

Novel light dark matter detection with a quantum parity detector using qubit arrays

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We present the design and the sensitivity reach of the qubit-based light dark matter detection experiment. We propose the novel two-chip design to reduce signal dissipation, with quantum parity measurement to enhance single-phonon detection sensitivity. We demonstrate the performance of the detector with full phonon and quasiparticle simulations. The experiment is projected to detect $\gtrsim 30$ meV energy deposition with nearly 100% efficiency and high energy resolution. The sensitivity to $m_\chi \gtrsim 0.01$ MeV dark matter scattering cross section is expected to be advanced by orders of magnitude for both light and heavy mediators, and similar improvements will be achieved for axion and dark photon absorption in the 0.04–0.2 eV mass range.

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Introduction. The properties of dark matter (DM) have long been one of the outstanding puzzles in fundamental physics. Over the years, multi-metric-ton scale direct detection experiments have placed stringent constraints on DM above the GeV mass scale [1–3], which motivates the search for DM in the sub-GeV mass range with transition-edge sensor (TES)- and semiconductor-based experiments [4–8]. Theoretical and experimental efforts are undertaken to explore even lower DM mass regimes toward sub-MeV [9–32].

For halo DM with velocity $v \sim 10^{-3}$, the energy deposition ω in scattering scales with the mass of DM m_χ as

$m_\chi v^2$. While MeV-GeV mass DM is heavy enough to ionize the target, sub-MeV DM typically excites only phonons [33], depositing energy in the sub-eV range below the threshold of conventional direct detection experiments [1–8]. On the other hand, axions [34–38] and dark photons [39–41] can be absorbed by the target and excite a phonon. In the meV mass range, such DM candidates are especially less explored by haloscopes, as the design and operation of resonant cavities at the corresponding frequency range remain challenging.

Recent advances at the interface of particle physics and quantum information science provide a promising path forward. Cosmic-ray-induced correlated errors in qubit arrays highlight the possibility of using qubits as the particle detector [42–47], and qubit-based devices have demonstrated their superior sensitivity to meV photons [48,49].

In this Letter, we introduce the qubit-based light dark matter detection experiment carried out at the China Jinping Underground Laboratory (CJPL). In contrast to

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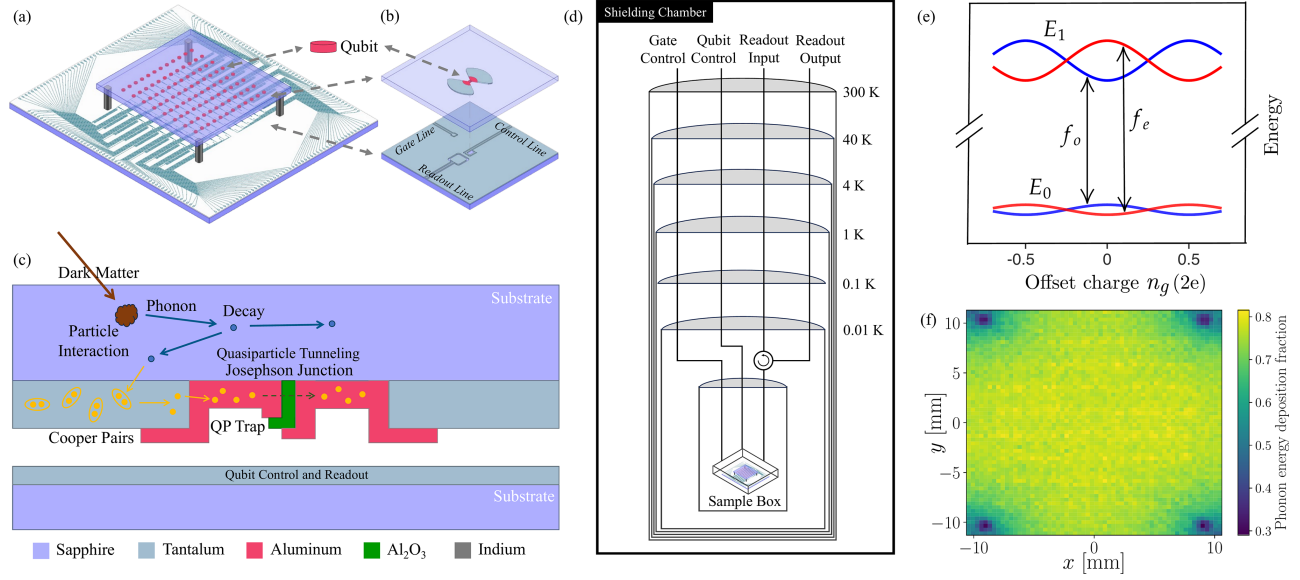


FIG. 1. Schematic drawing of the qubit array and its details. (a) 96 qubits are distributed evenly on the upper slice of the chip, and the lower slice loads the readout, gate, and control lines. The 3D structure of a single qubit is enlarged in (b). (c) The qubit response to DM interaction from the lateral view. The materials are labeled with different colors. (d) Lateral view of the full detector. (e) The energy split of the two lowest qubit levels due to even and odd charge parities. (f) The energy fraction of DM-induced phonons absorbed by the qubits as a function of the x – y location of the interaction in the substrate from simulations.

conceptual studies optimized for on small-scale devices (see, e.g., Refs. [50,51]), we propose a novel two-chip architecture that isolates the DM target from the control lines, employs qubit arrays and quasiparticle traps as single-phonon calorimeters, and reads out quasiparticle tunneling signals using the recently developed quantum parity detector (QPD) technique [46,50]. This design enables, for the first time, sensitive searches for light DM with both large exposure and high efficiency. Using dedicated simulations, we further develop the full analysis chain from DM scattering to signal processing and show that the proposed detector achieves high efficiency for $\mathcal{O}(10 \text{ meV})$ energy depositions, enabling sensitivity to DM scattering well beyond current limits, while probing both freeze-in and freeze-out DM production scenarios. The sensitivity for axions and dark photons could also be advanced by up to 2–5 orders of magnitude with kg year exposure.

Detector design. The detector employs a flip-chip architecture with a top *qubit chip* and a bottom *carrier chip*, as shown in Figs. 1(a)–1(c). The qubit chip with a sapphire substrate hosts 96 qubits, each consisting of a superconducting Al (aluminum)/ Al_2O_3 /Al Josephson junction, and large-area Ta (tantalum) films galvanically connected to the Al layer serving as capacitor pads. The carrier chip integrates readout resonators, as well as gate and control lines for individual qubits. Despite the dense packing of these lines, we leverage careful structural design to enable approximately 30 dB of isolation between adjacent lines to avoid crosstalk between QPDs [52]. DM interacts with the

substrate in the qubit chip, producing a phonon that propagates from the substrate to the Ta films, breaking Cooper pairs and creating quasiparticles (QPs). QPs will then be concentrated in the lower-gap Al in the junction. Tunneling of the QPs will change the *CP* state of the qubit and leads to observable signals.

To be specific, the parity-dependent Hamiltonian of the qubit is

$$H = 4E_C \left(\hat{n} - n_g + \frac{P-1}{4} \right)^2 - E_J \cos \hat{\phi}, \quad (1)$$

where E_C and E_J are the charge and Josephson energies, $\hat{n}$ and n_g are the number operator for Cooper pairs and the offset charge, $\hat{\phi}$ is the superconducting phase difference across the junction, and $P = +1$ (-1) labels the even (odd) *CP* state. The qubit then possesses two lowest energy levels shown in Fig. 1(e). Tunneling of a QP will induce a frequency shift $|f_e - f_o|$, which we exploit to map the *CP* states onto the eigenstates of qubit through a Ramsey-based sequence [53,54]. The qubit array therefore functions as a set of QPDs, capable of resolving individual QP-tunneling events and sensitive to low-energy single phonons. Experimentally, this method has already achieved a time resolution of a few microseconds [46,53]. Moreover, a fidelity of 99.9% for both single-qubit gates and the readout has been demonstrated [55,56]. Therefore, we adopt the *CP* detection fidelity $\mathcal{F} = 95\%$ in this work. We also equip each qubit with an additional gate line to compensate the

offset charge drift [43,57], which allows the detector to operate continuously for weeks to months.

Finally, the detector is packaged and operated at the base temperature of a dilution refrigerator around 10 mK [Fig. 1(d)], and the entire system is enclosed within γ and neutron shieldings at CJPL. The main low-energy background comes from the tunneling caused by residual QPs. Near-gap IR photons from the higher temperature stages of the refrigerator may break Cooper pairs and increase the residual QP density n_{res} , mainly through the coaxial wiring [58]. We apply light filtering in the wires, and use a compact sample box coated with IR-absorbing material to enhance shielding against IR and stray photons, which is expected to reduce the tunneling rate down to about 0.1 Hz [59,60], corresponding to the residual QP density $n_{\text{res}} \sim 10^{-4} \mu\text{m}^{-3}$. Conservatively, we adopt $n_{\text{res}} = 10^{-3} \mu\text{m}^{-3}$ as a benchmark.

As will be demonstrated below, we observe the following distinctive advantages of the detector: (1) The suspended design and the qubit array layout force DM-induced phonons to dissipate to the environment (carrier chip) only through the four In (indium) pillars in the corners. Simulations suggest that more than 80% of the phonon energy is absorbed in the qubits. (2) The Ta-Al design will concentrate QPs in the Al trap, which significantly increases the QP tunneling rate. (3) The detector is sensitive to single-QP tunneling and low-energy single phonons. The simulated detection efficiency is close to 100% in the sub-eV range, in contrast to $\mathcal{O}(\text{eV})$ threshold in TES- and skipper-charge-coupled device-based DM experiments [4,6]. We also reach a high energy resolution of about 50% at 100 meV, allowing us to reject higher-energy backgrounds. (4) The detector mass is scalable with little loss of the detection efficiency. We propose different geometries for the qubit chip—a “thin chip” of 0.82 g ($21.2 \times 22.6 \times 0.43 \text{ mm}$) typical for quantum computation [46] and a “thick chip” of 38 g ($21.2 \times 22.6 \times 20 \text{ mm}$). The final phase of the experiment will be kilogram-mass with arrays of thick chips.

DM interaction rate. Light DM χ may scatter with the electrons in the substrate and excite a sub-eV phonon, at a rate related to the response of the material. The differential scattering rate $dR/d\omega$ is computed with the PhonoDark [33] code. As inputs, we calculate the phonon spectra, equilibrium positions of the ions, the potential energy, and effective ionic charges using first-principle density functional theory with the VASP code [61,62].

The detector can also be used to detect DM absorption. The absorption rate of dark photon in the sapphire substrate is proportional to the imaginary part of the reciprocal of the dielectric function [63–68], which we extract from the darkELF code [63]. The energy deposition is nearly monochromatic in the form of a phonon at the mass of dark photon. Axions could be detected similarly by applying a strong magnetic field.

For both DM scattering and absorption, the expected number of signal events in the detector of mass M during

operation time T is

$$N_{\text{sig}} = \int d\omega M T \frac{dR}{d\omega} \int d\omega_{\text{rec}} \varepsilon(\omega) f_r(\omega_{\text{rec}}, \omega), \quad (2)$$

where ω_{rec} is the reconstructed phonon energy, and ε and f_r are the efficiency and the resolution functions.

Phonon transport and quasiparticle tunneling rate. We simulate propagation and full dynamics of the phonons from DM interaction with the G4CMP code [69], using the designed geometry of the qubit detector. The phonons are uniformly injected in the substrate at energy ω , with an initial polarization state sampled from the partition fractions of the possible polarization states. The phonons will scatter with lattice defects such as isotopes to change their direction and polarization states, at a rate $B\nu^4$, and the longitudinal phonons may decay at a rate $A\nu^5$. Upon reaching the sapphire-Ta interface, phonons have a probability of 94% to transmit into the Ta absorber computed from the acoustic mismatch model [70], and hardly escape back to the substrate once absorbed [69]. Unabsorbed phonons are reflected, assuming specular reflection as investigated in Ref. [71]. Phonons may be lost by exciting surface modes when interacting with imperfectly smooth substrate boundaries. Following Cryogenic Dark Matter Search [72], we assume a single-pass surface loss probability of 0.1%.

Figure 1(f) shows the fraction of phonon energy absorbed by the qubits (rather than the In pillars) as a function of the $x-y$ location of DM interaction. The average fraction is more than 80% in the majority of the substrate with the multiqubit design, as opposed to $\lesssim 10\%$ for similar quantum devices [71,73]. Near the pillars, the fraction drops to below 30%.

Phonons entering the Ta absorber with energy $E_{\text{ph}} > 2\Delta_{\text{abs}}$, twice the superconducting gap of the absorber, will be able to break Cooper pairs in the Kaplan cascade process [74] and produce QPs approaching Δ_{abs} . The average fraction of the energy released to QPs is quantified by η_{pb} , which includes the energy loss to subgap phonons. We adopt $\eta_{\text{pb}} = 0.6$ as suggested by the literature [75,76].

Since the superconducting gap of the Al trap Δ_{trap} is substantially lower than the Ta absorber, QPs will then transport from the absorber to the trap. We introduce the trapping efficiency η_{trap} to quantify the fraction of QPs in the absorber that are transmitted to and finally bound in the trap. We study the trapping process by solving the diffusion equation of QPs in between the absorber and the trap, showing $\eta_{\text{trap}} \sim 0.7$ in our setup. Hence, the number density of QPs in the trap due to the absorption of phonon energy E_{ph} in the absorber is $n_{\text{qp}} = \eta_{\text{pb}} \eta_{\text{trap}} E_{\text{ph}} / V_{\text{trap}} \Delta_{\text{trap}}$, where V_{trap} is the volume of the trap.

After creation, the QPs may deplete exponentially in the recombination process at a time scale τ_{qp} of a few ms [77,78]. Conservatively, we take $\tau_{\text{qp}} = 1 \text{ ms}$ in this work.

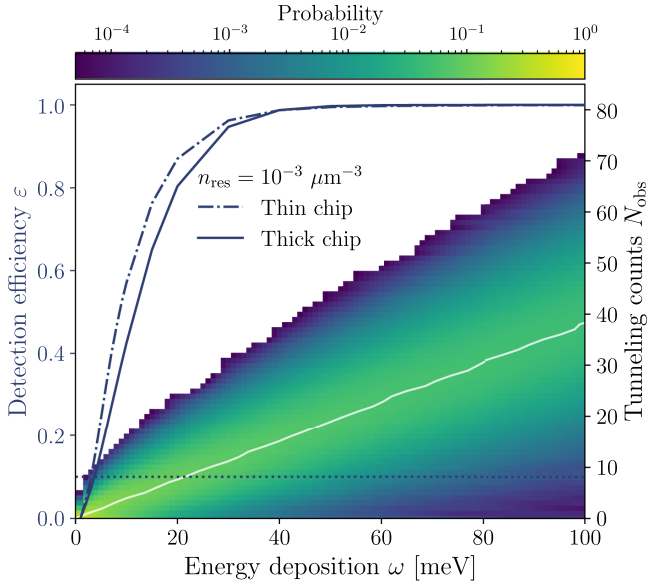


FIG. 2. Blue lines show the detection efficiency as a function of the energy deposition from DM interaction for a thin-chip (dash-dotted) and a thick-chip (solid) detector. The dotted line marks the 10% efficiency. The colors depict the probability distribution of tunneling counts in all qubits in one measurement time window N_{obs} for a thin chip as a function of the energy deposition, and the white line marks the reconstructed energy corresponding to the maximum likelihood as a function of N_{obs} .

The actual number of QPs in the trap may also deviate from expectation due to the correlation in the QP creation process captured by the Fano factor $F \sim 0.2$ [79], which then follows a normal distribution with a width $\sigma = \sqrt{Fn_{\text{qp}}V_{\text{trap}}}$ [80]. The tunneling rate is computed to be [81–84]

$$\Gamma_{\text{tun}}(t) \simeq \frac{16E_J k_B T}{h \mathcal{N}_{\text{qp}} \Delta_{\text{trap}}} n_{\text{qp}} e^{-t/\tau_{\text{qp}}} \quad (3)$$

in the low temperature limit $T \ll \Delta_{\text{trap}}$, where $\mathcal{N}_{\text{qp}}$ represents the number of quasiparticle states available in the trap. The background tunneling rate due to nonzero residual QP density n_{res} in the trap can be calculated similarly using Eq. (3), by replacing $n_{\text{qp}} e^{-t/\tau_{\text{qp}}}$ with n_{res} .

The setup, relevant parameters and the effects of different residual QP density are detailed in the Supplemental Material [85].

Detector resolution and efficiency. The number of tunnelings at a qubit in one measurement is the sum of phonon-induced tunnelings N_s and residual QP-induced tunnelings N_0 , which we draw from the Poisson distribution, considering the detection fidelity at the same time (we design a time-domain filtering process to suppress readout-induced dark counts to 2 orders of magnitude below the residual quasiparticle tunneling rate; see the Supplemental Material [85] for details).

We identify the DM-induced phonon energy ω from the observation of the total number of tunnelings N_{obs} of all qubits in a 1.5 ms time window. The reconstructed energy can be obtained using the maximum likelihood method, i.e., $\omega_{\text{rec}} = \max_{\omega} \mathcal{L}(N_{\text{obs}}|\omega)$, where the likelihood $\mathcal{L}$ is constructed from the simulations as shown in Fig. 2. The energy resolution, defined as the ratio of FWHM and ω_{rec} , decreases for larger phonon energy and reaches about 50% at 100 meV. The energy resolution function f_r is constructed as Gaussian with $\sigma = \text{FWHM}/2.355$. Therefore, high energy background events falling outside the detection window can be rejected.

We now find the detection efficiency given the background tunnelings from residual QPs. To identify a signal, we require that the total number of tunnelings for $N_{\text{qb}} = 96$ qubits in a measurement j to deviate from the background tunneling $N_b = \mathcal{F}N_0N_{\text{qb}}$ (background-only hypothesis) at least at 3σ C.L. assuming χ^2 distribution, i.e., $\sum_{N_{\text{obs}}=N_j}^{\infty} \text{Poisson}(N_{\text{obs}}, \mu = N_b) < 0.0027$. We then find the efficiency as the fraction of simulations that satisfy this condition.

The detection efficiency ϵ , displayed in Fig. 2, rapidly approaches 100% as the phonon energy increases. Ten percent efficiency corresponds to $\omega \sim 3$ meV both for thin- and thick-chip designs, orders of magnitude lower than the threshold of typical DM direct detection experiments. The thick-chip design degrades the efficiency only slightly compared to a thin chip. Although phonons travel longer in the thick-chip substrate and tend to decay more to lower energy phonons below the pair-breaking threshold, few-meV phonons have mean free paths exceeding the size of the thick chip, preventing efficient decay.

Sensitivity and background. We derive the projected limits on DM parameters by requiring the number of signal events from DM interaction computed in Eq. (2) not to exceed the expected background at 90% C.L. We only analyze the single-phonon regime where the energy $\omega_{\text{rec}} \leq 100$ meV; multiphonon and ionization signals will be explored in future work.

We incorporate two types of background—tunnelings caused by residual QPs and the soft scattering of high energy photons, with the former accounted for in the detection efficiency. Cosmic rays and radioactive decay typically lead to energy deposition much higher than keV away from the signal region and are largely shielded by the rock and shielding at CJPL. However, high energy photons produced inside the refrigerator may scatter softly and deposit energy below 100 meV, which is indistinguishable from DM interaction on an event-by-event basis. We adopt the background calculation in Ref. [86], using the benchmark background photon spectrum measured by the Expérience pour DEtecter les WIMPs en Site Souterrain Collaboration [87]. This amounts to the deployment of 20 cm of lead and 50 cm of polyethylene to shield against γ

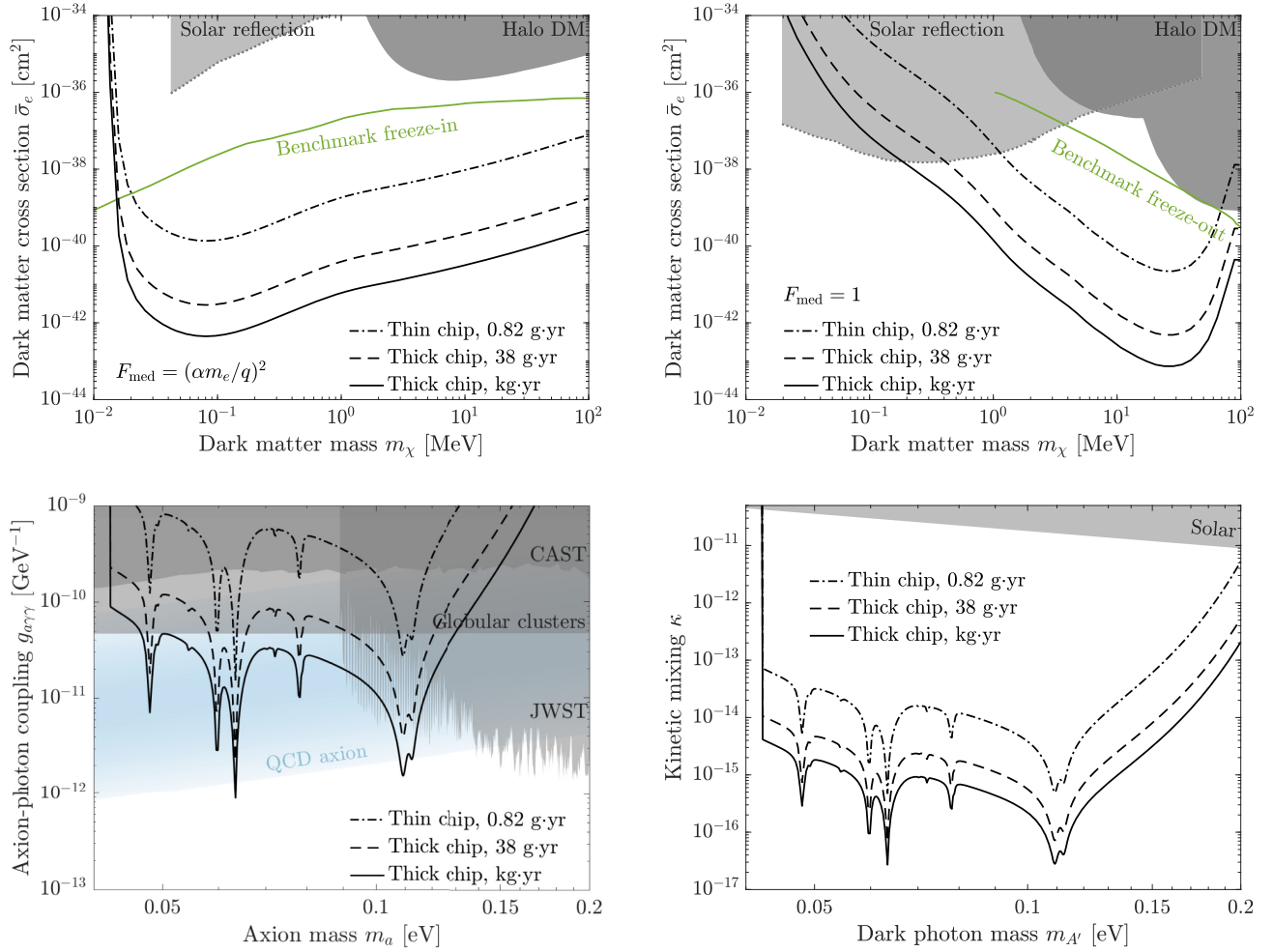


FIG. 3. Upper: 90% C.L. sensitivity on DM-electron scattering cross section. Black lines correspond to different exposures using the detector design in this work. We also show existing constraints from the direct detection of halo DM [4,6,7,91,92,102,103], and the DM accelerated and reflected by electrons in the Sun [93,94]. The green lines show the cross section to produce the correct DM relic density in the benchmark freeze-in process [9,11,95,96] for a light mediator (left) and freeze-out process [11,97–101] for a heavy mediator (right). Lower: 90% C.L. sensitivity on DM absorption. For axions, we also show existing constraints on the axion-photon coupling $g_{\gamma\gamma}$ from CERN Axion Solar Telescope [104,105], the globular clusters [106,107] and James Webb Space Telescope [108,109] (left). The blue band shows parameter space for QCD axions [34–38]. For dark photons, we show limits on kinetic mixing κ from solar cooling [110–112] (right).

and neutrons in our setup. The expected background rate is $5.27 \text{ kg}^{-1} \text{ yr}^{-1}$, which we use as a benchmark in this work.

In addition, the stress released due to the difference in the thermal contraction of the detector materials during the cooling phase may also cause phonon bursts in the qubit detector [88]. The stress-induced background decreases exponentially in a typical time scale of 6–10 days [88,89] and could be eliminated by waiting a long enough time before measurement. Therefore, we do not include them in the calculation.

We note that a low energy excess (LEE) above eV has been observed in several experiments using different technologies (see Ref. [90] for a review). The sub-100 meV background targeted by our qubit detector may or may not share the same origin as the LEE. The background in this specific energy range will be measured and characterized upon experimental operation, and the

ultimate sensitivity to scattering cross sections will scale proportionally with this background level. We refer to the Supplemental Material [85] for more detailed discussions on the anticipated origins and mitigation strategies for these backgrounds.

We show the projected sensitivity on the DM-electron scattering cross section in the upper panels of Fig. 3. For both light and heavy mediators, the projected limits of a single thin-chip detector with 0.82 g yr exposure surpass the existing constraints by orders of magnitude, including the limits from the direct detection of halo DM [6,7,91,92], and DM reflected from the Sun [93,94], allowing us to examine the benchmark freeze-in [9,11,95,96] and freeze-out [11,97–101] scenarios.

We also show the sensitivity on dark photon kinetic mixing, which improves over the constraints from solar cooling [110–112] by 4–5 orders of magnitude with a

single thin qubit chip. A similar process could be leveraged to detect axion DM with the application of strong magnetic field B_0 , the feasibility of which has recently been demonstrated experimentally in Ref. [113]. A single thin chip with one year running can already exclude new parameter space with $B_0 = 10$ T, and kg yr exposure can advance the current constraints from globular clusters by up to about 2 orders of magnitude.

Conclusions and prospects. We demonstrate the performance of a newly designed cryogenic qubit-array detector. Although we focus on the sensitivity to DM-electron scattering and DM absorption, similar sensitivity and mass reach could be achieved for DM coupling to nucleons [114].

In this study, we use only the total number of observed tunnelings to reconstruct the phonon energy. In a multiqubit setup, topology of tunneling qubits and timing correlations could further improve energy and position reconstruction, as well as signal-background separation—since phonon-induced tunnelings decay rapidly in time while residual tunneling events remain nearly constant. Moreover,

reducing Δ_{trap} could further enhance the detection efficiency, while changing the substrate material will modify the detector's response to different DM models [115,116]. A detailed exploration of these improvements is deferred to future work.

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Data availability. The data that support the findings of this article are openly available [85].

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