Axion detection with collective excitations

Andrea Mitridate

based on 2005.10256 with Tanner Trickle, Zhengkang Zhang and Kathryn M. Zurek

Caltech

axion searches: present

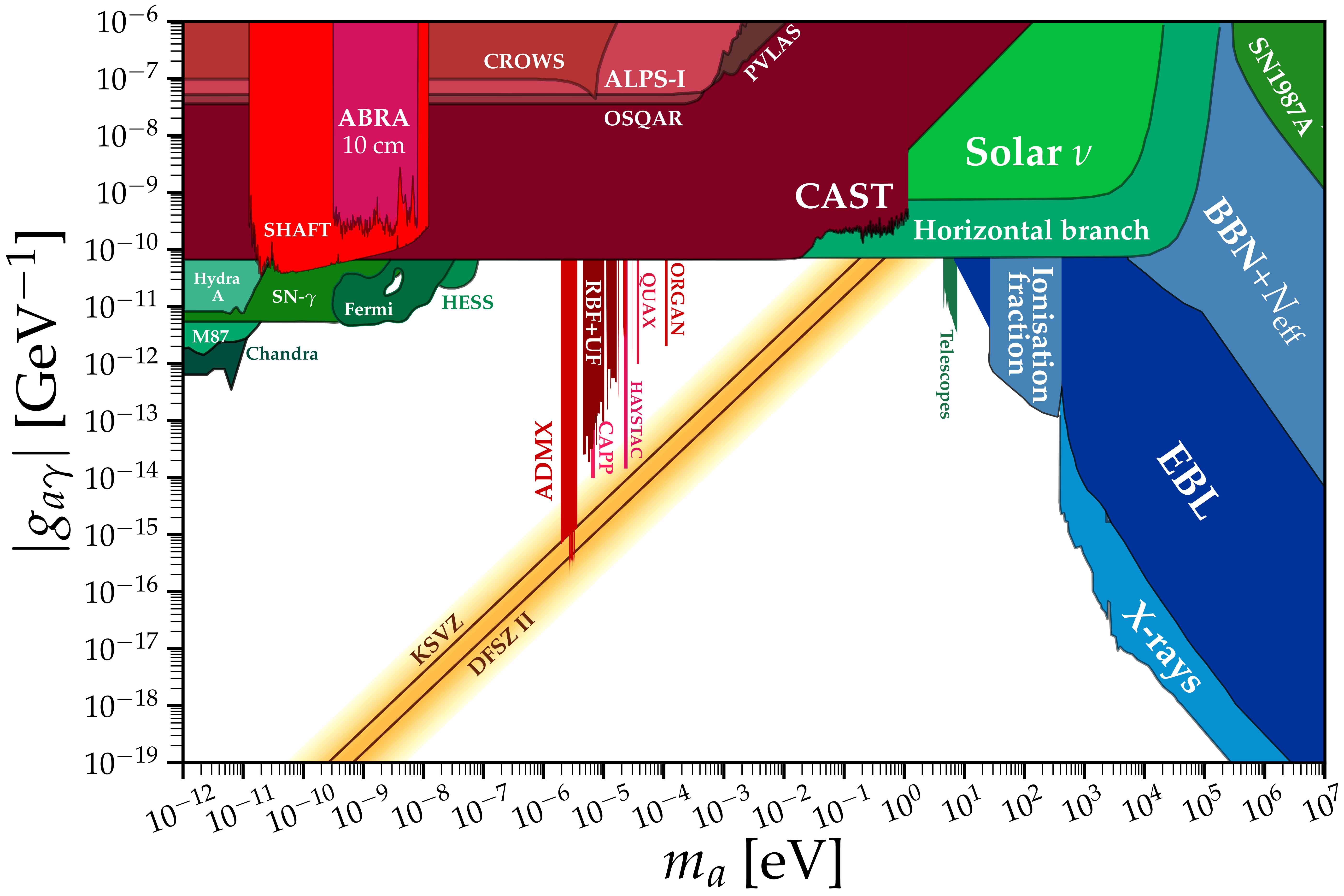
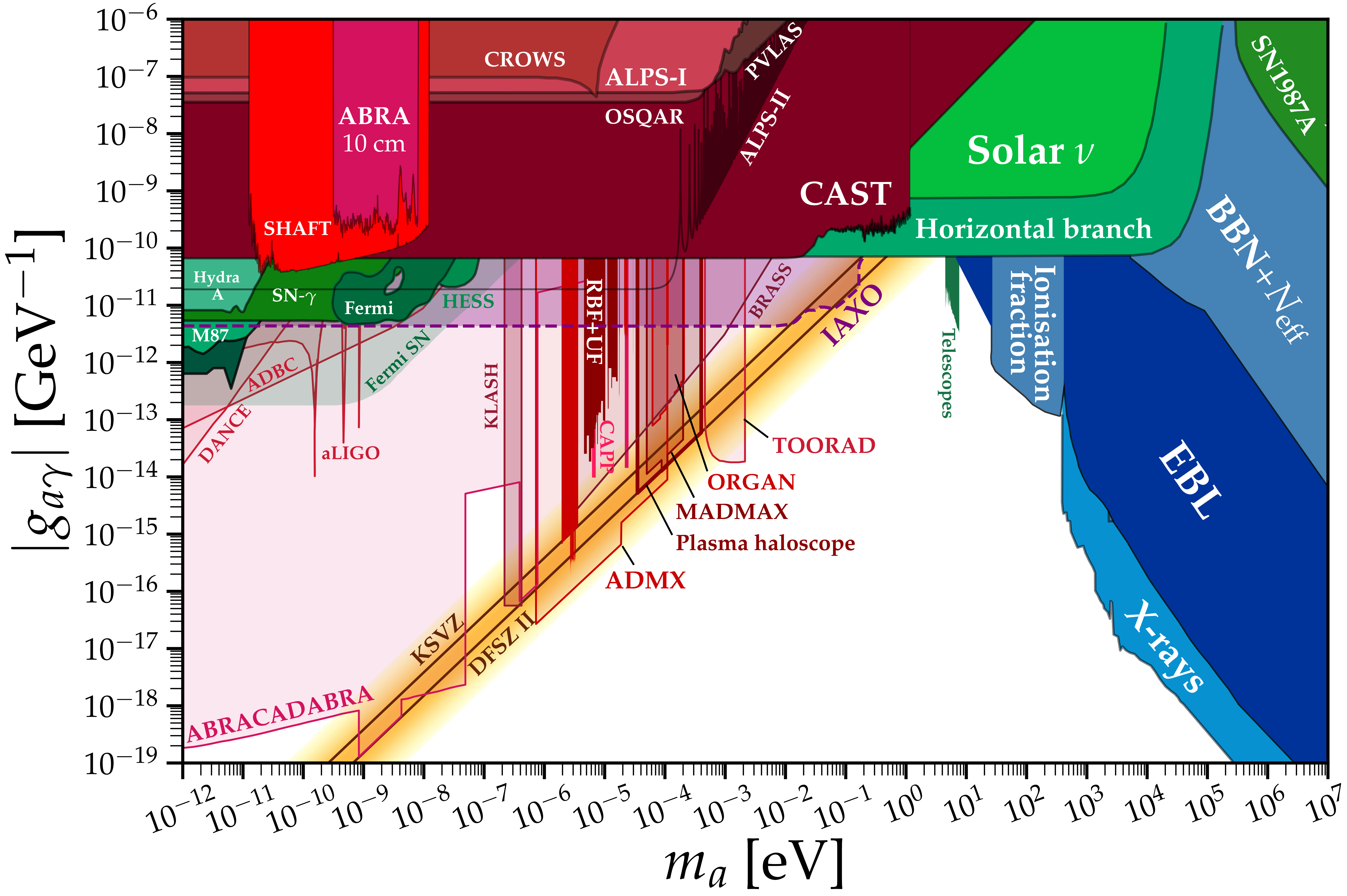


image taken from https://github.com/cajohare/AxionLimits



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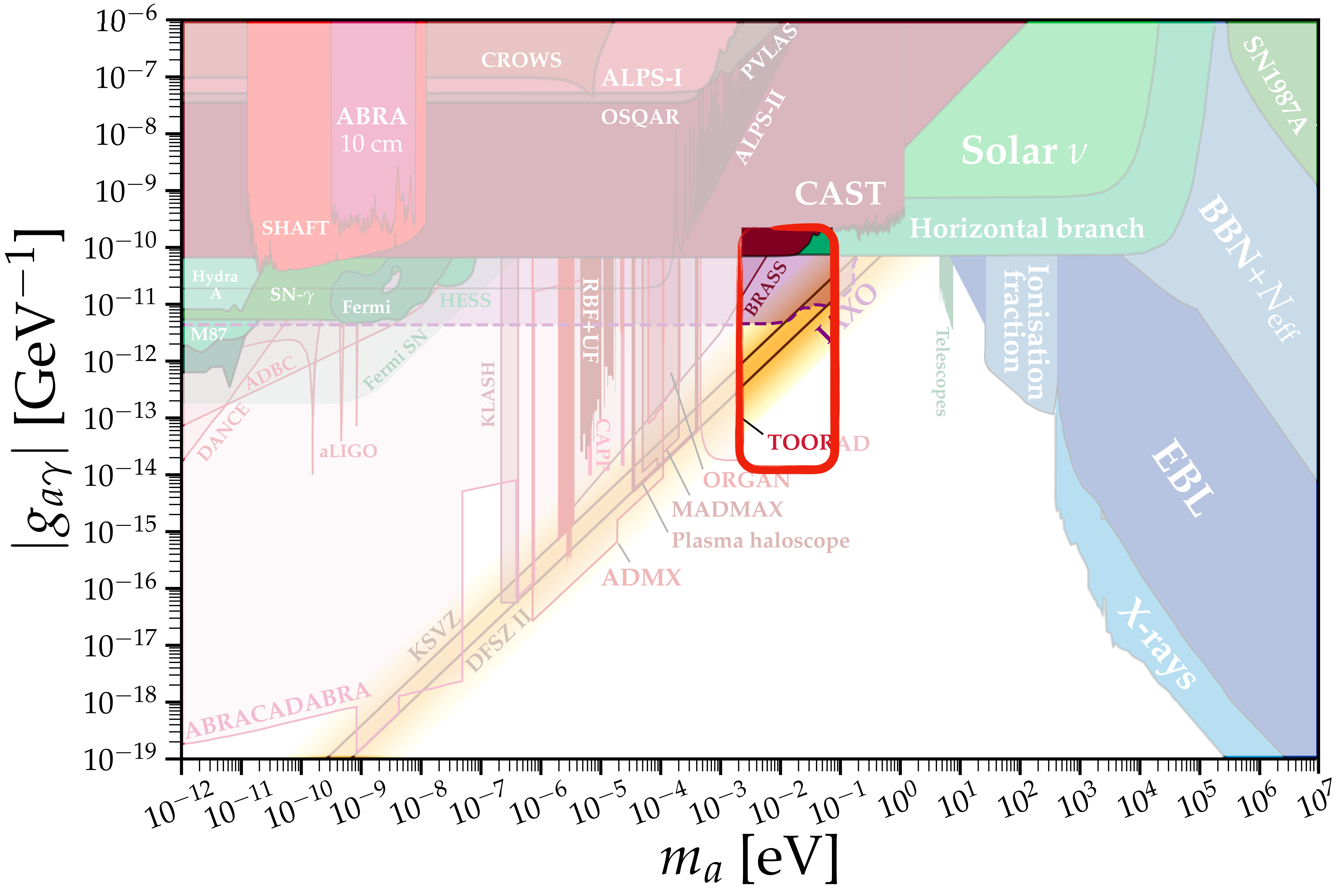
axion searches: present & future

unconstrained window in the $(1 \div 10^2)$ meV range



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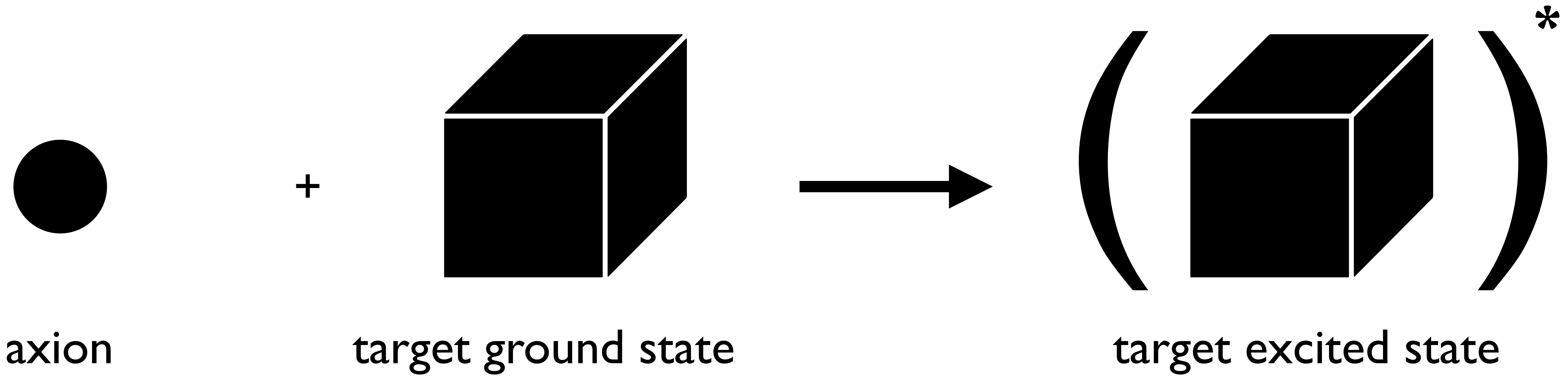
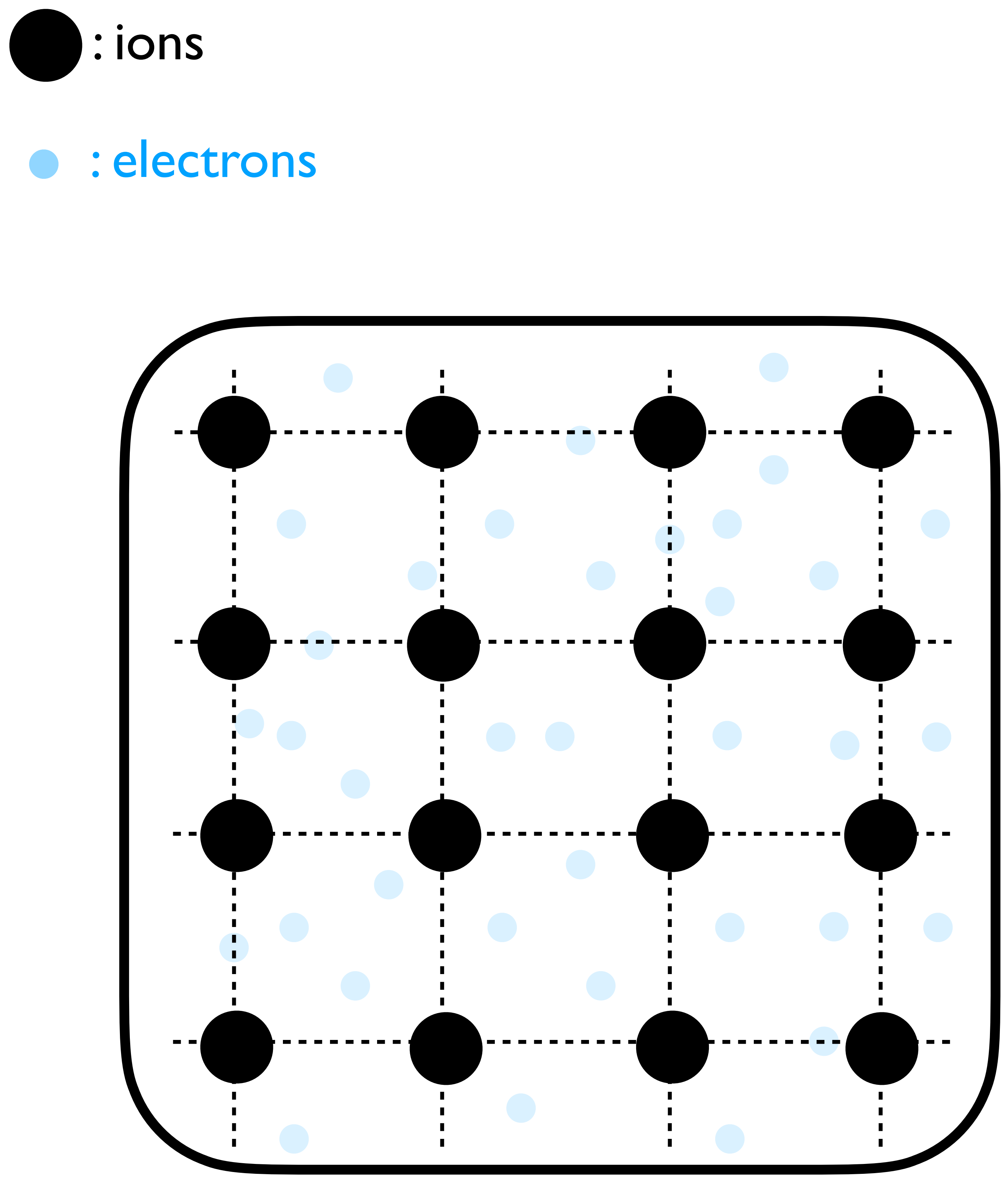
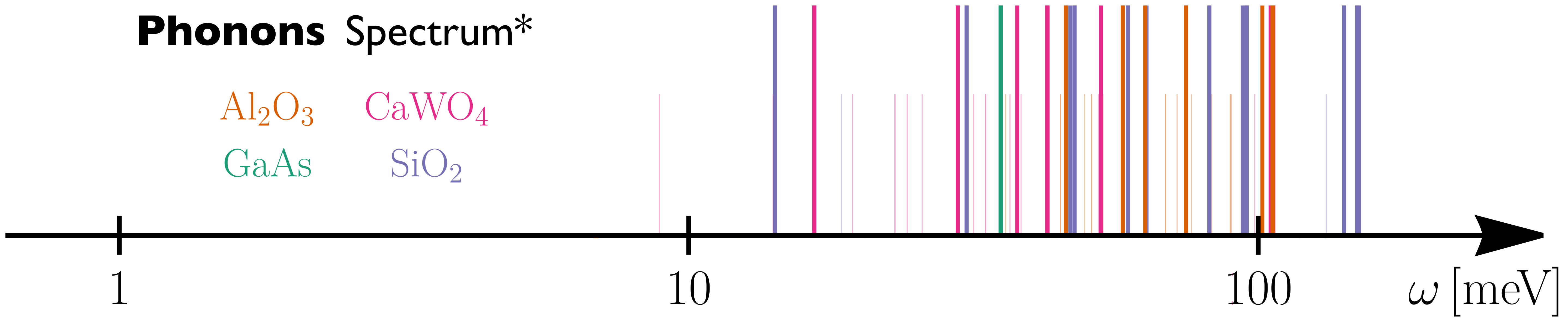


absorption kinematics

deposited energy $\simeq m_a$

deposited momentum $\simeq 10^{-3} m_a$

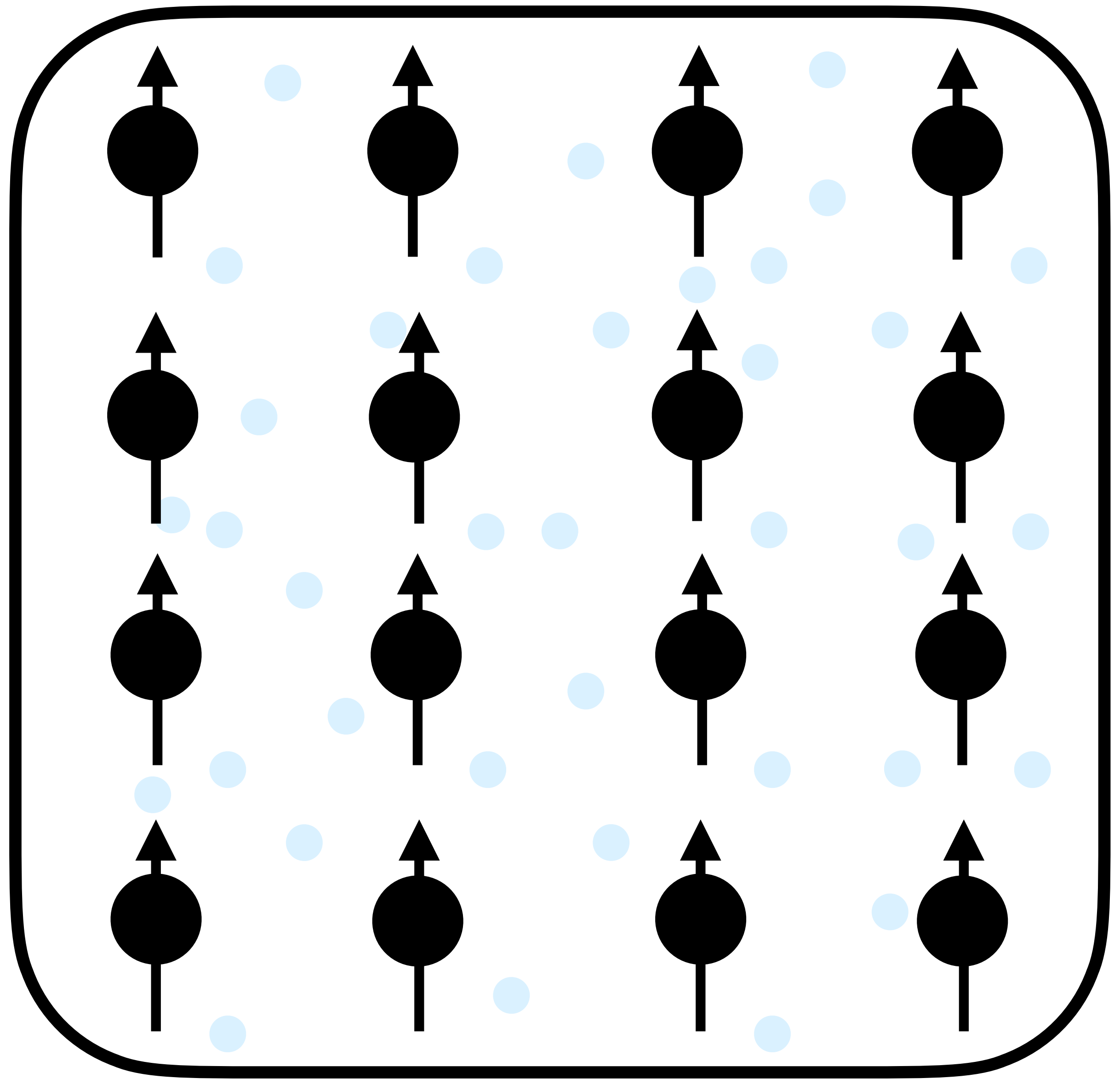


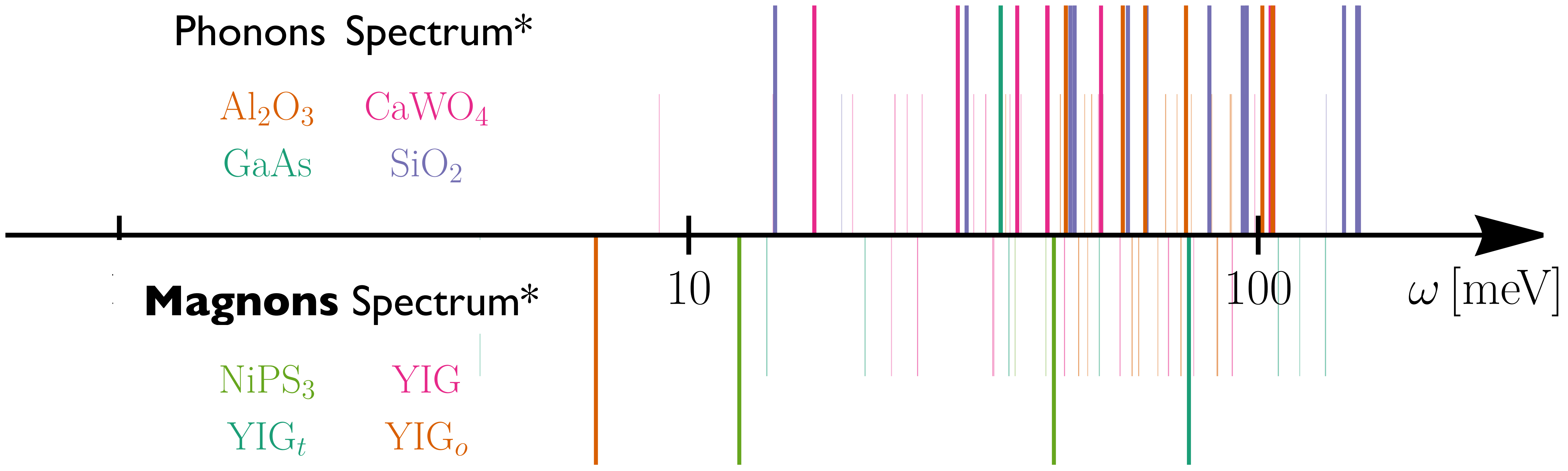


* at zero momentum

: ions

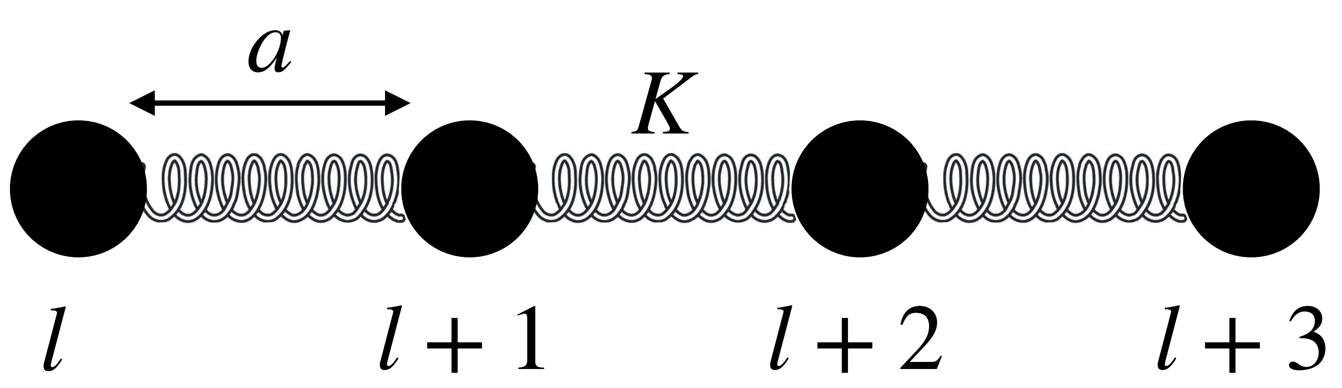
: electrons



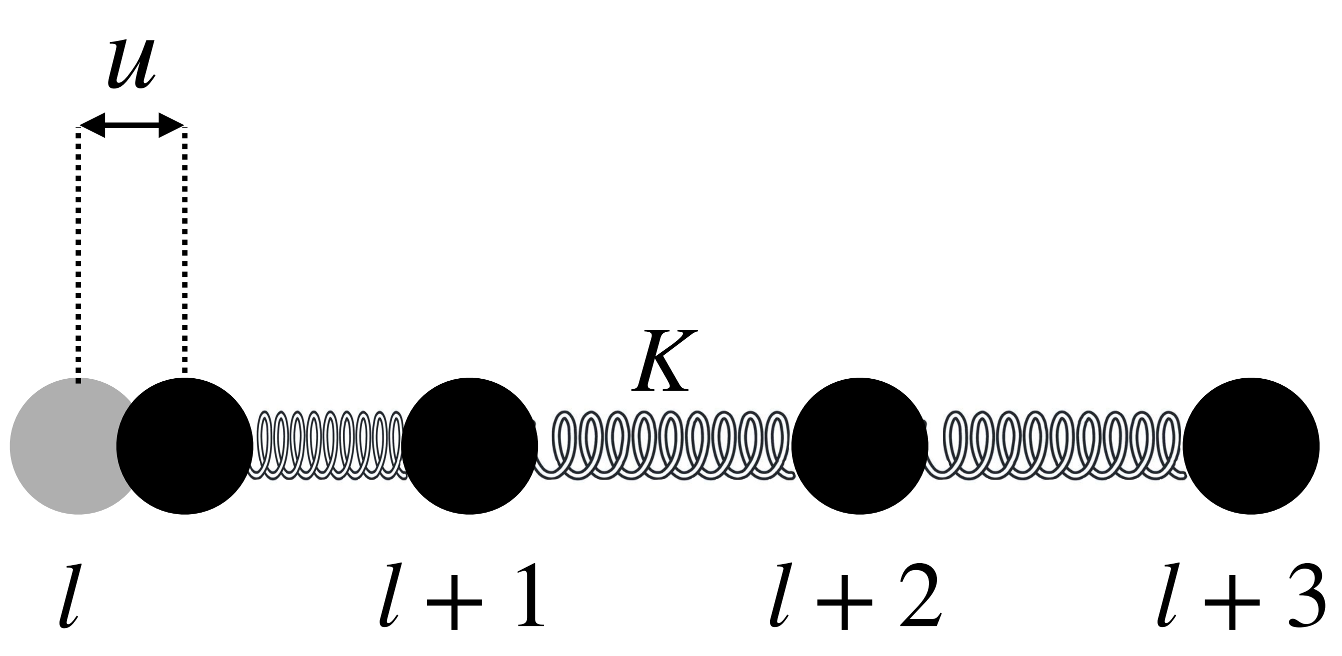


* at zero momentum

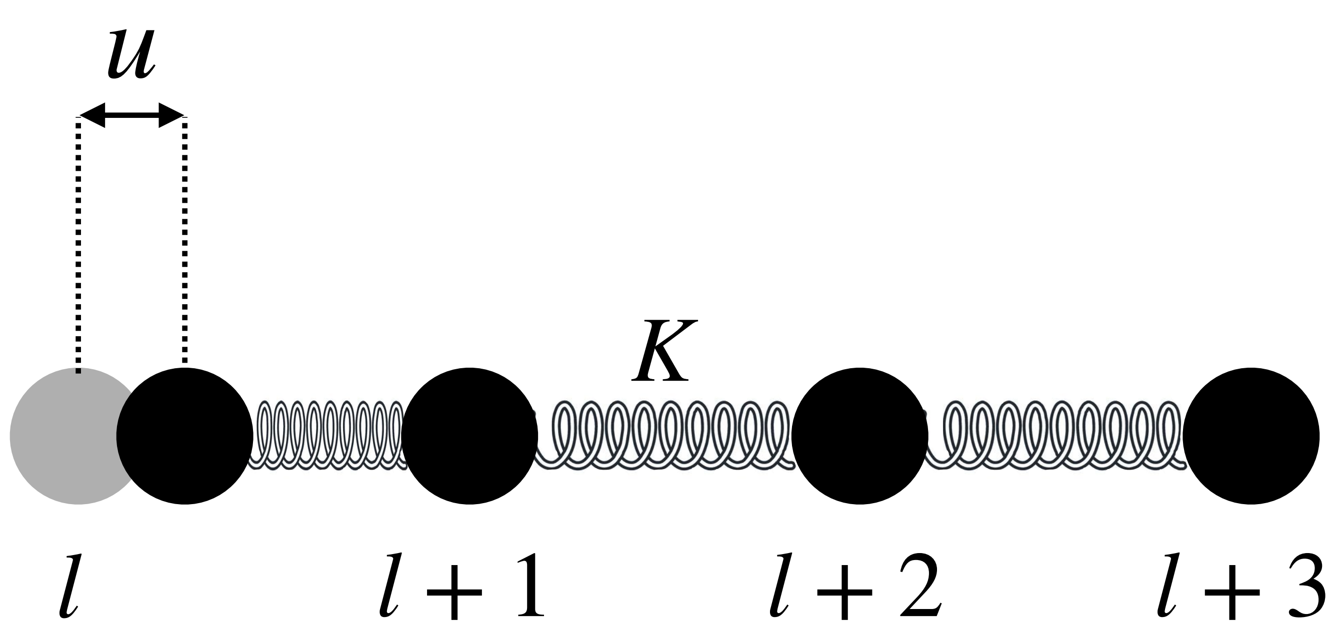
Phonons



a
K
l
$l+1$
$l+2$
$l+3$



$$\mathcal{H} = \frac{K}{2}\sum_{l}[u_l - u_{l+1}]^2$$



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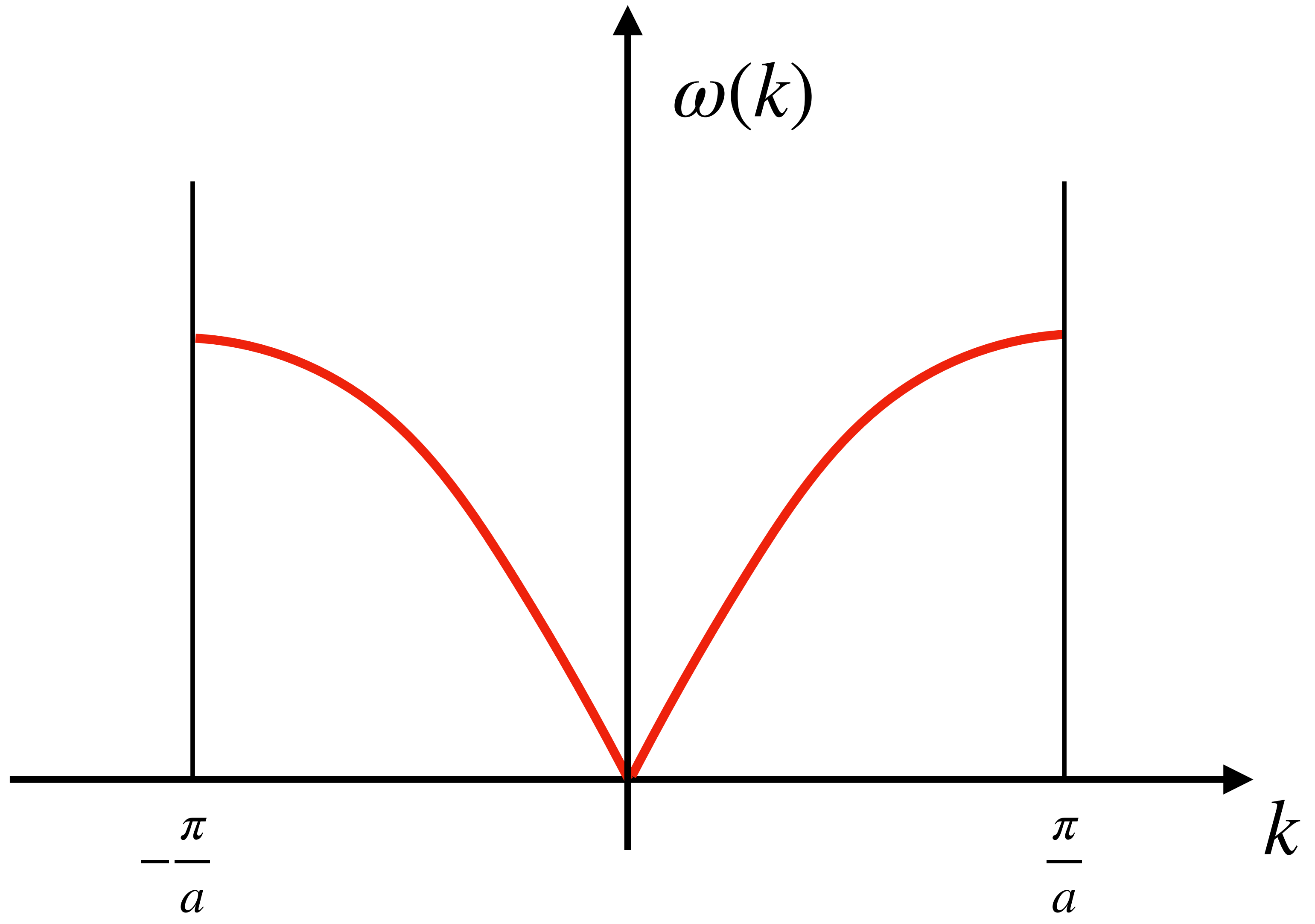
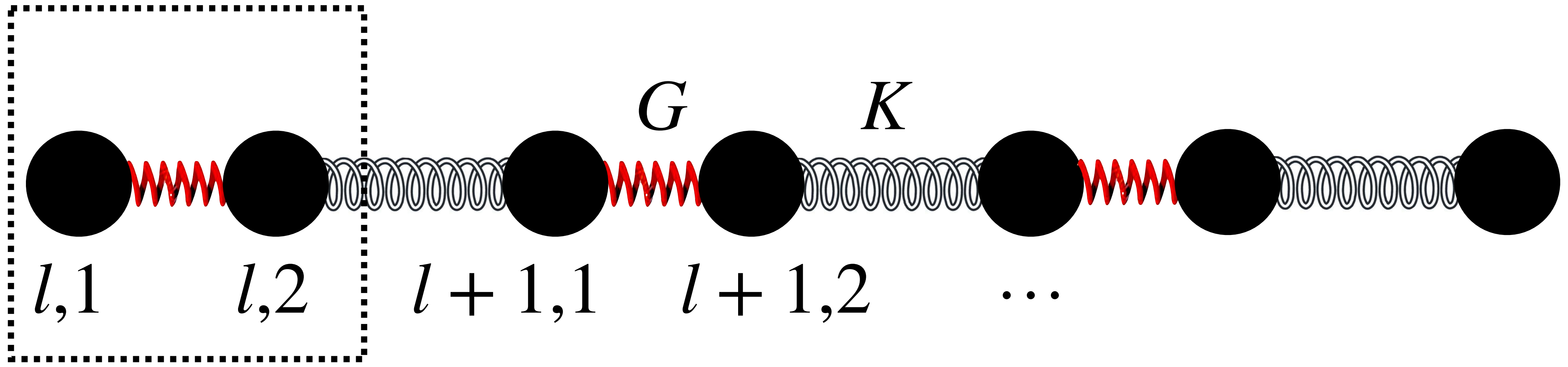


$$u_j \propto e^{i(k\cdot ja - \omega t)}$$

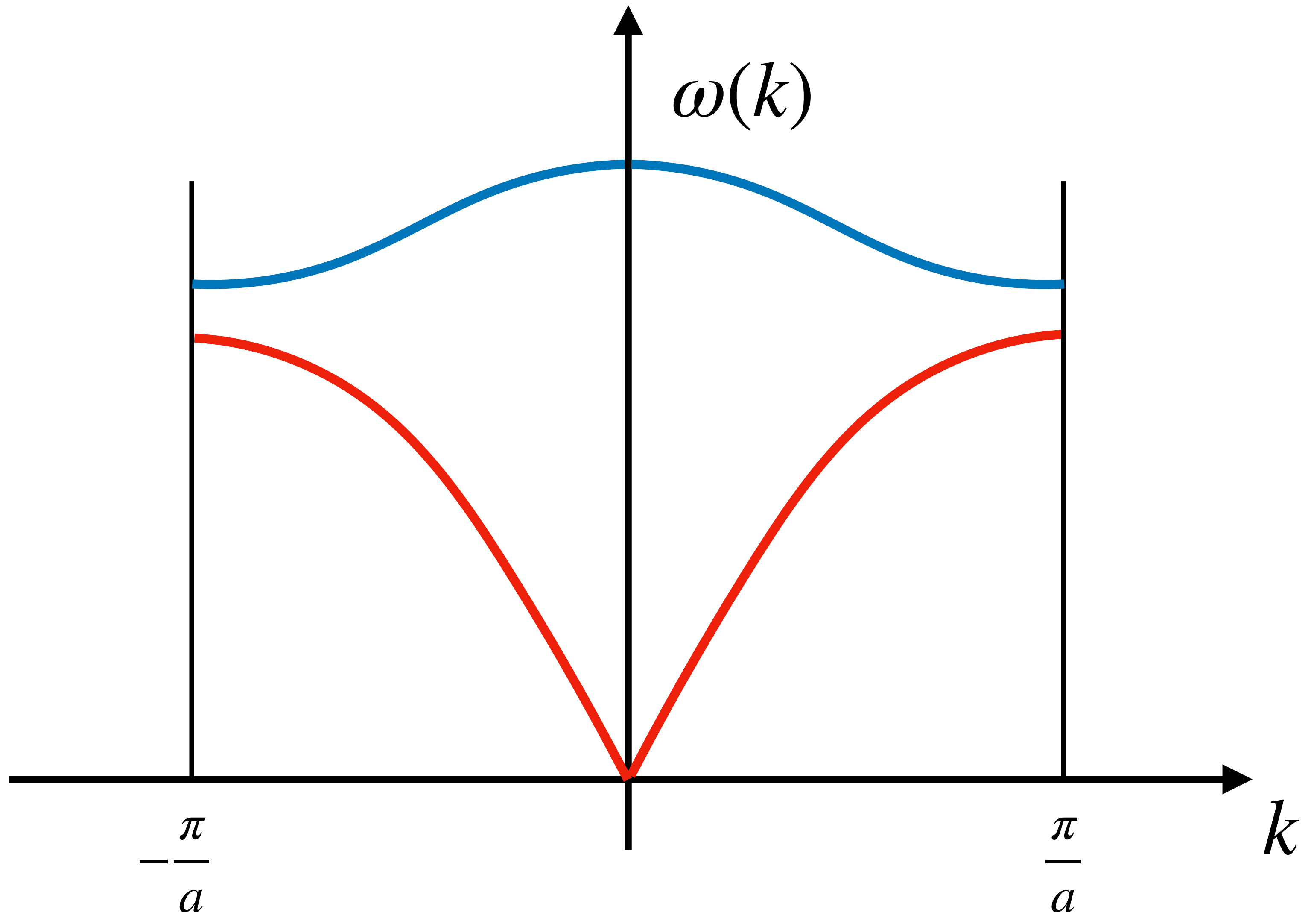
***in*-phase oscillations**

***gapless (acoustic)* mode**

(associated to broken translation symmetry) primitive cell



$$\mathcal{H} = \frac{G}{2}\sum_l [u_{l,1} - u_{l,2}]^2 + \frac{K}{2}\sum_j [u_{l,2} - u_{l+1,1}]^2$$



$$u_{lj} = \epsilon_j(k)\ e^{i(k\cdot la - \omega t)}$$

in and ***out***-of-phase oscillations

gapless (acoustic) and ***gapped (optical)*** modes

absorption kinematics

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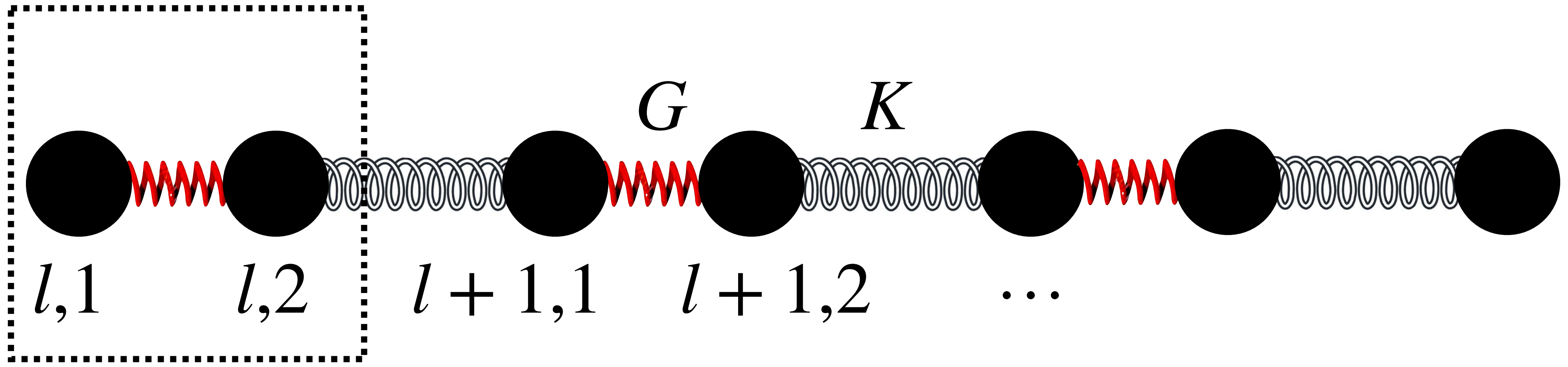
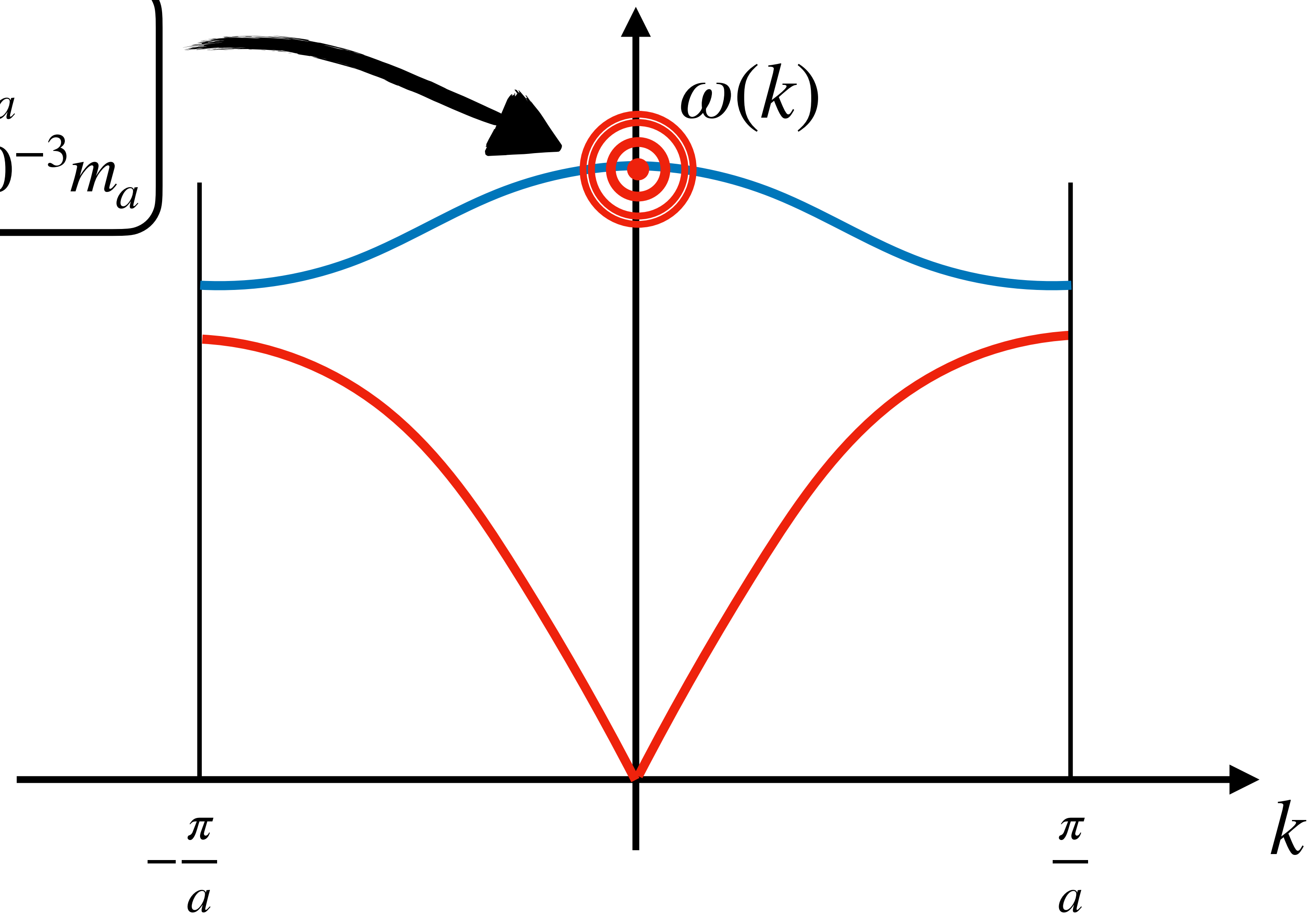
primitive cell





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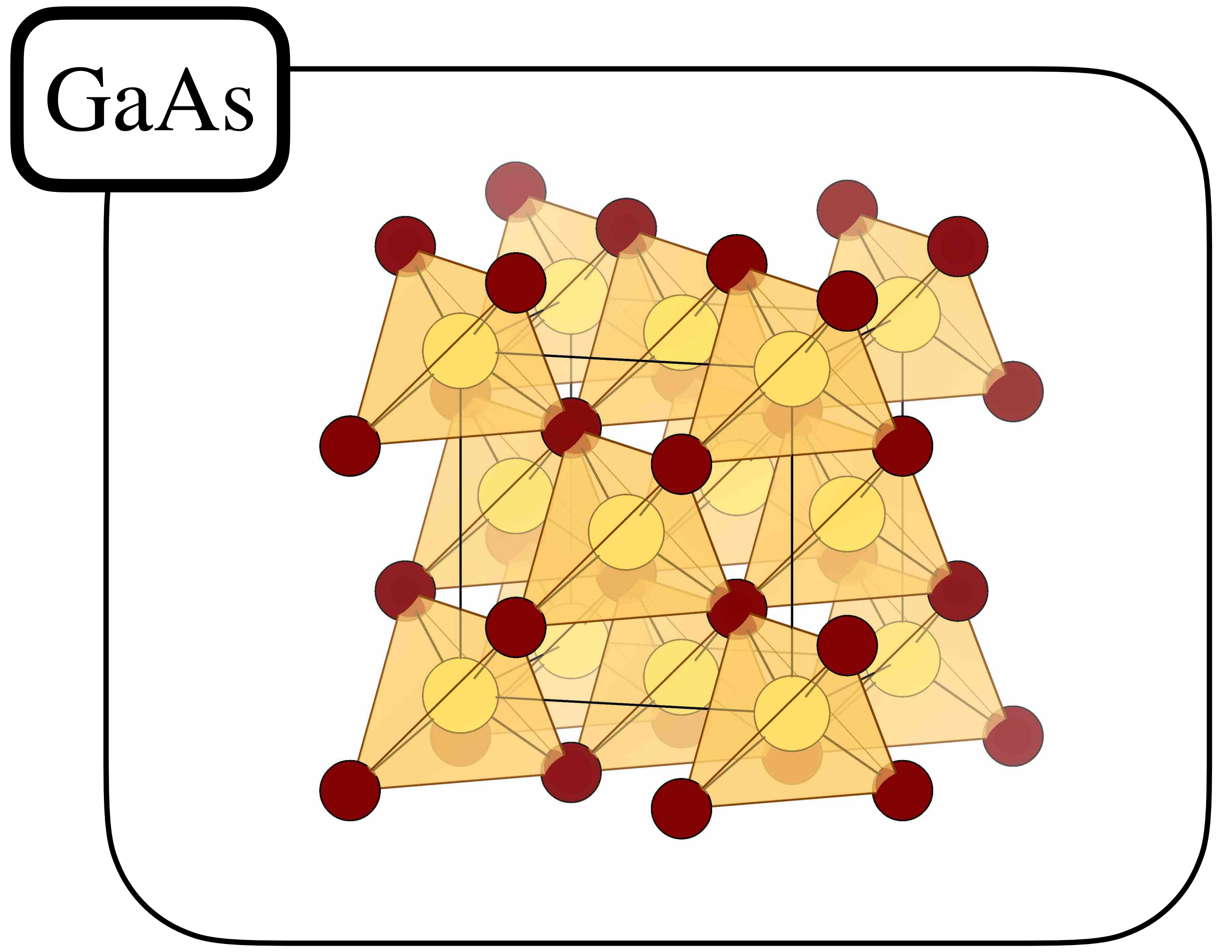
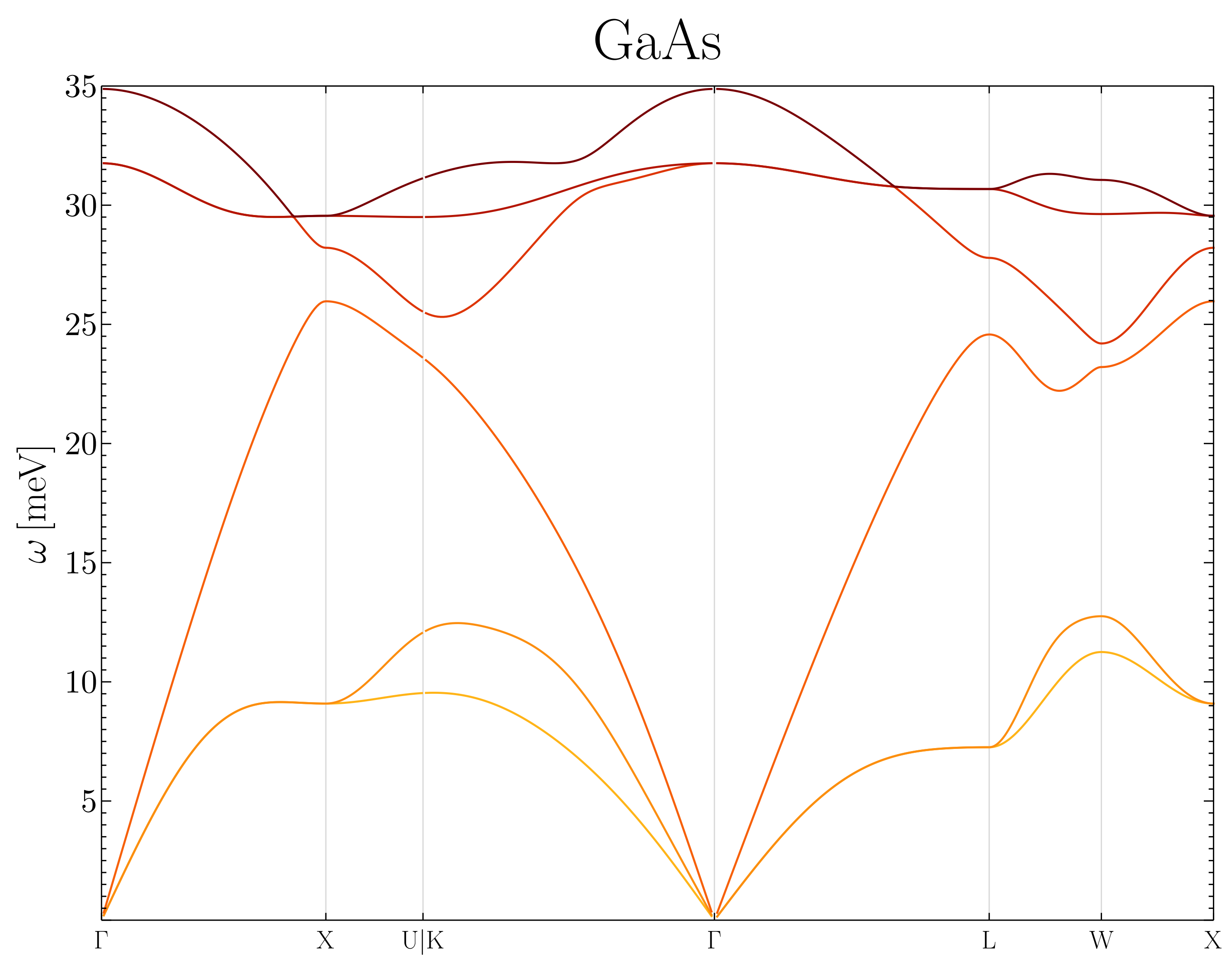




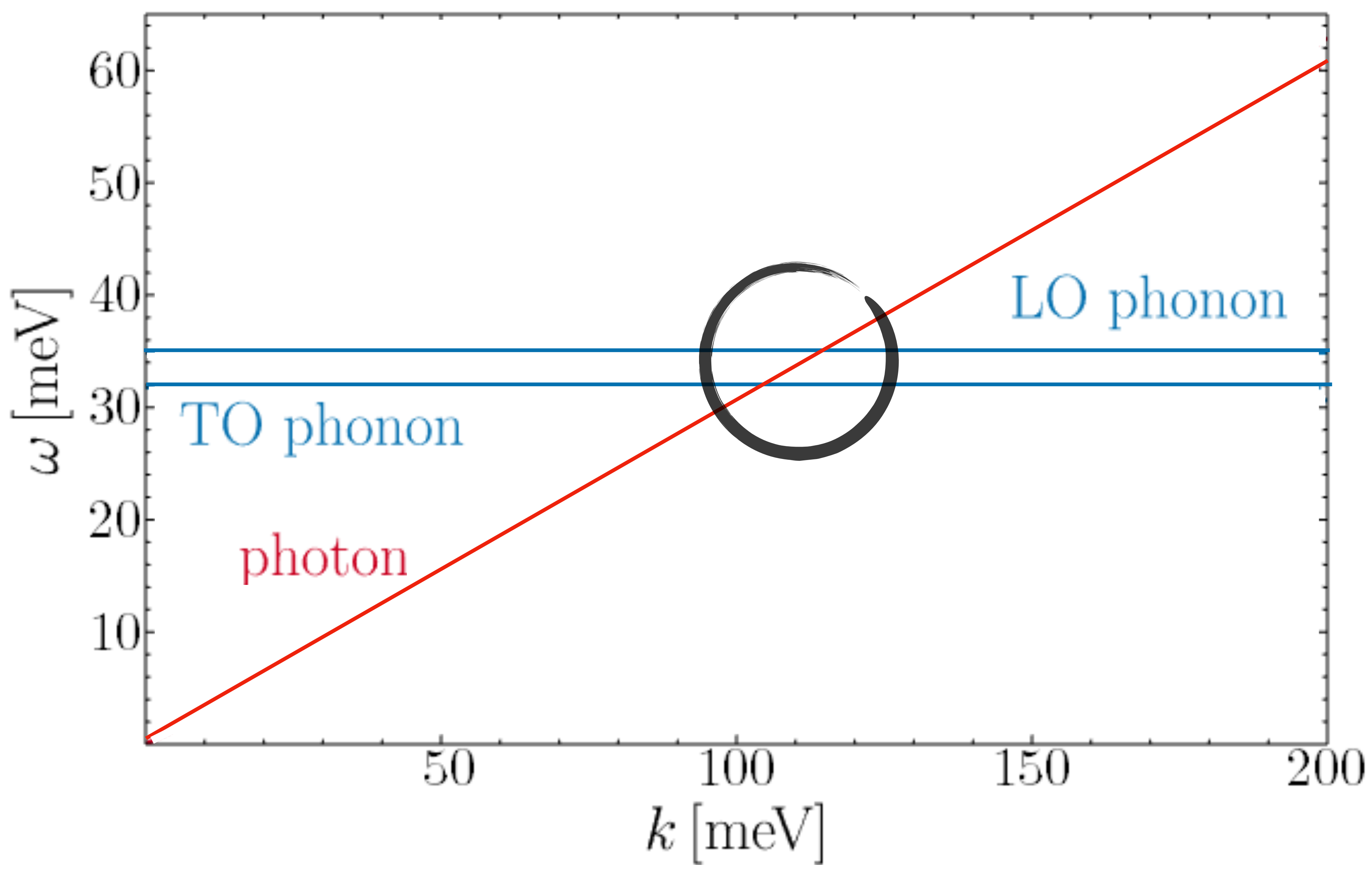
$$\mathcal{H} = \sum_{lj} \frac{\mathbf{p}_{lj}^2}{2m_j} + \frac{1}{2} \sum_{ll',jj'} \mathbf{u}_{lj} \cdot \mathbf{V}_{ll'jj'} \cdot \mathbf{u}_{l'j'}$$

force constant matrix from DFT methods

$$\mathbf{u}_{lj} = \sum_{\nu=1}^{3n} \sum_{\mathbf{k}} \frac{1}{\sqrt{2N m_j \omega_{\nu,\mathbf{k}}}} \left(\hat{a}_{\nu,\mathbf{k}} + \hat{a}^\dagger_{\nu,-\mathbf{k}} \right) e^{i\mathbf{k}\cdot\mathbf{x}^0_{lj}} \, \epsilon_{\nu,\mathbf{k},j}$$

a material with n ions in the primitive cell will have $3n$ phonon branches, 3 gapless and $3n-3$ gapped

figures from Griffin, Inzani, Trickle, Zhang, Zurek, 1910.10716 at low momenta TO phonon and photon mixing is non-negligible



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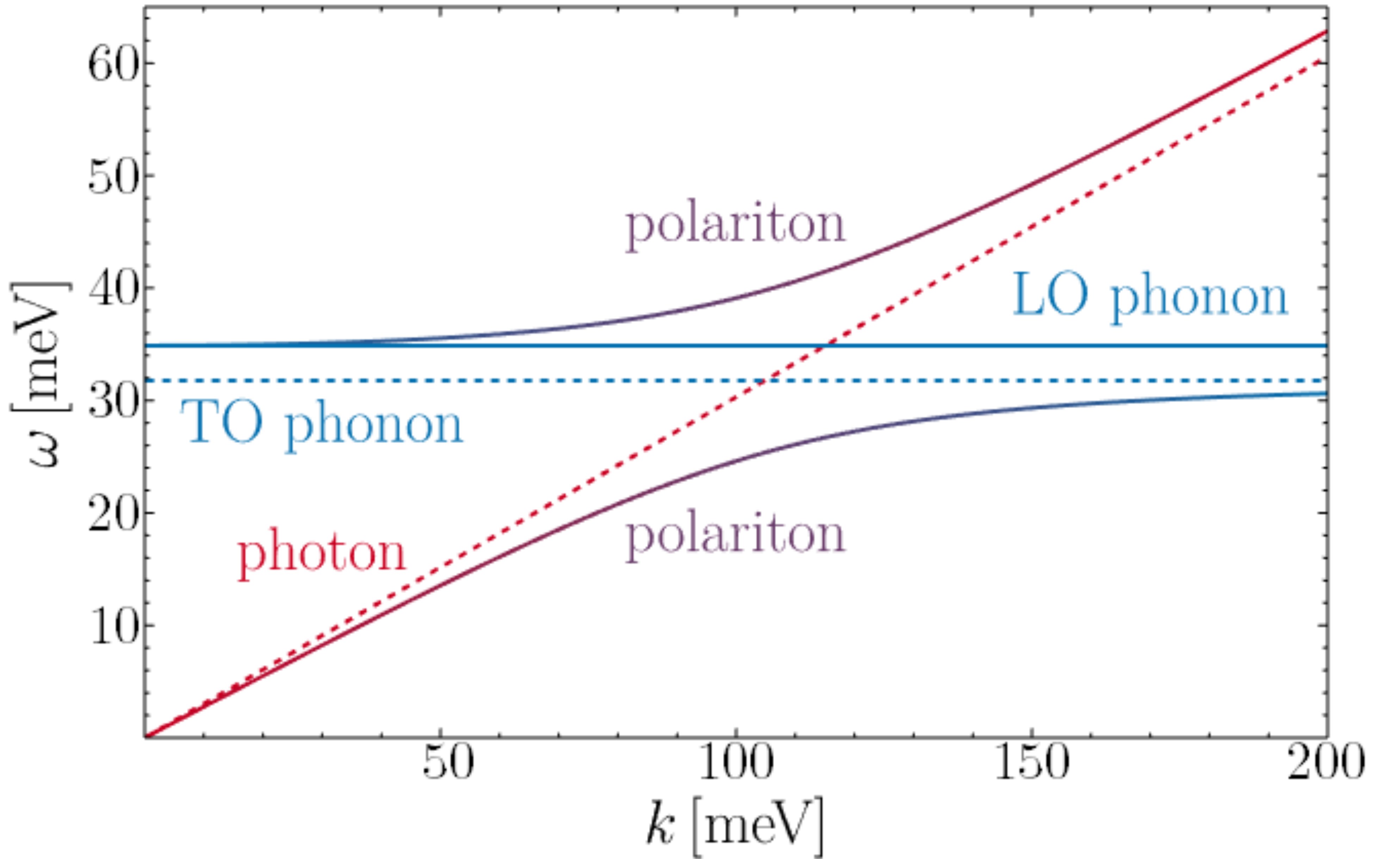

true physical states are **polaritons**, a mixing of photon and phonon states

in an external magnetic field the axion couples to ions displacement

Born charges $\sim$ ion charge

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \xrightarrow{\text{NR limit}} \delta\mathcal{H} = -g_{a\gamma\gamma} \int d^3x \, a \mathbf{E} \cdot \mathbf{B} \xrightarrow{\text{in an external } \mathbf{B} \text{ field}} \delta\mathcal{H} = -e \, g_{a\gamma\gamma} a \, \mathbf{B} \sum_{lj} \hat{B} \cdot \varepsilon_\infty^{-1} \cdot \mathbf{Z}_j^* \cdot \mathbf{u}_{lj}$$

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this induces a phonon excitations rate (per unit time and detector mass)

$$R = \frac{2e^2 g_{a\gamma\gamma}^2 B^2}{m_{\text{cell}}} \frac{\rho_a}{m_a^2} \int d^3v_a\, f(\mathbf{v}_a) \sum_{\nu=6}^{3n+2} \frac{m_a \omega'_{\nu,\mathbf{p}} \gamma_{\nu,\mathbf{p}}}{(m_a^2 - \omega'^2_{\nu,\mathbf{p}})^2 + (m_a \gamma_{\nu,\mathbf{p}})^2} \left| \sum_j \sum_{\nu'=1}^{3n} \frac{1}{\sqrt{m_j \omega_{\nu',\mathbf{p}}}} f_j \cdot \epsilon^*_{\nu',\mathbf{p},j} \left(\mathbb{U}^*_{\nu'\nu,\mathbf{p}} + \mathbb{V}_{\nu'\nu,-\mathbf{p}} \right) \right|^2$$

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axion phonon coupling strength

$$R = \frac{2e^2 g_{a\gamma\gamma}^2 B^2}{m_{\text{cell}}} \frac{\rho_a}{m_a^2} \int d^3v_a\, f(\mathbf{v}_a) \sum_{\nu=6}^{3n+2} \frac{m_a \omega'_{\nu,\mathbf{p}} \gamma_{\nu,\mathbf{p}}}{(m_a^2 - \omega'^2_{\nu,\mathbf{p}})^2 + (m_a \gamma_{\nu,\mathbf{p}})^2} \left| \sum_j \sum_{\nu'=1}^{3n} \frac{1}{\sqrt{m_j \omega_{\nu',\mathbf{p}}}} f_j \cdot \epsilon^*_{\nu',\mathbf{p},j} \left(\mathbb{U}^*_{\nu'\nu,\mathbf{p}} + \mathbb{V}_{\nu'\nu,-\mathbf{p}} \right) \right|^2$$

axion coupling to phonons

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local axion field amplitude

$$R = \frac{2e^2 g_{a\gamma\gamma}^2 B^2}{m_{\rm cell}} \frac{\rho_a}{m_a^2} \int d^3v_a\, f(\mathbf{v}_a) \sum_{\nu=6}^{3n+2} \frac{m_a \omega'_{\nu,\mathbf{p}} \gamma_{\nu,\mathbf{p}}}{(m_a^2 - \omega'^2_{\nu,\mathbf{p}})^2 + (m_a\gamma_{\nu,\mathbf{p}})^2} \left| \sum_j \sum_{\nu'=1}^{3n} \frac{1}{\sqrt{m_j \omega_{\nu',\mathbf{p}}}} f_j \cdot \epsilon^*_{\nu',\mathbf{p},j} \left(\mathbb{U}^*_{\nu'\nu,\mathbf{p}} + \mathbb{V}_{\nu'\nu,-\mathbf{p}}\right) \right|^2$$

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DM velocity integral

$$R = \frac{2e^2 g_{a\gamma\gamma}^2 B^2}{m_{\rm cell}}\frac{\rho_a}{m_a^2}\int d^3v_a\, f(\mathbf{v}_a)\sum_{\nu=6}^{3n+2}\frac{m_a\omega'_{\nu,\mathbf{p}}\gamma_{\nu,\mathbf{p}}}{(m_a^2-\omega'^2_{\nu,\mathbf{p}})^2+(m_a\gamma_{\nu,\mathbf{p}})^2}\left|\sum_j\sum_{\nu'=1}^{3n}\frac{1}{\sqrt{m_j\omega_{\nu',\mathbf{p}}}}f_j\cdot\epsilon^*_{\nu',\mathbf{p},j}\left(\mathbb{U}^*_{\nu'\nu,\mathbf{p}}+\mathbb{V}_{\nu'\nu,-\mathbf{p}}\right)\right|^2$$

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this induces a phonon excitations rate (per unit time and detector mass)

sum over final states

$$R = \frac{2e^2 g_{a\gamma\gamma}^2 B^2}{m_{\text{cell}}} \frac{\rho_a}{m_a^2} \int d^3v_a \, f(\mathbf{v}_a) \sum_{\nu=6}^{3n+2} \frac{m_a \omega'_{\nu,\mathbf{p}} \gamma_{\nu,\mathbf{p}}}{(m_a^2 - \omega'^2_{\nu,\mathbf{p}})^2 + (m_a \gamma_{\nu,\mathbf{p}})^2} \left| \sum_j \sum_{\nu'=1}^{3n} \frac{1}{\sqrt{m_j \omega_{\nu',\mathbf{p}}}} f_j \cdot \epsilon^*_{\nu',\mathbf{p},j} \left(\mathbb{U}^*_{\nu'\nu,\mathbf{p}} + \mathbb{V}_{\nu'\nu,-\mathbf{p}} \right) \right|^2$$

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this induces a phonon excitations rate (per unit time and detector mass)

Breit–Wigner

$$R = \frac{2e^2 g_{a\gamma\gamma}^2 B^2}{m_{\text{cell}}} \frac{\rho_a}{m_a^2} \int d^3v_a\, f(\mathbf{v}_a) \sum_{\nu=6}^{3n+2} \frac{m_a \omega'_{\nu,\mathbf{p}} \gamma_{\nu,\mathbf{p}}}{(m_a^2 - \omega'^2_{\nu,\mathbf{p}})^2 + (m_a \gamma_{\nu,\mathbf{p}})^2} \left| \sum_j \sum_{\nu'=1}^{3n} \frac{1}{\sqrt{m_j \omega_{\nu',\mathbf{p}}}} f_j \cdot \epsilon^*_{\nu',\mathbf{p},j} \left(\mathbb{U}^*_{\nu'\nu,\mathbf{p}} + \mathbb{V}_{\nu'\nu,-\mathbf{p}} \right) \right|^2$$

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this induces a phonon excitations rate (per unit time and detector mass)

fixes selection rules

$$R = \frac{2e^2 g_{a\gamma\gamma}^2 B^2}{m_{\text{cell}}} \frac{\rho_a}{m_a^2} \int d^3v_a\, f(\mathbf{v}_a) \sum_{\nu=6}^{3n+2} \frac{m_a \omega'_{\nu,\mathbf{p}}\gamma_{\nu,\mathbf{p}}}{(m_a^2-\omega'^2_{\nu,\mathbf{p}})^2 + (m_a\gamma_{\nu,\mathbf{p}})^2} \left| \sum_j \sum_{\nu'=1}^{3n} \frac{1}{\sqrt{m_j\omega_{\nu',\mathbf{p}}}} f_j \cdot \epsilon^*_{\nu',\mathbf{p},j} (\mathbb{U}^*_{\nu'\nu,\mathbf{p}} + \mathbb{V}_{\nu'\nu,-\mathbf{p}}) \right|^2$$

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photon - phonon mixing close to $\delta_{\nu\nu'}$

$$R = \frac{2e^2 g_{a\gamma\gamma}^2 B^2}{m_{\text{cell}}} \frac{\rho_a}{m_a^2} \int d^3 v_a \, f(\mathbf{v}_a) \sum_{\nu=6}^{3n+2} \frac{m_a \omega'_{\nu,\mathbf{p}} \gamma_{\nu,\mathbf{p}}}{(m_a^2 - \omega'^2_{\nu,\mathbf{p}})^2 + (m_a \gamma_{\nu,\mathbf{p}})^2} \left| \sum_j \sum_{\nu'=1}^{3n} \frac{1}{\sqrt{m_j \omega_{\nu',\mathbf{p}}}} f_j \cdot \epsilon^*_{\nu',\mathbf{p},j} \left(\mathbb{U}^*_{\nu'\nu,\mathbf{p}} + \mathbb{V}_{\nu'\nu,-\mathbf{p}} \right) \right|^2$$

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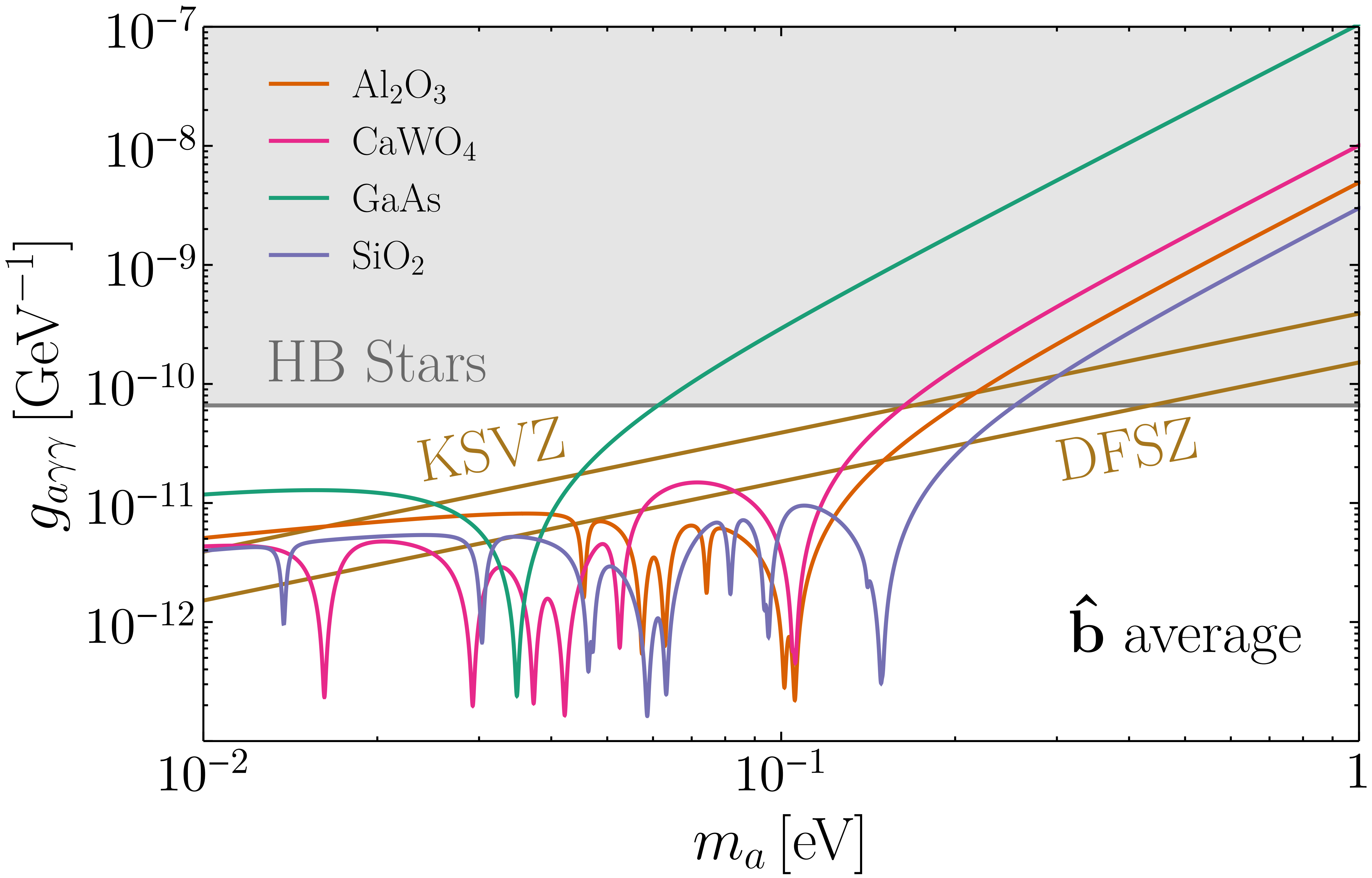
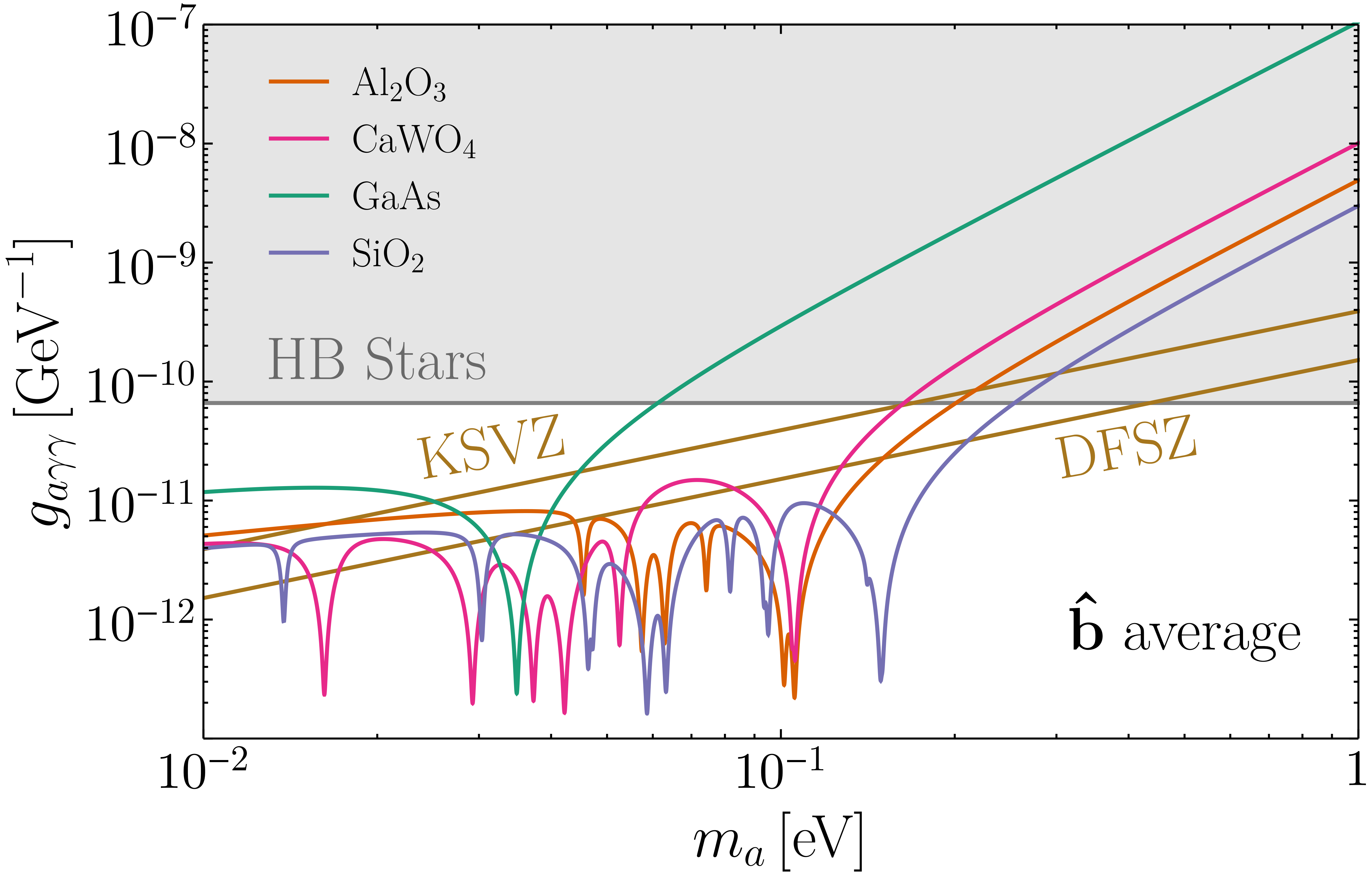
on resonance

$$R \sim \frac{g_{a\gamma\gamma}^2\rho_a}{m_a^3}\frac{Z^{*2}e^2B^2}{\varepsilon_\infty^2 m_{\text{ion}}^2\gamma} \sim (\text{kg}\cdot\text{yr})^{-1}\left(\frac{g_{a\gamma\gamma}}{10^{-13}\,\text{GeV}^{-1}}\right)^2\left(\frac{100\,\text{meV}}{m_a}\right)^3\left(\frac{B}{10\,\text{T}}\right)^2\left(\frac{\text{meV}}{\gamma}\right)$$



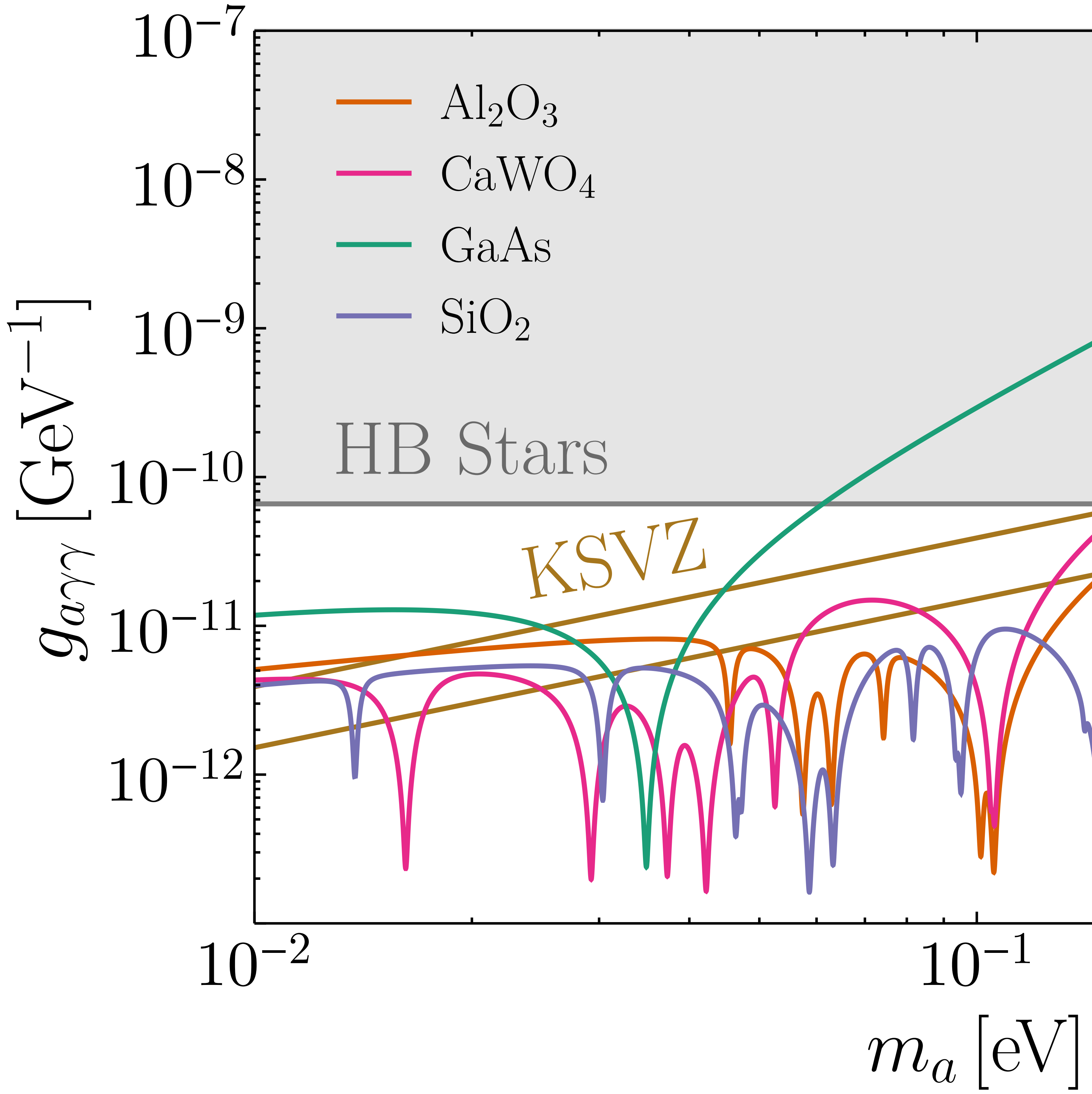
Al_2O_3
$CaWO_4$
GaAs
SiO_2
HB Stars
KSVZ
DFSZ
$\hat{\mathbf{b}}$ average
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$g_{a\gamma\gamma}$ [GeV^{-1}]
10^{-2}
10^{-1}
1
m_a [eV]

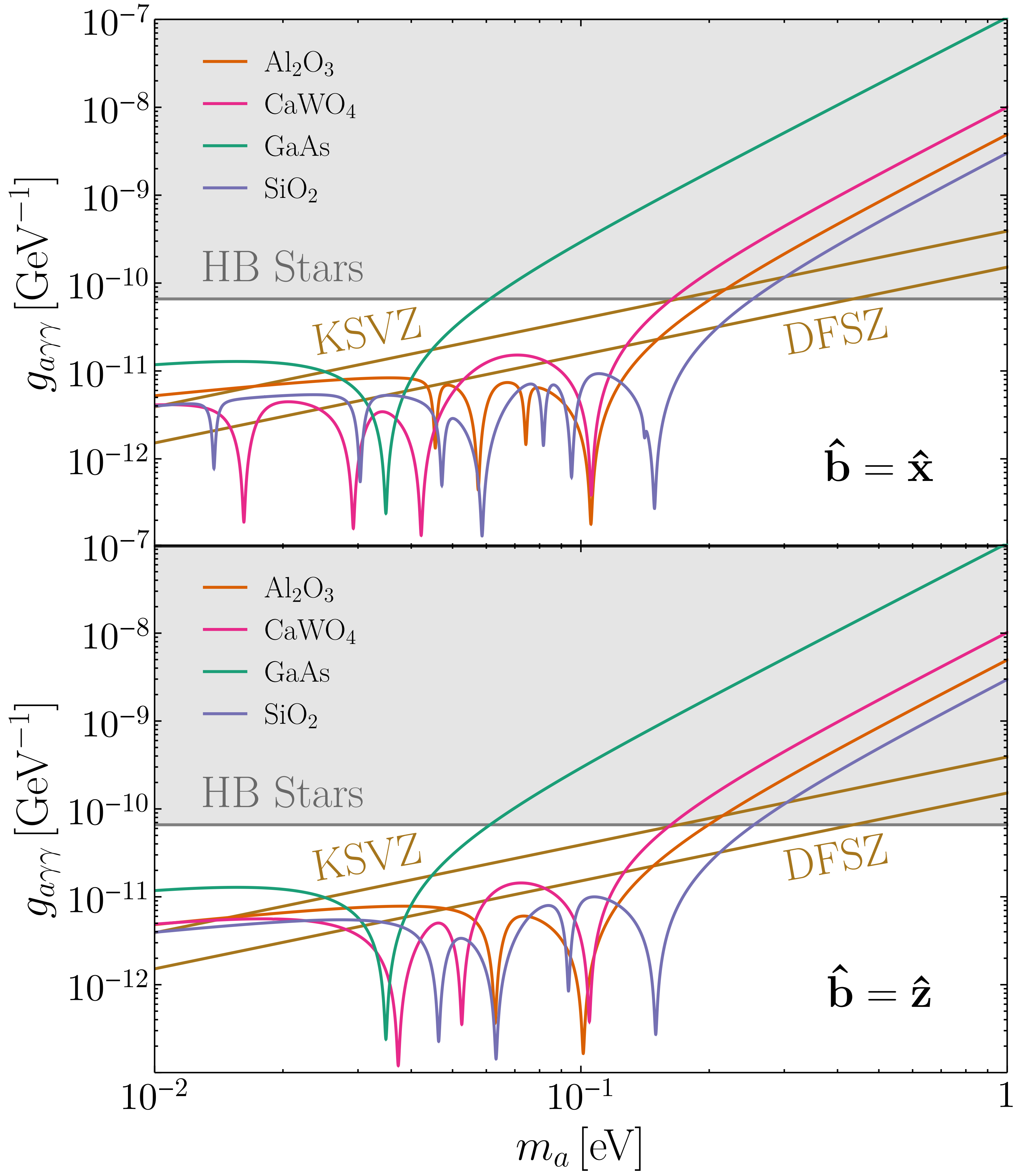


Optical branches

	tot	Coupled
Al_2O_3	27	10
$CaWO_4$	33	11
GaAs	3 (deg)	3
SiO_2	24	20

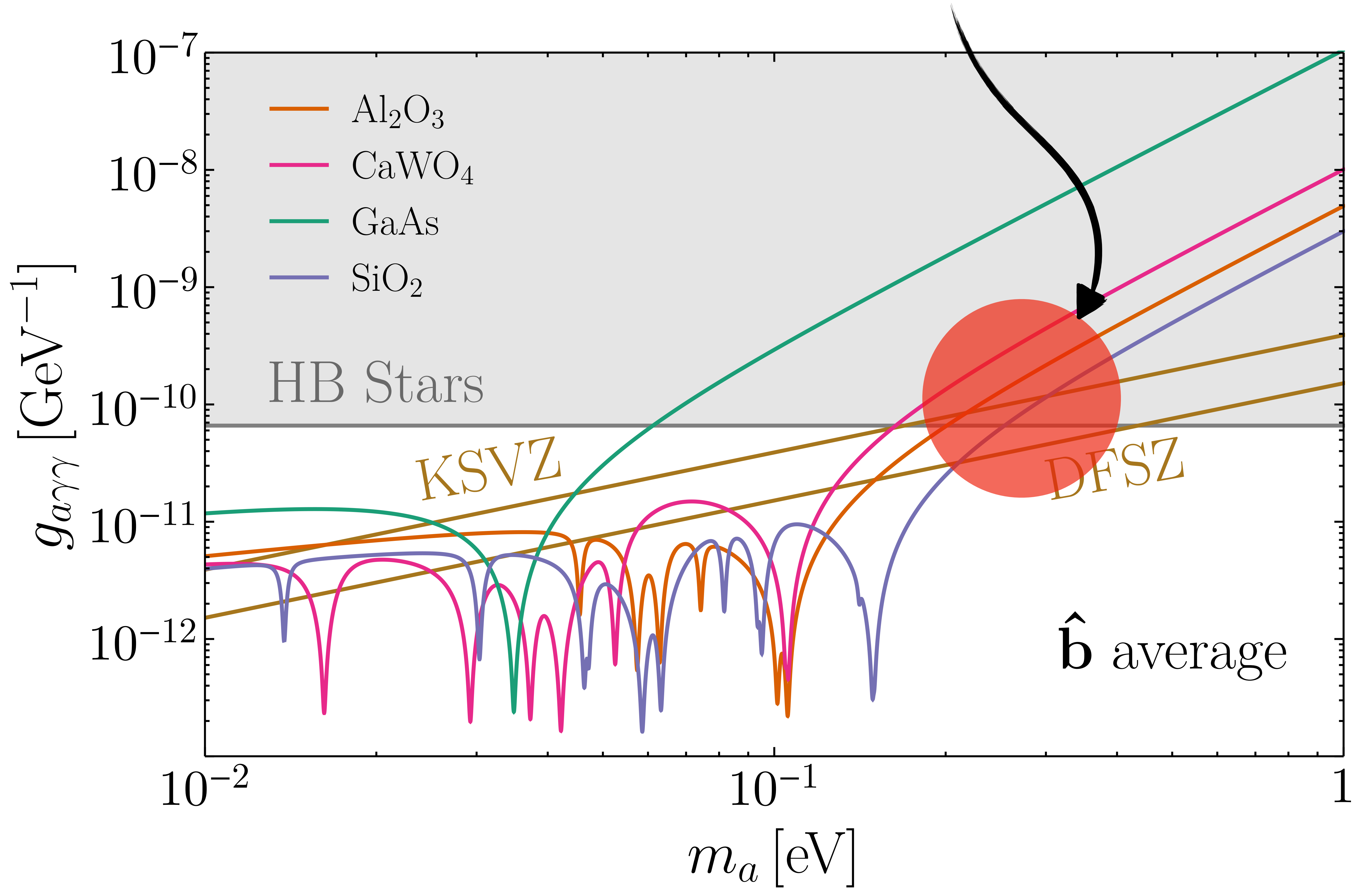
coupled modes depend on the magnetic field orientation

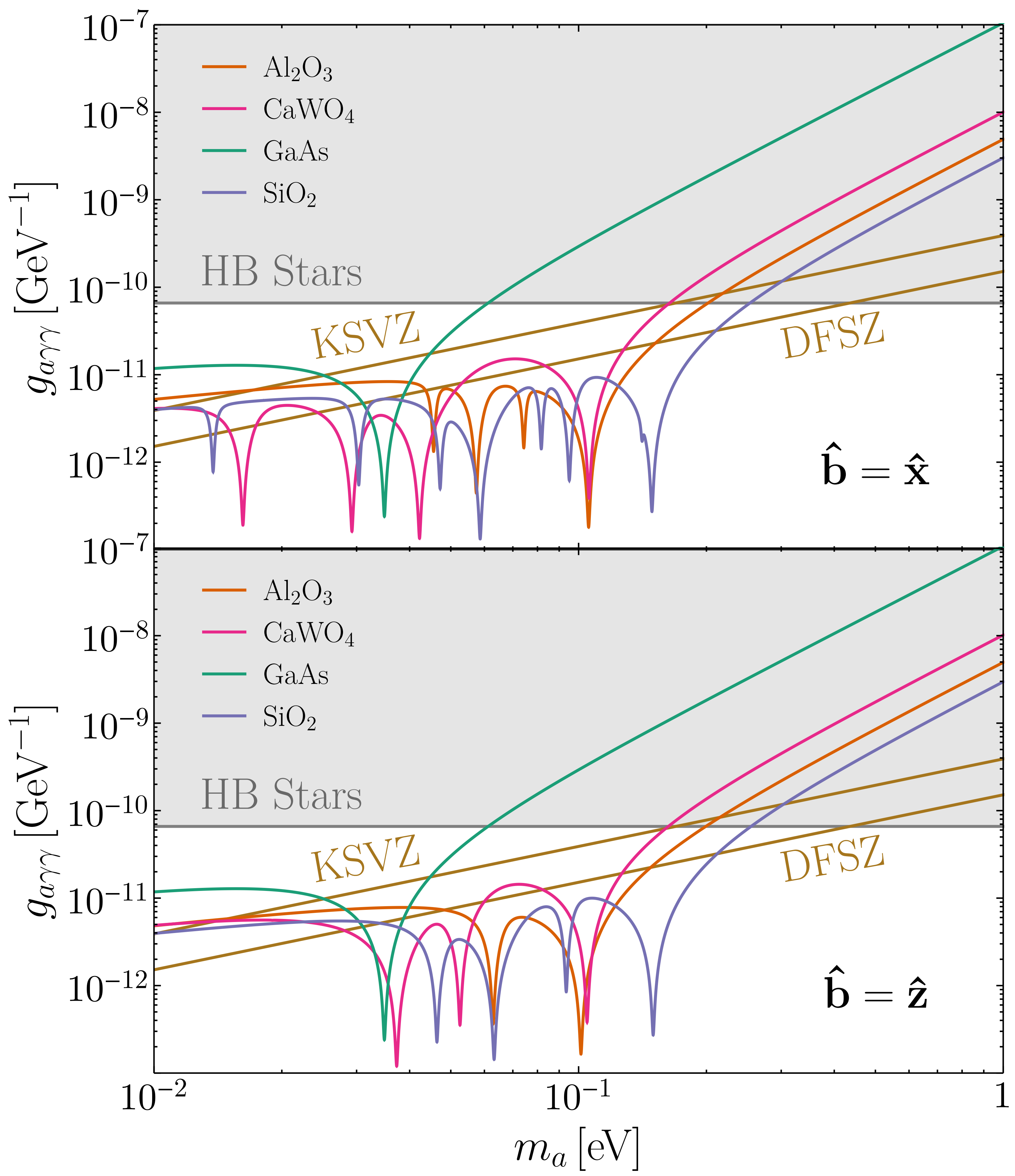




coupled modes depend on the magnetic field orientation

XENON anomaly?





read-out complicated by the strong external magnetic field
standard TES read out does not work

possible solutions

helium evaporation

- 👍 good efficiency
- 👎 need very well polished samples
- …

photon read-out

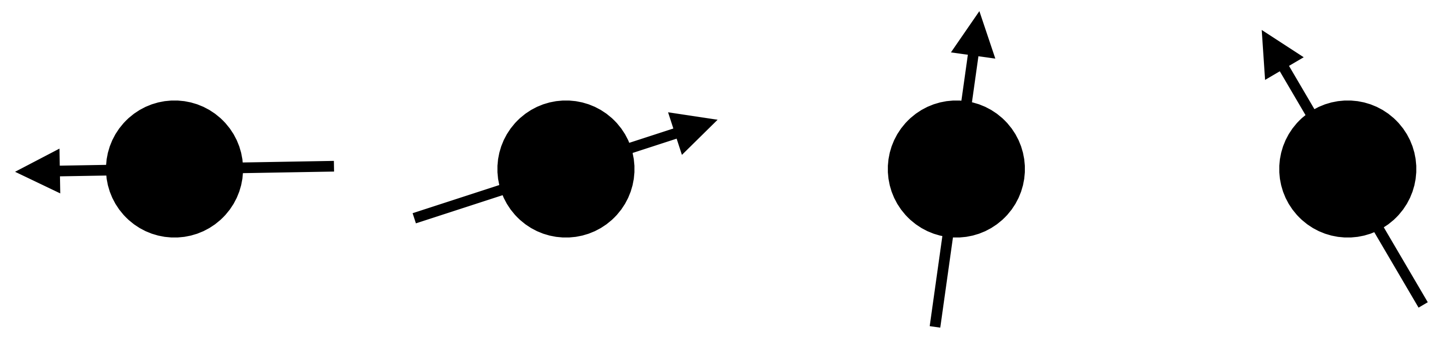
???

main open question: TO-phonon BR into photons

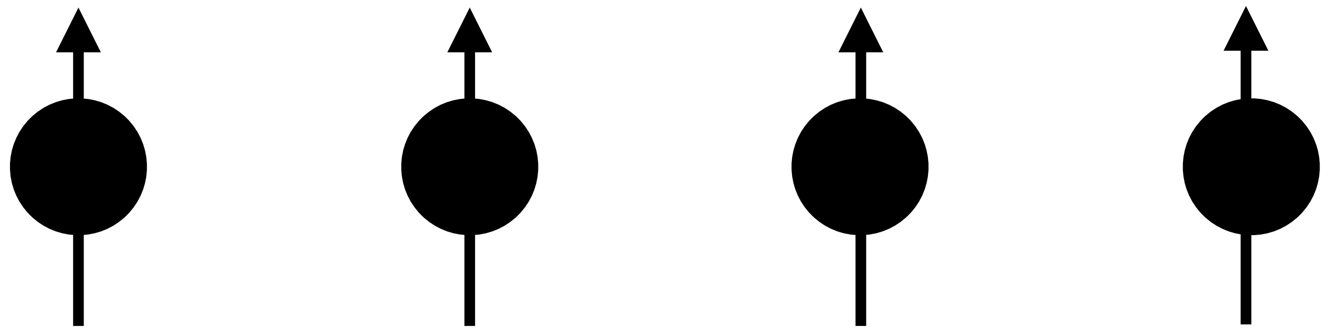
???

Magnons

generic material



ferromagnet ($J > 0$)



$$\mathcal{H} = -J \sum_{ij} \mathbf{S}_i \cdot \mathbf{S_j}$$

magnons

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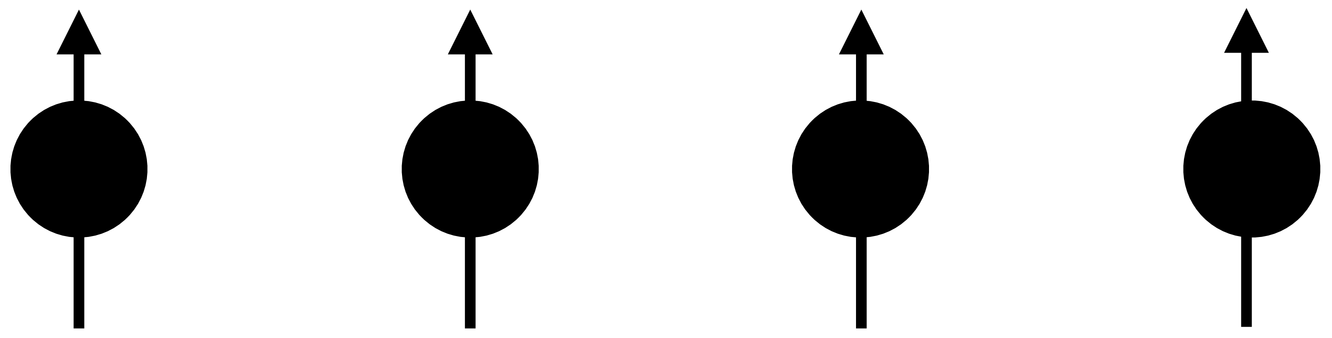

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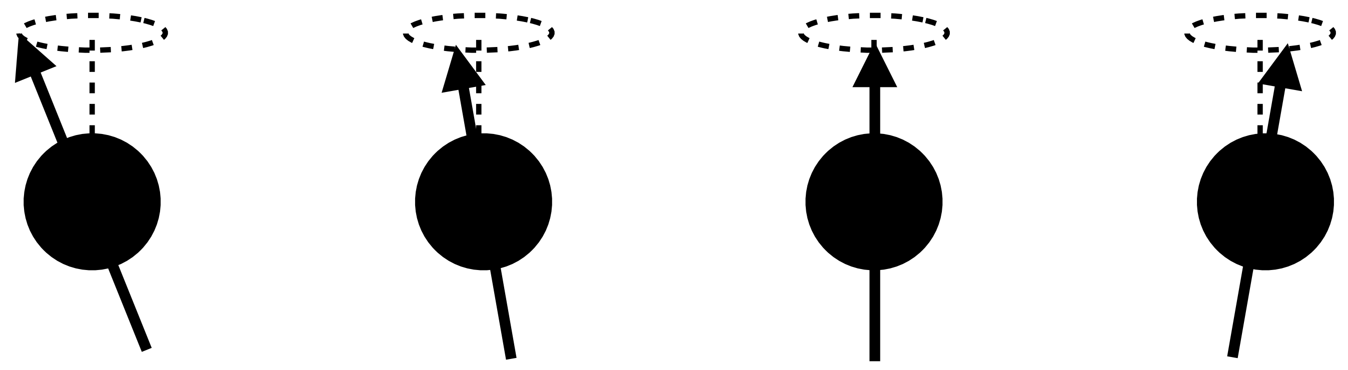
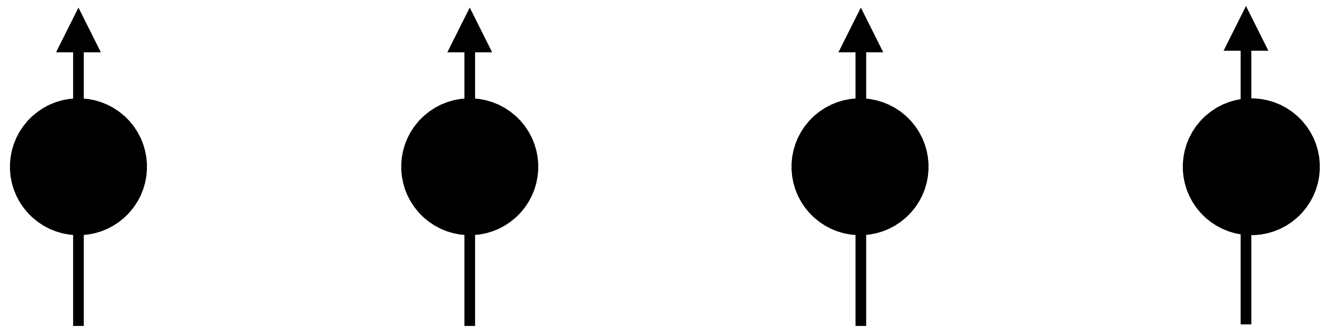
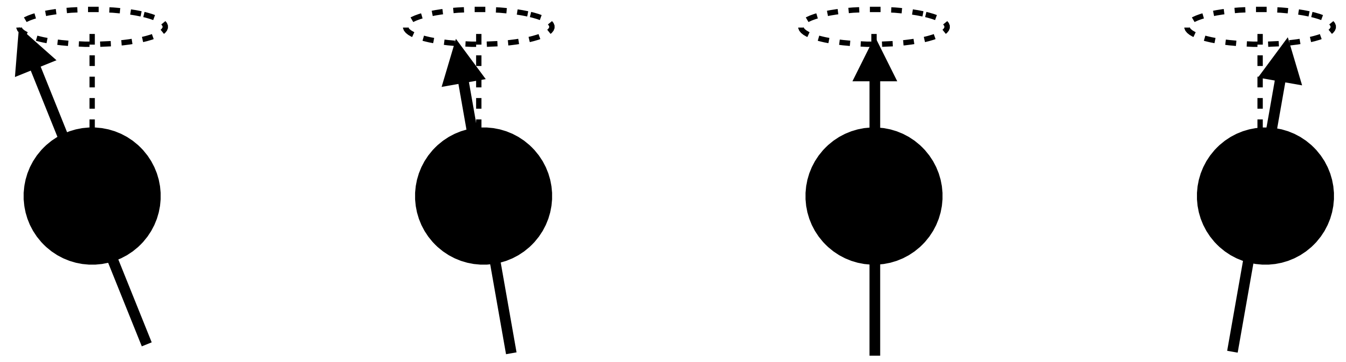


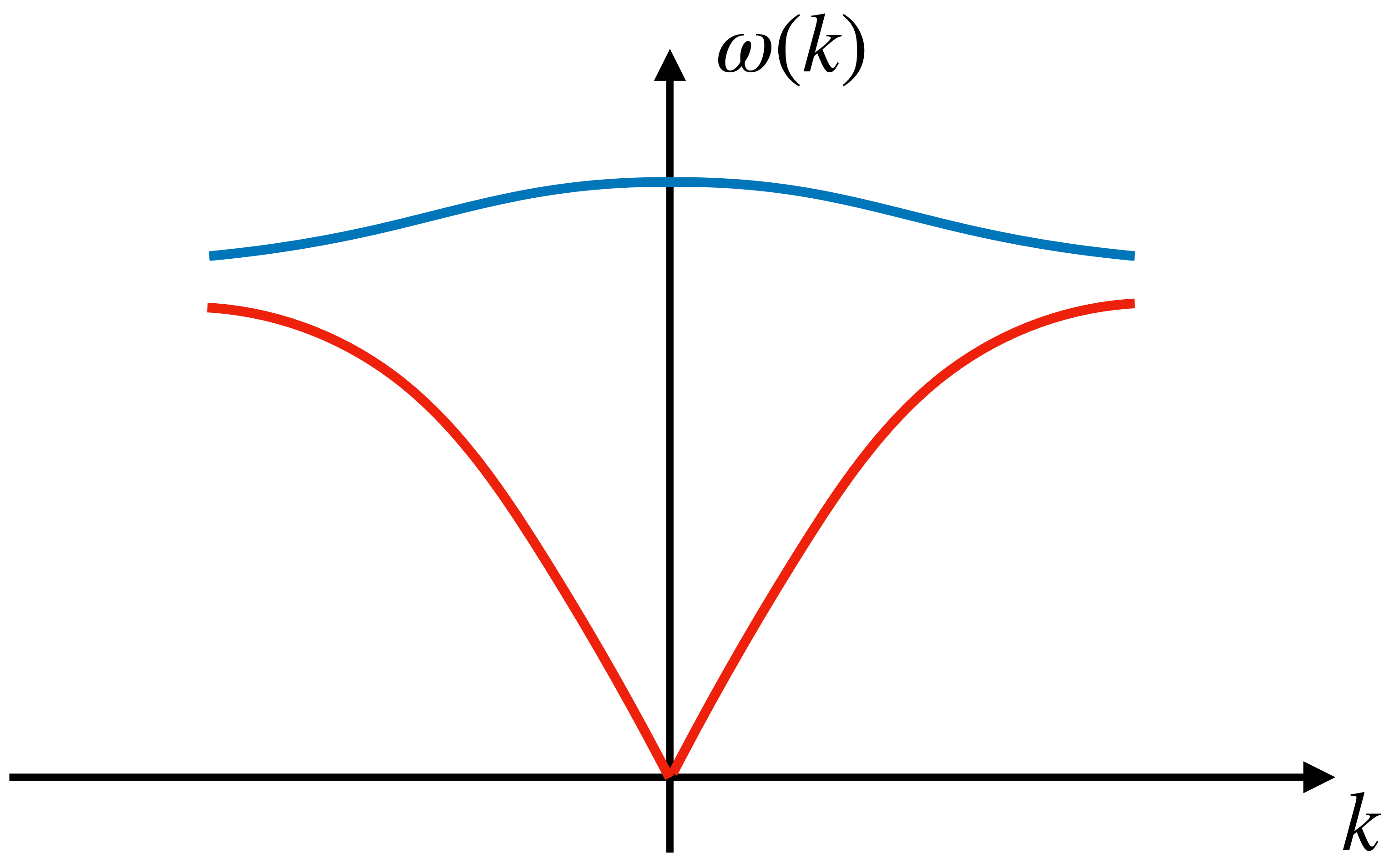
quanta of excitations about the magnetically order ground states are **magnons** ferromagnet ($J > 0$)



$$\mathcal{H} = -J \sum_{ij} \mathbf{S}_i \cdot \mathbf{S}_\mathbf{j}$$



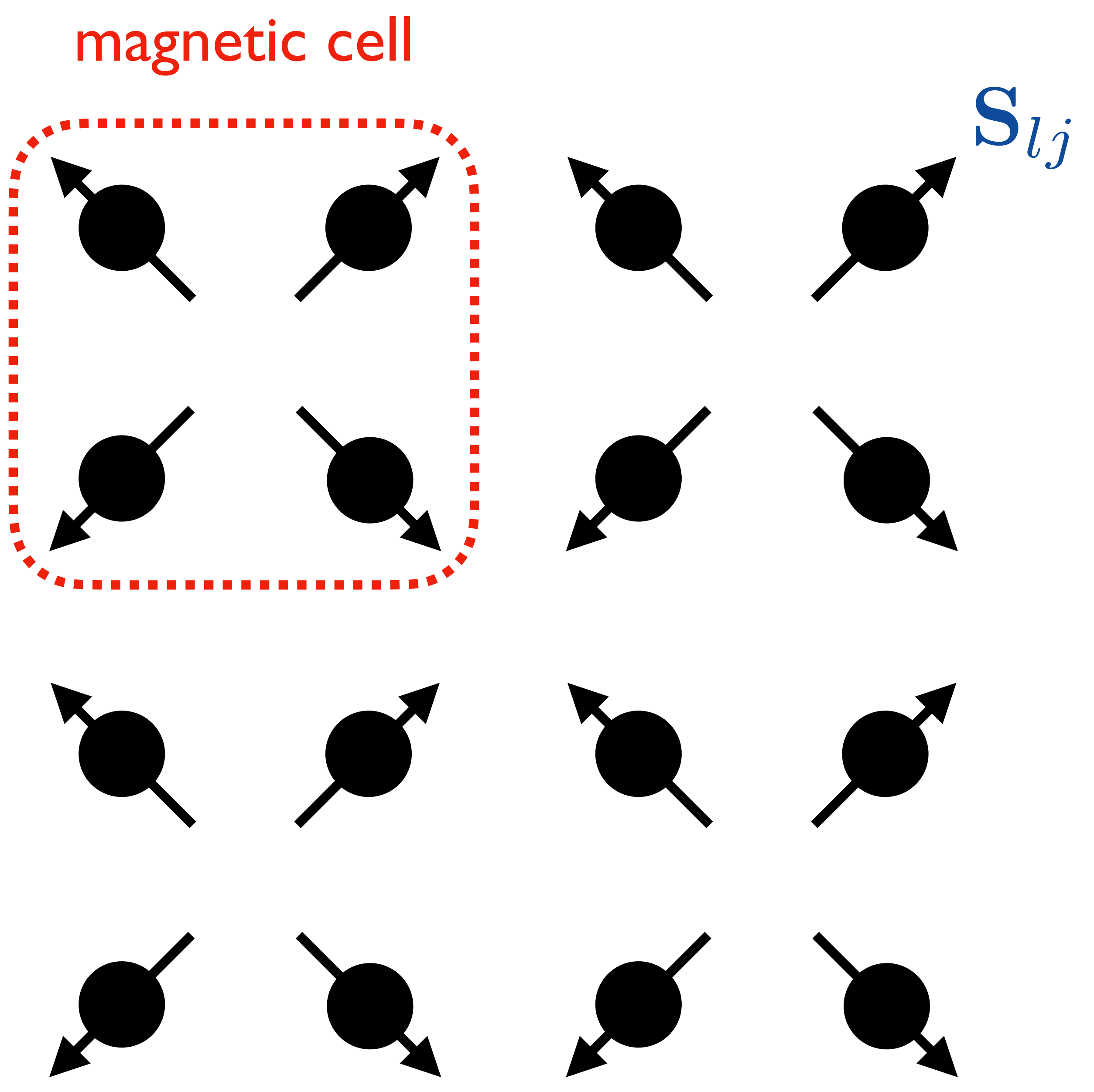
quanta of excitations about the magnetically order ground states are **magnons**



gapless mode associated to broken rotation symmetry

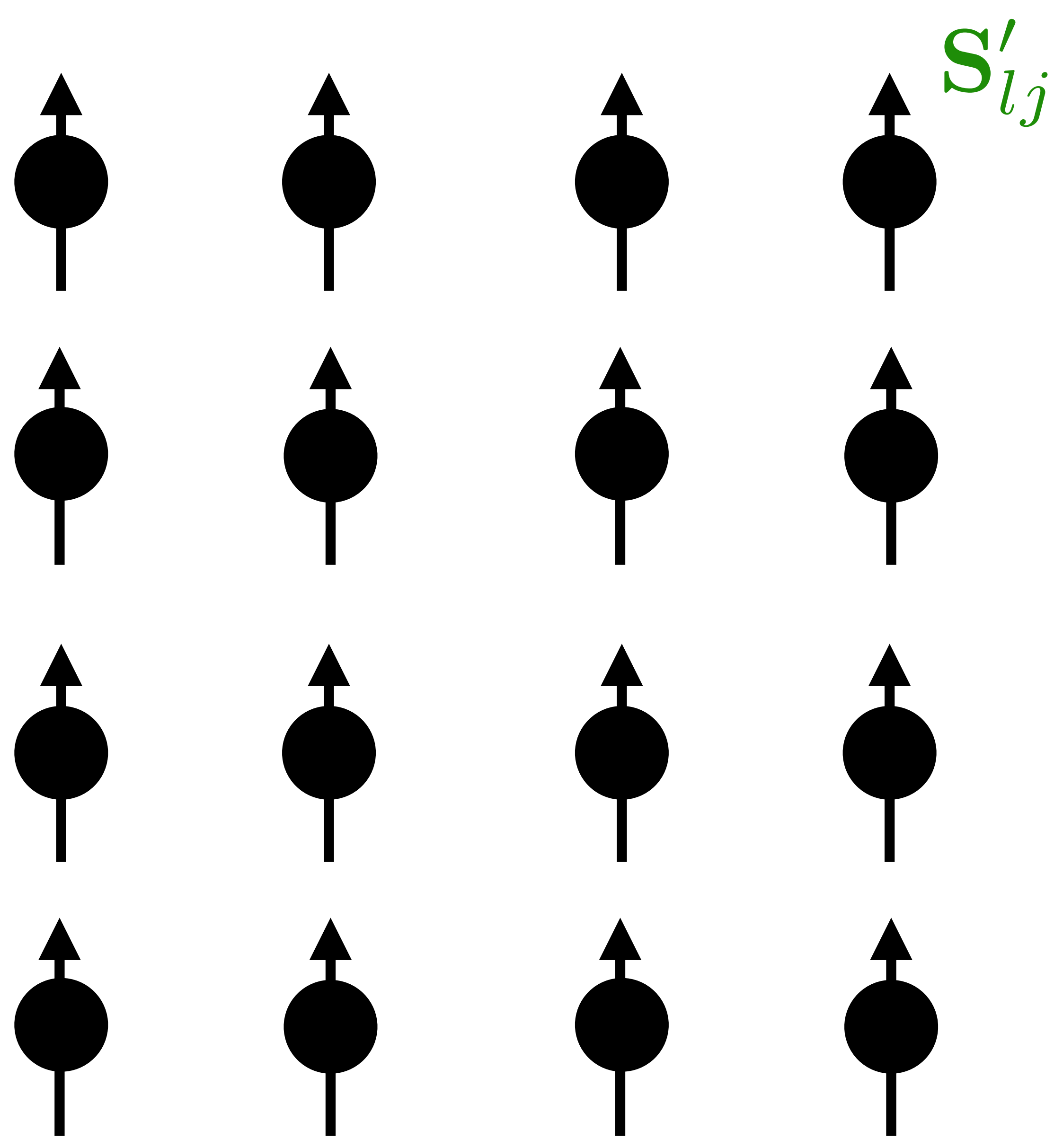
gapped modes arise when inequivalent ions are present in the primitive cell

magnons in real life



$$S^{\alpha}_{lj} = R^{\alpha\beta}_{j} S'^{\beta}_{lj}$$

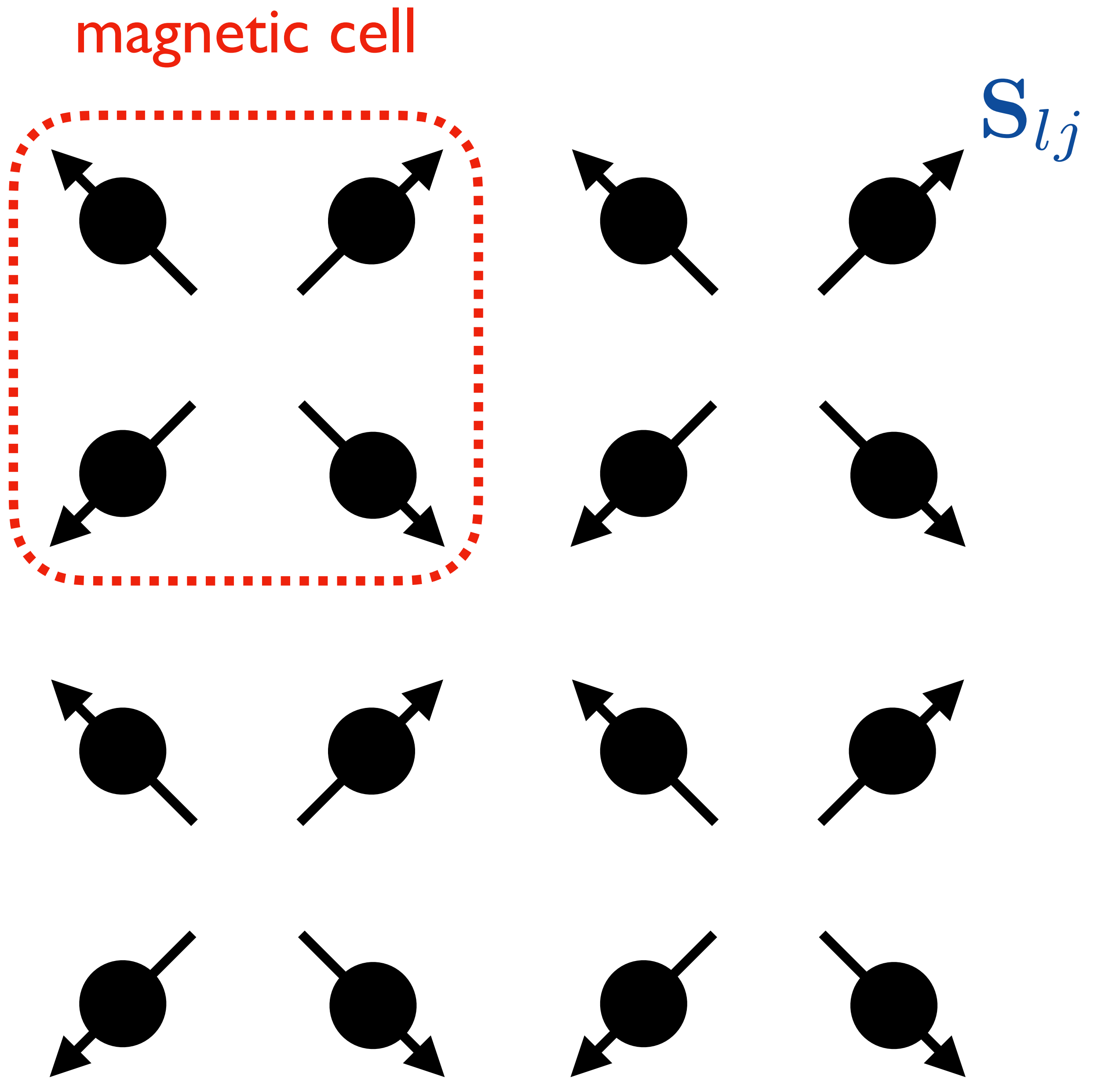
rotation from global to local coordinates



$$S'^{+}_{lj} = \left(2S_j - \hat{a}^{\dagger}_{lj}\hat{a}_{lj}\right)^{1/2} \hat{a}_{lj}$$

$$S'^{-}_{lj} = \hat{a}^{\dagger}_{lj} \left(2S_j - \hat{a}^{\dagger}_{lj}\hat{a}_{lj}\right)^{1/2}$$

$$S'^{z}_{lj} = S_j - \hat{a}^{\dagger}_{lj}\hat{a}_{lj}$$



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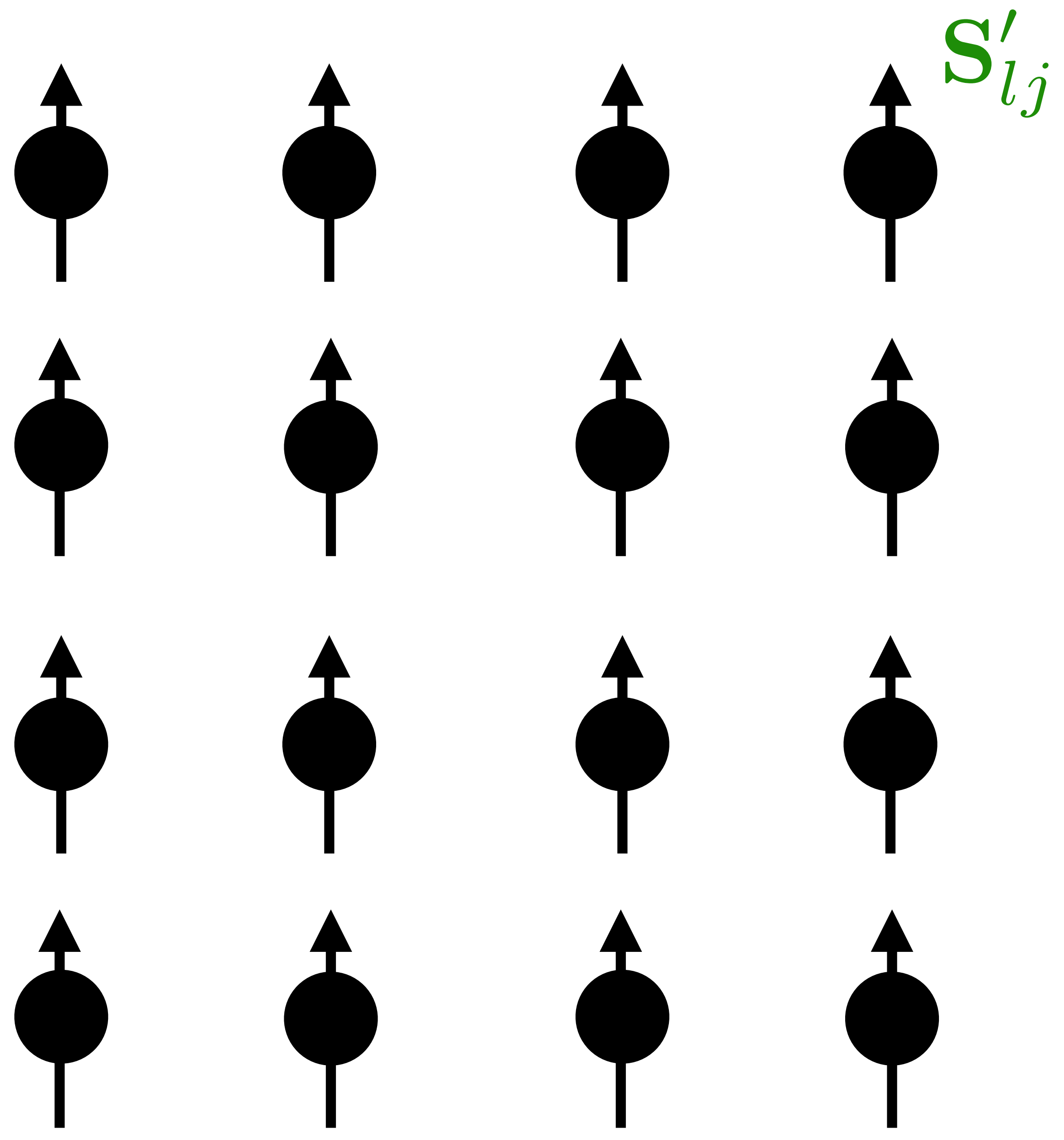


$$S'^{+}_{lj} = \left(2S_j - \hat{a}^{\dagger}_{lj}\hat{a}_{lj}\right)^{1/2} \hat{a}_{lj} \qquad S'^{-}_{lj} = \hat{a}^{\dagger}_{lj} \left(2S_j - \hat{a}^{\dagger}_{lj}\hat{a}_{lj}\right)^{1/2} \qquad S'^{z}_{lj} = S_j - \hat{a}^{\dagger}_{lj}\hat{a}_{lj}$$

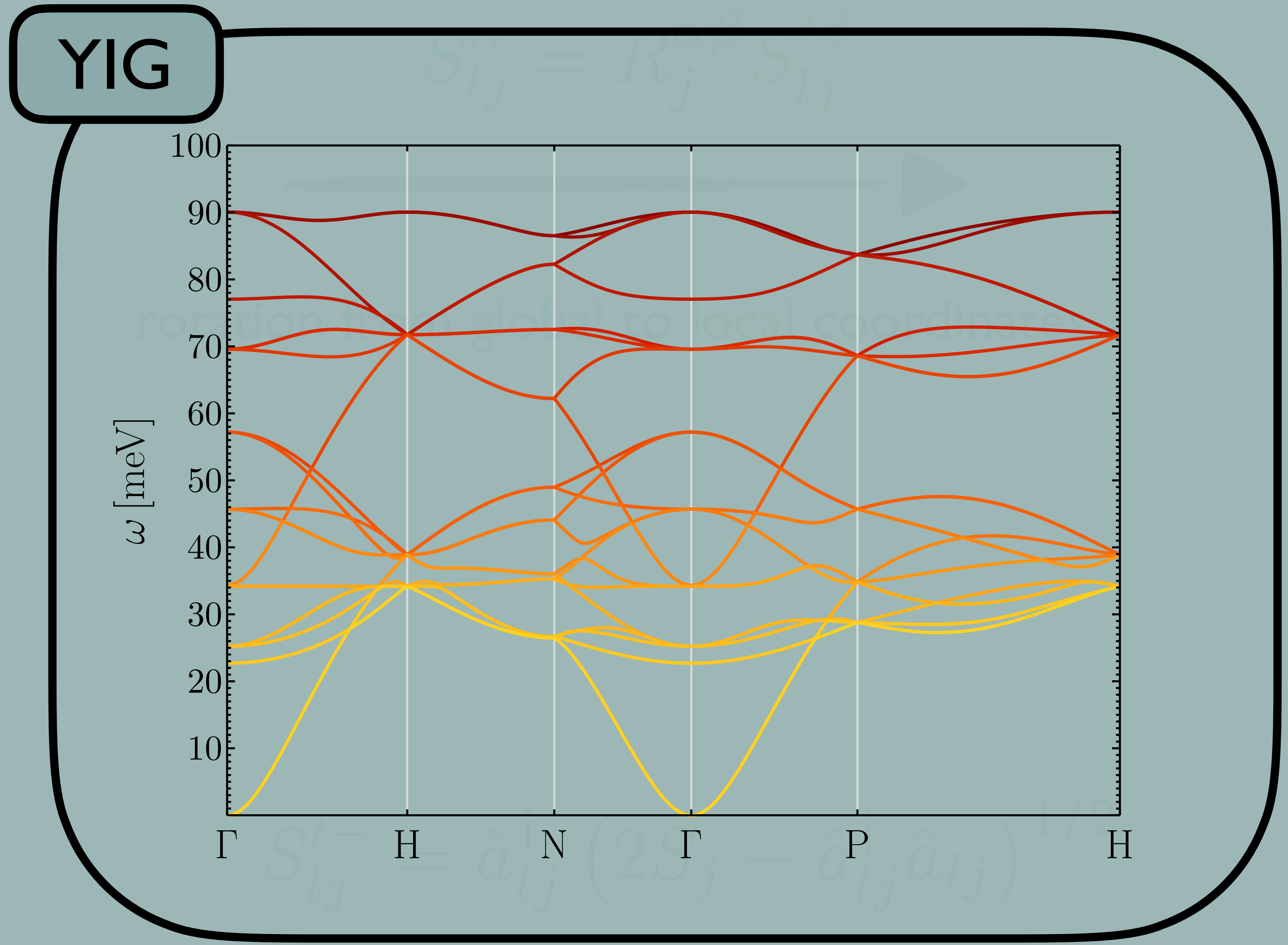
$$\mathcal{H} = \sum_{ll'jj'} \mathbf{S}_{lj} \cdot \mathbf{J}_{ll'jj'} \cdot \mathbf{S}_{l'j'}$$

$$\mathbb{a}_{\mathbf{k}} = \mathbb{T}_{\mathbf{k}} \cdot \mathbb{a}'_{\mathbf{k}}$$

$$\mathbb{a}_{\mathbf{k}} \equiv \left[\hat{a}'_{1,\mathbf{k}}, \ldots, \hat{a}'_{n,\mathbf{k}}, \hat{a}'^{\dagger}_{1,-\mathbf{k}}, \ldots, \hat{a}'^{\dagger}_{n,-\mathbf{k}}\right]^{\mathbb{T}}$$

$$\mathcal{H} = \sum_{\nu=1}^{n} \sum_{\mathbf{k}} \omega_{\nu,\mathbf{k}} \hat{a}'^{\dagger}_{\nu,\mathbf{k}} \hat{a}'_{\nu,\mathbf{k}}$$

figure from Trickle, Zhang, Zurek, 1905.13744



one phonon branch (one of which gapless) for each magnetic ion in the unit cell

the axion wind couples to ions spins

g_j : Landé g-factor

$$\mathcal{L} \supset \frac{g_{aee}}{2m_e}(\partial_\mu a)(\bar{\psi}\gamma^\mu\gamma^5\psi) \xrightarrow{\text{NR limit}} \delta\mathcal{H} = \frac{g_{aee}}{m_e}\nabla a \cdot \mathbf{s}_e \longrightarrow \delta\mathcal{H} = \sum_j \frac{g_{aee}(g_j - 1)}{m_e}\nabla a \cdot \mathbf{S}_j$$

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this induces a magnon excitations rate (per unit time and detector mass)

$$R = \frac{g_{aee}^2}{m_e^2\, m_{\text{cell}}}\frac{\rho_a}{m_a^2}\int d^3v_a\, f(\mathbf{v}_a)\sum_{\nu=6}^{3n+2}\frac{m_a\omega'_{\nu,\mathbf{p}}\gamma_{\nu,\mathbf{p}}}{(m_a^2-\omega'^2_{\nu,\mathbf{p}})^2+(m_a\gamma_{\nu,\mathbf{p}})^2}\left|\sum_j\sum_{\nu'=1}^{3n}\frac{(g_j-1)}{\sqrt{m_j\omega_{\nu',\mathbf{p}}}}\,\mathbf{p_a}\cdot\epsilon^*_{\nu',\mathbf{p},j}\left(\mathbb{U}^*_{\nu'\nu,\mathbf{p}}+\mathbb{V}_{\nu'\nu,-\mathbf{p}}\right)\right|^2$$

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sets the signal intensity

sets selection rules

the axion wind couples to ions spins

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sets the signal intensity

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on resonance

$$R \sim \frac{g_{aee}^2\,\rho_a v_a^2}{m_e^2}\frac{n_s}{\rho_T\gamma} \sim (\text{kg}\cdot\text{yr})^{-1}\left(\frac{g_{aee}}{10^{-15}}\right)^2\left(\frac{\mu\text{eV}}{\gamma}\right)$$

selection rules and ways around them

for $\mathbf{k} \to 0$ only gapless modes can be excited

perturbation $\sim \sum_{jl} g_j \, \mathbf{f_j} \cdot \mathbf{S_{jl}}$

$$\frac{d}{dt}\left(\mathbf{S}_{lj} \cdot \mathbf{S}_{l'j'}\right) = (g_j \mathbf{f}_j - g_{j'} \mathbf{f}_{j'}) \cdot (\mathbf{S}_{lj} \times \mathbf{S}_{l'j'}) = 0 \quad \Longrightarrow \quad \delta E = 0$$

i.e. only gapless mode can be excited

$\mathbf{f}_j = \mathbf{f}_{j'}$ for $\mathbf{k} \to 0$

$g_j = g_{j'}$

$$\mathcal{H} \propto \sum \mathbf{S}_{lj} \cdot \mathbf{S}_{l'j'}$$

for $\mathbf{k} \to 0$ only gapless modes can be excited

Non-degenerate g factors

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Non-degenerate g factors

External magnetic field

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i.e. only gapless mode can be excited

$\mathbf{f}_j = \mathbf{f}_{j'}$ for $\mathbf{k} \to 0$

$g_j = g_{j'}$

$\mathcal{H} \propto \sum \mathbf{S}_{lj} \cdot \mathbf{S}_{l'j'}$ → $\mathcal{H} \propto \sum \mathbf{S}_{lj} \cdot \mathbf{S}_{l'j'} + \mu_B \mathbf{B} \cdot \sum g_j \mathbf{S}_{lj}$

idea exploited by QUAX exp.

Barbieri, Cerdonio, Fiorentini, Vitale ('89)
Barbieri et al 1606.02201

selection rules **and ways around them**

for $\mathbf{k} \to 0$ only gapless modes can be excited

Non-degenerate g factors

External magnetic field

Anisotropic interactions

perturbation $\sim \sum_{jl} g_j \, \mathbf{f_j} \cdot \mathbf{S_{jl}}$

$$\frac{d}{dt}(\mathbf{S}_{lj} \cdot \mathbf{S}_{l'j'}) = (g_j \mathbf{f}_j - g_{j'} \mathbf{f}_{j'}) \cdot (\mathbf{S}_{lj} \times \mathbf{S}_{l'j'}) = 0 \quad \Longrightarrow \quad \delta E = 0$$

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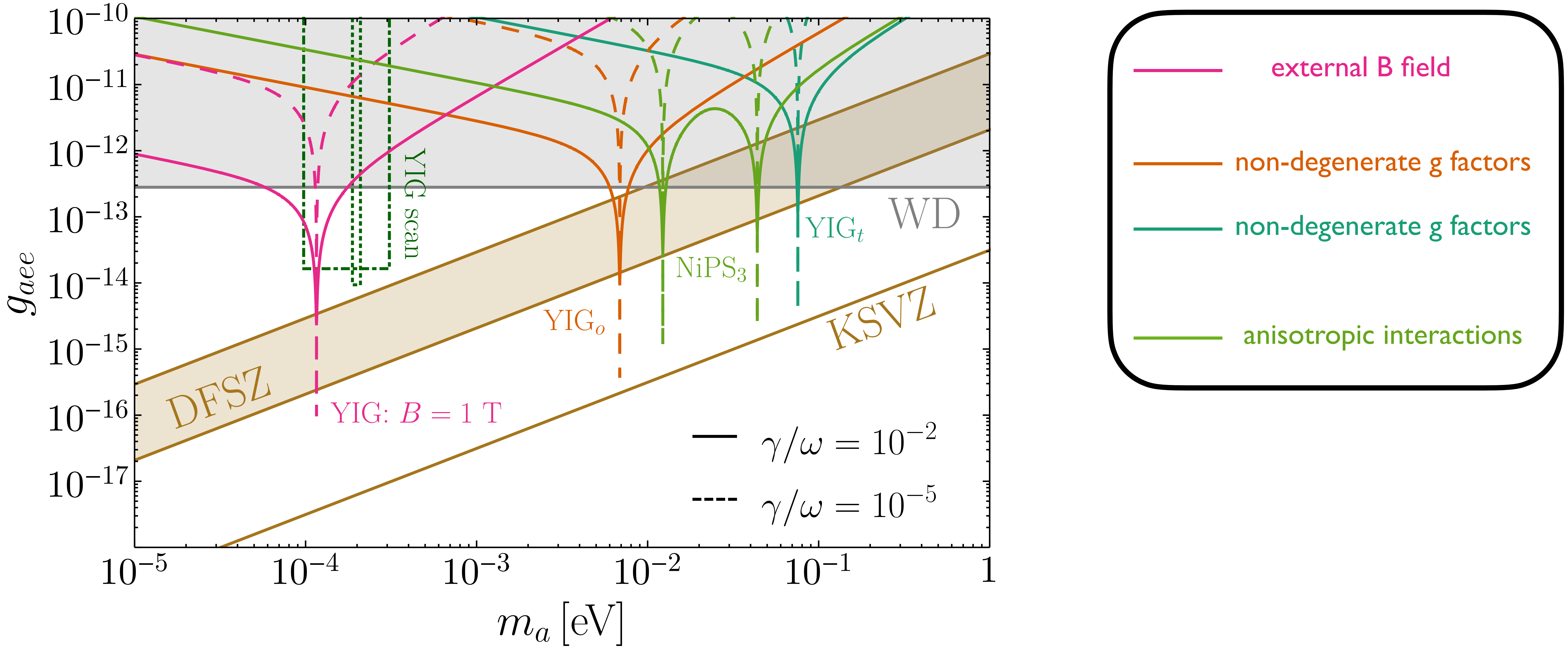
$\mathcal{H} \propto \sum \mathbf{S}_{lj} \cdot \mathbf{S}_{l'j'}$ → $\mathcal{H} \propto \sum \mathbf{S}_{lj} \cdot \mathbf{J}_{ll',jj'} \cdot \mathbf{S}_{l'j'}$

projected reach



conclusions

phonon polariton and magnon excitations can probe the QCD axion DM in the $(1 \div 100)\,\mathrm{meV}$ mass range

a thoughtful choice of complementary target can offer a broadband coverage

we identified two new ways to couple axion to gapped magnons

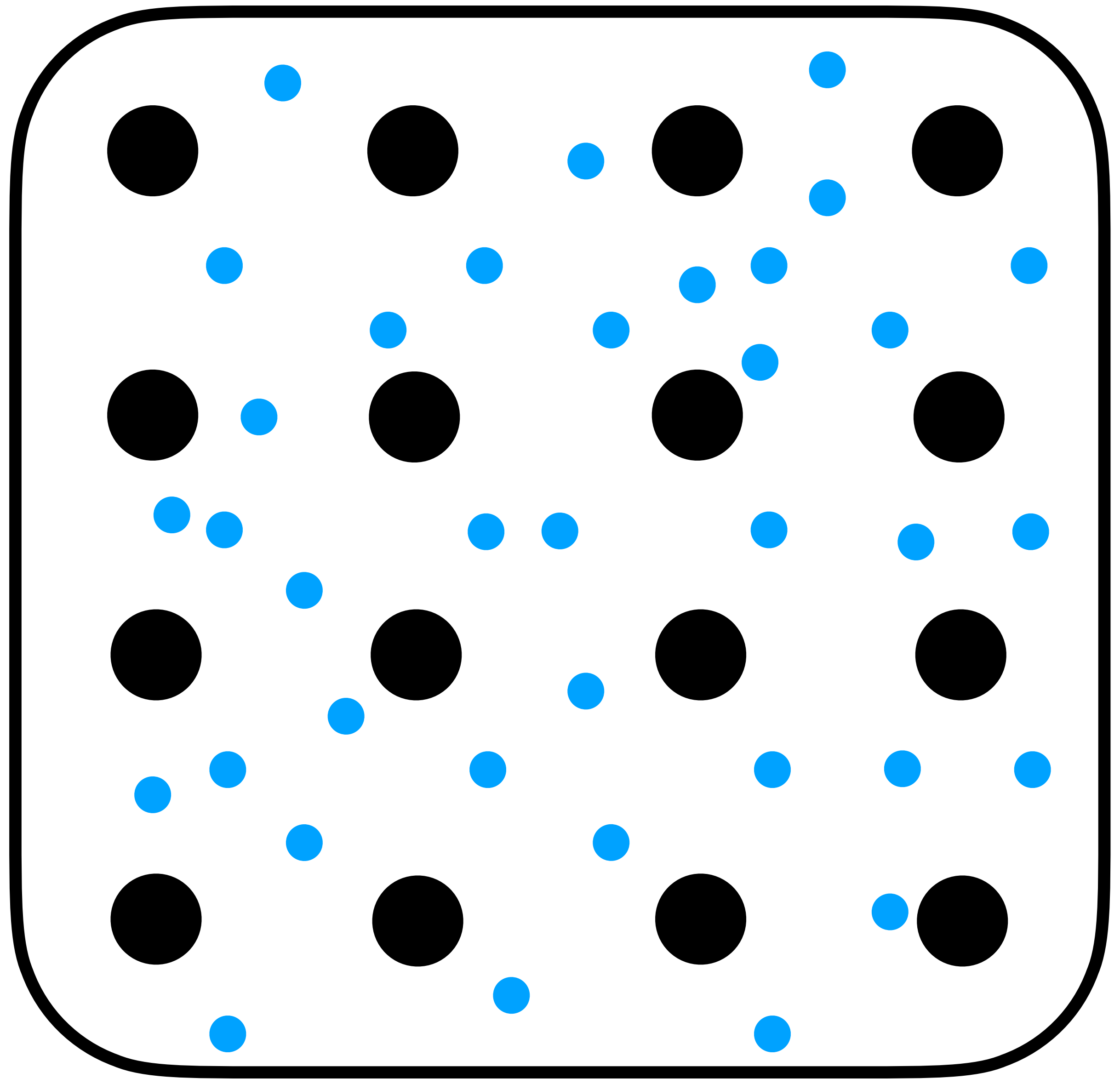
a better knowledge of magnon and phonon line-shape is needed to get more precise results

we suggest possible read-out schemes, R&D will be crucial to identify realistic experimental set-up

Backup slides

: ions

: electrons



band gap is too large $\mathcal{O}$(eV)

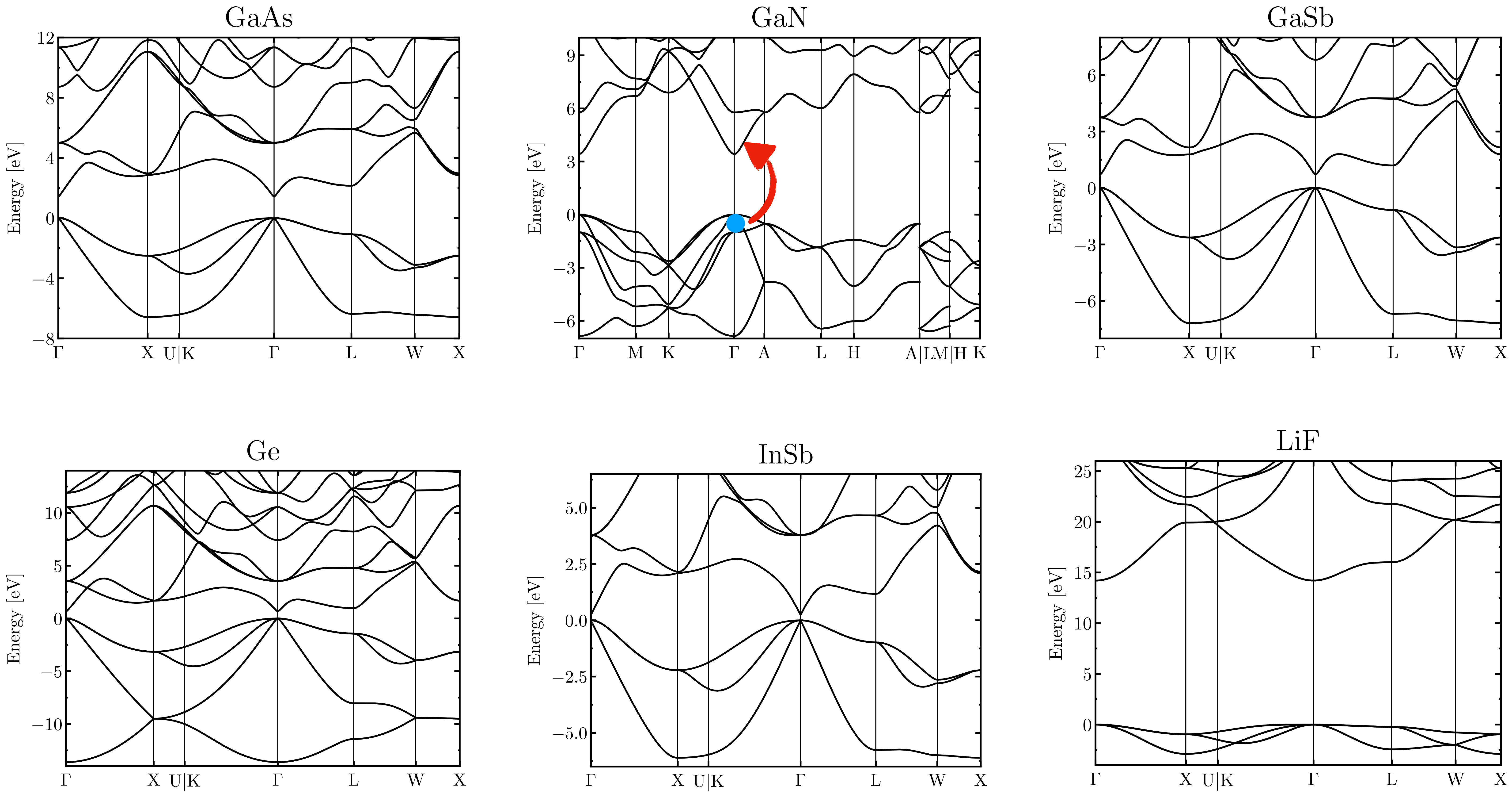


figure from Griffin, Inzani, Trickle, Zhang, Zurek, 1910.10716