Axion DM detection using shift current

Genta Osaki (Utokyo)

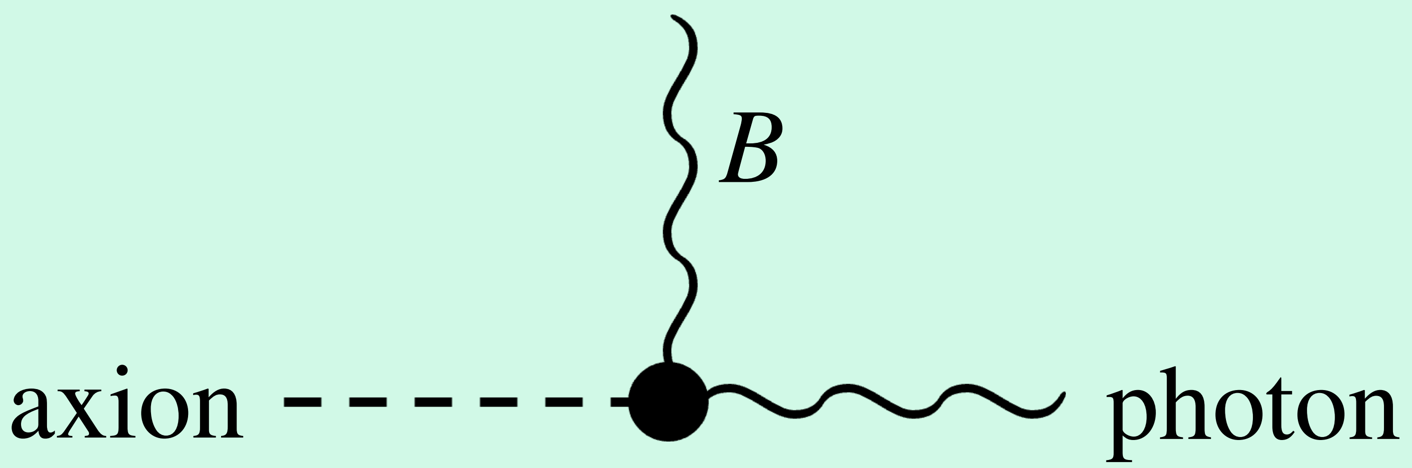
Based on the work: 2505.17007 in collaboration with Dan Kondo, Takahiro Morimoto, and Thanaporn Sichanugrist

Today’s topic

Axion

Dark matter candidate

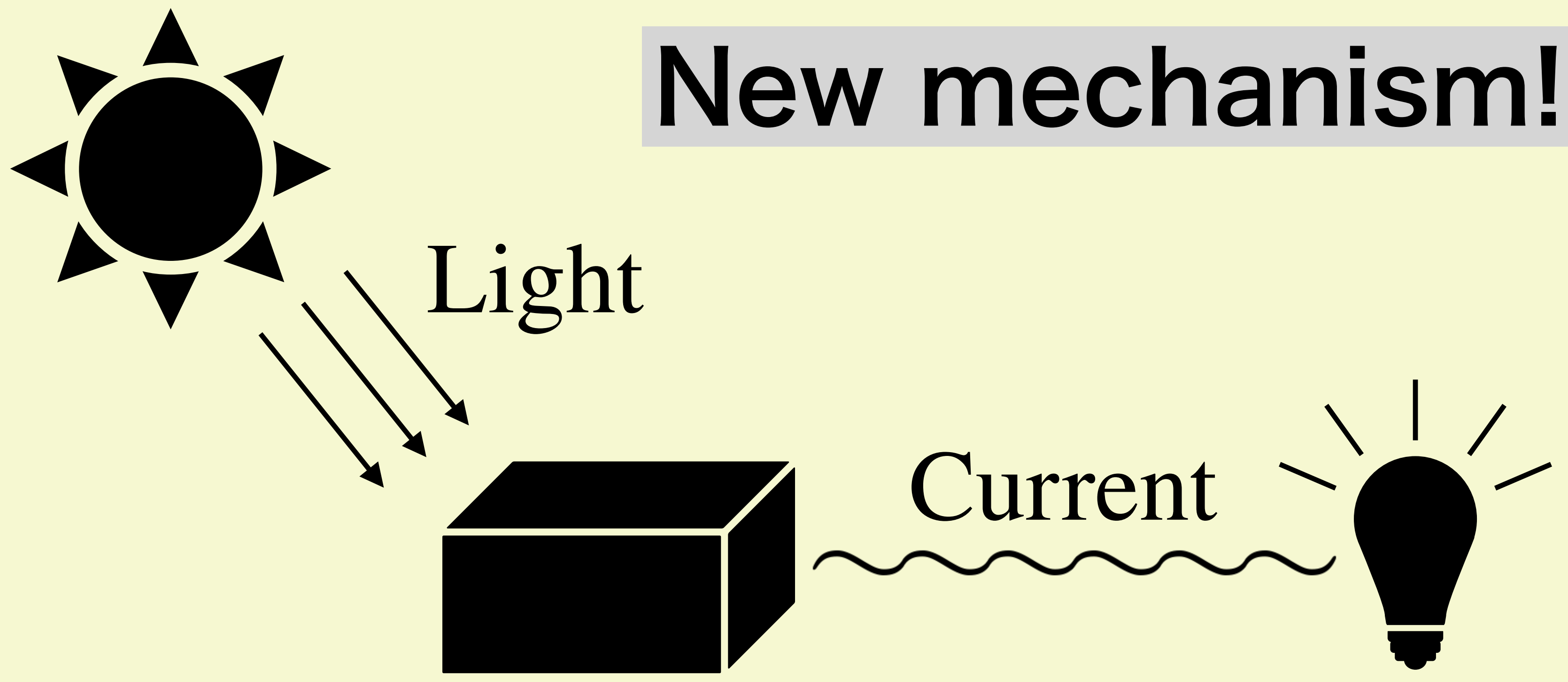
Axion-photon coupling



Shift current

Light-induced current

New mechanism!



Our idea: Axion DM → photon → shift current

Outline

- What is the shift current?
- Method to detect the axion-induced shift current

Outline

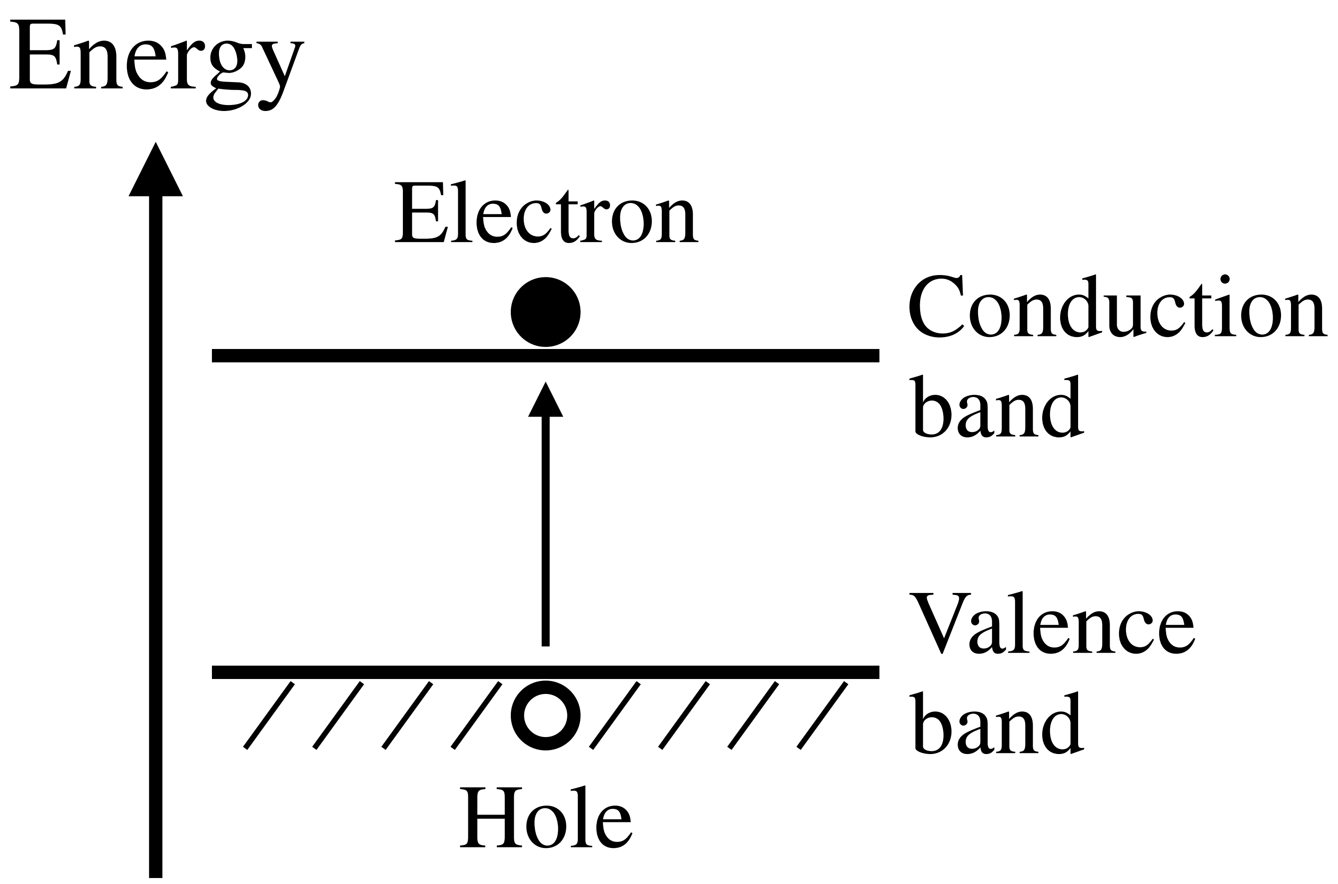
- **What is the shift current?**
- Method to detect the axion-induced shift current

Light-induced current

Usual semiconductor junctions

・Light creates electron-hole pairs.

・The p-n junction allows spatial separation of electron-hole pairs.

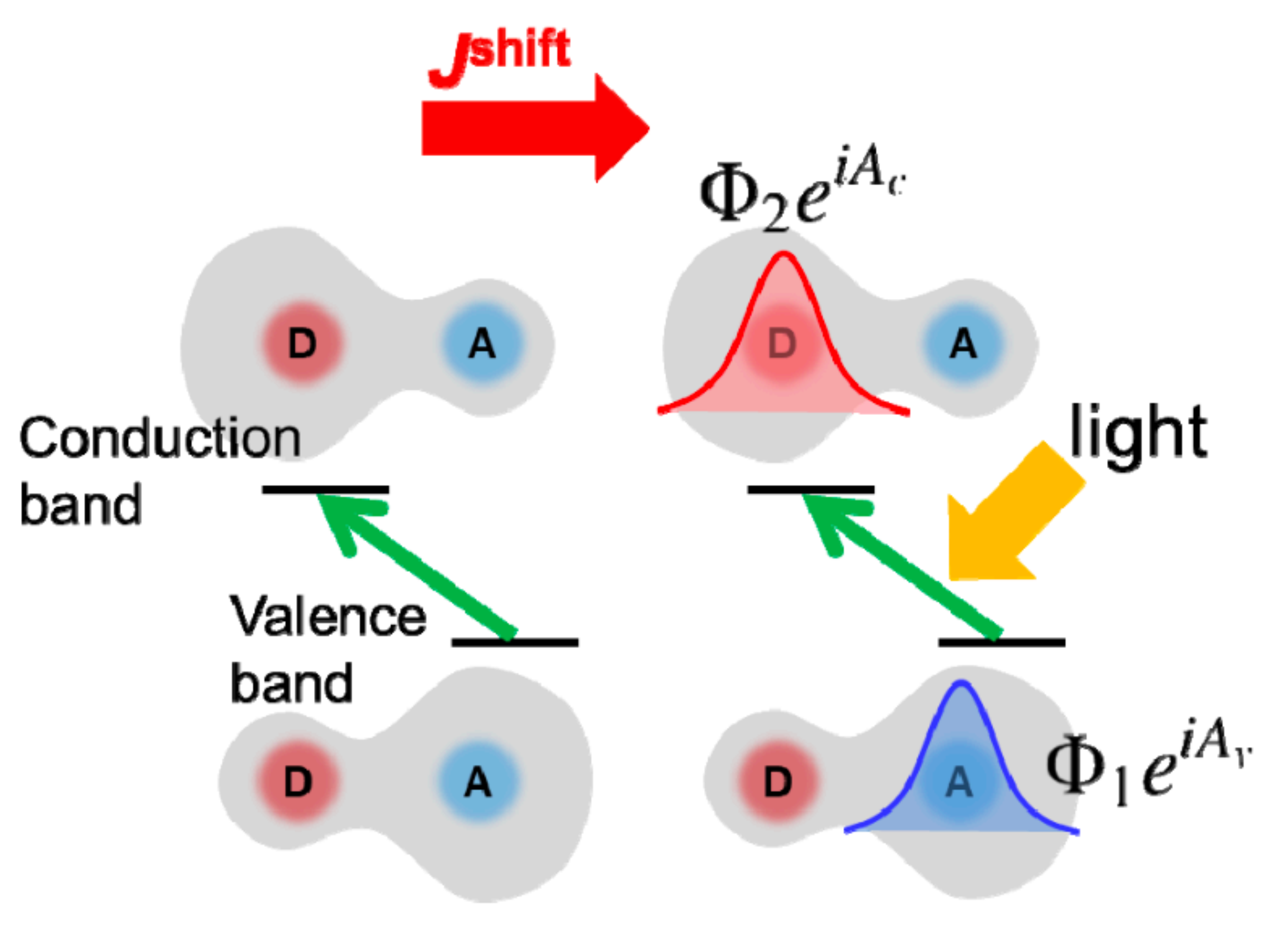


https://www.yomiuri.co.jp/national/20240403-OYT1T50042/

Shift current

・Occurs in the inversion-broken materials.

・It arises from spatial shift of the electron wave function during state transitions.



T. Morimoto and N. Nagaosa Sci. Adv. **2**, e1501524 (2016)

Google Scholar "shift current"

記事 約 3,140 件 (0.05 秒) プロフィール マイ

期間指定なし
2025 年以降
2024 年以降
2021 年以降
期間を指定...
2011 — 2020
検索

Year	Papers
— 1960	25
1961 — 1970	26
1971 — 1980	63
1981 — 1990	107
1991 — 2000	344
2001 — 2010	913
2011 — 2020	**3140**
2021 —	**3000**

← Discovered around 1960

Exciting topic recently!!

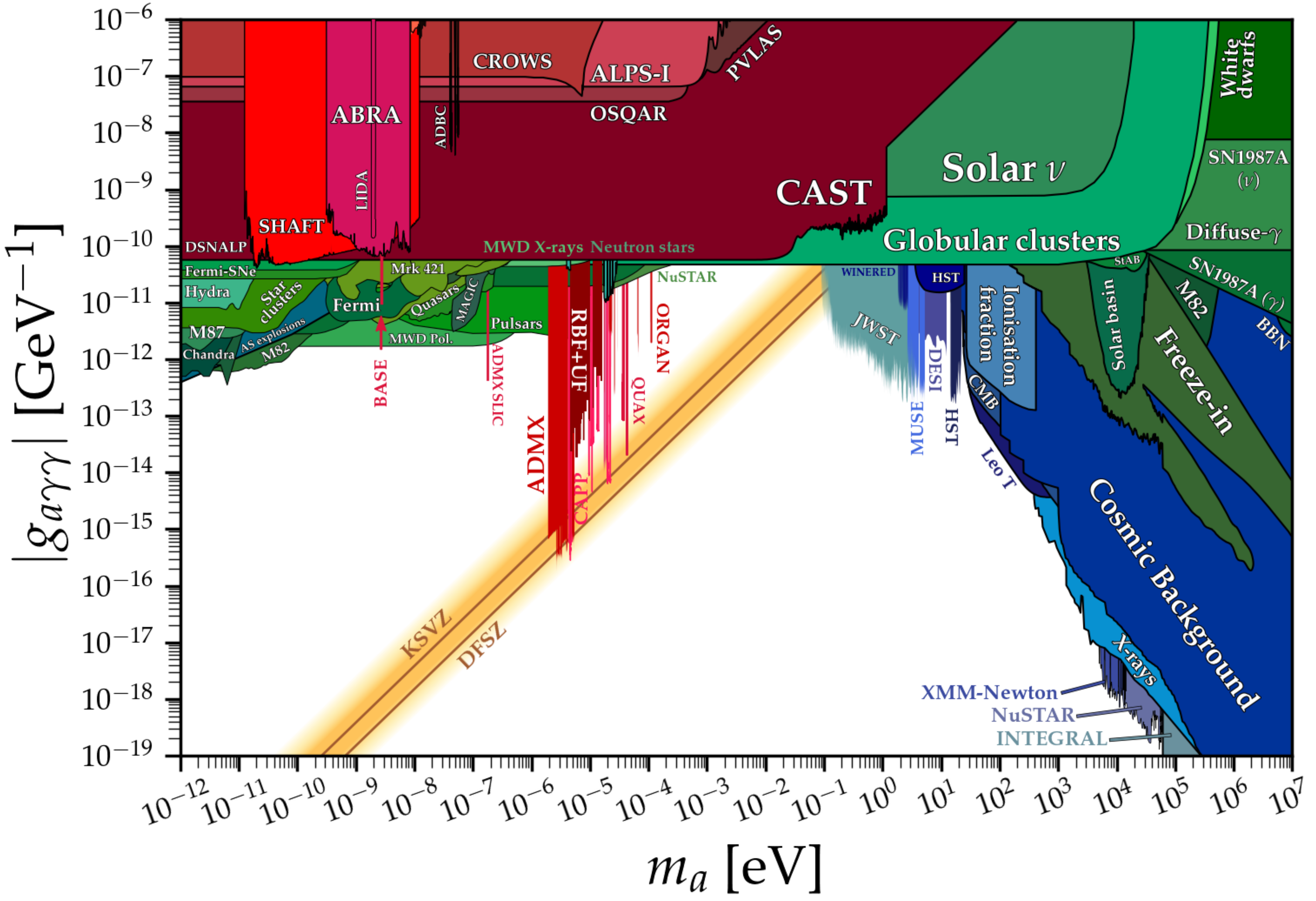
Search for materials with high efficiency

Application for new photo devices

← Theoretically well understood (by first principle calculation)

S. M. Young and A. M. Rappe, Phys. Rev. Lett. 109, 116601 (2012).

Shift current is applied in studies of THz dynamics

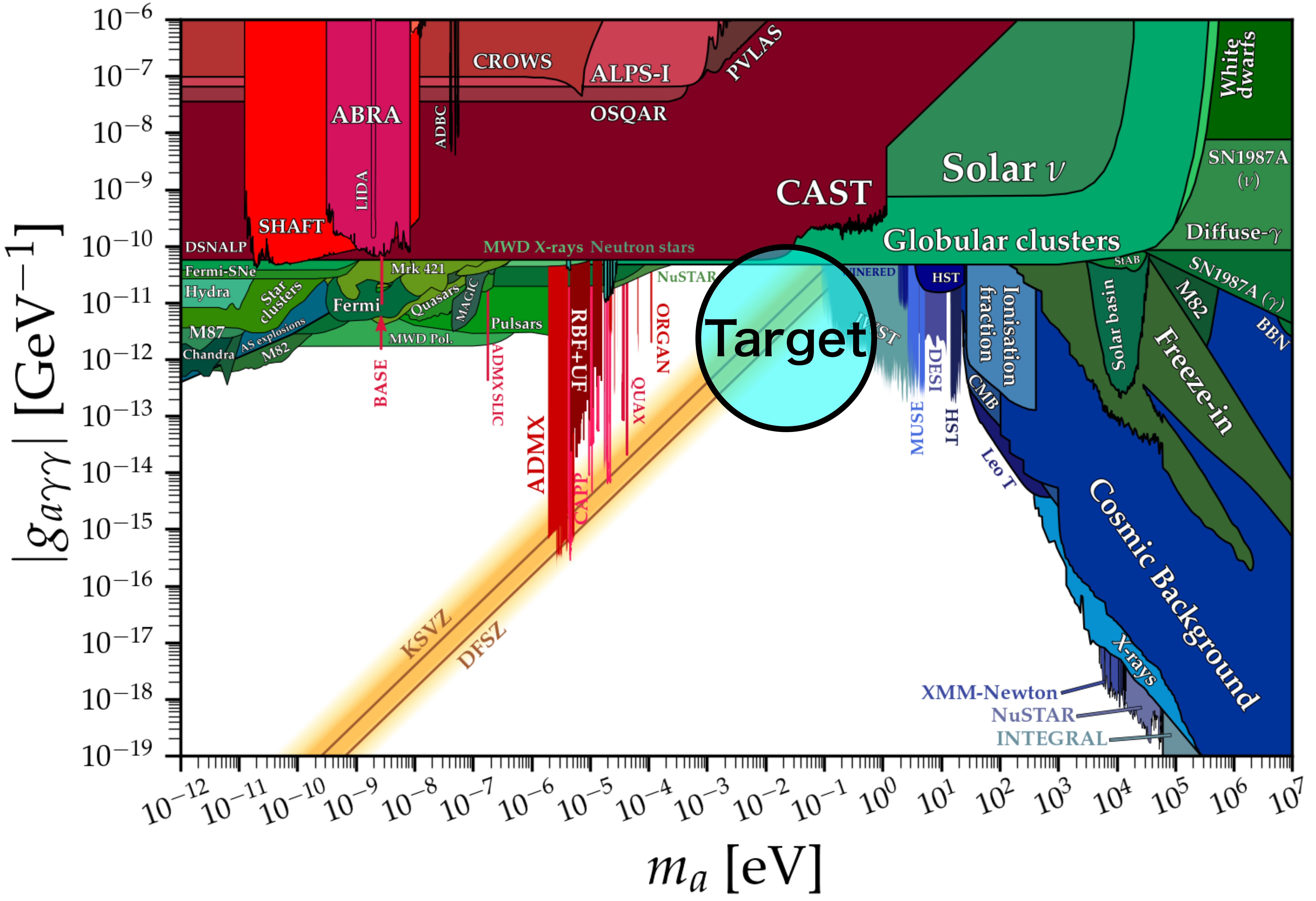


← Current constraints on

- Axion-photon coupling
- Axion mass

Ciaran O'HARE. (2020). doi.org/10.5281/zenodo.3932430

Shift current is applied in studies of THz dynamics



← Current constraints on

- Axion-photon coupling
- Axion mass

THz shift current

↓

meV axion search

Ciaran O'HARE. (2020). doi.org/10.5281/zenodo.3932430

Theoretical form of the shift current

Shift current is regarded as **the second-order DC response**.

The same effect is also observed with **a small output frequency**.

Theoretical expression for general inputs:

$$\langle \hat{J}^{\mu}_{\mathrm{shift}} \rangle^{(2)}(\omega) = \frac{1}{2}\sum_{ab}\int \frac{d^d\boldsymbol{k}}{(2\pi)^d}\int d\omega_1 d\omega_2 \left(\frac{-e^3}{\omega_1\omega_2}\right) E^{\alpha_1}(\omega_1)E^{\alpha_2}(\omega_2)\delta(\omega-\omega_1-\omega_2)$$

$$\times\, r^{\mu\alpha_1}_{\boldsymbol{k}ab} r^{\alpha_2}_{\boldsymbol{k}ba}\left(\frac{f_{ab}}{\omega_2-\varepsilon_{\boldsymbol{k}ba}+i\gamma}\right) + (\alpha_1,\omega_1 \leftrightarrow \alpha_2,\omega_2)$$

arXiv: 2505.17007

I will pick up some key points.

Important features for axion search

Output **Input**

$$\boxed{\langle \hat{J}^{\mu}_{\text{shift}} \rangle^{(2)}(\omega)} = \frac{1}{2}\sum_{ab}\int \frac{d^d\boldsymbol{k}}{(2\pi)^d}\int d\omega_1 d\omega_2 \left(\frac{-e^3}{\omega_1\omega_2}\right)\boxed{E^{\alpha_1}(\omega_1)E^{\alpha_2}(\omega_2)}\delta(\omega-\omega_1-\omega_2)$$

$$\times\, r^{\mu\alpha_1}_{\boldsymbol{k}ab} r^{\alpha_2}_{\boldsymbol{k}ba}\left(\frac{f_{ab}}{\omega_2-\varepsilon_{\boldsymbol{k}ba}+i\gamma}\right)+(\alpha_1,\omega_1\leftrightarrow\alpha_2,\omega_2)$$

Point!

The second-order response $\langle \hat{J}^{\mu}\rangle^{(2)}_{\text{shift}}(\omega) = \sigma^{\mu\alpha_1\alpha_2}_{\text{shift}}\, E^{\alpha_1}(\omega_1)E^{\alpha_2}(\omega_2)$

→ We can enhance the signal by applying another strong electric field.

$$J_{\text{shift}}(\omega) = \sigma_{\text{shift}} E_{\text{DM}}(\omega_{\text{DM}}) E_{\text{exp}}(\omega_{\text{exp}}) \qquad \sigma_{\text{shift}}:\ \text{conductivity}$$

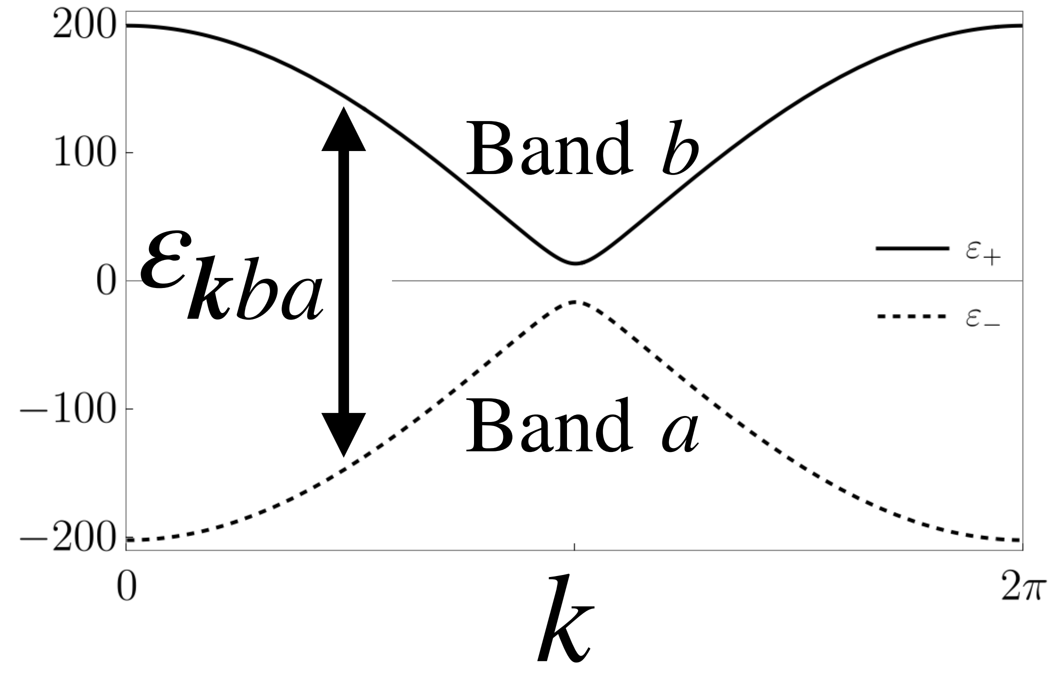
Important features for axion search

$$\langle \hat{J}^{\mu}_{\text{shift}} \rangle^{(2)}(\omega) = \frac{1}{2}\sum_{ab}\int \frac{d^d\boldsymbol{k}}{(2\pi)^d}\int d\omega_1 d\omega_2 \left(\frac{-e^3}{\omega_1\omega_2}\right) E^{\alpha_1}(\omega_1)E^{\alpha_2}(\omega_2)\delta(\omega-\omega_1-\omega_2)$$

$$\times\, r^{\mu\alpha_1}_{\boldsymbol{k}ab} r^{\alpha_2}_{\boldsymbol{k}ba}\left(\frac{f_{ab}}{\omega_2 - \varepsilon_{\boldsymbol{k}ba} + i\gamma}\right) + (\alpha_1,\omega_1 \leftrightarrow \alpha_2,\omega_2)$$

Input energy

Band gap of the material



Point!

Band structure restricts the resonant input frequency.

→ Given the input frequency, the summation and the integration $\sum_{ab}\int d^d\boldsymbol{k}$ selects the corresponding energy gap $\varepsilon_{\boldsymbol{k}ba}$ to be resonant.

Important features for axion search

$$\langle \hat{J}^{\mu}_{\rm shift} \rangle^{(2)}(\omega) = \frac{1}{2}\sum_{ab}\int \frac{d^d\boldsymbol{k}}{(2\pi)^d}\int d\omega_1 d\omega_2 \left(\frac{-e^3}{\omega_1\omega_2}\right) E^{\alpha_1}(\omega_1)E^{\alpha_2}(\omega_2)\delta(\omega-\omega_1-\omega_2)$$

$$\times\, r^{\mu\alpha_1}_{\boldsymbol{k}ab} r^{\alpha_2}_{\boldsymbol{k}ba} \left(\frac{f_{ab}}{\omega_2 - \varepsilon_{\boldsymbol{k}ba} + i\gamma}\right) + (\alpha_1,\omega_1 \leftrightarrow \alpha_2,\omega_2)$$

Electron scattering effect

$$\text{resonant} : \int d^d\boldsymbol{k} \frac{1}{\omega_2 - \varepsilon_{\boldsymbol{k}ba} + i\gamma} \sim \gamma \times \frac{1}{i\gamma}$$

Point!

Non-dissipative nature $\langle \hat{J}^{\mu} \rangle^{(2)}_{\rm shift}(\omega)$ is independent of γ

→ This nature, and the wide range of the allowed energy gap supports the broadband search for the axion DM-induced photon.

I skip the detail of "r", but···

$$\langle \hat{J}^{\mu}_{\mathrm{shift}} \rangle^{(2)}(\omega) = \frac{1}{2}\sum_{ab}\int \frac{d^d\boldsymbol{k}}{(2\pi)^d}\int d\omega_1 d\omega_2 \left(\frac{-e^3}{\omega_1\omega_2}\right) E^{\alpha_1}(\omega_1)E^{\alpha_2}(\omega_2)\delta(\omega-\omega_1-\omega_2)$$

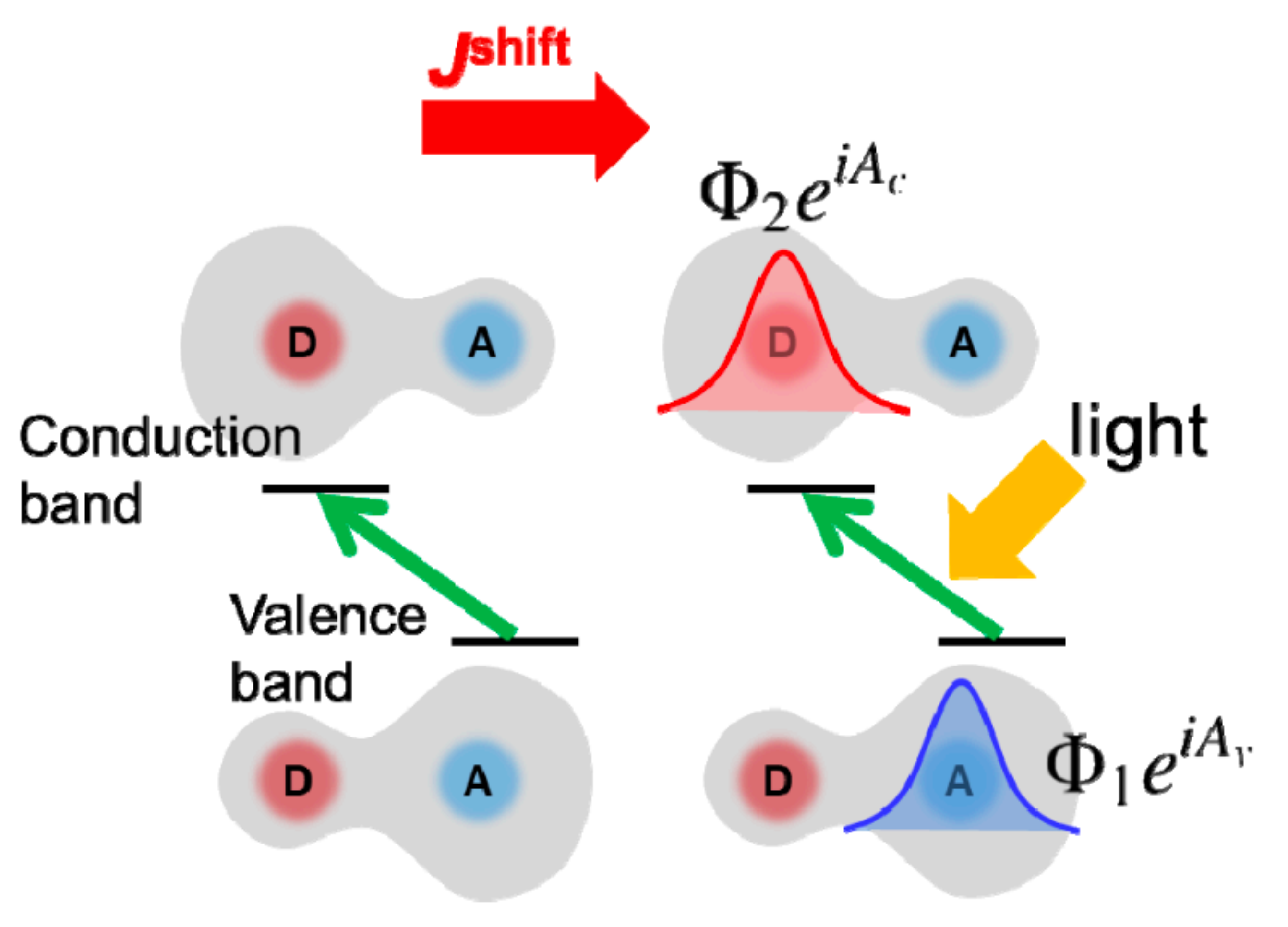
$$\times r^{\mu\alpha_1}_{\boldsymbol{k}ab} r^{\alpha_2}_{\boldsymbol{k}ba}\left(\frac{f_{ab}}{\omega_2-\varepsilon_{\boldsymbol{k}ba}+i\gamma}\right) + (\alpha_1,\omega_1 \leftrightarrow \alpha_2,\omega_2)$$

Contains the information of the Berry connection

Shift current

・Occurs in the inversion-broken materials.

・It arises from **spatial shift** of the electron wave function during state transitions.



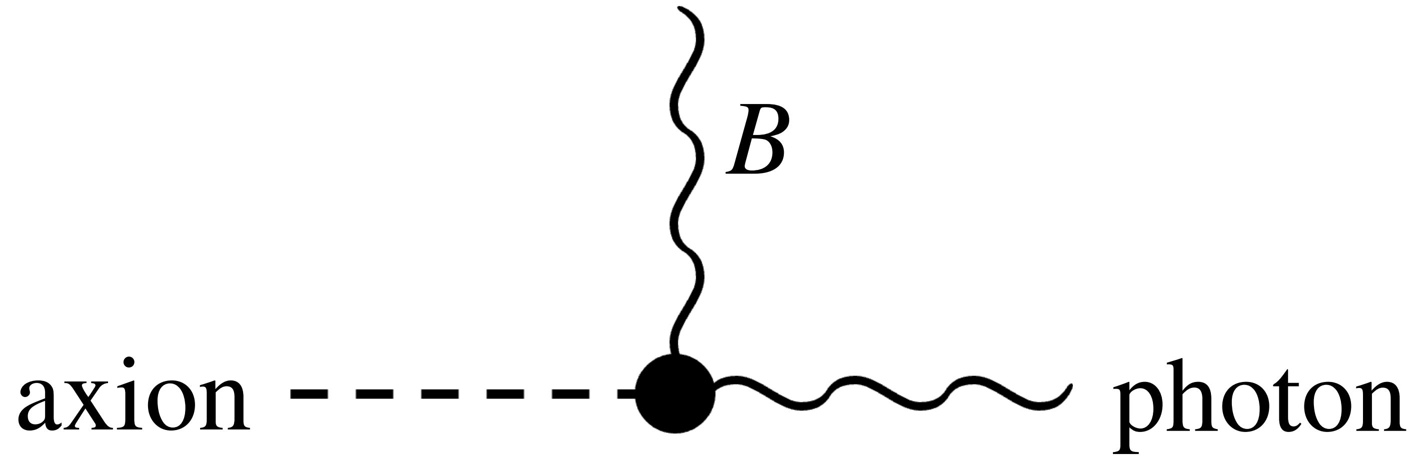
Outline

- What is the shift current?
- Method to detect the axion-induced shift current

Step1: Axion-photon conversion

Interaction: $\mathscr{L}_{\rm int} = g_{a\gamma\gamma}\, a\, \boldsymbol{E}\cdot\boldsymbol{B}$ $\qquad a = \dfrac{\sqrt{2\rho_{\rm DM}}}{m_{\rm DM}}\cos(m_{\rm DM}t + \phi_{\rm DM})$

In the presence of the static magnetic field,



$$E_{\rm DM} = g_{a\gamma\gamma}B_0\frac{\sqrt{2\rho_{\rm DM}}}{m_{\rm DM}}$$

$$\simeq 7.9\times 10^{-12}\frac{\rm V}{\rm m}\left(\frac{g_{a\gamma\gamma}}{10^{-11}\ {\rm GeV}^{-1}}\right)\left(\frac{B_0}{1\ {\rm T}}\right)\left(\frac{m_{\rm DM}}{1\ {\rm meV}}\right)^{-1}\left(\frac{\rho_{\rm DM}}{0.45\ {\rm GeVcm}^{-3}}\right)^{\frac{1}{2}}$$

→ Too small to detect directly. (It requires an enhancement mechanism.)

Step2: Shift current response

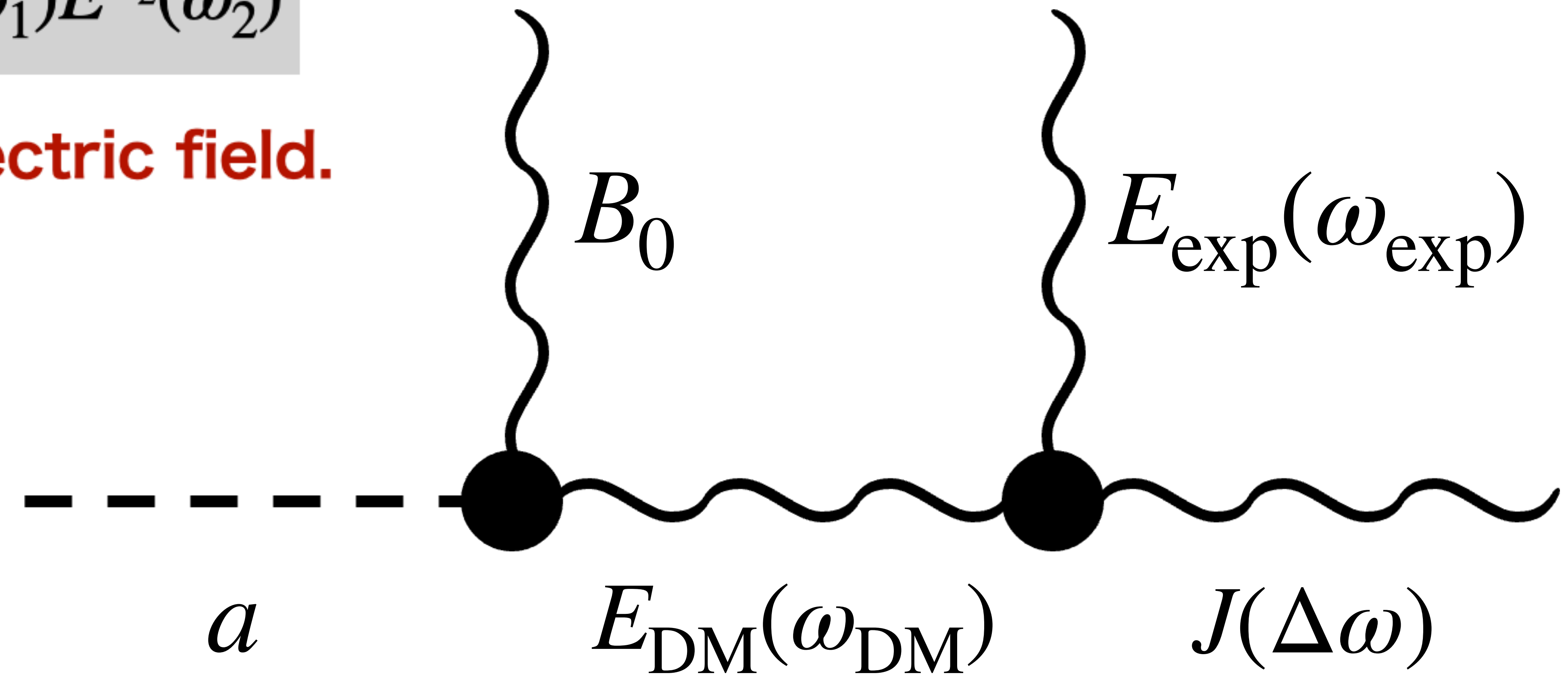
Point!

The second-order response $\langle \hat{J}^{\mu} \rangle^{(2)}_{\text{shift}}(\omega) = \sigma^{\mu\alpha_1\alpha_2}_{\text{shift}} E^{\alpha_1}(\omega_1) E^{\alpha_2}(\omega_2)$

→ **We can enhance the signal by applying another strong electric field.**

Input

$$E(t) = \mathrm{Re}\left[E_{\mathrm{DM}} e^{i m_{\mathrm{DM}} t - i\phi_{\mathrm{DM}}} + E_{\exp} e^{-i\omega_{\exp} t}\right]$$



Output

$$\langle \hat{J}^{\mu} \rangle^{(2)}_{\text{shift}}(\Delta\omega) = \sigma^{\mu\alpha_1\alpha_2}_{\text{shift}}(\Delta\omega) E^{\alpha_1}_{\mathrm{DM}} e^{-i\phi_{\mathrm{DM}}} E^{\alpha_2}_{\exp}$$

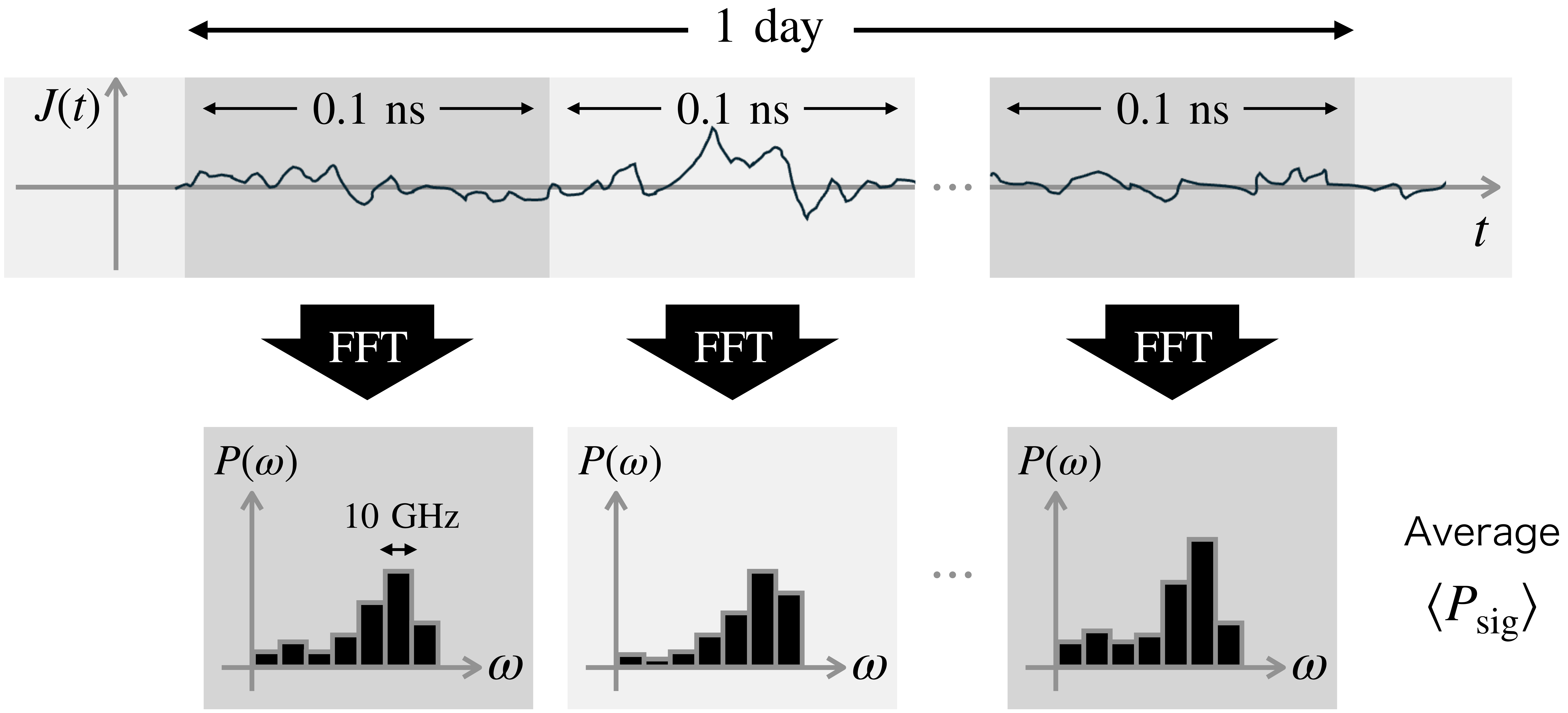
$$\Delta\omega = -m_{\mathrm{DM}} + \omega_{\exp}$$

Other terms

$J \propto E_{\mathrm{DM}} E_{\mathrm{DM}}$ → Negligible

$J \propto E_{\exp} E_{\exp}$ → Background

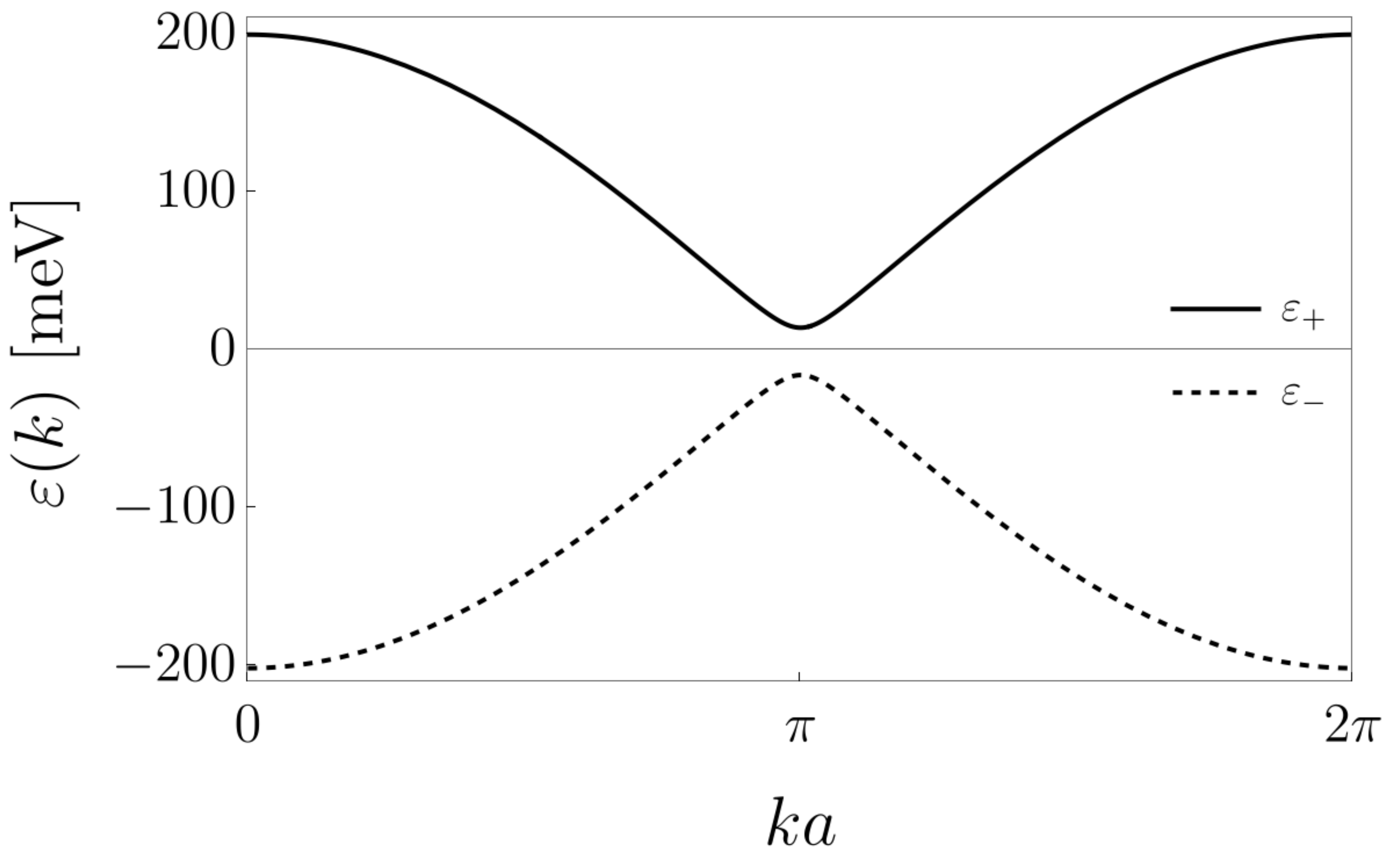
Step3: Collection of sample data



Toy model: 1D Rice-mele

$$H(k) = \boldsymbol{d}(k) \cdot \boldsymbol{\sigma} \quad (\boldsymbol{\sigma}: \ \text{Pauli matrix})$$

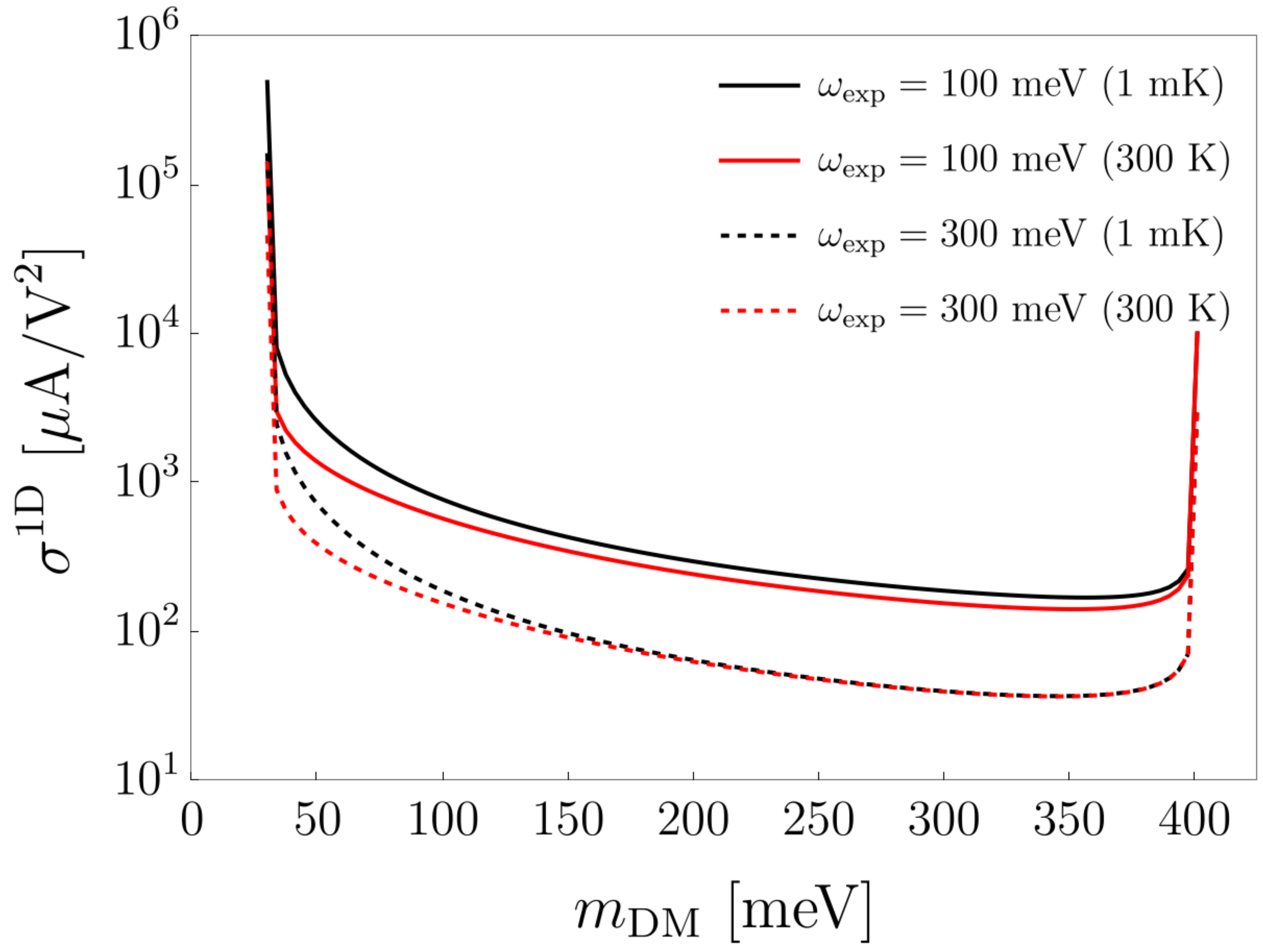
$$d_x = t(1 + \cos ka),\ d_y = -t \sin ka,\ d_z = \frac{V_A - V_B}{2}$$



Point!

Band structure determines the resonant input energy.

→ Sensitive axion mass range is estimated from the band structure.



arXiv: 2505.17007

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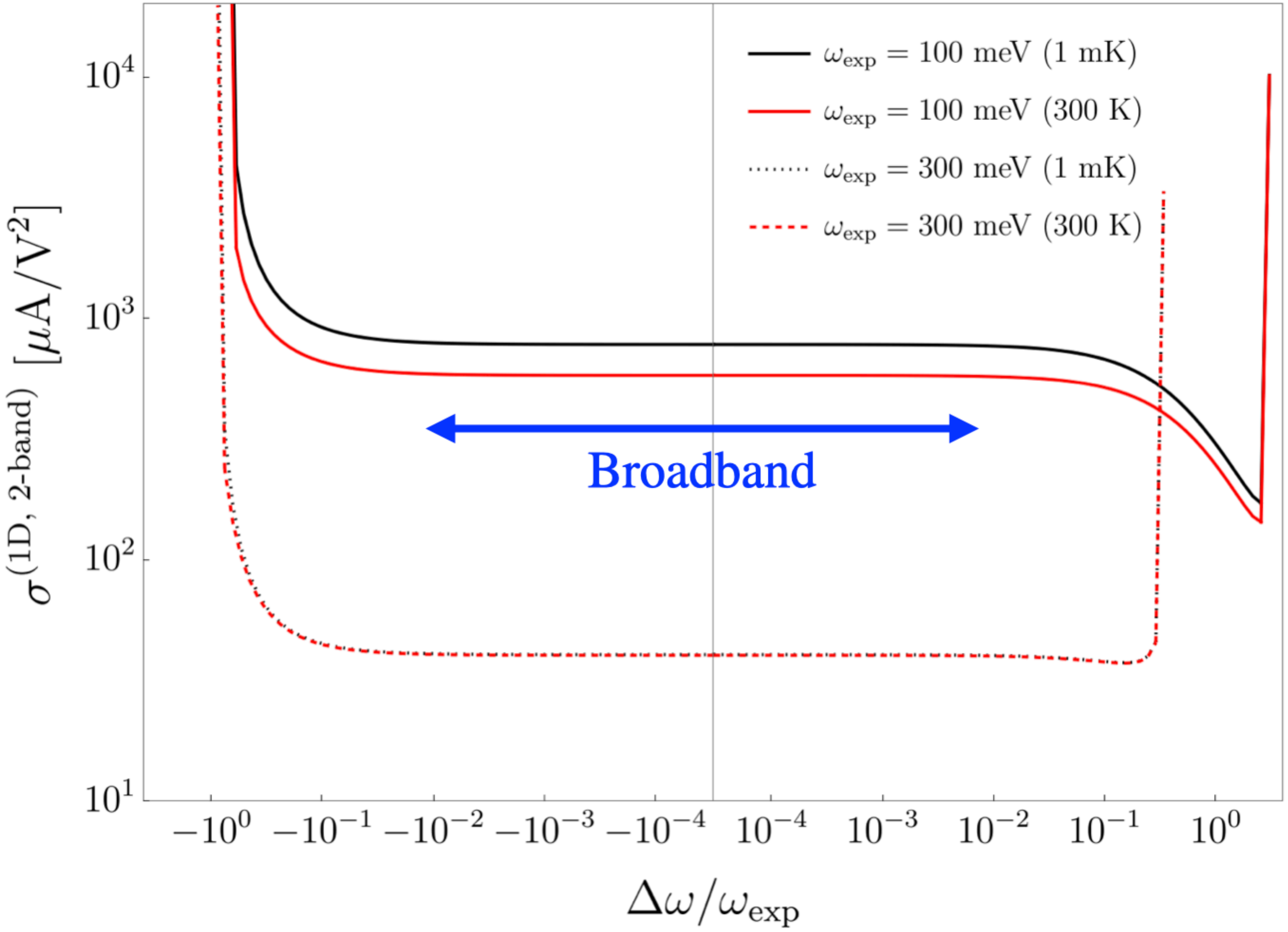


The conductivity is almost the same for small $\Delta\omega$.

$$\Delta\omega = -m_{\rm DM} + \omega_{\rm exp}$$

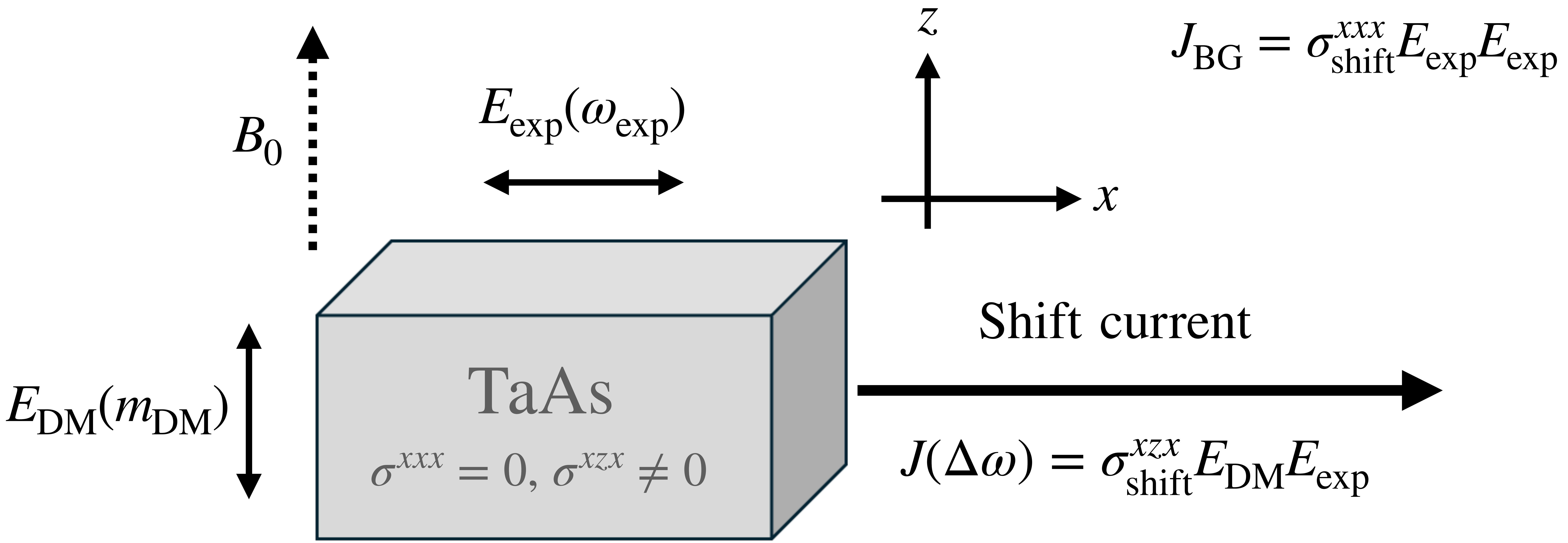
The search width is not determined by the effect of the electron scattering γ .

Broadband search is supported!

arXiv: 2505.17007

Real material setup

- TaAs: Type-I Weyl semimetal
- $\sigma_{\rm shift} \sim 200\ \mu{\rm A/V^2}$ for $25 - 350$ meV
- Mirror symmetry $(x \to -x)$ is used for cutting backgrounds



arXiv: 2505.17007

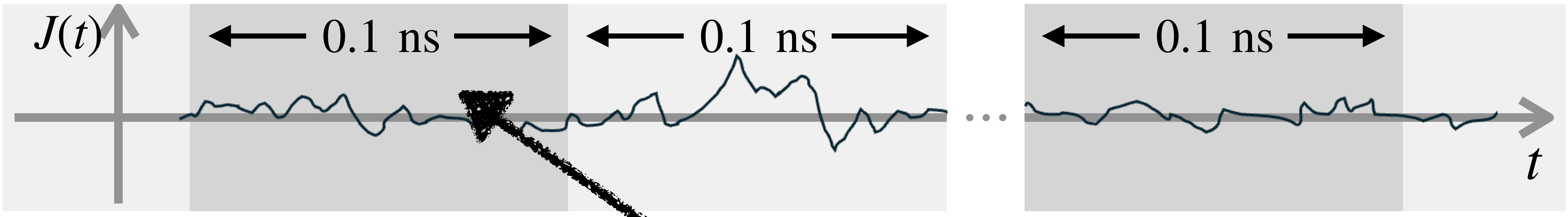
Signal power

$$E(t) = \mathrm{Re}\left[E_{\mathrm{DM}} e^{i m_{\mathrm{DM}} t - i\phi_{\mathrm{DM}}} + E_{\exp} e^{-i\omega_{\exp} t}\right]$$

We have to take into account the randomness of the unknown relative phase ϕ_{DM}.

$$\langle \hat{J}^{\mu} \rangle^{(2)}_{\mathrm{shift}}(\Delta\omega) = \sigma^{\mu\alpha_1\alpha_2}_{\mathrm{shift}}(\Delta\omega) E^{\alpha_1}_{\mathrm{DM}} e^{-i\phi_{\mathrm{DM}}} E^{\alpha_2}_{\exp}$$

$$\Delta\omega = -m_{\mathrm{DM}} + \omega_{\exp}$$



The time interval $0.1\ \mathrm{ns}$ is chosen so that it is within the coherent time scale of input fields.

→For each interval, the phase is fixed and we can safely take the average $\langle P_{\mathrm{sig}} \rangle$.

$$\langle P_{\mathrm{sig}} \rangle = \frac{1}{2} R_{\exp} |\sigma^{xzx}_{\mathrm{shift}}|^2 E^2_{\mathrm{DM}} E^2_{\exp} L^4_{\exp}$$

$$= 6.2 \times 10^{-15}\ \mu\mathrm{W} \left(\frac{R_{\exp}}{50\ \Omega}\right)\left(\frac{\sigma^{xzx}_{\mathrm{shift}}}{200\ \mu\mathrm{A/V^2}}\right)^2 \left(\frac{g_{a\gamma\gamma}}{10^{-11}\ \mathrm{GeV^{-1}}}\right)^2 \left(\frac{B_0}{1\ \mathrm{T}}\right)^2$$

$$\times \left(\frac{m_{\mathrm{DM}}}{1\ \mathrm{meV}}\right)^{-2} \left(\frac{\rho_{\mathrm{DM}}}{0.45\ \mathrm{GeVcm^{-3}}}\right) \left(\frac{E_{\exp}}{10^8\ \mathrm{V/m}}\right)^2 \left(\frac{L_{\exp}}{1\ \mathrm{cm}}\right)^4$$

Signal power

$$E(t) = \mathrm{Re}\left[E_{\mathrm{DM}} e^{i m_{\mathrm{DM}} t - i\phi_{\mathrm{DM}}} + E_{\mathrm{exp}} e^{-i\omega_{\mathrm{exp}} t}\right]$$

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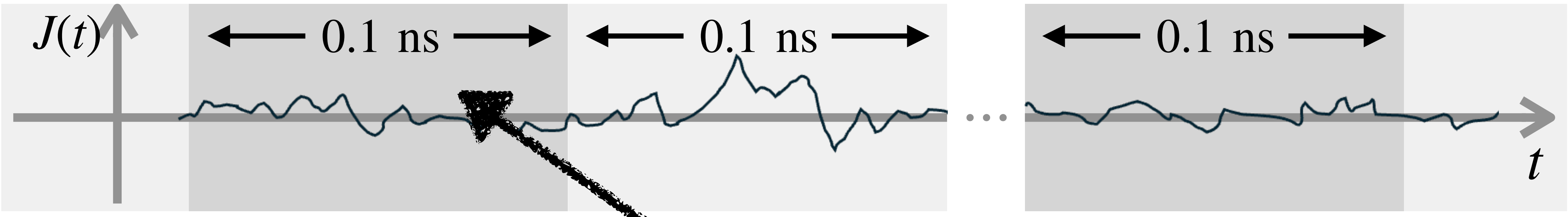
$$\Delta\omega = -m_{\mathrm{DM}} + \omega_{\mathrm{exp}}$$



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$$\times \left(\frac{m_{\mathrm{DM}}}{1\ \mathrm{meV}}\right)^{-2} \left(\frac{\rho_{\mathrm{DM}}}{0.45\ \mathrm{GeVcm}^{-3}}\right) \left(\frac{E_{\mathrm{exp}}}{10^8\ \mathrm{V/m}}\right)^2 \left(\frac{L_{\mathrm{exp}}}{1\ \mathrm{cm}}\right)^4$$

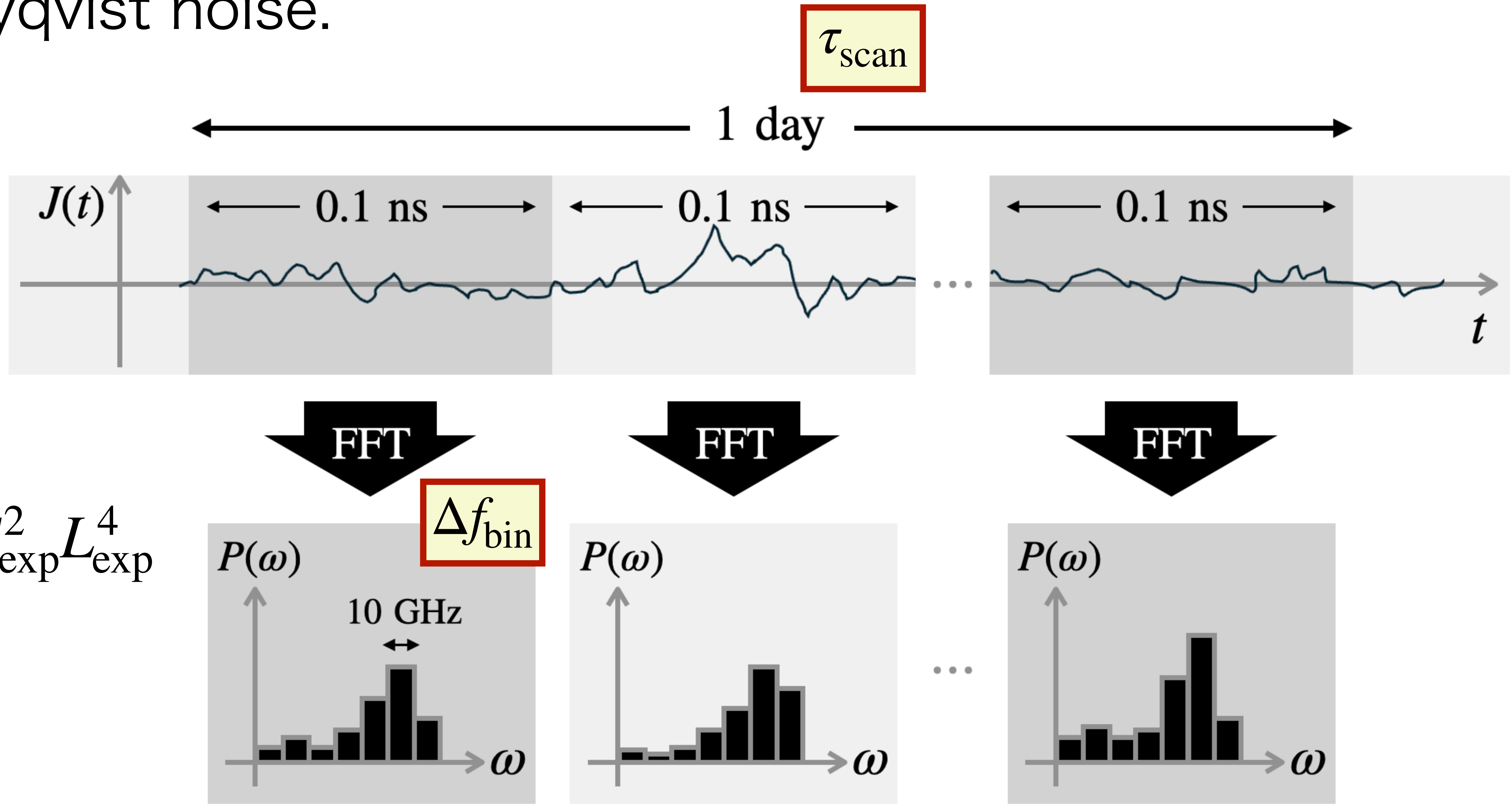
The effect of ϕ_{DM}.

Signal to Noise Ratio

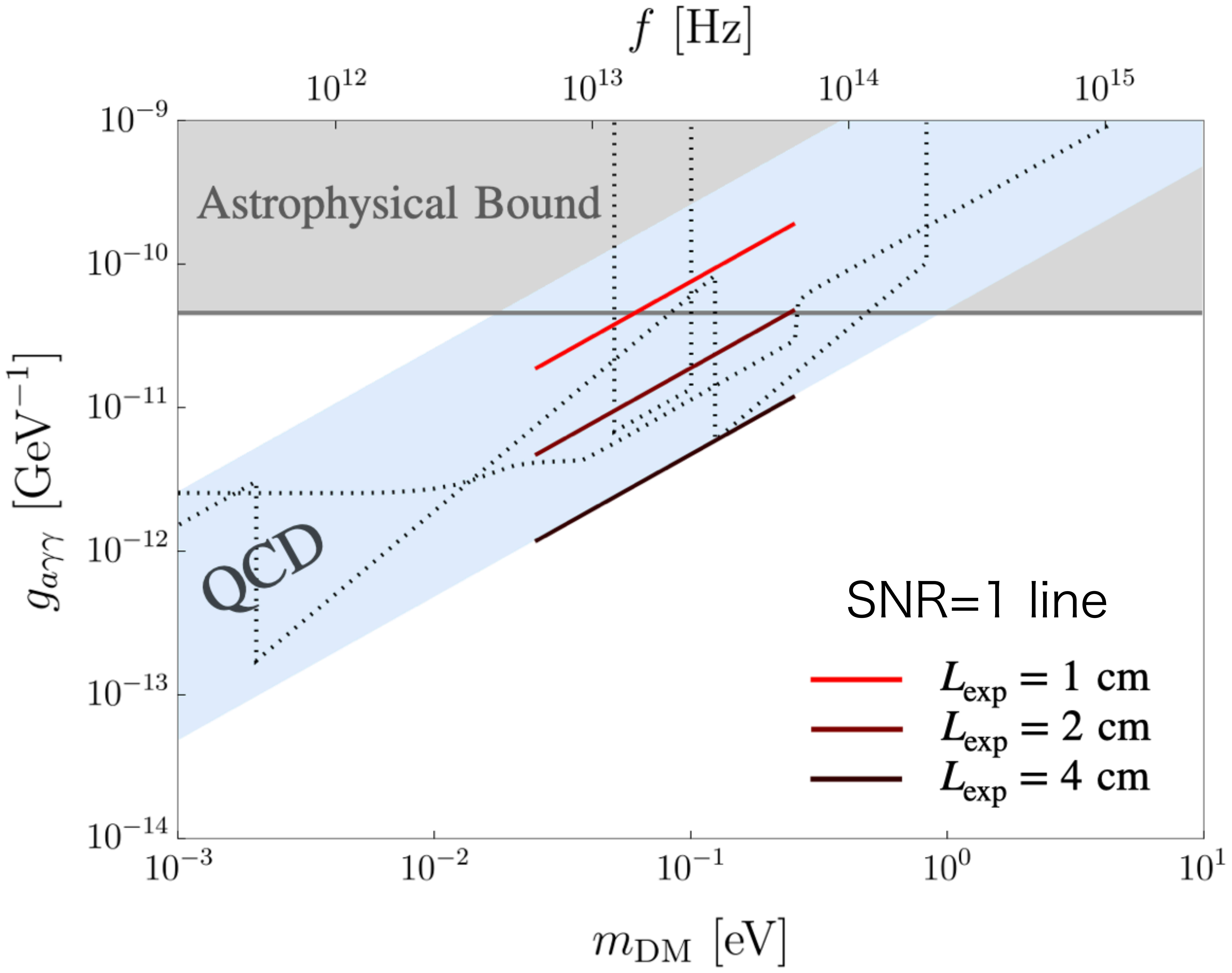
We assume that the main noise comes from Johnson-Nyqvist noise.

$$\mathrm{SNR} = \frac{\langle P_{\mathrm{sig}} \rangle}{4 k_{\mathrm{B}} T} \sqrt{\frac{\tau_{\mathrm{scan}}}{\Delta f_{\mathrm{bin}}}}$$

$$\langle P_{\mathrm{sig}} \rangle = \frac{1}{2} R_{\mathrm{exp}} |\sigma^{xzx}_{\mathrm{shift}}|^2 E^2_{\mathrm{DM}} E^2_{\mathrm{exp}} L^4_{\mathrm{exp}}$$



Result



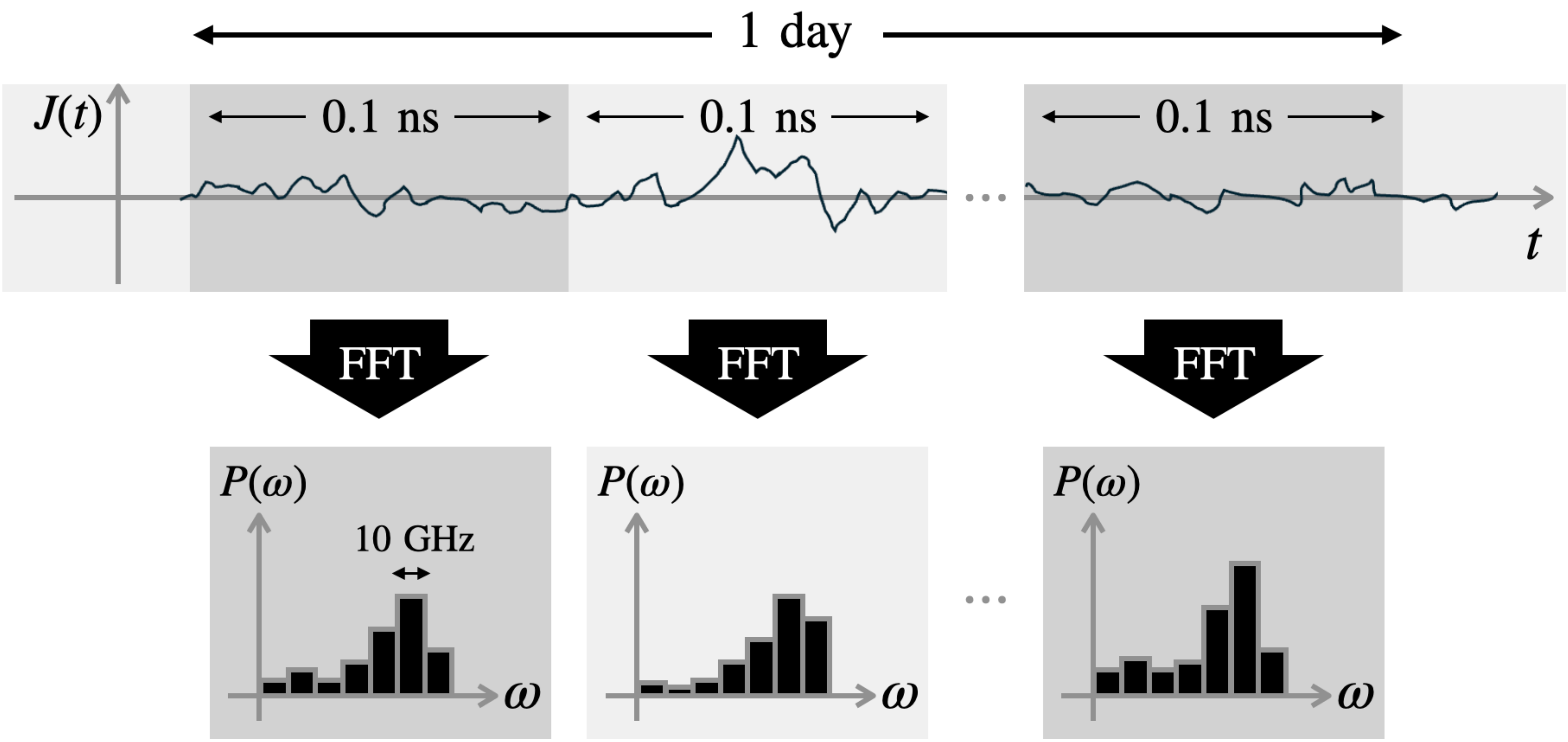
Total mass range: $25 - 350$ meV

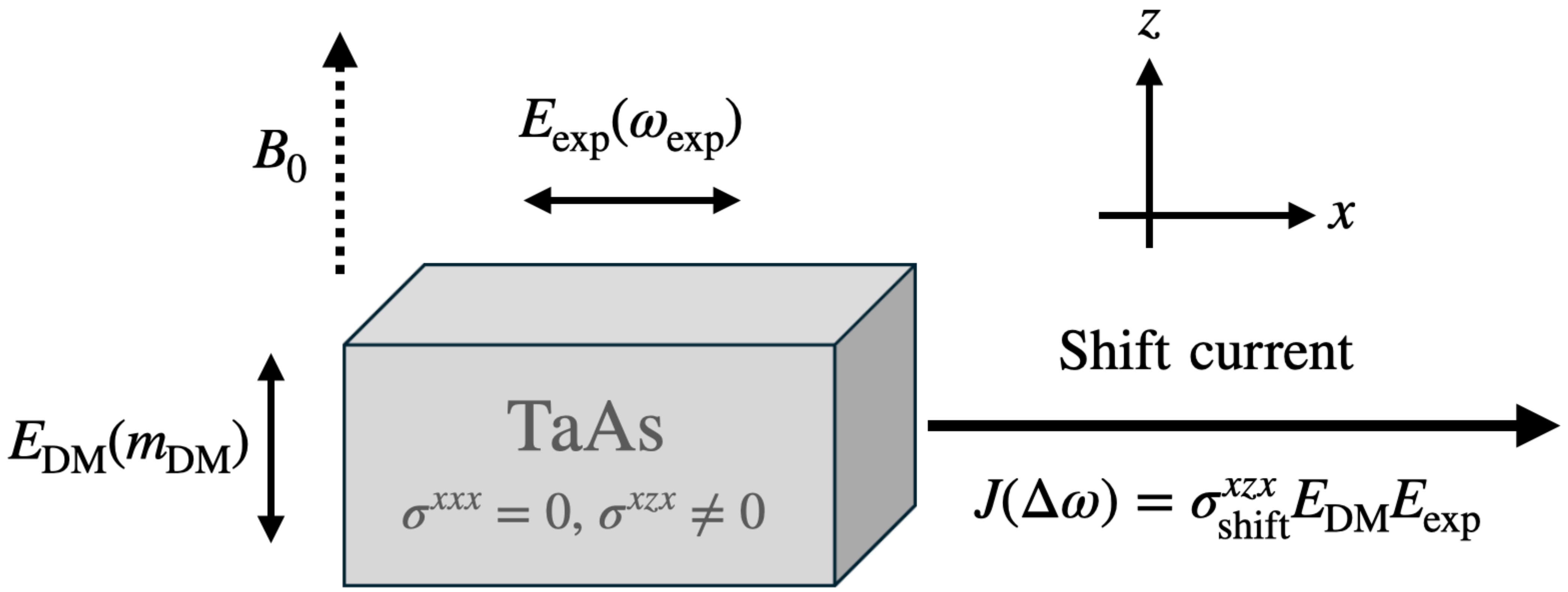
Given $\omega_{\rm exp} \sim \mathcal{O}(100)$ meV, the simultaneous scanning range is $\mathcal{O}(1)$ meV.

Spending 1day for each scan, it takes about 300 days to cover the whole detectable mass range.

arXiv: 2505.17007

Some experimental difficulties





① The value of $E_{\mathrm{exp}} \sim 10^8\ \mathrm{V/m}$ is currently achievable using short-time THz pulse laser technology.

$\mathcal{O}(0.1)$ ps

Y. Sanari, et Al. (2020)

However, our setup requires at least 0.1 ns pulse.

② We excluded the background response by using the symmetry of the material TaAs (Applying the experimental field in x-direction).

But technically, the directional fluctuation of the experimental field cannot be zero. → background

To distinguish the signal from this background, a Gaussian pulse laser must be required.

Conclusion

We proposed a novel method to detect axion DM using shift current.

Based on our method, it is possible to probe the parameter space of QCD axions in the mass range of $\mathcal{O}(10)$ - $\mathcal{O}(100)$ meV.

For now, there are several difficulties to realize the experiment ⋯
but this is just the beginning of the journey!!

Shift current is the cutting-edge study in condense matter physics.
(Search for materials with high efficiency, theory, applications, etc.)

→ **The development of shift current study helps axion DM search !?**.