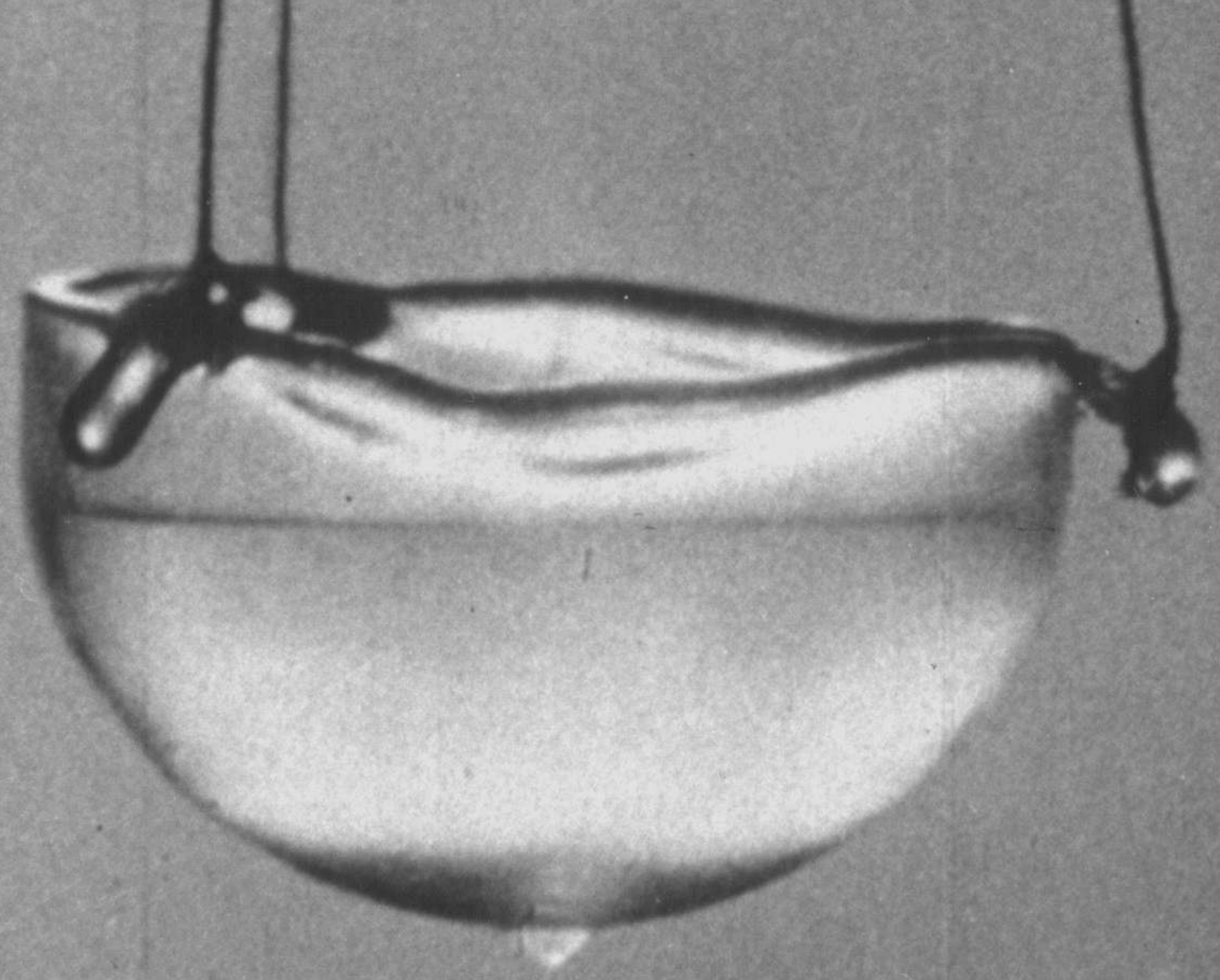


Axion Detection using Quantum Technologies and Materials

Christina Gao 09/09/2022

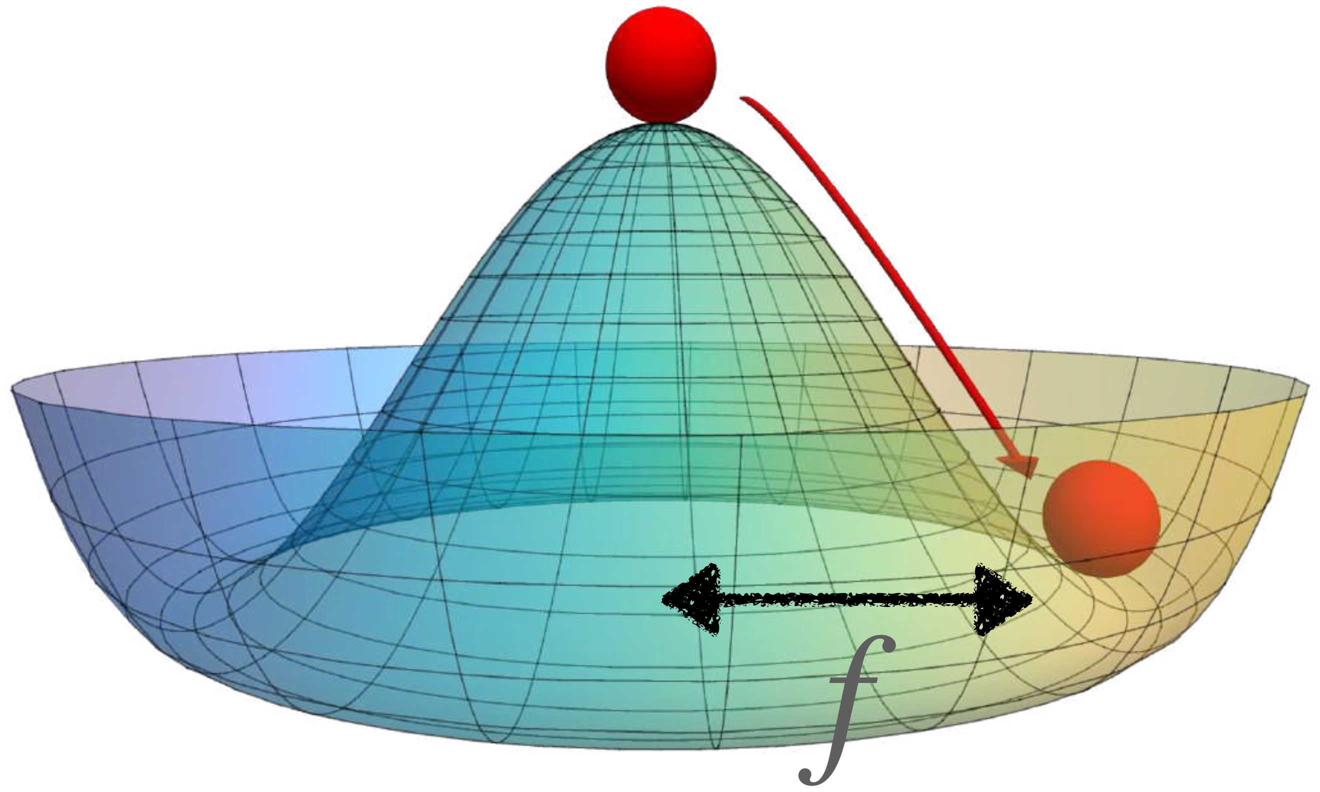
New Directions in Particle Physics, ICTP-SAIFR, São Paulo, Brazil

Axions are light Pseudo-scalars

- Goldstone bosons from new symmetries, naturally light.

Spontaneous breaking

$$\Rightarrow \partial_\mu \left(\frac{a}{f}\right) \mathcal{O}^\mu_{\rm SM}$$

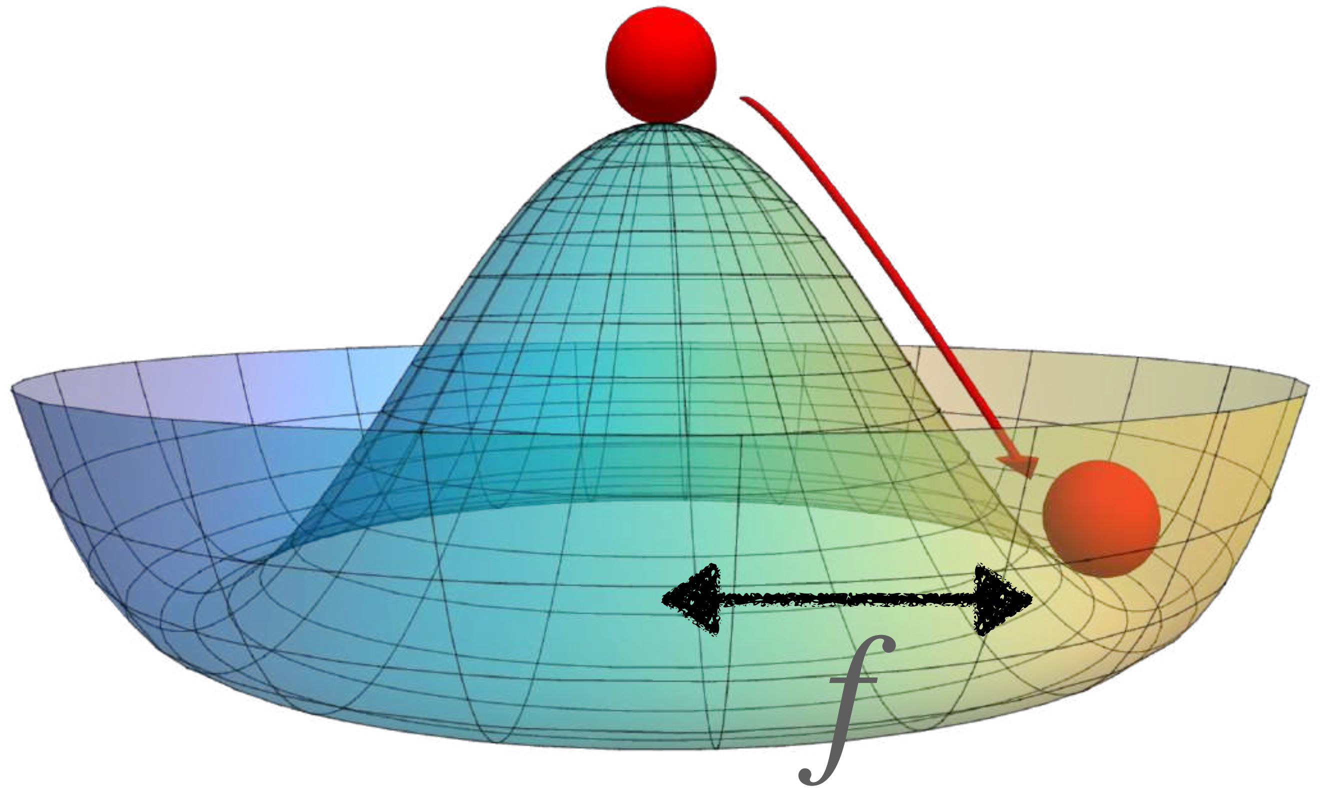


Axions are light Pseudo-scalars

- Goldstone bosons from new symmetries, naturally light.
- Couplings to SM are naturally small.

Spontaneous breaking

$$\Rightarrow \partial_\mu \left(\frac{a}{f}\right) \mathcal{O}^\mu_{\rm SM}$$

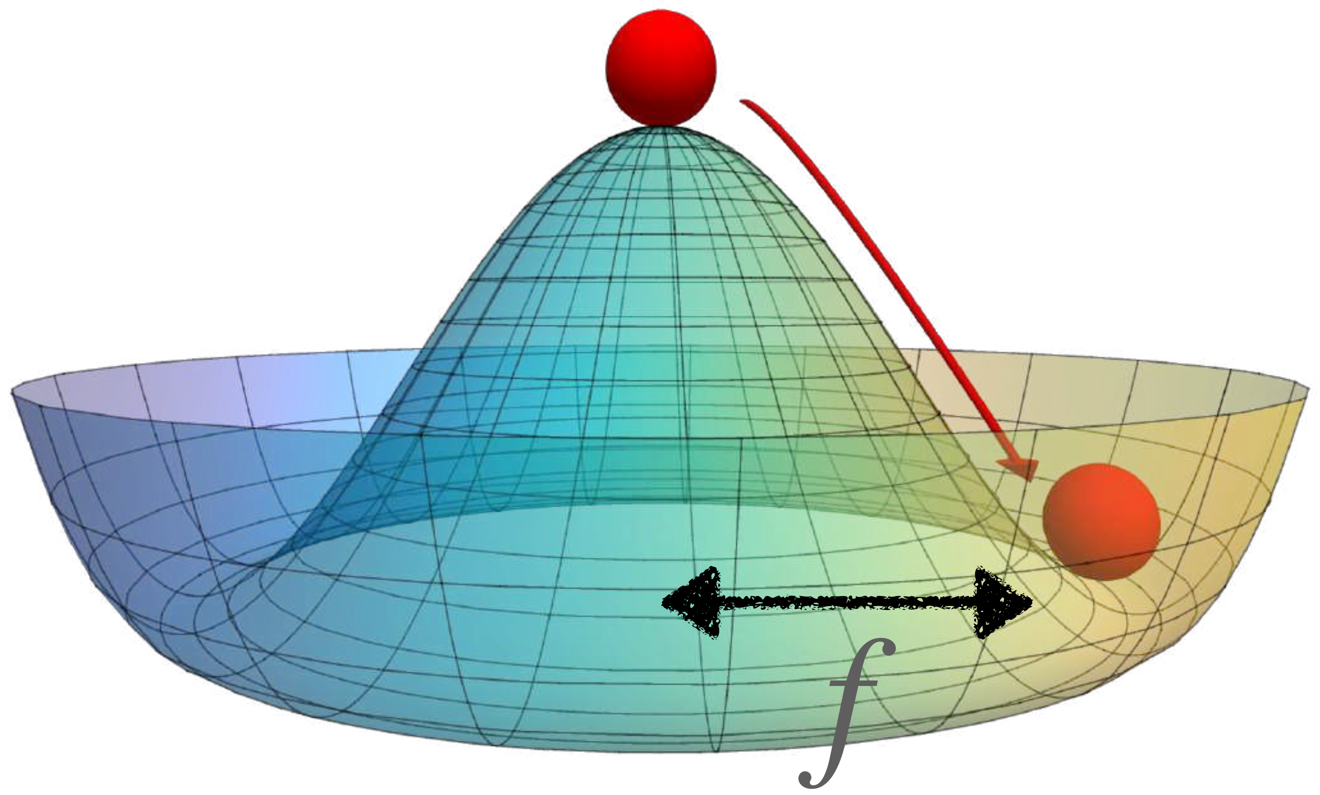


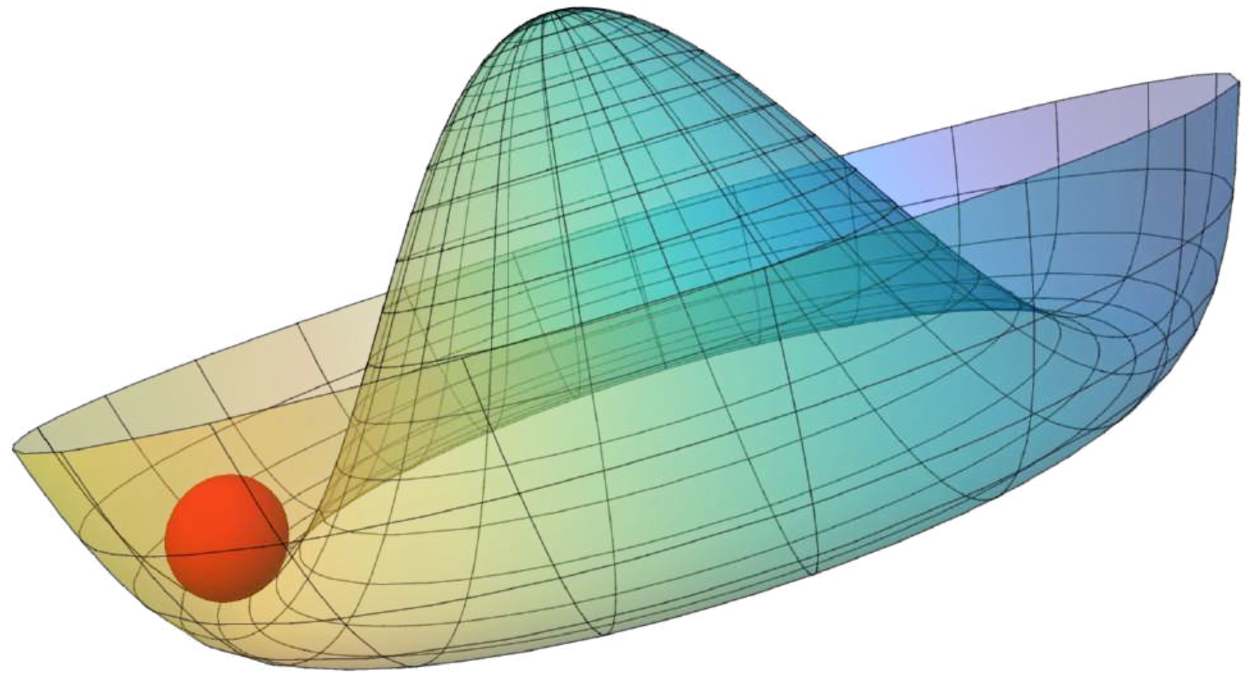
Axions are light Pseudo-scalars

- Goldstone bosons from new symmetries, naturally light.
- Couplings to SM are naturally small.
- Axion’s mass comes from breaking of the new symmetry.

Spontaneous breaking $\Rightarrow \partial_\mu \left(\frac{a}{f}\right) \mathcal{O}^\mu_{\rm SM}$

Explicit breaking $\Rightarrow V\left(\frac{a}{f}\right)$





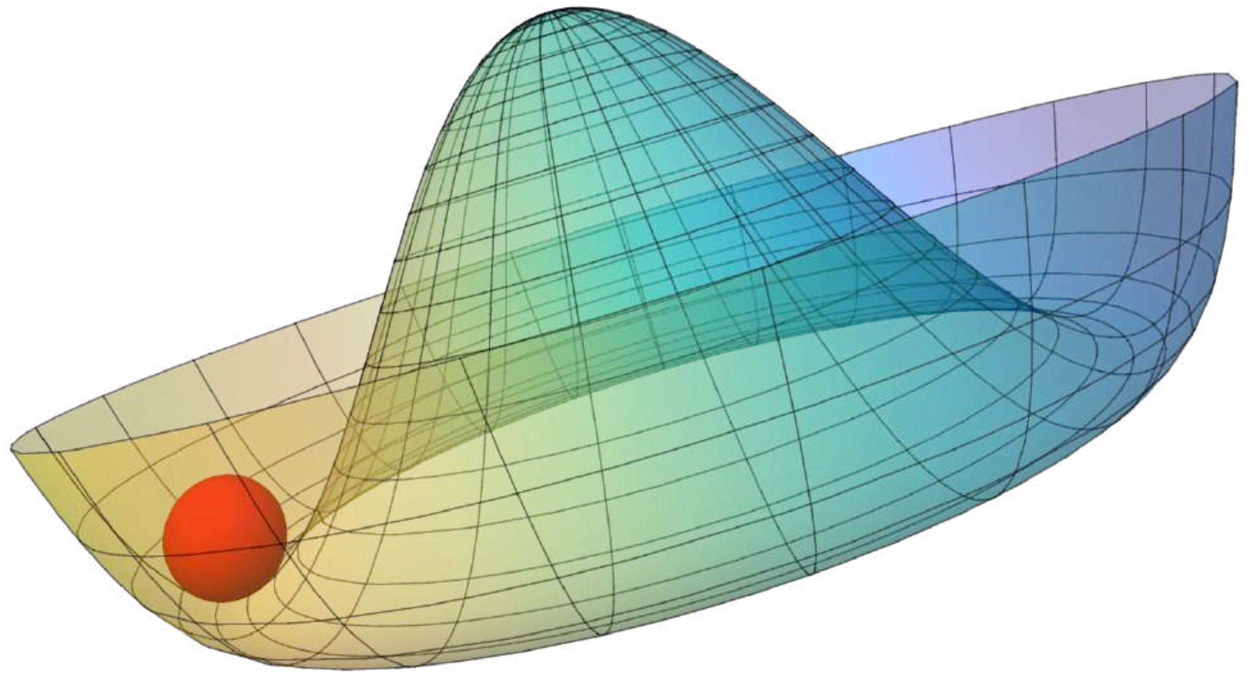
Axions can solve the Strong CP problem

- QCD Axion $m_a f_a \sim m_\pi f_\pi$

Peccei & Quinn (1977)
Weinberg (1978)
Wilczek (1978)

Kim (1979),
Dine et. al (1981)

$U(1)_{PQ}$ +
QCD instantons



Axion Like Particles

- QCD Axion $m_a f_a \sim m_\pi f_\pi$

Peccei & Quinn (1977)
Weinberg (1978)
Wilczek (1978)

Kim (1979),
Dine et. al (1981)

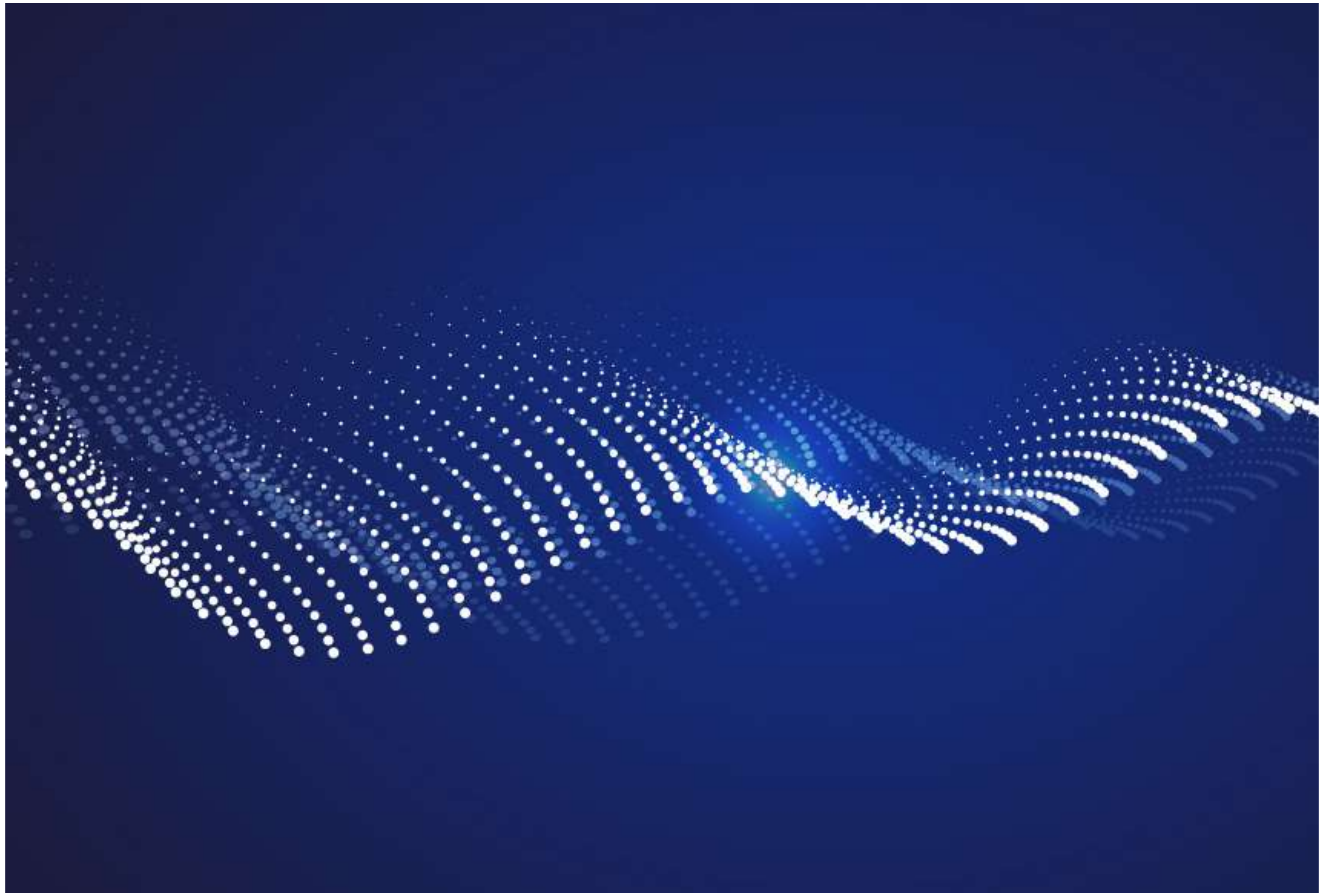
Svrcek & Witten (2006), Arvanitaki et. al (2009)

- Many axion-like particles (ALPs) from string theories

f is usually at Grand Unification scale: $10^{16}\ \mathrm{GeV}$

Masses of ALPs independently span a vast range.

Axions can be Dark Matter (DM)



Preskill et. al (1983), Abbott & Sikivi (1983), Dine & Fischler (1983)

- Large occupation number
- Cold dark matter $v \sim 10^{-3} c$
- Behave like wave

$$a_{\rm DM}(t) \sim a_0 \cos\left(m_a t\right)$$

$$\rho_{\rm DM} \simeq \frac{1}{2} m_a^2 a_0^2$$

This Talk

- Axion-photon coupling
  - ✦ Superconducting radio-frequency (SRF) cavity, $< \sim 10\mu$eV

    CG, Roni Harnik (JHEP 2021)
  - ✦ Microring resonator, 0.1~10eV, DM

    Nikita Blinov, CG, Ryan Janish, Roni Harnik, Neil Sinclair (In progress)
- Axion-nucleon coupling
  - ✦ Superfluid Helium Three, $\sim 0.1\mu$eV, DM

    CG, William Halperin, Yonatan Kahn, Man Nguyen, Jan Schütte-Engel, John William Scott (2208.14454)

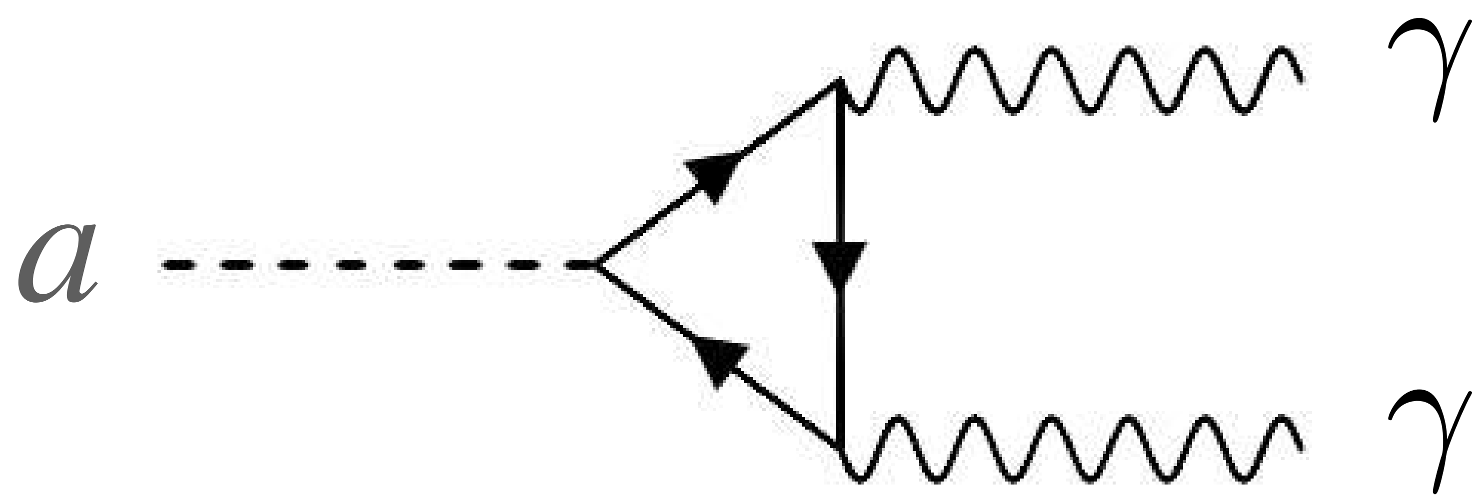
    Joshua Foster, CG, Yonatan Kahn, Jan Schütte-Engel (In progress)

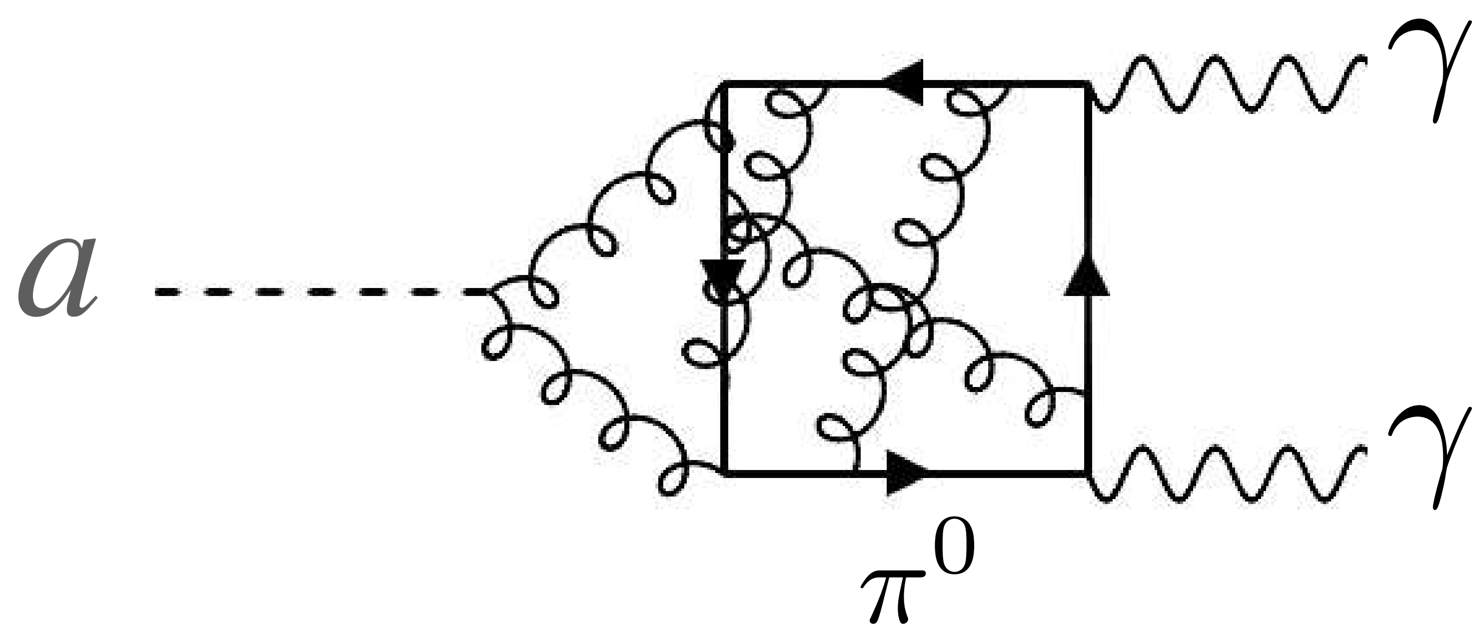
Axion's Two Photon Vertex

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

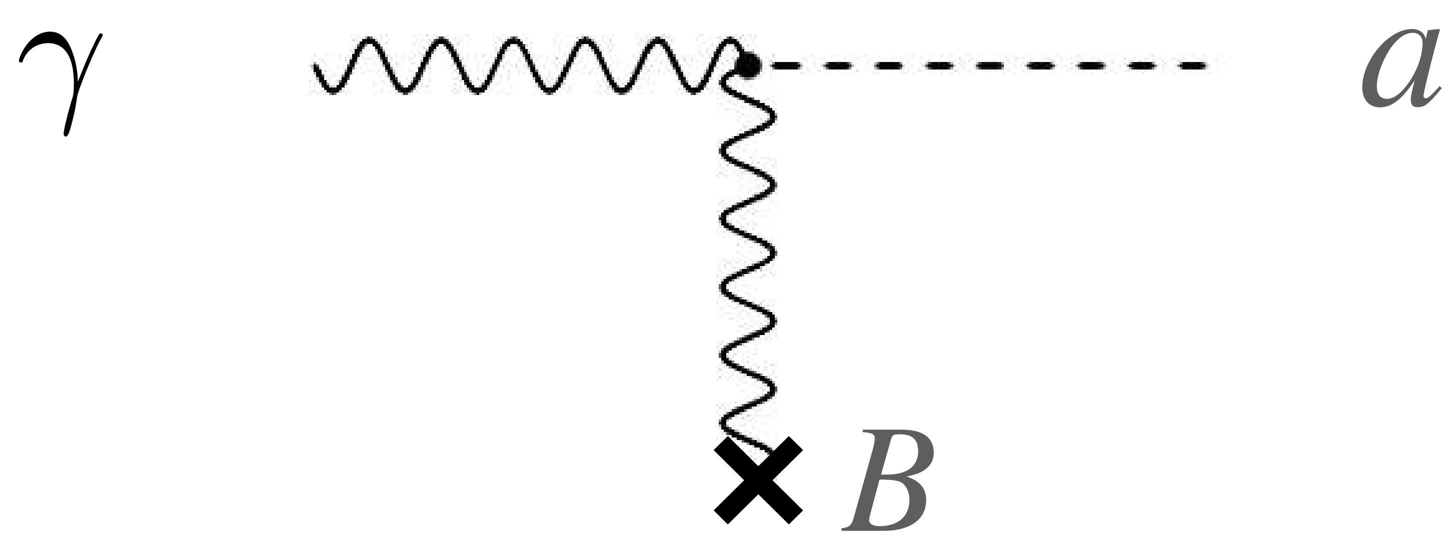
$$= g a \boldsymbol{E} \cdot \boldsymbol{B}$$

$$g \propto 1/f$$

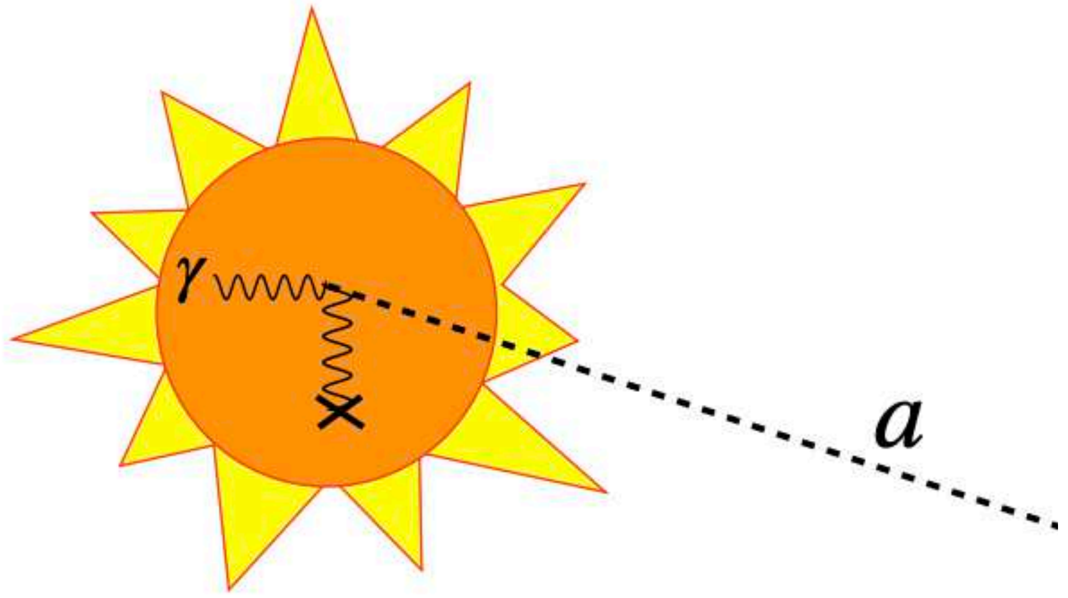




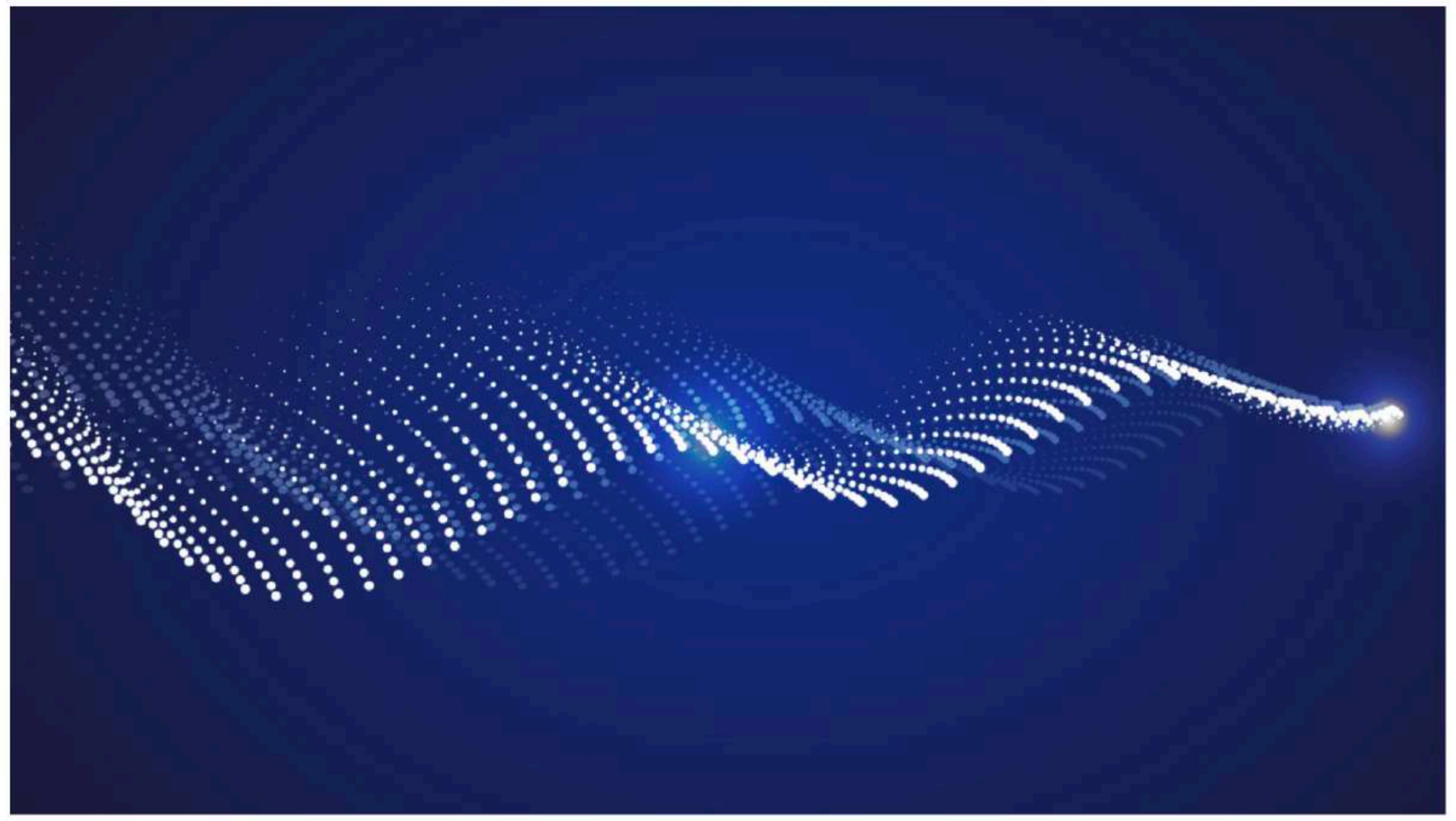
Axion searches usually rely on axion-photon conversion in a background magnetic field.



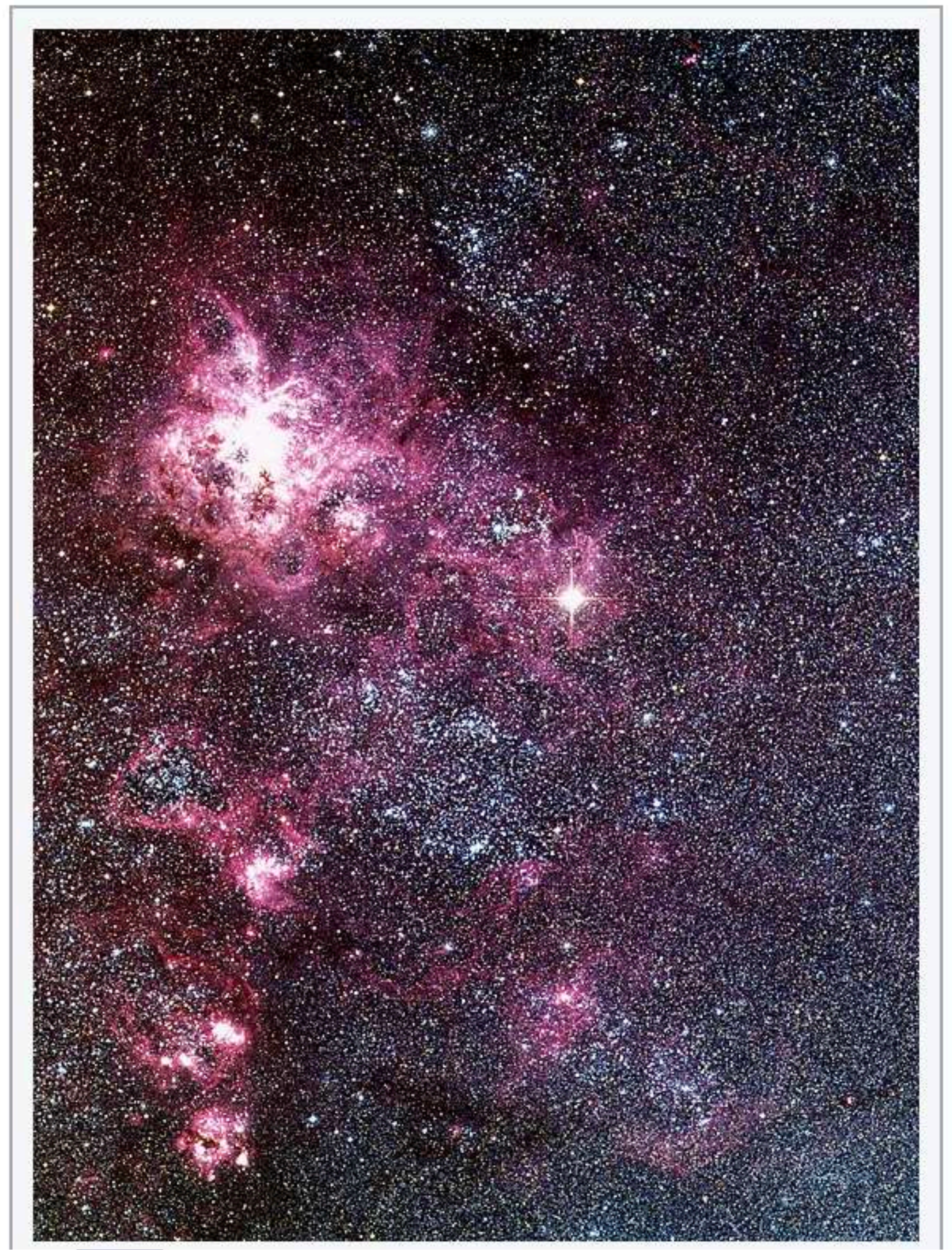
Sources of Axion Detection



$$g\,a\,\boldsymbol{E}\cdot\boldsymbol{B}$$

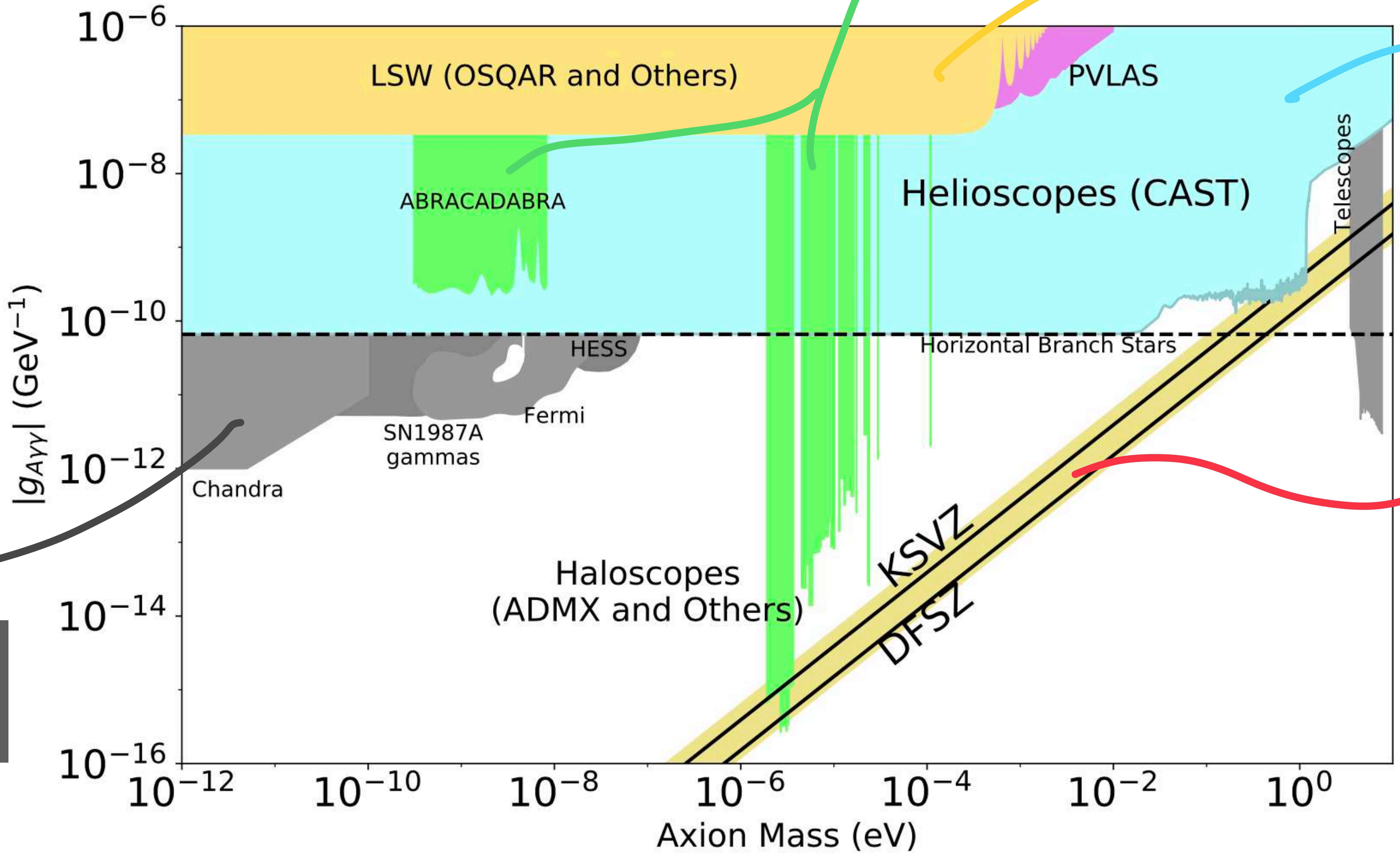


SN 1987A



- Solar axion
- Axion dark matter
- Other astronomical sources, e.g. SN 1987A
- Produced in the laboratory

From The Review of Particle Physics (2020)



DM

Very narrow bandwidth, requires scanning

Lab

Solar

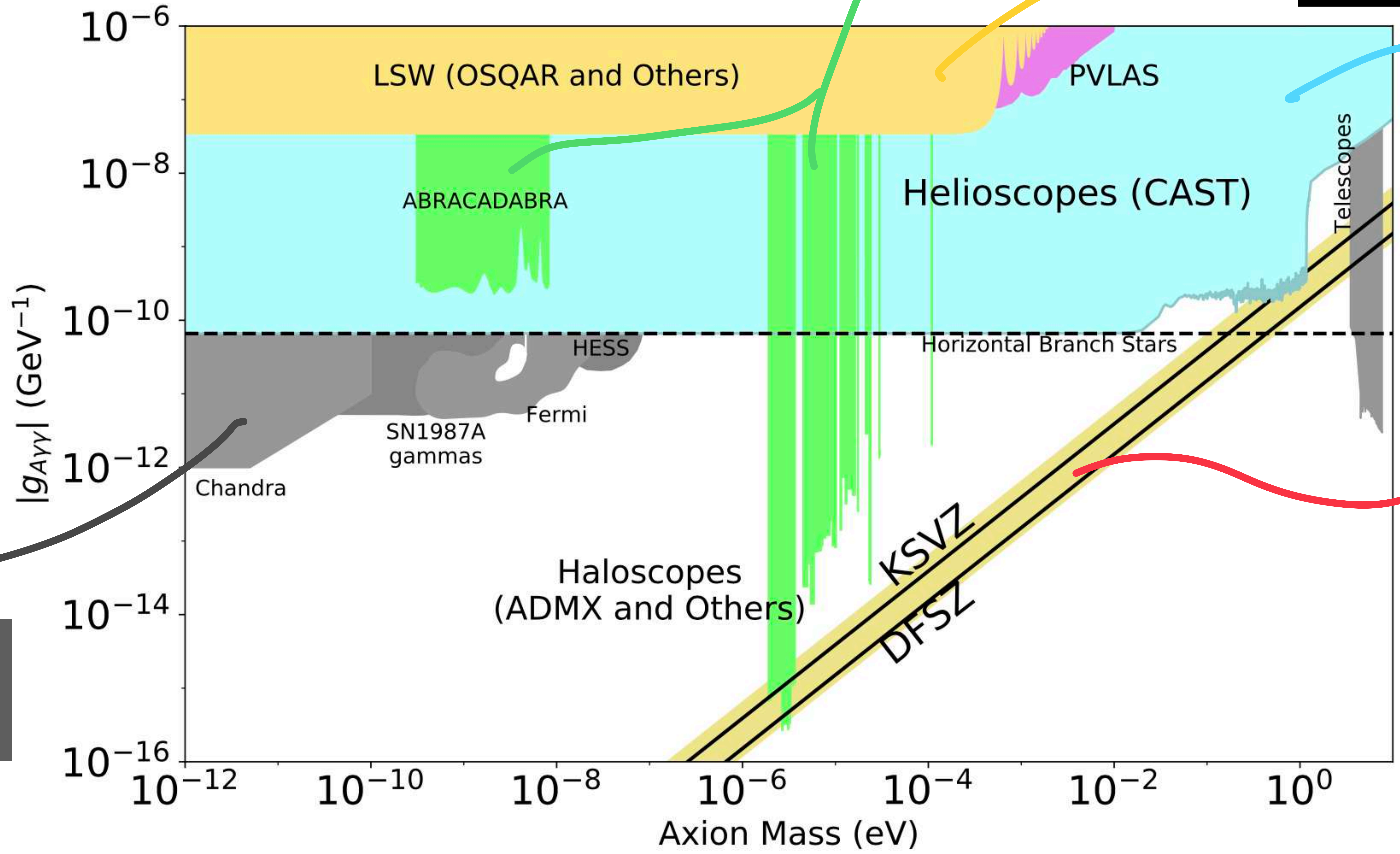
Broadband, pretty robust

QCD axion

Astro

Relies on modeling of astrophysics

From The Review of Particle Physics (2020)



DM

Very narrow bandwidth, requires scanning

Lab

Broadband, clean, can be improved by quantum technology!

Solar

Broadband, pretty robust

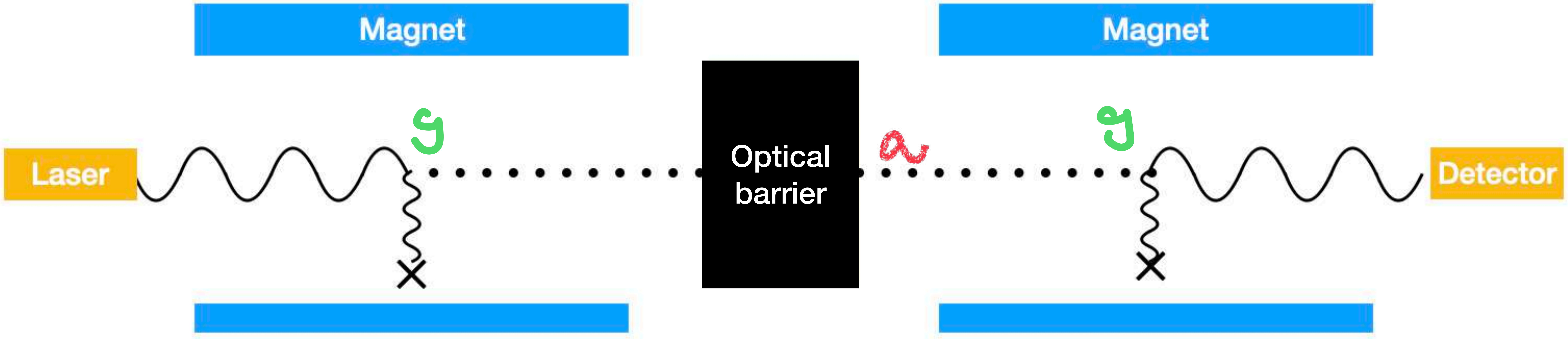
QCD axion

Astro

Relies on modeling of astrophysics

Light-Shining-Through-Walls (LSW)

$g\, a\, \boldsymbol{E} \cdot \boldsymbol{B}$



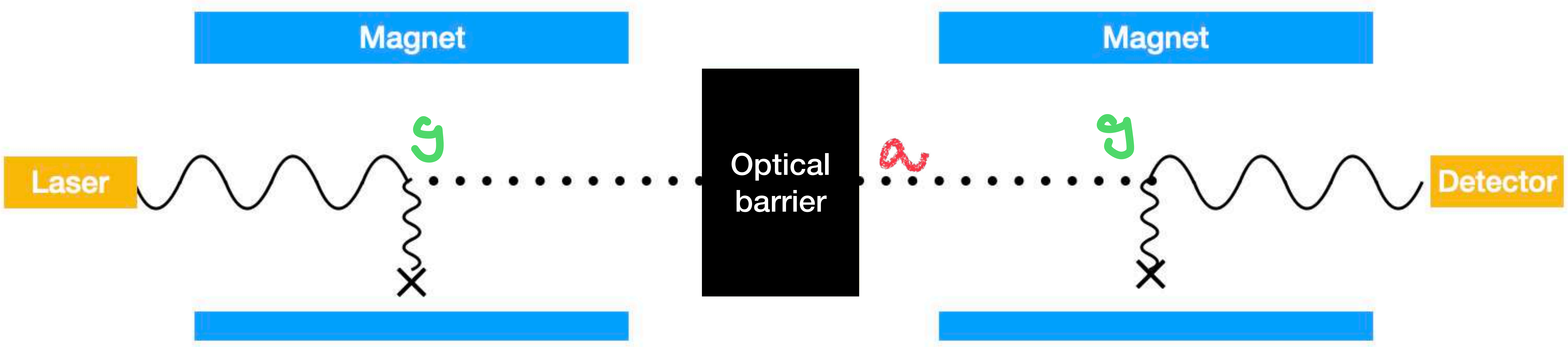
- ✦ Tiny signal rate ∝ g^4

☐ Want large number of photons to source the axion

☐ Want a low noise detector

Light-Shining-Through-Walls (LSW)

$g\, a\, \boldsymbol{E} \cdot \boldsymbol{B}$



- ✦ Tiny signal rate ∝ g^4

High Quality Cavity {
- ☑ Want large number of photons to source the axion
- ☑ Want a low noise detector

Quality Factor of Cavities

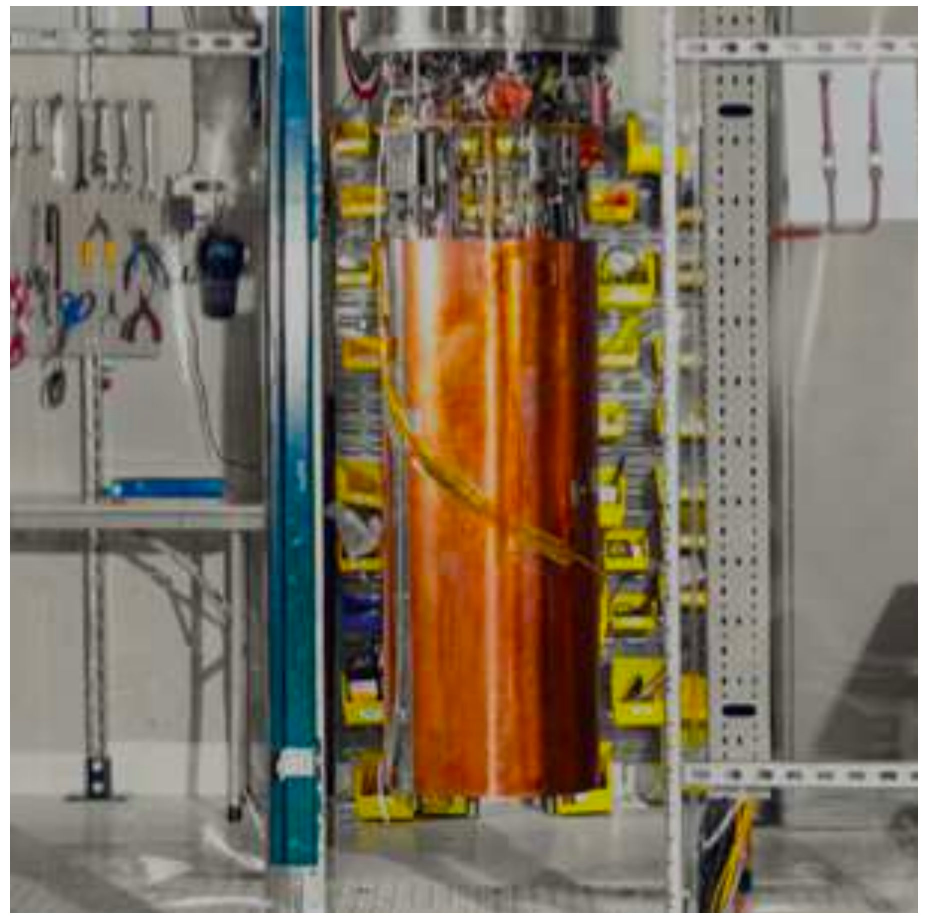
$$Q \equiv 2\pi \times \frac{\text{energy stored}}{\text{energy dissipated per cycle}}$$

The **higher** the Q is, the **lower** the loss is, and the **larger** the number of photons are stored in a cavity.

Quality Factor of Cavities

Earth Ionosphere
$Q = 3$

ADMX
$Q \sim 10^5$



Phys. Rev. Lett. **127** (2021)

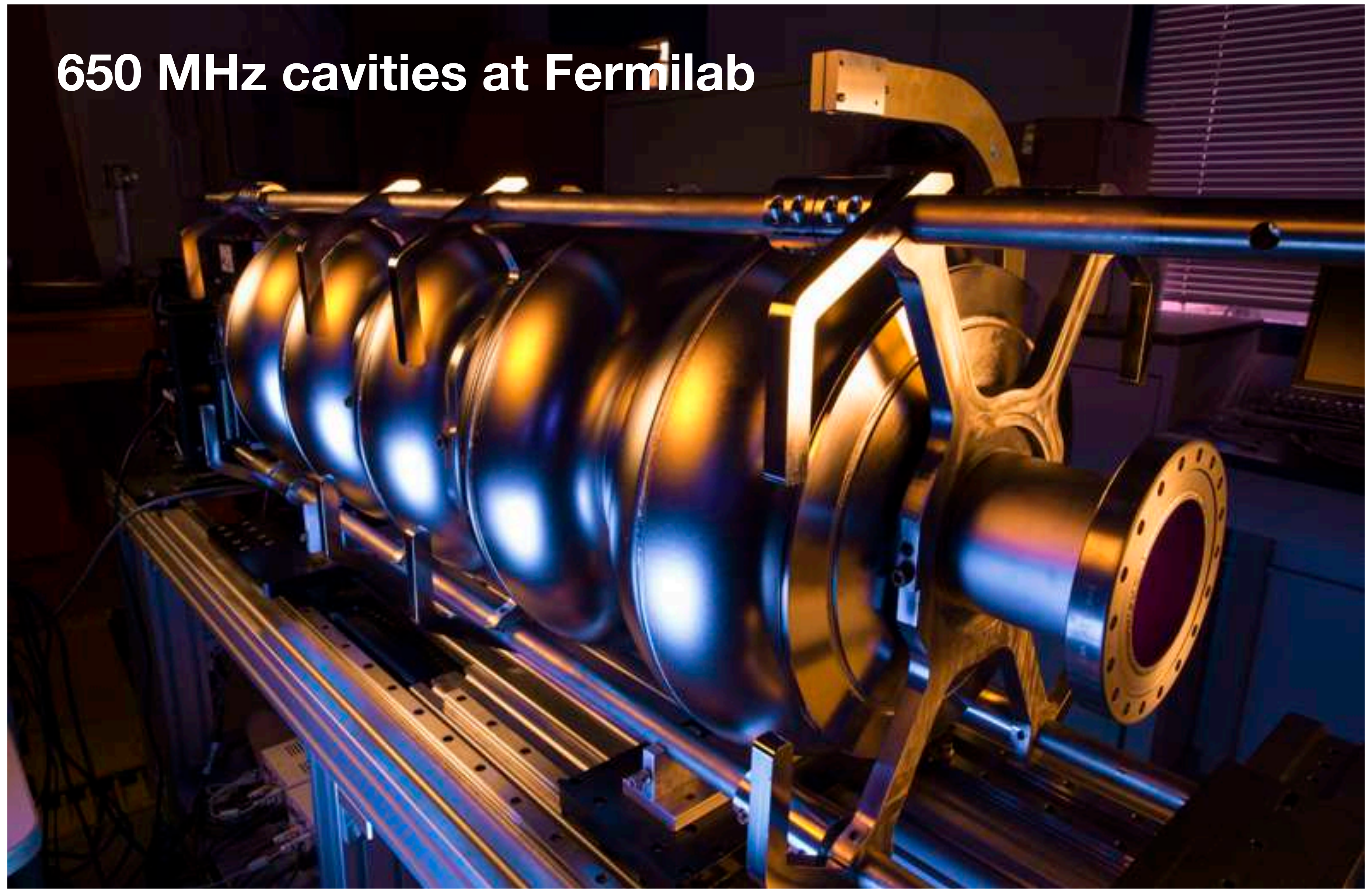
High quality cavities have $Q \gtrsim 10^7 \sim 10^{12}$
(depending on the resonant frequencies).

Superconducting Radio-frequency Cavities

- Superconducting radio frequency (SRF) cavity has a resonance frequency around $\mathrm{GHz}\ (10\mu\mathrm{eV})$

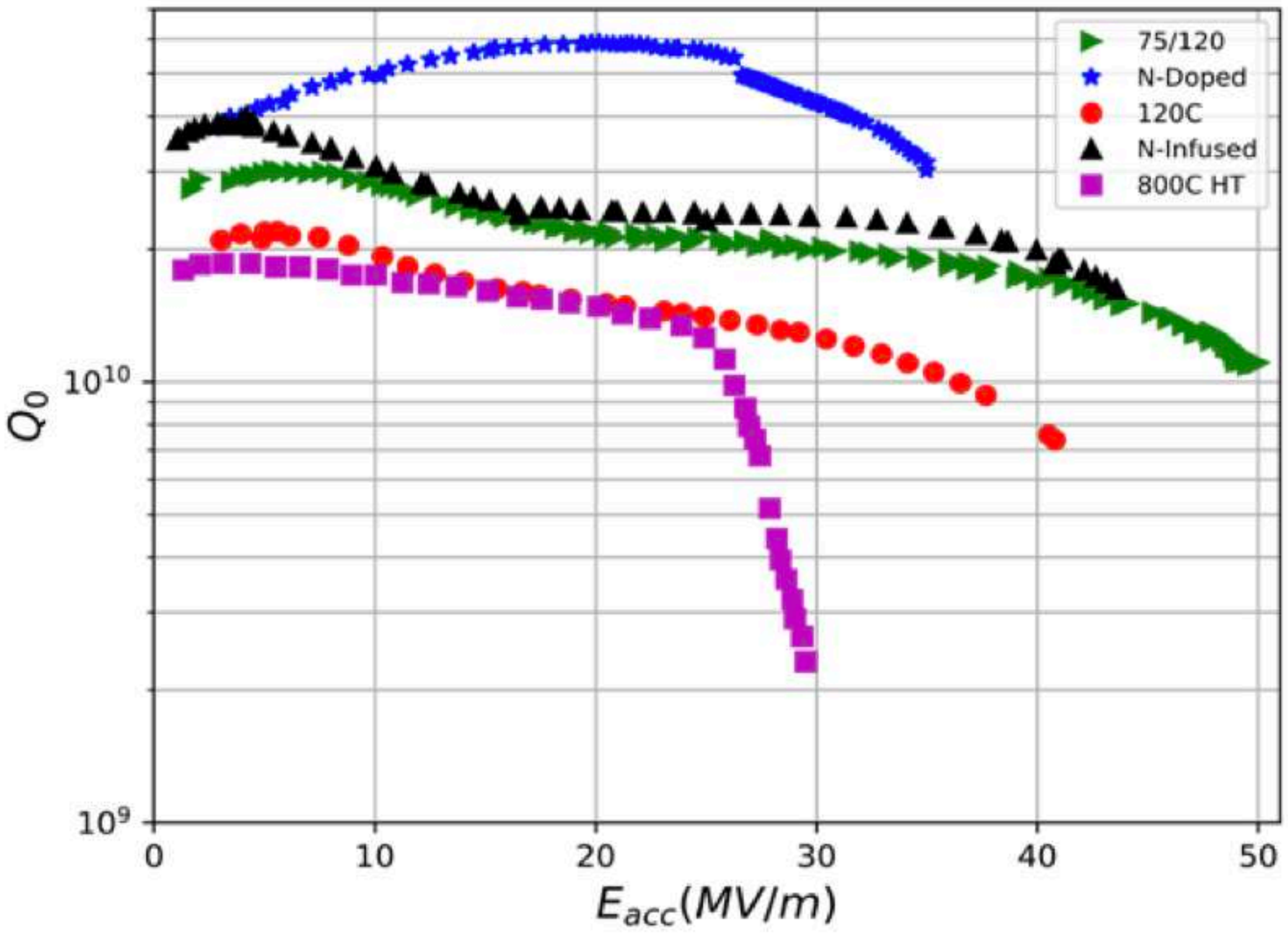
- $Q = 10^{10}$, can store 10^{26} photons with a field of peak amplitude

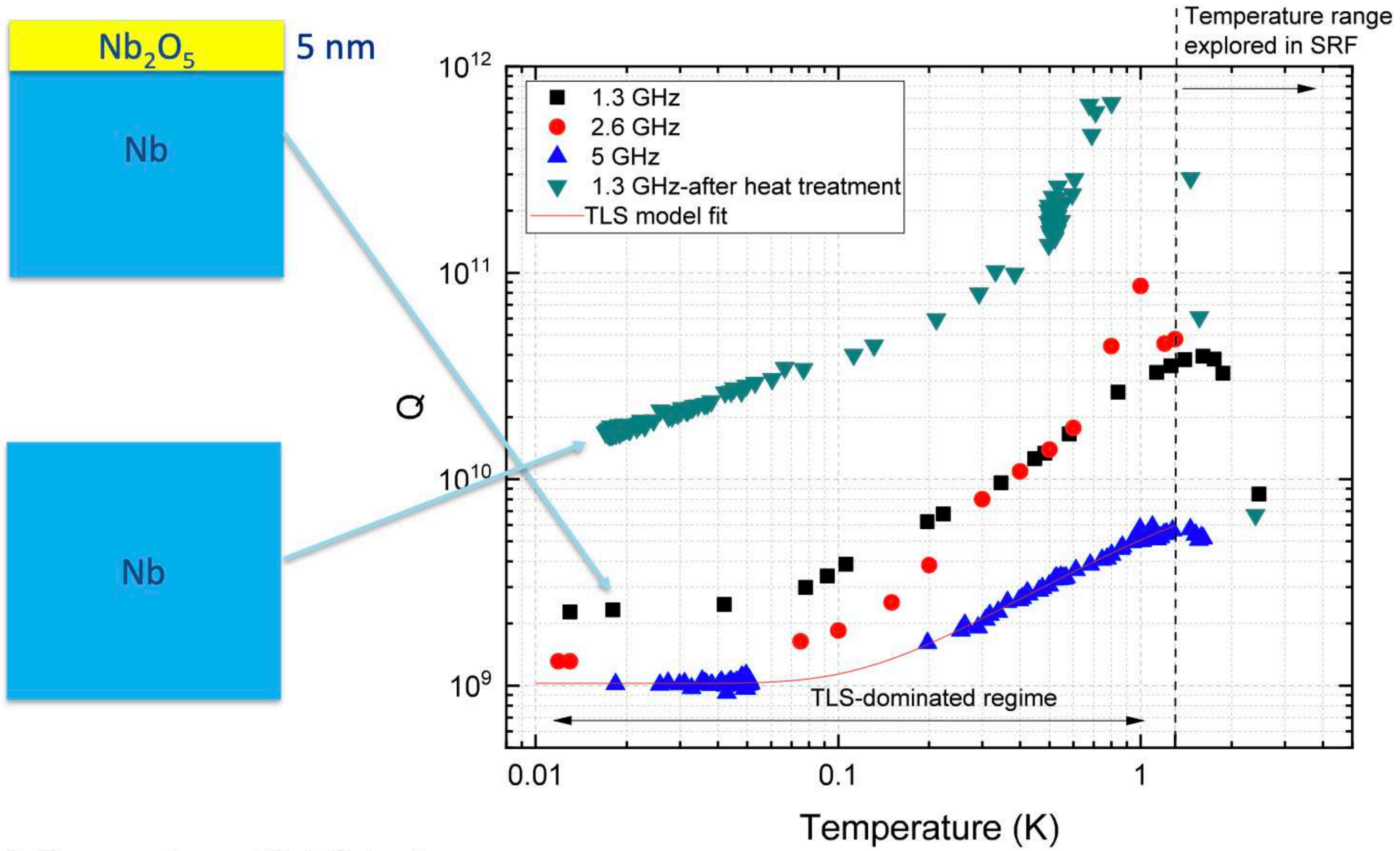
$$E_{\mathrm{peak}} = 80\,\mathrm{MV\,m^{-1}}$$


650 MHz cavities at Fermilab

Superconducting Radio-frequency Cavities

$$E_{acc} \sim \frac{1}{2} E_{\text{peark}}$$





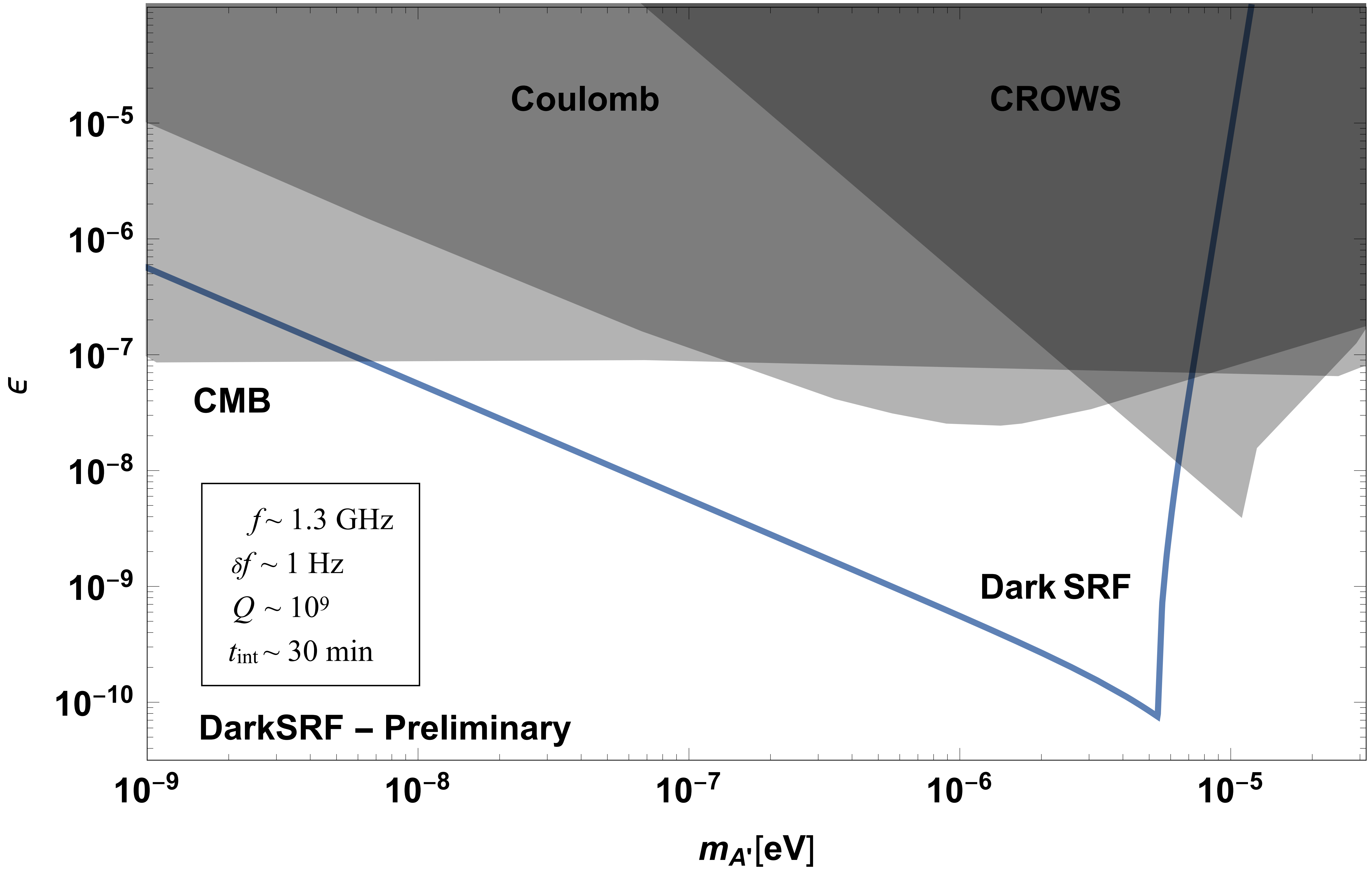
A. Romanenko and D. I. Schuster
Phys. Rev. Lett. **119**, 264801 – Published 28 December 2017

https://accelconf.web.cern.ch/srf2019/papers/mop031.pdf

SRF Cavities - Dark SRF

Emitter

Receiver



A dark photon LSW search at Fermilab using SRF cavities. Demonstrated high Q and frequency control.

Dark SRF - A. Grasselino, R. Harnik, S. Posen, Z. Liu, A. Romanenko (to appear).

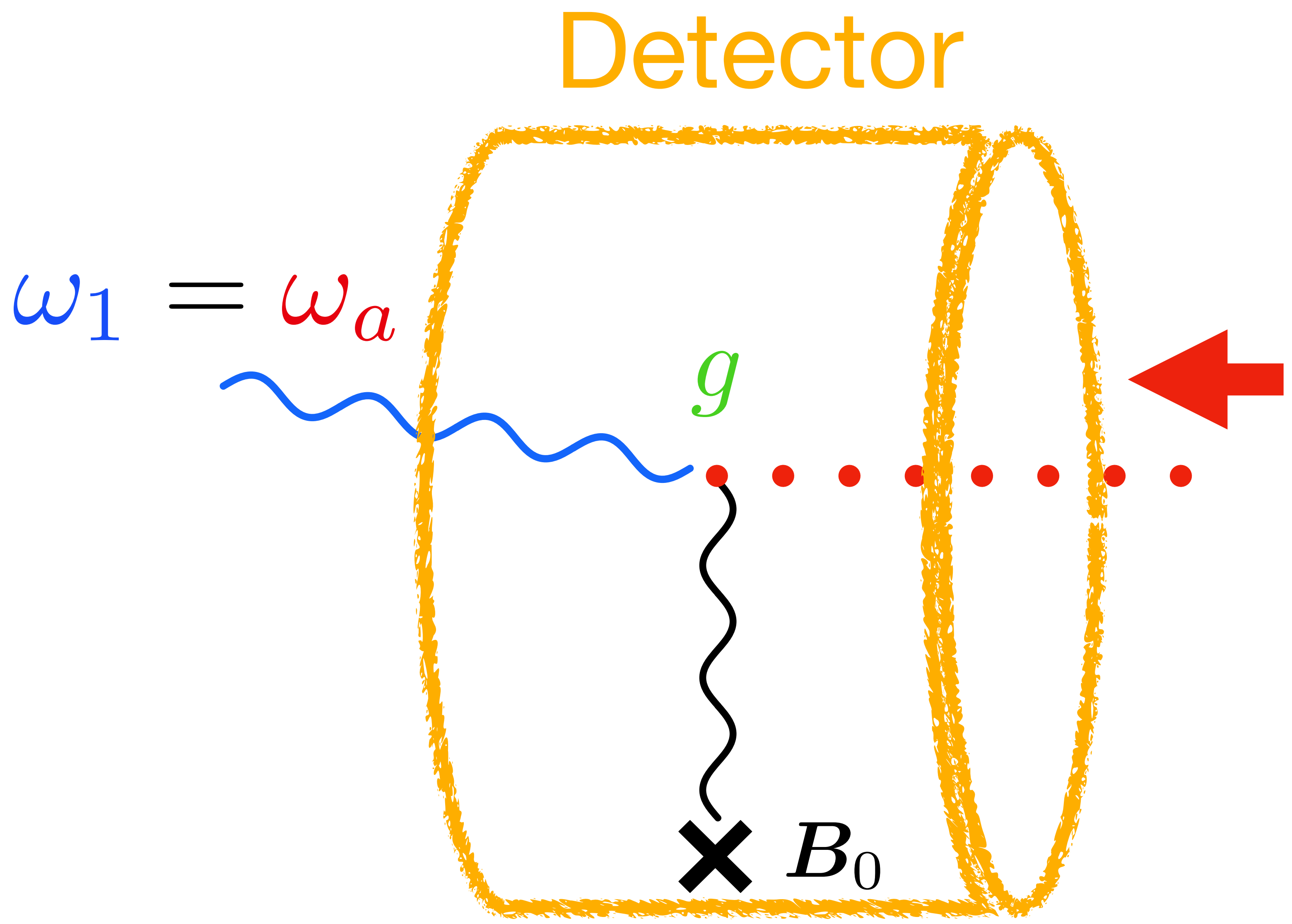
Superconducting Radio-frequency Cavities

Snowmass white paper

“Searches for New Particles, Dark Matter, and Gravitational Waves with SRF Cavities”

Review of Cavity Axion Searches

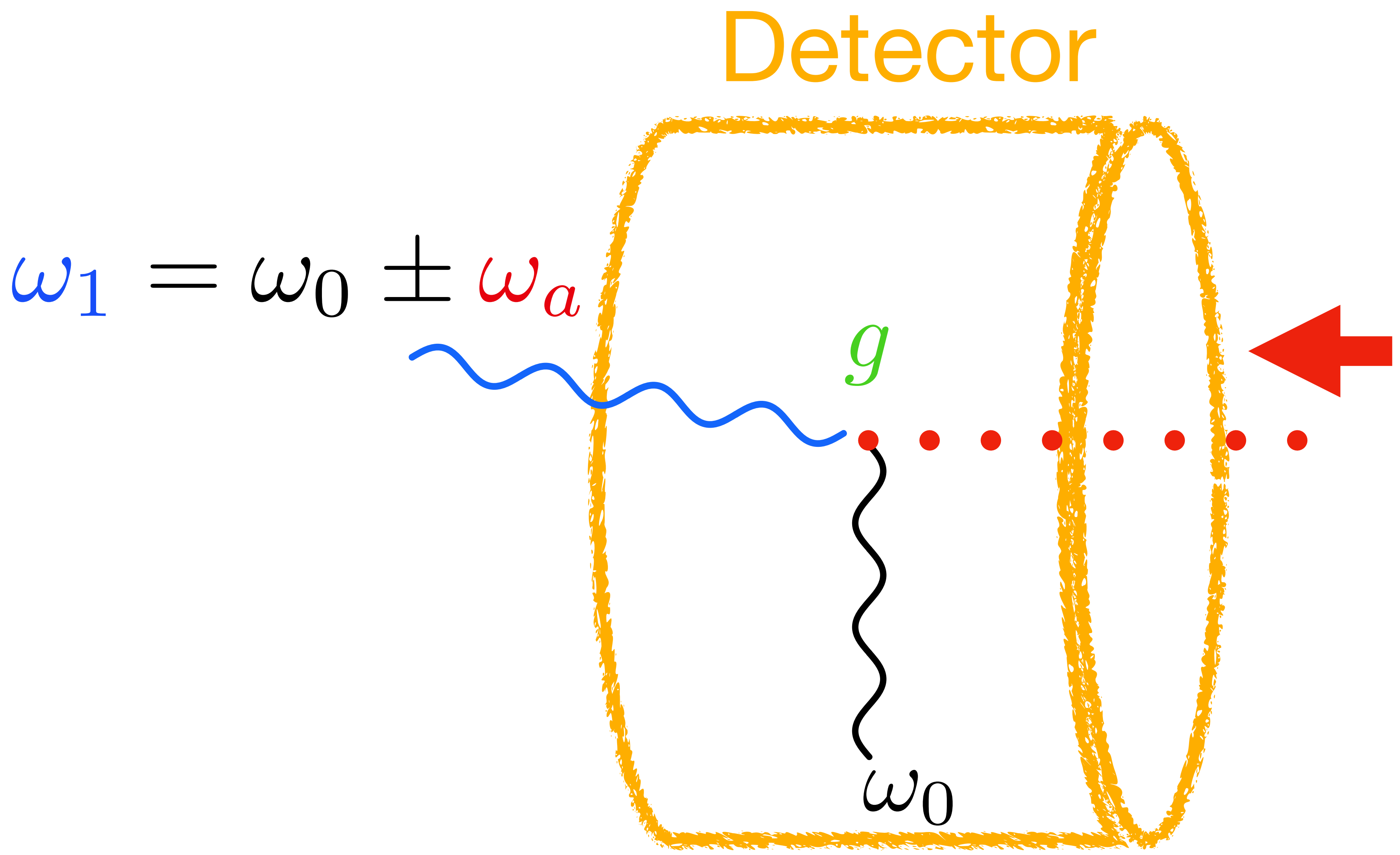
$$g\, a\, \boldsymbol{E}_1 \cdot \boldsymbol{B}_0$$



- ✦ a quiet cavity + static B
- ✦ signal ω_1 is a cavity mode, enhanced by Q.
- ✦ tiny g ⇒ large B desired, but large B may penetrate SRF cavity.

Review of Cavity Axion Searches

$$g\, a\, \boldsymbol{E}_1 \cdot \boldsymbol{B}_0$$



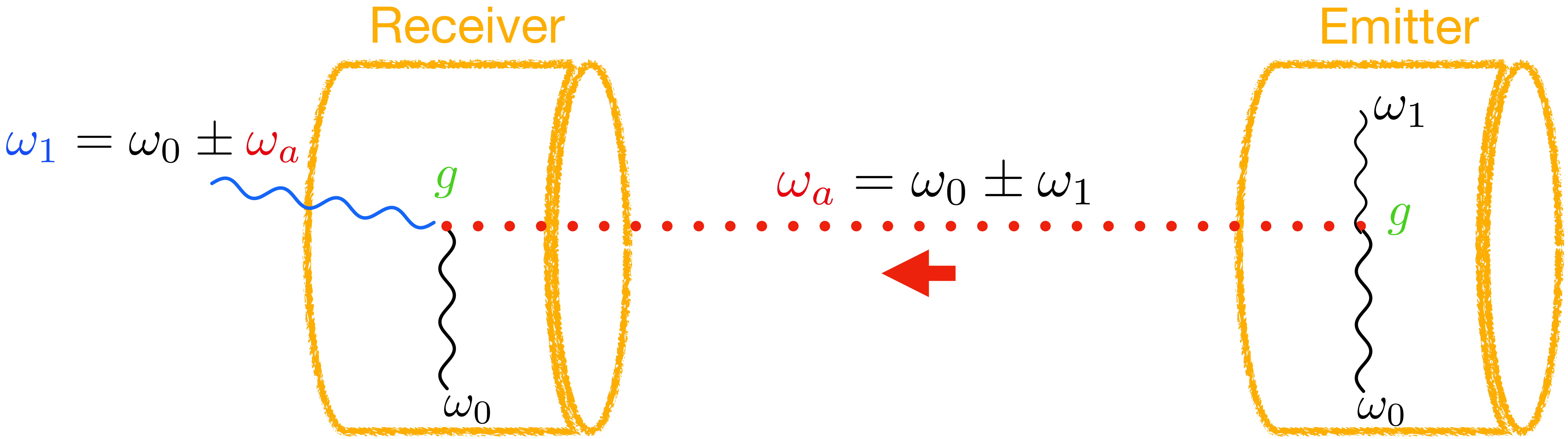
- static B → **active** cavity mode ω_0
- signal $\omega_1 =$ 2nd cavity mode
- frequency matching: $\omega_1 = \omega_0 \pm \omega_a$
- new DM axion search strategies

Sikivie (2010), Berlin et. al (2019)

Our proposal

LSW Axion Searches with SRF Cavities

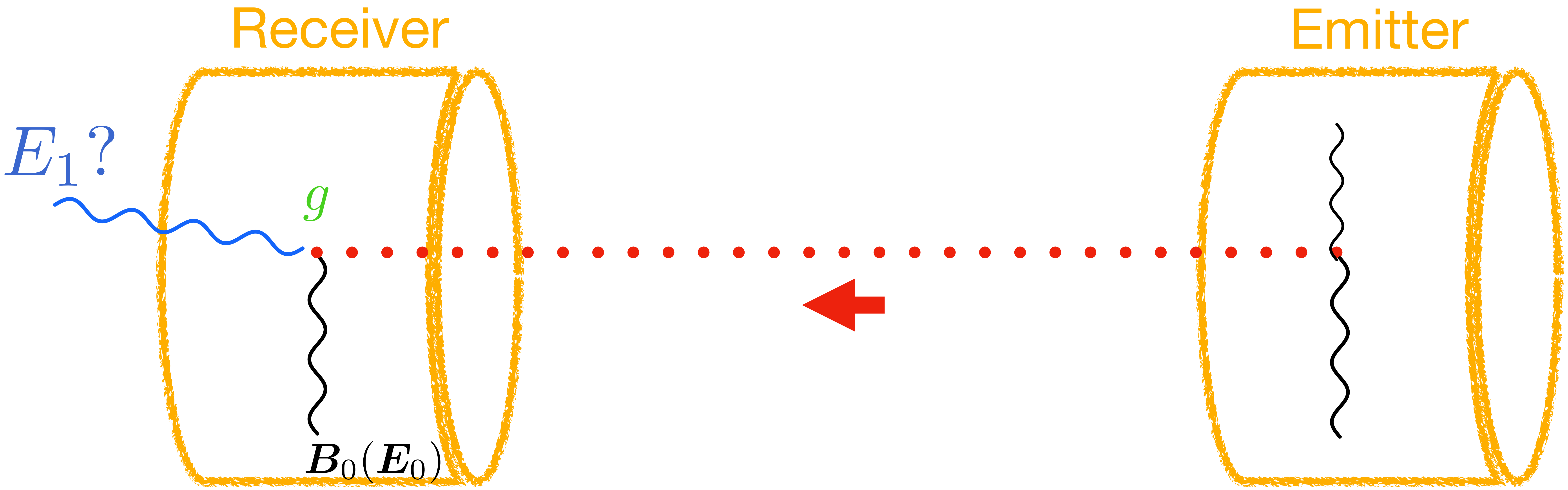
$$g\, a\, \boldsymbol{E}_1 \cdot \boldsymbol{B}_0$$



- 2 active cavity modes to source axion in the emitter.
- 3rd active mode in the receiver, satisfying frequency matching.

Signal Field

$$g\, a\, \boldsymbol{E}_1 \cdot \boldsymbol{B}_0$$



Maxwell’s equations

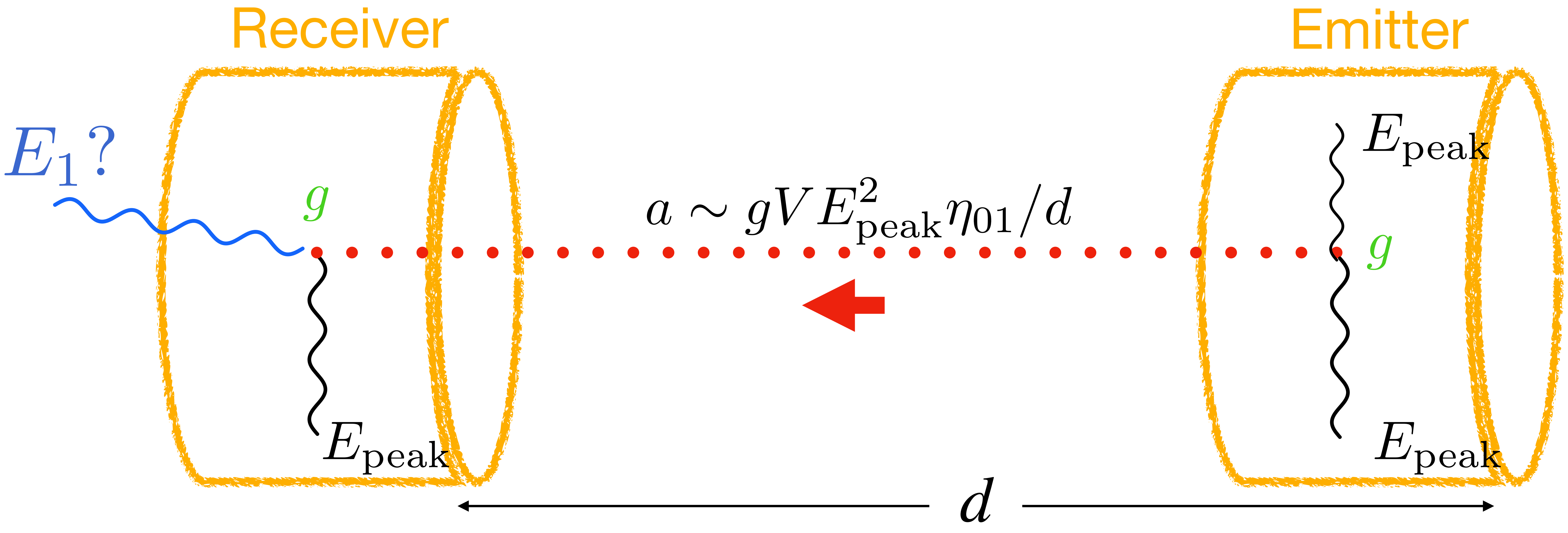
$$\nabla \cdot \boldsymbol{E} = -g_{a\gamma} \boldsymbol{B} \cdot \nabla a \qquad \nabla \times \boldsymbol{B} = \partial_t \boldsymbol{E} - g_{a\gamma} \left(\boldsymbol{E} \times \nabla a - \boldsymbol{B} \partial_t a \right)$$

$$\nabla \cdot \boldsymbol{B} = 0 \qquad \nabla \times \boldsymbol{E} = -\partial_t \boldsymbol{B}$$

(under natural unit)

Signal Power

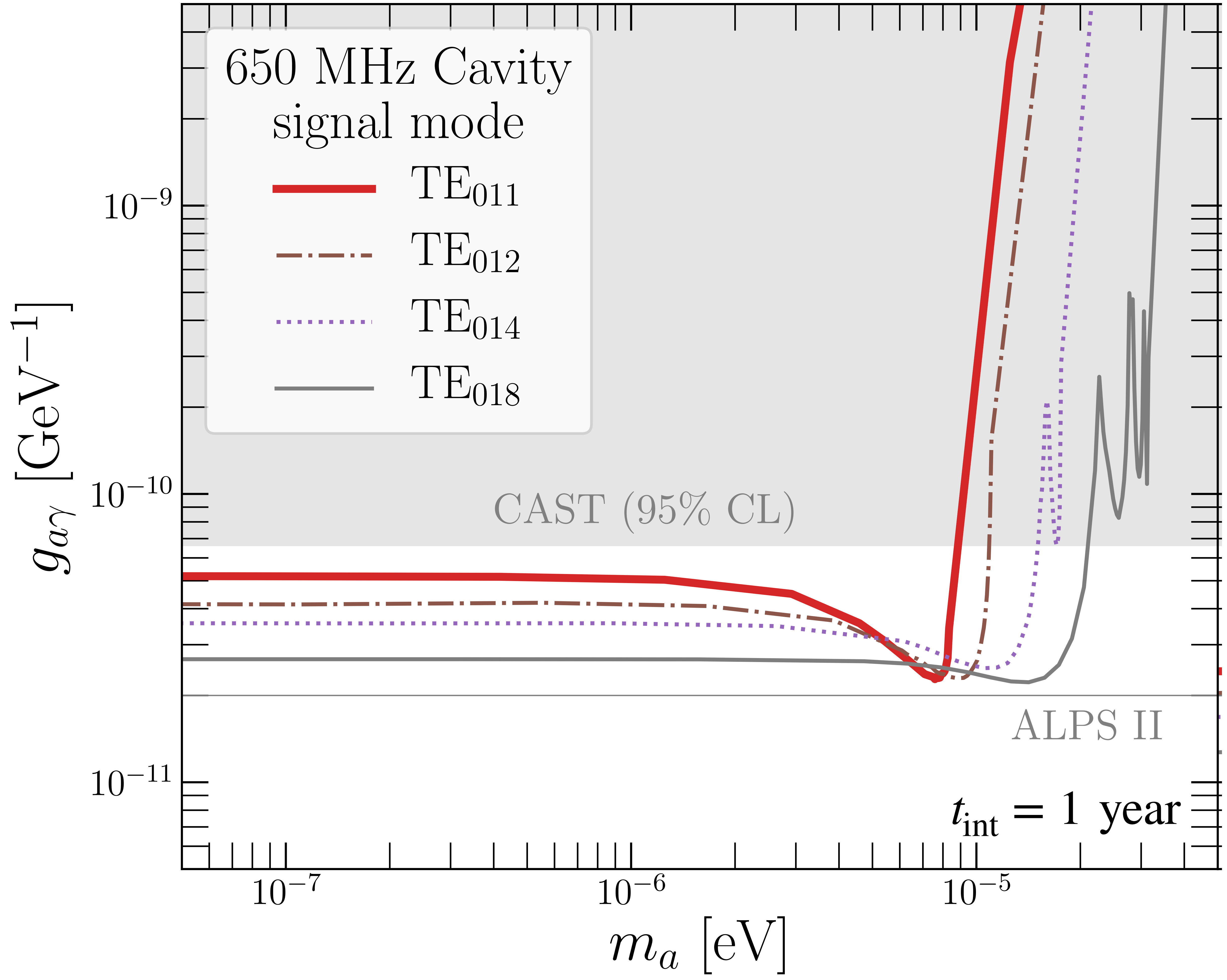
$$g\, a\, \boldsymbol{E}_1 \cdot \boldsymbol{B}_0$$



$$P_{\text{sig}} = \frac{\text{energy}}{\text{time}} = \frac{1}{\tau_1}\int_V |\boldsymbol{E}_1|^2 \propto \frac{Q V^3 g^4 \eta_{01}^4 E^6_{\text{peak}}}{d^2}$$

Q = quality factor
V = volume of cavity
η_{01} = geometric factor
E_{peak} = field amplitude

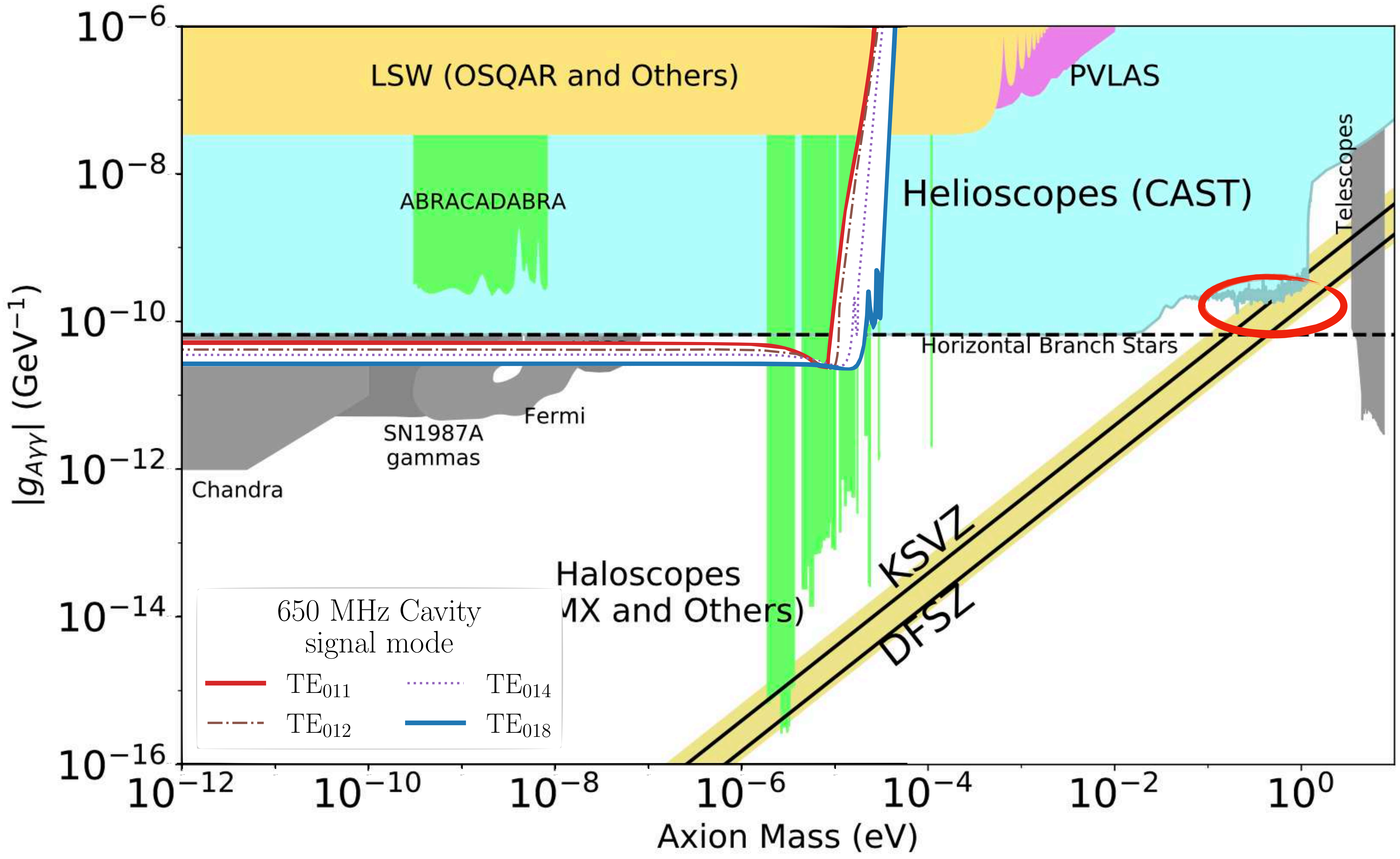
Sensitivity of the LSW Axion Search



$$\mathrm{SNR} = \frac{P_{\mathrm{sig}}}{P_{\mathrm{bkg}}}\sqrt{t_{\mathrm{int}}\Delta\omega_1} > 5$$

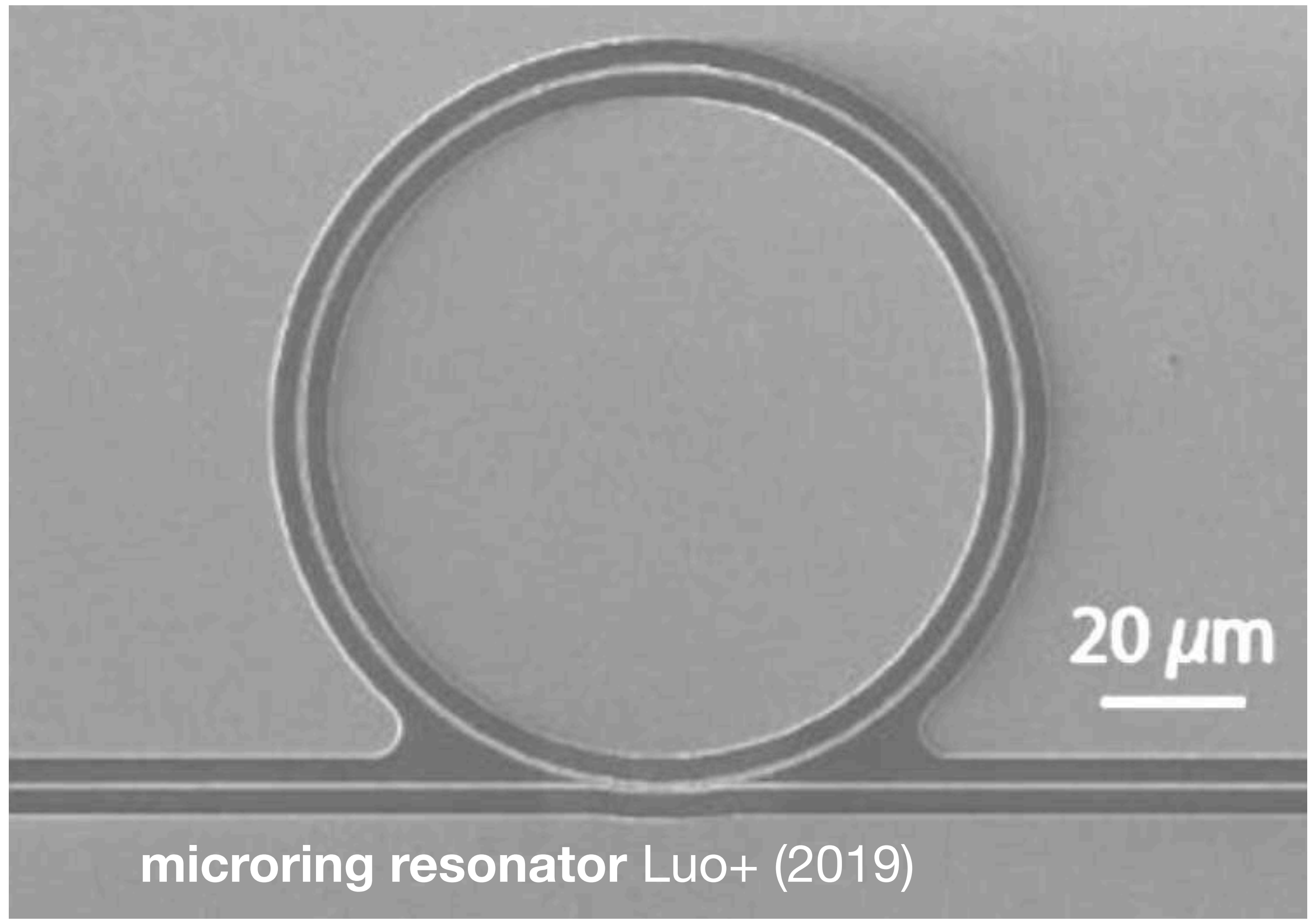
$$Q = 10^{10}$$
$$E_{\mathrm{peak}} = 80\,\mathrm{MV\,m^{-1}}$$

Axion Searches at Optical Frequency

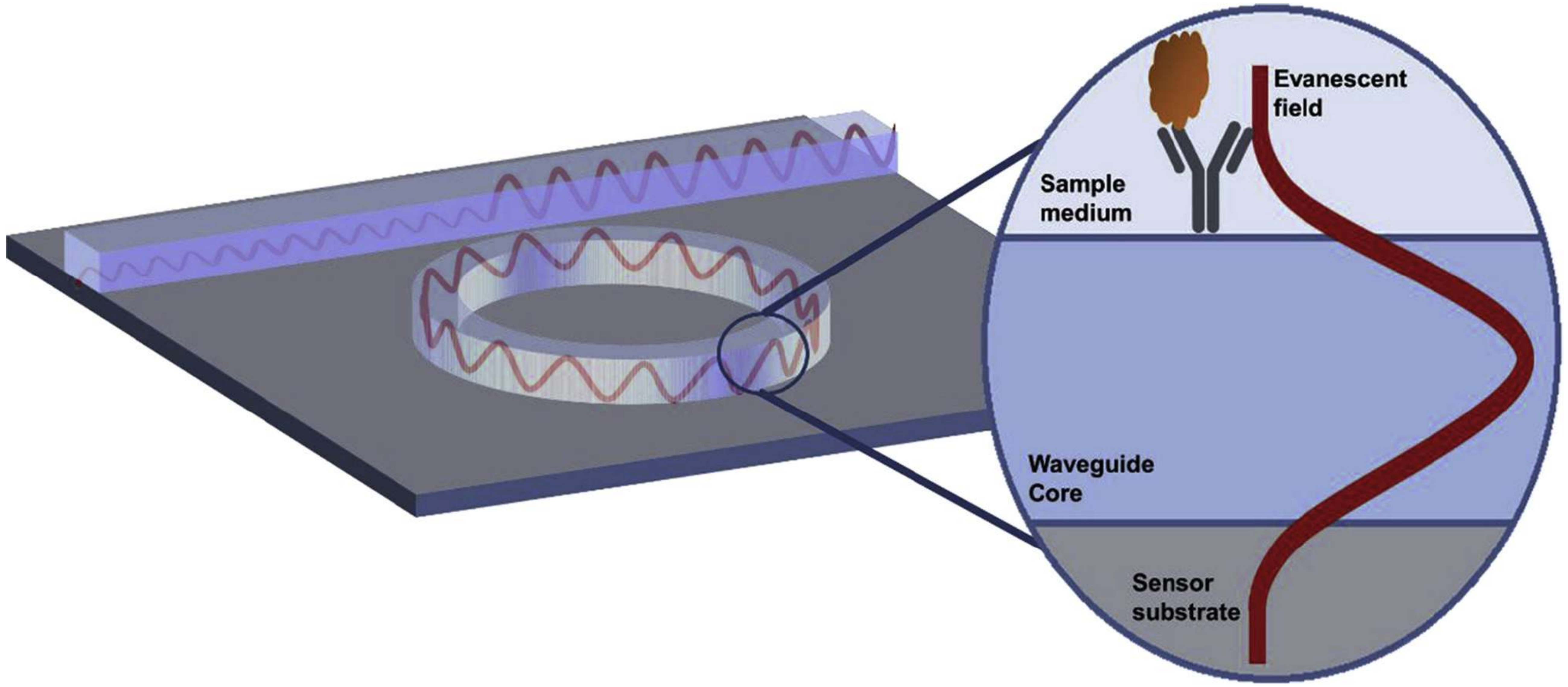


Axion Searches at Optical Frequency

Optical Cavity: eV



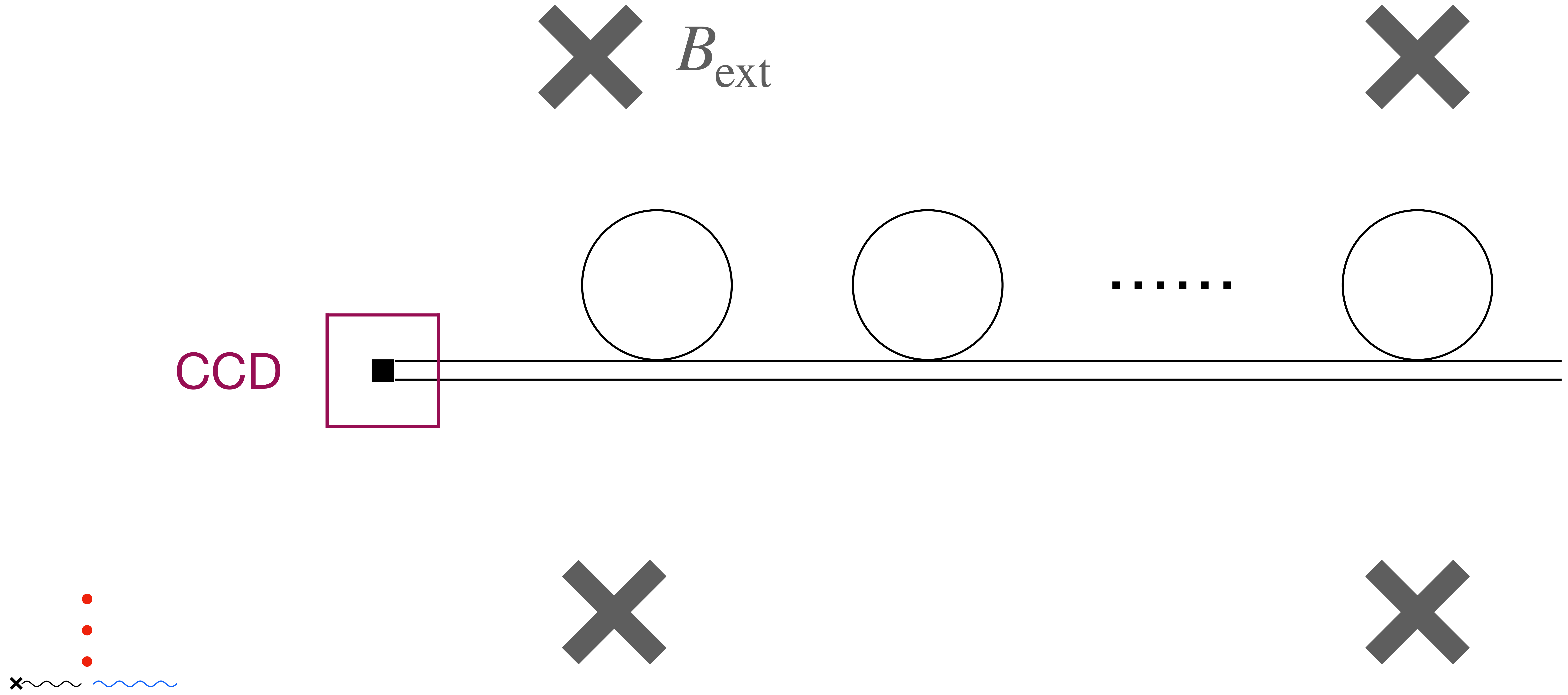
microring resonator Luo+ (2019)



$$Q \sim 10^7$$

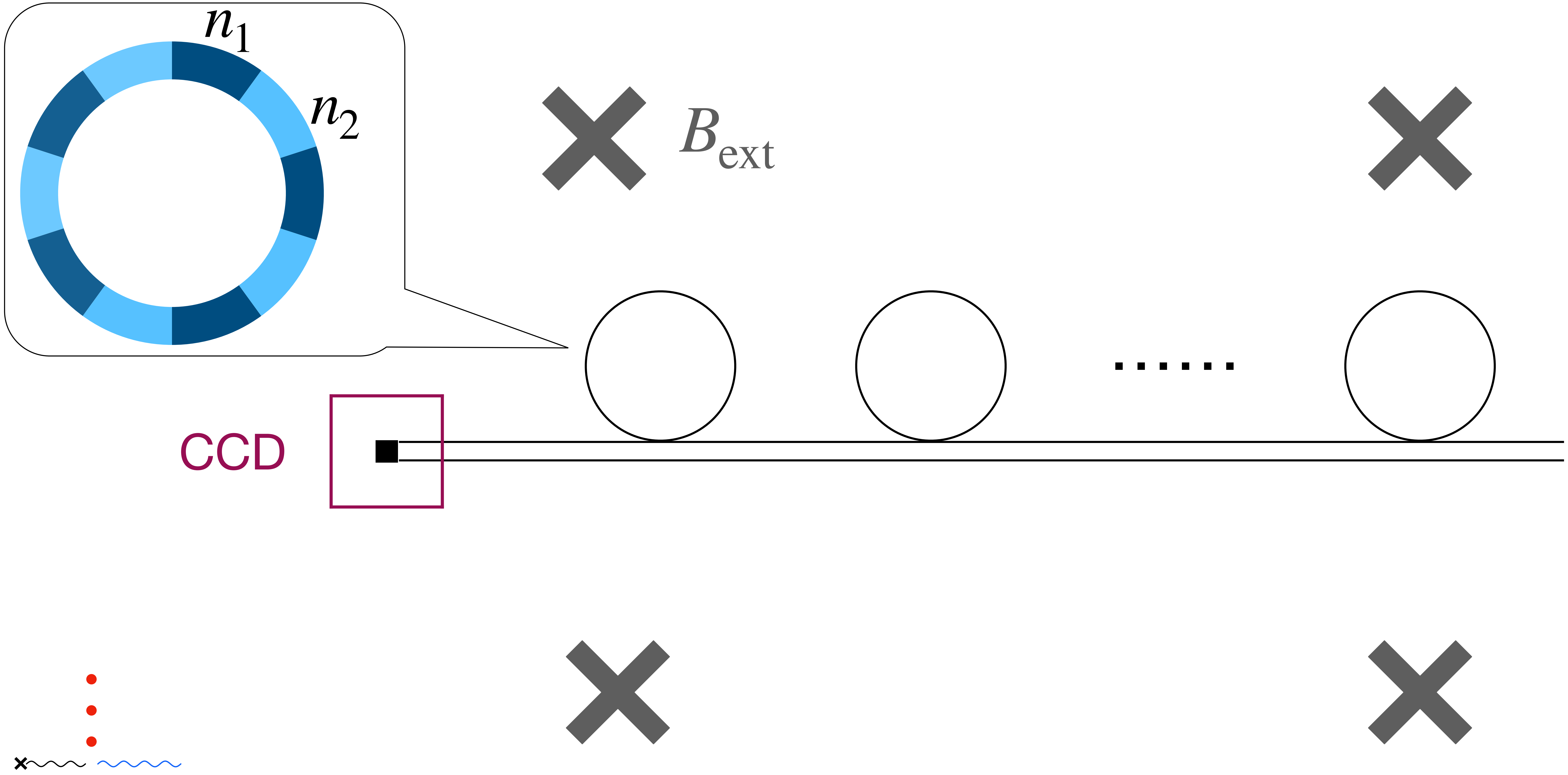
can be mass produced

Axion DM Searches on a Chip



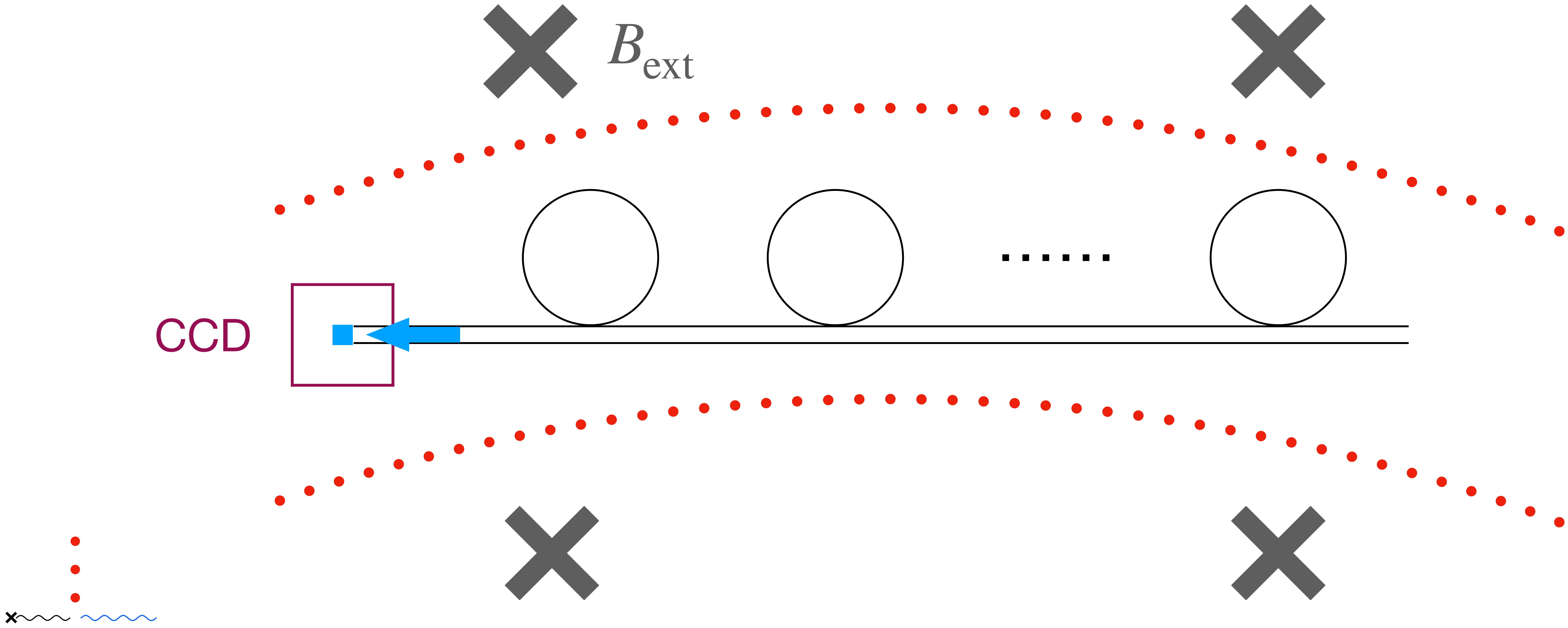
Signal photons can be resonantly produced if frequency and momentum match.

Axion DM Searches on a Chip



Signal photons can be resonantly produced if frequency and momentum match.

Axion DM Searches on a Chip

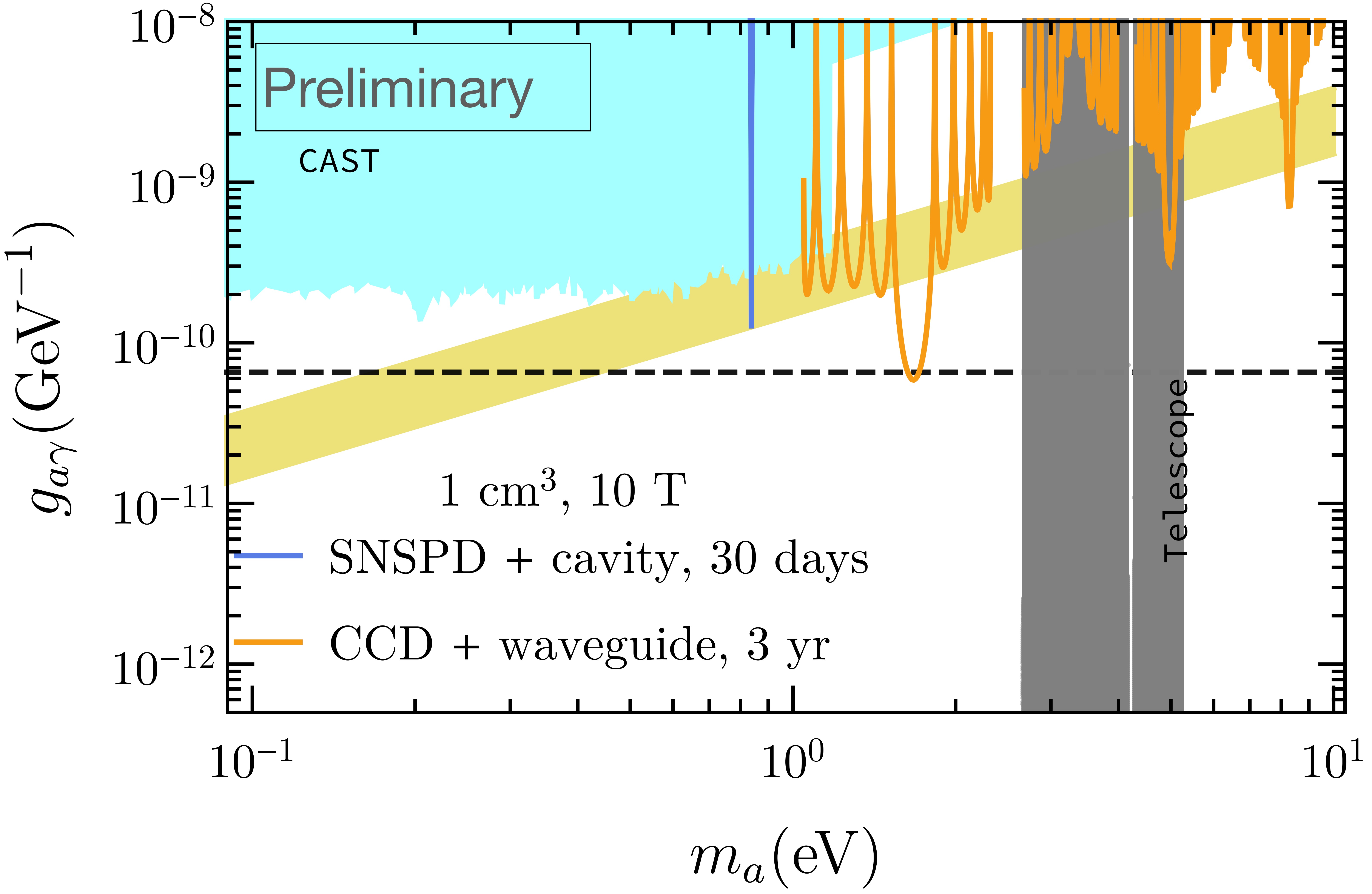


Signal photons can be resonantly produced if frequency and momentum match.

Axion DM Searches on a Chip

A million to a billion rings integrated (printed) on to chips

Background: dark count



Axion Nucleon Coupling

Axions nucleon coupling

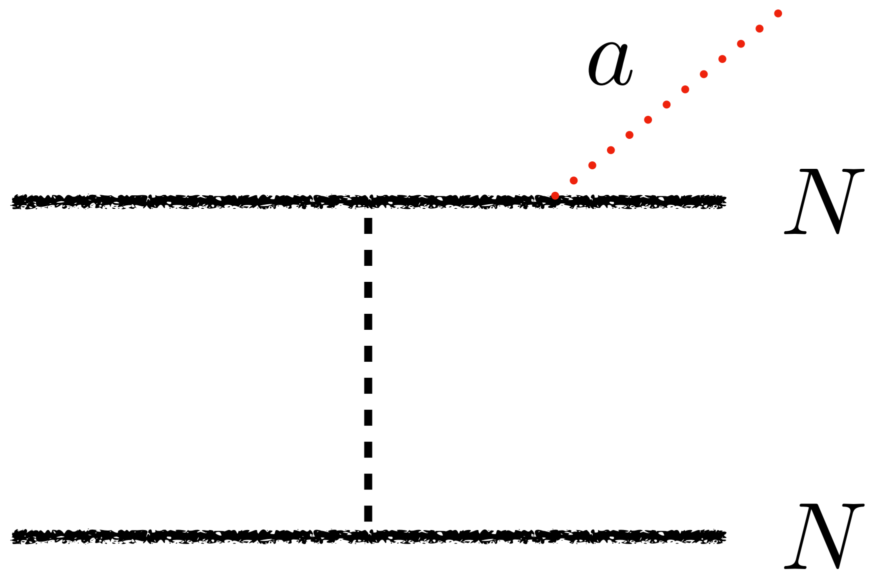
$$\mathcal{L}_{\text{int}} \supset g_{aN} \partial_\mu a \bar{N} \gamma^\mu \gamma^5 N$$

$$g_{aN} = \frac{1}{2f_a} c_N$$

- g_{aN} constrained by astrophysical processes, such as star cooling.

Beznogov et. al (2018)

$$g_{ann} < 2.8 \times 10^{-10} \text{GeV}^{-1} \ (90\%\text{C.L.}) \qquad m_a \ll 10\text{keV}$$



Axions couple to nuclear spins

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

$$g_{aN} = \frac{1}{2f_a}c_N$$

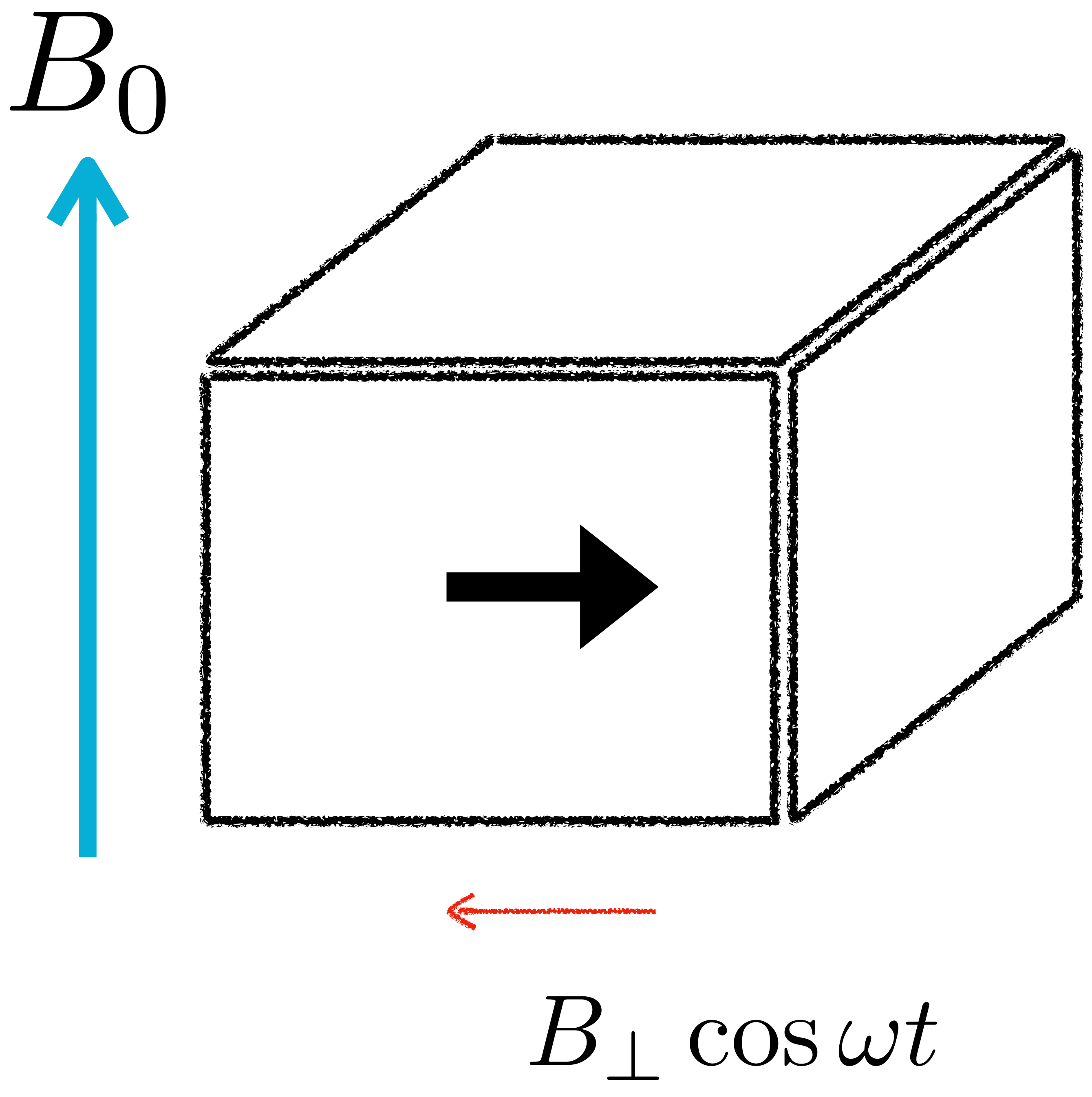
- g_{aN} allows us to search for axion DM using Nuclear Magnetic Resonance (NMR).

$$H_{\text{eff}} \supset \vec{S}\cdot(\underbrace{g_{aN}\vec{\nabla}a}_{\vec{B}_{a_{\text{DM}}} \sim 10^{-16}\text{T}\left(\frac{g_{aN}}{10^{-10}\text{GeV}^{-1}}\right)})$$

$$a_{\text{DM}}(t) \sim a_0\cos(m_a t)$$

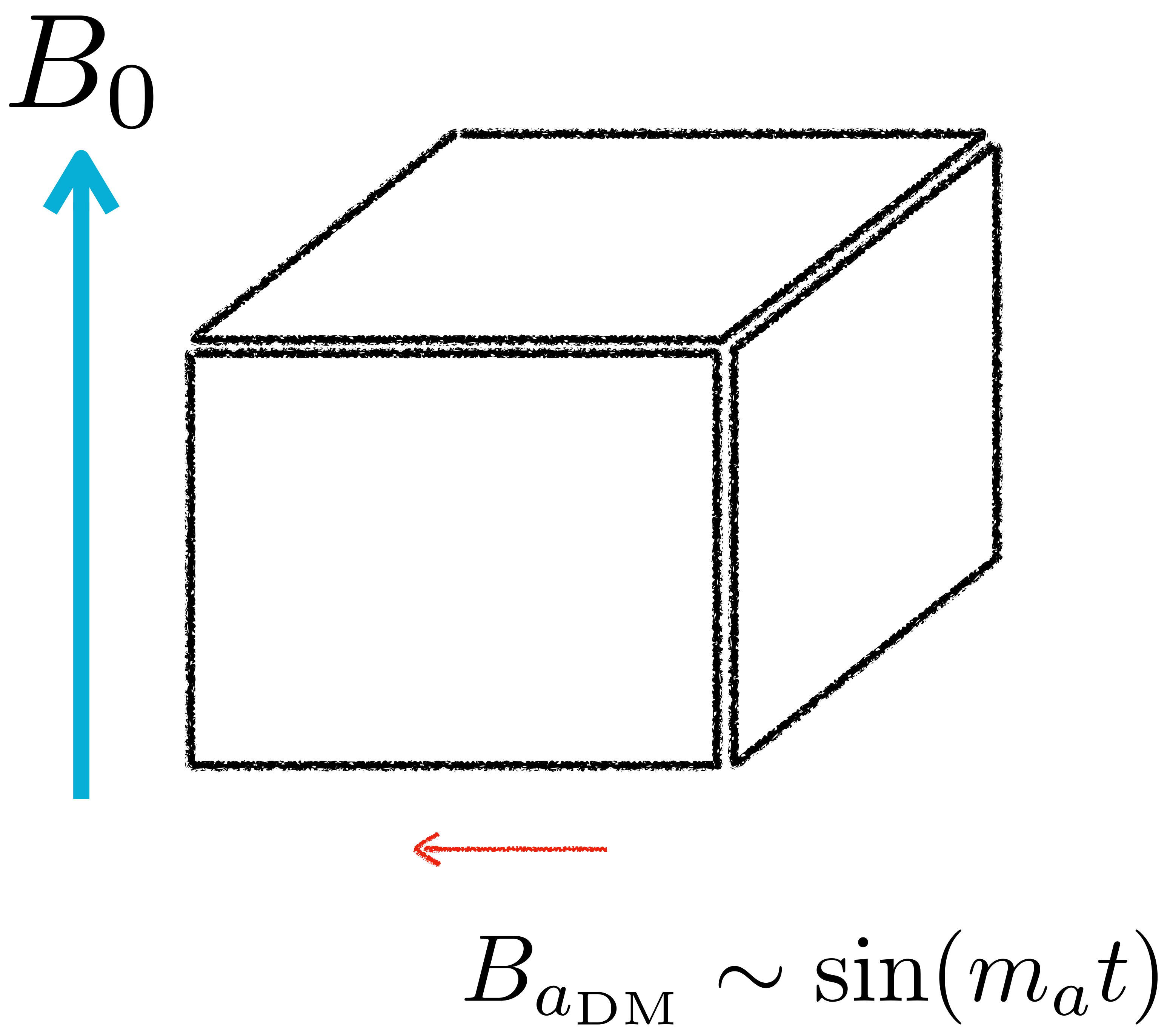
Nuclear magnetic resonance

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



NMR: axion DM search

- Tune B_0 to match axion mass with Larmor frequency ω_L



NMR: axion DM search

- Tune B_0 to match axion mass with Larmor frequency ω_L

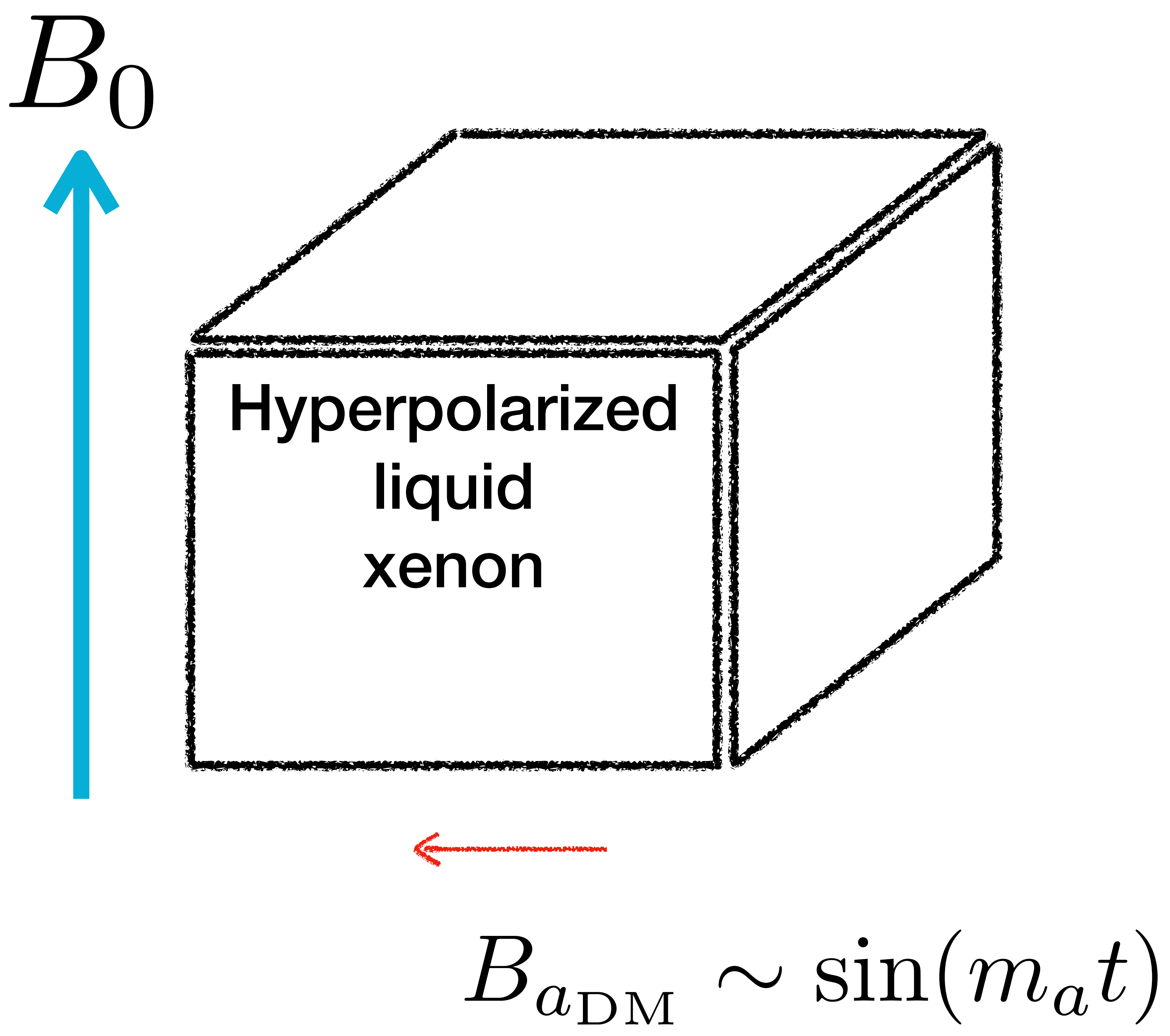
- CASPEr-gradient

$$g_{aN} < 5 \times 10^{-5}\mathrm{GeV}^{-1} \;\; (95\%\mathrm{C.L.})$$

$$m_a \in (1e{-}22, 1.3e{-}17) \cup (1.8e{-}16, 7.8e{-}14)\mathrm{eV}$$

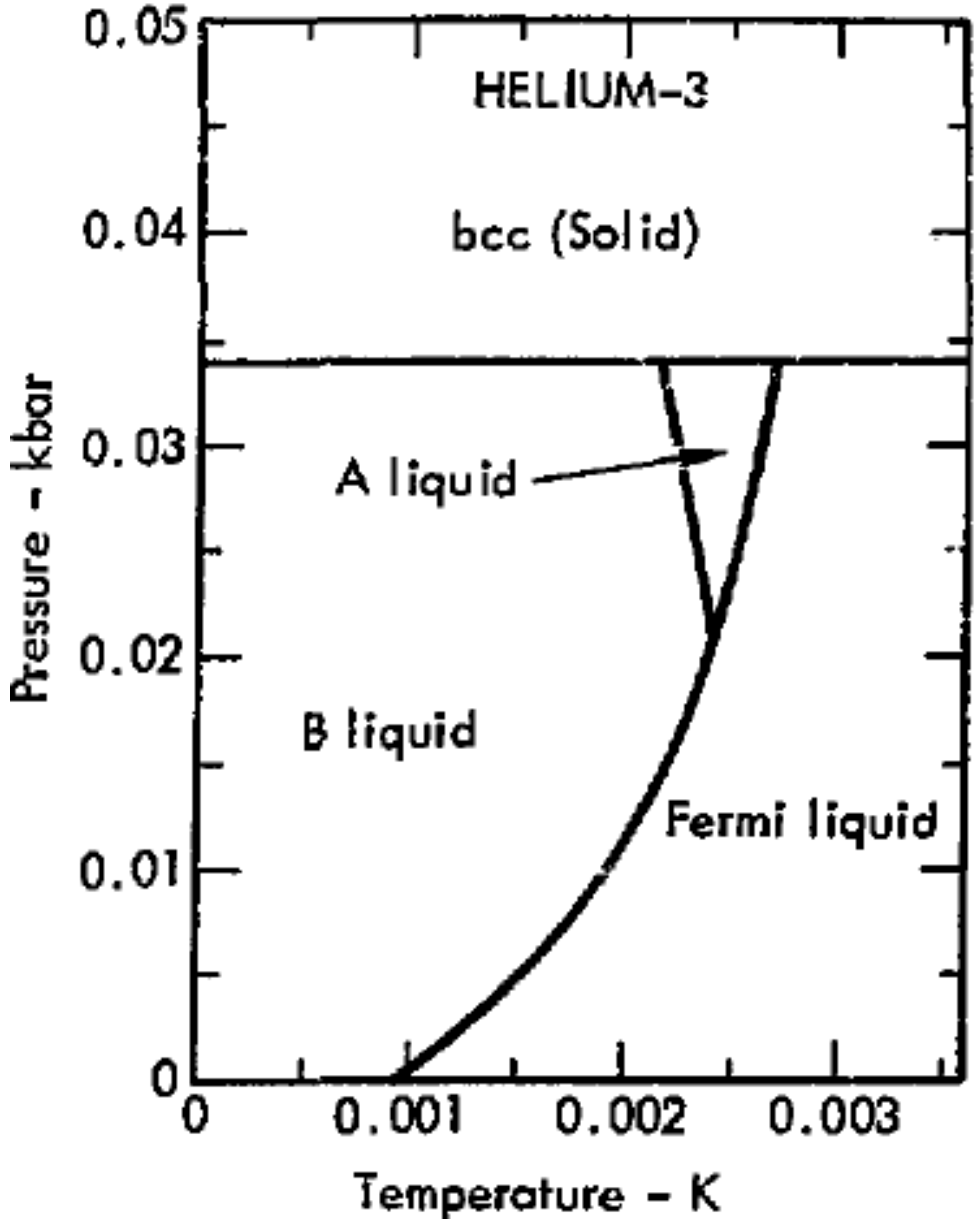
- Many challenges to improve sensitivity, but direct evidence of g_{aN} is crucial for testing QCD axion.

CASPEr-gradient



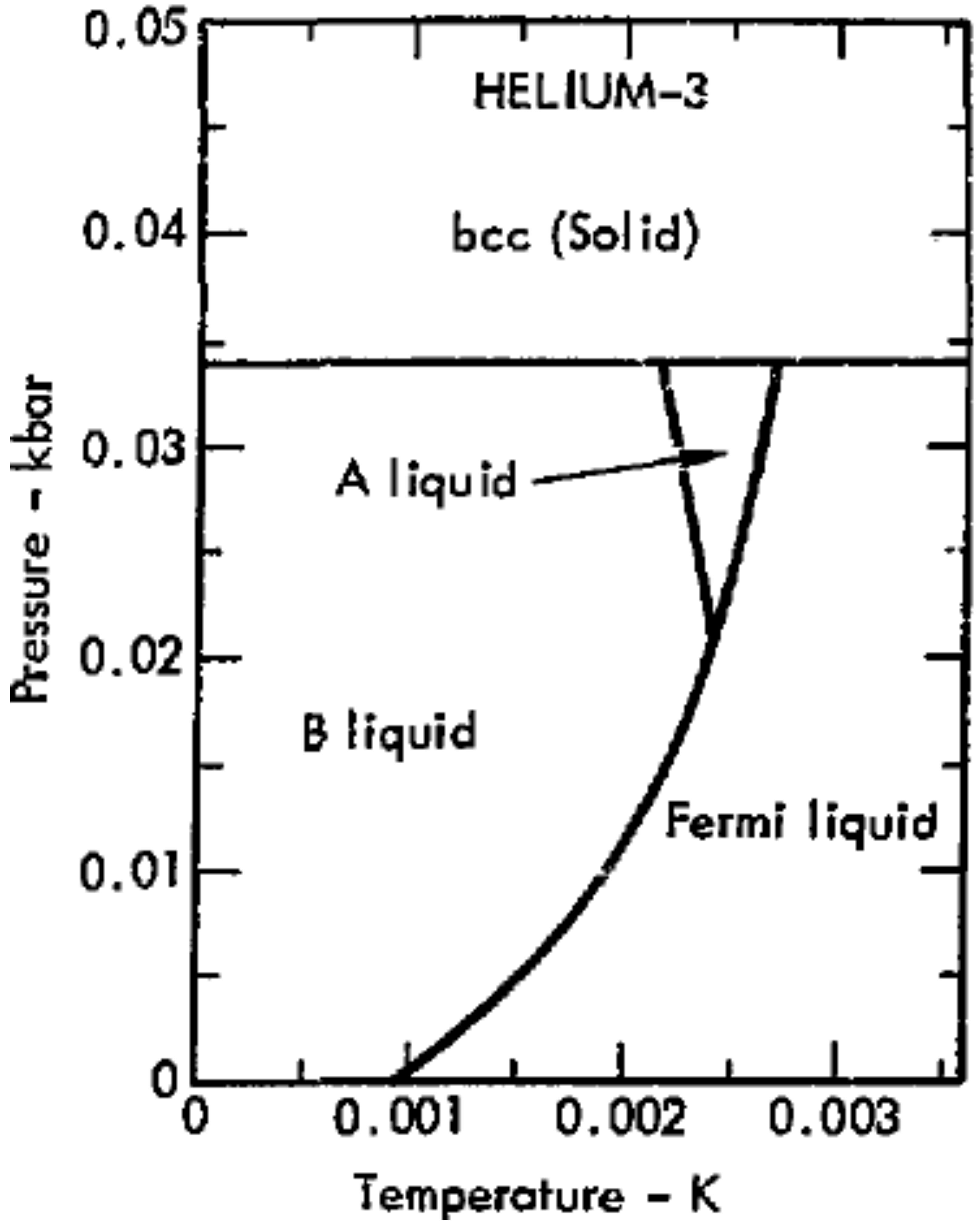
Superfluid Helium 3

Properties of $^3\mathrm{He}$



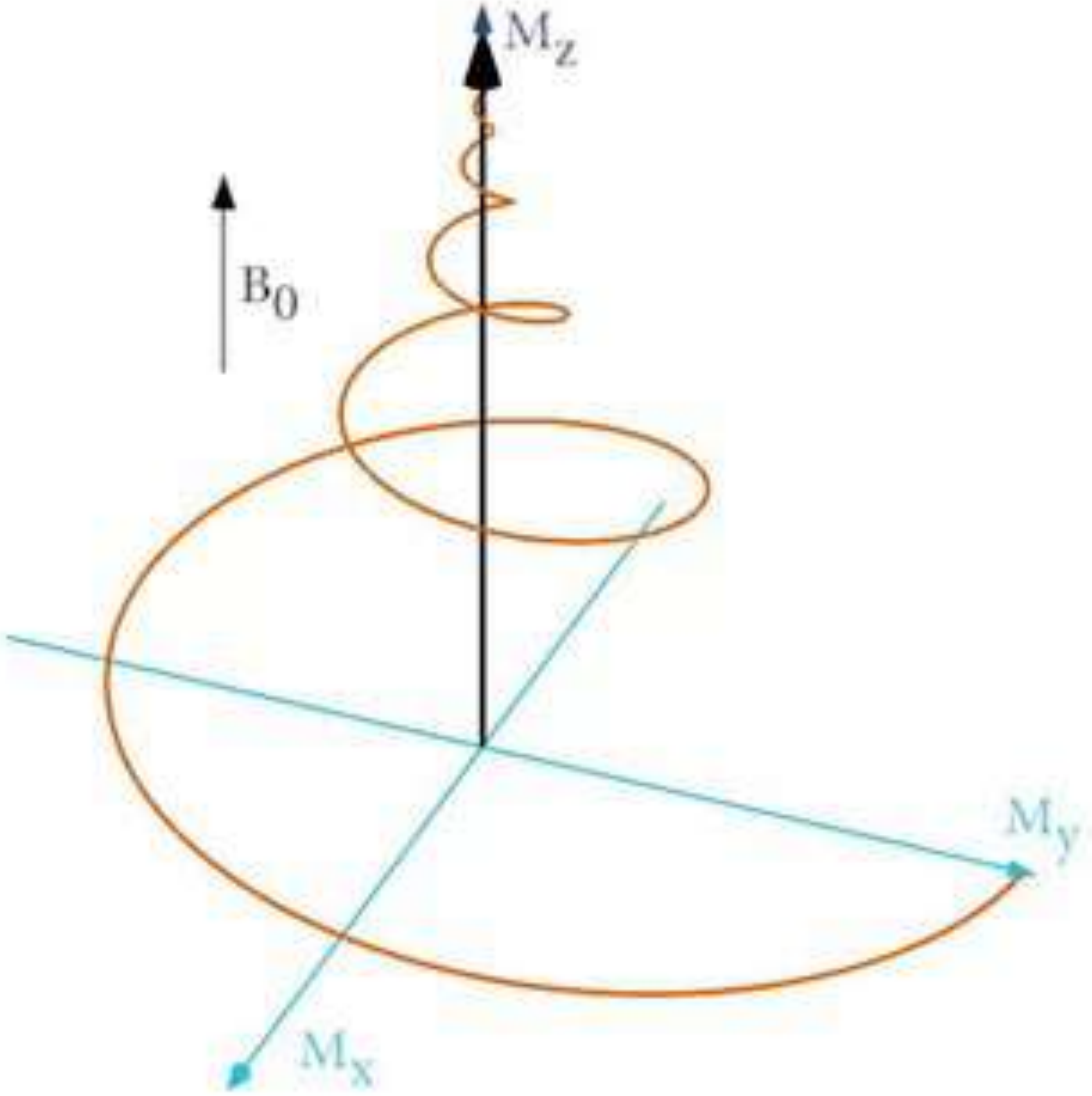
- Spin 1/2
- Very low temperature, superfluid phase (~ Bose Einstein Condensate)

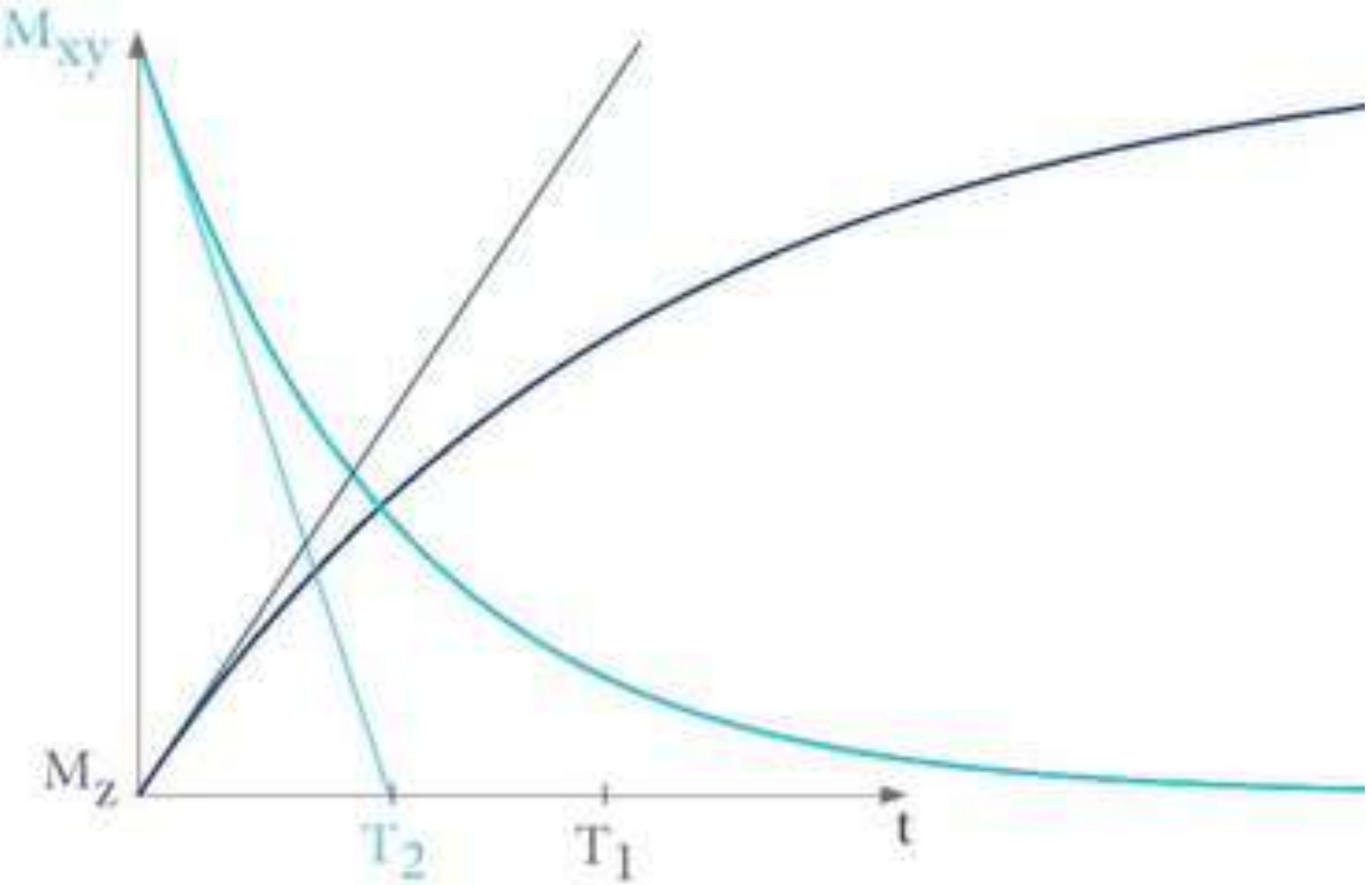
Properties of $^3\mathrm{He}$



- Spin 1/2
- Very low temperature, superfluid phase (~ Bose Einstein Condensate)
- Cooper pairs: $S = 1$ $L = 1$ magnons
- Our setup is based on the B phase, almost a perfect magnon BEC

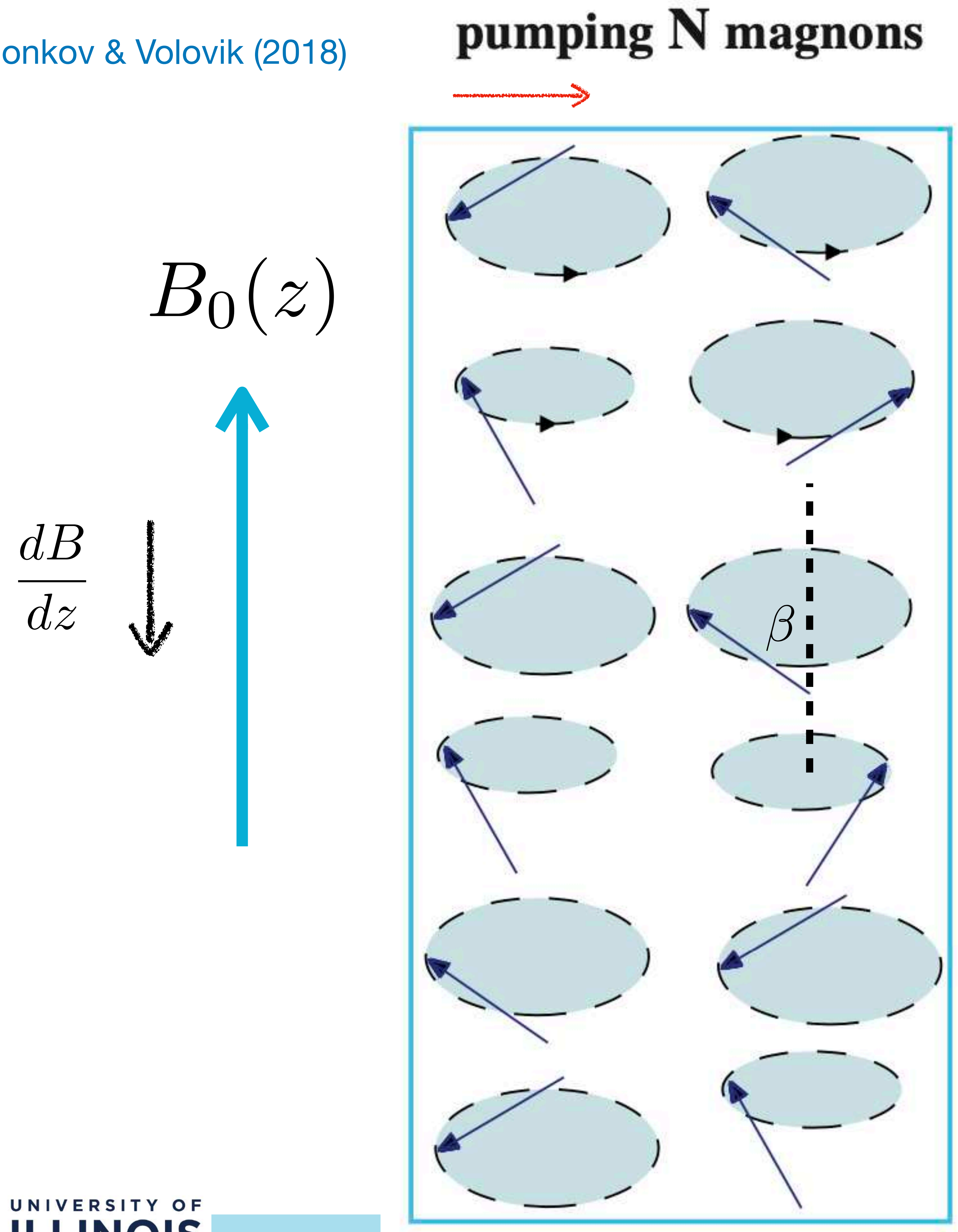
Pulsed NMR





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

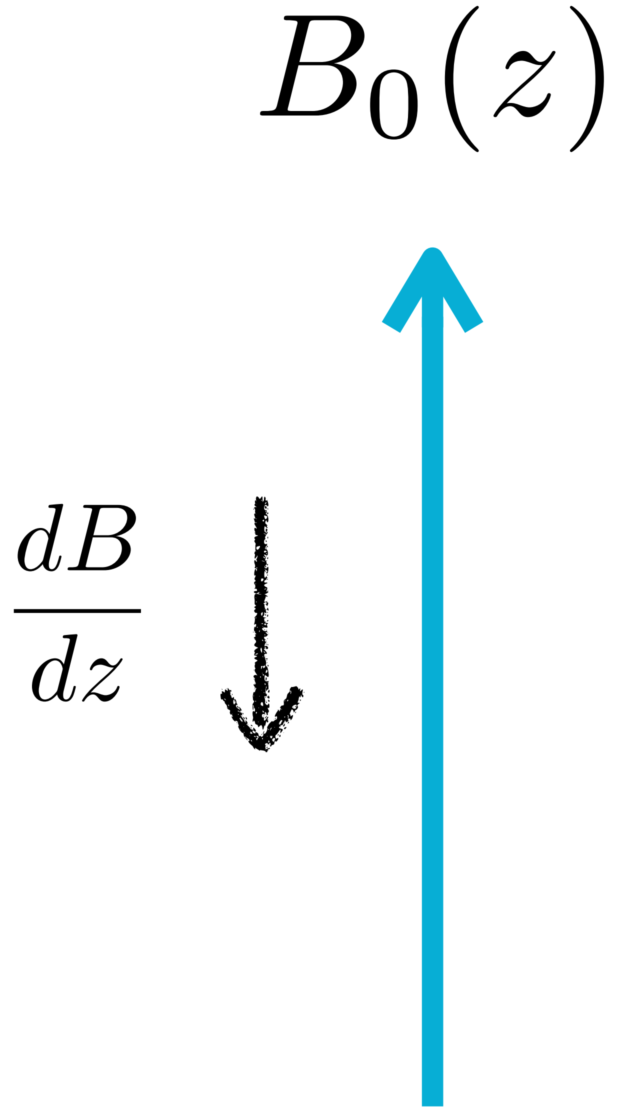
Bonkov & Volovik (2018)



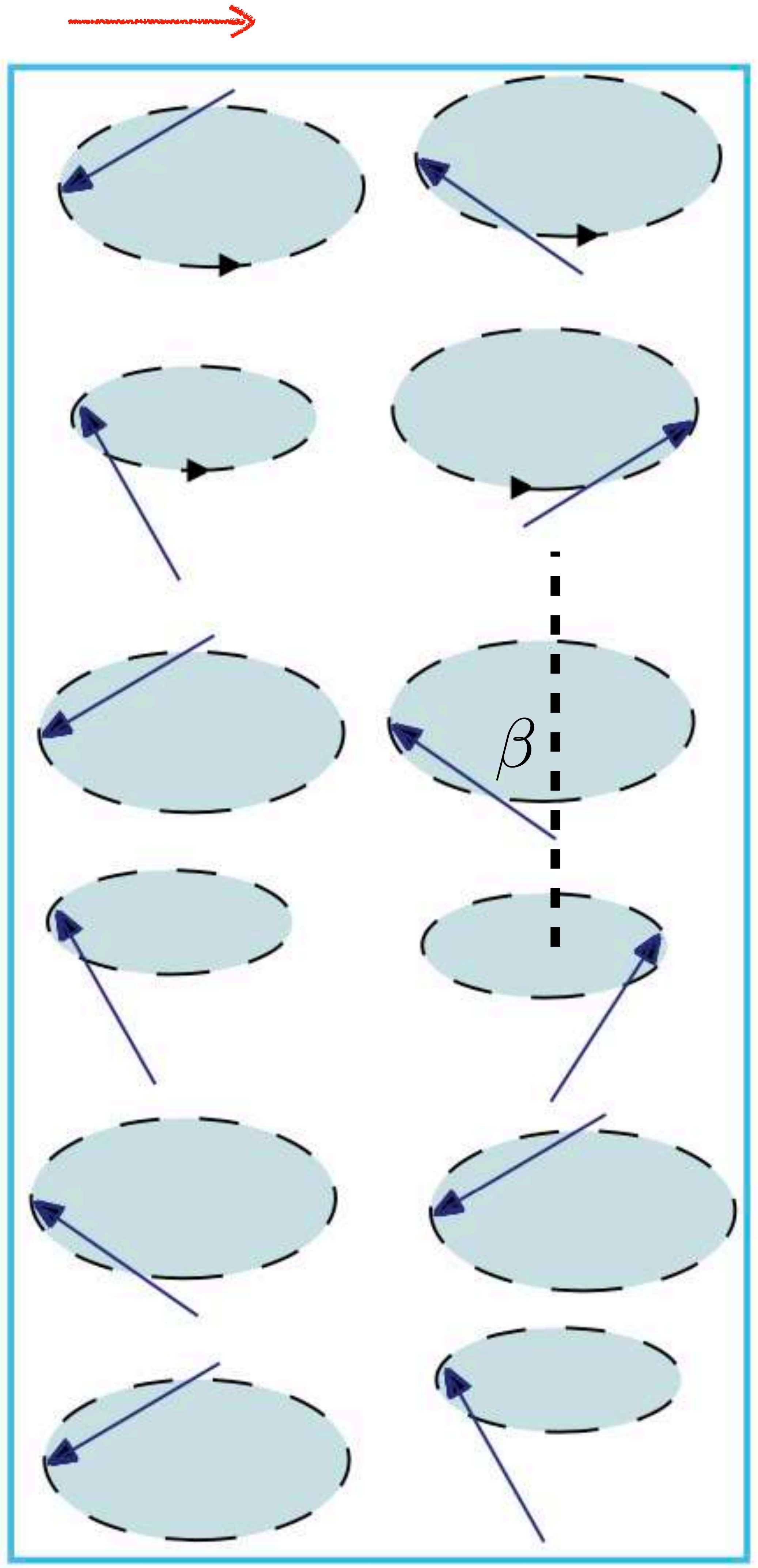
$$N = Vn,\ \ n \propto 1-\cos\beta$$

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

Bonkov & Volovik (2018)



pumping N magnons



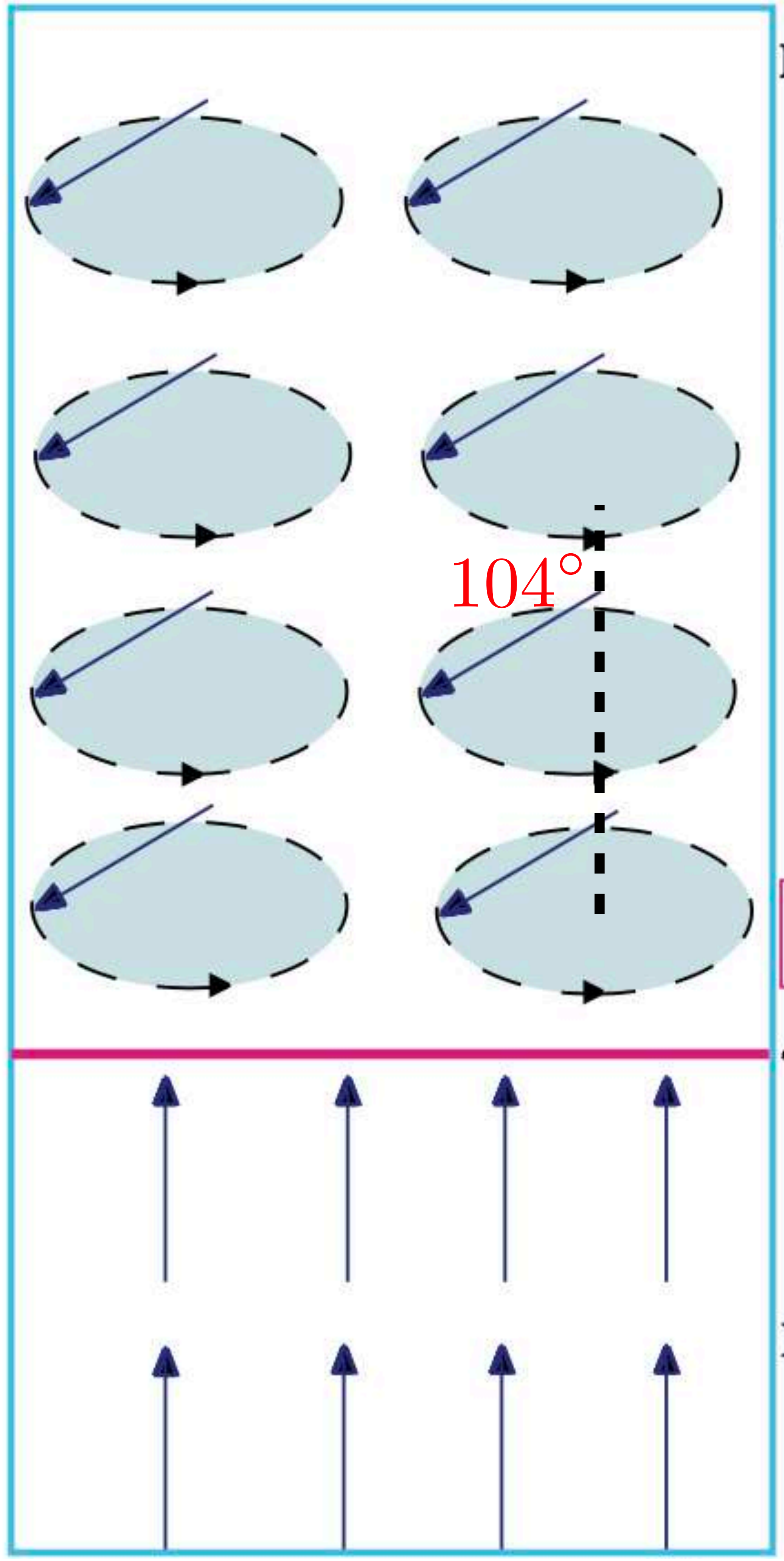
$$N = Vn,\ \ n \propto 1-\cos\beta$$

Fomin (1984)

$$V_{\mathrm{HPD}} = \frac{N}{n_c}, n_c \propto 1-\cos 104^\circ$$

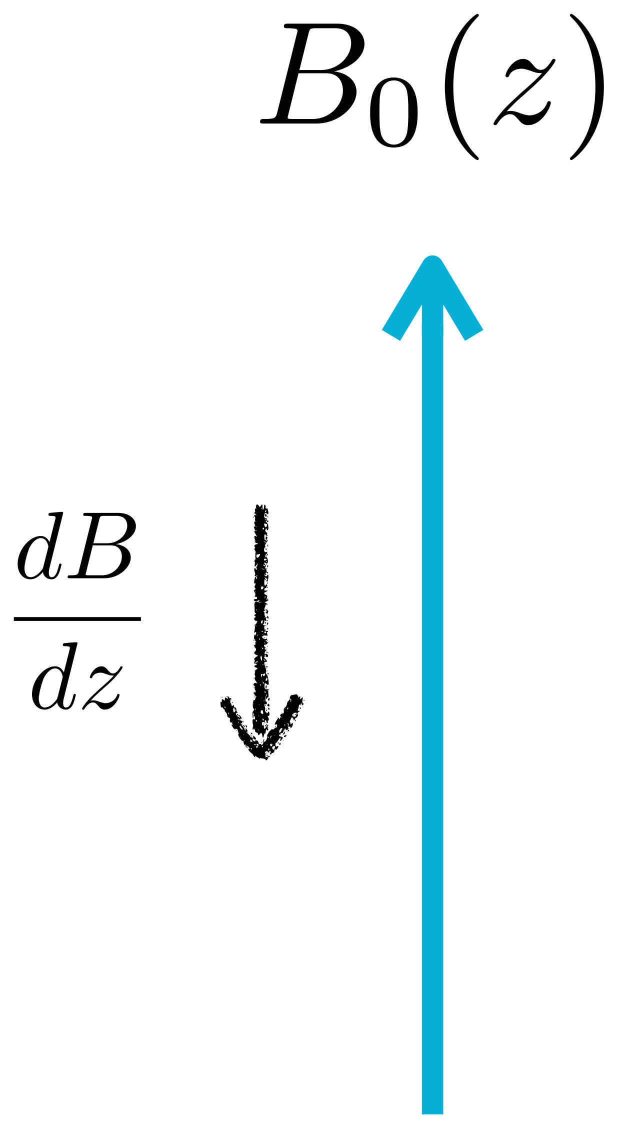
Leggett angle

magnon BEC formed with the same N

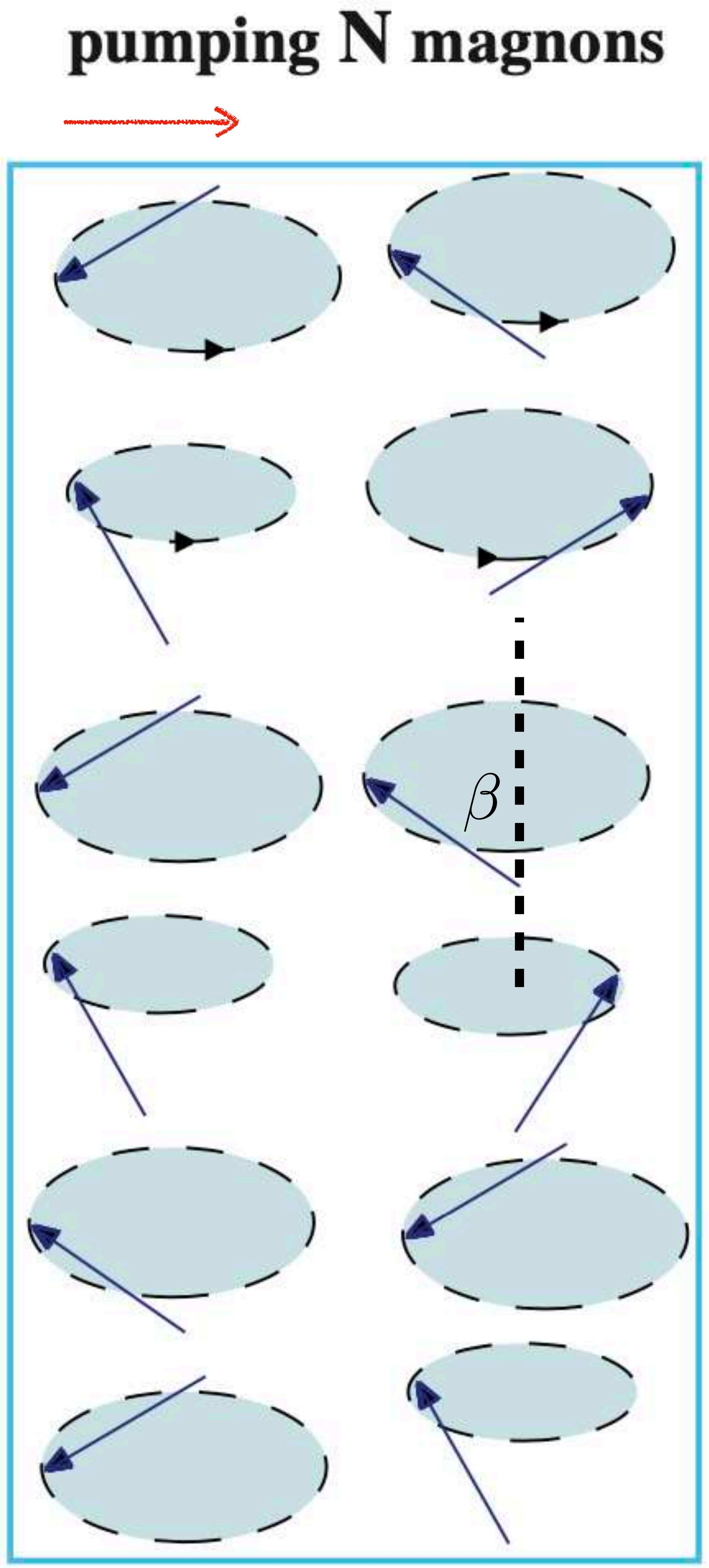


Pulsed NMR with $^3\mathrm{He}-\mathrm{B}$

Bonkov & Volovik (2018)



pumping N magnons



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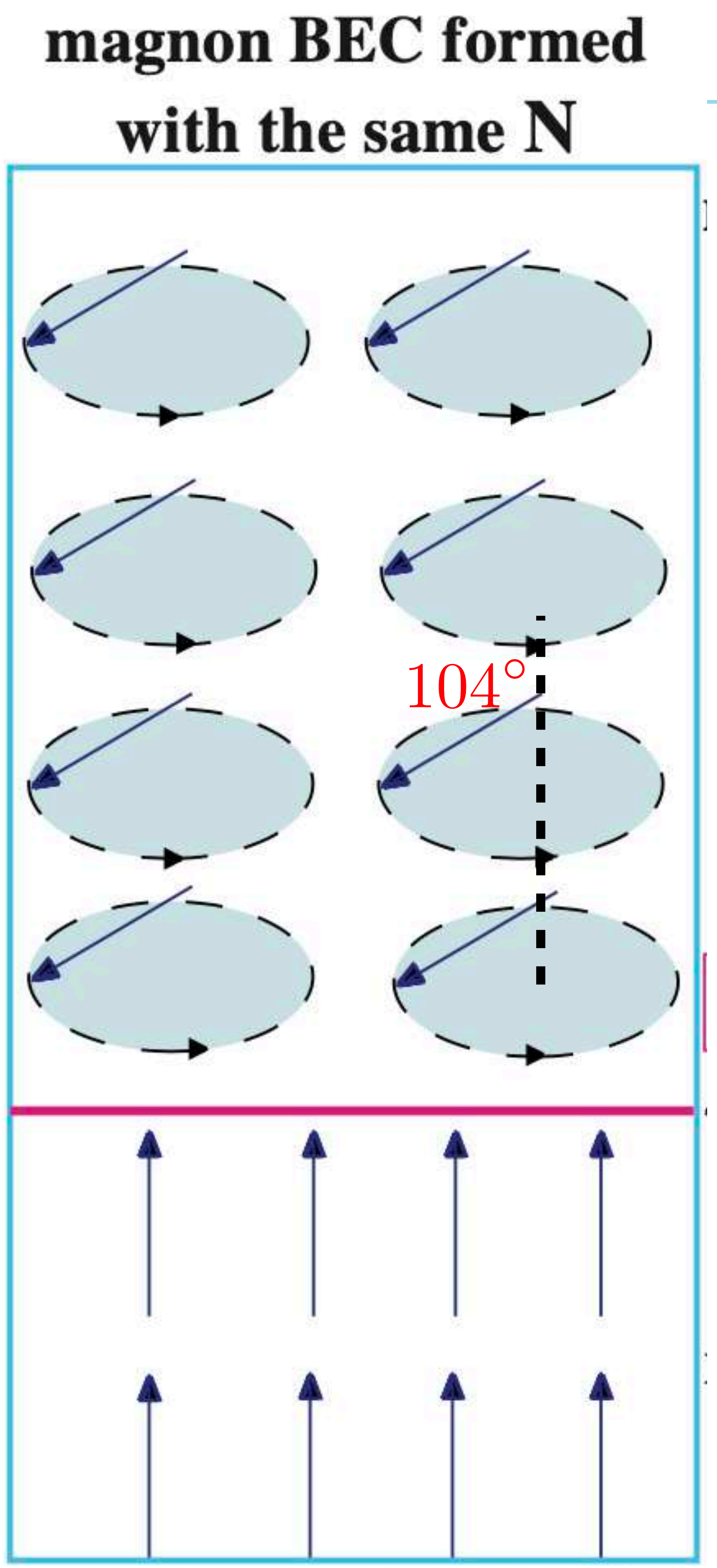
Leggett angle

$$\omega_L = \gamma B(z_{\mathrm{wall}})$$

magnon BEC formed with the same N



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

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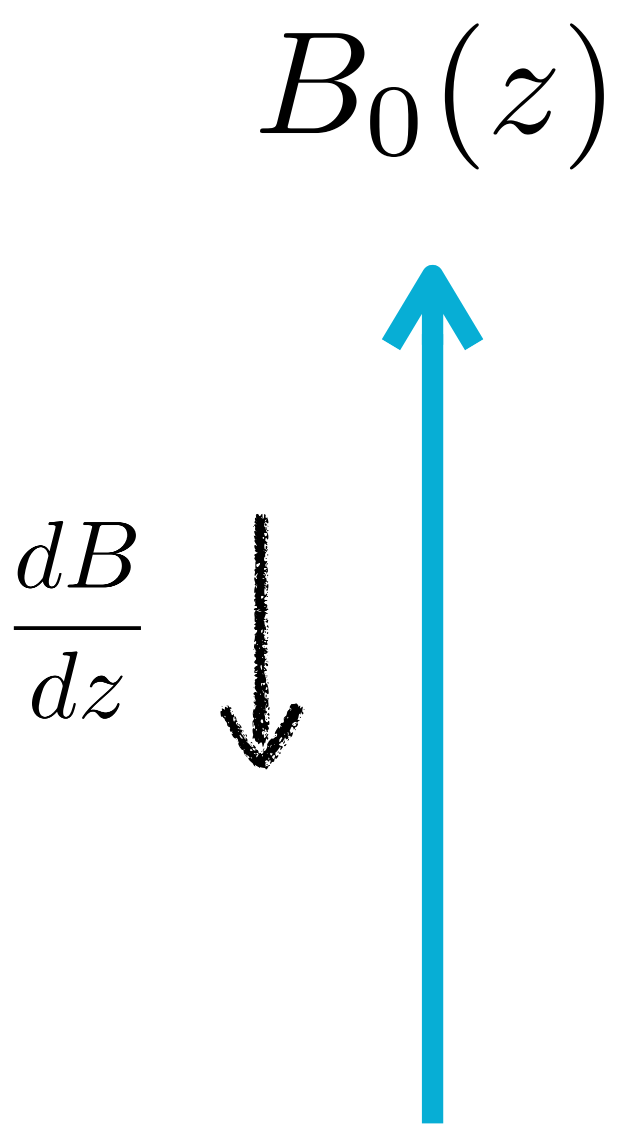


$$N = Vn,\ \ n \propto 1 - \cos\beta$$

Fomin (1984)

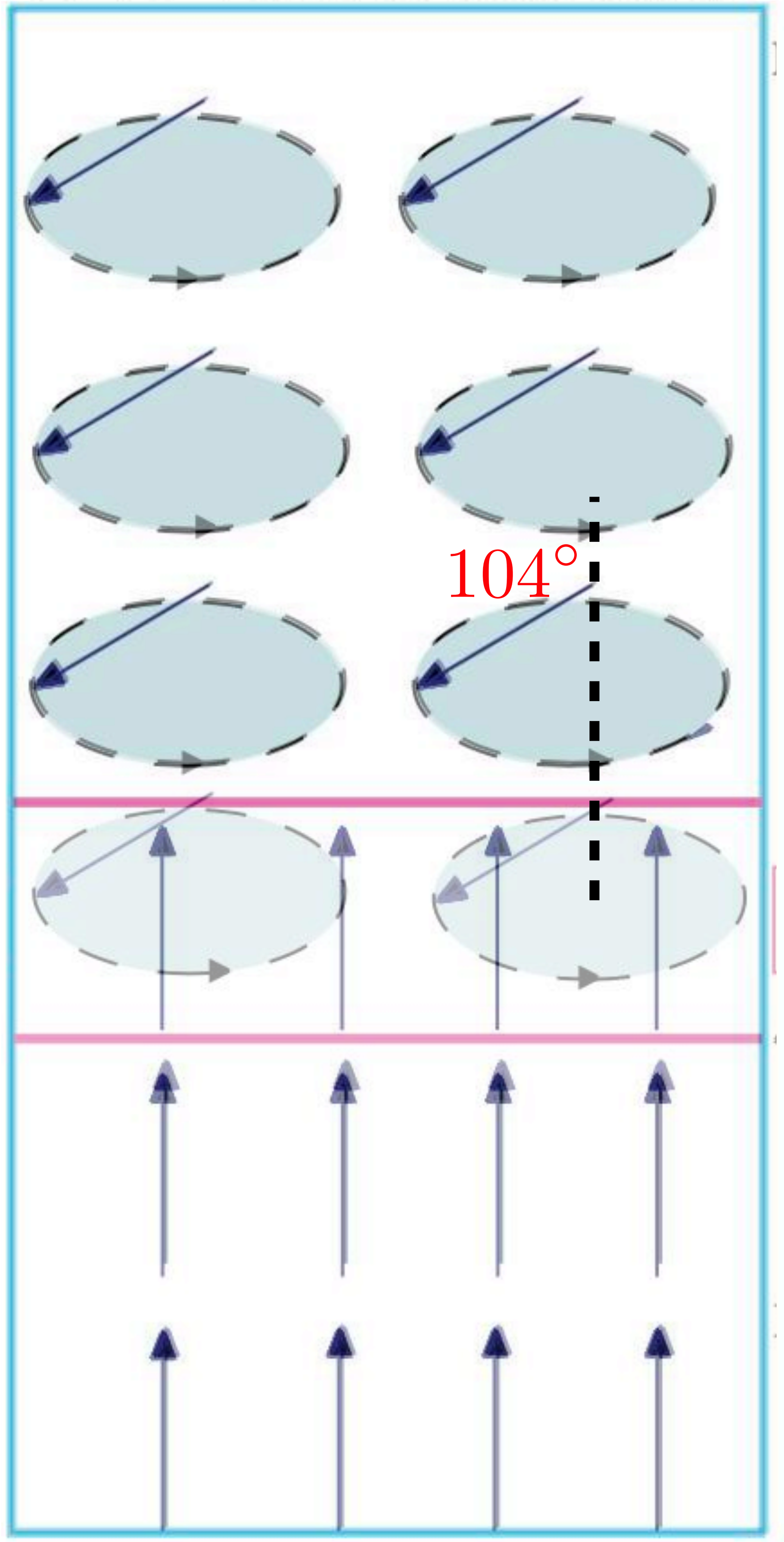
$$V_{\mathrm{HPD}} = \frac{N}{n_c}, n_c \propto 1 - \cos 104^\circ$$

Leggett angle

$$\omega_L = \gamma B(z_{\mathrm{wall}})$$

Decay of HPD $\rightarrow v_{\mathrm{wall}} \rightarrow \omega_L(t)$

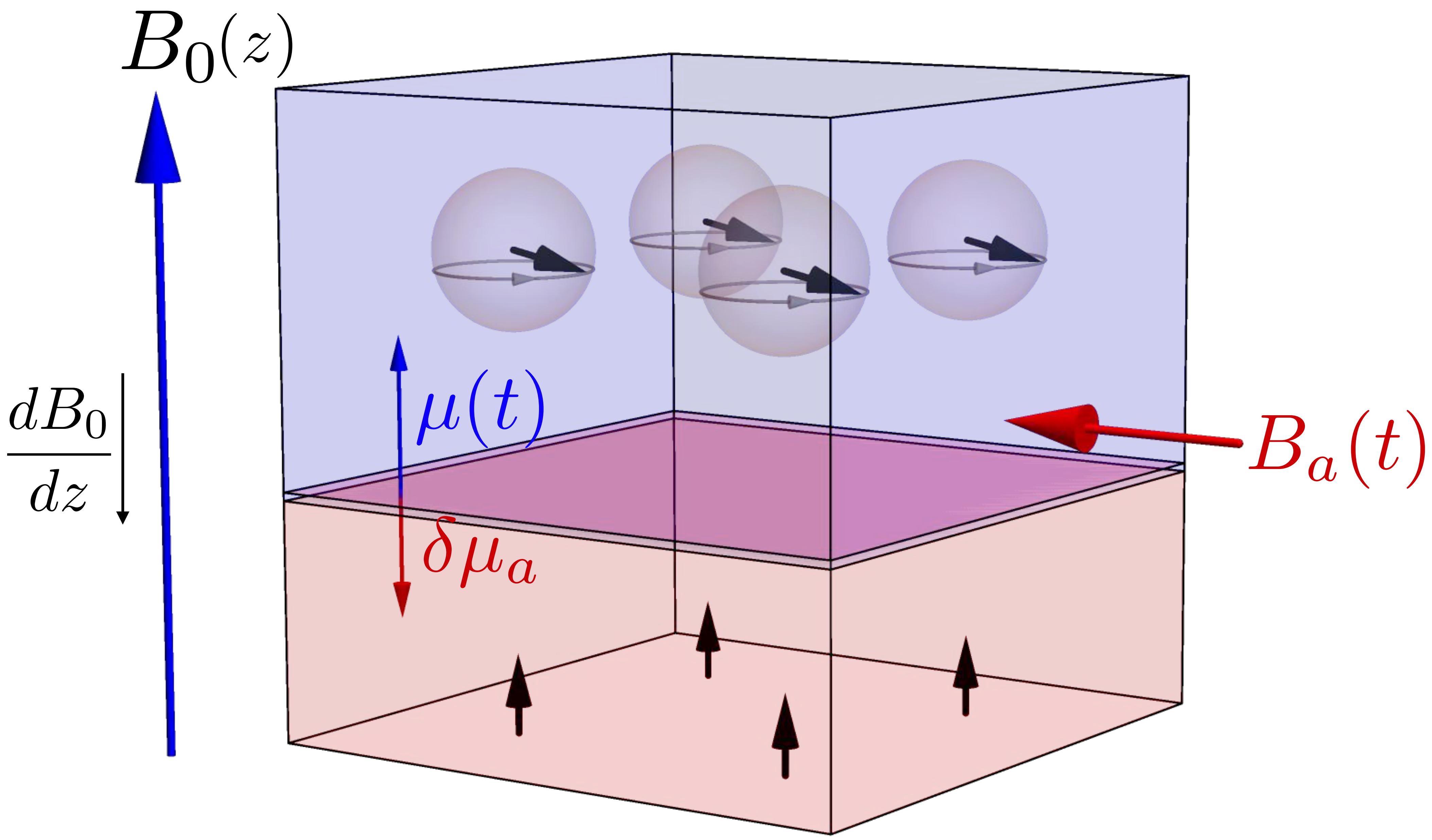
coherent decay of BEC:
N decreases
V_{HPD} **decreases**



Adding axions

Axion DM detection with HPD

$$\vec{B}_{a_{\mathrm{DM}}} \sim \gamma^{-1} g_{aN} \vec{v} \sqrt{\rho_{\mathrm{DM}}} \cos(m_a t + \phi_a)$$



Axion DM detection with HPD

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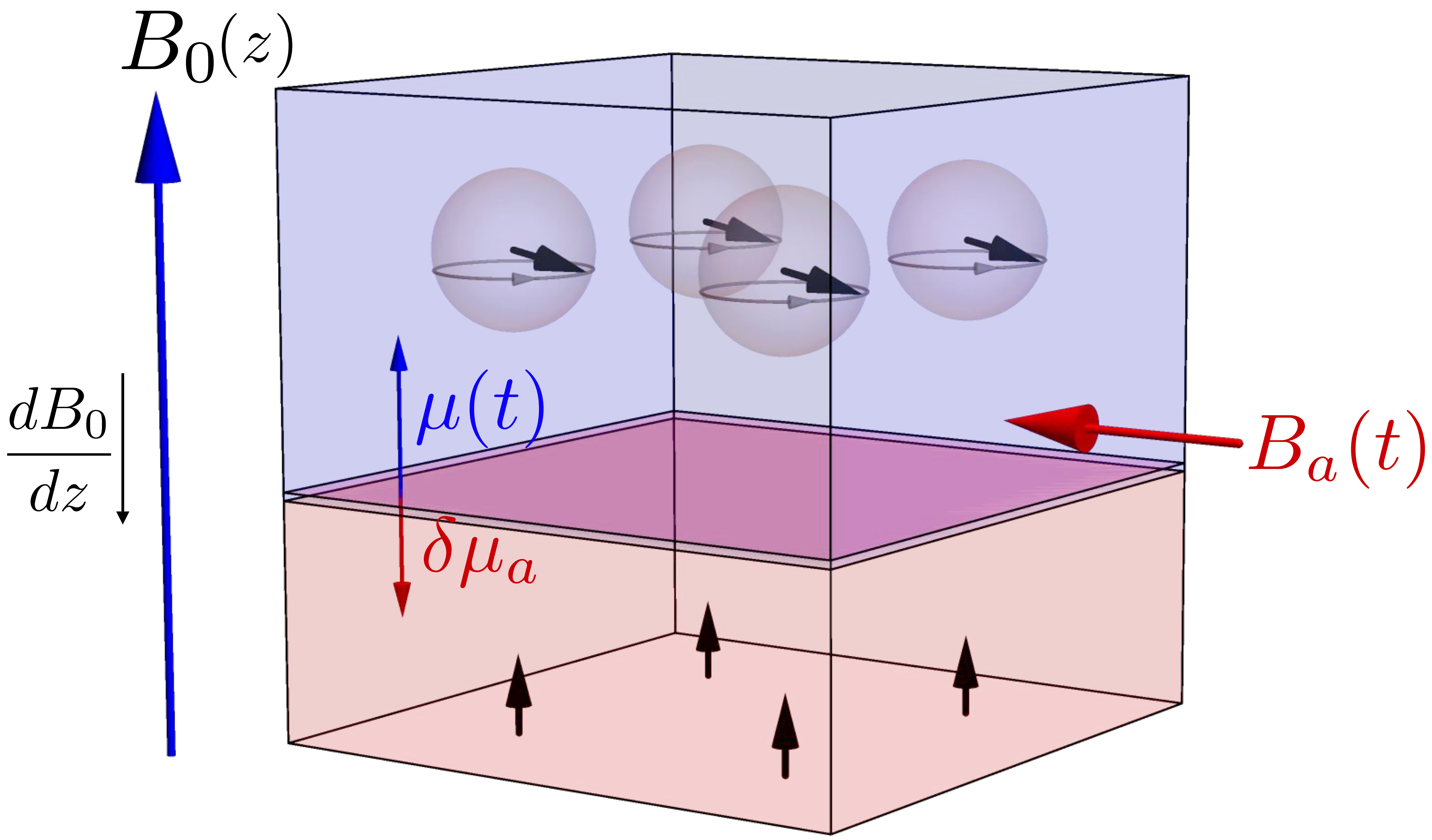
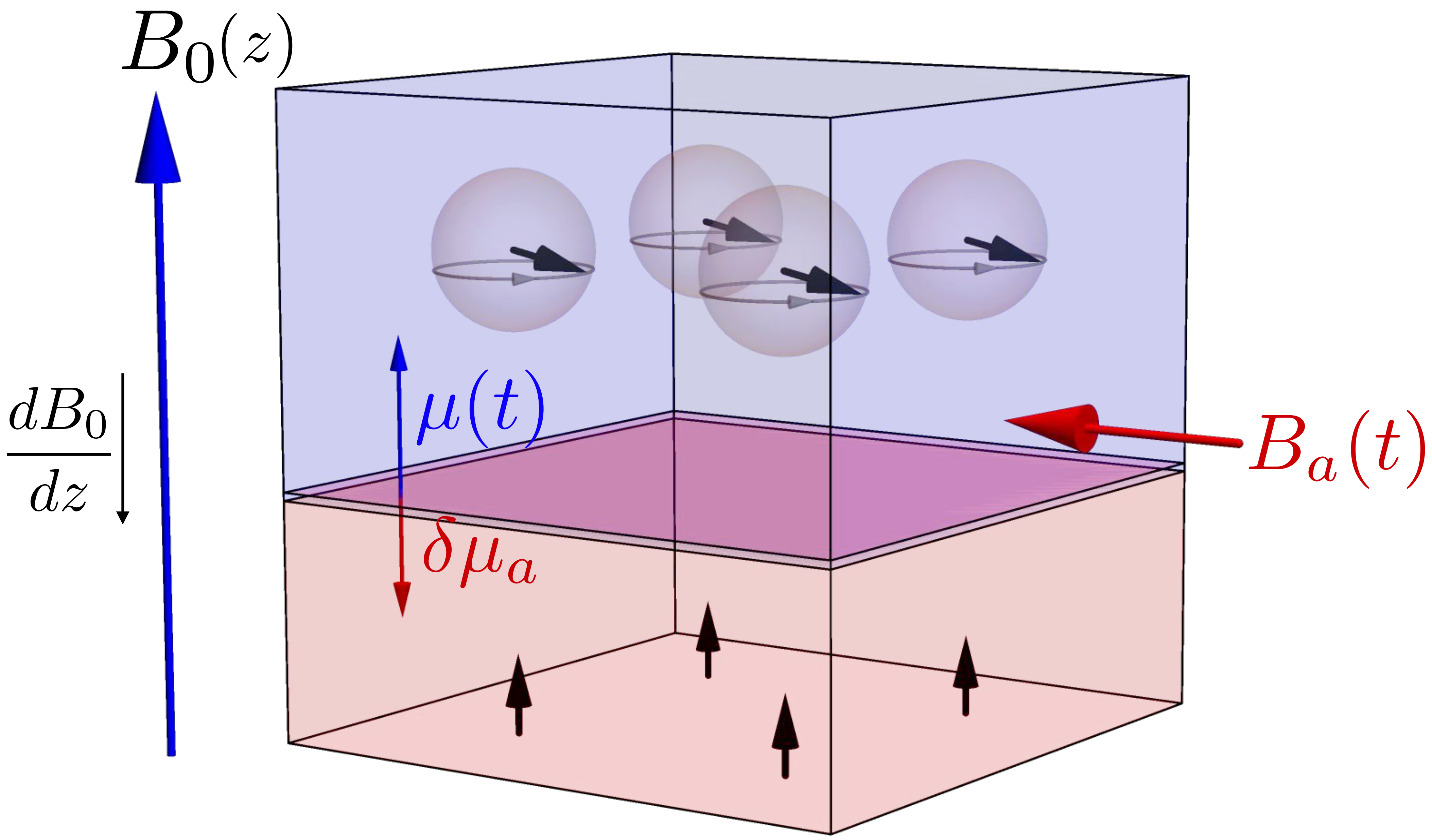


$$\frac{1}{N}\frac{dN}{dt} \sim -\frac{1}{T_1} - \gamma B_a \cos(m_a t + \phi_a) \sin(\omega_L(t) t)$$

- No axion: $N \sim e^{-t/T_1}$

Axion DM detection with HPD

$$\vec{B}_{a_{\rm DM}} \sim \gamma^{-1} g_{aN} \vec{v} \sqrt{\rho_{\rm DM}} \cos(m_a t + \phi_a)$$



$$\frac{1}{N}\frac{dN}{dt} \sim -\frac{1}{T_1} - \gamma B_a \cos(m_a t + \phi_a) \sin\left(\omega_L(t) t\right)$$

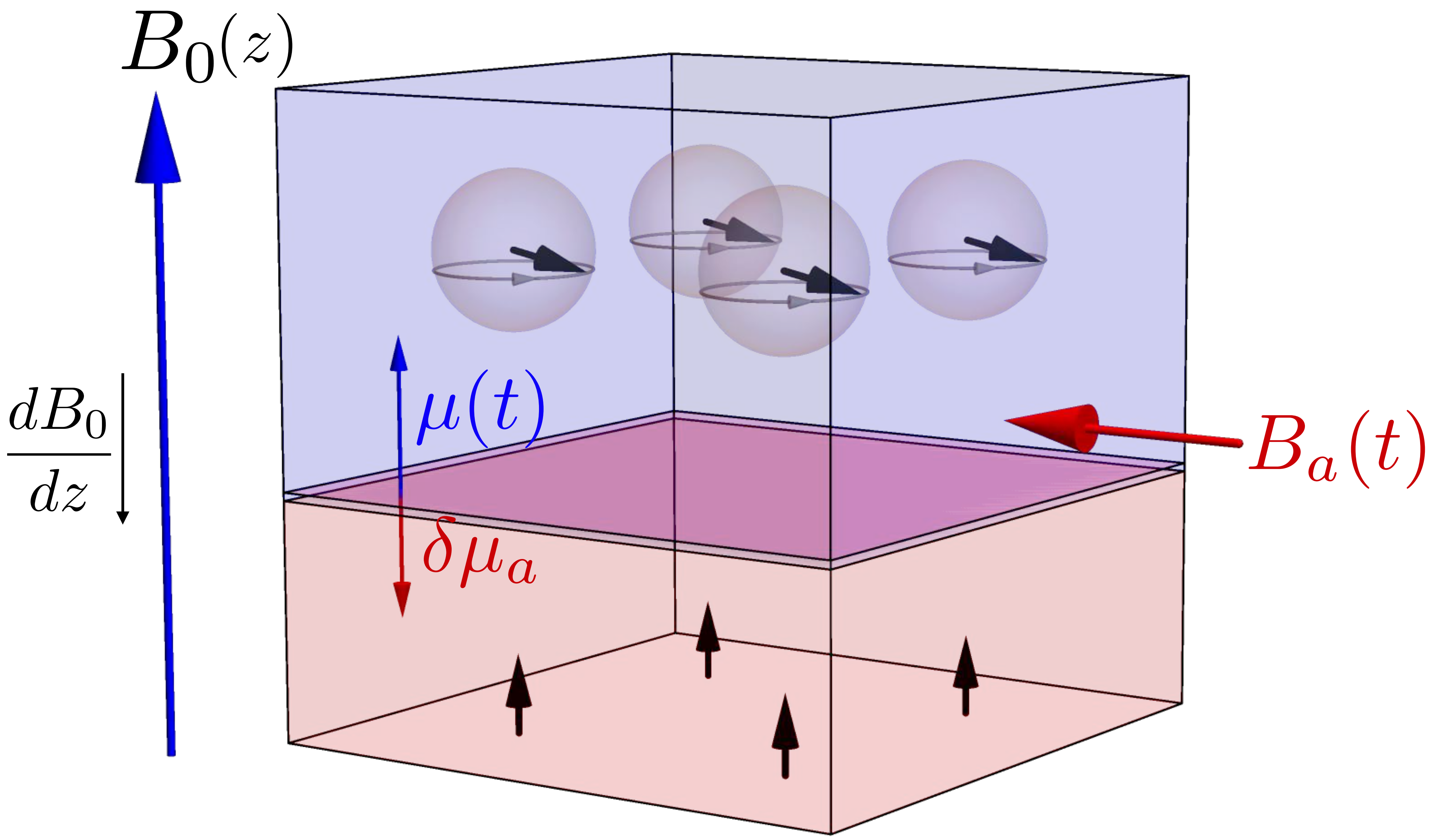
- No axion: $N \sim e^{-t/T_1}$
- When $\omega_L(t) = m_a \pm \Delta m_a$

$$N_a \sim \gamma B_a \tau_a \sin\phi_a$$

τ_a = axion coherence time

Axion DM detection with HPD

$$\vec{B}_{a_{\rm DM}} \sim \gamma^{-1} g_{aN} \vec{v} \sqrt{\rho_{\rm DM}} \cos(m_a t + \phi_a)$$



$$\frac{1}{N}\frac{dN}{dt} \sim -\frac{1}{T_1} - \gamma B_a \cos(m_a t + \phi_a) \sin(\omega_L(t) t)$$

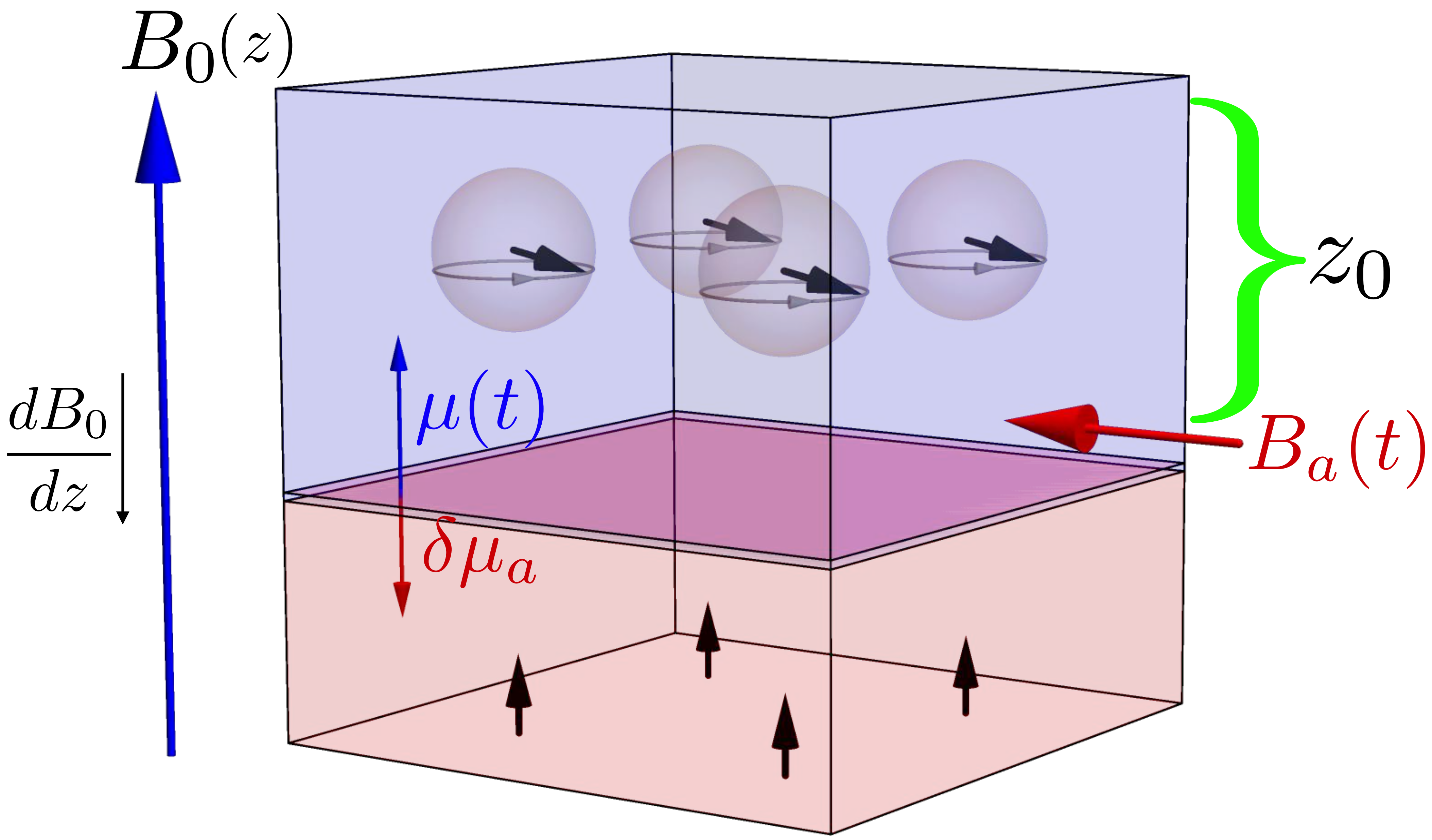
- No axion: $N \sim e^{-t/T_1}$
- When $\omega_L(t) = m_a \pm \Delta m_a$

$$N_a \sim \gamma B_a \tau_a \sin\phi_a$$

Since n_c is fixed by Leggett angle, $N_a \to \Delta V_{\rm HPD} \to \Delta\omega_L$

Resonant frequency shift

$$\vec{B}_{a_{\rm DM}} \sim \gamma^{-1} g_{aN} \vec{v}\sqrt{\rho_{\rm DM}}\cos(m_a t + \phi_a)$$



$$\alpha \equiv \frac{dB}{dz}\frac{1}{B_0}\Big|_{z_0}$$

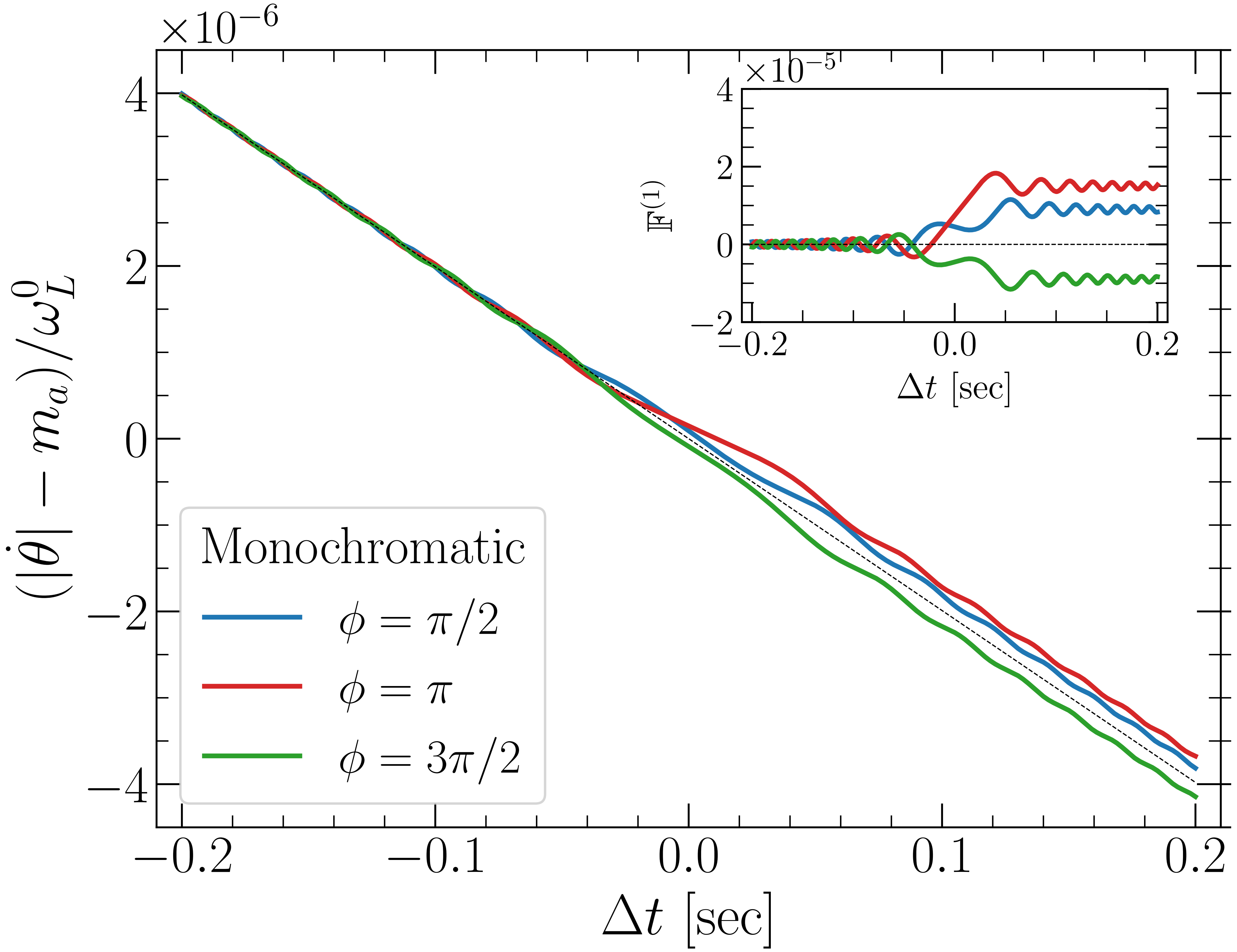
$$\frac{\Delta\omega_L^{\rm DM}}{\omega_L^0} \sim \gamma B_a \alpha z_0 \tau_a$$

$$\sim 3\times 10^{-13}\left(\frac{g_{aN}}{10^{-10}\,{\rm GeV}^{-1}}\right)\left(\frac{10^{-7}\,{\rm eV}}{m_a}\right)\left(\frac{\alpha z_0}{0.02}\right)$$

Resonant frequency shift

$$\vec{B}_{a_{\rm DM}} \sim \gamma^{-1} g_{aN} \vec{v} \sqrt{\rho_{\rm DM}} \cos(m_a t + \phi_a)$$

$$m_a \sim 10^{-7}{\rm eV} \qquad g_{aN} = 5 \times 10^{-5}{\rm GeV}^{-1}$$



- Frequency can increase or decrease depending on the instantaneous phase.
- The frequency shift is permanent after $\omega_L < m_a$
- Resonance only works for transverse component of the axion wind.

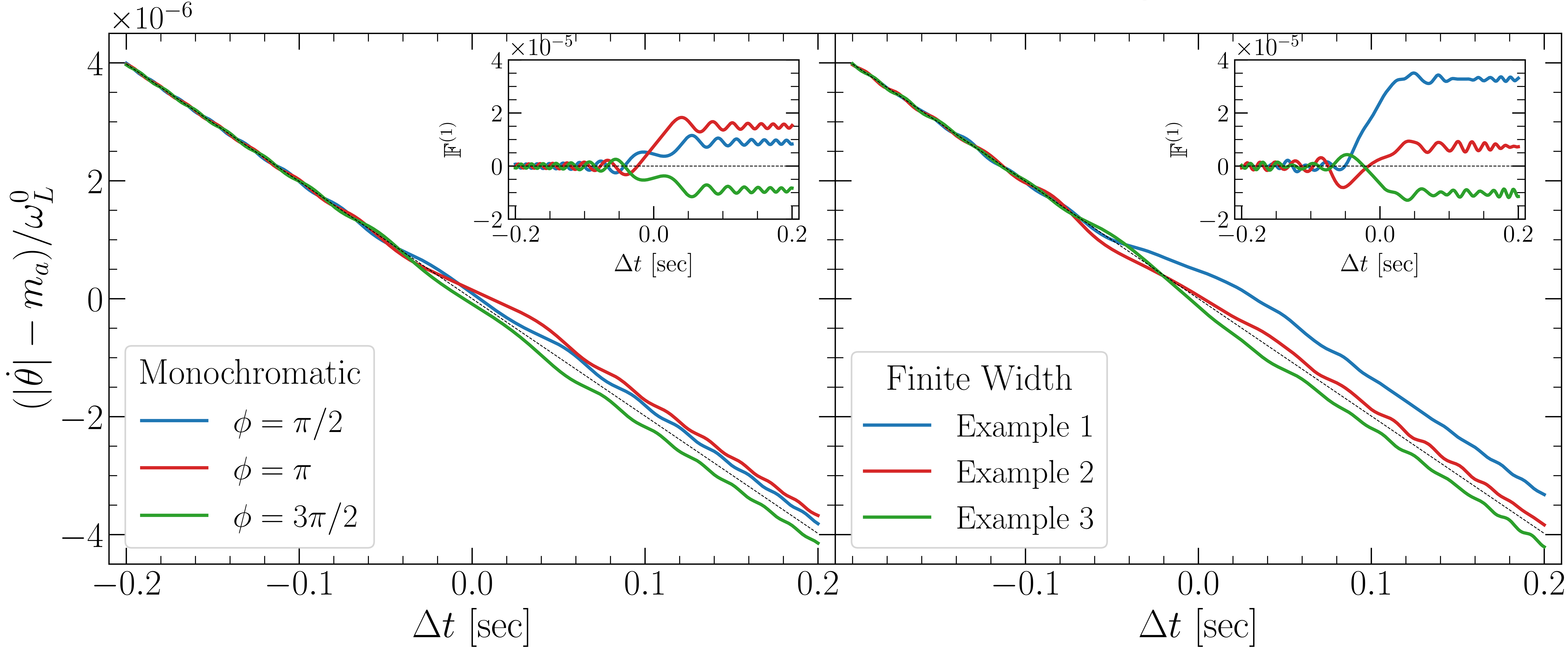
Resonant frequency shift

$$\vec{B}_{a_{\rm DM}} \sim \gamma^{-1} g_{aN} \vec{v} \sqrt{\rho_{\rm DM}} \cos(m_a t + \phi_a)$$

$$m_a \sim 10^{-7}\text{eV} \qquad g_{aN} = 5 \times 10^{-5}\text{GeV}^{-1}$$

$$\vec{B}_a = g_{aNN} \frac{\sqrt{2\rho_{\rm DM}}}{\gamma} \vec{v}_0 \times \sum_j \alpha_j \sqrt{f(v_j)\Delta v} \cos\left(m_a \left(1 + v_j^2/2\right) t + \phi_j\right)$$

Foster et. al (2018)

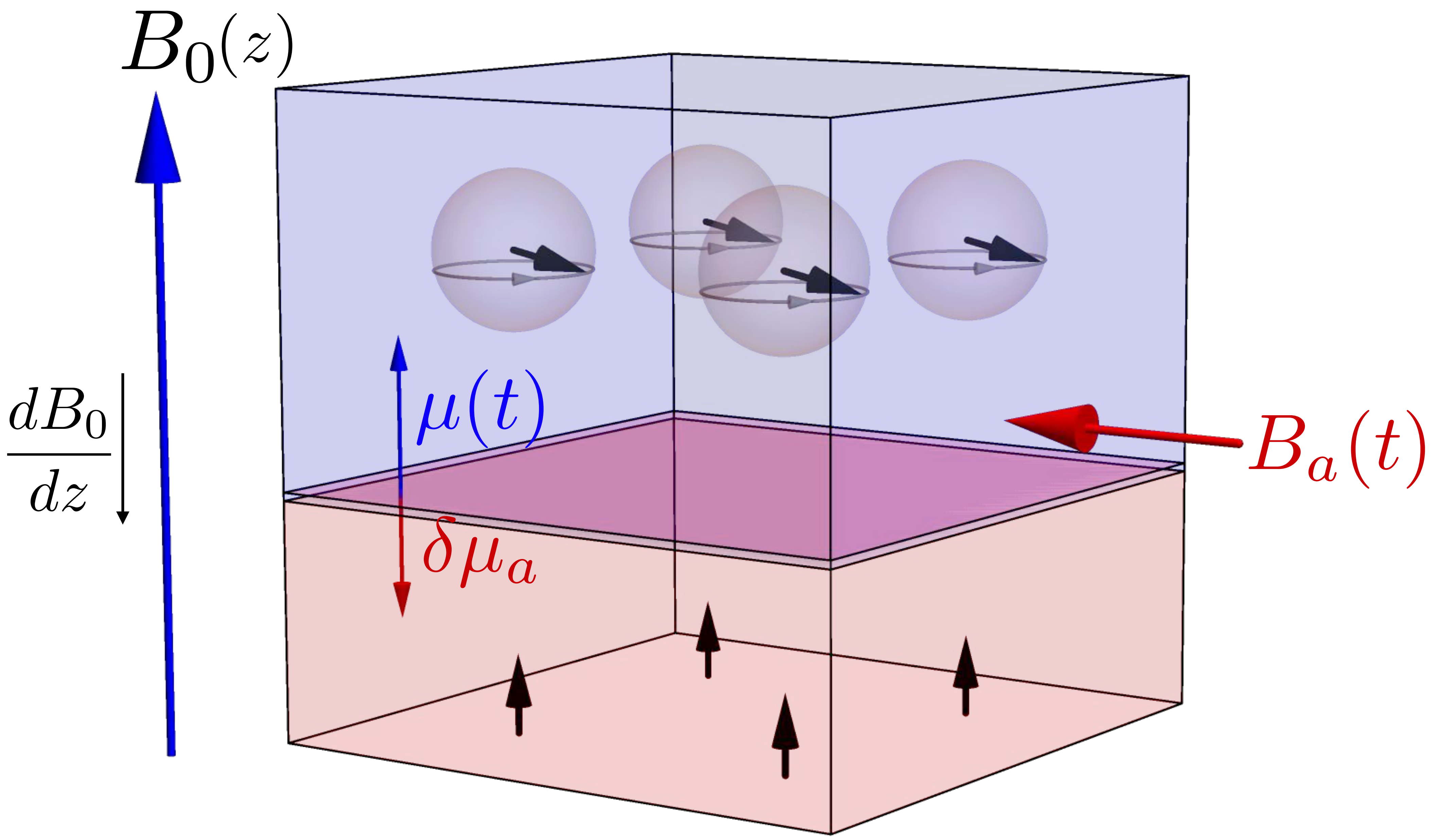


Scan axion mass

$$\vec{B}_{a_{\rm DM}} \sim \gamma^{-1} g_{aN} \vec{v} \sqrt{\rho_{\rm DM}} \cos(m_a t + \phi_a)$$

$$\omega_L = \gamma B(z_{\rm wall})$$

$$\alpha \equiv \frac{dB}{dz} \frac{1}{B_0}\bigg|_{z_0}$$



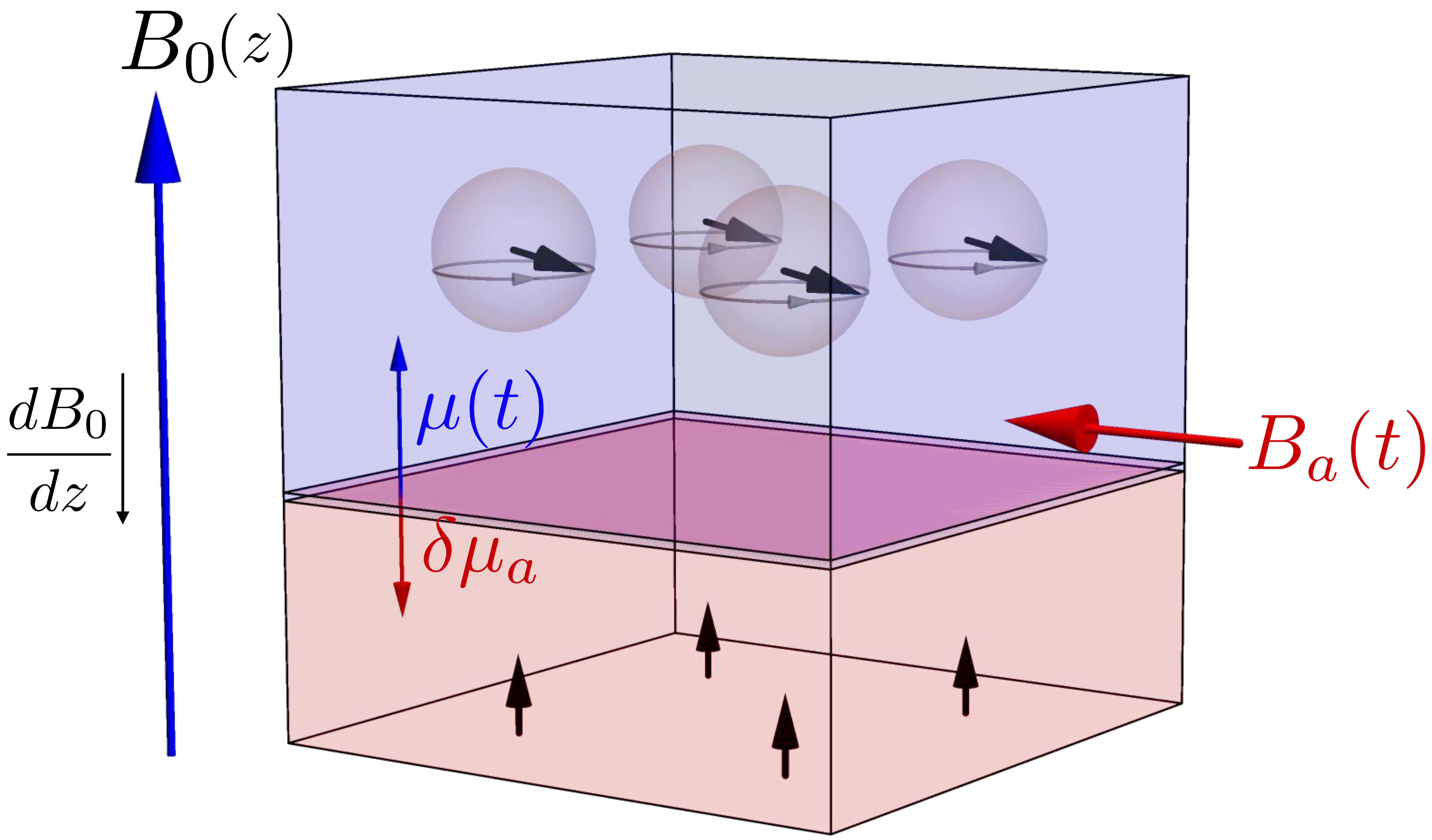
- Decay of HPD naturally sweeps through many axion masses.
- Choosing large gradient α covers more axion masses, but spends less time on each mass.
- Choosing small α may result in more than one axion coherence time spent on each axion mass.

Signal to noise

$$\vec{B}_{a_{\rm DM}} \sim \gamma^{-1} g_{aN} \vec{v} \sqrt{\rho_{\rm DM}} \cos(m_a t + \phi_a)$$

$$\omega_L = \gamma B(z_{\rm wall})$$

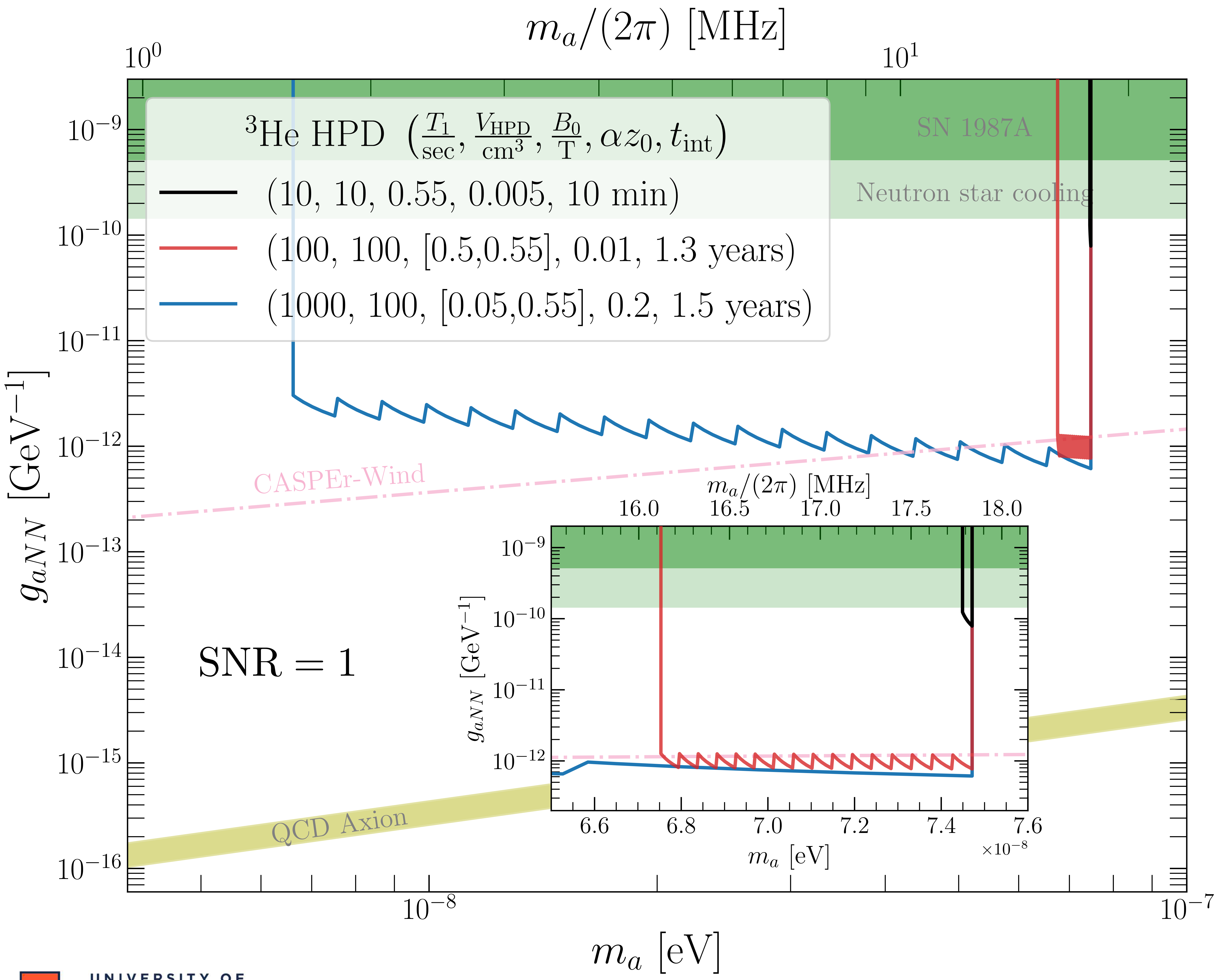
$$\alpha \equiv \frac{dB}{dz}\frac{1}{B_0}\Big|_{z_0}$$



$$\frac{\Delta\omega_L^{\rm stochastic}}{\omega_L^0} \sim \alpha z_0 \sqrt{\frac{\tau_a}{T_1}}$$

$$\mathrm{SNR} \sim \mathcal{N}^{1/4} \frac{\Delta\omega^{\rm DM}}{\Delta\omega^{\rm stochastic}} \qquad \mathcal{N} = \text{number of experiments}$$

Axion nucleon coupling limit



$$\mathrm{SNR} \approx \gamma B_a \sqrt{V_{\mathrm{HPD}} n_M} (T_1 t_{\mathrm{int}})^{1/4} \times \min[\sqrt{t_r}, \sqrt{\tau_a}].$$

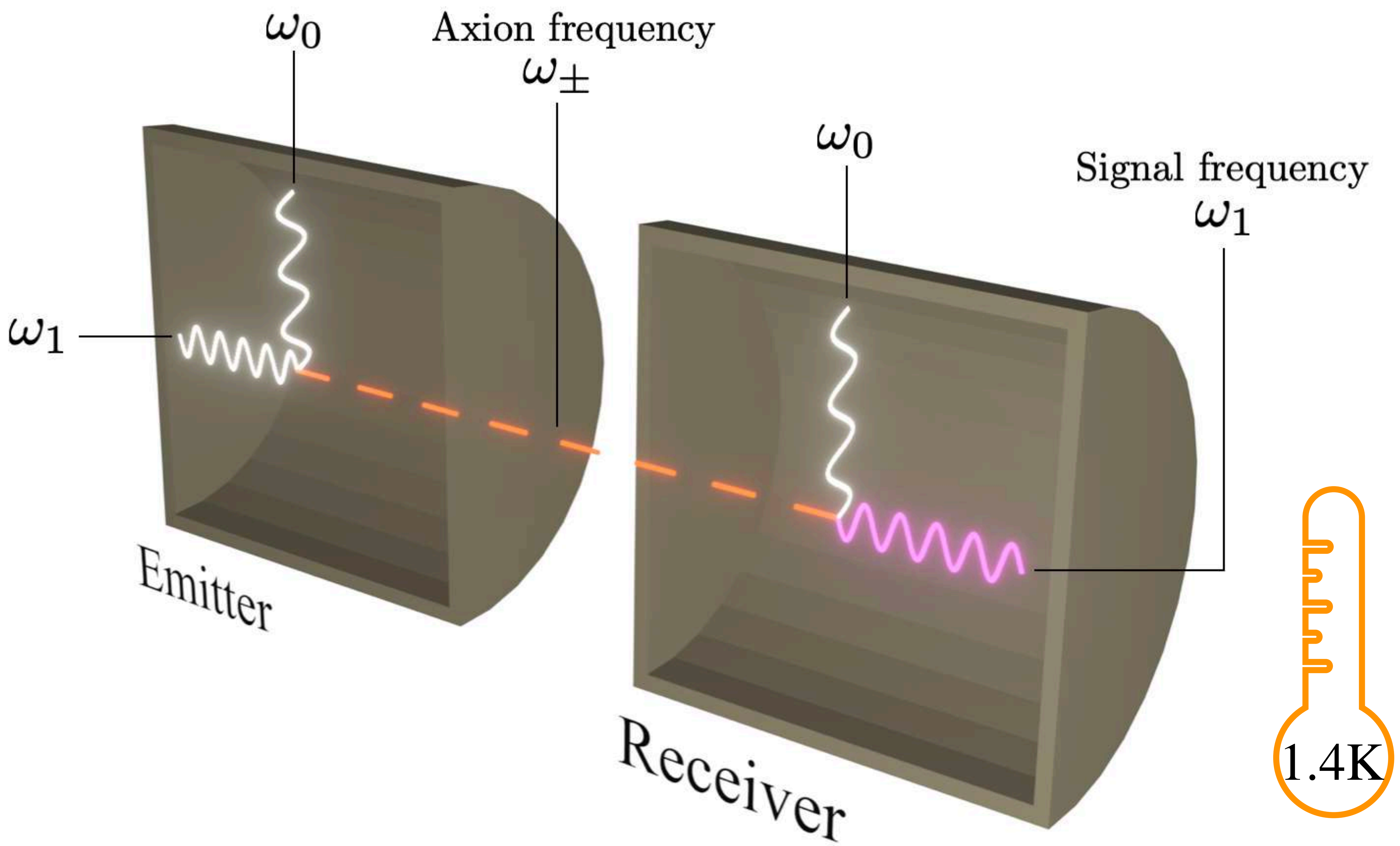
$$\mathcal{N} = t_{\mathrm{int}}/T_1$$

- $B_0 \lesssim 0.55\mathrm{T}$ to prevent $^3\mathrm{He}-\mathrm{B}$ from destabilization
- very compelling reach even with a conservative setup
- more careful statistical treatment required

Backups

Setup

- Fundamental frequency: 650 MHz
- Quality factor $Q = 10^{10}$
- $E_{\text{peak}} = 80\,\text{MVm}^{-1}$ (or 0.26 Tesla) for all active modes



Ongoing work at Fermilab SQMS center.

Z. Bogorad et al 19

R. Janish et al 19