International Center for Quantum-field Measurement System for Studies of the Universe and Particles

Light dark matter detection with collective excitation in matter

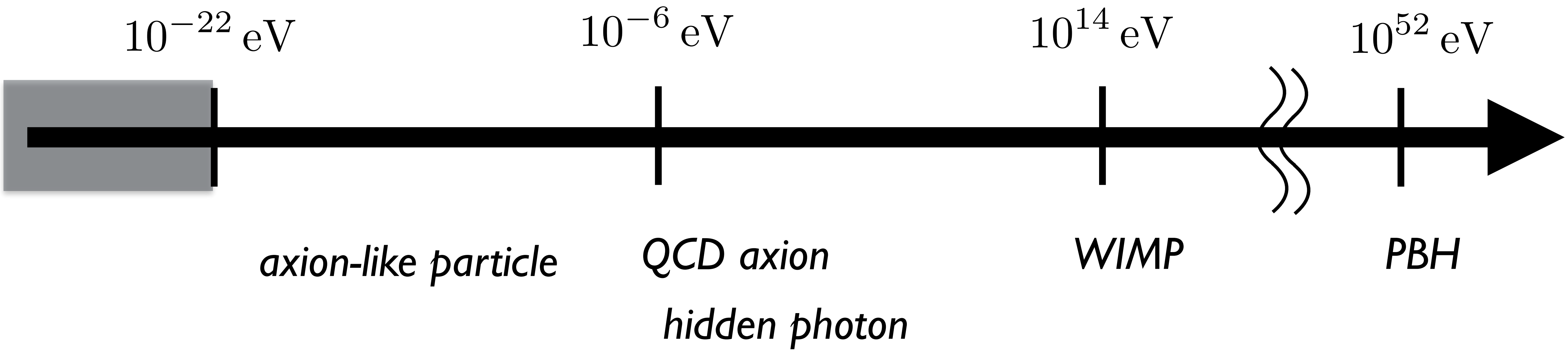
Kazunori Nakayama (Tohoku Univ & QUP)

Physics in LHC and beyond (2022/5/14)

Introduction

Dark matter search

- Dark matter mass range



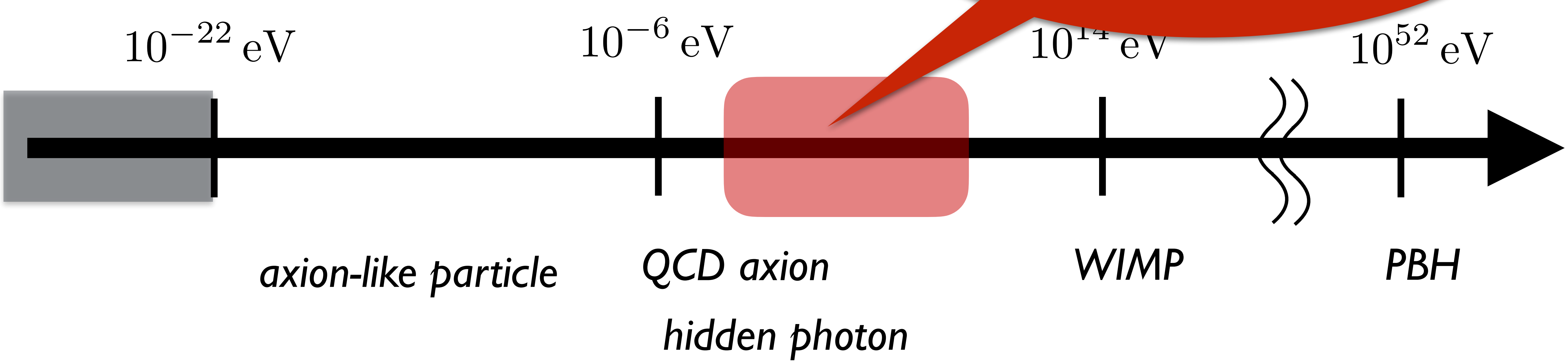
- We need broad ideas for broad energy scales

Direct detection, cosmic rays, accelerator experiments, astronomical/cosmological observations,…

Dark matter search

- Dark matter mass range

Dark matter detection with condensed-matter ideas



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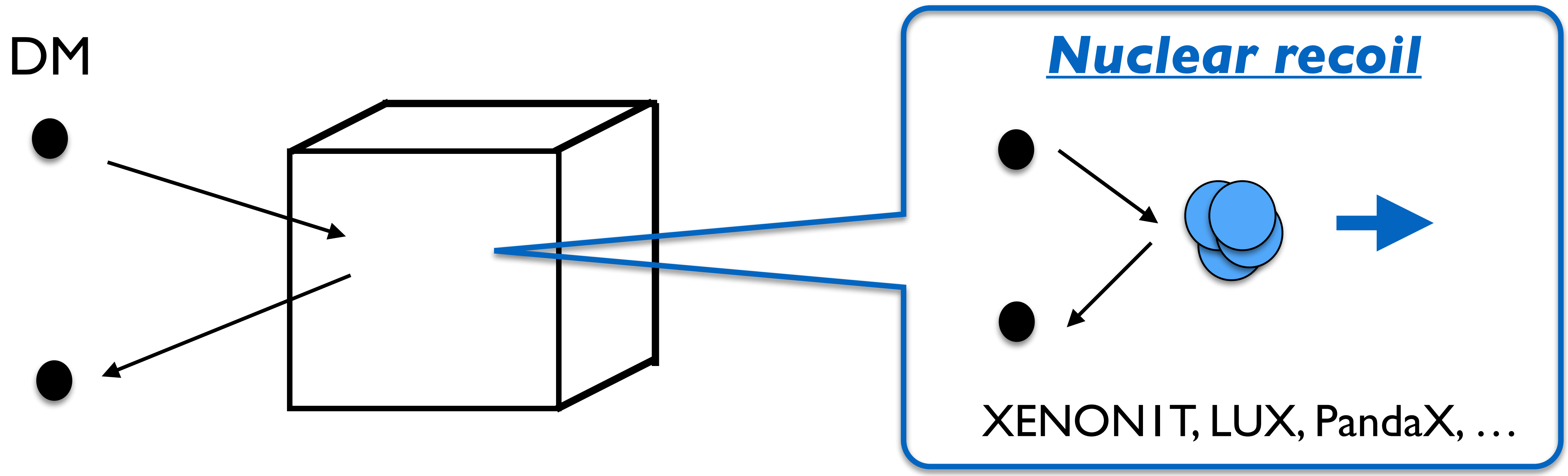
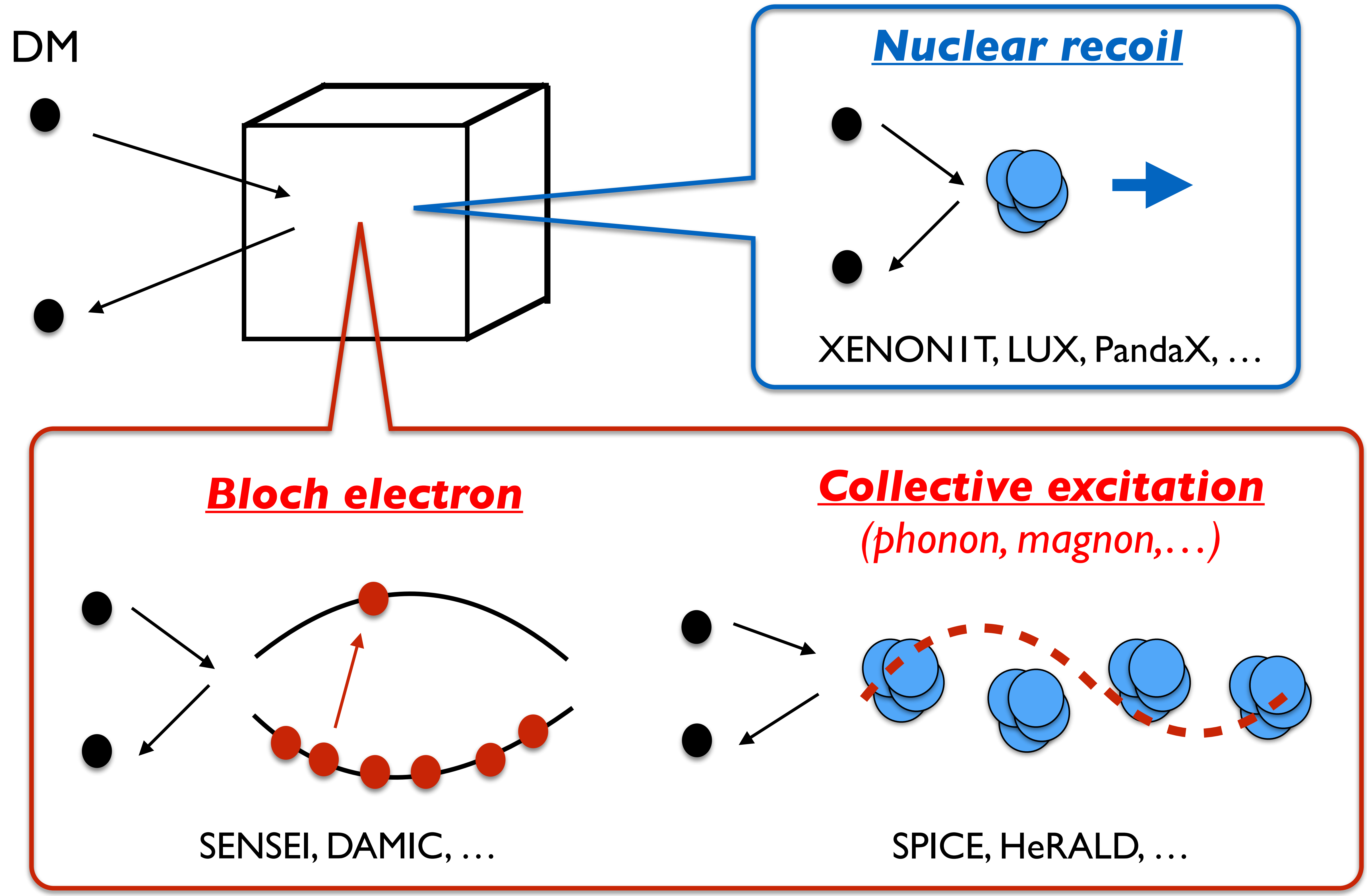
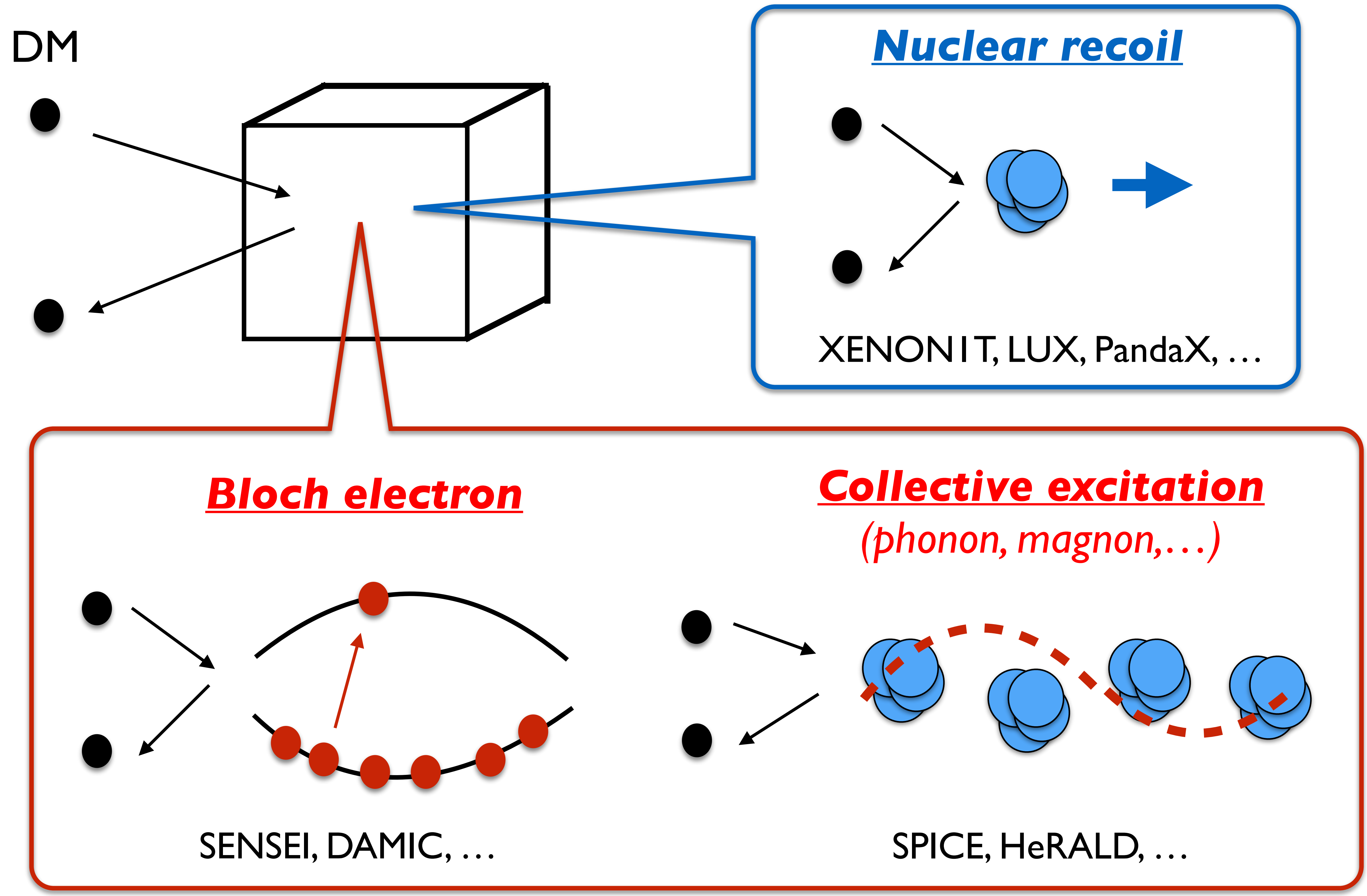
Dark matter direct detection



Dark matter direct detection



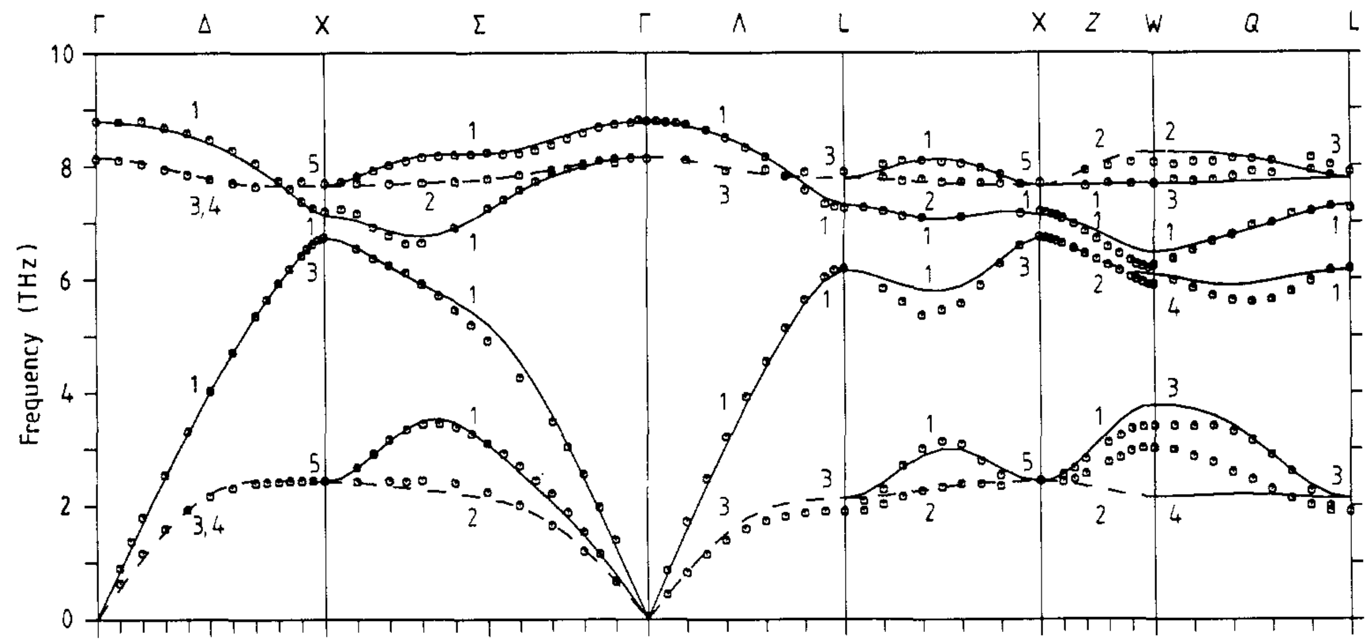
Dark matter direct detection



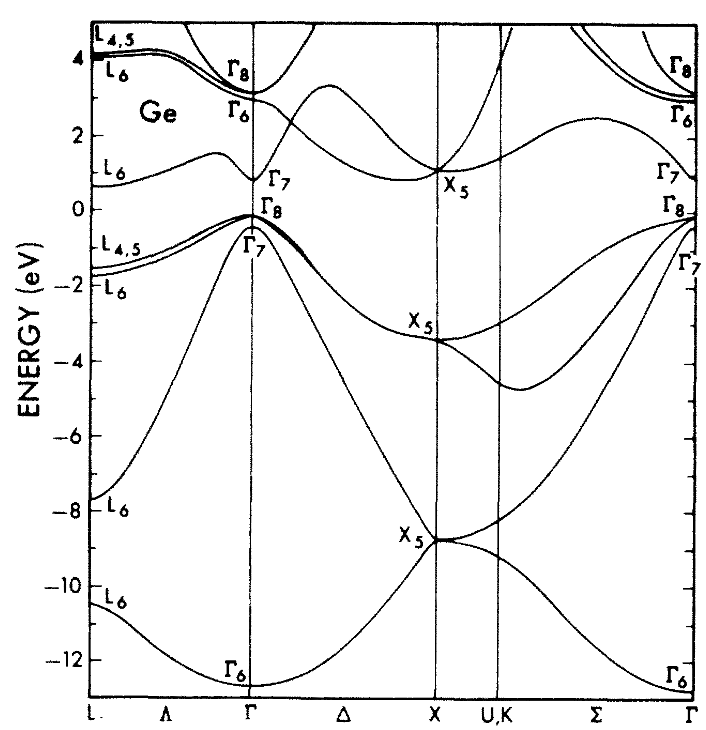
In this talk I will focus on magnetic collective excitations.

Dispersion of (quasi)particles in solids

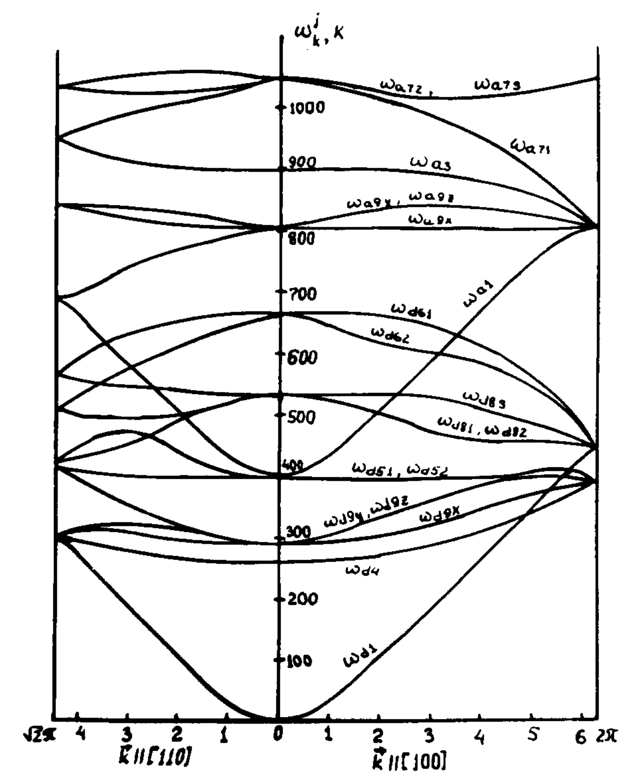
Phonon (GaAs)



Electron (Ge)



Magnon (YIG)



Dispersion of (quasi)particles in solids

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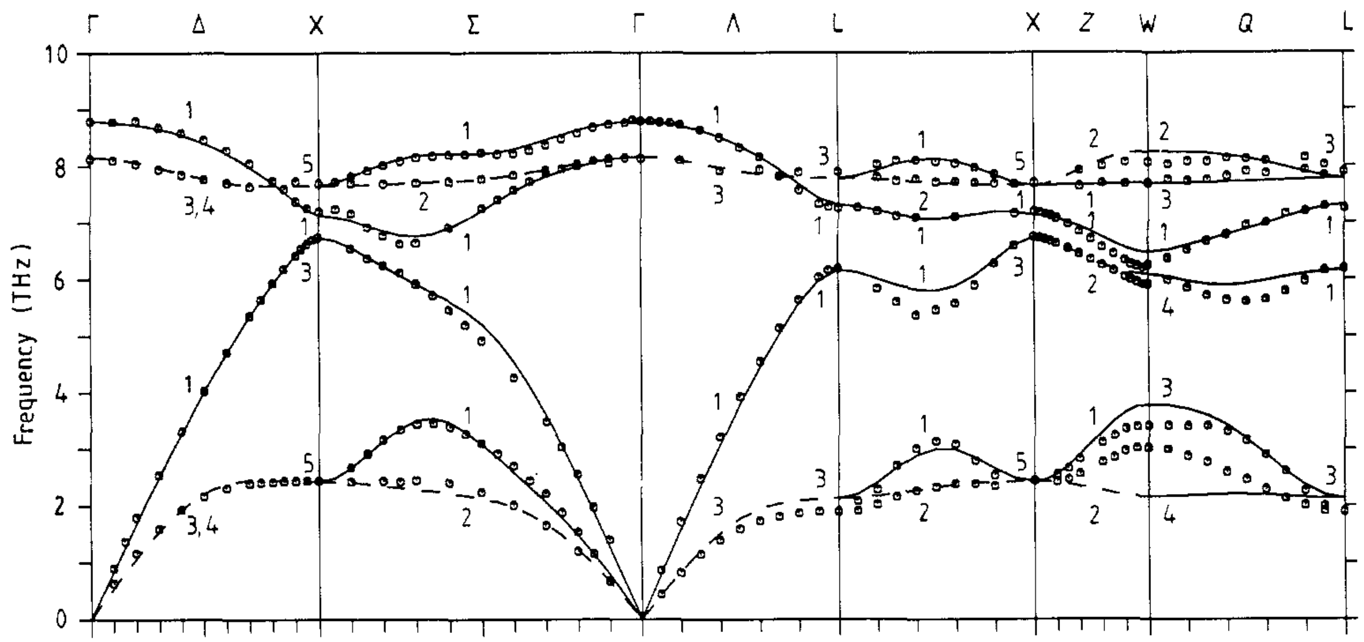

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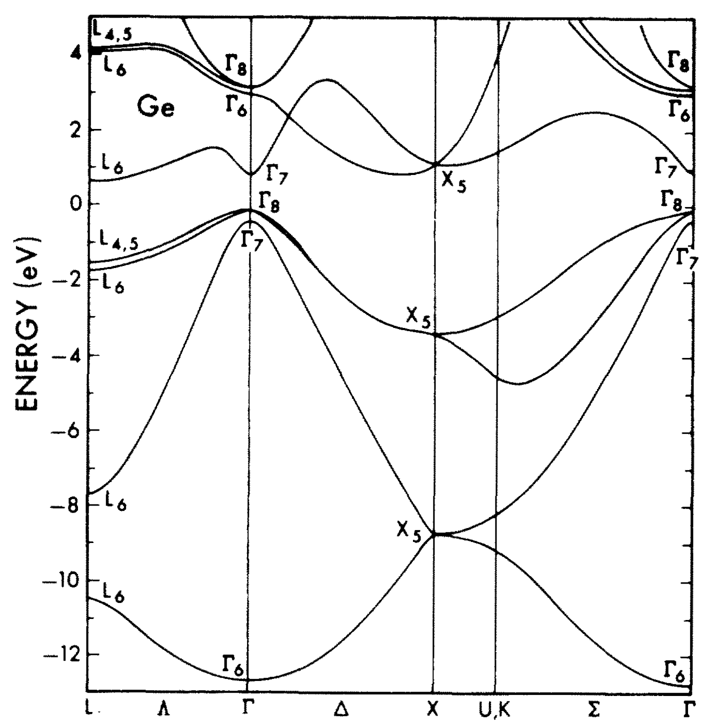

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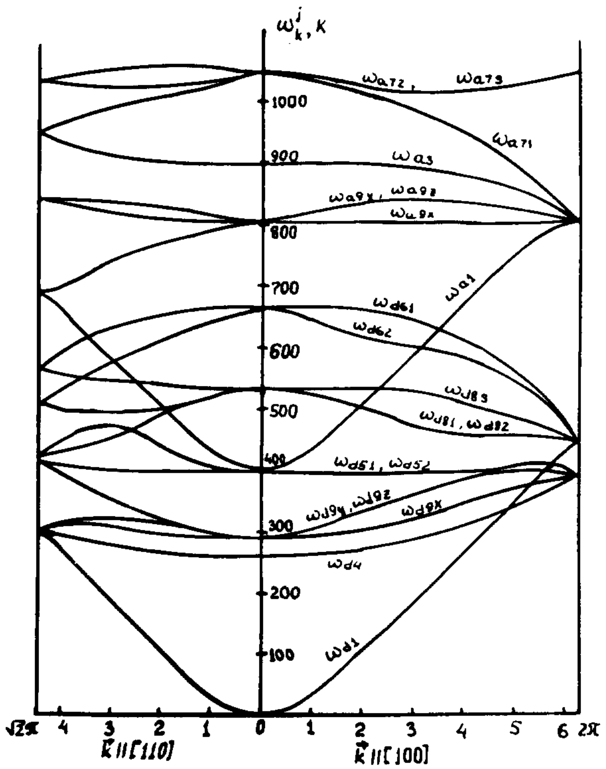


Rich structure: useful for new particle search !

Towards light DM detection

- ***<u>Low reaction threshold</u>***

Dispersion of (quasi-)particles in material

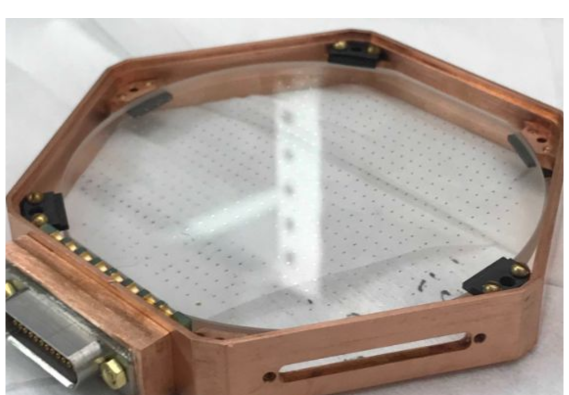
$$1\,\mathrm{meV} \lesssim m_{\mathrm{DM}} \lesssim 1\,\mathrm{keV}$$ (absorption : axion, hidden photon)

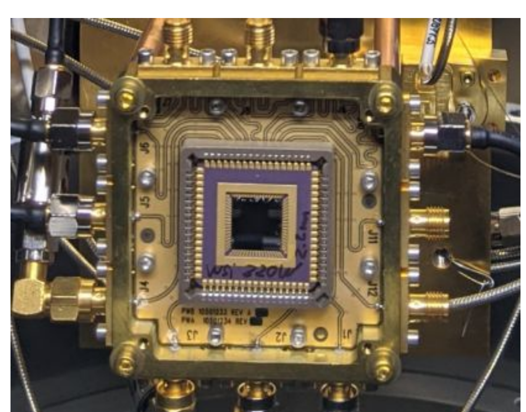
$$1\,\mathrm{MeV} \lesssim m_{\mathrm{DM}} \lesssim 1\,\mathrm{GeV}$$ (scatter)

- ***<u>Low detection threshold</u>***

Developments of TES, Qubits, SNSPD, Opto-mechanical cavity, …

$\longrightarrow$ Single photon/phonon/electron detection





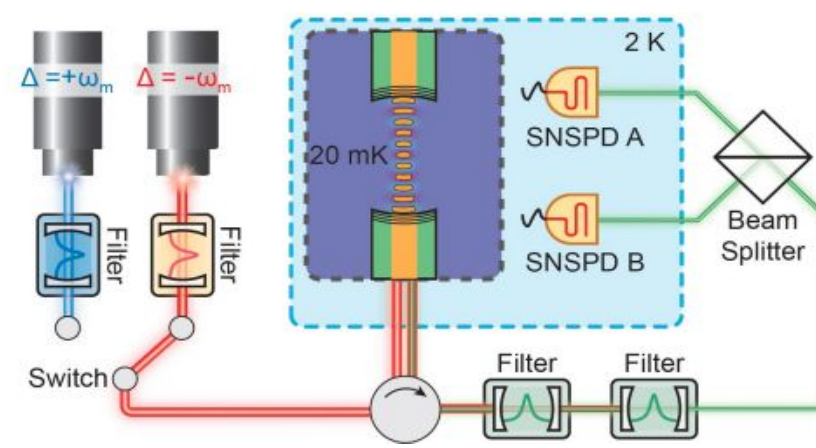
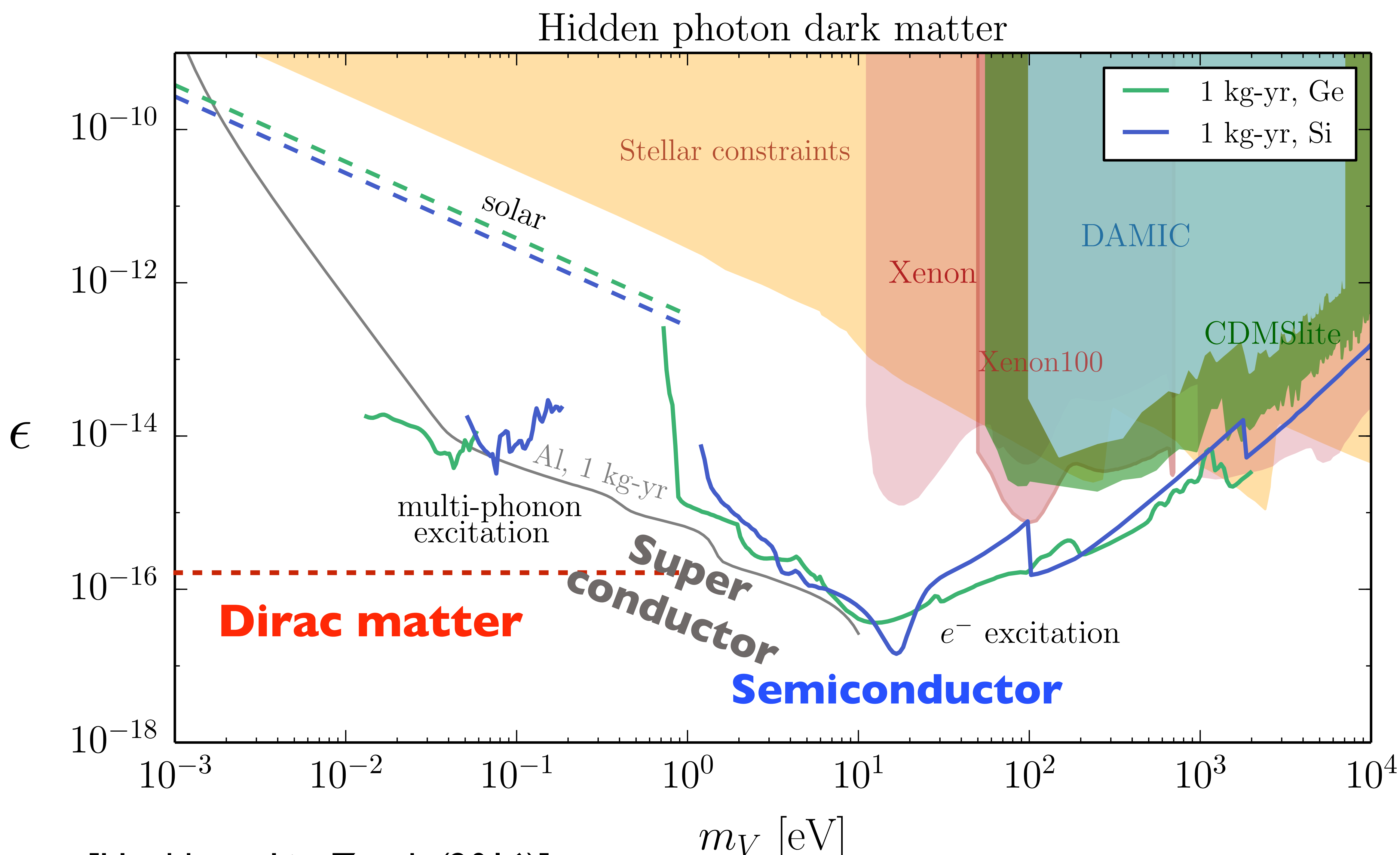


Figure from slides by M. Garcia-Sciveres (see Appendix)

DM detection with electron/phonon

DM absorption (hidden photon)

$$\mathcal{L} = -\frac{\epsilon}{2} F_{\mu\nu} H^{\mu\nu}$$



[Hochberg, Lin, Zurek (2016)]

DM detection with electron/phonon

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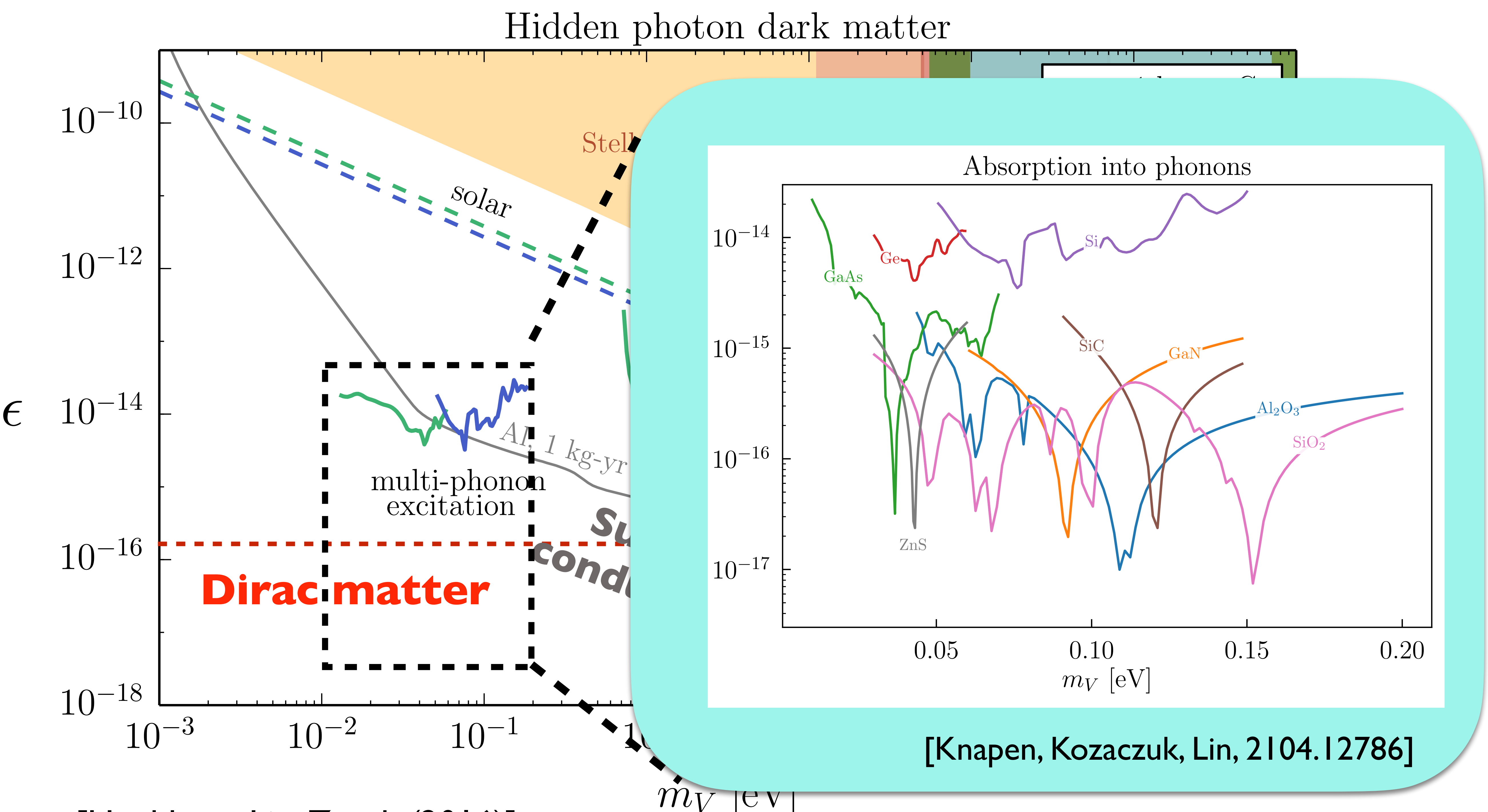
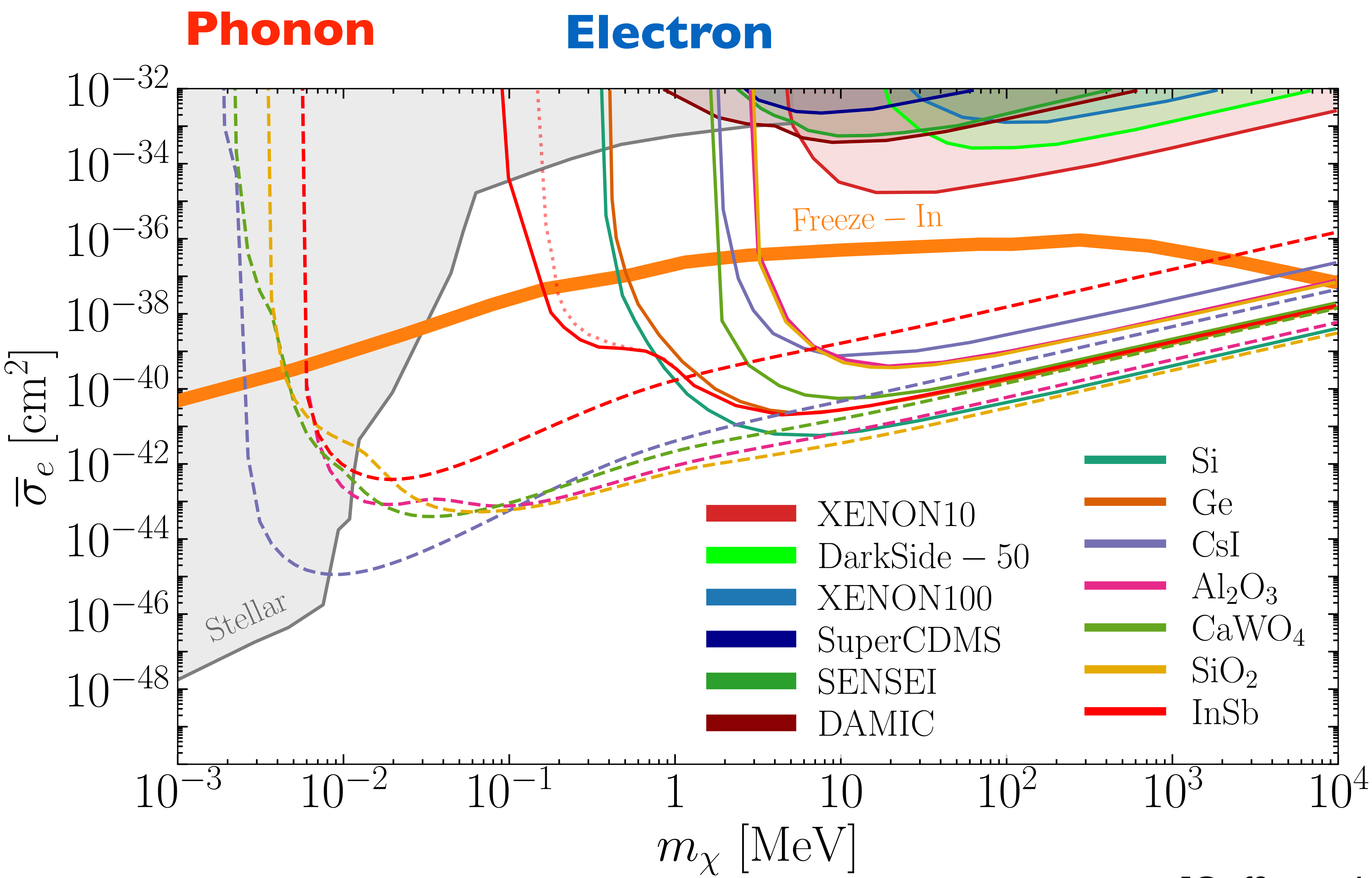


[Knapen, Kozaczuk, Lin, 2104.12786]

[Hochberg, Lin, Zurek (2016)]

DM detection with electron/phonon

DM scatter



[Griffin et al. (2019)]

1. DM detection with magnon

[Chigusa, Moroi, KN (2020)]

2. DM detection with condensed-matter axion

[Chigusa, Moroi, KN (2021)]

1. DM detection with magnon

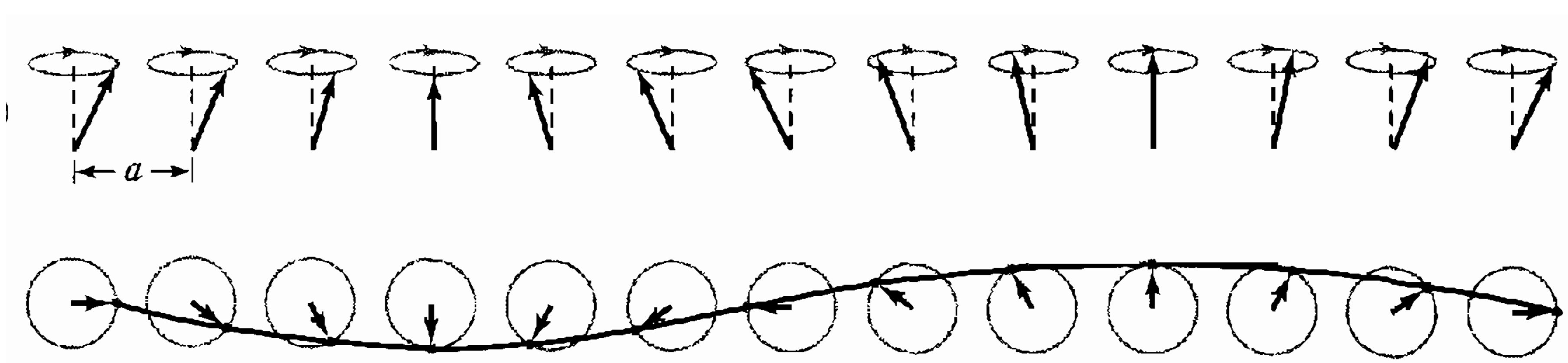
Heisenberg model for ferromagnet

- 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 for T=0 and B=0（**Ferromagnet**）

- Fluctuation around the ground state : collective spin wave

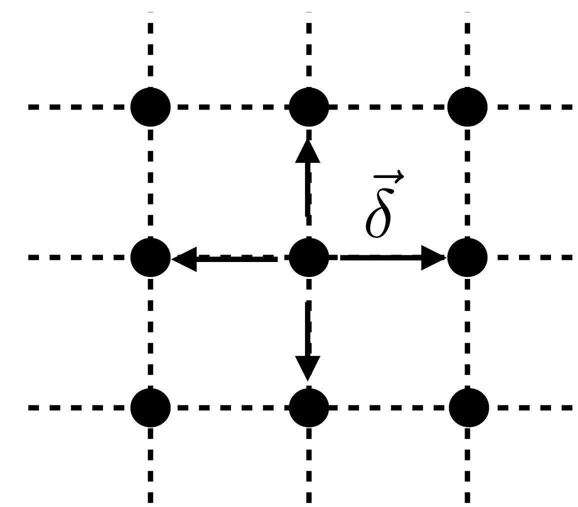


Magnon

- Quantized Hamiltonian in momentum space

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

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



- Magnon dispersion relation:

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

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

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

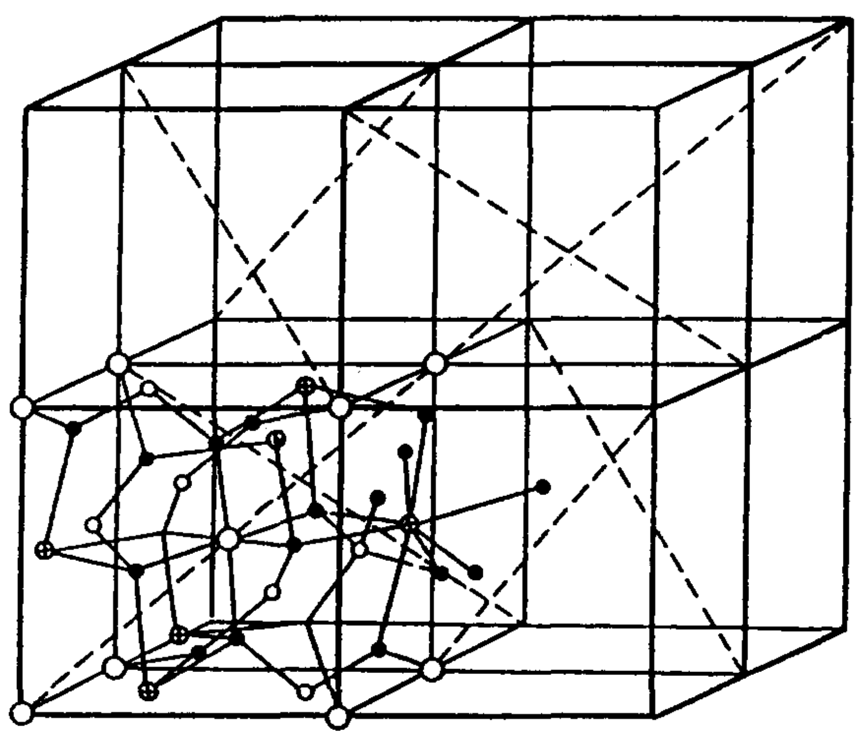
Magnon dispersion (YIG)

YIG= $Y_3Fe_5O_{12}$

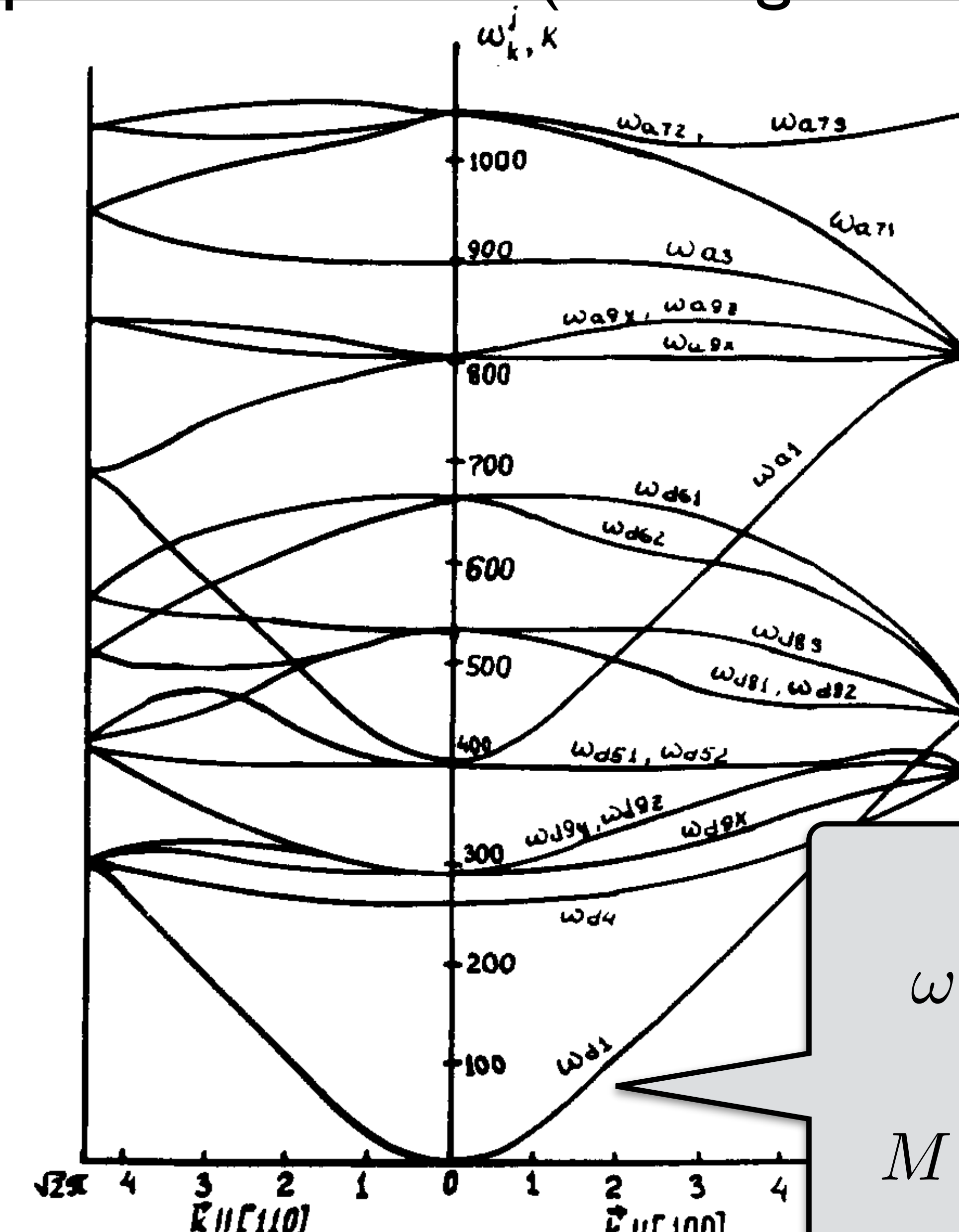
- 20 Fe^3+ ions in magnetic unit cell
- "Ferri-magnet"

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

8 Fe : $-\frac{5}{2}\mu_B \times 8$ ↓



dispersion relation (20 magnon branches)



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

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

Cherepanov, Kolokolov, L'vov (1993)

Axion-magnon conversion

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

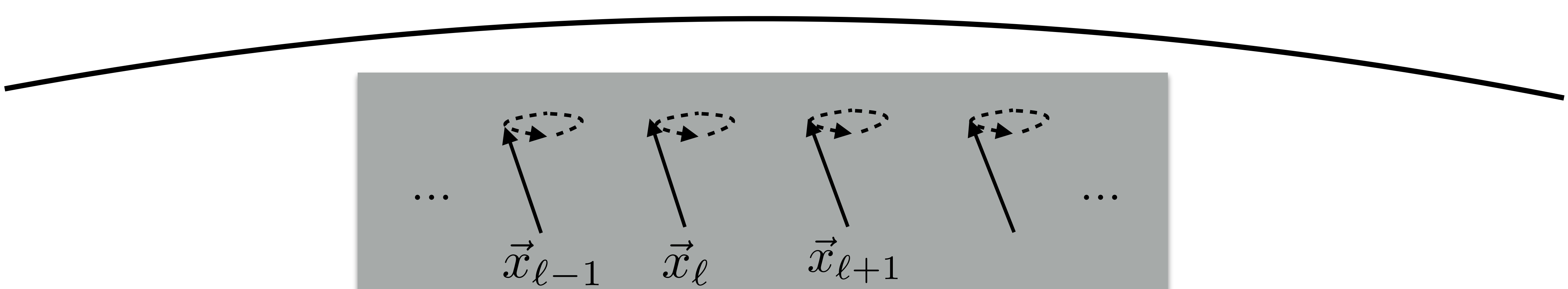
- Axion-electron interaction

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

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

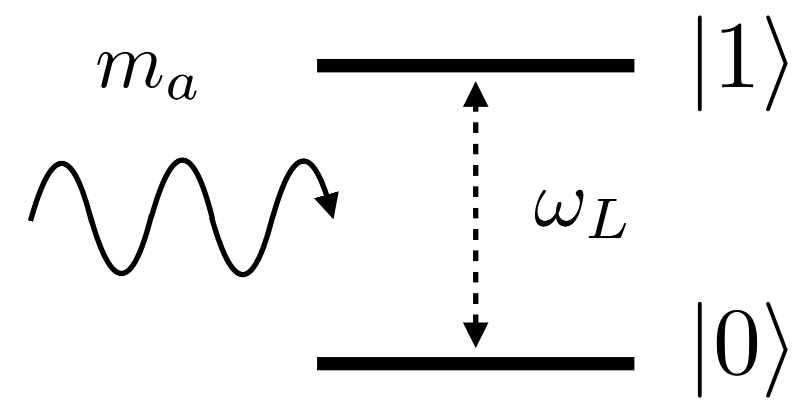


Resonant conversion

- 2-level system

  $|0\rangle$: 0-magnon state

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

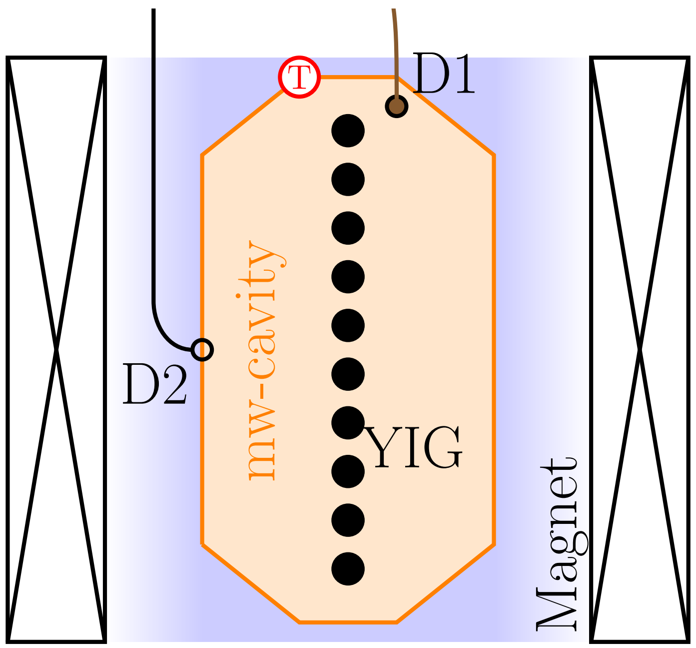


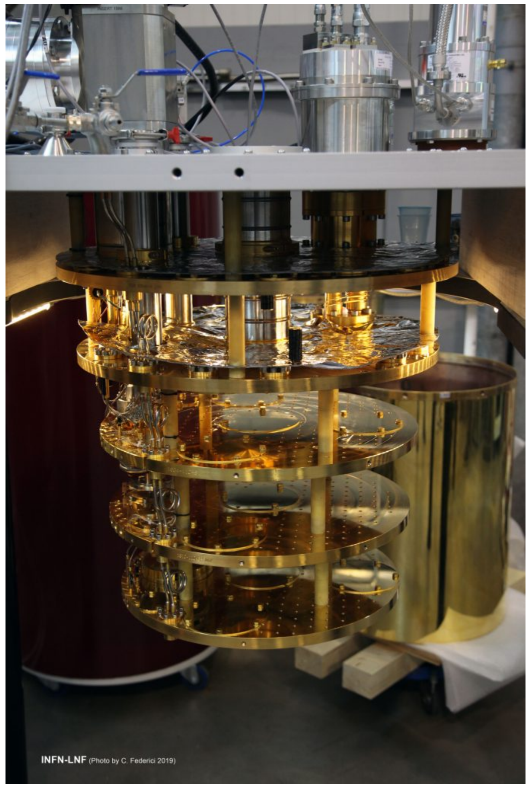
- Signal power at resonance: $m_a = \omega_L$

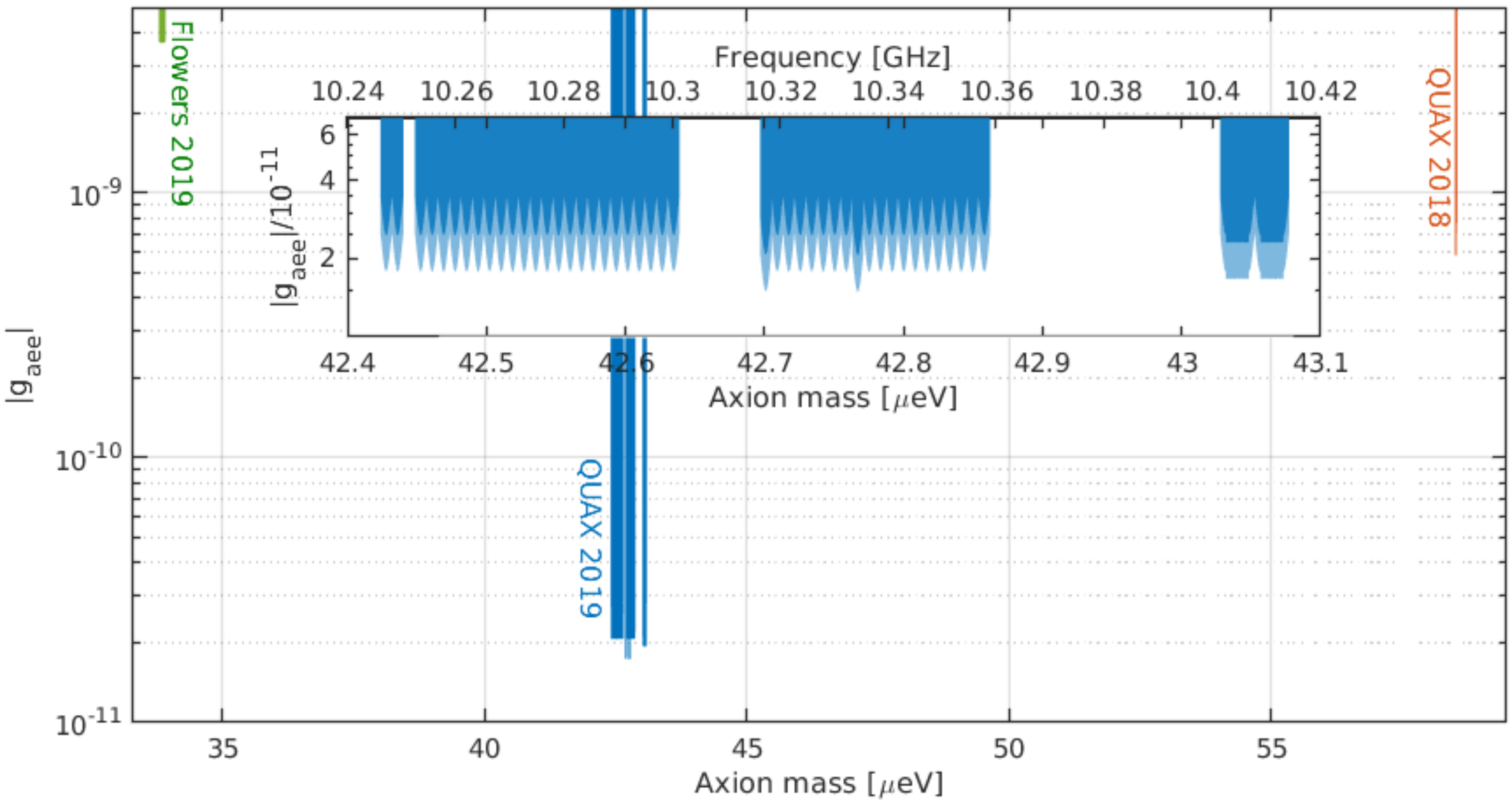
$$\frac{dE_{\rm signal}}{dt} = \frac{\omega_L P(t)}{2t} = \frac{\omega_L |V|^2 t}{8} \qquad V \equiv \sqrt{\frac{sN}{2}}\frac{m_a a_0 v_a^+}{f}$$

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

QUAX experiment

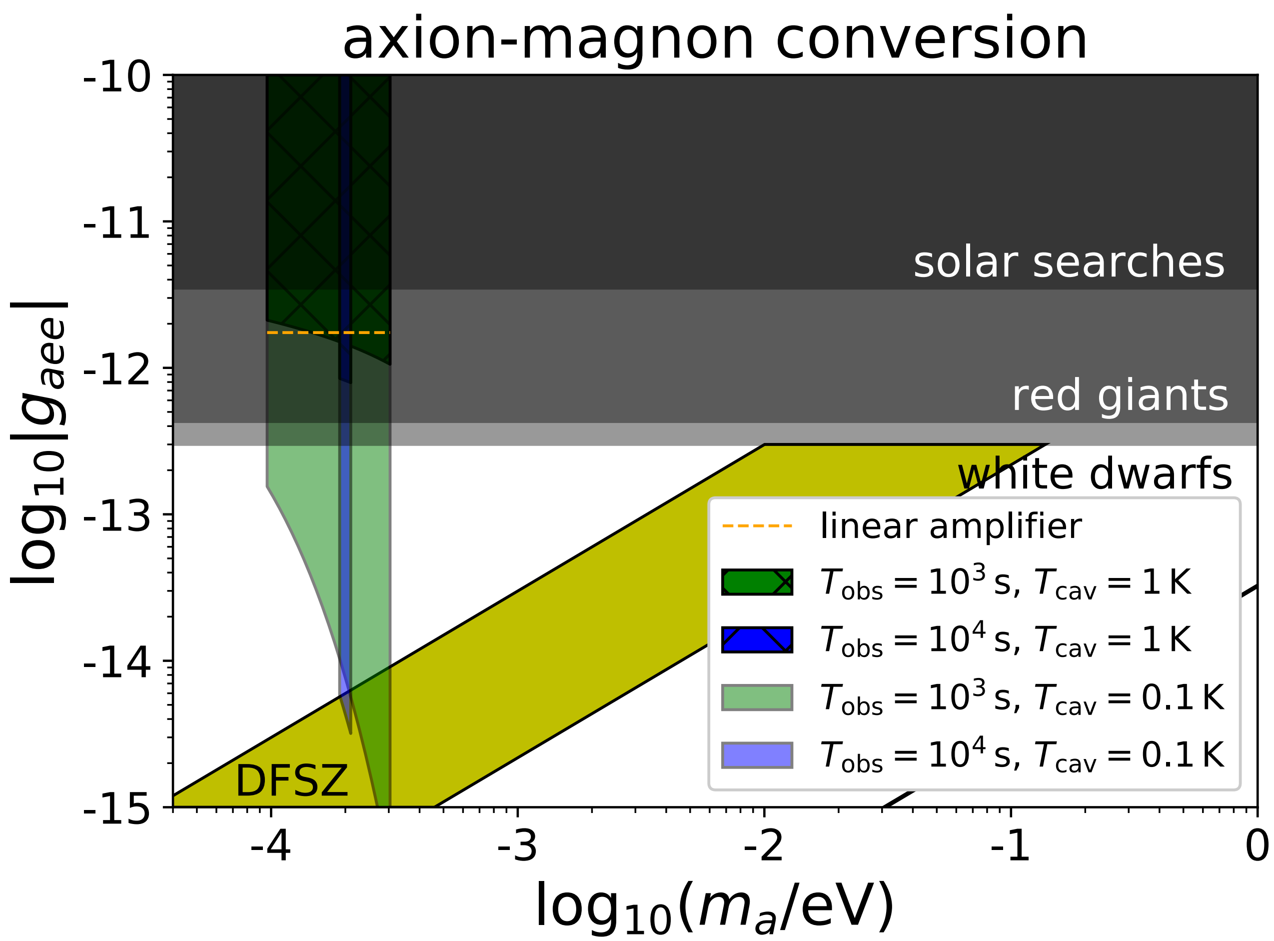


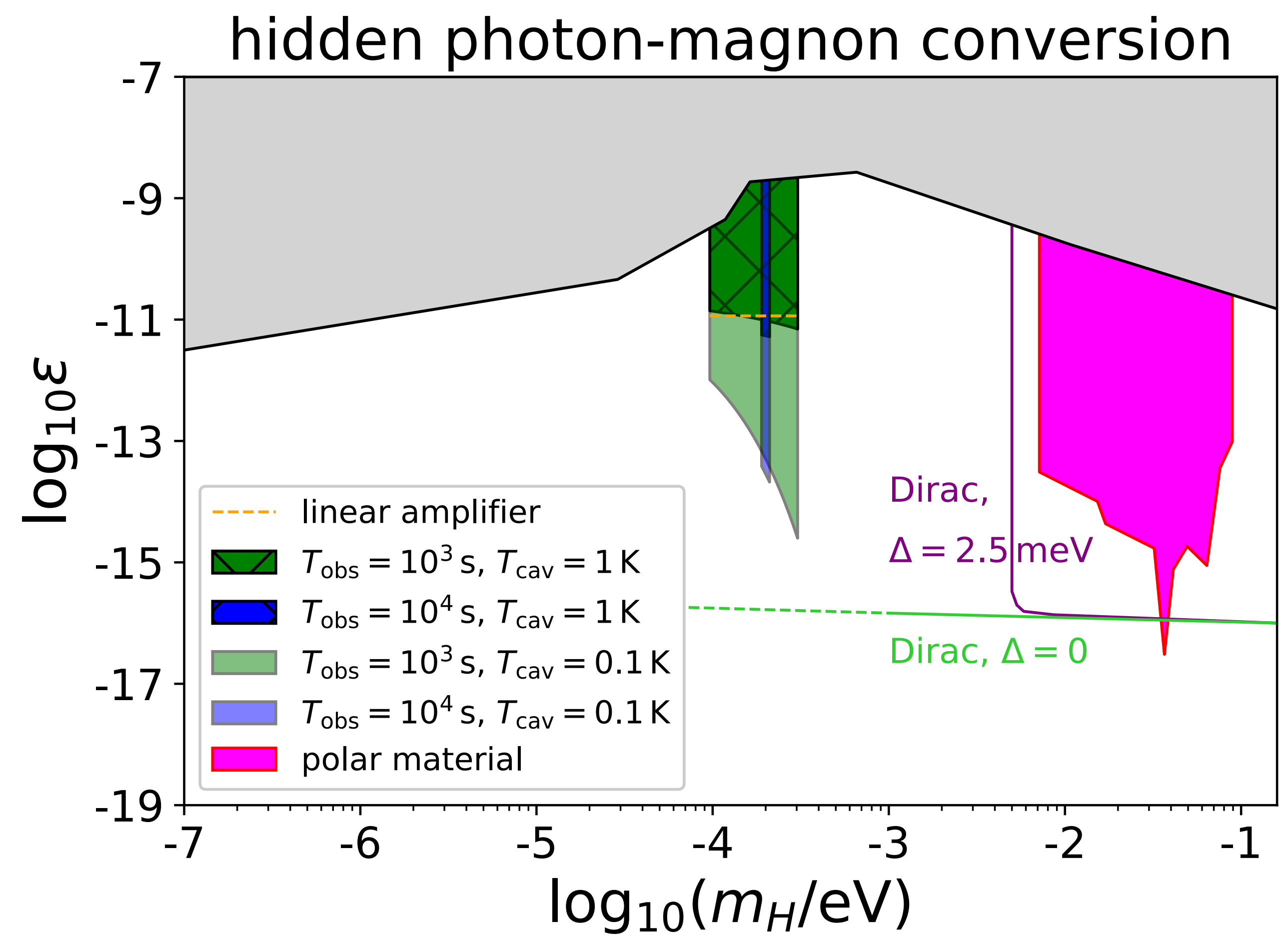




[QUAX collaboration (2020)]

Ultimate sensitivity from DM-magnon conversion





[Chigusa, Moroi, KN (2020)]

2. DM detection with condensed-matter axion

Axion in condensed-matter

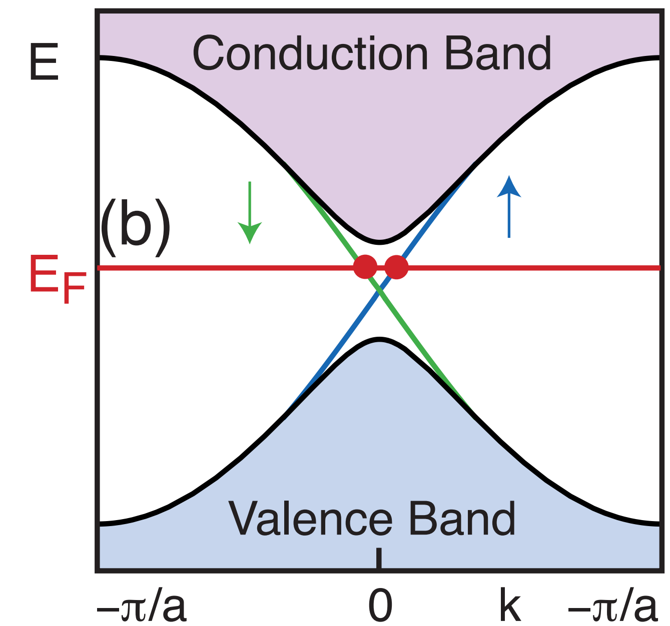
- Topological insulator [Kane, Mele (2005), Fu, Kane, Mele (2007)]

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

$\theta = 0$: normal insulator

$\theta = \pi$: topological insulator

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



[Hasan, Mele (2010)]

Dynamical axion

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

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

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

Example: Fu-Kane-Mele-Hubbard model

[Sekine, Nomura (2014)]

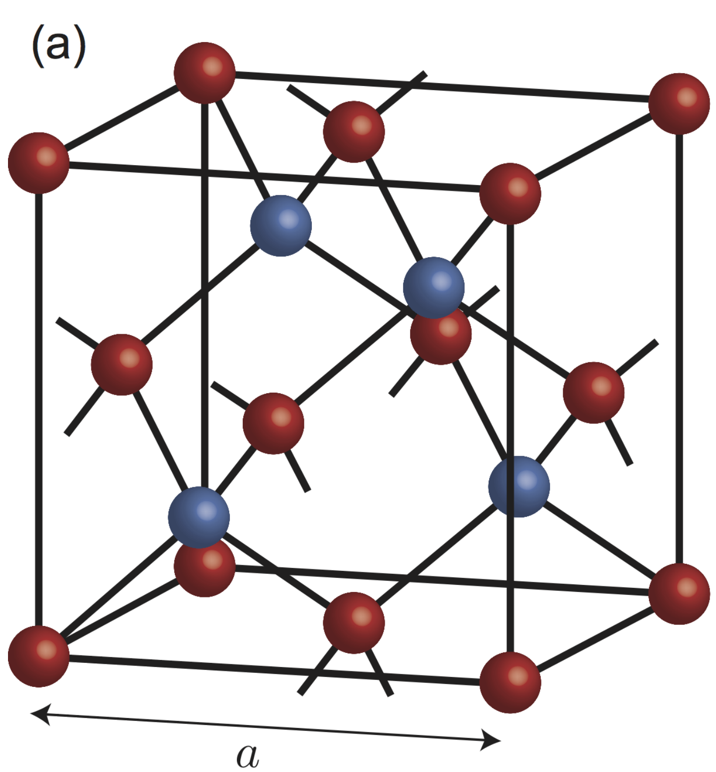
$$H_0 = \sum_{\langle i,j \rangle \sigma} t_{ij} c^\dagger_{i\sigma} c_{j\sigma} + i\frac{4\lambda}{a^2} \sum_{\langle\langle i,j \rangle\rangle} c^\dagger_i \vec{\sigma} \cdot (\vec{d}^1_{ij} \times \vec{d}^2_{ij}) c_j$$

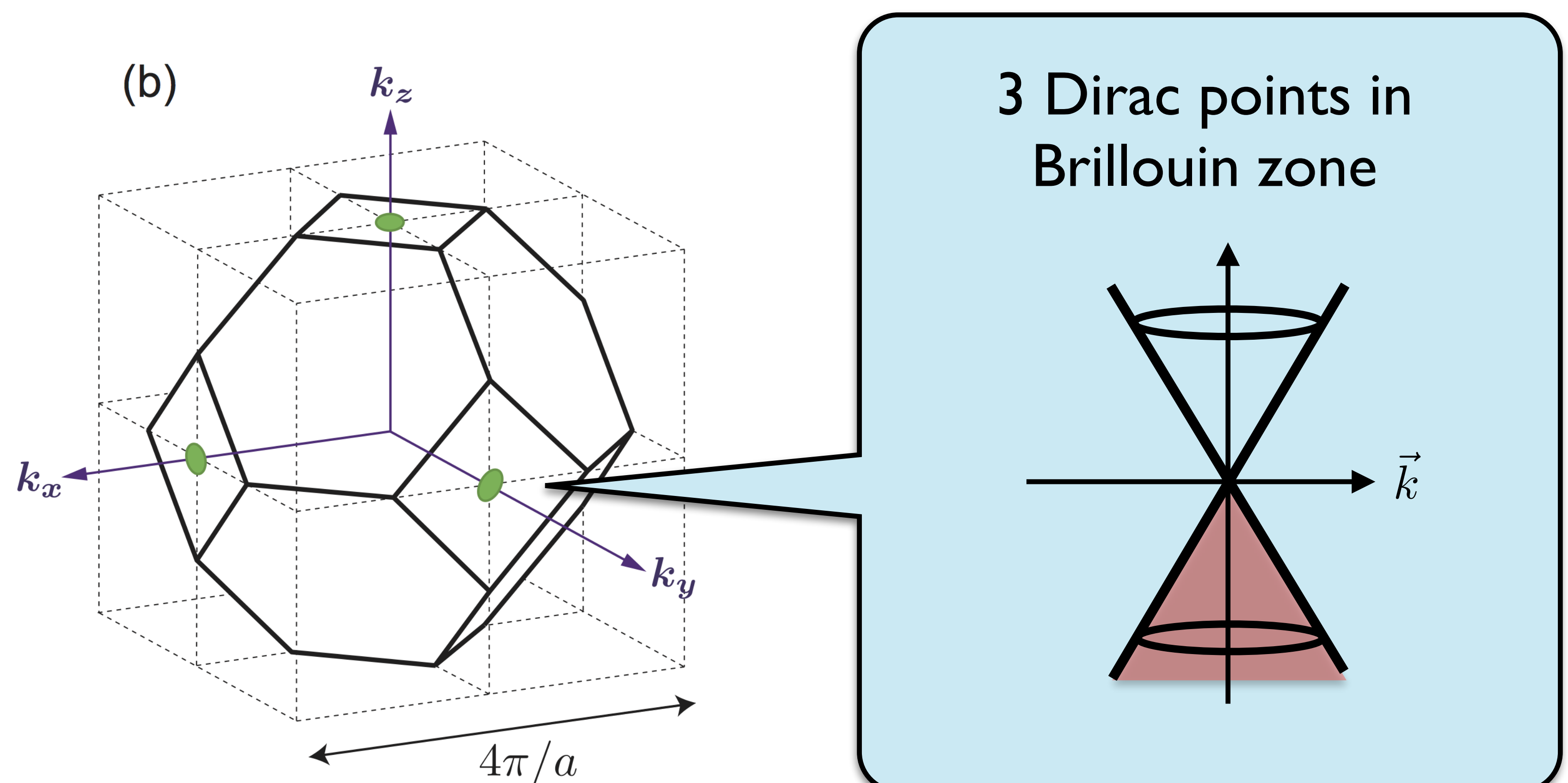
nearest neighbor tight-binding term

next nearest neighbor spin-orbit interaction term

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

Hubbard interaction term





- 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:

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

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

Axion ~ magnon in FKMH anti-ferromagnet model.

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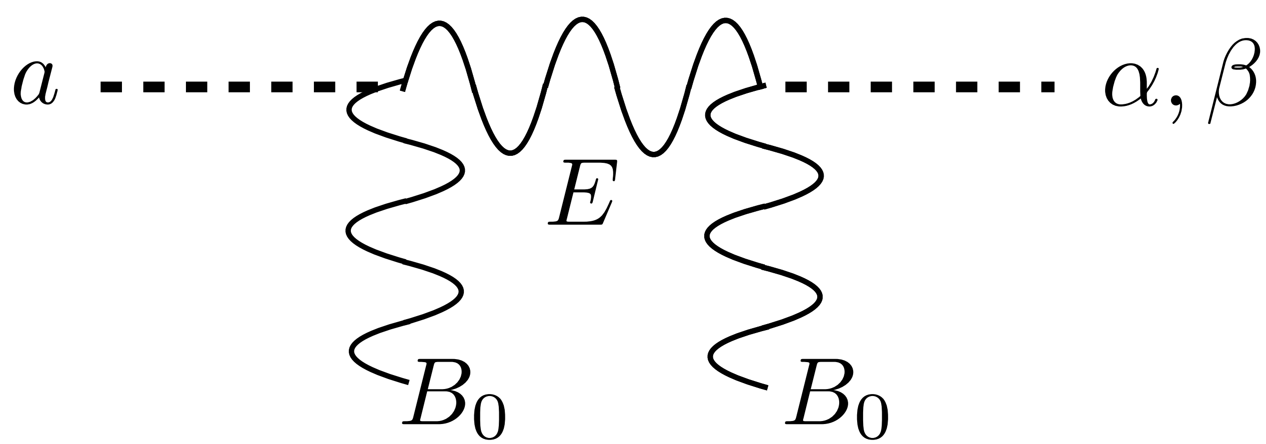
Fluctuation of magnetic order parameter
= **dynamical axion**

Axion ~ magnon in FKMH anti-ferromagnet model.

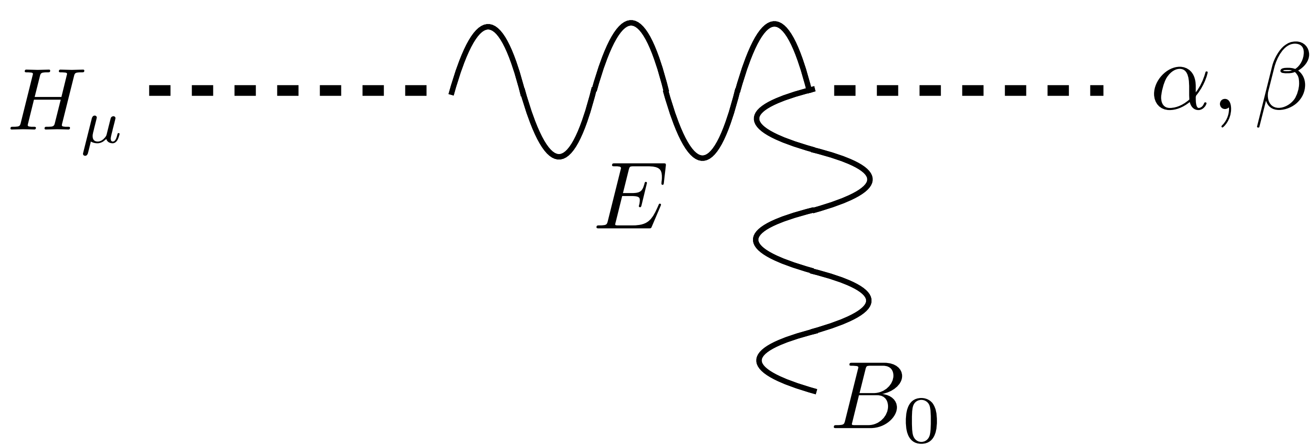
DM-axion to CM-axion

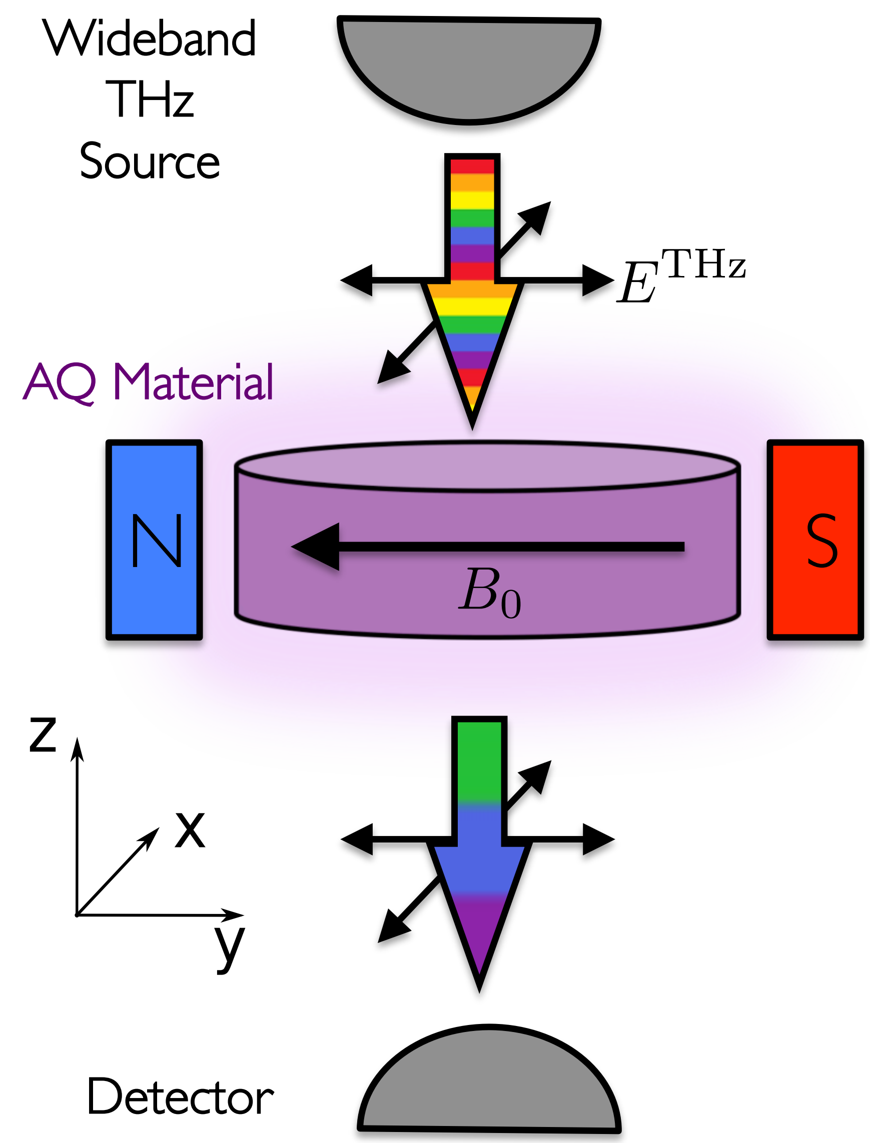
[Marsh et al (2018), Schutte-Engel et al. (2021), Chigusa, Moroi, KN (2021)]

- DM axion to CM axion conversion under magnetic field



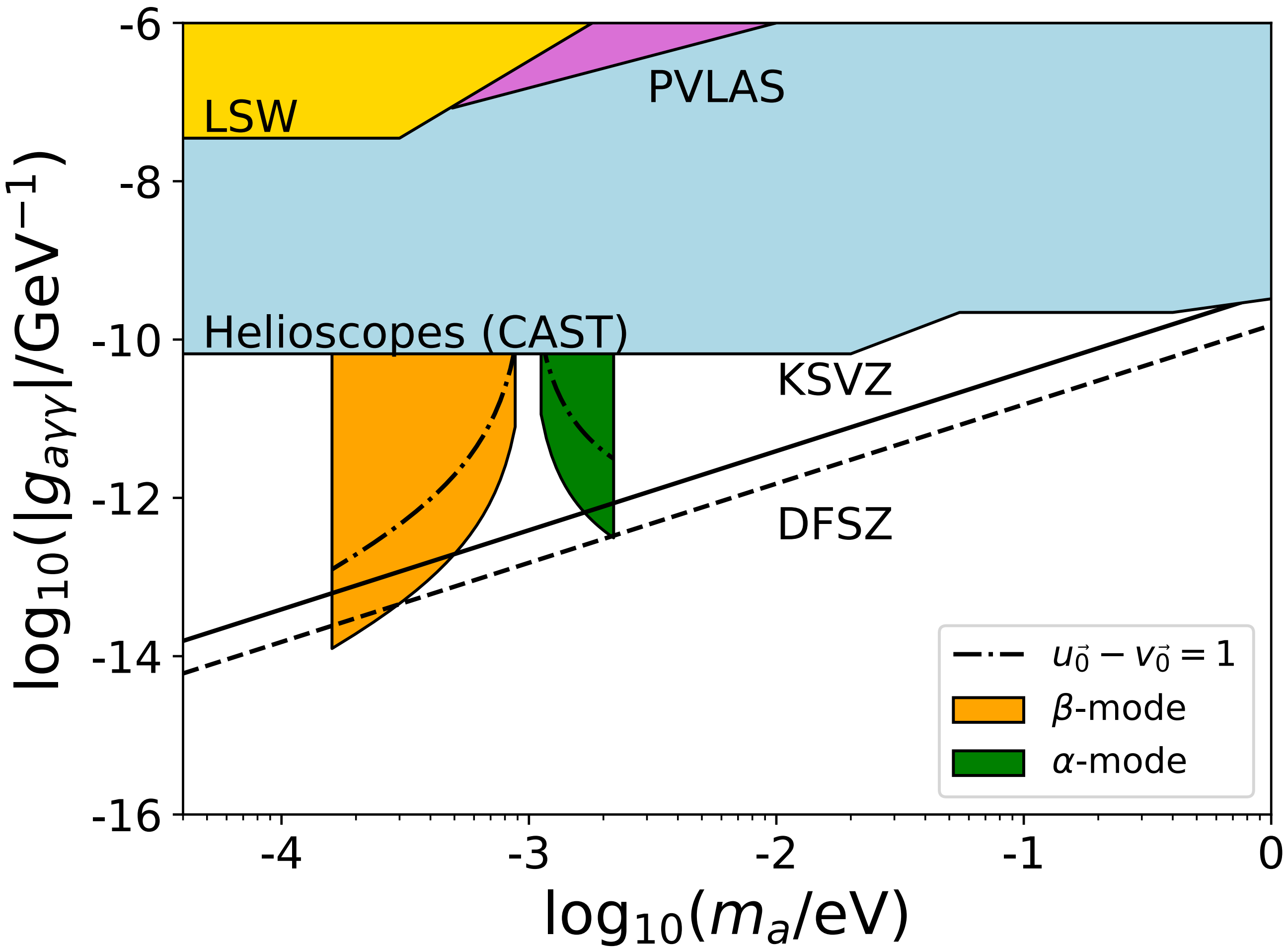
- DM hidden photon to CM axion



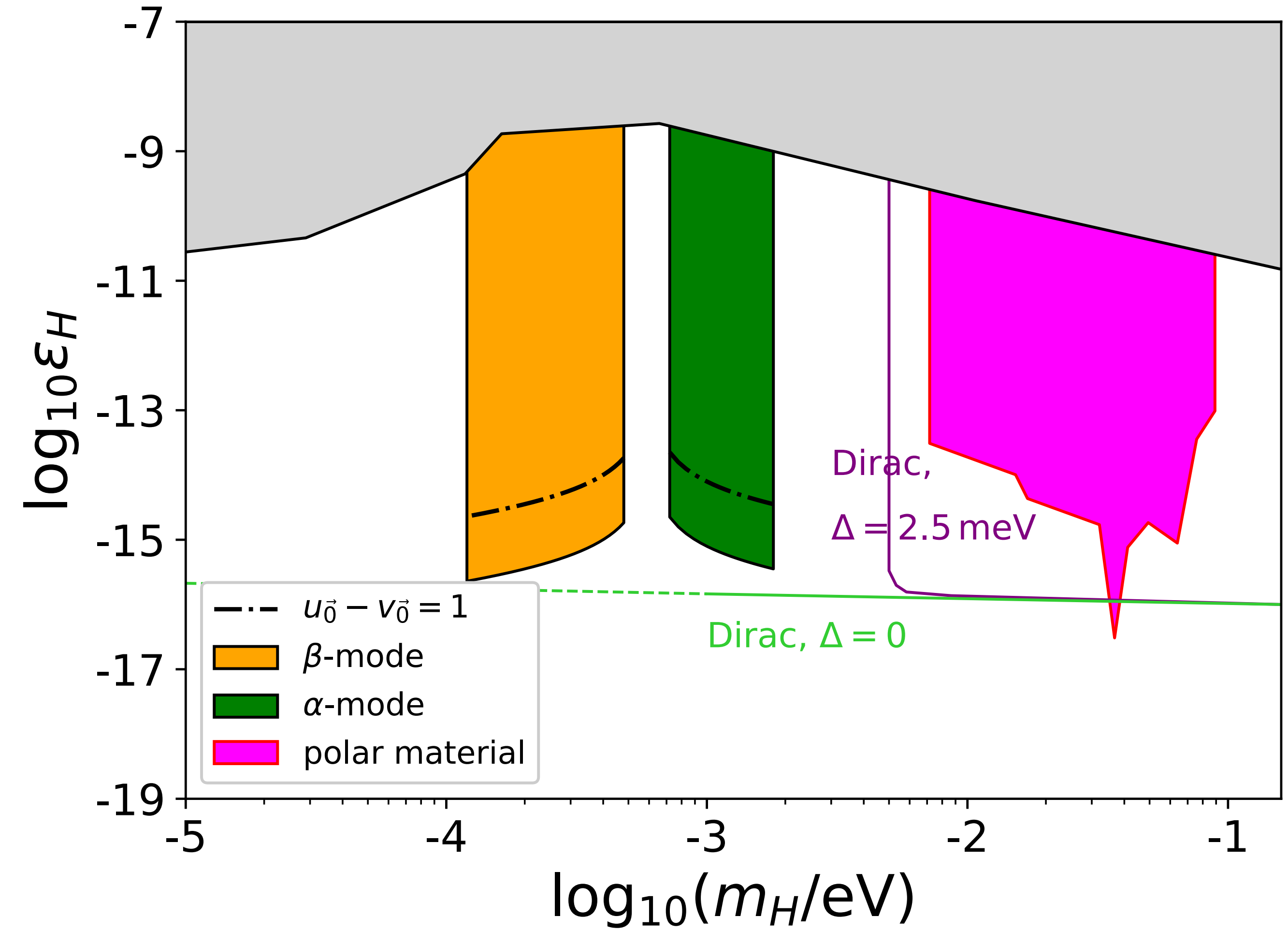


[Schutte-Engel et al. (2021)]

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: $1\,\mathrm{yr}$

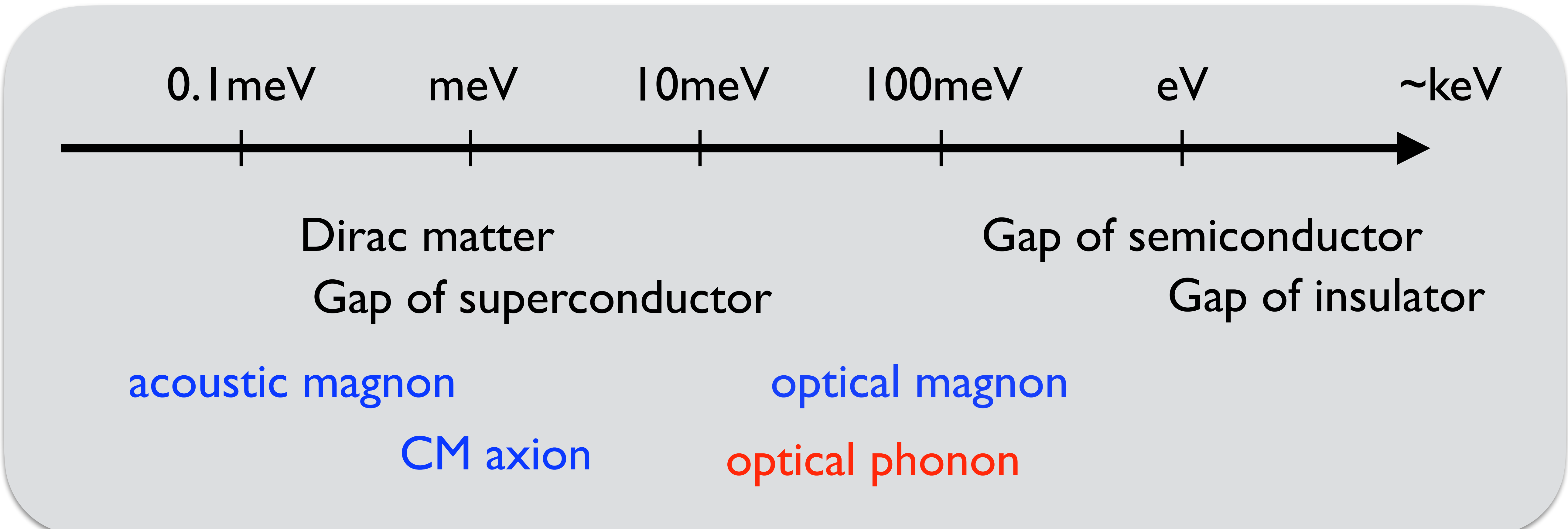
Target volume: $V = (10\,\mathrm{cm})^3$

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

[Chigusa, Moroi, KN (2021)]

Summary

- Quantum fields in condensed-matter
  : useful for DM detection!



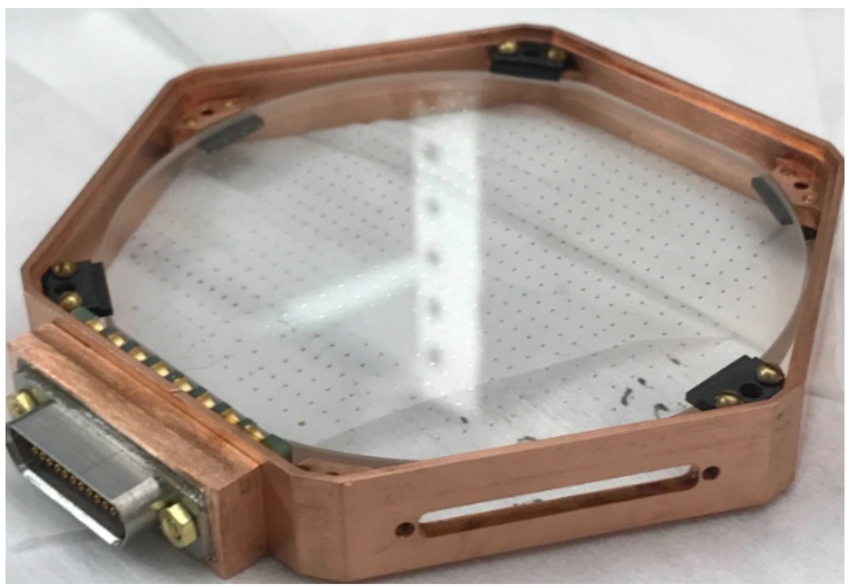
- New particle search frontier in particle and condensed-matter interdisciplinary field ?

Appendix

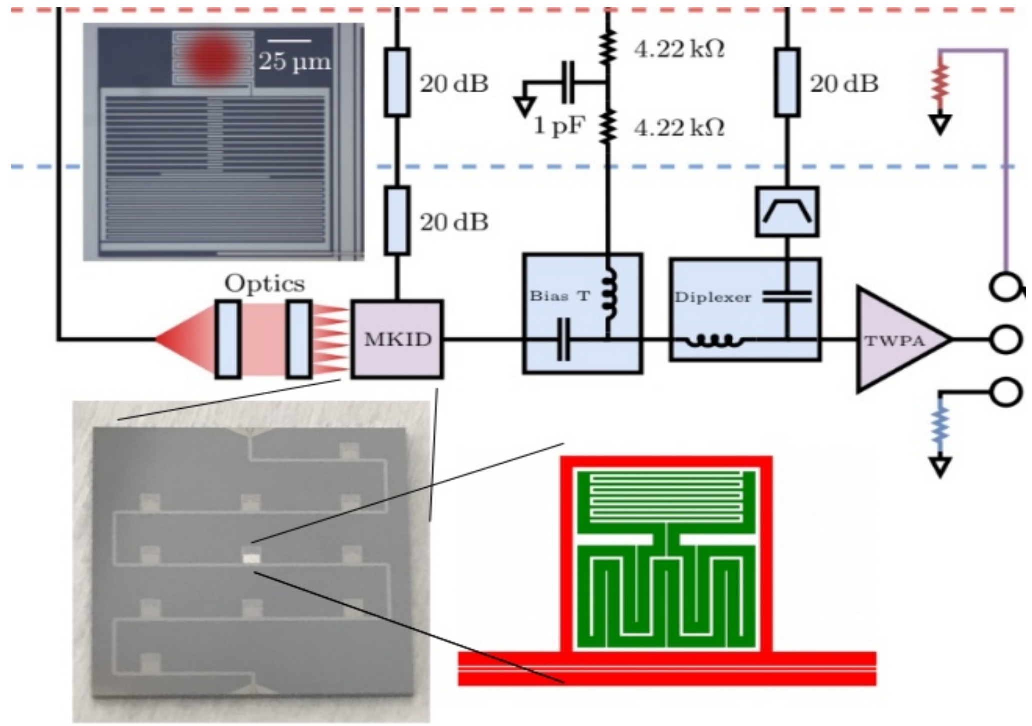
Development of sensors

Additional sensors of interest besides TES APDs

Golden reference
TES athermal phonon detector

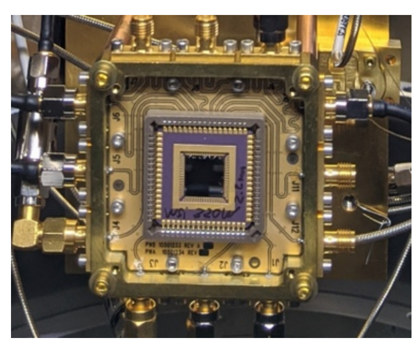


we're close to achieving 1eV energy threshold in a large area (3" dia.) This is the current world's best microcalorimeter



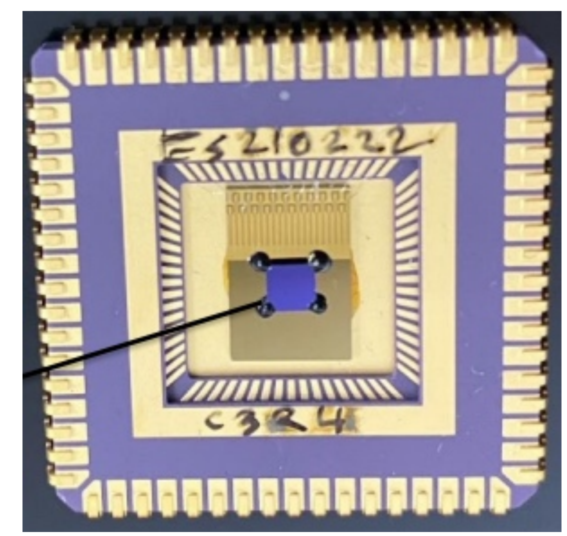
MKIDs

Limited by readout-dominated noise. Need to reduce and apply squeezing



SNSPDs

Have to increase area while keeping threshold low. Want to reach 20meV threshold



1sq.mm. SNSPD with GaAs crystal on top

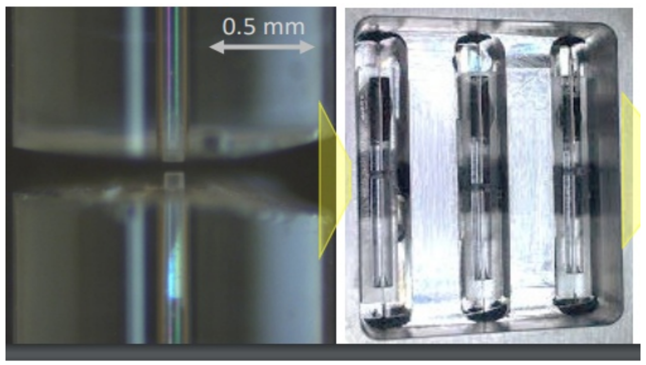
Still others with longer term potential in backup

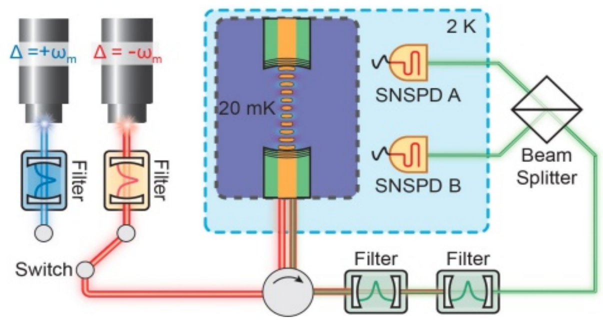
Slide by M. Garcia-Sciveres @ KEK IPNS-IMSS-QUP joint workshop

Development of sensors

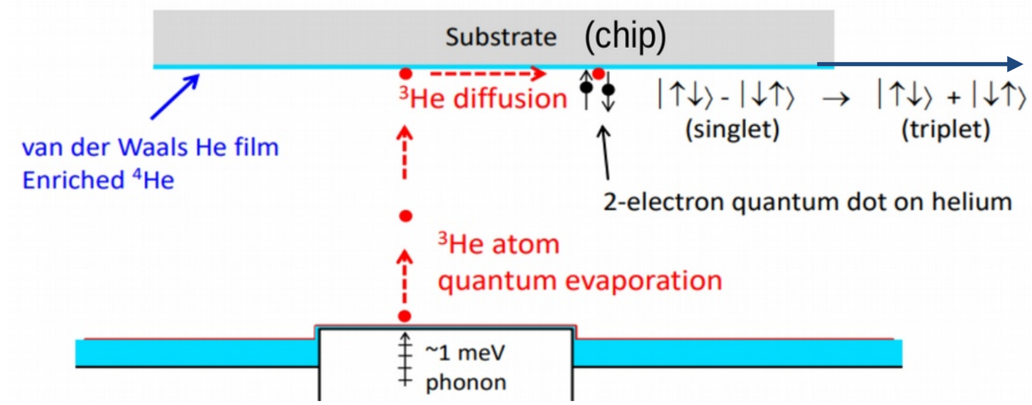
Additional quantum sensors under investigation

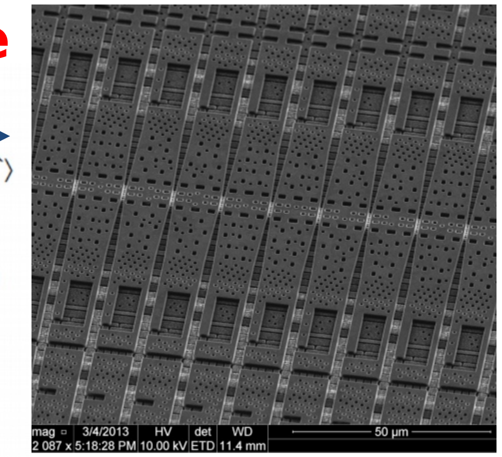
Opto-Mechanical cavities



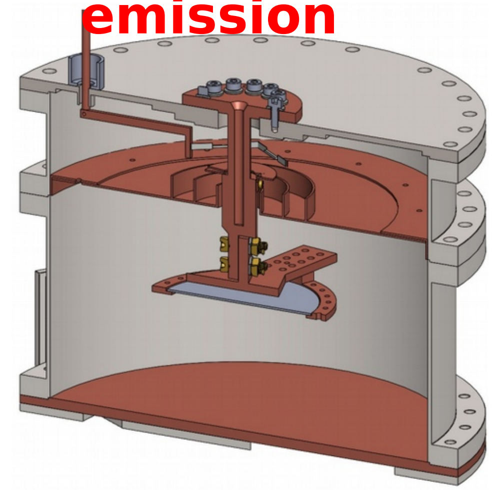


Electron surface states in LHe





He Quantum Evaporation emission



film-stopping setup to suspend dry sensor above LHe bath is up and running.

He surface

Slide by M. Garcia-Sciveres @ KEK IPNS-IMSS-QUP joint workshop