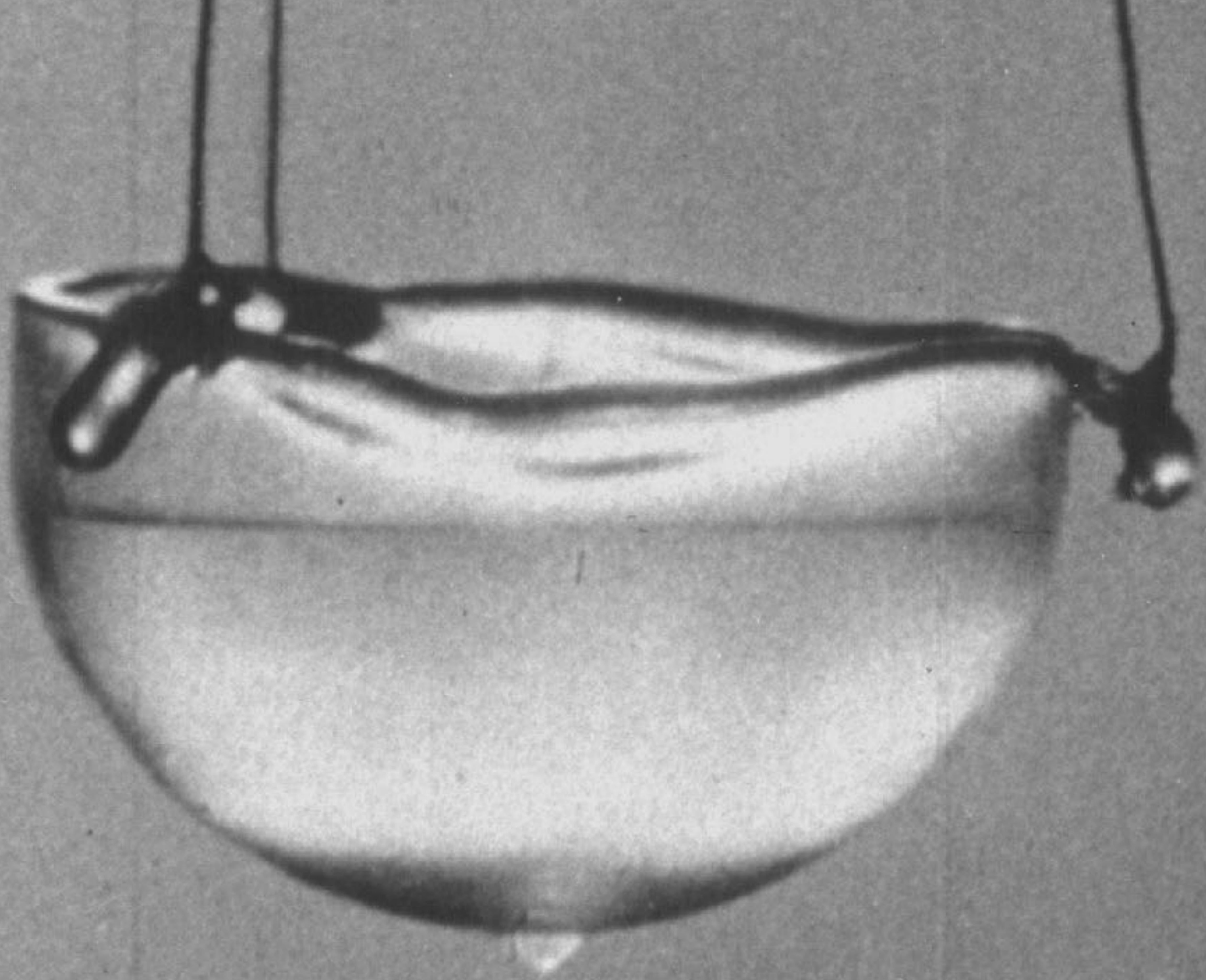


Axion Wind Detection with the Homogeneous Precession Domain of Superfluid Helium-3

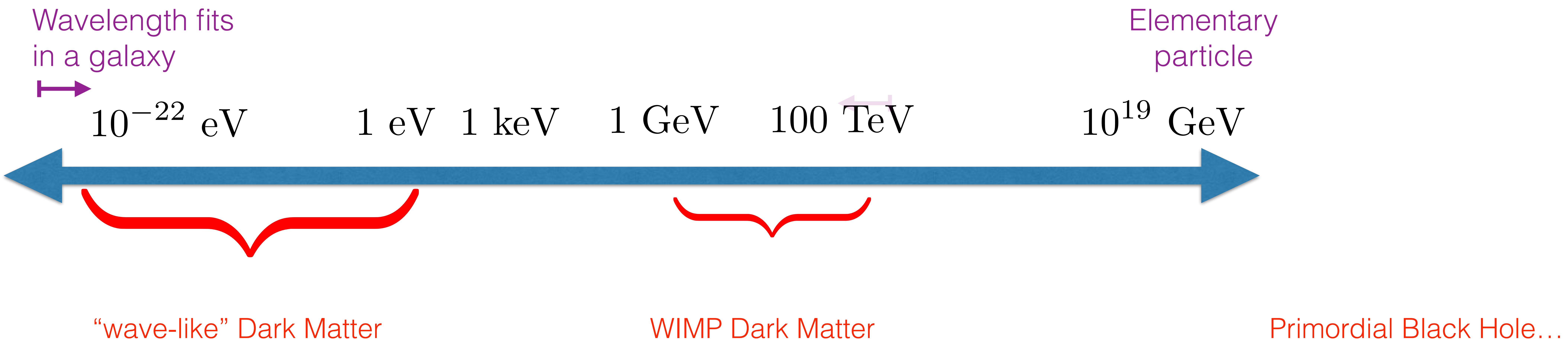
Christina Gao 1/30/2023

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Fermilab

SQMS

50 Orders of Magnitude



$$n_{\rm DM}\lambda_{\rm dB}^3 \gg 1$$

Behaves as classical field

Outline

- Axion dark matter
- Axion nucleon coupling, nuclear magnetic resonance
- Superfluid Helium 3, homogeneous precession domain
- Searching for axion dark matter with Superfluid Helium 3

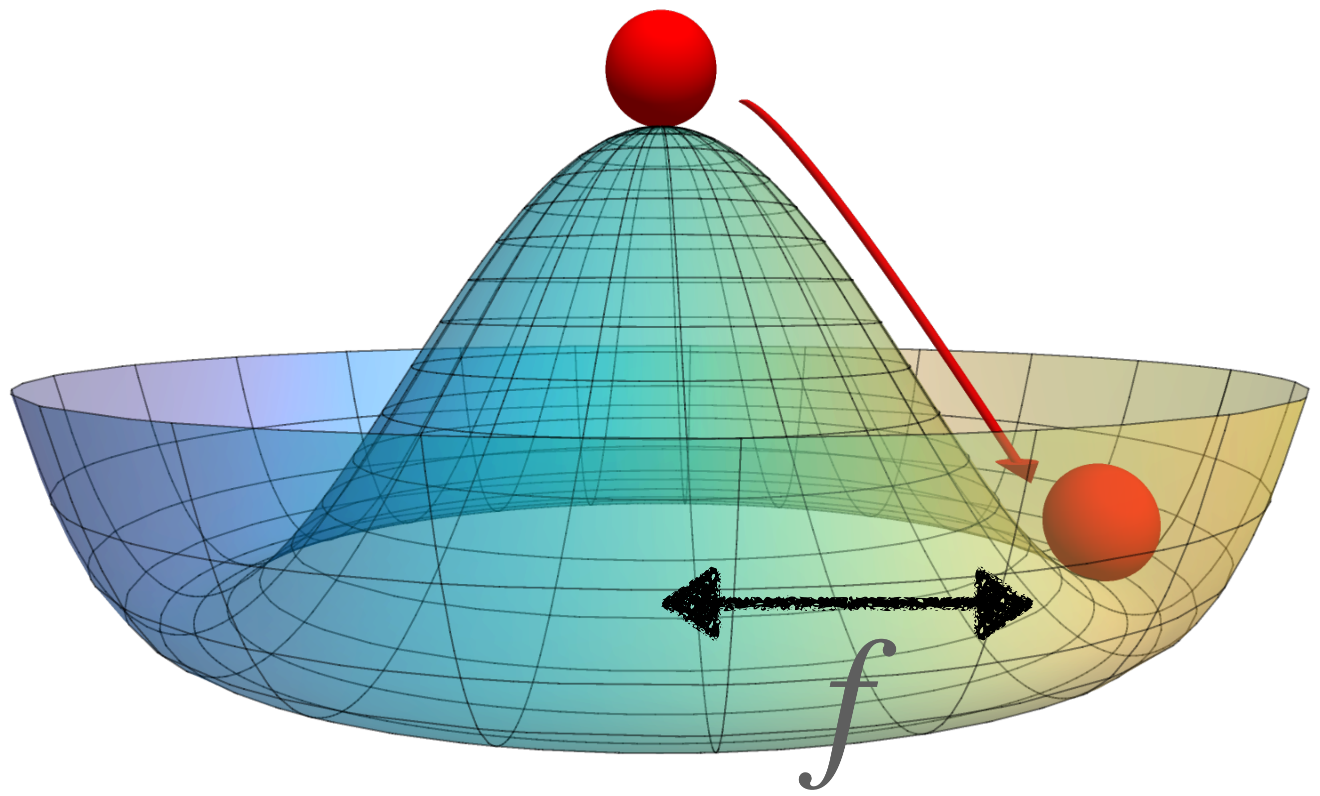
with Y. Kahn, J. Schütte-Engel, M. Backlund, B. DeMarco,
E. Goldschmidt, A. Mande (UIUC);
W.P. Halperin, M. Nguyen, J.W. Scott (Northwestern);
J. Foster (MIT)
arXiv:2208.14454 (PRL 2022)

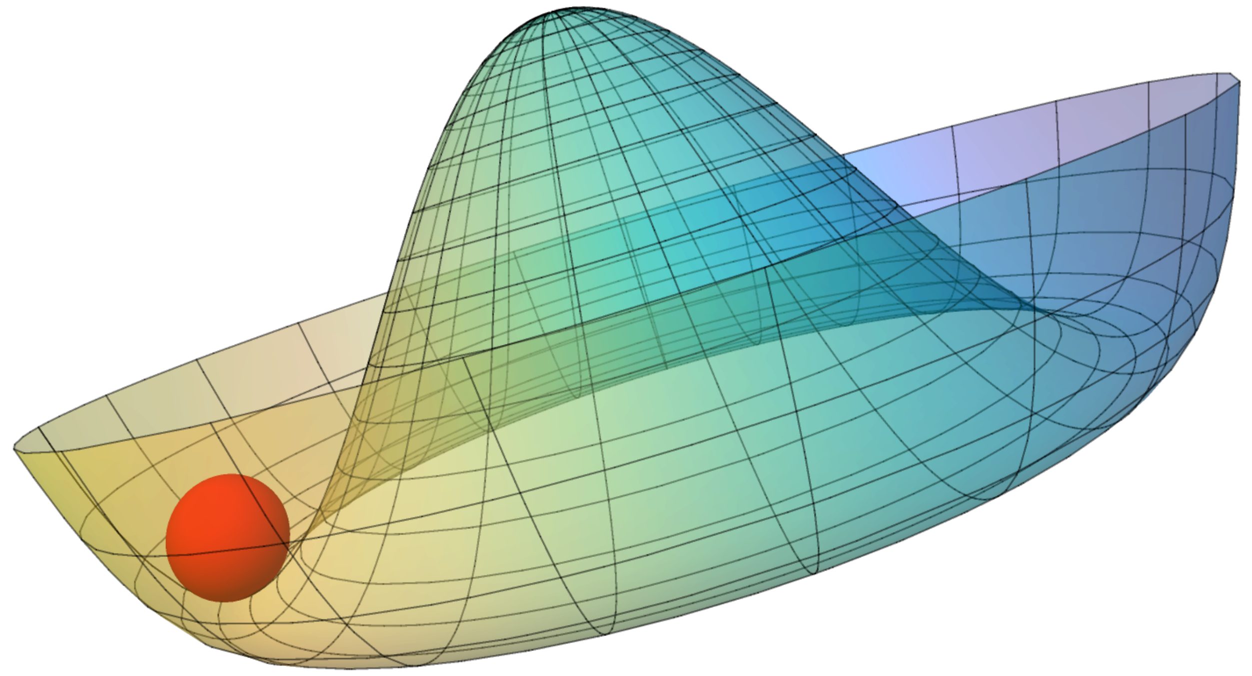
Axions are light Pseudo-scalars

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





Axion and Axion Like Particles

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

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

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

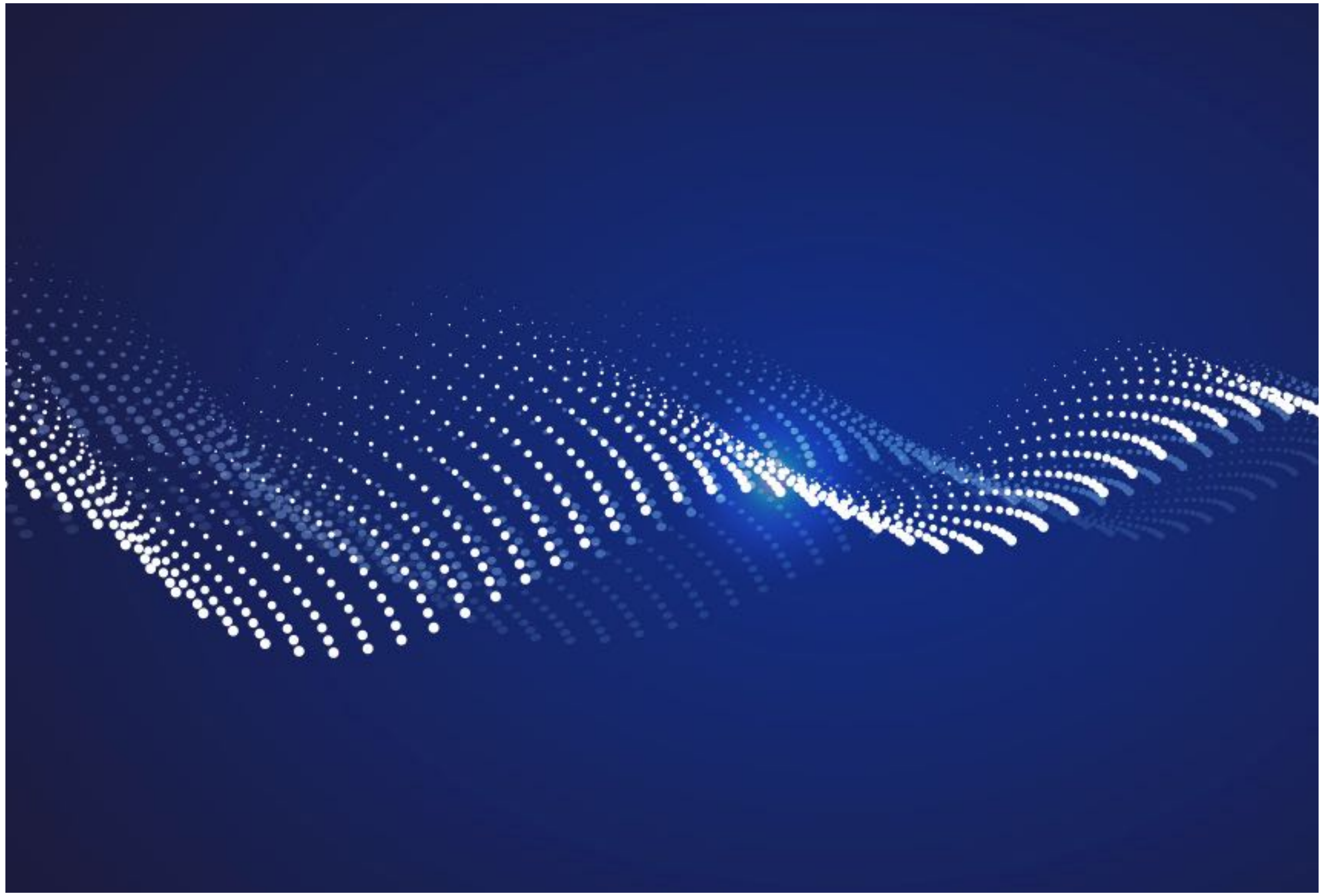
Svrcek & Witten (2006), Arvanitaki et. al (2009)

- Many axion-like particles (ALPs) exist in the string landscape:

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

  Masses of ALPs independently span a vast range.

Axions can be Dark Matter



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

- Large occupation number
- Cold dark matter $v \sim 10^{-3} c$
- An example of Wave-like DM

$$a_{\rm DM}(t) \sim a_0 \cos\left(m_a t - m_a \mathbf{v} \cdot \mathbf{x}\right)$$

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

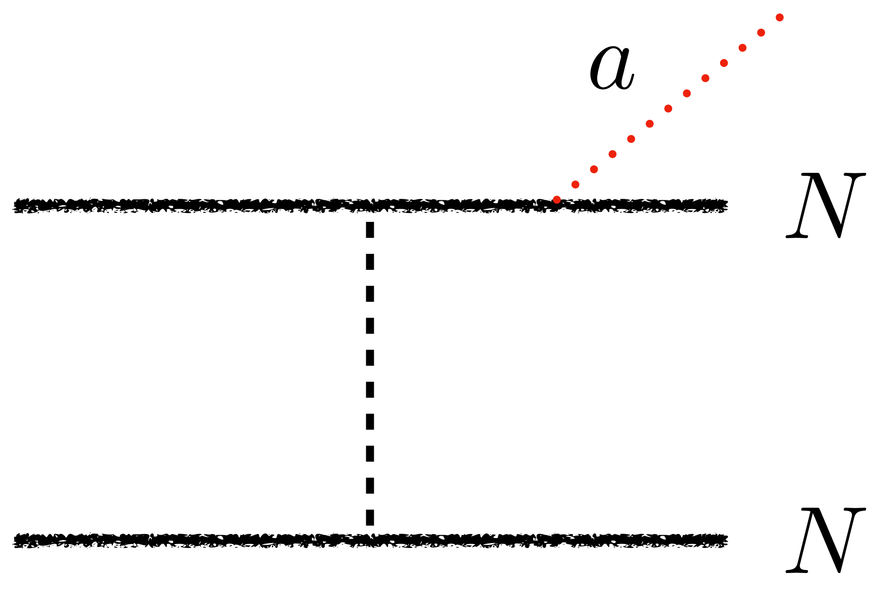
Axion Nucleon Coupling

Axion nucleon coupling

$$\mathcal{L}_{\text{int}} \supset g_{aN} \partial_\mu a \bar{N} \gamma^\mu \gamma^5 N \qquad g_{aN} = \frac{1}{2f_a} c_N$$

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

Beznogov et. al (2018) $g_{ann} < 2.8 \times 10^{-10} \text{GeV}^{-1}$ (90%C.L.) $m_a \ll 10\text{keV}$



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).

$$H_{\text{eff}} \supset \vec{S}\cdot\underbrace{(g_{aN}\vec{\nabla}a)}$$

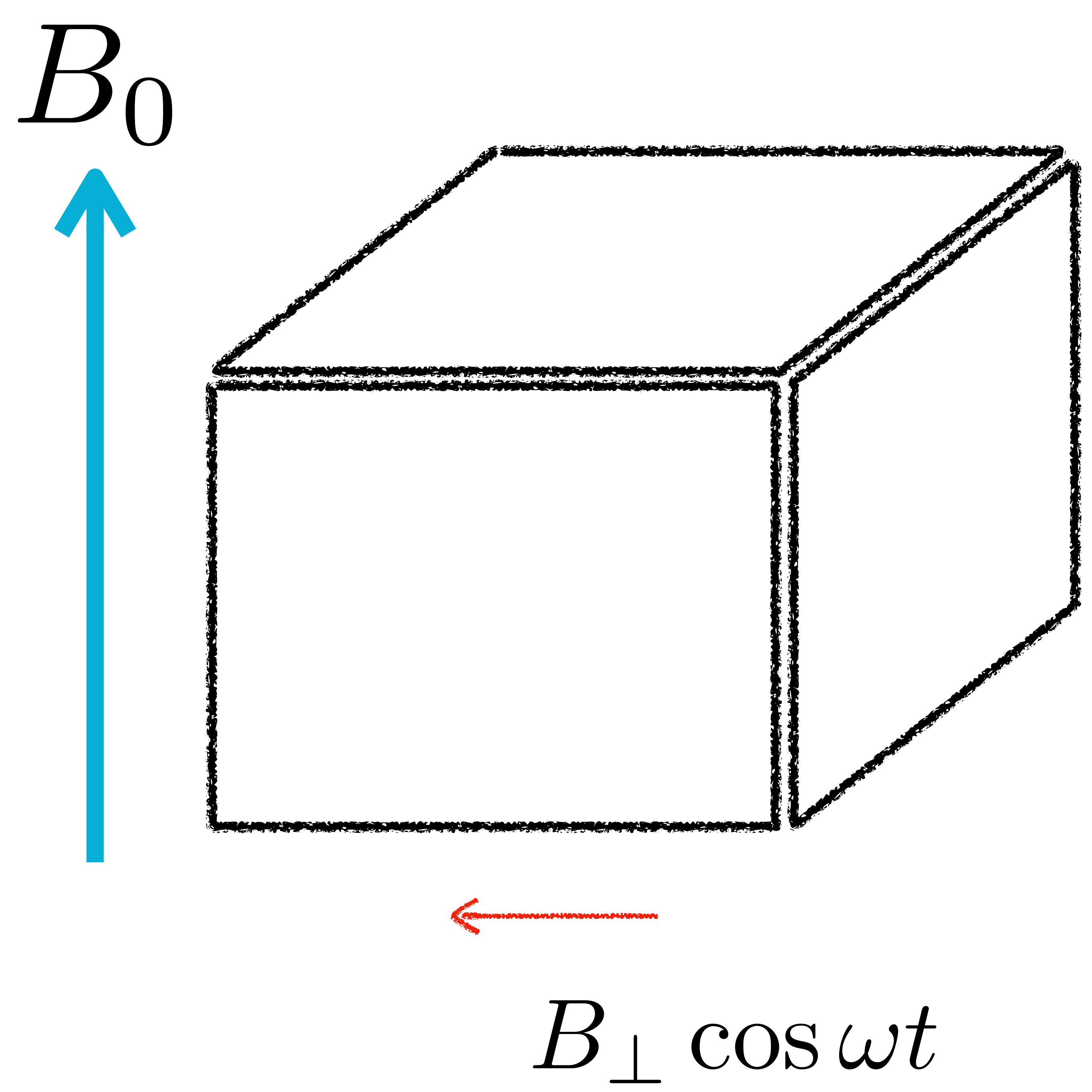
$$a_{\text{DM}}(t) \sim \cos\left(m_a t - \mathbf{k}\cdot\mathbf{x}\right)$$

$$\vec{S} \sim \bar{N}\vec{\sigma}N$$

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

Nuclear magnetic resonance

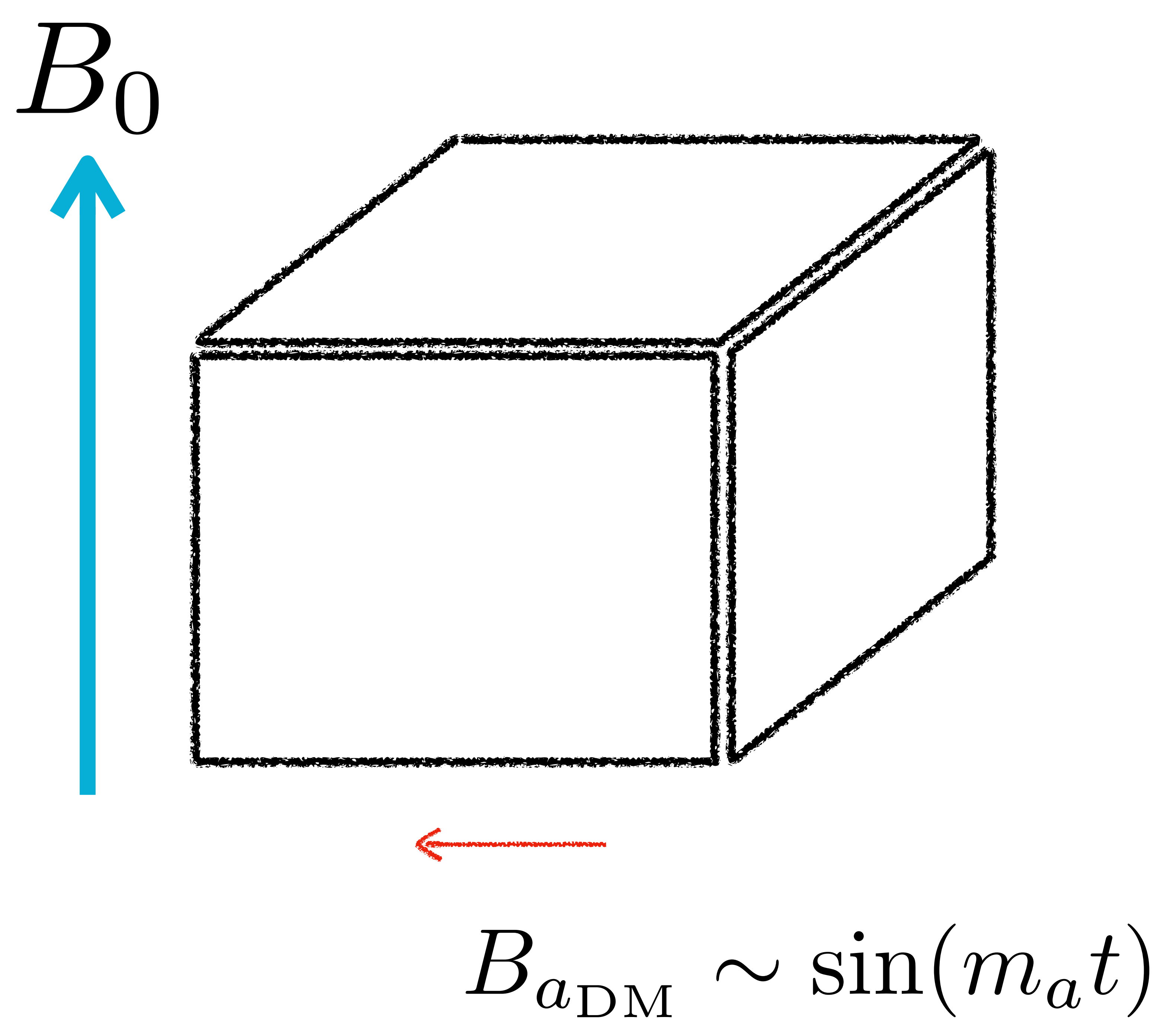
- Resonance condition: $\omega = \omega_L = \gamma B_0$



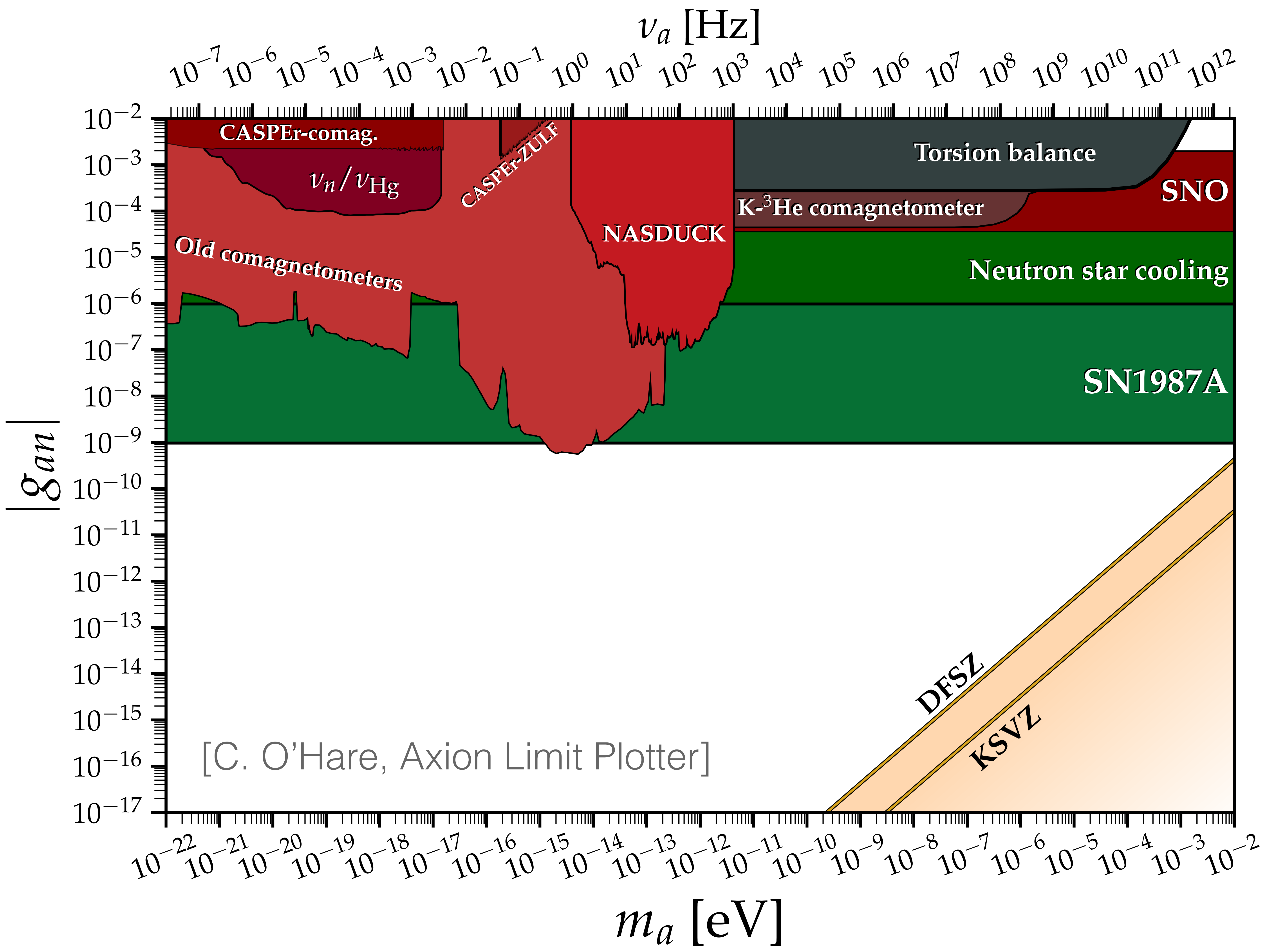
Nuclear magnetic resonance

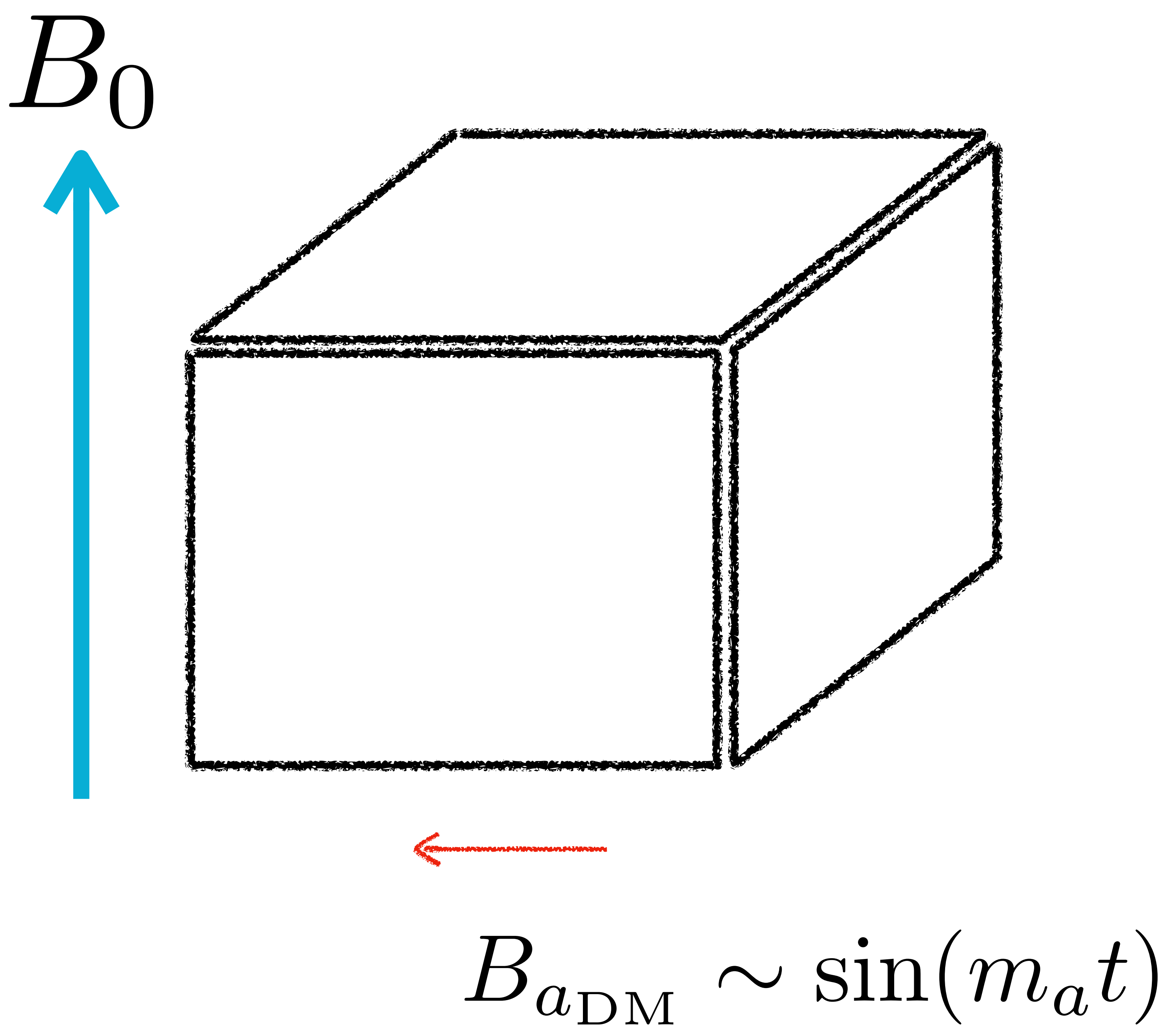
- Resonance condition: $m_a = \omega_L = \gamma B_0$

- Tune B_0 to match axion mass with Larmor frequency ω_L Graham, Rajendran (2013)



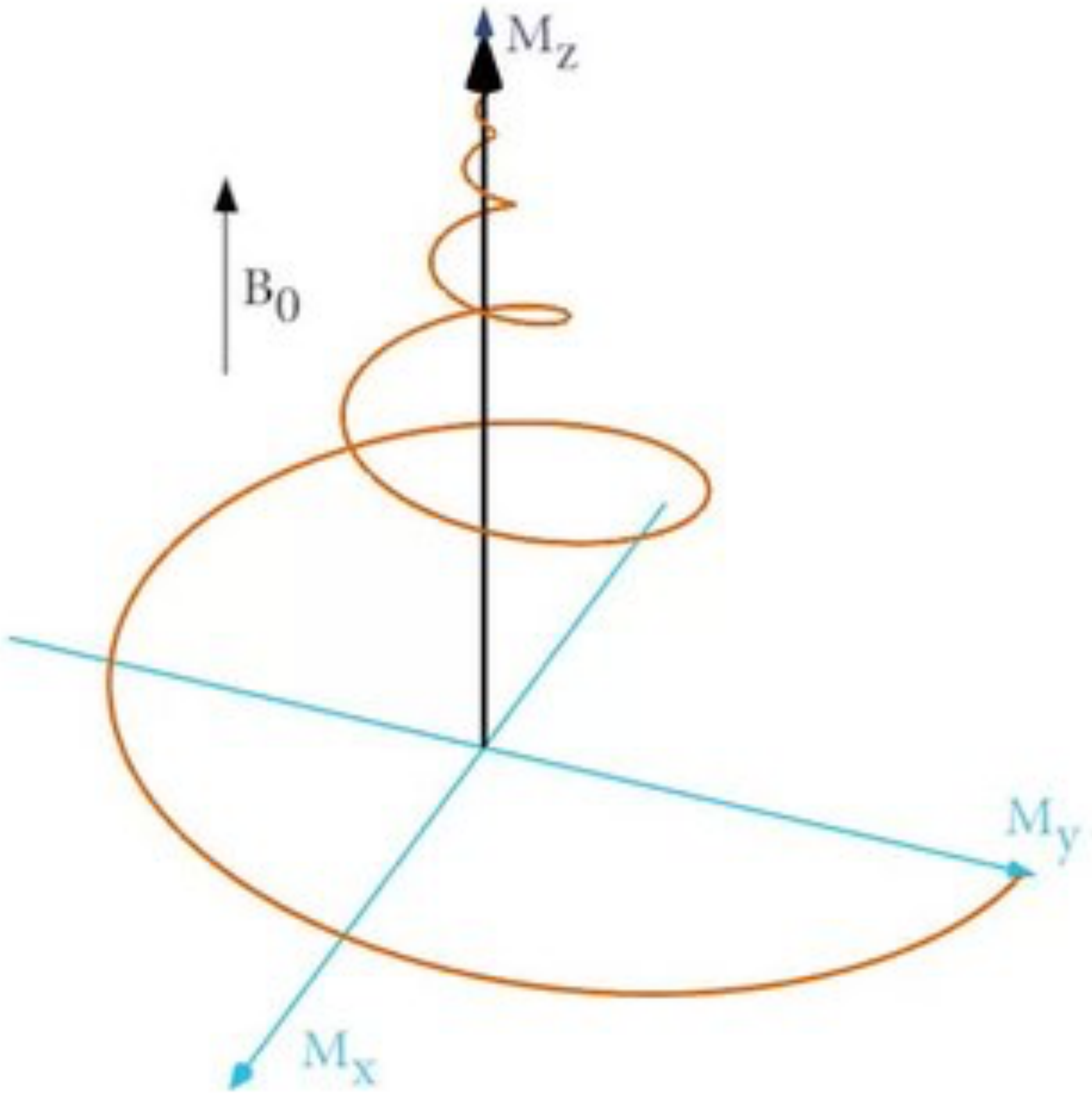
Constraints on axion nucleon coupling

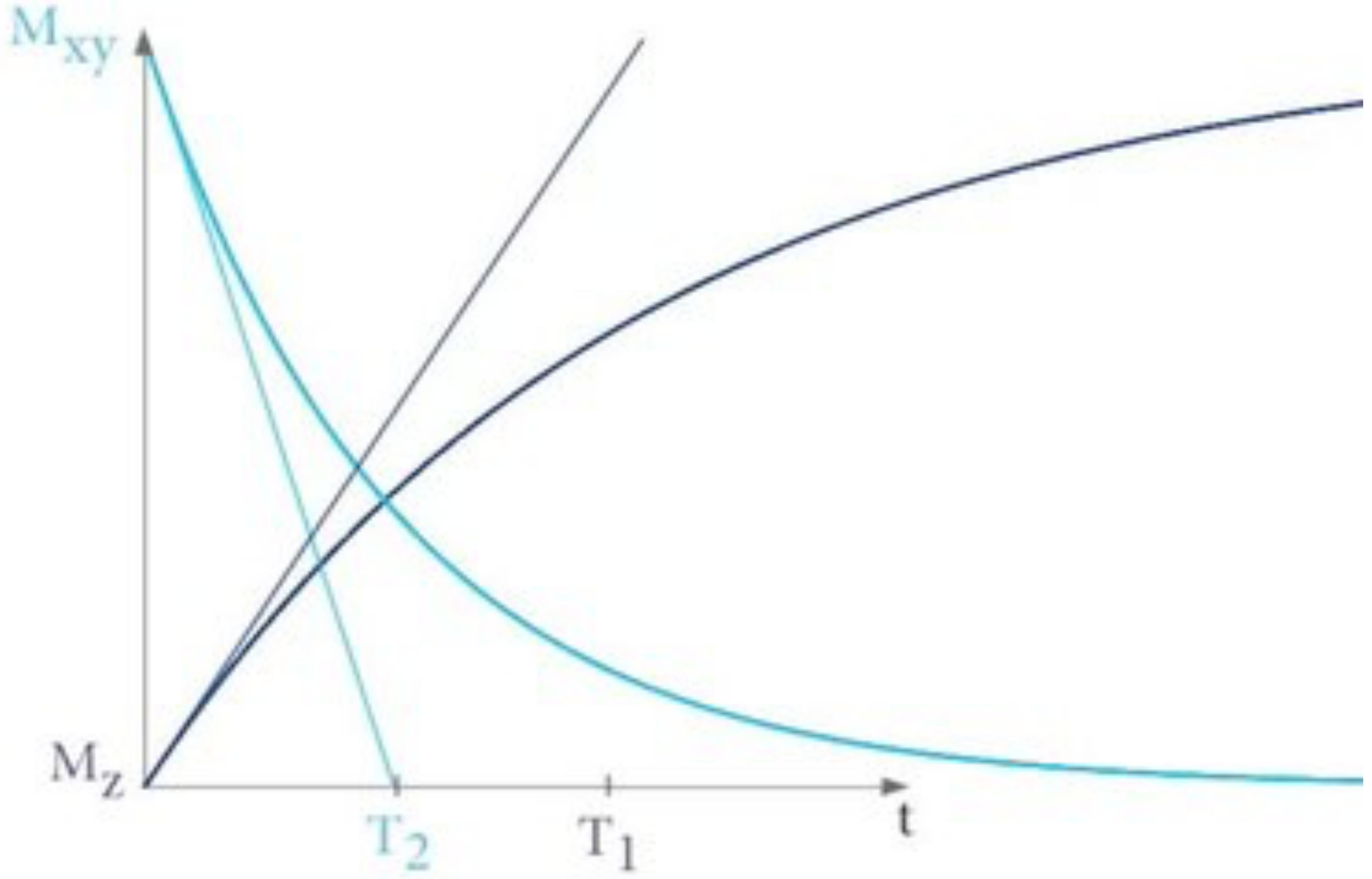




Pulsed NMR

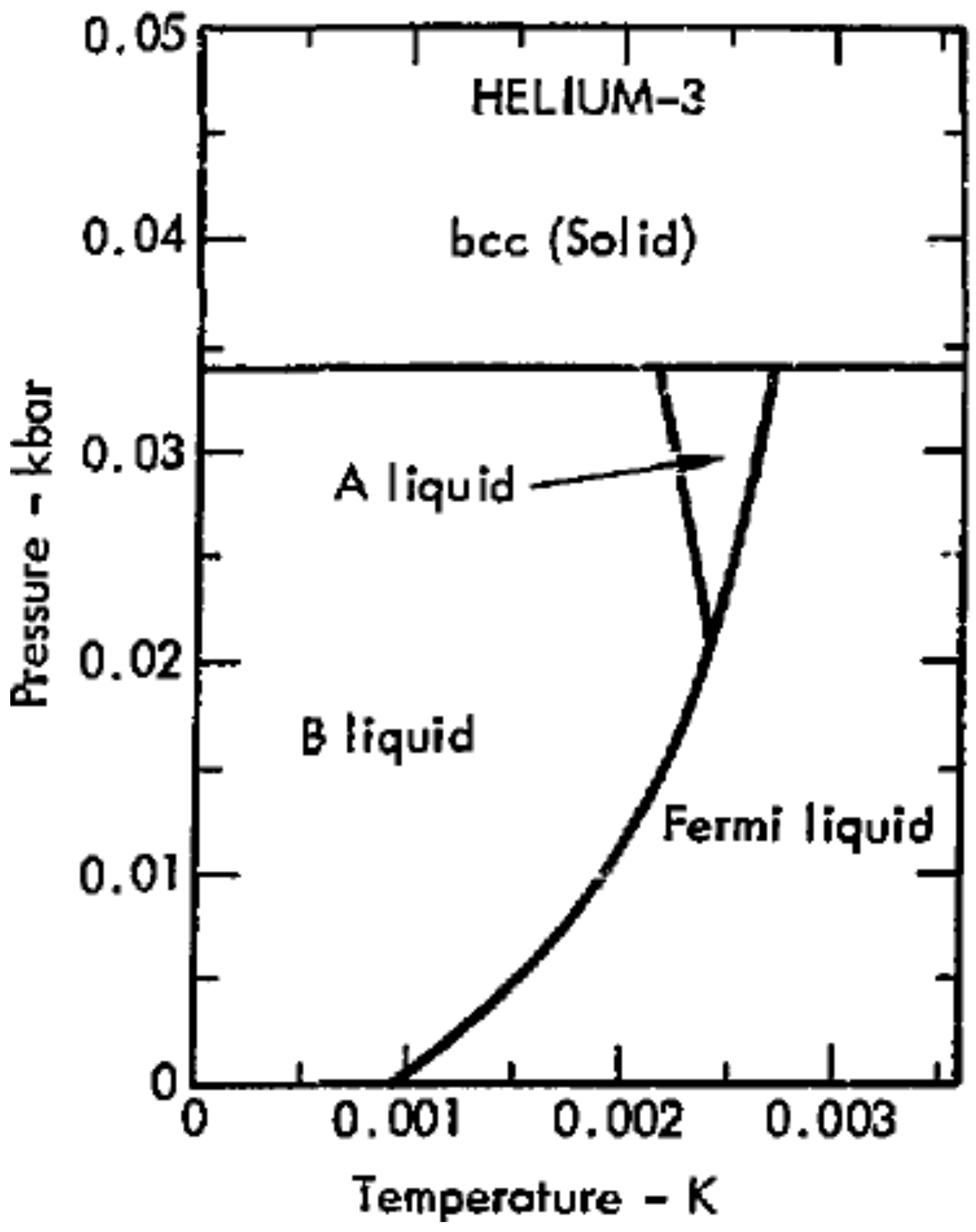
$$\frac{d\mathbf{M}}{dt} = \mathbf{M} \times \gamma \mathbf{B} - \frac{M_x \hat{\mathbf{x}} + M_y \hat{\mathbf{y}}}{T_2} - \frac{(M_z - M_0)\hat{\mathbf{z}}}{T_1}$$





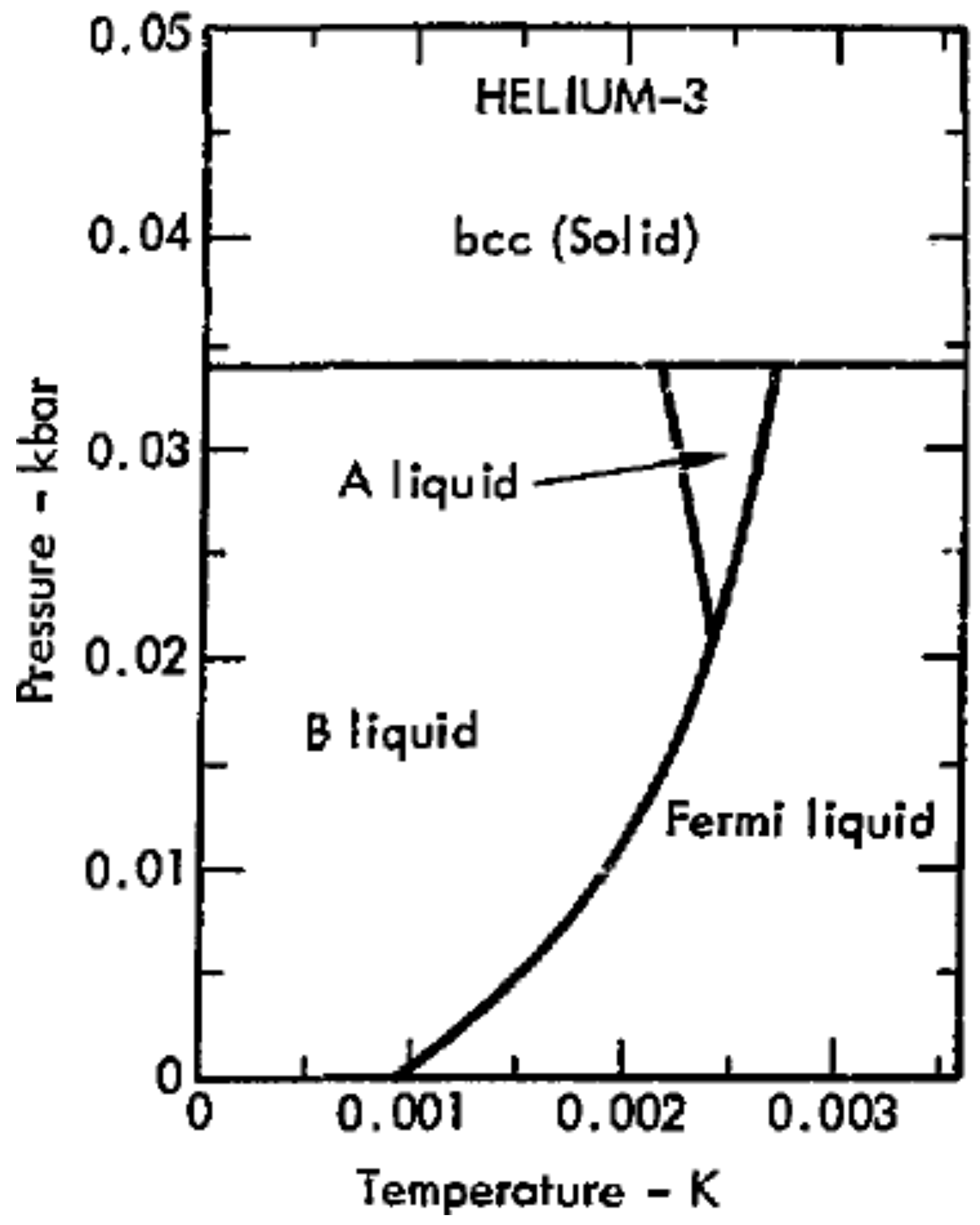
Superfluid Helium 3

Properties of $^3\mathrm{He}$

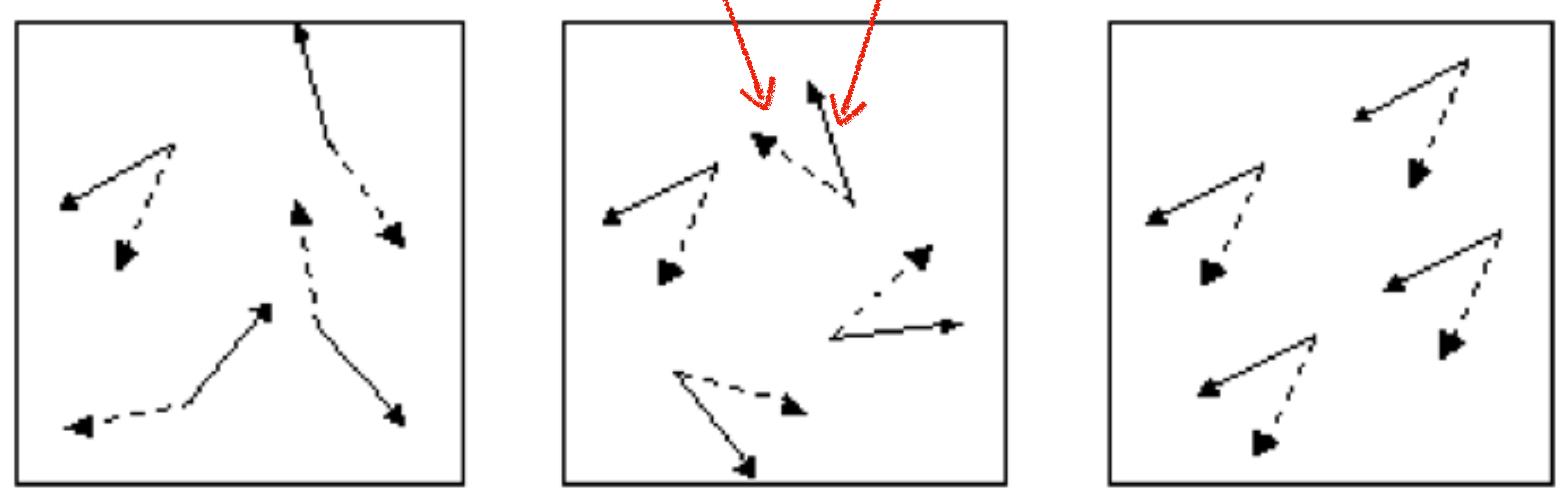


- Spin 1/2
- Very low temperature, superfluid phase (~ Bose Einstein Condensate)

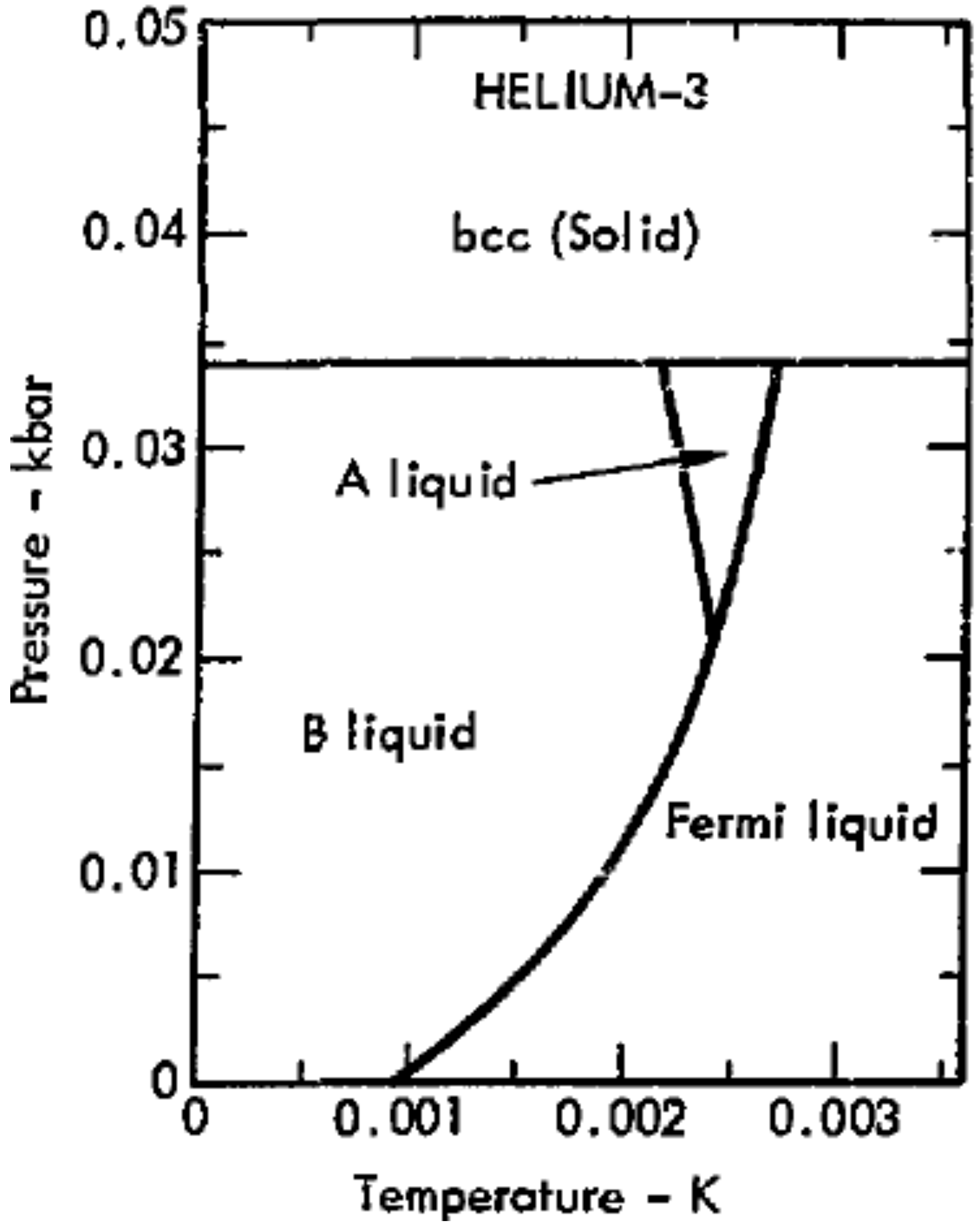
Properties of $^3\mathrm{He}$



- Spin 1/2
- Very low temperature, superfluid phase (~ Bose Einstein Condensate)
- Cooper pairs $S = 1$ $L = 1$



Properties of $^3\mathrm{He}$



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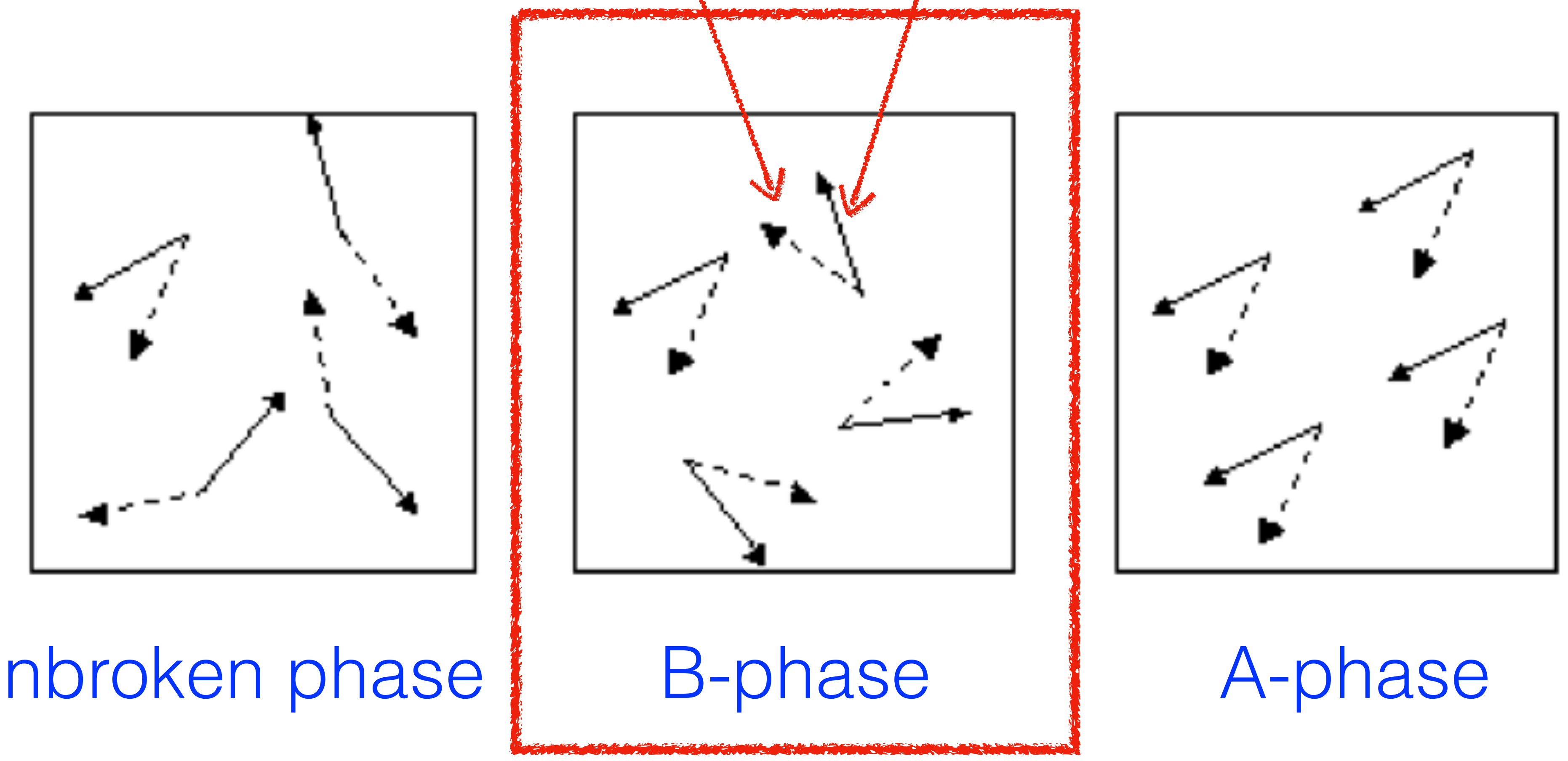
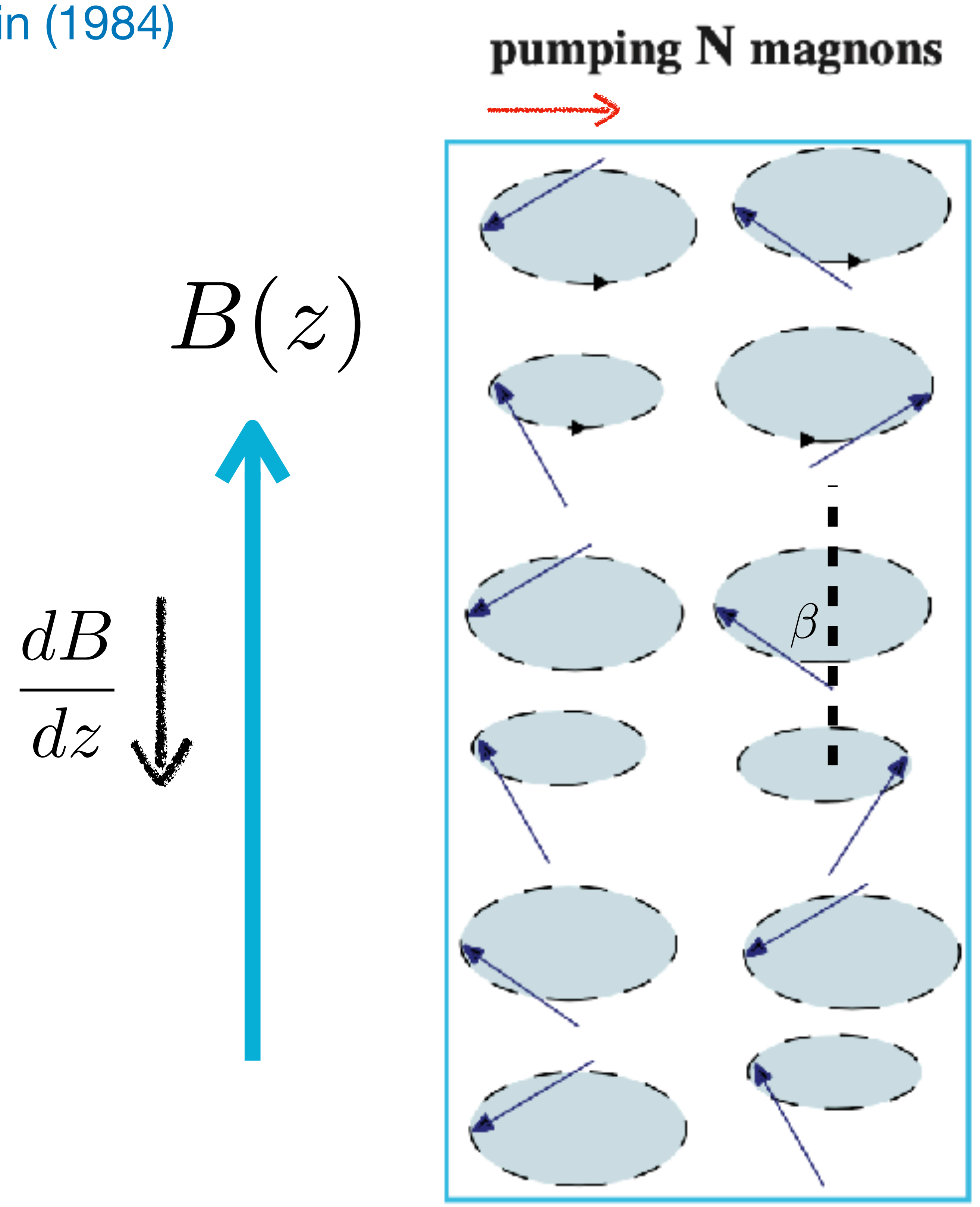


Pulsed NMR with $^3\mathrm{He}-\mathrm{B}$

[Bunkov and Volovik, arXiv:0904.3889 and arXiv:1003.4889]

Fomin (1984)



spins randomly oriented

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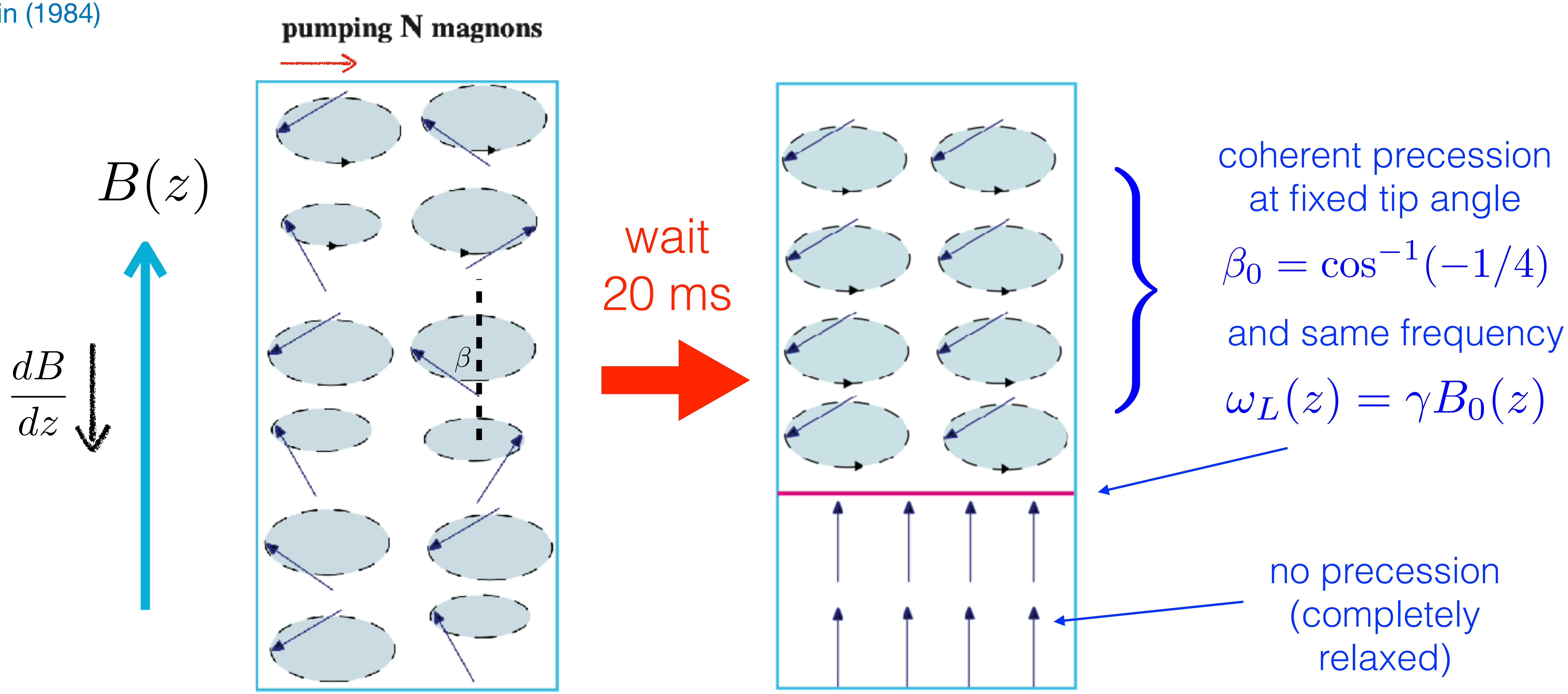

spins randomly oriented

two domains!

This behavior is known as the homogeneous precession domain (HPD)

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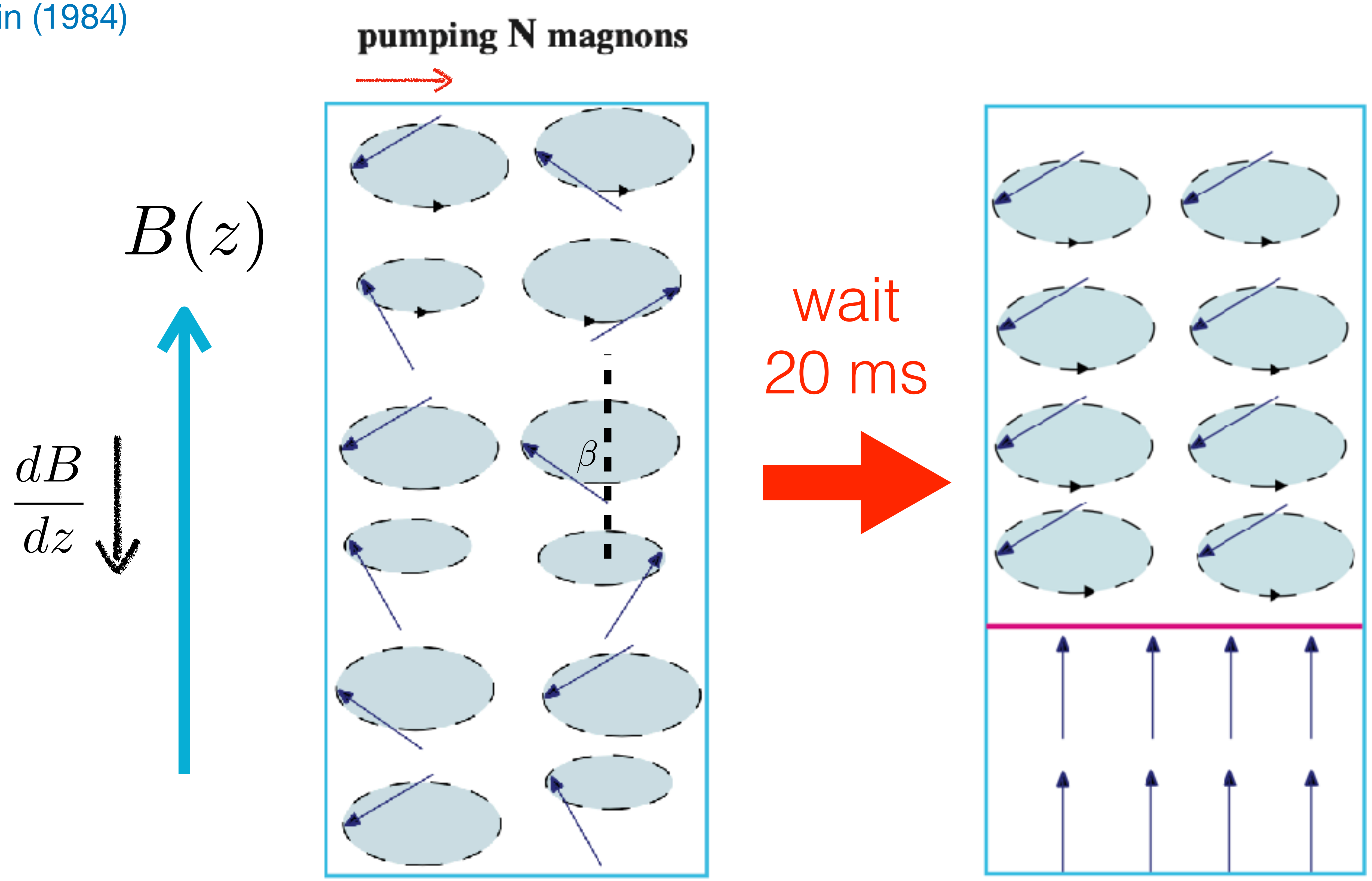
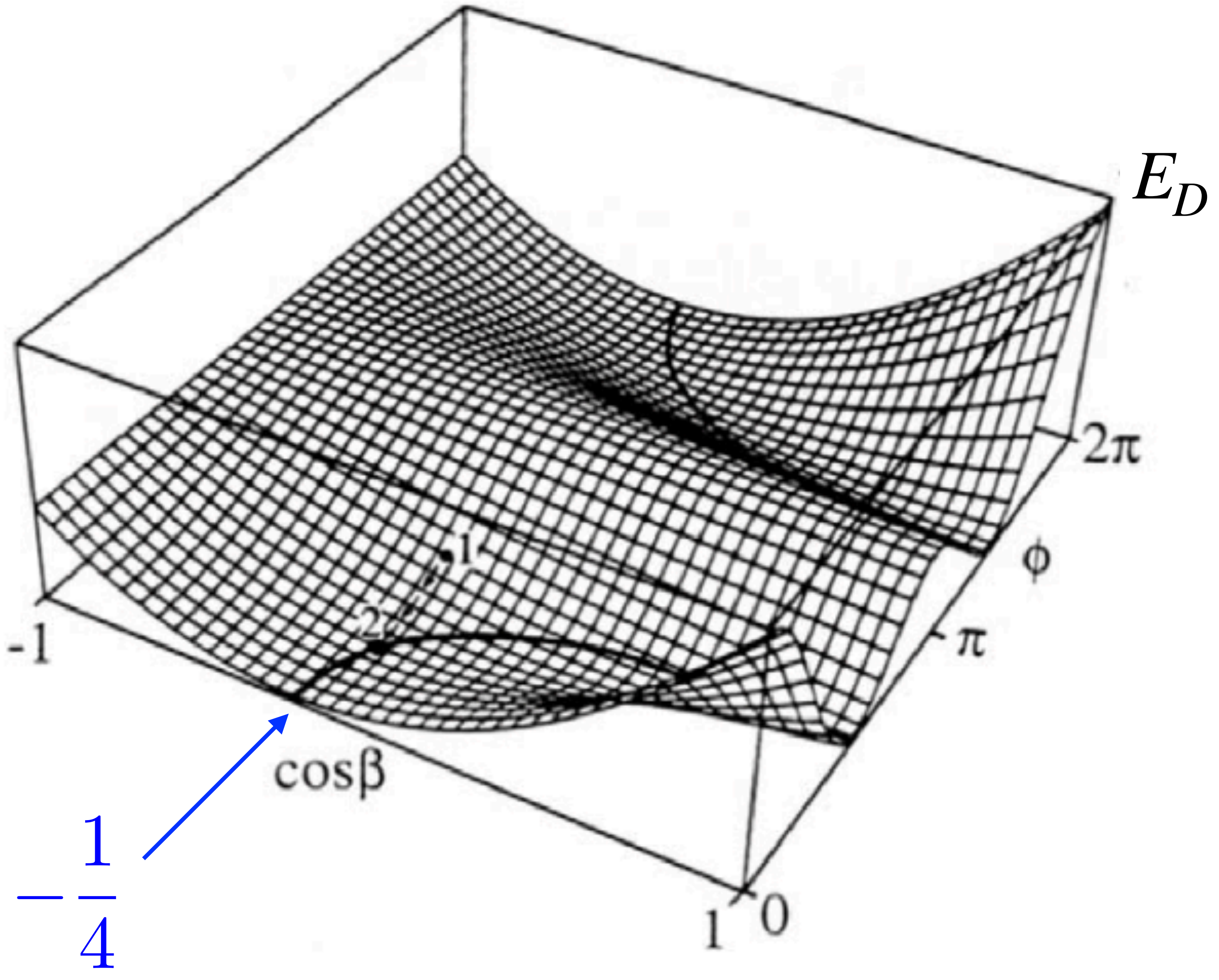


spins randomly oriented   two domains!

DOF: Euler angles

$$\omega(z) = \gamma B(z) - E_D(\cos\beta(z) + \frac{1}{4})$$



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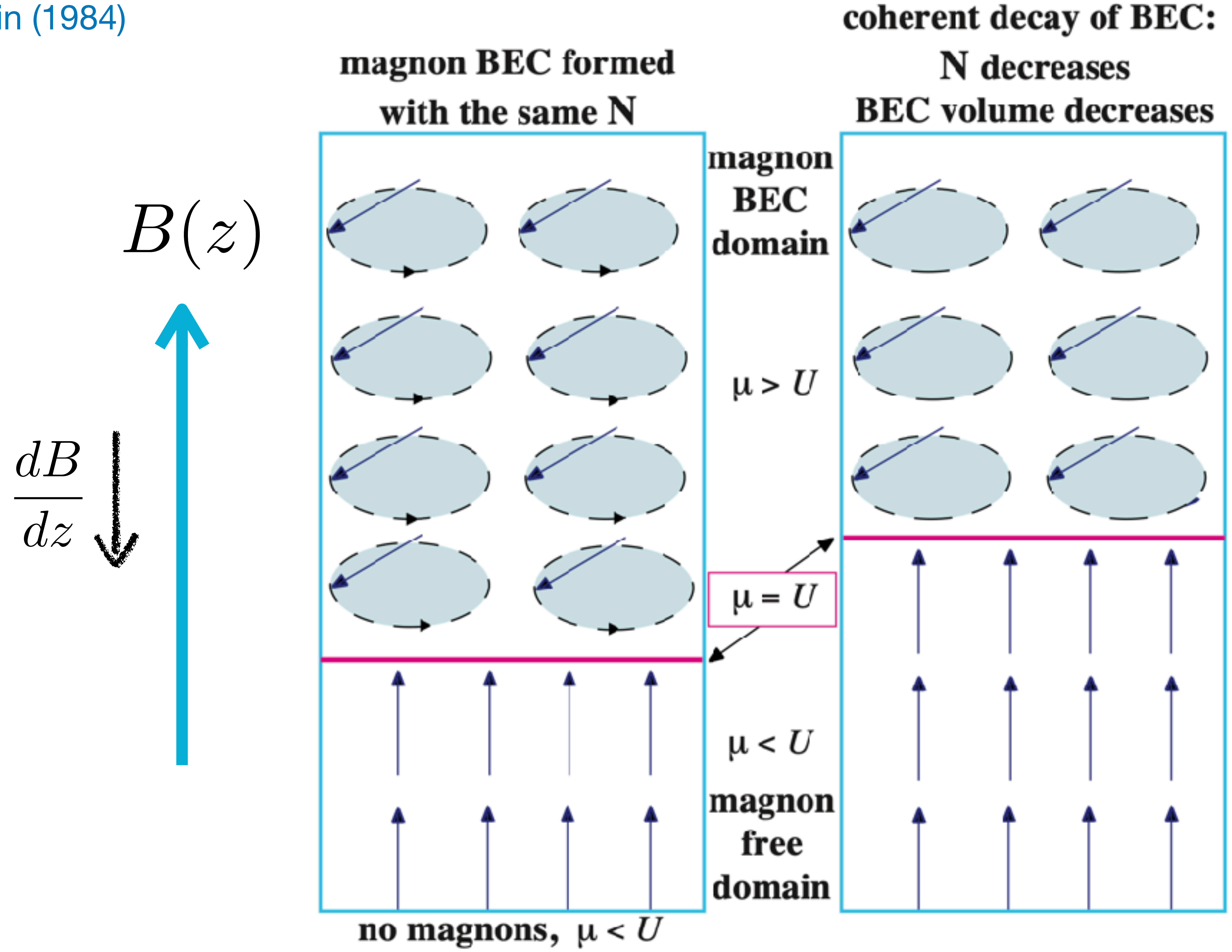
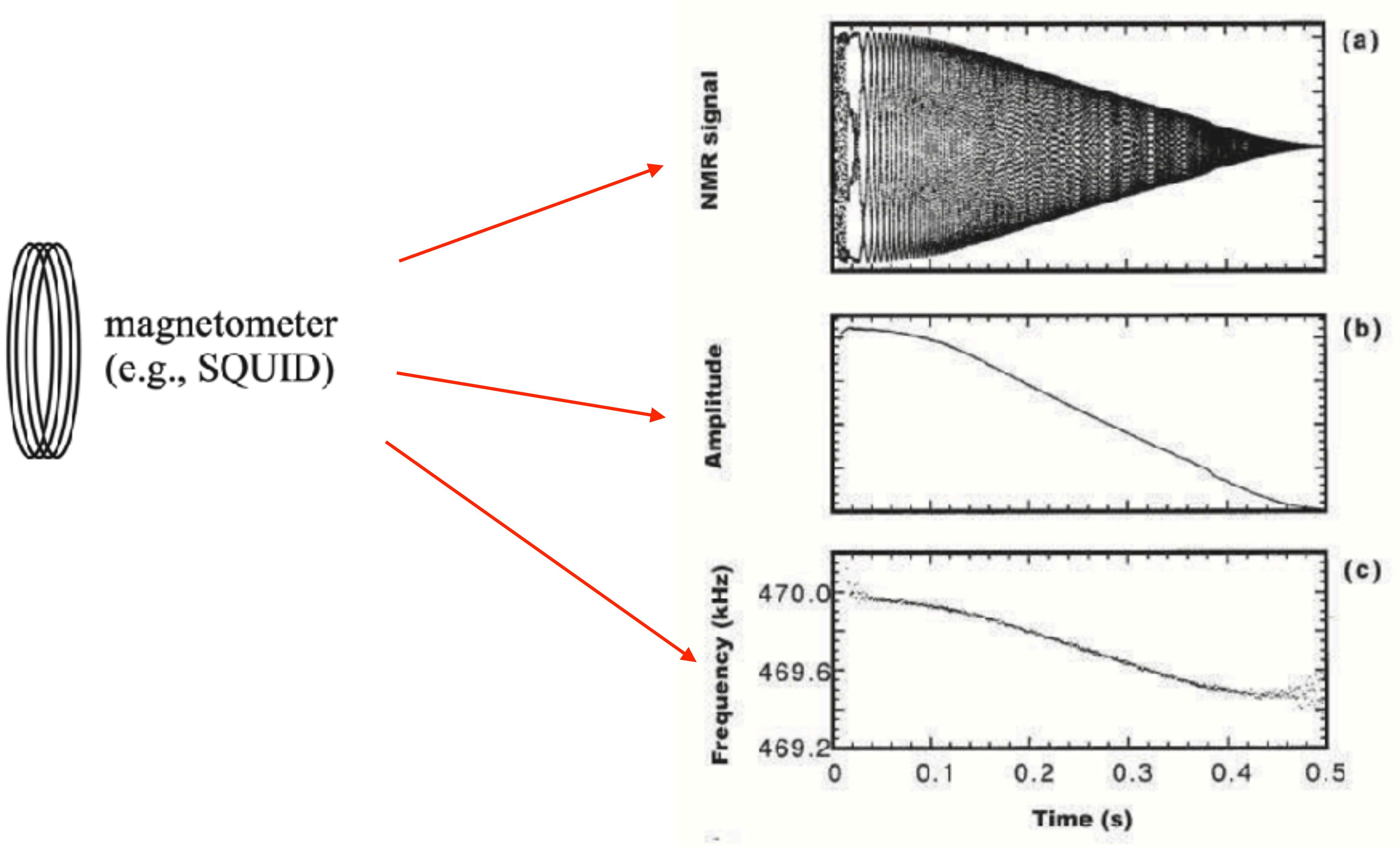




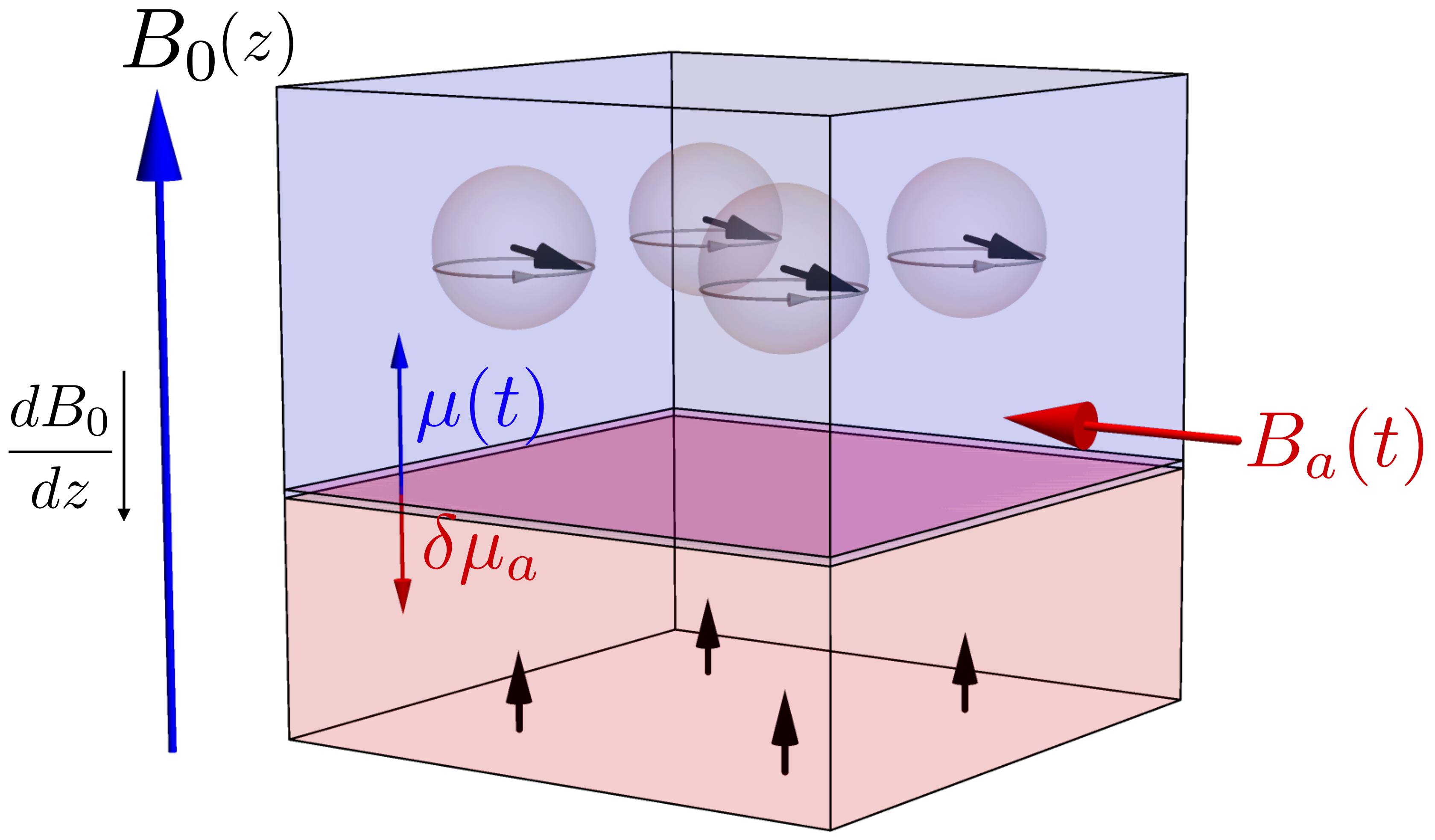
This behavior is known as the homogeneous precession domain (HPD)

Adding axions

Axions wind pumps magnons into HPD

$$\vec{B}_{a_{\rm DM}} \sim B_a \cos(m_a t + \phi)$$

$$\frac{1}{V_{\rm HPD}}\frac{dV_{\rm HPD}}{dt} \sim -\frac{1}{T_1} - B_a \cos(m_a t + \phi_a)\sin\left(\omega_L(t)t\right)$$

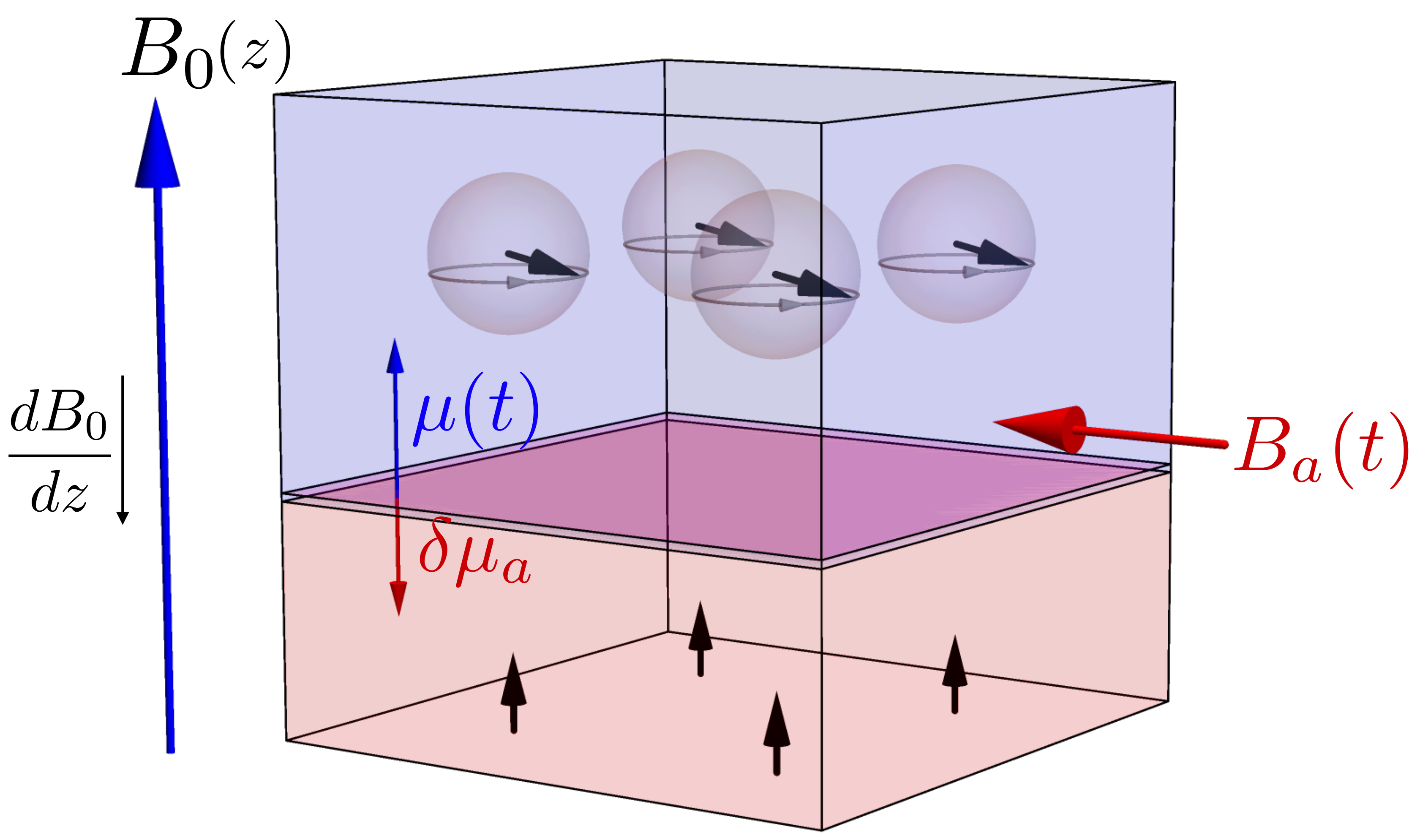


- No axion: $V \sim V_0 e^{-t/T_1}$

Assuming transverse axion wind

Axions wind pumps magnons into HPD

$$\vec{B}_{a_{\rm DM}} \sim B_a \cos(m_a t + \phi)$$



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- No axion: $V \sim V_0 e^{-t/T_1}$
- When $\omega_L(t) = m_a \pm \Delta m_a$

$$\Delta V_{\rm HPD}\Big|_{\rm resonance} \sim B_a \tau_a$$ axion coherence time

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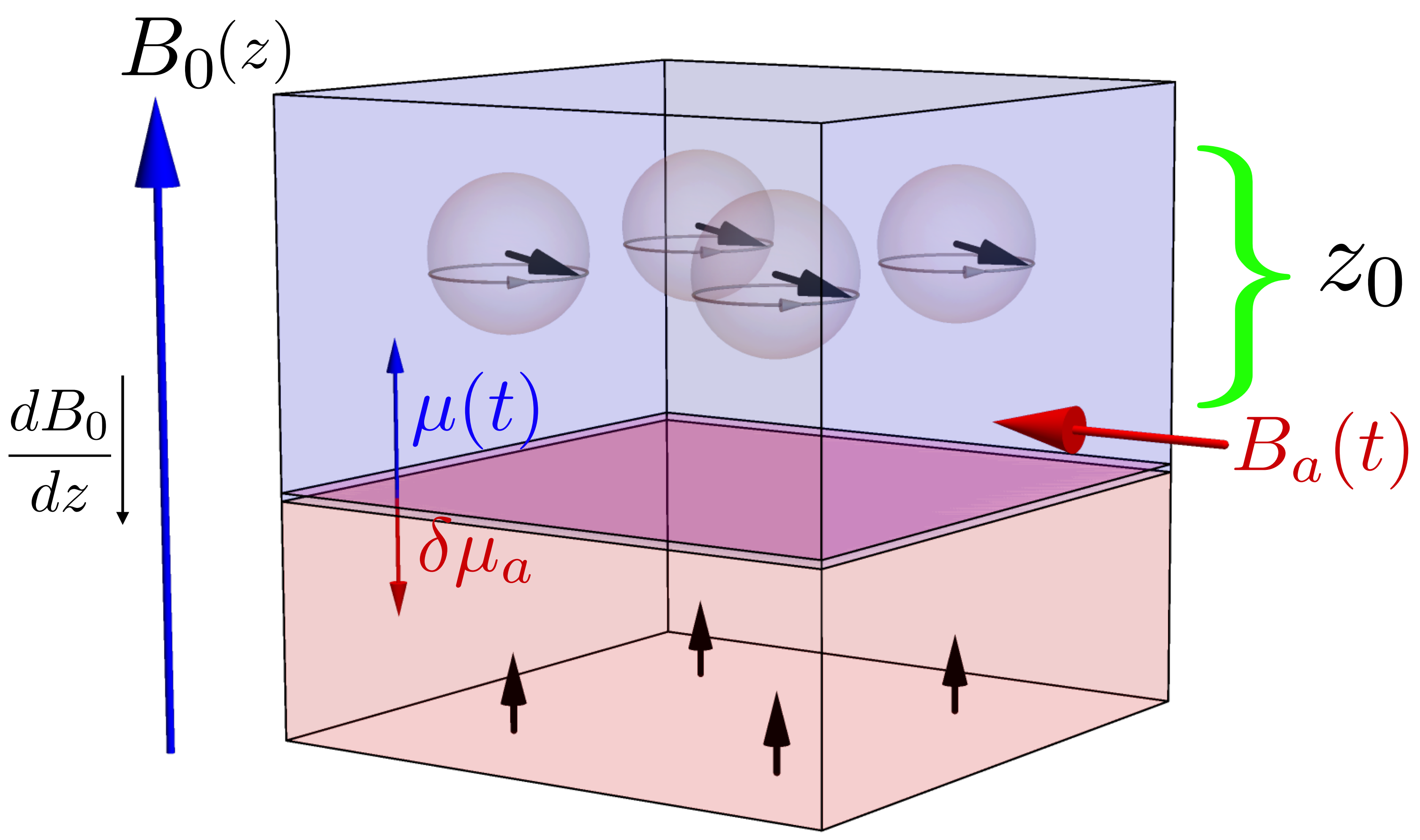

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- When $\omega_L(t) = m_a \pm \Delta m_a$

$$\Delta V_{\rm HPD}\Big|_{\rm resonance} \sim B_a \tau_a$$ axion coherence time

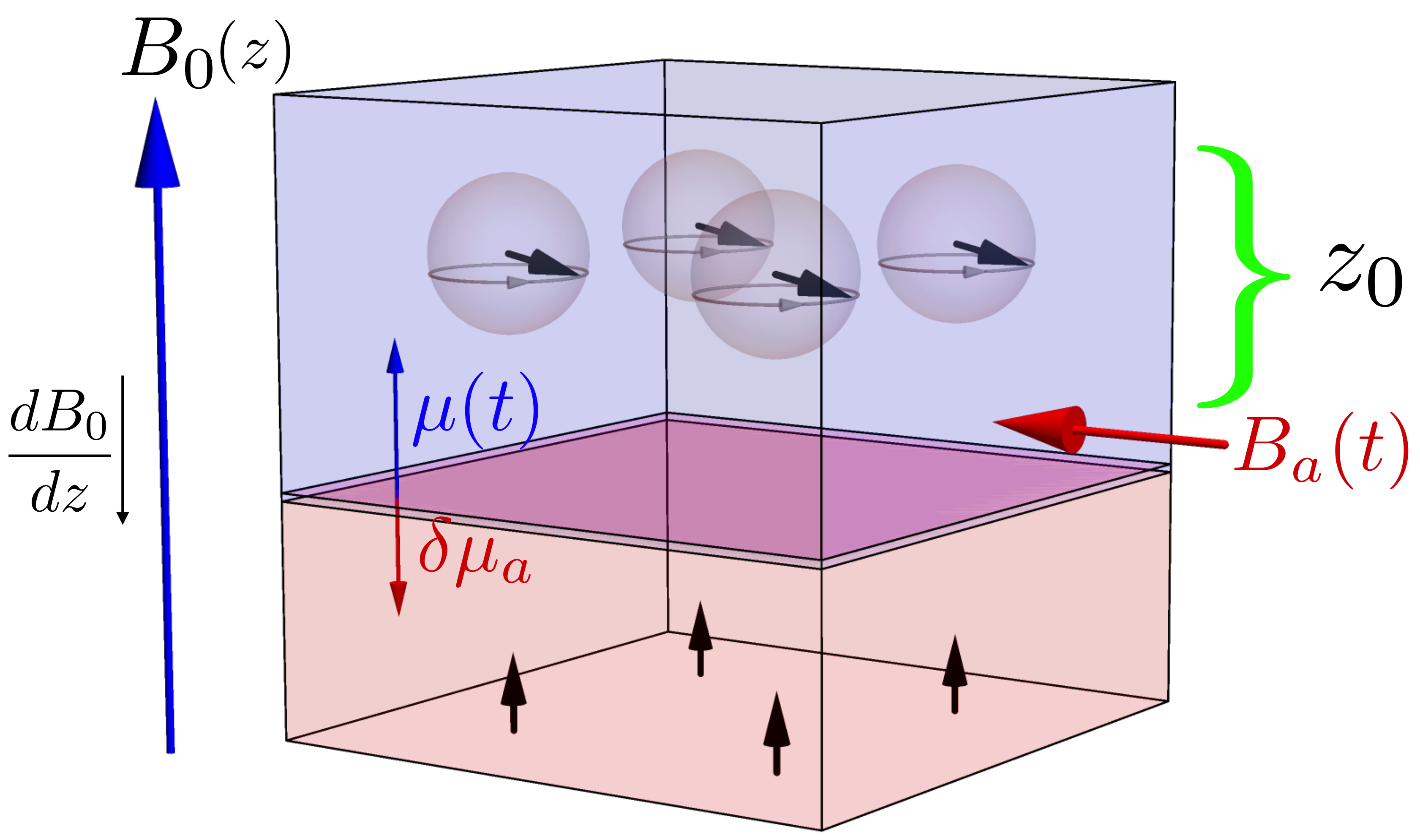
$$\Delta V_{\rm HPD} \rightarrow \Delta\omega_L \sim \omega_L \frac{z_0 \nabla_z B}{B_0} \frac{\Delta V_{\rm HPD}}{V_0}$$

Signal is a frequency shift

Signal $$\left.\frac{\Delta\omega}{\omega_0}\right|_{\rm DM} \sim g_{aN}\nabla a \frac{\partial_z B}{B_0} z_0 \tau_a$$

$$\vec{B}_{a_{\rm DM}} \sim B_a \cos(m_a t + \phi)$$

$$\sim 3 \times 10^{-13} \left(\frac{g_{aN}}{10^{-10}\text{GeV}^{-1}}\right)\left(\frac{10^{-7}\text{eV}}{m_a}\right)\left(\frac{z_0 \partial_z B/B_0}{0.02}\right)$$



Assuming transverse axion wind

Signal is a frequency shift

Signal $$\left.\frac{\Delta\omega}{\omega_0}\right|_{\rm DM} \sim g_{aN}\nabla a \frac{\partial_z B}{B_0} z_0 \tau_a$$

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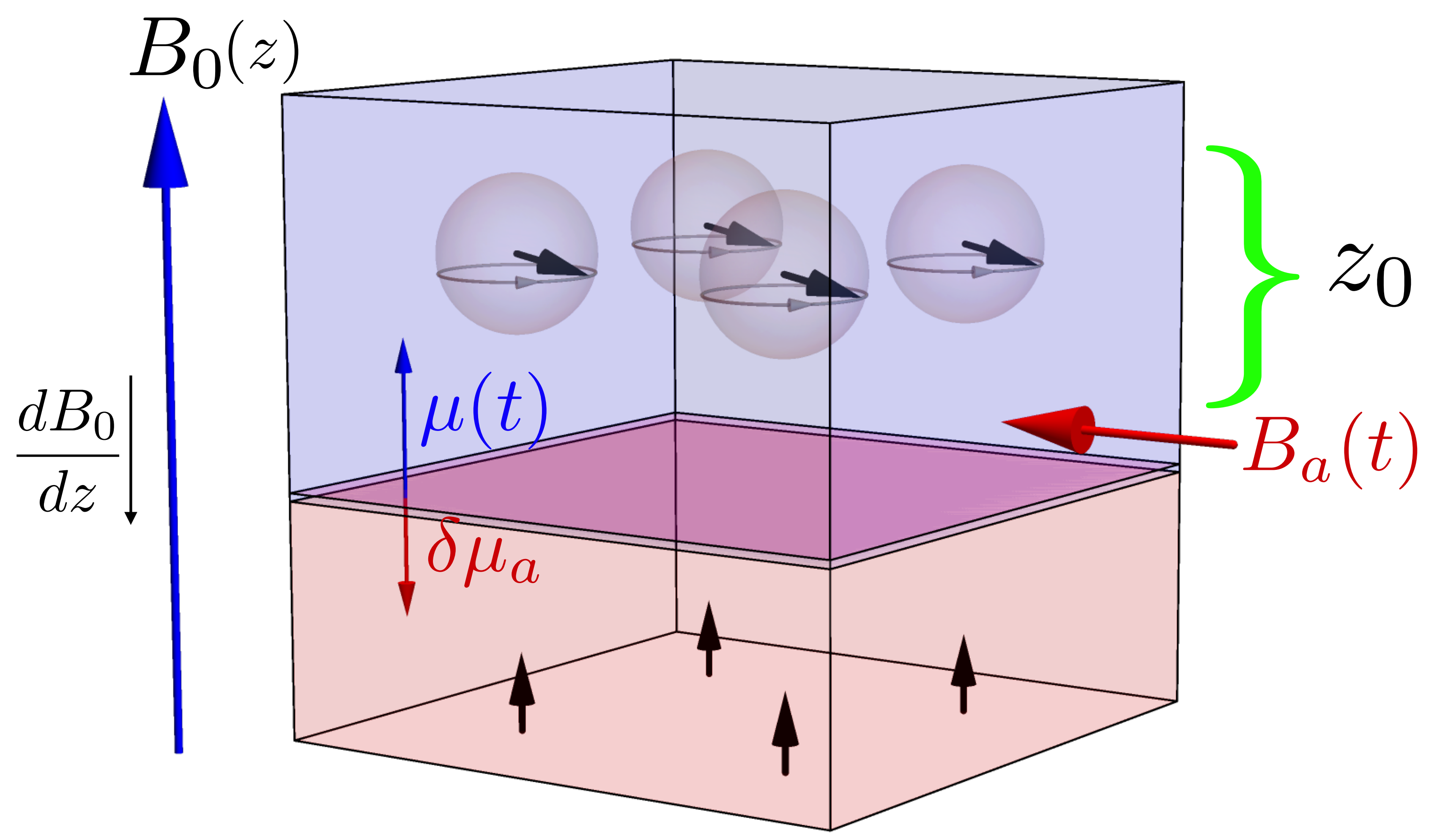
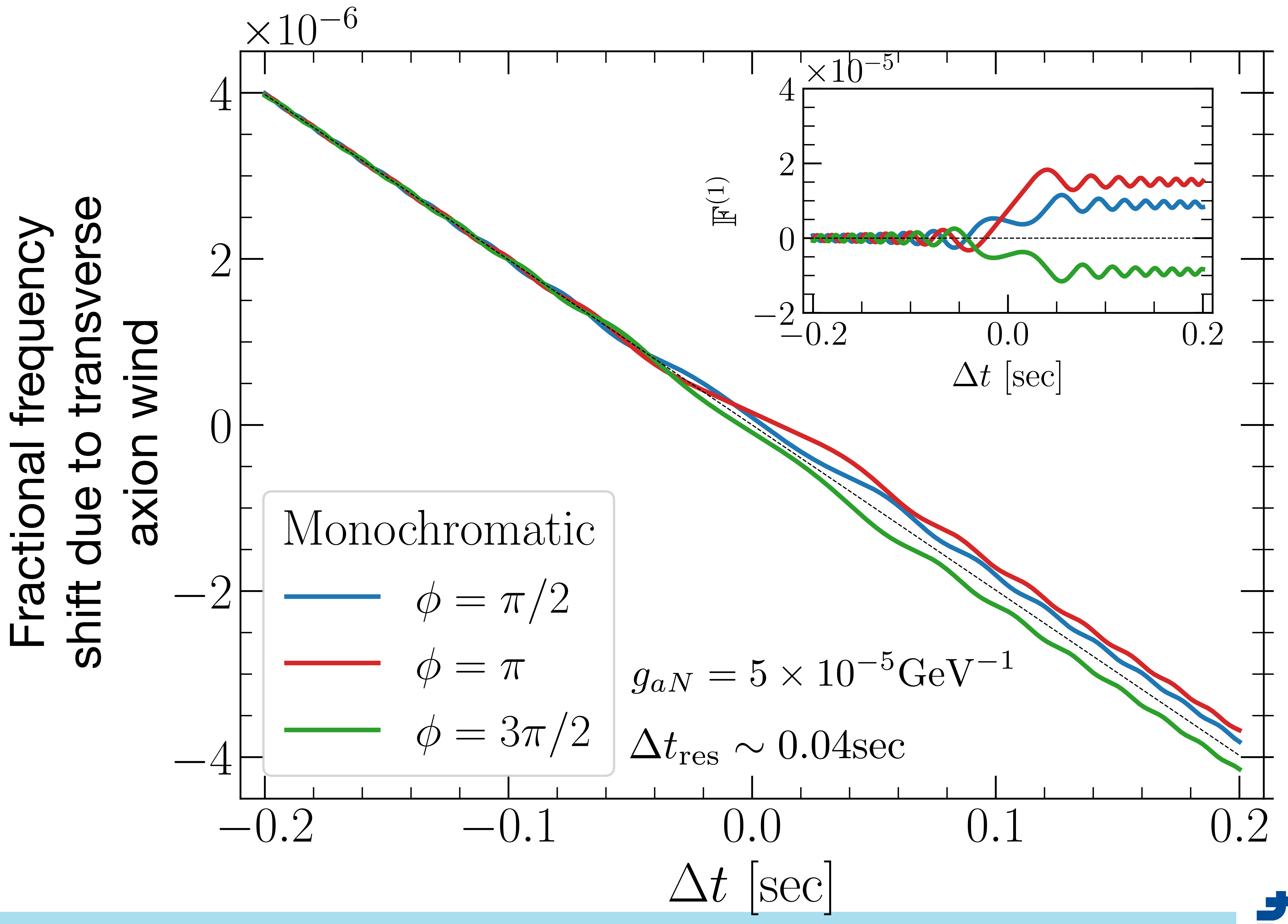


Assuming transverse axion wind



Statistical analysis (Ongoing work)

Fractional volume change due to axion wind

$$\frac{dx^{(1)}}{dt} \sim -B_a \cos(m_a t + \phi_a) \sin(\omega_L(t)t)$$

$$x^{(1)}(t, T_m) = g_{aN} \cos(\omega_\oplus T_m) \int_0^t dt' \nabla_\parallel a(t') \sin(\omega_L(t')t') + g_{aN} \sin(\omega_\oplus T_m) \int_0^t dt' \nabla_\perp a(t') \sin(\omega_L(t')t')$$

Assume Standard Halo Model $\langle x^{(1)}(t) \rangle = 0$

Statistical analysis (Ongoing work)

Fractional volume change due to axion wind

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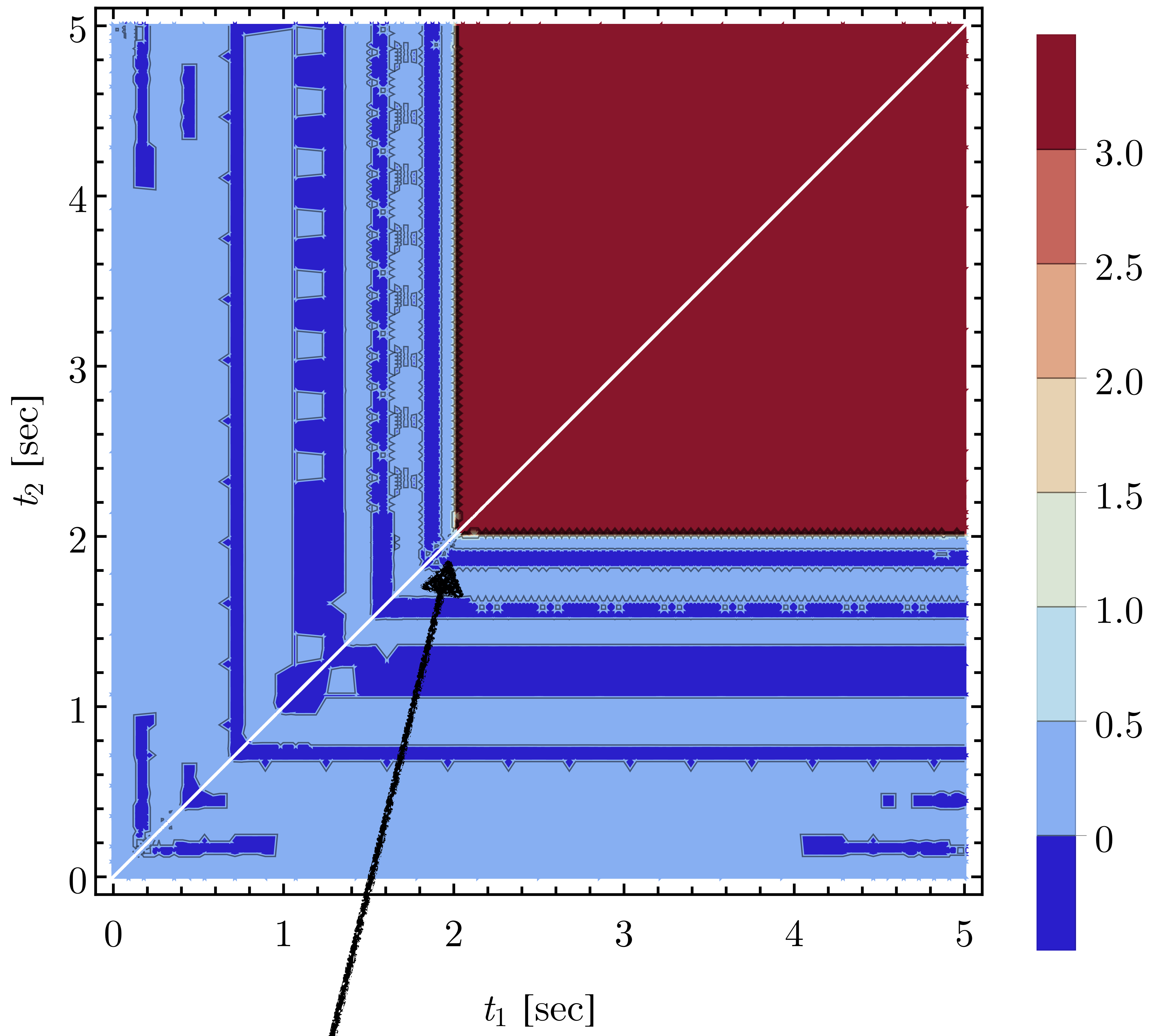
Assume Standard Halo Model $\langle x^{(1)}(t) \rangle = 0$

$\langle x^{(1)}(t_1) x^{(1)}(t_2) \rangle$



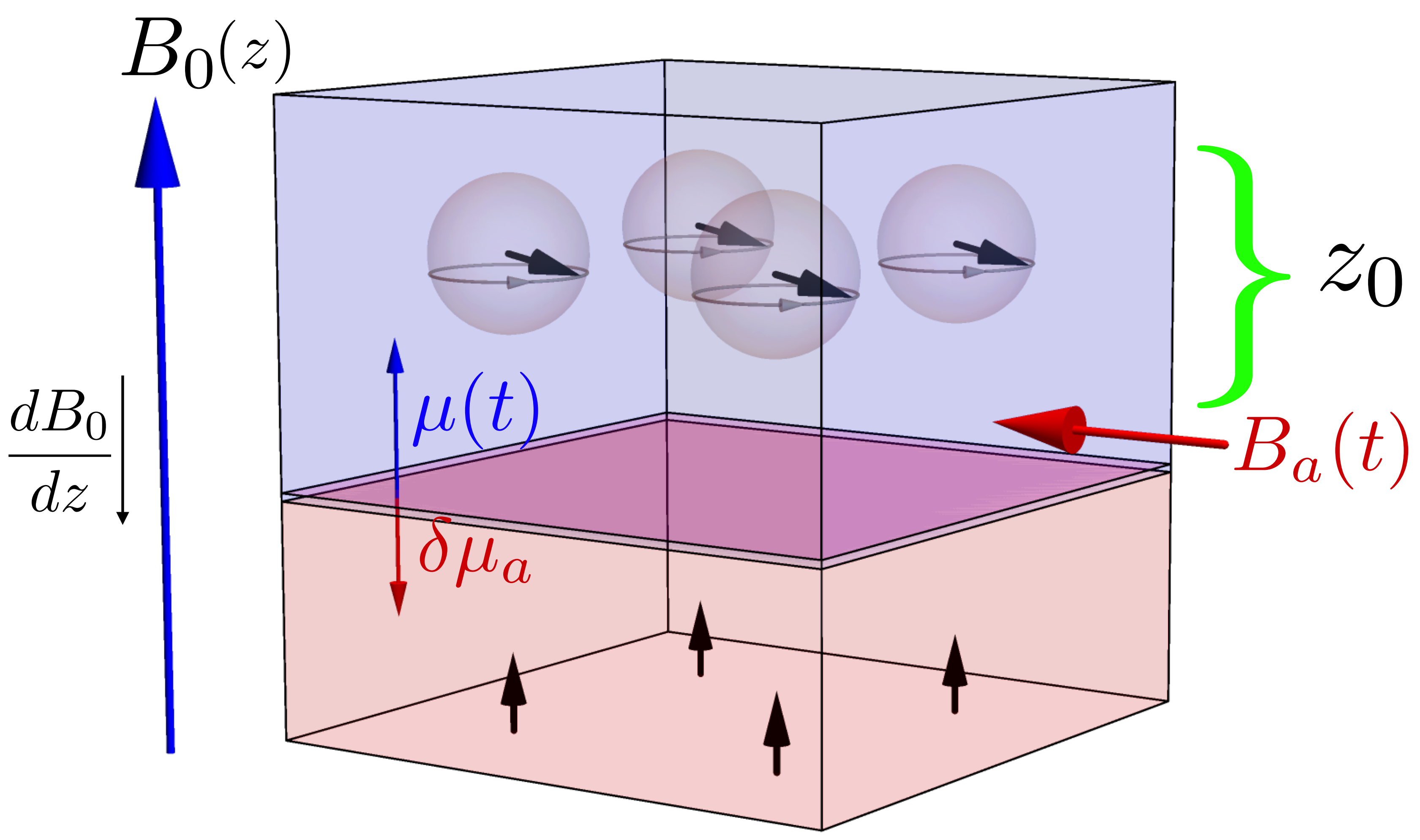
Resonance occurs

$\tau_a \sim 0.04\text{sec}$

Scan axion mass

$$\frac{dx^{(1)}}{dt} \sim -B_a \cos(m_a t + \phi_a) \sin\left(\omega_L(t) t\right)$$

$$\omega_L = \gamma B(z_{\rm wall}) \sim \omega_L^0 \left(1 - \frac{z_0 \partial_z B}{B_0} \frac{t}{T_1}\right)$$



- Decay of HPD naturally sweeps through many axion masses.

$$\frac{\omega_L(0) - \omega_L(T_1)}{\Delta m_a} \sim 10^6 \frac{z_0 \partial_z B}{B_0} \sim 10^4$$

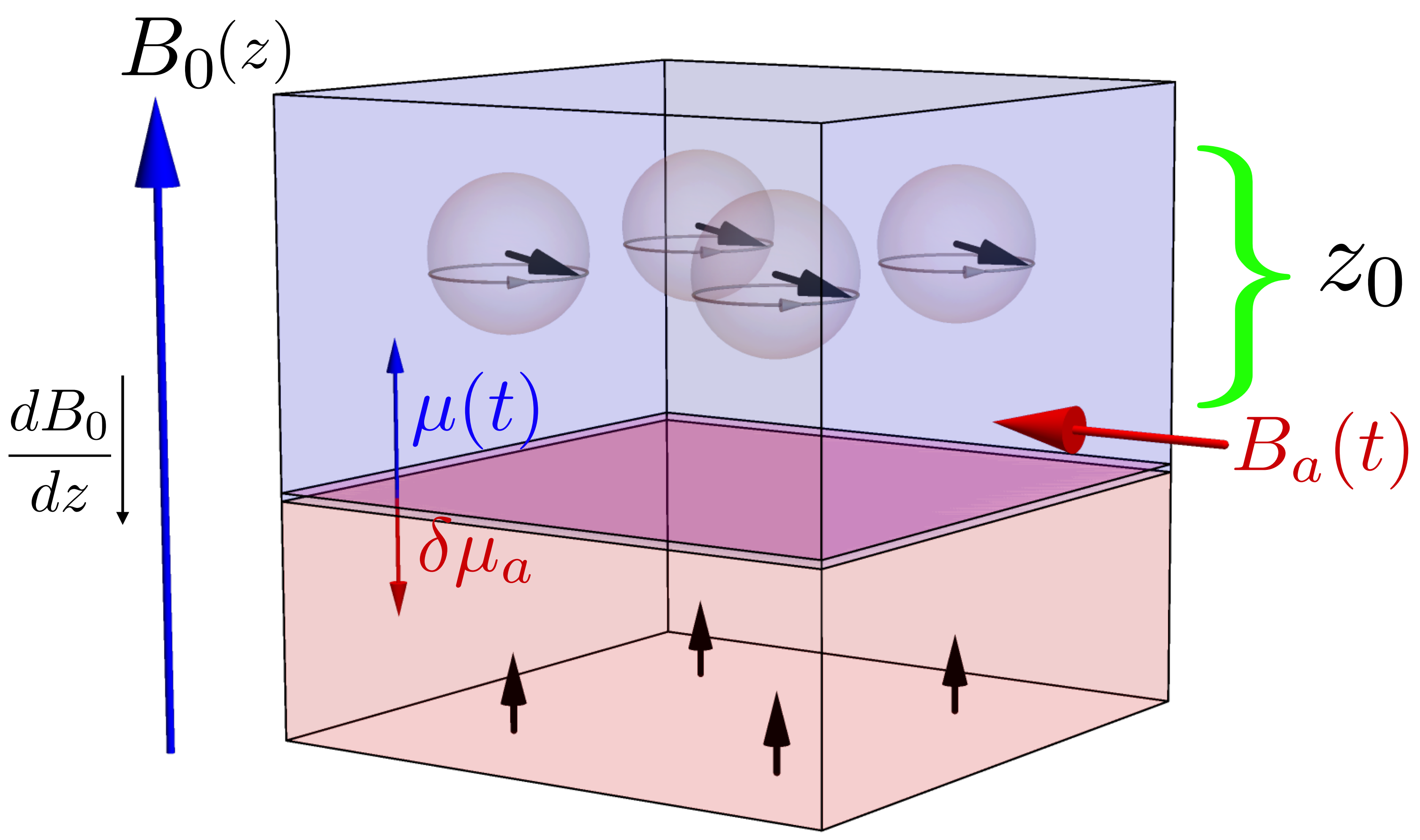
Signal to noise

$$\frac{dx^{(1)}}{dt} \sim -B_a \cos(m_a t + \phi_a) \sin\left(\omega_L(t) t\right)$$

Signal $\quad \Delta\omega_a^2 \sim \rho_a v_0^2 g_{aN}^2 \omega_L T_1 \alpha$ $\qquad \alpha \equiv \frac{z_0 \partial_z B}{B_0}$

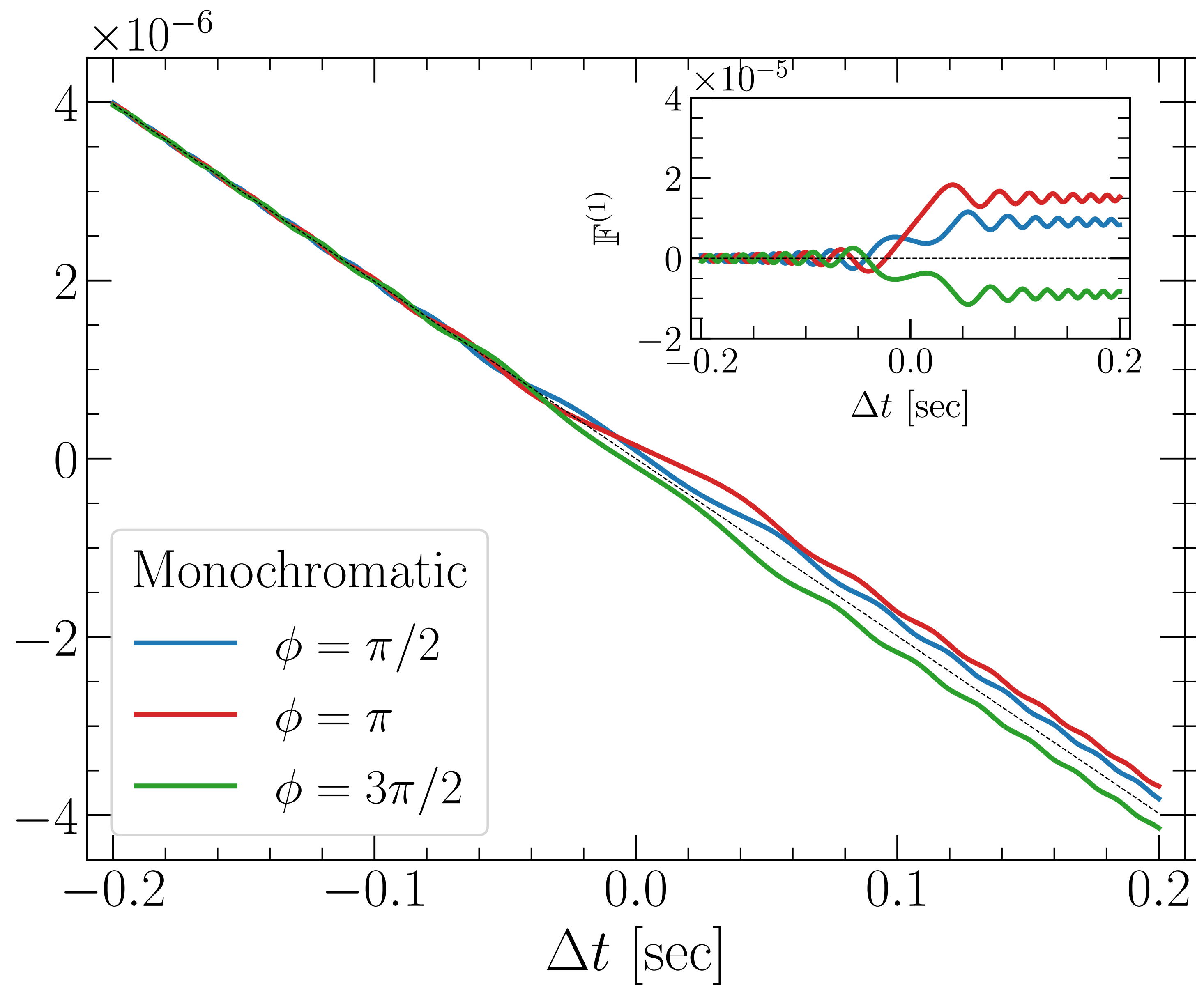
Noise $\quad \Delta\omega_{\rm bkg}^2 \sim \frac{1}{N_0} \omega_L^2 \alpha^2$

Assume poisson noise in magnon number N_0

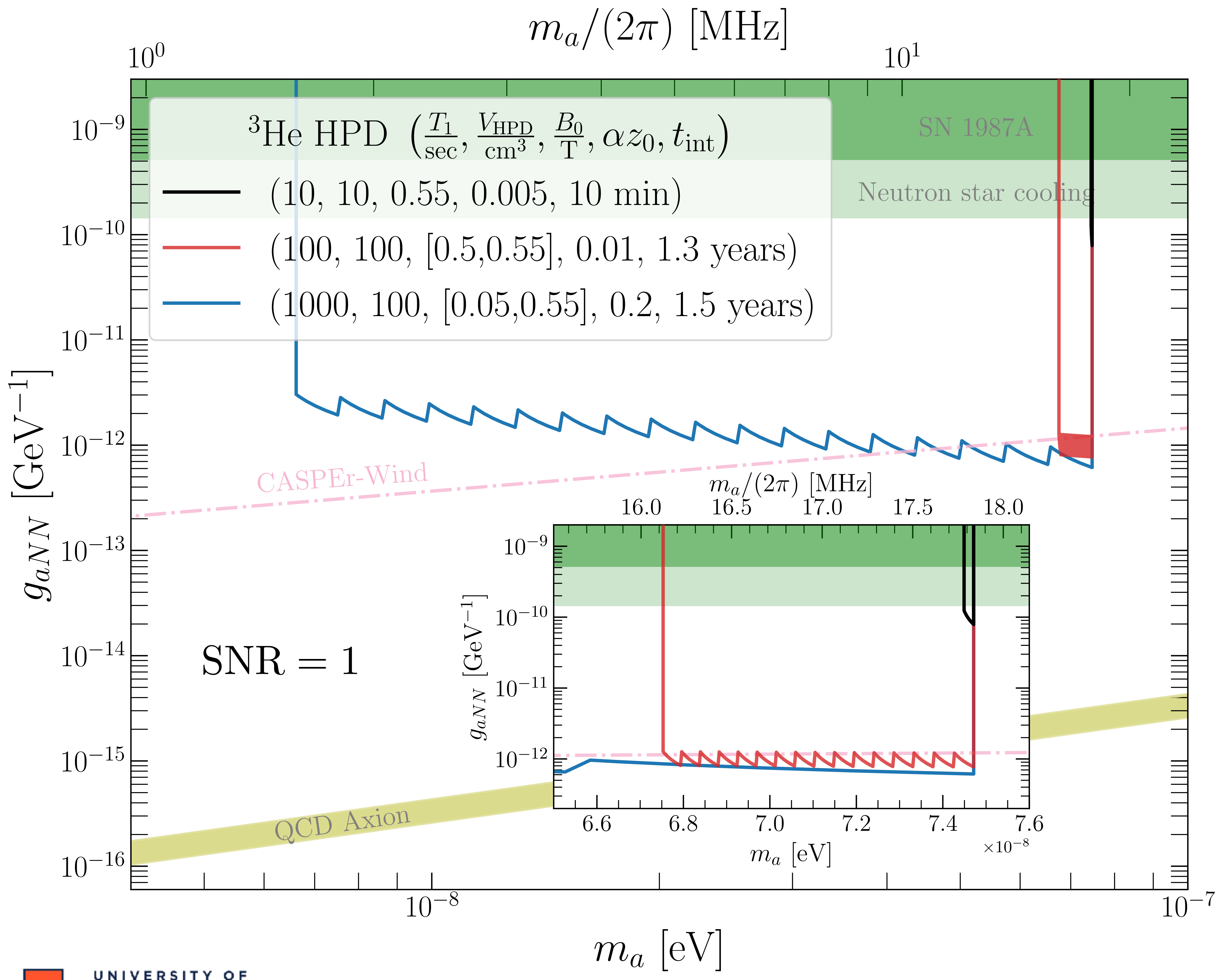


$$\mathrm{SNR} \sim \mathcal{N}^{1/2} \sqrt{\frac{\Delta\omega_a^2}{\Delta\omega_{\rm bkg}^2}}$$

$\mathcal{N}$ = number of measurements



Axion nucleon coupling limit



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

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

- $B_0 \lesssim 0.55\text{T}$ to prevent $^3\text{He} - \text{B}$ from destabilization
- Very compelling reach even with a conservative setup
- More rigorous treatment ongoing, stay tuned!

NMR: axion DM search

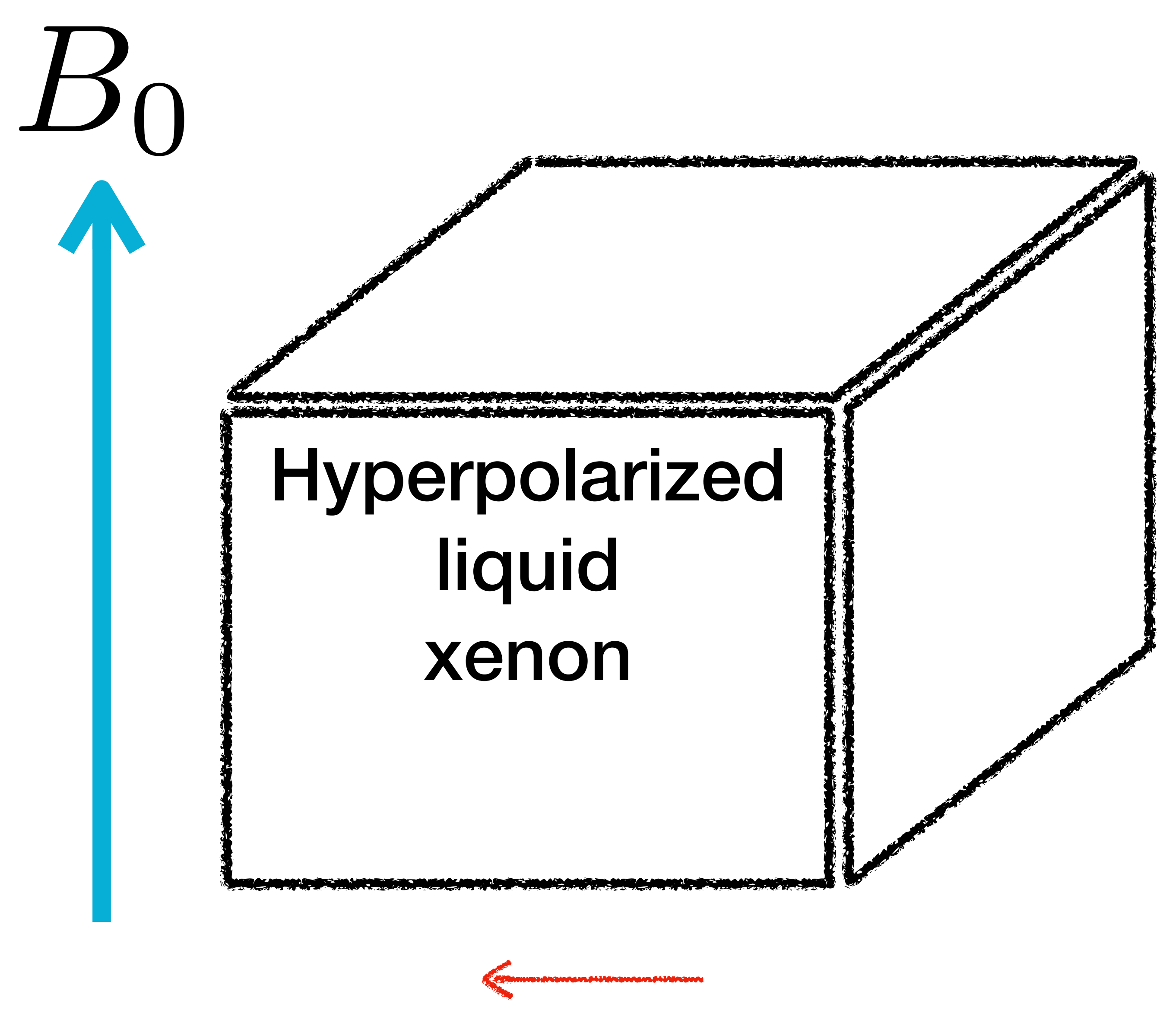
- Tune B_0 to match axion mass with Larmor frequency ω_L Graham, Rajendran (2013)

- CASPEr-ZULF- comagnetometer

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

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

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



$$B_{a_{\mathrm{DM}}} \sim \sin(m_a t)$$