Axion dark matter detection with exotic phases of matter

Christina Gao 11/20/2024

YOUNGST@RS - Quantum Sensing for Fundamental Physics

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JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

mitp Mainz Institute for Theoretical Physics

Axion dark matter

Basic Properties:

- Bosonic, high occupation number, behave like a classical field
- Velocity ~100 km/sec

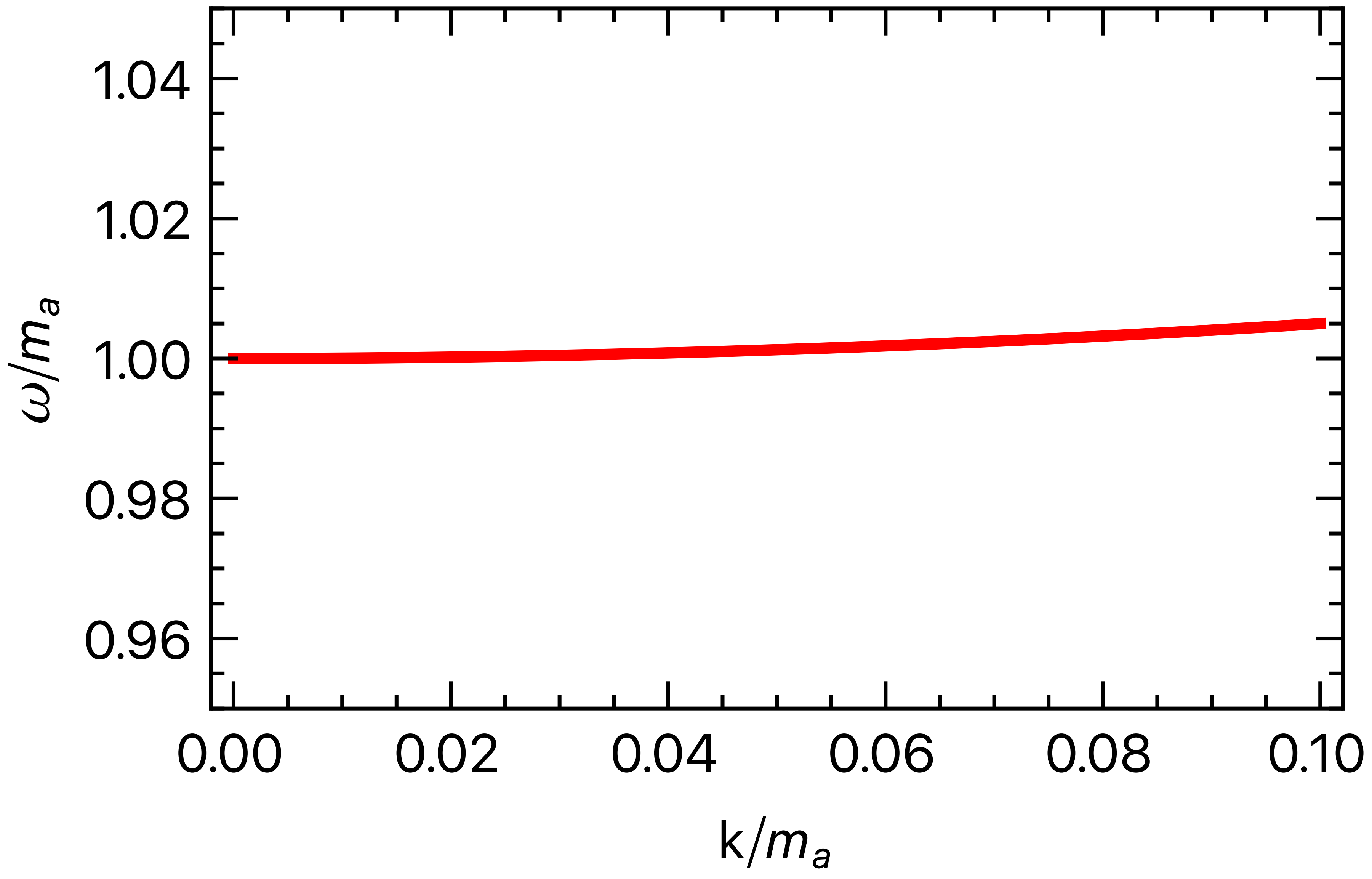
$$a_{\rm DM}(t) \sim A\cos\left(\omega t - \mathbf{k}\cdot\mathbf{x}\right) \sim A\cos(m_a t)$$

$$A \leftarrow \frac{\sqrt{\rho_{\rm DM}}}{m_a} \qquad \omega \leftarrow m_a + \frac{1}{2}m_a v^2 \qquad \mathbf{k} \leftarrow m_a\mathbf{v}$$

Axion dark matter

Dispersion relation

$$\frac{\omega}{m_a} = 1 + \frac{1}{2}\left(\frac{k}{m_a}\right)^2$$



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$$\frac{\sqrt{\rho_{\rm DM}}}{m_a} \qquad m_a + \frac{1}{2}m_a v^2 \qquad m_a\mathbf{v}$$

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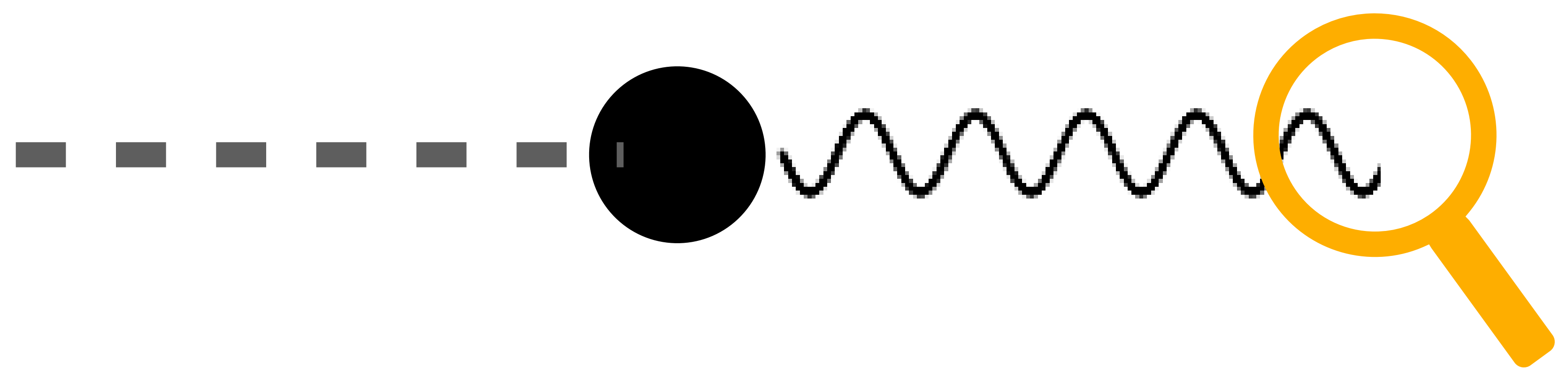
Outline

- Examples of axion absorption
- NMR with helium-3B, an example of forward scattering
- An example with scattering

Detection via absorption

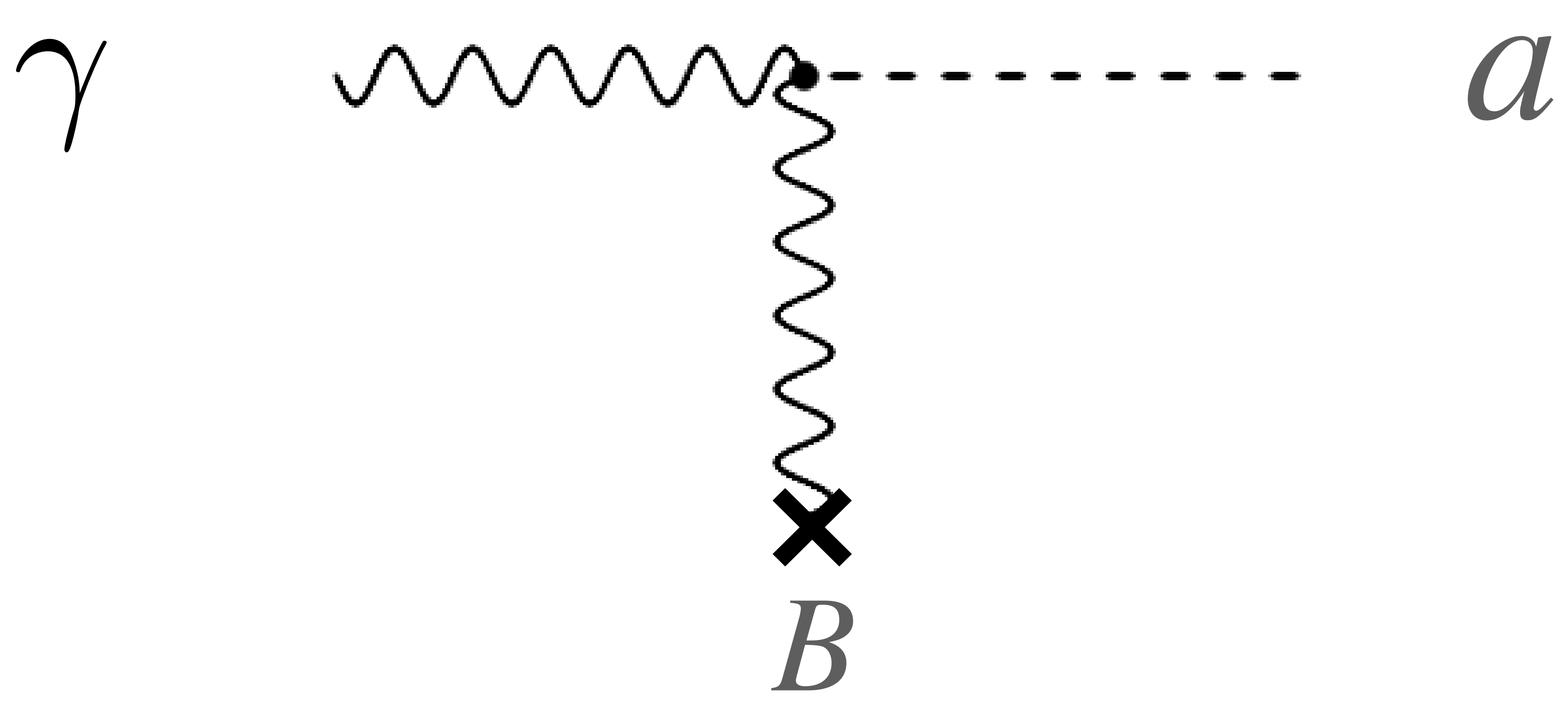


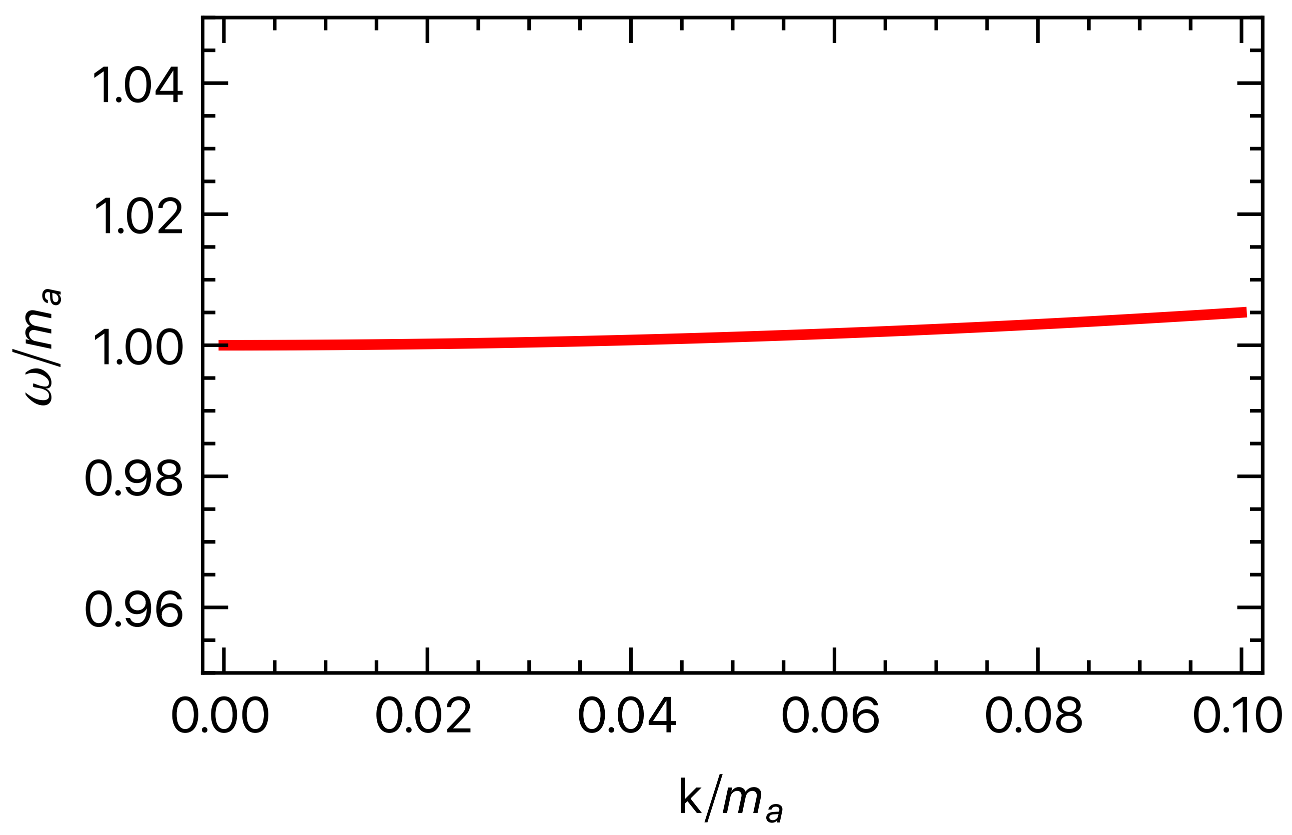
Axions can interact with photons

$$\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$$

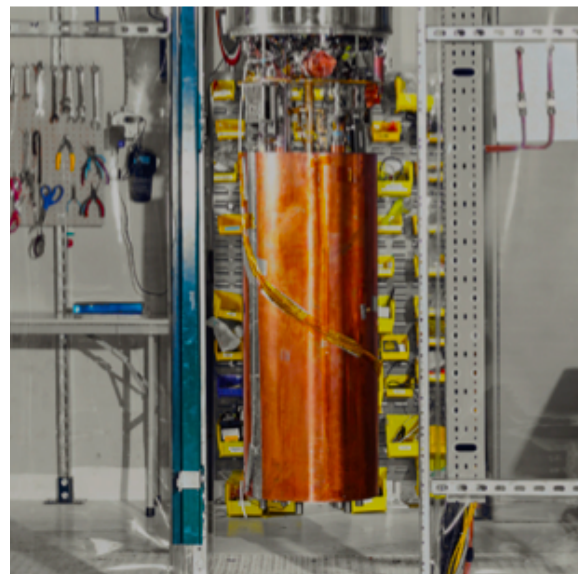
$$\mathcal{L}_{\text{int}} \supset -\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$= g_{a\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$





- Axions can convert to photons in a background magnetic field
- Better conversion efficiency if photon's dispersion is similar to axion's, e.g. cavity photon

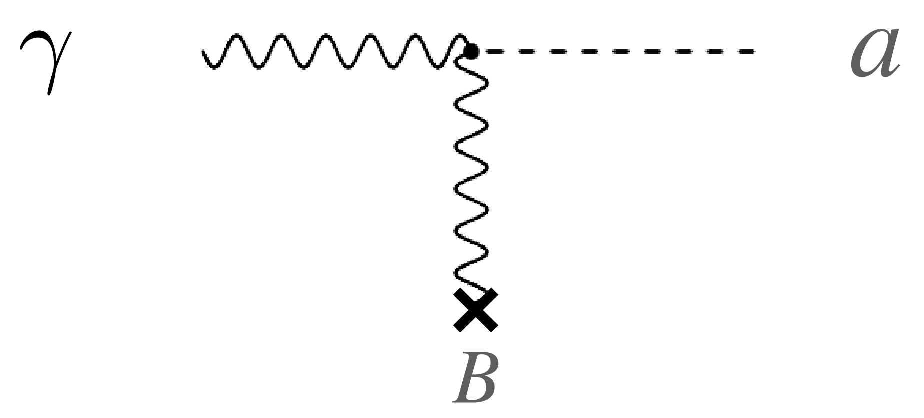


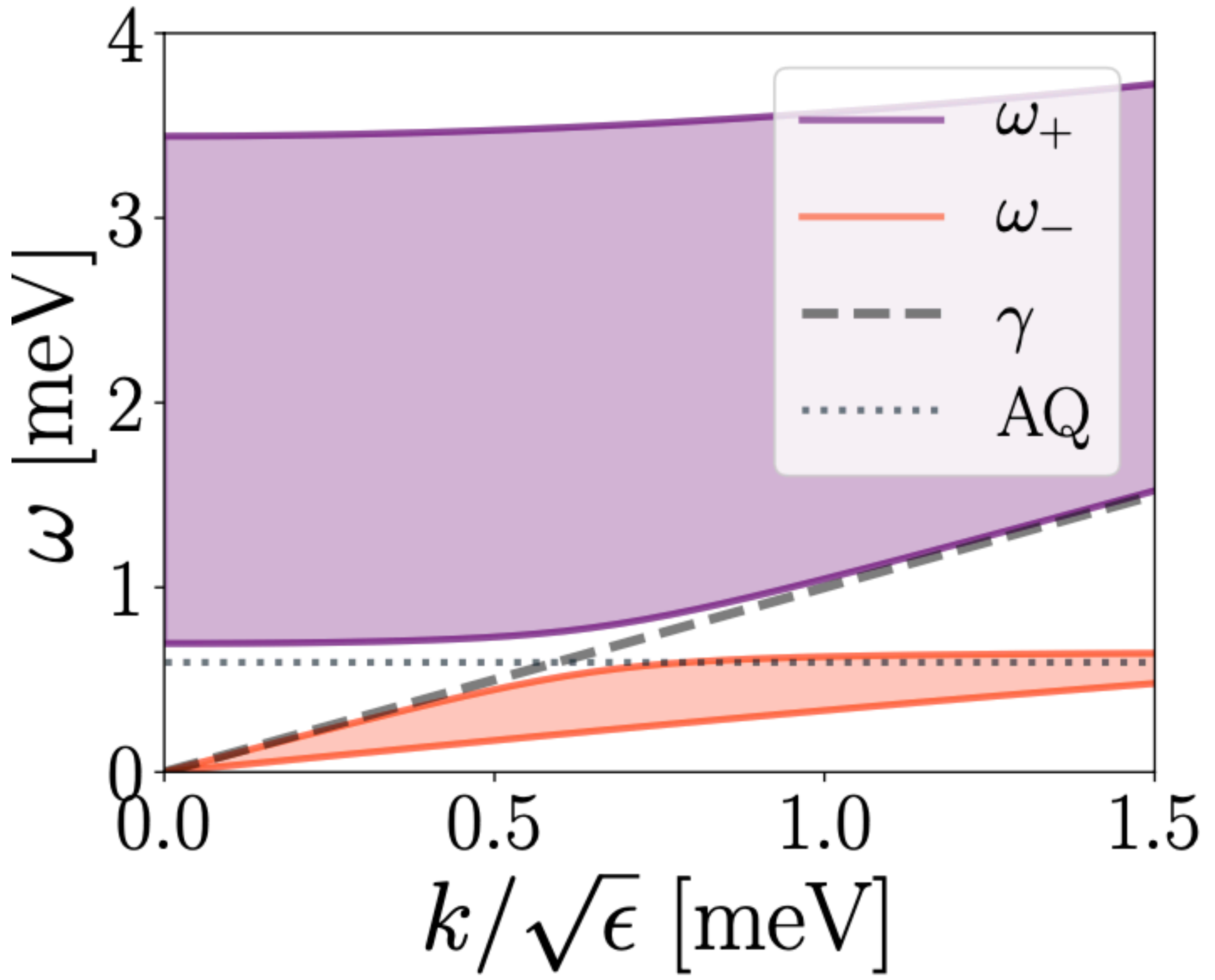
ADMX @ GHz

Light in special materials

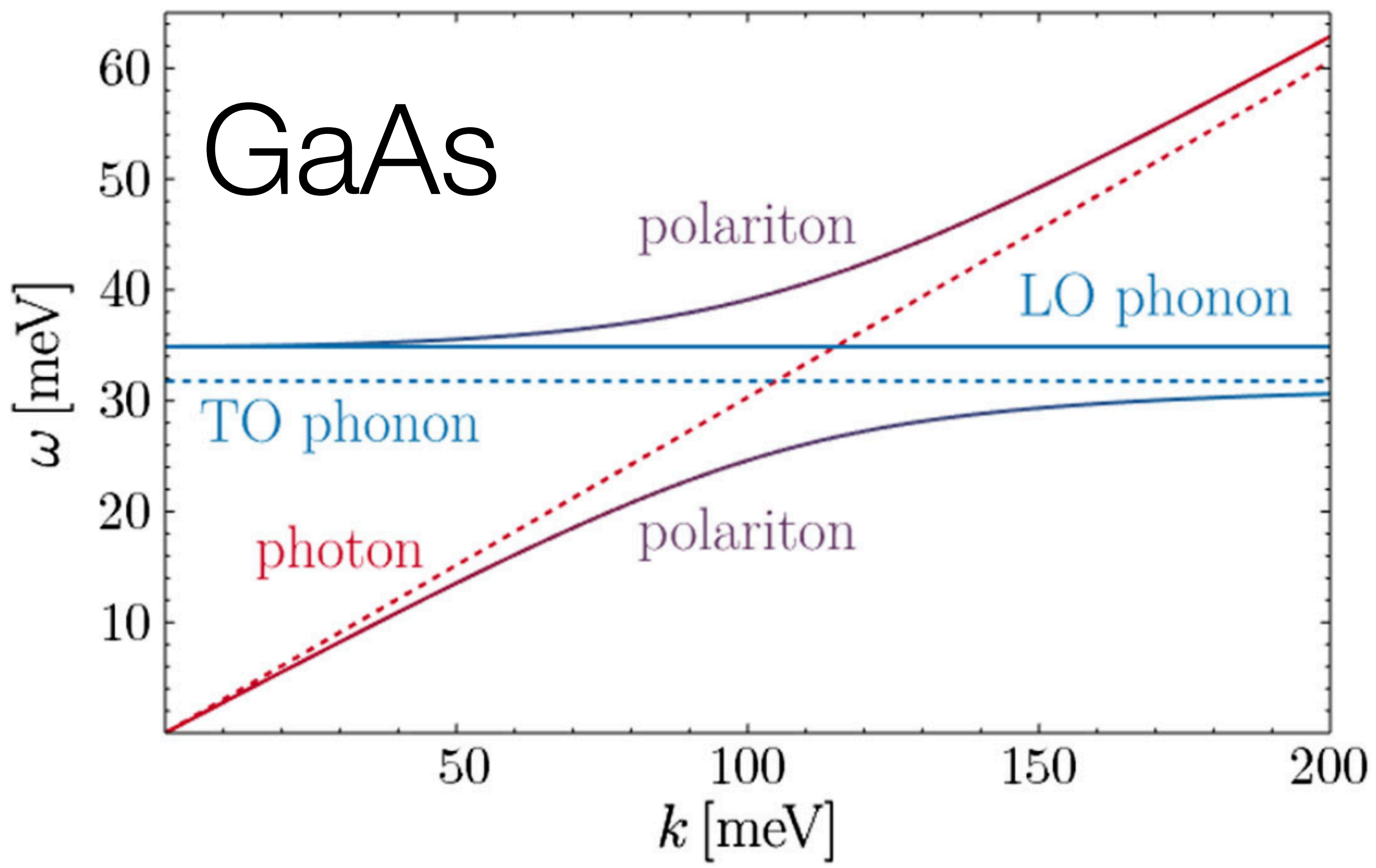
Antiferromagnetically doped topological insulators

Polar crystals





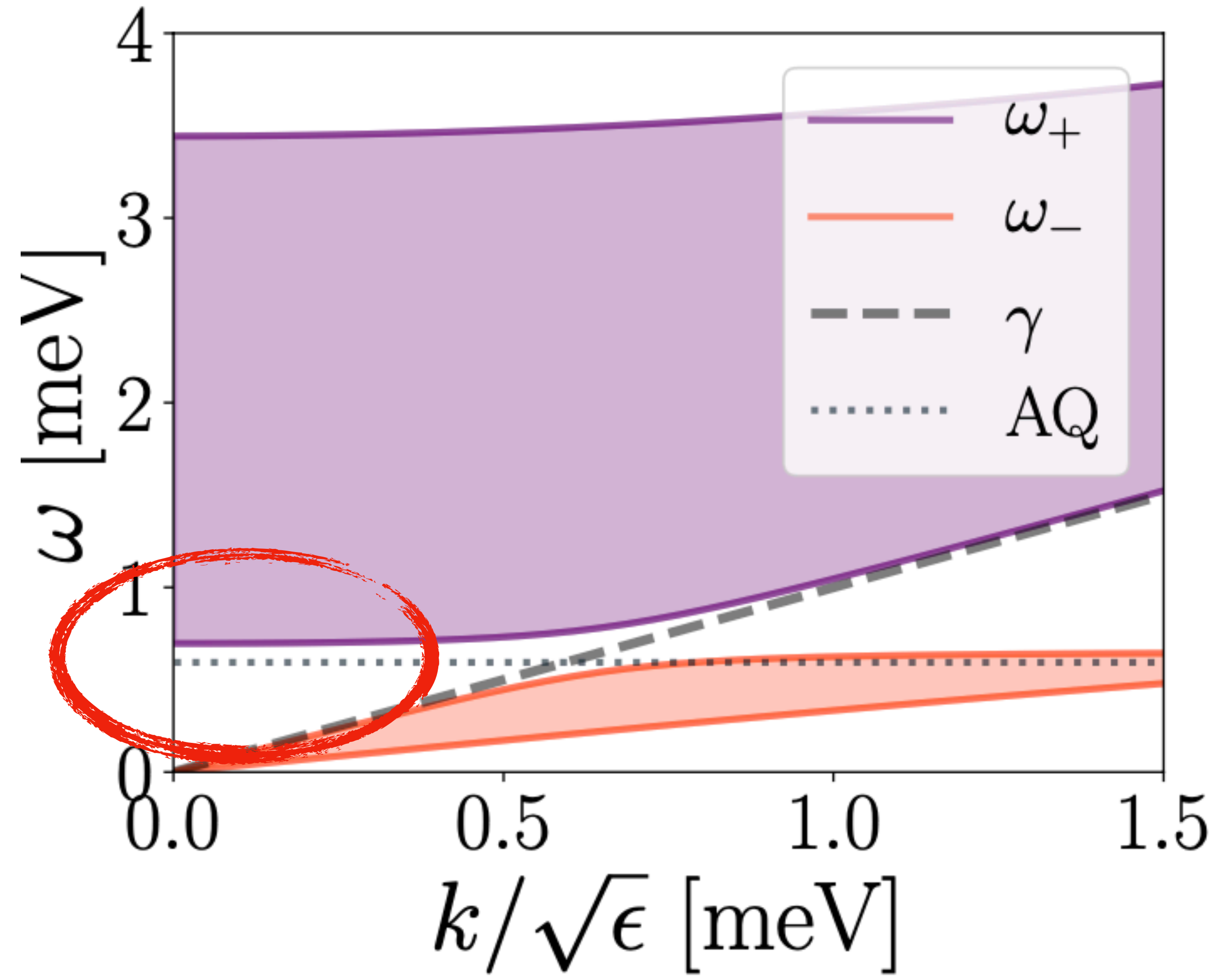
MARSH, FONG, LENTZ, SMEJKAL and ALI (2019)



MITRIDATE, TRICKLE, ZHANG, and ZUREK (2020)

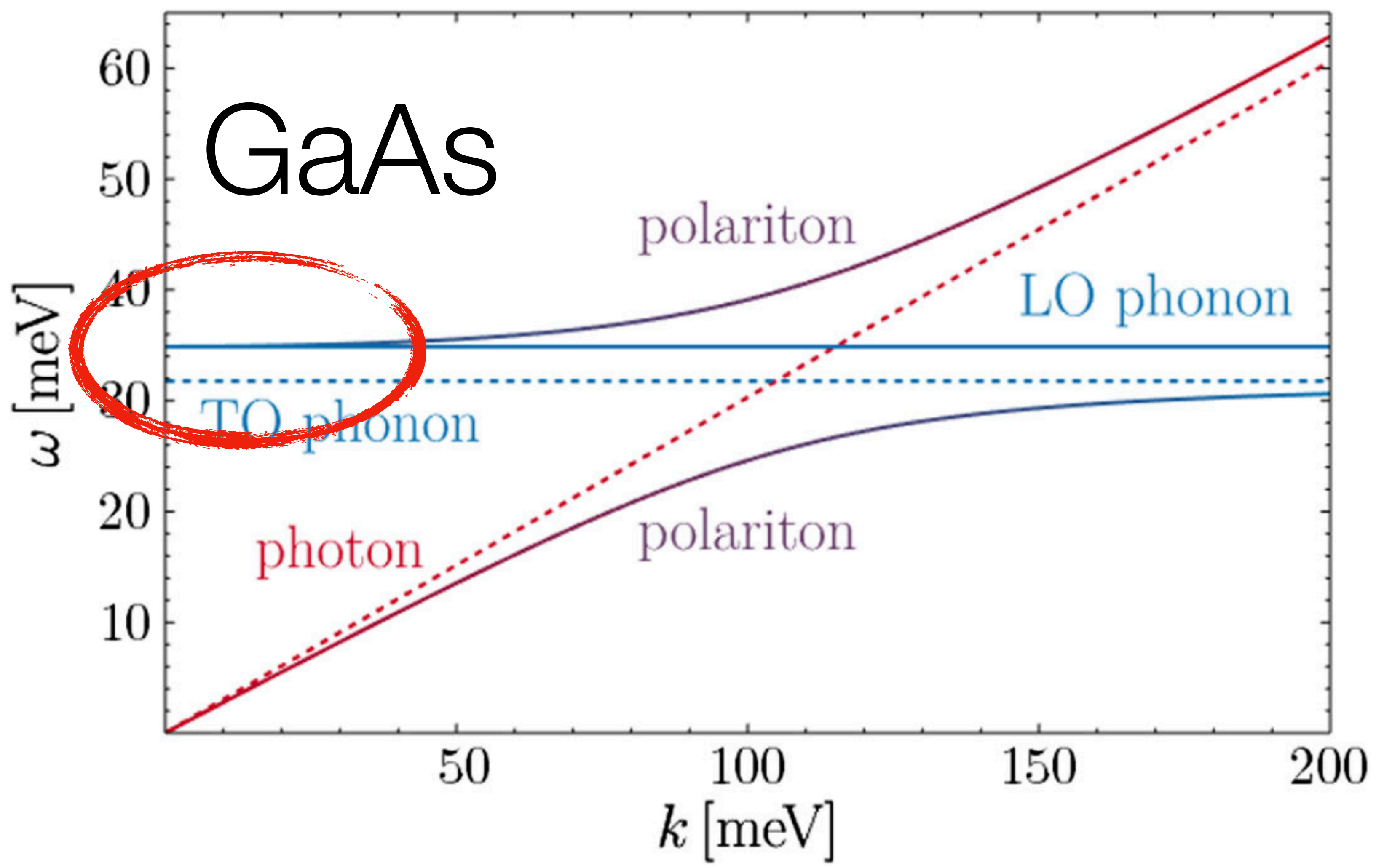
Light in special materials

Antiferromagnetically doped topological insulators



MARSH, FONG, LENTZ, SMEJKAL and ALI (2019)

Polar crystals



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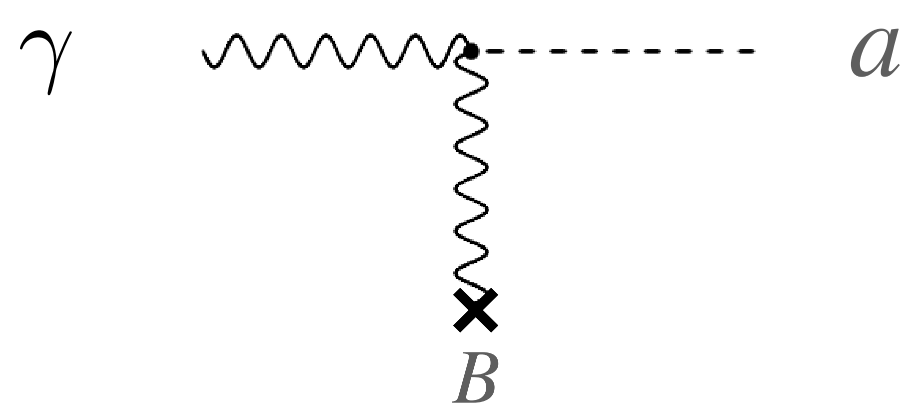
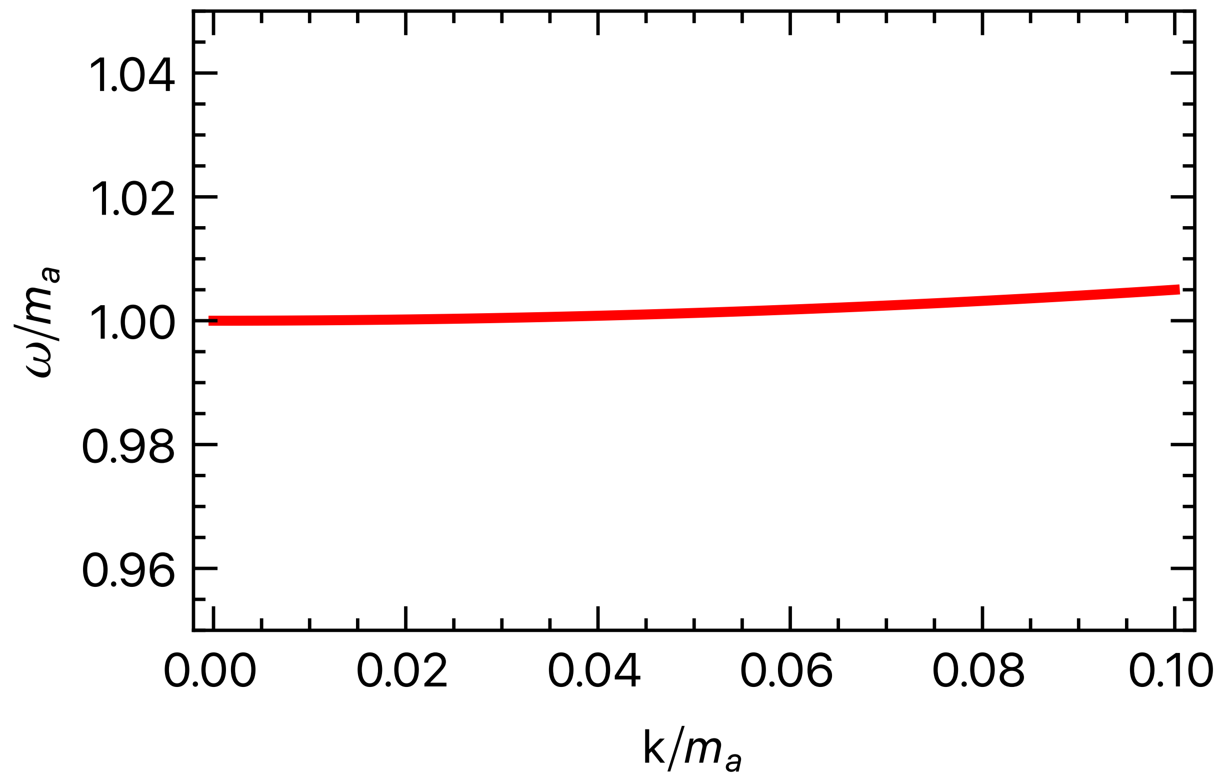
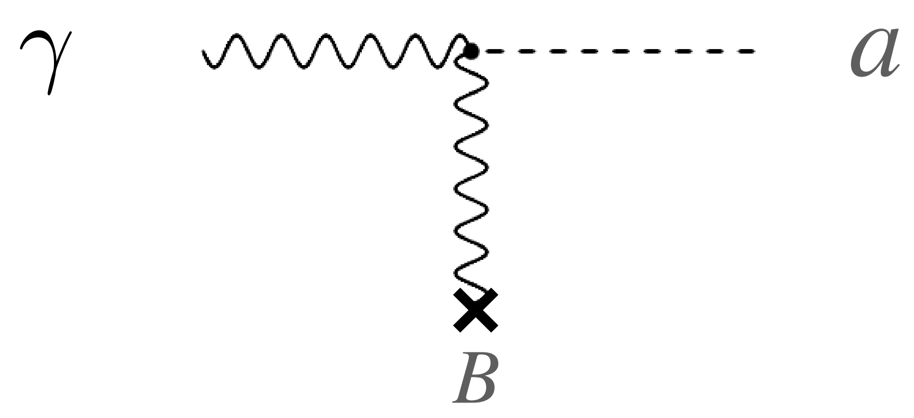




Light in special materials

Antiferromagnetically
doped
topological insulators

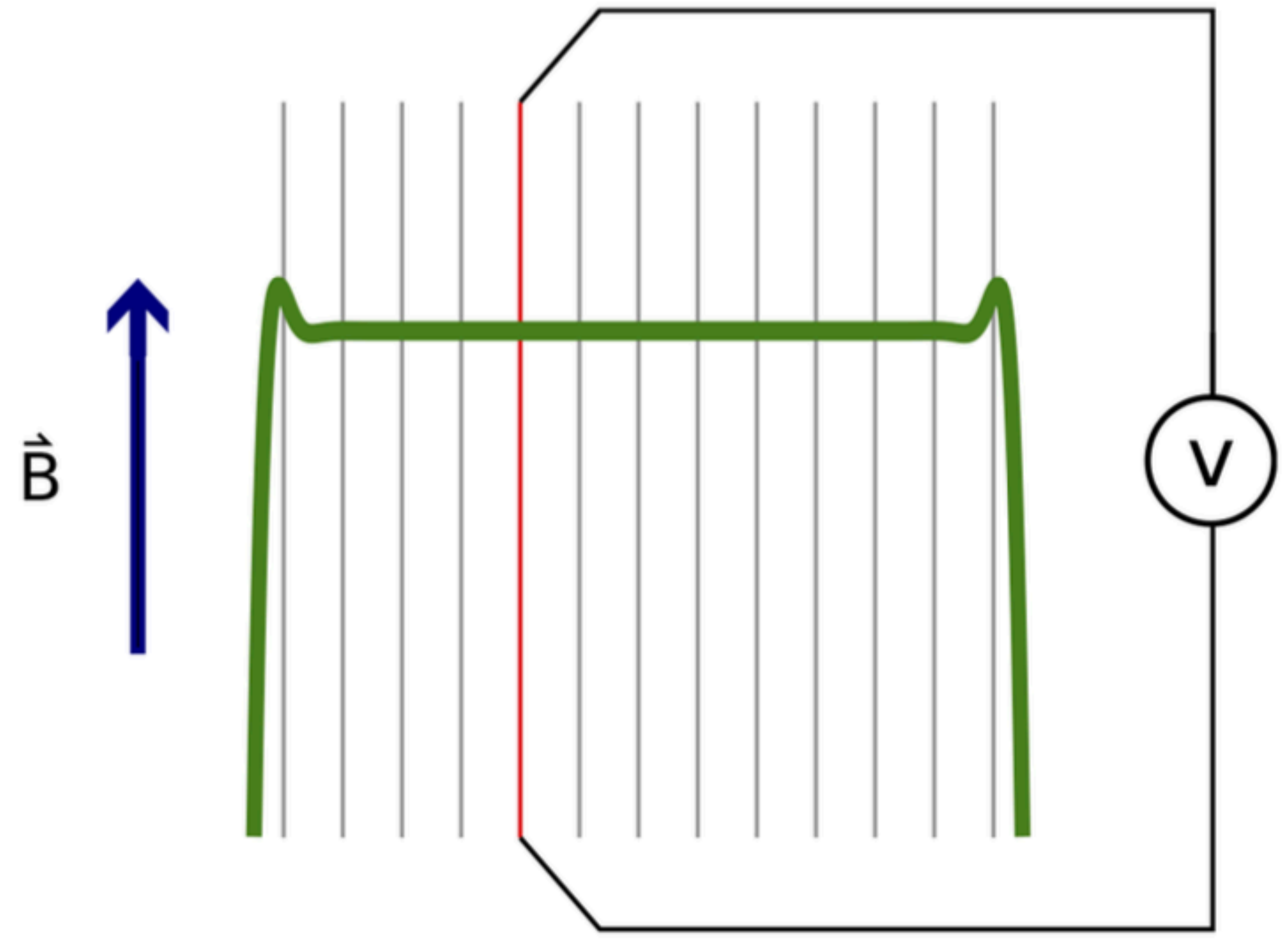
Polar crystals



- Axions can convert to quasiparticles, such as phonons and magnons.
- Target frequency: meV and above.
- Detection of axion via detection of quasiparticles, itself challenging.
- Quasiparticles must have high Q, or very little loss.

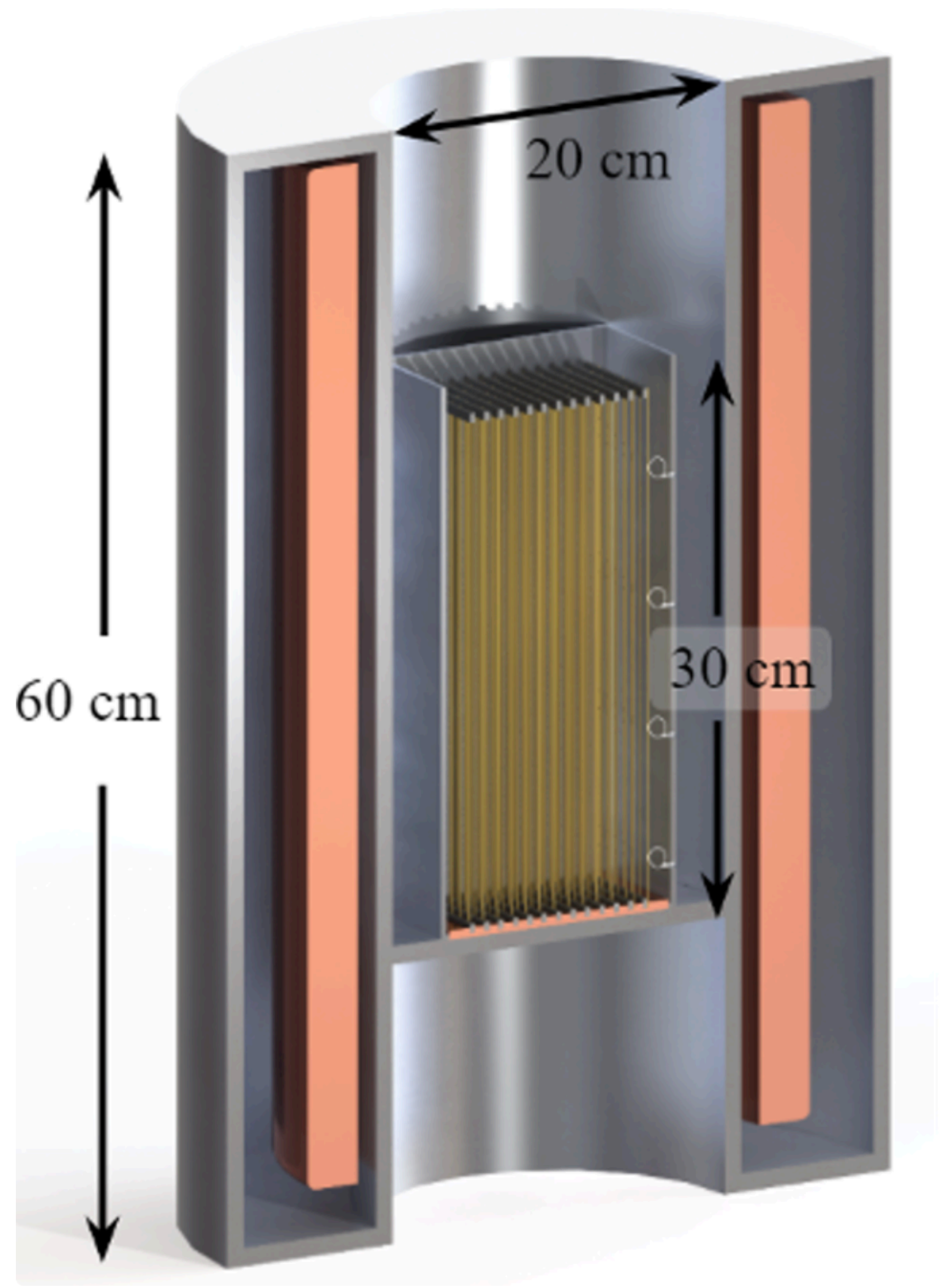
Light in meta-materials

Array of wires, targeting 10^{-4} eV



LAWSON, MILLAR, PANCALDI, VITAGLIANO AND WILCZEK (2019)

alpha



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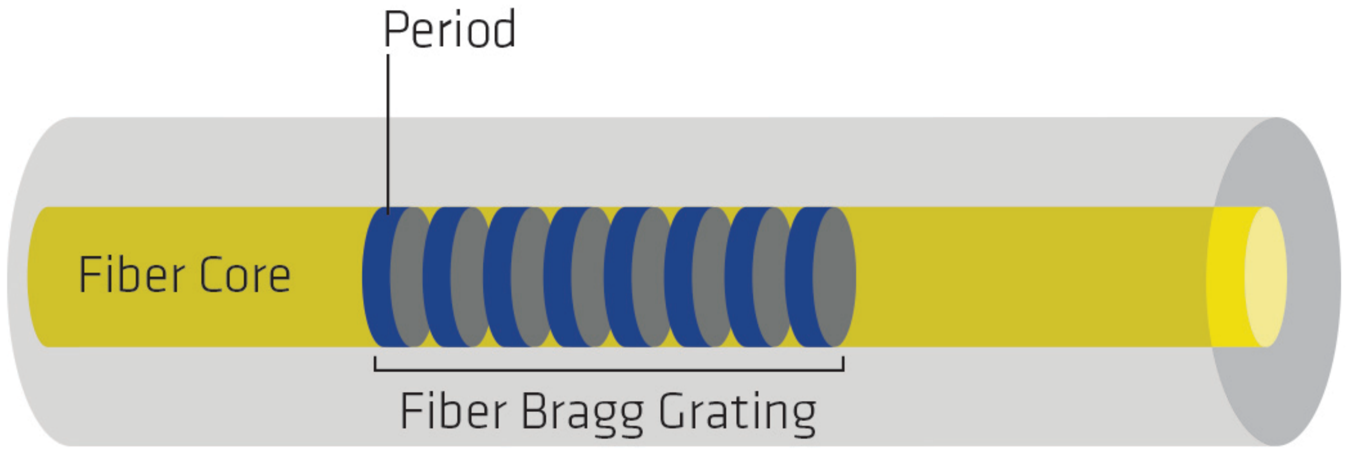
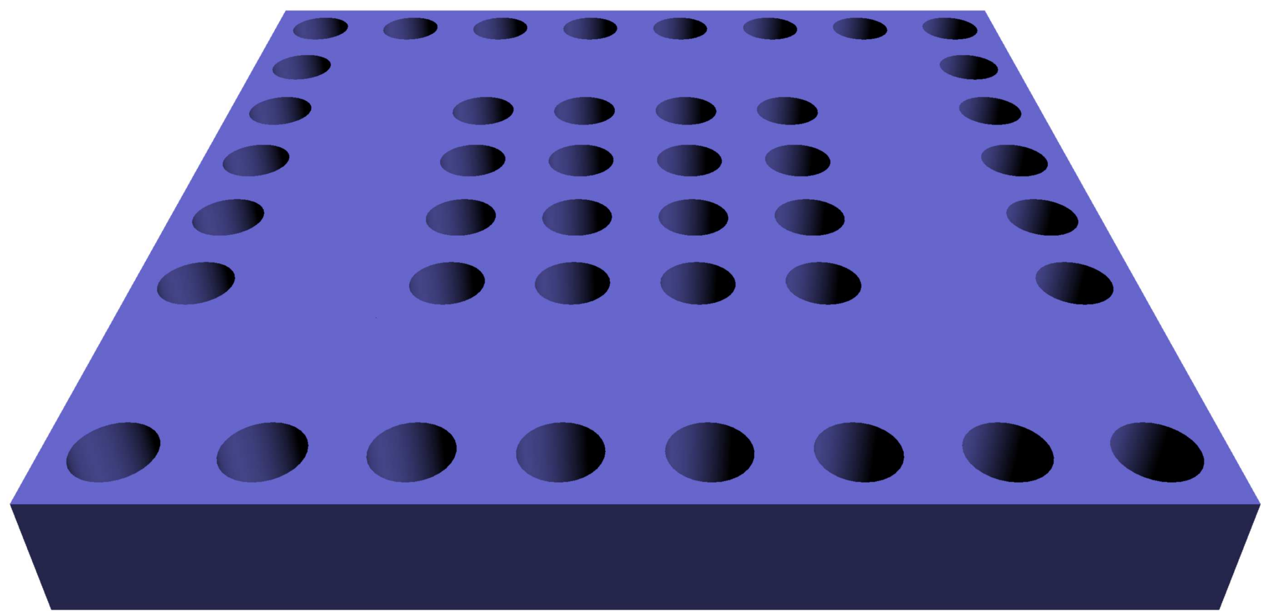
Light in meta-materials

Nature Reviews Materials
volume
1, Article number: 16048 (2016)

Photonic crystals, targeting eV

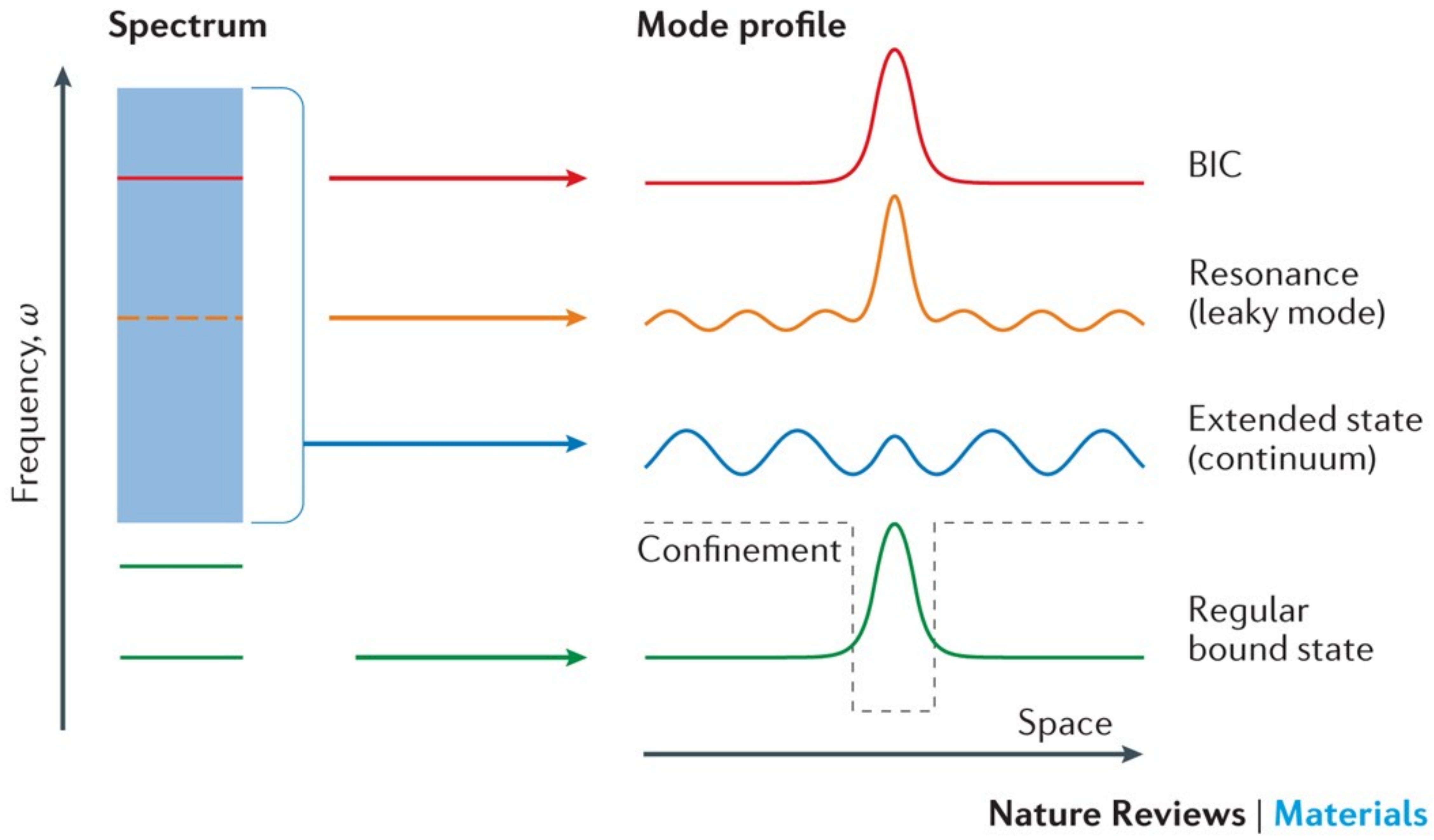


https://www.teraxion.com/en/company/fiberbragggrating/



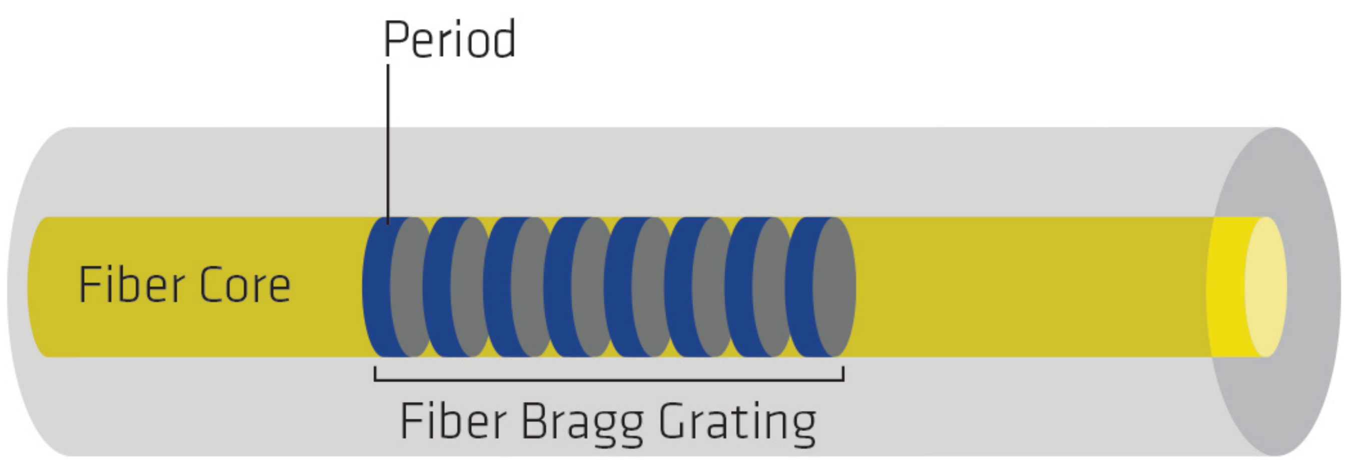
BLINOV, GAO, HARNIK, JANISH and SINCLAIR (2024)

Bound States in Continuum



Light in meta-materials

Photonic crystals, targeting eV



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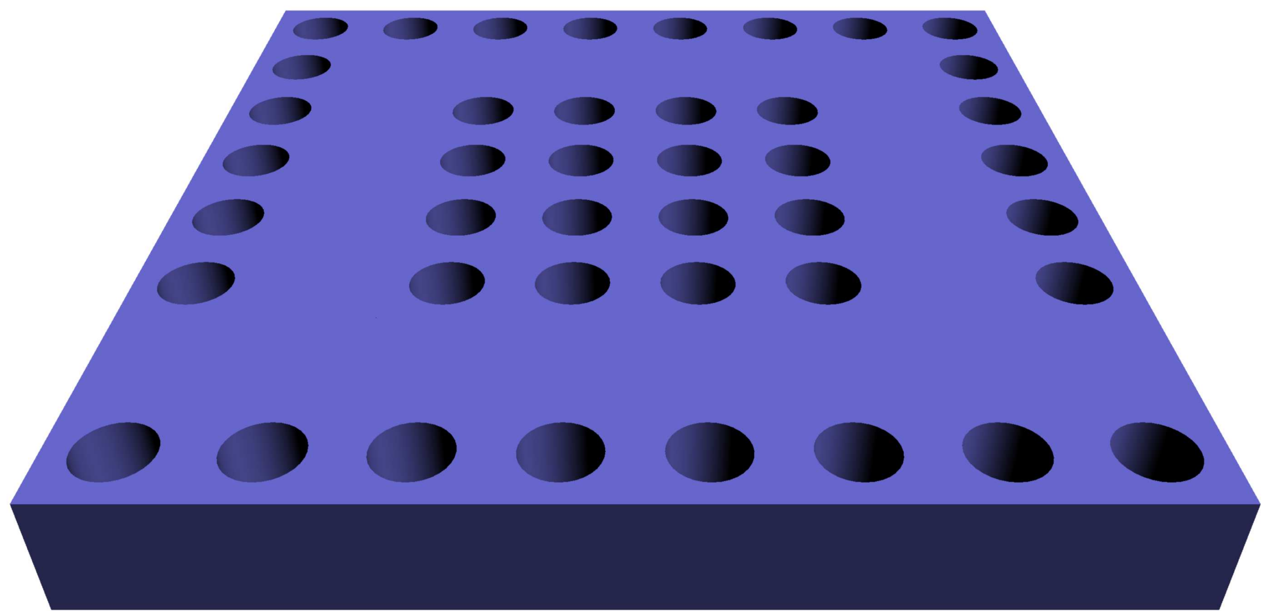

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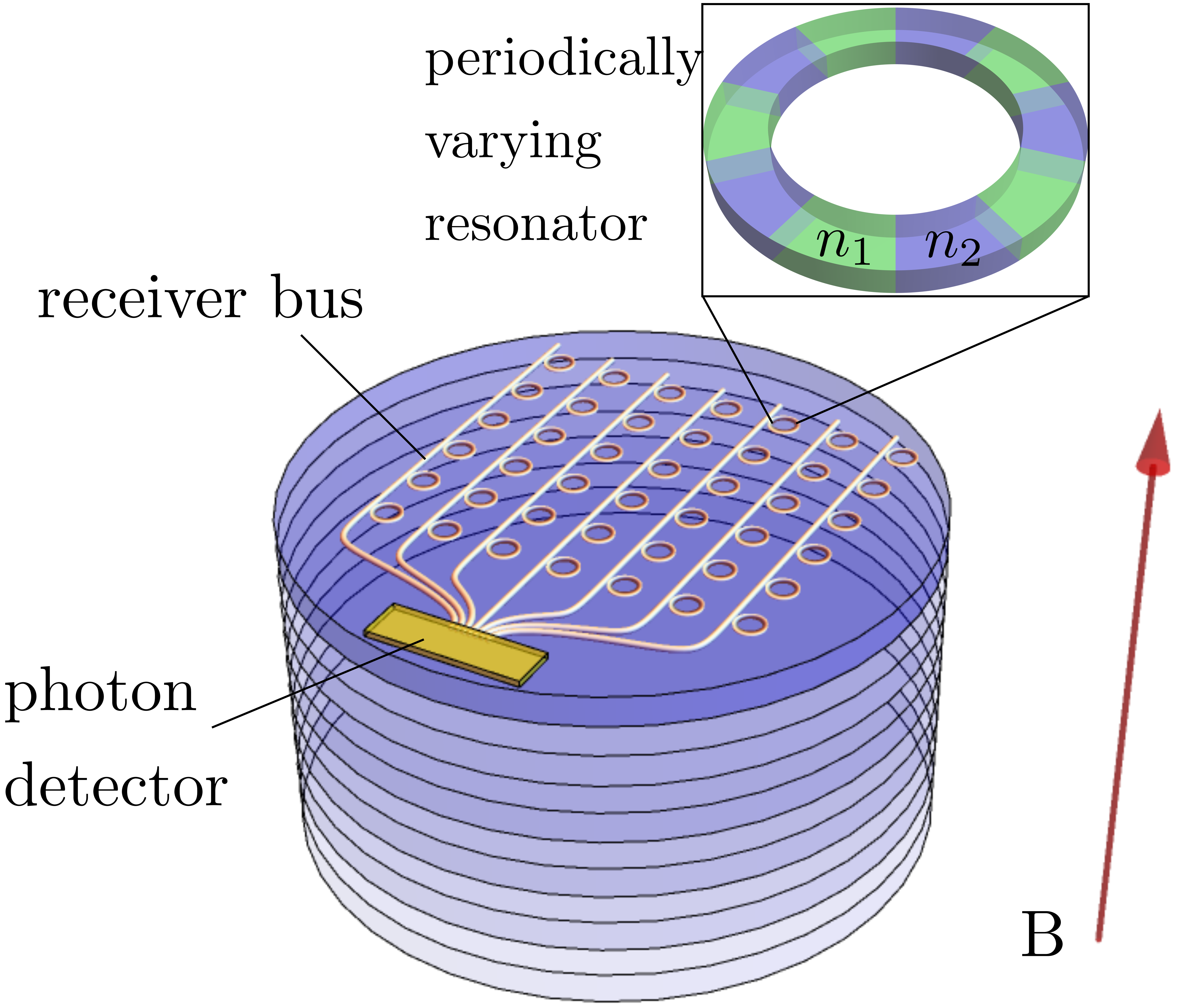

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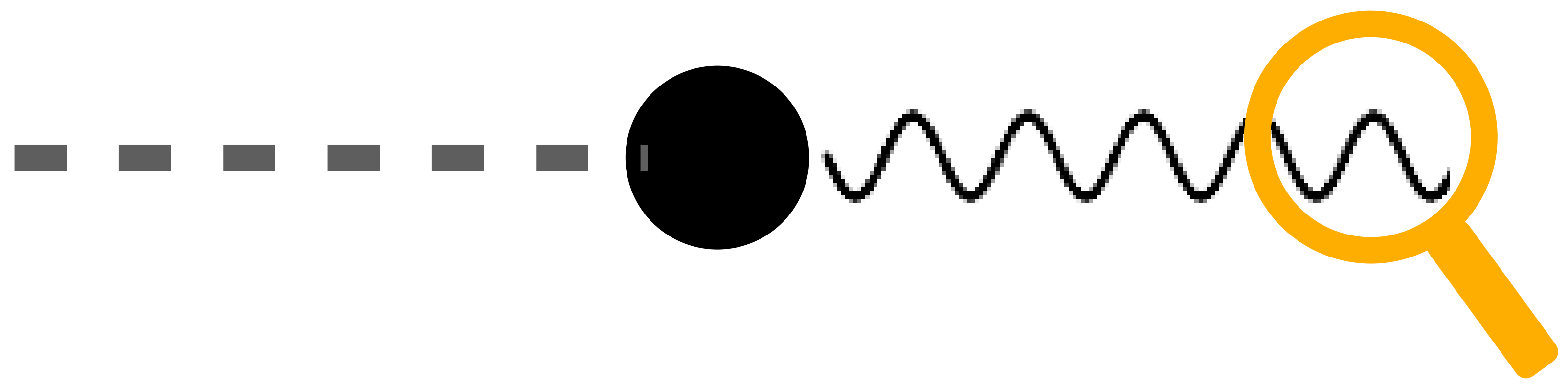
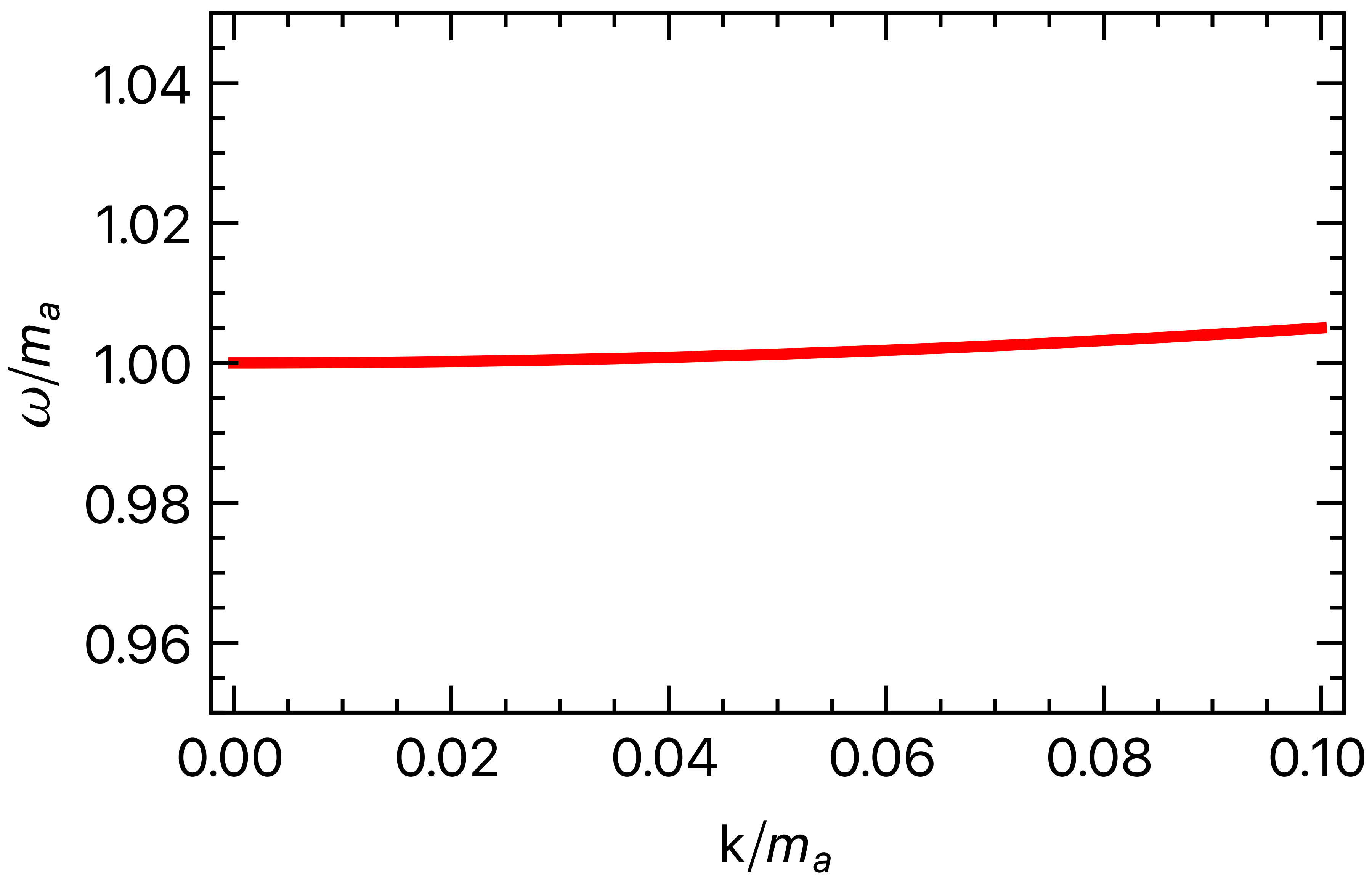
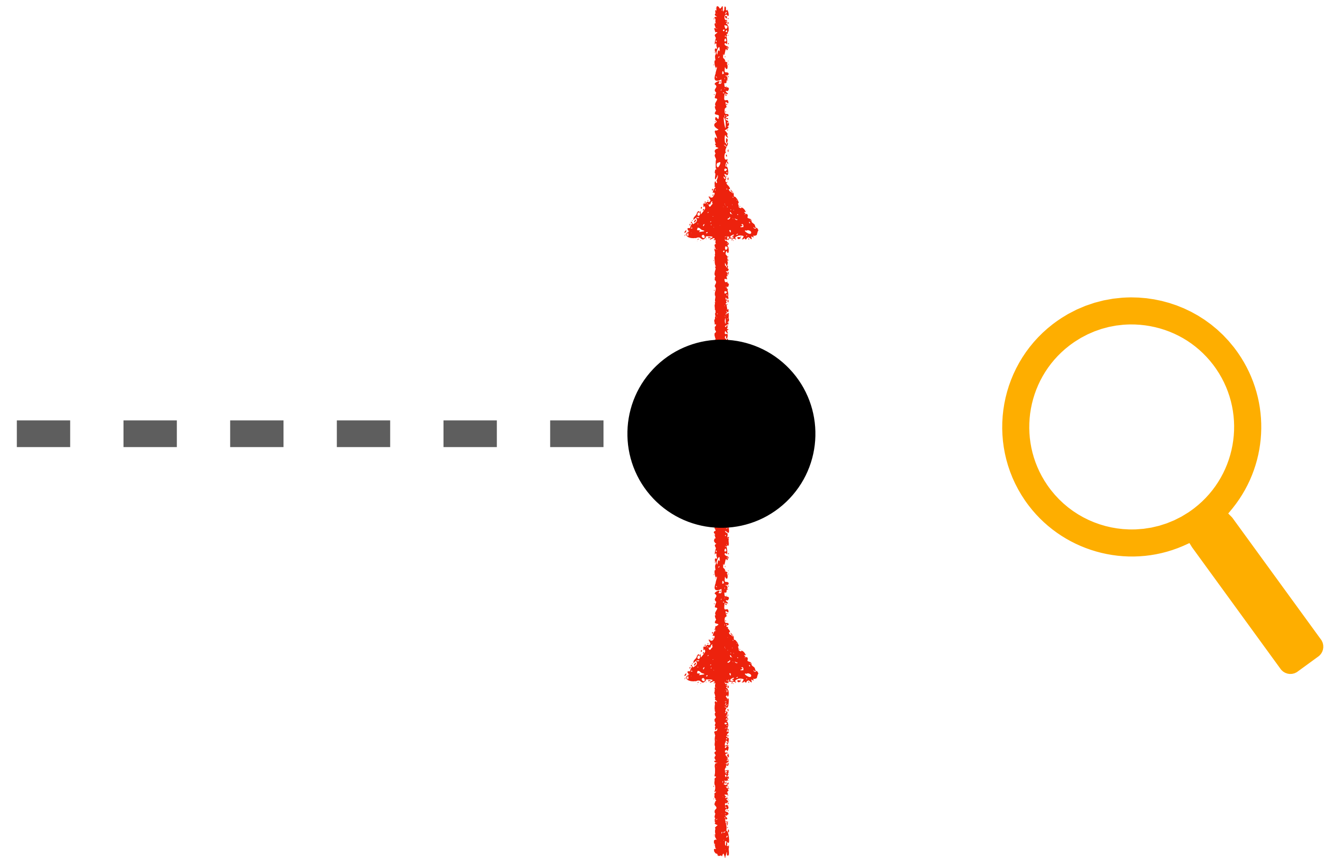
Summary of detection via absorption





- Used axion-photon coupling as an example
- Want photons with a gapped “flat” dispersion
- Can exist in the form of polaritons in certain special materials, or in the form of “slow” light in meta-materials
- Axion-electron coupling can also allow conversion into gapped magnon

Forward scattering (NMR)



Axions can couple to spins of fermions

$$\mathcal{L}_{\text{int}} \supset g_{af} \partial_\mu a \bar{f} \gamma^\mu \gamma^5 f \qquad g_{af} \sim \frac{1}{f_a}$$

NR fermions $$V(\mathbf{x}) = i \frac{\dot{a}^{\text{cl}}}{f_a} \frac{\mathbf{p}' + \mathbf{p}}{m} \cdot \mathbf{S} - i \frac{2 \nabla a^{\text{cl}} \cdot \mathbf{S}}{f_a}$$

Compared with $\gamma_f \mathbf{S} \cdot \mathbf{B}$

$$B_a \sim g_{af} \frac{\nabla a}{\gamma_f}$$

gyromagnetic ratio

$$\gamma_n = \frac{e\hbar}{2m_p} g_n \qquad \gamma_e = \frac{e\hbar}{2m_e} g_e$$

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Axions can couple to nuclear spins

$$\mathcal{L}_{\rm int} \supset g_{aN}\partial_\mu a\bar{N}\gamma^\mu\gamma^5 N$$

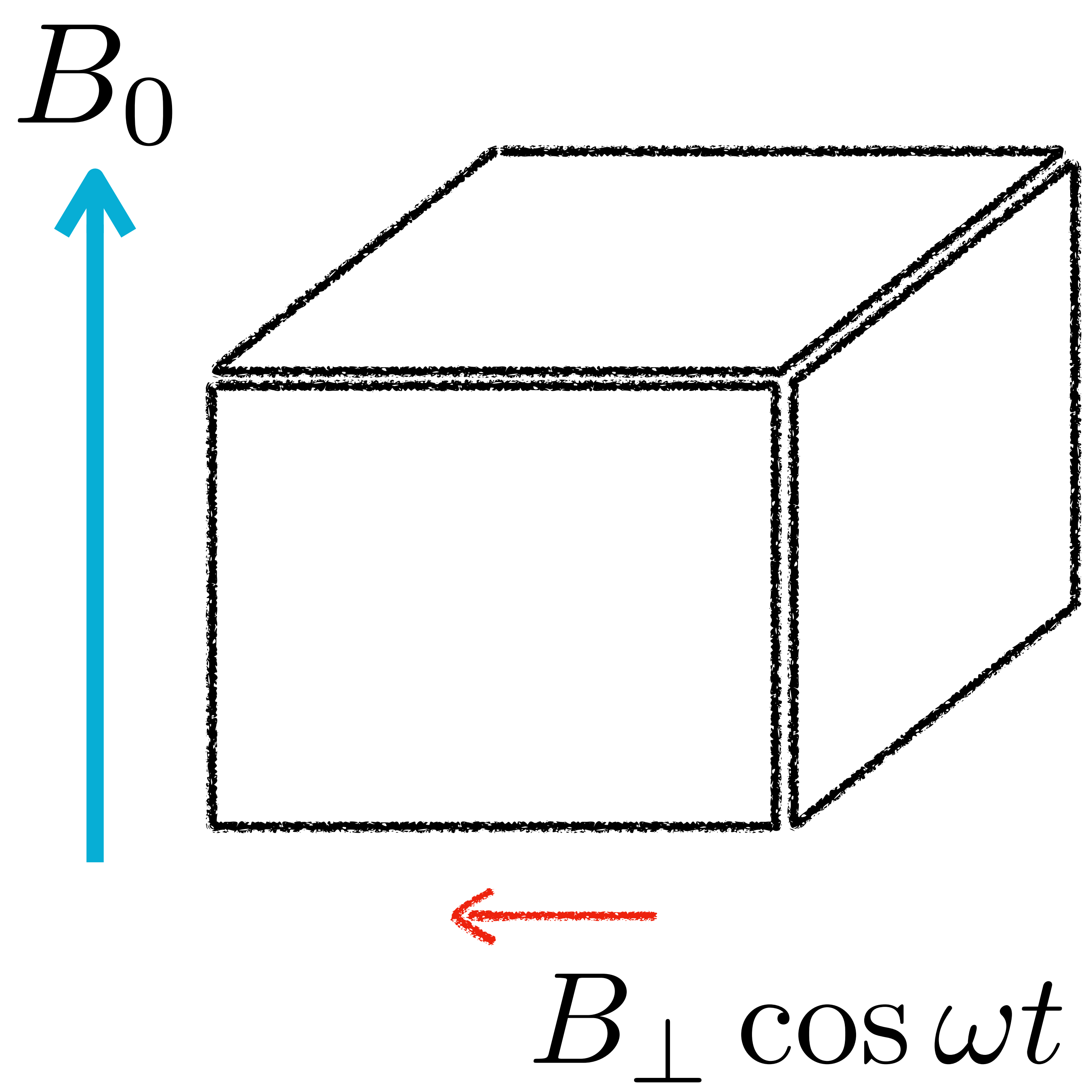
g_{aN} allows us to search for axion DM using Nuclear Magnetic Resonance (NMR).

$$H_{\rm eff} \supset \langle\vec{\mu}_n\rangle \cdot \underbrace{g_{aN}\frac{\vec{\nabla}a}{\gamma_n}}$$

$$\vec{B}_{a_{\rm DM}} \sim 10^{-16}{\rm T}\left(\frac{g_{aN}}{10^{-10}{\rm GeV}^{-1}}\right)$$

Nuclear magnetic resonance

- Resonance condition: $\omega = \omega_L = \gamma B_0$

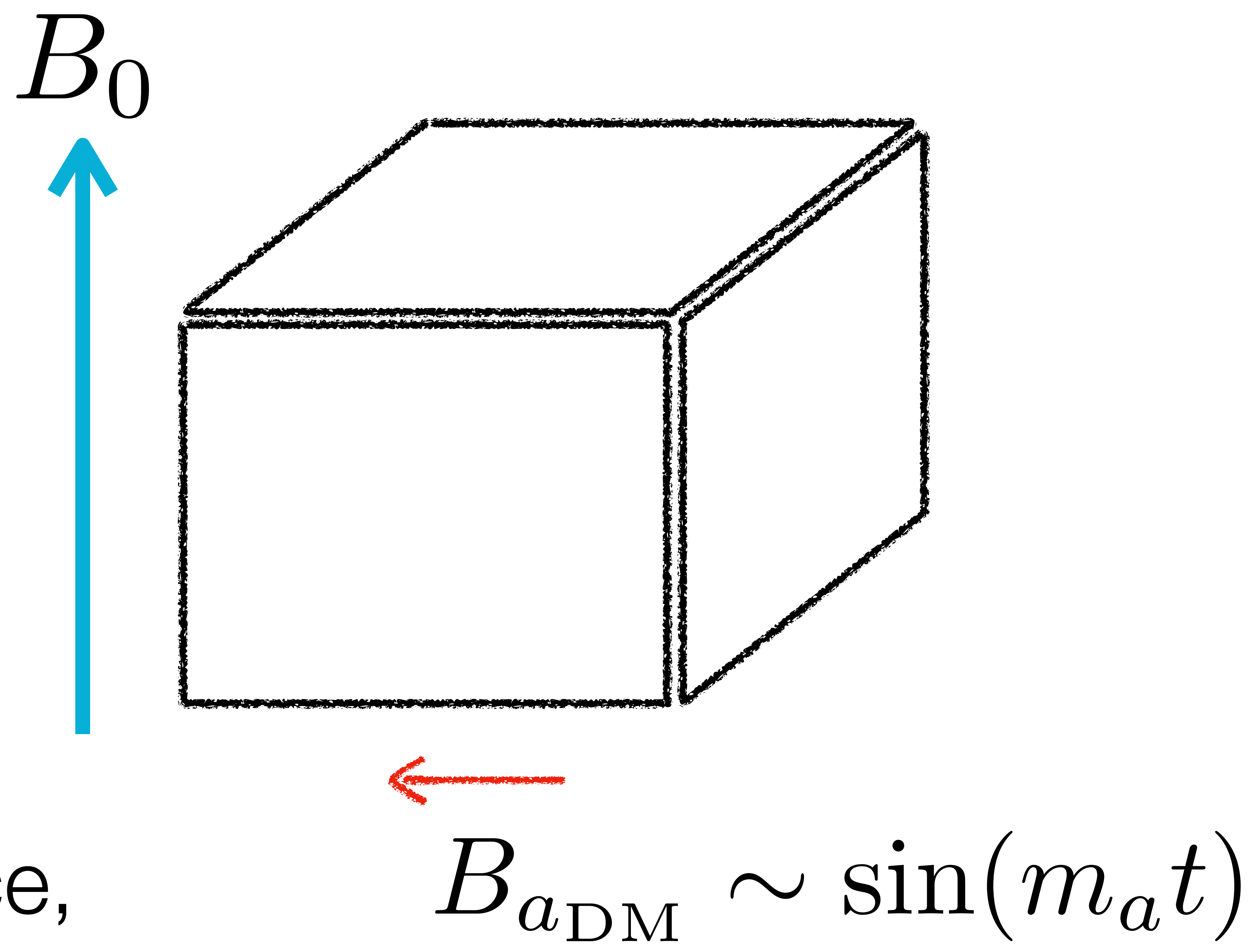


Nuclear magnetic resonance

- Resonance condition: $\omega = \omega_L = \gamma B_0$
- Tune B_0 to match axion mass with Larmor frequency ω_L

Graham and Rajendran (2013)

- Signal to noise is limited by decoherence of nuclear spins
- Special phases of helium-3 have large coherence, can be a good NMR material



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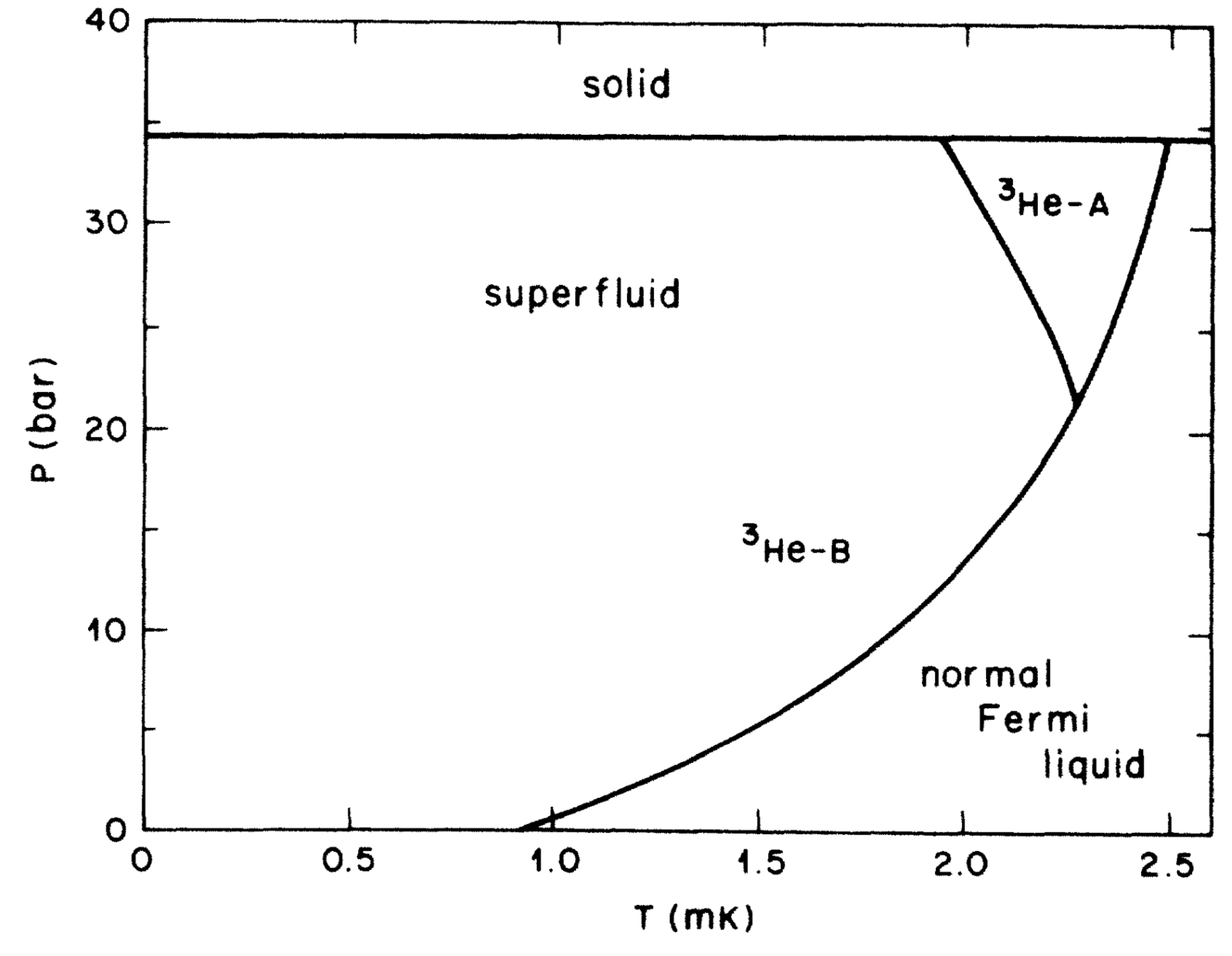
Helium 3 B, homogeneous precession domain

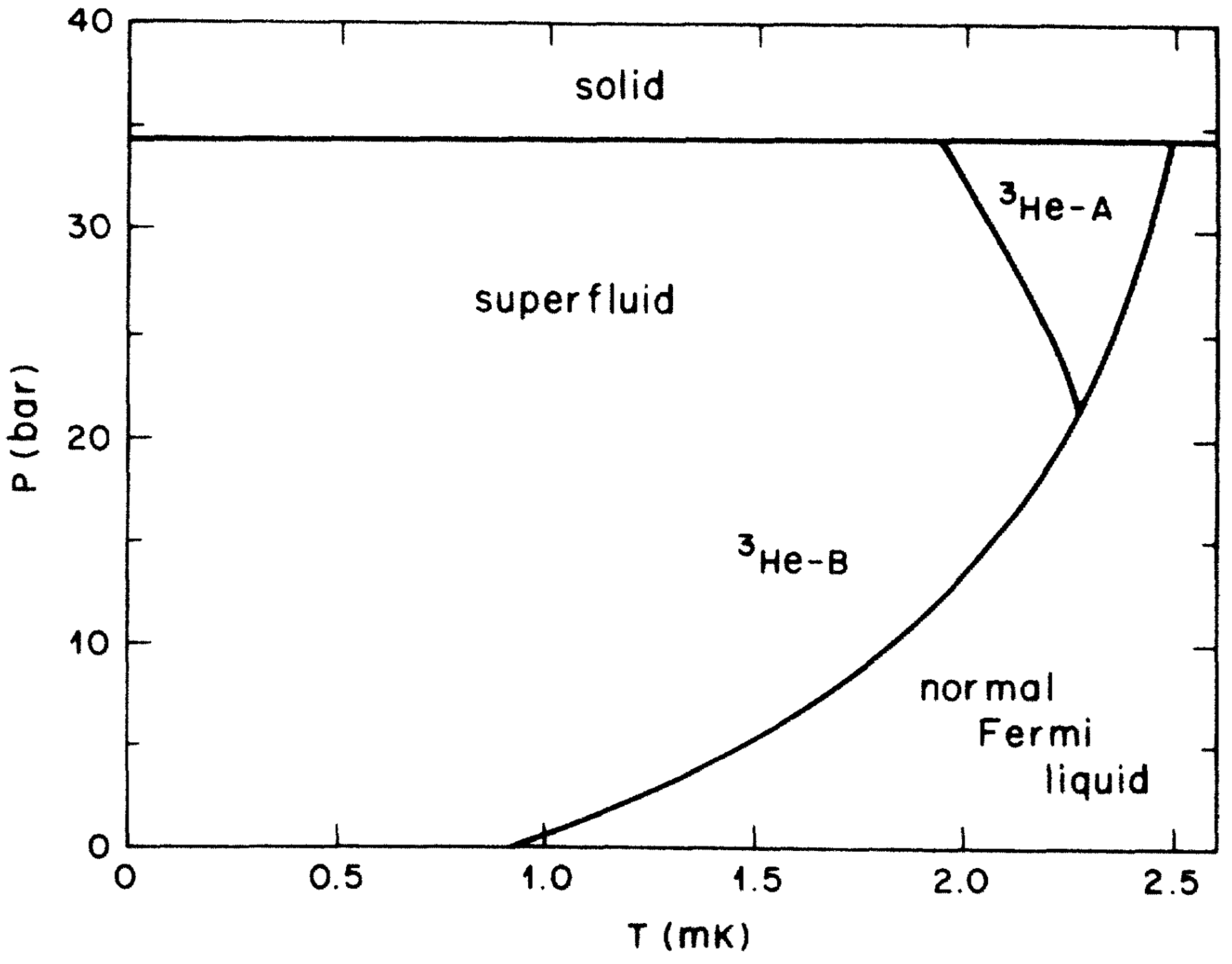
Properties of $^3\mathrm{He}$



Phys. Rev. B **33**, 7520 (1986)

- T<~1K, Fermi liquid, He-3 quasiparticles

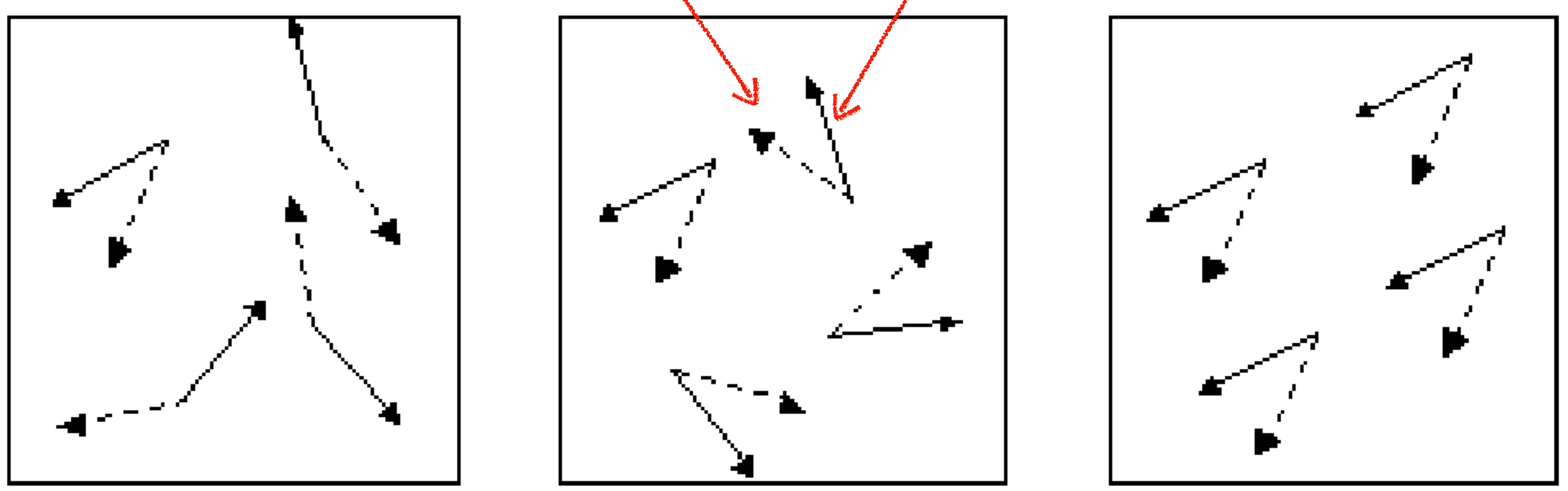
Properties of $^3\mathrm{He}$



Phys. Rev. B **33**, 7520 (1986)

- T<~mK, superfluid phase (~ BEC of Cooper pairs of He-3 quasiparticles)

$$L = 1 \; S = 1$$



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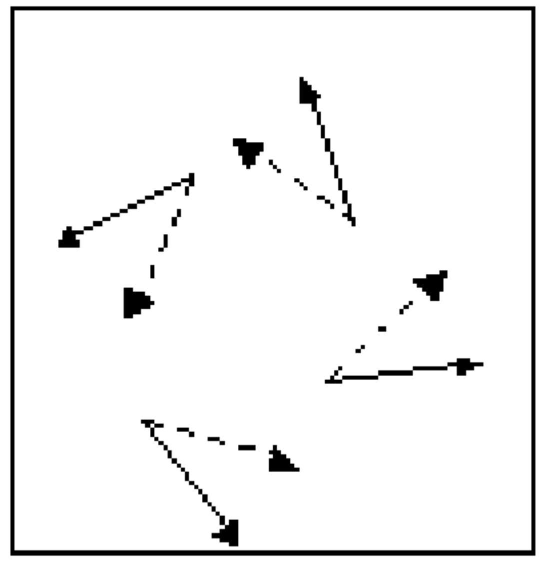
$^3\mathrm{He} - \mathrm{B}$

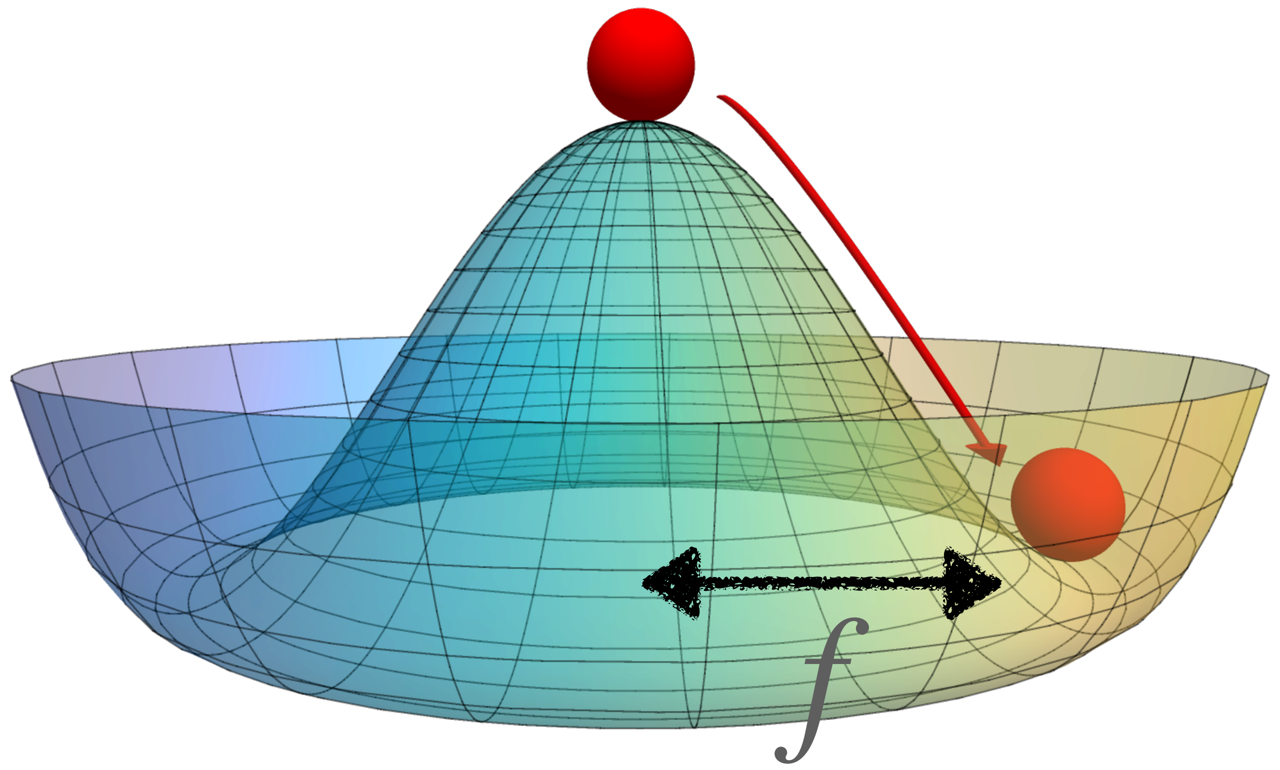
B-phase



spontaneously broken spin orbit symmetry

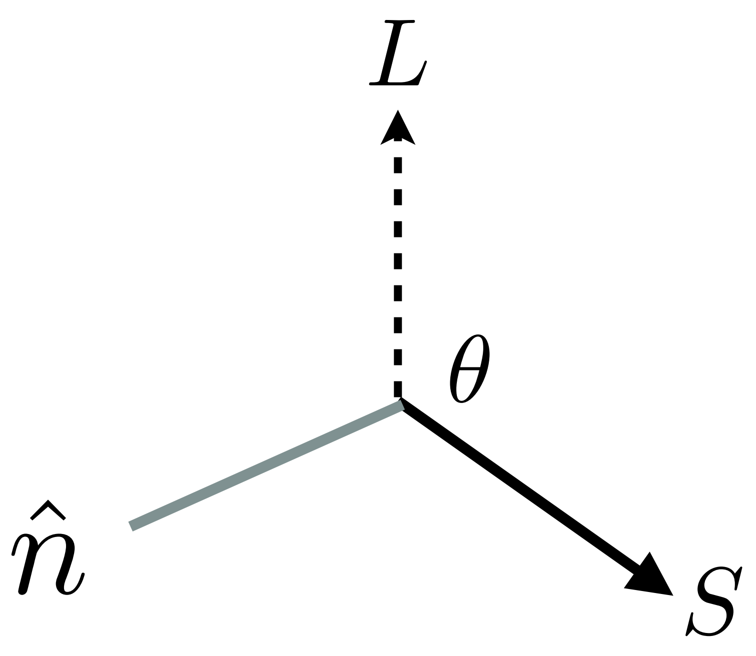
Leggett Rev. Mod. Phys. 47, 331 (1975)

$$SO(3)_S \times SO(3)_L \times U(1)_\phi \to SO(3)_{L+S}$$



$$e^{i\phi} R_{\mu j}(\hat{n}, \theta)$$

But, a lot of degenerate ground states



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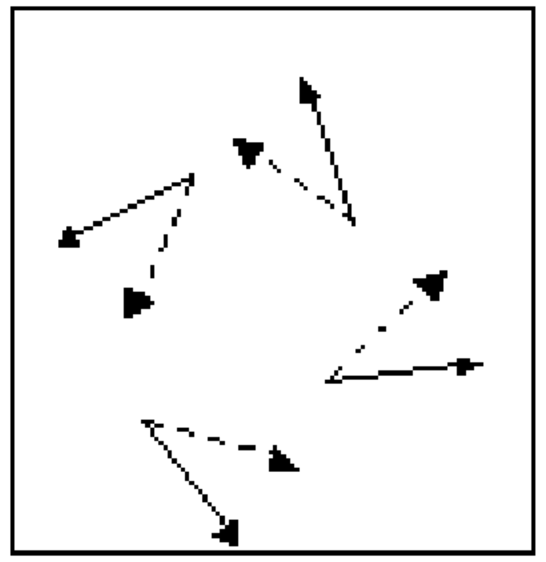
$^3\mathrm{He} - \mathrm{B}$

B-phase



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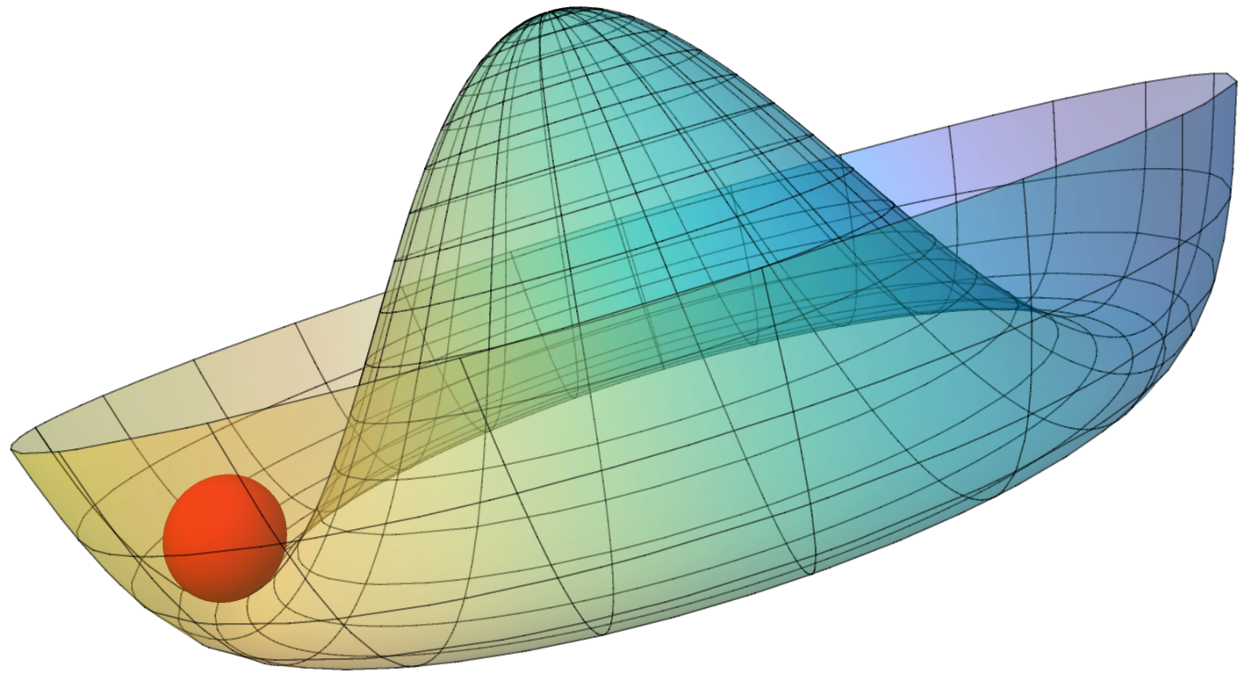
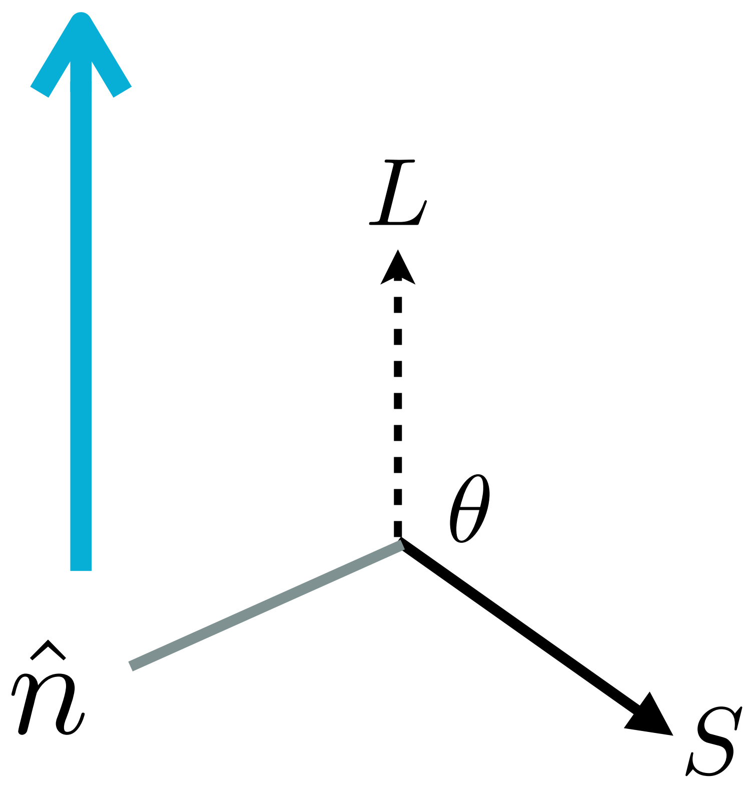


$$e^{i\phi} R_{\mu j}(\hat{n}, \theta)$$

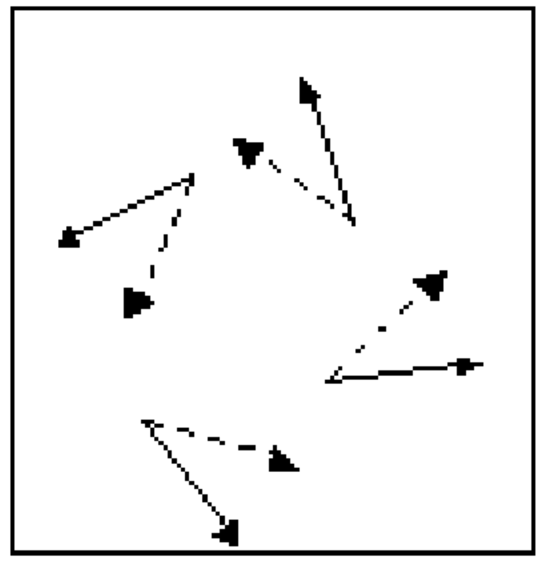
$H\,\hat{z}$



External magnetic field: $H\,\hat{z}$

$^3\mathrm{He} - \mathrm{B}$

B-phase



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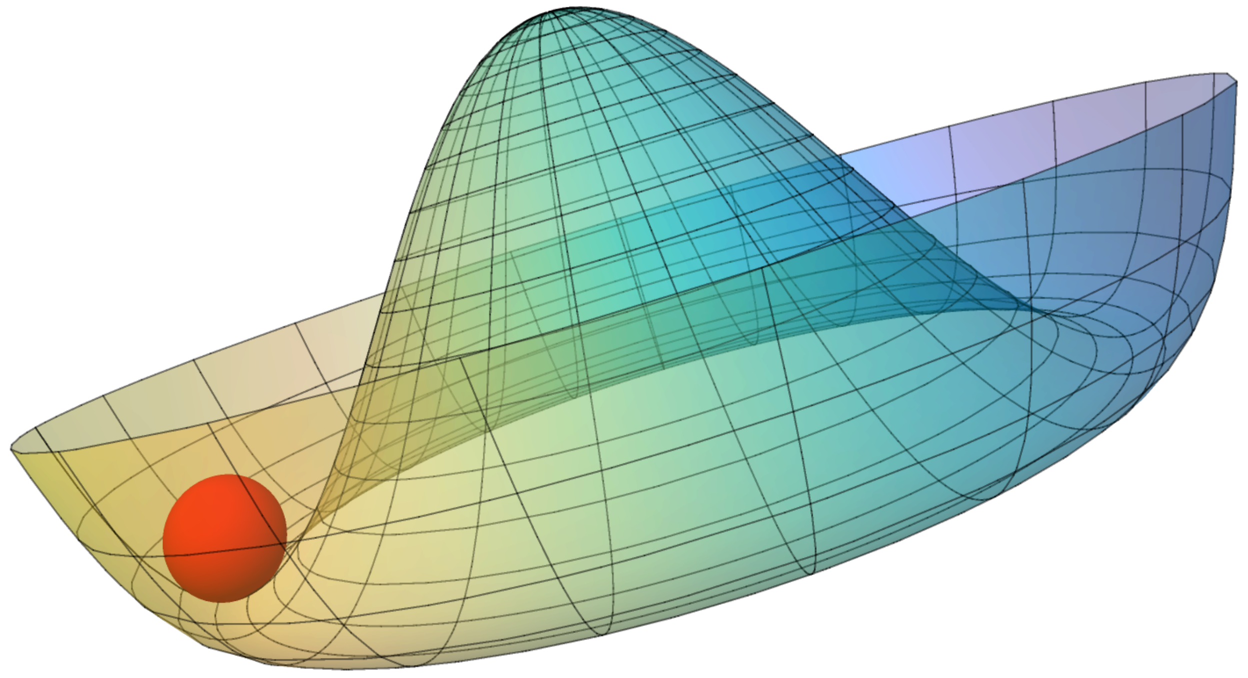
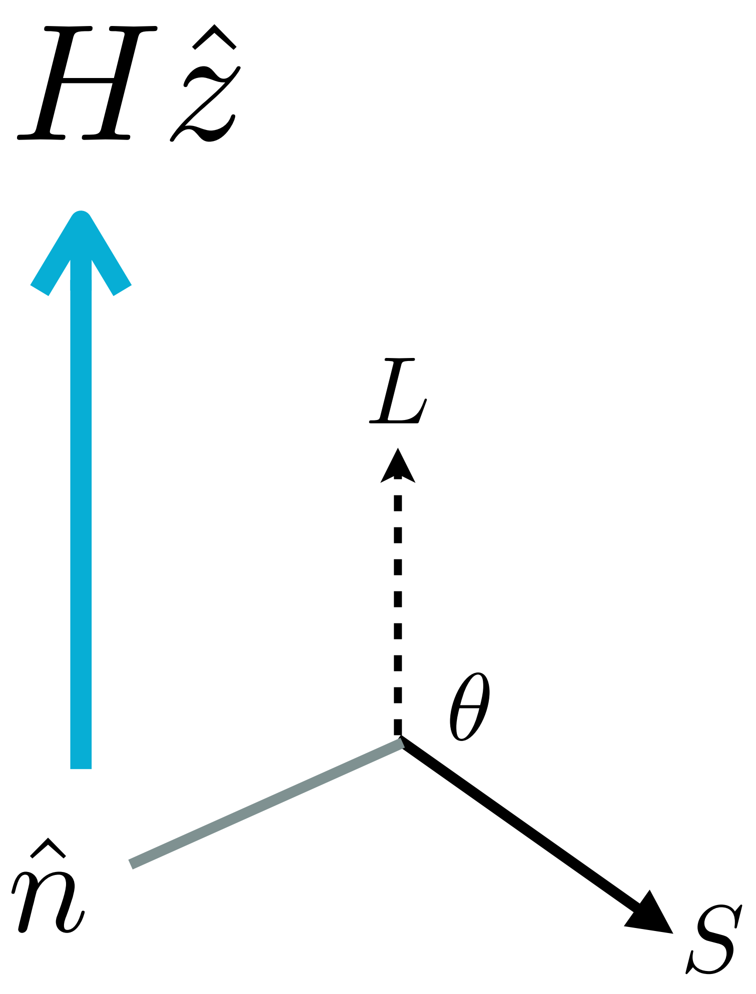


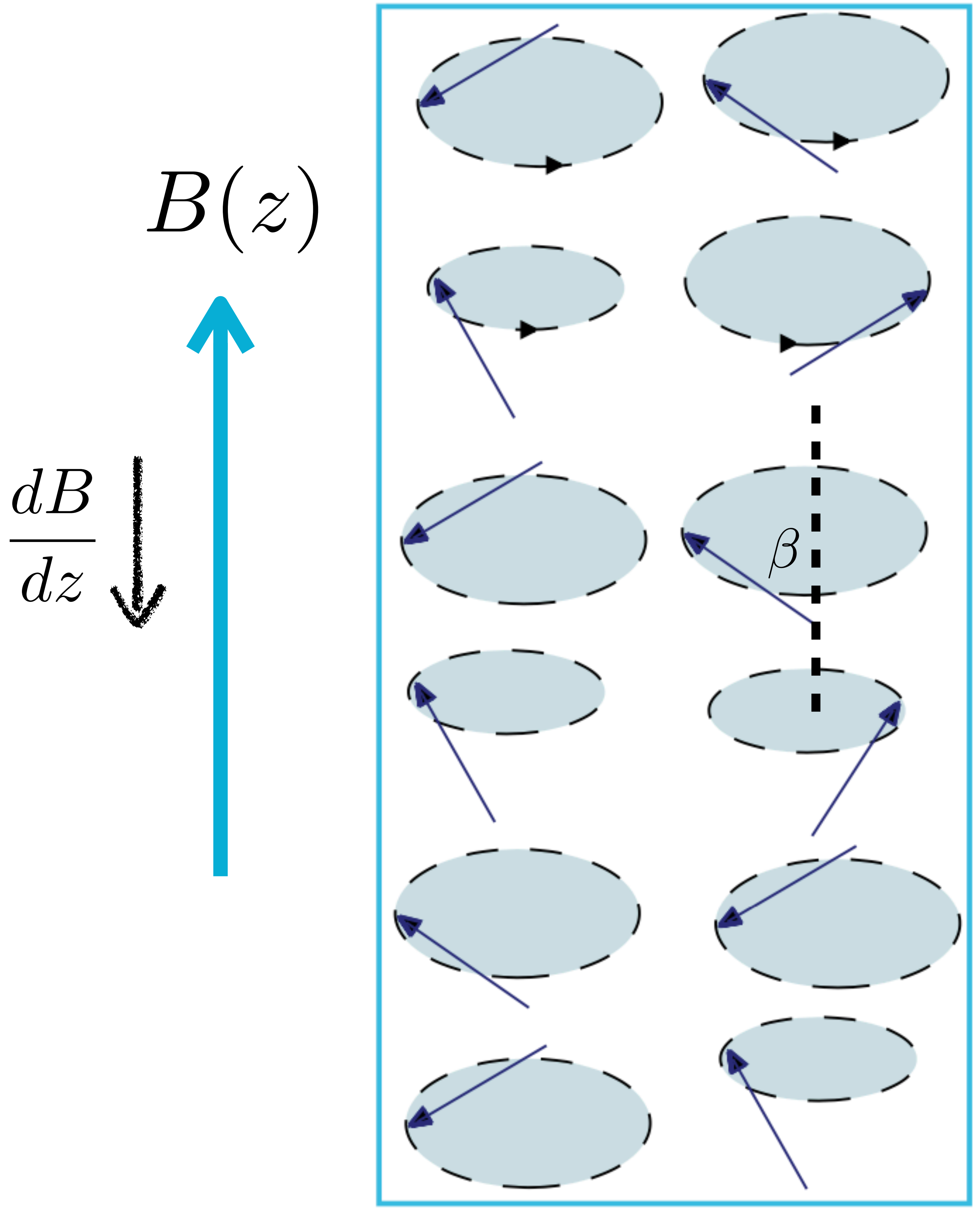


External magnetic field: $H\hat{z}$

Dipole interaction: $\cos\theta = -\dfrac{1}{4}$

Pulsed NMR with $^3\mathrm{He}-\mathrm{B}$

[Bunkov and Volovik, 0904.3889 and 1003.4889]
Fomin Sov. Phys. JETP 61, 1207 (1985)



spins disoriented

Spins tipped by a tip angle β immediately after the pulse

Characteristic time scale with superfluid $\hbar/\Delta(T)$

$$\Delta(T) \sim 10^2(1-T/T_c)^{1/2}\mathrm{MHz}$$

Pulsed NMR with $^{3}\mathrm{He}-\mathrm{B}$

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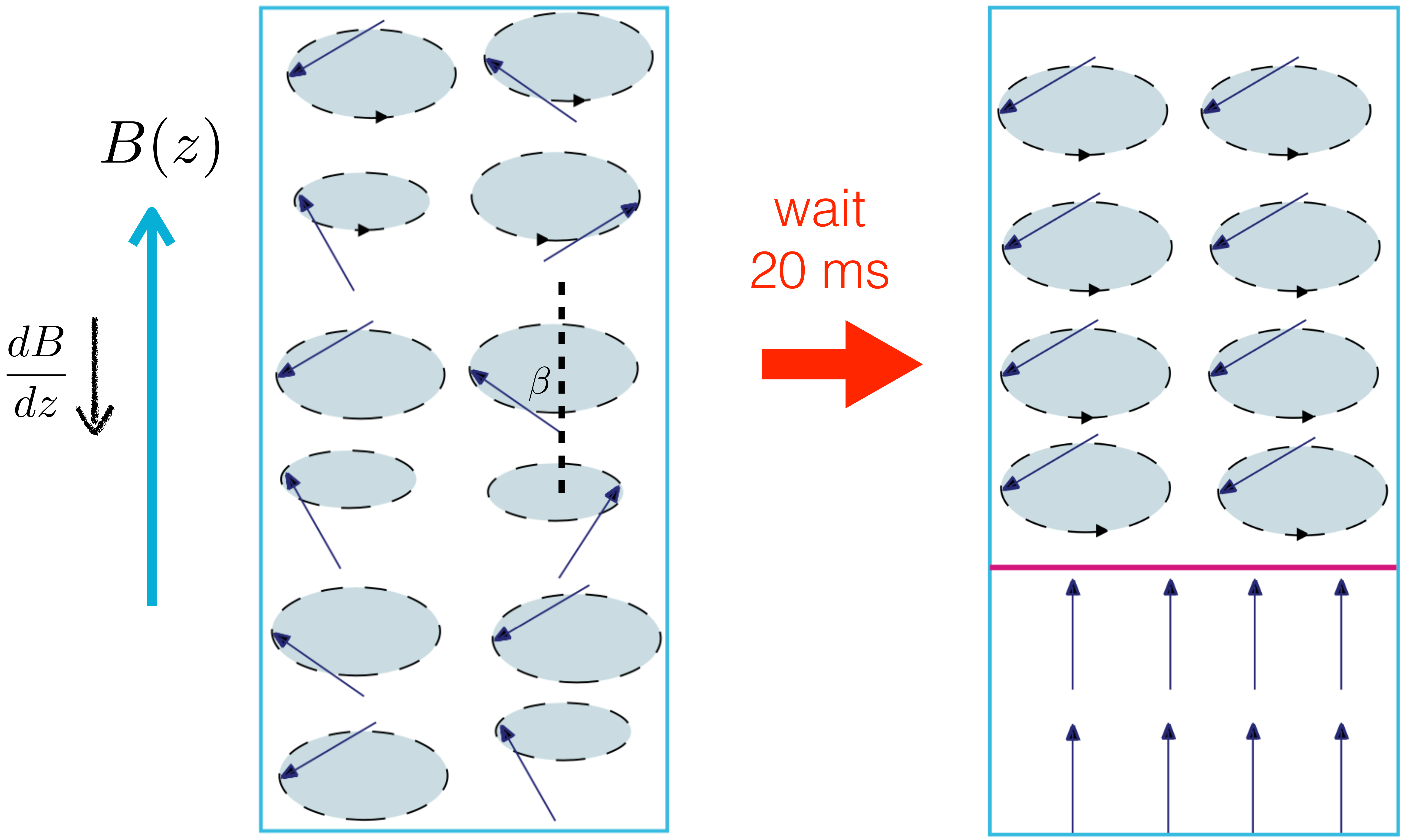
BEC of N Magnons



spins disoriented

two domains

Pulsed NMR with $^3\mathrm{He}-\mathrm{B}$

[Bunkov and Volovik, 0904.3889 and 1003.4889]
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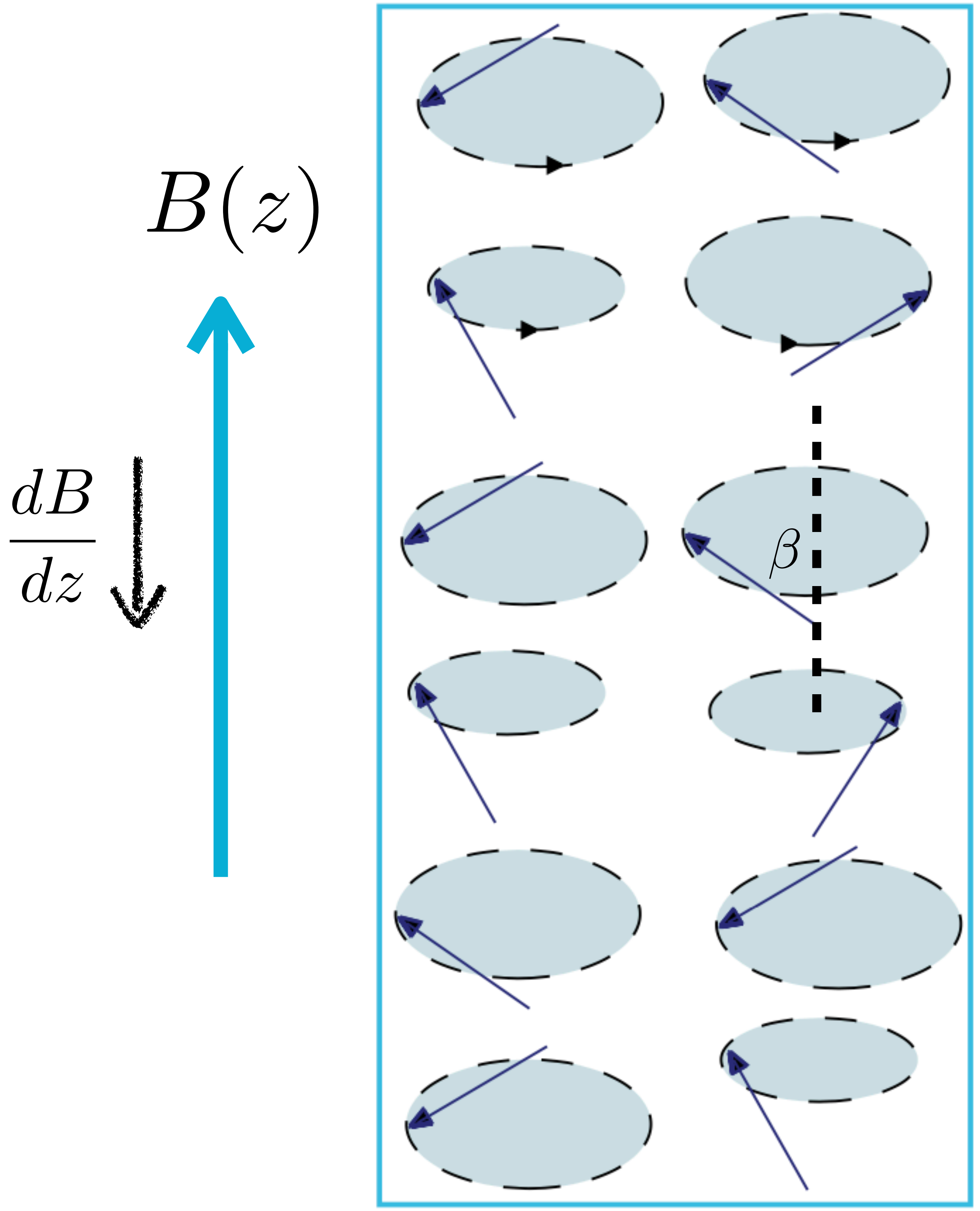
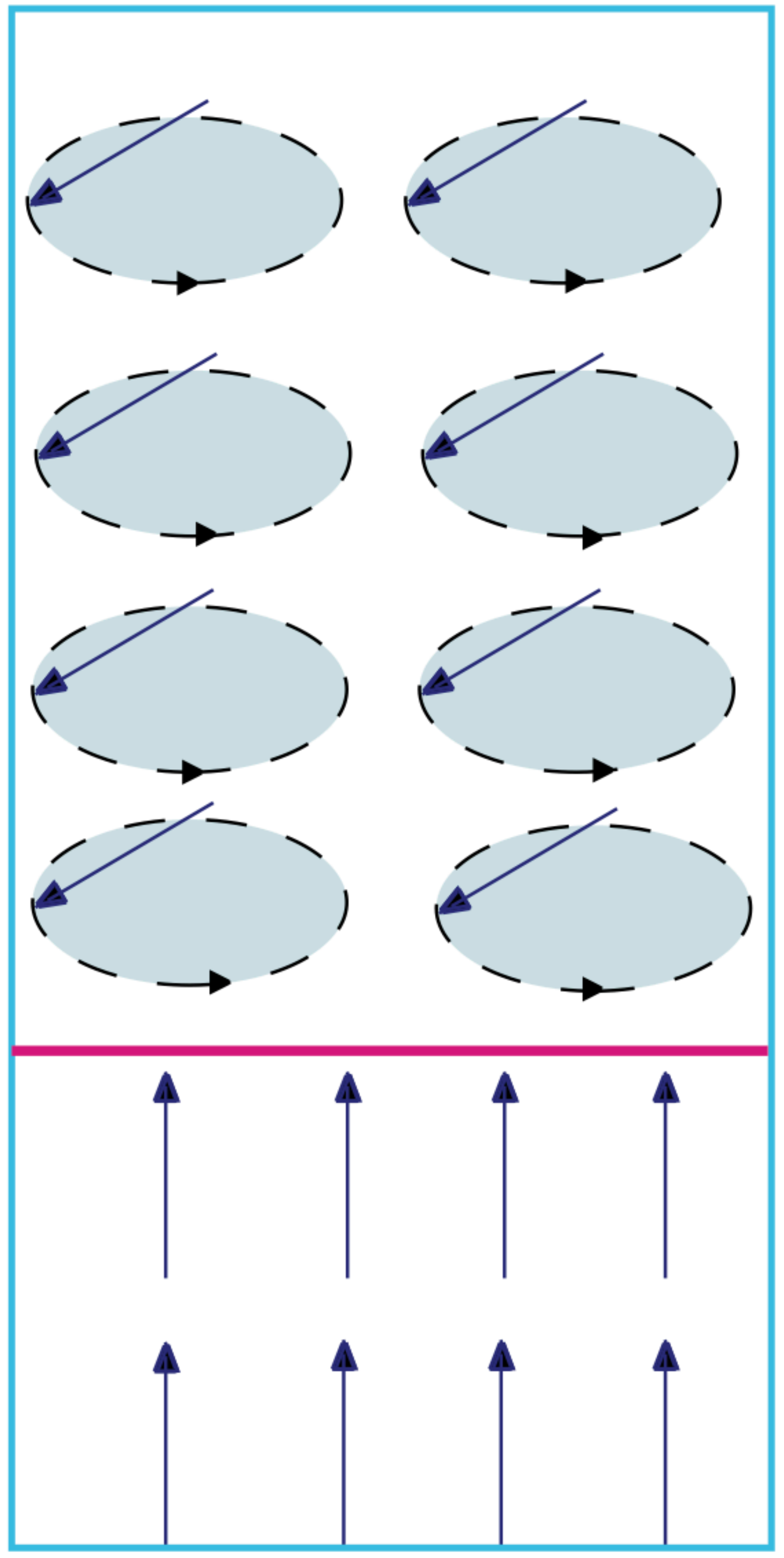


spins disoriented

wait
20 ms

BEC of N Magnons



two domains

coherent precession
at fixed angle

$$\beta_0 = \cos^{-1}(-1/4)$$

and same frequency

$$\omega_L(z_0) = \gamma B_0(z_0)$$

homogeneous
precession domain
(HPD)

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Pulsed NMR with $^3\mathrm{He}-\mathrm{B}$

[Bunkov and Volovik, 0904.3889 and 1003.4889]
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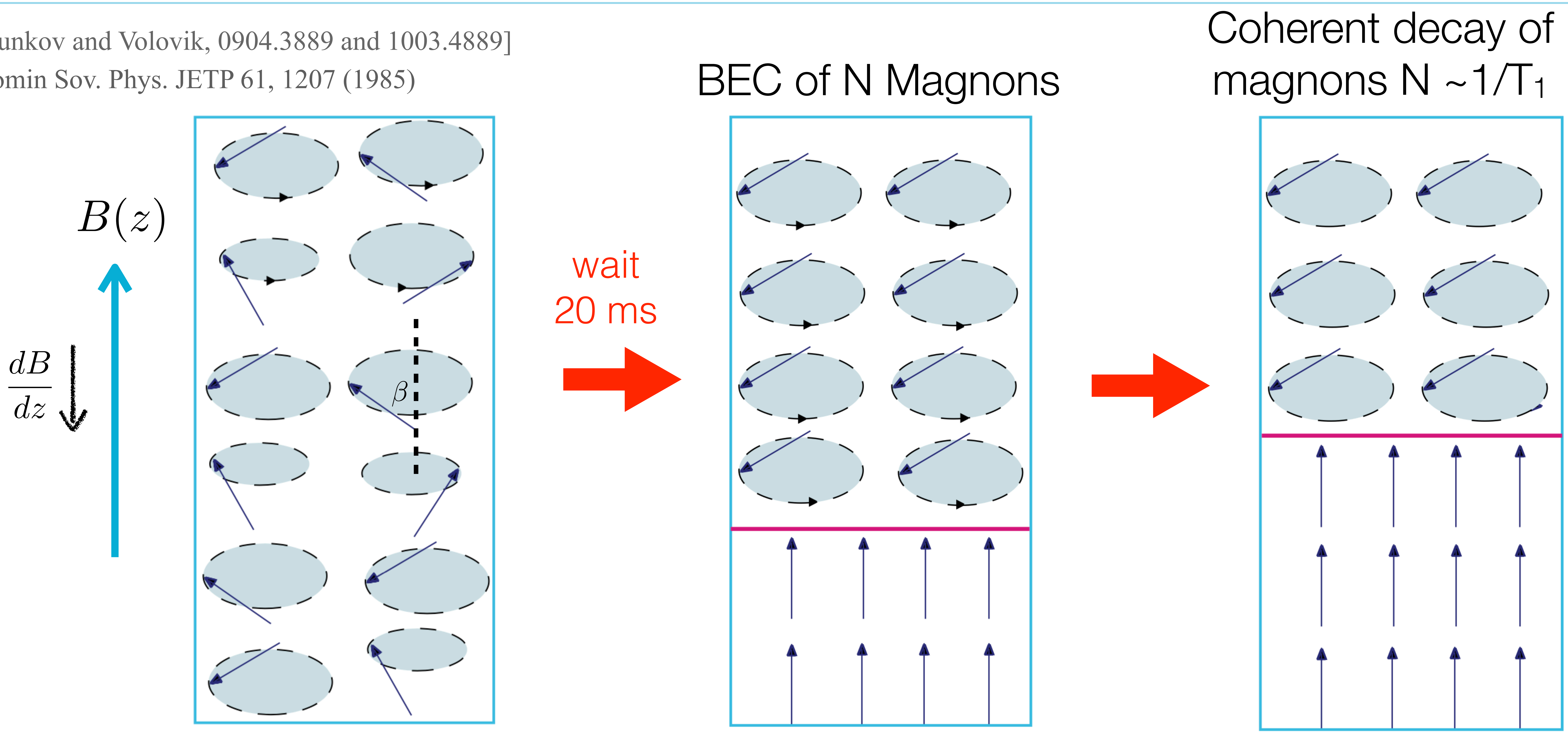

spins disoriented

two domains

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Pulsed NMR with $^3\mathrm{He} - \mathrm{B}$

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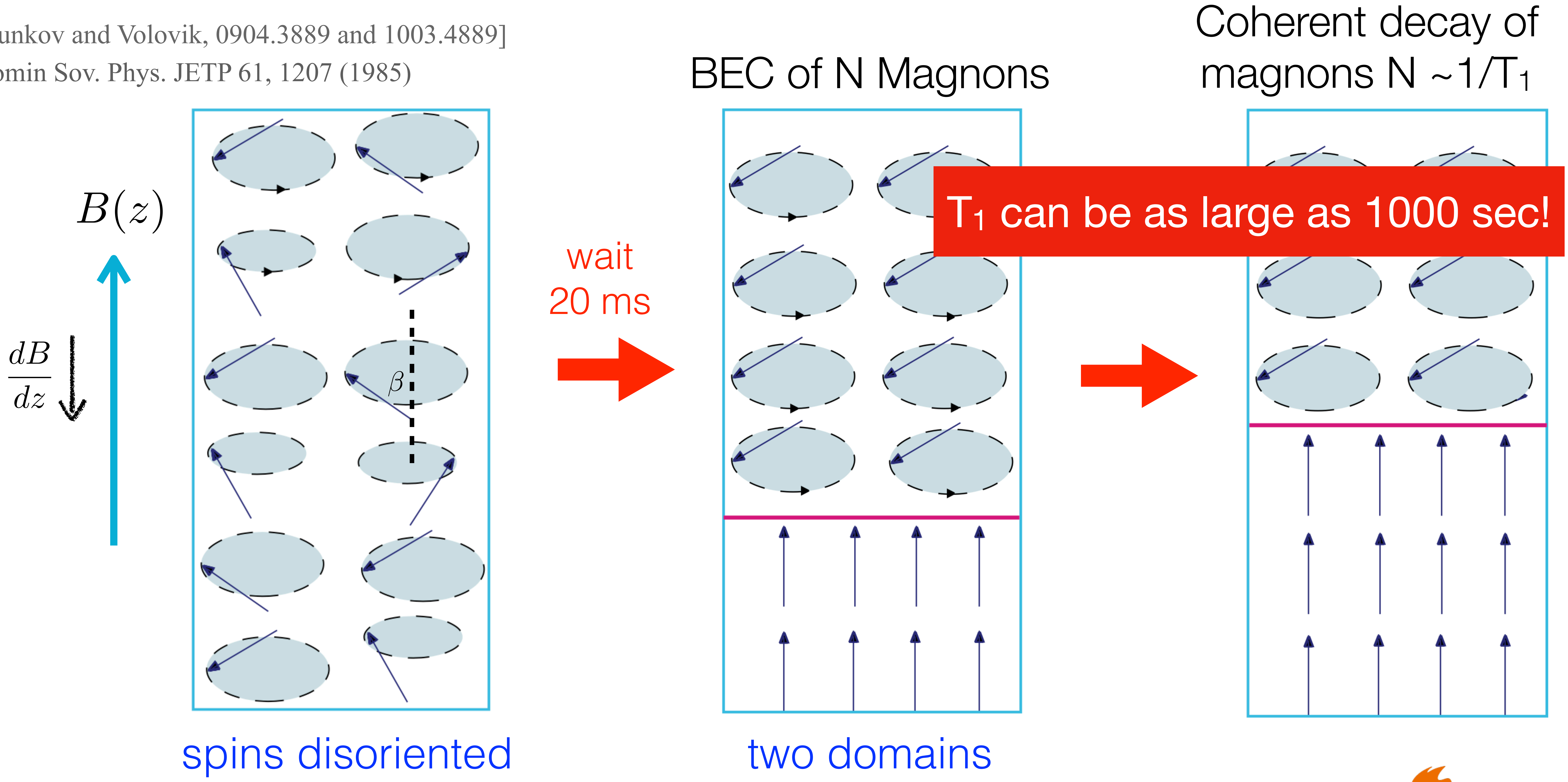
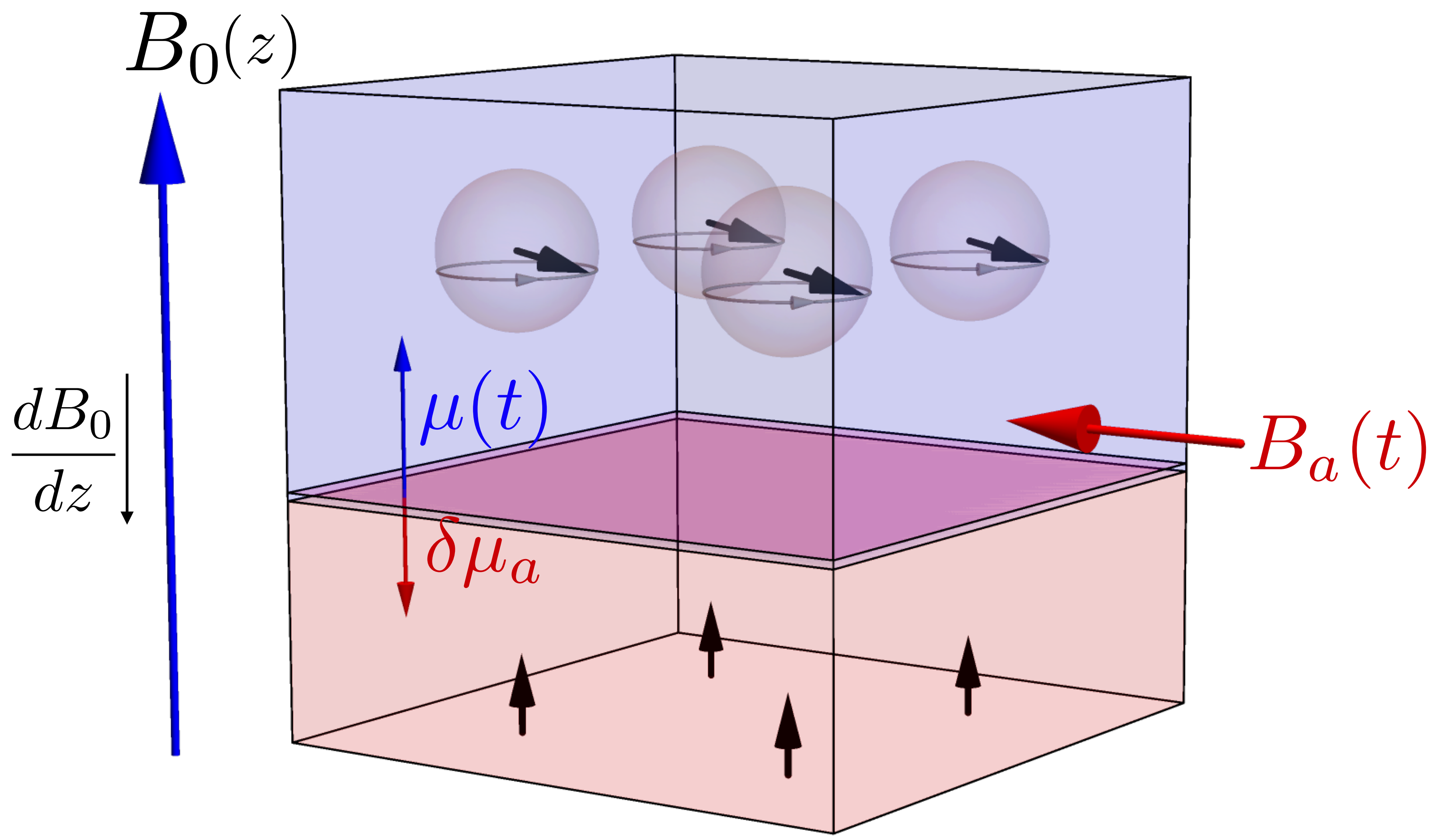


Axion wind detection using the HPD of He-3



- Rely on axion-nucleon coupling
- Target frequency: 10neV range
- Scan axion masses naturally during decay of the HPD
- Challenging to read out the signal, see Yoni's talk

GAO, HALPERIN, KAHN, NGUYEN, Schütte-Engel and SCOTT (2022)

FOSTER, GAO, HALPERIN, KAHN, MANDE, NGUYEN, Schütte-Engel and SCOTT (2023)

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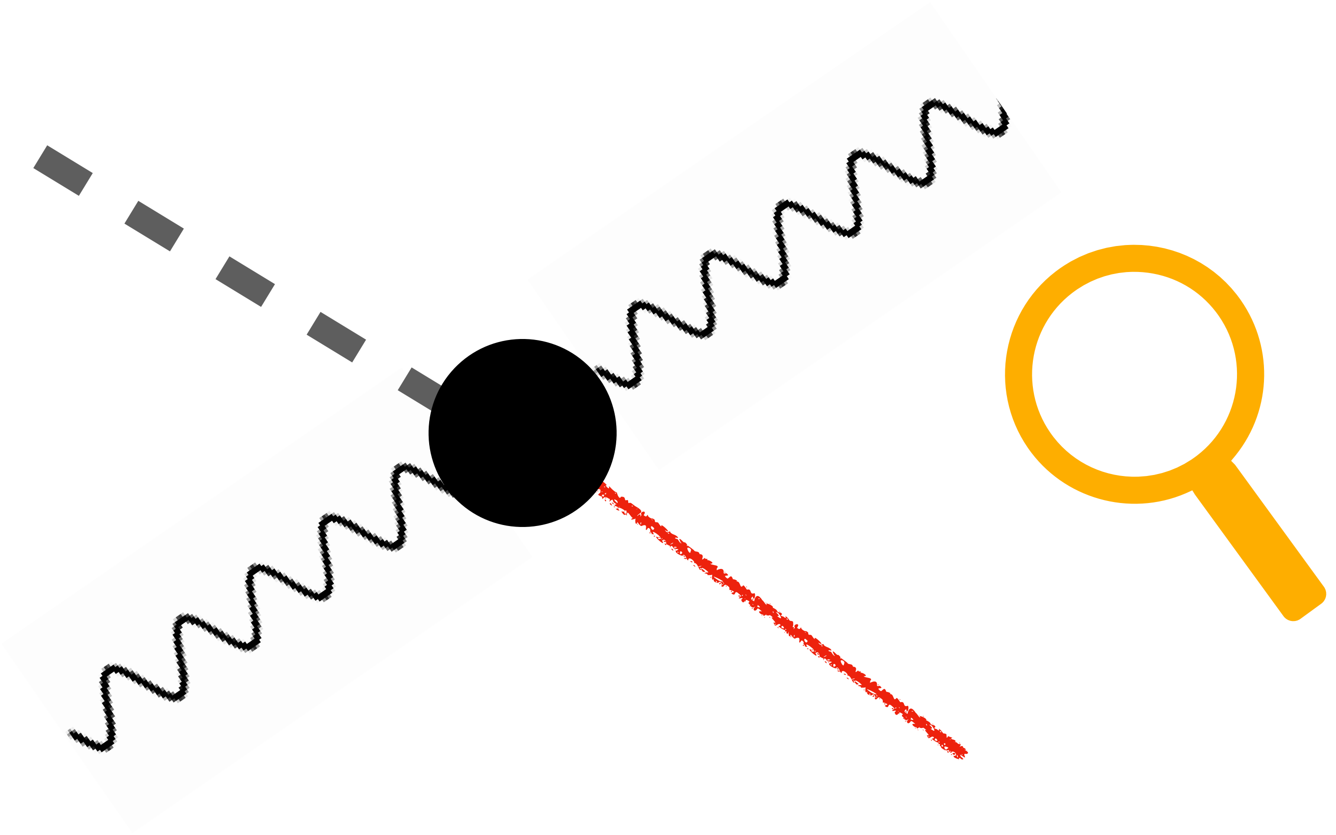
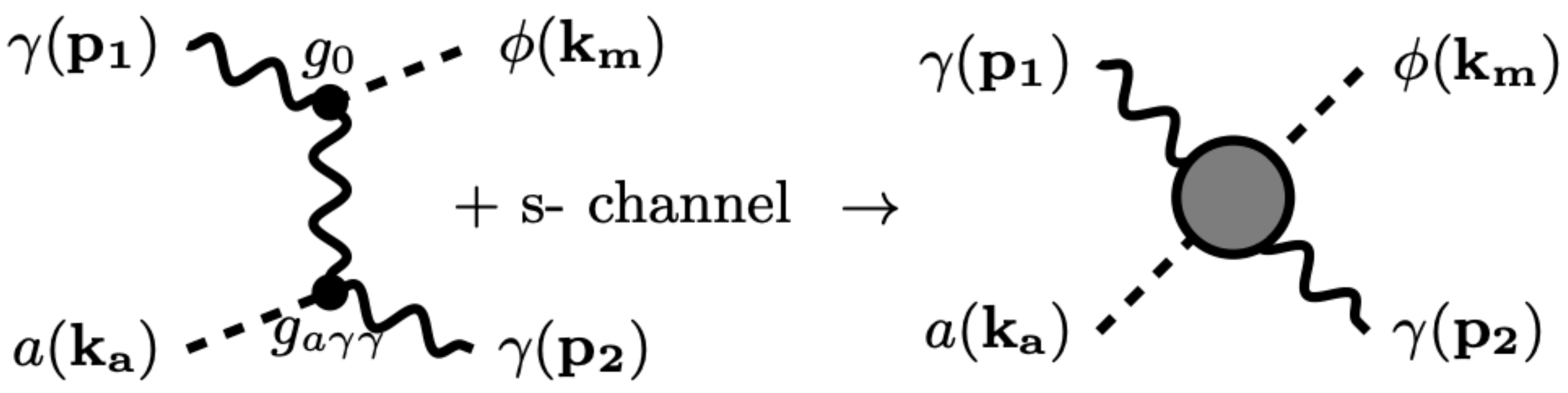
An example of 2-2 scattering



Optomechanical cavity filled with Superfluid He-4

MURGUI, WANG and ZUREK (2023)



Momentum conservation

$$\mathbf{p_1} + \mathbf{k_a} = \mathbf{p_2} + \mathbf{k_m}$$

Energy conservation

$$|\mathbf{p_1}| + m_a \simeq |\mathbf{p_2}| + c_s|\mathbf{k_m}|$$

- Works because of phonon's dispersion: $c_s \ll 1$
- Target frequency: μeV ~ meV

Conclusion

- The landscape of axion dark matter is extremely broad, covering many orders of magnitude in mass range. Discovering different possibilities requires a varied set of experimental techniques.
- Special materials /exotic matter can be advantageous in terms of better phase matching between axion and signal photon, unique target frequencies due to the quasiparticle dispersion, as well as lower noise in some cases.
- In the future, more investigations, such as background noise characterization, signal readout optimization, for each proposed setup, are required.

Thank you for your attention!