粒子与天体物理学多前沿奇异现象研讨会（MEPA 2025）

# Probing light dark matters using gravitational waves, superfluid and Transmon Qubits

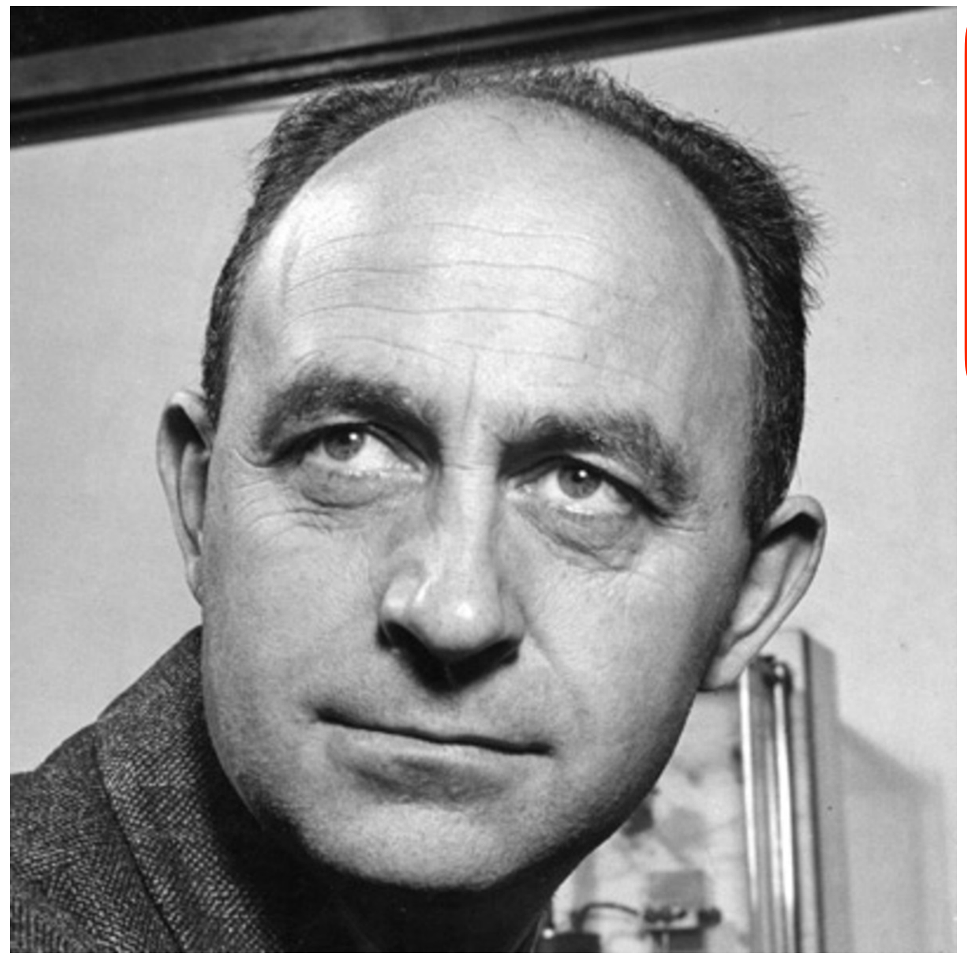
晁 伟（WEI CHAO）
北京师范大学（BEIJING NORMAL UNIVERSITY）

2025.04.13@NANJING

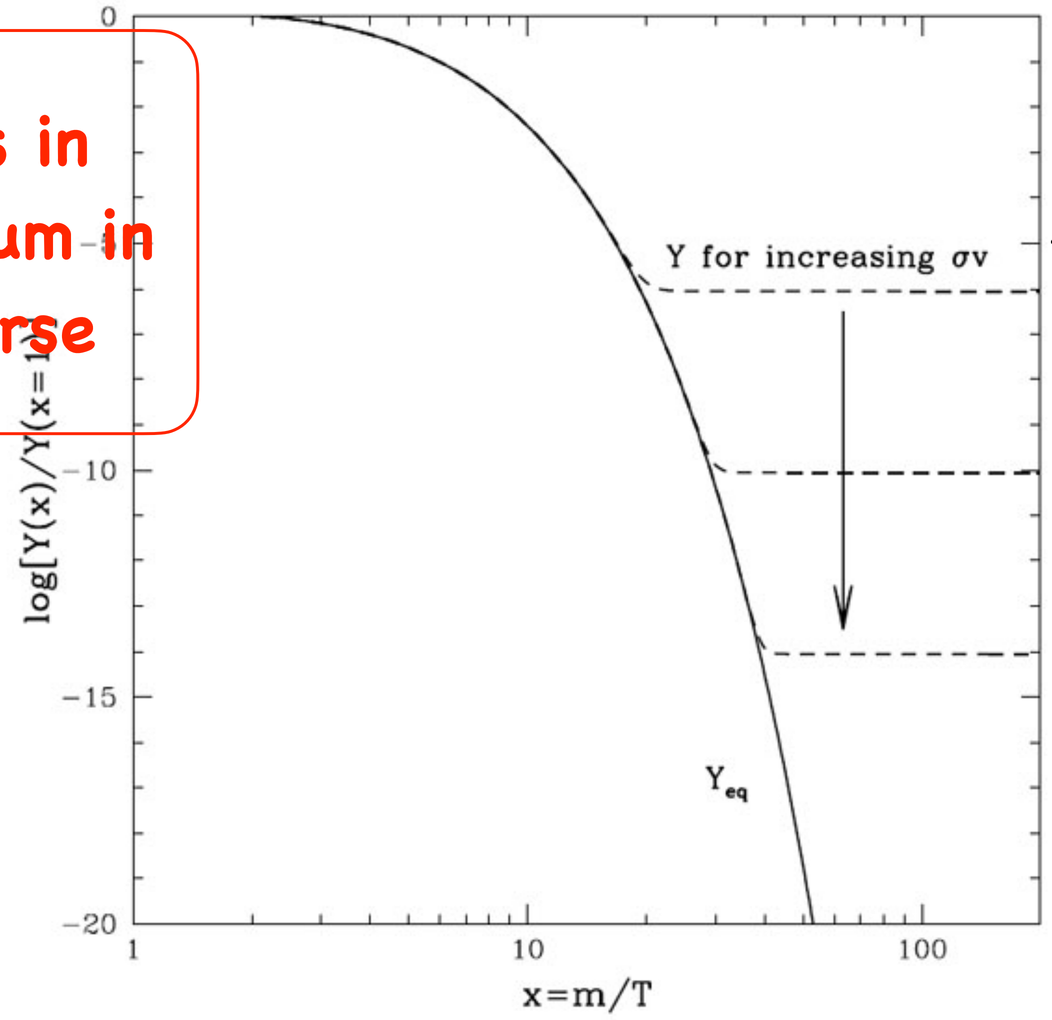
# Possible dark matter candidate

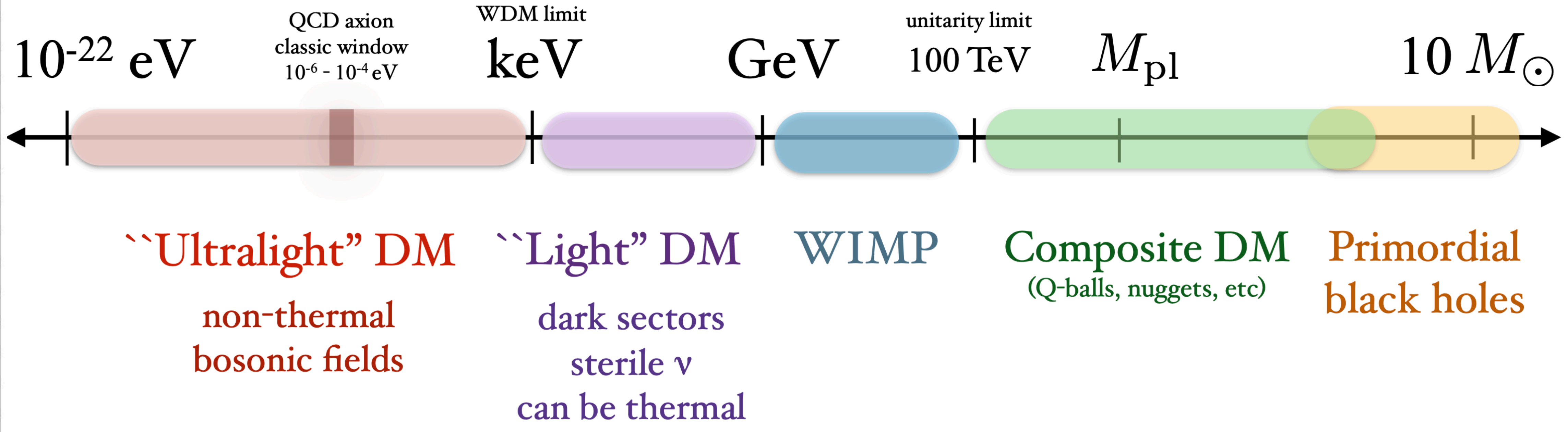
The WIMP Miracle!

Dark matter candidate



Assuming DM is in thermal equilibrium in the early universe




Fermi's constant introduced in 1930s to describe beta decay

The relic density: $\Omega_\chi \sim \frac{1}{\langle \sigma v \rangle} \sim \frac{m_\chi^2}{g_\chi^4}$

$m_\chi \sim 100$ GeV

$g_\chi \sim 0.6$

$\Omega_\chi \sim 0.1$

$G_F \approx 1.1 \times 10^{-5}\ \mathrm{GeV}^{-2}$

New mass scale: 100 GeV

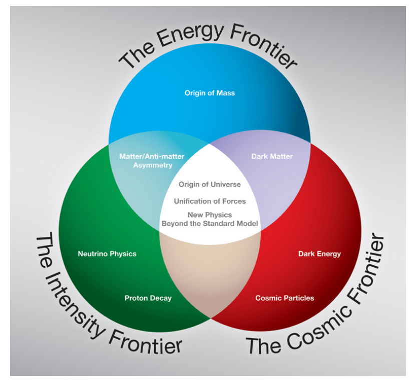
The weak coupling

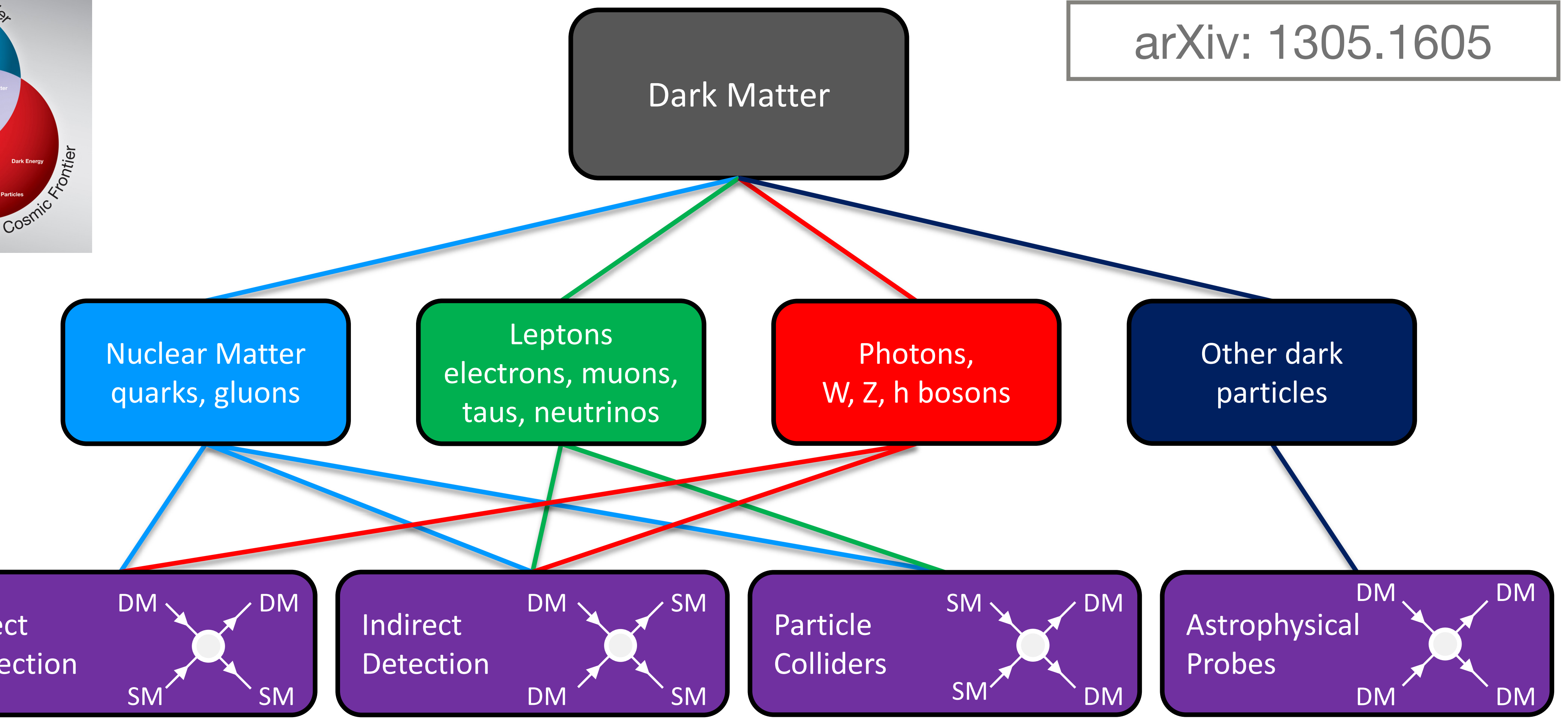
Brief History:

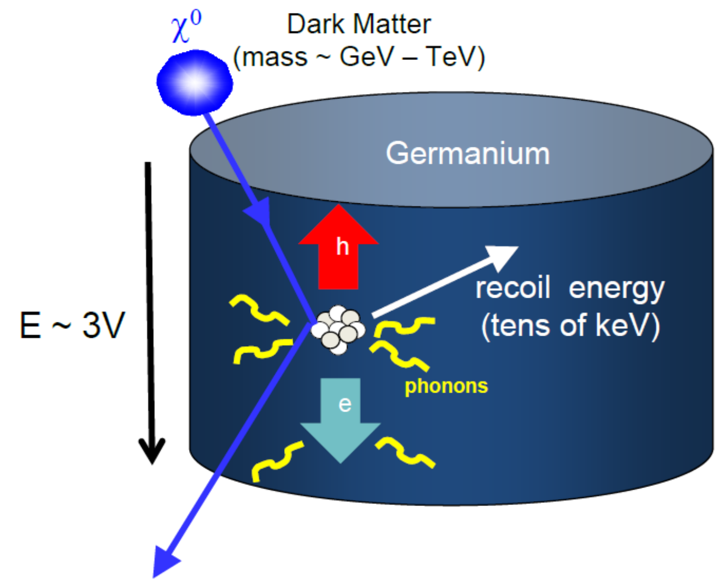
- WIMP
- Axion
- Sub-GeV
- Primordial black hole
- Super heavy DM
- Super light DM
- ……

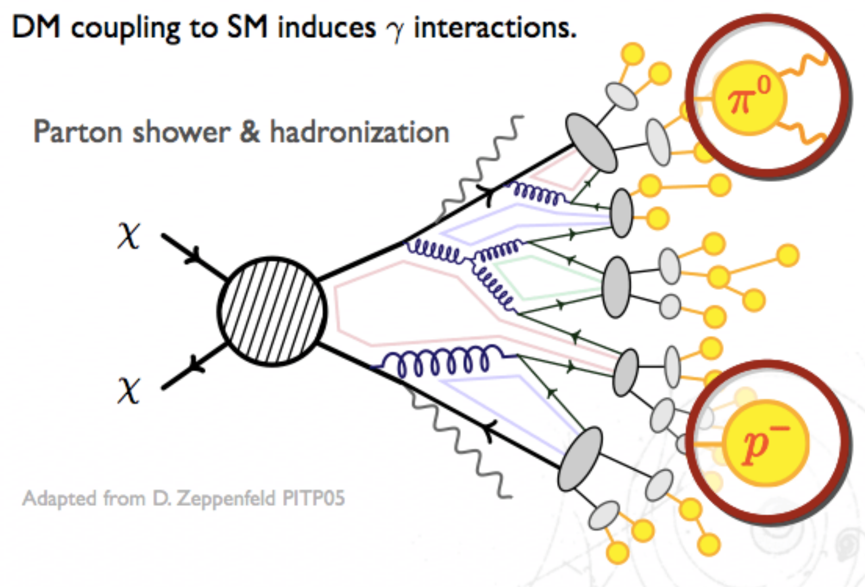
# DM Dectections

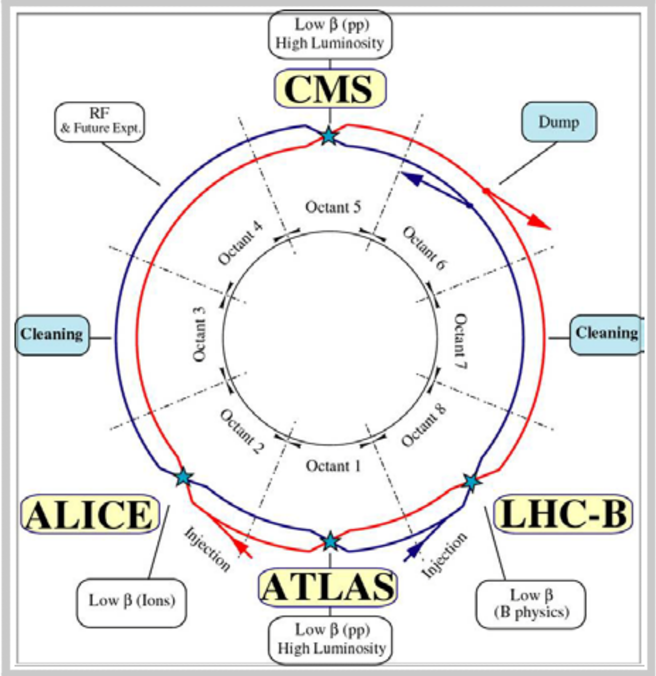
## Traditional methods



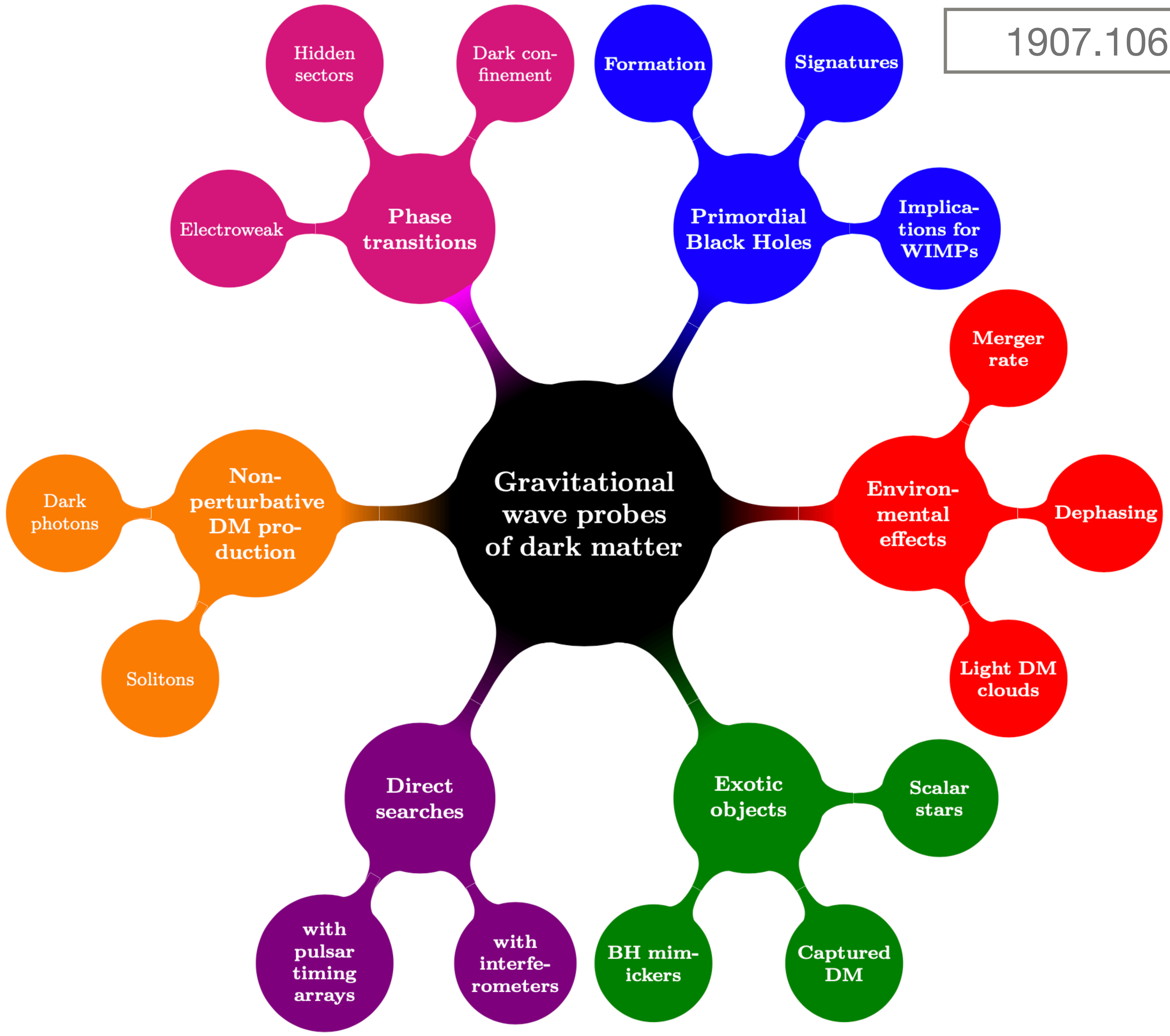




## Modern strategies

1907.10610



# Outline

- Gravitational wave signals of dark photon dark matter.

Oscillations of Ultralight Dark Photon into Gravitational Waves

Chao, Jingjing Feng, Huai-ke Gul and , Tong Li, Nucl.Phys.B(2024)

- Constraining exotic light DM with superfluid.

Axion and Dark Fermion Electromagnetic Form Factors in Superfluid He-4,

Chao, Sichun Sun, Xin Wang, Chenhui Xie, Phys.Rev.D（2024）

- Constraining bosonic DM using transmon qubit

Probing light bosonic DM with transmon qubits,

Chao, Yu Gao, Mingjie Jin, Xiaosheng Liu and Xilei Sun, e-Print: 2412.20850 [hep-ph]

# Outline

✔

- Gravitational wave signals of dark photon dark matter.

Oscillations of Ultralight Dark Photon into Gravitational Waves

Chao, Jingjing Feng, Huai-ke Gul and , Tong Li, Nucl.Phys.B(2024)

- Constraining exotic light DM with superfluid.

Axion and Dark Fermion Electromagnetic Form Factors in Superfluid He-4,

Chao, Sichun Sun, Xin Wang, Chenhui Xie, Phys.Rev.D（2024）

- Constraining bosonic DM using transmon qubit

Probing light bosonic DM with transmon qubits,

Chao, Yu Gao, Mingjie Jin, Xiaosheng Liu and Xilei Sun, e-Print: 2412.20850 [hep-ph]

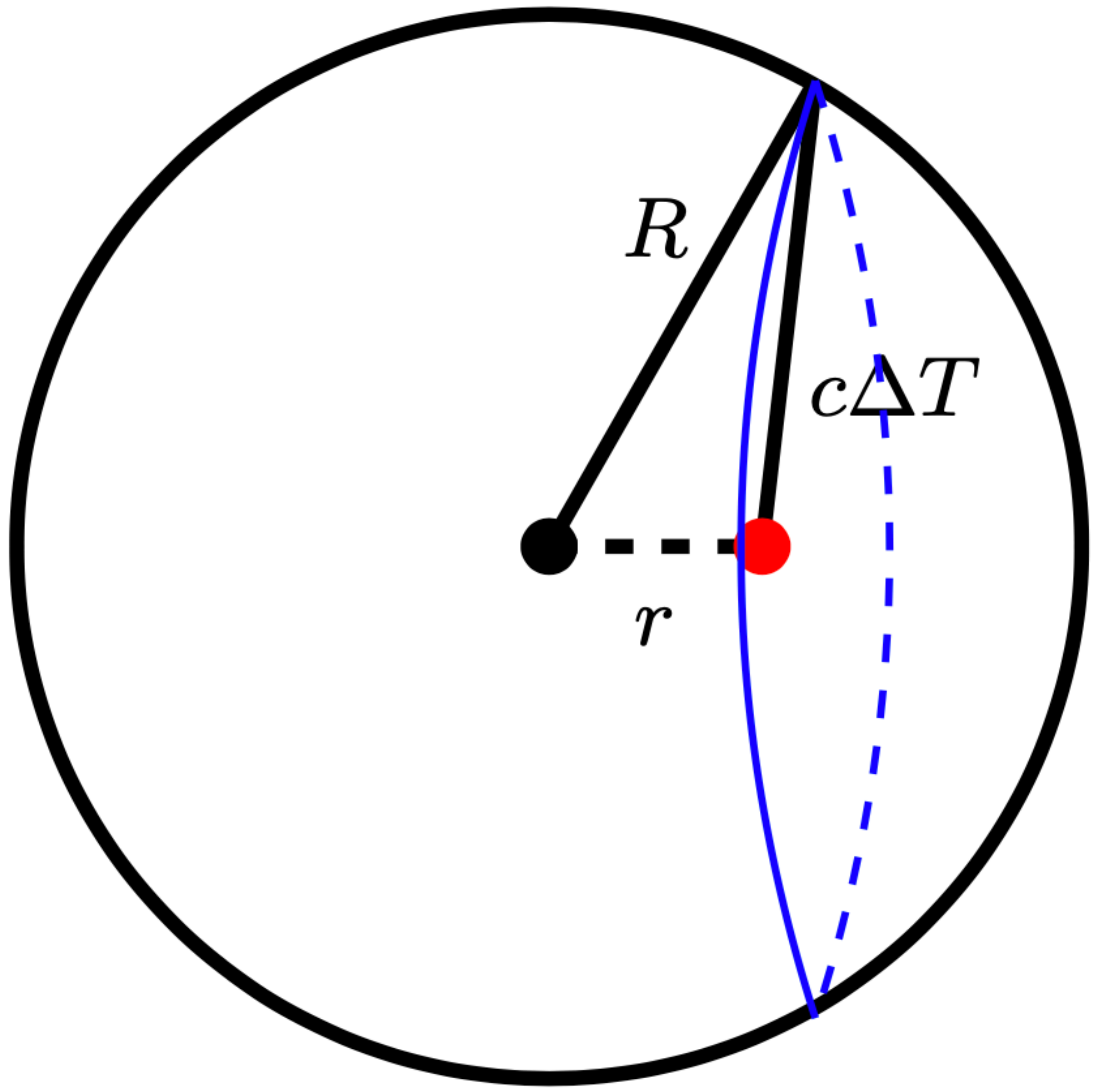
# Gravitational waves from DP oscillations

**Where to start?: Photon-Graviton oscillation**

G. Raffelt and L. Stodolsky, Phys. Rev. D 37, 1237 (1988).

| | |
|---|---|
| Action | $S = \int d^4x\sqrt{-g}\left(\frac{1}{2}M_{pl}^2 R - \frac{1}{4}\hat{F}_{\mu\nu}g^{\alpha\mu}\hat{F}_{\alpha\beta}g^{\beta\nu} - \frac{\varepsilon}{2}F_{\mu\nu}g^{\alpha\mu}\hat{F}_{\alpha\beta}g^{\beta\nu}\right)$ |
| EOM | $i\frac{\partial}{\partial z}\begin{pmatrix}\gamma_\parallel \\ \gamma'_\parallel \\ G_\times\end{pmatrix} = \left[\omega + \begin{pmatrix}\Delta_{\gamma\gamma} & \Delta_{\gamma\gamma'} & \Delta_{\gamma h} \\ \Delta_{\gamma\gamma'} & \Delta_{\gamma'\gamma'} & \Delta_{\gamma' h} \\ \Delta_{\gamma h} & \Delta_{\gamma' h} & 0\end{pmatrix}\right]\begin{pmatrix}\gamma_\parallel \\ \gamma'_\parallel \\ G_\times\end{pmatrix}$ |
| Oscillation probability | $P(i \to j) = \left\lvert \sum_\alpha \mathcal{U}^*_{i\alpha} e^{-ip_\alpha z} \mathcal{U}_{j\alpha} \right\rvert^2 , \quad i,j \in \gamma, \gamma', G_\times .$ |
| Two flavors | $P(\gamma' \to G_\times) = \frac{4\Delta^2_{\gamma' h}}{4\Delta^2_{\gamma' h} + \Delta^2_{\gamma'\gamma'}} \sin^2\left(\frac{1}{2}\sqrt{4\Delta^2_{\gamma' h} + \Delta^2_{\gamma'\gamma'}}\, z\right) .$ |

# Local relic density of GW




$$f(r,\ \Delta T) = \begin{cases} 1\ , & c\Delta T \le R - r\ , \\ \frac{1}{2}\left(1 - \frac{r^2 + c^2\Delta T^2 - R^2}{2rc\Delta T}\right)\ , & c\Delta T > R - r\ , \\ 0\ , & c\Delta T \ge R + r\ , \end{cases}$$

## Energy density

$$\rho_{\rm LGW}(t_0) = \frac{1}{V_{\rm GC}} \int_{t_0-2T}^{t_0} dt \int_0^R dr \mathscr{L}(r) \cdot f(r, t_0 - t) 4\pi r^2\ .$$

$\mathscr{L}$: luminosity of the oscillation

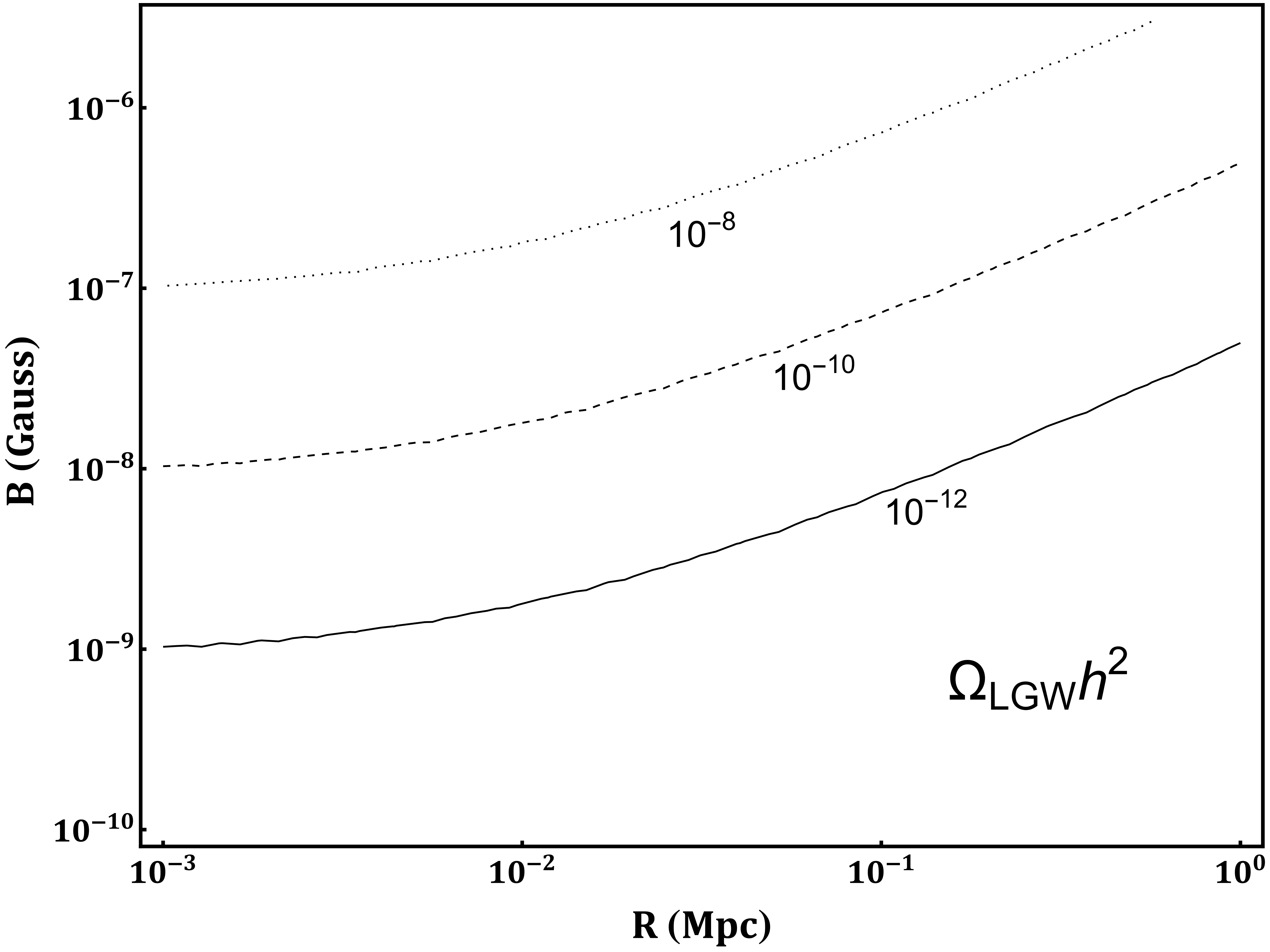
## Flux of GW

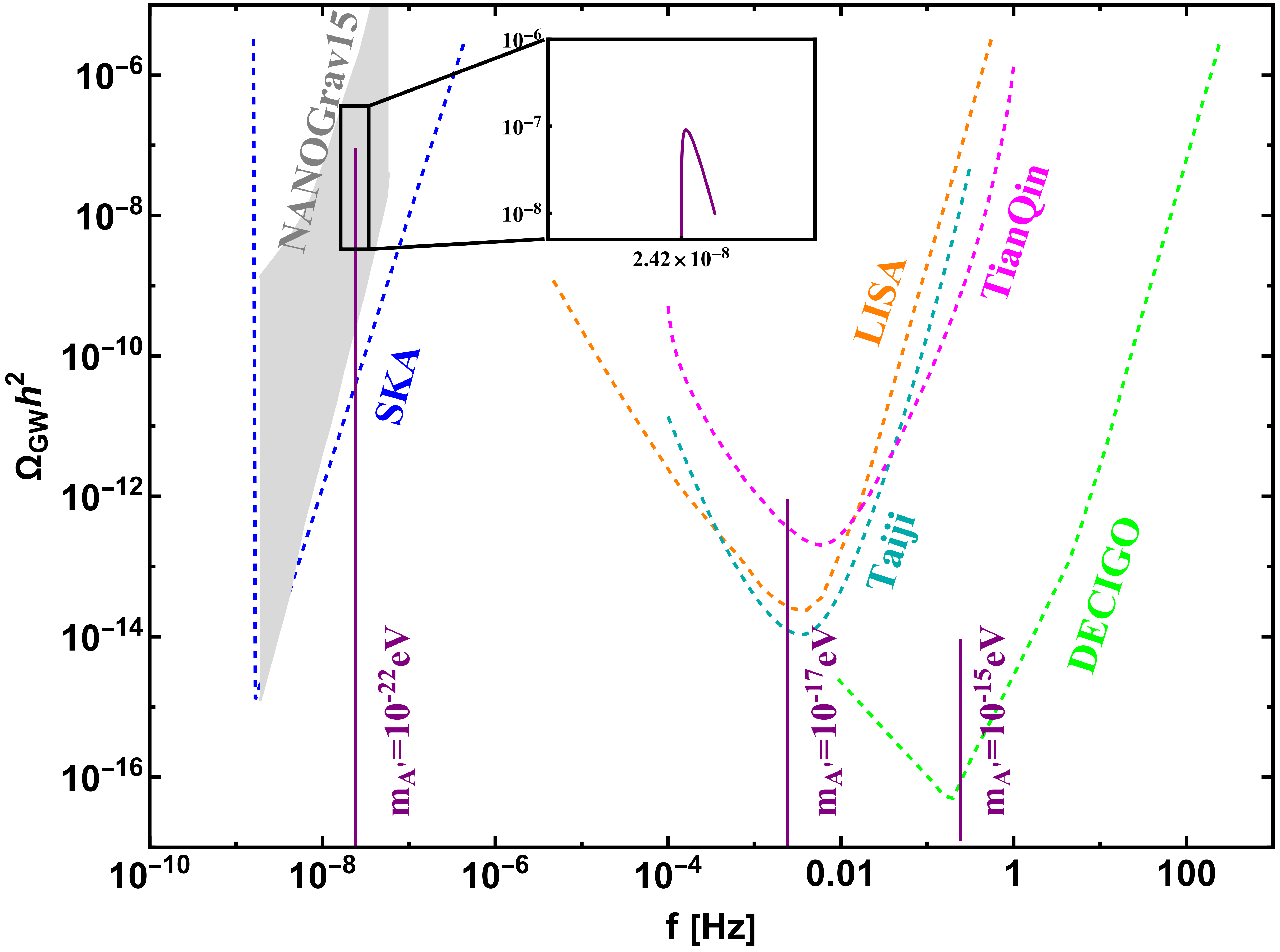
$$\mathscr{D}_{\rm GW} = \int \frac{dn_{\rm DM}(r)}{dE} \frac{\mathscr{R} d^3 r}{4\pi |\vec{r} - \vec{d}|^2}$$

$$\mathcal{R} = \begin{cases} \frac{2\Delta^2_{\gamma' h}}{4\Delta^2_{\gamma' h} + \Delta^2_{\gamma'\gamma'}} \frac{1}{\mathbb{T}}\ , & L \gg v\mathbb{T}\ , \\ P(\gamma' \to G_\times) \frac{1\mathrm{kpc}}{L} \times 1.02 \times 10^{-14}\ , & L \ll v\mathbb{T}\ , \end{cases}$$

$$\sim 1.72 \times 10^{-7} / m^2_{\rm ULDP}\ {\rm cm}^{-2} \cdot {\rm s}^{-1} \cdot {\rm eV}^{-1}$$

# Local relic density of GW



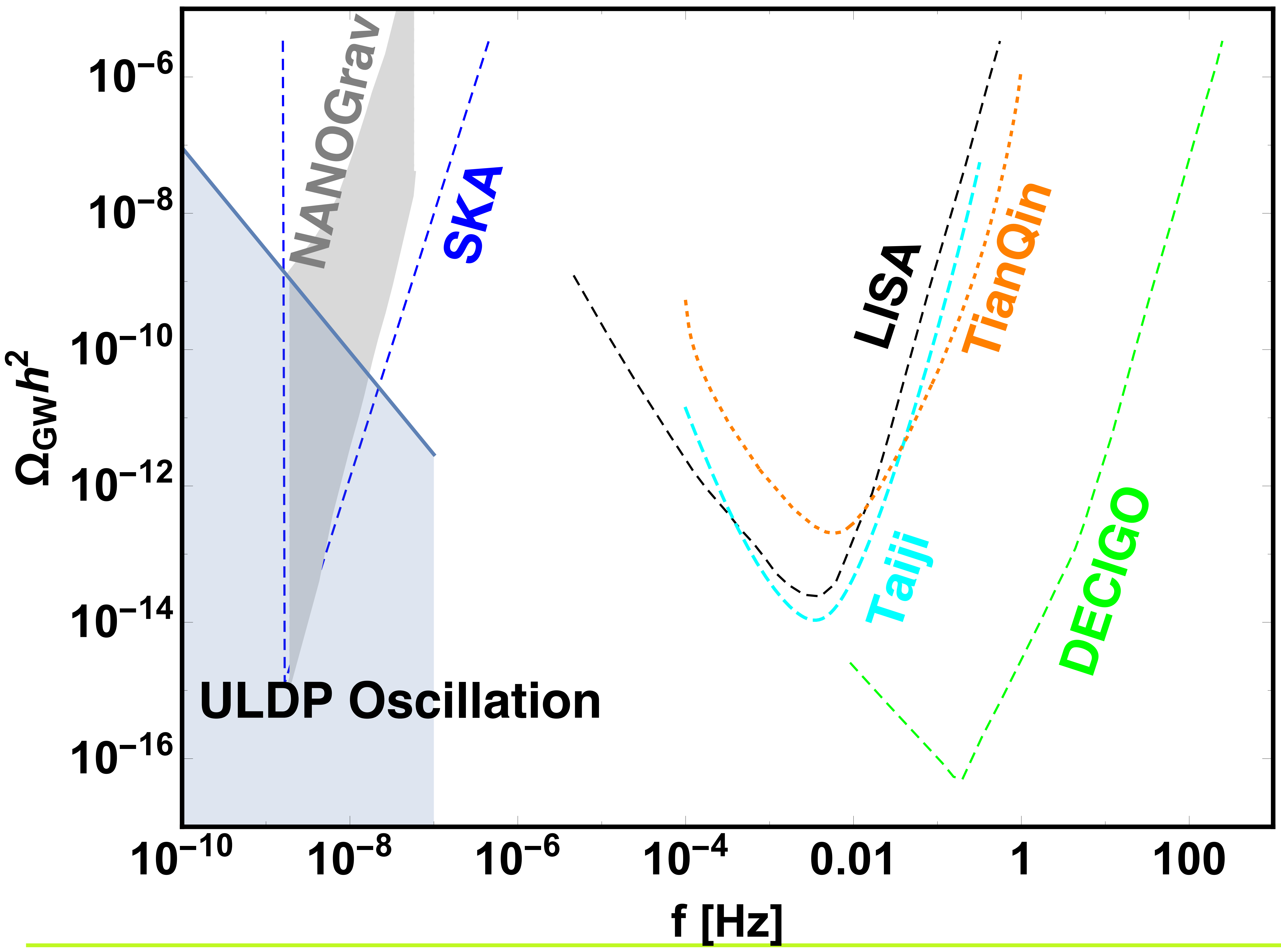
# Dark photon oscillations in the early universe

## Mechanisms for the production of primordial dark magnetic field

- PDMF can be generated during the pseudo-scalar inflation, $\phi$, with the Chern-Simons interaction, $\frac{\phi}{4\pi f_a} F\widetilde{F}$ .
- PDMF can be produced from the axion oscillations.
- PDMF can be generated from the oscillation of photon in the axion or some other exotic background.

**Redshifted as $(1+z)^{-2}$**

# Dark photon oscillations in the early universe




$$\frac{d\rho_{\rm GW}}{dt} = E_{\rm ULDP} n_{\rm ULDP} \mathscr{R}\left(\gamma' \to {\rm SGW}\right) \ ,$$

$$\rho_{\rm SGW} = \int_{z_0}^{z_1} n_{\rm ULDP}(z_0)\mathscr{R}(z) m_{\rm ULDP} \frac{dz}{(1+z)^2 H(z)}$$

$$\Omega_{\rm GW}(f) = \frac{n_{\rm ULDP}\mathscr{R}(f)}{H(f)} \frac{f}{\rho_C} \ ,$$

$$B(z_1) \sim 1 \text{ Gauss}$$

$$m_{DP} \sim 10^{-20} \text{ eV}$$

# Outline

- Gravitational wave signals of dark photon dark matter.

Oscillations of Ultralight Dark Photon into Gravitational Waves

Chao, Jingjing Feng, Huai-ke Gul and , Tong Li, Nucl.Phys.B(2024)

✔ 
- Constraining exotic light DM with superfluid.

Axion and Dark Fermion Electromagnetic Form Factors in Superfluid He-4,

Chao, Sichun Sun, Xin Wang, Chenhui Xie, Phys.Rev.D（2024）

- Constraining bosonic DM using transmon qubit

Probing light bosonic DM with transmon qubits,

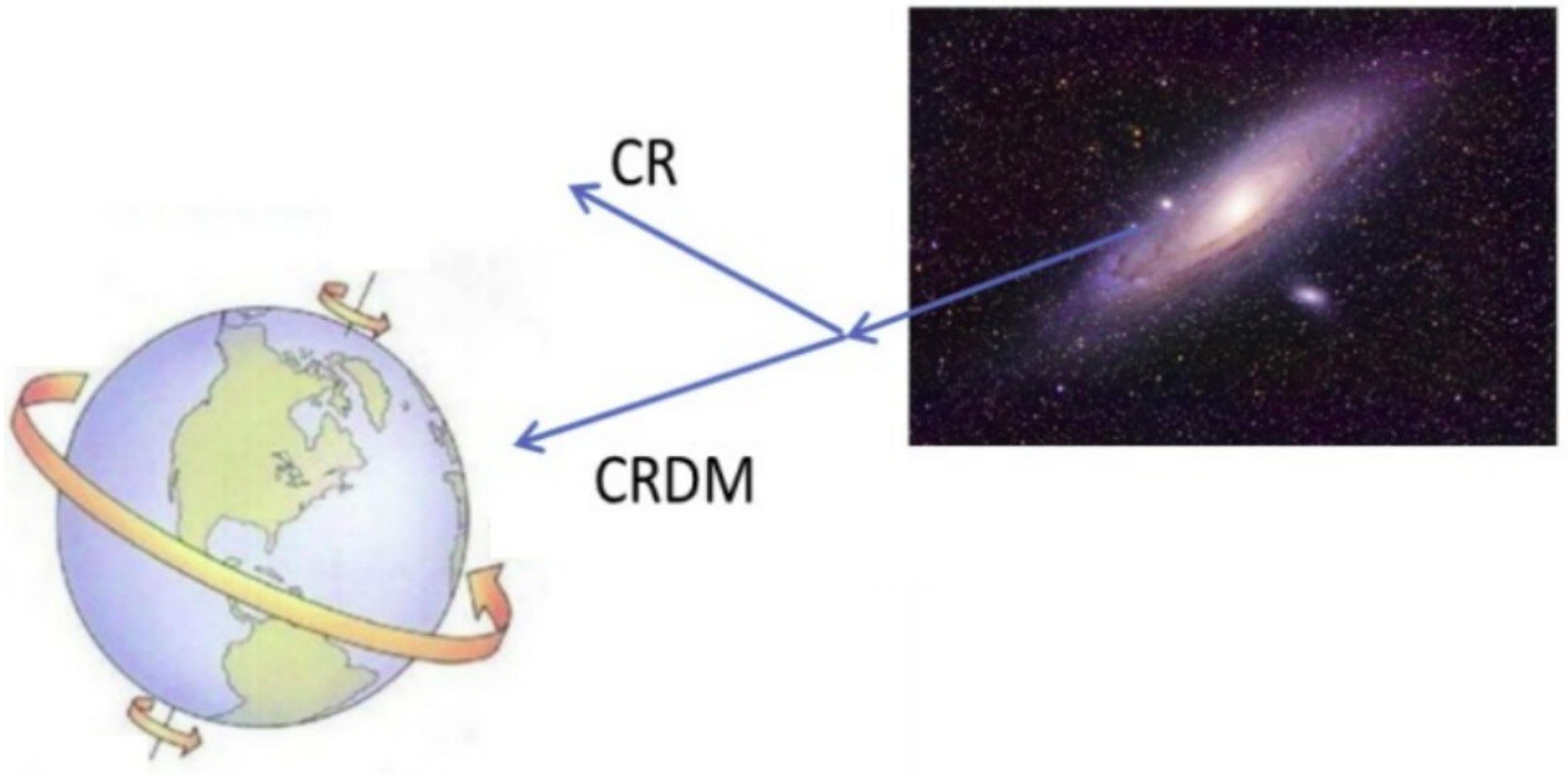
Chao, Yu Gao, Mingjie Jin, Xiaosheng Liu and Xilei Sun, e-Print: 2412.20850 [hep-ph]

# Direct detections of light DM

**Problem: Kinetic energy of light DM is too small**

$$v_{\rm DM} \sim 10^{-3}$$

$$E_R \sim \frac{(p_{\rm DM} - p'_{\rm DM})^2}{2m_T} \ll E_{\rm Threshold}$$

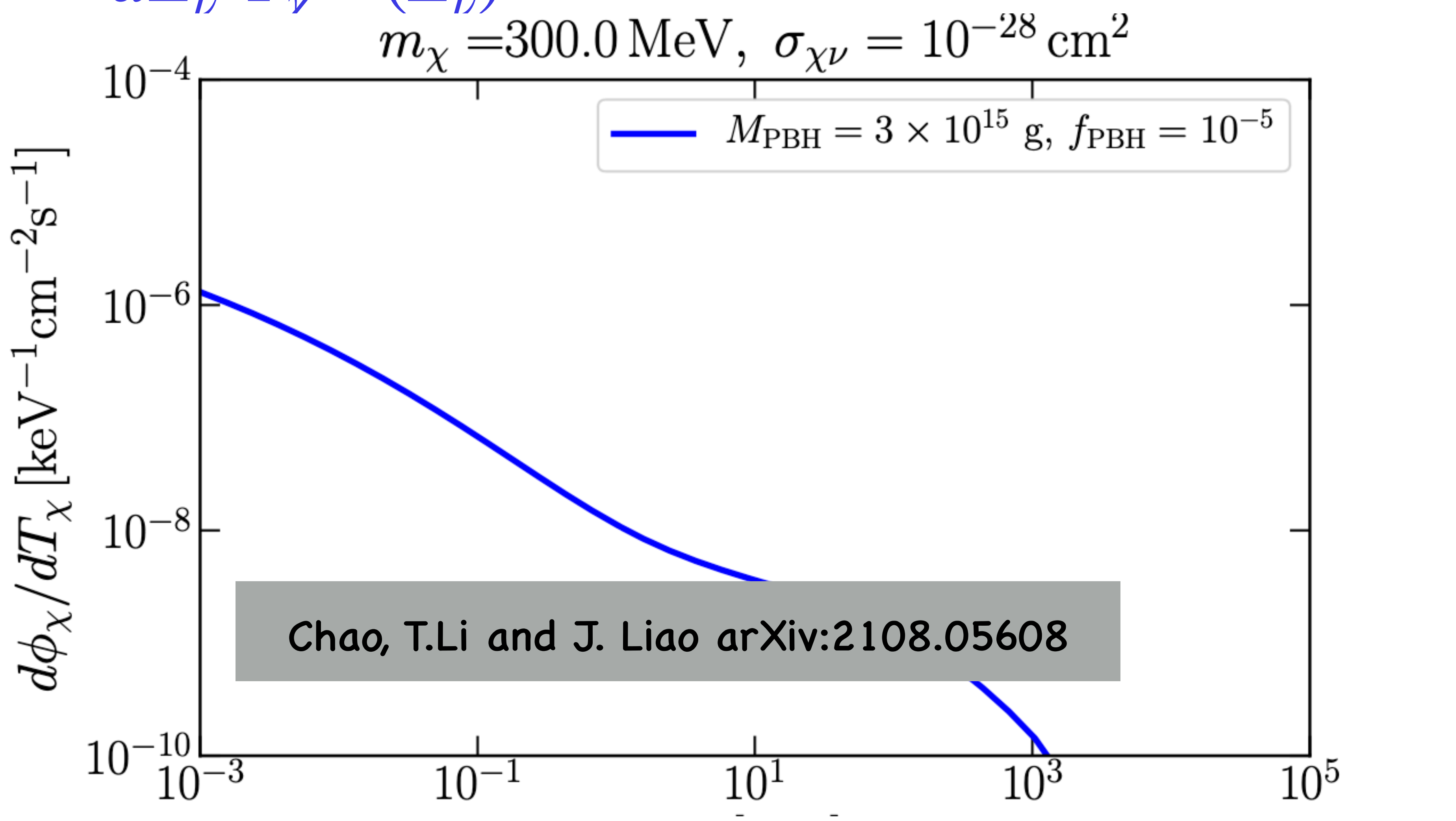



**Strategy-1: Boosted DM**

$$\frac{d\phi_\chi}{dE_\nu} = \int \frac{d\Omega}{4\pi}\int d\ell \frac{\rho_\chi}{m_\chi}\Phi_\nu(E_\nu)\sigma_{\chi\nu} = D_{\rm halo}\Phi_\nu(E_\nu)\frac{\sigma_{\chi\nu}}{m_\chi}$$

$$D_{\rm halo} = 2.02\times 10^{25}{\rm MeV}\cdot{\rm cm}^{-2}$$

$$\frac{d\phi_\chi}{dT_\chi} = \int dE_\nu \frac{d\phi_\chi}{dE_\nu}\frac{1}{T_\chi^{\rm max}(E_\nu)}\Theta(T_\chi^{\rm max} - T_\chi)$$



# Direct detections of light DM

**Strategy-II: Searching for DM using Condense Matter system!**

| DM mass | DM energy or momentum | CM scale |
|---|---|---|
| 50 MeV | $p_\chi \sim 50$ keV | zero-point ion momentum in lattice |
| 20 MeV | $E_\chi \sim 10$ eV | atomic ionization energy |
| 2 MeV | $E_\chi \sim 1$ eV | semiconductor band gap |
| 100 keV | $E_\chi \sim 50$ meV | optical phonon energy |

**Fermi's Golden Rule**

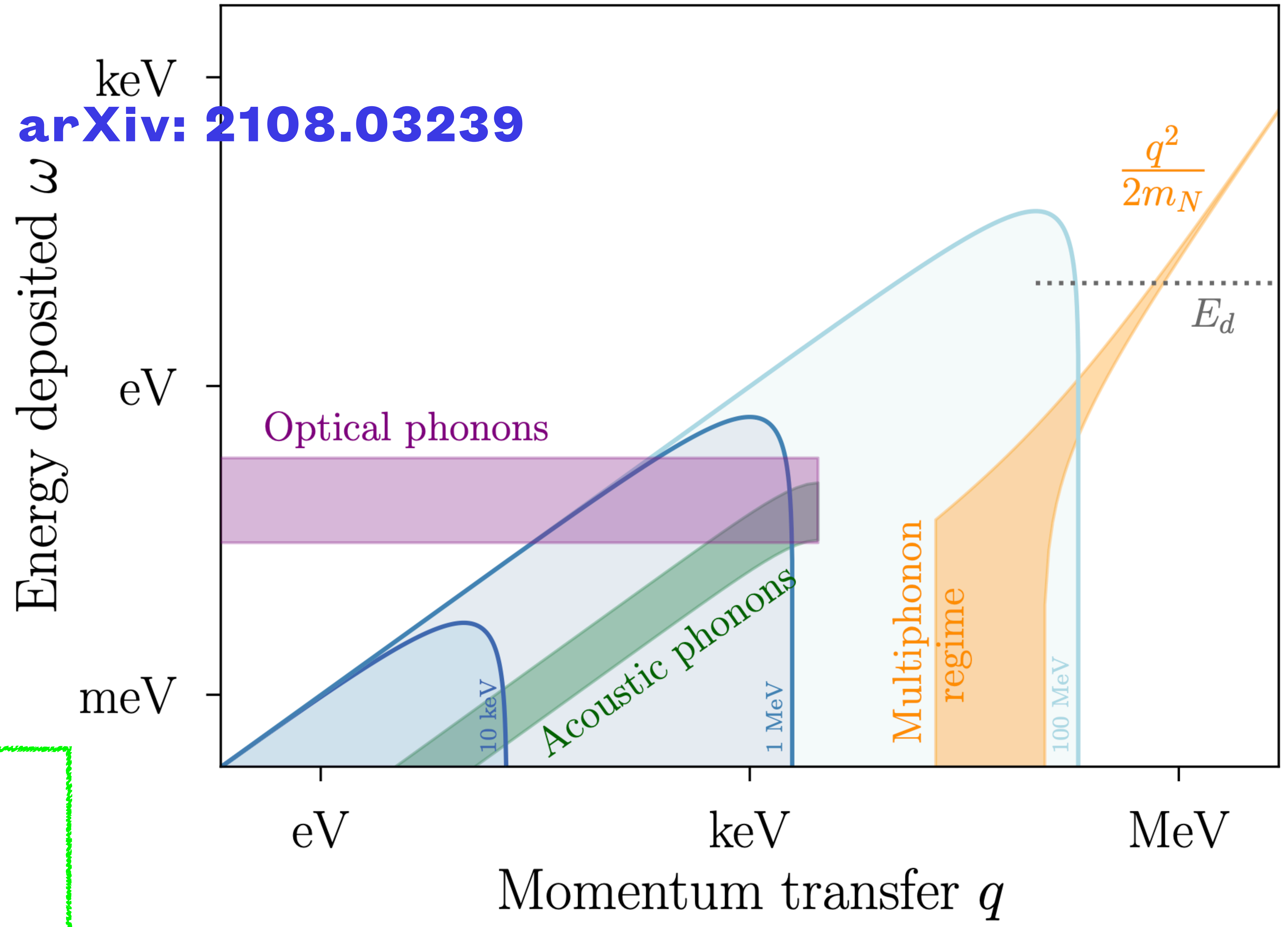
$$R_\chi = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}\int d^3v f_\chi(v)\frac{Vd^3p'_\chi}{(2\pi)^3}\sum_f |\langle f, p'_\chi | \Delta H_\chi | i, p_\chi\rangle|^2 2\pi\delta(E_f - E_i - \omega)$$

$$= \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}\int \frac{d^3q}{(2\pi)^3} d\omega g(q,\omega)\tilde{V}(q)S(q,\omega)$$

$$= \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}\frac{\pi\bar{\sigma}(q)}{\mu_\chi^2}\int \frac{qdq}{(2\pi)^2} d\omega \eta(v_{\min}(q,\omega)) \times S(q,\omega)$$

- $S(q,\omega)$: dynamical structure factor from condensed matter
- $\tilde{V}(q)$: potential felled by DM

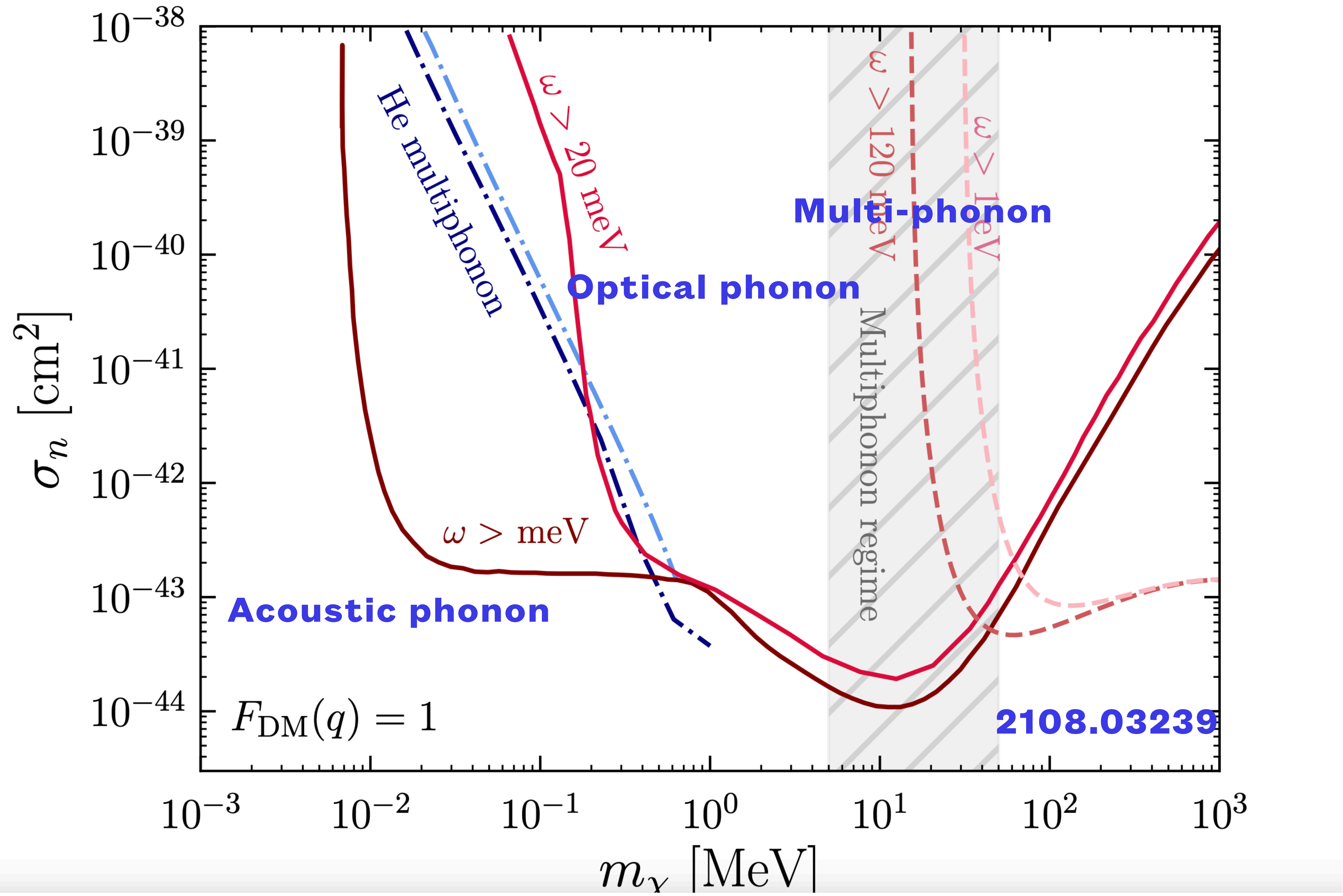
arXiv: 2108.03239

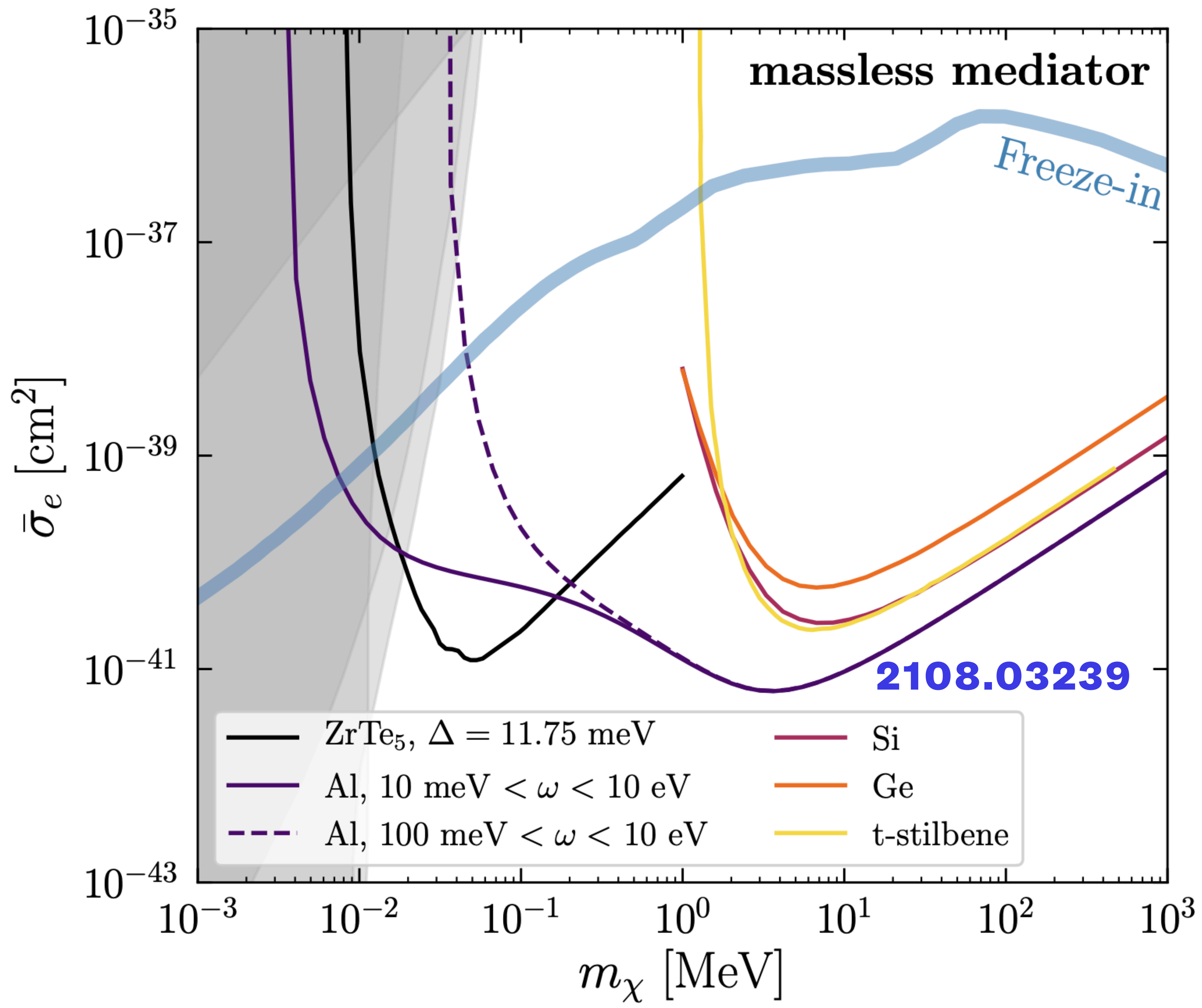


# Direct detections of light DM

$$R = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}\frac{\pi\bar{\sigma}(q)}{\mu_\chi^2}\int \frac{q dq}{(2\pi)^2} d\omega \eta(v_{\rm min}(q,\omega)) \times S(q,\omega)$$

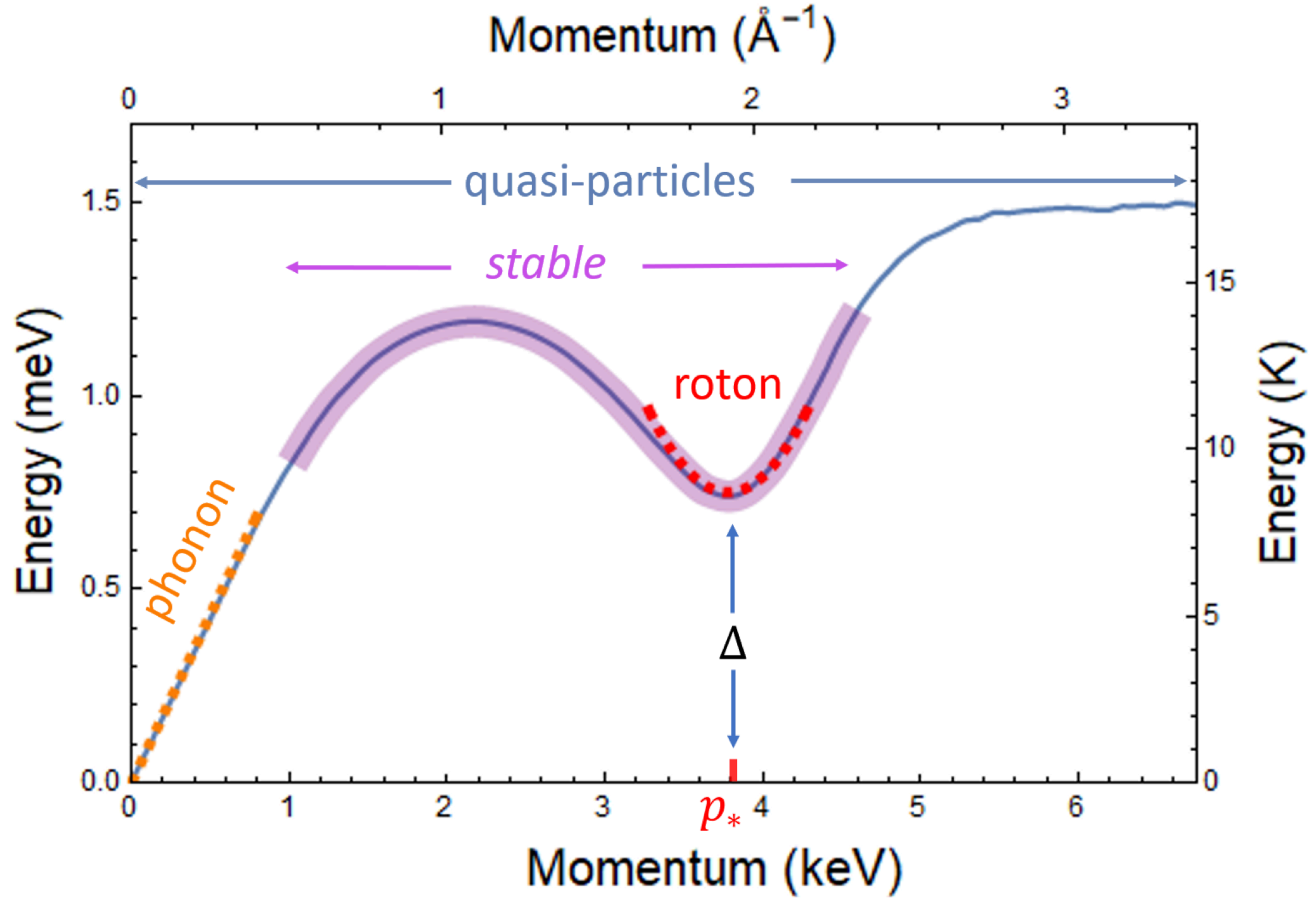
$$\frac{dR}{d\ln E_R} = N_T \frac{\rho_\chi}{m_\chi}\frac{\bar{\sigma}_e}{8\mu_{\chi e}^2}\int dq q\,|F_{\rm DM}(q)|^2 |f_{\rm ion}(k,q)|^2 \eta(v_{\rm min})$$



# Detecting light DM using superfluid

**Phonon (quasiparticle) in Superfluid Helium-4：** A Goldstone-like particle from the spontaneous breaking of the U(1) symmetry as well as the breaking of the boosts and the time translations in the superfluid He-4.




**Action of phonon field**

$$S_{int} \sim \int d^4x \sqrt{\frac{\mu}{\bar{n}}} c_s \left[ \left( \frac{\mu^2}{2} \frac{db}{d\mu} + \mu b \right) \dot{\pi} F^{0\rho} F^0{}_\rho - \mu b \partial_j \pi F^{ij} F_{0i} + \frac{b}{2} \sqrt{\frac{\mu}{\bar{n}}} c_s \partial_\mu \pi \partial_\nu \pi F^{\mu\rho} F^\nu{}_\rho \right]$$

**Phonon-photon conversion in external electric field**

- A. Caputo, A. Esposito, E. Geoffray, A. D. Polosa, and S. Sun, Phys. Lett. B 802, 135258 (2020), arXiv:1911.04511 [hep-ph].

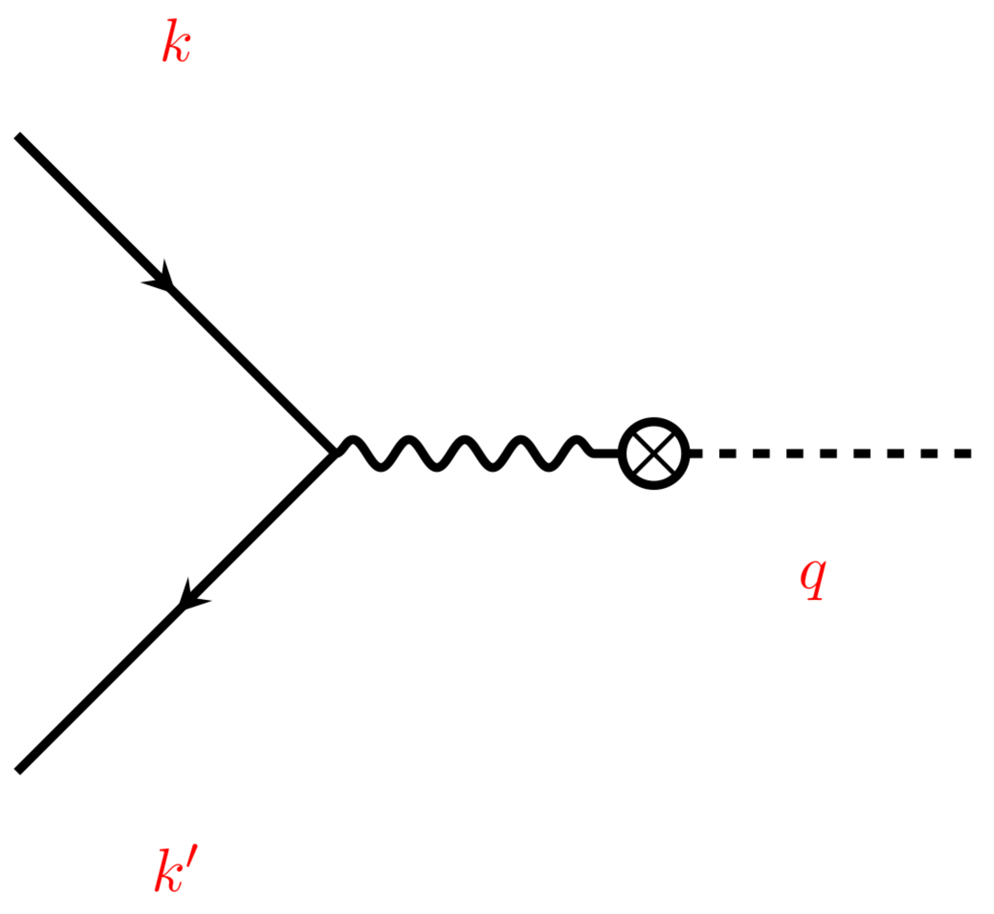
# DM electromagnetic form factors in superfluid

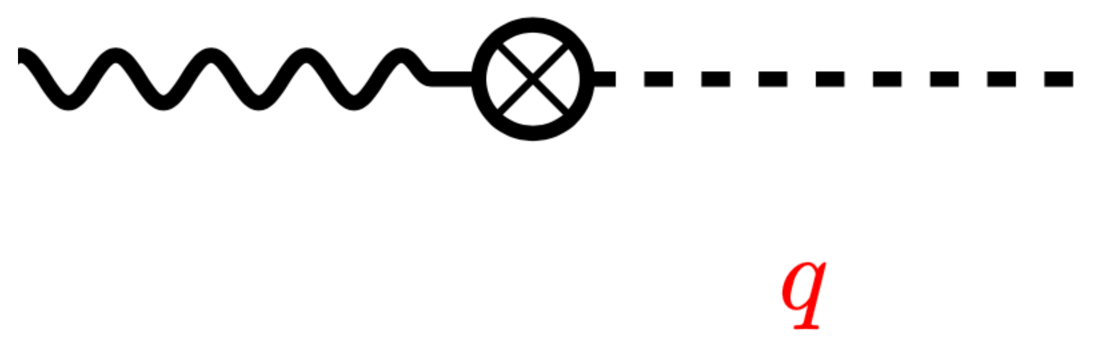
**Lagrangian:**

$$S_{\rm eff} = \int d^4x \Big[\bar\chi(i\partial\!\!\!/ - m_\chi)\chi - \alpha\bar\chi\gamma^\mu\chi\partial^\nu F_{\mu\nu} - \beta\bar\chi\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu} - \frac{\lambda}{2}\bar\chi\sigma^{\mu\nu}\chi F_{\mu\nu} - \frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde F^{\mu\nu} - \frac{1}{2}g_{a\gamma\gamma'}aF_{\mu\nu}\tilde F'^{\mu\nu} + \text{H.c.}$$
$$+\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}a(X)F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}b(X)F^{\mu\rho}F^{\nu}_{\rho}\partial_\mu\phi\partial_\nu\phi\Big],$$

**$\alpha$: charge radius; $\beta$: Anapole moment; $\lambda$: magnetic moment.**

**Feynman diagram for DM-Helium scattering:**




$$= i\frac{\alpha_E\bar n}{m_{He}c_s}\sqrt{\frac{m_{He}}{\bar n}}E_i\omega_q(\omega_q\delta_i^\mu + q_i\delta_0^\mu),$$

# DM electromagnetic form factors in superfluid

**Event rate:**

$$R = \int dv_\chi f_{\rm MB}(v_\chi) \frac{\rho_\chi}{m_{\rm He}\bar{n} m_\chi} \int_{\omega_{\rm min}}^{\omega_{\rm max}} d\omega \frac{d\Gamma}{d\omega},$$

$$\frac{d\Gamma}{d\omega} = \frac{\bar{n}\alpha_E^2\alpha^2}{4\pi c_s^6 m_{He} v_\chi} |\mathbf{E}|^2 \omega_q^4 \cos^2\theta_E,$$

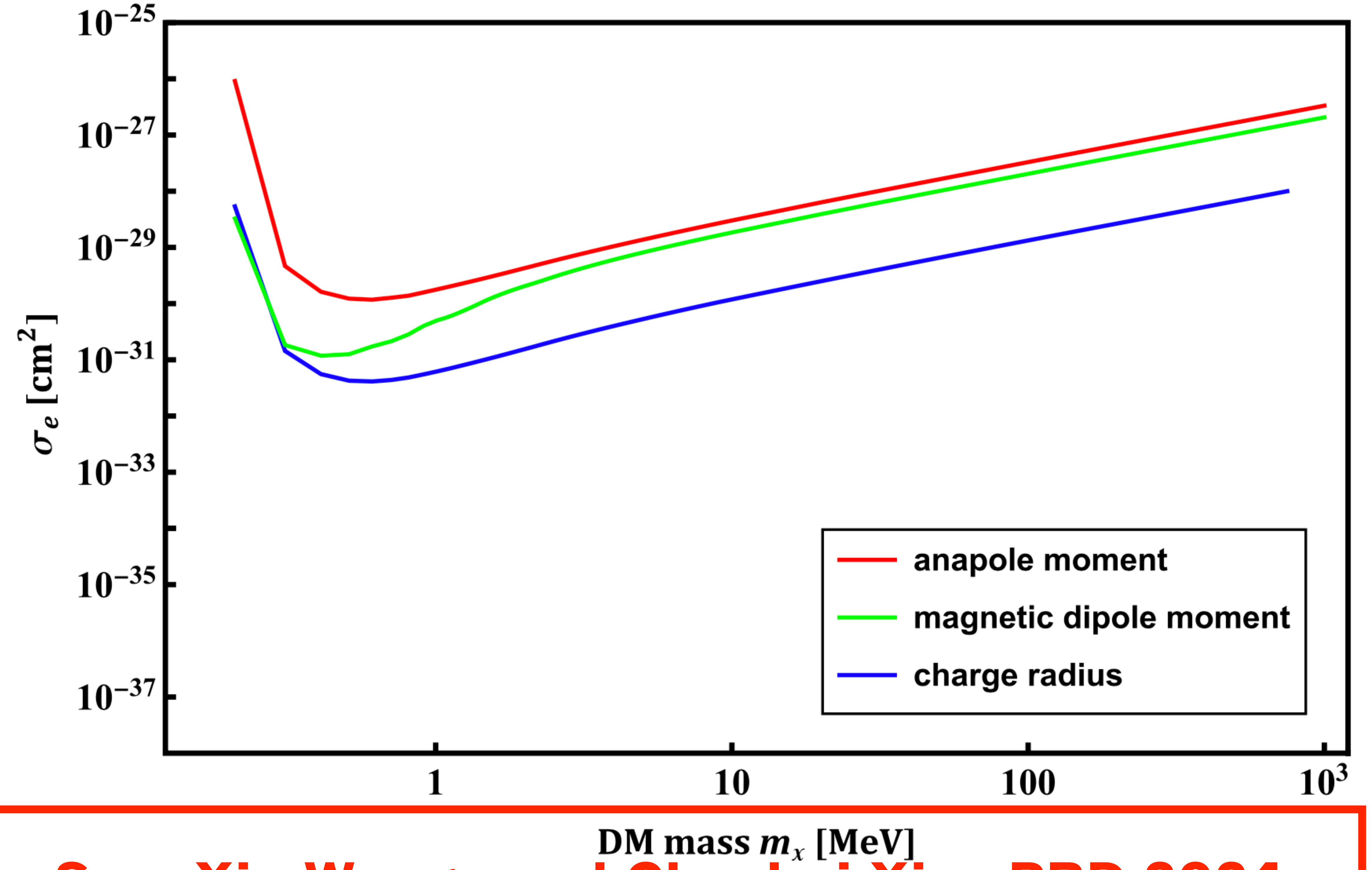
**Projected constraints:**

$$\sigma_e \equiv \frac{1}{16\pi(m_e + m_\chi)^2} \overline{|\mathcal{M}_{\chi e}(q)|^2}_{q^2=\alpha_{em}^2 m_e^2},$$

charge radius: $\overline{|\mathcal{M}_{\chi e}(q)|^2}_{q^2=\alpha_{em}^2 m_e^2} = 64\pi\alpha^2\alpha_{em} m_e^2 m_\chi^2,$ (20a)

anapole moment: $\overline{|\mathcal{M}_{\chi e}(q)|^2}_{q^2=\alpha_{em}^2 m_e^2} = 16\pi\beta^2\alpha_{em} m_\chi^2 q^2,$ (20b)

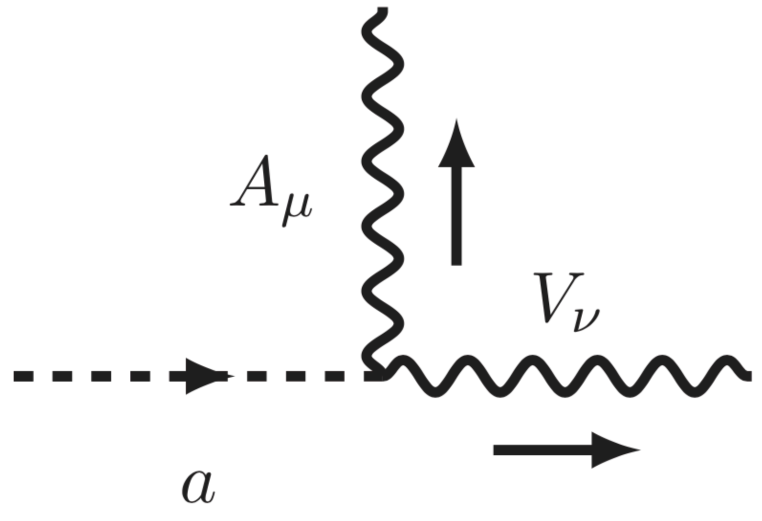
magnetic moment: $\overline{|\mathcal{M}_{\chi e}(q)|^2}_{q^2=\alpha_{em}^2 m_e^2} = 16\pi\lambda^2\alpha_{em} m_\chi^2$



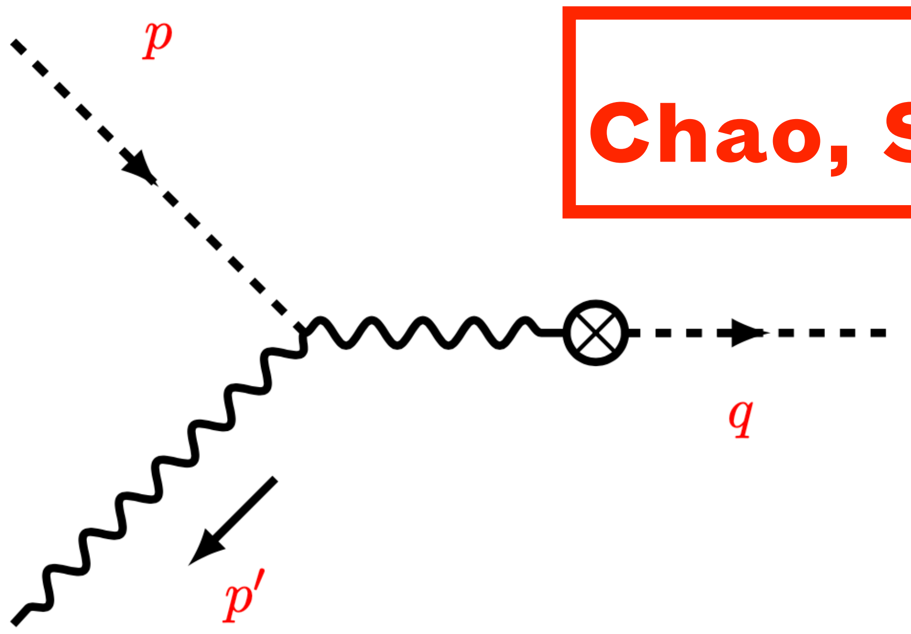

**Chao, Sichun Sun, Xin Wang, and Chenhui Xie, PRD 2024**

# Detecting ALP using superfluid

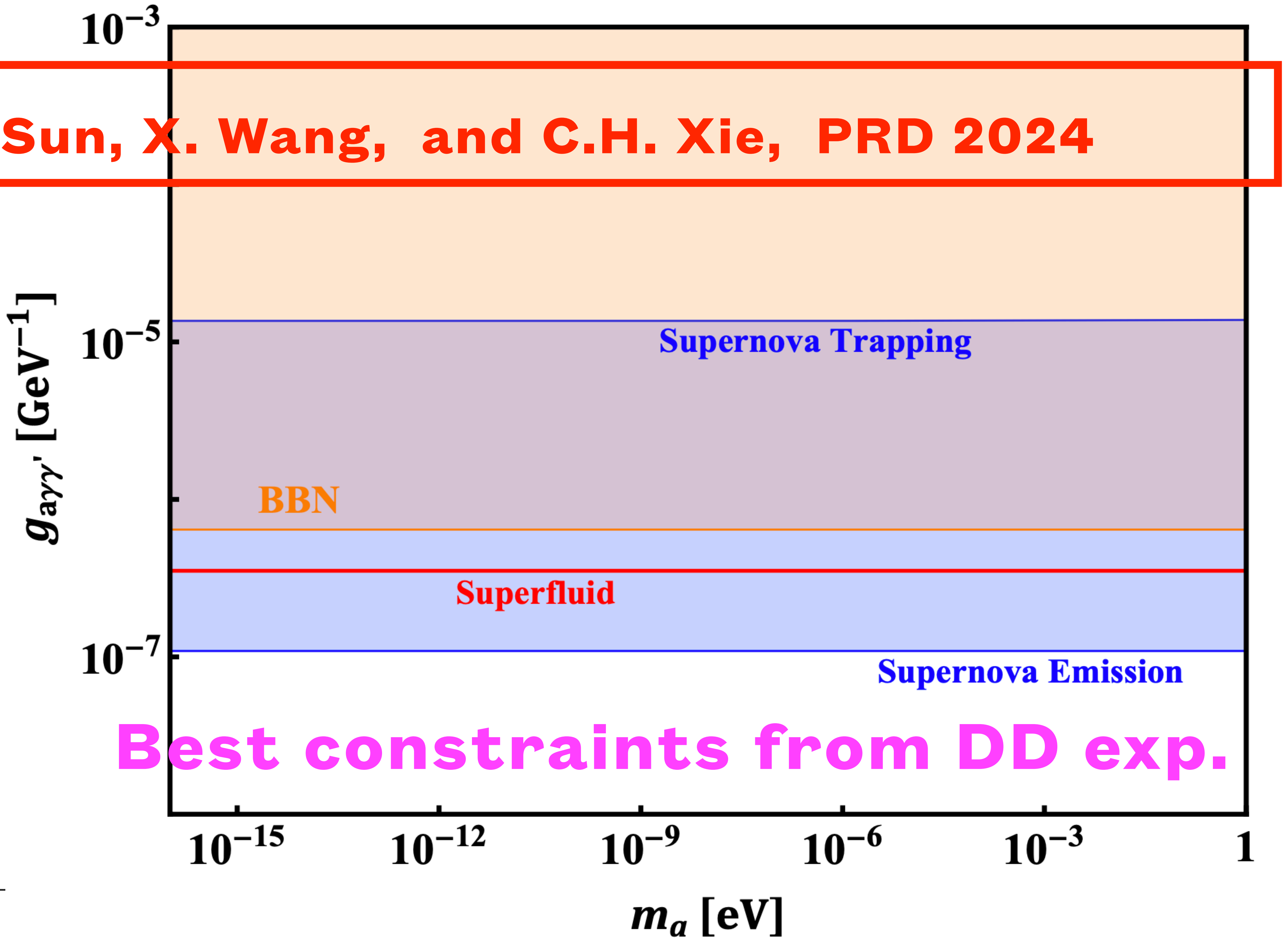
**Why? (1) No DD constraint on this coupling ; (2) There are already strong constraint on $g_{a\gamma\gamma}$.**




$$= g_{a\gamma\gamma'}\epsilon^{\mu\alpha\nu\beta}q_\mu p'_\nu,$$




$$\frac{d\Gamma}{d\omega} = \frac{g^2_{a\gamma\gamma'}\bar{n}\alpha_E^2}{16\pi m_a \omega^2 m_{He} E v_a}\frac{|\mathbf{E}|^2\omega^2}{c_s^2}\Bigg\{(\cos^2\theta_E - c_s^2)\omega^2\left(1-\frac{1}{c_s^2}\right)\Big[E^2(1-v_a^2) + 2E\omega\left(\frac{v_a}{c_s}\cos\theta - 1\right) + \omega^2\left(1-\frac{1}{c_s^2}\right)\Big] - \omega^2\left(1-\frac{1}{c_s^2}\right)(E\cos\theta_E - |\mathbf{p}|^2 c_s\cos\theta_a)^2 - (\cos^2\theta_E - c_s^2)\Big[\omega\left(E-\frac{|\mathbf{p}|}{c_s}\cos\theta\right) - \omega^2\left(1-\frac{1}{c_s^2}\right)\Big]^2\Bigg\}.$$




**Chao, S. Sun, X. Wang, and C.H. Xie, PRD 2024**

**Best constraints from DD exp.**

# Outline

- Gravitational wave signals of dark photon dark matter.

Oscillations of Ultralight Dark Photon into Gravitational Waves

Chao, Jingjing Feng, Huai-ke Gul and , Tong Li, Nucl.Phys.B(2024)

- Constraining exotic light DM with superfluid.

Axion and Dark Fermion Electromagnetic Form Factors in Superfluid He-4,

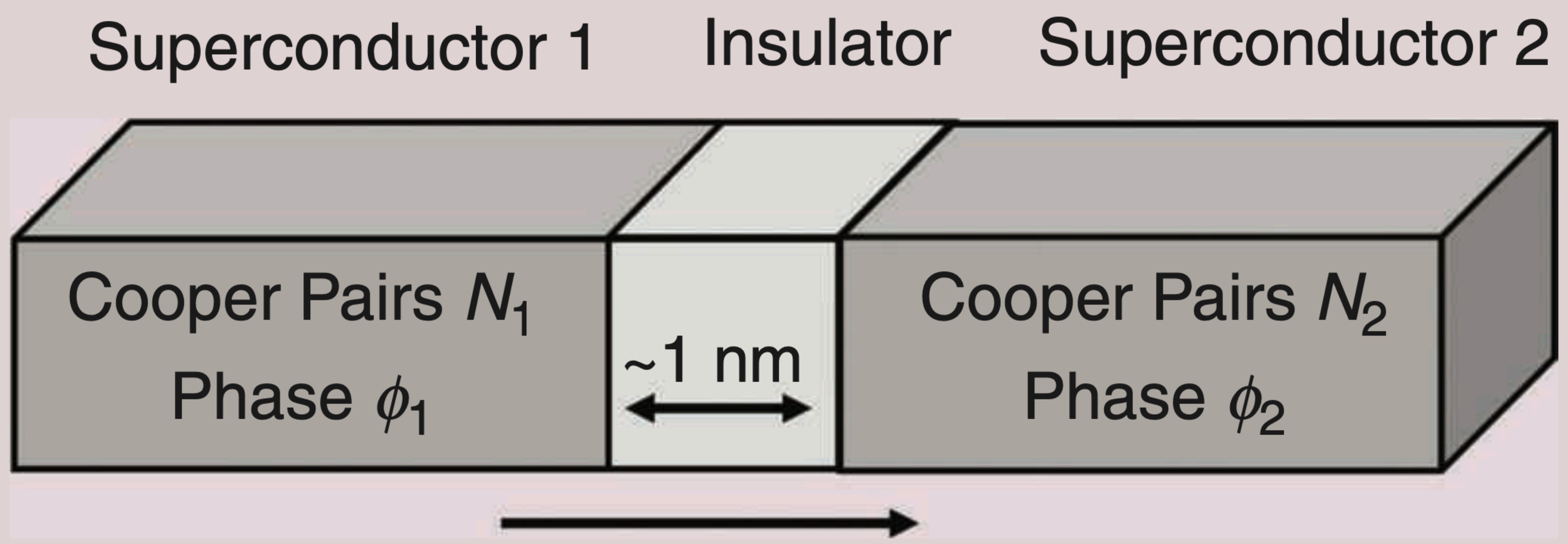
Chao, Sichun Sun, Xin Wang, Chenhui Xie, Phys.Rev.D (2024)

✔ 
- Constraining bosonic DM using transmon qubit

Probing light bosonic DM with transmon qubits,

Chao, Yu Gao, Mingjie Jin, Xiaosheng Liu and Xilei Sun, e-Print: 2412.20850 [hep-ph]

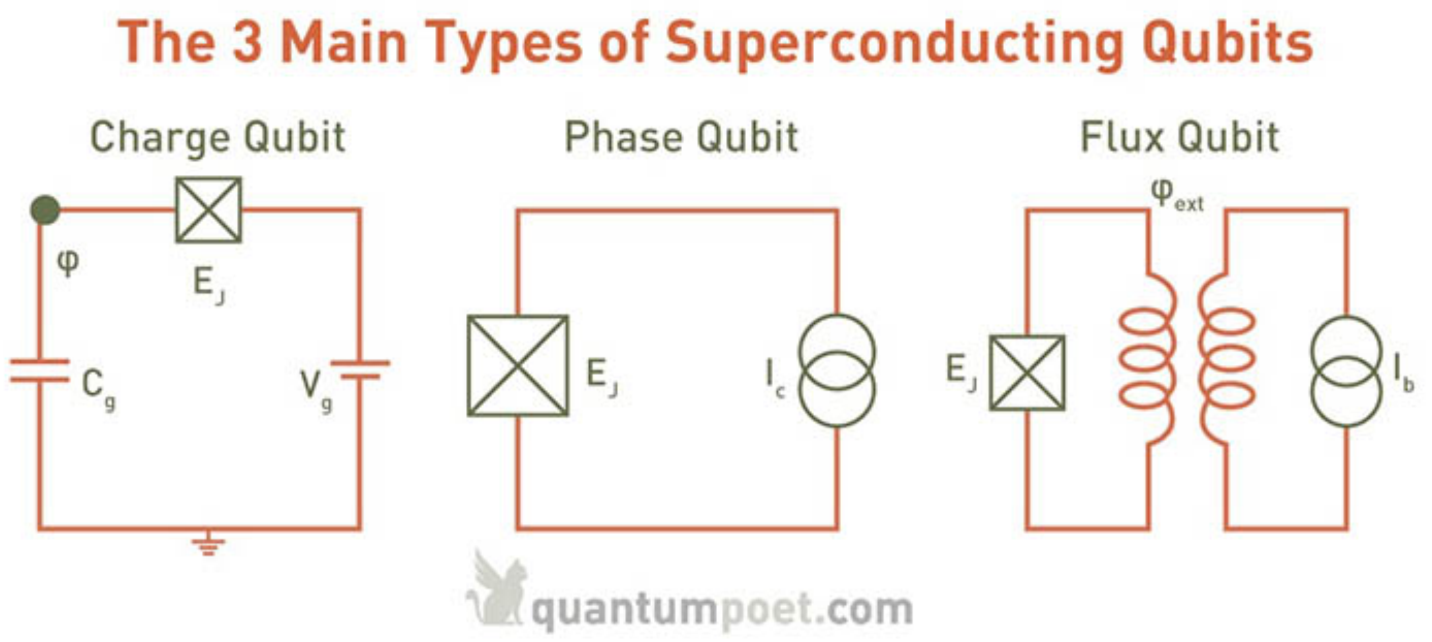
# Transmon qubit

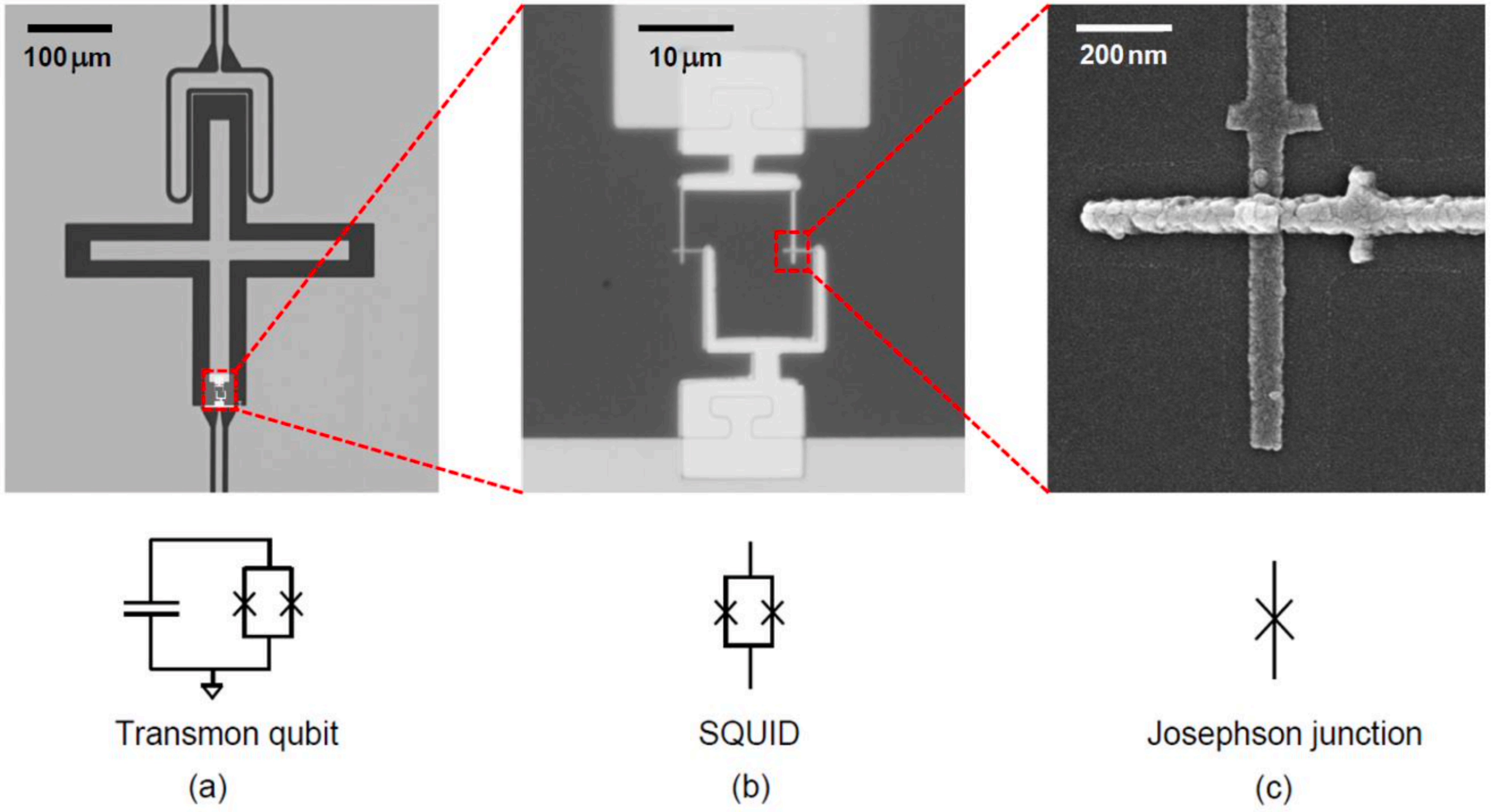



Supercurrent $\propto \varphi$

$$\text{Dynamical Variables} = \begin{cases} n = N_1 - N_2 \\ \varphi = \phi_1 - \phi_2 \end{cases}$$

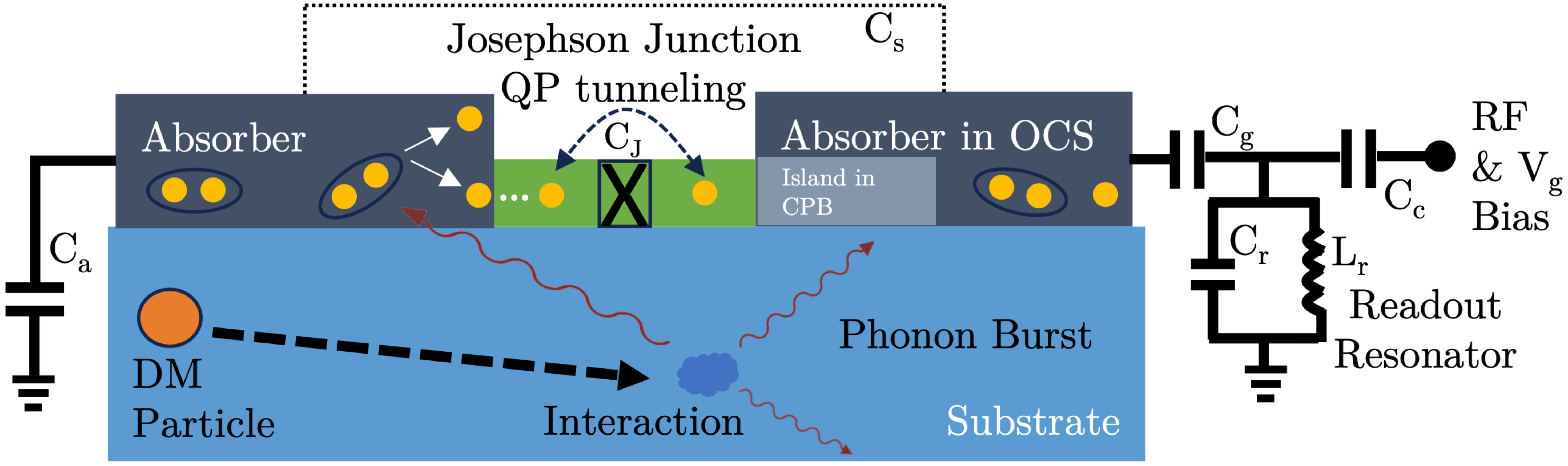
$$H = 4E_C n^2 - E_J \cos \varphi$$

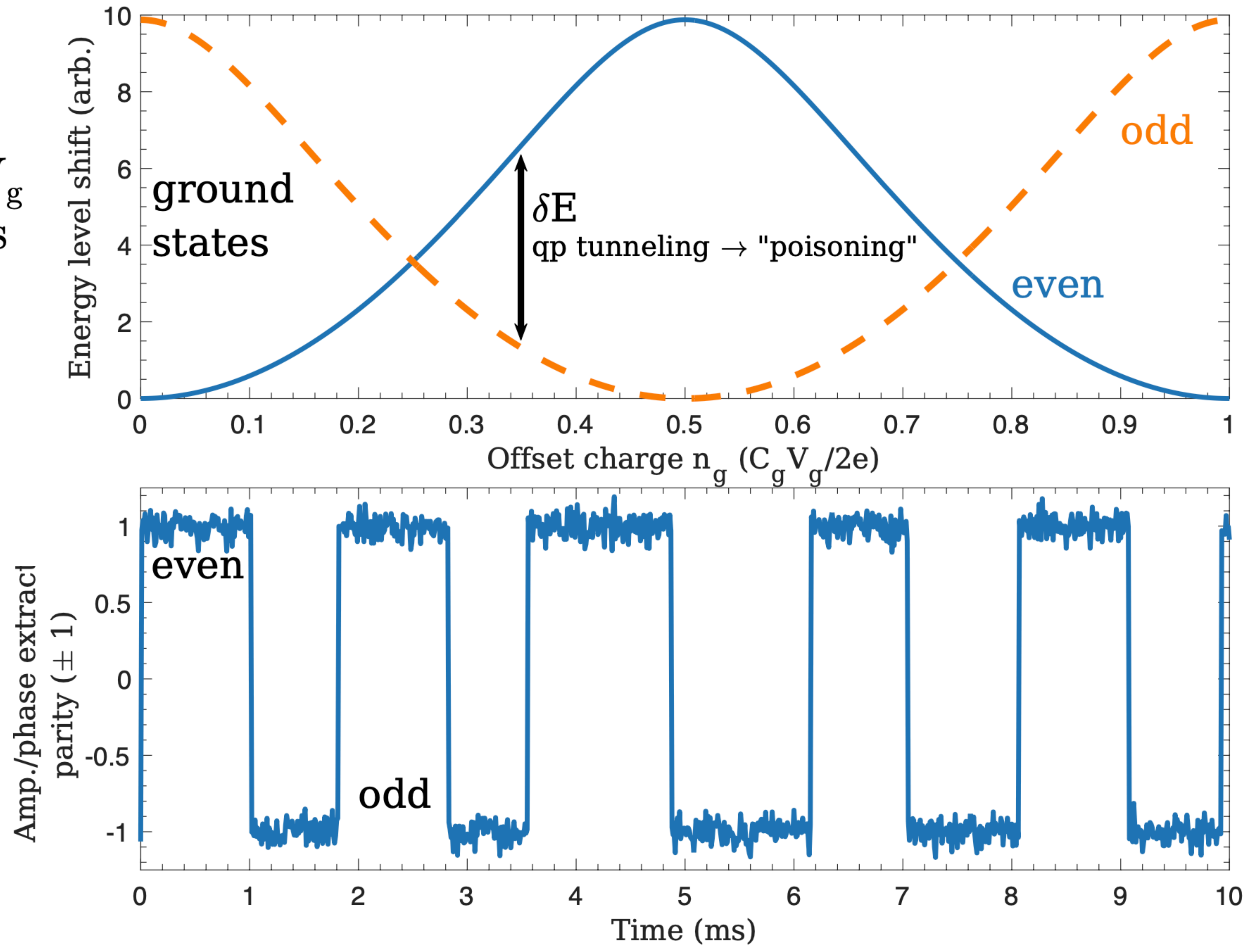


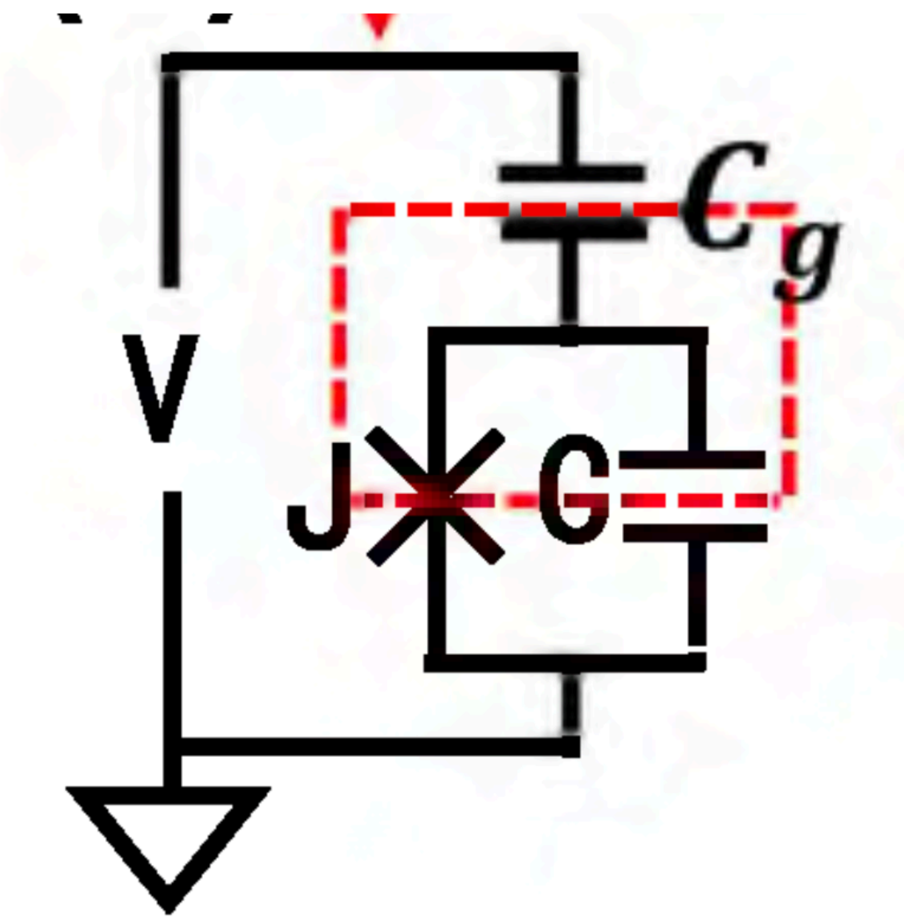




Equivalent to simple mechanical pendulum.

# Superconducting qubit as a light DM detector




$$H_{CPB} = 4E_C\left(\hat{n} - n_g + \frac{P-1}{4}\right)^2 - E_j \cos\hat{\phi}$$

Ej: Josephson energy

P:parity dependent shift

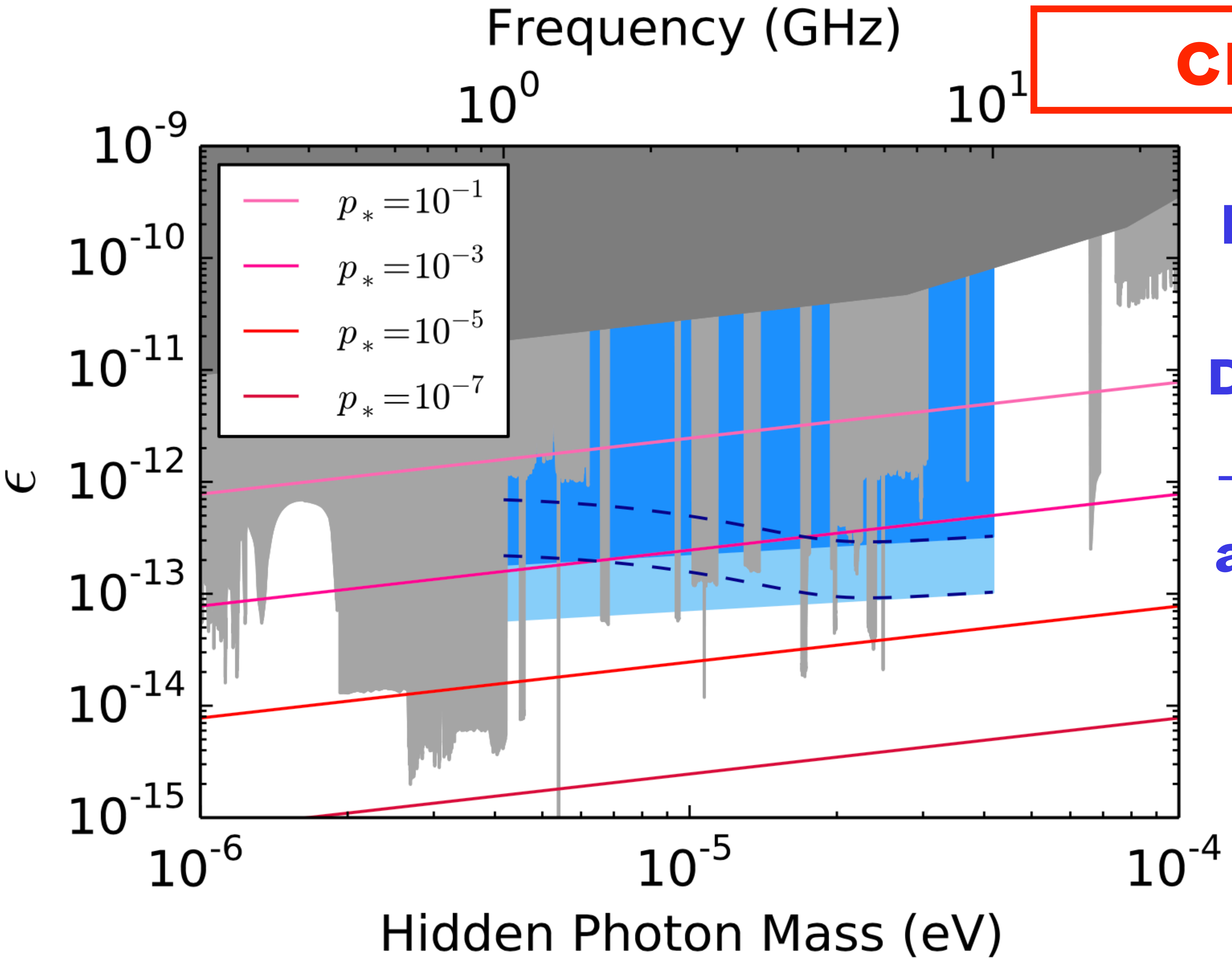
$\hat{n}$: number of Cooper pairs on island

$\hat{\phi}$: phase difference

$n_g$: offset charge

Plots taken from arXiv: 2405.17192

# Transmon qubit as a dark photon detector




**Chen, et al., PRL 131, 211001 (2023)**

**Hamiltonian** $H_0 = \frac{1}{2}CV^2 - J\cos\theta$

**DP induced electric field** $\vec{E}^X = \varepsilon\sqrt{2\rho_{\rm DM}}\vec{n}_X \sin m_x t$

**→Oscillations between the ground state and the excited state!**

$$p_{ge}(\tau) \simeq 0.12 \times \kappa^2 \cos^2\Theta \left(\frac{\epsilon}{10^{-11}}\right)^2 \left(\frac{f}{1\ \text{GHz}}\right) \times \left(\frac{\tau}{100\ \mu\text{s}}\right)^2 \left(\frac{C}{0.1\ \text{pF}}\right) \left(\frac{d}{100\ \mu\text{m}}\right)^2 \times \left(\frac{\rho_{\rm DM}}{0.45\ \text{GeV/cm}^3}\right),$$

# Transmon qubit constraint on bosonic DM

**Quasiparticle excitation:** $$\frac{dn_{qp}}{dt} = -\Gamma_R - \Gamma_T + \Gamma_G$$

- Phys. Rev. Lett. 117, 117002 (2016).

**$\Gamma_R$: Recombination rate** $$\Gamma_R = \bar{\Gamma} n_{PQ}^2$$

**$\Gamma_T$:Trapping rate** $$\Gamma_T = \bar{\Gamma}' n_{PQ}$$

**$\Gamma_G$: Generating rate induced by DM absorption or scattering!**

**In equilibrium:** $$\Gamma_G = \bar{\Gamma} n_{\mathrm{QP}}^2 + \Gamma_T n_{\mathrm{QP}}$$

# Transmon qubit constraint on bosonic DM

**The number of phonon per unit time per unit mass:**

$$R = \frac{\pi\sigma_\chi n_\chi}{\rho_T \mu^2}\int d^3v f_\chi(v)\int \frac{d^3q}{(2\pi)^3}F^2_{\rm med}(q)S(q,\omega_q)$$

**Full phonon energy:**

$$E = \int d\omega\omega \times \frac{dR}{d\omega} \times M \times T$$

**Number of quasiparticles produced:**

$$N = \frac{\varepsilon}{2\Delta}\omega RMT$$

**Produced quasi particle density per unit time:**

$$n'_{qp} = N/V/T = \frac{\varepsilon}{2\Delta}\omega R\rho_T = \frac{\varepsilon}{2\Delta}\int d\omega\omega\frac{dR}{d\omega} \times \rho_T$$

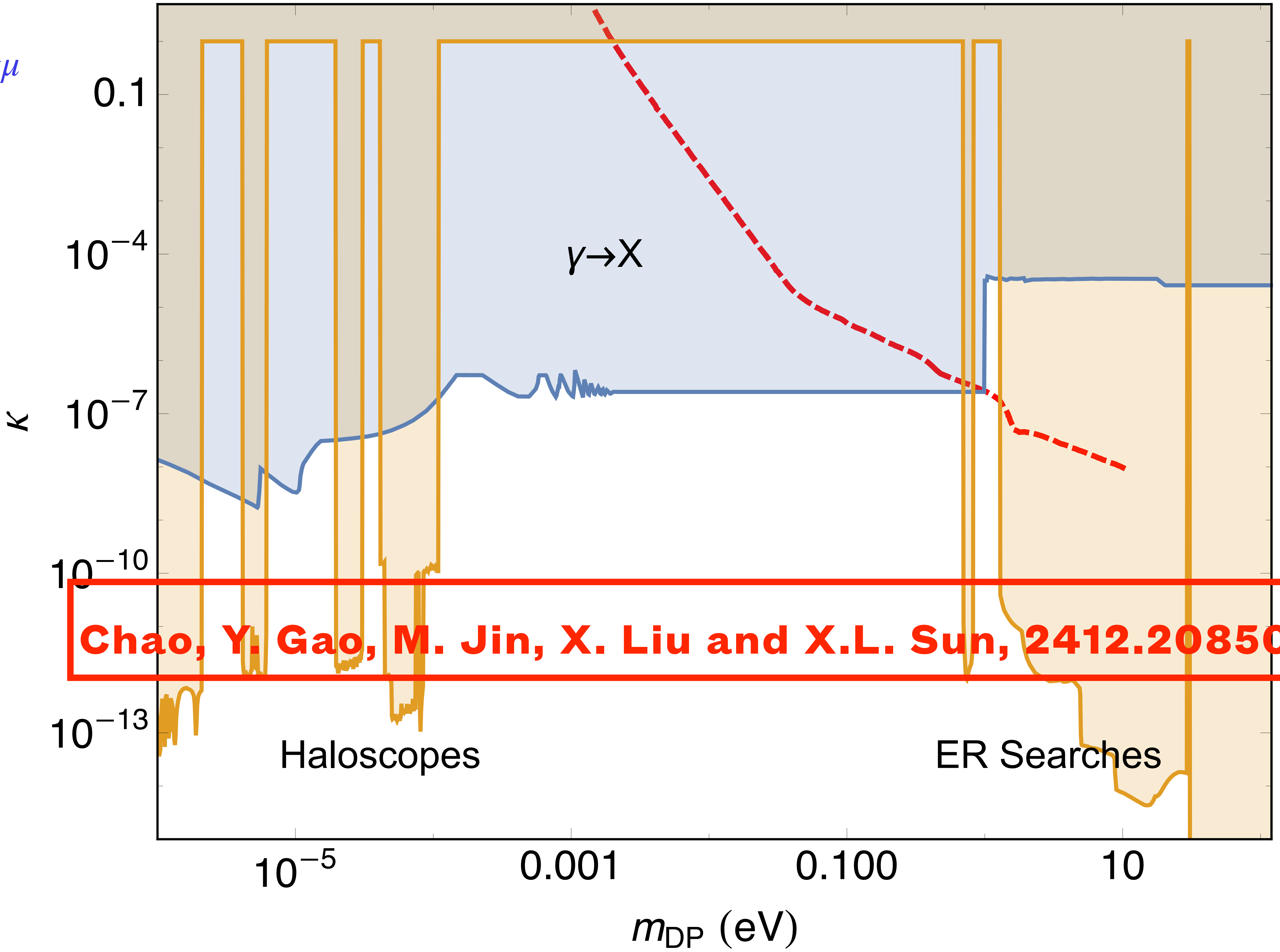
# Transmon qubit constraint on the DP

$$\mathscr{L}_{\rm DP} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\varepsilon}{2}F_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_X^2 X_\mu X^\mu$$

$$R_{\rm DP} = \frac{\rho_{\rm DP}}{\rho_T}\kappa^2 {\rm Im}\left[-\frac{1}{\varepsilon(\omega)}\right]$$

$$n_{qp} < 0.04\ \mu m^{-3}$$

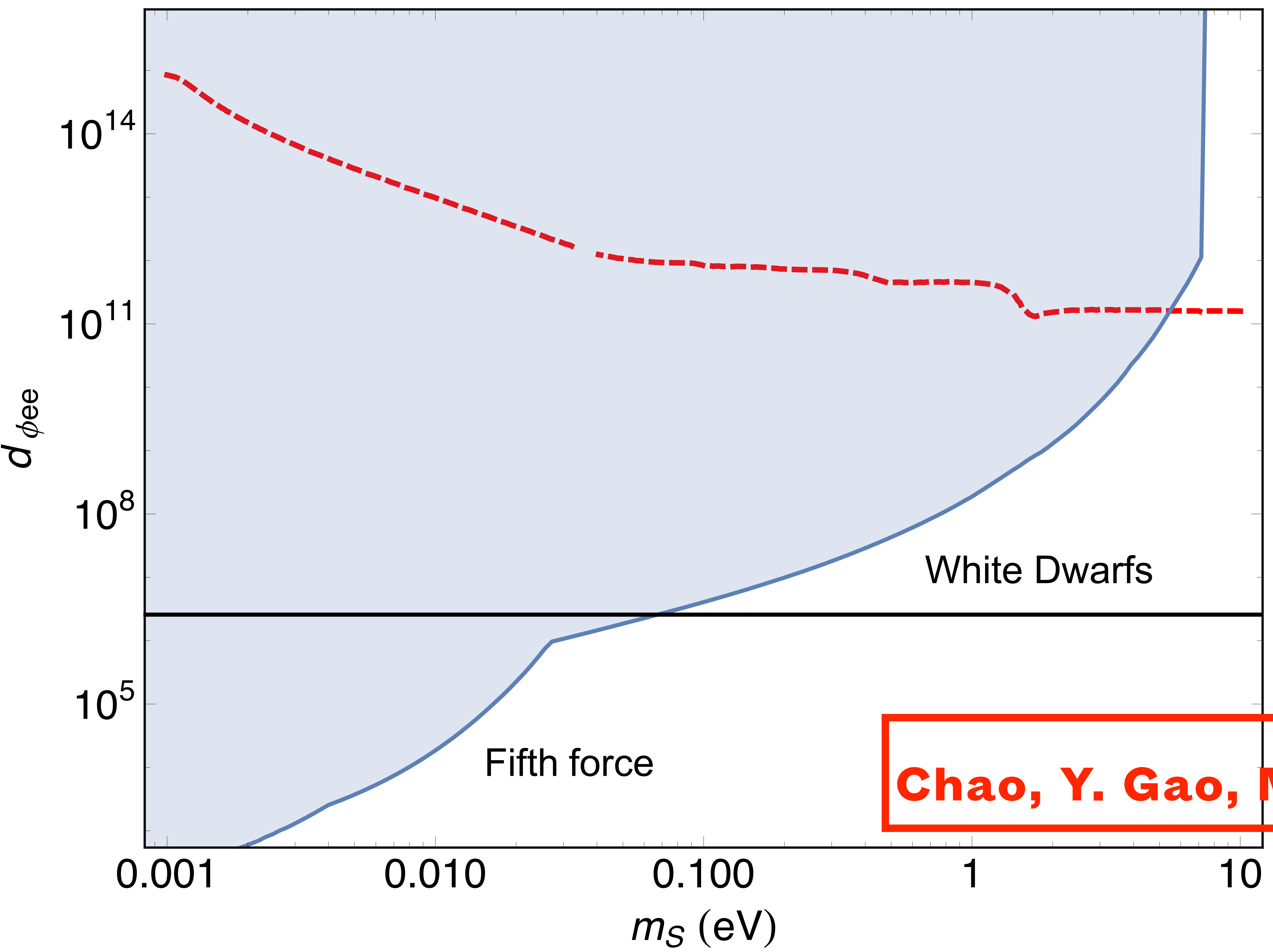
D. Riste et al., Nature Communications 4 (2013), 10.1038/ncomms2936



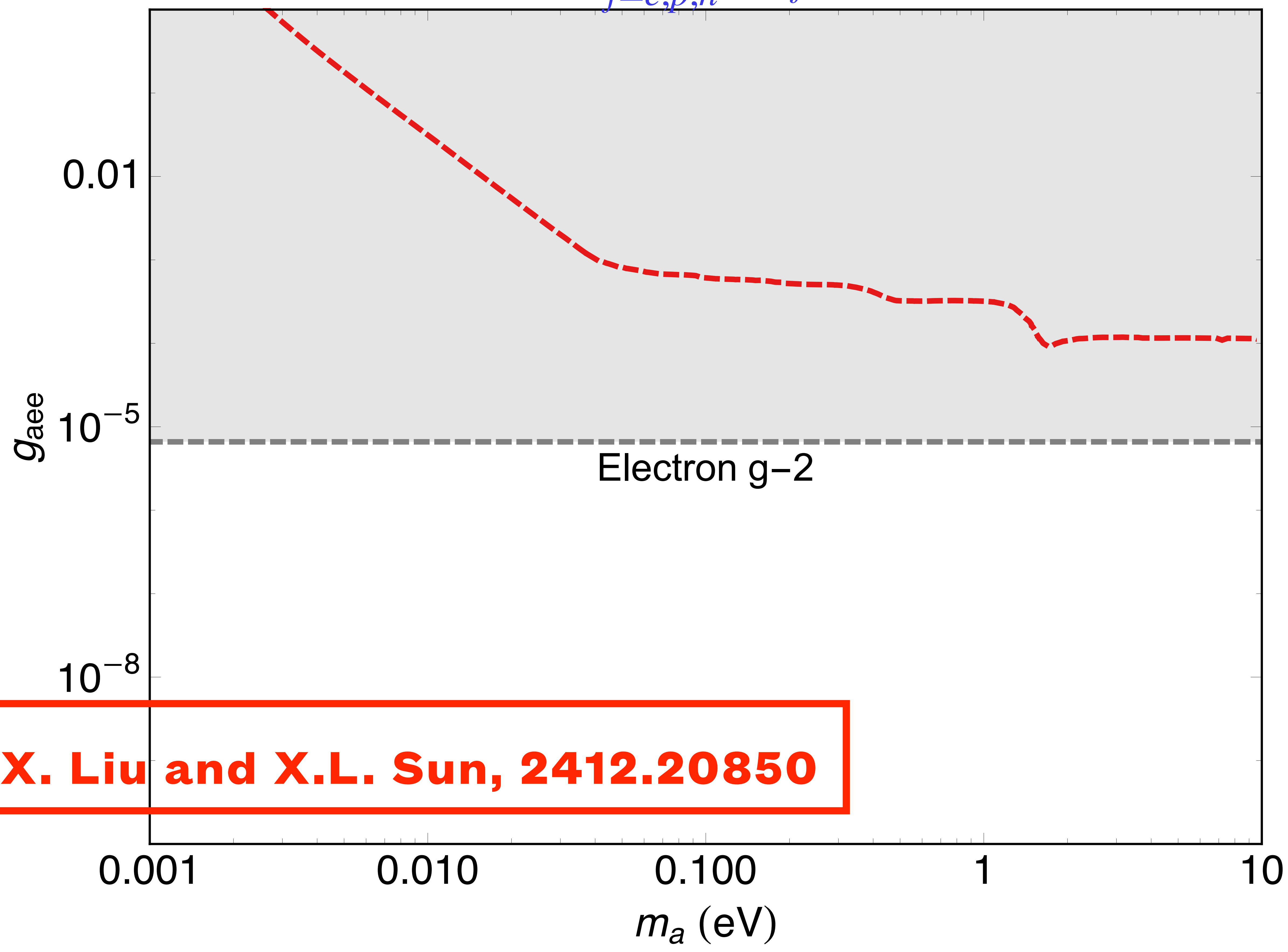

Chao, Y. Gao, M. Jin, X. Liu and X.L. Sun, 2412.20850

# Transmon qubit constraint on Scalar and ALP DM

$$\mathscr{L} \supset \sum_{f=e,p,n} d_{\phi f f} \phi \bar{f} f$$




$$\mathscr{L} \supset \sum_{f=e,p,n} \frac{g_{aff}}{2m_f} \partial_\mu a \bar{f} \gamma^\mu \gamma^5 f$$




**Chao, Y. Gao, M. Jin, X. Liu and X.L. Sun, 2412.20850**

# Summary

New strategy of detecting light dark matters, is a topic deserving deep investigation.

A. Possible gravitational signal from dark photon oscillation is investigated.
B. Detecting light dark matters using superfluid is investigated.
C. New strategy for the DD of bosonic DM using superconducting qubit is investigated.

# Thank you for your attention!