Detecting axion/dark-photon dark matter with magnon

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Today's topics:

➡ Basics of axion/dark-photon

Axion/dark photon search

With magnon [Chigusa, Moroi, KN (2020)]

With condensed-matter axion

[Chigusa, Moroi, KN (2021)]

QCD axion

- Strong CP problem in QCD

$$\mathcal{L} = \theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu a} \qquad \theta \lesssim 10^{-10}$$ from neutron EDM

- Axion with coupling to QCD

$$\mathcal{L} = \frac{g_s^2}{32\pi^2} \frac{a}{F_a} G^a_{\mu\nu} \tilde{G}^{\mu\nu a} \longrightarrow \theta + \frac{a}{F_a} = 0$$ dynamically

Peccei, Quinn (1977)

- Axion is Goldstone boson with spontaneous U(1) breaking (PQ symmetry)

KSVZ model: $\mathcal{L} = |\partial\phi|^2 + (\lambda\phi Q\bar{Q} + \mathrm{h.c.}) - V(|\phi|)$ [Kim (1979), Shifman, Vainstein, Zakharov (1980)]

DFSZ model: $\mathcal{L} = |\partial\phi|^2 + (\mu\phi H_u H_d + \mathrm{h.c.}) - V(|\phi|, |H|)$ [Dine, Fischler, Srednicki (1981), Zhitnitsky (1980)]

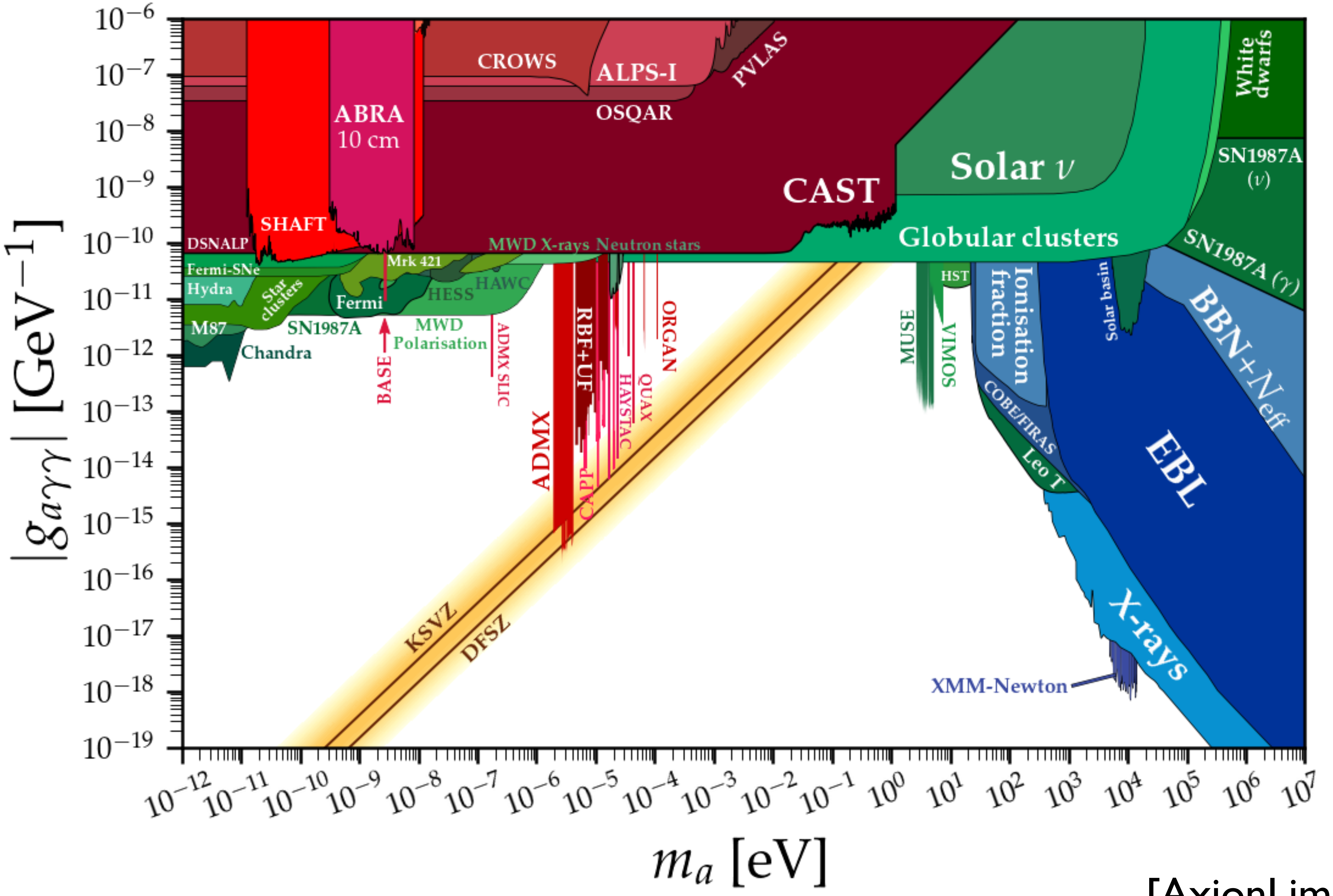
Flaxion/axiflavon [Ema, Hamaguchi, Moroi, KN (2016), Calibbi, Goertz, Redigolo, Ziegler, Zupan (2016)]

QCD axion & axion-like particle (ALP)

- ***QCD axion***
  - motivated by strong CP problem & dark matter
  - mass & coupling are related: $m_a \simeq 6\,\mu\mathrm{eV}\left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)$
  - coupling to quark/gluon: $\mathcal{L} = \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G^a_{\mu\nu}\widetilde{G}^{\mu\nu a}$ $\quad \mathcal{L} = \frac{\partial_\mu a}{f_a}\bar{q}\gamma^\mu\gamma_5 q$
- ***Axion-like particle (ALP)***
  - motivated by string theory (axiverse) & dark matter [Arvanitaki et al., (2009)]
  - mass & coupling are arbitrary
  - coupling to photon: $\mathcal{L} = -\frac{g_{a\gamma}}{4}aF_{\mu\nu}\widetilde{F}^{\mu\nu}$ $\longrightarrow$ rich phenomenology

Constraints on axion-photon coupling

$$\mathcal{L} = -\frac{g_{a\gamma}}{4} a F_{\mu\nu} \widetilde{F}^{\mu\nu}$$



[AxionLimits, C.O'Hare]

Axion dark matter (I)

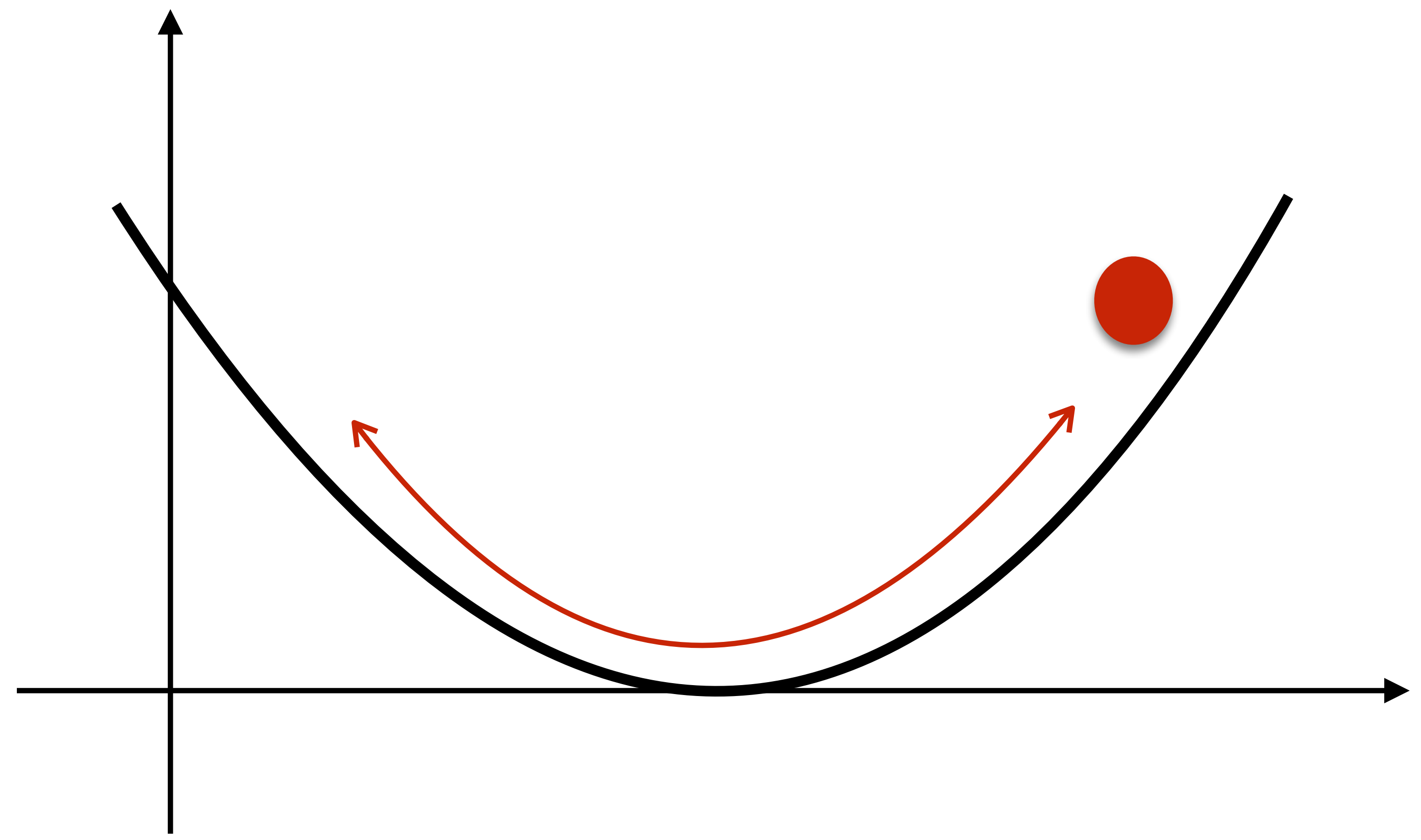
- ***Coherent oscillation***

[Preskill, Wise, Wilczek (1983), Abbott, Sikivie (1983), Dine Fischler (1983)]

- Equation of motion of axion

$$\ddot{a} + 3H\dot{a} + \frac{\partial V}{\partial a} = 0$$

$$V(a) = m_a^2(T) f_a^2 \left(1 - \cos\frac{a}{f_a}\right)$$



- For QCD axion:

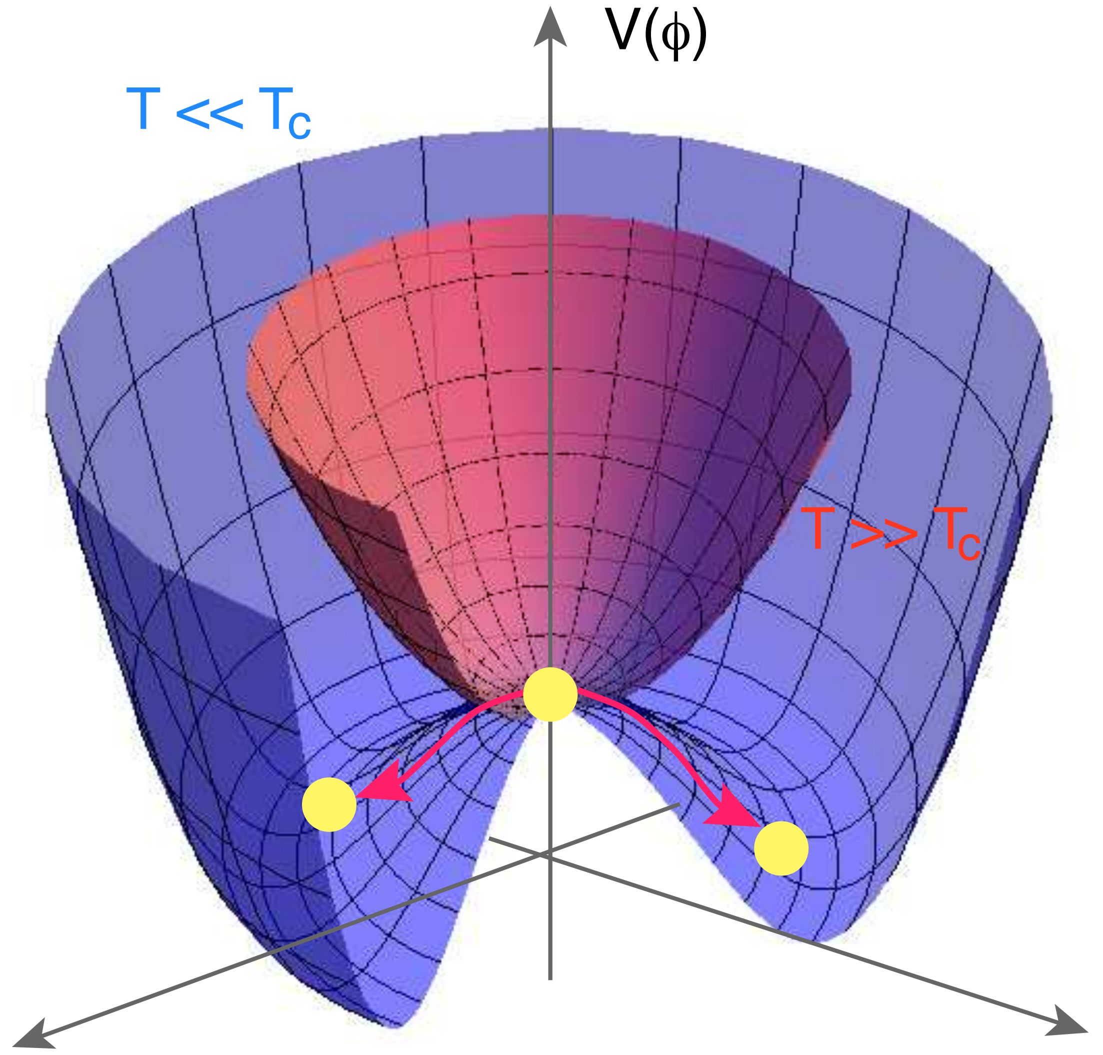
$$\Omega_a h^2 = 0.18\ \theta_1^2 \left(\frac{F_a}{10^{12}\mathrm{GeV}}\right)^{1.19} \left(\frac{\Lambda}{400\mathrm{MeV}}\right)$$

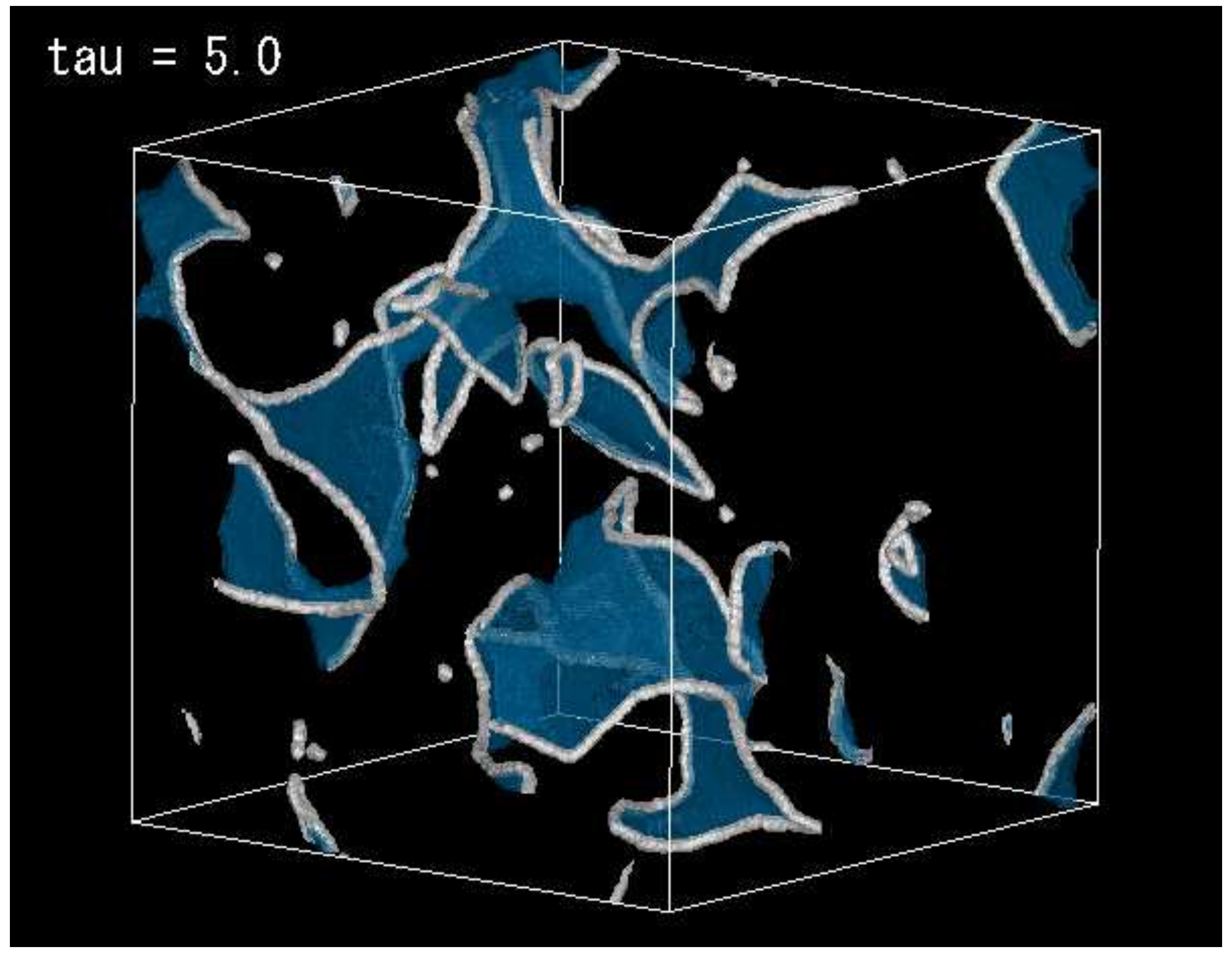
Axion dark matter (2)

- ***Topological defects***
  - PQ symmetry breaking after inflation

    $\longrightarrow$ string-wall network decay at QCD

    $\longrightarrow$ axion emission





[Hiramatsu et al., (2010)]

$$\Omega_{a,\mathrm{tot}} h^2 = (8.4 \pm 3.0) \left(\frac{F_a}{10^{12}\mathrm{GeV}}\right)^{1.19} \left(\frac{\Lambda}{400\mathrm{MeV}}\right)$$

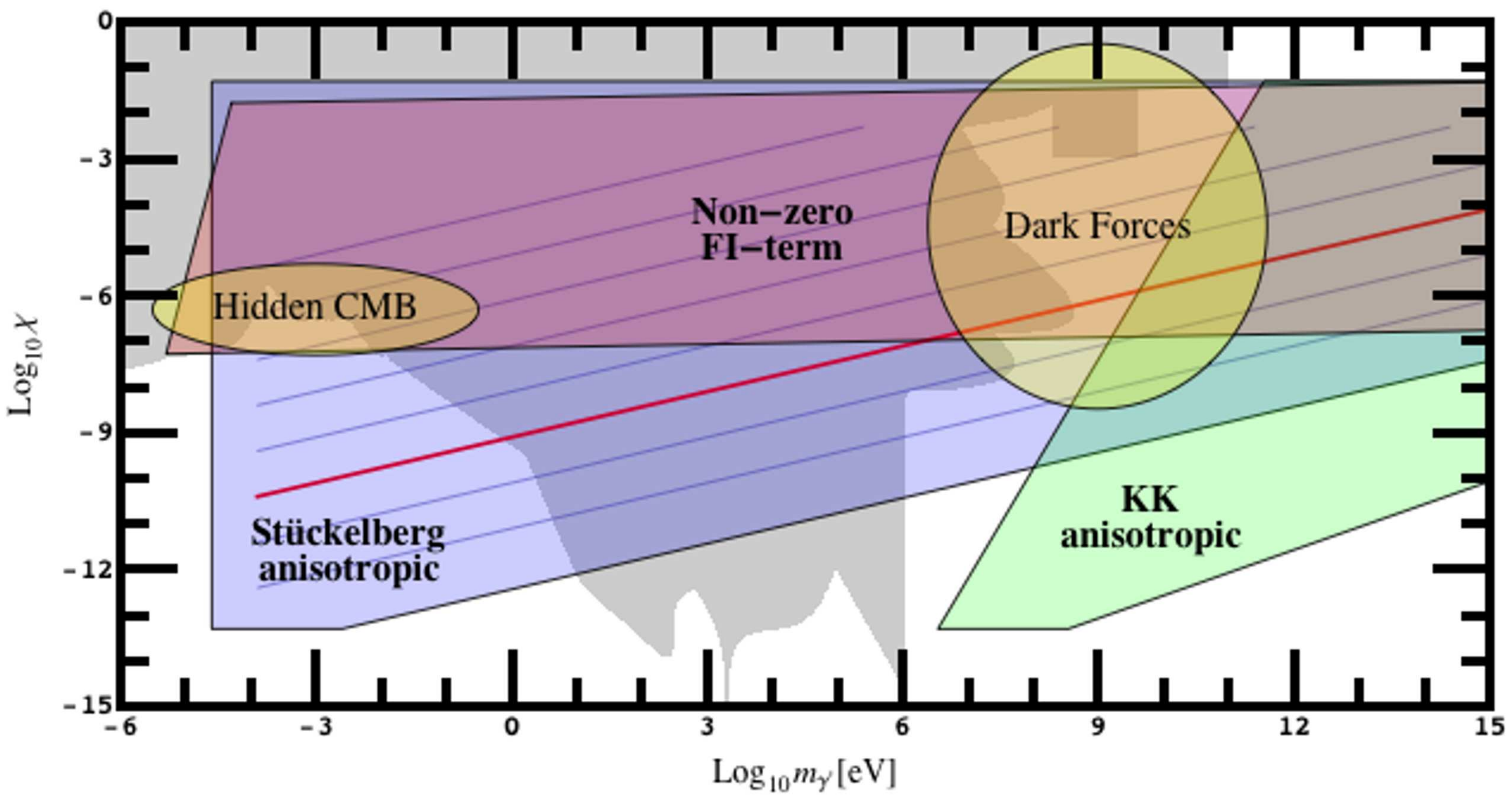
- Recent discussions on scaling law of global string: [Gorghetto et al. (2018), Kawasaki et al (2018), Klaer, Moore (2019), Hindmarsh et al. (2019), Buschmann et al. (2021)]

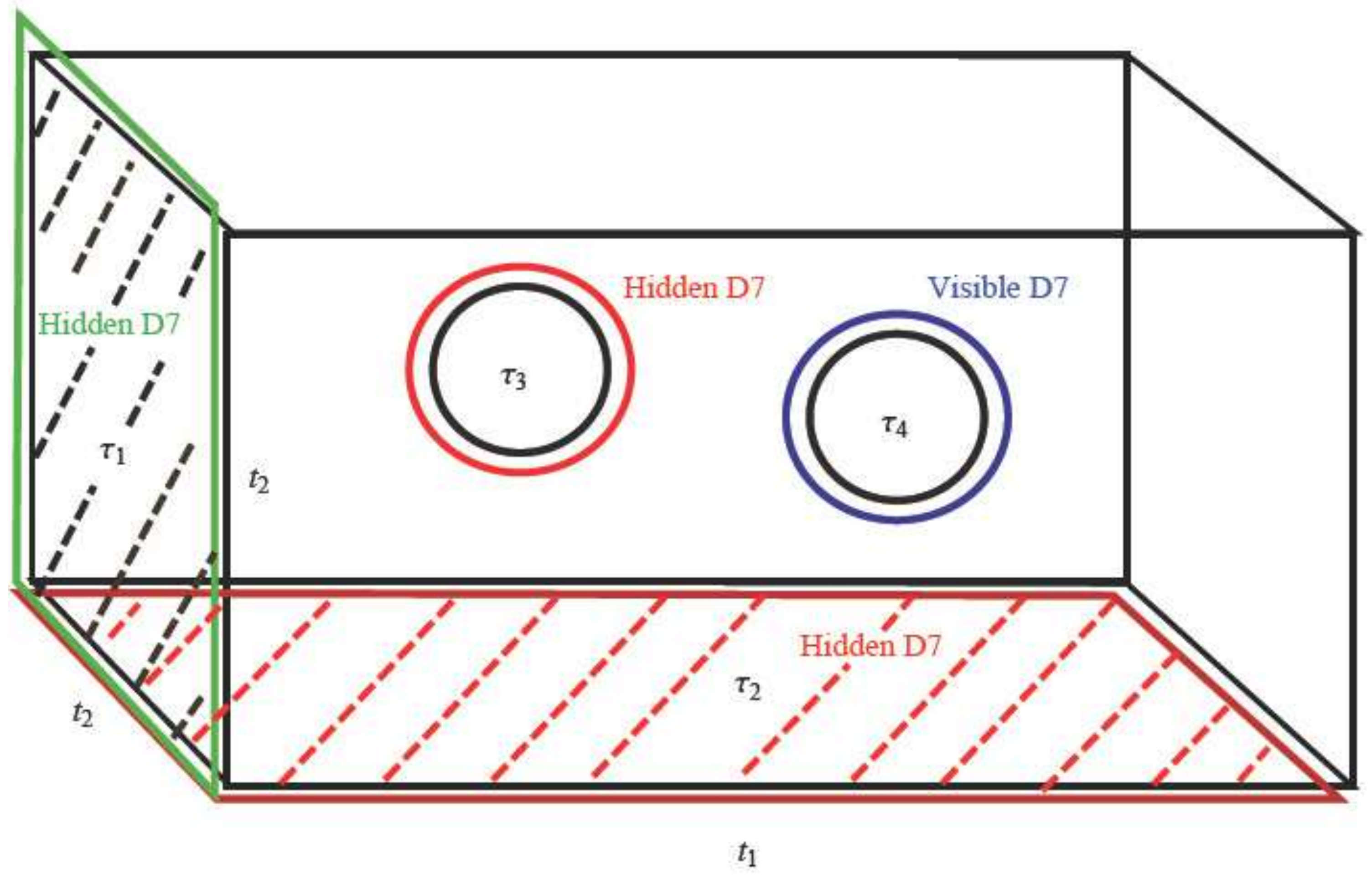
Dark photon

- Parametrized by mass & kinetic mixing

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}H_{\mu\nu}H^{\mu\nu} - \frac{1}{2}m_H^2 H_\mu H^\mu - \frac{\epsilon}{2}F_{\mu\nu}H^{\mu\nu}$$

- Motivated by string theory & dark matter [Goodsell, Jaeckel, Redondo, Ringwald (2009)]

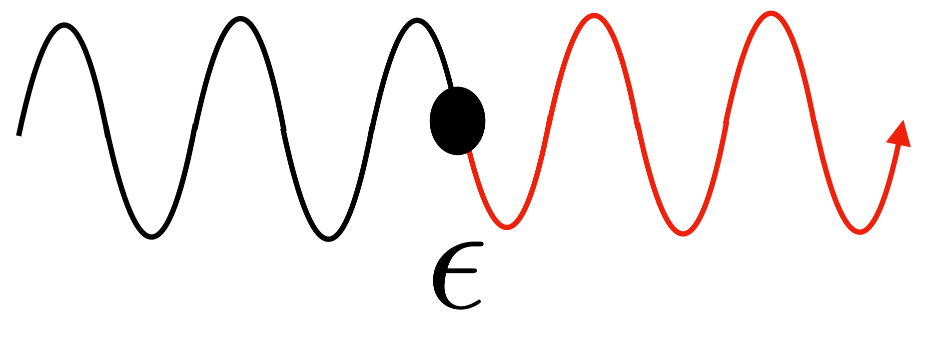


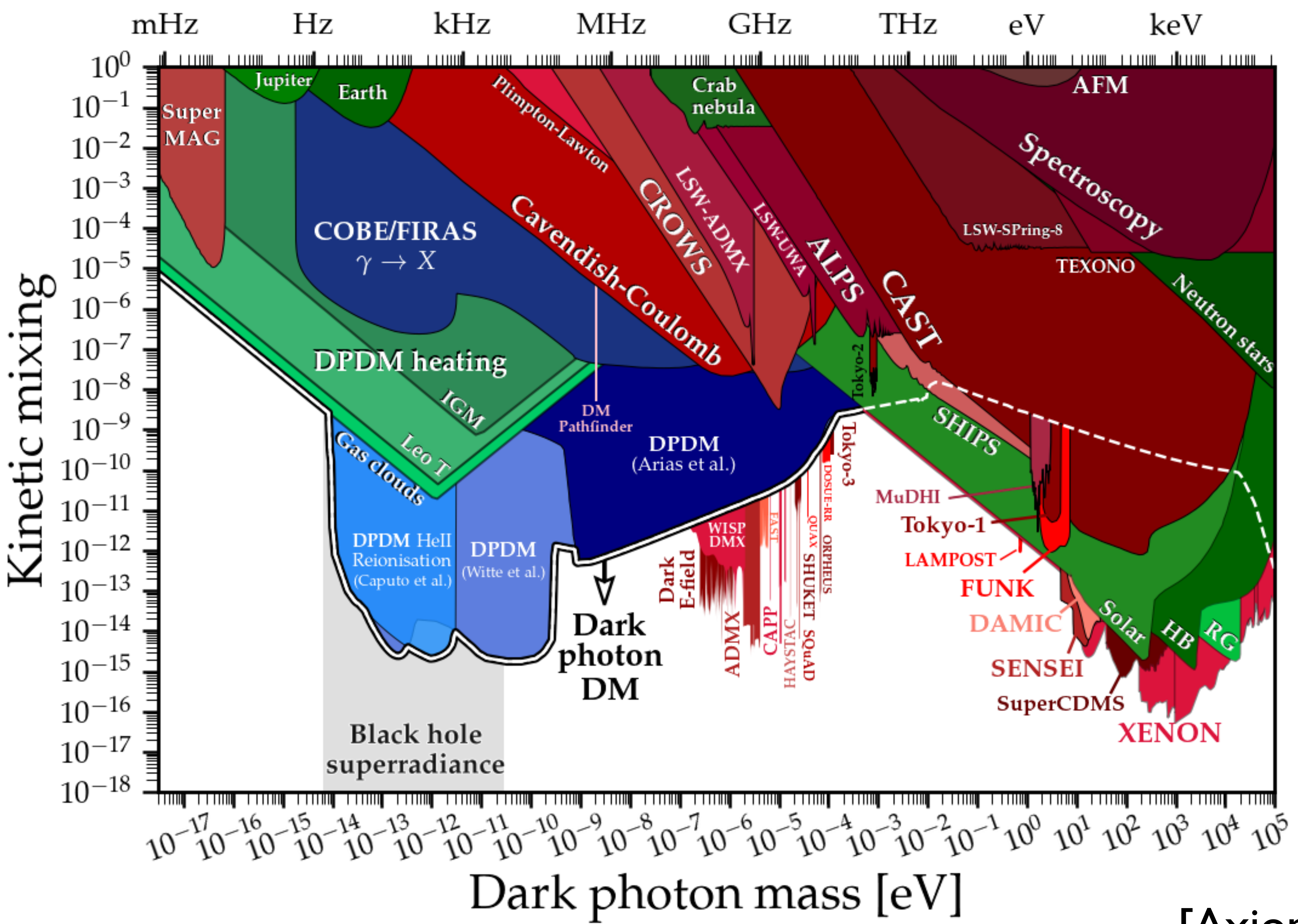


Type IIB flux compactification [Cicoli, Goodsell, Jaeckel, Ringwald (2011)]

Constraints on kinetic mixing

Through kinetic mixing, dark photon interacts with ordinary matter.





[AxionLimits, C.O'Hare]

Dark photon dark matter

- ***Coherent oscillation*** [Nelson, Scholtz (2011), Arias et al. (2012)]

  Serious theoretical/observational problems [KN (2019), KN (2020)]

- ***Gravitational production***

  Inflationary fluctuation $m_H \gtrsim 1\,\mu\text{eV}$

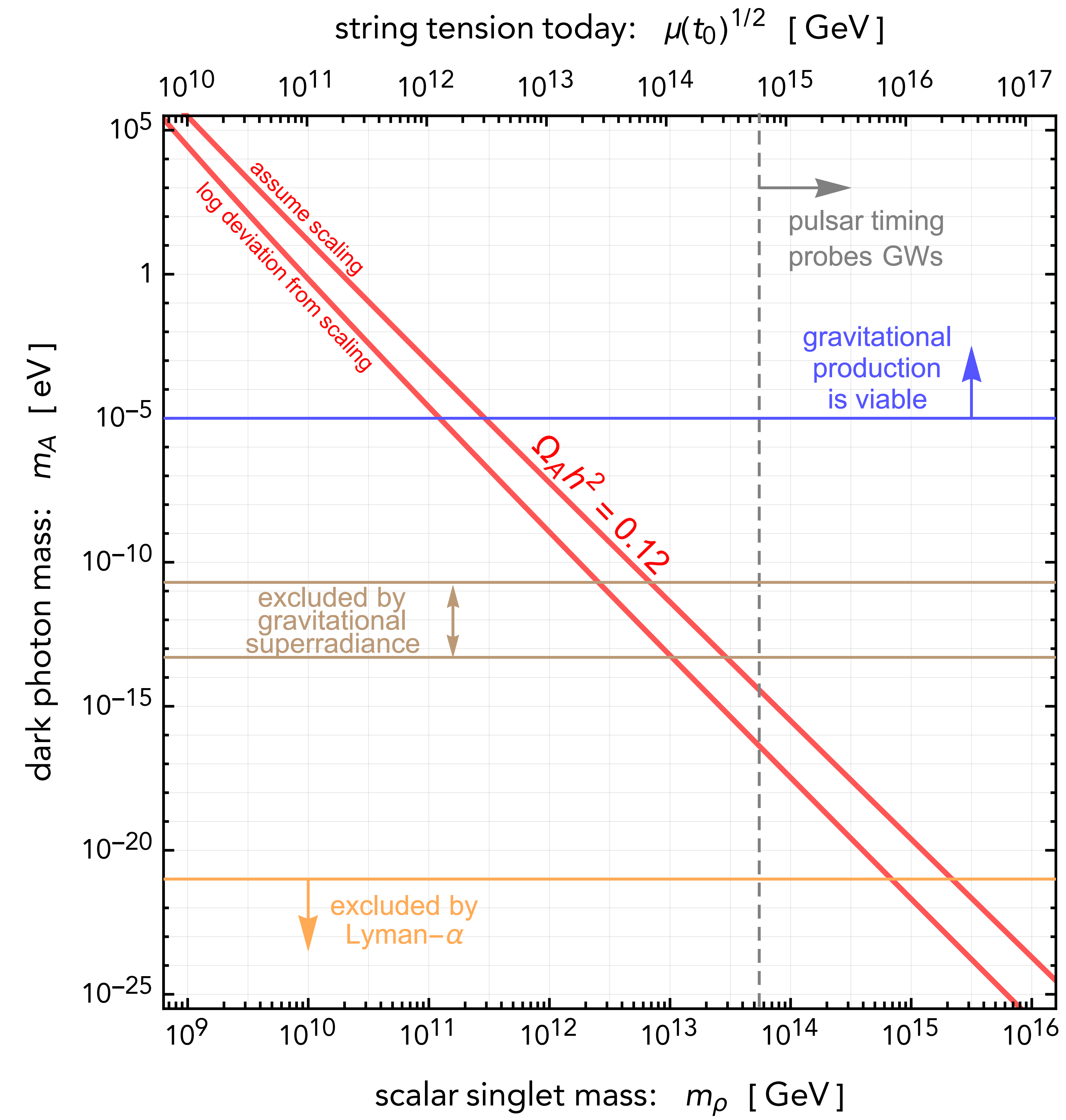
  [Graham, Mardon, Rajendran (2015)]

  Gravitational production during reheating

  [Ema, Jinno, Mukaida, KN (2015), Ema, KN, Tang (2019)]

- ***Topological defects*** [Long, Wang (2019)]

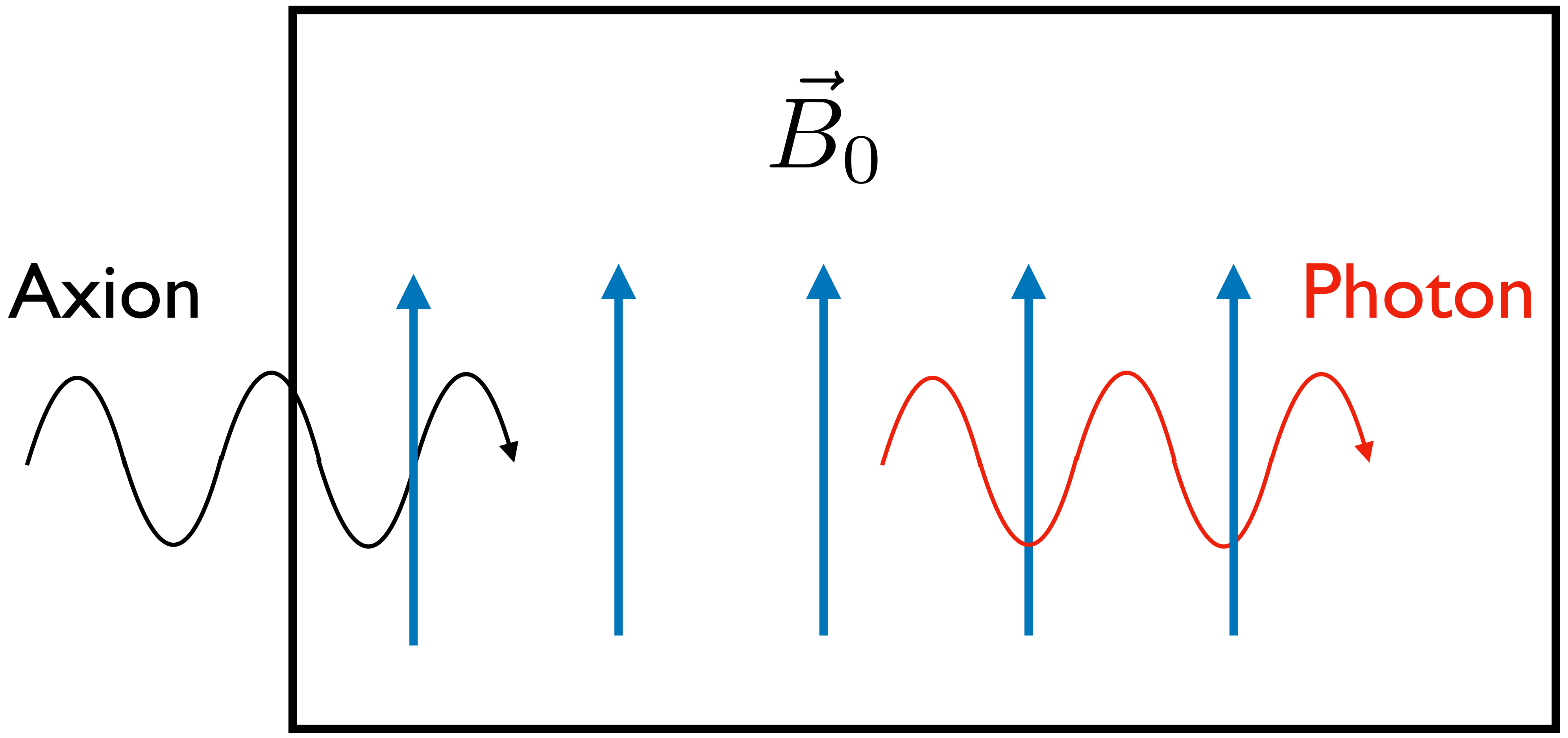
  Dark photon emission from cosmic strings.



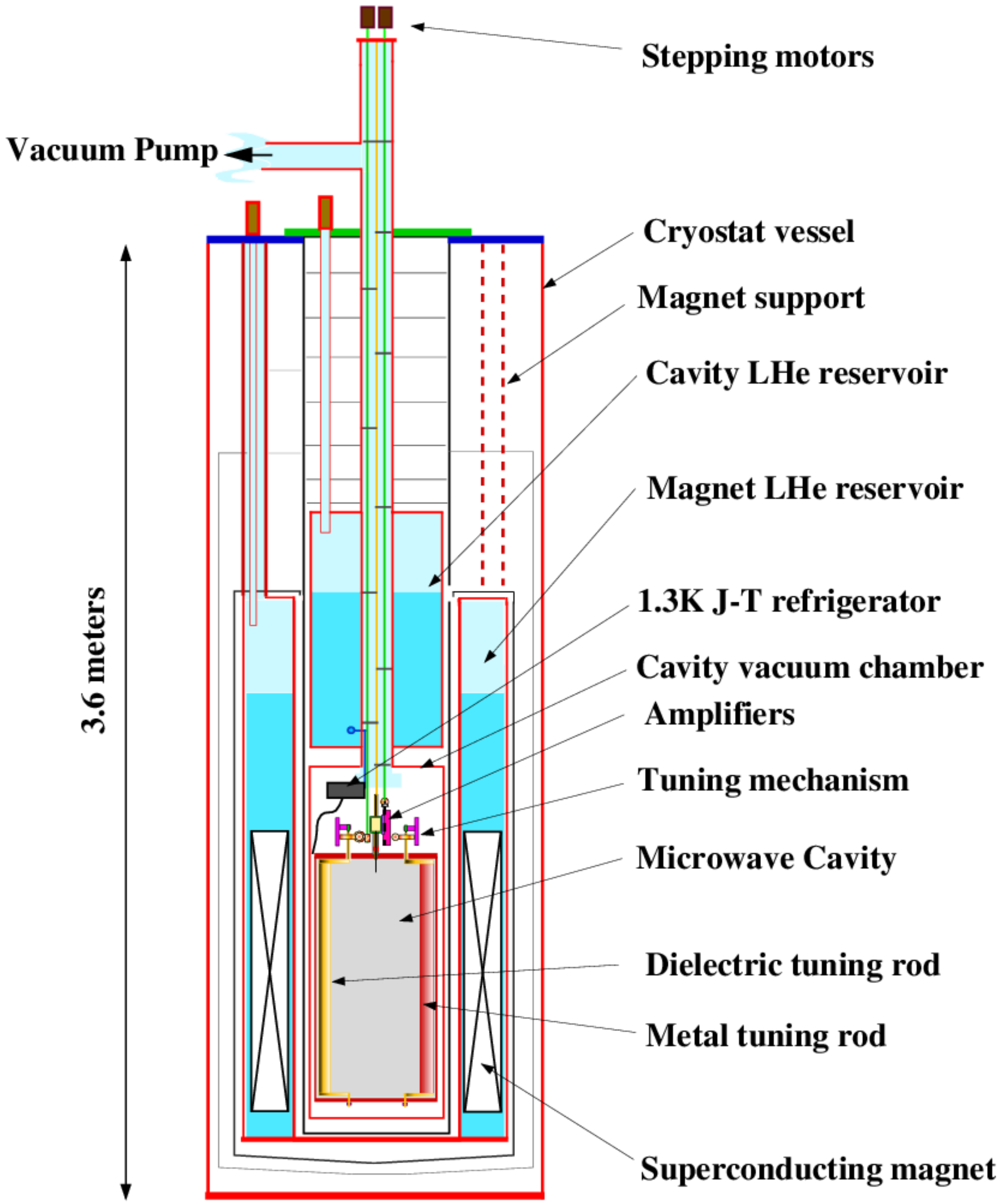
Axion DM search experiments

- Axion haloscope [Sikivie (1983)]
  - DM axion resonantly conversion into cavity photon under magnetic field

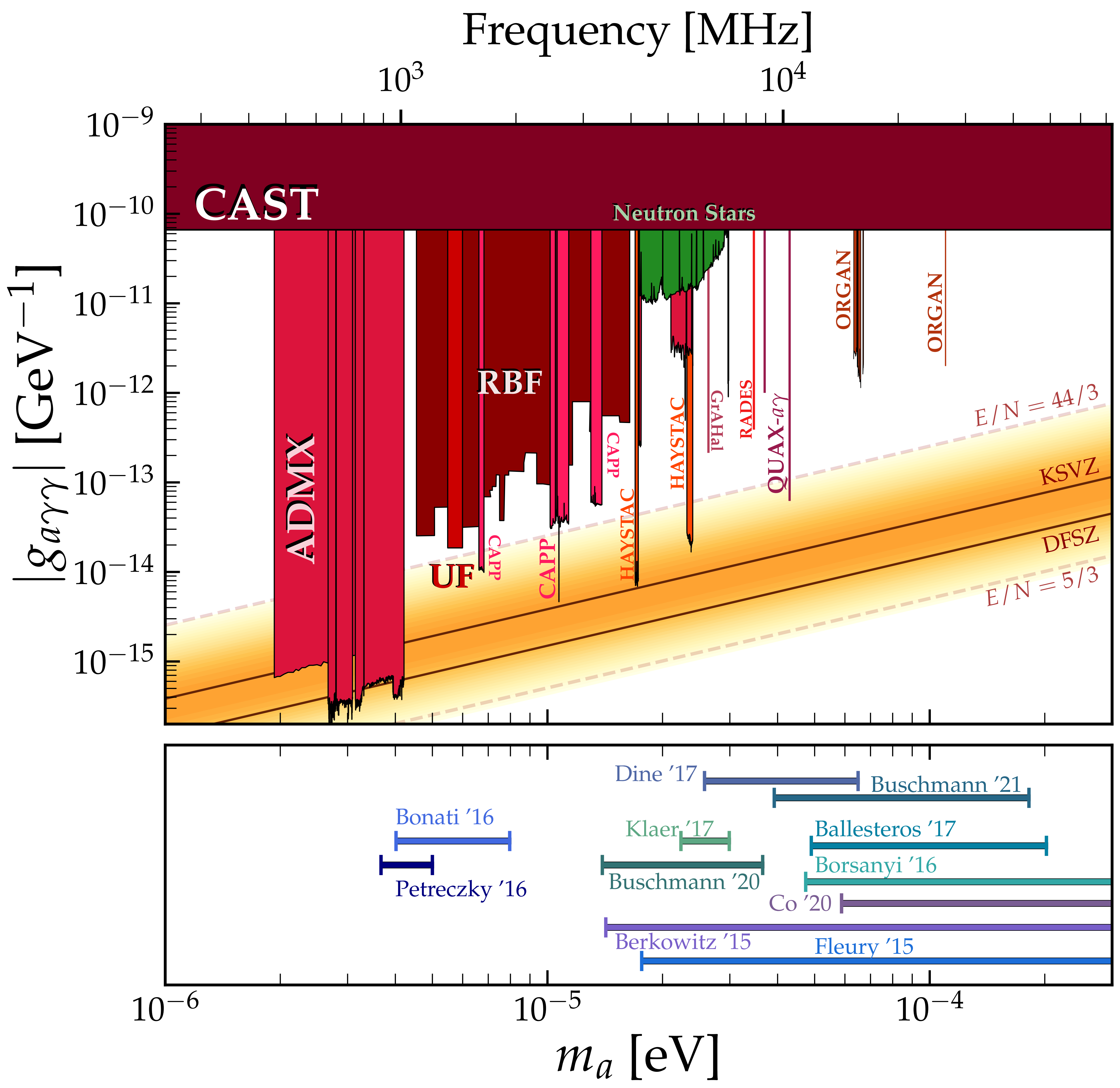
$$\mathcal{L} = -\frac{g_{a\gamma}}{4} a F_{\mu\nu} \widetilde{F}^{\mu\nu} \simeq -g_{a\gamma} a \vec{E} \cdot \vec{B}$$



[ADMX]



[Carosi, van Bibber (2008)]



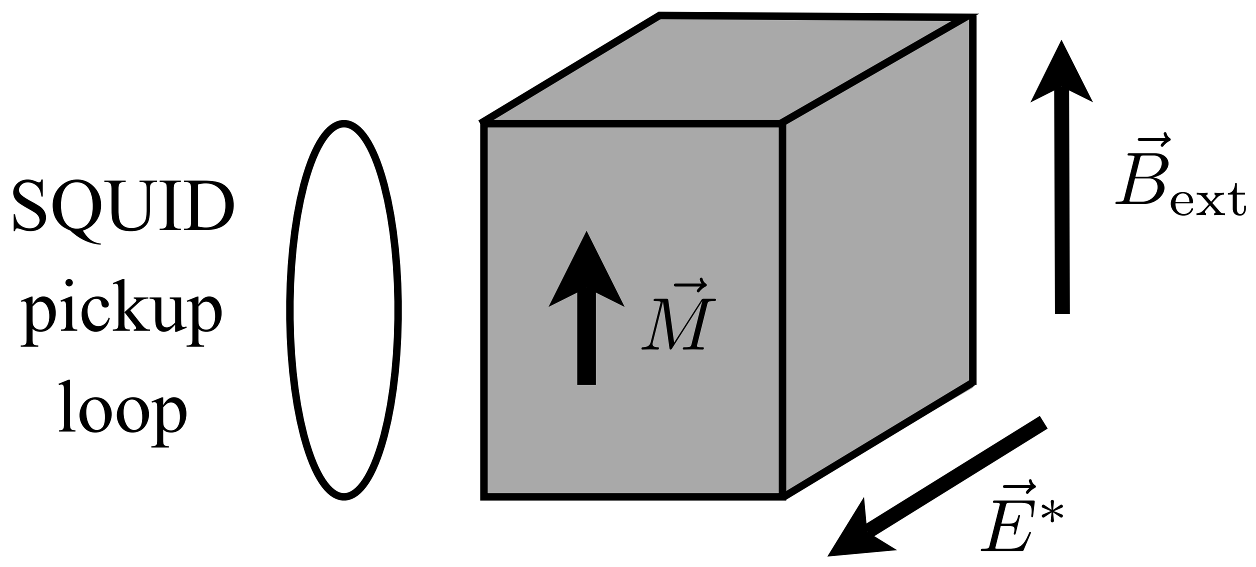
[AxionLimits, C.O'Hare]

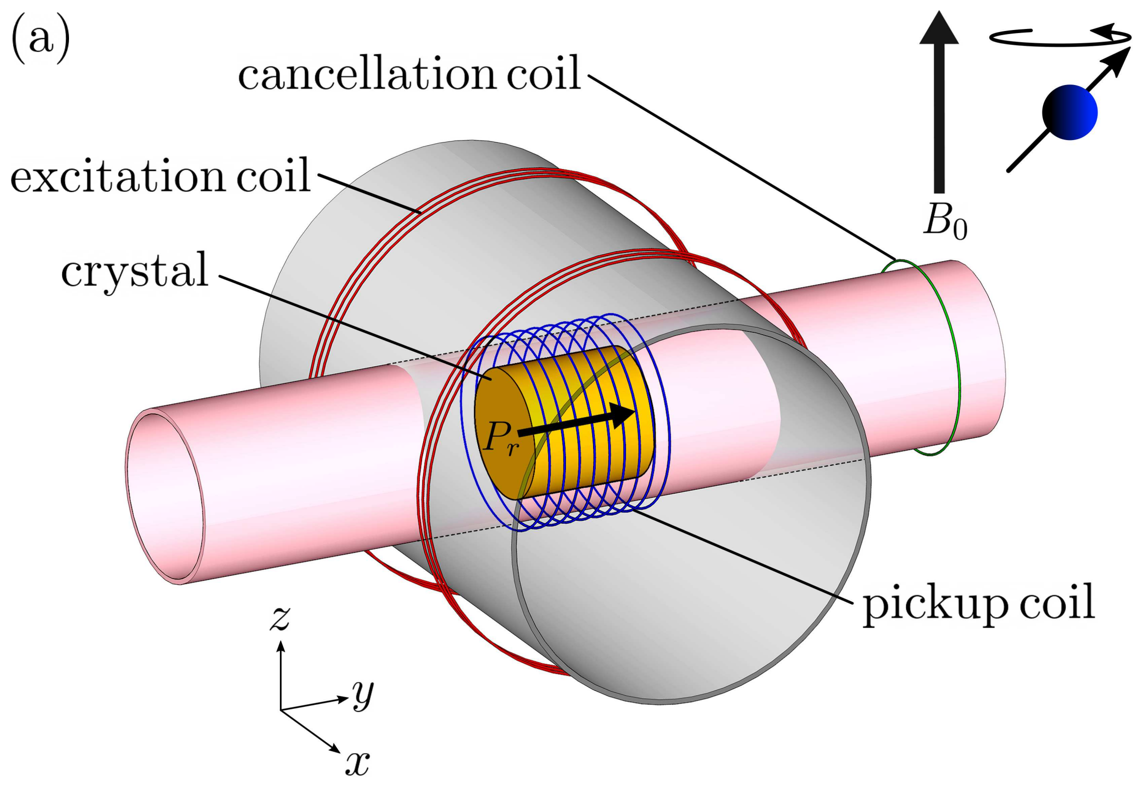
Axion DM search experiments

- CASPEr [Budker et al. (2013)]
  - DM axion ⟶ oscillating E

    ⟶ amplify nuclear spin precession

    (axion-nucleon coupling)

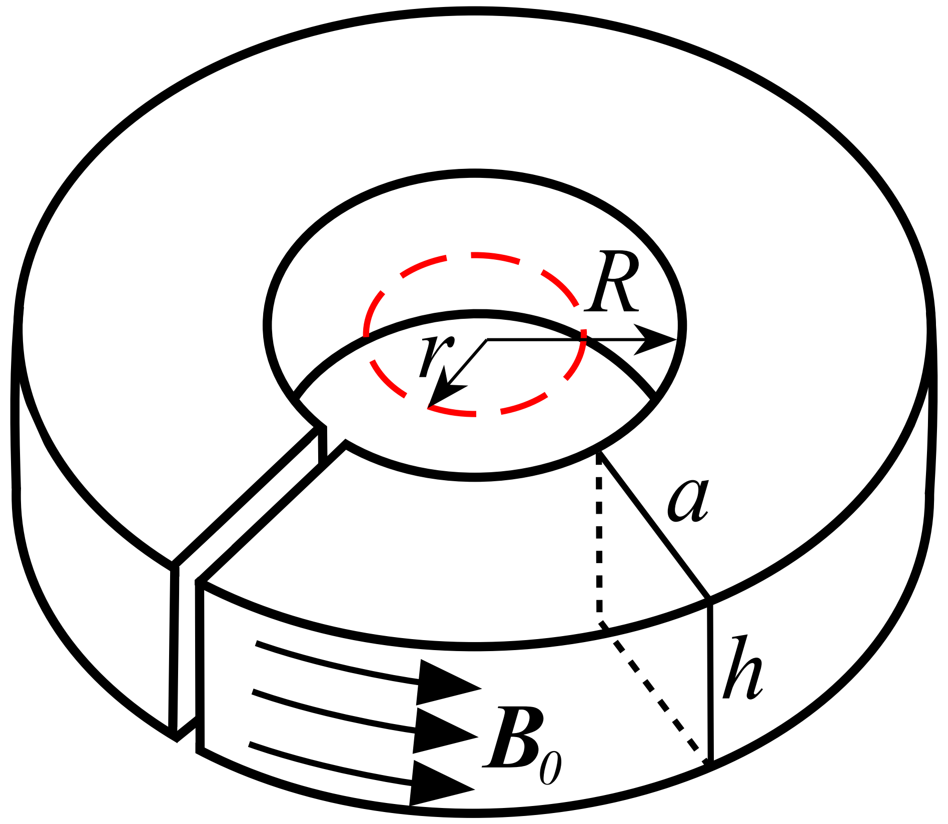


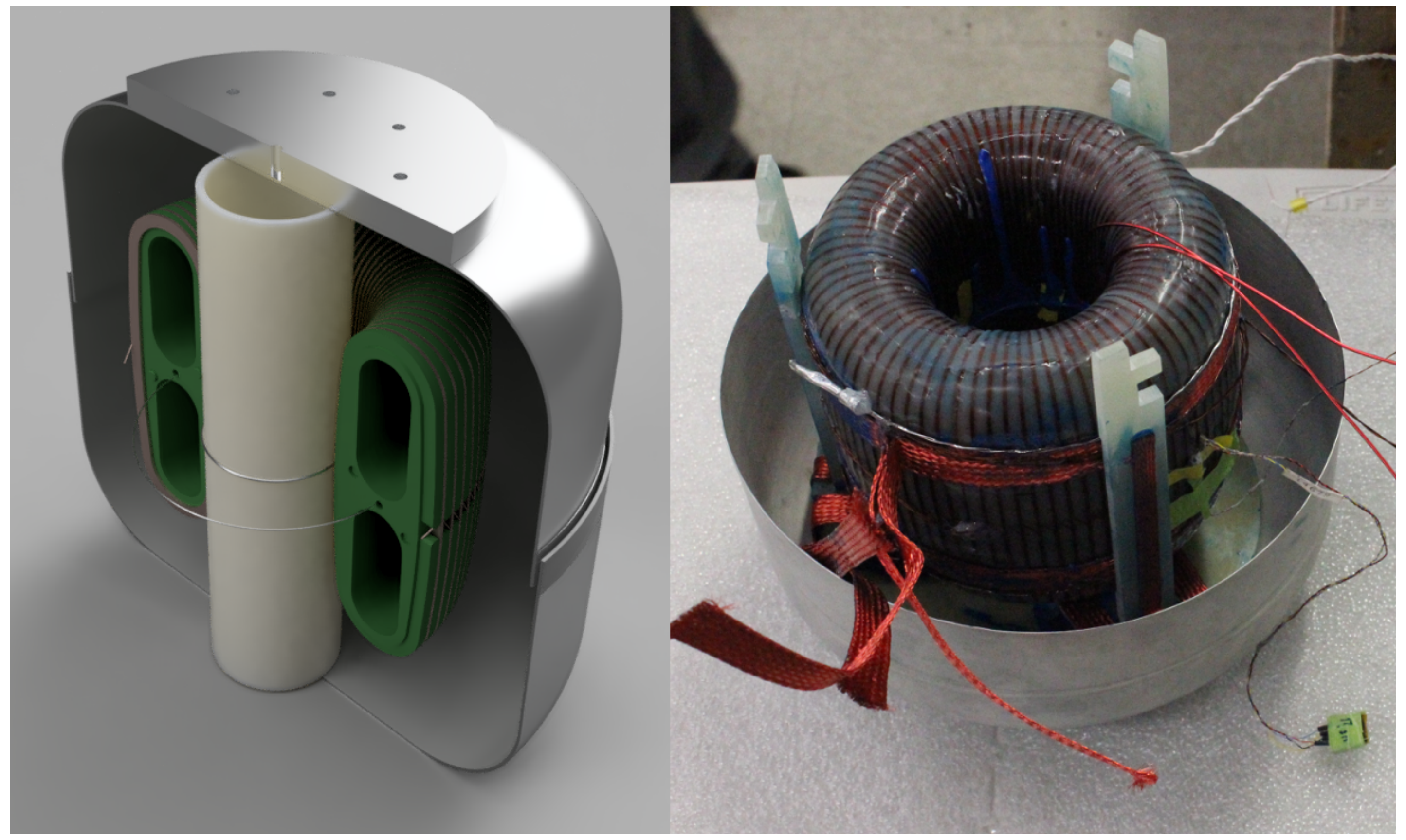


[Aybas et al. (2021)]

- ABRACADABRA [Kahn, Safdi, Thaler (2016)]
  - $\mathbf{J}_{\rm eff} = g_{a\gamma\gamma}\sqrt{2\rho_{\rm DM}}\cos(m_a t)\mathbf{B}_0.$

    ⟶ oscillating real magnetic field





[Ouellet et al. (2018)]

(Sorry, I cannot cover many ideas for axion DM detection …)

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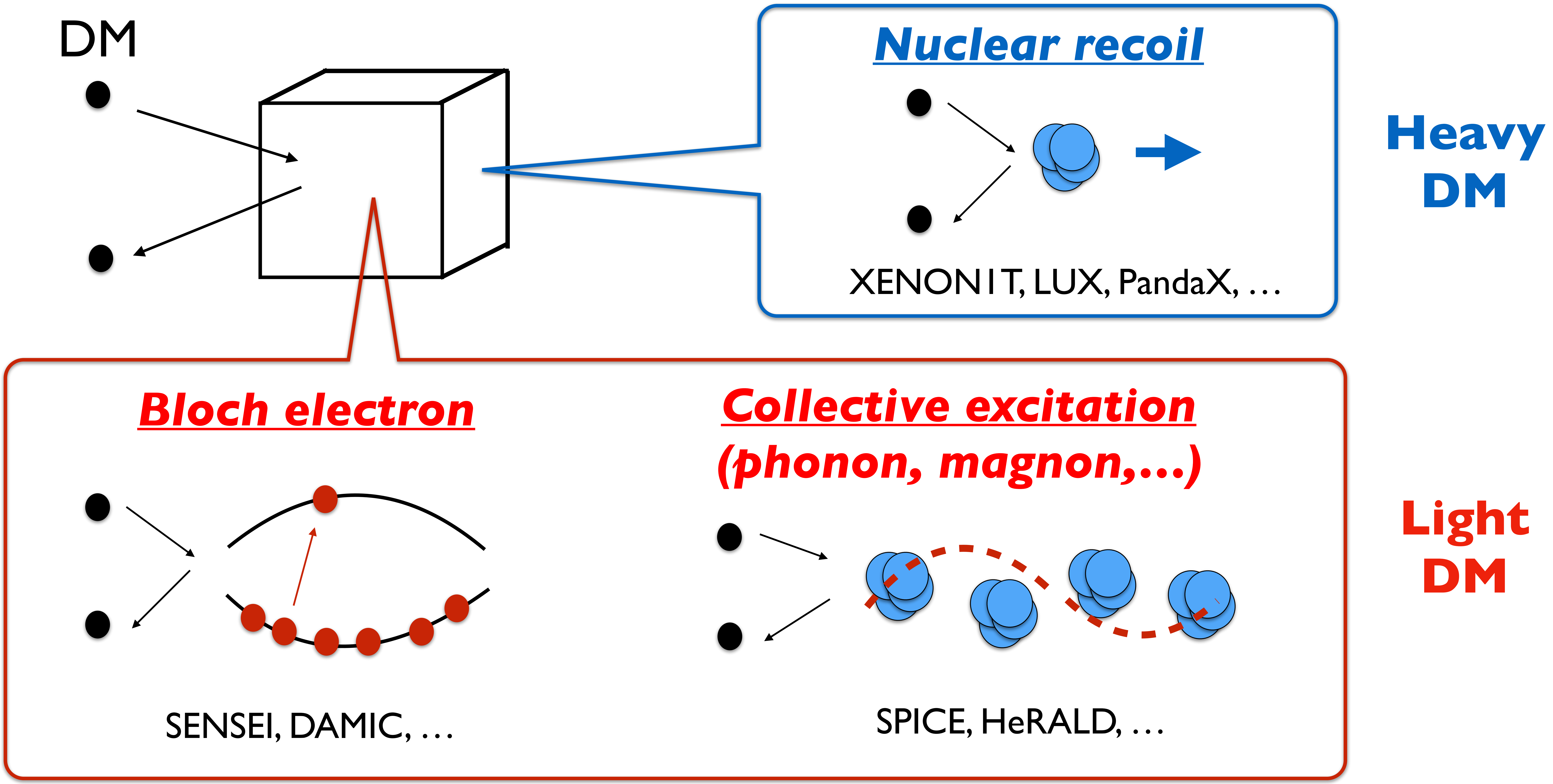
Axion/dark photon search

➡ With magnon [Chigusa, Moroi, KN (2020)]

With condensed-matter axion

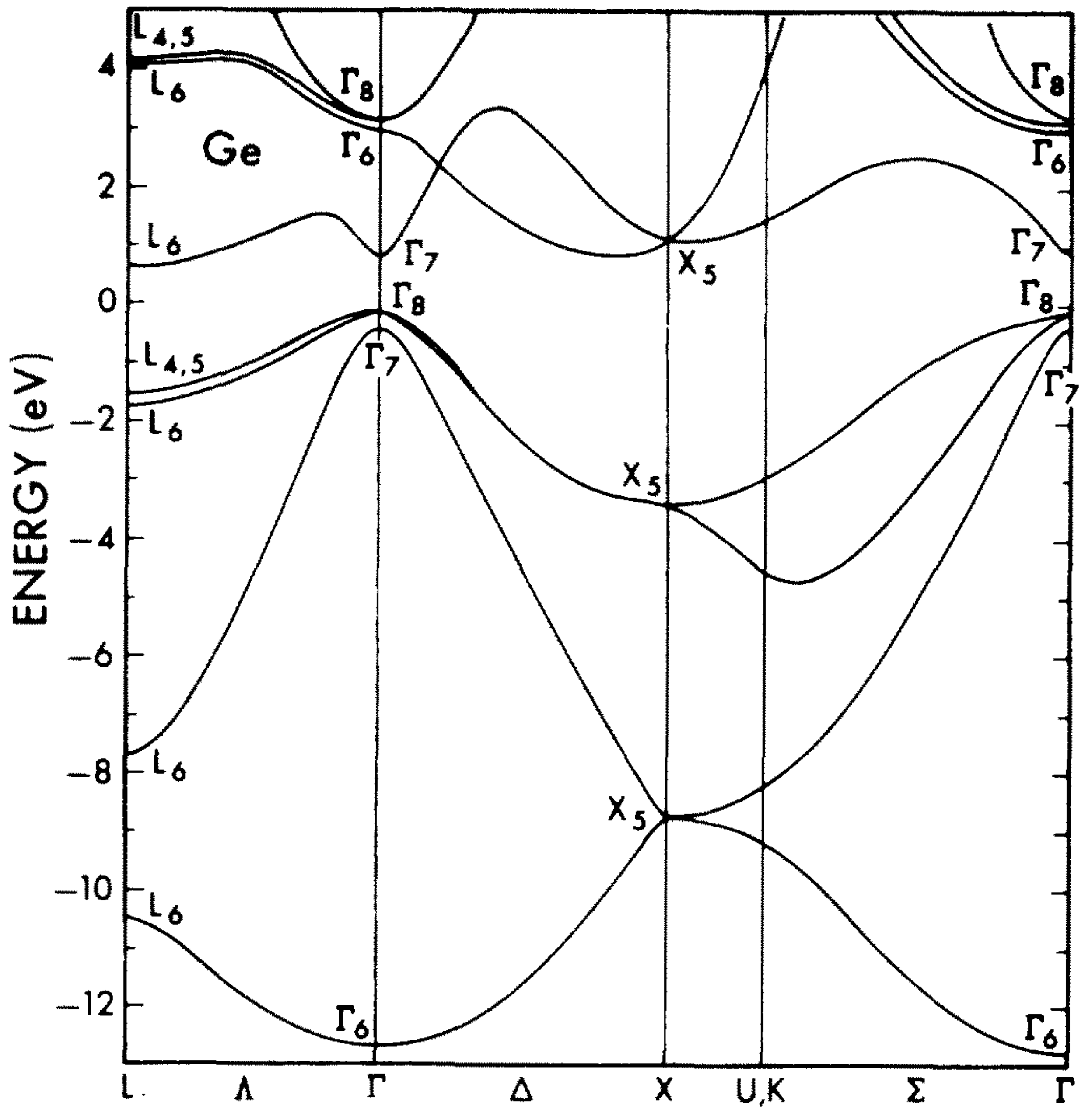
[Chigusa, Moroi, KN (2021)]

New ideas for dark matter direct detection

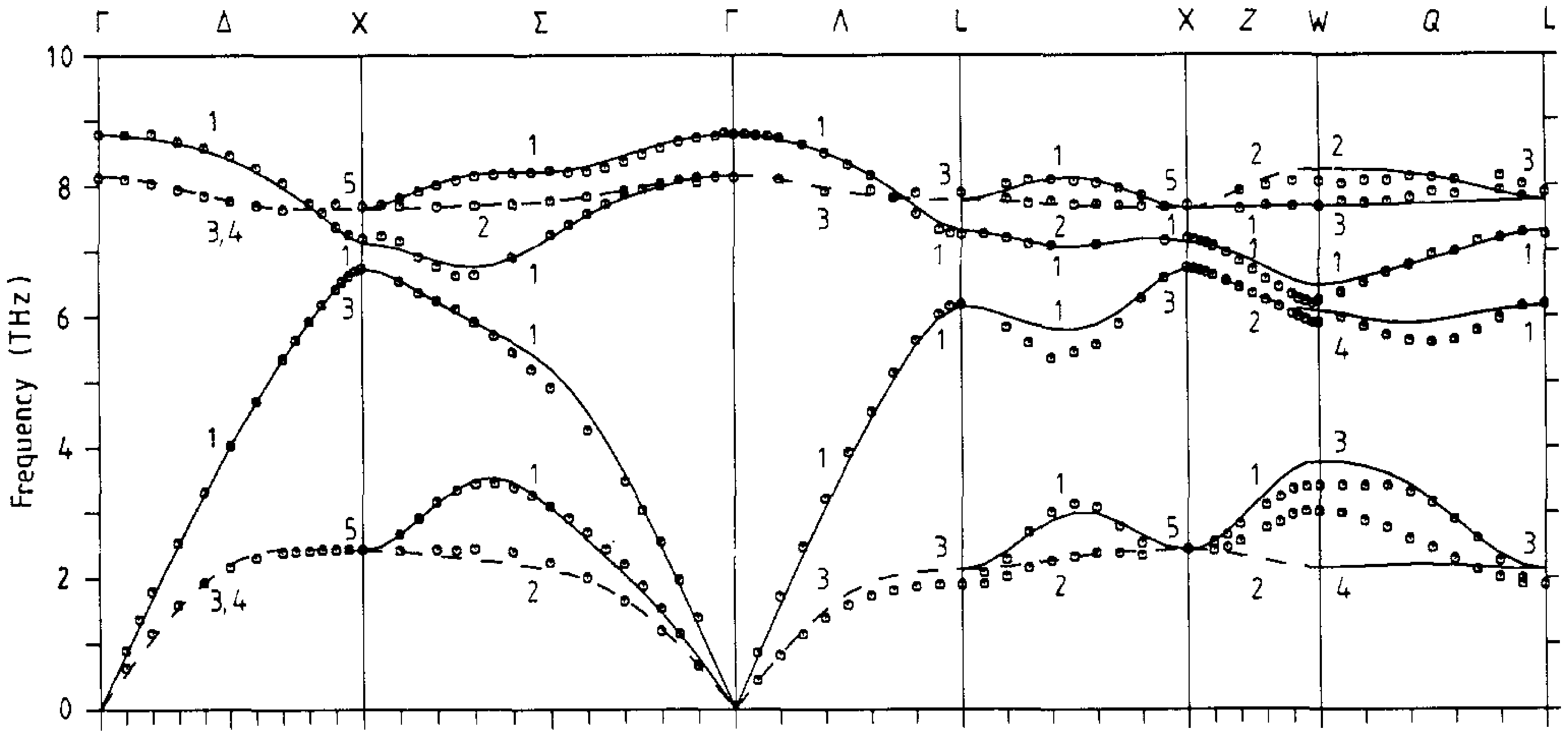


Dispersion of (quasi)particles in solids

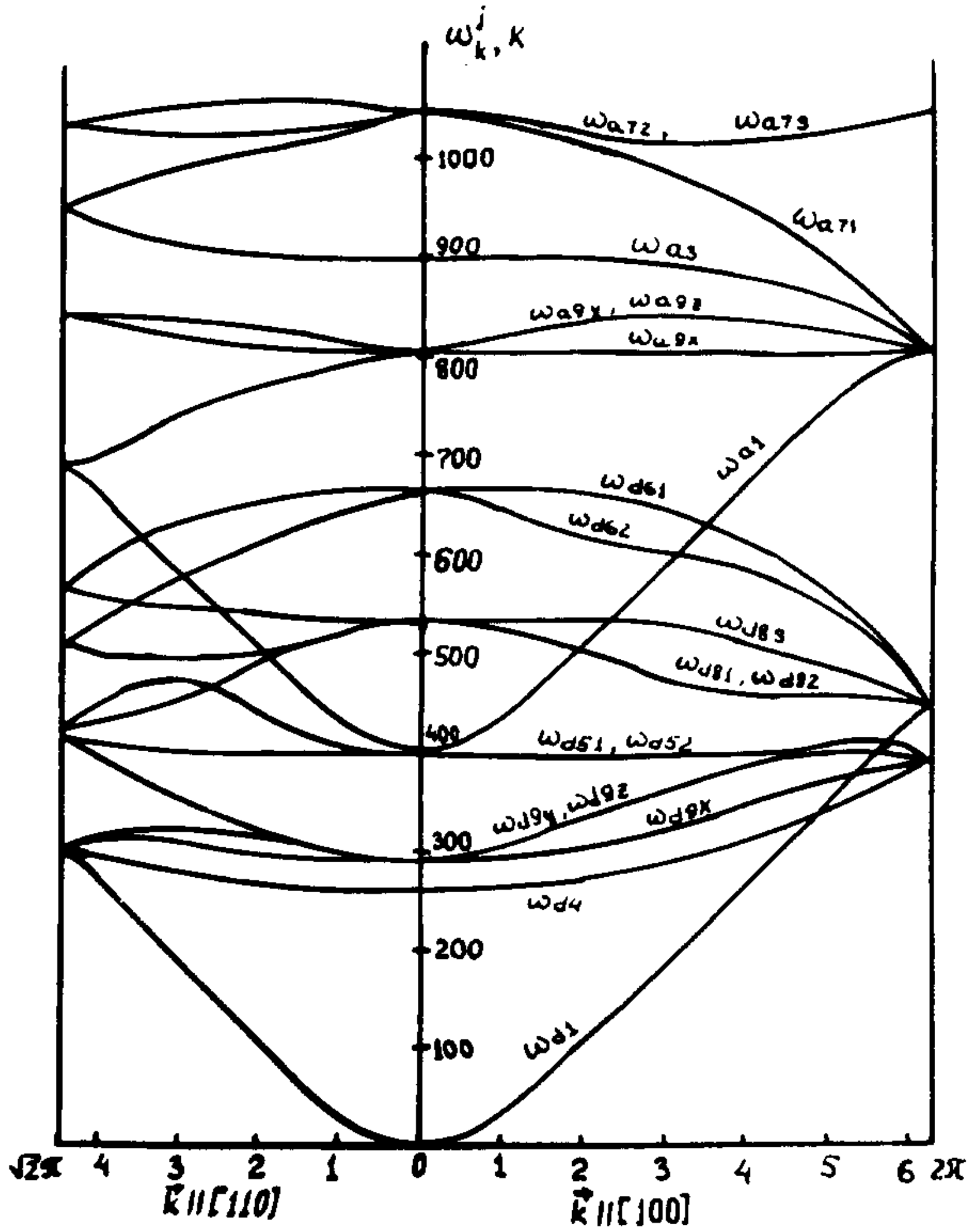
Electron (Ge)



Phonon (GaAs)



Magnon (YIG)



Rich structure: useful for new particle search !

DM absorption: meV~keV, DM scatter: keV~GeV

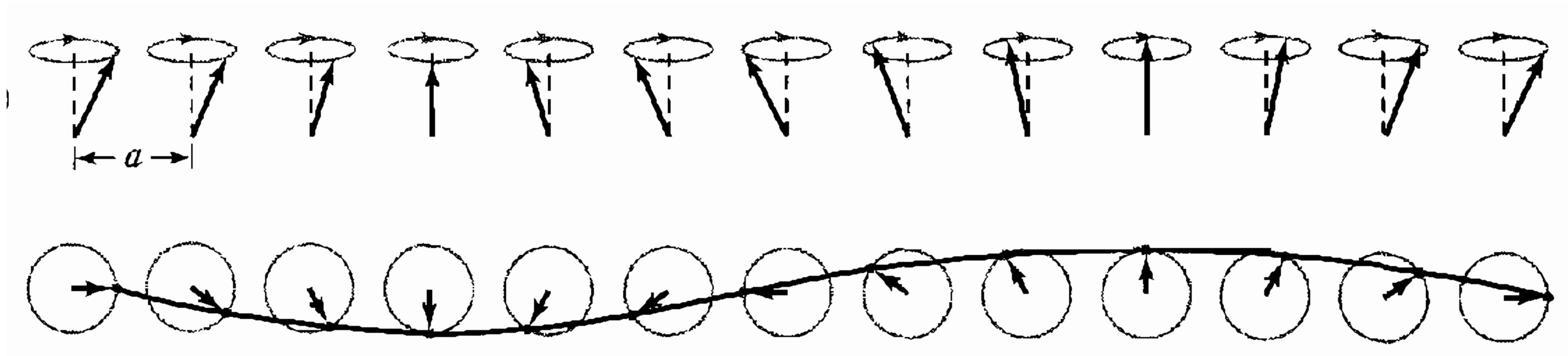
Heisenberg model for ferromagnet and magnon

- Magnetic material : electron spins are aligned
- Heisenberg Hamiltonian

$$H_{\text{eff}} = -g\mu_B \sum_{\ell} \vec{B}^0 \cdot \vec{S}_\ell - \frac{J}{2} \sum_{\ell,\ell'} \vec{S}_\ell \cdot \vec{S}_{\ell'},$$

J>0 : spins are aligned
(Ferromagnet)

- Fluctuation around the ground state : collective spin wave = Magnon



Magnon Hamiltonian

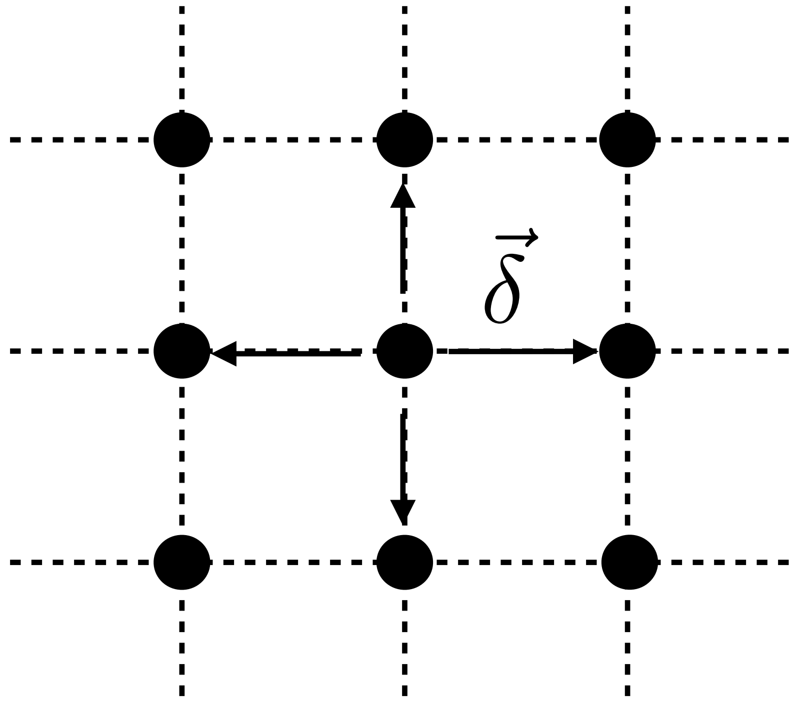
- Quantized Hamiltonian in momentum space

Holstein-Primakoff transformation

$$S_\ell^+ = \sqrt{2s - \tilde{c}_\ell^\dagger \tilde{c}_\ell}\, \tilde{c}_\ell \qquad S_\ell^- = \tilde{c}_\ell^\dagger \sqrt{2s - \tilde{c}_\ell^\dagger \tilde{c}_\ell} \qquad S_\ell^z = s - \tilde{c}_\ell^\dagger \tilde{c}_\ell \qquad (S_\ell^\pm \equiv S_\ell^x \pm i S_\ell^y)$$

$$H = \sum_k \left[\omega_L + Js \sum_{\vec{a}} (1 - \gamma_{\vec{k}}) \right] c_{\vec{k}}^\dagger c_{\vec{k}} = \sum_k \omega_k c_{\vec{k}}^\dagger c_{\vec{k}}$$

$$\gamma_{\vec{k}} = \frac{1}{z} \sum_{\vec{\delta}} e^{i\vec{k}\cdot\vec{\delta}}$$



- Magnon dispersion relation:

$$\omega_{\vec{k}} \simeq \omega_L + JsL^2k^2 \equiv \omega_L + \frac{k^2}{2M}$$

$$\omega_L \equiv g\mu_B B_z^0 \simeq 1.2 \times 10^{-4}\,\mathrm{eV} \left(\frac{B_z^0}{1\,\mathrm{T}} \right)$$: Larmor frequency

Magnon dispersion (YIG)

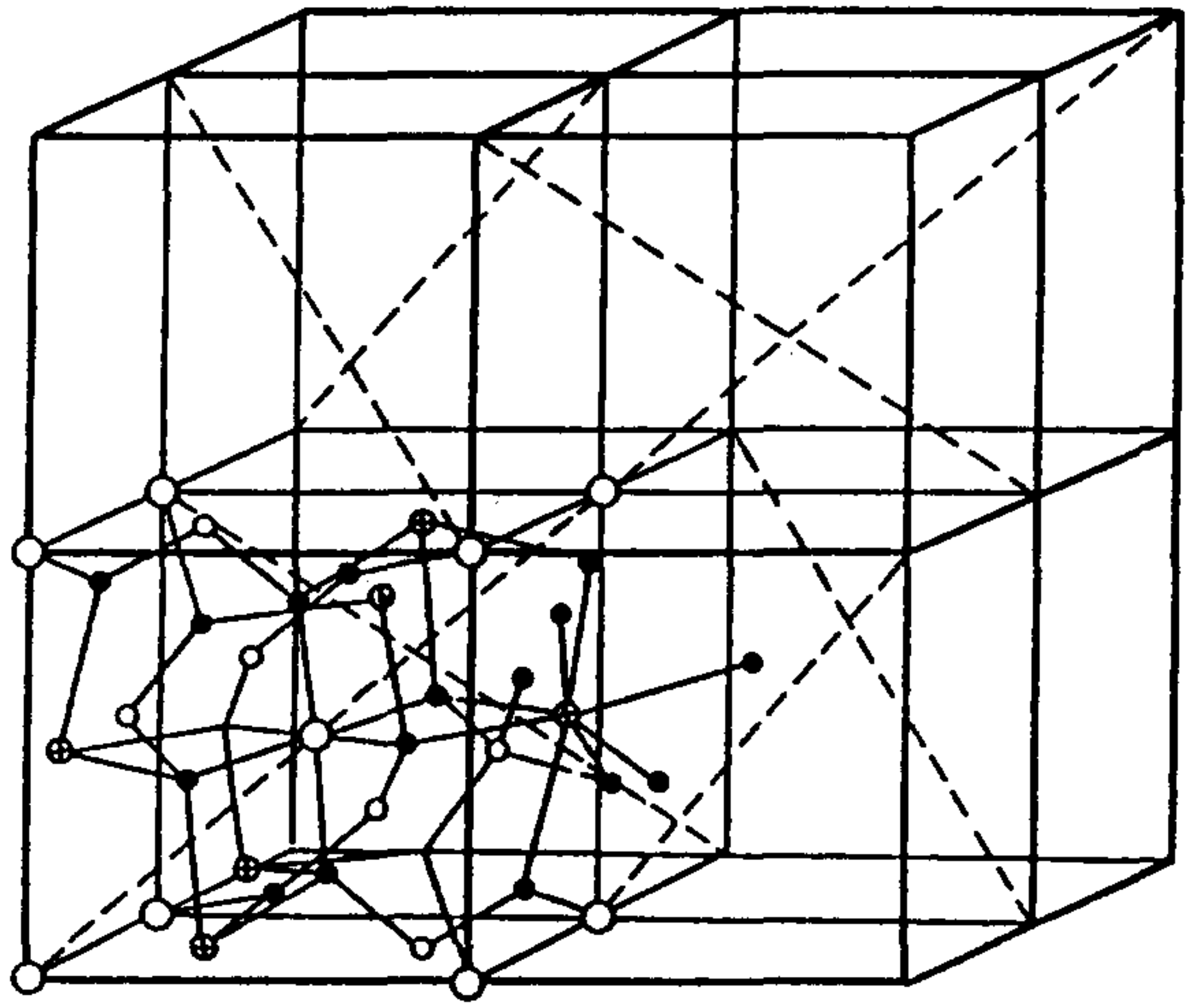
YIG= $Y_3Fe_5O_{12}$

Wikipedia

- 20 Fe^3+ ions in magnetic unit cell
- "Ferri-magnet"

12 Fe : $\frac{5}{2}\mu_B \times 12$ ↑

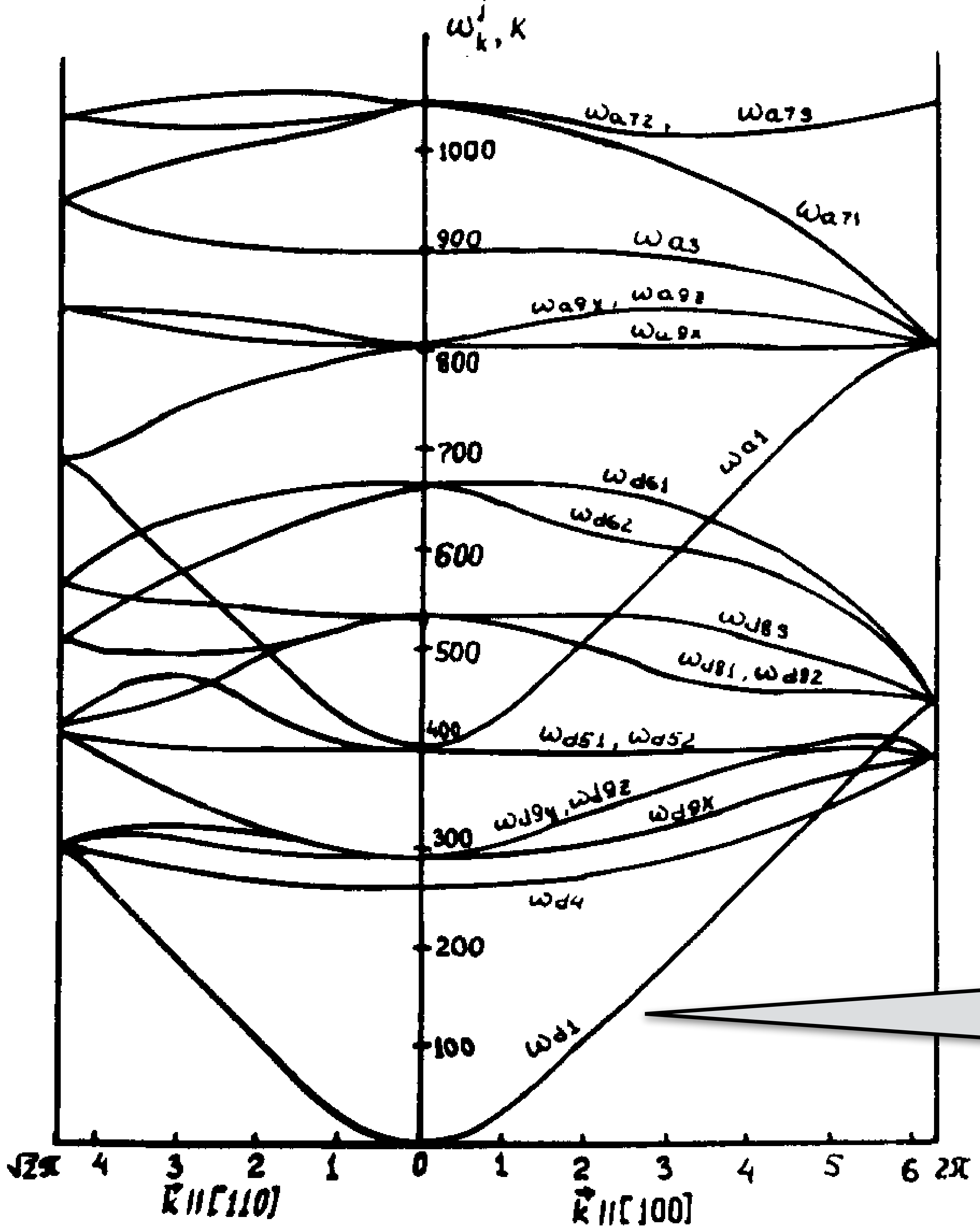
8 Fe : $-\frac{5}{2}\mu_B \times 8$ ↓



○1 ⊕2 ○3 •4

Fe Y Fe O

- dispersion relation (20 magnon branches)



$$\omega \simeq \frac{k^2}{2M}$$

$$M \sim 7\,\mathrm{MeV}$$

[Cherepanov, Kolokolov, L'vov (1993)]

Axion-magnon interaction

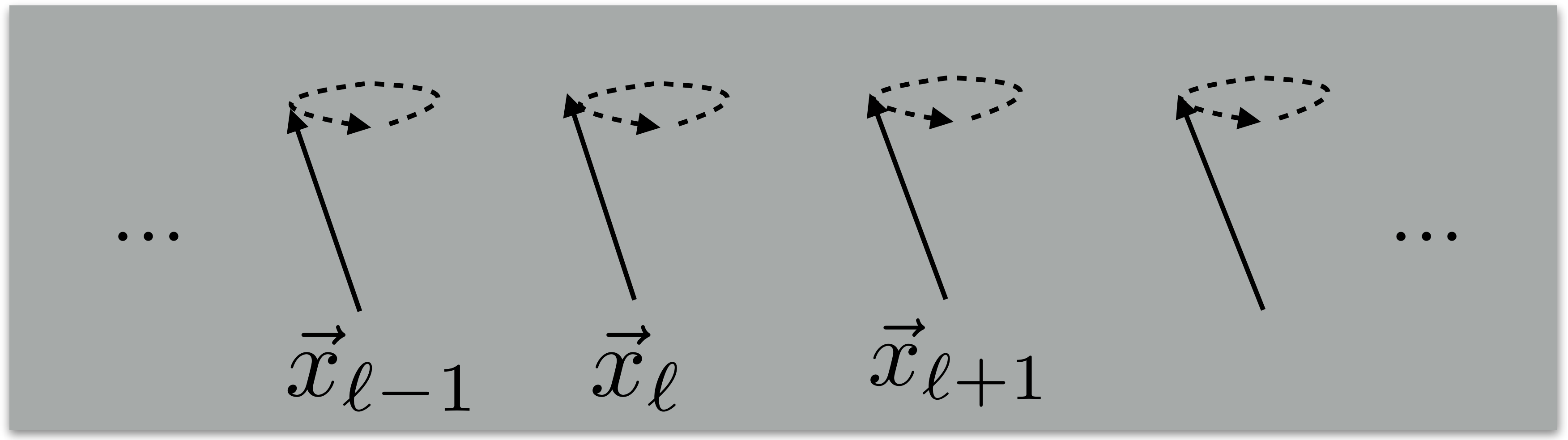
[Barbieri et al (1989,2016), Chigusa, Moroi, KN (2020)]

- Axion-electron interaction

$$\mathcal{L} = \frac{\partial_\mu a}{2f}\overline{\psi}\gamma^\mu\gamma_5\psi \quad \longrightarrow \quad H_{\rm int} = \frac{1}{f}\sum_\ell \vec{\nabla}a(\vec{x}_\ell)\cdot\vec{S}_\ell$$

- **Axion-magnon interaction Hamiltonian**

$$H_{\rm int} = \frac{m_a a_0 \sin(m_a t + \delta)}{f}\sqrt{\frac{s}{2}}\sum_\ell \left(v_a^- \widetilde{c}_\ell + v_a^+ \widetilde{c}_\ell^\dagger\right)$$



Axion DM:

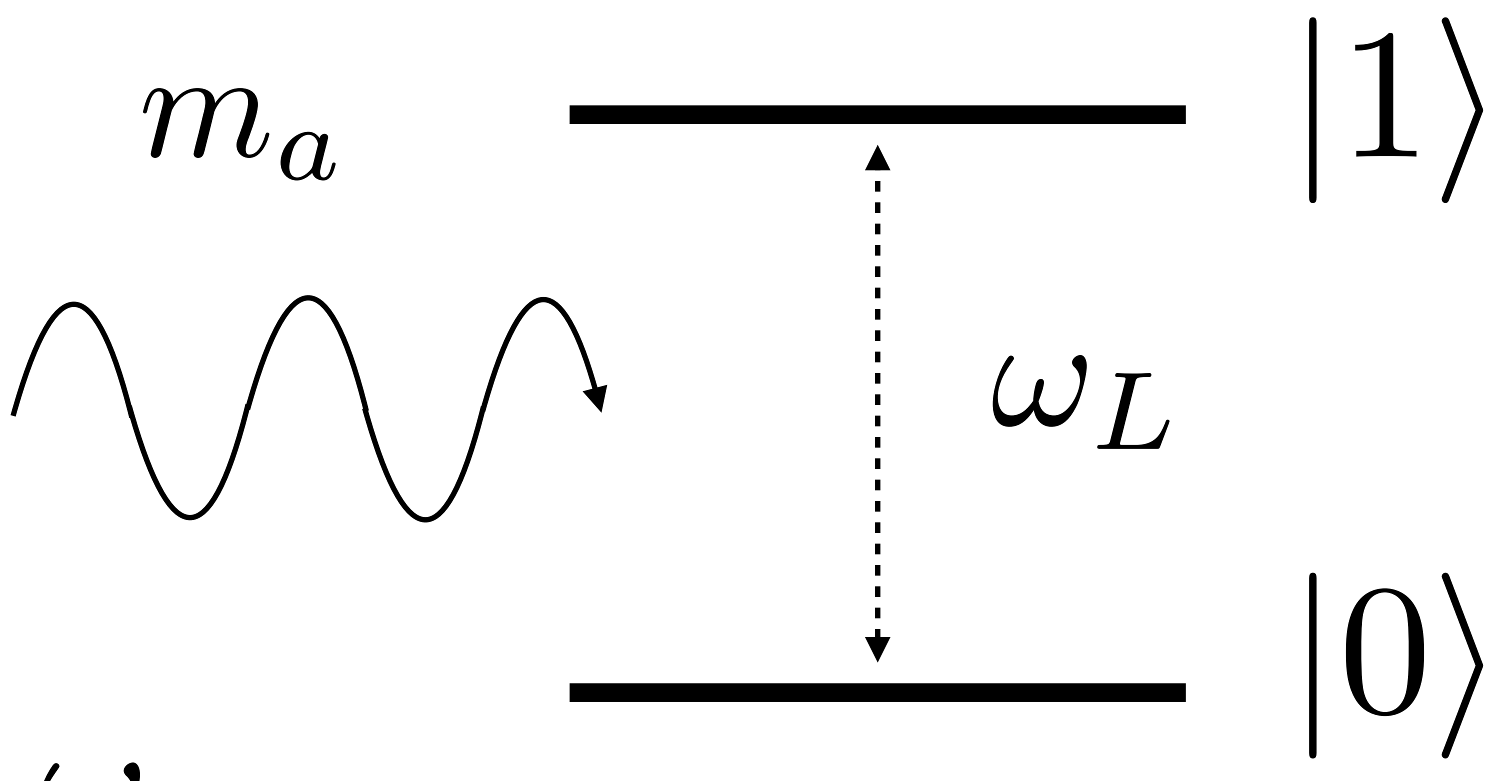
$$a(\vec{x},t) = a_0\cos(m_a t - m_a\vec{v}_a\cdot\vec{x} + \delta)$$

Resonant conversion

- 2-level system

  $|0\rangle$: 0-magnon state

  $|1\rangle$: 1-magnon state (k=0 mode)



- Signal power at resonance: $m_a = \omega_L$

$$\frac{dE_{\rm signal}}{dt} = \frac{\omega_L P(t)}{2t} = \frac{\omega_L |V|^2 t}{8}. \qquad V \equiv \sqrt{\frac{sN}{2}} \frac{m_a a_0 v_a^+}{f}$$

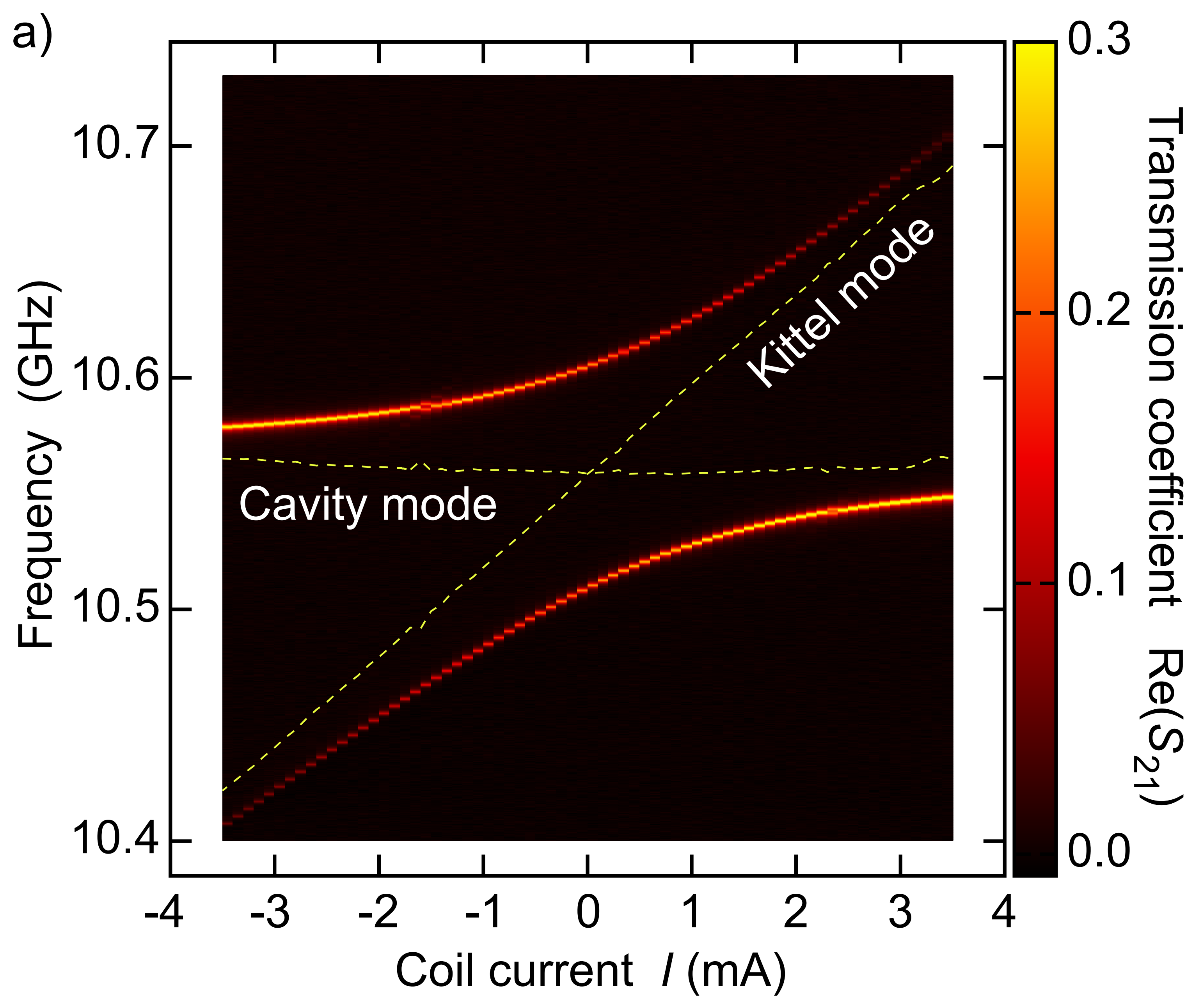
- Limitation:
  - Axion coherence time $\tau_a \sim (m_a v_a^2)^{-1}$
  - Magnon relaxation time $\tau_{\rm magnon} \sim (1/\tau_{\rm spin-spin} + 1/\tau_{\rm spin-lattice})^{-1}$

- **Magnon-photon mixing (magnon-polariton)**

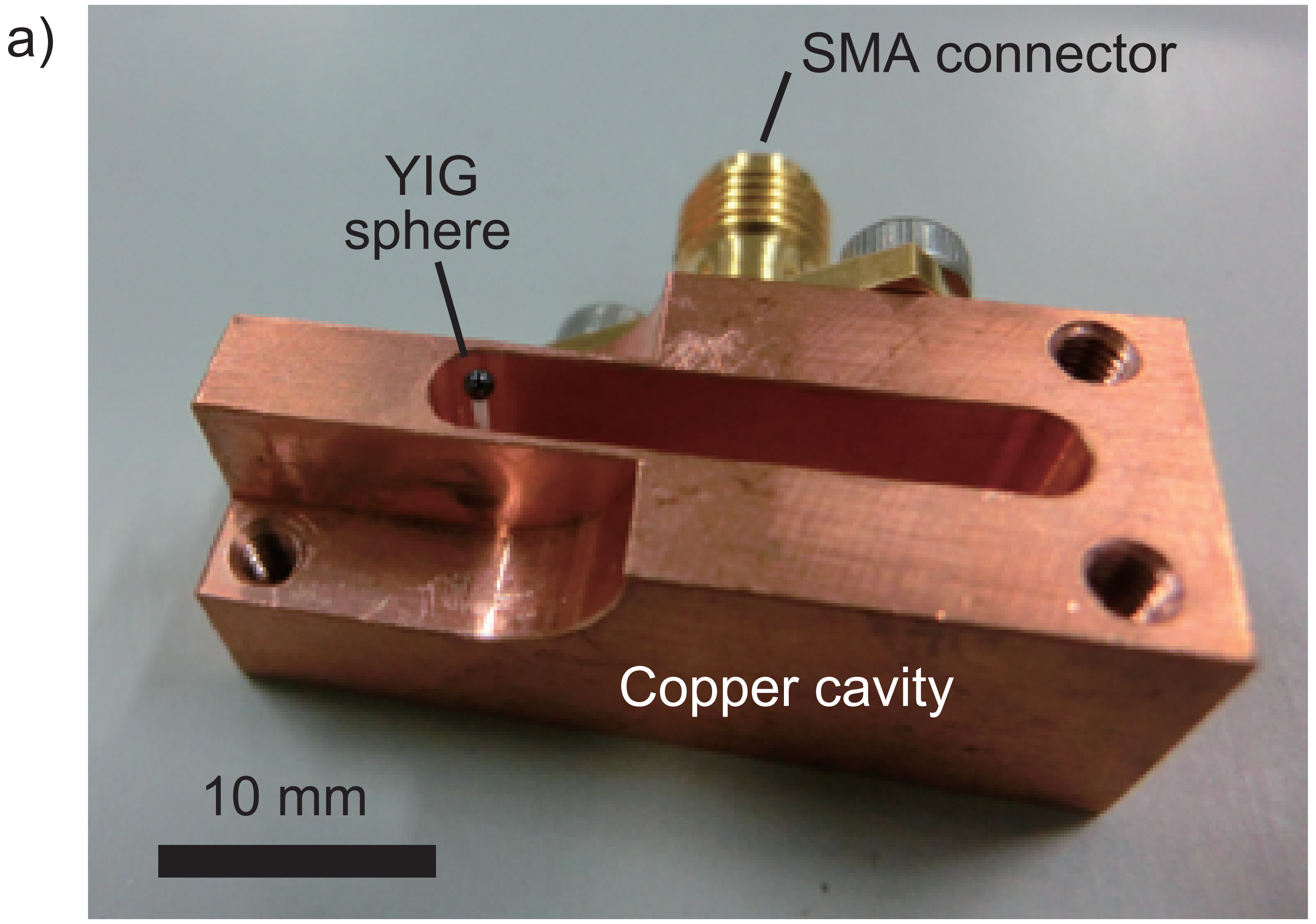
There is a mixing of cavity photon and magnon (“hybridization”)

$$H = \omega_L c_0^\dagger c_0 + \omega_{\rm cav} b^\dagger b + g_{\rm cm}(b^\dagger c_0 + c_0^\dagger b)$$

$$H = g\mu_B \vec{B}\cdot\vec{S}$$

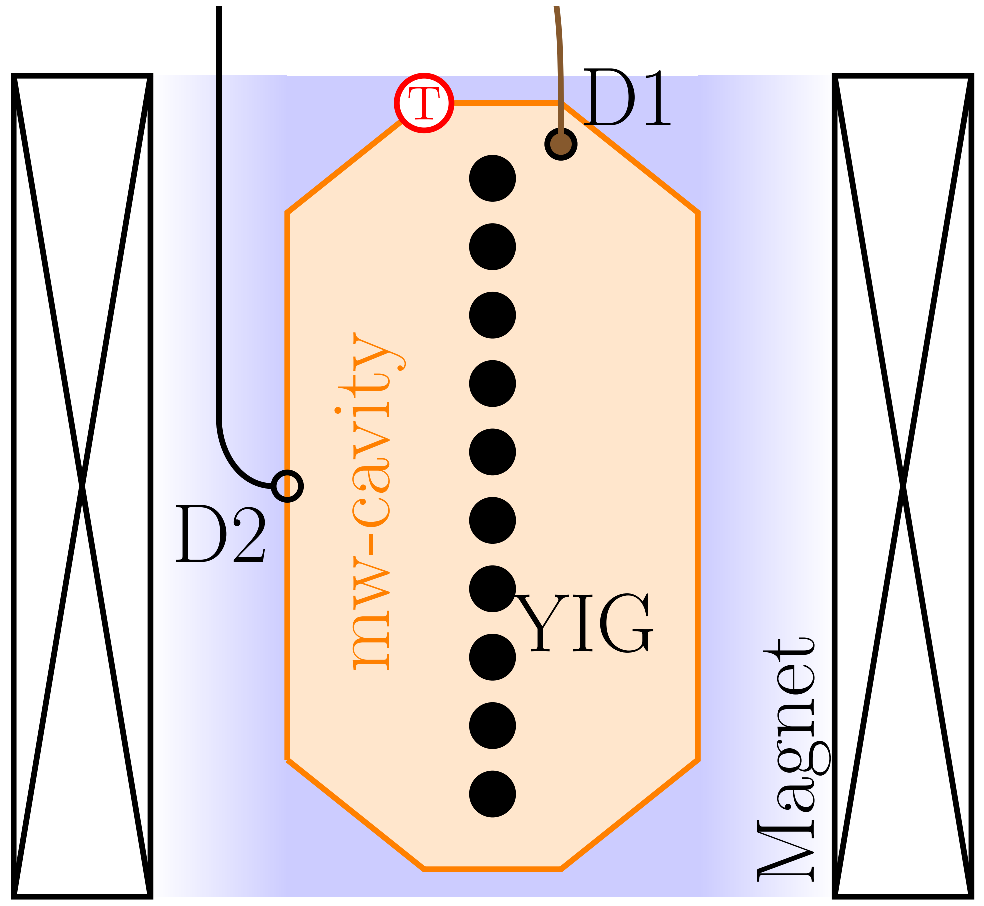


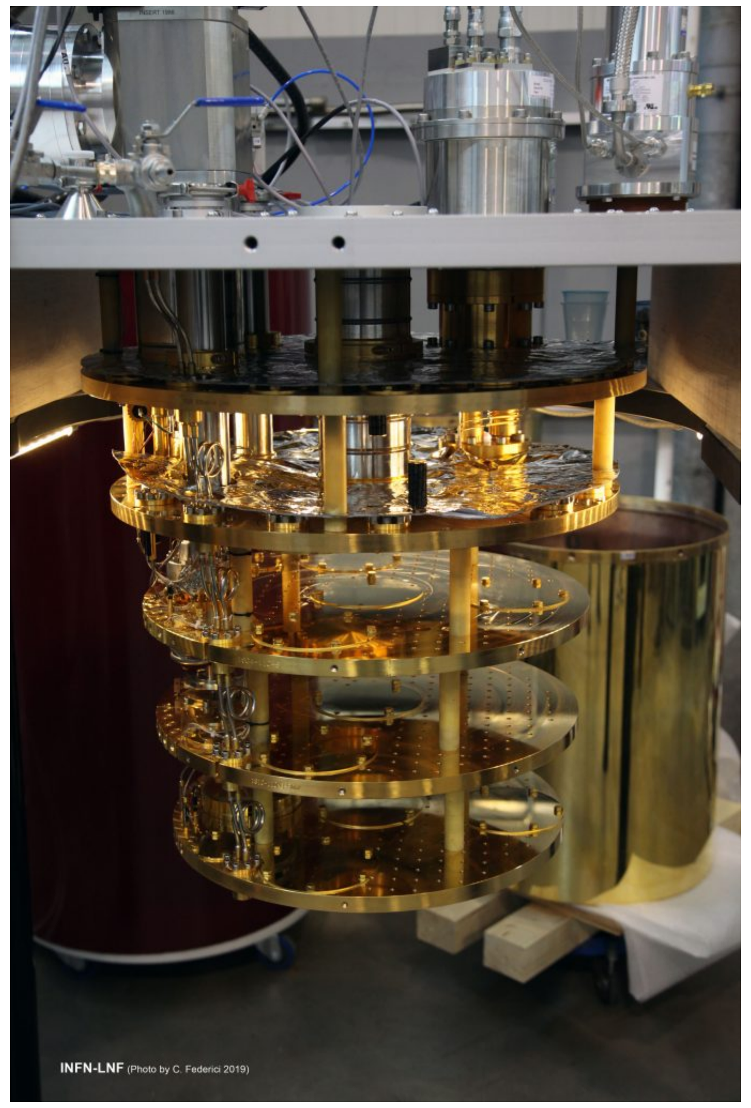
$\propto B_0$



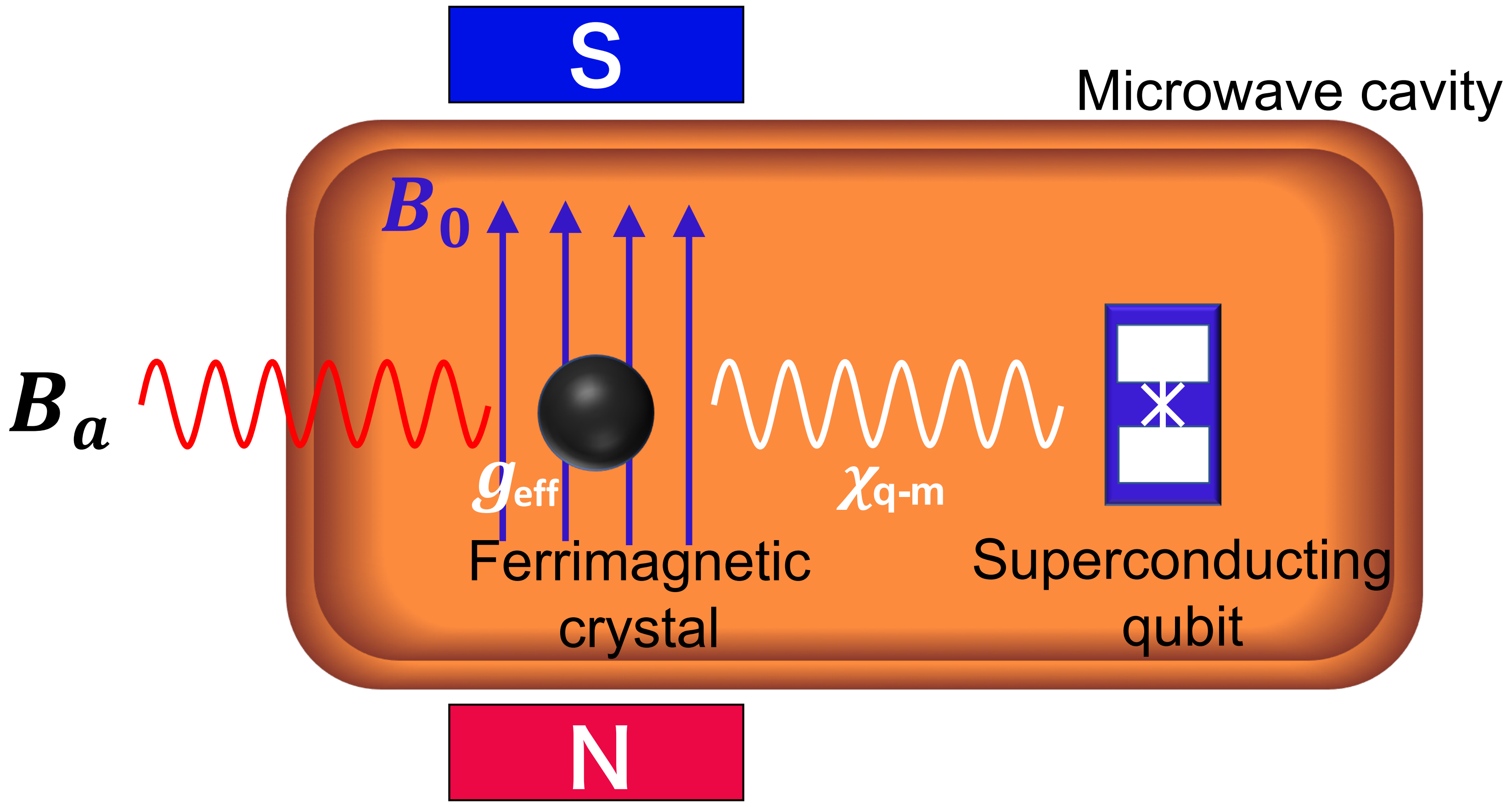
[Tabuchi et al., 1508.05290]

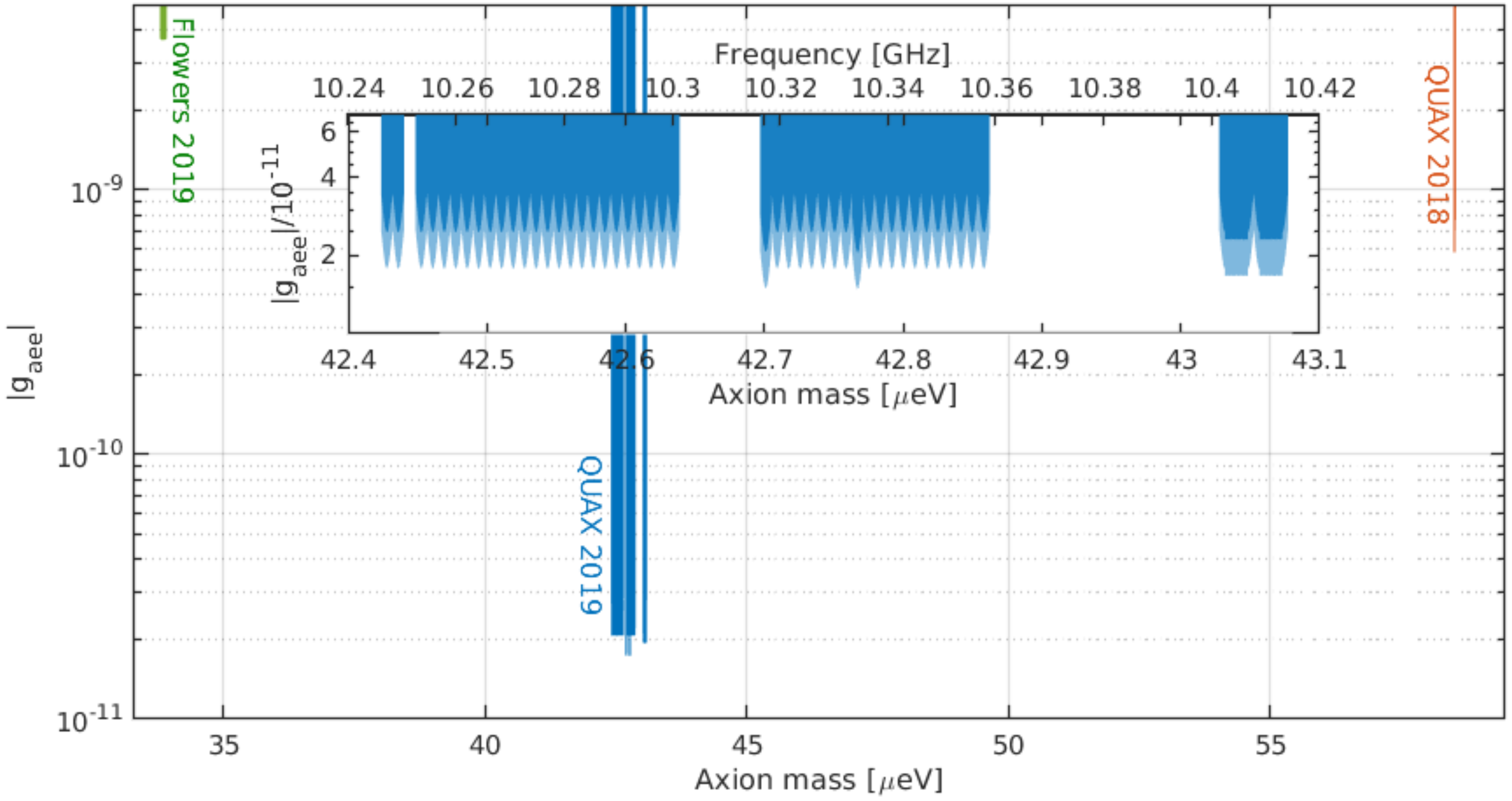
QUAX experiment



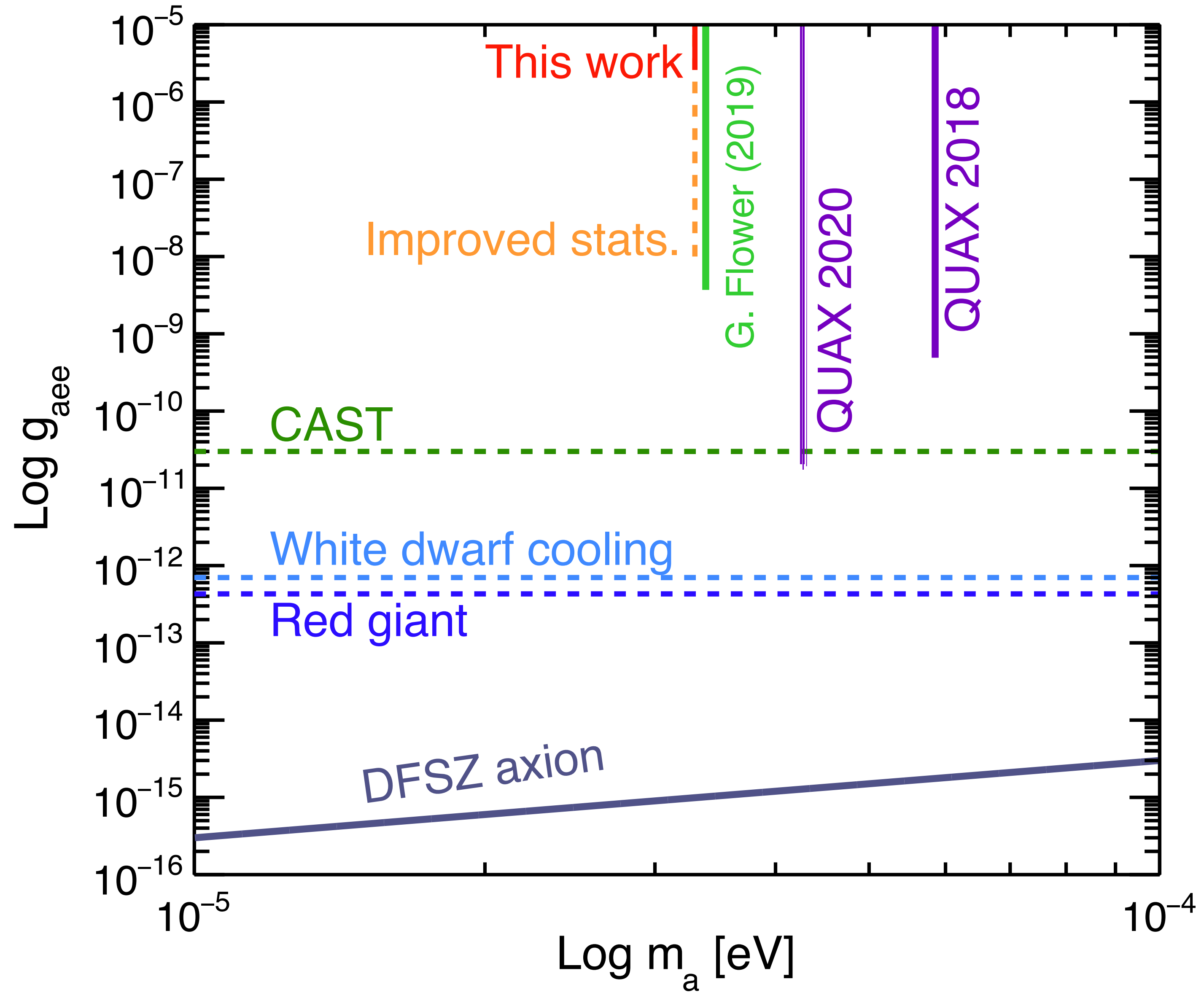


Use of Qubit



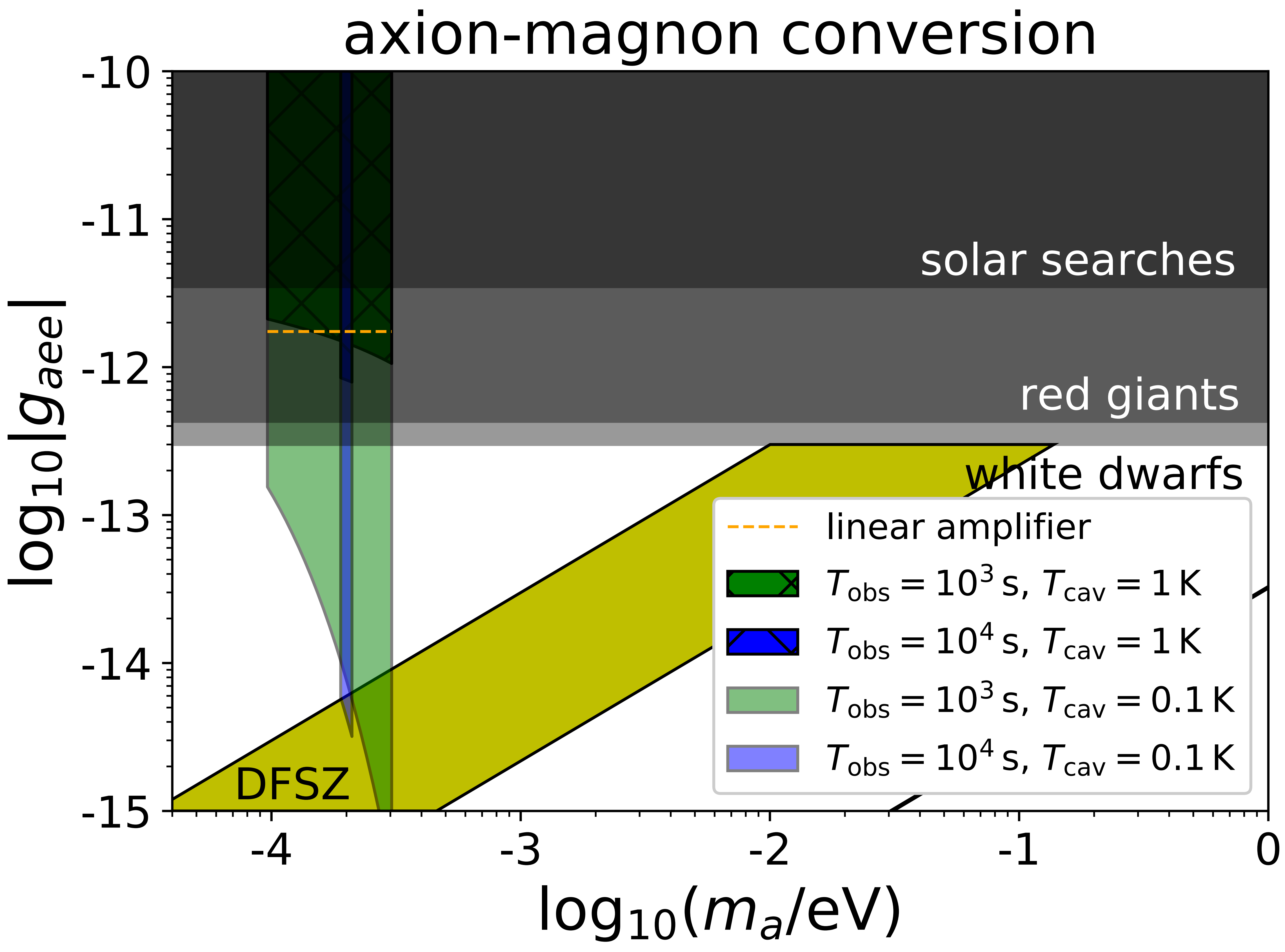


[QUAX collaboration (2020)]

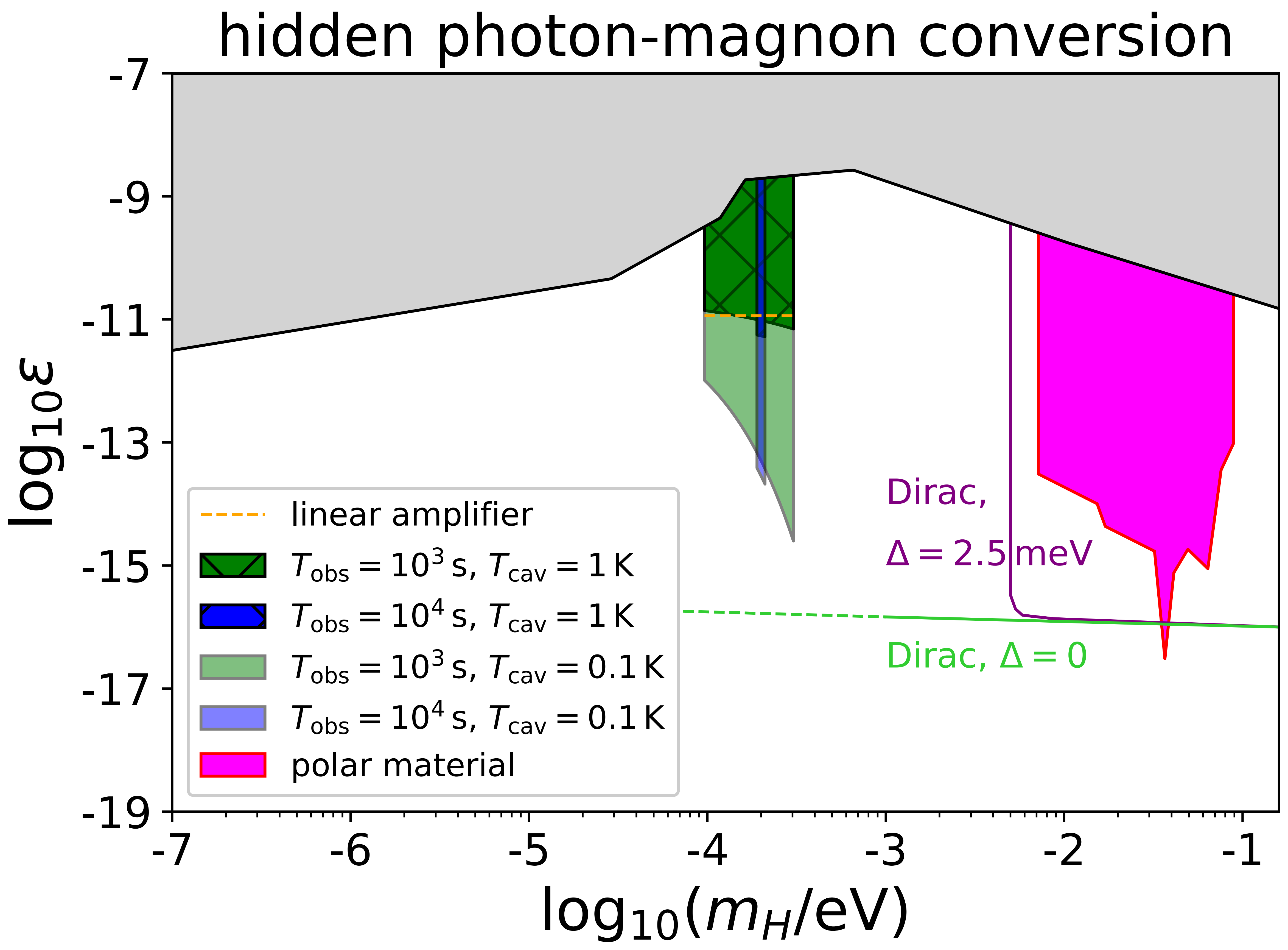


[Ikeda, Ito, Miuchi, Soda, Kurashige, Shikano (2020)]

Ultimate goal for DM search with magnon



(1kg year)



[Chigusa, Moroi, KN (2020)]

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➡ With condensed-matter axion

[Chigusa, Moroi, KN (2021)]

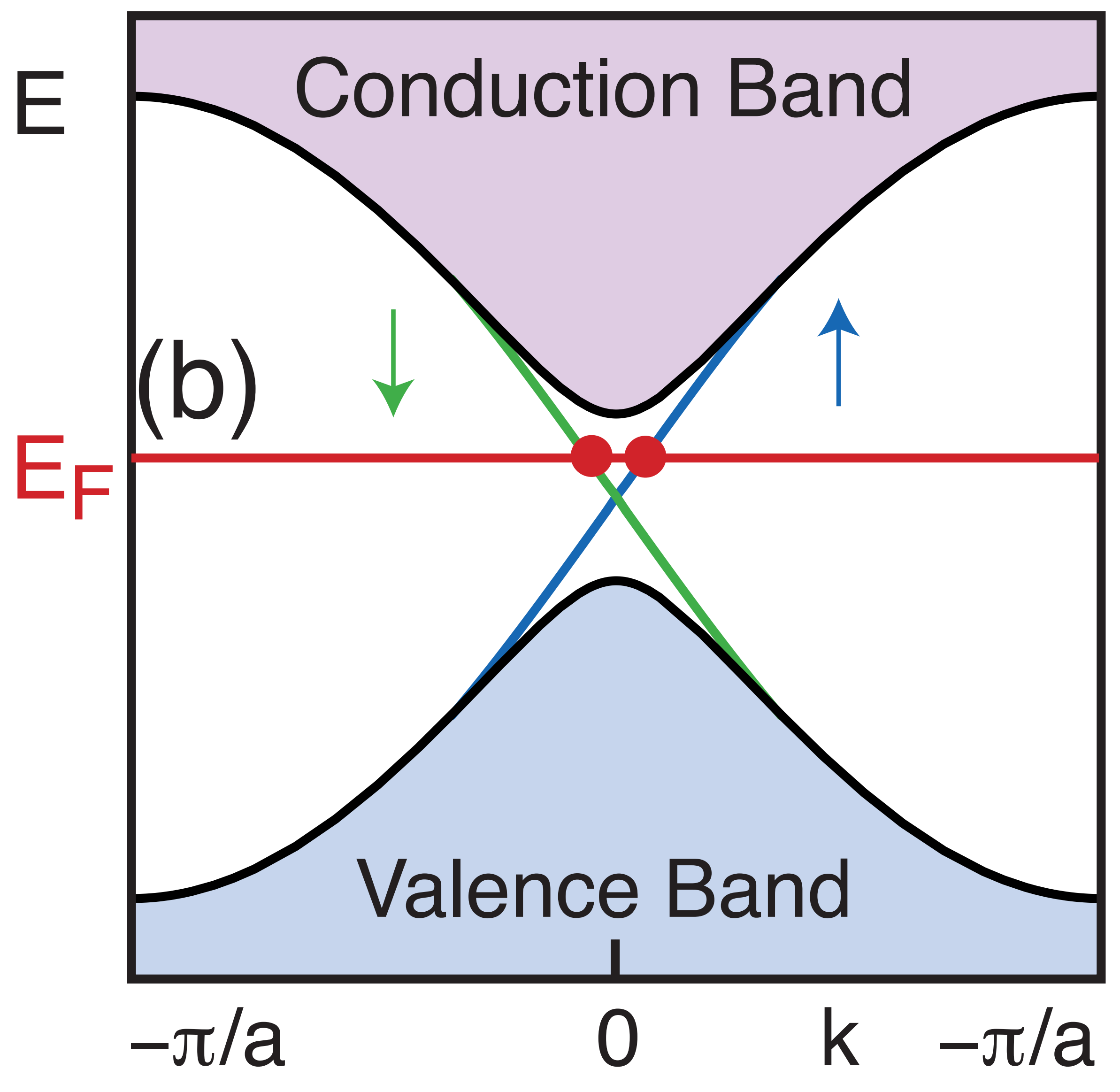
Axion in condensed-matter

- Topological insulator [Kane, Mele (2005), Fu, Kane, Mele (2007)]

$$\mathcal{L} = \theta \frac{\alpha_e}{4\pi} F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

$\theta = 0$: normal insulator

$\theta = \pi$: topological insulator



[Hasan, Mele (2010)]

- Can θ be dynamical? [Wilczek (1987)]
  - Arbitrary value if there is no T, P invariance
  - Magnetic ordering can violate T, P-invariance

Dynamical axion

(axion quasi-particle, condensed-matter axion,…)

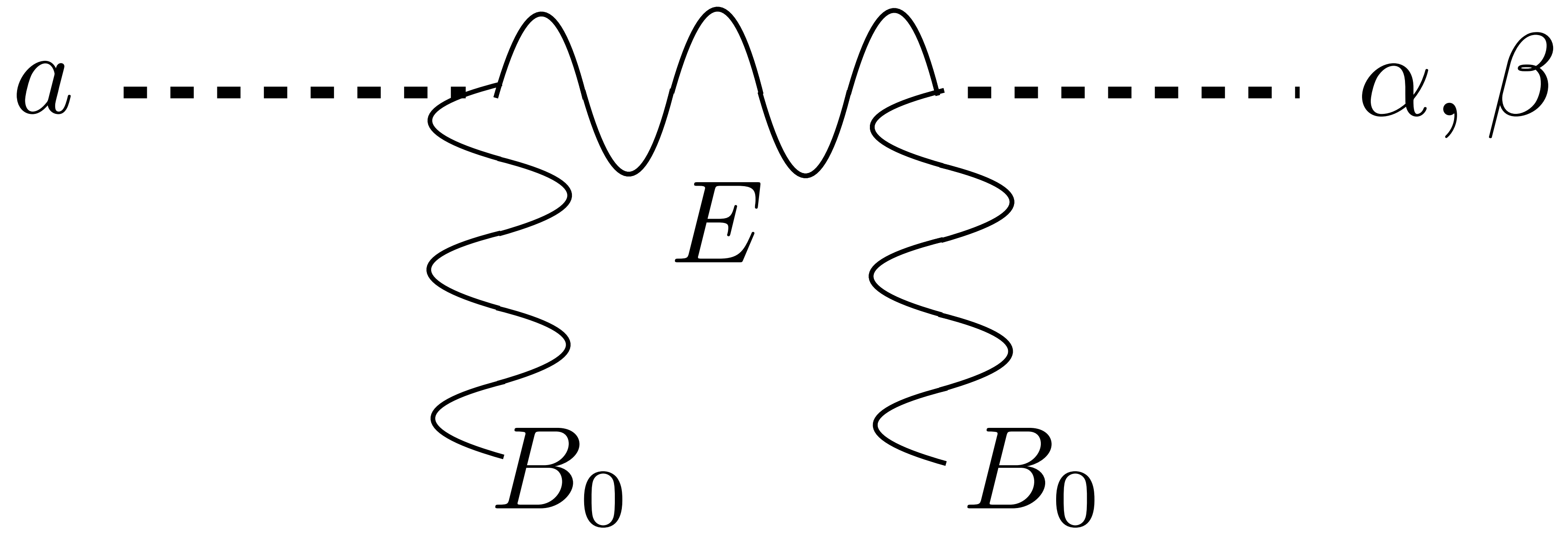
- "***Axion***" in topological (anti-)ferromagnet

First proposal: Fe-doped Bi2Se3 [Li, Wang, Qi, Zhang (2009)]

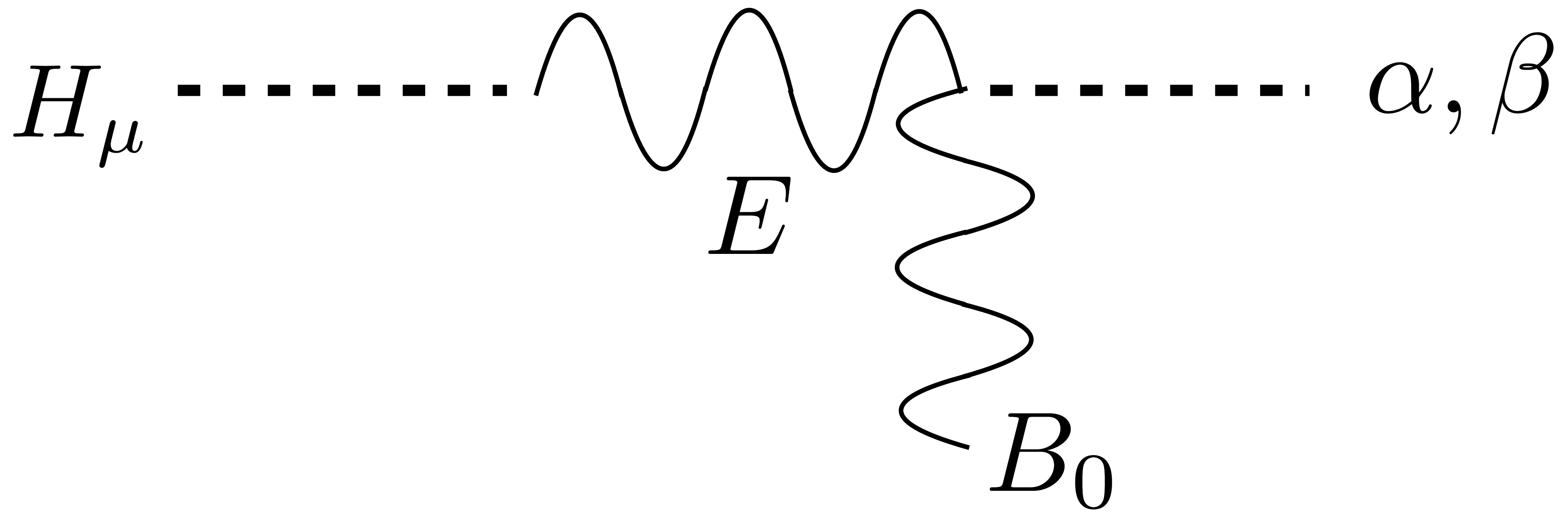
DM-axion to CM-axion conversion

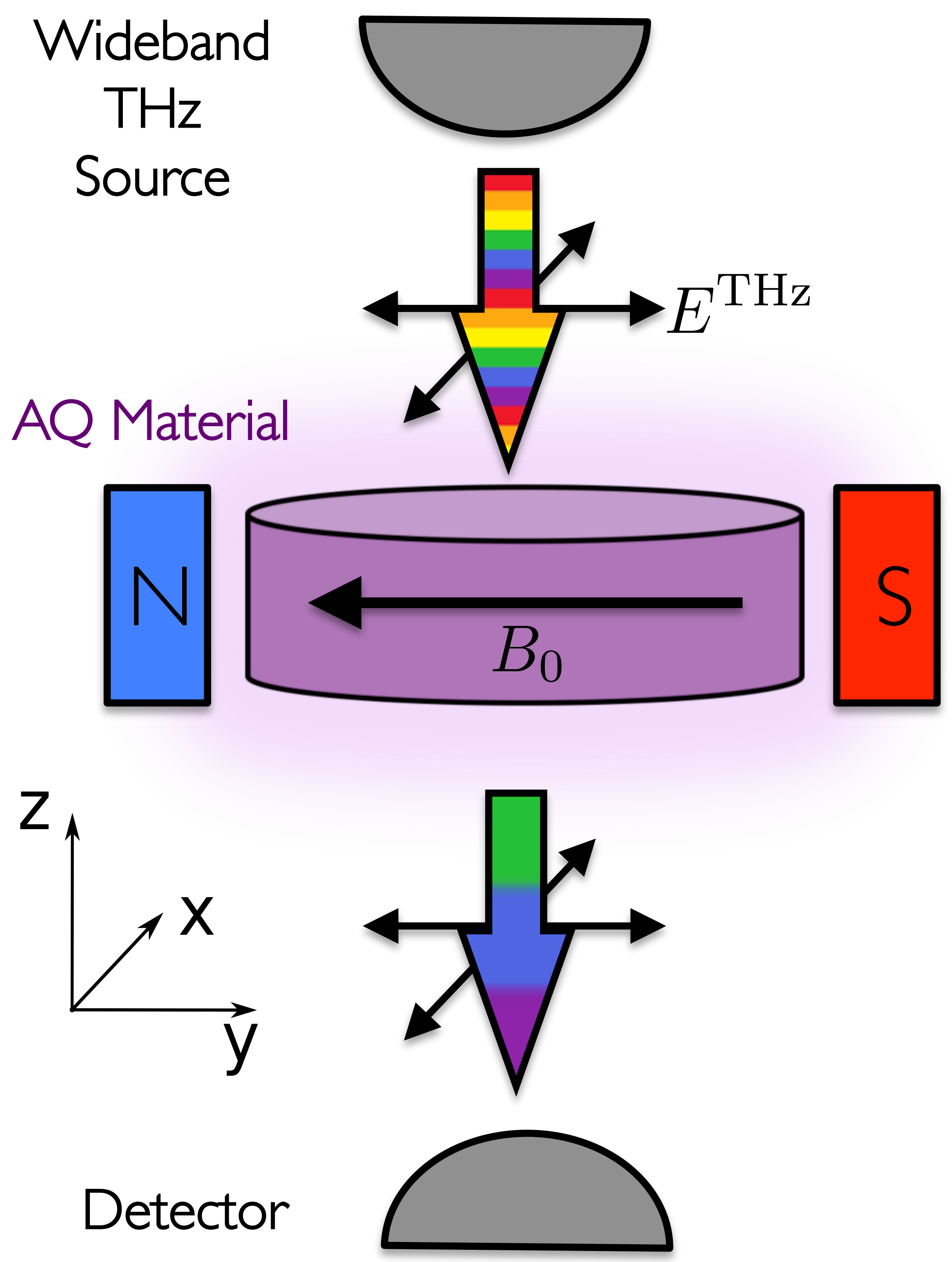
[Marsh et al (2018)] [Schutte-Engel et al. (2021)] [Chigusa, Moroi, KN (2021)]

- DM axion to CM axion conversion under magnetic field



- DM hidden photon to CM axion





[Schutte-Engel et al. (2021)]

Example: Fu-Kane-Mele-Hubbard model

[Sekine, Nomura (2014)]

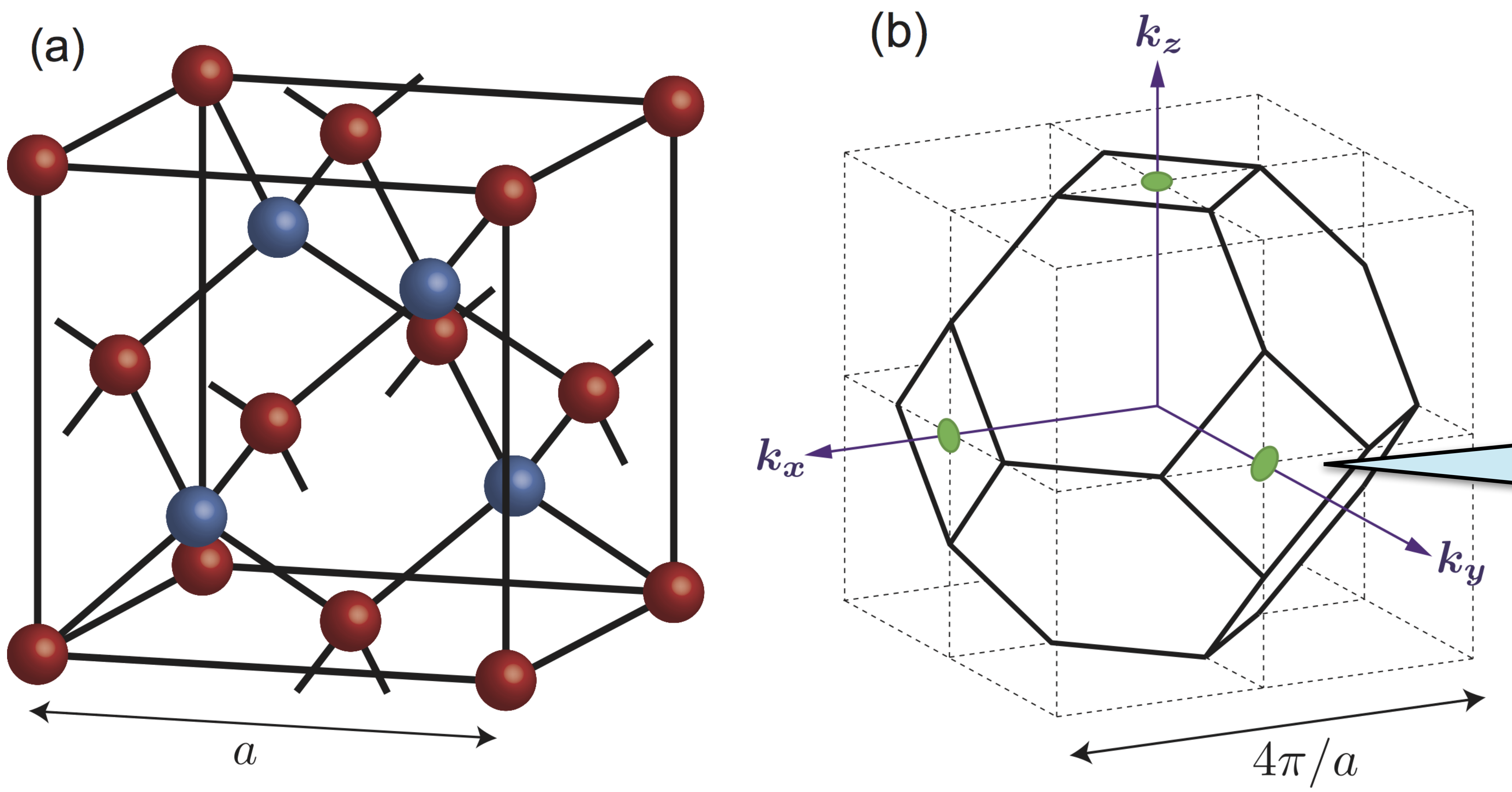
$$H_0 = \sum_{\langle i,j \rangle \sigma} t_{ij} c^\dagger_{i\sigma} c_{j\sigma} + i\frac{4\lambda}{a^2} \sum_{\langle\langle i,j \rangle\rangle} c^\dagger_i \vec{\sigma} \cdot (\vec{d}^1_{ij} \times \vec{d}^2_{ij}) c_j$$

nearest neighbor tight-binding term

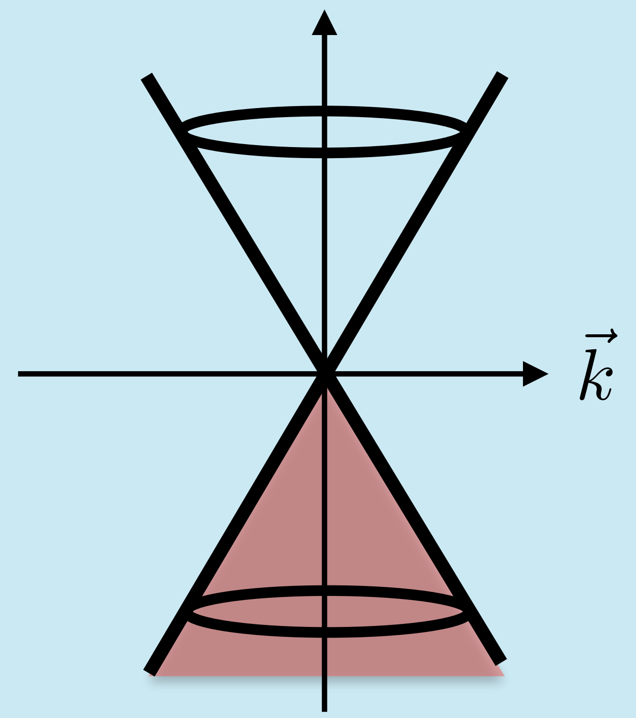
next nearest neighbor spin-orbit interaction term

$$H_U = U \sum_i n_{i\uparrow} n_{i\downarrow}$$

Hubbard interaction term



3 Dirac points in Brillouin zone



- Hamiltonian in terms of electron creation/annihilation operator

$$H_0 = \sum_{\vec{k}} c^\dagger_{\vec{k}} \mathcal{H} c_{\vec{k}}, \qquad \mathcal{H} = \sum_{\mu=1}^{5} R_\mu(\vec{k})\alpha_\mu$$

$$R_1(\vec{k}) = \lambda \left[\sin(\vec{k}\cdot\vec{a}_2) - \sin(\vec{k}\cdot\vec{a}_3) - \sin(\vec{k}\cdot(\vec{a}_2-\vec{a}_1)) - \sin(\vec{k}\cdot(\vec{a}_3-\vec{a}_1))\right]$$
$$R_2(\vec{k}) = \lambda \left[\sin(\vec{k}\cdot\vec{a}_3) - \sin(\vec{k}\cdot\vec{a}_1) - \sin(\vec{k}\cdot(\vec{a}_3-\vec{a}_2)) - \sin(\vec{k}\cdot(\vec{a}_1-\vec{a}_2))\right]$$
$$R_3(\vec{k}) = \lambda \left[\sin(\vec{k}\cdot\vec{a}_1) - \sin(\vec{k}\cdot\vec{a}_2) - \sin(\vec{k}\cdot(\vec{a}_1-\vec{a}_3)) - \sin(\vec{k}\cdot(\vec{a}_2-\vec{a}_3))\right]$$
$$R_4(\vec{k}) = t\left[1 + \cos(\vec{k}\cdot\vec{a}_1) + \cos(\vec{k}\cdot\vec{a}_2) + \cos(\vec{k}\cdot\vec{a}_3)\right] + \delta t,$$
$$R_5(\vec{k}) = t\left[\sin(\vec{k}\cdot\vec{a}_1) + \sin(\vec{k}\cdot\vec{a}_2) + \sin(\vec{k}\cdot\vec{a}_3)\right],$$

3 Dirac points: $\vec{k}_{X_1} = \frac{2\pi}{a}(1,0,0),\ \vec{k}_{X_2} = \frac{2\pi}{a}(0,1,0),\ \vec{k}_{X_3} = \frac{2\pi}{a}(0,0,1)$

- Large Hubbard interaction $\longrightarrow$ Magnetic ordering

- Dirac-like electron interacts with spin through

$$S = \int d^4x \sum_{r=1,2,3} \overline{\psi}_r \left[i\gamma^\mu(\partial_\mu - ieA_\mu) - \delta t - i\gamma_5 U m_r \right] \psi_r$$

$$\left\langle \vec{S}_{i,A} \right\rangle = - \left\langle \vec{S}_{i,B} \right\rangle \equiv \vec{m}$$: anti-ferromagnetic order for U/t>>1

- Chiral rotation of Dirac fermion gives axion-photon interaction:

$$S = \int d^4x \, \theta \frac{\alpha_e}{4\pi} F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

$$\theta \equiv \theta_0 + \sum_r \theta_r = \theta_0 + \sum_r \tan^{-1}\left(\frac{U m_r}{\delta t} \right)$$

Fluctuation of magnetic order parameter = **dynamical axion**

Axion ~ magnon in FKMH anti-ferromagnet model.

- Magnon in anti-ferromagnet: Two modes

$$H = -\frac{J}{2}\sum_{\langle \ell,\ell' \rangle} \vec{S}_\ell \cdot \vec{S}_{\ell'} - g\mu_B(B_A + B_0)\sum_{\ell \in A} S^z_\ell + g\mu_B(B_A - B_0)\sum_{\ell' \in B} S^z_{\ell'},$$

$$S^+_\ell = \sqrt{2s - a^\dagger_\ell a_\ell}\, a_\ell, \quad S^-_\ell = a^\dagger_\ell \sqrt{2s - a^\dagger_\ell a_\ell}, \quad S^z_\ell = s - a^\dagger_\ell a_\ell,$$
$$S^+_{\ell'} = b^\dagger_{\ell'} \sqrt{2s - b^\dagger_{\ell'} b_{\ell'}}, \quad S^-_{\ell'} = \sqrt{2s - b^\dagger_{\ell'} b_{\ell'}}\, b_{\ell'}, \quad S^z_{\ell'} = -s + b^\dagger_{\ell'} b_{\ell'},$$

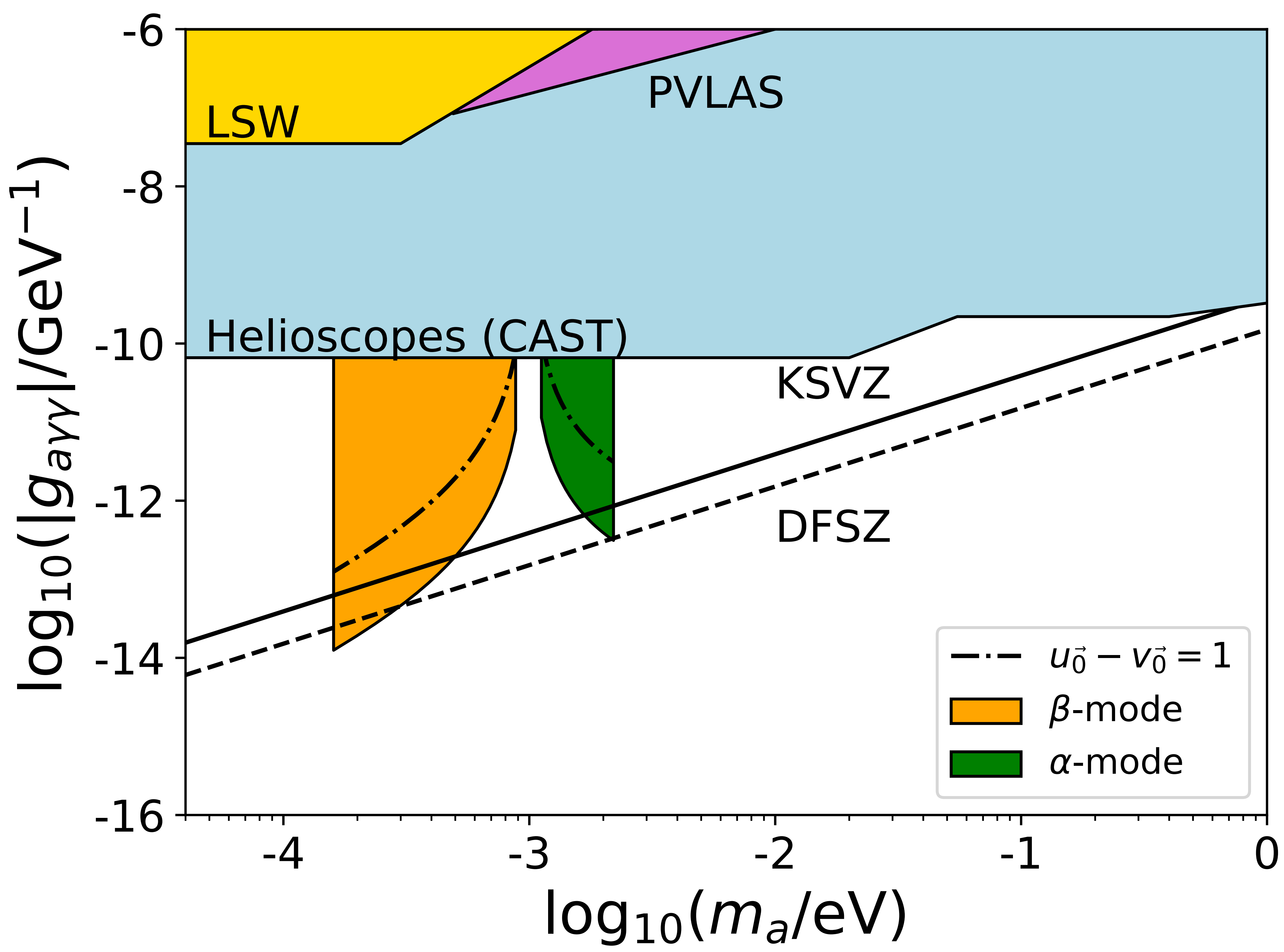
- Express Hamiltonian taking account of fluctuation of magnetization

$$H_U \ni \sum_{\vec{k}} c^\dagger_{\vec{k}} \widetilde{\mathcal{H}}_U c_{\vec{k}}, \qquad \widetilde{\mathcal{H}}_U = \sum_{\mu=1}^{5} \widetilde{R}_\mu \alpha_\mu + \widetilde{R}_{12}\alpha_{12} + \widetilde{R}_{23}\alpha_{23} + \widetilde{R}_{31}\alpha_{31}$$

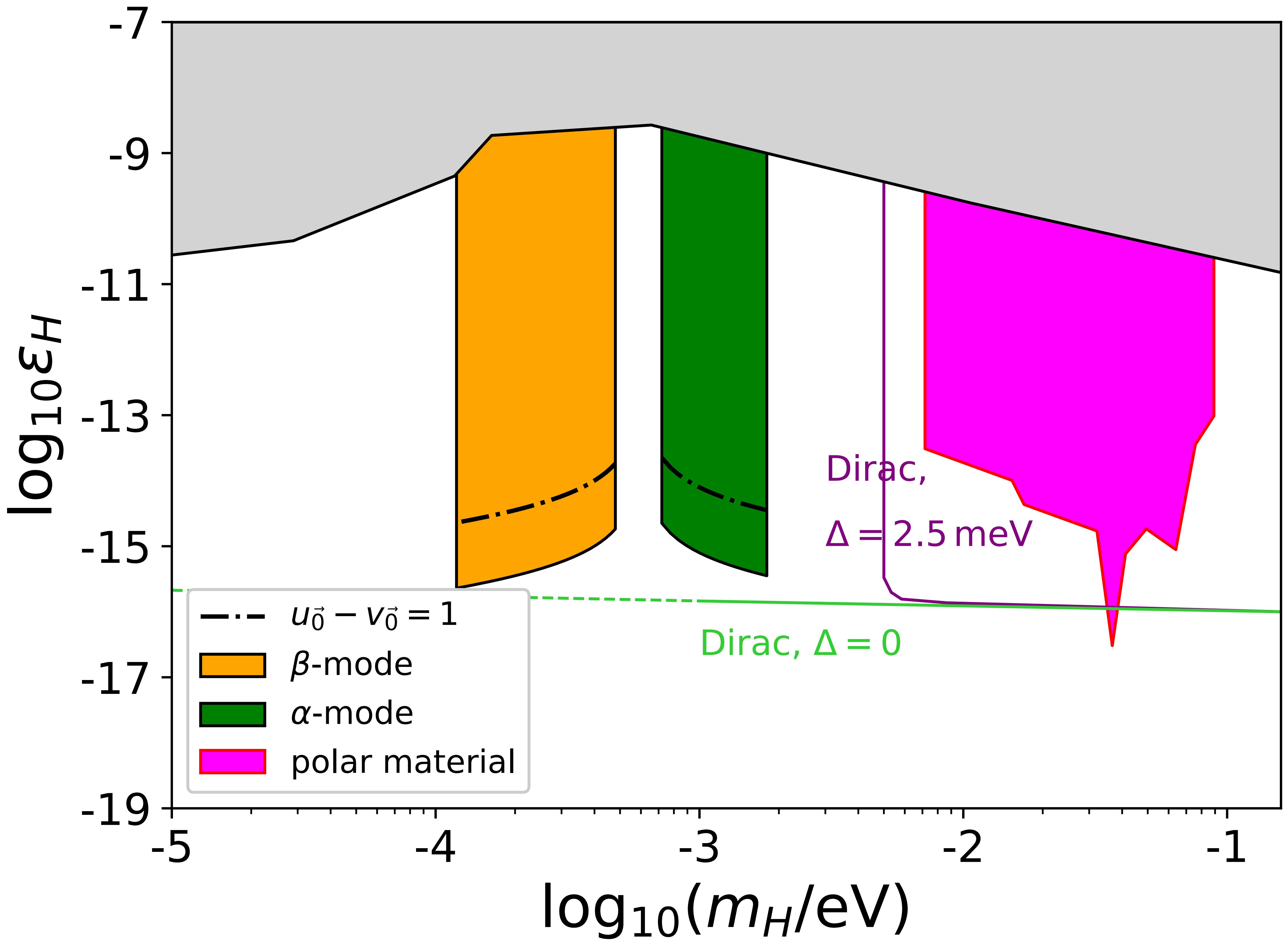
- CM-axion (magnon)-EM field interaction Hamiltonian $D = \sum_r \frac{U/\delta t}{1 + U^2 m_r^2/\delta t^2}(O_{r1} - iO_{r2})$

$$H_{\rm int} = -\frac{\alpha_e}{4\pi}\sqrt{\frac{s}{2N}}(u_{\vec{0}} - v_{\vec{0}})\left[D^* \alpha^\dagger_{\vec{0}} - D\beta^\dagger_{\vec{0}} + \text{h.c.}\right]\int d^3x\, \vec{E} \cdot \vec{B},$$

Axion DM



Hidden photon DM



Scan of magnetic field: $1\,\mathrm{T} < B_0 < 10\,\mathrm{T}$

Each time step: $\Delta t = 10^2\,\mathrm{s}$

Total observation time: $1\,\mathrm{yr}$

Target volume: $V = (10\,\mathrm{cm})^3$

Noise rate: $dN_{\mathrm{noise}}/dt \sim 10^{-3}\,\mathrm{s}^{-1}$

[Chigusa, Moroi, KN (2021)]

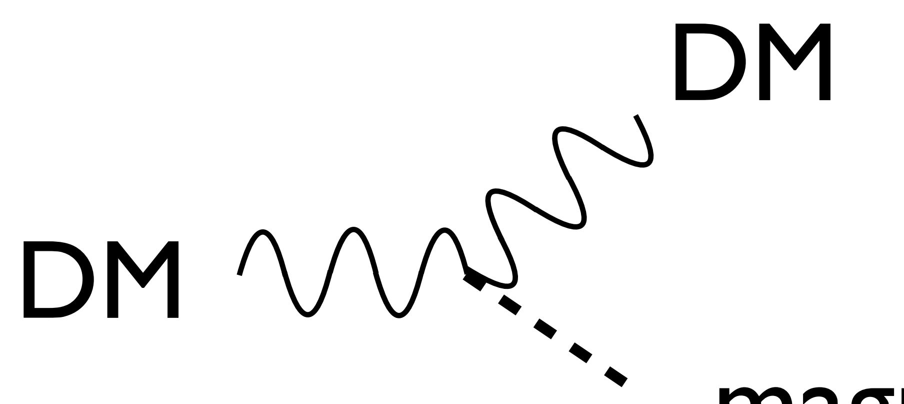
Note Proposal using different material : [Schutte-Engel et al. (2021)]

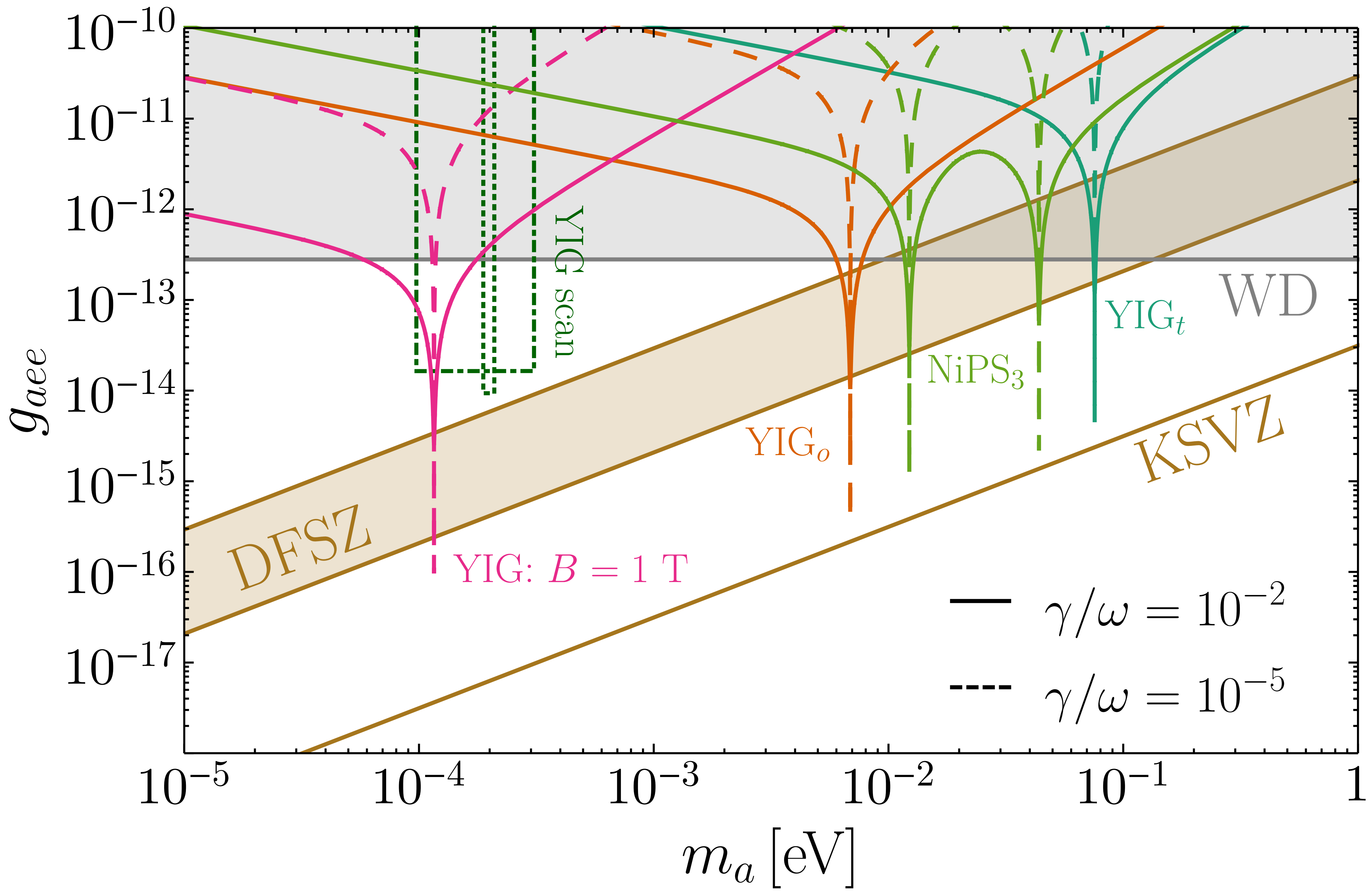
Applications of condensed-matter ideas

Magnon

- Axion detection with optical magnons [Mitridate, Trickle, Zhang, Zurek (2020)]
- Multi-magnon [Esposito, Pavaskar (2022)]
- Light DM scatter off magnon

[Trickle, Zhang, Zurek (2019)]





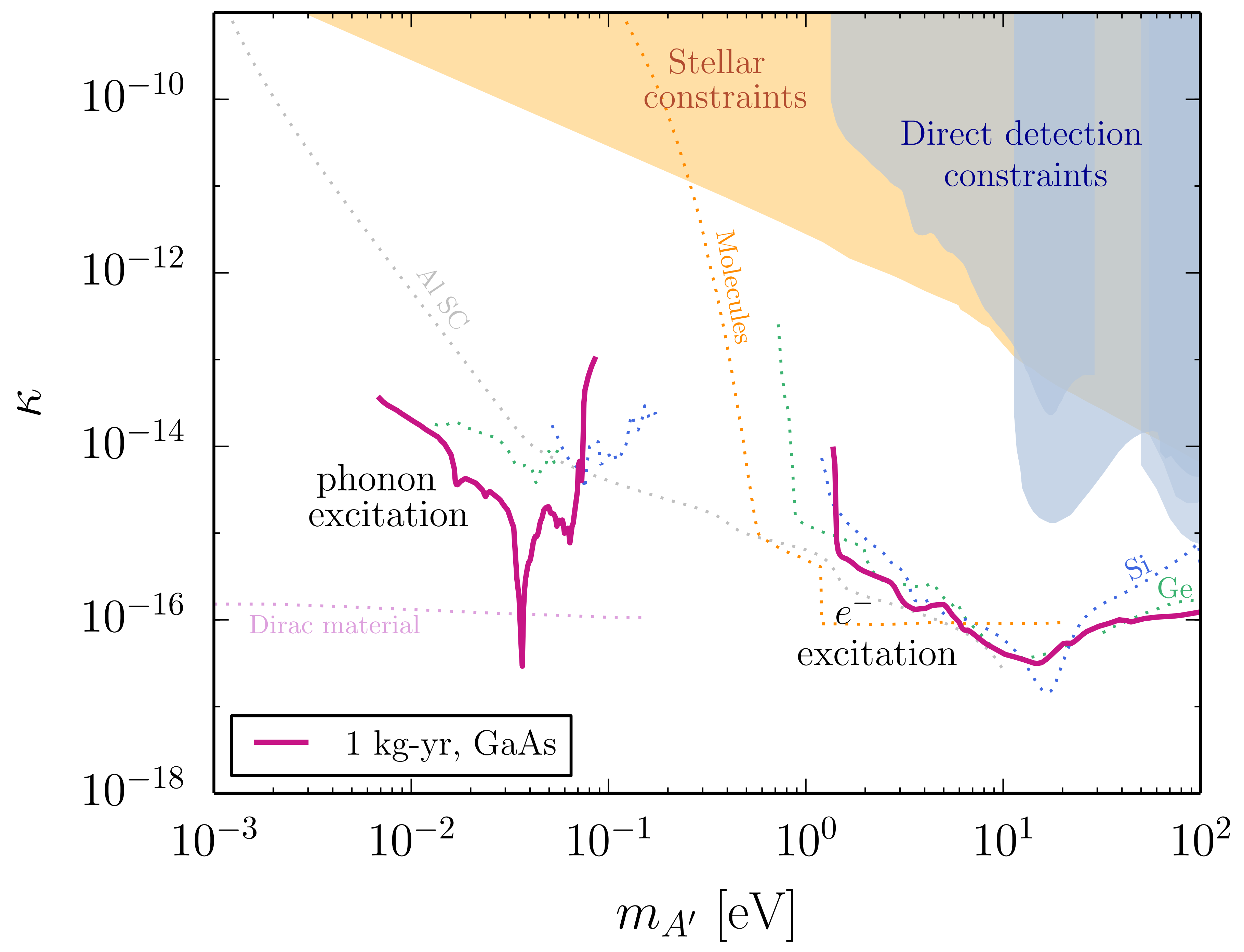
Applications of condensed-matter ideas

Phonon

[Knapen, Lin, Pyle, Zurek (2017)]

- Dark photon absorption by phonon/ light DM scatter off phonon in polar material

[Griffin et al., (2019)] [Knapen, Kozaczuk, Lin (2021)]



- Axion detection with phonon-polariton

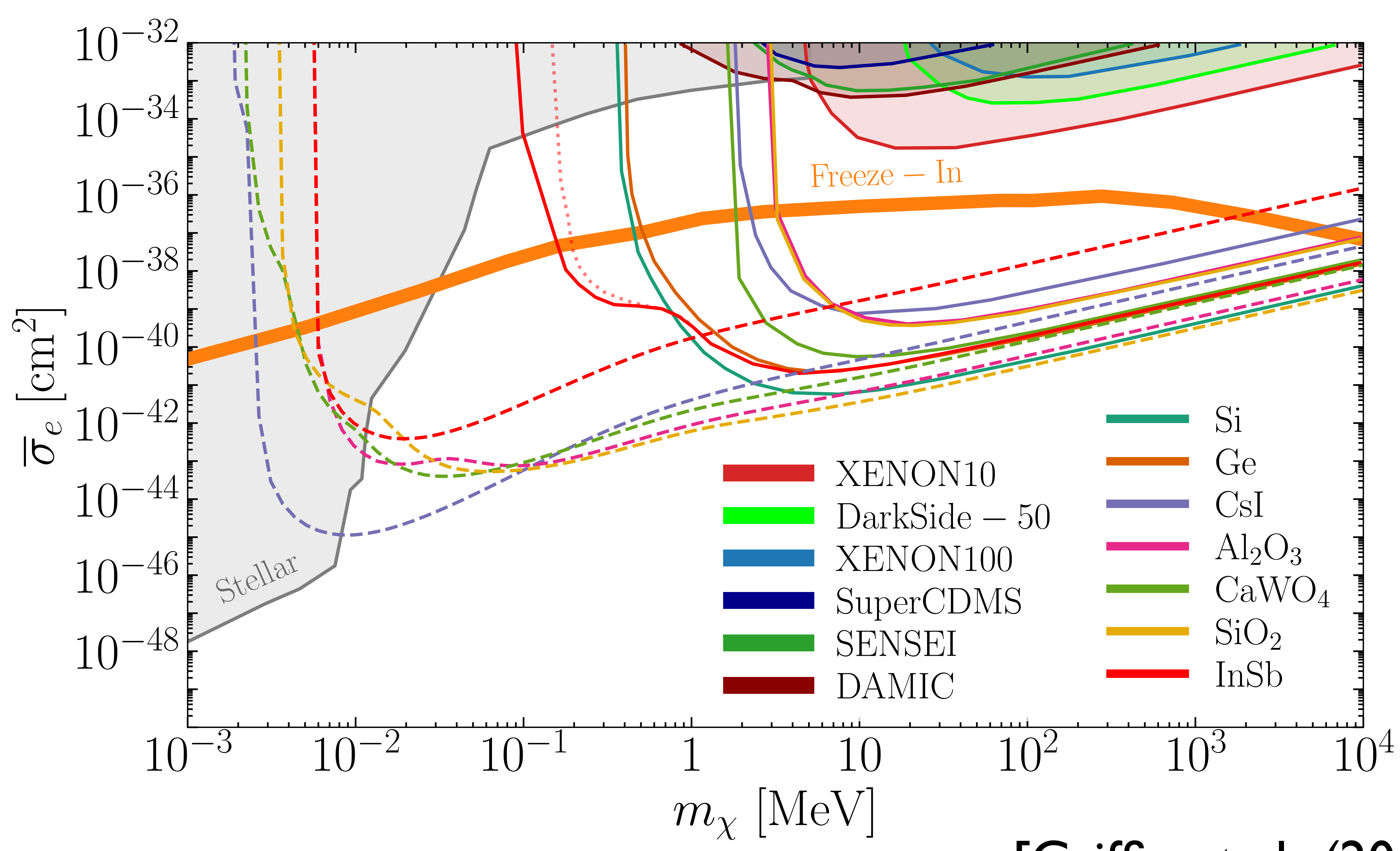
[Mitridate, Trickle, Zhang, Zurek (2020)] [Marsh, McDonald, Millar, Schutte-Engel (2022)]

Applications of condensed-matter ideas

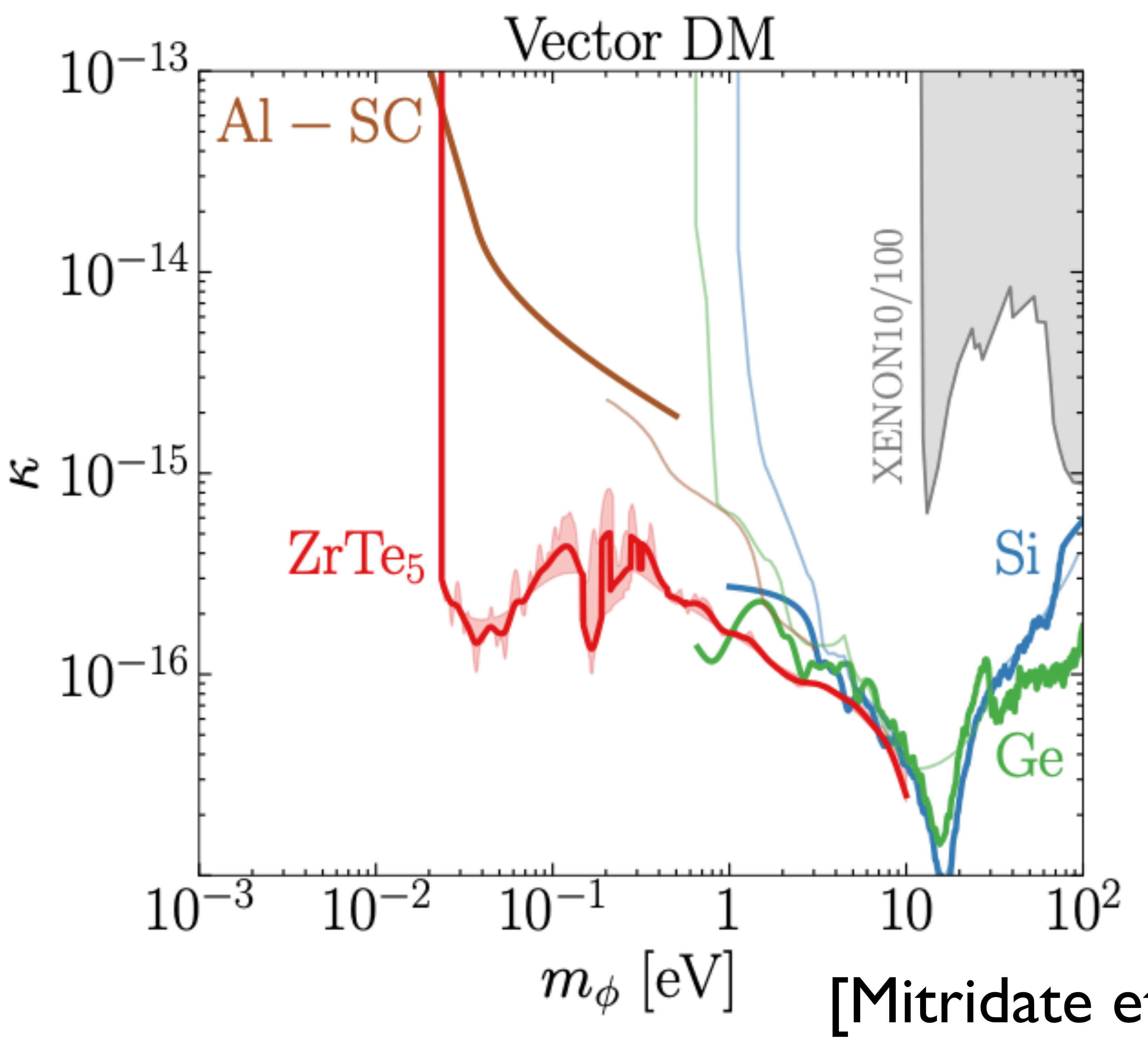
Electron

DM absorption/scatter by electron in various materials

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



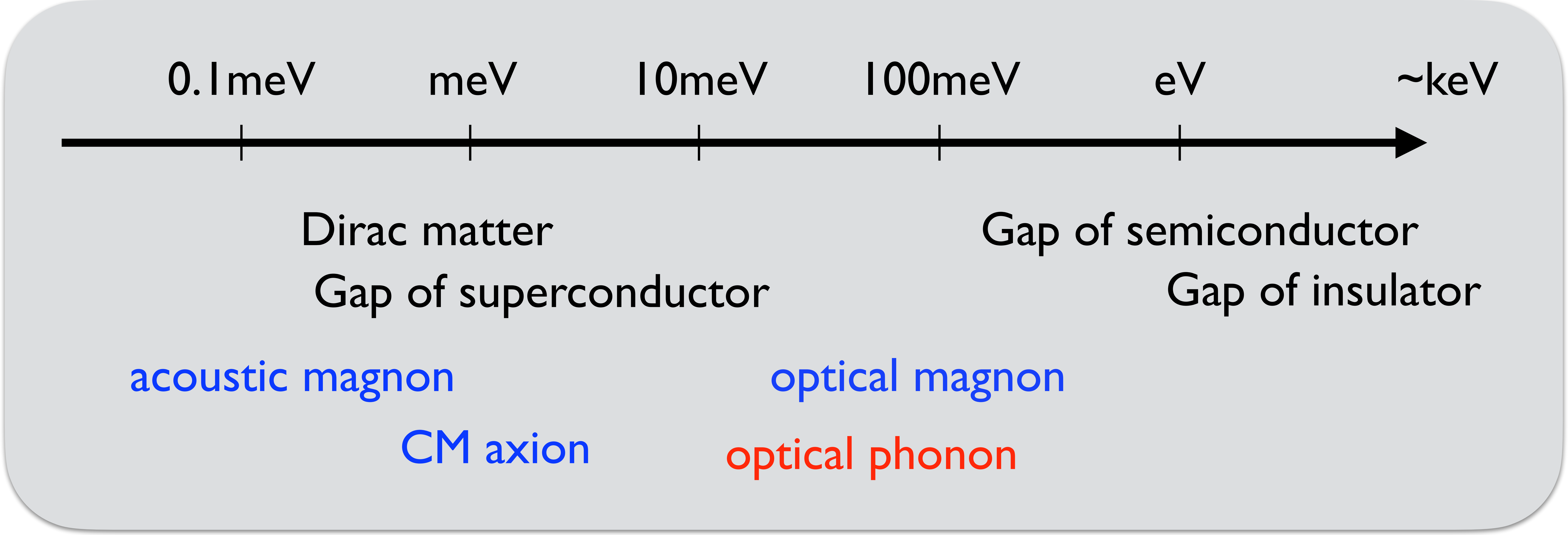
[Griffin et al., (2019)]



[Mitridate et al. (2021)]

Summary

- Quantum fields in condensed-matter may be useful for DM detection



- Particle and condensed-matter physics interdisciplinary field for New Physics Search.