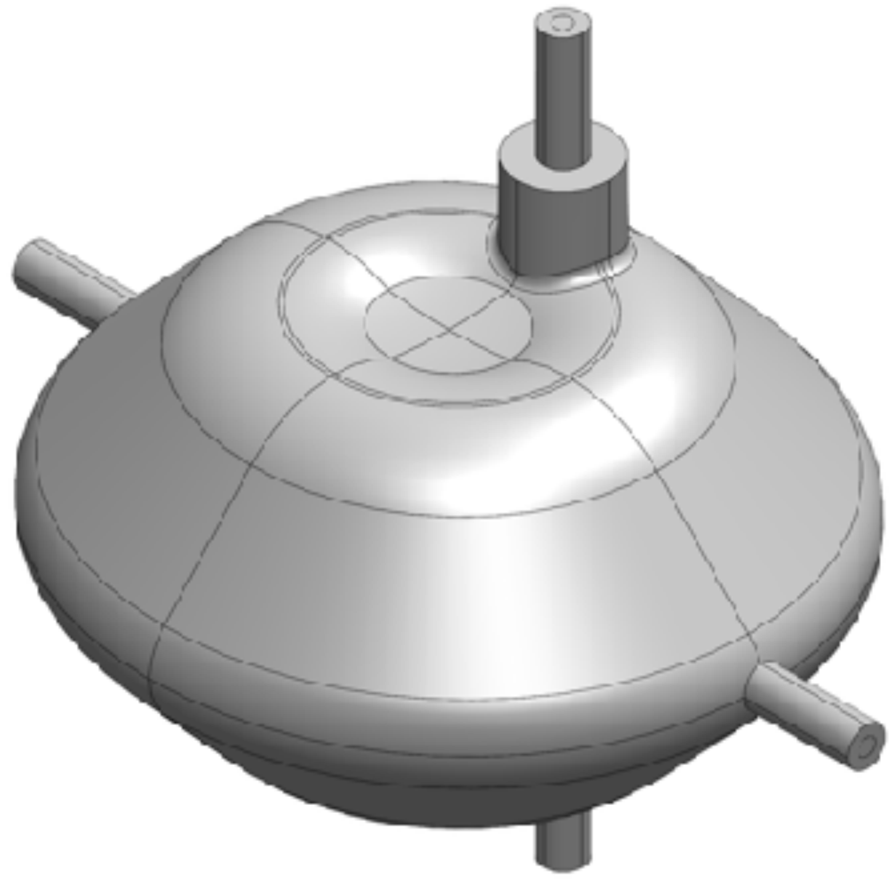
Research content: axion-DM search via superconducting resonator transitions

One measurement, two outcomes:

Reanalyzed axion data enables high-frequency GWs searches

Research Plan

- Phase I (P1) proof-of-principle experiment:
  - Use existing niobium cavities from accelerators; resonance frequency $200\mathrm{MHz}$
  - Measure via mechanical squeezing; scan range $1\mathrm{MHz}$
  - Projected beyond current axion-photon coupling limits $10^{-11}\mathrm{GeV}^{-1}$, down to about $10^{-12}\mathrm{GeV}^{-1}$
- Phase II (P2) transition-measurement experiment:
  - Complete new cavity design and fabrication; level splitting about $1\mathrm{MHz}$
  - Tune level splitting to achieve scan range $100\mathrm{KHz} \sim 1\mathrm{MHz}$
  - Control noise near thermal-noise floor; target coupling limits of $10^{-13} \sim 10^{-14}\mathrm{GeV}^{-1}$



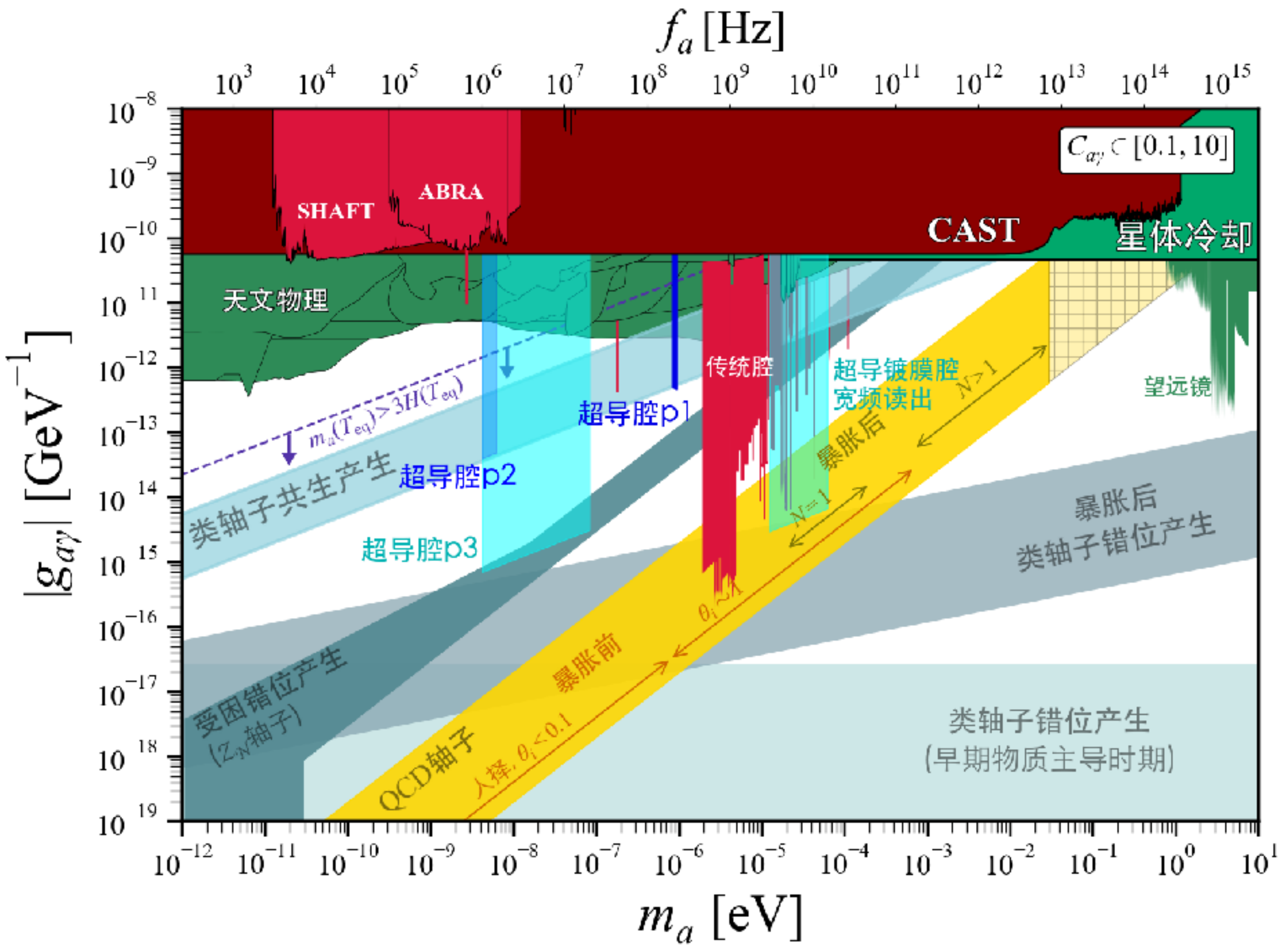
Research Plan and Methods

- P3: multimode resonator network for broadband/resonant readout:
  - Broadband readout over orders of magnitude; per-band bandwidth > MHz
  - Sensitivity: ~ $10^{-15}\ \mathrm{GeV}^{-1}$

Process optimization:

improve antenna design/fabrication,

mode isolation, and cavity fabrication precision to reduce mechanical and phase noise



SRF Cavity with qubits (Quantum Non-demolition Detection)

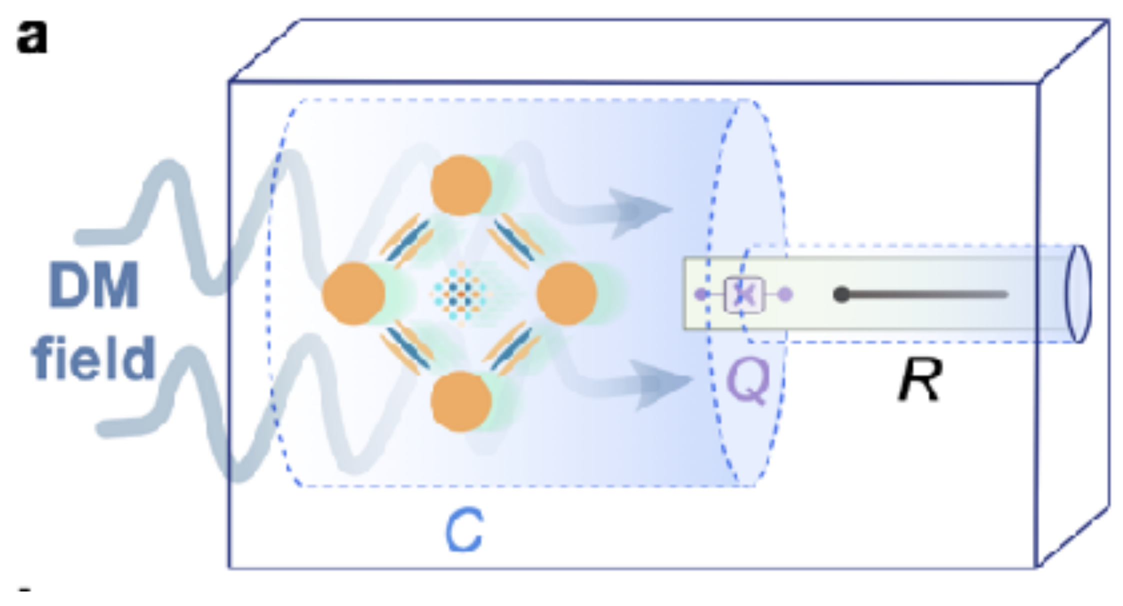
Key Result: Cat-State DM Detection

Al SC cavity for quantum sensing

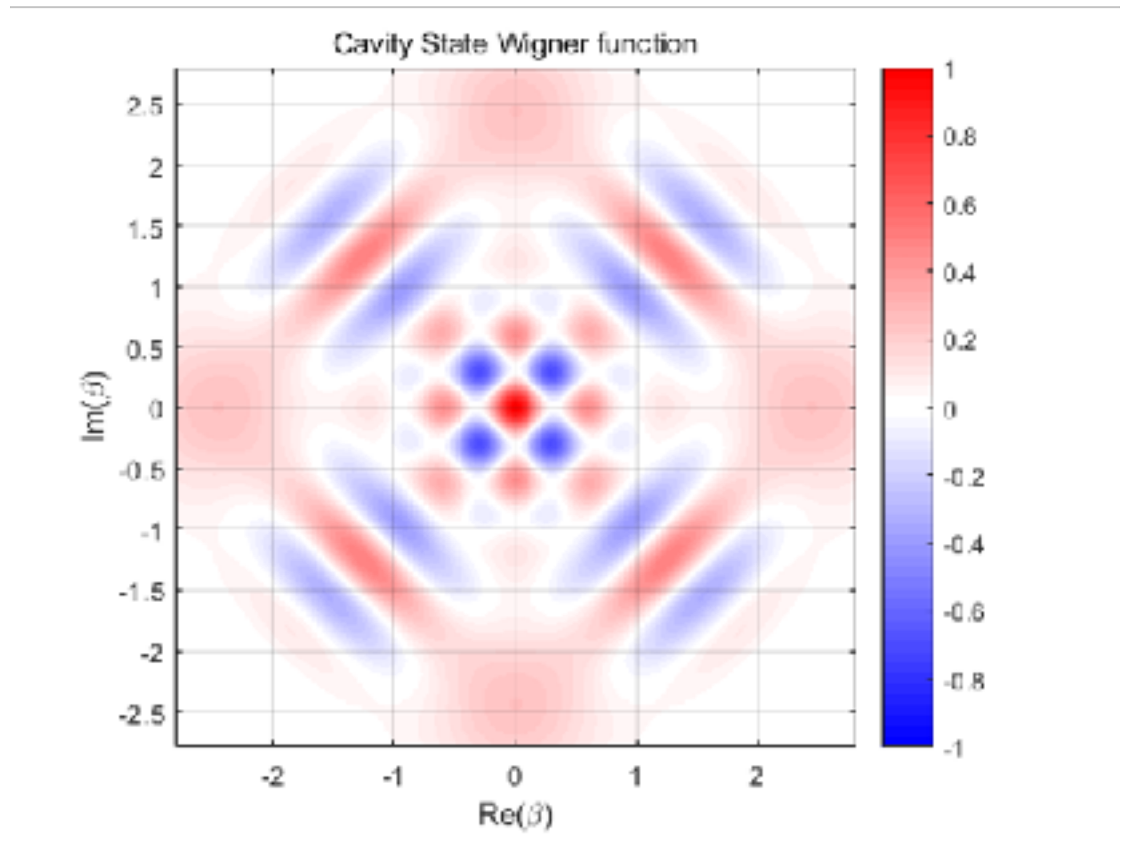
Based on accelerator SC-cavity upgrade

Nb-based quantum-sensing SC cavity
$Q = 1.62 \times 10^8$
1 order improvment

$$\left|\left\langle \phi_1 \right| \widehat{D}(\beta) \left| \phi_0 \right\rangle\right|^2 \approx |\beta|^2 |\alpha|^2$$



Single-photon readout:
non-destructive, lower quantum noise



Prepare
four-legged cat states
higher sensitivity

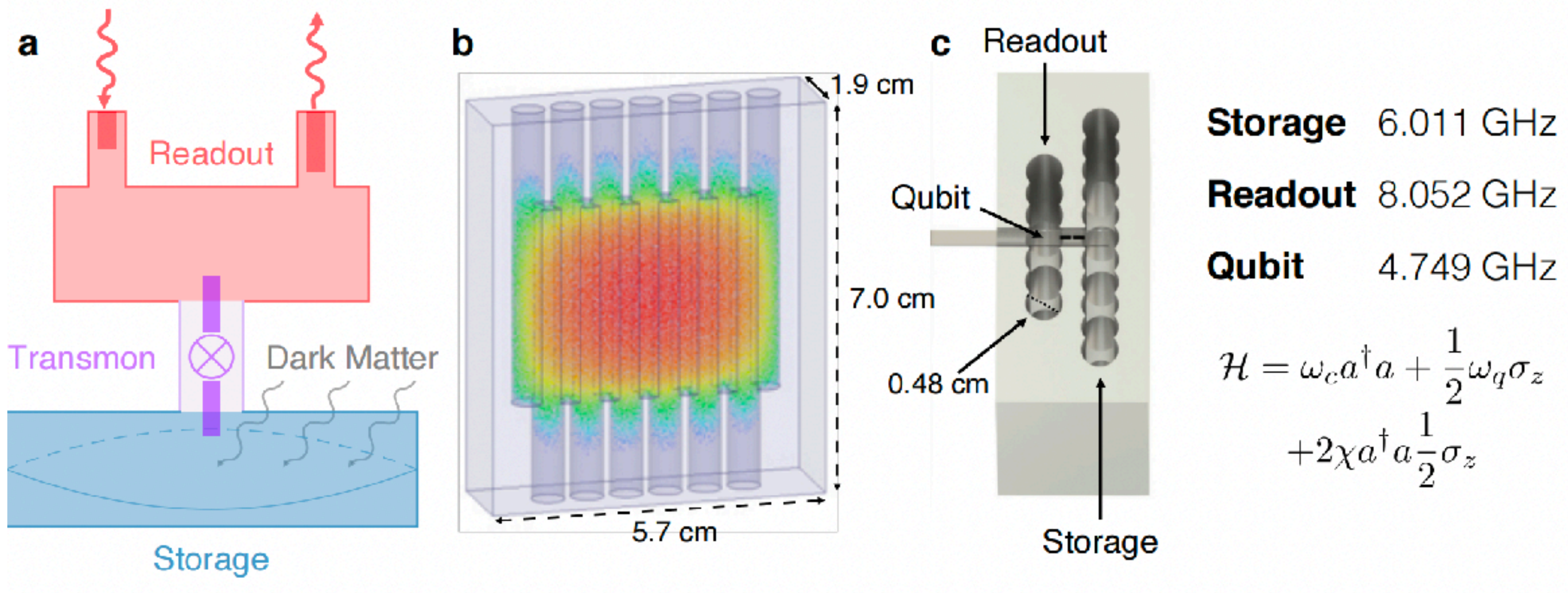
$\epsilon < 7.3 \times 10^{-16}$

Phys. Rev. Lett. 136 (2026) 17, 171002

Interdisciplinary quantum precision tech accelerates dark matter searches!

Quantum qubits measure DPDM

$U(1)_Y$



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

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

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

$U(1)_Y$

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

$\hat{D}(\beta) = e^{\beta a^\dagger - \beta^* a}$, 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

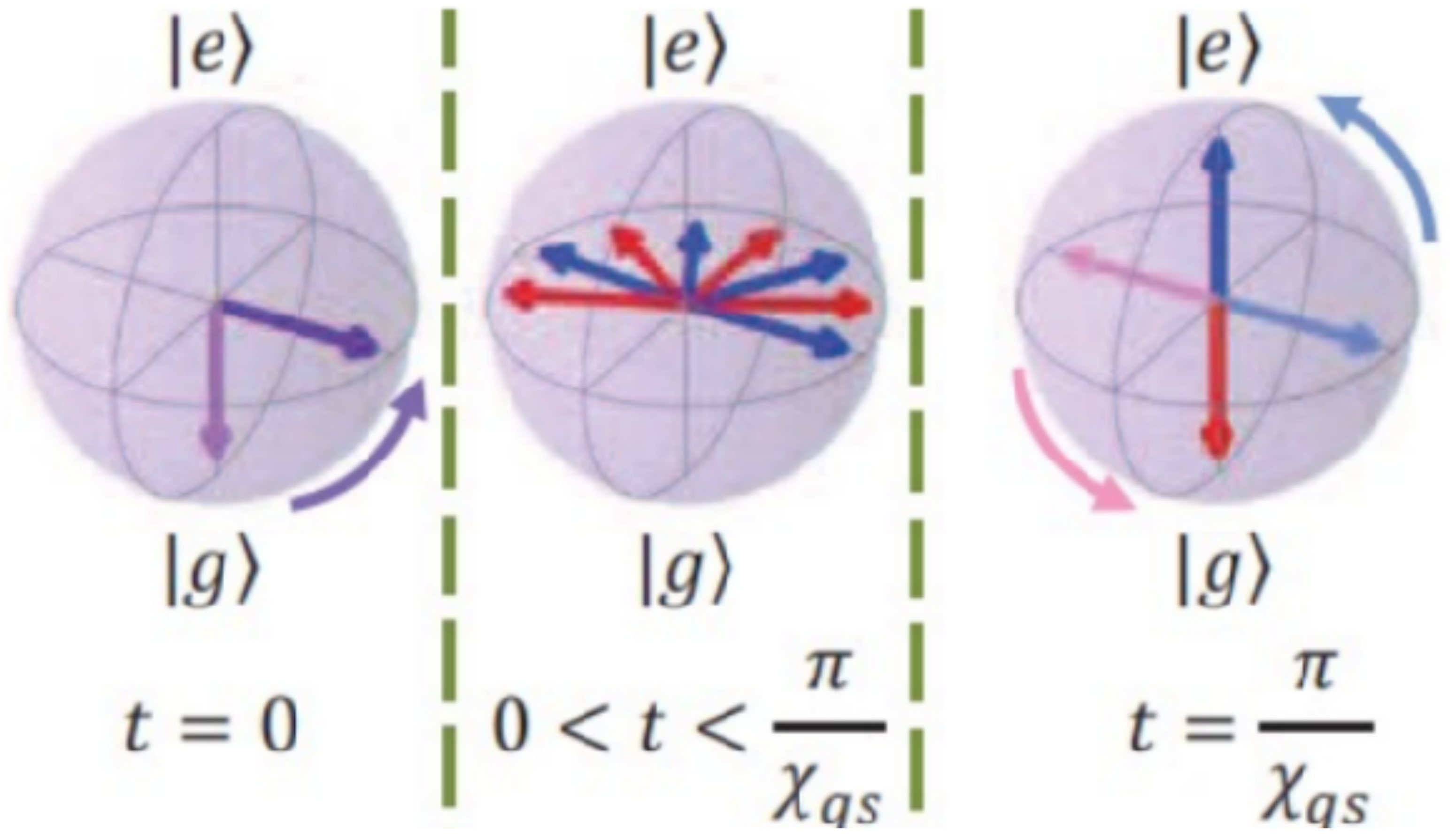
- Sensitivity mainly given by the background photon number $\bar{n}_c$

Quantum parity measurement

Ramsey interferometry in Bloch Sphere

$\frac{\pi}{2}$ pulse   Evolve π period $-\frac{\pi}{2}$ pulse

$$\frac{|g\rangle \pm |e\rangle}{\sqrt{2}}$$

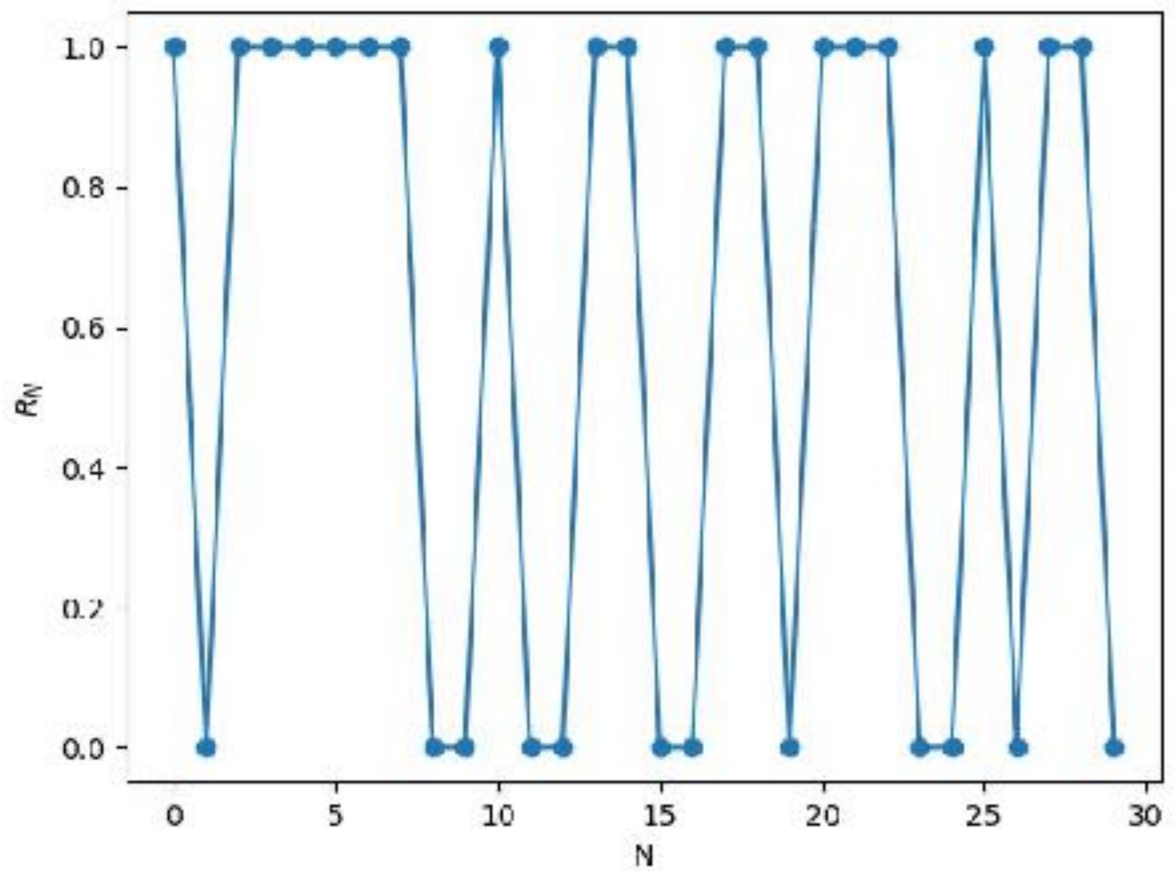


$$e^{-iH_{\rm int}t}(|g\rangle+|e\rangle)/\sqrt{2} = (e^{i\frac{n}{2}\chi t}|g\rangle+e^{-i\frac{n}{2}\chi t}|e\rangle)/\sqrt{2}$$

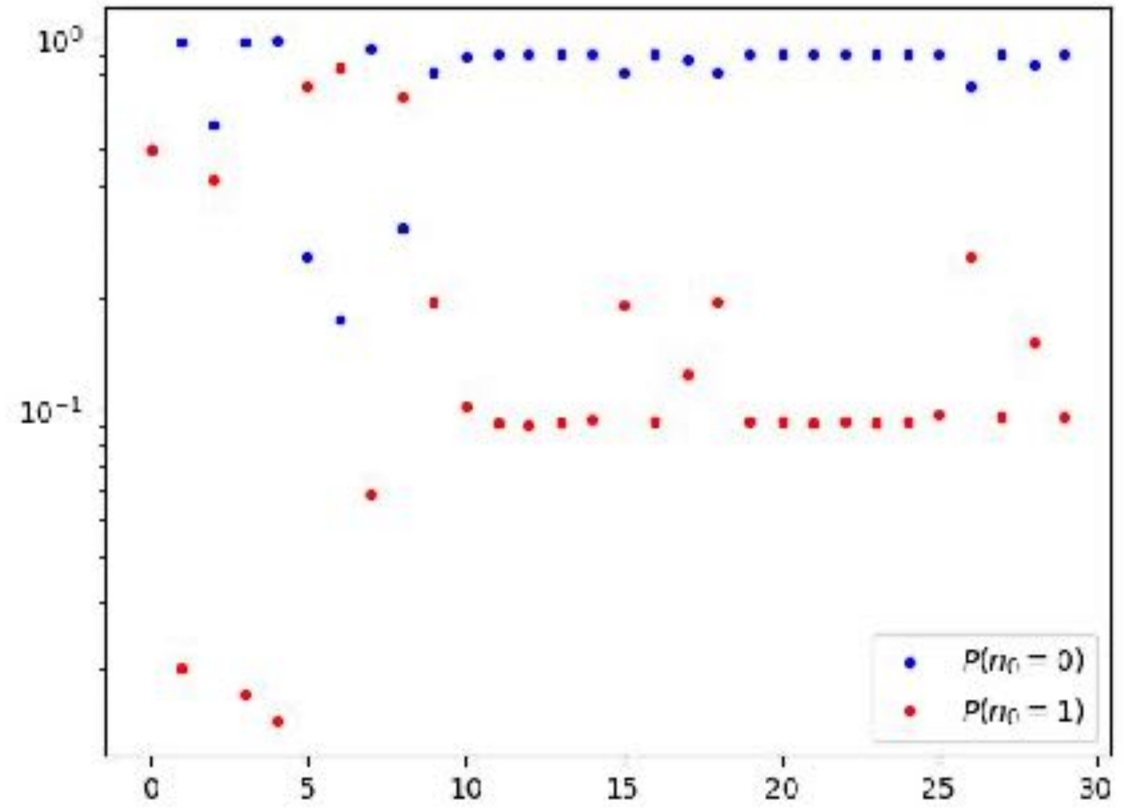
$$H_{int} = 2\chi a^\dagger a\frac{\sigma_z}{2}, \quad t = \frac{\pi}{\chi}$$

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

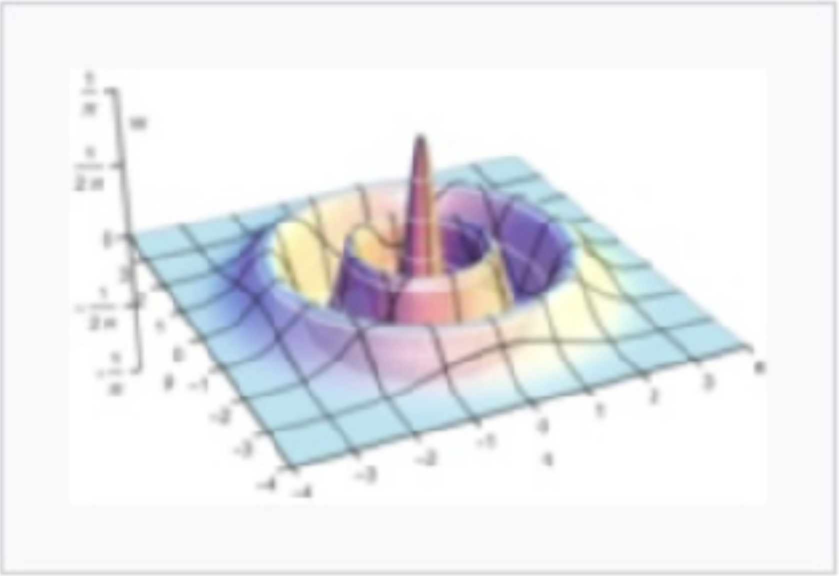


Quantum qubits measure DPDM

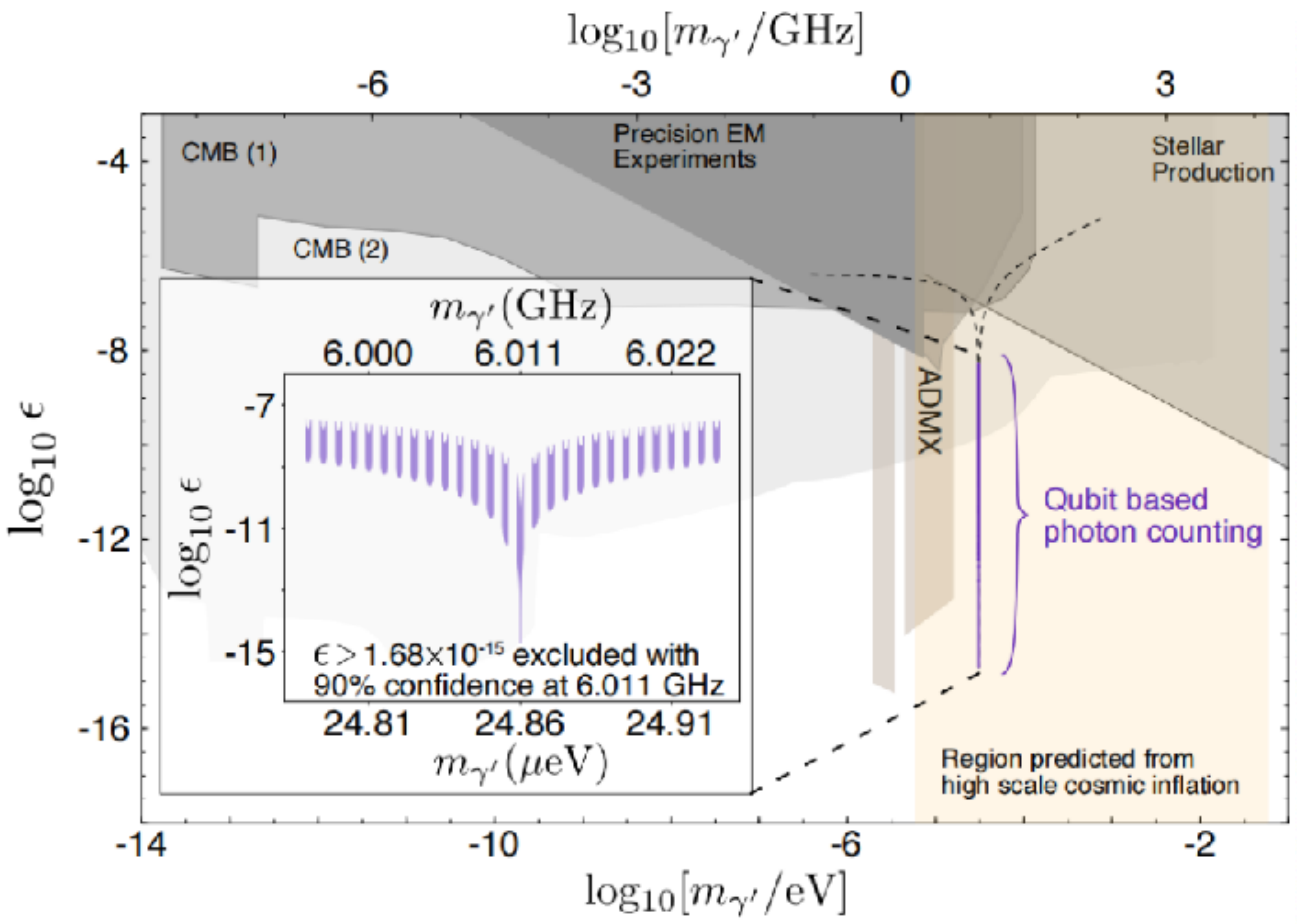
$U(1)_Y$

DPDM: Using the Vacuum state to measure

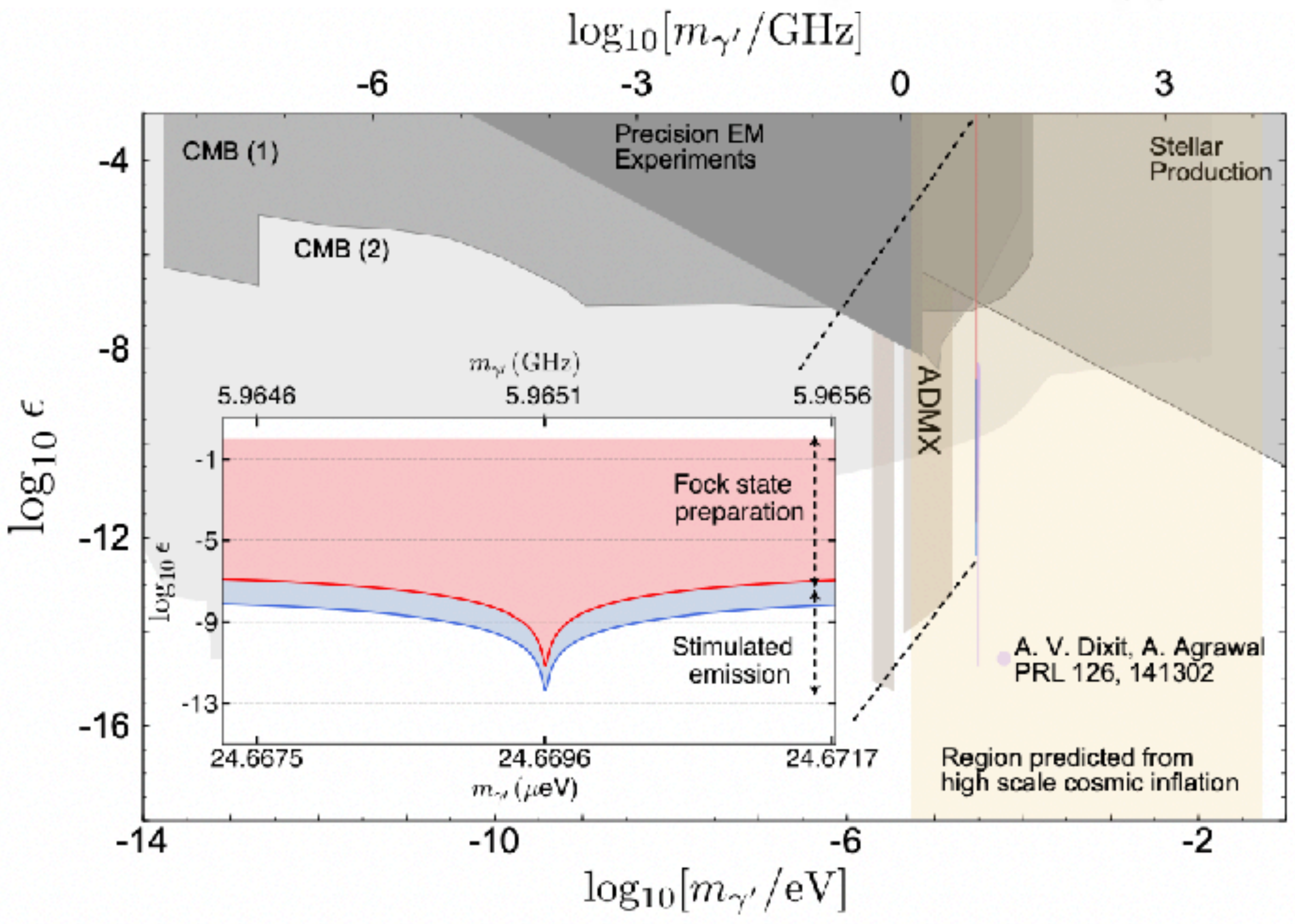
DPDM: Using the Fock state (N=4) to measure



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)

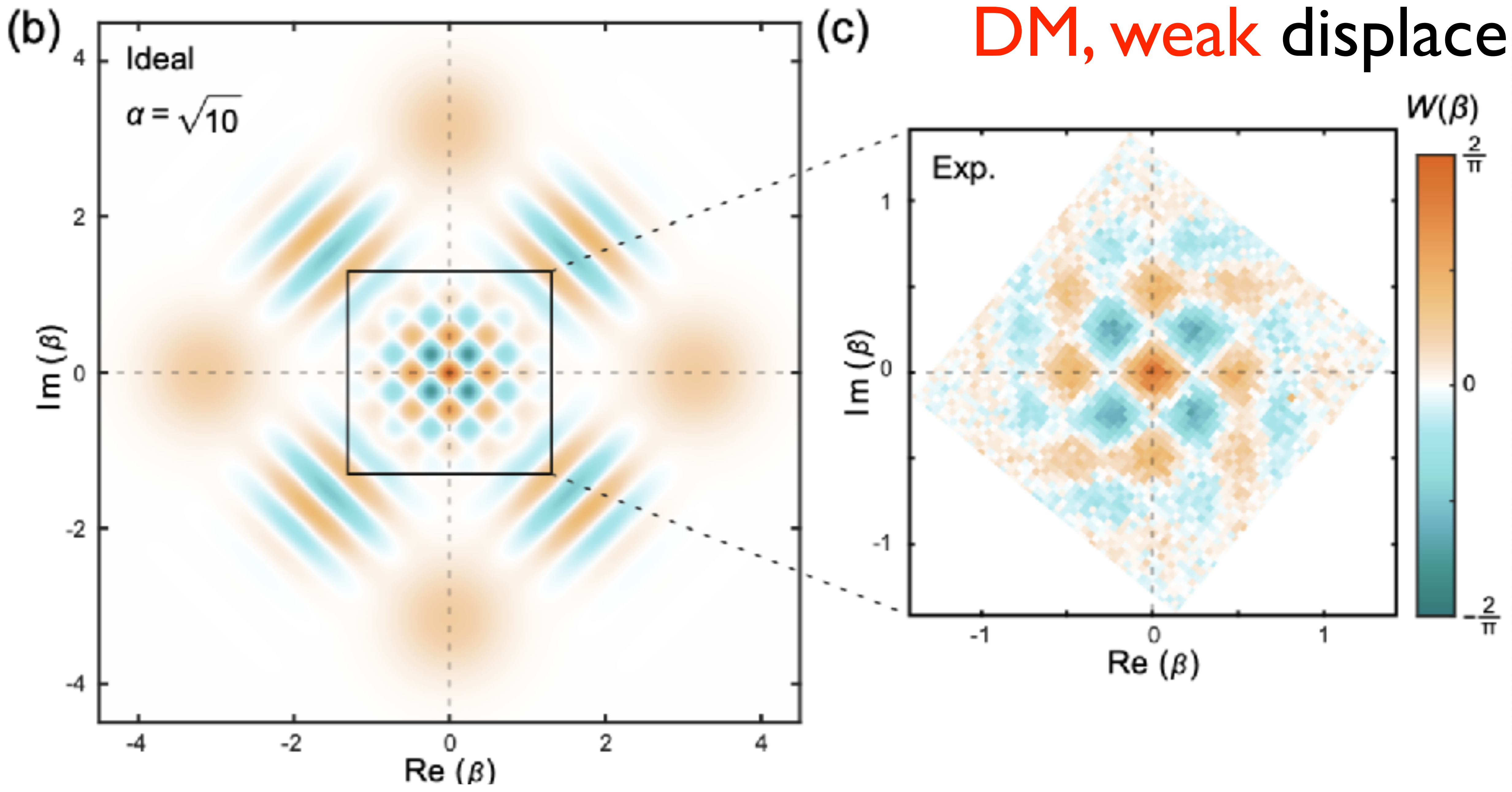
Measure DPDM using cat state

$U(1)_Y$

Here we define the 4-component cat state (compass state)

Start with: $|\phi_0(\alpha)\rangle \propto |\alpha\rangle + |-\alpha\rangle + |i\alpha\rangle + |-i\alpha\rangle$

Signal: $|\phi_1(\alpha)\rangle$ Separate Backgrounds: $|\phi_3(\alpha)\rangle$



DM, weak displacement

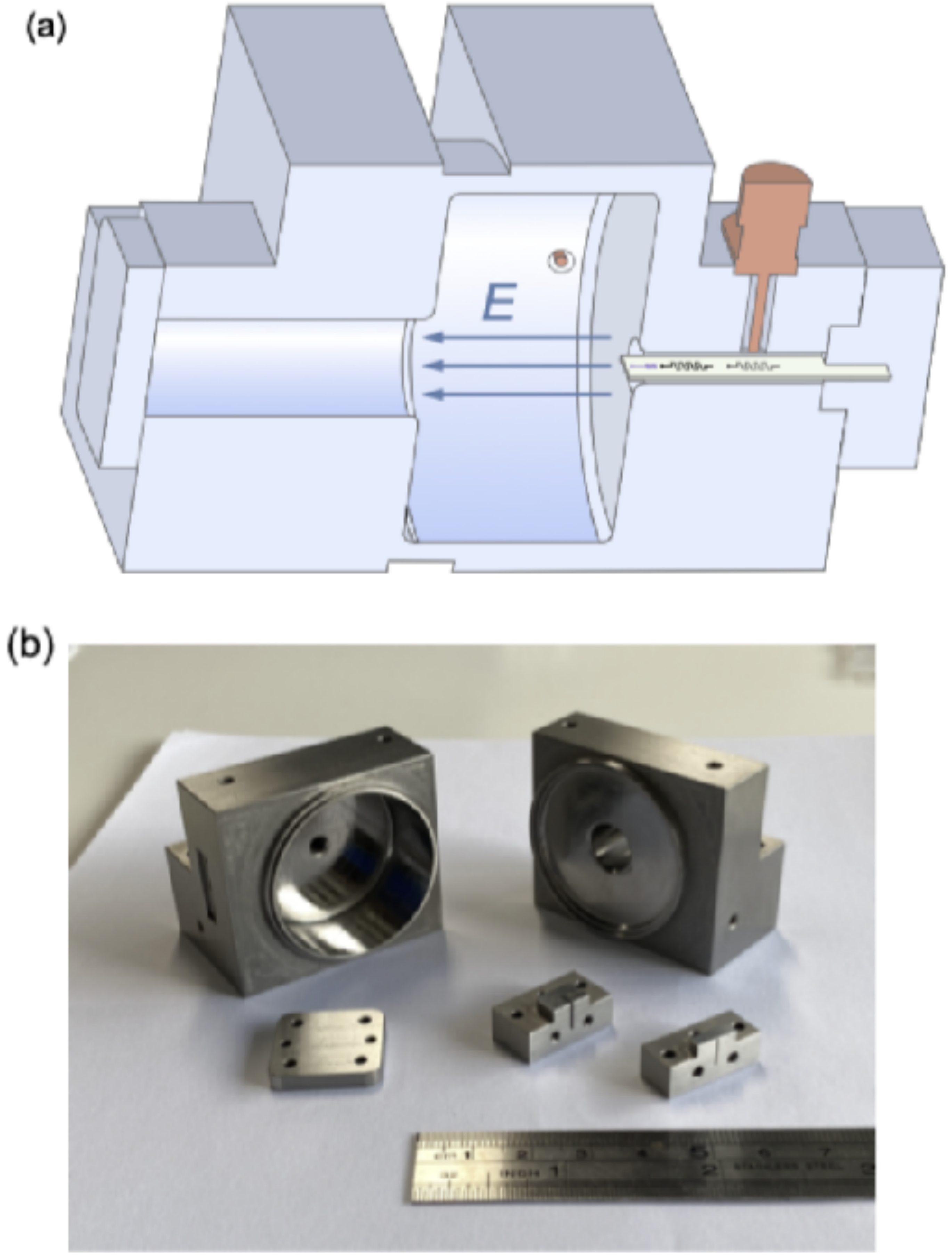
$$P_\alpha(\beta) = \left|\langle\phi_1(\alpha)|\hat{D}(\beta)|\phi_0(\alpha)\rangle\right|^2 \approx |\beta|^2|\alpha|^2,$$

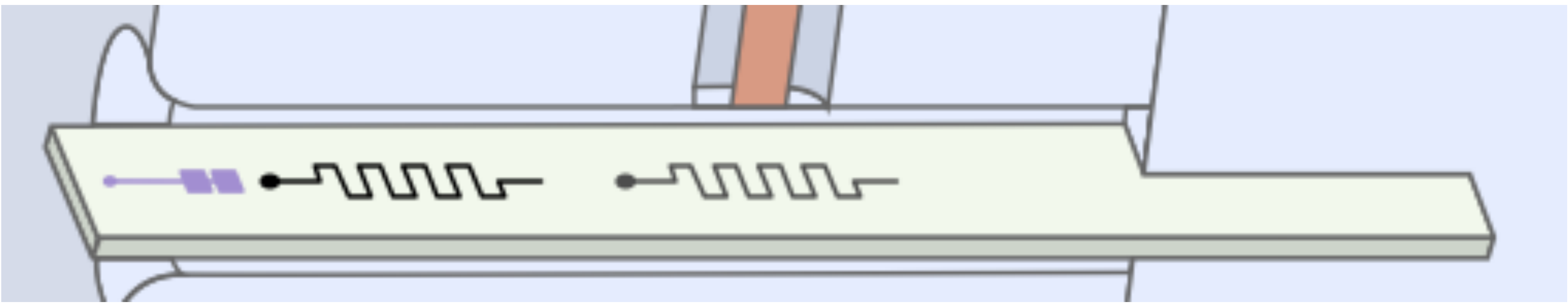
$U(1)_Y$

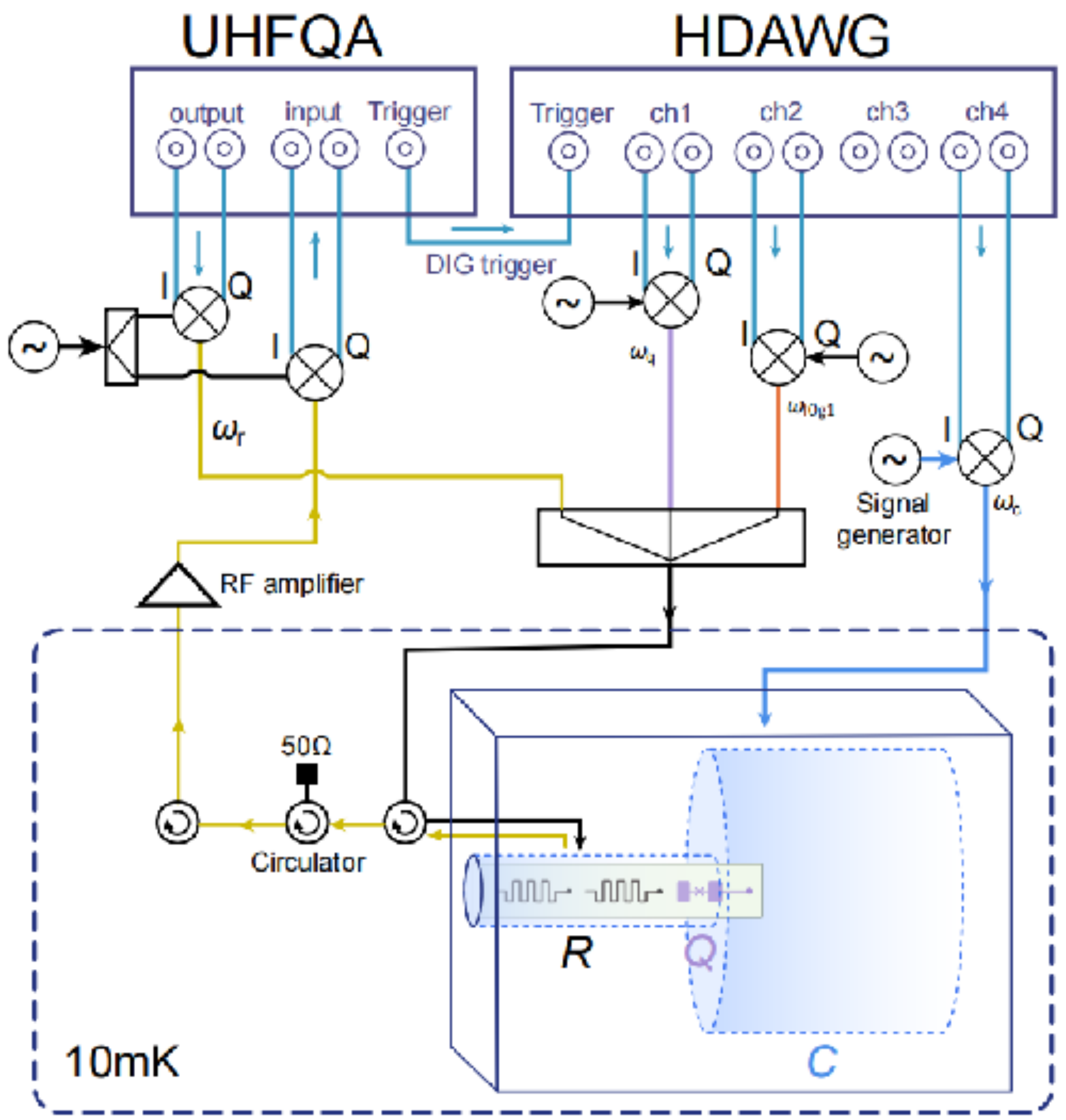
Experimental setup

We design a high-Quality superconducting cavity based on Nb

T_1 = 4.6ms, Q ~ 10^8 One order better than Al







$U(1)_Y$

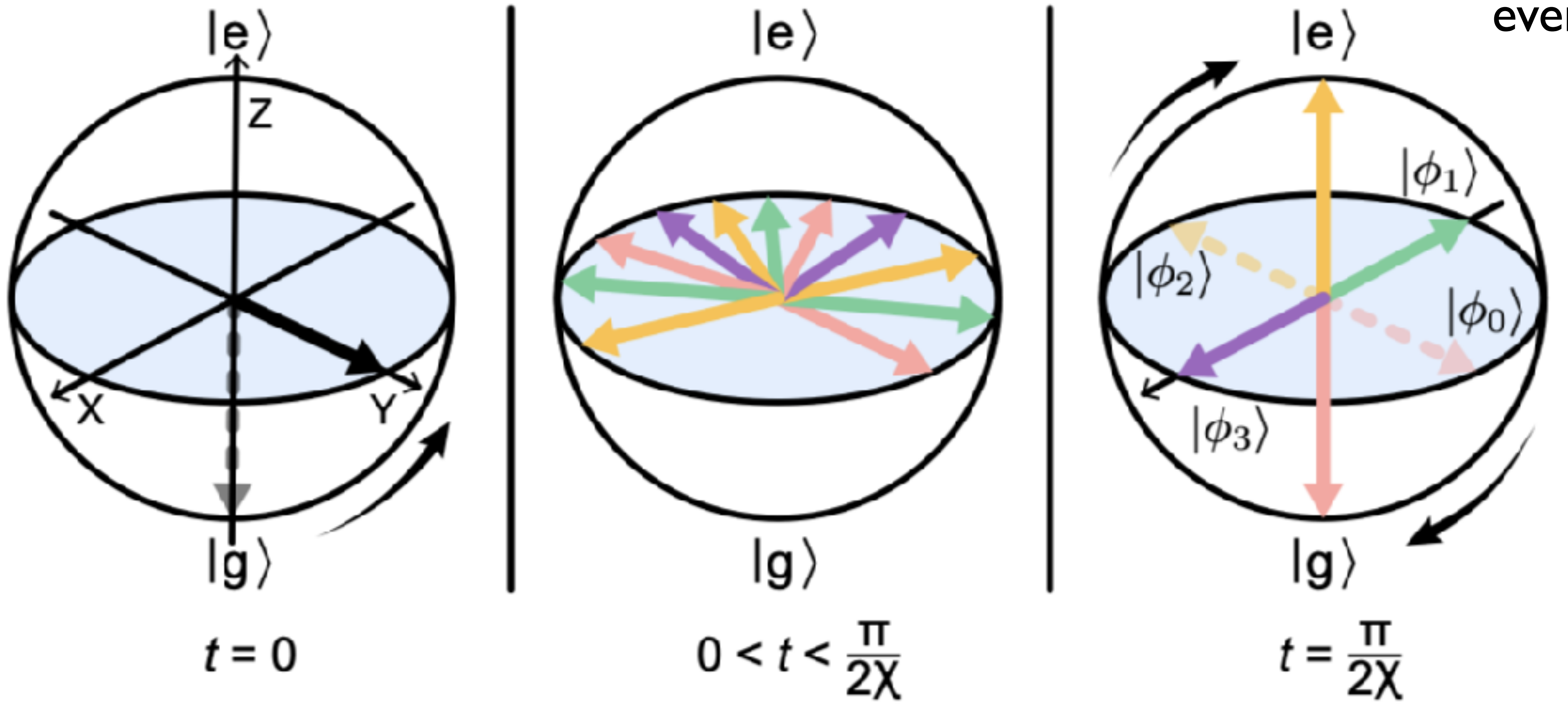
Ramsey Interferometry

The compass state has to use a 4-fold parity for the Ramsey interference

$\frac{\pi}{2}$ pulse about x-axie

Evolve $\pi/2$ period

$-\frac{\pi}{2}$ pulse about x(y)-axie for even (odd) state



1-st start the 2-fold parity as before: $|\alpha\rangle \otimes |g\rangle \rightarrow |\phi_+\rangle \otimes |g\rangle + |\phi_-\rangle \otimes |e\rangle.$

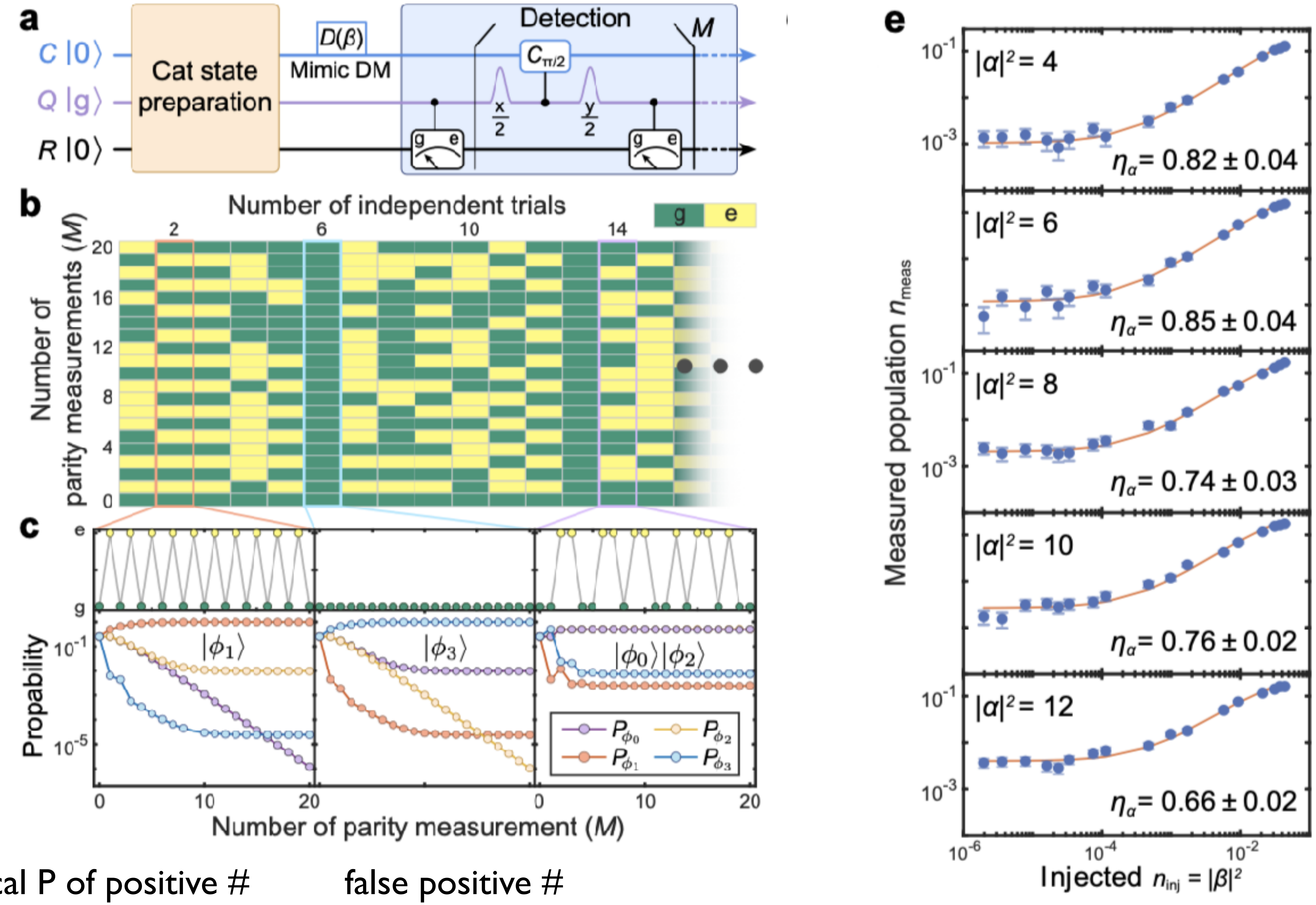
$$|\phi_+\rangle \otimes |g\rangle \rightarrow |\phi_0\rangle \otimes |g\rangle + |\phi_2\rangle \otimes |e\rangle,$$
$$|\phi_-\rangle \otimes |e\rangle \rightarrow |\phi_1\rangle \otimes |e\rangle + |\phi_3\rangle \otimes |g\rangle.$$

$-\frac{\pi}{2}$ pulse about y-axie for odd state

sequences: *alternating* for $|\phi_1\rangle$, *constant* for $|\phi_3\rangle$, and *random* the even-parity states $|\phi_0\rangle$ or $|\phi_2\rangle$.

Preparing the cat state & calibration

$U(1)_Y$



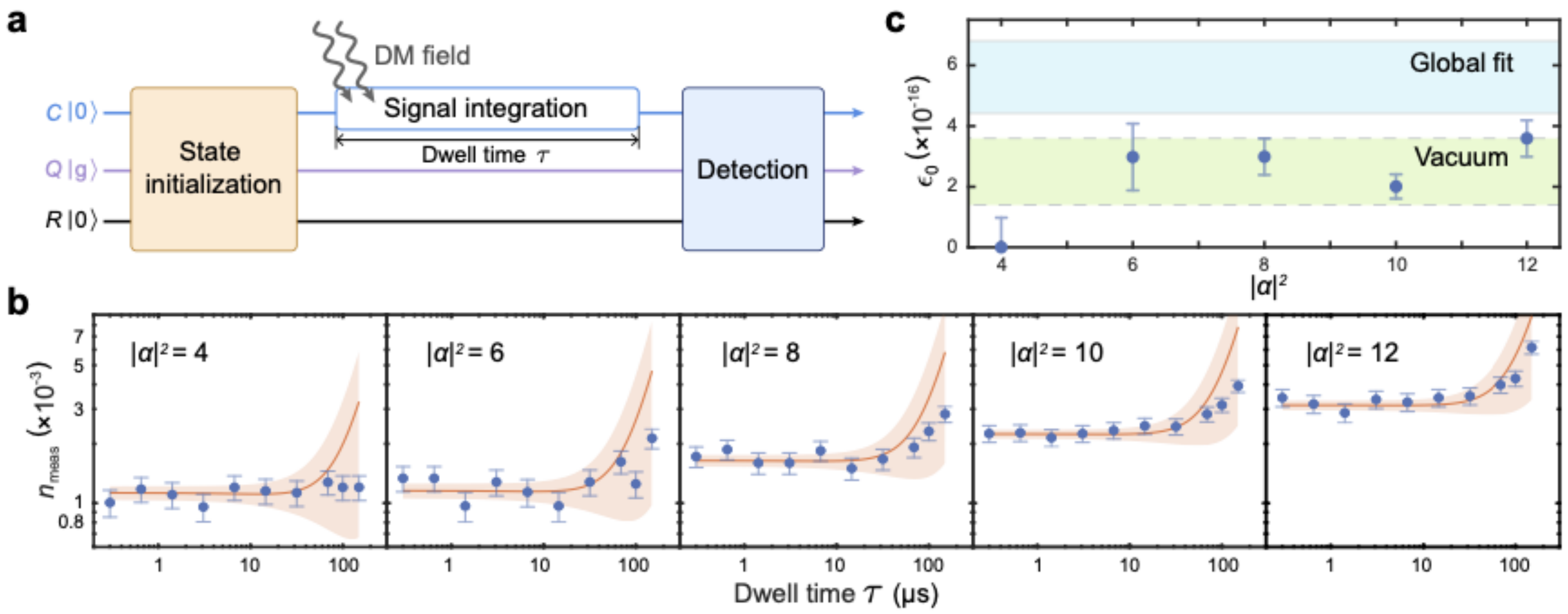
statistical P of positive # false positive #

$$n_{\text{meas}} = \eta_\alpha P_\alpha(\beta) + \delta_\alpha, \qquad P_\alpha(\beta) = |\alpha|^2 n_{\text{inj}}$$

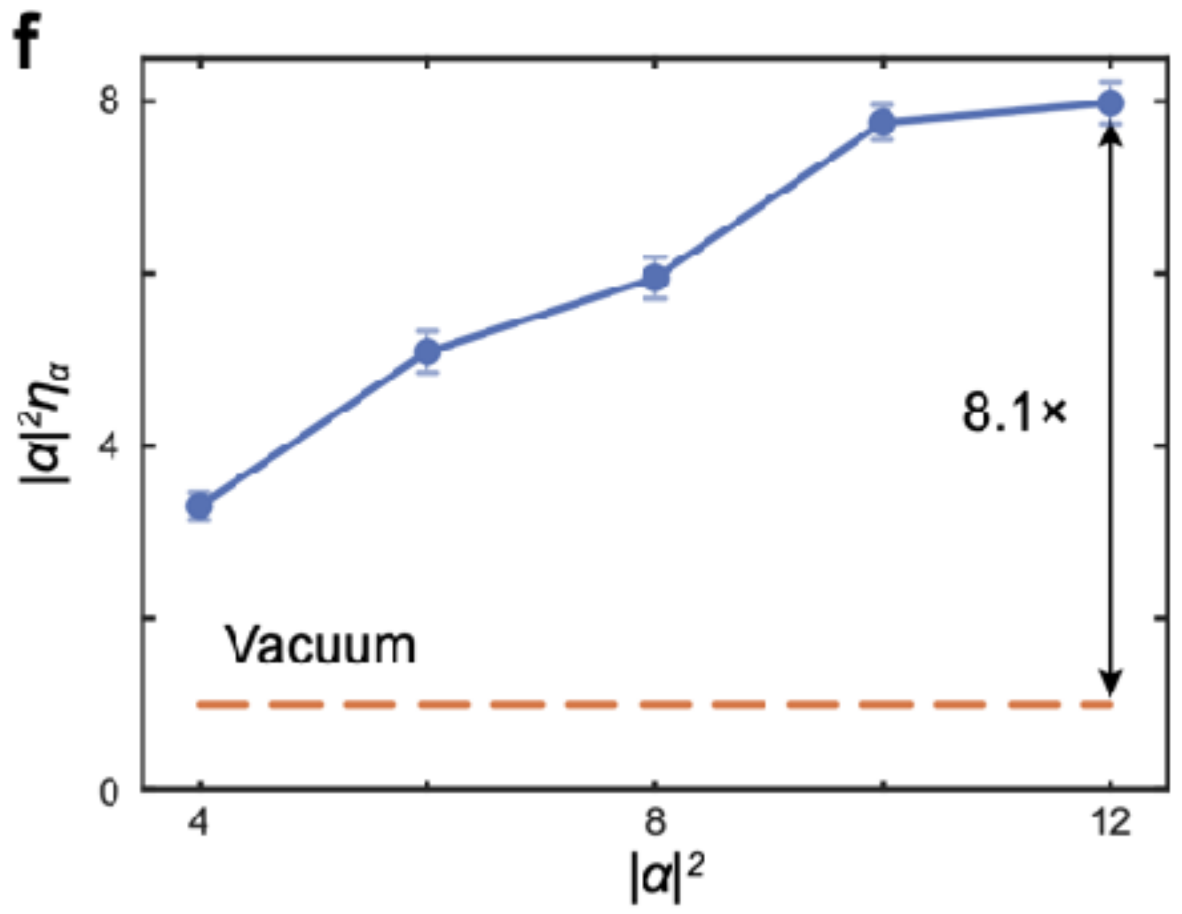
detector efficiency

DP search using cat state

$U(1)_Y$



DPDM：Using compass state get a real enhancement 8.1



DP search using cat state

$U(1)_Y$

Within the DM coherent time, the probability of positive events

$$n_{\rm meas} = a_0 \eta_\alpha |\alpha|^2 g(\tau) + b_\alpha \tau + c_\alpha .$$

$$g(t) \simeq \begin{cases} t^2 & \text{if } 0 < t < \tau_{\rm DM}, \\ \tau_{\rm DM} t & \text{if } t > \tau_{\rm DM}. \end{cases}$$

$$\tau_{\rm DM} \approx 152\,\mu\text{s}$$

$\vert\phi_0(\alpha)\rangle$	N_{trials}
$\alpha = \sqrt{4}$	40719
$\alpha = \sqrt{6}$	35129
$\alpha = \sqrt{8}$	40621
$\alpha = \sqrt{10}$	47017
$\alpha = \sqrt{12}$	28885
vacuum	81040

Fitted Parameter	Θ	σ_Θ
$a_0(\text{s}^{-2})$	3.441×10^4	2.710×10^4
$b_4(\text{s}^{-1})$	-2.759	3.324
$b_6(\text{s}^{-1})$	0.889	3.433
$b_8(\text{s}^{-1})$	3.542	3.279
$b_{10}(\text{s}^{-1})$	6.913	3.473
$b_{12}(\text{s}^{-1})$	13.215	4.073
c_4	1.130×10^{-3}	8.879×10^{-5}
c_6	1.158×10^{-3}	9.848×10^{-5}
c_8	1.645×10^{-3}	10.863×10^{-5}
c_{10}	2.244×10^{-3}	11.726×10^{-5}
c_{12}	3.142×10^{-3}	17.638×10^{-5}

$$\epsilon_0 = \sqrt{a_0/(\rho_{\rm DM} m_{\rm DM} V_{\rm eff})}$$

$$\rho_{\rm DM} m_{\rm DM} V_{\rm eff} = 1.10 \times 10^{35}\,\text{s}^{-2}.$$

$$\epsilon < 7.5 \times 10^{-16} \text{ near } 6.44\text{ GHz } (26.6\,\mu\text{eV})$$

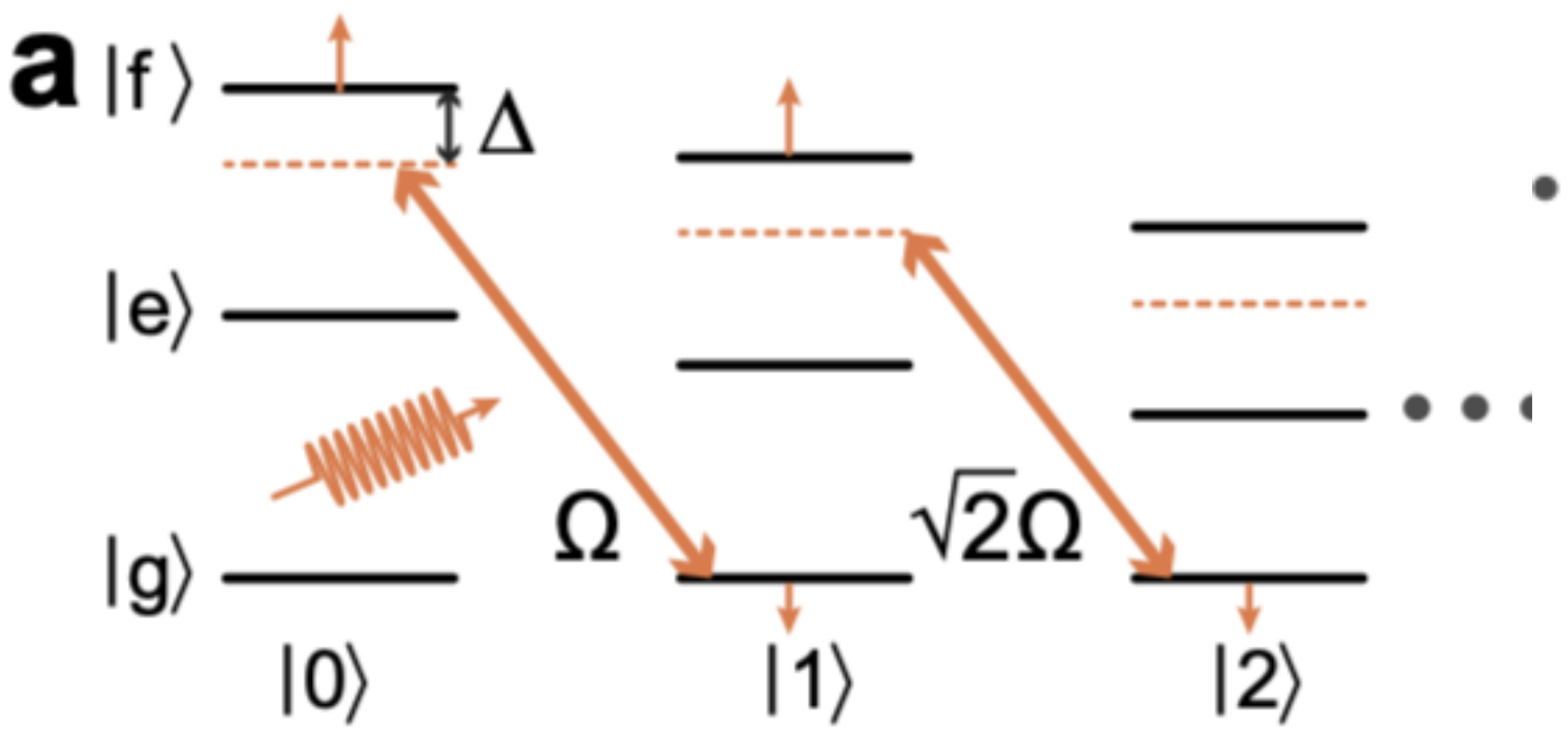
Sideband tuning

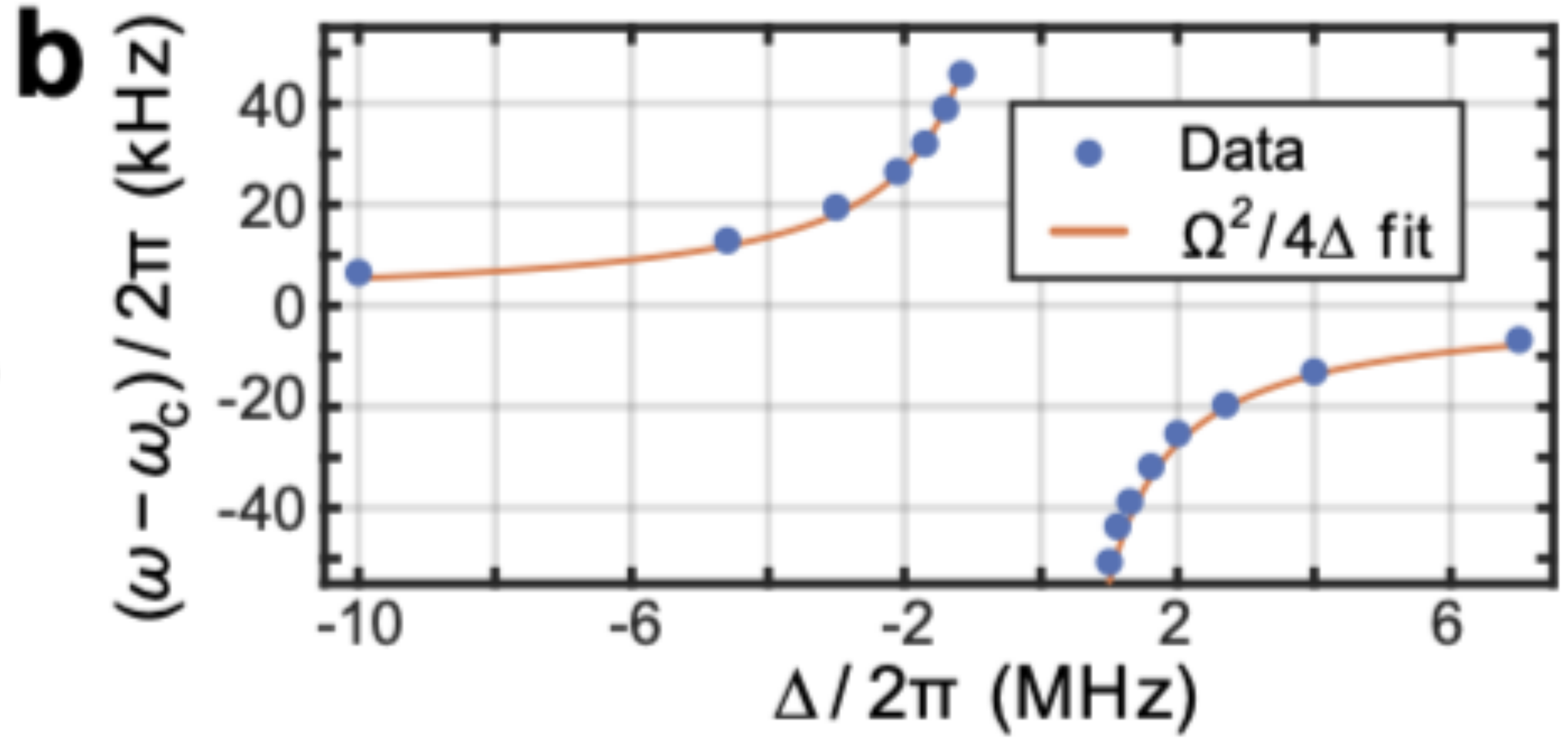
$U(1)_Y$

$$H_d = \frac{\Omega}{2} a^\dagger |g\rangle\langle f| e^{i\Delta t} + \mathrm{h.c.}.$$

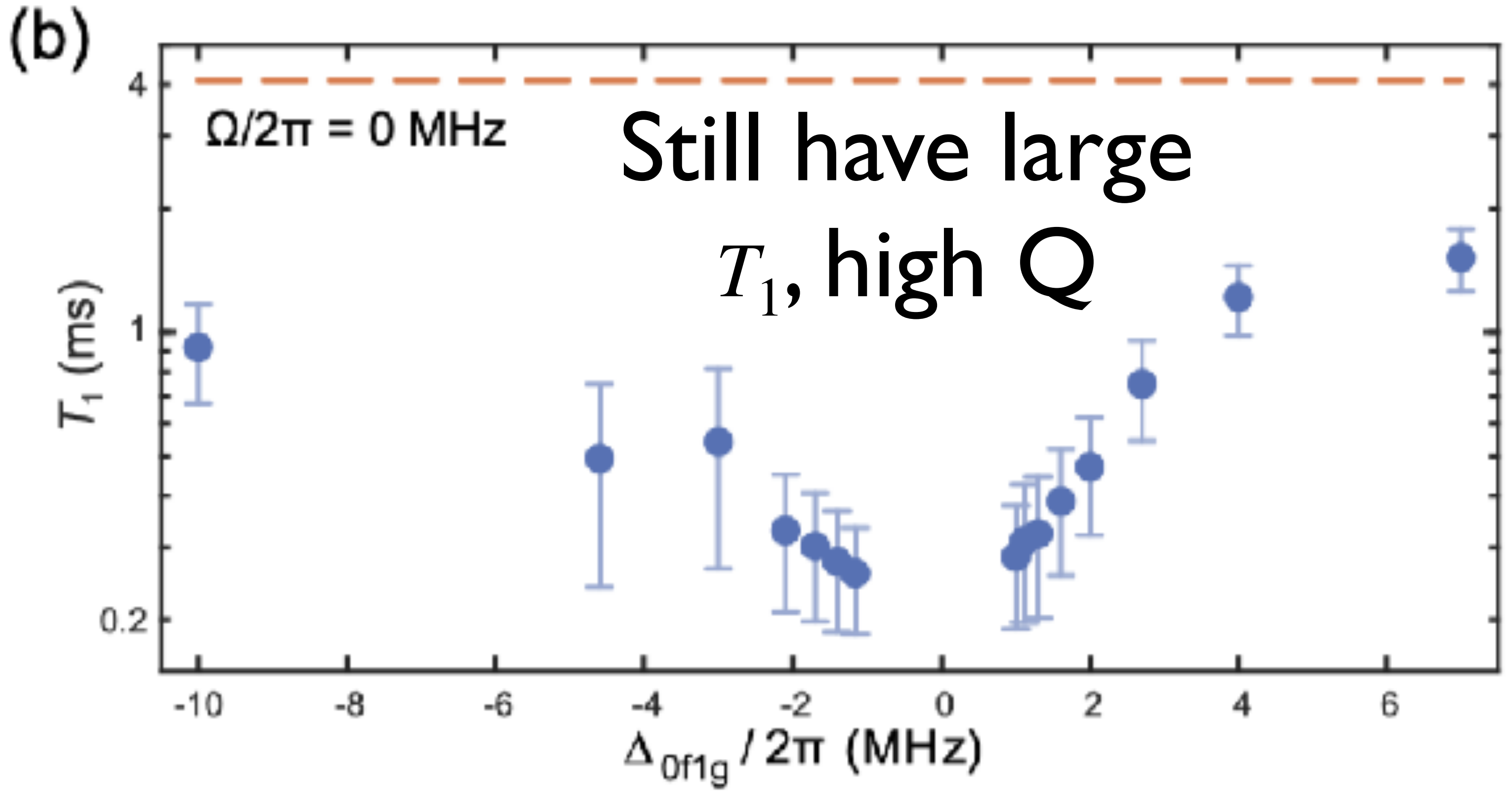
Use Δ to tune the cavity f

Couple $|n, f\rangle$ to $|n+1, g\rangle$,





Moderate tunning f for O(100) kHz



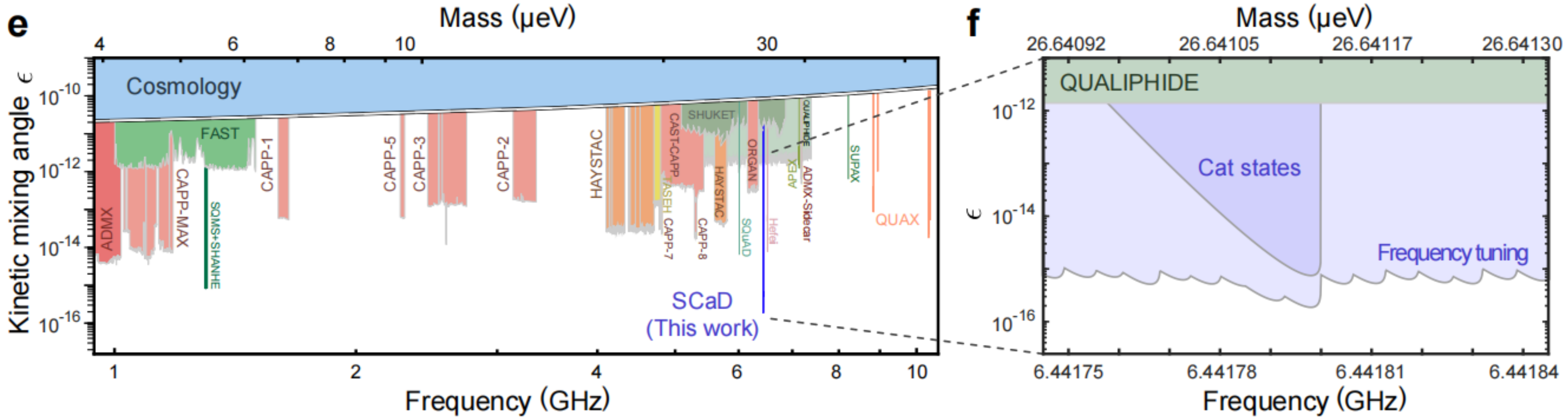
Still have large T_1, high Q

See Fang Zhao et. al, arXiv:2501.06882 [hep-ph]
for wide f tuning using flux tunable SQUID

Measure DPDM using cat state

$U(1)_Y$

Finally we achieve 10^{-16} sensitivity for 6.43 GHz

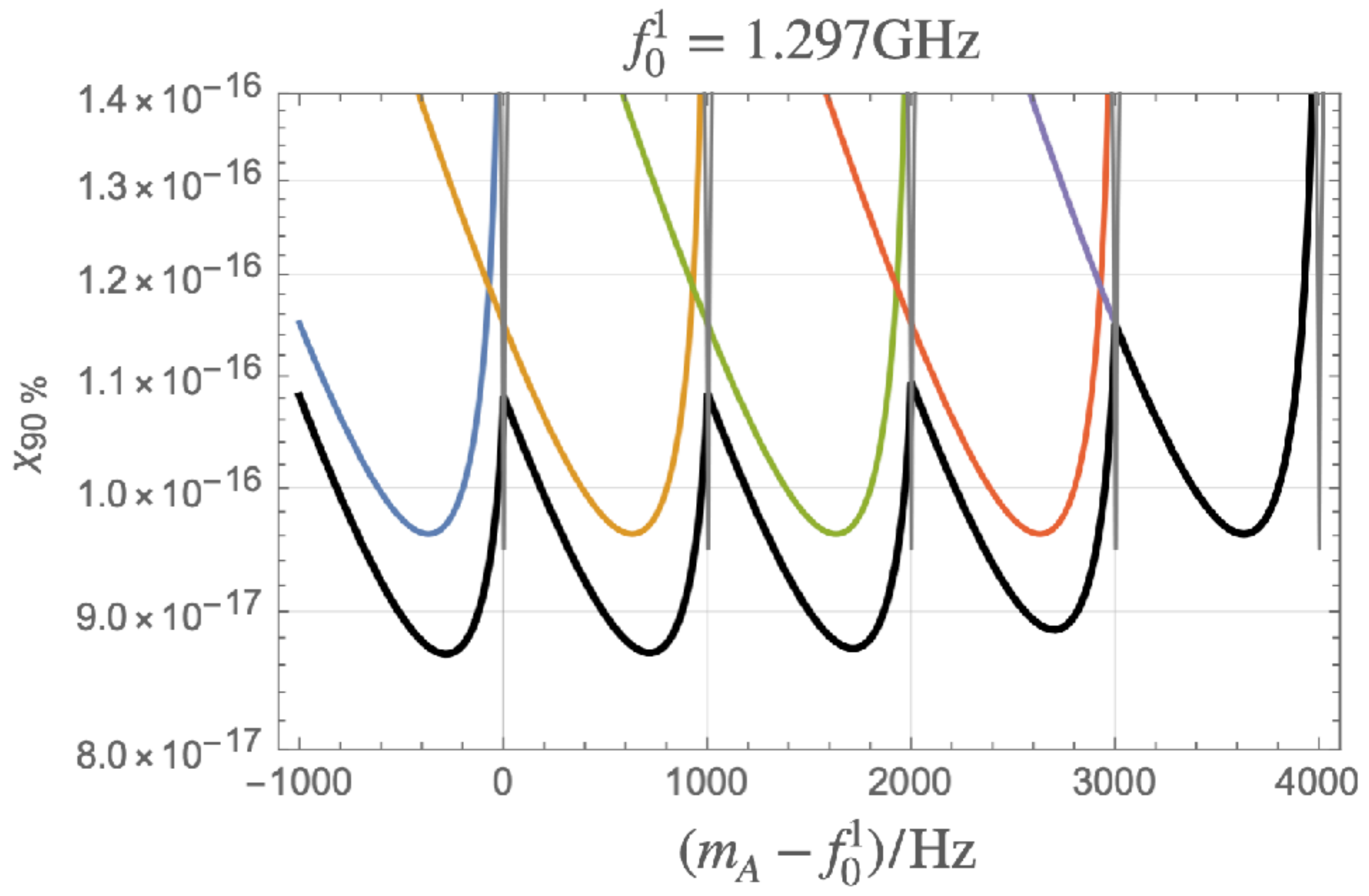


Phys. Rev. Lett. 136 (2026) 17, 171002

“Simultaneous resonant and broadband” detection

Research I: Coupled Multimode Resonators Break Narrow-Band Limits

- Key challenge: the sensitivity-bandwidth trade-off in wave-like dark matter searches.



Longer efold time gives higher sensitivity but narrower bandwidth

Superconducting cavities: ultra-high sensitivity; must cover broader frequency ranges

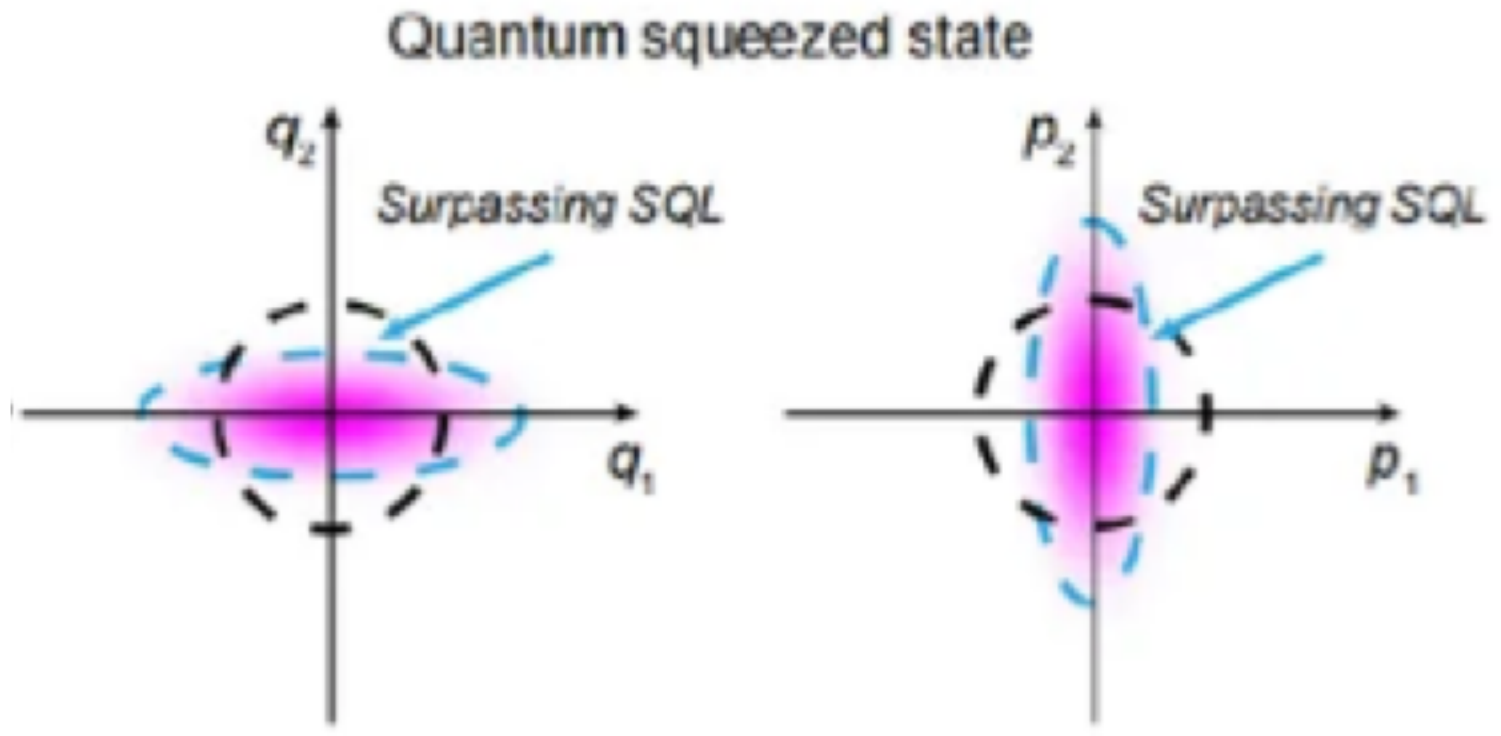
$\epsilon < 2.2\times10^{-16}$ 1.3 GHz Phys.Rev.Lett. (2024)

$\epsilon < 7.3\times10^{-16}$ 6.5 GHz Phys.Rev.Lett. (2026)

World-leading sensitivity

SQL: quantum uncertainty bounds scan rate × sensitivity in conventional scans.

Squeezing can surpass SQL: O(1)



HAYSTAC: ~1.9× sensitivity gain

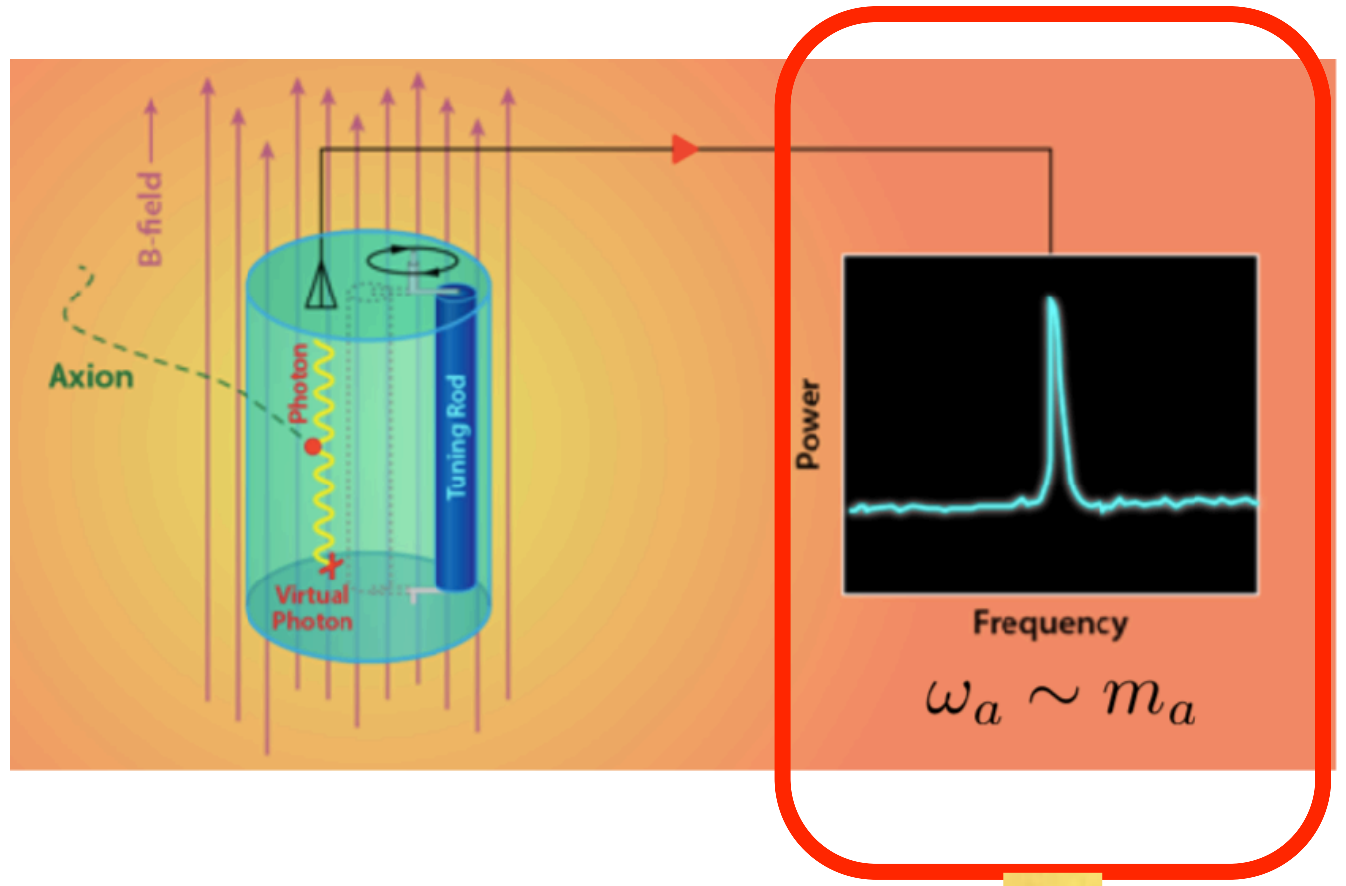
K. M. Backes, D. A. Palken, S. Al Kenany, et al., Nature 590 238-242 (2021)

LIGO: 15-18% sensitivity gain

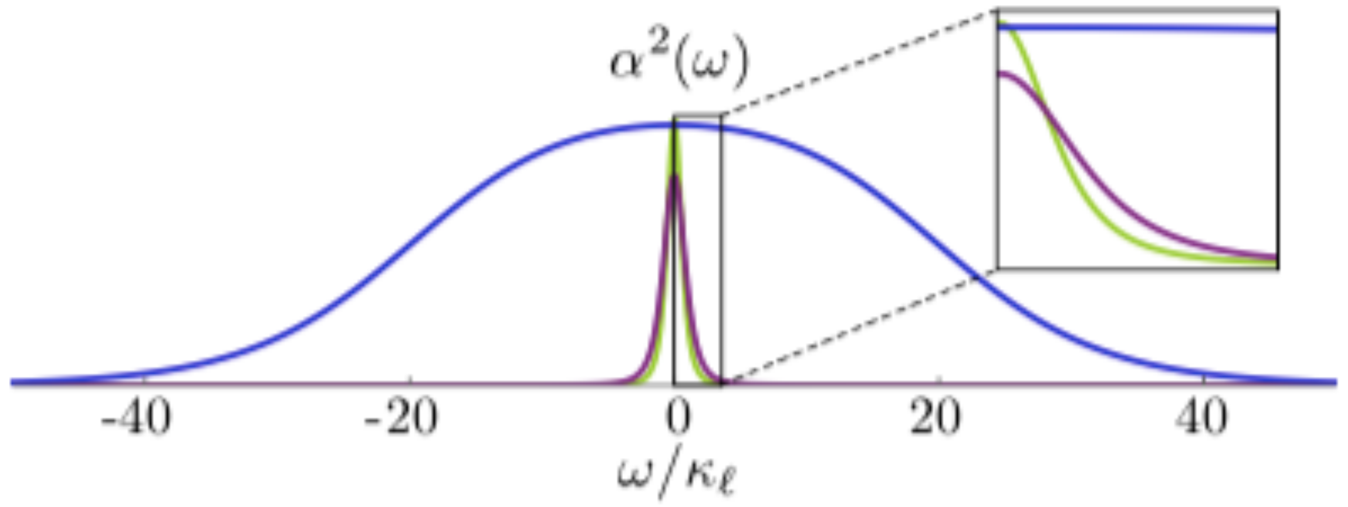
LIGO Collaboration, D. Ganapathy et al, Phys.Rev.X 13 (2023) 4, 041021

Need much higher scan-rate efficiency at fixed sensitivity

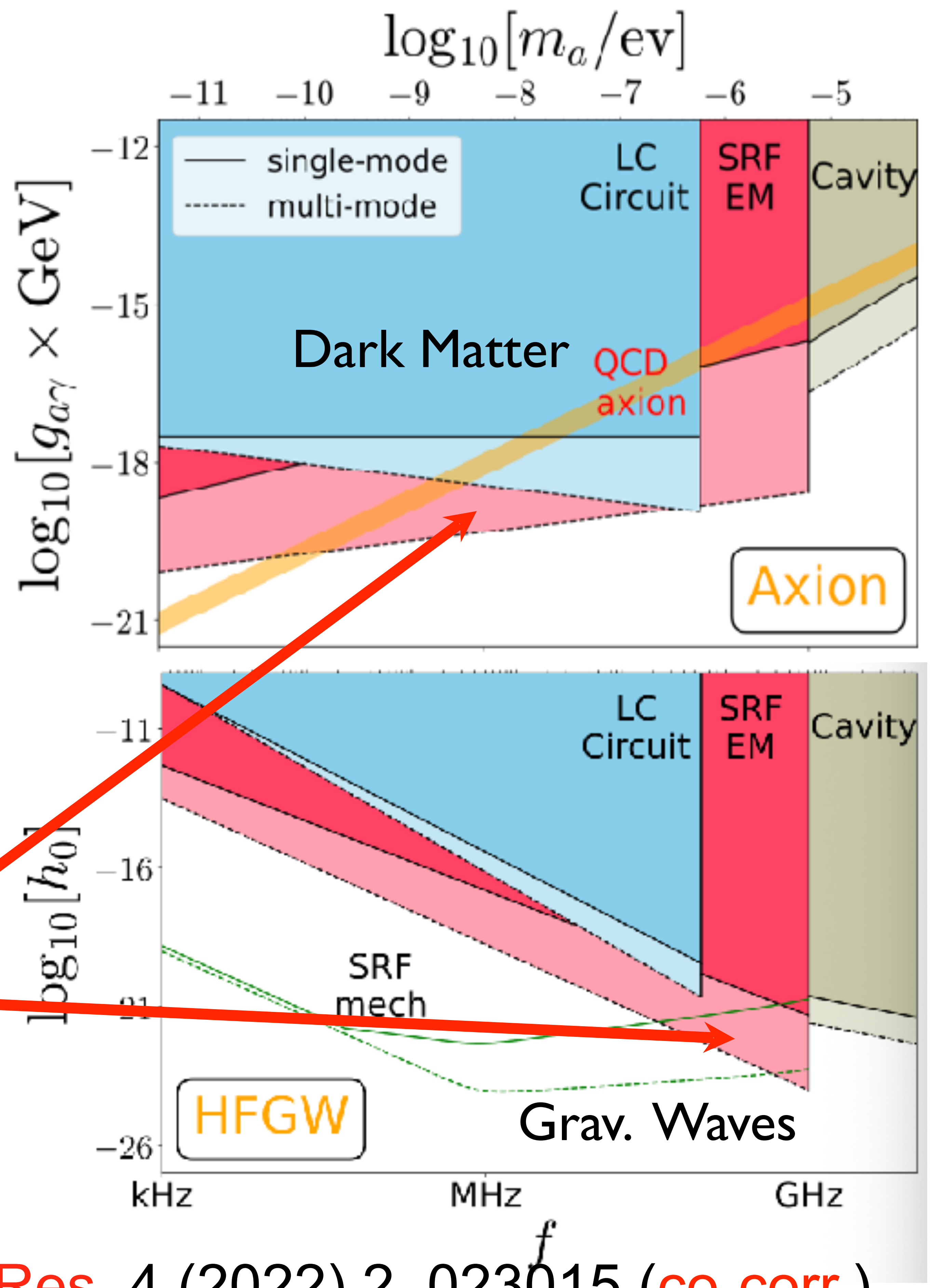
Key Result: Quantum Enhancement Broadens Resonant Scans



Readout upgrade,
broadband scan



- Engineered multimode coupling in cavities and LC circuits boosts scan efficiency
- Surpasses the standard quantum limit of conventional detectors.
- Same run time: 100-1000x higher sensitivity (light dashed lines)



Phys.Rev.Res. 4 (2022) 2, 023015 (co-corr.)

Rept.Prog.Phys. 88 (2025) 5, 057601 (co-corr.)

Interdisciplinary quantum precision tech accelerates dark matter searches!

Media Comment

Physics World featured our quantum multimode approach
for broadening resonant-detector bandwidth.

RESEARCH HIGHLIGHT

Searching for dark matter particles

15 Oct 2025 Paul Mabey

A research team from China and Denmark have proposed a new, far more efficient, method of detecting ultralight dark matter particles in the lab

Our method is novel
and far more efficient

physicsworld

Their method allows us to search for these elusive dark matter particles in a faster, more efficient way.

Our proposed dark-matter search
method is fast and effective

Research Innovation

- Novel idea: multimode coupling boosts bandwidth

Phys.Rev.Res. 4 (2022) 2, 023015

Same principle for any resonator

$$v_r(\Omega) \sim \frac{1}{\Omega + i\gamma_r} \boxed{\left(\frac{g}{\Omega}\right)^n}$$

readout coupling term

$$\boxed{\frac{\Delta\Omega_{\mathrm{PT}}}{\Delta\Omega_{\mathrm{cavity}}} \sim \frac{g}{\gamma}}$$

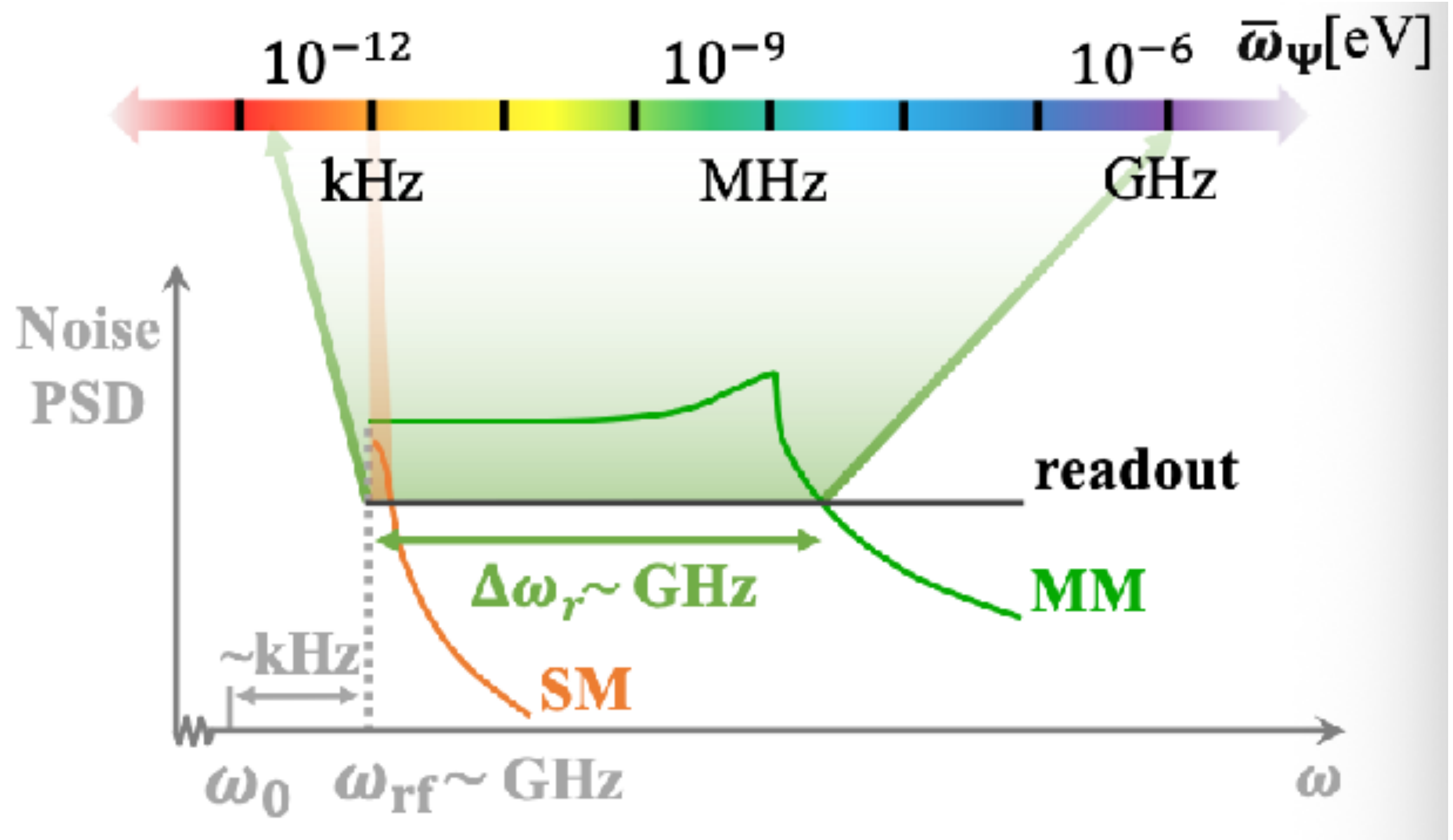
$$\Omega \equiv \omega - \omega_{\mathrm{rf}}$$

Bandwidth depends only on readout coupling g, not on cavity broadening γ (signal unchanged)

Proposed binary-tree: tolerance-robust, scalable

Bandwidth: boost kHz to GHz

(up to 10^6-fold)

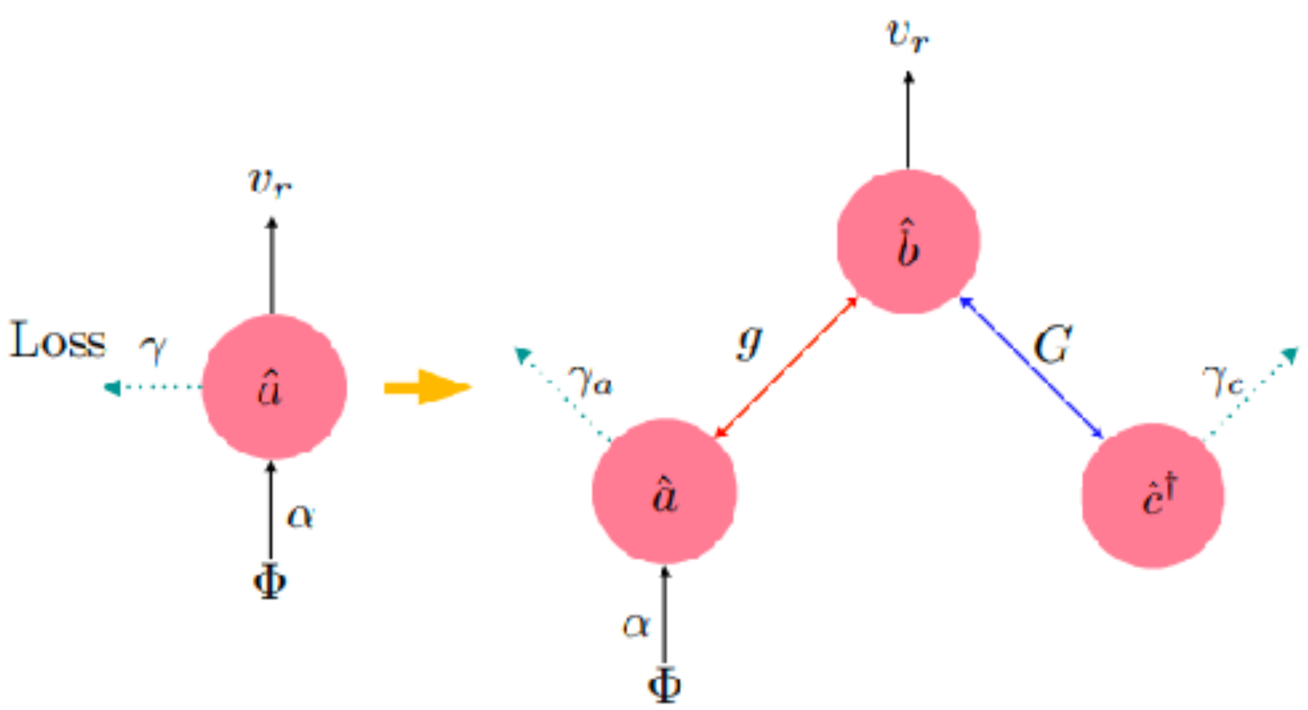


Rept.Prog.Phys. 88 (2025) 5, 057601

HAYSTAC: similar single-mode prototype, ~5.6x sensitivity gain

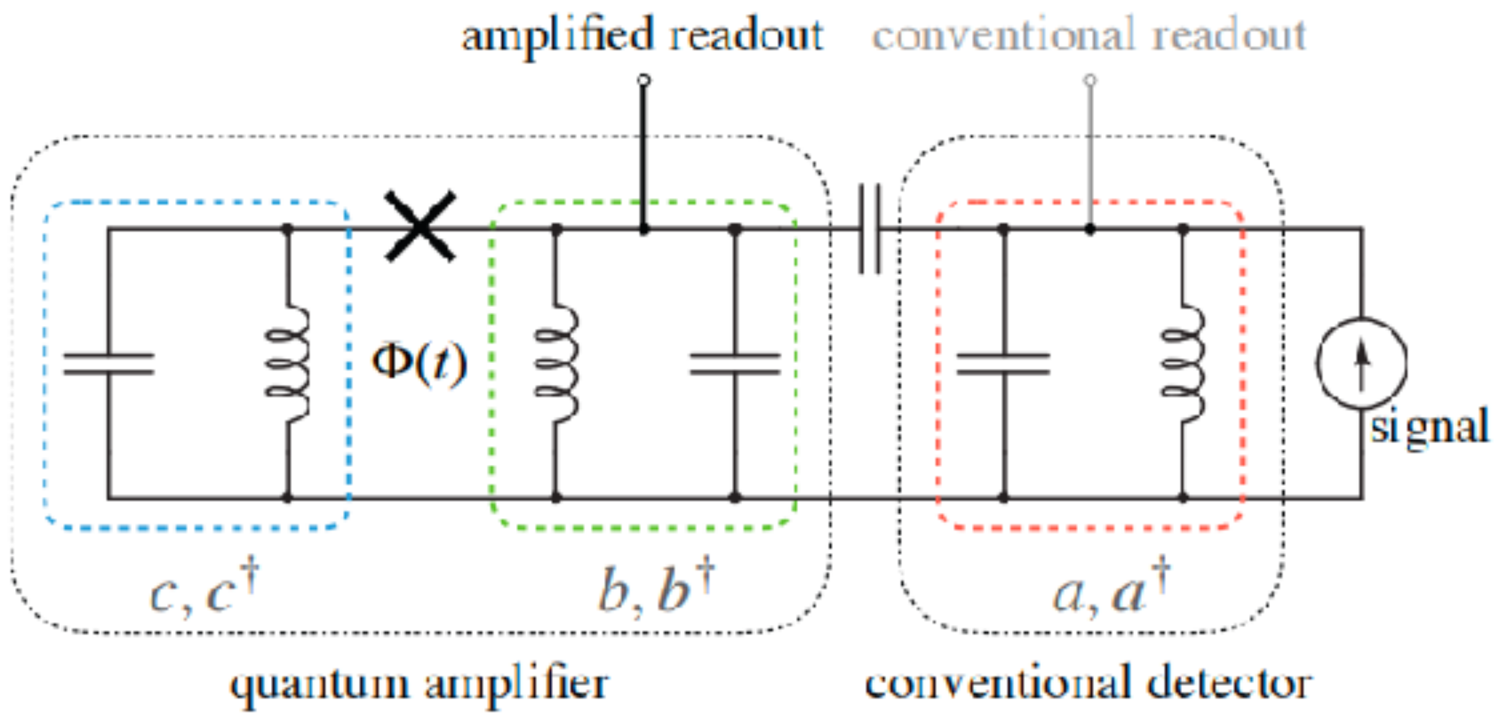
Y. Jiang, et.al, PRX Quantum 4 (2023) 2, 020302

Chain and Binary tree



Single Cavity Design

Detector Design with $\mathcal{PT}$ symmetry



Probing mode: $\hbar\alpha(\hat{a}+\hat{a}^\dagger)\Psi$

- **Beam-splitting**: $\hbar g(\hat{a}\hat{b}^\dagger + \hat{a}^\dagger\hat{b})$.
- **Non-degenerate parametric interaction**: $\hbar G(\hat{b}\hat{c} + \hat{b}^\dagger\hat{c}^\dagger)$.
- **$\mathcal{PT}$-symmetry ($\hat{a} \leftrightarrow \hat{c}^\dagger$)** emerges when $g = G$.

$$\begin{aligned} (\dot{\hat{a}} + \dot{\hat{c}}^\dagger) &= -i(g-G)\hat{b} - i\alpha\Psi + \cdots ; \\ \dot{\hat{b}} &= -\gamma_r\hat{b} - ig(\hat{a}+\hat{c}^\dagger) + \cdots . \end{aligned}$$

- **Double resonance** when $g \gg$ **intrinsic dissipation** γ:

$$S_{\rm sig}^{\rm WLC}(\Omega) = \frac{2\gamma_r\alpha^2 S_\Psi(\Omega)}{(\gamma+\gamma_r)^2+\Omega^2}\left(\frac{g^2}{\gamma^2+\Omega^2}\right).$$

Readout coupling γ_r

Multi-mode resonators

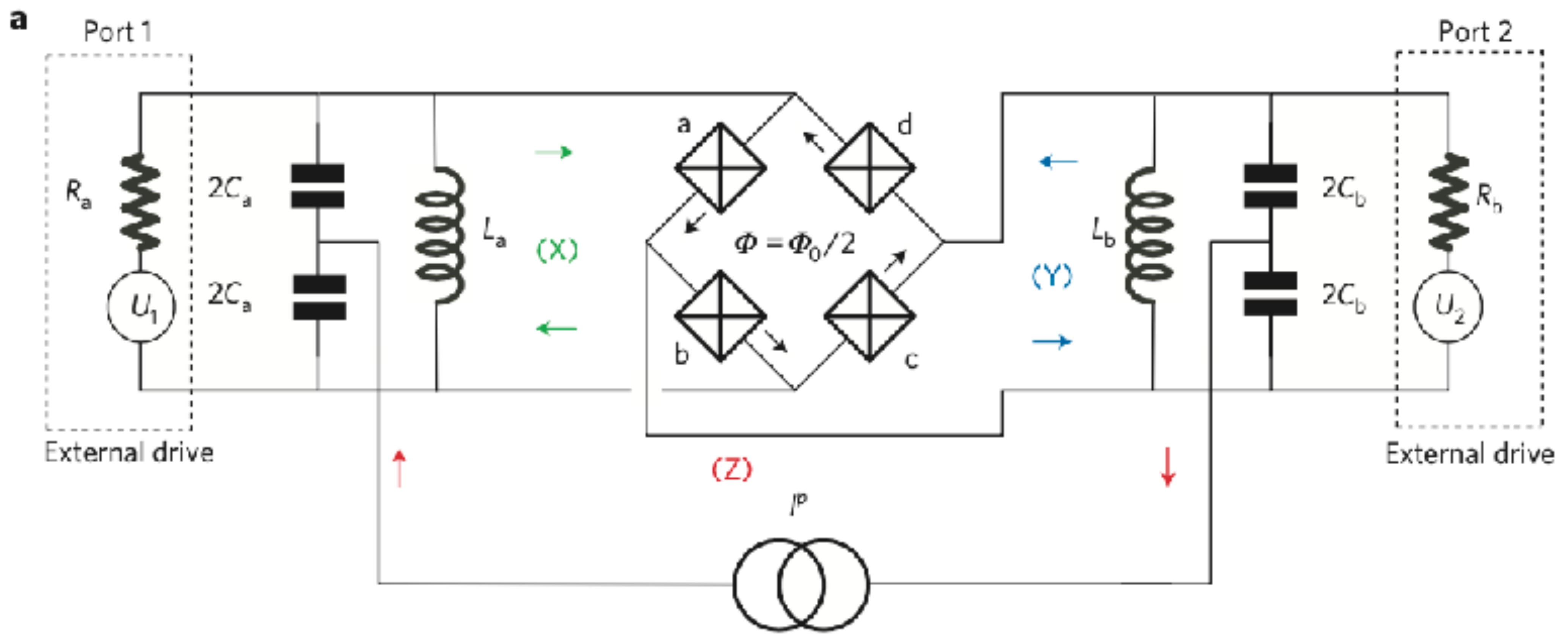
- Nonlinear element → ϕ_p ϕ_1 ϕ_2 → $ga_1a_2^\dagger$, $Ga_1a_2, \cdots$

  Classic pump mode quantum mode

- How to realize three wave mixing:

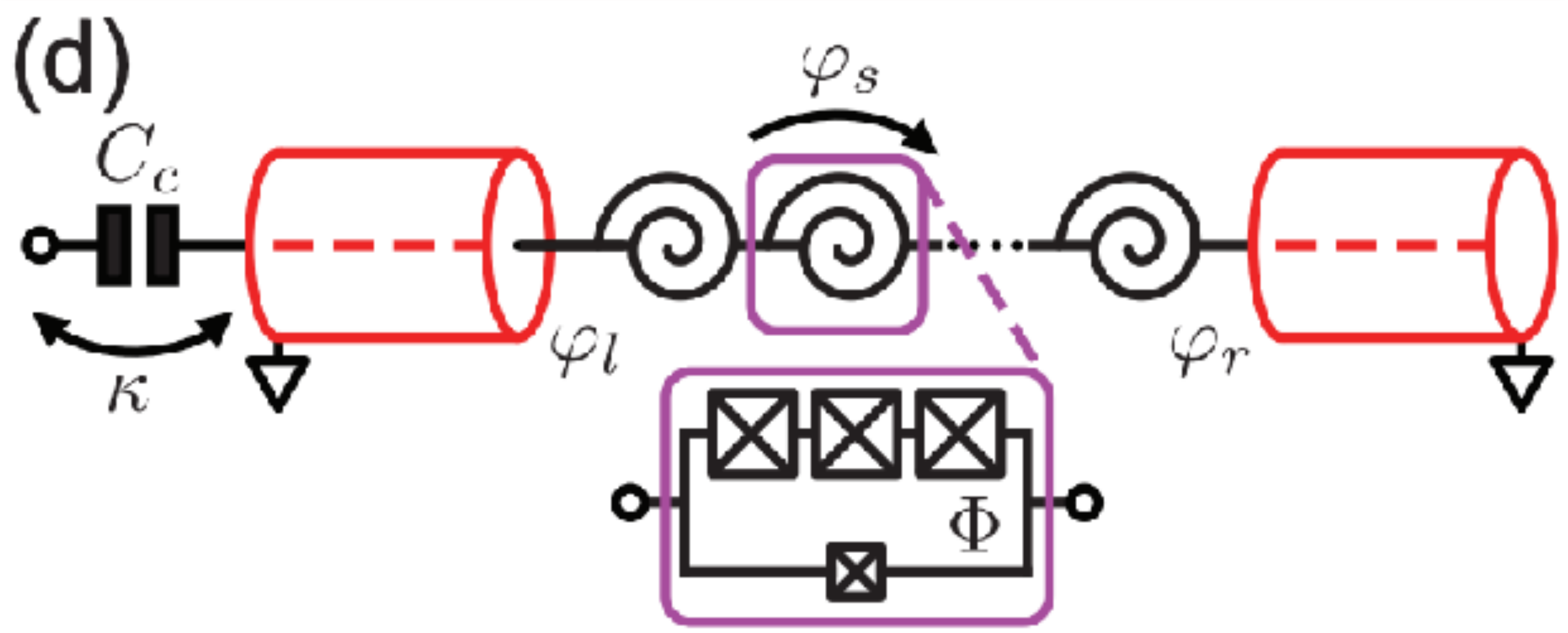
  Josephson Ring Modulator (JRM)

  used for JPC and other quantum device



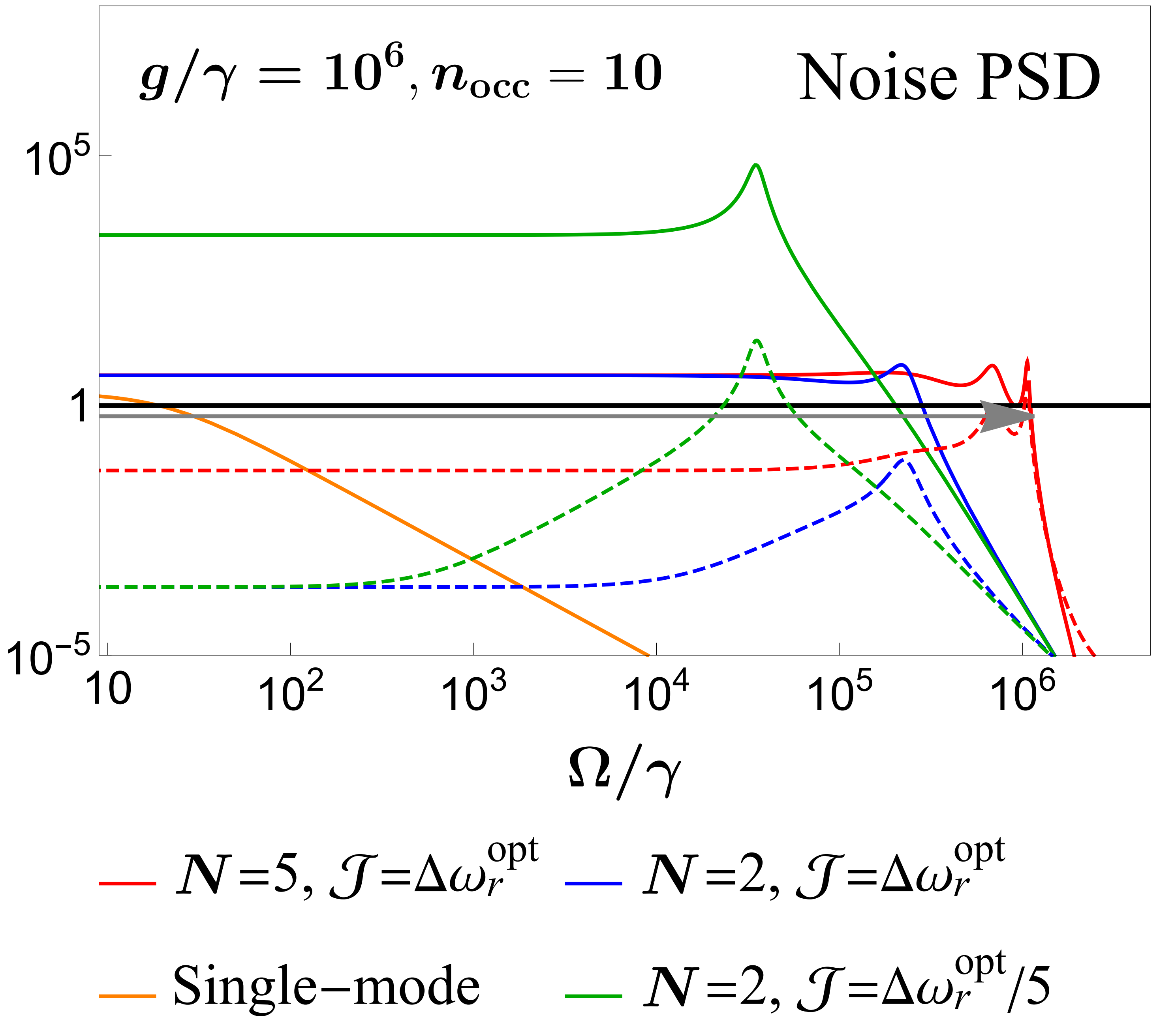
Bergeal et al 10

Superconducting Nonlinear Asymmetric Inductive eLements (SNAIL)

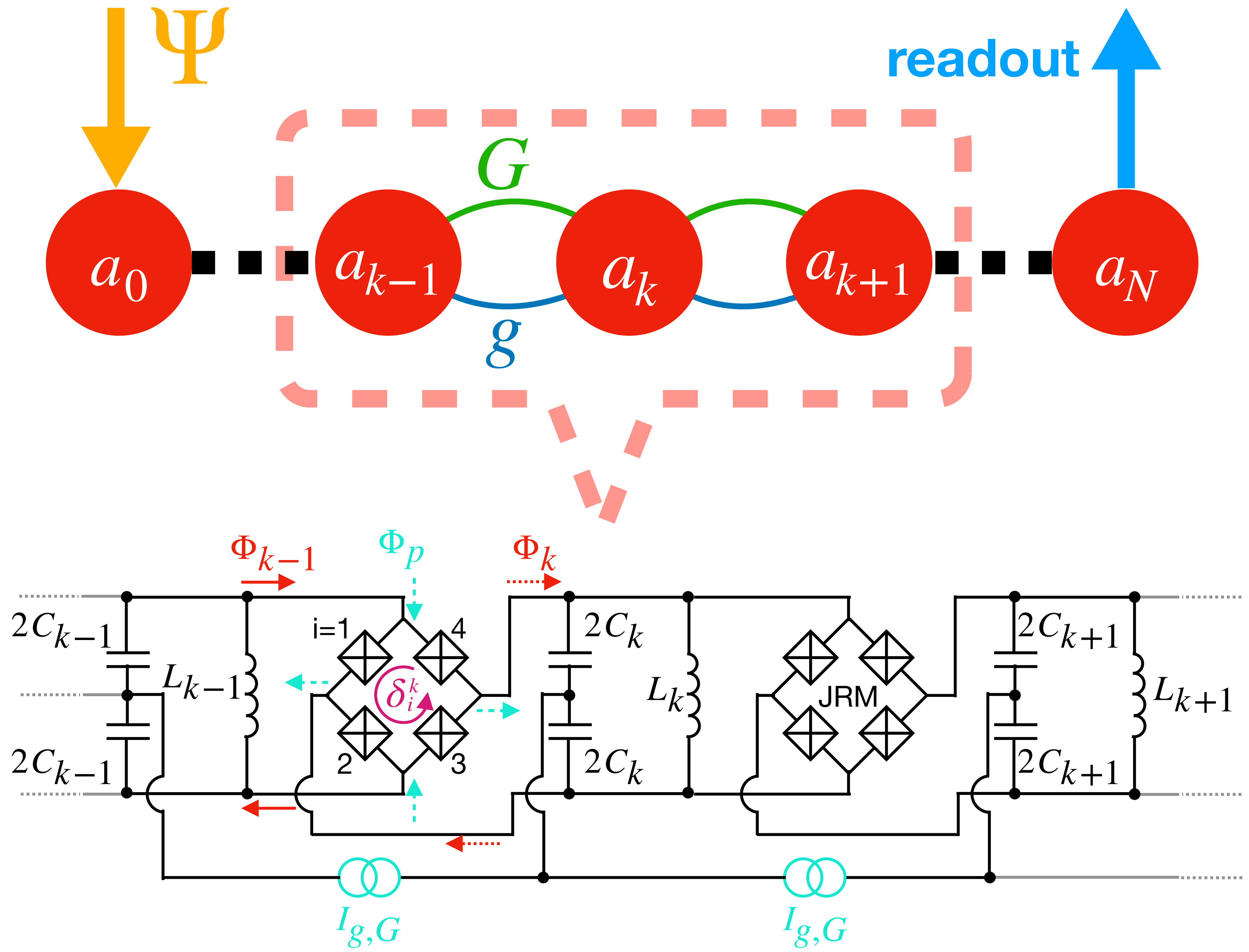


Devoret et al 18

Response for multi-mode resonators

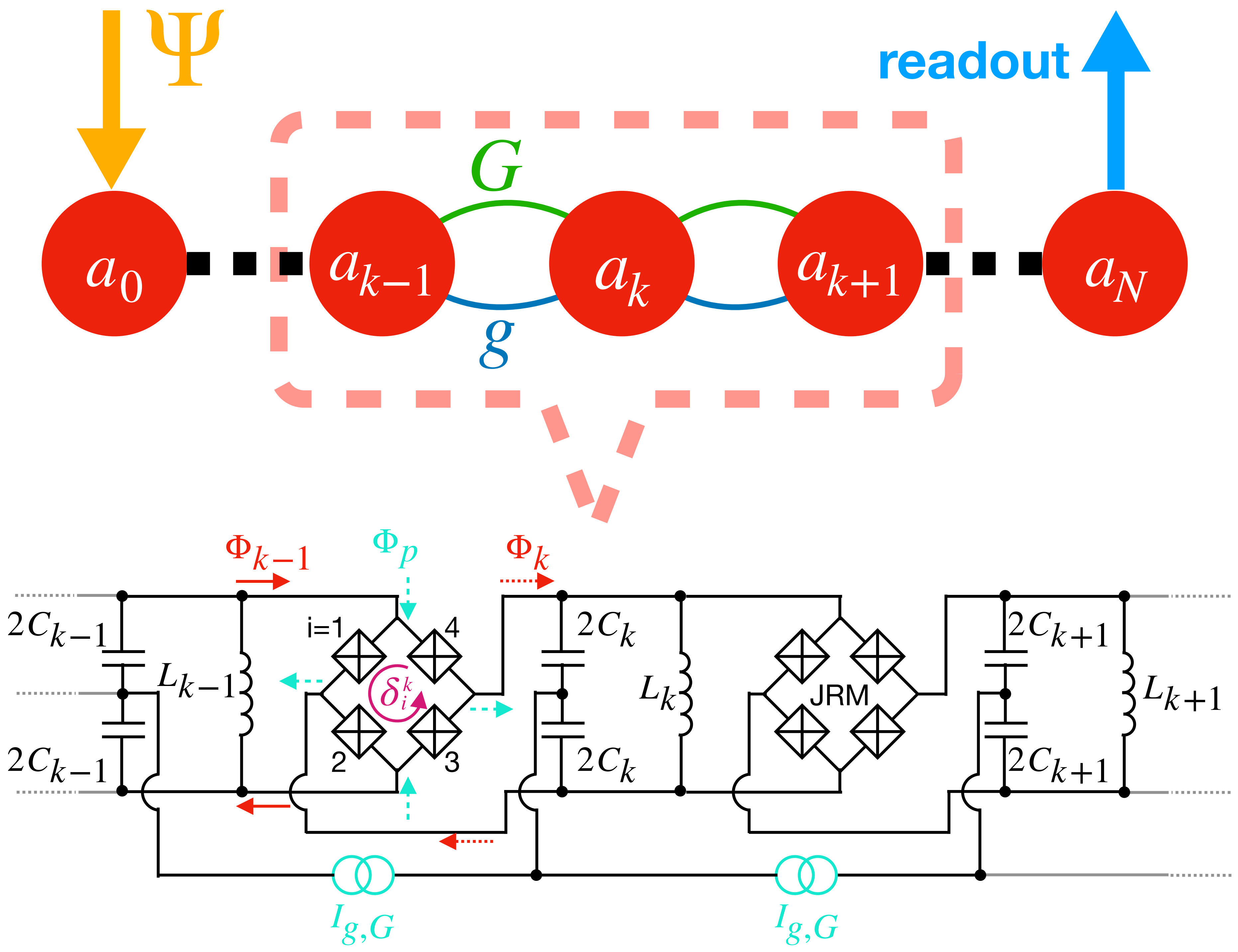


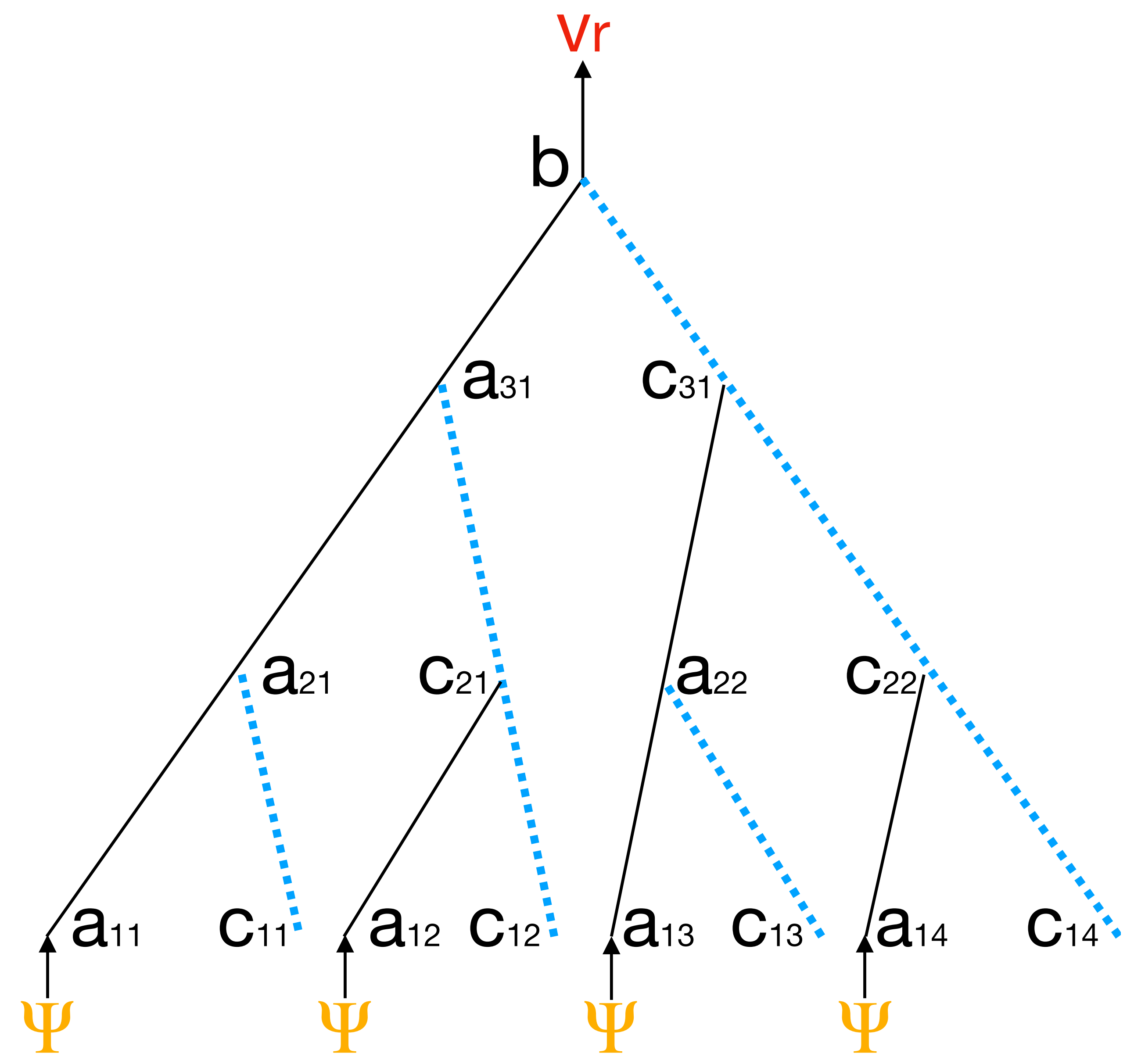
$$\mathcal{J} \equiv \left(|g|^2 - |G|^2\right)^{1/2}$$



$$H_{\rm ch} = \sum_{k=0}^{N-1} \left(\mathrm{i}|g|\mathrm{e}^{\mathrm{i}\varphi_k^g} \hat{a}_k \hat{a}_{k+1}^\dagger + \mathrm{i}|G|\mathrm{e}^{\mathrm{i}\varphi_k^G} \hat{a}_k \hat{a}_{k+1} + h.c. \right)$$

Chain and Binary tree

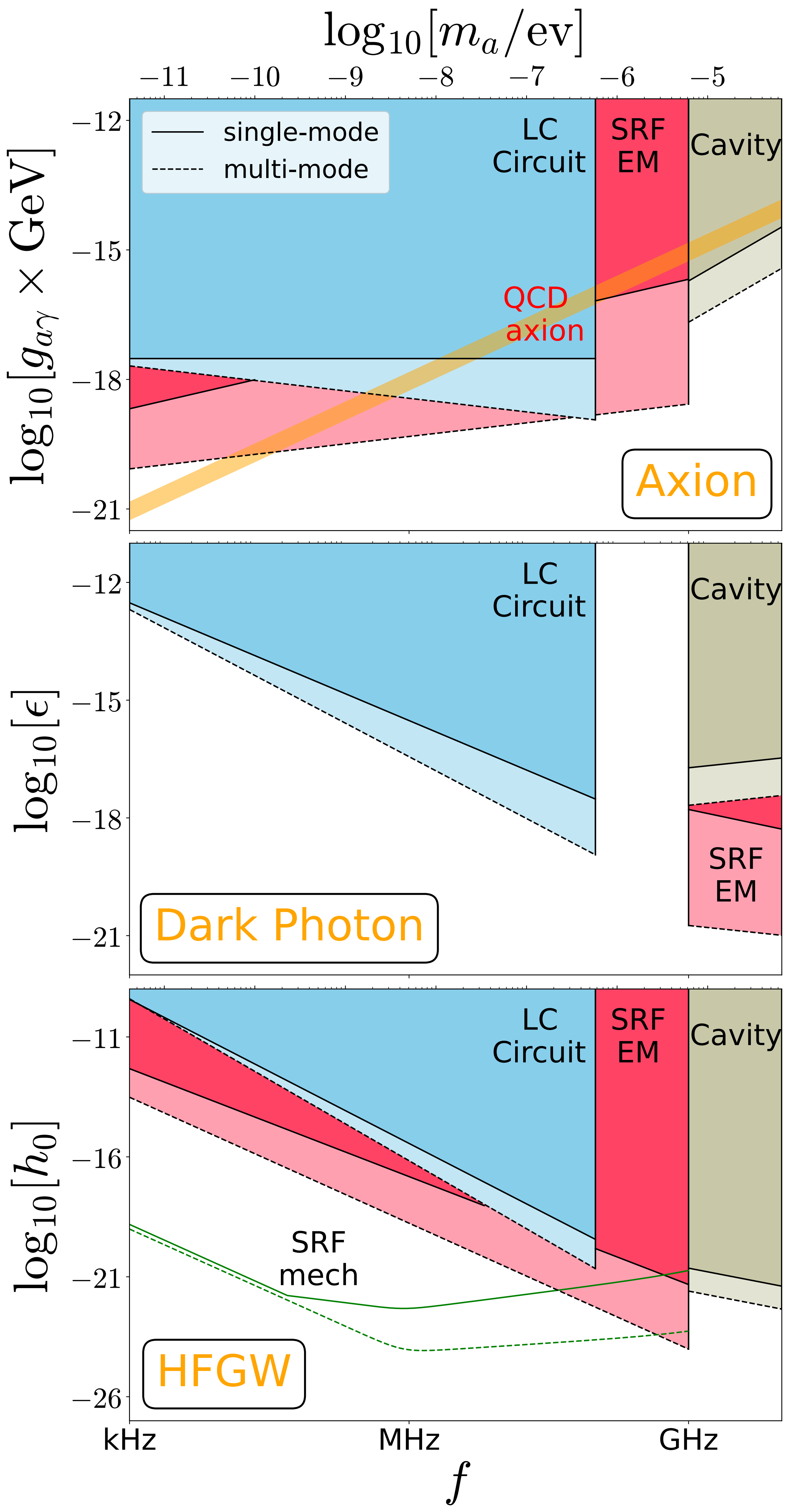




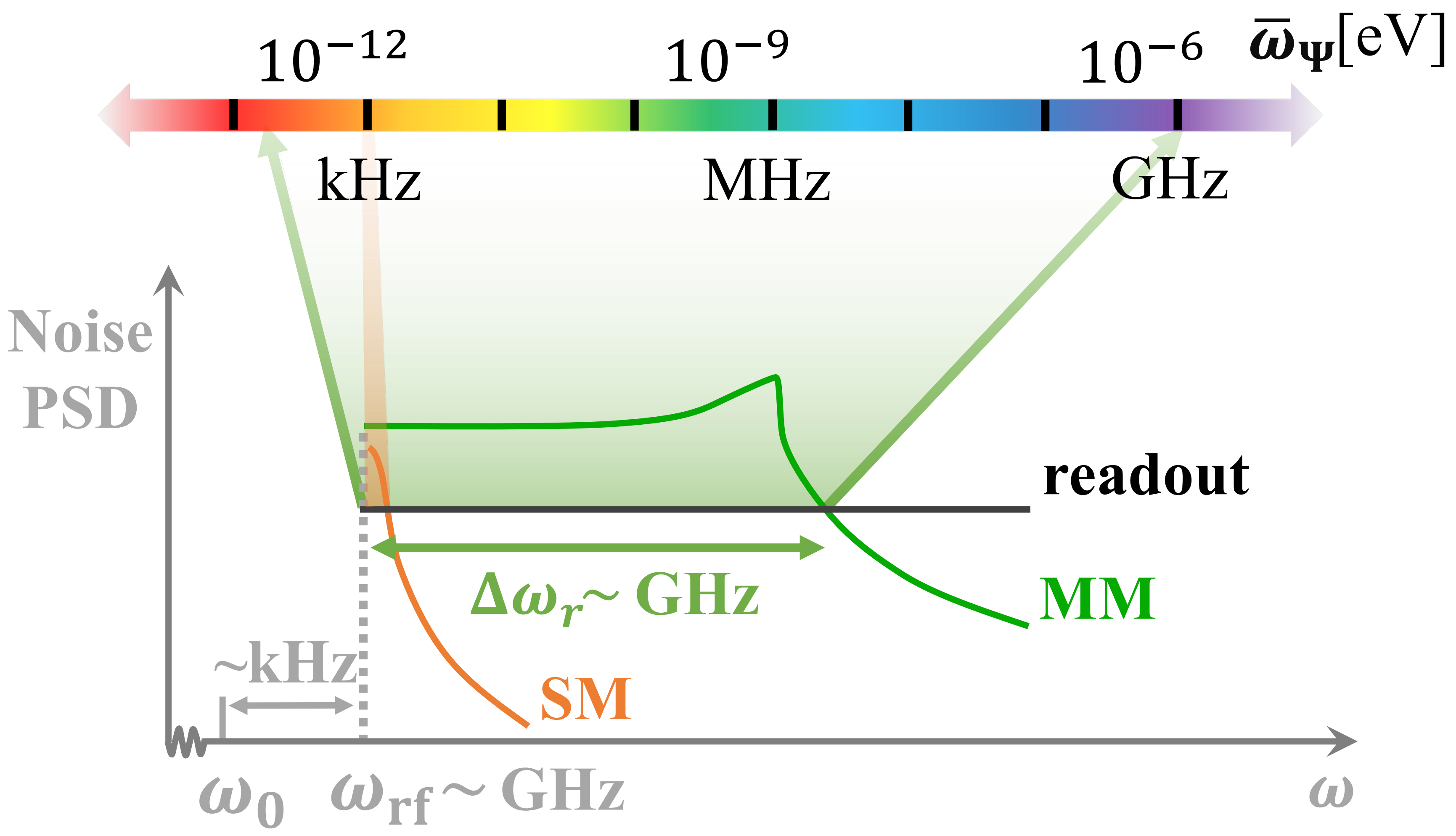
- Non-Hermitian chain (McDonald et al 18, Chen et al 25 ROPP)
- Amplify **single quadrature**
- Sensitive to phase fluctuation and higher order interaction
- HAYSTAC realized a prototype of N=1 (Jiang et al 23)

- Binary tree: (Chen et al 21 PRR, Chen et al 25 ROPP)
- Amplify **both quadratures**
- Robust to phase fluctuation

Sensitivity enhancement



- Solid line: **single mode SQL** with e-fold time$\sim 10^7$ s
- Dashed line: **multi-mode** with bandwidth$\sim \omega_{\mathrm{rf}}$



$$\frac{\mathrm{SNR}^2_{\mathrm{HUMM}}}{\mathrm{SNR}^2_{\mathrm{HUSM}}} \simeq N_e \frac{\bar{\omega}_\Psi \, Q_{\mathrm{int}}}{\omega_{\mathrm{rf}} \, n_{\mathrm{occ}}}$$

- Simultaneously scan $N_e = 6$ orders for **high-Q detection case**

Large sensor-array to eliminate the noise

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) ?

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

Relax and dephasing

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

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

Thermal population

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

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

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

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

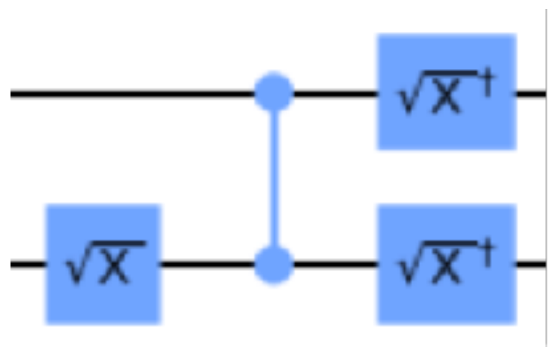
increases with N_q

How to eliminate the noise?

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

- Define

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



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 $\mathscr{U}_c$

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

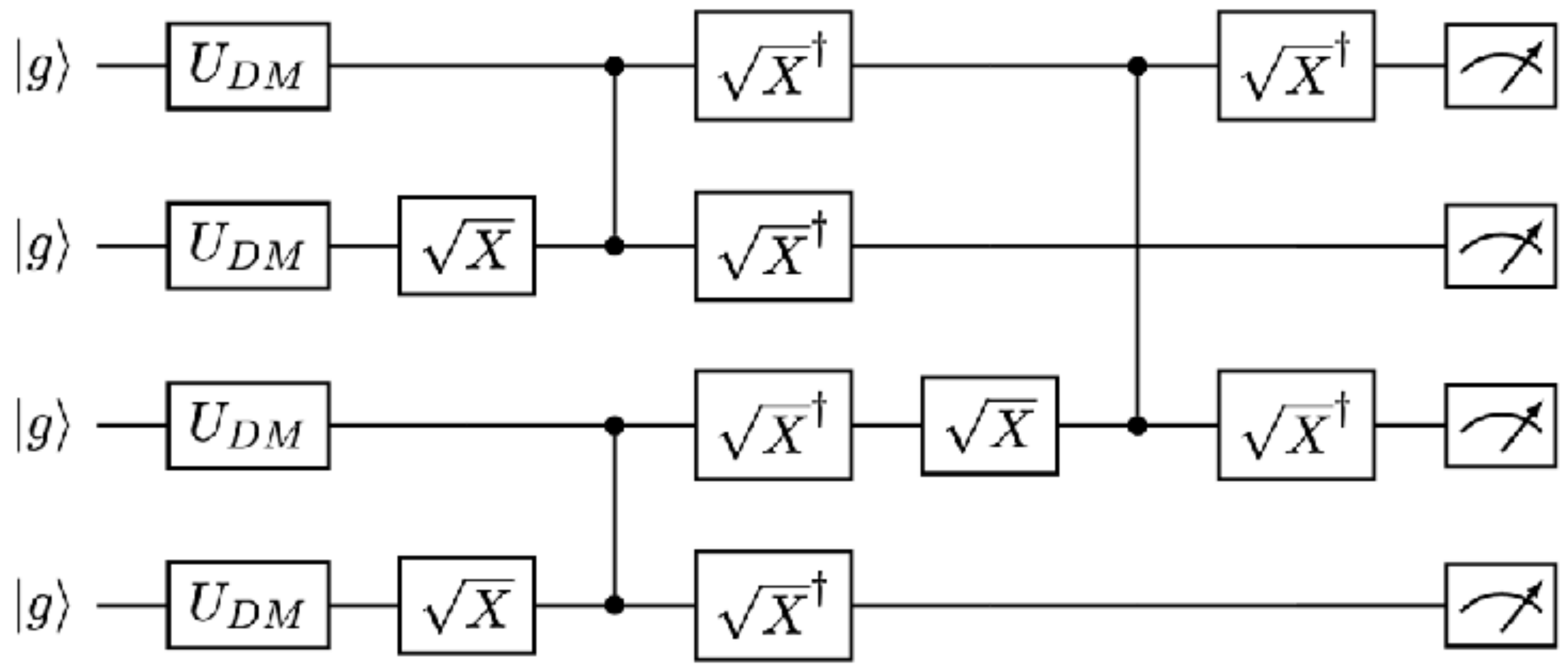
- Pure signal given by

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

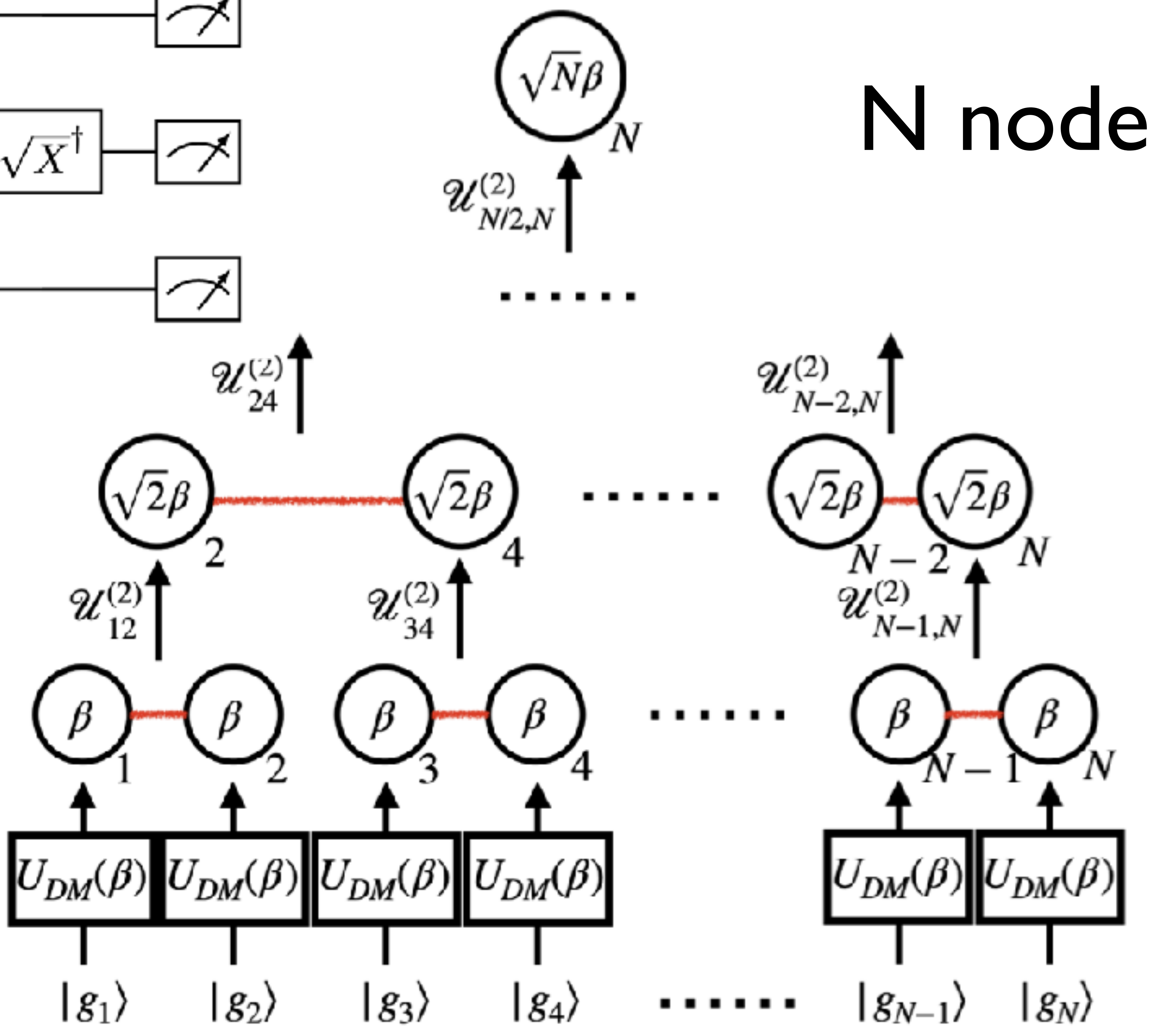
No incoherent noise!!!

Generalize to N nodes

Four nodes



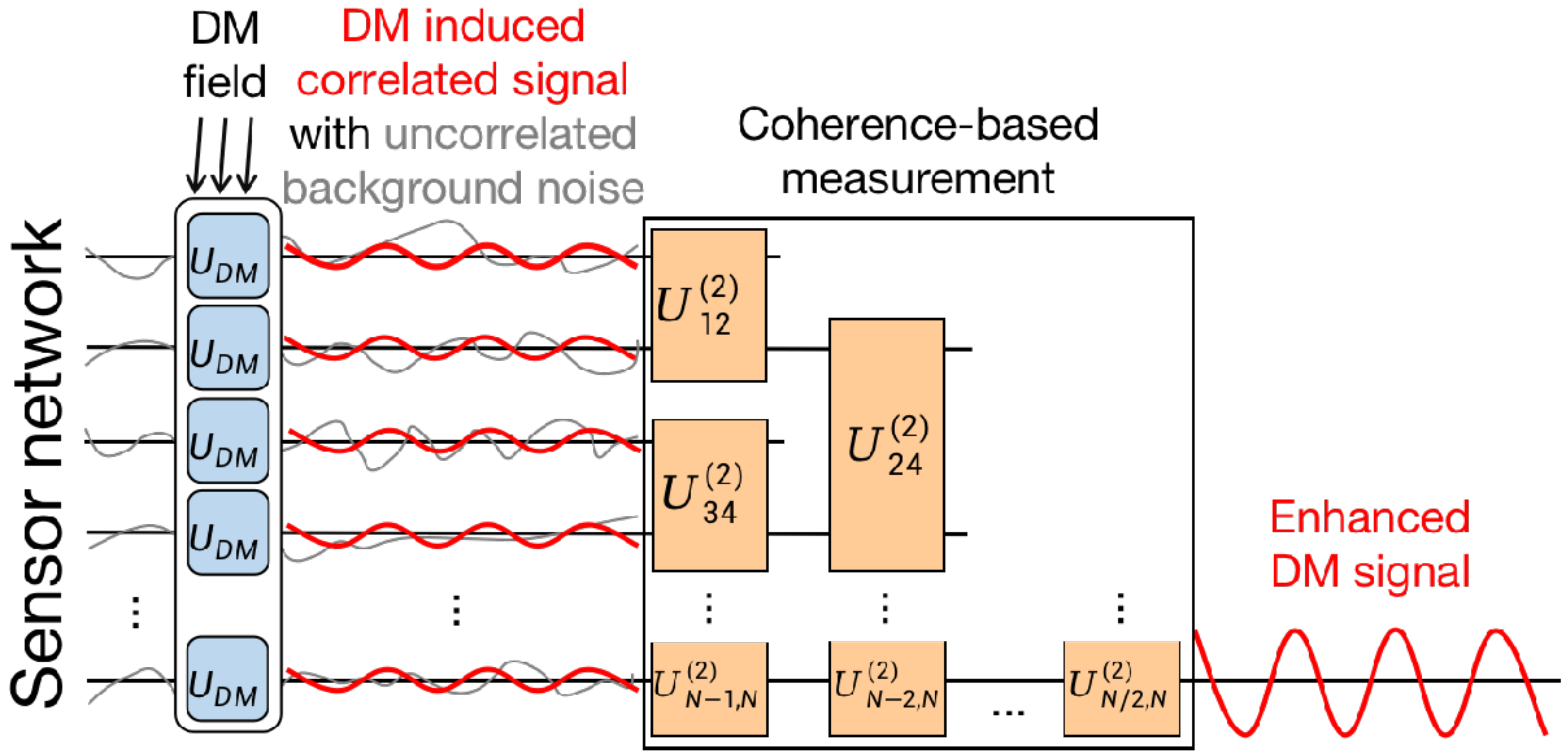
N nodes



Signal (off-diagonal) goes like N^2

Backgrounds go like N

How to eliminate the noise?

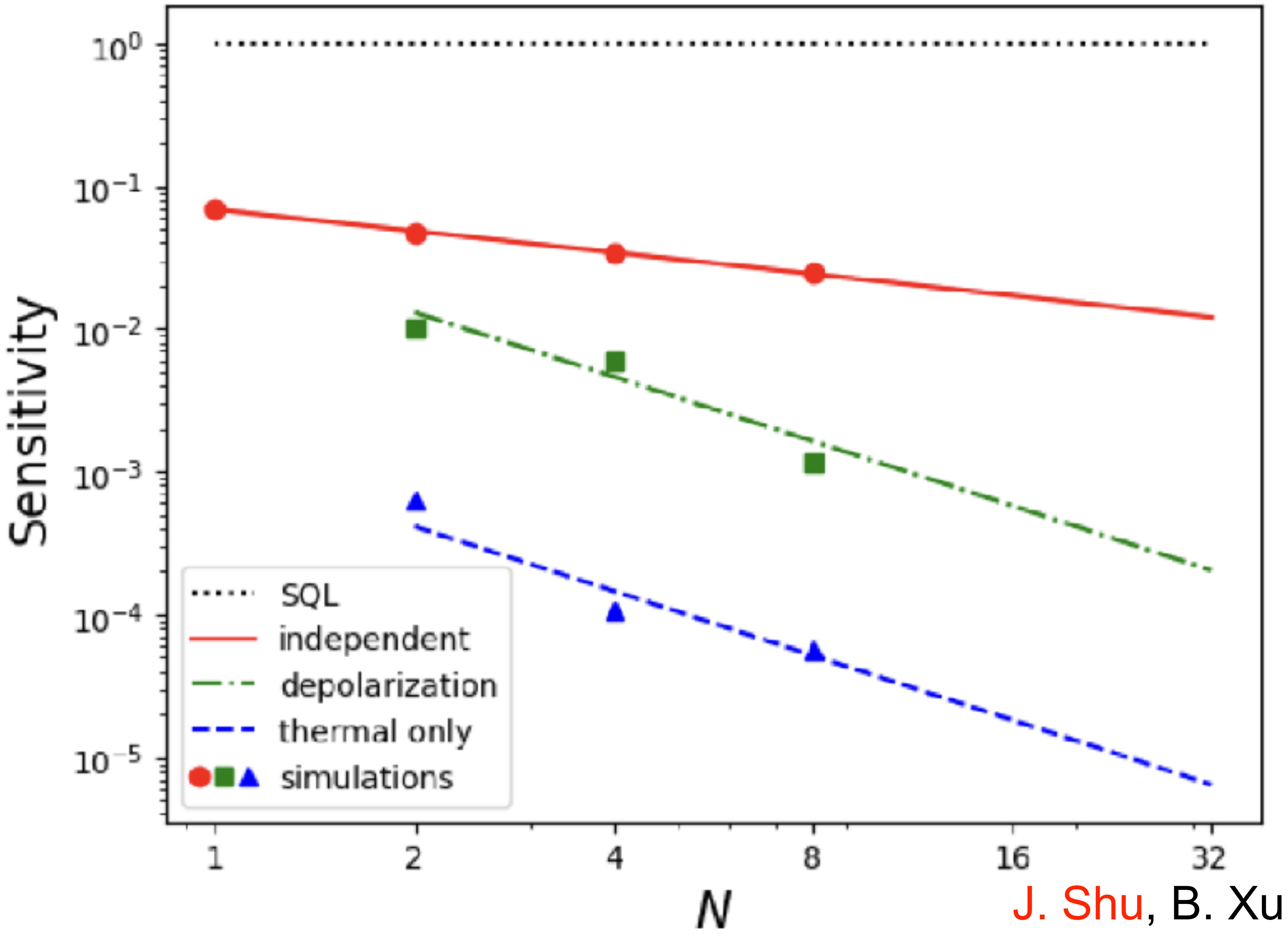


J. Shu, B. Xu, … arXiv:2410.22413

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

Application to the real quantum qubit - chips

Outlook

Summary and outlook

- High-Q SRF is extremely interesting in Haloscope wave-like DM searches (get deepest constraints).
- Using advanced high quantum technology like QND and "Simultaneous resonant and broadband" can greatly improve the sensitivity
- DP backgrounds has rich information (polarization & angular distribution).
- Can be extended to sensors arrays (quantum 2.0)
- In the future (axion, GWs, quantum qubit, etc), much more can be done .

Backup

Magnetometer for DM Search

Key Result: Magnetometer-Array DM Search

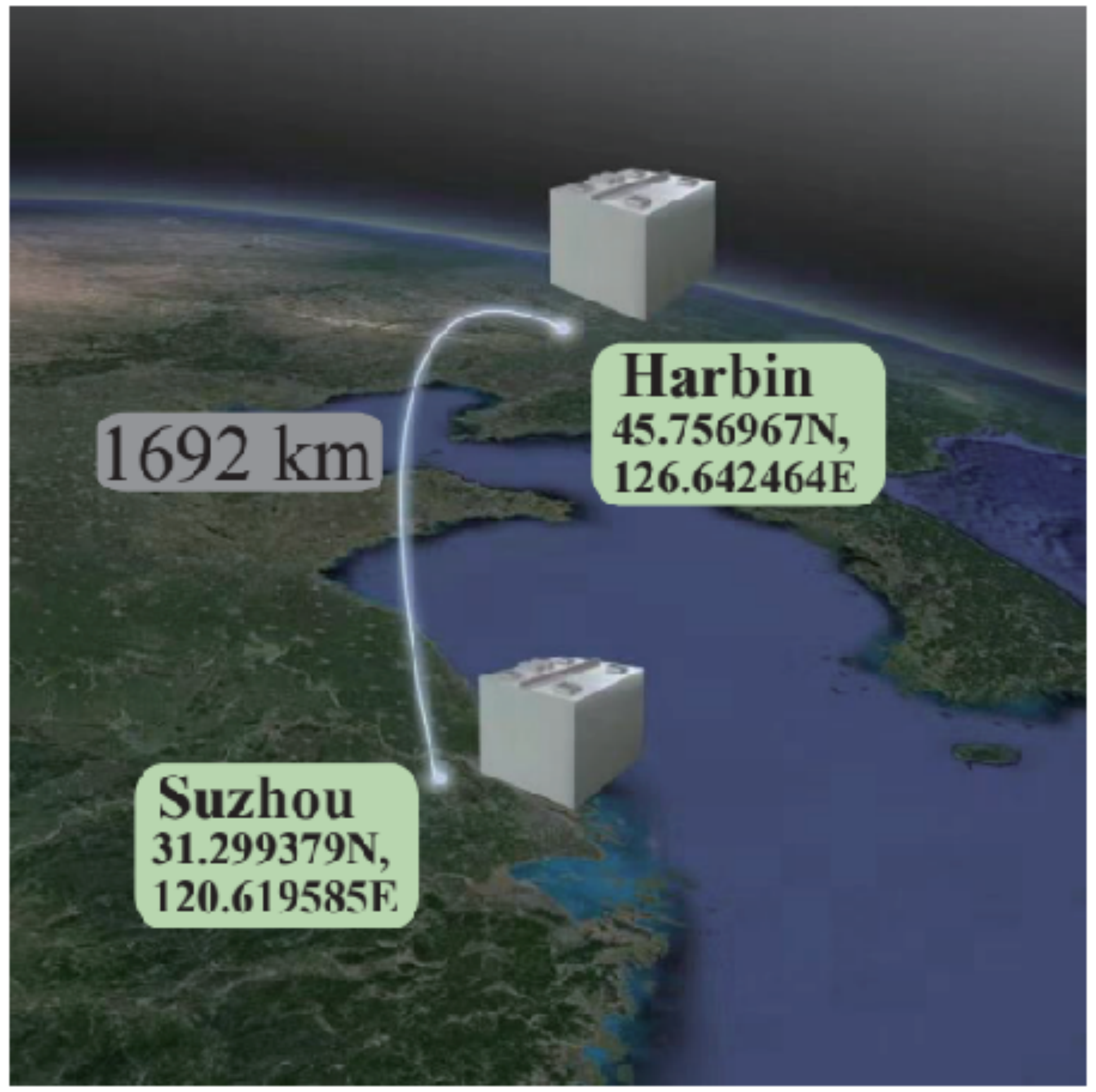
Theory: quantum sensor arrays enhance sensitivity and measure particle spin polarization

Phys. Rev. Res. 4 (2022) 3, 033080

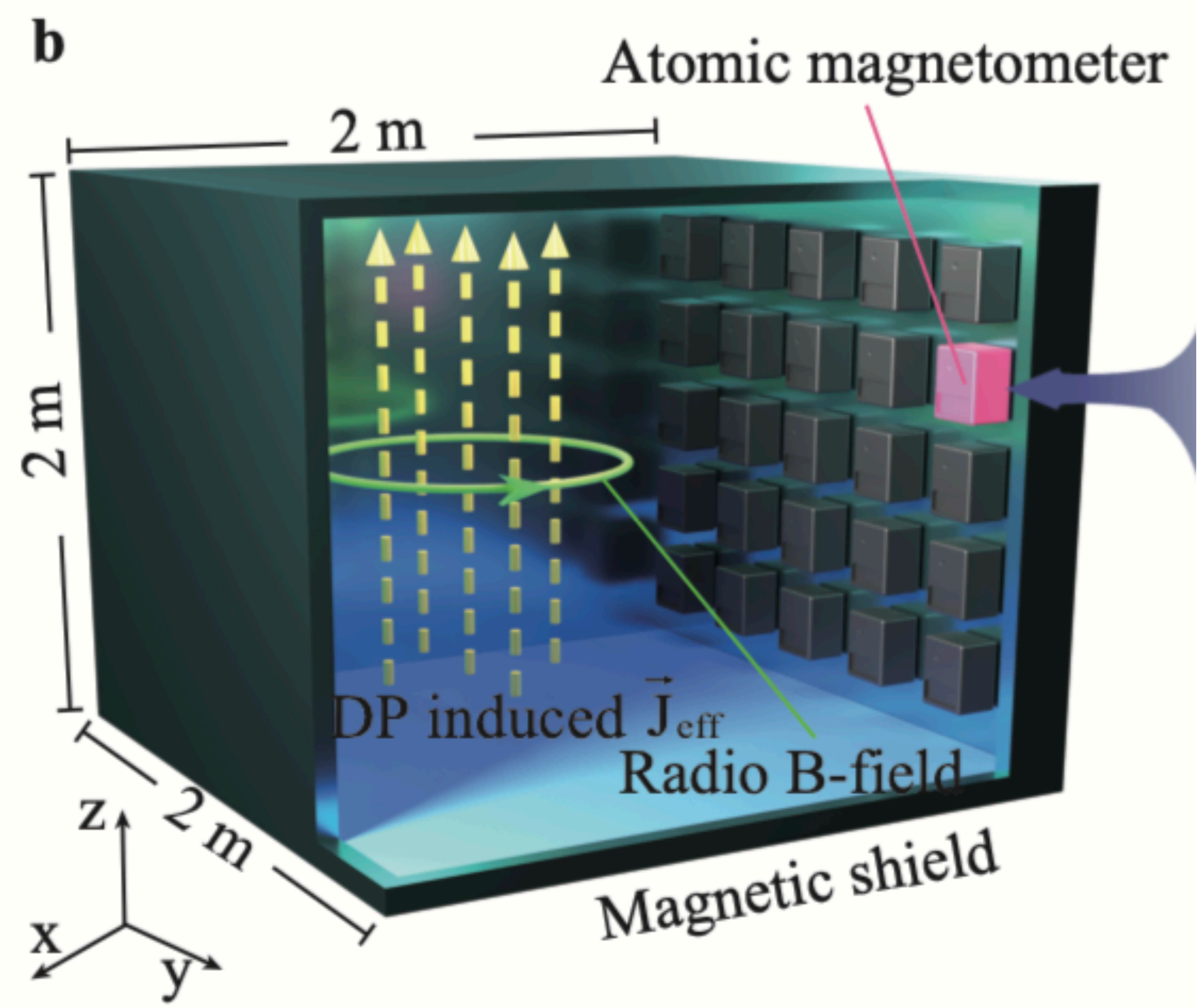
Experimental realization: magnetometers precisely probe dark photons; two-site correlation removes common-mode noise

Nature Commun. 15 (2024) 1, 3331

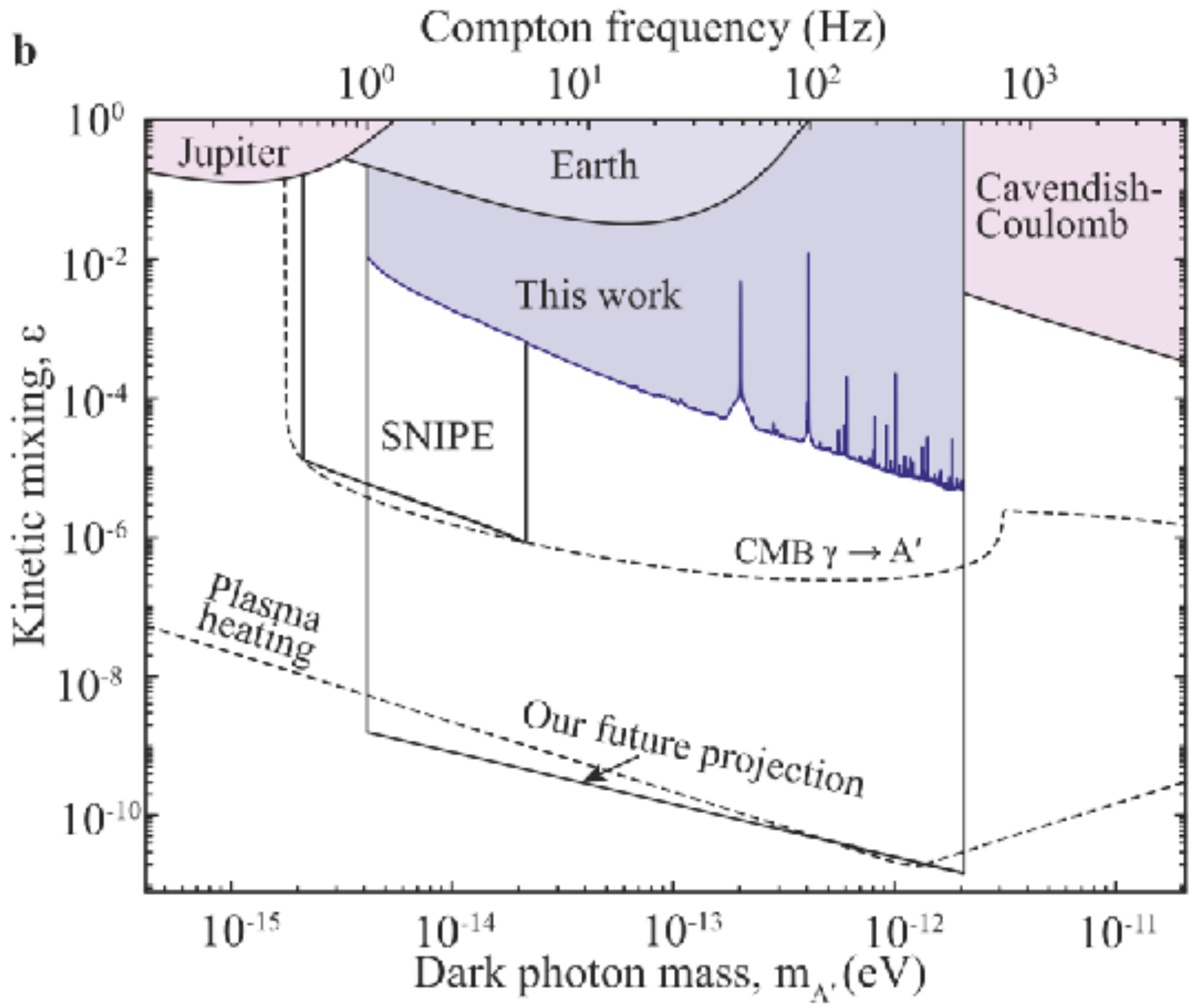
Two-site rejection of common-mode noise



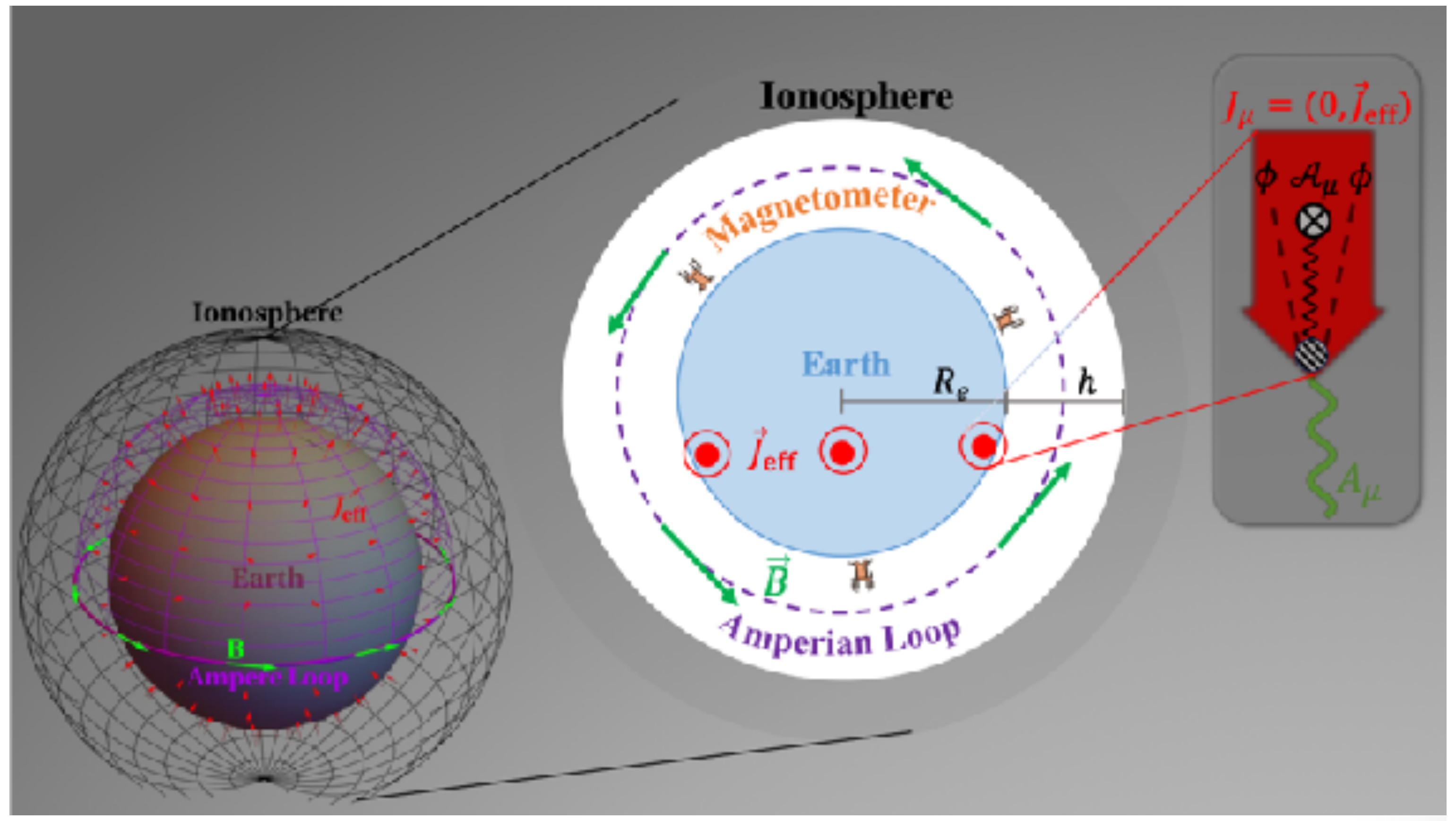
New shielded-room search apparatus and method

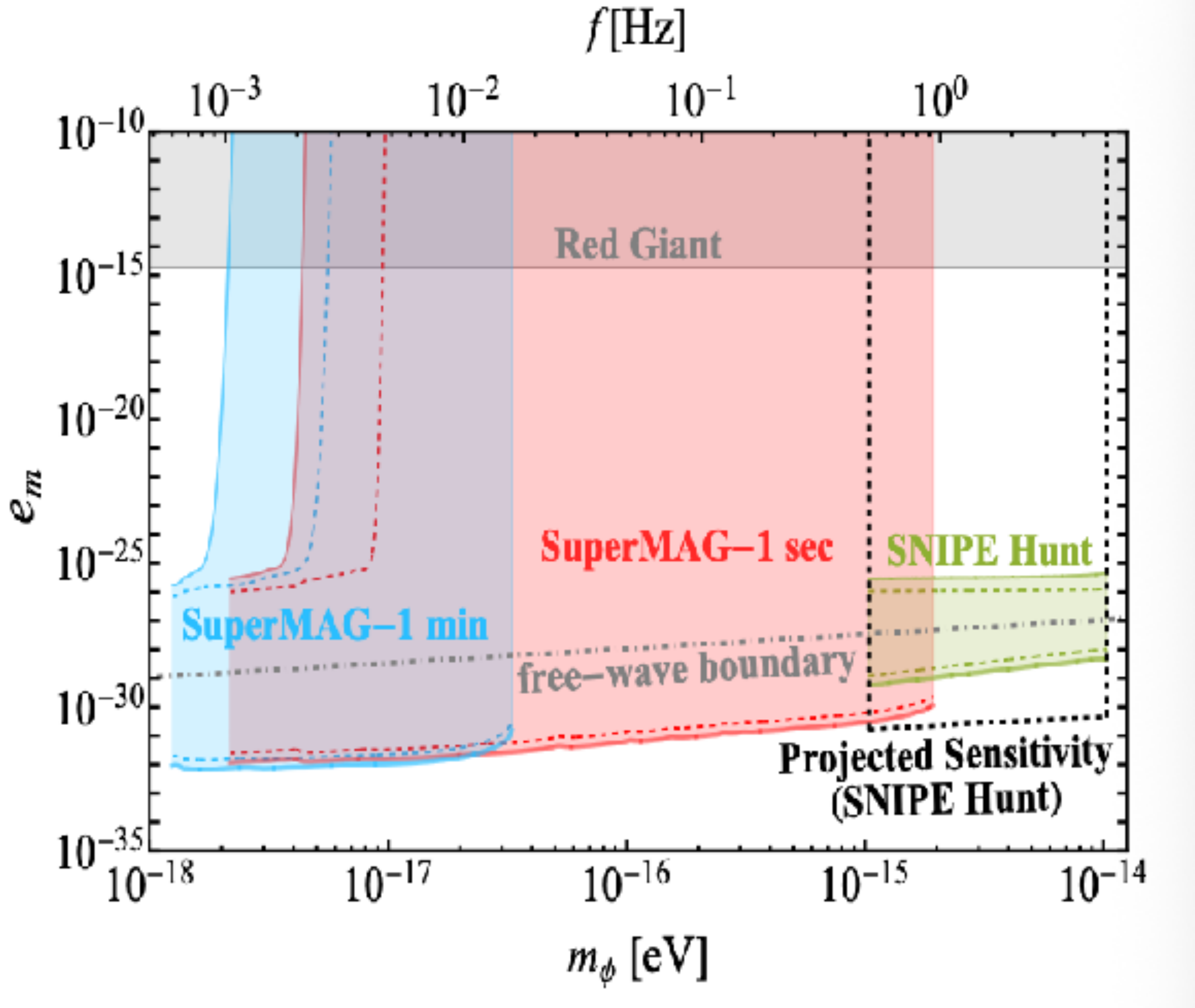


Experimental result: USTC collaboration



Key Result: Earth as a Shielding Cavity for mCP Dark Matter





Phys. Rev. Lett. 136 (2026) 4, 041001
(Featured in Physics, co-corr)

Earth's ionosphere as a conducting cavity: geomagnetic search for ultralight millicharged DM, improves stellar-cooling limits by 13 orders of magnitude.

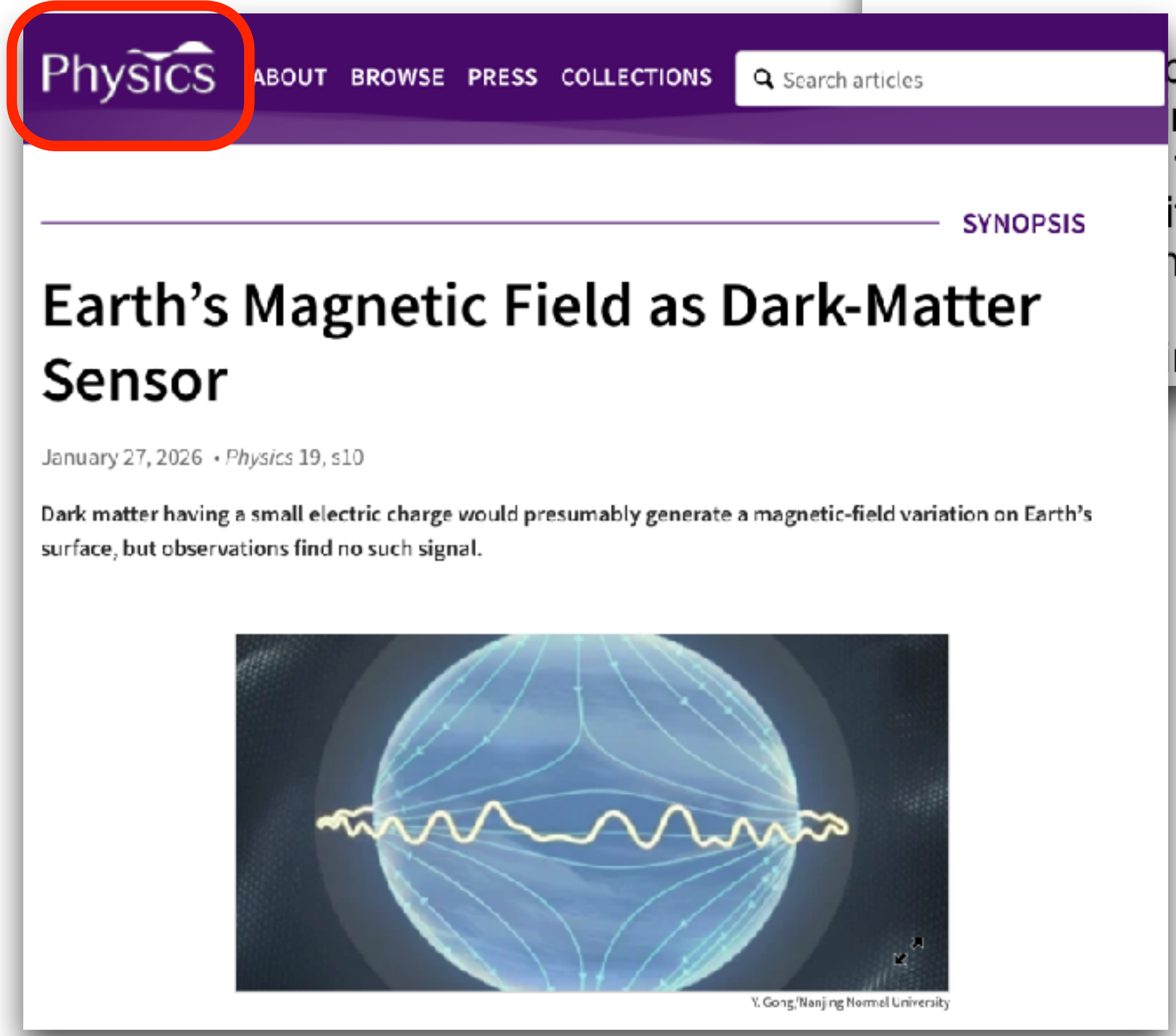
SS Sabnam Shrestha 2026年2月25日 06:04
Request for your comments for Physics World Article on you...
收件人: jshu@pku.edu.cn
详细信息

Dear Dr. Jing Shu,

I am a PhD student contributor for *Physics World*, the international magazine published by the Institute of Physics.

...per **"Geomagnetic Constraints on Millicharged**
...n The Physical Review Letters, and I thought it
...the readers of *Physics World*. I am therefore
...ite a short news story about the paper for a general
...nce.

...me to answer a few questions about your work?



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SYNOPSIS

Earth's Magnetic Field as Dark-Matter Sensor

January 27, 2026 • *Physics* 19, s10

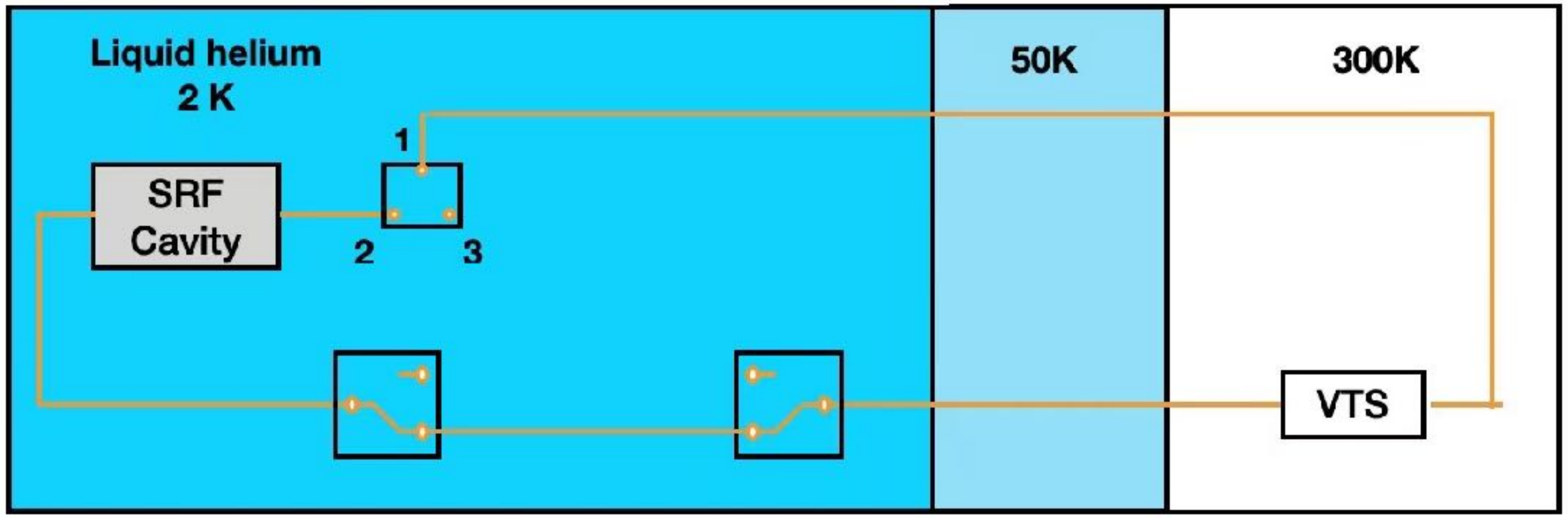
Dark matter having a small electric charge would presumably generate a magnetic-field variation on Earth's surface, but observations find no such signal.

Y. Gong/Nanjing Normal University

Featured by APS Physics

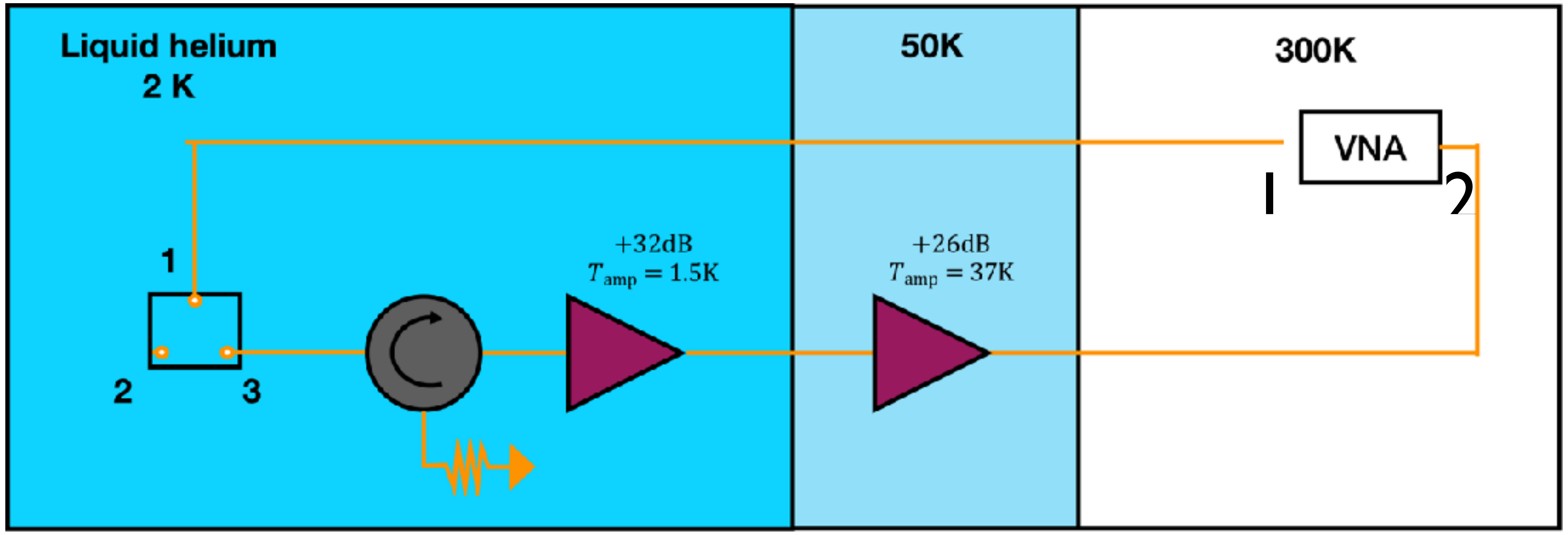
Invited by Physics World

Step 1: Measure Cavity property



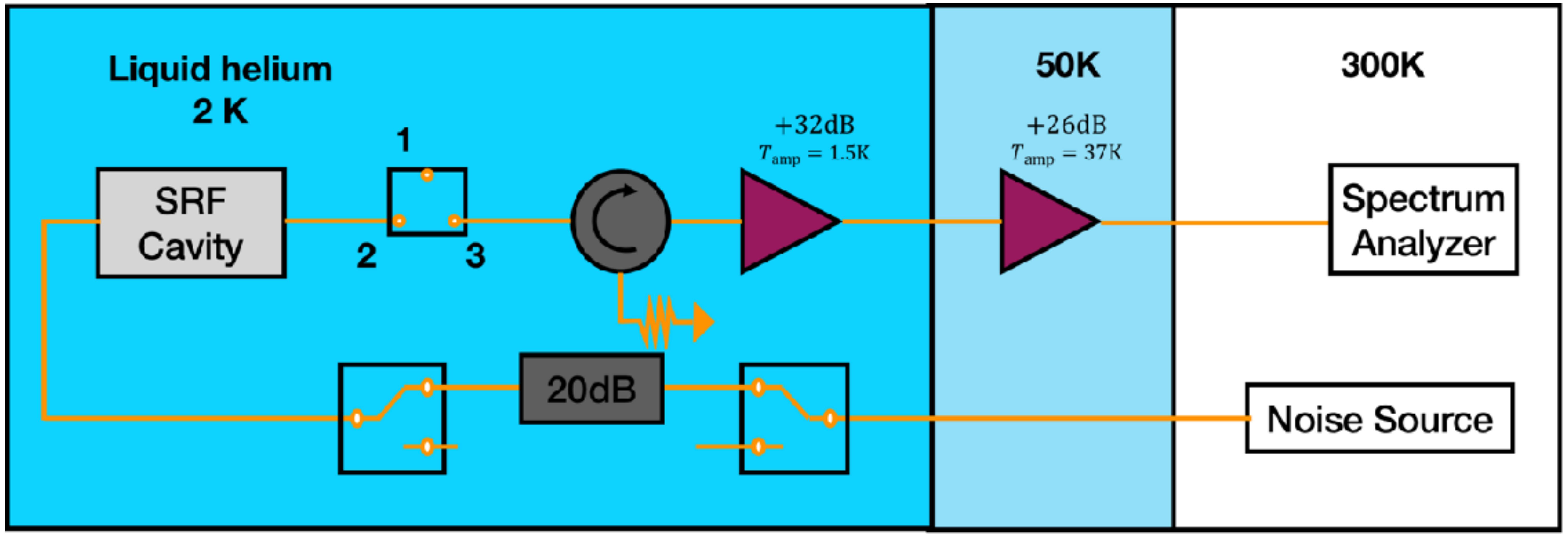
1-2 connection: VTS measurement for the cavity property.

Step 2: calibration



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

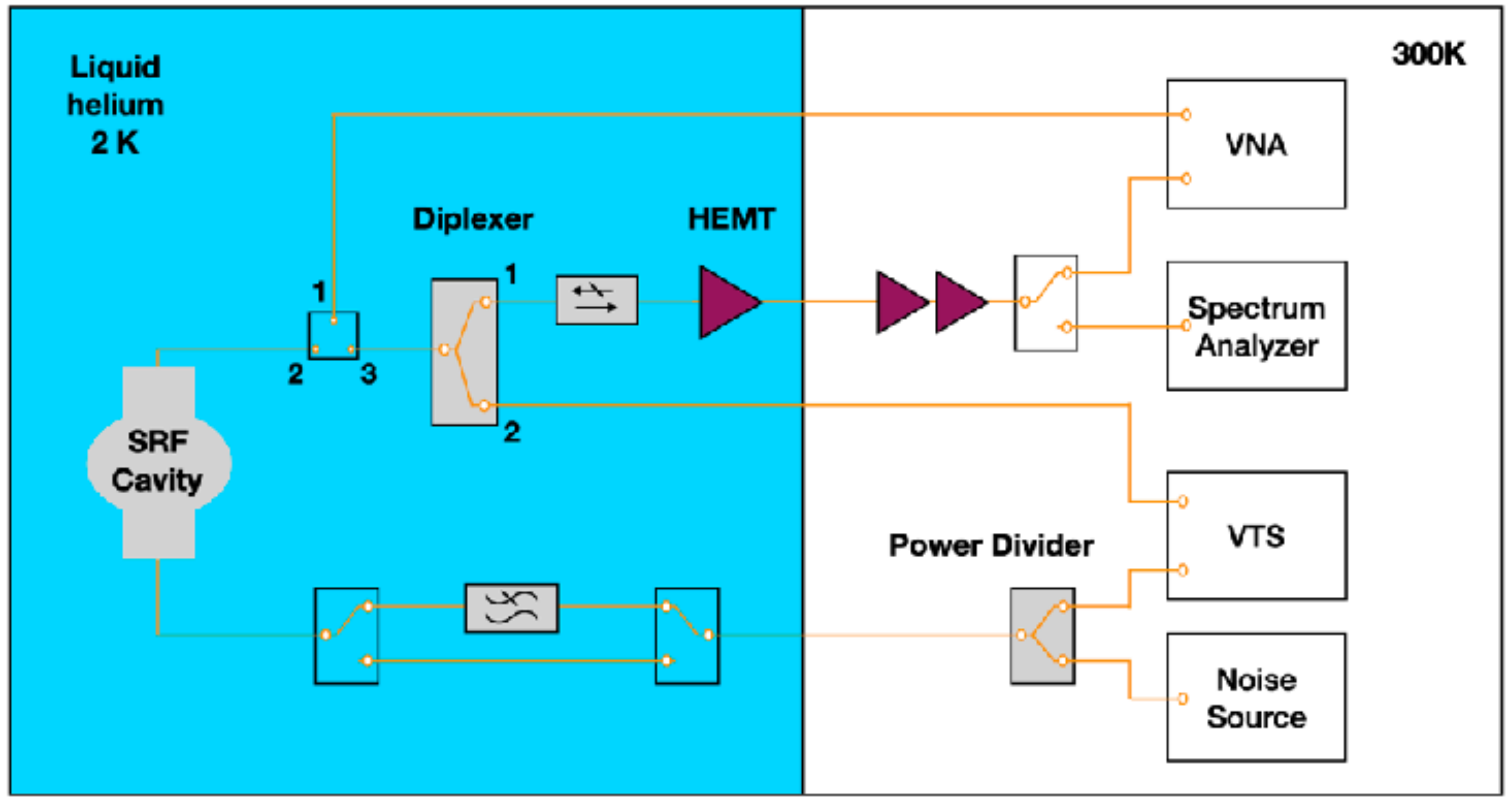
Step 3: Do experiment

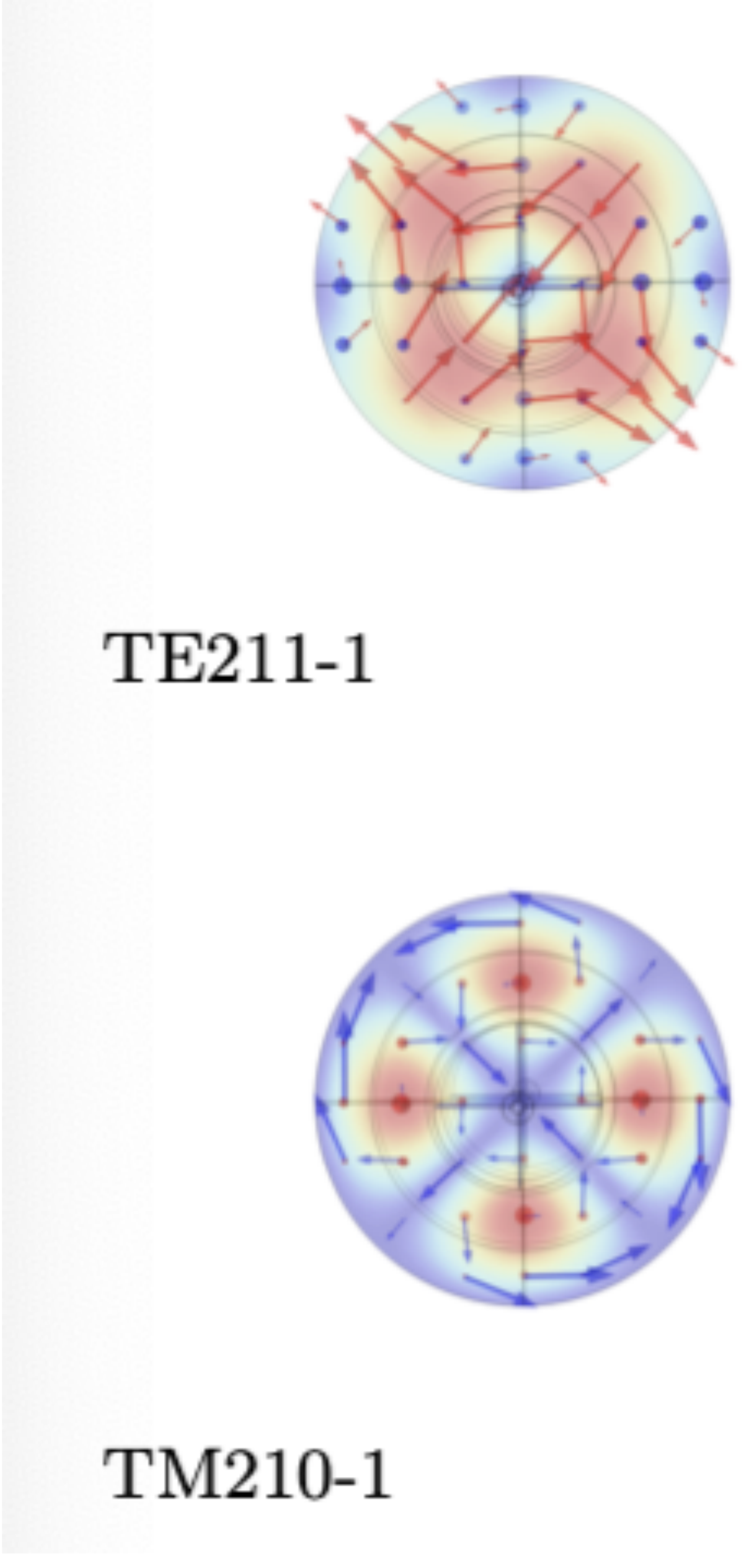


2-3 connection: tune the cavity resonant frequency to do the experiment

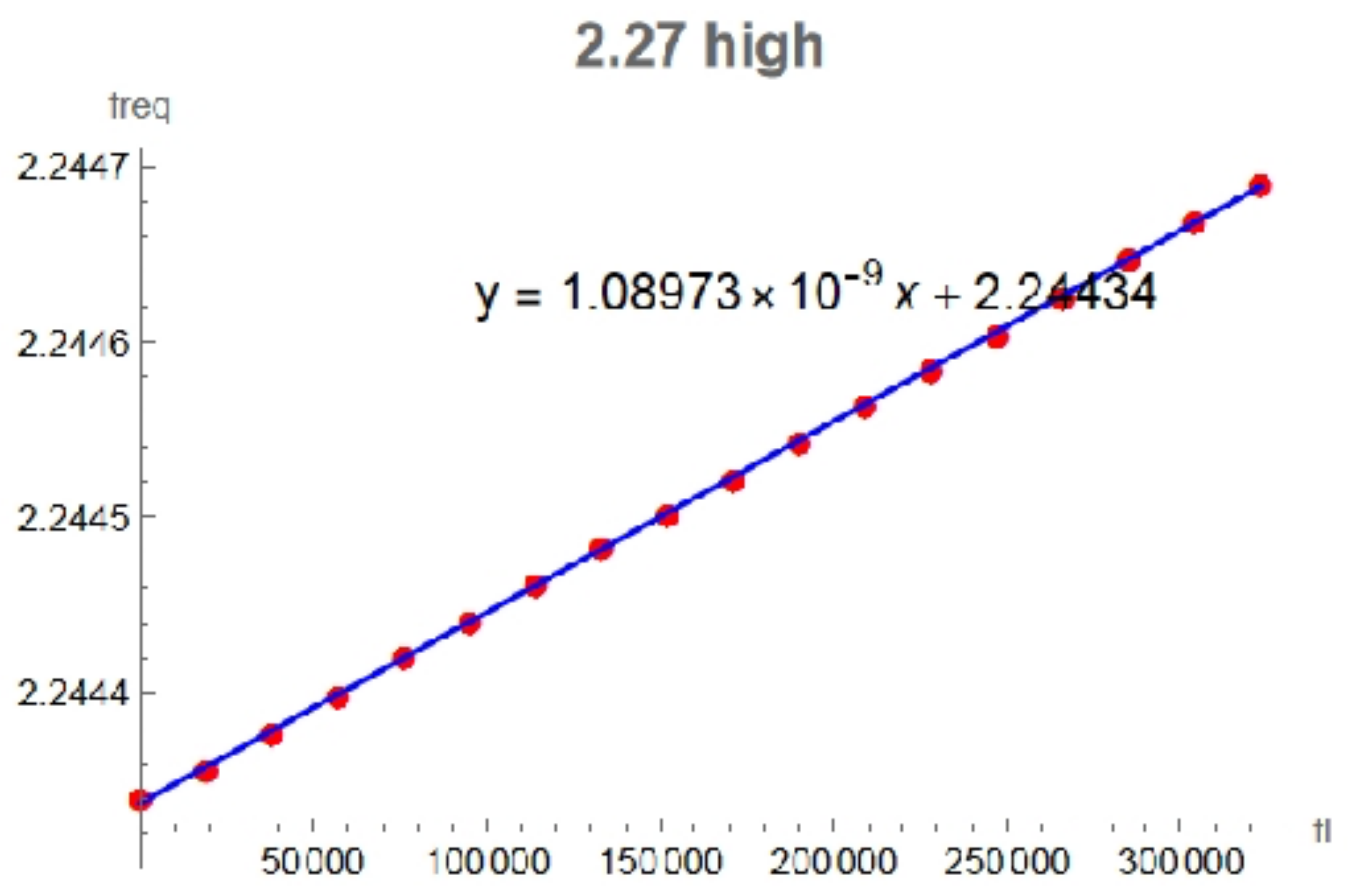
Axion detection

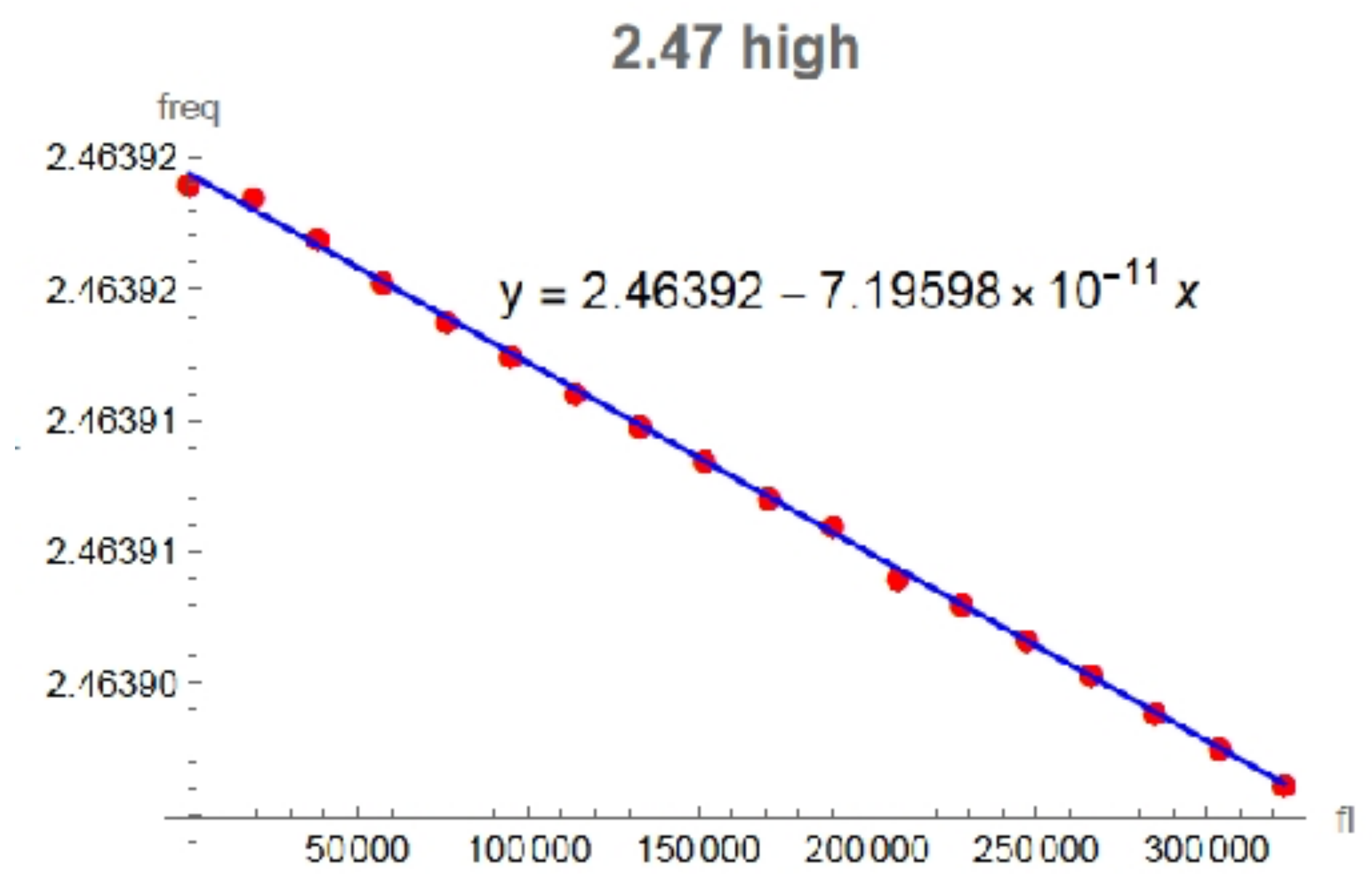
- 1.3GHz SRF, using two levels at 2.27 and 2.47GHz (modes different from 2207.11346)
- Preliminary run still has some problems for the antenna coupling
  - Two modes can only be coupled at 4K, with $Q \sim 10^8$
  - AC field energy 0.2J (B ~ mT)



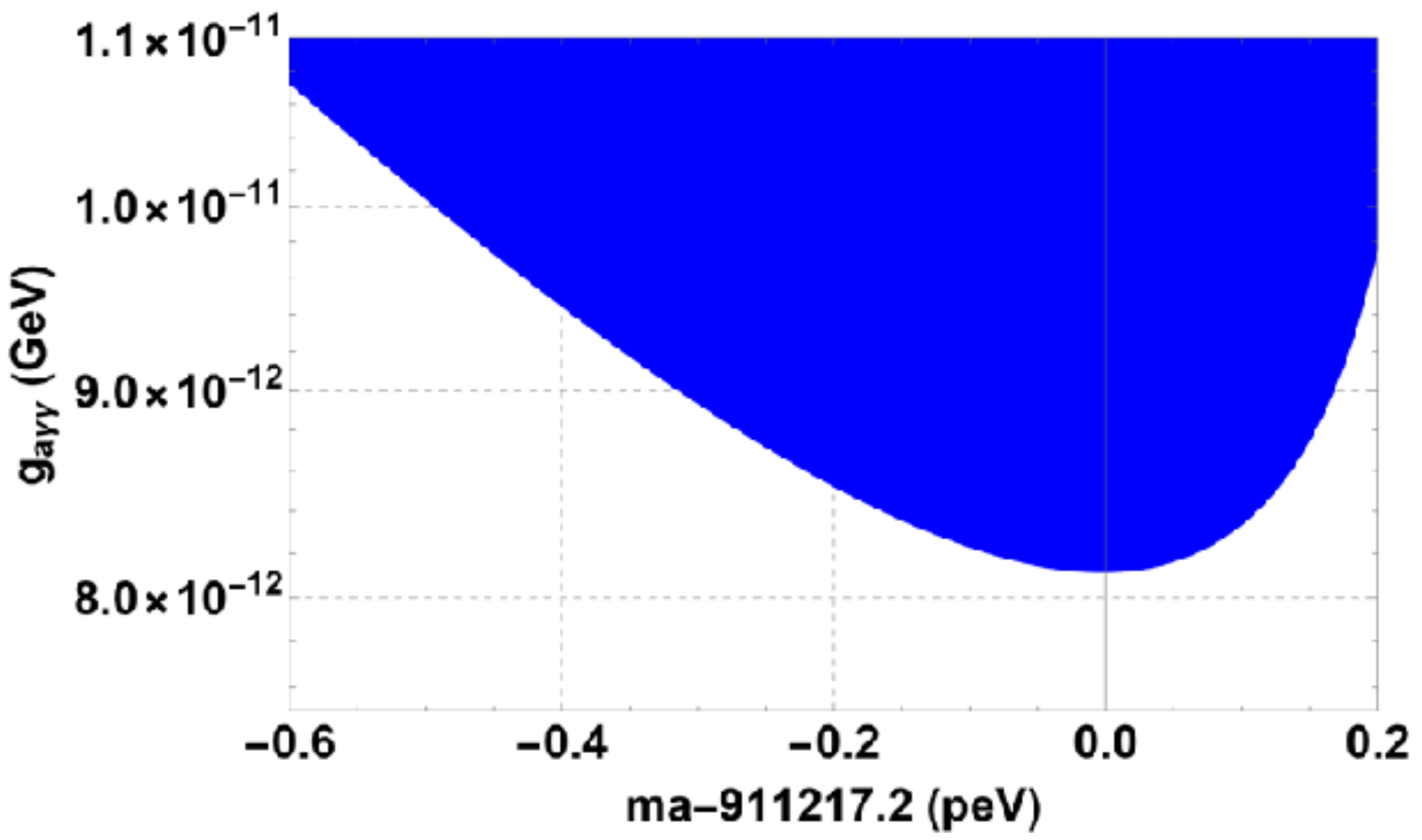


Axion detection



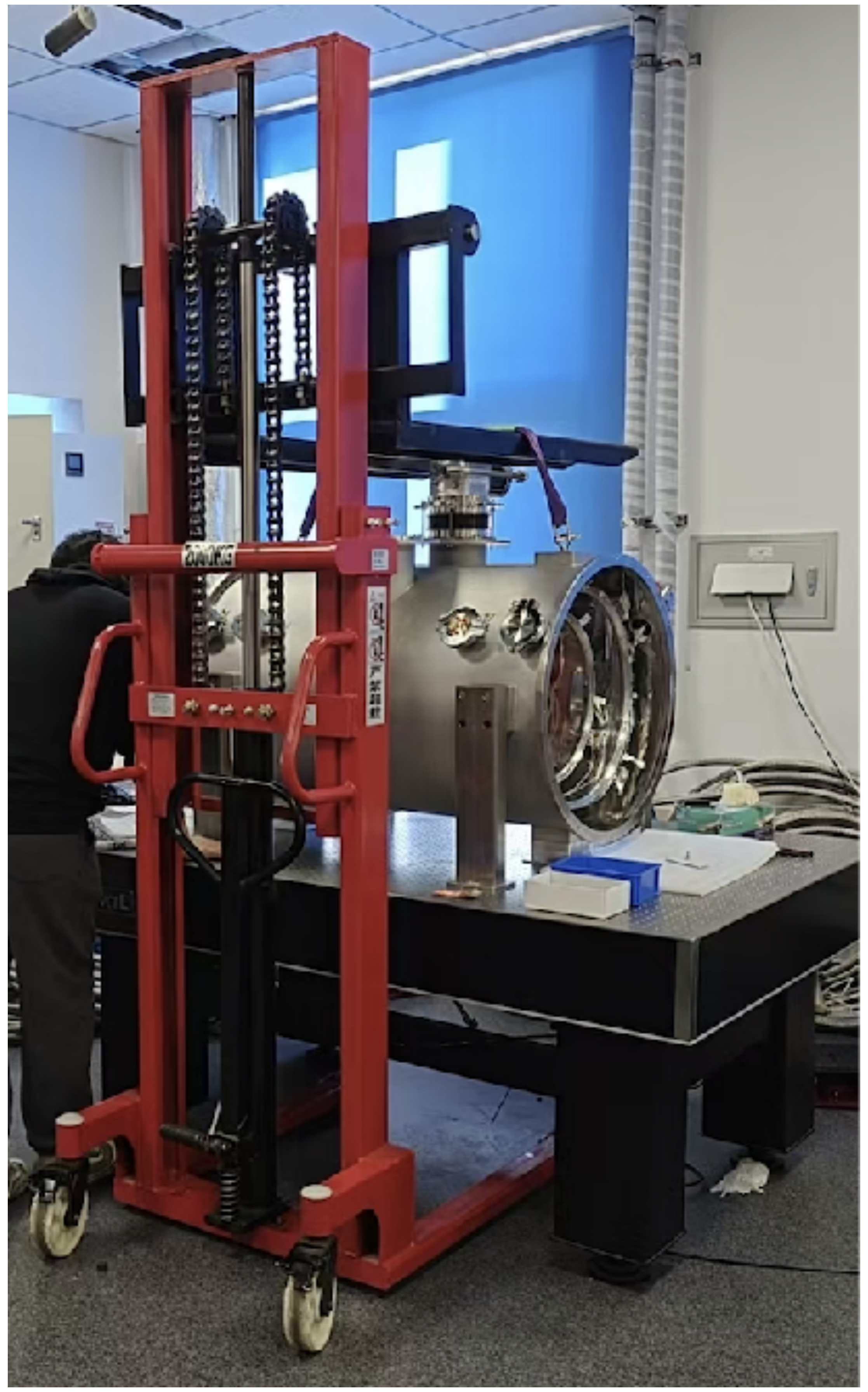


- Mechanical tuning
  - Increase 2.27 GHz mode f
  - Decrease 2.47GHz mode f
  - >1MHz axion mass scan range
- Bounds around $g_{a\gamma\gamma} \sim 8 \times 10^{-12}\text{GeV}$



2K plan

Need the new Cryostat to determine the antenna position at 2K



- Future 2K pathfinder plan
  - Use a better HEMT and optimize some circuit
  - Decrease the noise down to 5K, $Q \sim 10^{10}$
  - AC energy 200J (B~0.07T)
  - 1MHz axion mass scan
  - Hope to gain the sensitivity $g_{a\gamma\gamma} \sim 10^{-14}$GeV

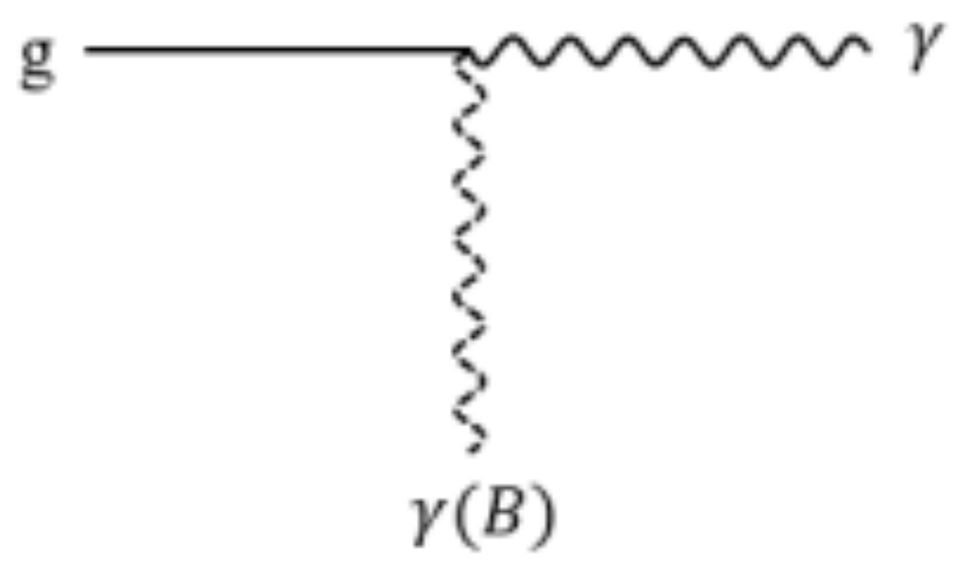
HFGW

$$\left(\partial_t^2 + \frac{\omega_n}{Q_n}\,\partial_t + \omega_n^2\right) e_n(t) = -\,\frac{\int_{V_{\rm cav}} d^3\mathbf{x}\; \mathbf{E}_n^* \cdot \partial_t \boldsymbol{j}_{\rm eff}}{\int_{V_{\rm cav}} d^3\mathbf{x}\; |\mathbf{E}_n|^2}\;,$$

$$P_{\rm sig} = \frac{1}{2}\, Q\, \omega_g^3\, V_{\rm cav}^{5/3}\, (\eta_n\, h_0\, B_0)^2\;,$$

Overlapping factor

$$\eta_n \equiv \frac{\left|\int_{V_{\rm cav}} d^3\mathbf{x}\; \mathbf{E}_n^* \cdot \hat{\boldsymbol{j}}_{+,\times}\right|}{V_{\rm cav}^{1/2}\left(\int_{V_{\rm cav}} d^3\mathbf{x}\; |\mathbf{E}_n|^2\right)^{1/2}}\;,$$

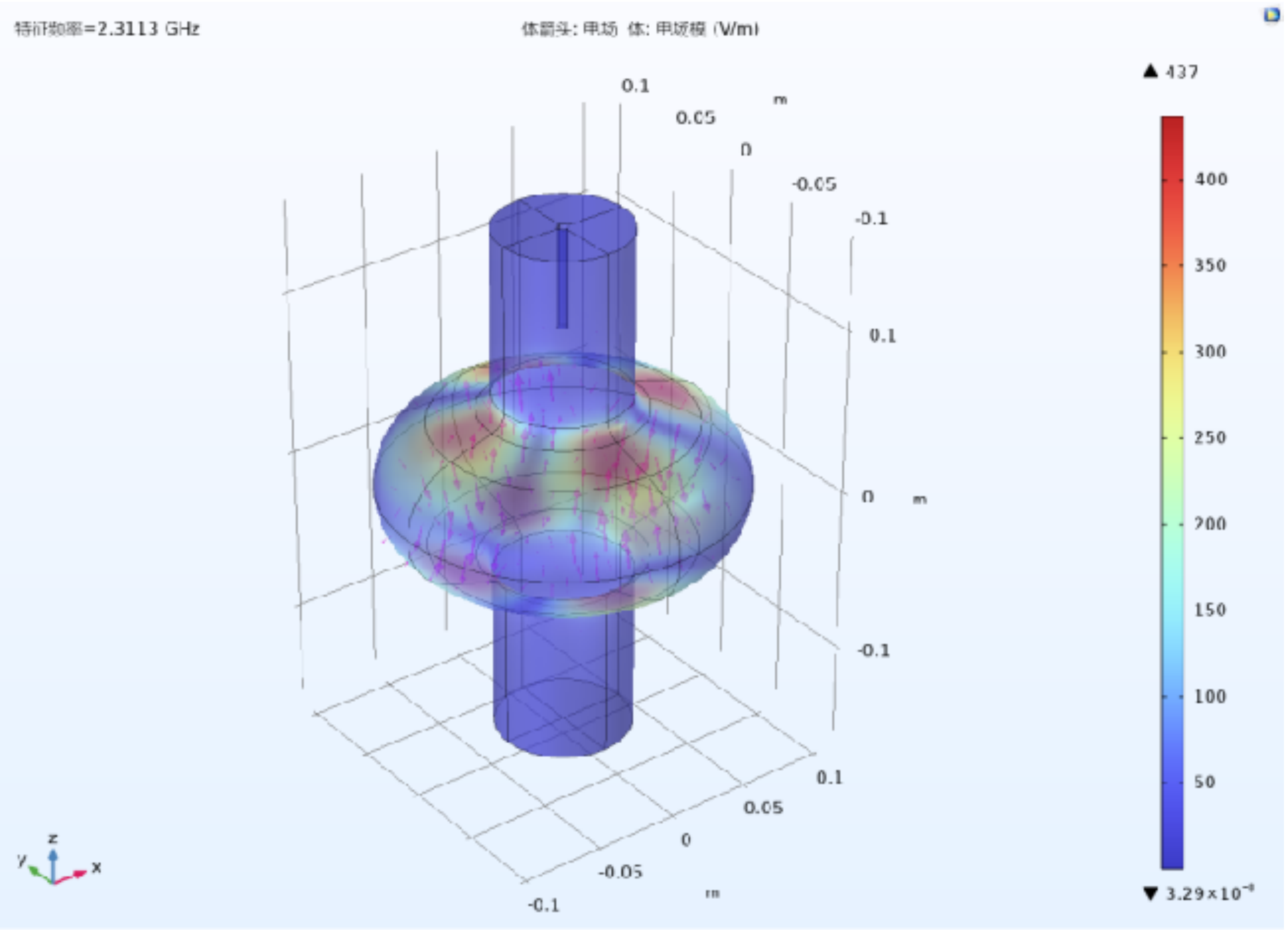


Inverse Gertsenshtein Effect

Neglect the mechanical effect, sub-dominate

HFGW angular sensitivity

For an incoming (θ,ϕ) GWs, for our pumping modes, in the PD frame



The overlapping function