

物性・量子とダークマター探査

Kazunori Nakayama (Tohoku Univ & QUP)

micro workshop on Quantum detection of (dark) waves (2025/4/22)

Contents

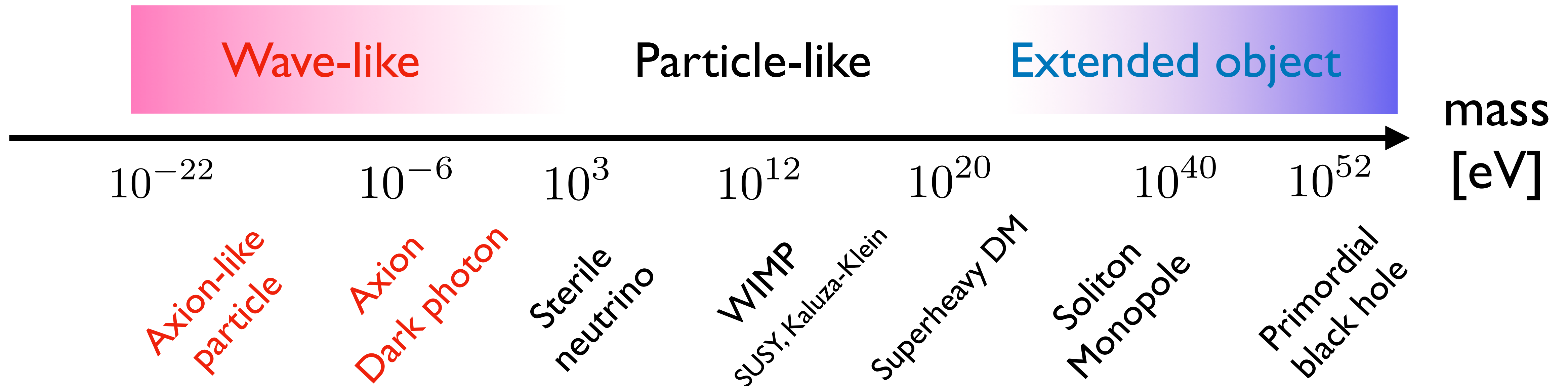
軽いダークマター

物性を利用した探査

量子技術を利用した探査

軽いダークマター

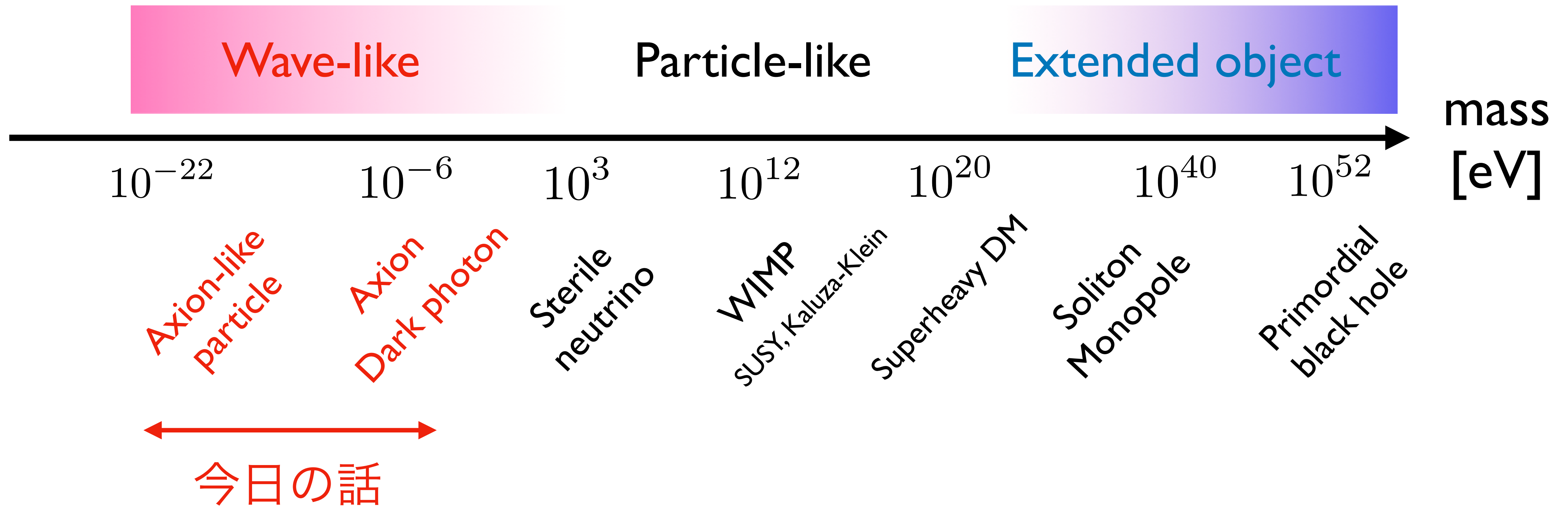
ダークマター質量



初期宇宙での生成方法は？

どうやって検出するか？

ダークマター質量



初期宇宙での生成方法は？

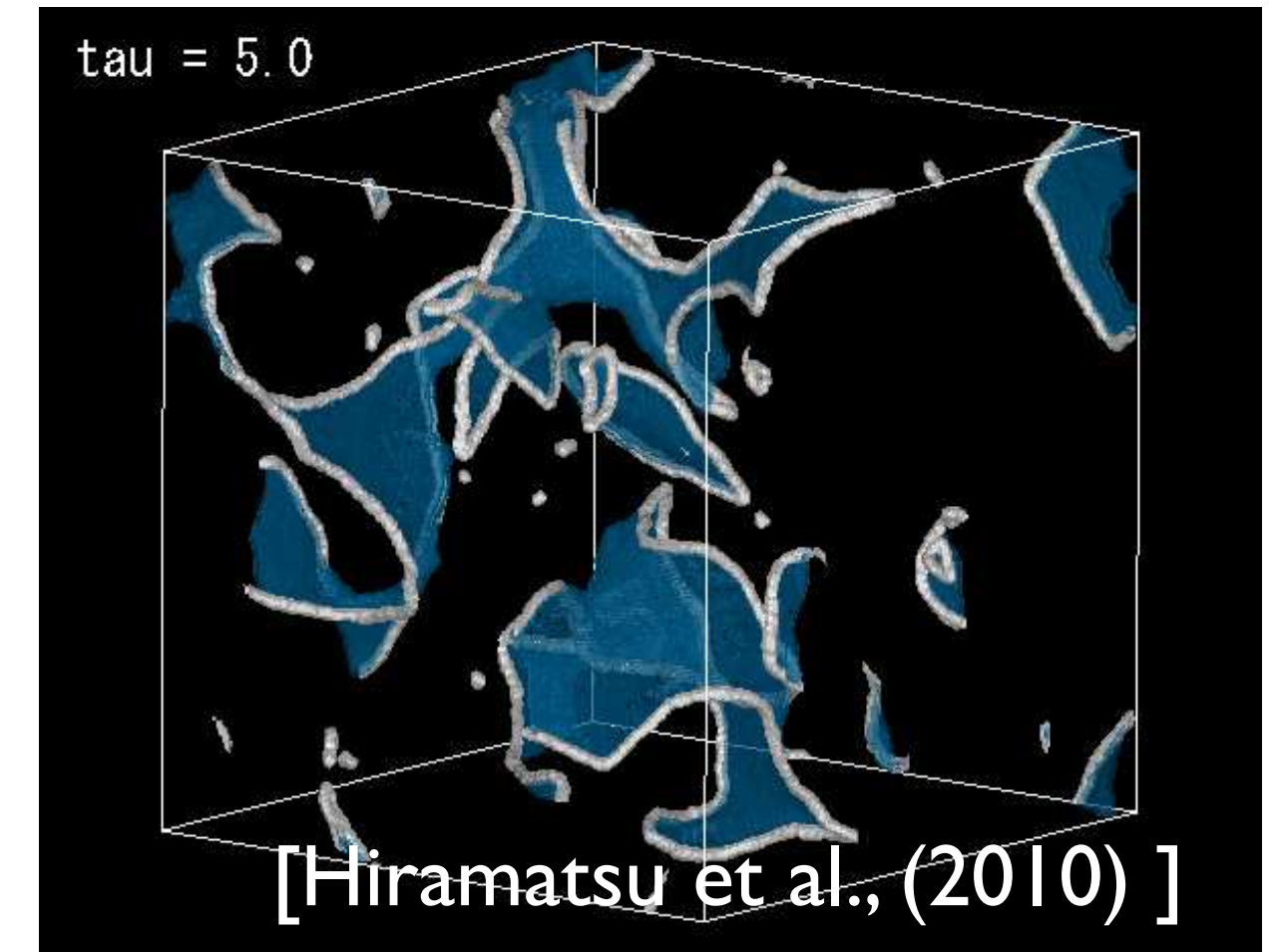
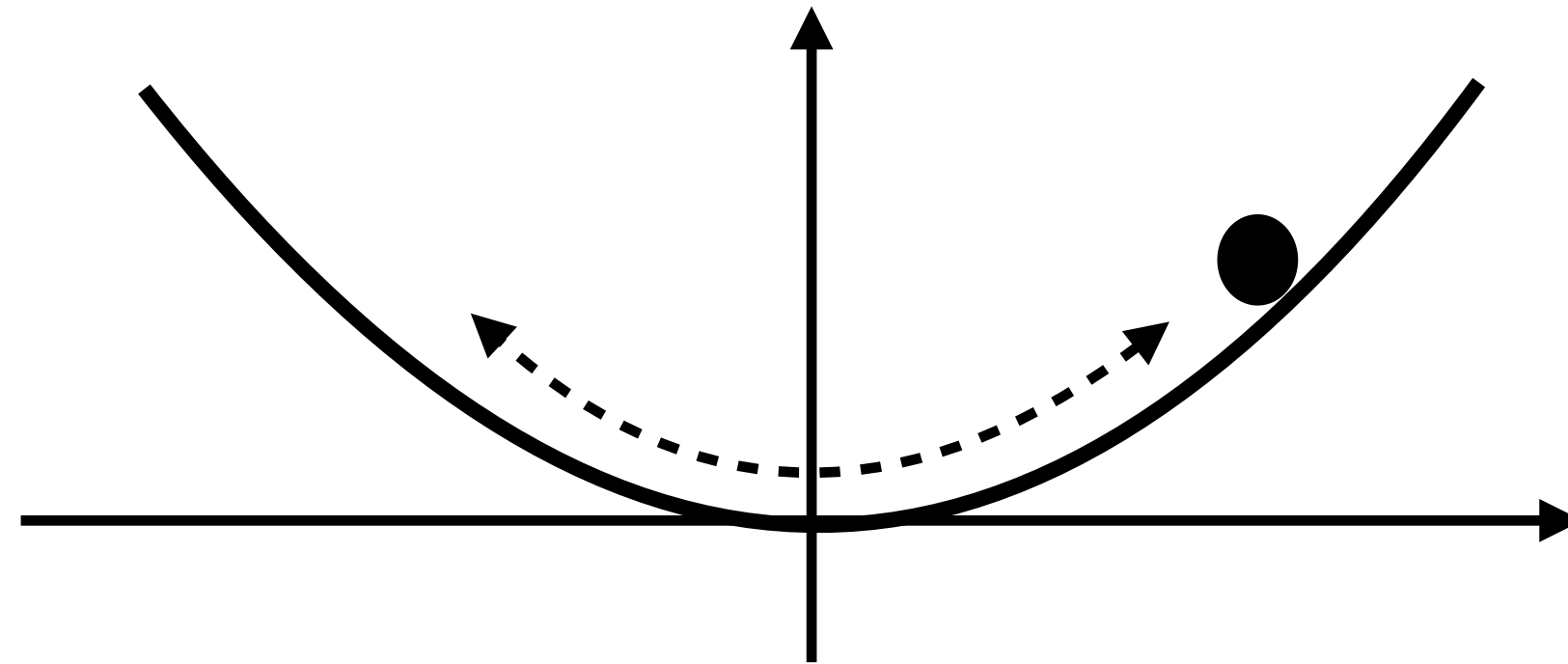
どうやって検出するか？

ダークマター生成機構

● Scalar/pseudo-scalar

コヒーレント振動

位相欠陥



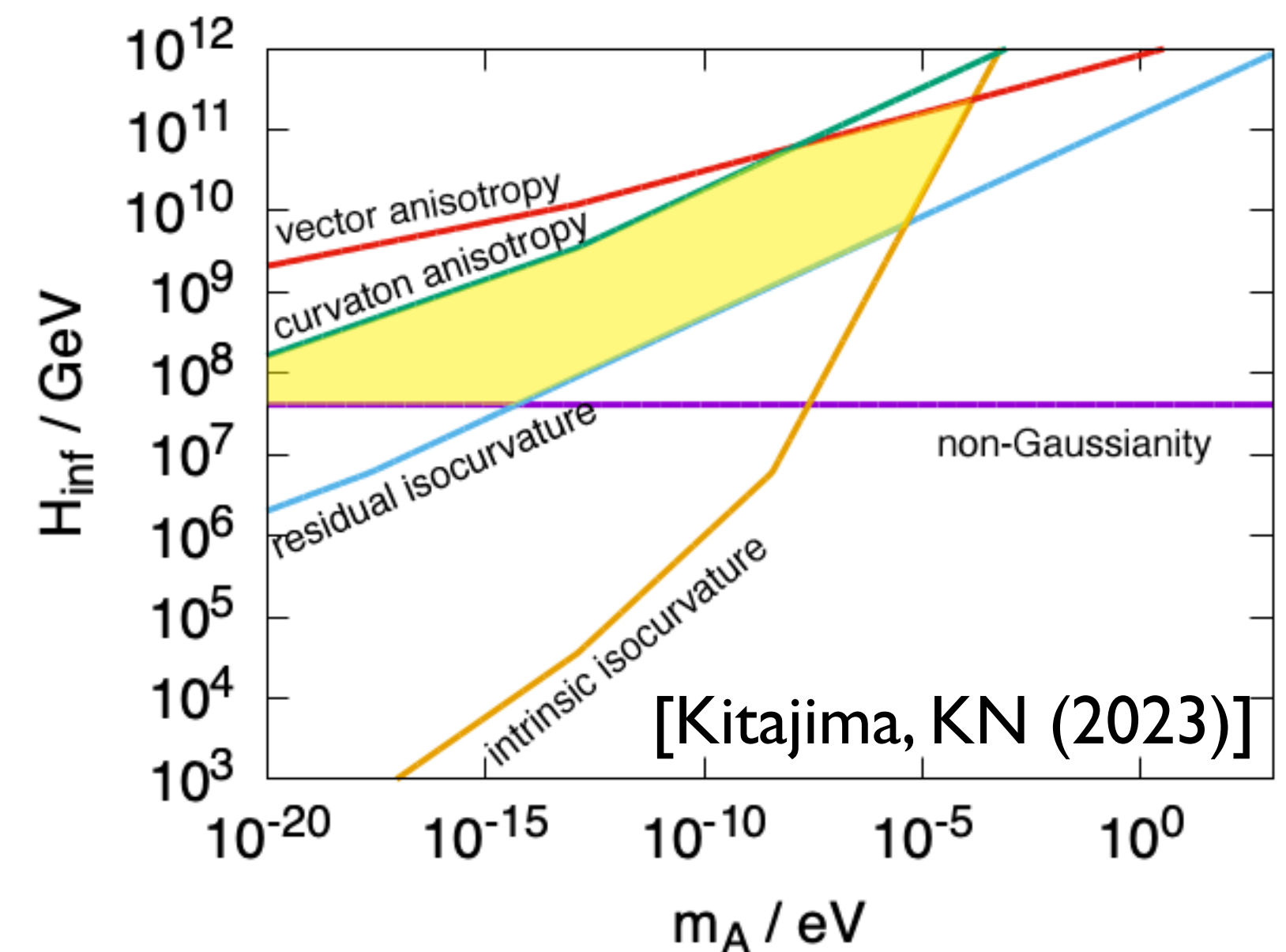
● Vector

インフレーション揺らぎ [Graham, Mardon, Rajendran (2015)]

重力的粒子生成 [Ema, KN, Tang (2019)]

宇宙紐 [Long, Wang (2019), Kitajima, KN (2022)]

コヒーレント振動 [KN (2020), Kitajima, KN (2023)]



ダークマターの結合

- **Scalar**

Dilaton/moduli

$$\mathcal{L} = g\phi\bar{\psi}\psi + \frac{g\phi\gamma}{4}\phi F_{\mu\nu}F^{\mu\nu}$$

- **Pseudo-scalar**

Axion/Axion-like

$$\mathcal{L} = \frac{g_{ae}}{2m_e}(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi + \frac{g_{a\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

- **Vector**

Dark photon

$$\mathcal{L} = \frac{\kappa}{2}H_{\mu\nu}F^{\mu\nu}$$

New gauge boson

$$\mathcal{L} = gH_\mu\bar{\psi}\gamma^\mu\psi$$

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fifth forceから制限

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磁場の下で光子に
変換

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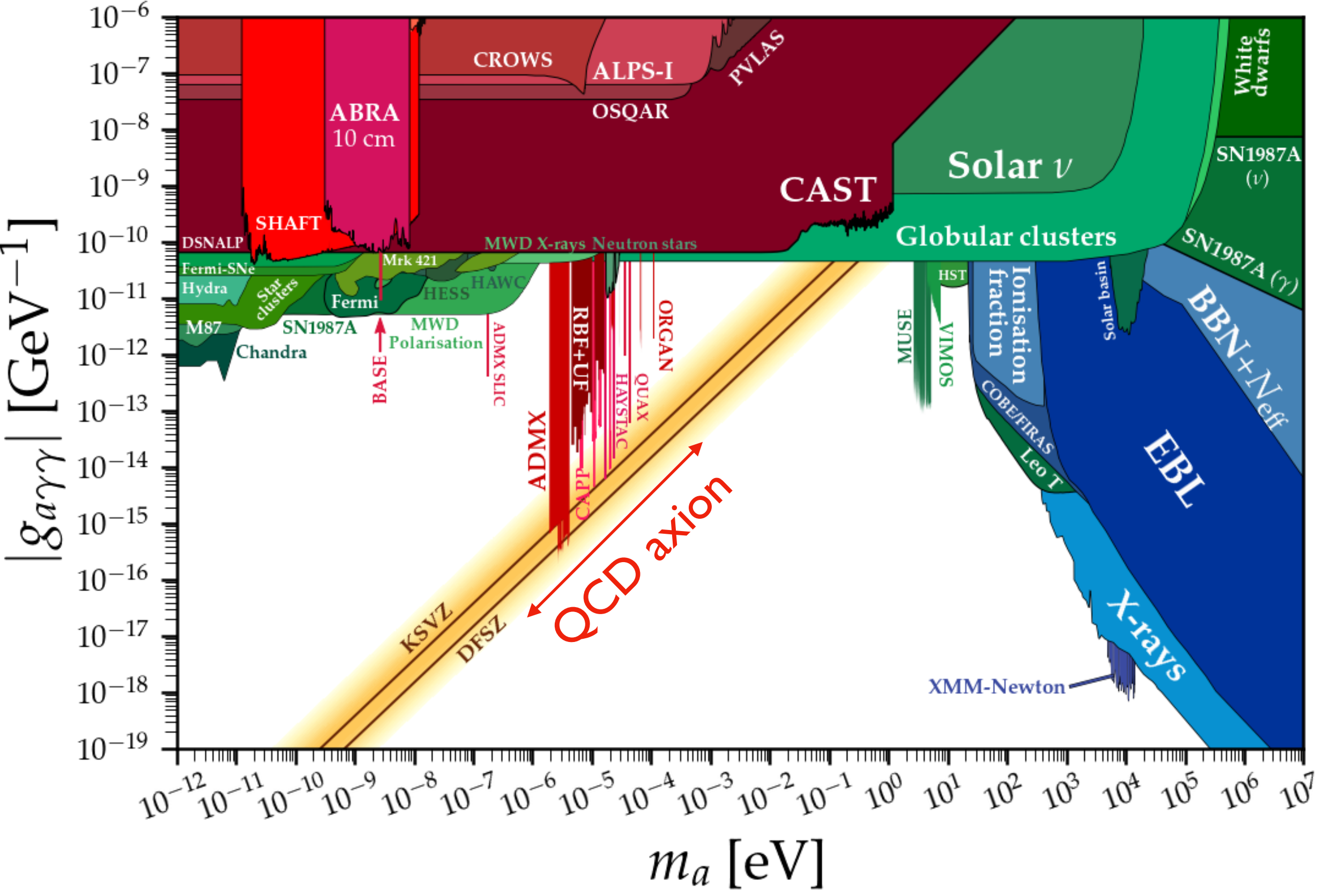
ダークマタと

物質の反応

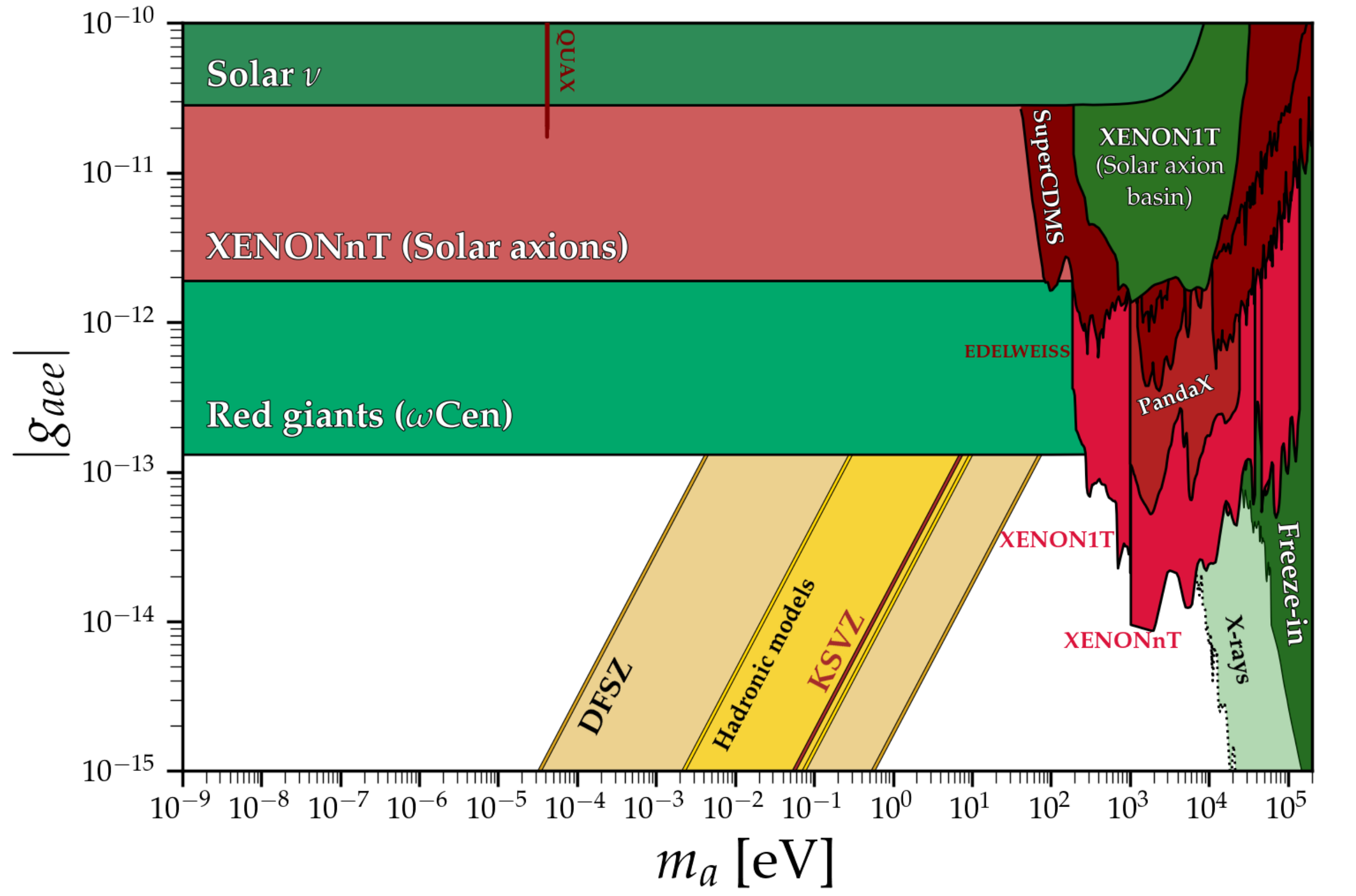
磁場の下で光子に
変換

fifth forceから制限

アクシオン-光子結合に対する制限

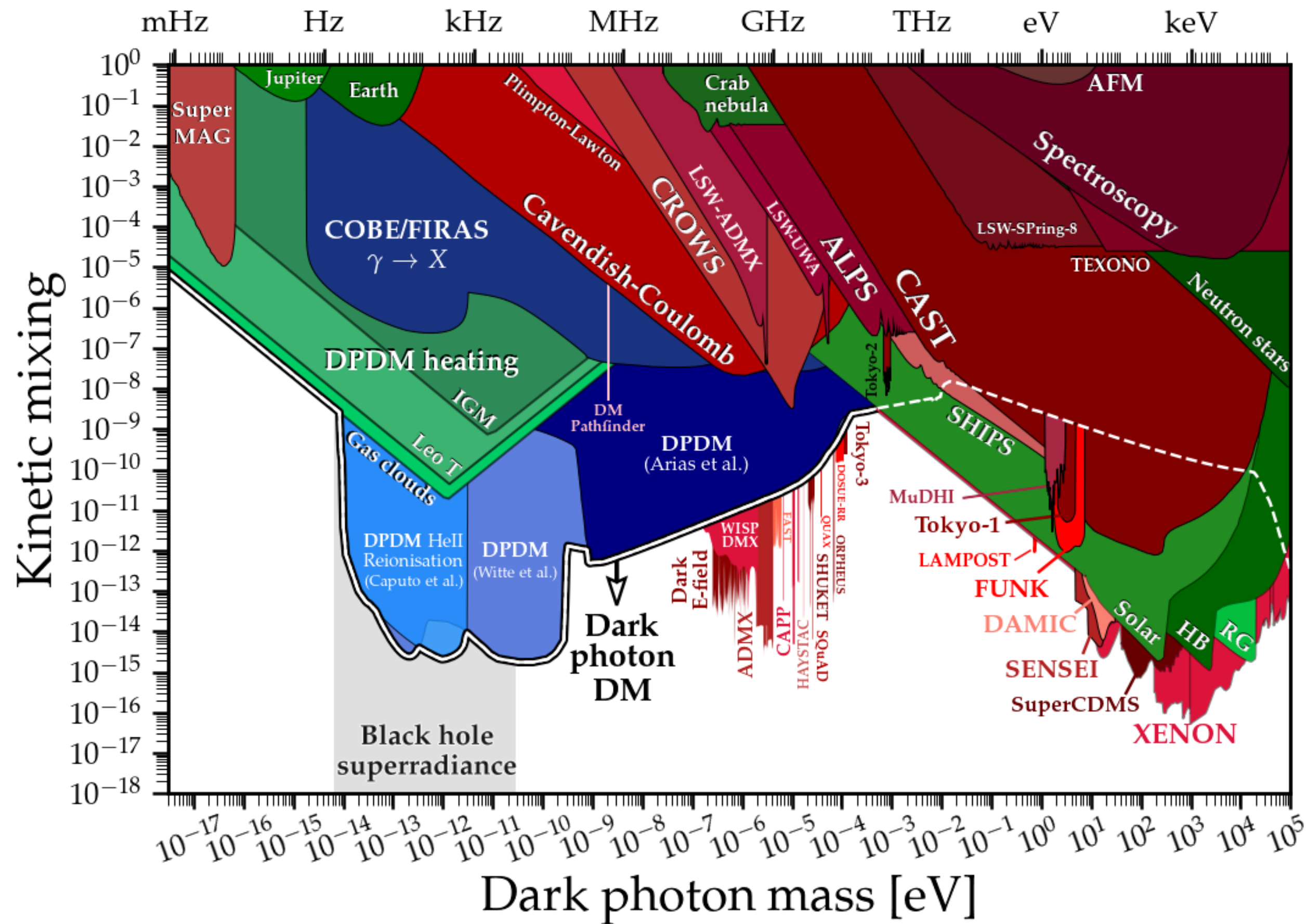


アクシオン-電子結合に対する制限

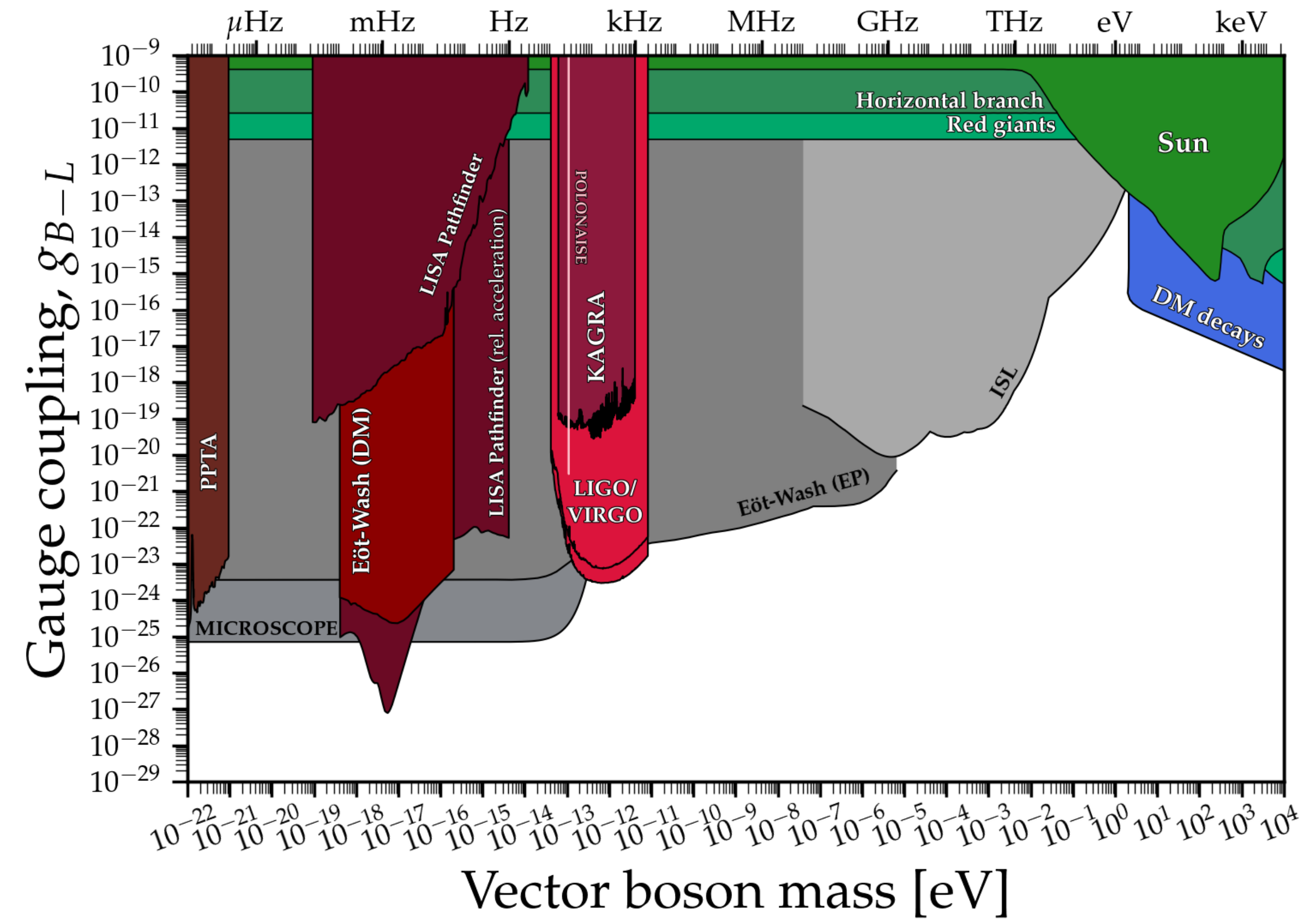


ダークフォトン-光子

kinetic mixing に対する制限

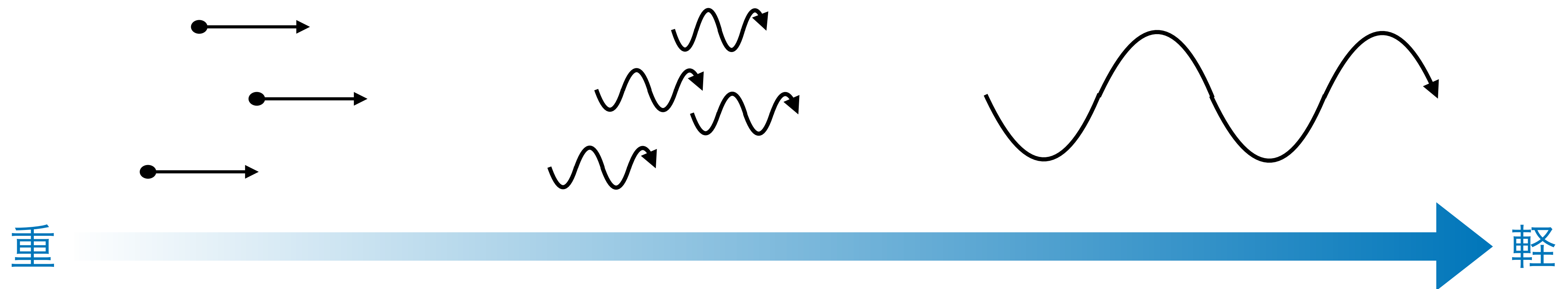


B-L ゲージ結合に対する制限



軽い暗黒物質

- 典型的なアクシオン/ダークフォトン暗黒物質： $m \ll 1 \text{ eV}$
- 質量が軽い $\longrightarrow$ 数密度が大きい $\longrightarrow$ 「波」のように振る舞う

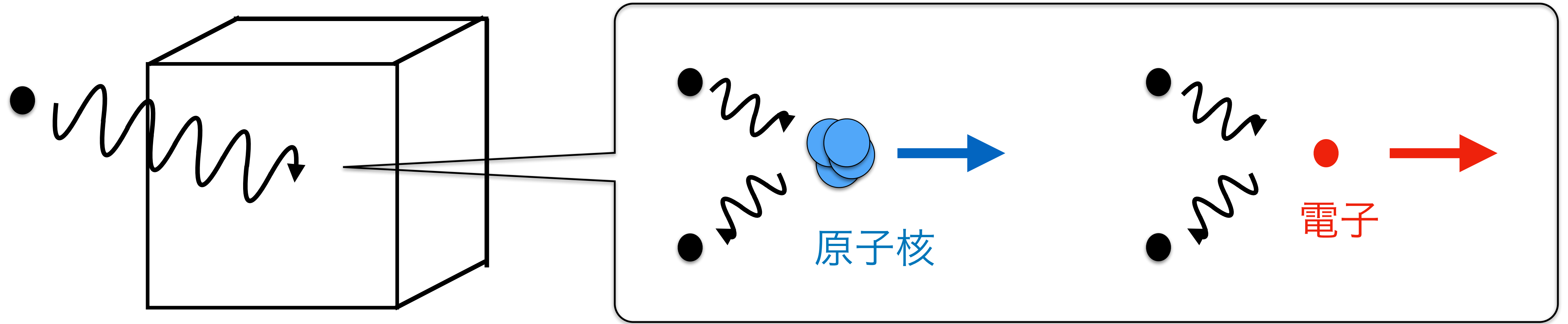


- アクシオン暗黒物質： $a(\vec{x}, t) = a_0 \cos(m(t - \vec{v} \cdot \vec{x}))$
ダークフォトン暗黒物質： $\vec{H}(\vec{x}, t) = \vec{H}_0 \cos(m(t - \vec{v} \cdot \vec{x}))$
このような振動場の下での特徴的な反応を探す

物性を利用した探査

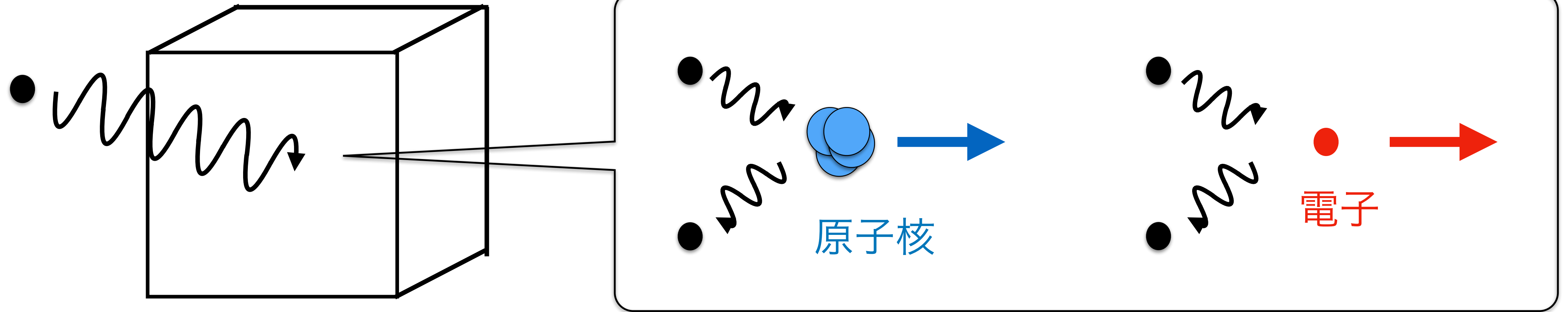
暗黒物質と物質との反応

暗黒物質（重い場合）

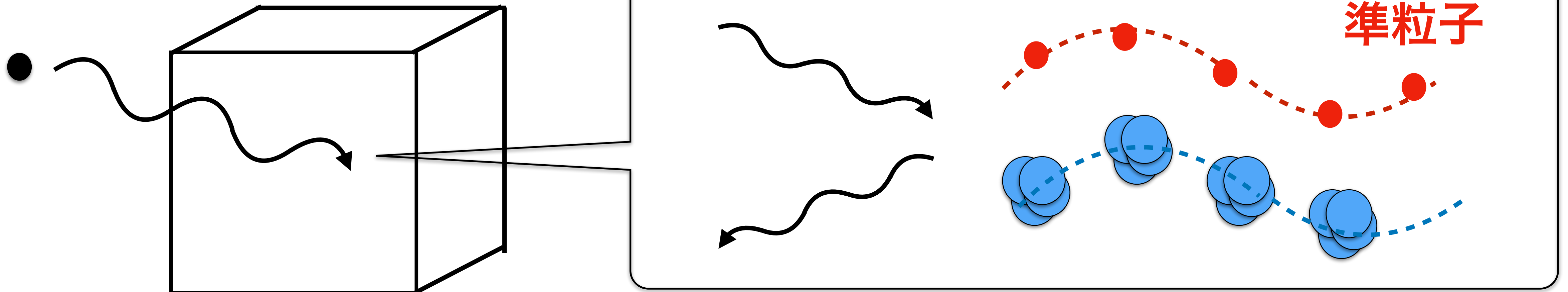


暗黒物質と物質との反応

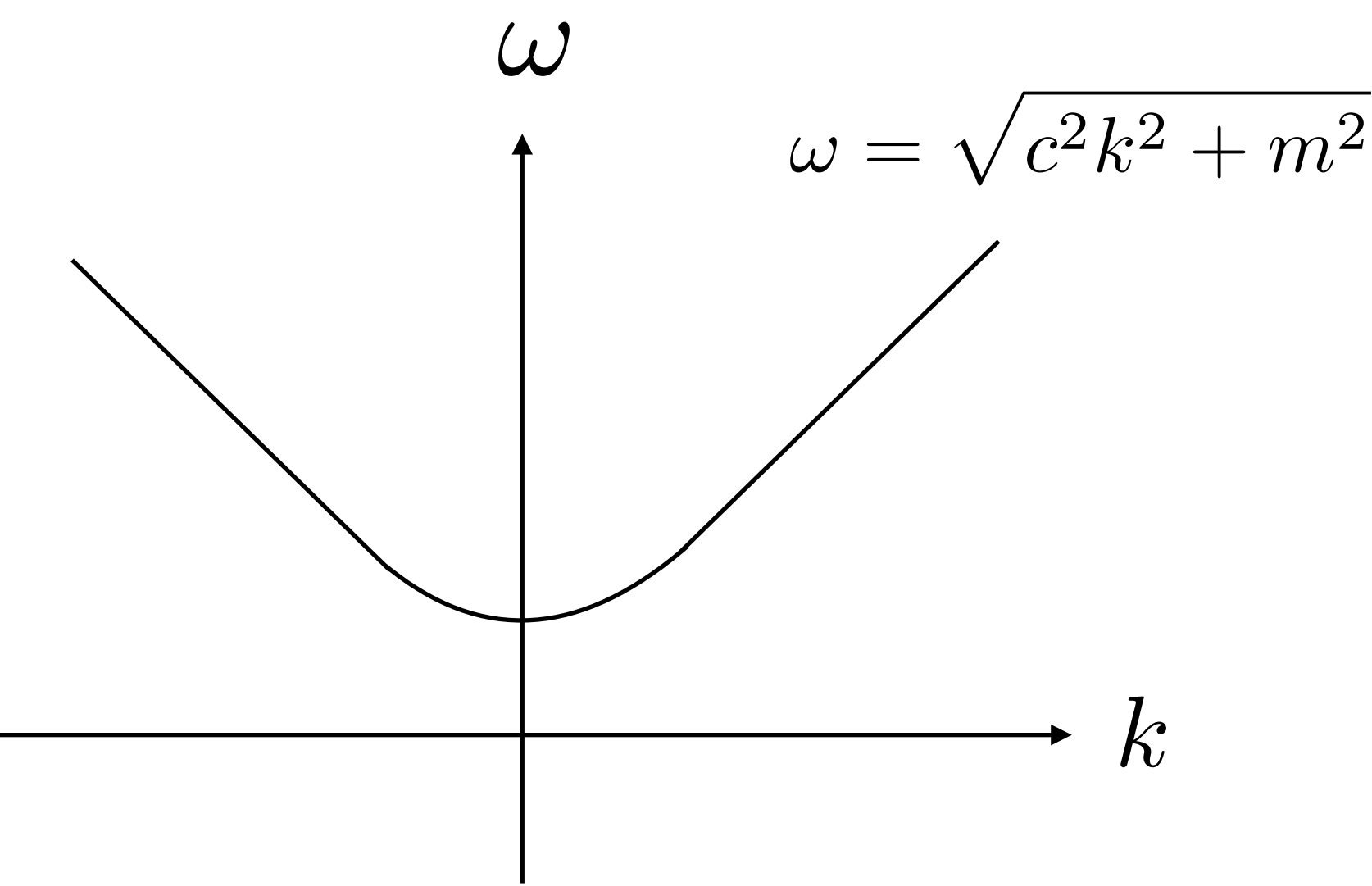
暗黒物質（重い場合）



暗黒物質（軽い場合）

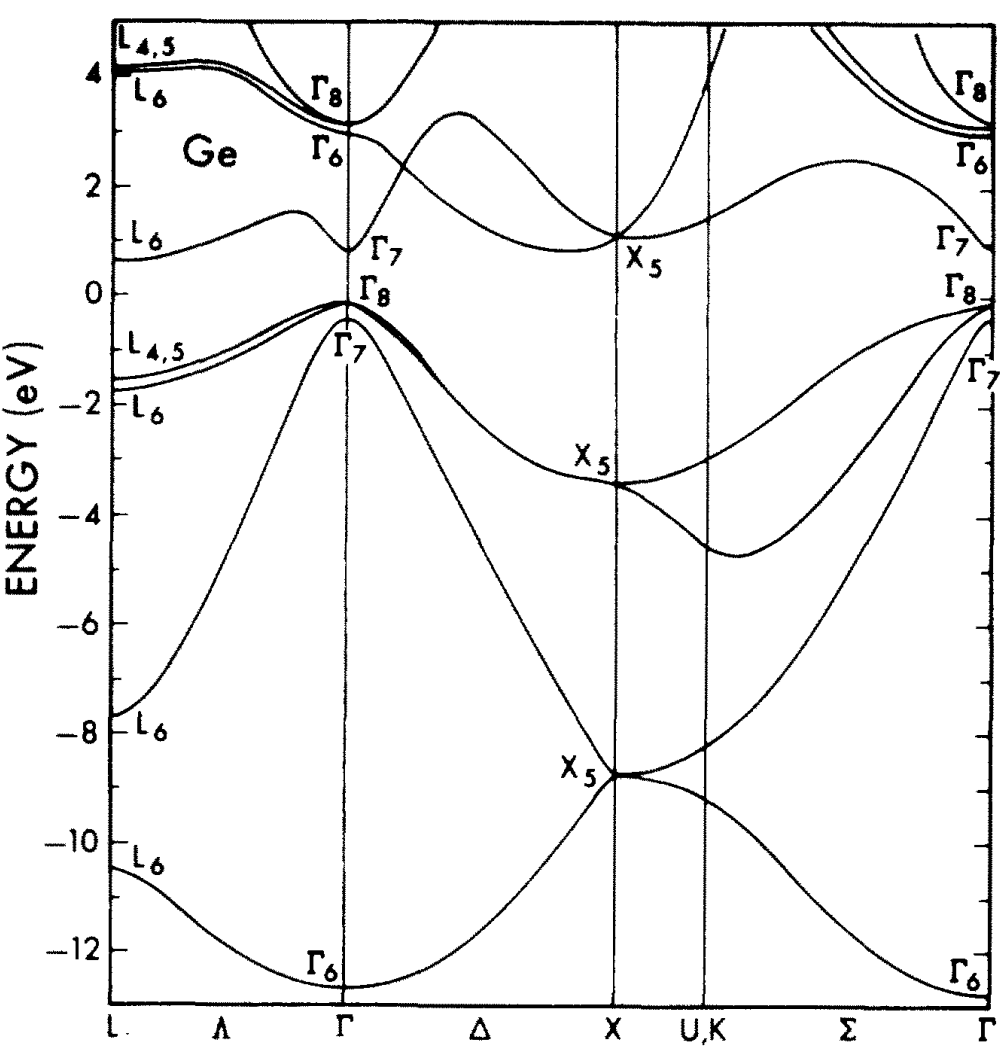


真空中の粒子の分散関係

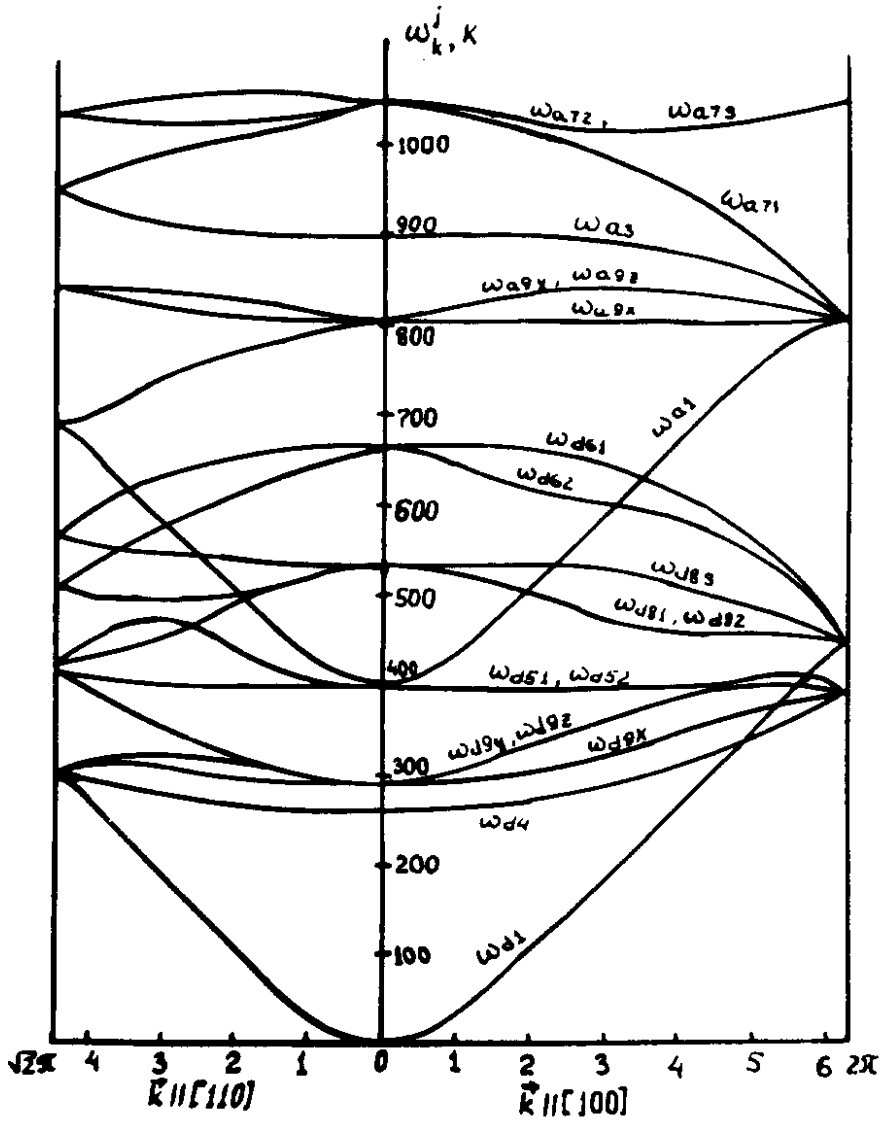


固体中の準粒子の分散関係

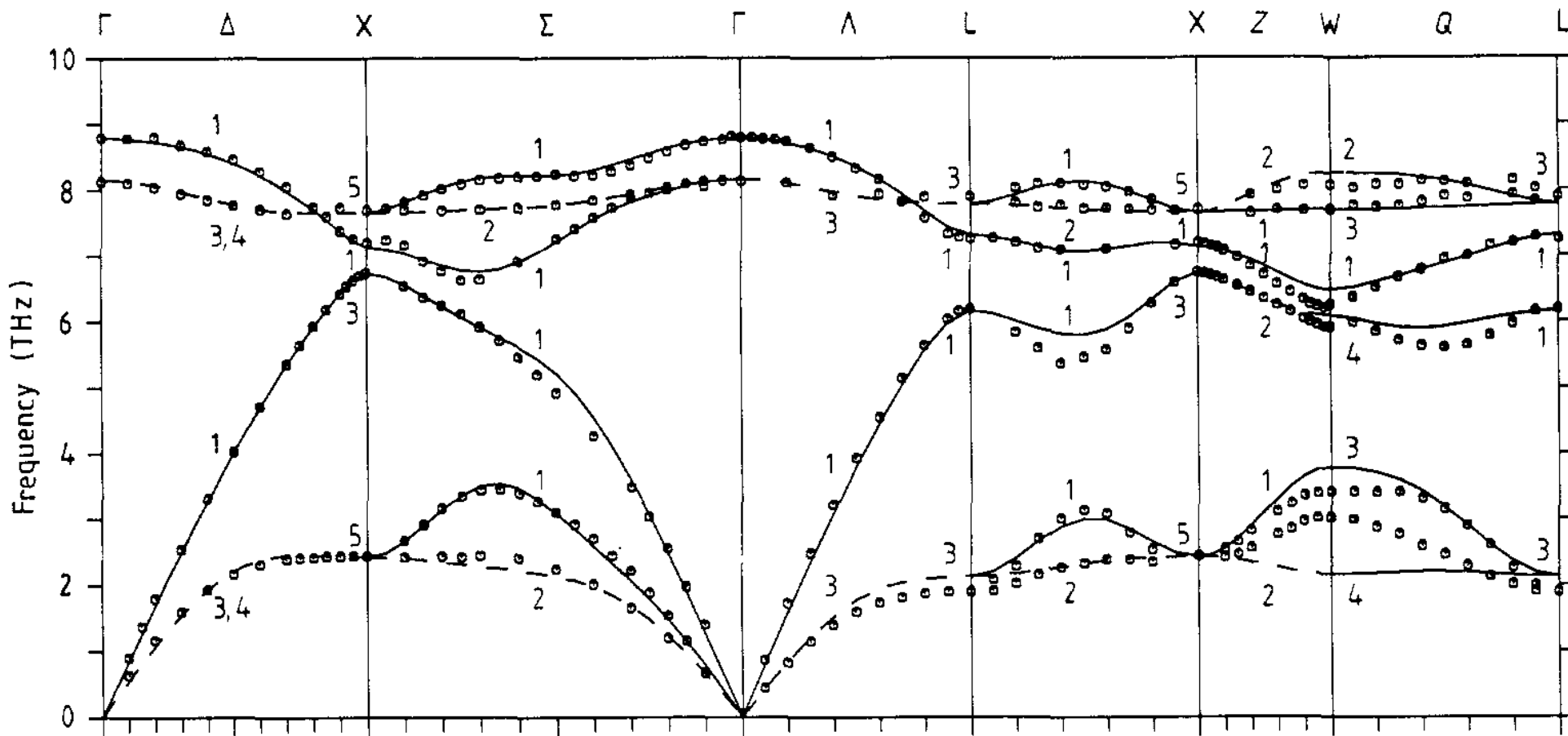
電子 (Ge)



マグノン (YIG)



フォノン (GaAs)



固体中には様々な準粒子が存在
暗黒物質との反応に利用可能

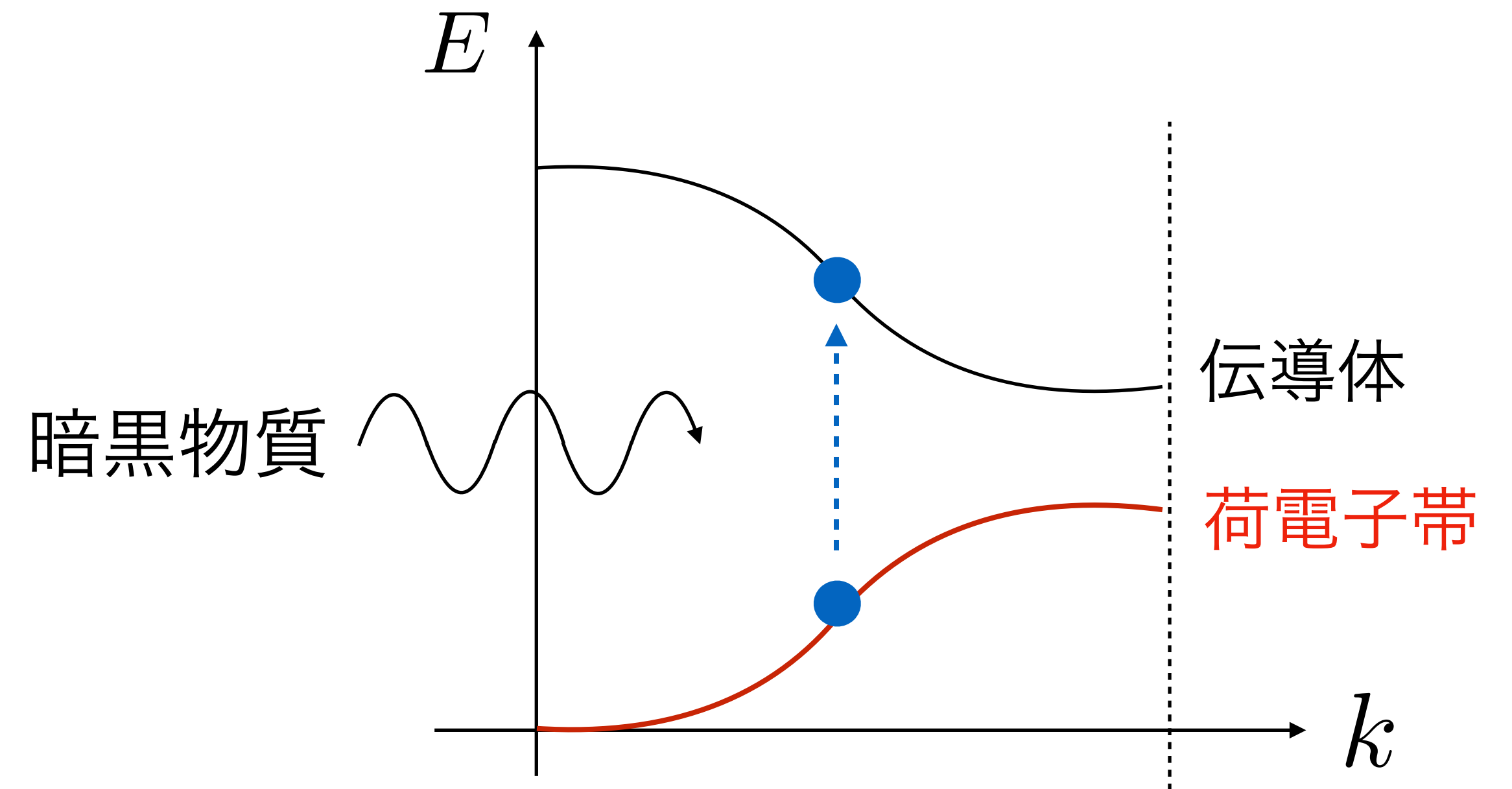
固体電子による暗黒物質の吸収

- 暗黒物質が電子を励起状態に
(光による励起と同じ原理)

[Hochberg, Lin, Zurek (2016)]

- 典型的な半導体のギャップ
エネルギー $\sim 1\text{eV}$

1eV より重い暗黒物質であれば可能



- 超伝導体のギャップ $\sim 1\text{meV}$

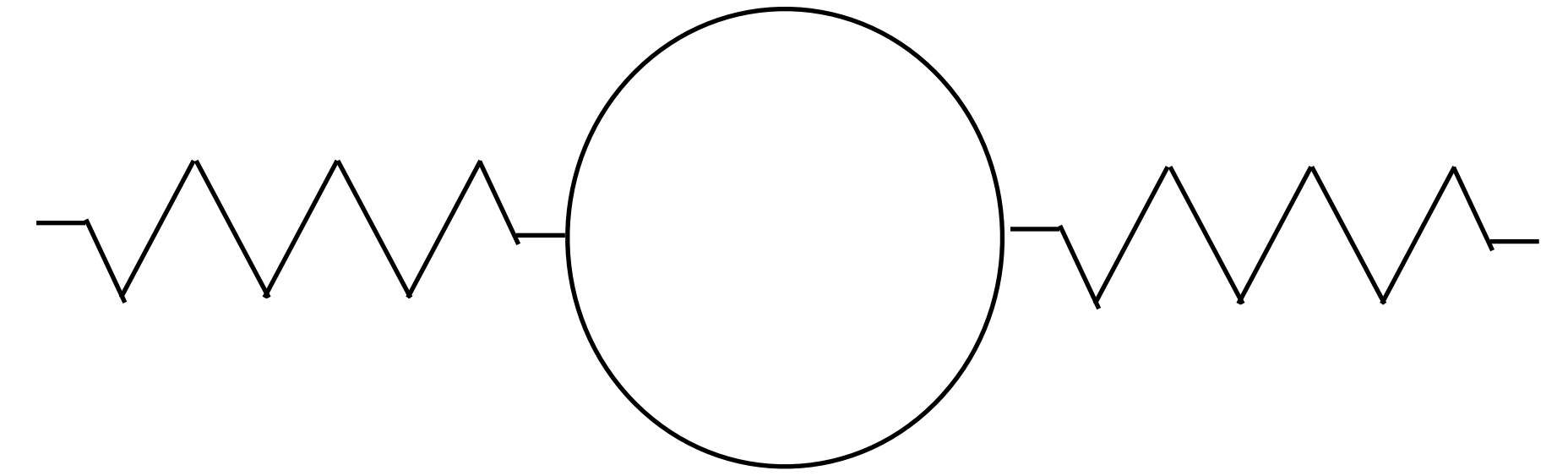
[Hochberg et al (2015), Hochberg, Lin, Zurek (2016)]

Dirac 物質のギャップ $\sim 10\text{meV}$

[Hochberg et al (2017), Geilhufe, Kahlhoefer, Winkler (2019)]

固体電子による暗黒物質の吸収

- 物性：外場を加えた時の電流への応答
を線形応答理論で計算 (RPA)



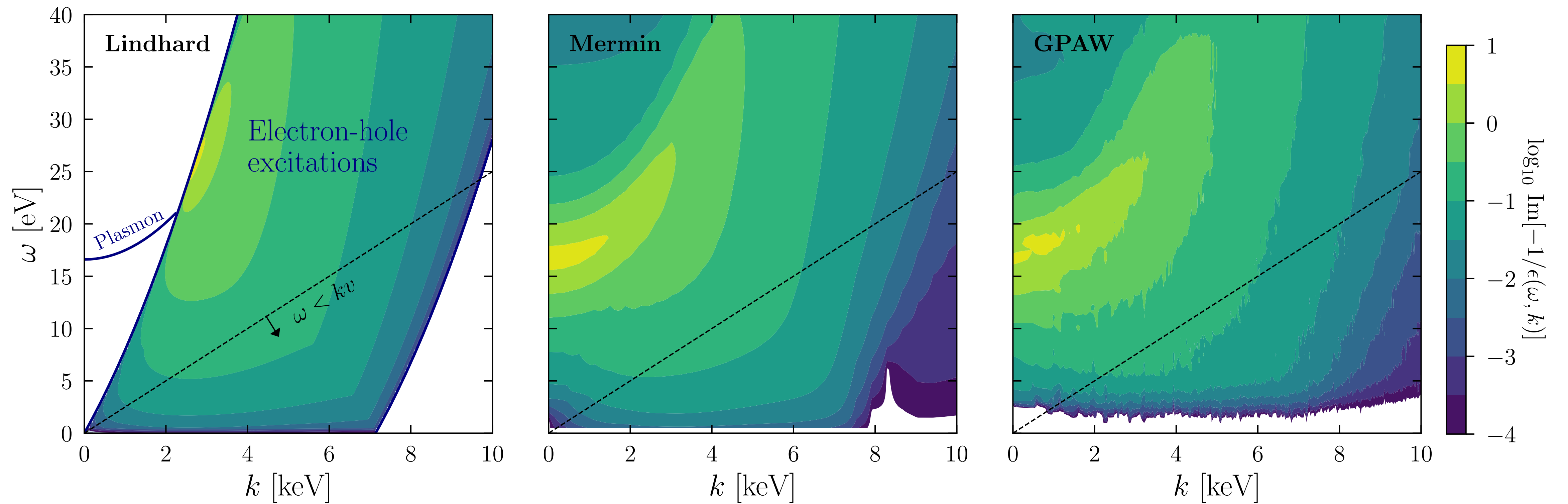
素粒子：自己エネルギーを1-loopで計算

- 実際にはバンド構造やplasmon共鳴とその幅を取り入れる必要がある
 - Energy loss function (ELF) の測定値を使う $\text{Im} \left[\frac{-1}{\epsilon(\omega, \mathbf{k})} \right]$
(誘電率の虚部)
 - 第一原理計算の結果を使う

—————→ 光子の結果をダークマターに変換する

(注：CP-even スカラーの場合はELFでパラメトライズできない [Mitridate et al. (2021)])

例 : Contour of ELF for Si



[Knapen, Kozaczuk, Lin (2021)]

● 固体電子

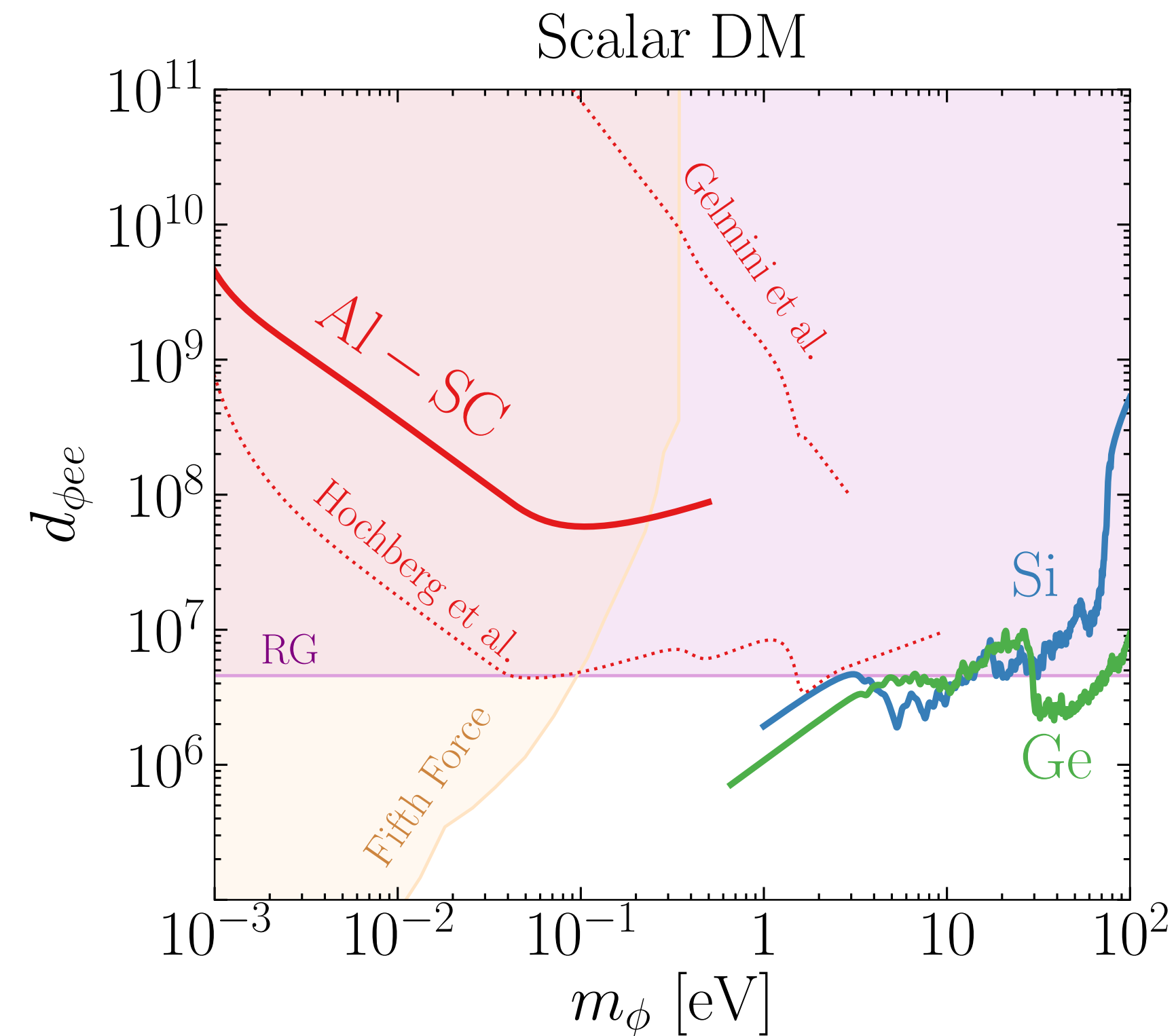
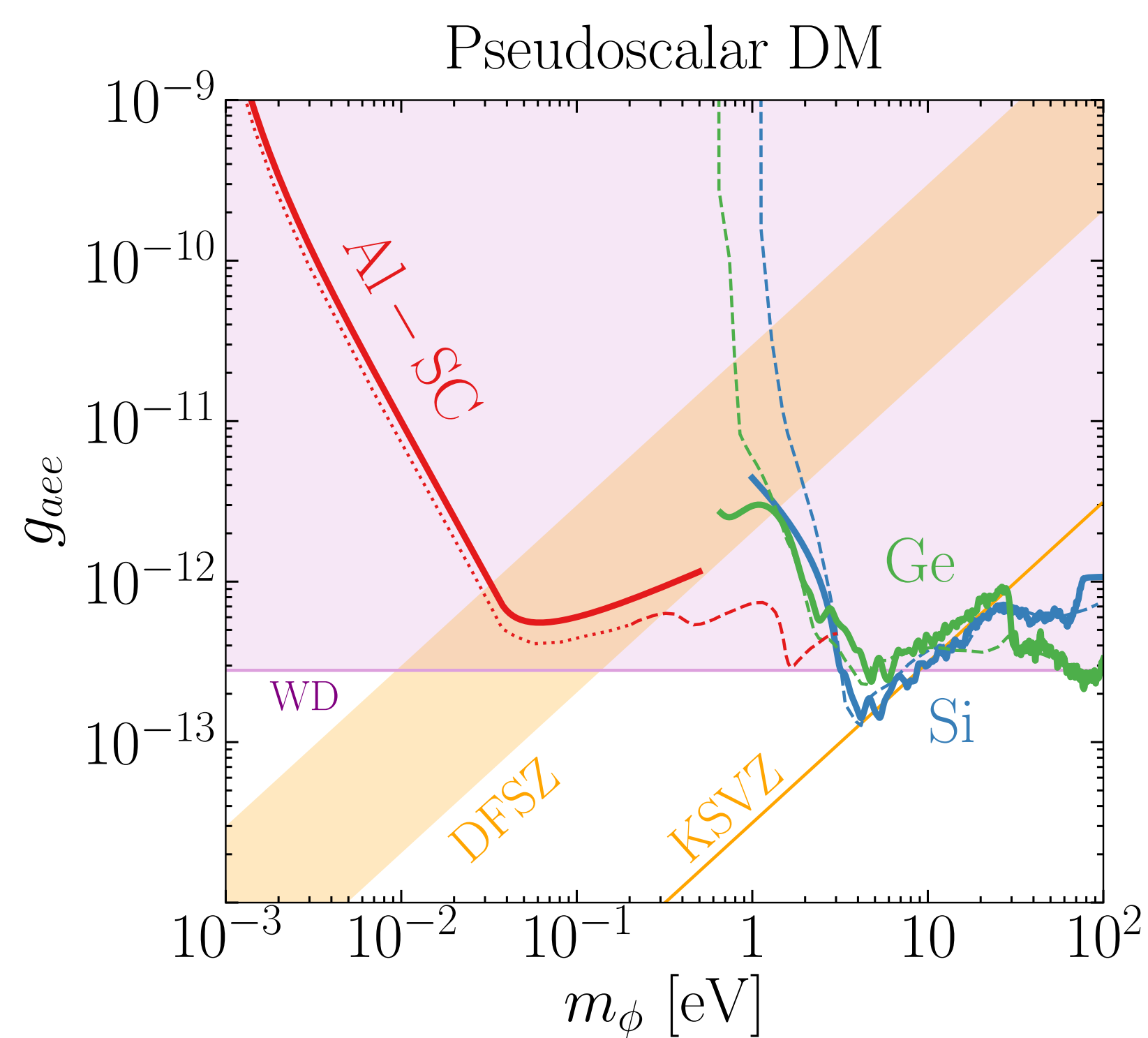
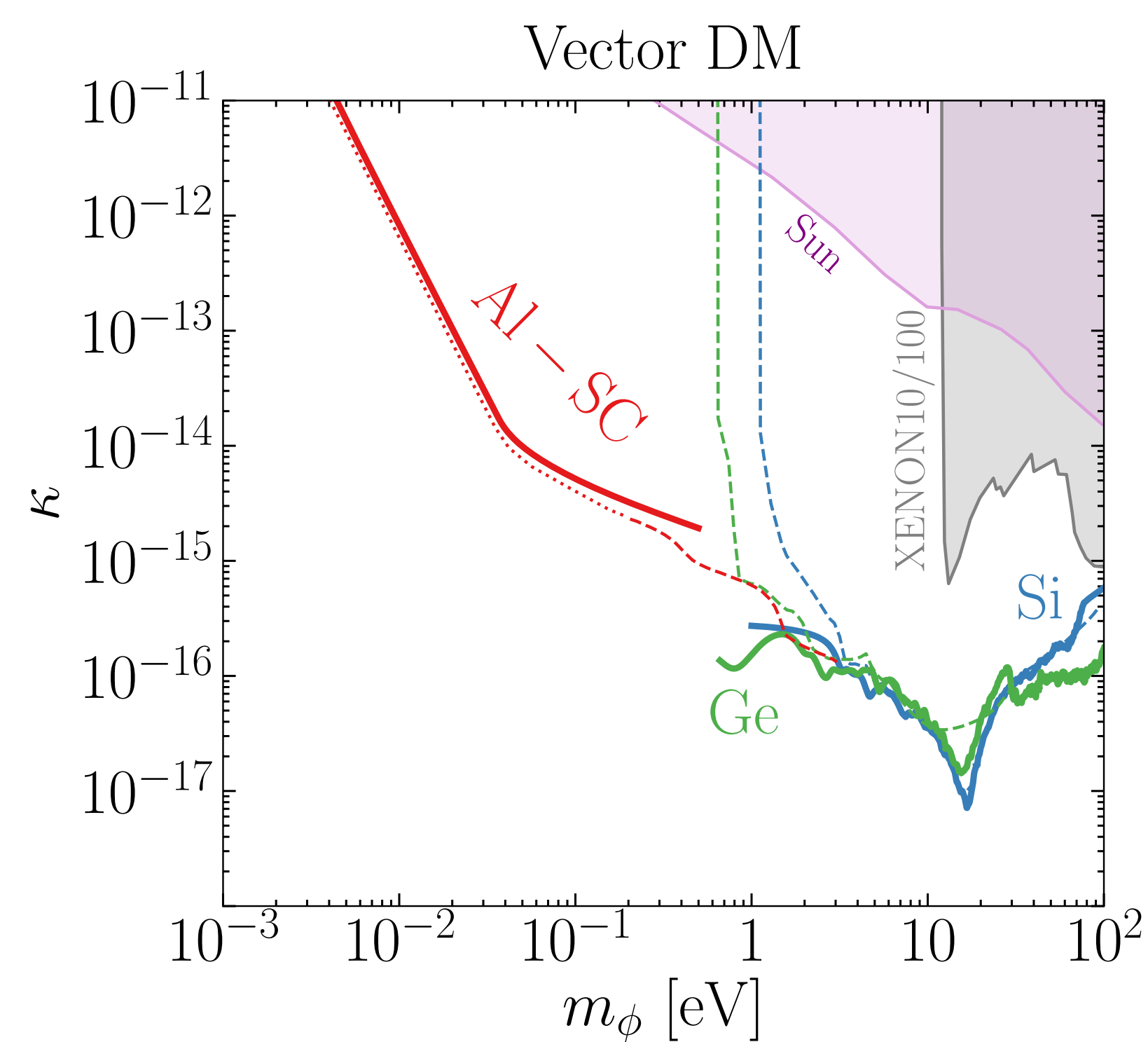
半導体 $\sim 1\text{ eV}$

[Hochberg, Lin, Zurek (2016), Bloch et al.]

超伝導体 $\sim 1\text{ meV}$

[Hochberg et al (2015), Hochberg, Lin, Zurek]

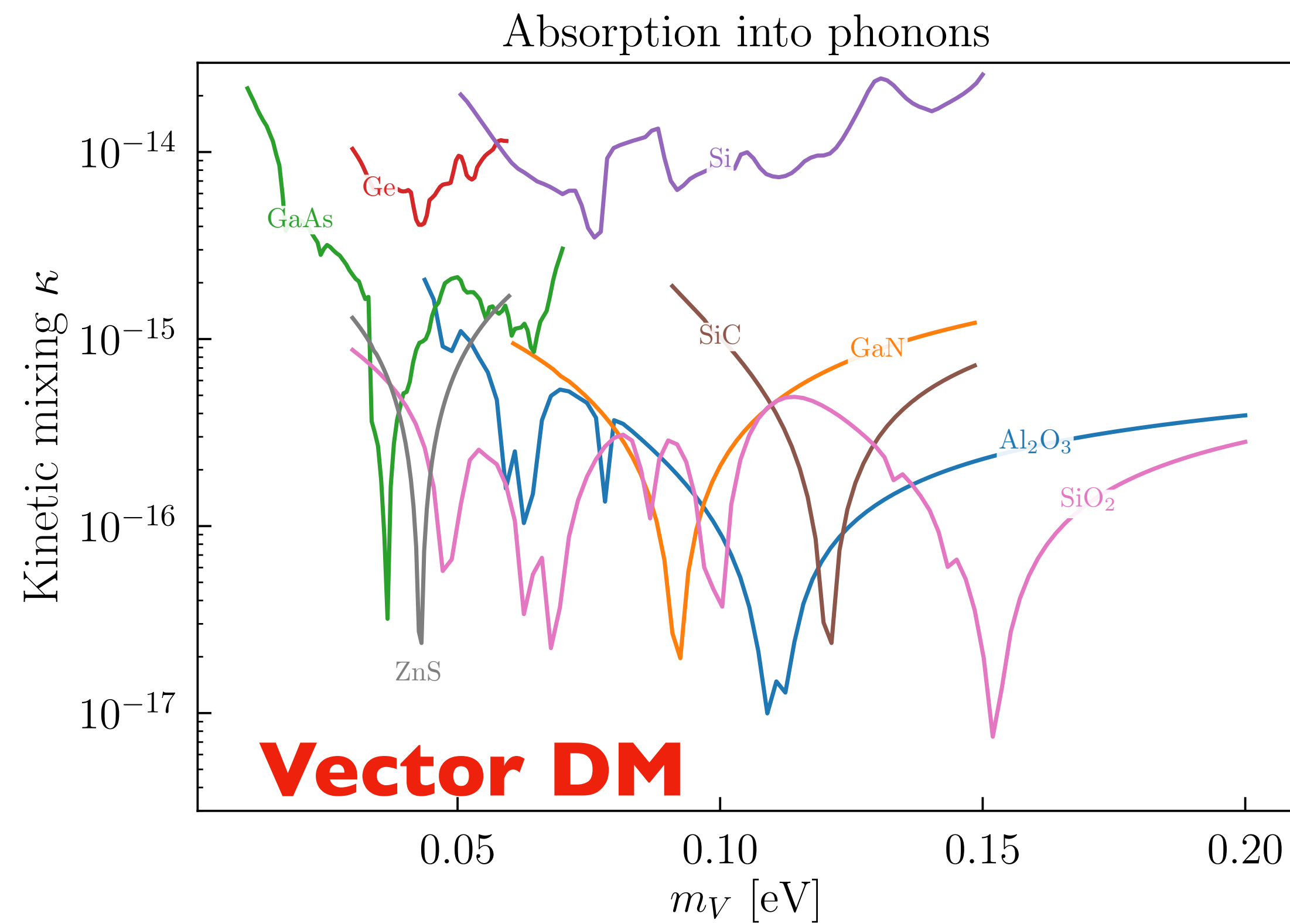
Dirac物質 $\sim 10\text{ meV}$ [Hochberg et al (2017), Geilhufe, Kahlhoefer, Winkler (2019)]



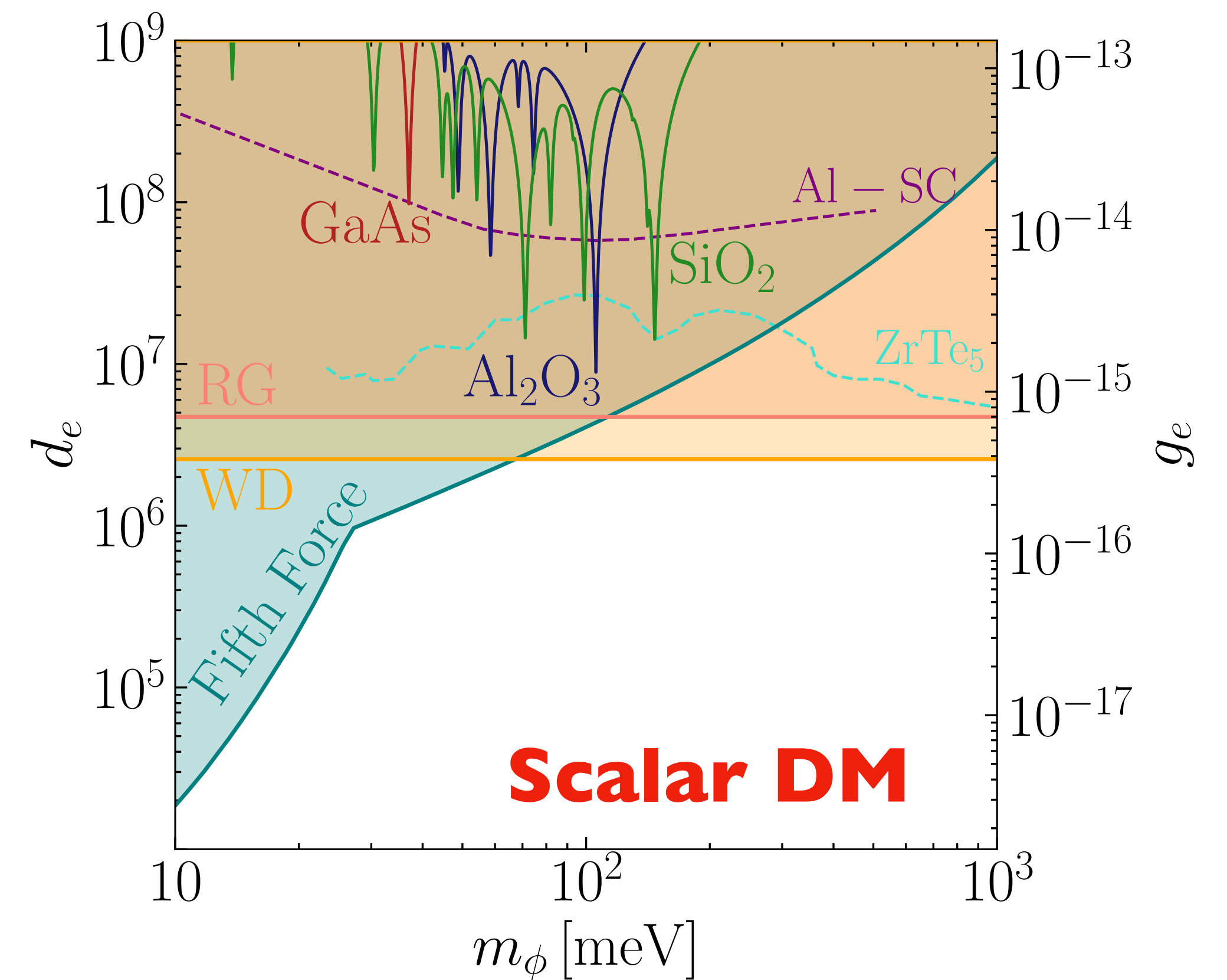
[Mitridate, Trickle, Zhang, Zurek (2021)]

● フォノン

Polar material では、**optical phonon** の典型的なエネルギーは $\sim 0.1\text{eV}$
軽い領域をカバー可能



[Knapen, Kozaczuk, Lin (2021)]

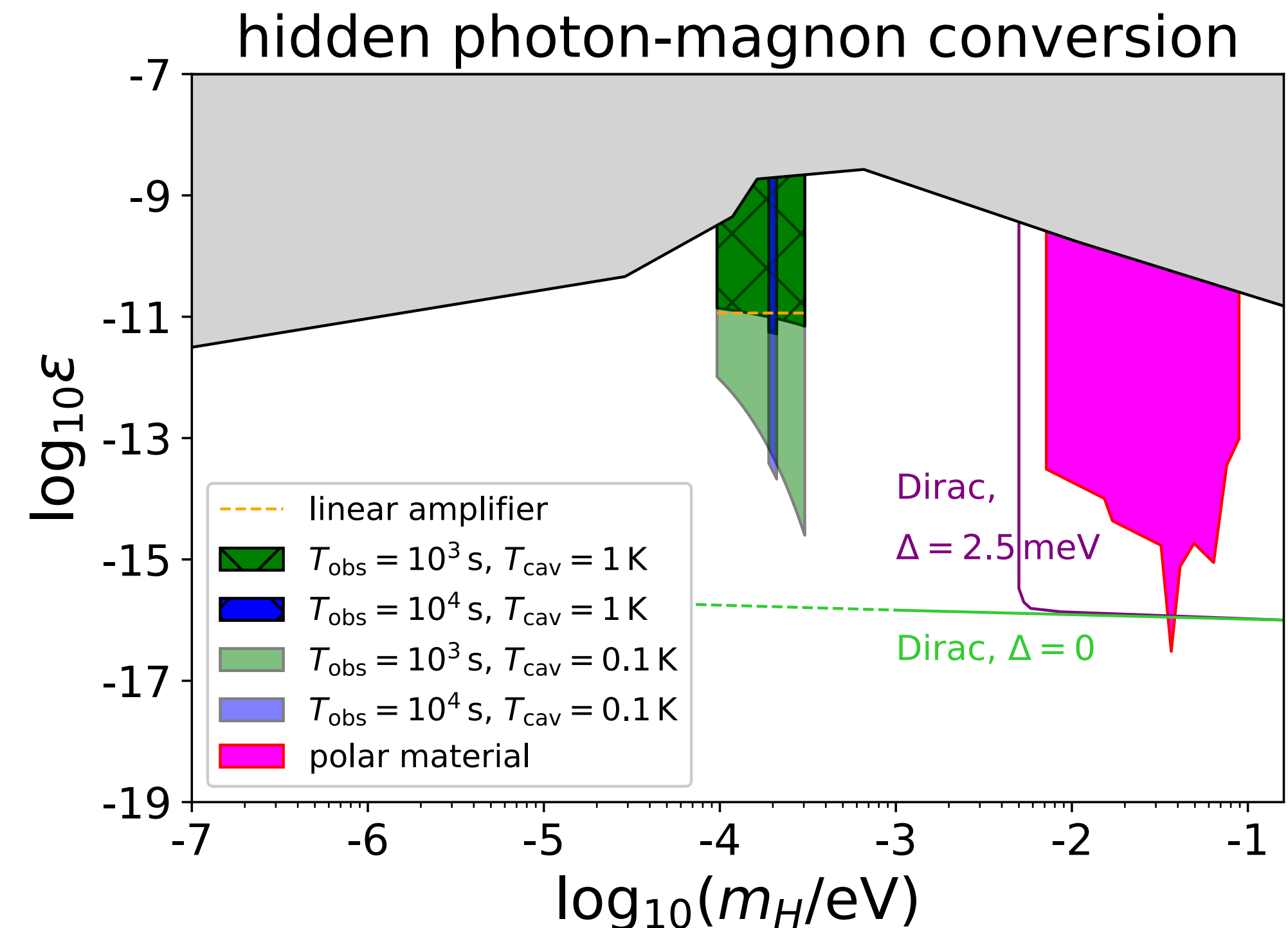
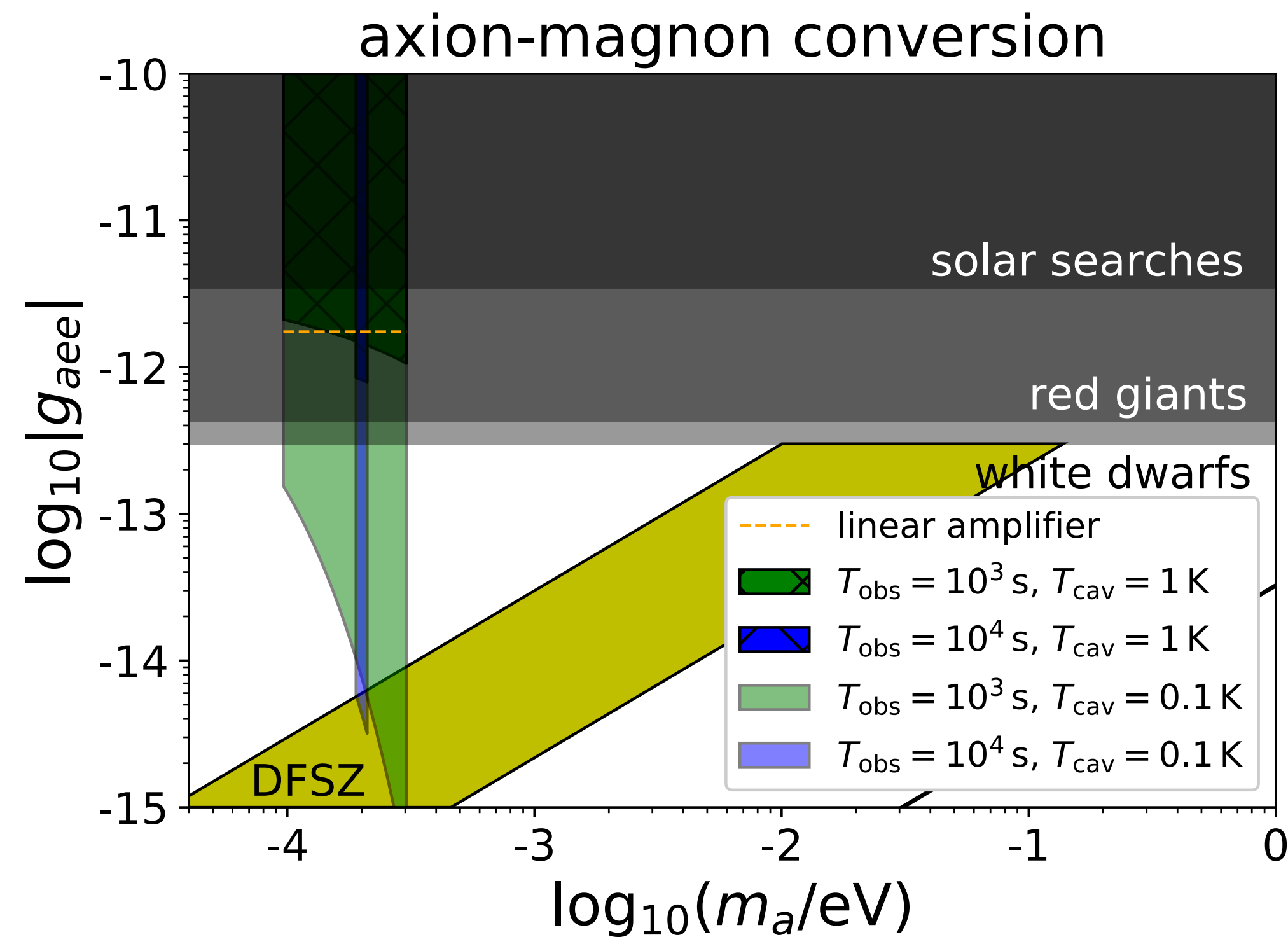


[Mitridate, Pardo, Trickle, Zurek (2023)]

● マグノン

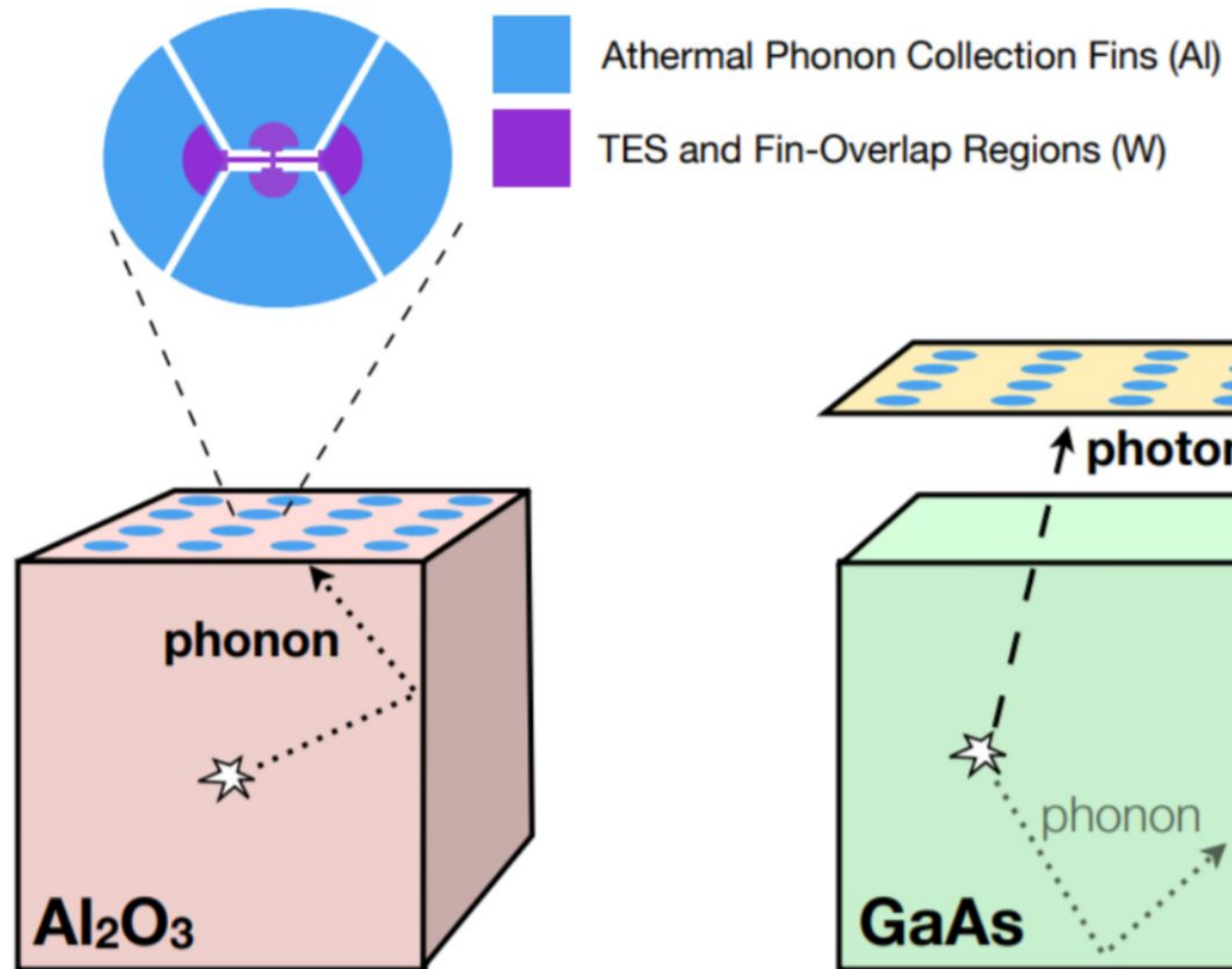
磁性体でのマグノンのギャップエネルギー： $\omega_L \equiv g\mu_B B_z^0 \simeq 1.2 \times 10^{-4} \text{ eV} \left(\frac{B_z^0}{1 \text{ T}} \right)$

アクシオンは電子スピンと結合するのでマグノンを励起する



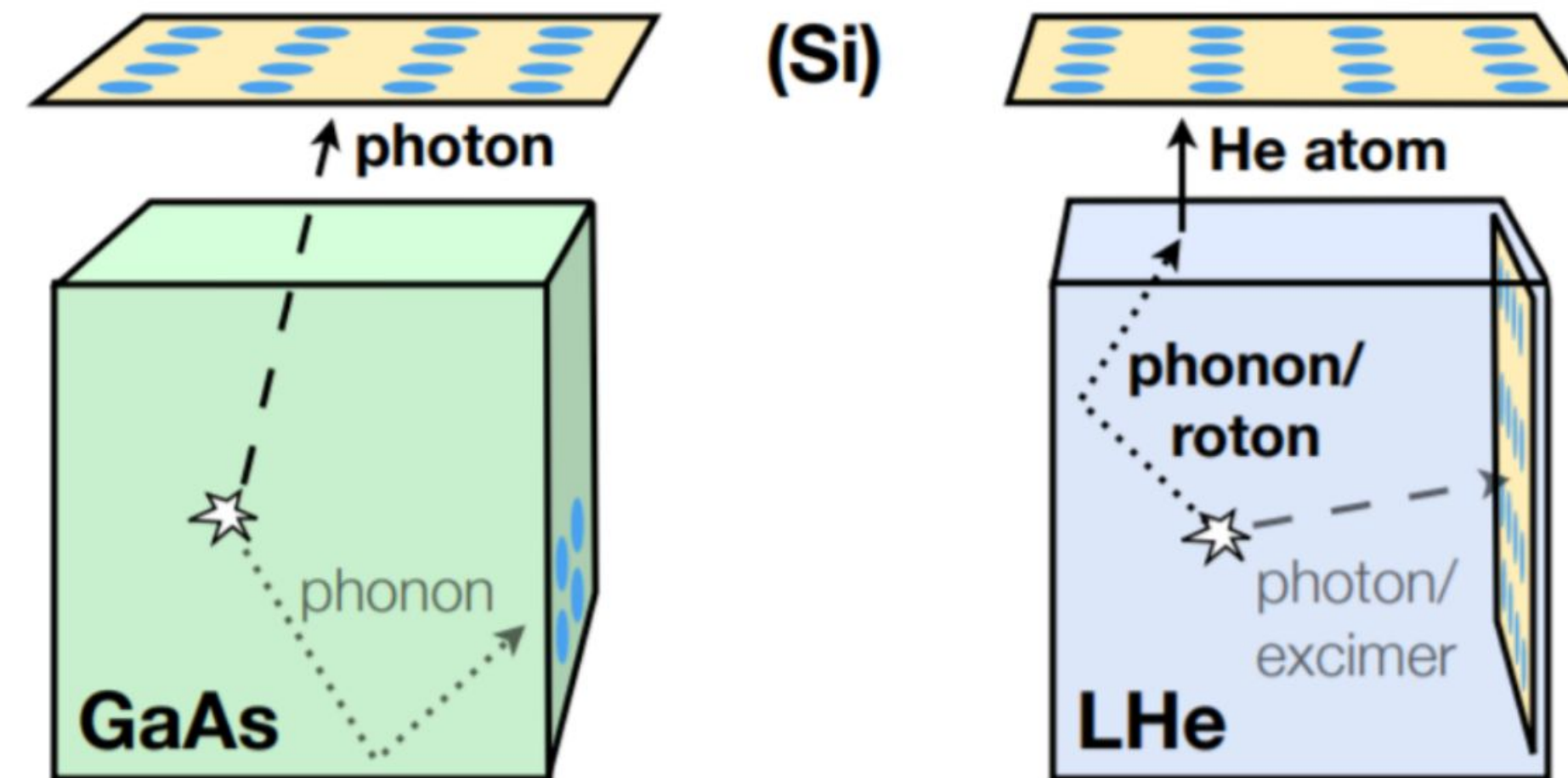
[Chigusa, Moroi, KN (2020)]

SPICE

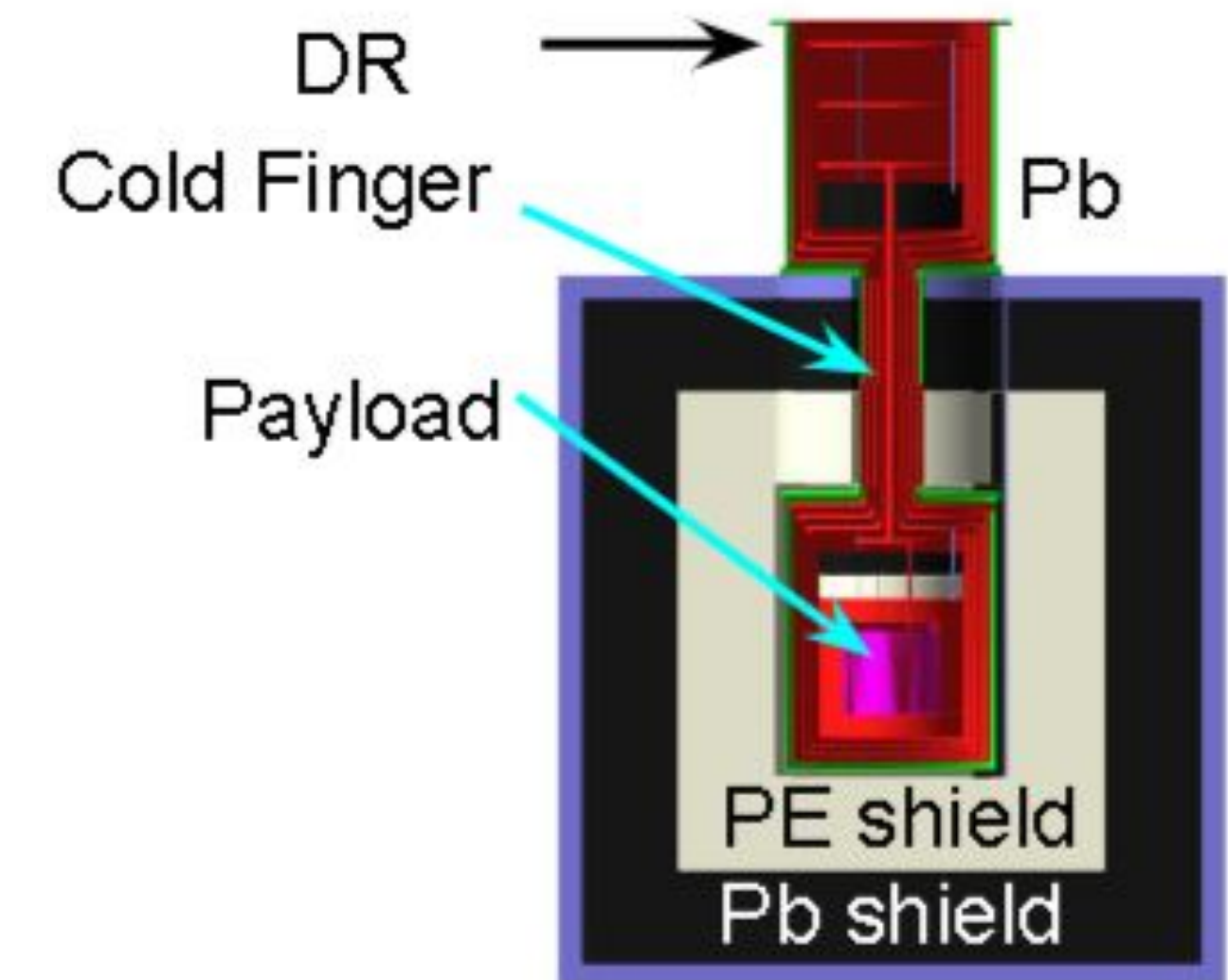


[From talk slide by R.K. Romani (2023)]

HeRALD



Kamioka LDM

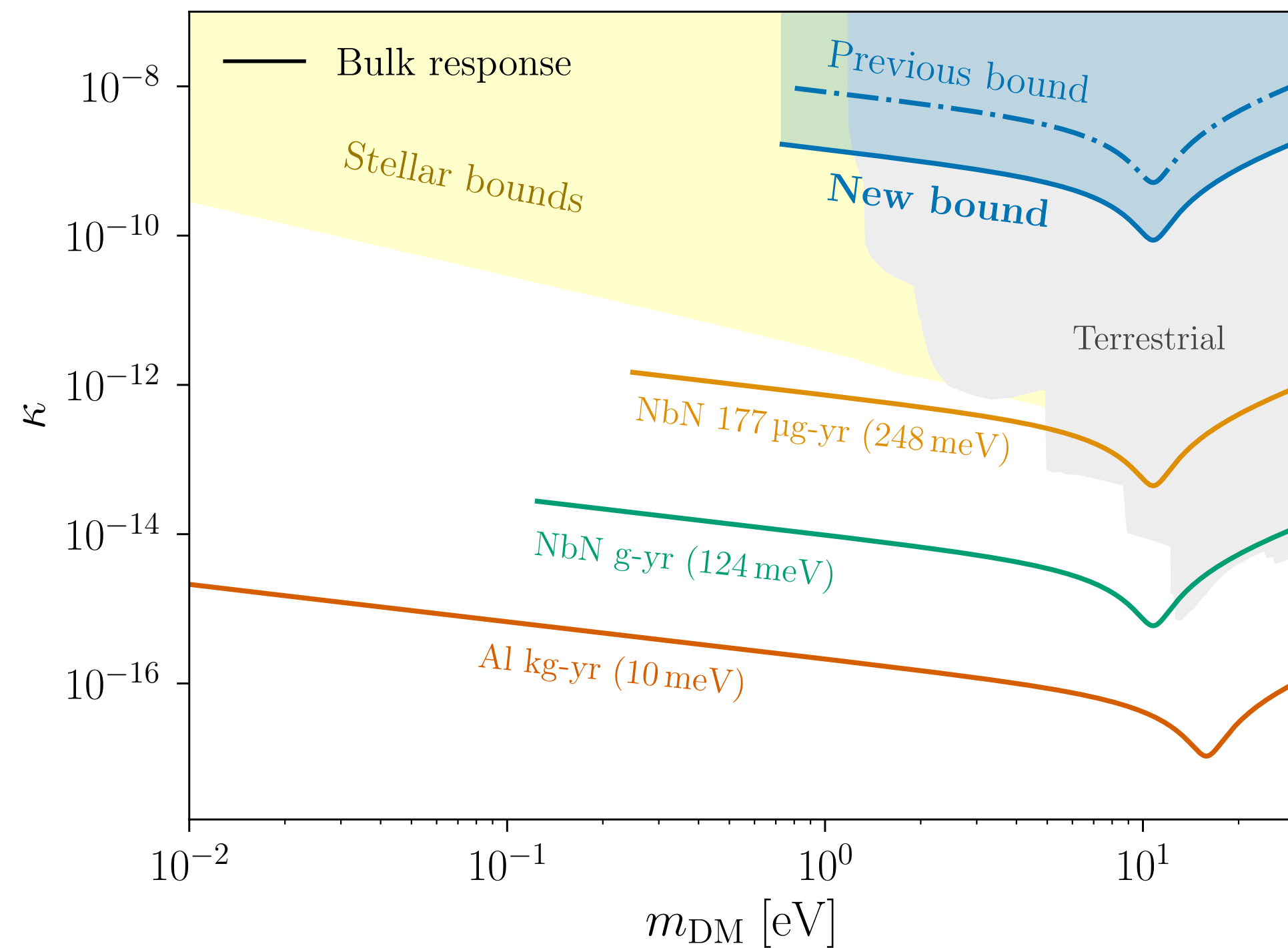


[From talk slide by
S. Burkhan (2025)]

検出器自体を吸収体として利用

- 検出器やセンサー自体がダークマターを吸収する
- 吸収率の計算は全く同じ

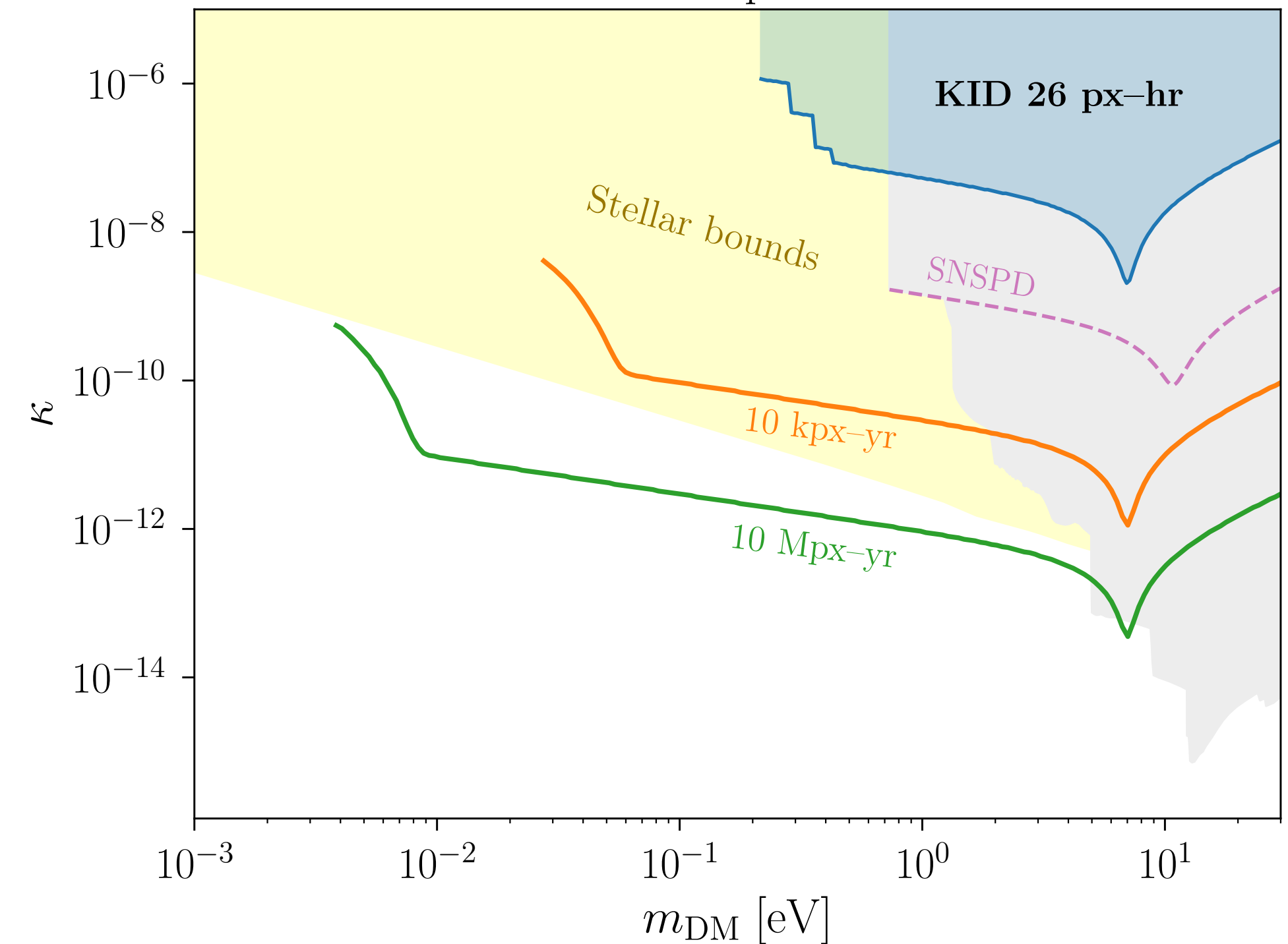
SNSPD



[Hochberg et al. (2021)]

MKID

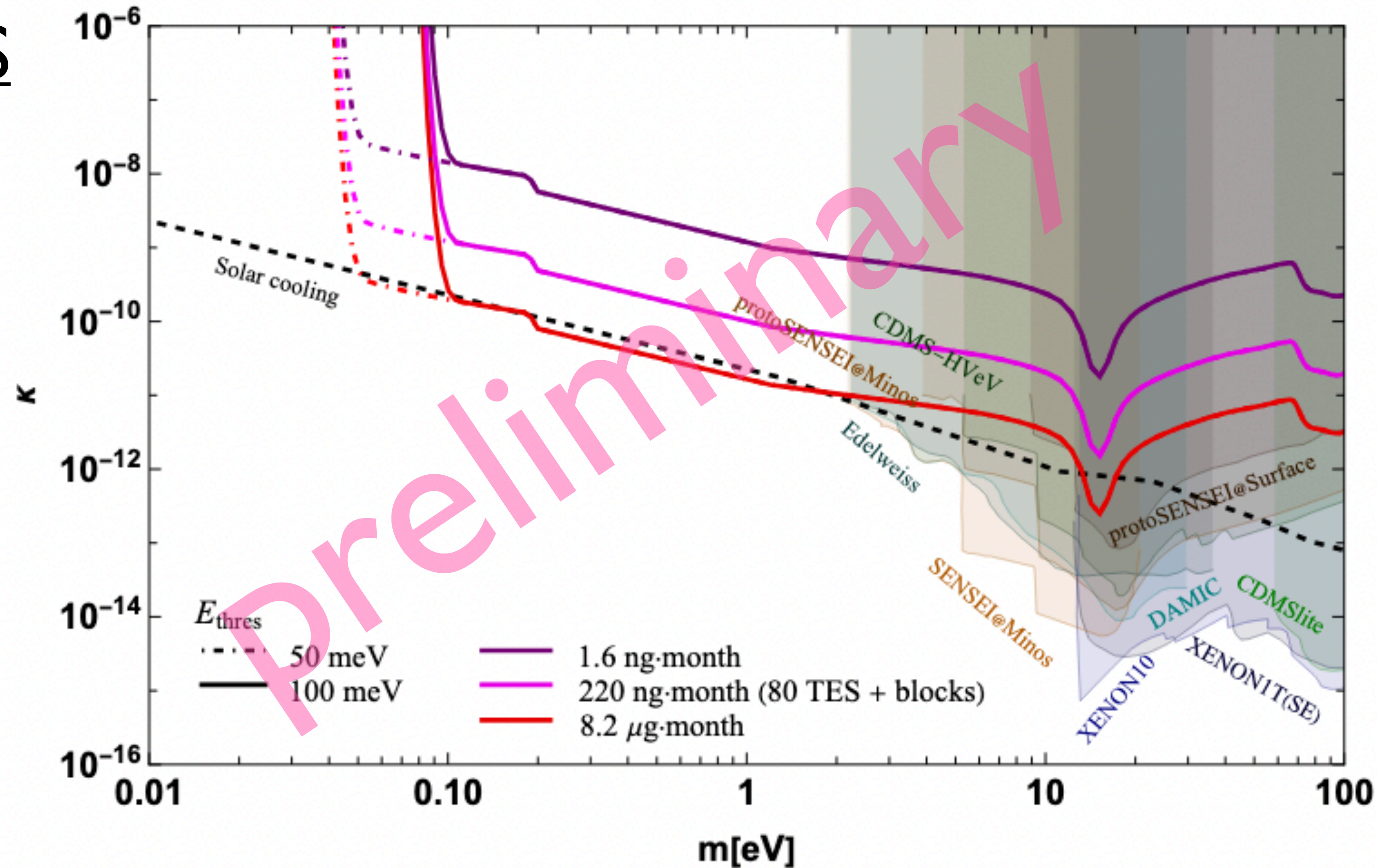
Absorption



[Gao et al. (2024)]

検出器自体を吸収体として利用

Optical TES



[Chen, Hattori, KN, Takhistov, in prep.]

量子技術を利用した探査

Qubit

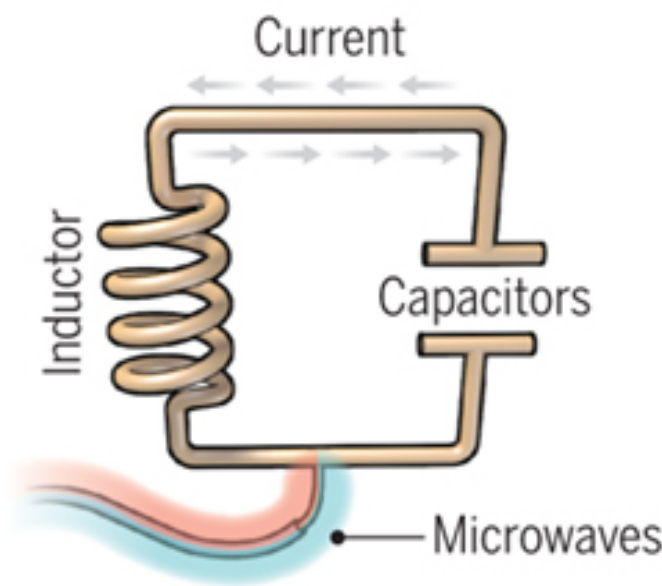
- Qubit : 量子力学的な 2 準位系
色んな種類のqubitがある
- 量子コンピュータ/量子センシング
の基礎要素
- ダークマターもqubitと反応する
ダークマターやqubitの種類によって
反応の仕方は様々



IBM, 20 superconducting qubits
[figure from wikipedia
“Quantum computing”]

A bit of the action

In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.



Superconducting loops

A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.

Longevity (seconds)
0.00005

Logic success rate
99.4%

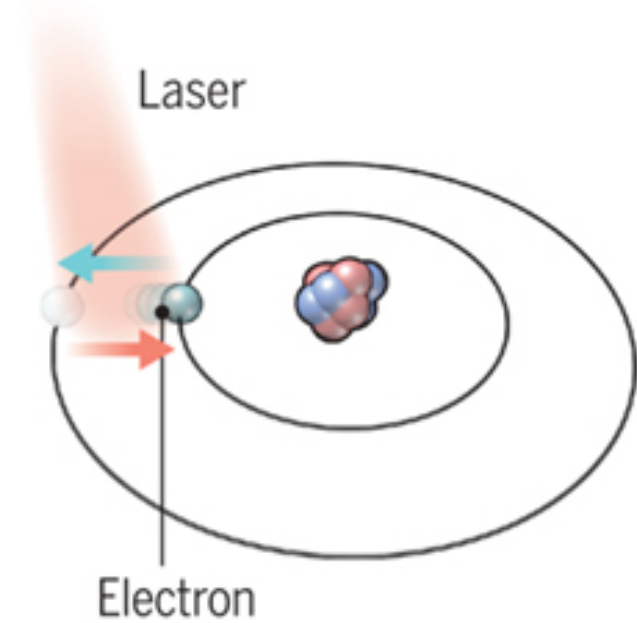
Number entangled
9

Company support

Google, IBM, Quantum Circuits

+ Pros
Fast working. Build on existing semiconductor industry.

- Cons
Collapse easily and must be kept cold.



Trapped ions

Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.

>1000

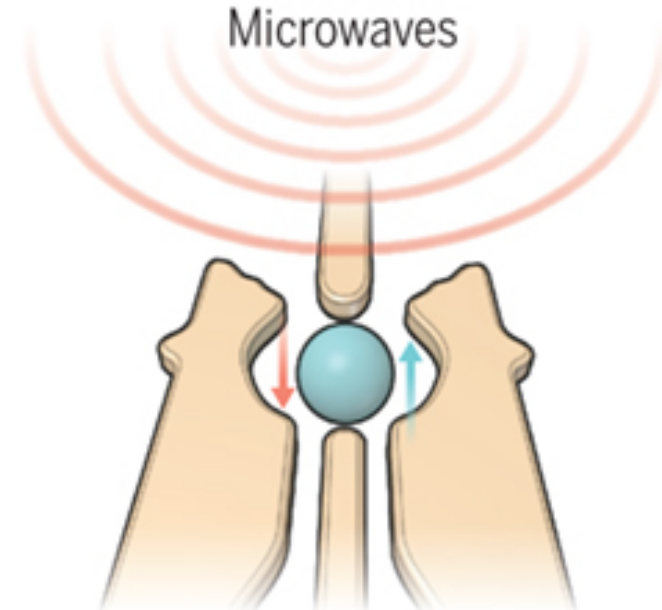
99.9%

14

ionQ

Very stable. Highest achieved gate fidelities.

Slow operation. Many lasers are needed.



Silicon quantum dots

These “artificial atoms” are made by adding an electron to a small piece of pure silicon. Microwaves control the electron’s quantum state.

0.03

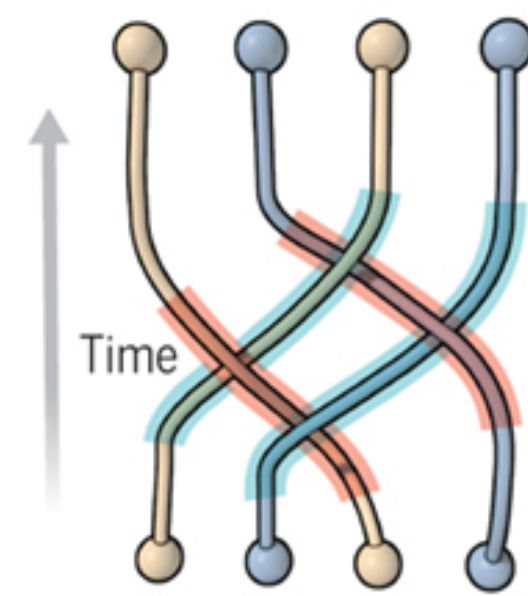
~99%

2

Intel

Stable. Build on existing semiconductor industry.

Only a few entangled. Must be kept cold.



Topological qubits

Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.

N/A

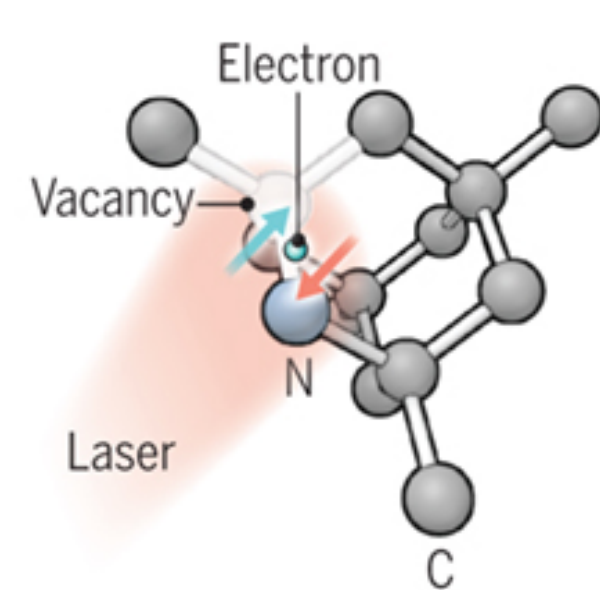
N/A

N/A

Microsoft, Bell Labs

Greatly reduce errors.

Existence not yet confirmed.



Diamond vacancies

A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.

10

99.2%

6

Quantum Diamond Technologies

Can operate at room temperature.

Difficult to entangle.

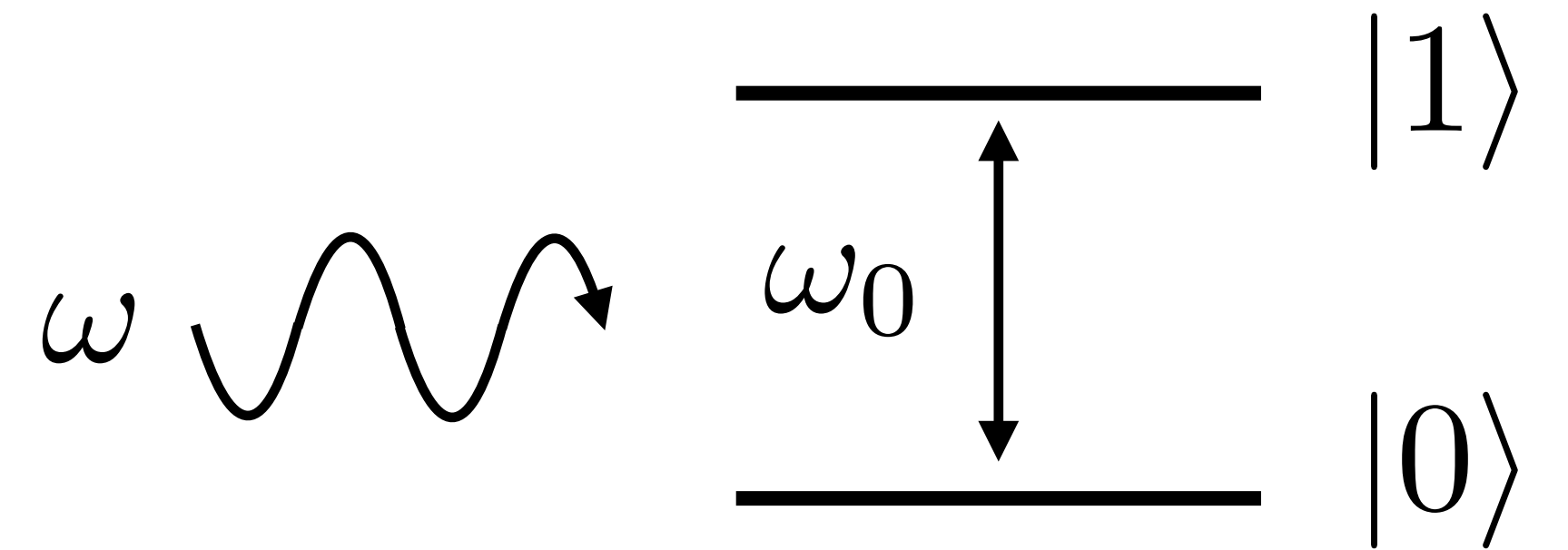
Note: Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

Qubit と外場の相互作用

- Qubitと振動外場の相互作用：

$$H = H_0 + H_1$$

$$H_0 = -\frac{\omega_0}{2}\sigma_z \quad H_1 = \vec{\epsilon} \cdot \vec{\sigma} \cos(\omega t)$$

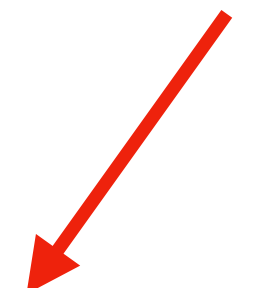


- Schrodinger 方程式: $i\frac{\partial}{\partial t} |\psi\rangle = H |\psi\rangle$
- $\epsilon_x \sigma_x \longrightarrow$ 0と1の間の遷移 (特に $\omega = \omega_0$ のときRabi共鳴)
- $\epsilon_z \sigma_z \longrightarrow$ 0と1の相対位相 Ramsey干渉などで測定

Rabi 振動

- 相互作用： $H_1 = \epsilon \sigma_x \cos(\omega t)$

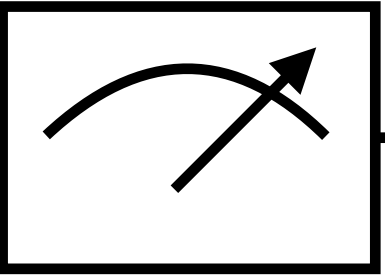
- 相互作用描像でのハミルトニアンと時間発展：

$$H_{1,I} = \frac{\epsilon}{2} \begin{pmatrix} 0 & e^{i(\omega_0 + \omega)t} + e^{i(\omega_0 - \omega)t} \\ e^{-i(\omega_0 + \omega)t} + e^{-i(\omega_0 - \omega)t} & 0 \end{pmatrix} \simeq \epsilon \sigma_x \frac{1}{2}$$


$$|\psi_I(t)\rangle = e^{-iH_{1,I}t} |\psi_I(0)\rangle = \left[\cos\left(\frac{\epsilon t}{2}\right) - i\sigma_x \sin\left(\frac{\epsilon t}{2}\right) \right] |\psi_I(0)\rangle$$

- 励起状態の確率： $P \simeq \left(\frac{\epsilon t}{2}\right)^2$

Ramsey 干涉

- 相互作用： $H_1 = \epsilon \sigma_z \cos(\omega t)$ $|0\rangle$ — $R_x\left(\frac{\pi}{2}\right)$ — $R_z(\phi)$ — $R_y\left(\frac{\pi}{2}\right)$ —  —

- Ramsey sequence :

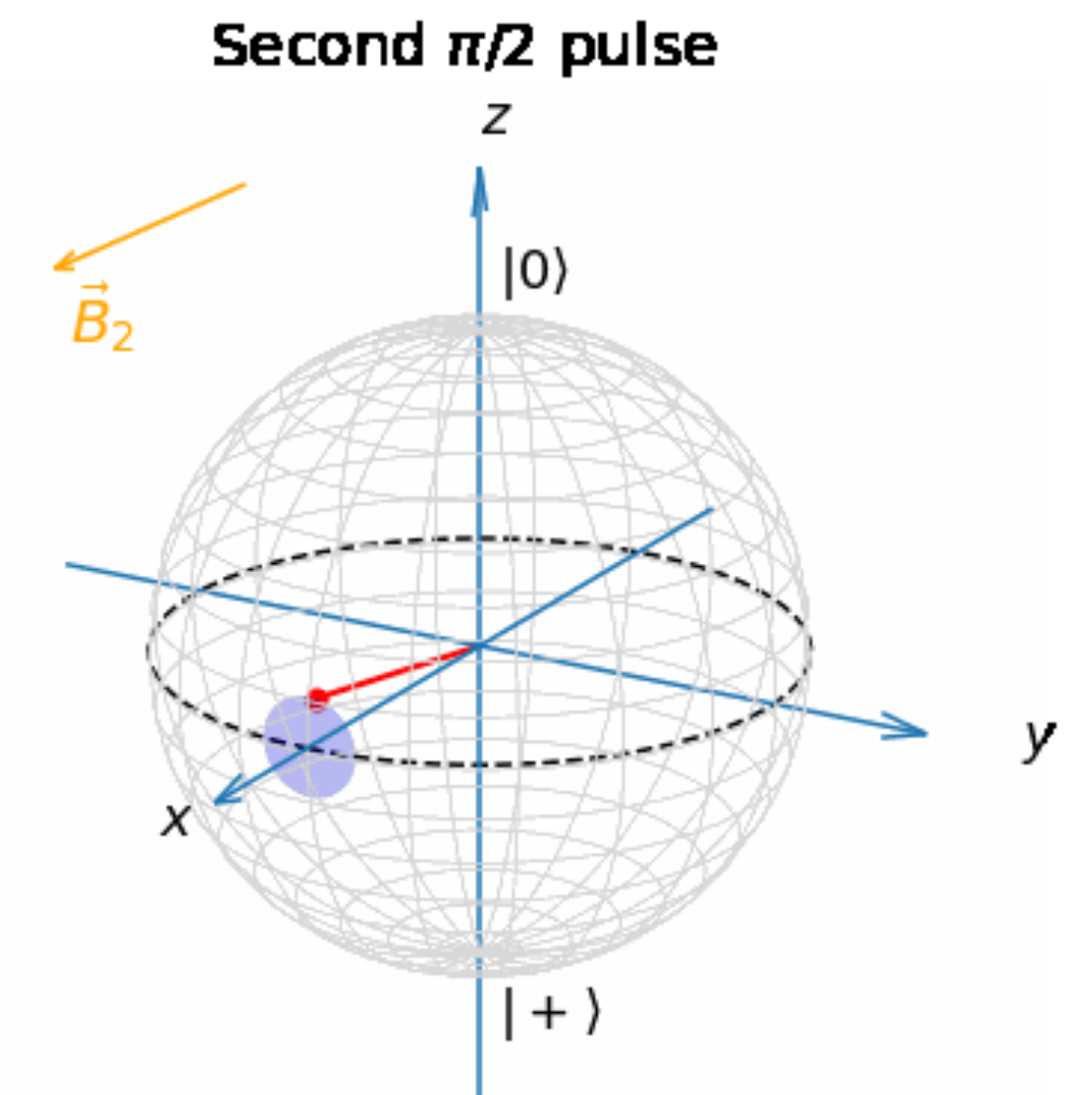
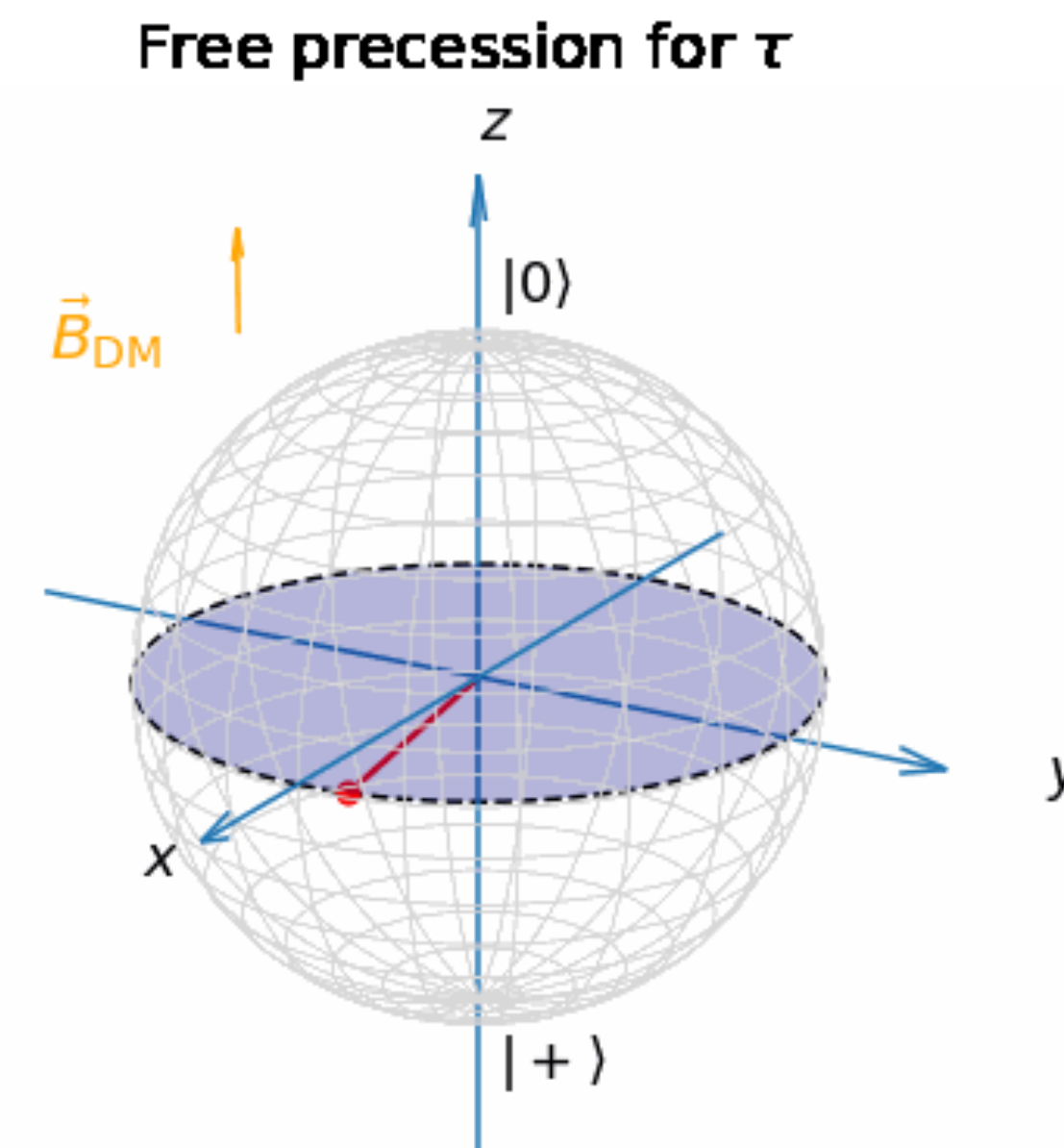
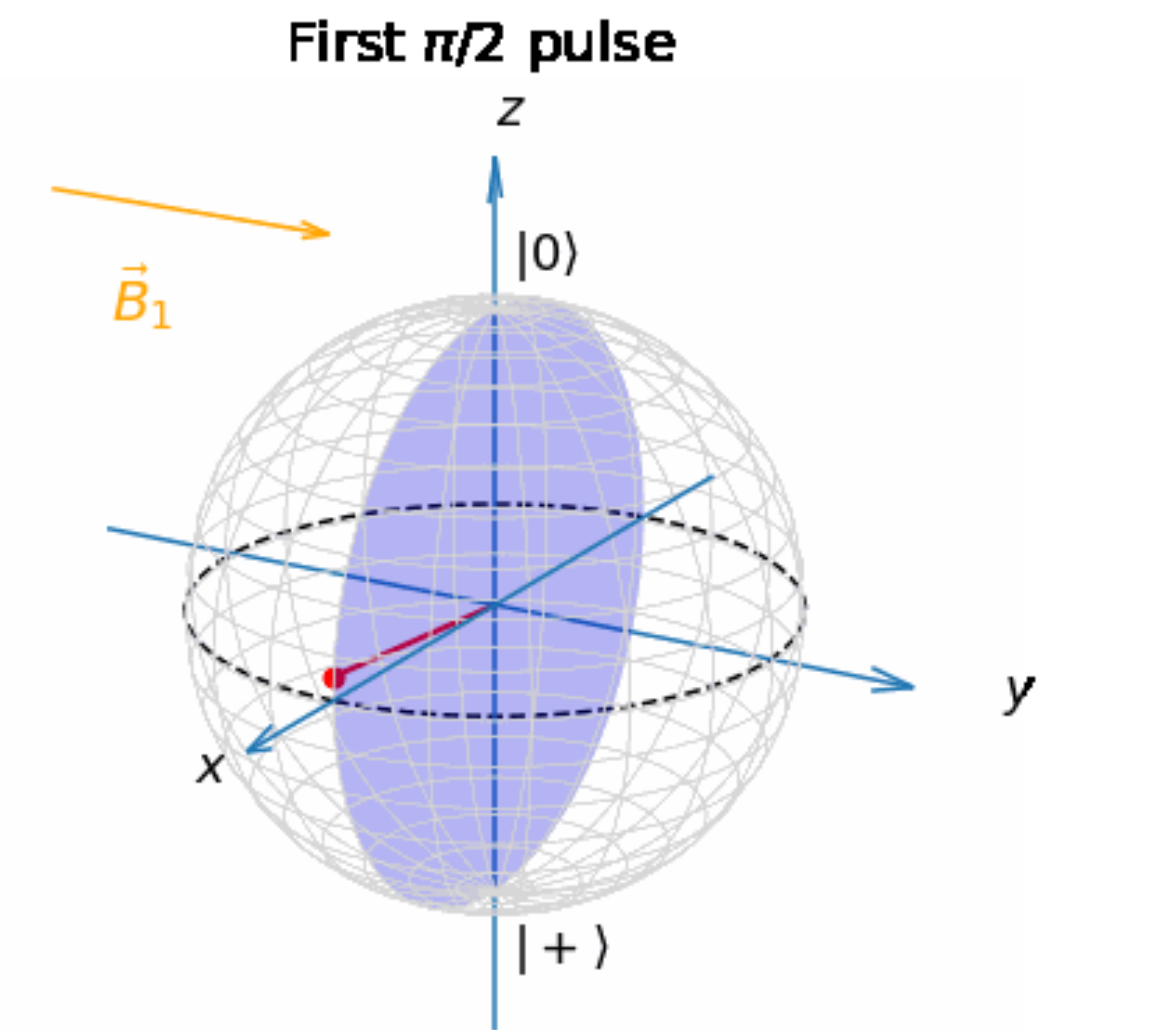
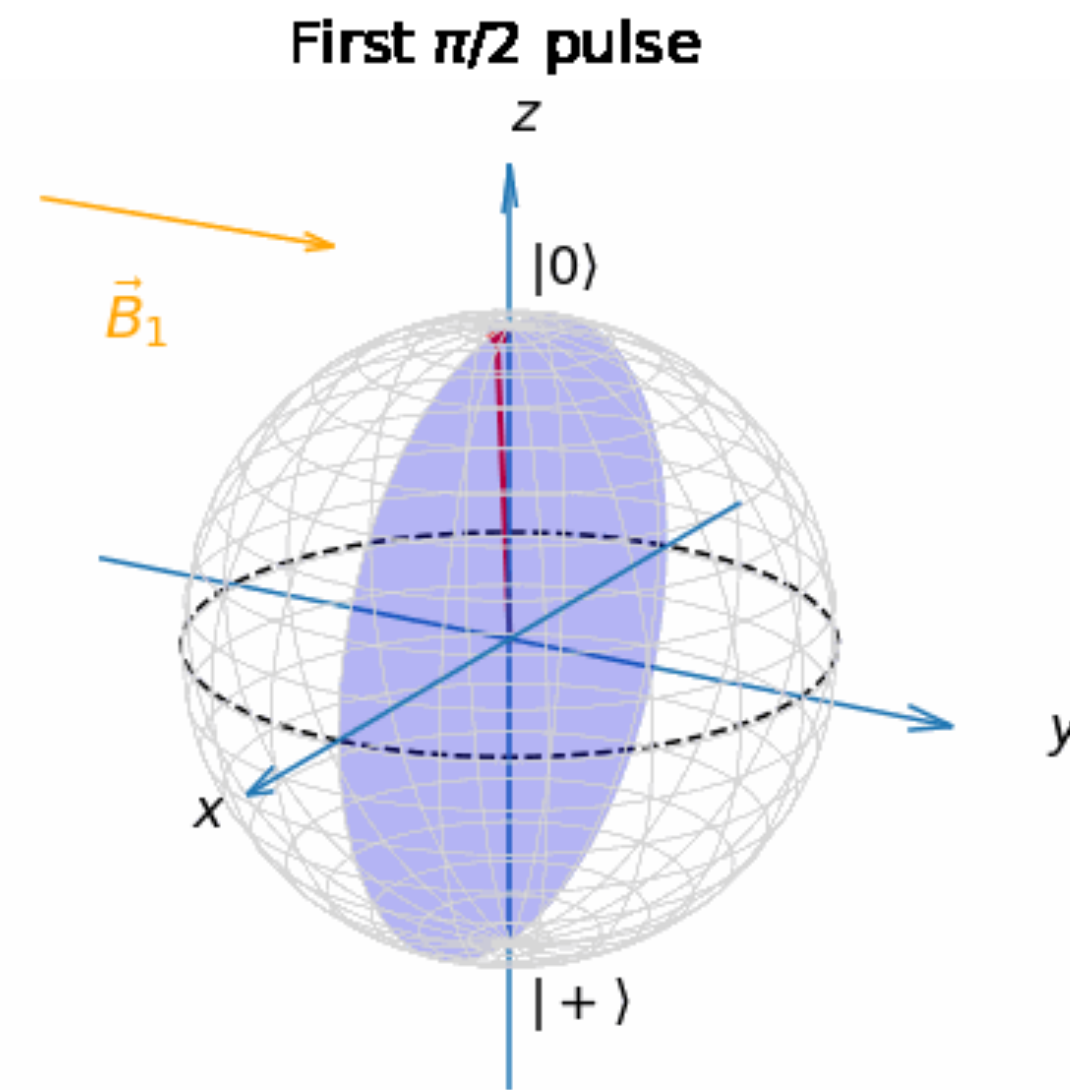
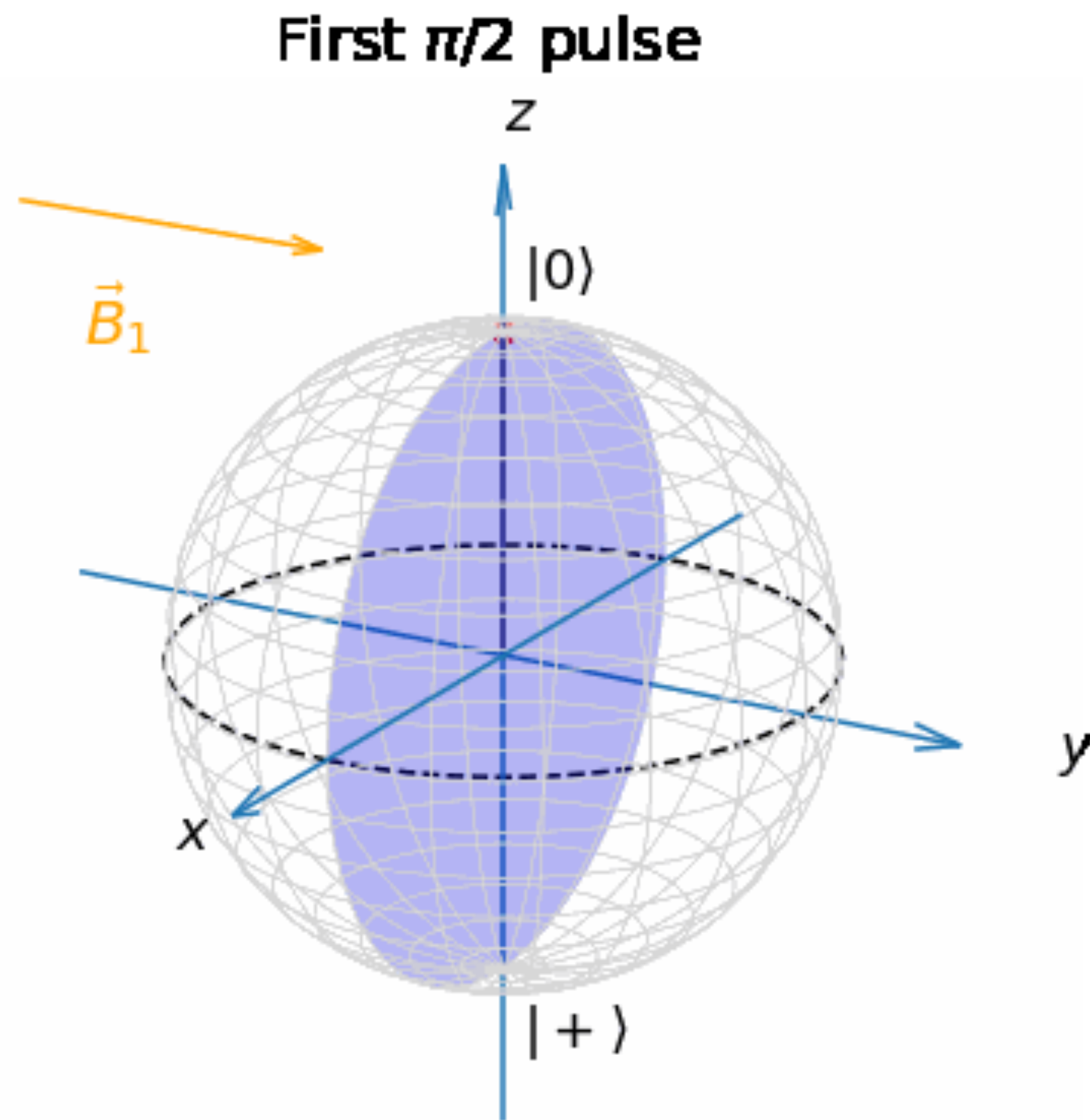
Apply $\pi/2$ -pulse : $|\psi\rangle = \frac{1}{\sqrt{2}} (|0\rangle - |1\rangle)$ $(\omega\tau \ll 1)$

Free precession : $|\psi\rangle = \frac{1}{\sqrt{2}} \left(e^{i\phi/2} |0\rangle - e^{-i\phi/2} |1\rangle \right)$ $\phi = 2\epsilon\tau$

Apply $\pi/2$ -pulse : $|\psi\rangle = -e^{-i\pi/4} \cos\left(\epsilon t - \frac{\pi}{4}\right) |1\rangle + ie^{i\pi/4} \sin\left(\epsilon t - \frac{\pi}{4}\right) |0\rangle$

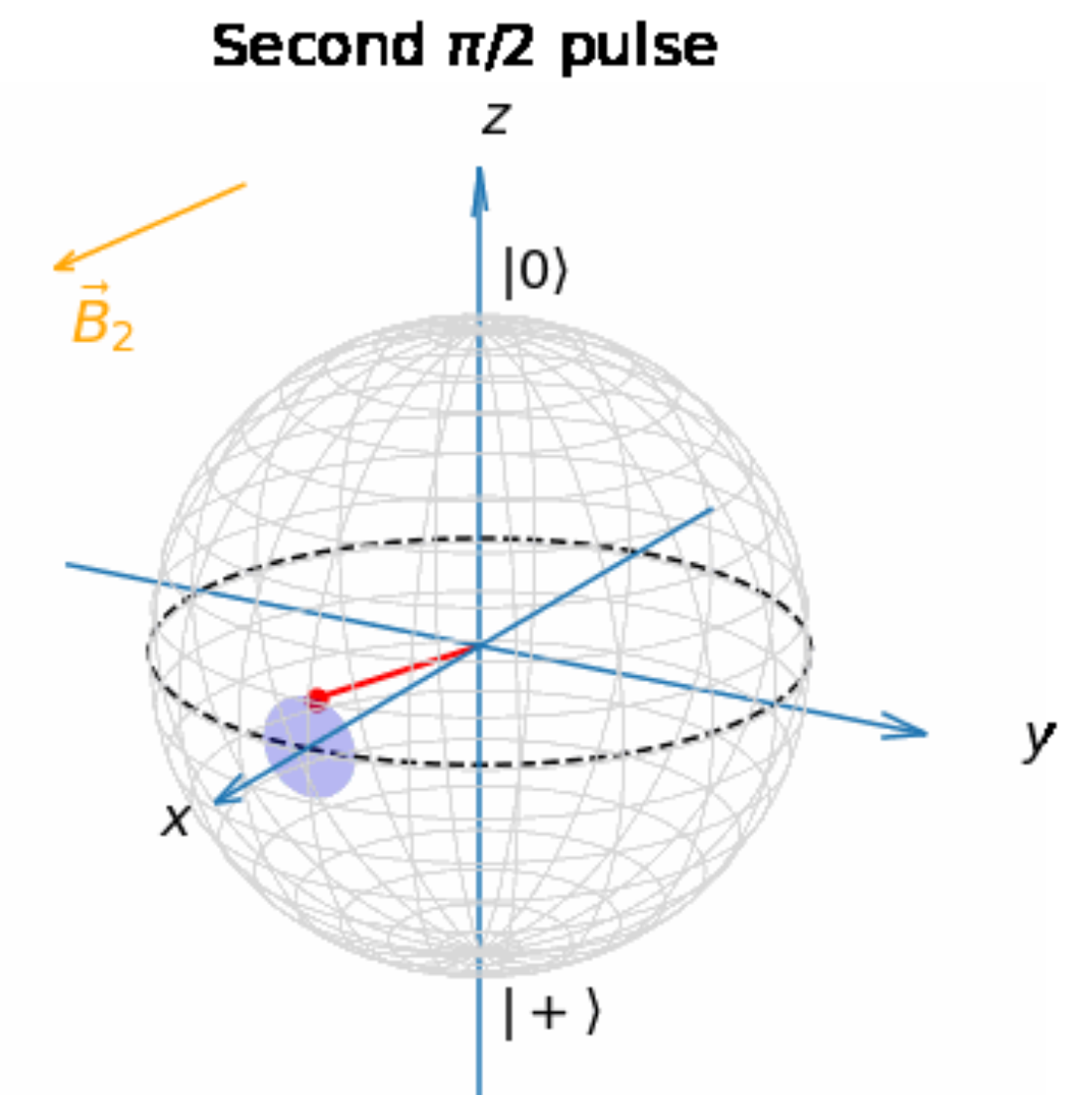
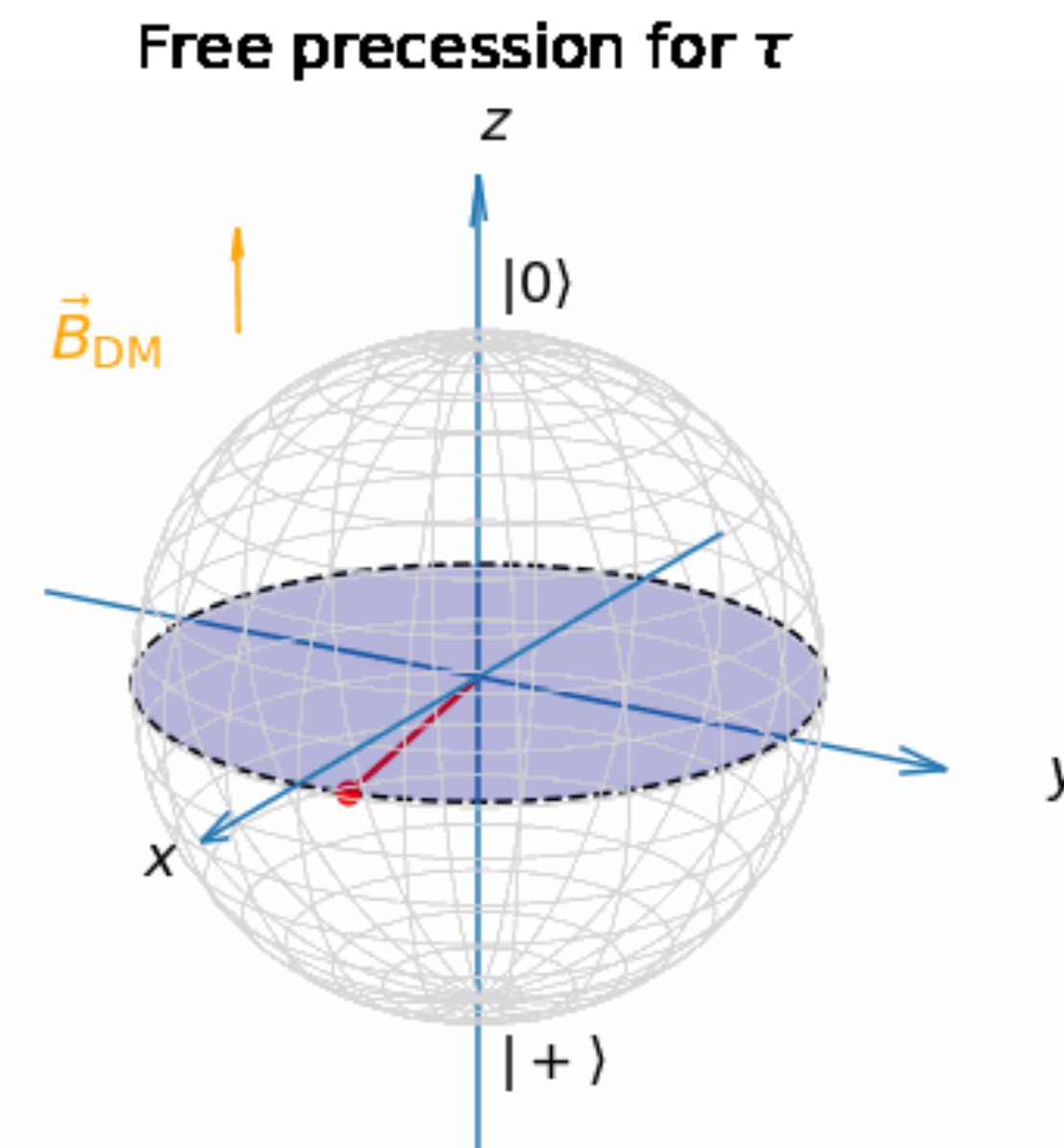
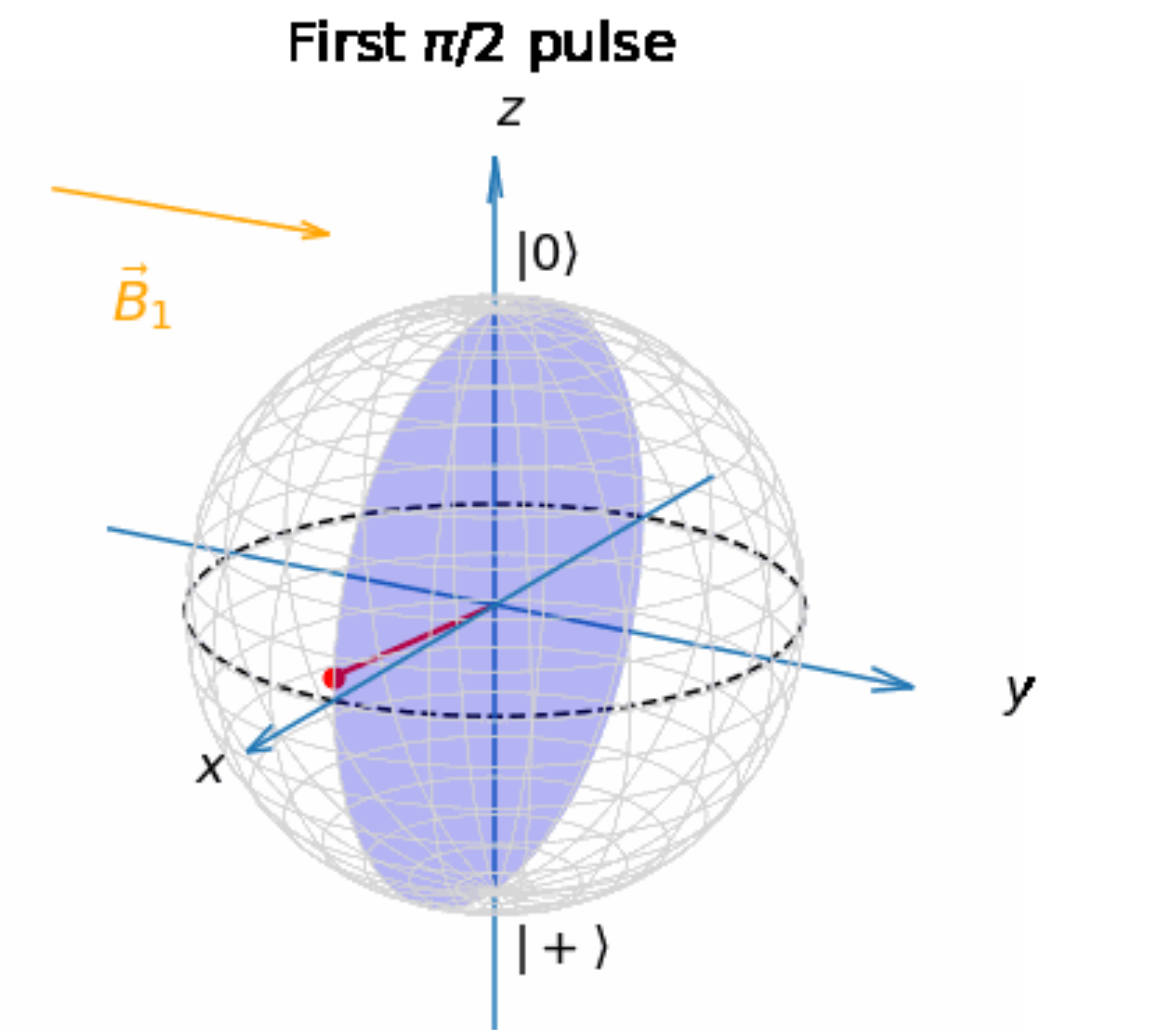
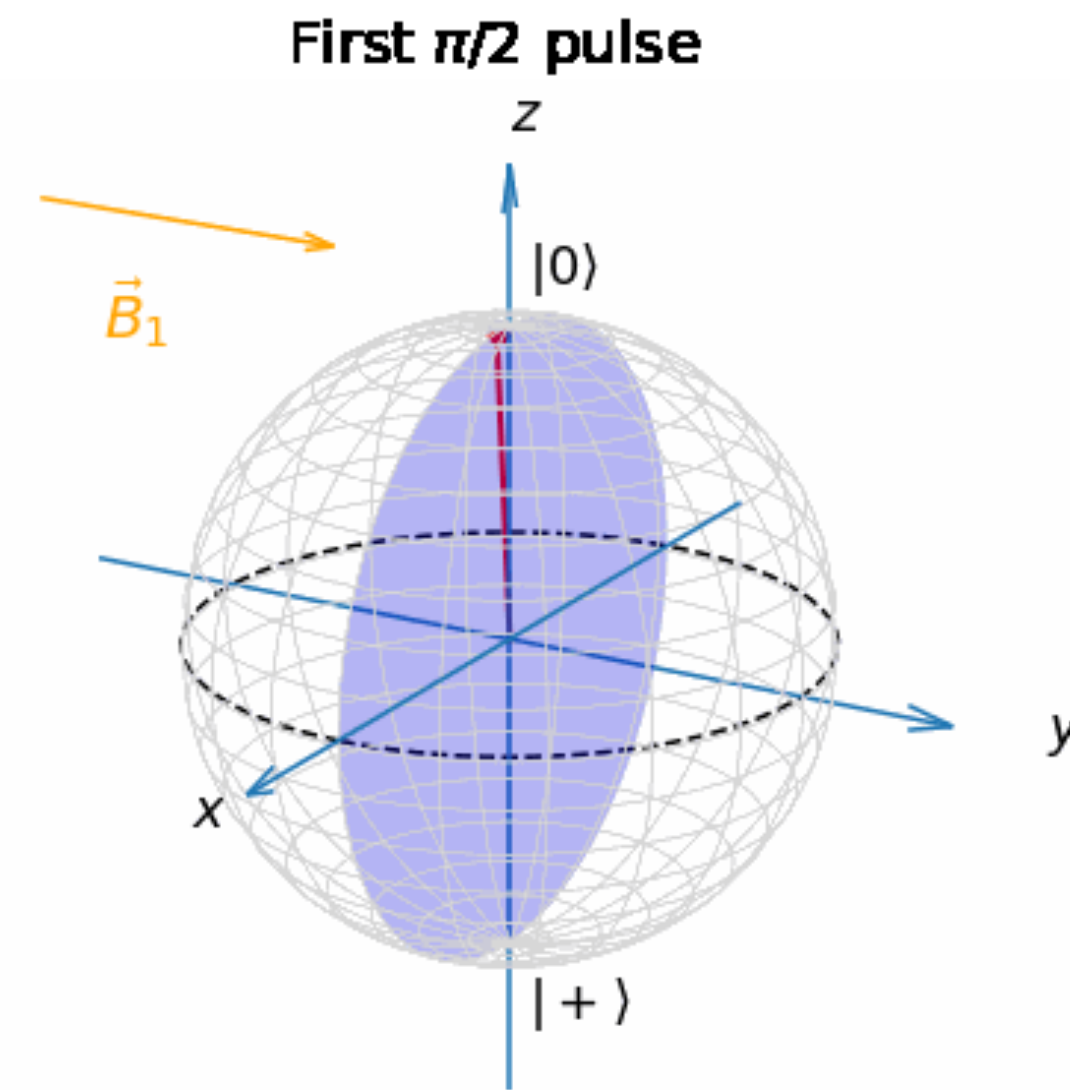
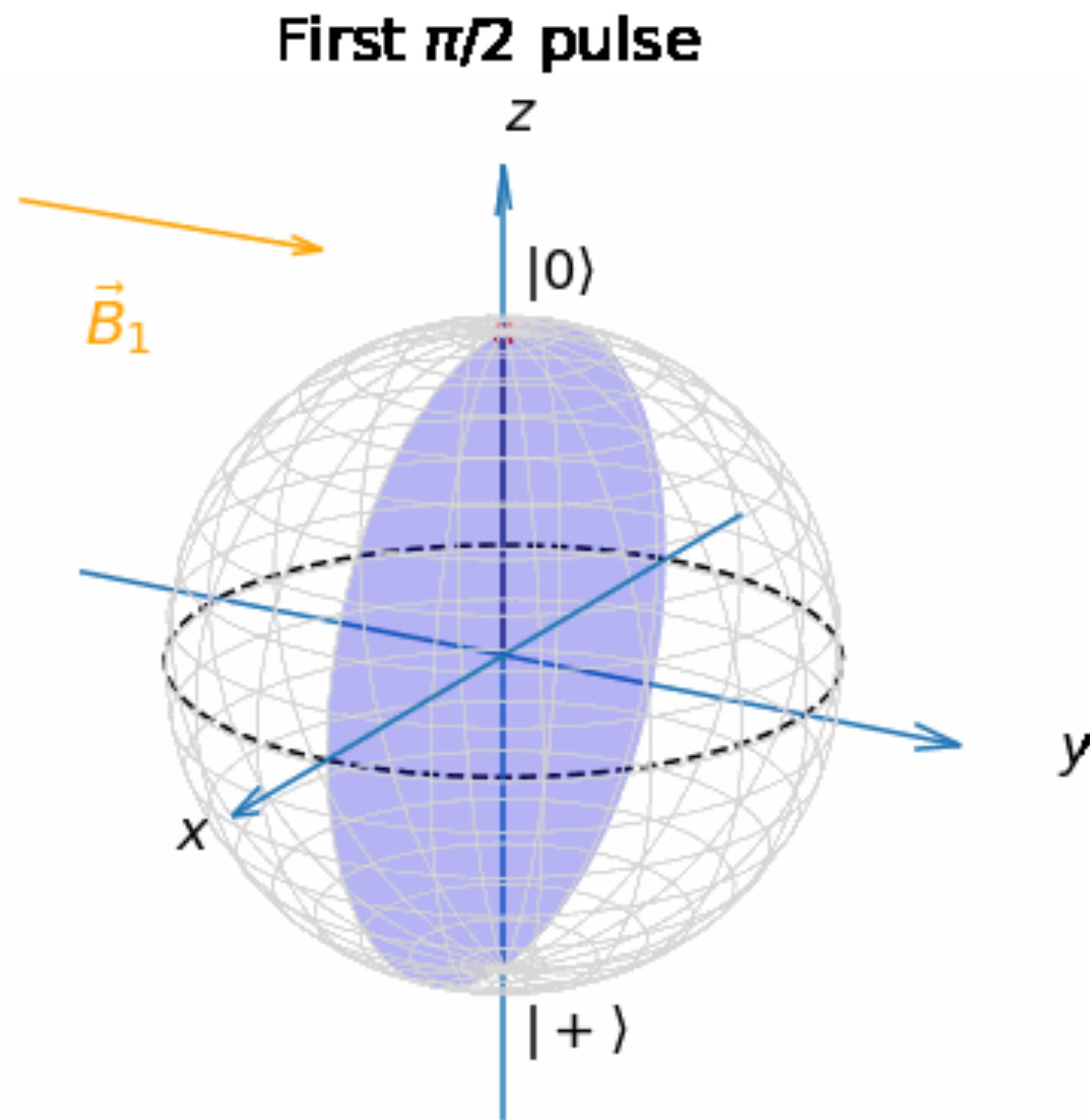
- 測定量： $S \equiv \frac{1}{2} \langle \psi | \sigma_z | \psi \rangle \simeq \epsilon\tau$

ブロッホ球での表示



[Figure created by S.Chigusa]

ブロッホ球での表示



[Figure created by S.Chigusa]

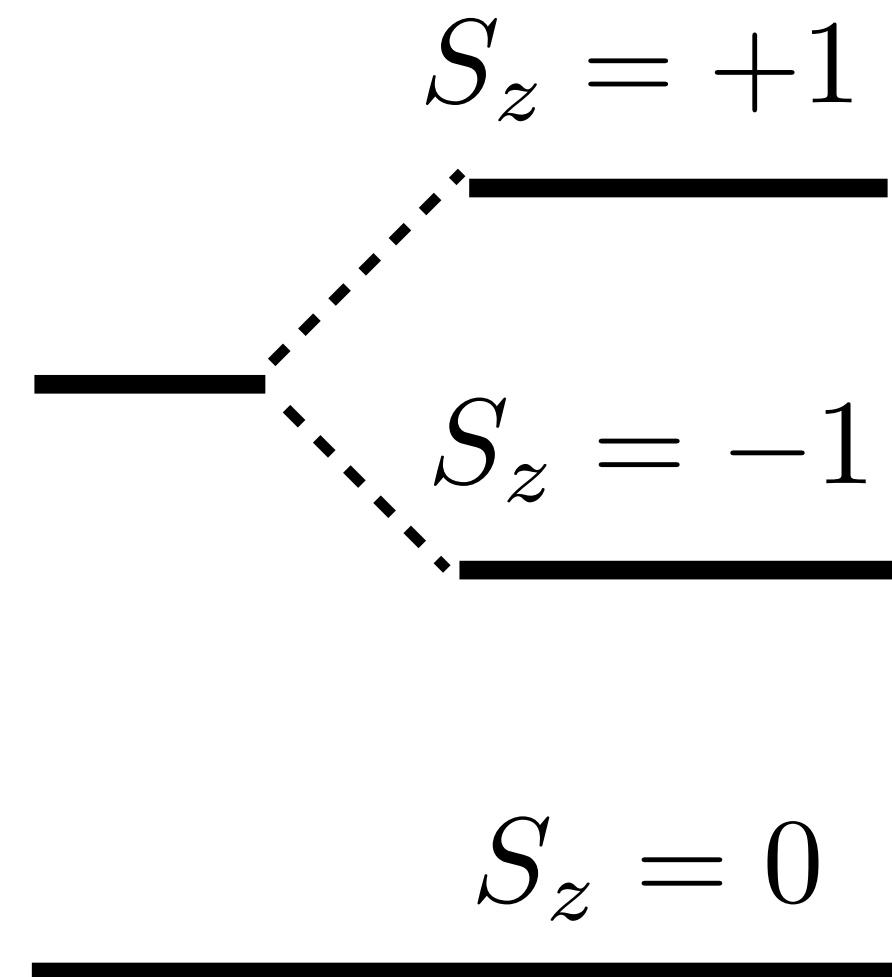
Qubitによるダークマター検出

- ダイヤモンドのNV中心

- NV中心の電子はspin tripletを形成

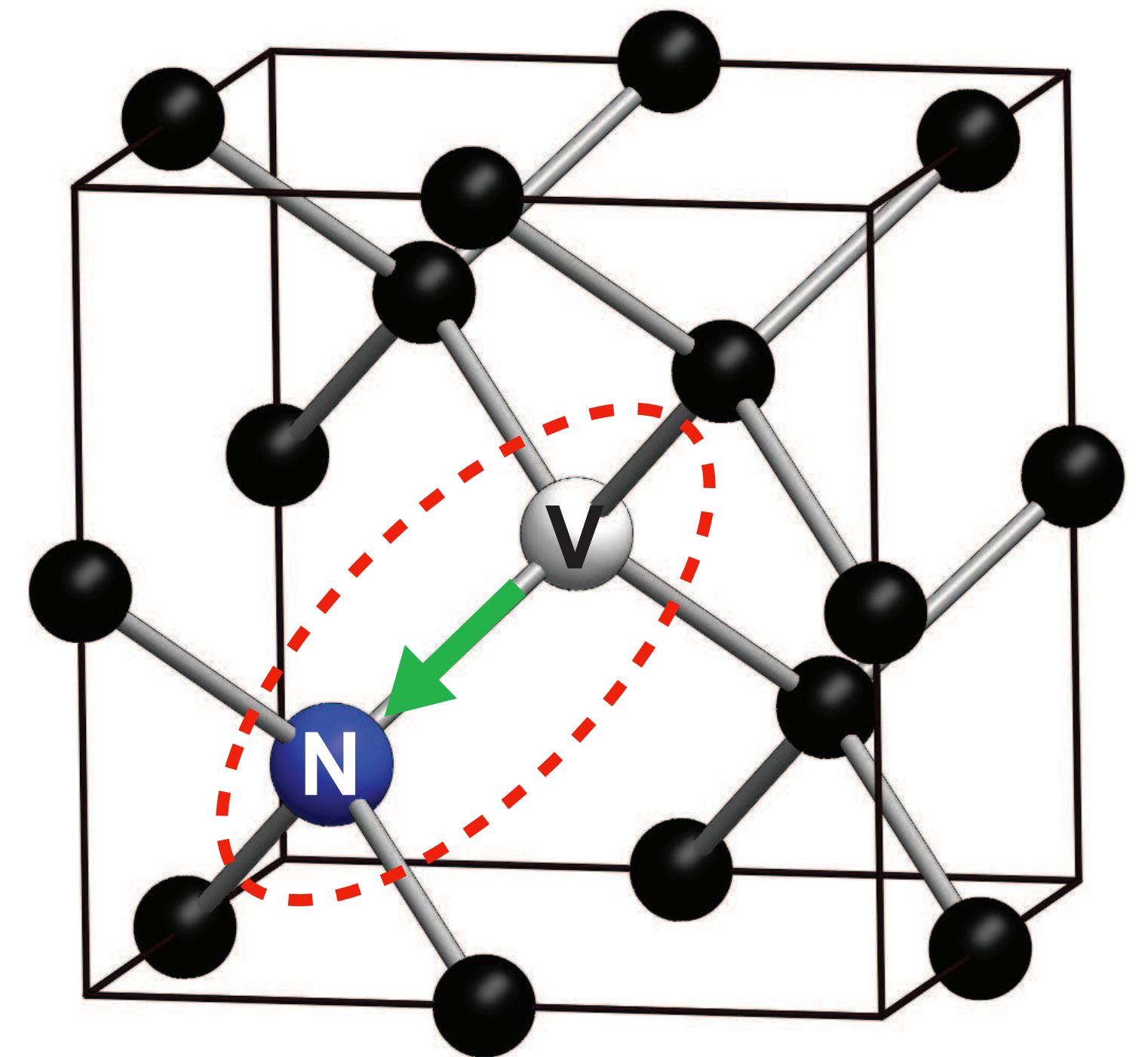
$$H = \omega_D S_z^2 + g_e \mu_B \vec{B} \cdot \vec{S}$$

$(\vec{S} = \vec{S}_1 + \vec{S}_2)$



- qubit = スピン 0, 1 状態

- 量子センサーとして利用

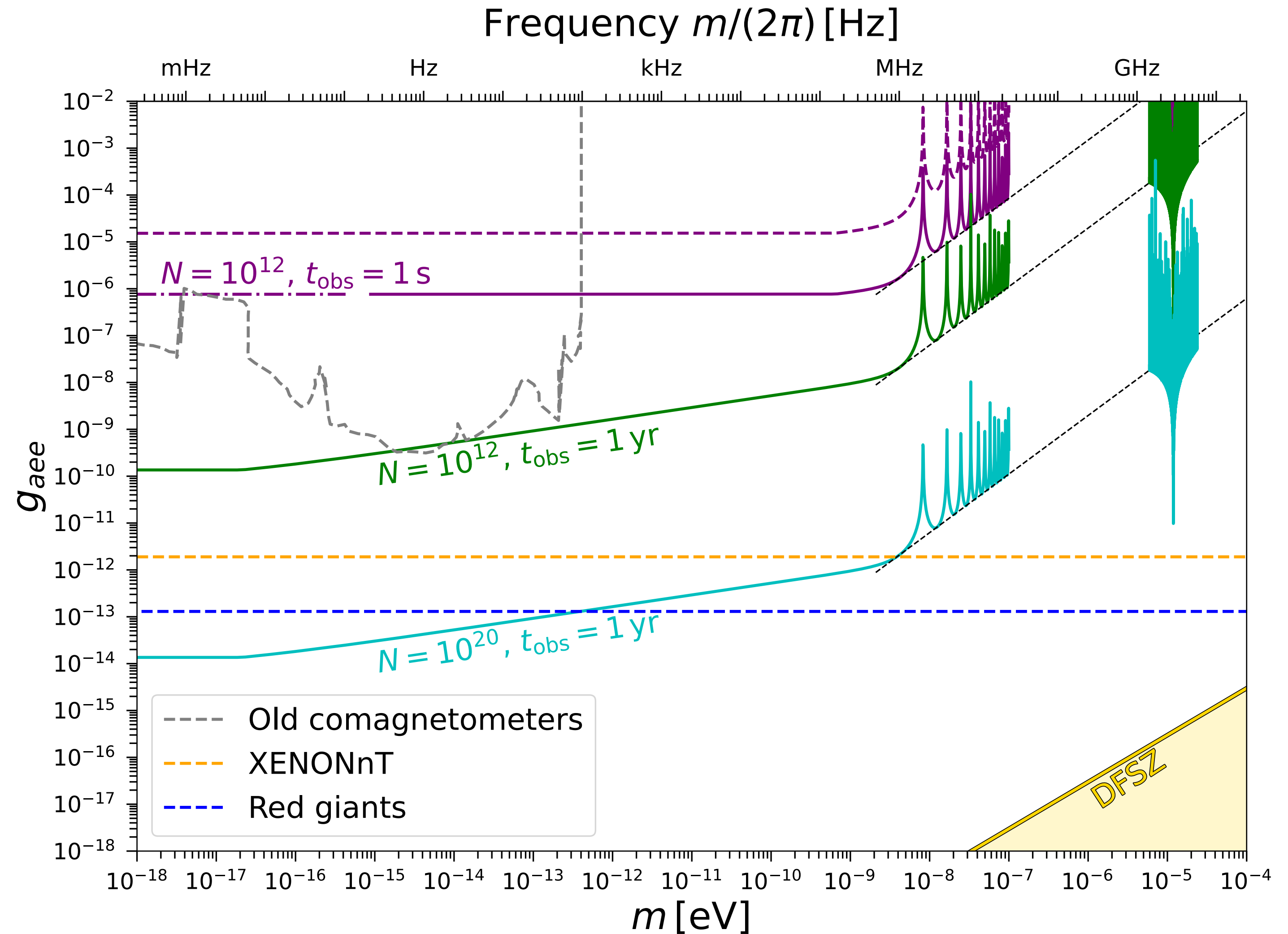
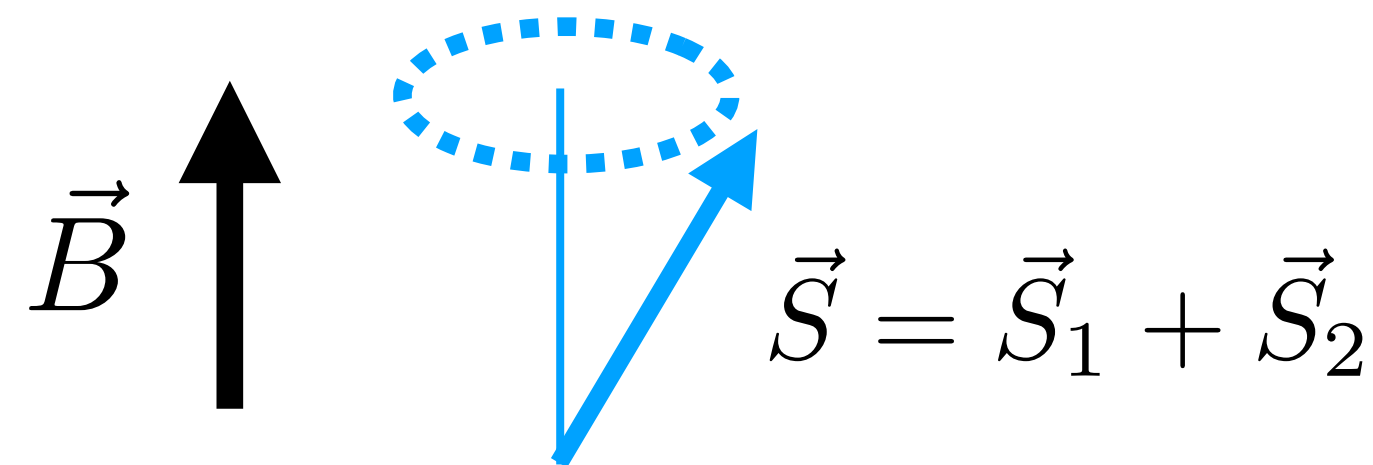


● アクシオン・電子結合

$$\mathcal{L} = \frac{g_{ae}}{2m_e} (\partial_\mu a) \bar{\psi} \gamma^\mu \gamma_5 \psi$$

$$\longrightarrow H = \frac{g_{ae}}{m_e} \vec{\nabla} a \cdot \vec{S}$$

磁場センシングと同じ
理屈でアクシオン検出



[Chigusa, Hazumi, Herbschleb, Mizuochi, KN (2023)]

- アクシオン・核子結合

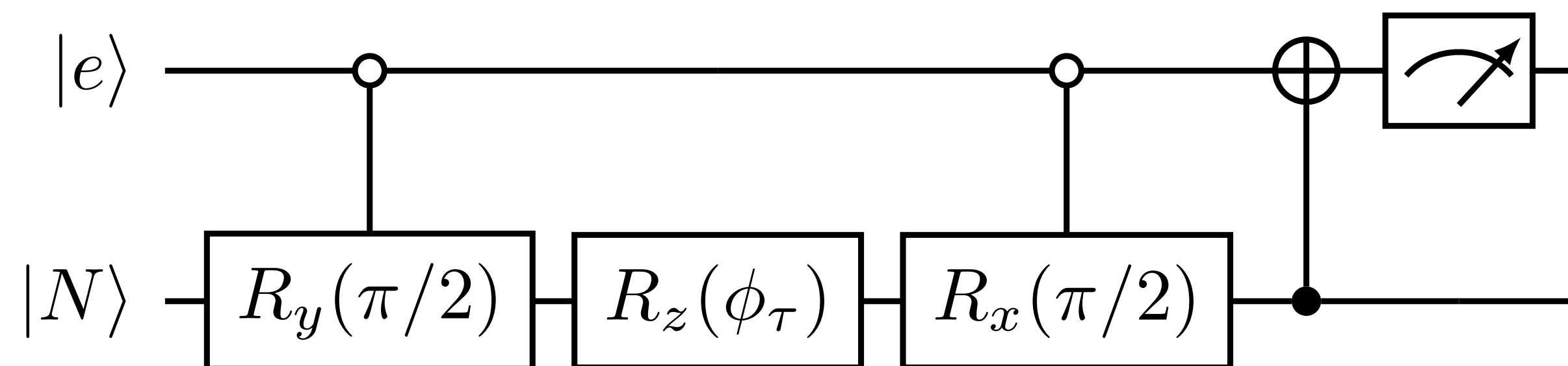
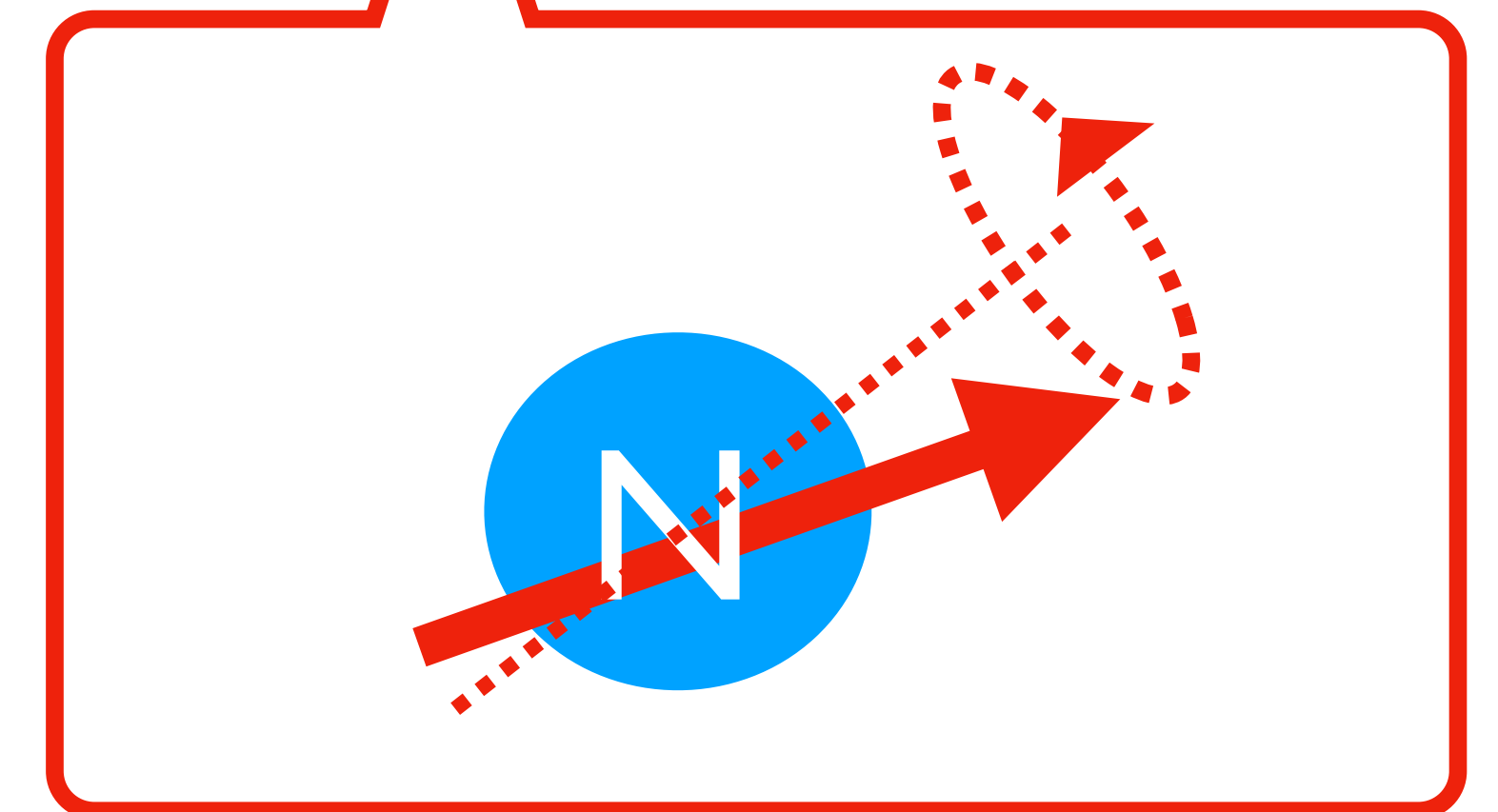
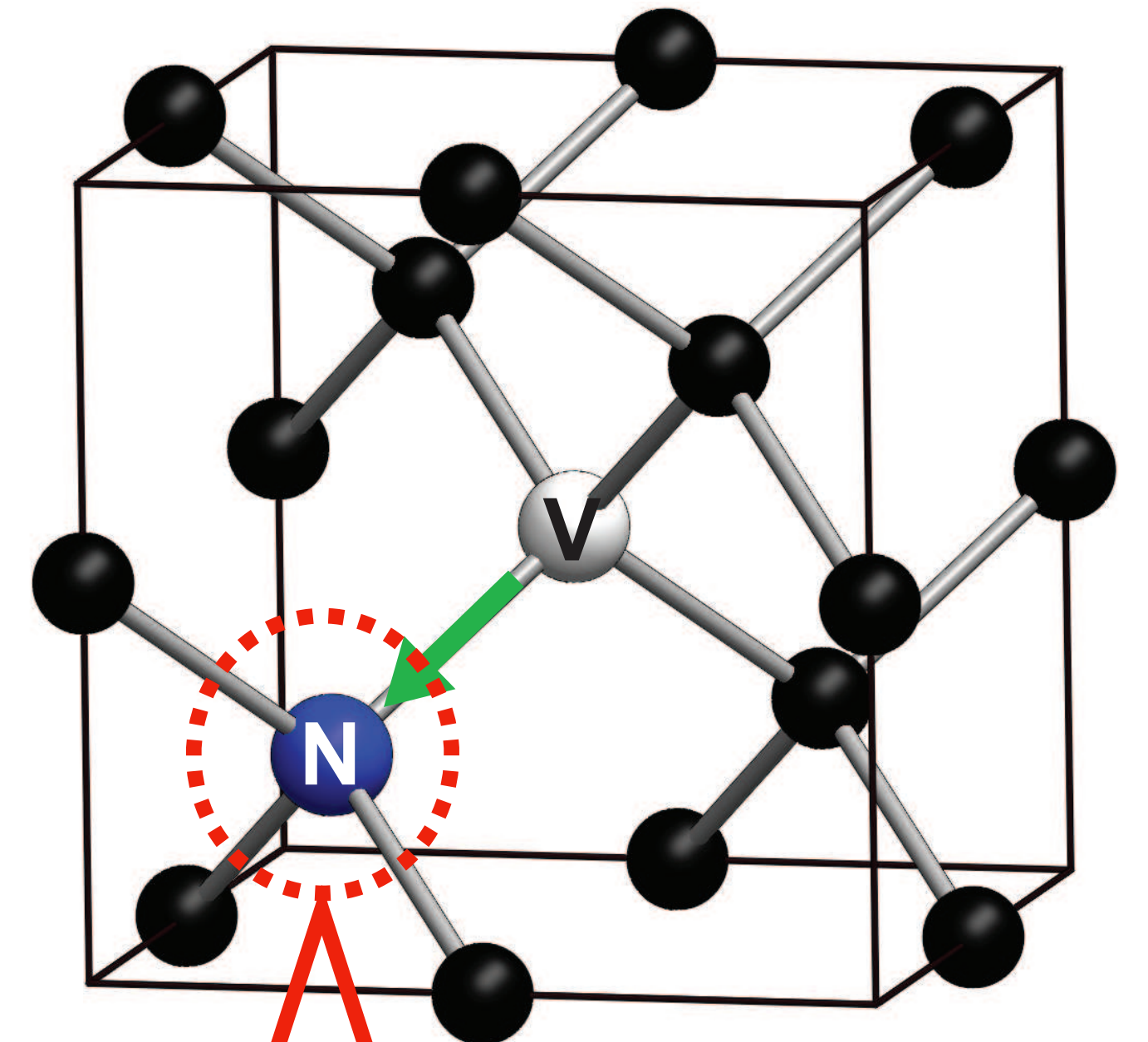
窒素原子の核スピンを利用すると
アクシオン・核子結合にも制限が付けられる

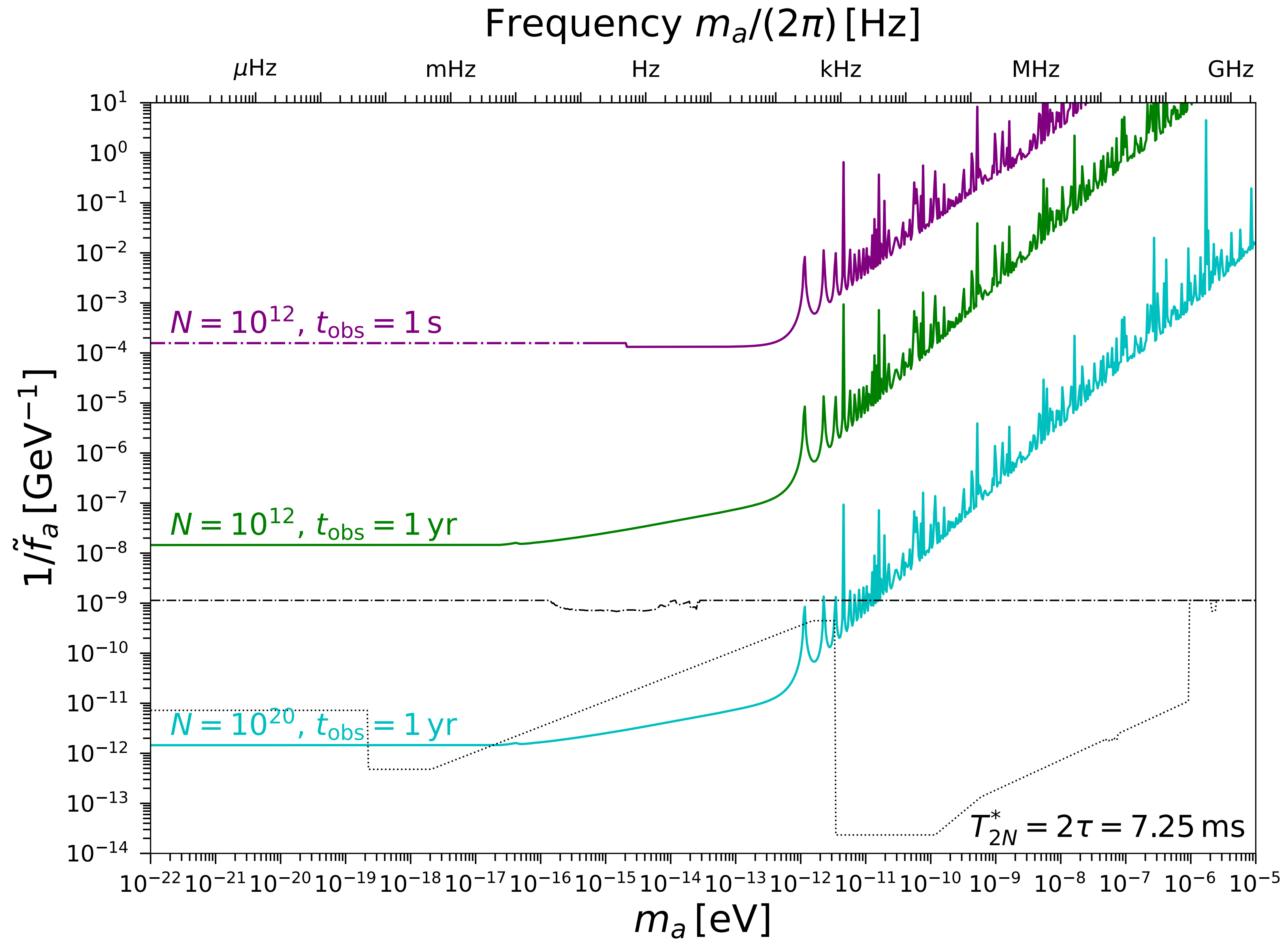
$$H = H_{\parallel} + H_{\perp}$$

hyperfine splitting

$$H_{\parallel} = \Delta_0 S^{z2} + Q_0 I^{z2} + B^z (\gamma_e S^z + \gamma_N I^z) + A_{\parallel} S^z I^z$$

$$H_{\perp} = \gamma_e \vec{B}_{\perp} \cdot \vec{S}_{\perp} + \gamma_N \vec{B}_{\perp} \cdot \vec{I}_{\perp} + A_{\perp} \vec{S}_{\perp} \cdot \vec{I}_{\perp}$$

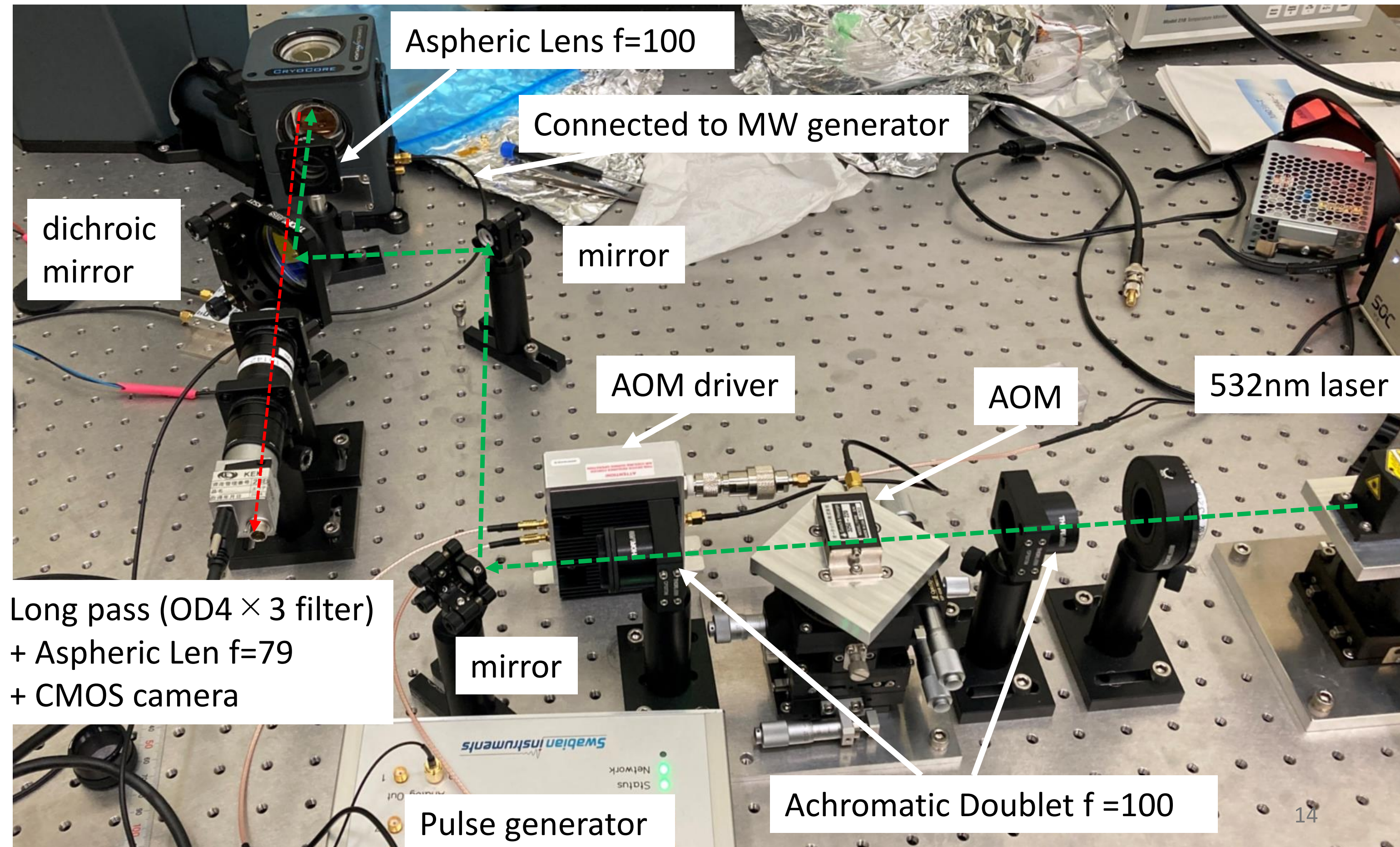




[Chigusa, Hazumi, Herbschleb, Matsuzaki, Mizuochi, KN (2024)]

Current measurement setup

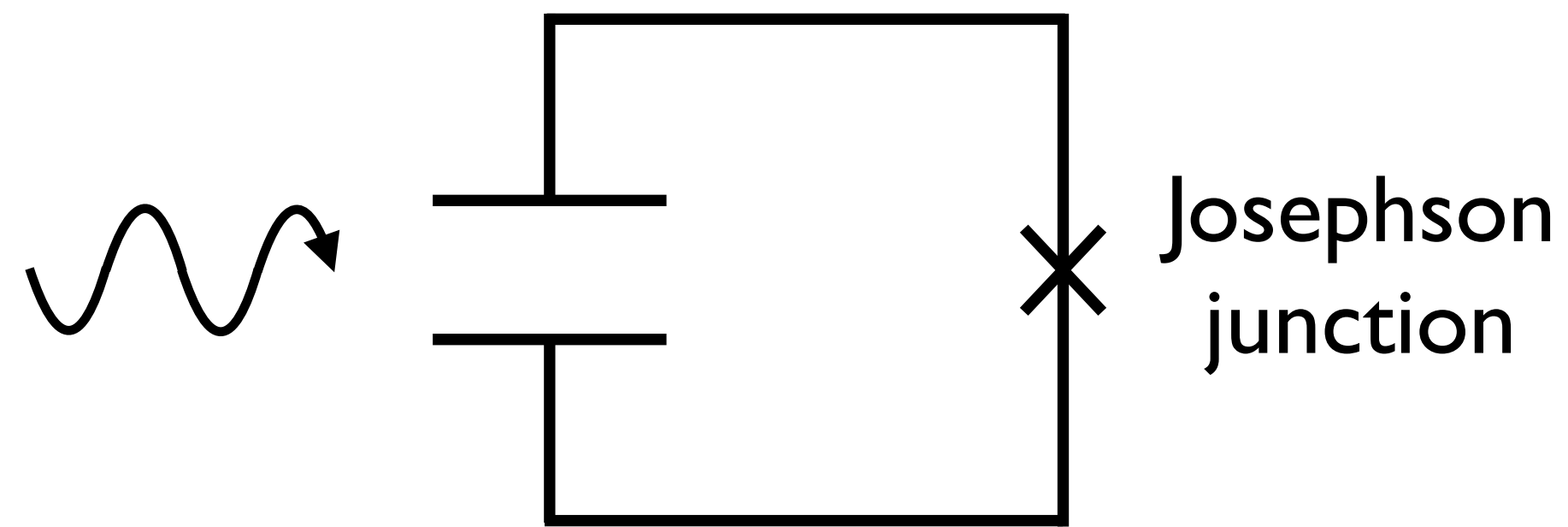
Diamond in cryochamber



[Slide by A. Umemoto @ QUP workshop (2025)]

● 超伝導 qubit

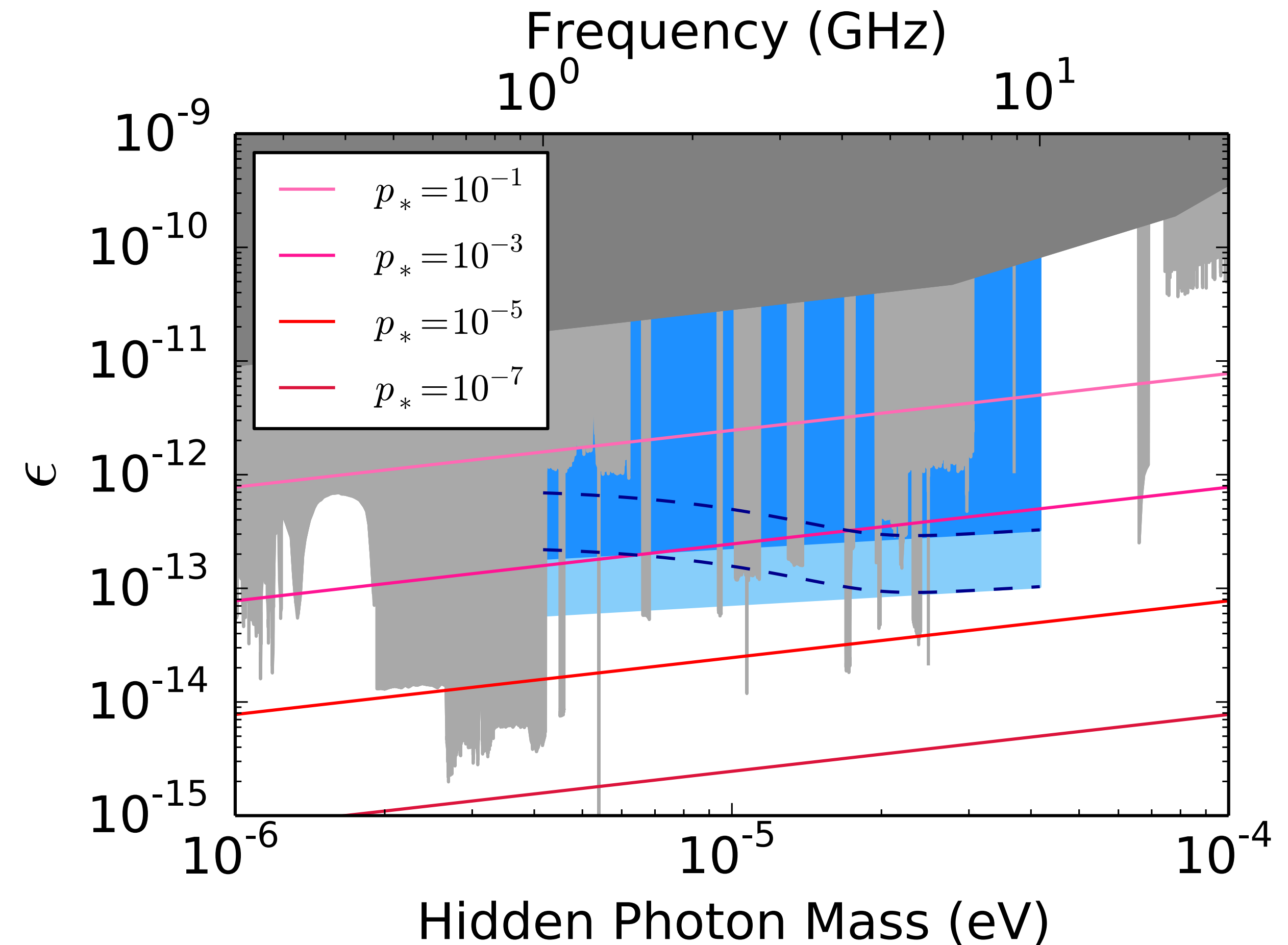
- qubit = 回路の基底状態と励起状態



- ダークフォトン
は
キャパシタに作用

$$H_1 = \eta \cos(\omega t) \sigma_x$$

$$\eta = \frac{1}{2} \epsilon \kappa d \sqrt{C \omega \rho_{\text{DM}}} \cos \Theta$$

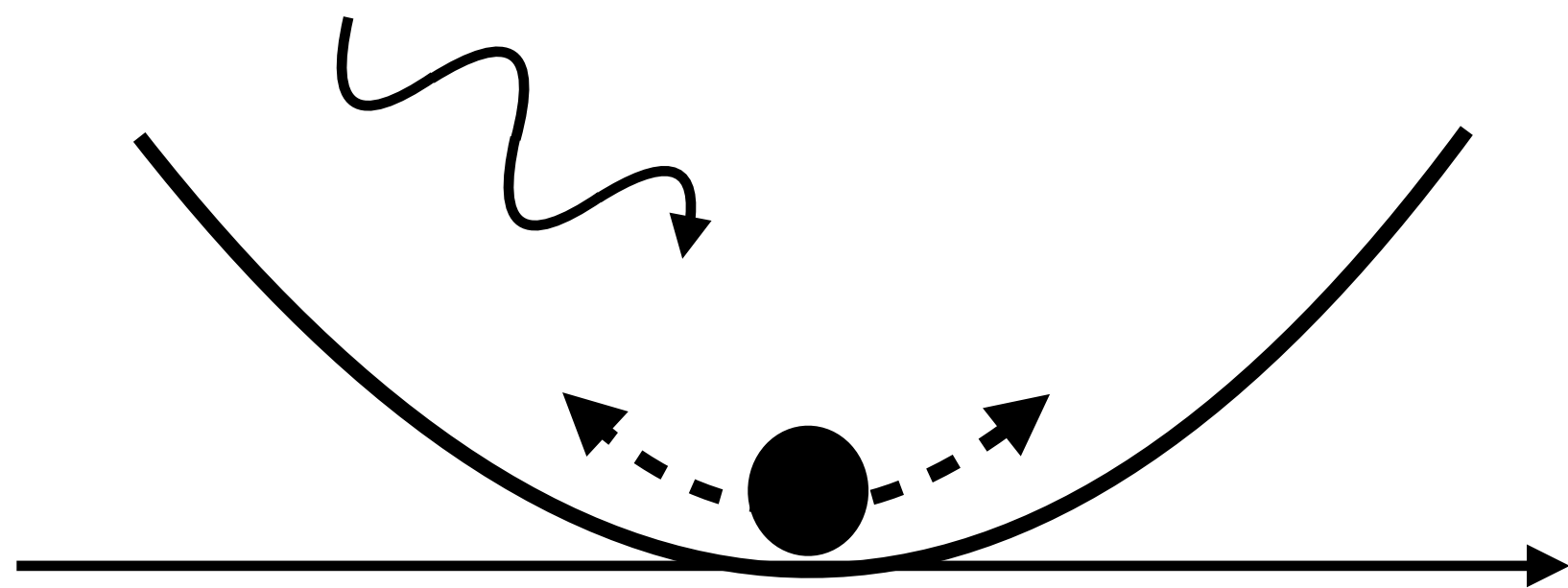


[Chen, Fukuda, Inada, Moroi, Nitta, Sichanugrist (2022)]

————→ DarQ実験

● イオントラップ

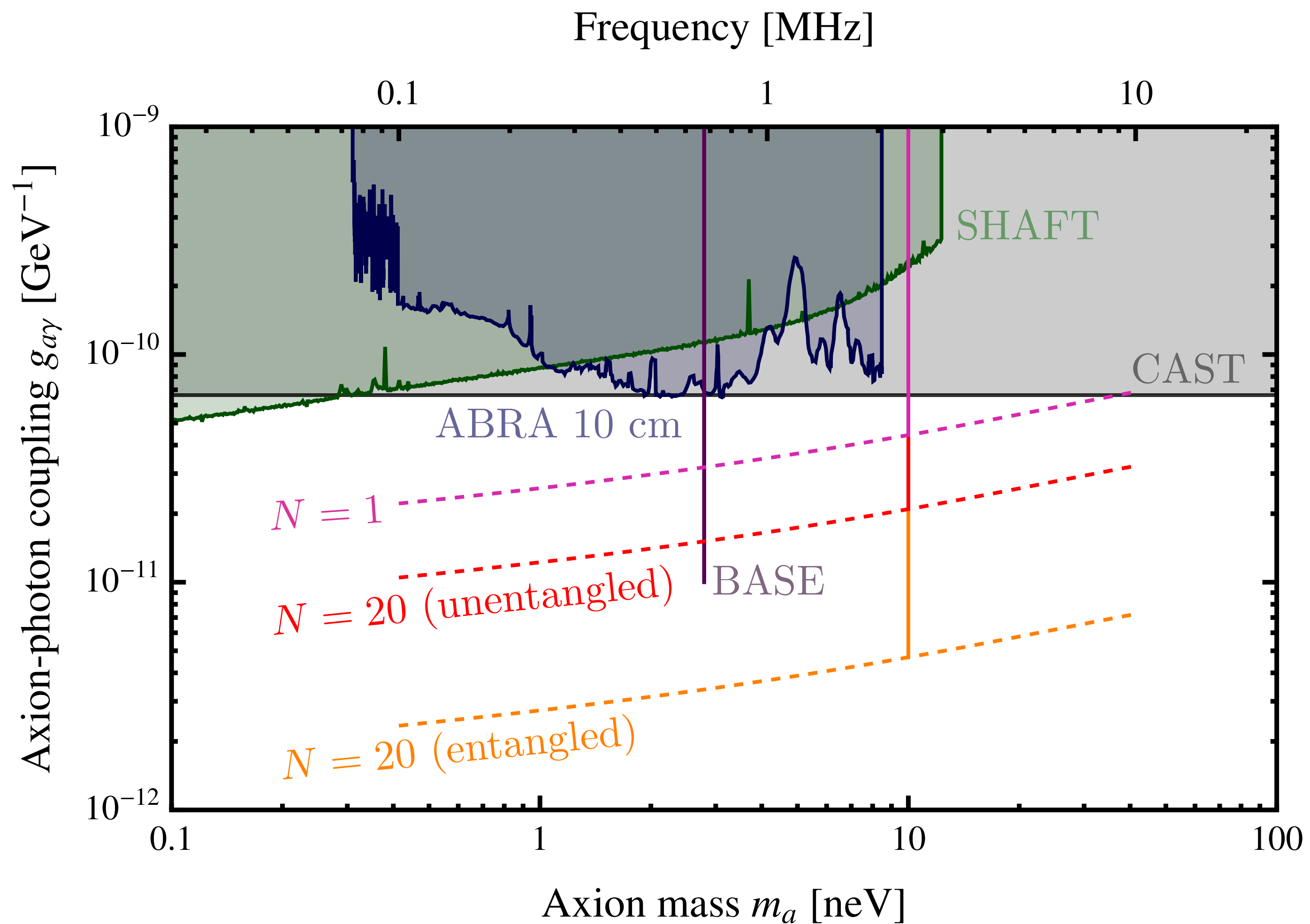
- qubit = イオンの振動モード



- ダークフォトン
は
イオンに作用

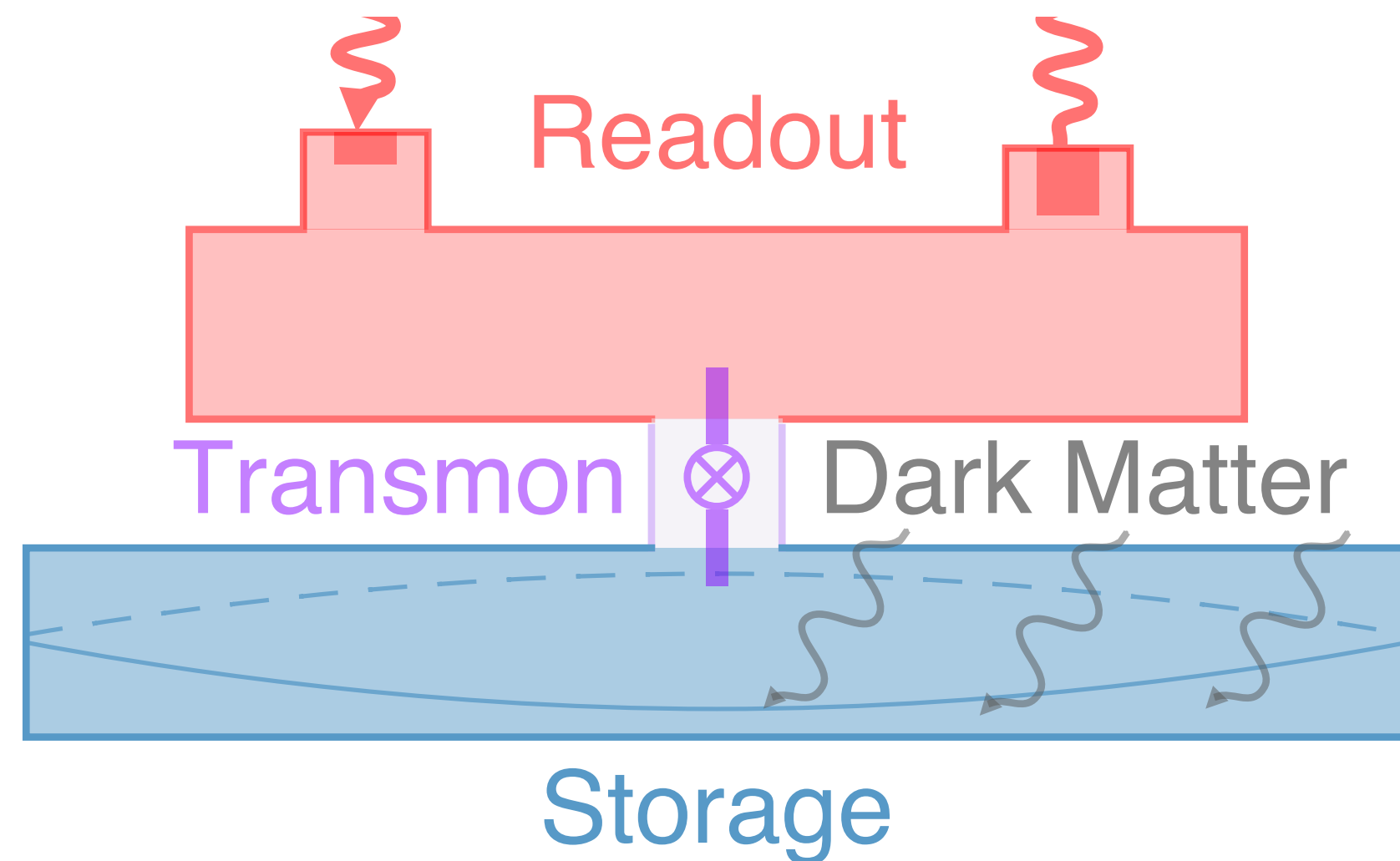
$$H_1 = \eta \cos(\omega t) \sigma_x$$

$$\eta = \kappa e \sqrt{\frac{\rho_{\text{DM}}}{M \omega_z}}$$

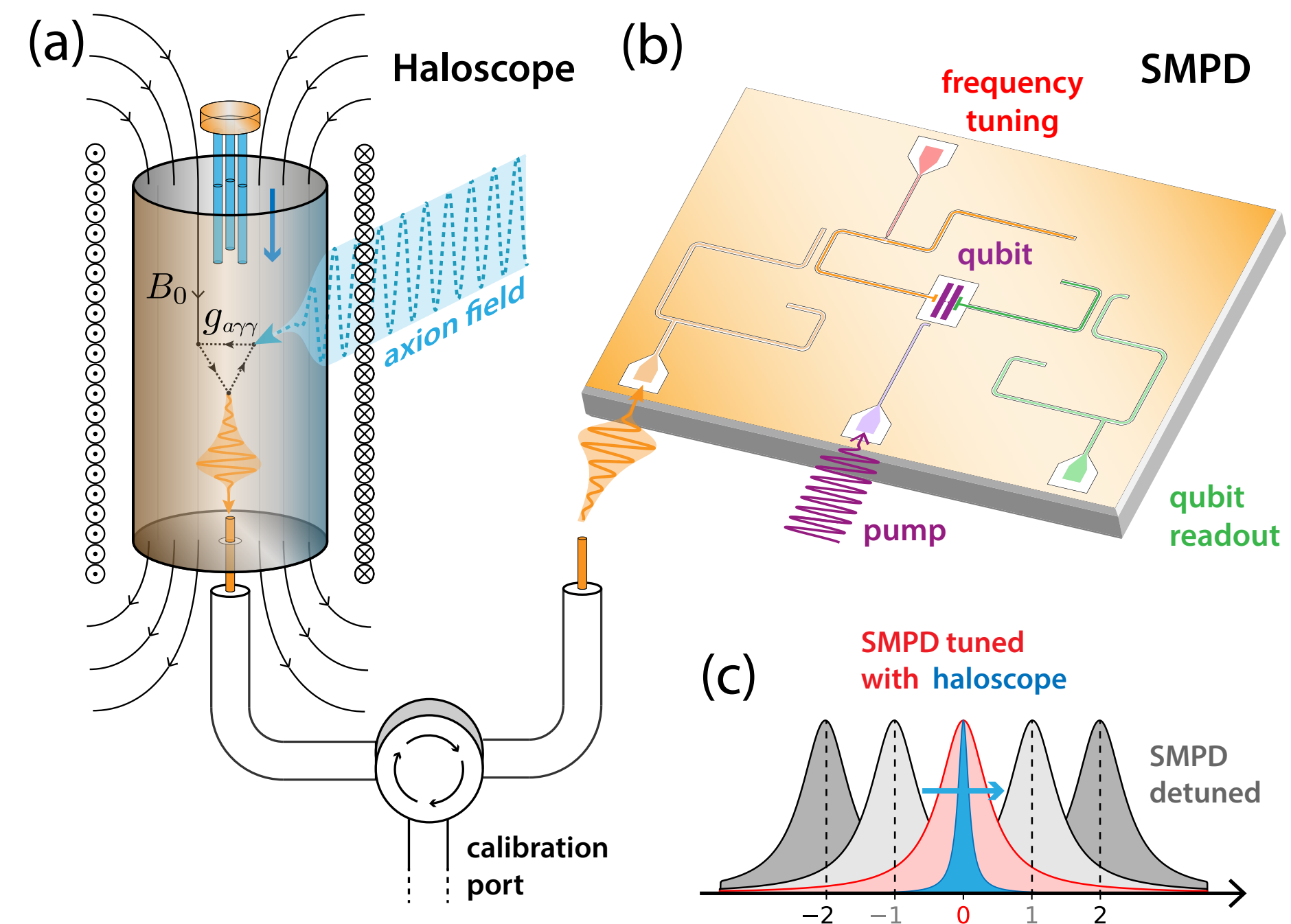


[Ito, Kitano, Nakano, Takai (2023)]

検出器としてのqubit



[Dixit et al. (2020)]



[Braggio et al. (2024)]

理論家も、検出器を含めた全体のセットアップがダークマターとどのように反応するかを考える必要が出てきている

Entanglement enhancement

- 1つのqubitのRabi振動：
$$\begin{aligned} |+\rangle &\rightarrow e^{i\epsilon t} |+\rangle \\ |-\rangle &\rightarrow e^{-i\epsilon t} |-\rangle \end{aligned} \quad |\pm\rangle \equiv \frac{1}{\sqrt{2}} (|0\rangle \pm |1\rangle)$$

- エンタングルした N qubit のRabi振動：

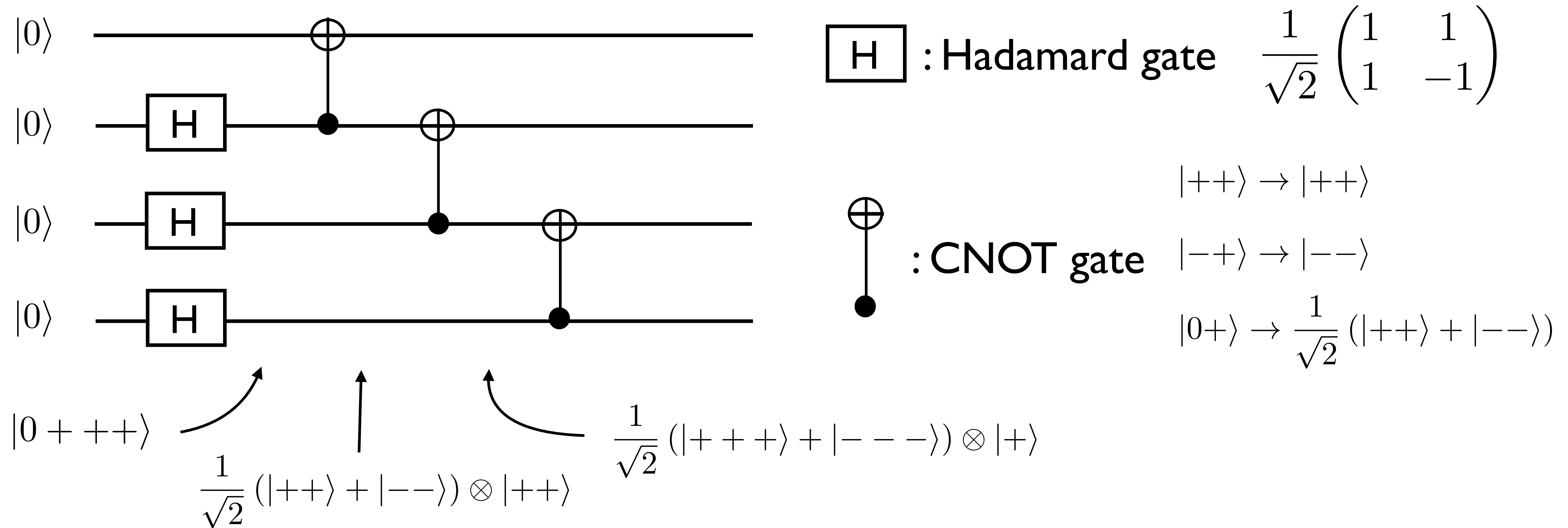
$$\frac{1}{\sqrt{2}} \left(|+\rangle^{\otimes N} + |-\rangle^{\otimes N} \right) \rightarrow \frac{1}{\sqrt{2}} \left(e^{iN\epsilon t} |+\rangle^{\otimes N} + e^{-iN\epsilon t} |-\rangle^{\otimes N} \right)$$

- 遷移確率： $P \simeq (N\epsilon t)^2$

(エンタングルしていない N qubitの場合： $P \simeq N(\epsilon t)^2$)

Entanglement enhancement !

● Quantum circuit for entangled state preparation



$$|0\rangle^{\otimes N} \rightarrow \frac{1}{\sqrt{2}} \left(|+\rangle^{\otimes N} + |-\rangle^{\otimes N} \right) : \text{Greenberger-Horne-Zelinger (GHZ) state}$$

Decoherenceの効果

- エンタングル状態は **decoherence** に弱い

1つのqubitのdecoherence rate : $\Gamma_1 \longrightarrow \tau \sim \tau_1 = \Gamma_1^{-1}$

GHZ状態のdecoherence rate : $N\Gamma_1 \longrightarrow \tau \sim \tau_1/N$

- Coherence時間内の遷移確率 :

独立なN qubit : $\sim N(\epsilon\tau_1)^2$

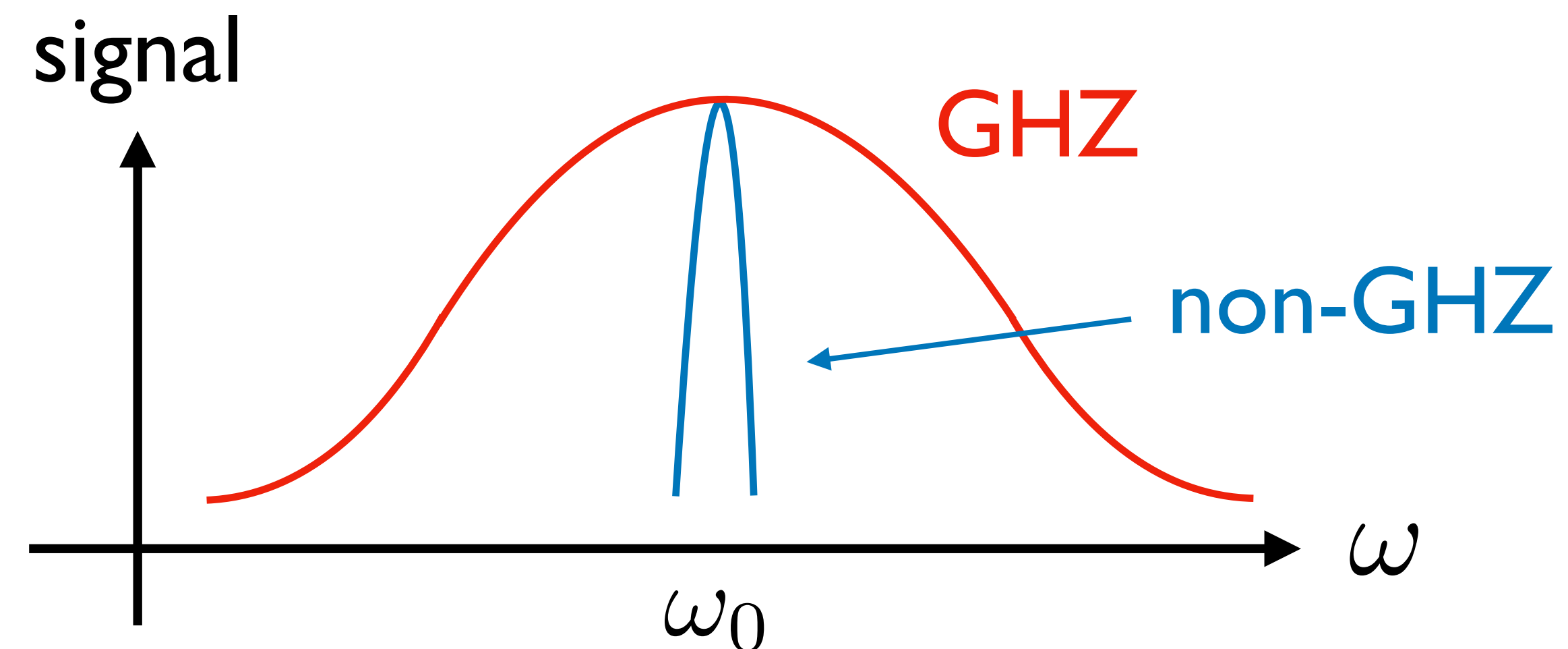
GHZ状態 : $\sim (\epsilon\tau_1)^2$

- 総観測時間を固定すると、
GHZ状態ではN倍の測定が可能 $\longrightarrow$ **結局、独立なN qubit
と同程度の感度**

エンタングル状態の優位性

[Sichanugrist, Fukuda, Moroi, KN, Chigusa, Hazumi, Mizuochi, Matsuzaki (2024)]

- ではGHZ状態のメリットはないのか？ → **超あります！**
- 一回の測定自体は GHZ 状態の方が N 倍短い
→ 一回の測定の **バンド幅** は N 倍広い (cf. 不確定性原理)
- 広い周波数領域をスキャン
したい場合にとっても有利！
ダークマター探査に使える！

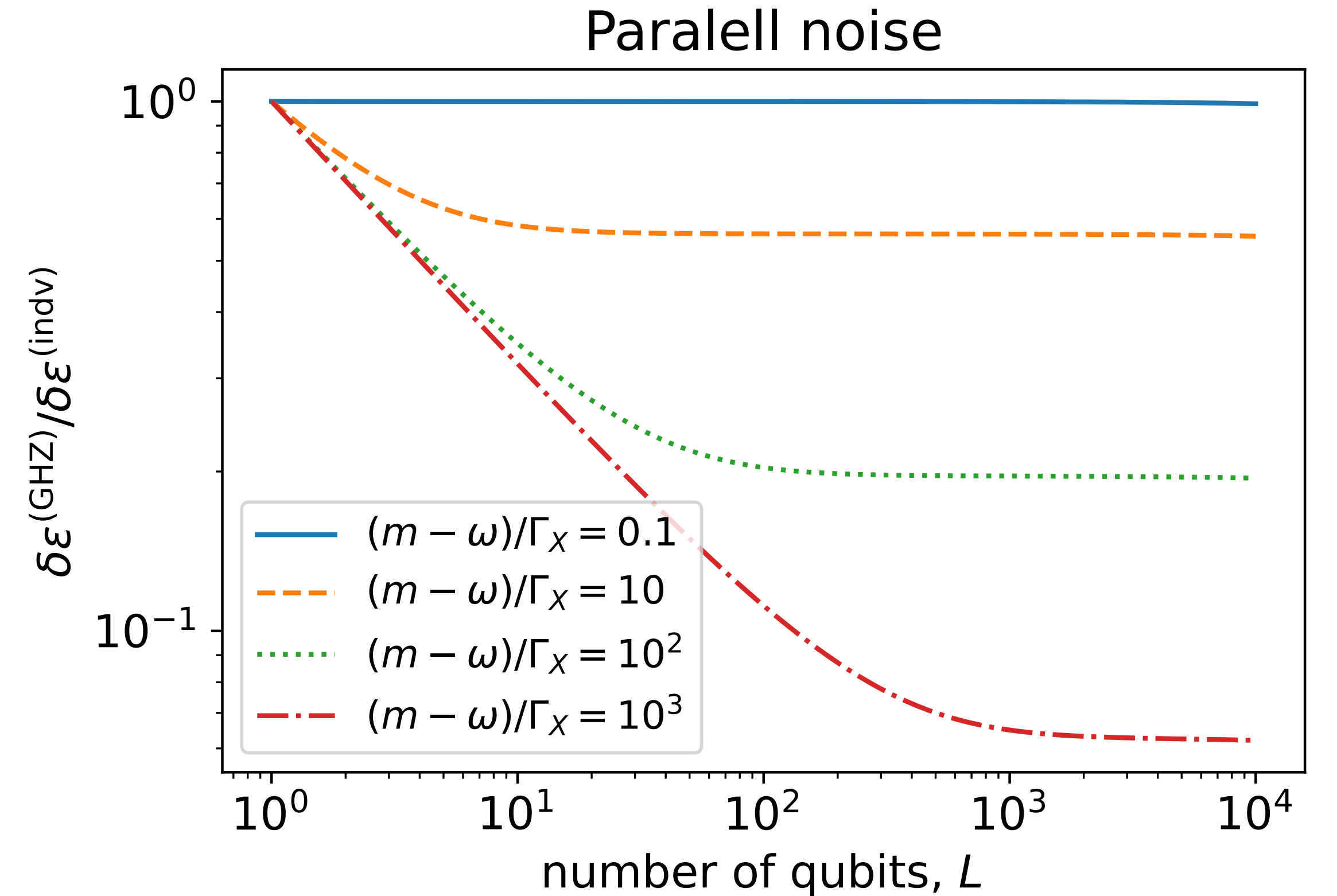


● Lindblad equation including noise

$$\frac{d\rho(t)}{dt} = \sum_{j=1}^L \left(-i[H_I^j, \rho] + D_j[\rho] \right) \quad D_j[\rho] = \frac{\Gamma_X}{2} \left(\sigma_X^j \rho \sigma_X^j - \frac{1}{2} \rho \right)$$

$$\begin{aligned} \rho_{\text{GHZ}}(t) = & \frac{1}{2} |+\rangle^{\otimes L} \langle +|^{\otimes L} + \frac{1}{2} |-\rangle^{\otimes L} \langle -|^{\otimes L} \\ & + \frac{1}{2} e^{-L\Gamma_X t} (1 + 2iL\epsilon t W(t)) |+\rangle^{\otimes L} \langle -|^{\otimes L} \\ & + \frac{1}{2} e^{-L\Gamma_X t} (1 - 2iL\epsilon t W(t)) |-\rangle^{\otimes L} \langle +|^{\otimes L} \end{aligned}$$

$$W(t) = \frac{\sin[(\omega + m)t]}{(\omega + m)t} + \frac{\sin[(\omega - m)t]}{(\omega - m)t}$$



まとめ

- 様々な **物質** が様々なダークマターと反応する
- 様々な **qubit** が様々なダークマターと反応する
- 量子センシングや量子コンピューティングなどの
色々な技術が応用可能
- やれることはたぶんたくさんある

Appendix

● Molecular orbital approx.

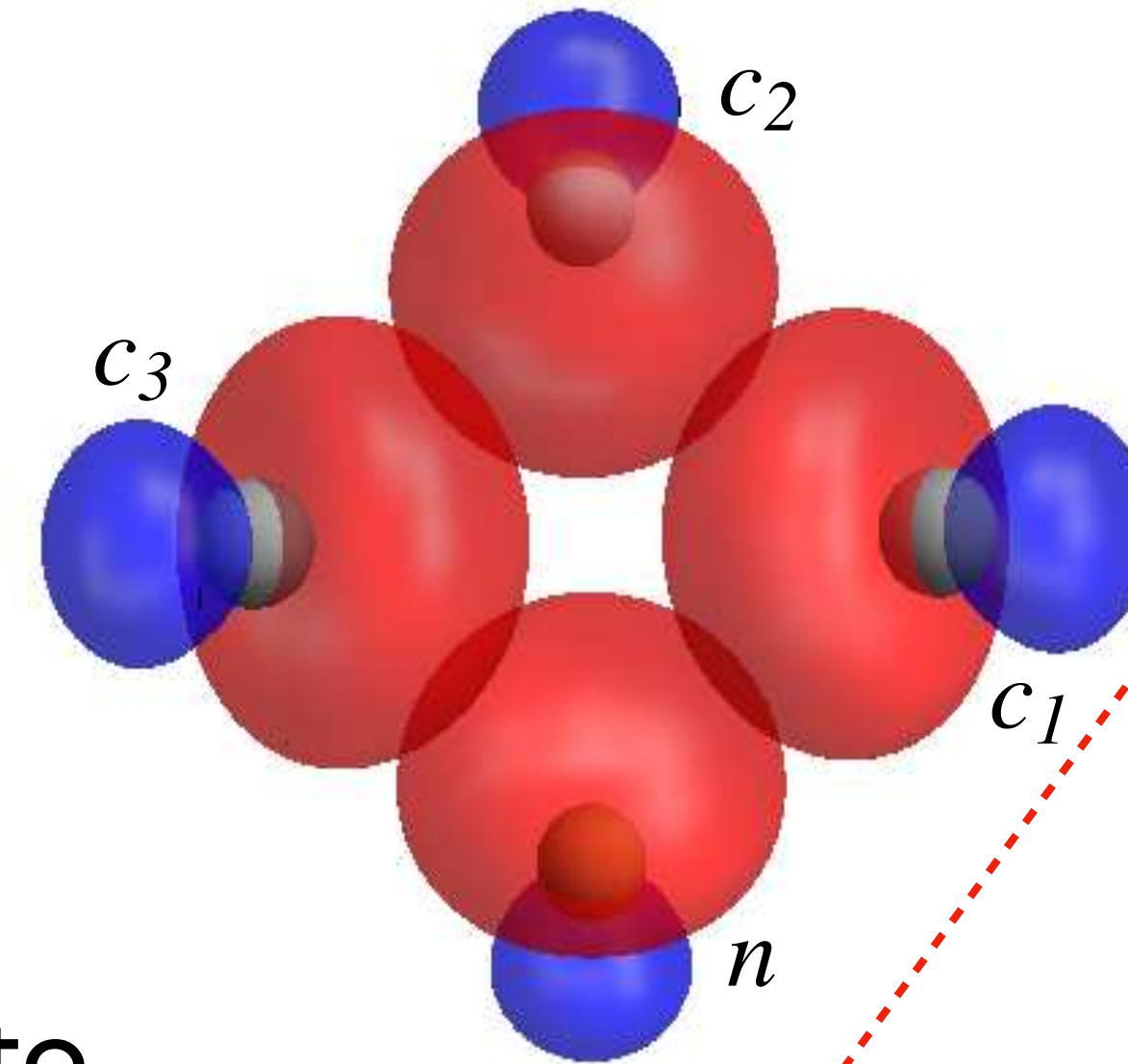
- Four sp³ mixed orbital from neighbor C and N around V
- C_{3v} point group around NV axis
- (4x4) Hamiltonian decomposed into irreducible representation of C_{3v}
- two 1-dim rep (A₁, A₂) + one 2-dim rep (E)

non-degenerate

degenerate

- Equivalent to diagonalize Hamiltonian of the form

$$H \sim \begin{pmatrix} a & b & b & b \\ b & c & d & d \\ b & d & c & d \\ b & d & d & c \end{pmatrix}$$



Conduction Band

spin triplet is ground state due to orbital degeneracy

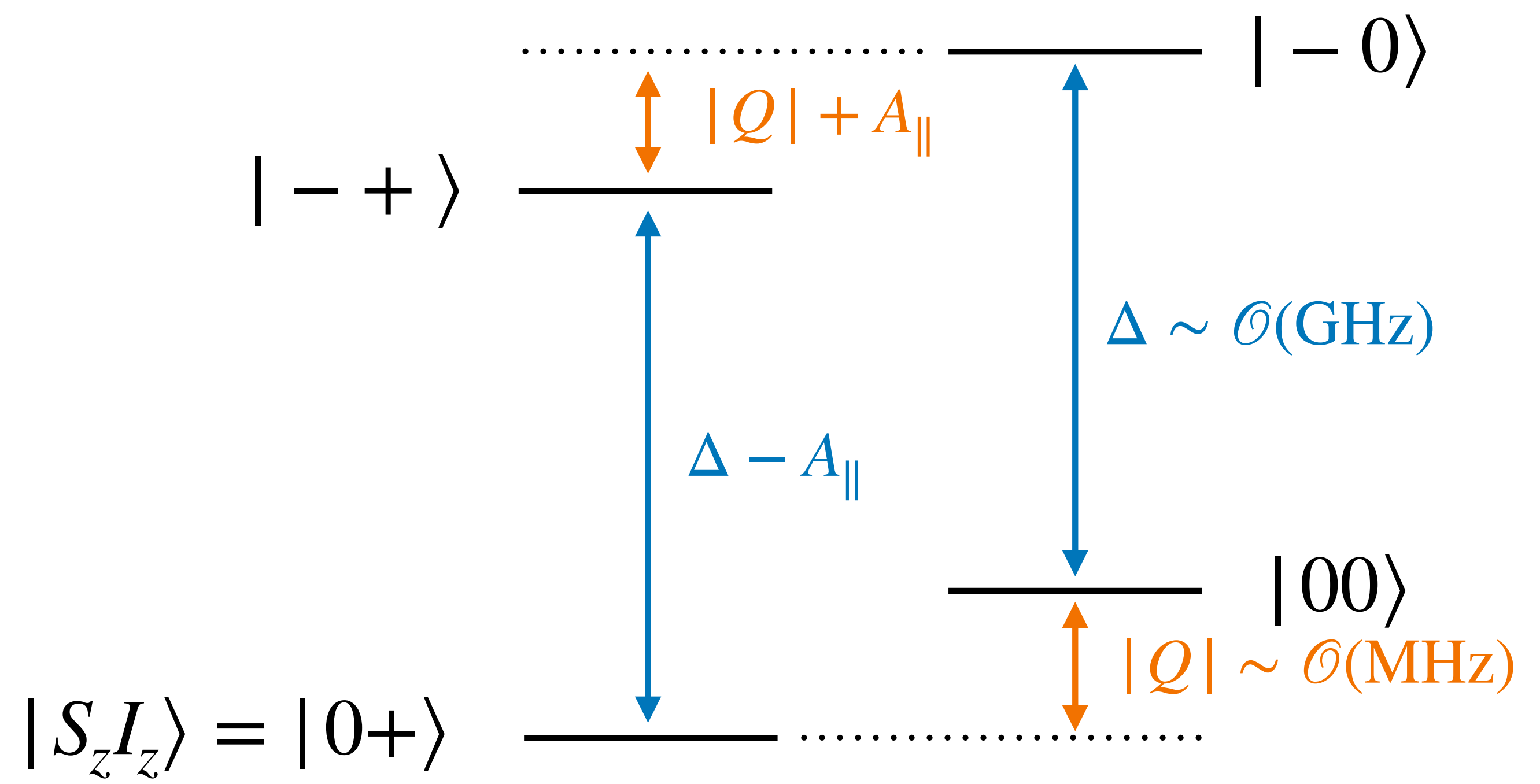
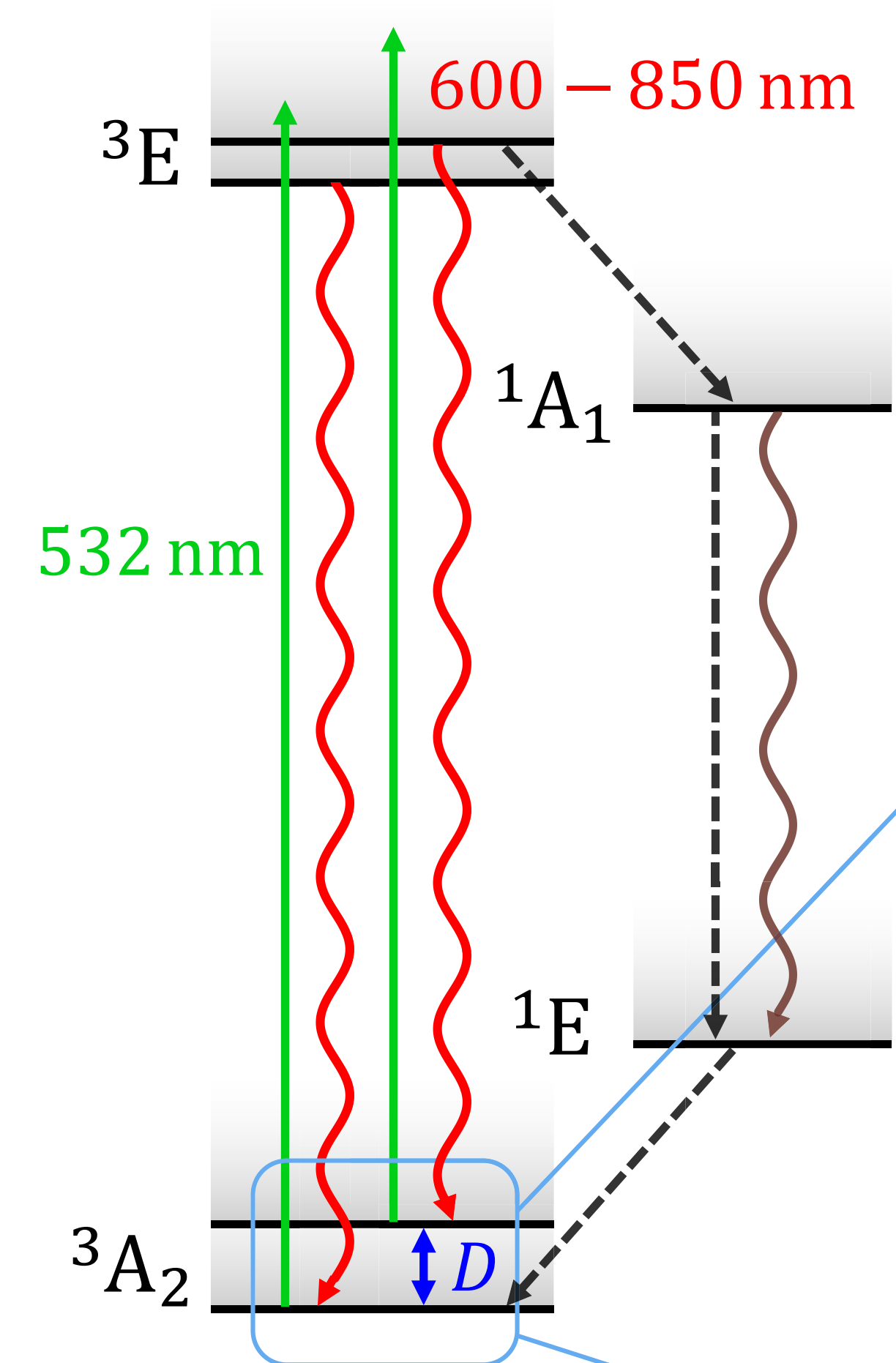
$$\begin{array}{l} e_x, e_y \quad \uparrow\uparrow \quad (2c_1 - c_2 - c_3), \\ \quad \quad \quad \downarrow\downarrow \quad (c_2 - c_3) \\ a_1 \quad \quad \uparrow\downarrow \quad (c_1 + c_2 + c_3) + \lambda n \end{array}$$

$$a'_1 \quad \quad \uparrow\downarrow \quad n - \lambda'(c_1 + c_2 + c_3)$$

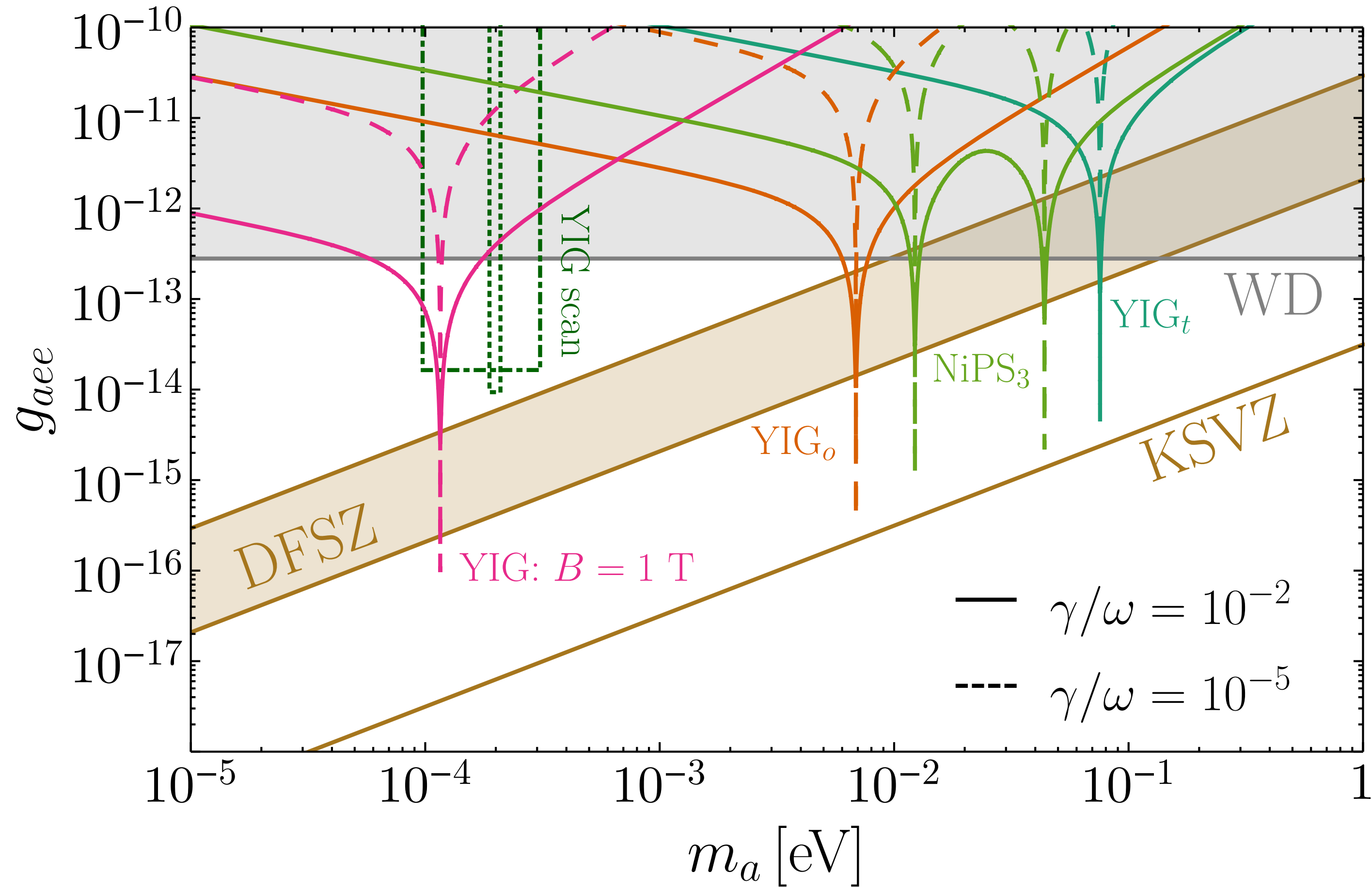
Valence Band

character table of C_{3v}

C_{3v}	E	$2C_3$	$3\sigma_v$
A_1	1	1	1
A_2	1	1	-1
E	2	-1	0

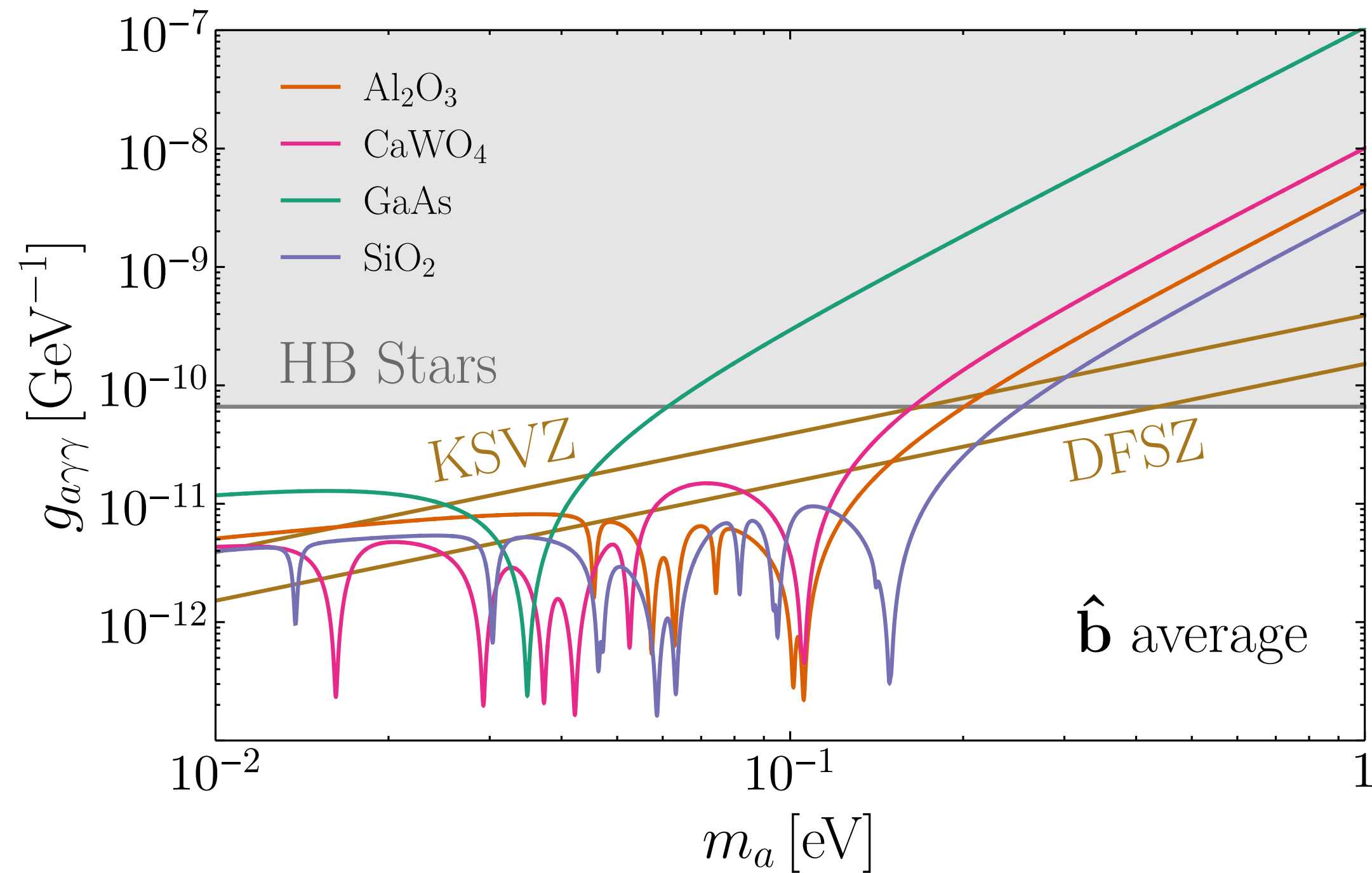


- Use of optical magnons for broadband search

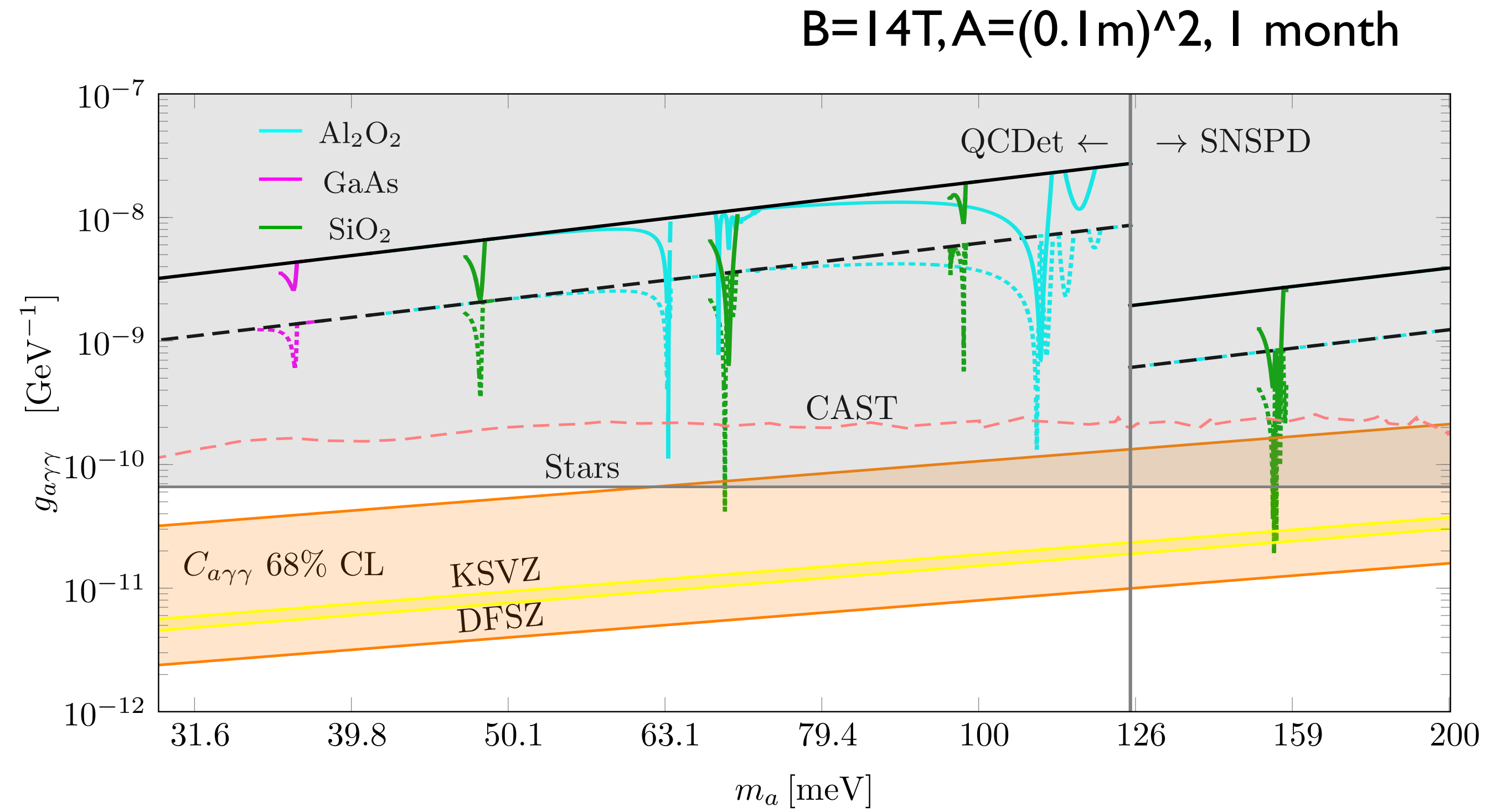


[Mitridate, Trickle, Zhang, Zurek (2020)]

● Axion conversion to phonon-polariton under magnetic field

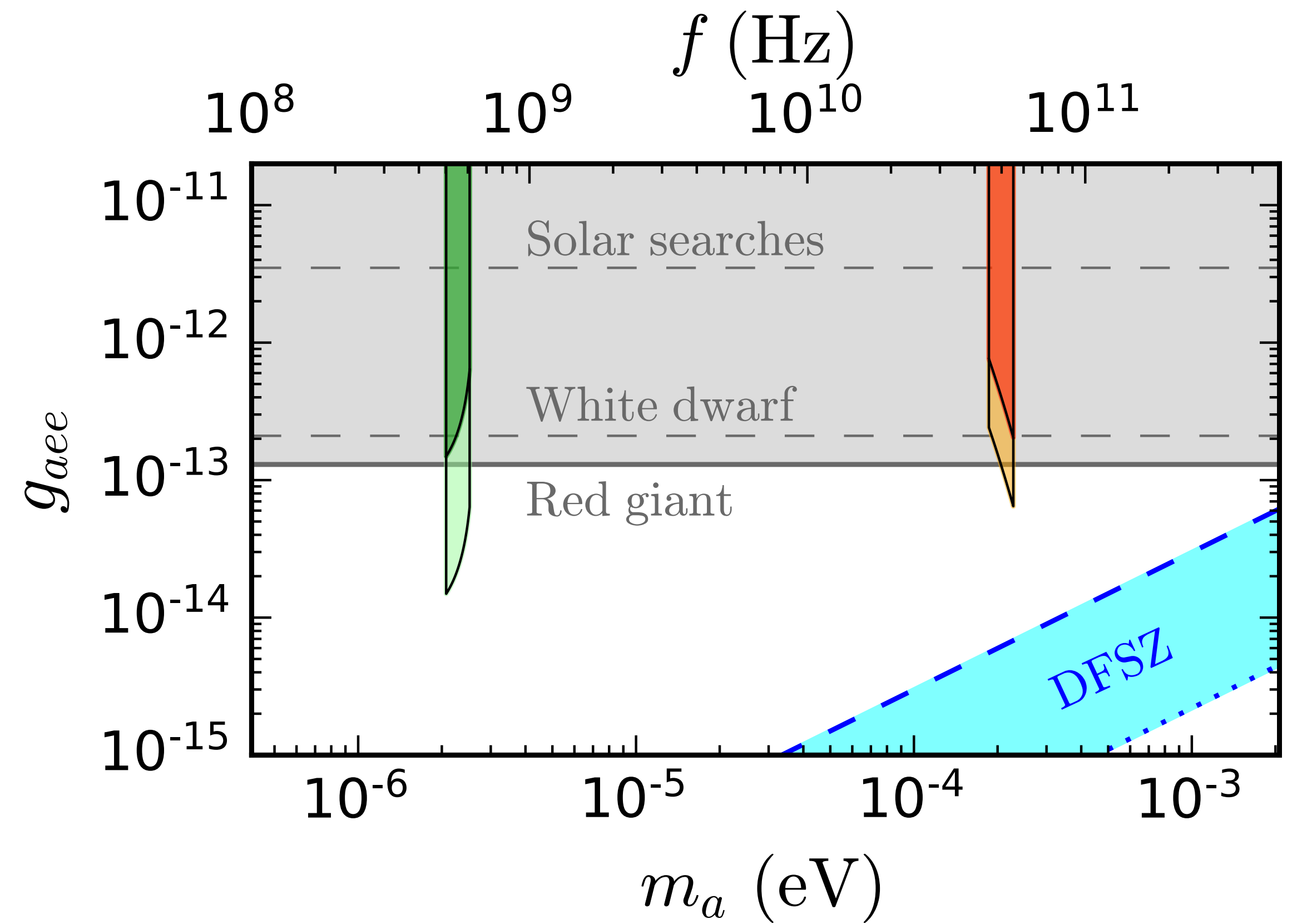
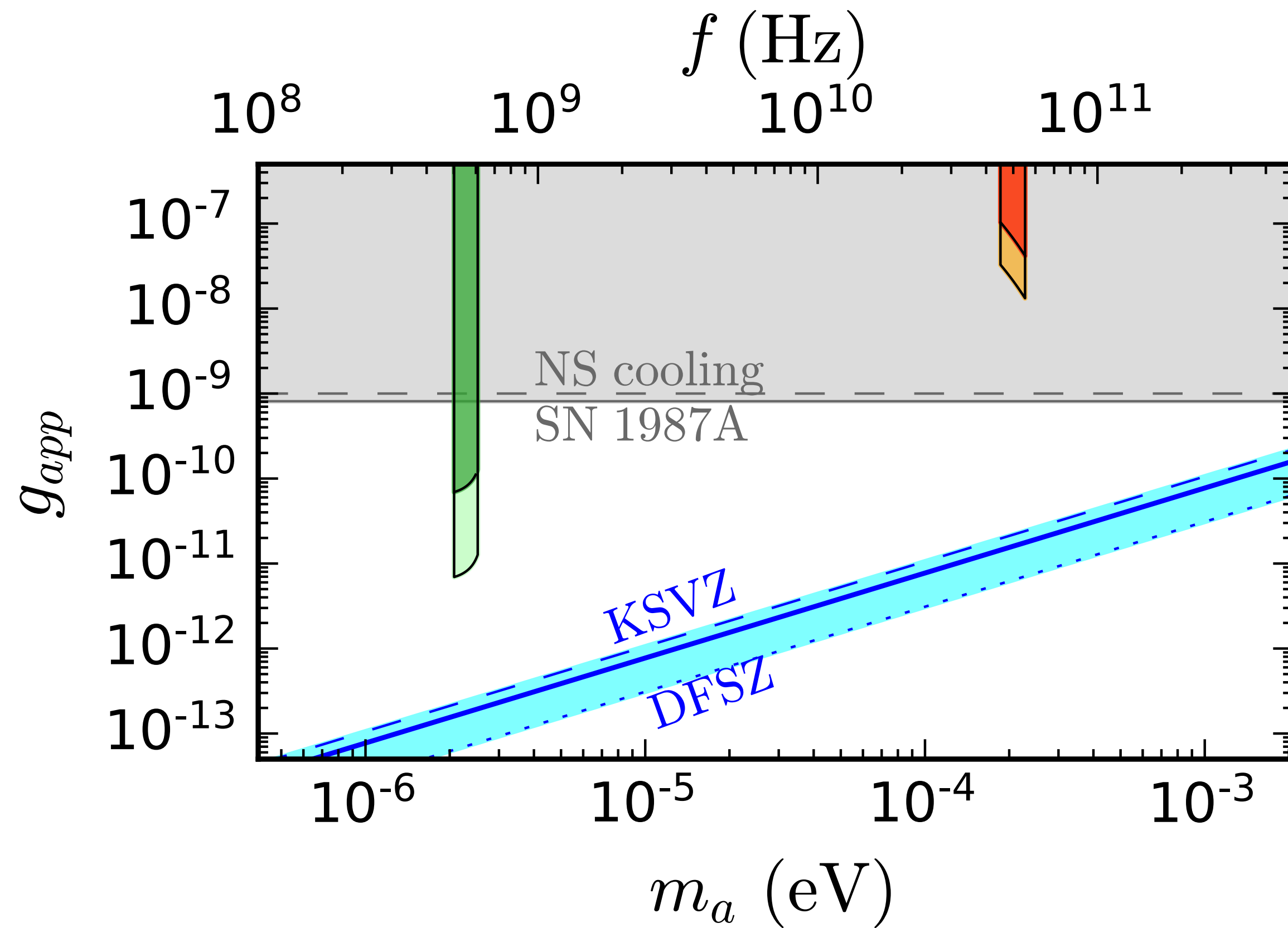


[Mitridate, Trickle, Zhang, Zurek (2020)]



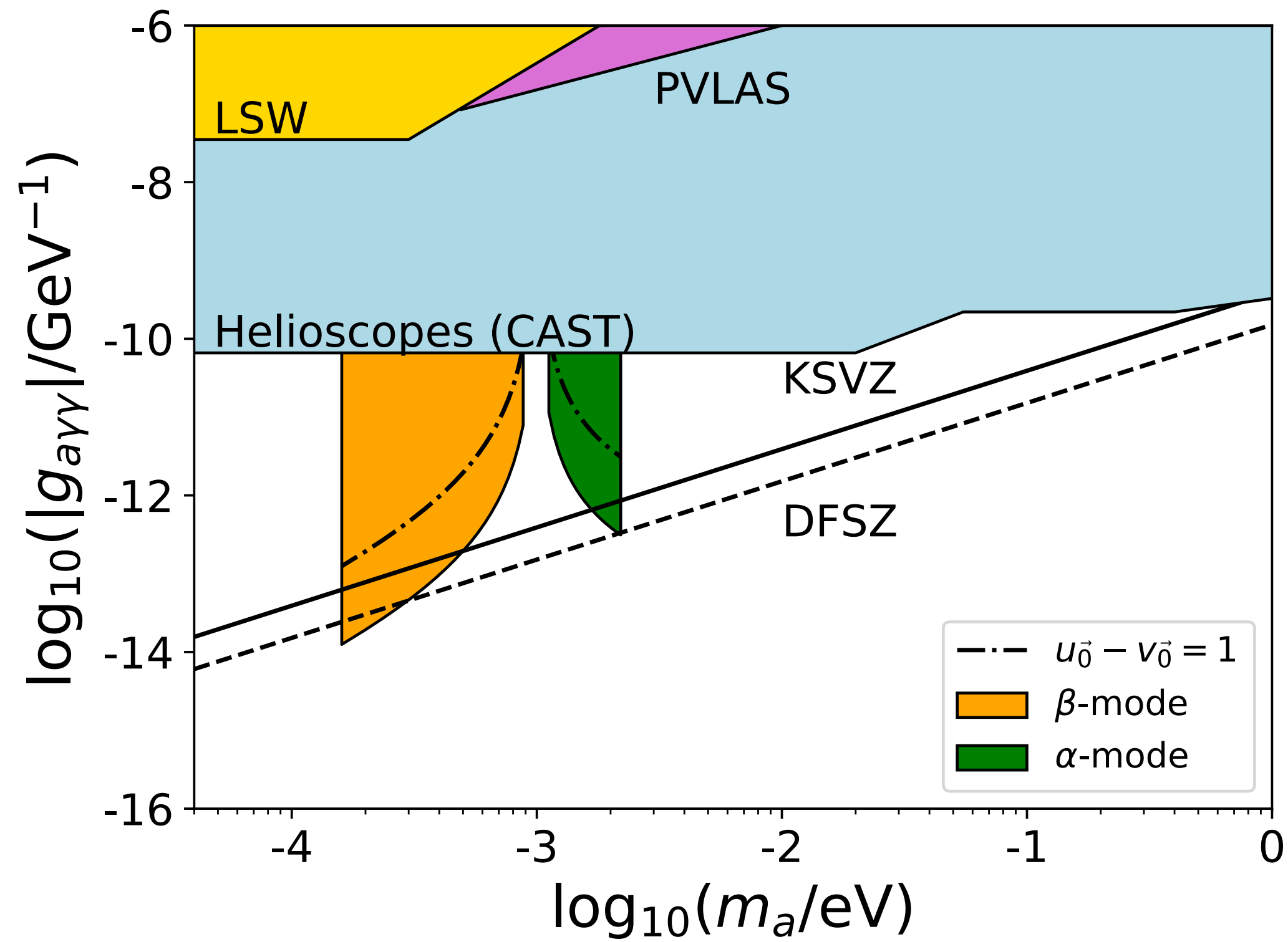
[Marsh, McDonald, Millar, Schutte-Engel (2022)]

- Use of nuclear magnons

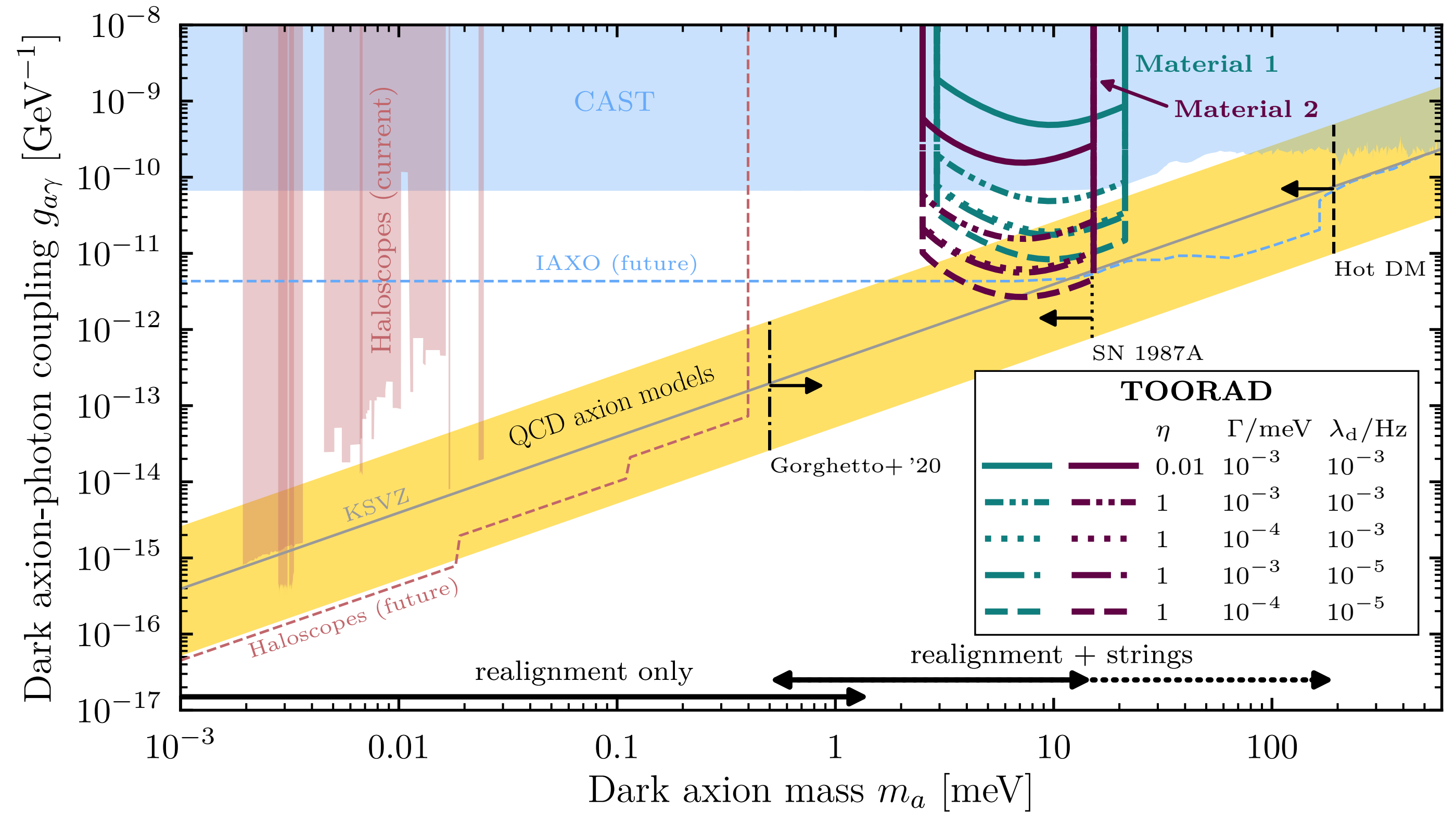


[Chigusa, Moroi, KN, Sichanugrist (2023)]

● Topological ferromagnet



[Chigusa, Moroi, KN (2021)]



[Schutte-Engel et al. (2021)]