Axion detection using Helium-3

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Abstract

Strong CP problem

Dark Matter

Hypothetical particle

Axion

Interacts with **nucleons** (e.g. neutrons, protons)

What we have shown

Axion-**neutron** interaction can be probed via a ferromagnetic phase of **superfluid ^{3}He**

+

Evaluate application of **quantum measurement**

Contents

1. **Introduction**
   - Theory of axion
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   - Superfluid Helium-3
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   - Mixing between magnon and cavity photon
   - Quantum measurement techniques
3. **Result**
   - Constraint on axion-neutron coupling by our method

Axion

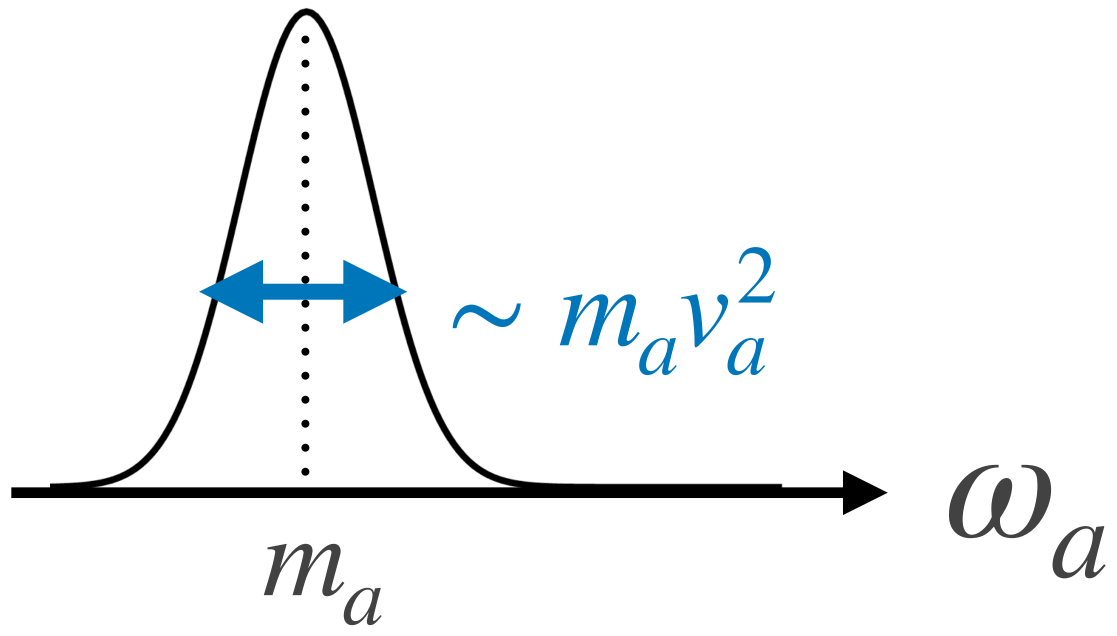
- Quantum chromodynamics (QCD) has a problem of unnaturalness
  - **Strong CP problem**
- This can be solved by introducing an additional symmetry $\mathrm{U}(1)_{\mathrm{PQ}}$
  - Spontaneous symmetry breaking of $\mathrm{U}(1)_{\mathrm{PQ}}$ generates a (pseudo-)Nambu-Goldstone boson = **Axion**
- Axion is also a candidate for **Dark Matter** (DM) because it has mass m_a
- $m_a = O(1 - 10)\,\mu\mathrm{eV}$ is favored for DM axion

Axion as Dark Matter

- DM axion is non-relativistic and light ($\sim \mu$eV)
  - behaves like classical waves oscillating coherently

$$a(t,\vec{x}) = A\sin[\omega_a(t - \vec{v}_a\cdot\vec{x}) + \varphi]$$

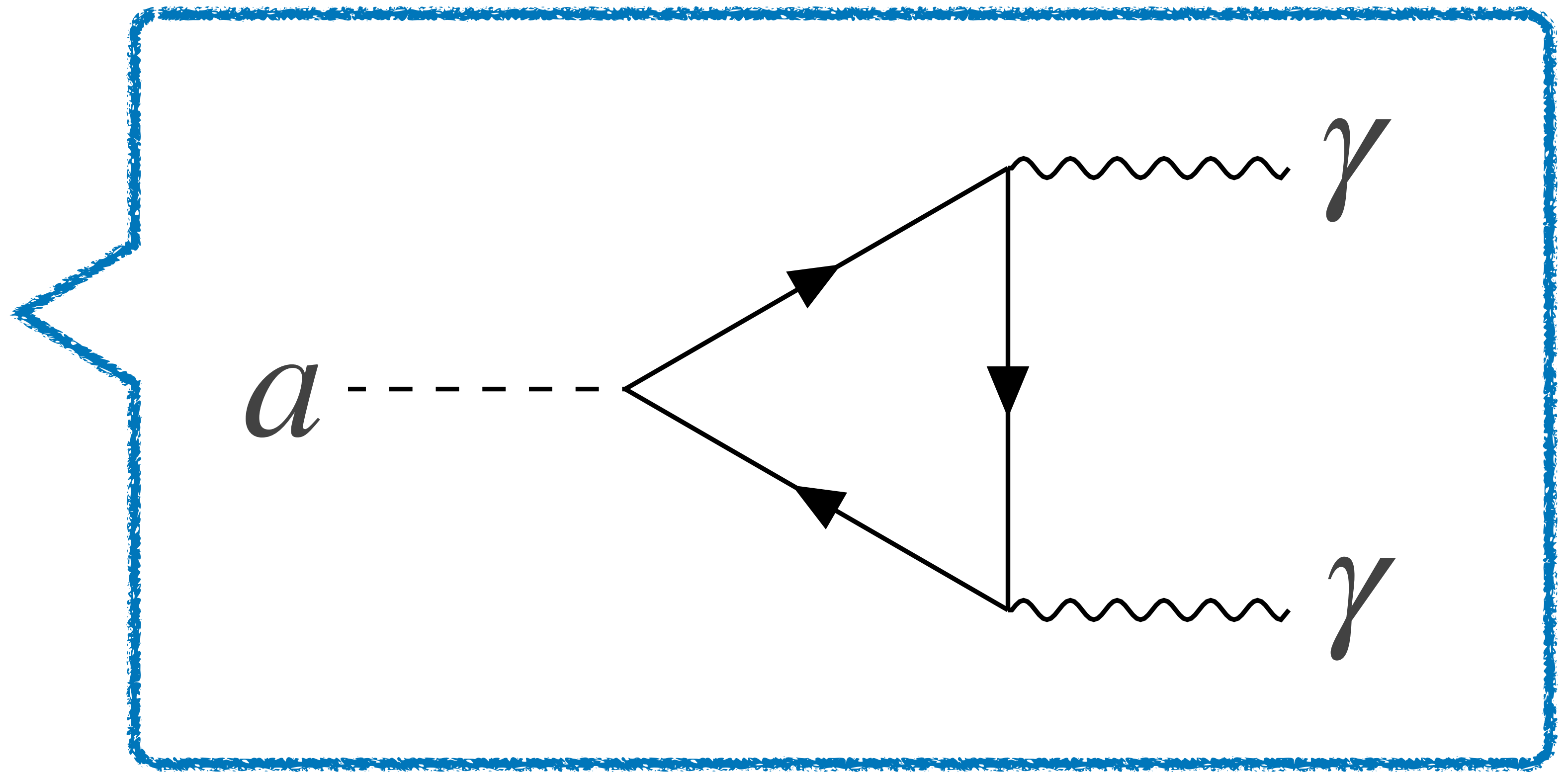
  - Angular momentum: $\omega_a \simeq m_a + m_a v_a^2/2 \simeq m_a \quad (\because v_a \sim 10^{-3})$
- Coherence length $\simeq (m_a v_a)^{-1} \sim \mathrm{km} \gg$ typical laboratory size
- Coherence time $\simeq (m_a v_a^2)^{-1} \sim \mathrm{msec}$



Interaction between axion and Standard Model particles

- Photon

$$-\frac{1}{4}g_{a\gamma\gamma}\,a\tilde{F}^{\mu\nu}F_{\mu\nu} = g_{a\gamma\gamma}\,a\,\overrightarrow{E}\cdot\overrightarrow{B}$$

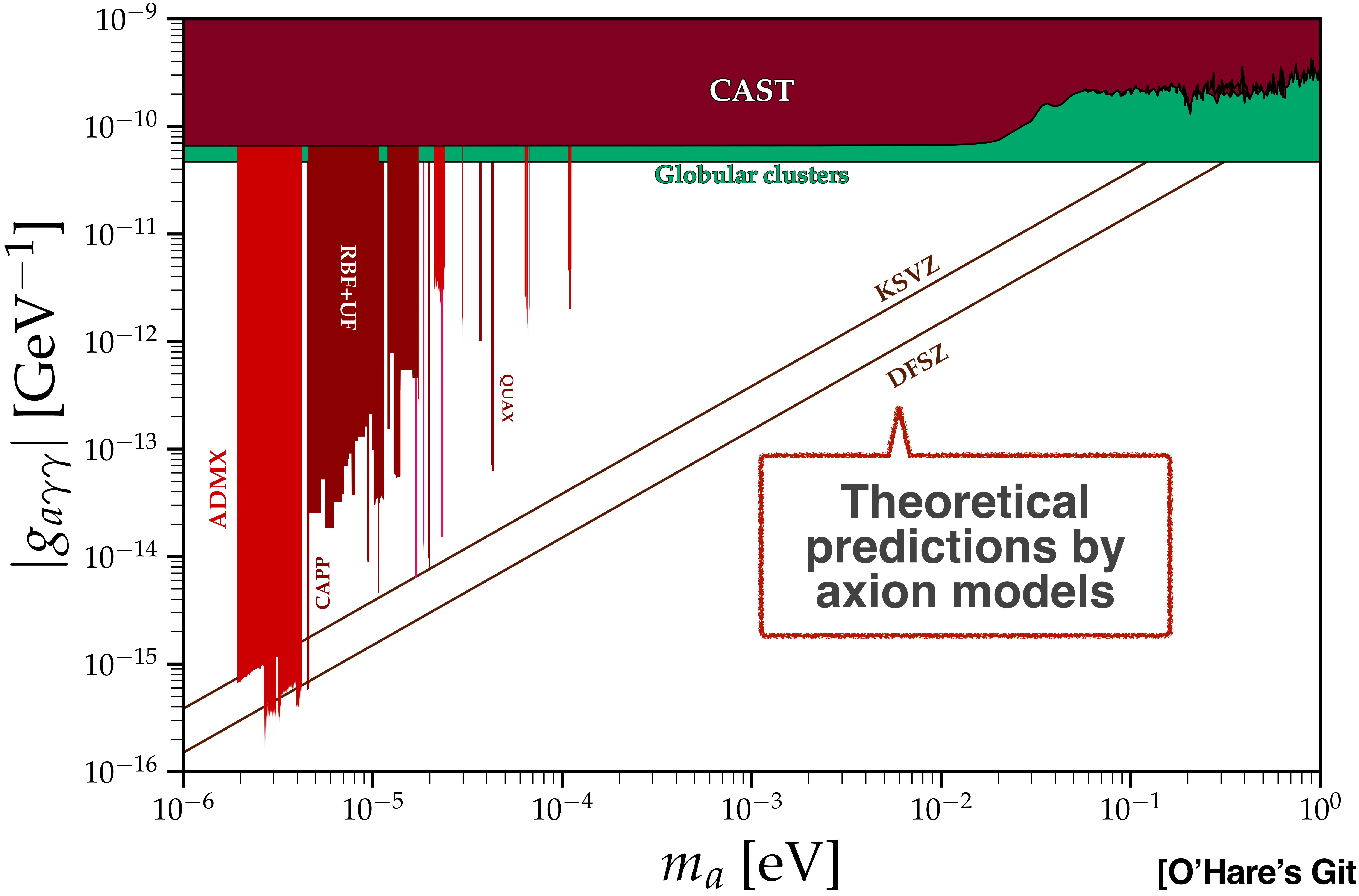


- Fermion

$$\frac{g_{aff}}{2m_f}(\partial^\mu a)\bar{\Psi}_f\gamma^\mu\gamma^5\Psi_f \xrightarrow{\text{non-relativistic limit}} -\frac{g_{aff}}{m_f}\overrightarrow{\nabla}a\cdot\vec{s}_f$$

($\vec{s}_f$: spin of fermion f)

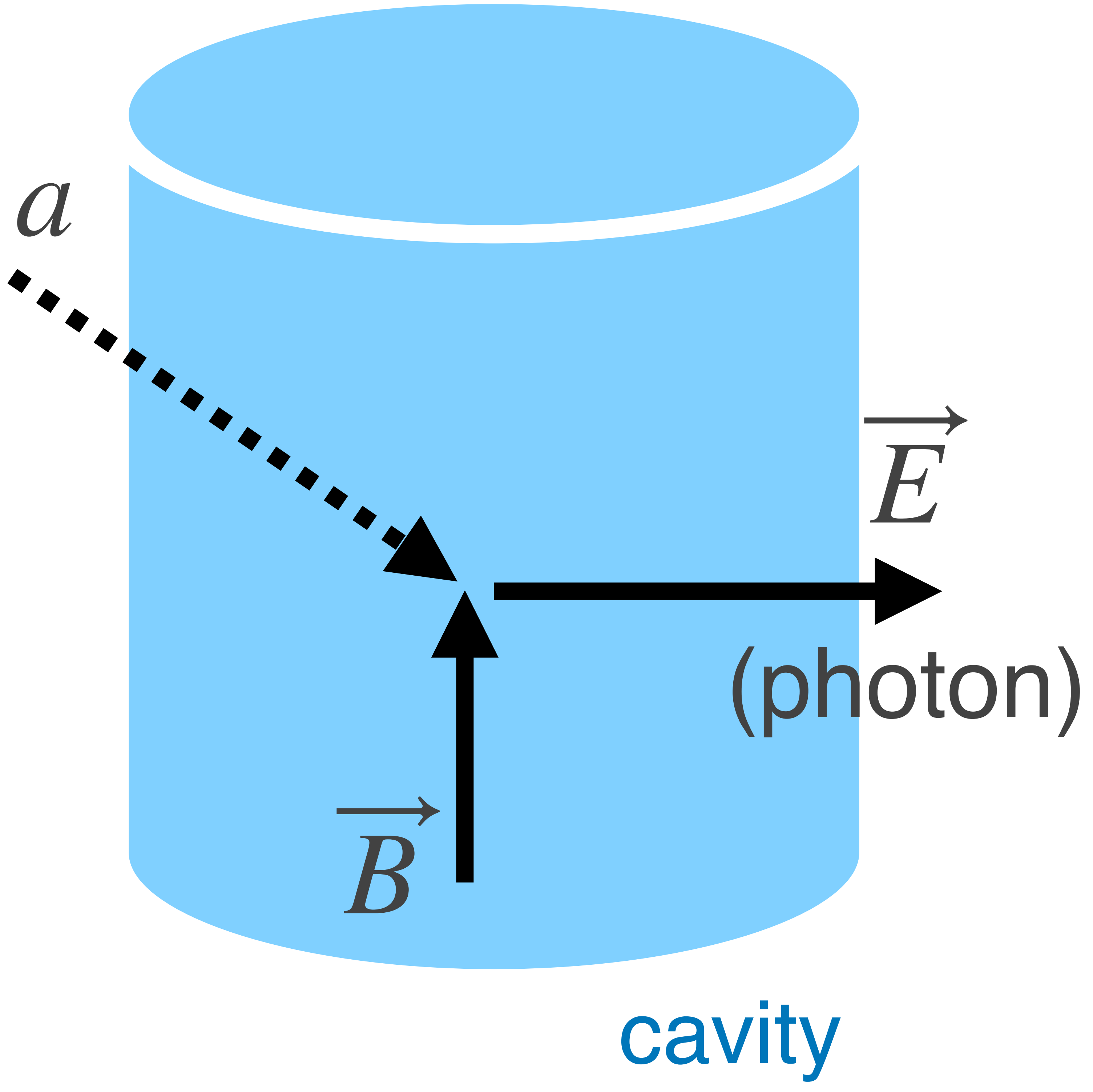
Constraints on axion-photon coupling



Theoretical predictions by axion models

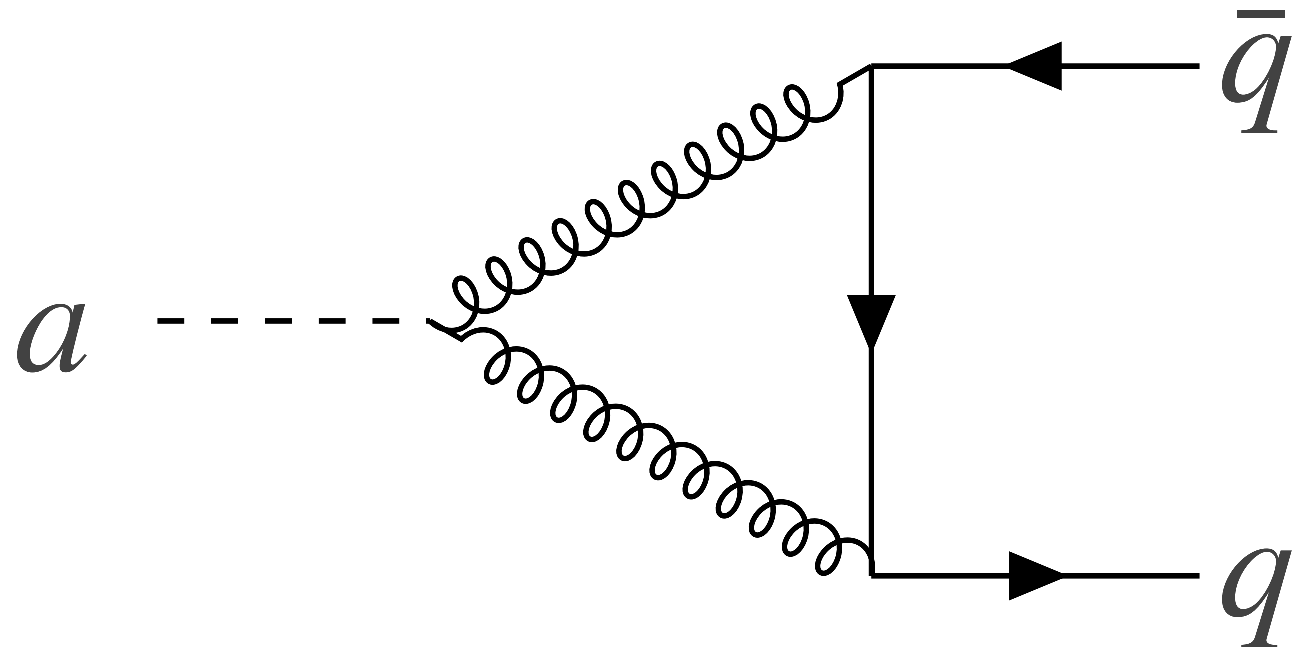
[O'Hare's GitHub]

$$g_{a\gamma\gamma}\, a\, \vec{E} \cdot \vec{B}$$



Axion-nucleon coupling

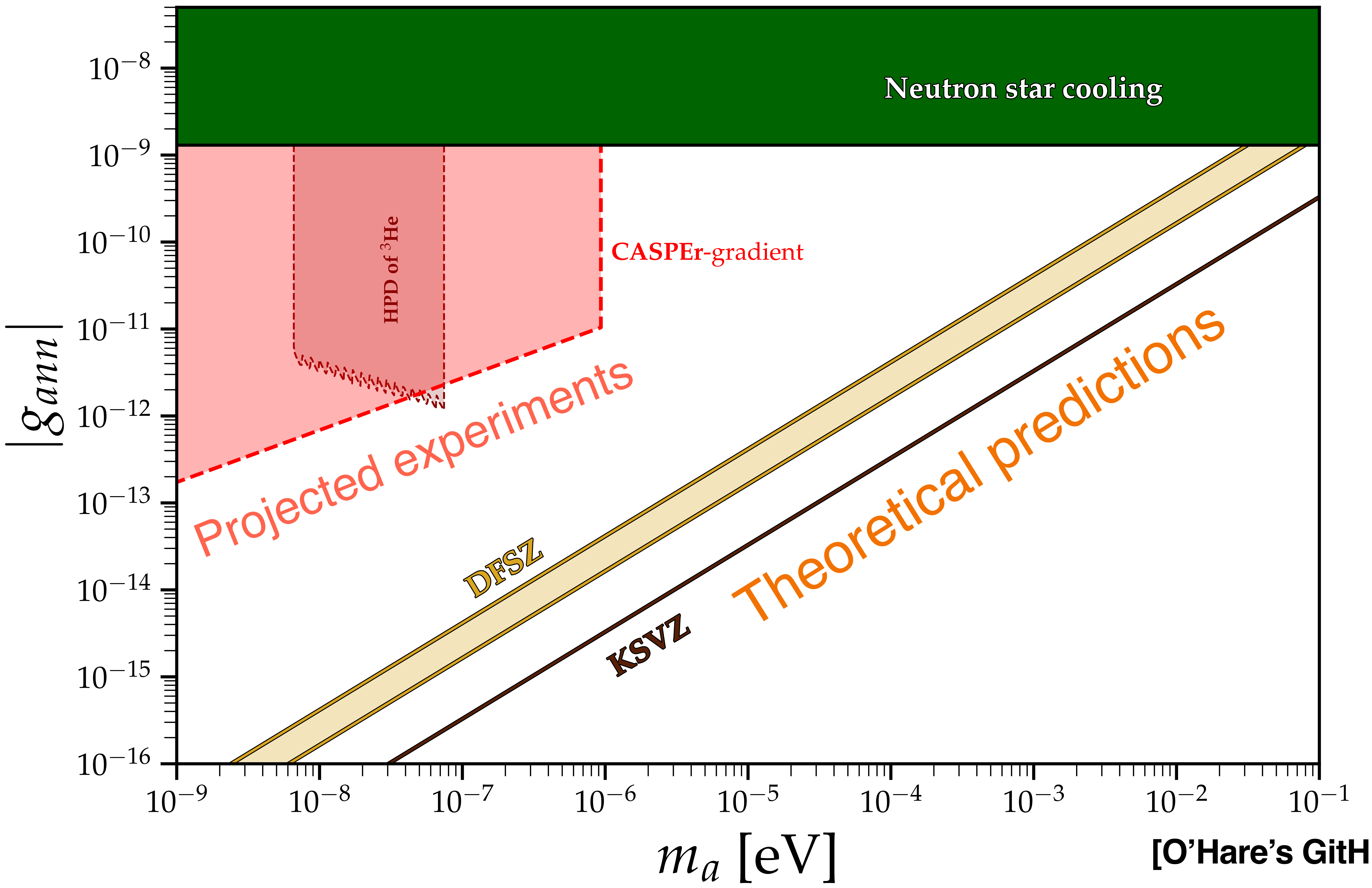
- Axion-**nucleon** coupling is an important property of axion



▷ $$\frac{g_{aNN}}{m_N}\vec{\nabla} a \cdot \vec{s}_N$$

  - Interaction with nucleons is crucial for axions, which is directly related to strong interaction
  - This coupling is **less model-dependent** than other couplings with photons or electrons
- However, axion-nucleon coupling has not been well probed

Constraints on axion-neutron coupling



[O’Hare’s GitHub]

$$\boxed{\frac{g_{ann}}{m_n}\vec{\nabla} a \cdot \vec{s}_n}$$

We propose a new experiment

to explore axion-neutron coupling

using superfluid Helium-3

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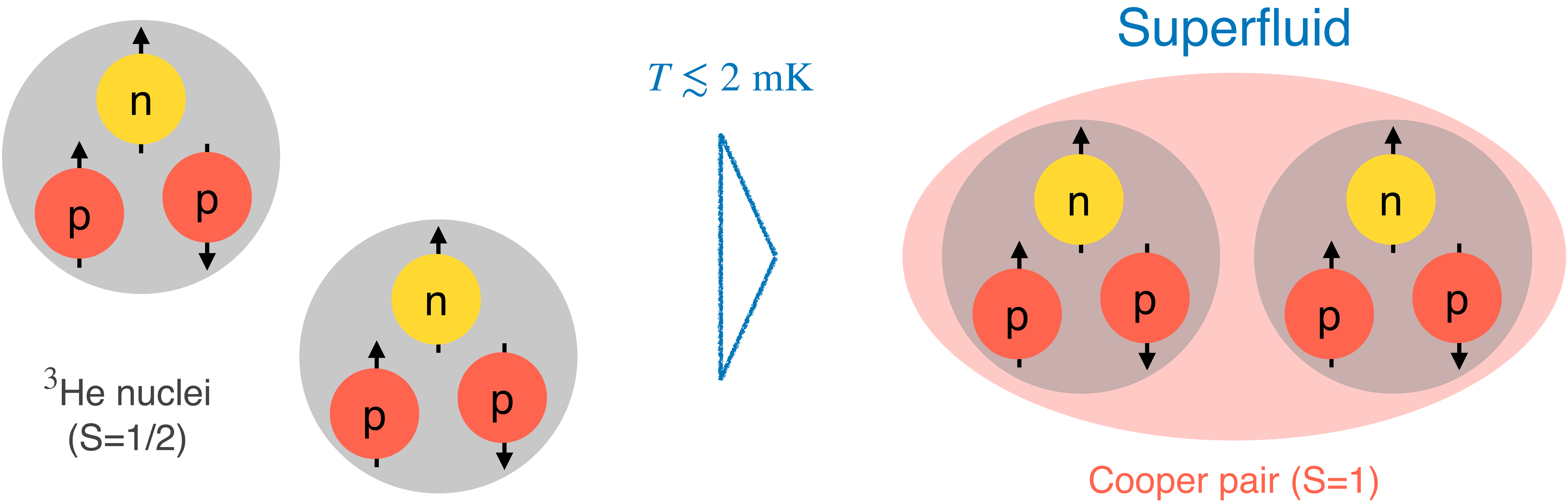
Superfluid Helium-3

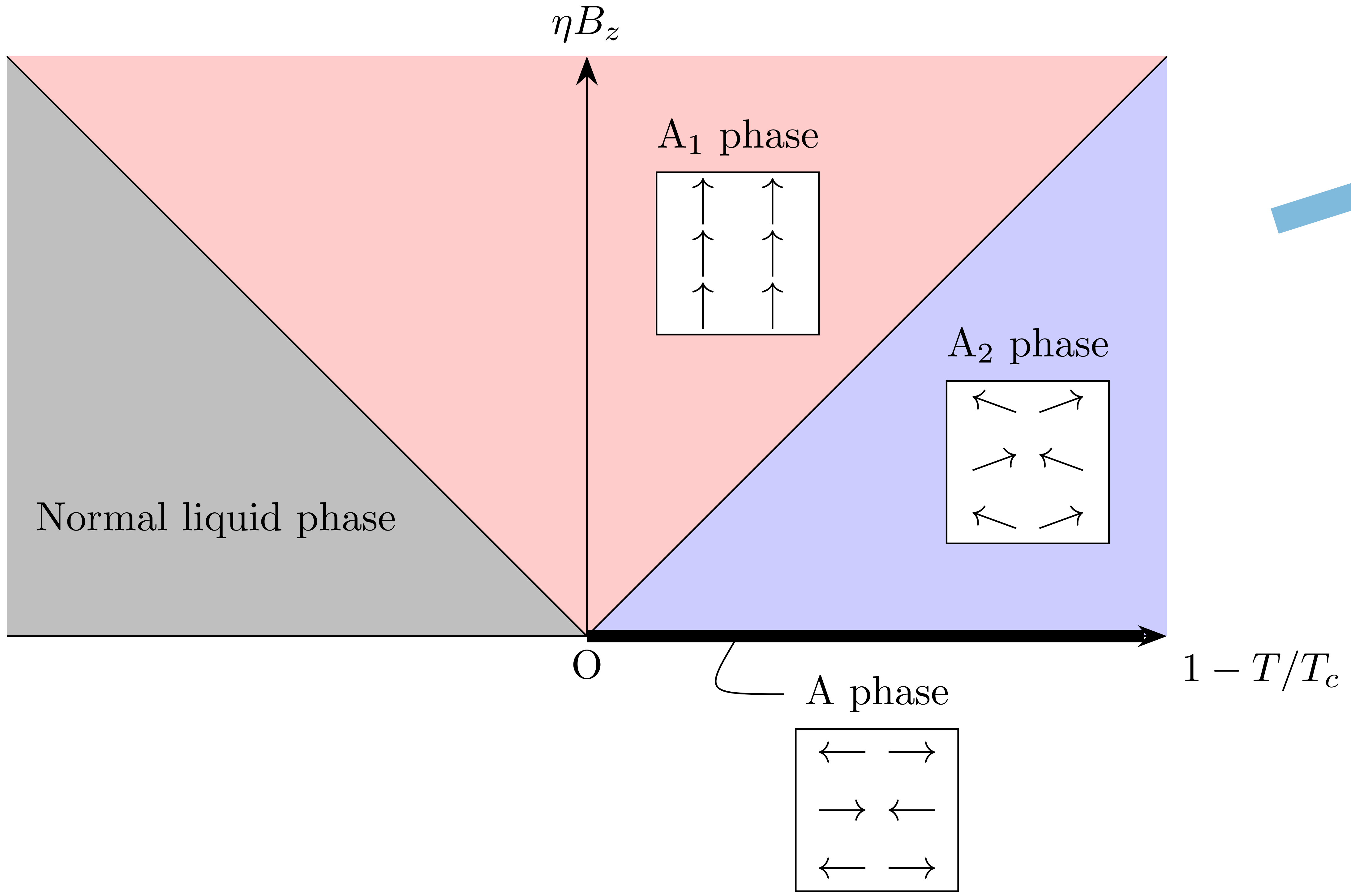


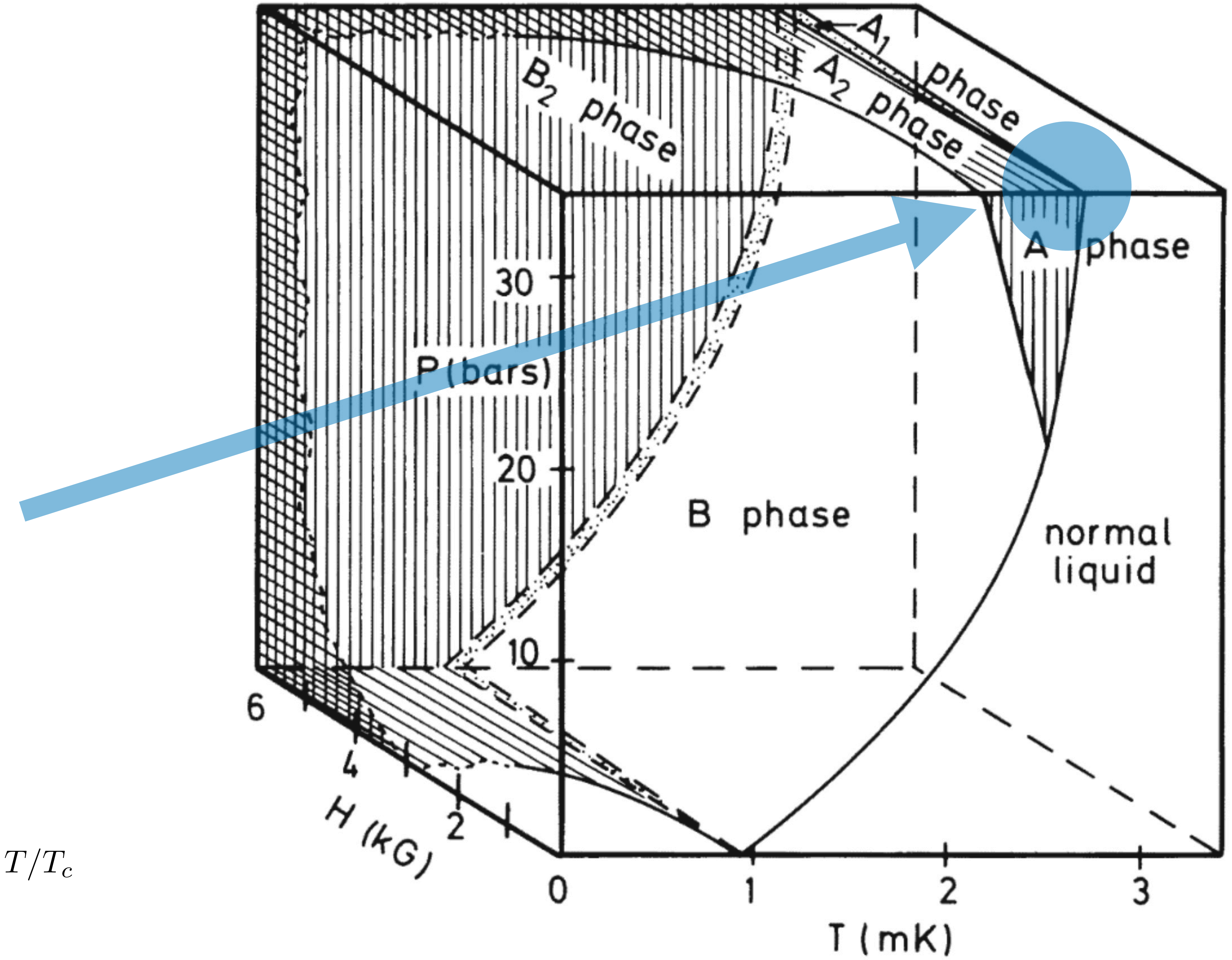
Spins of protons and electrons are canceled

- Interaction between axion & ^{3}He $\simeq$ interaction between axion & **neutron**

A1 phase of superfluid ^{3}He

- **Ferromagnetic** for nuclear spin
    - Spin polarization ~ few %
- has a **magnon** mode

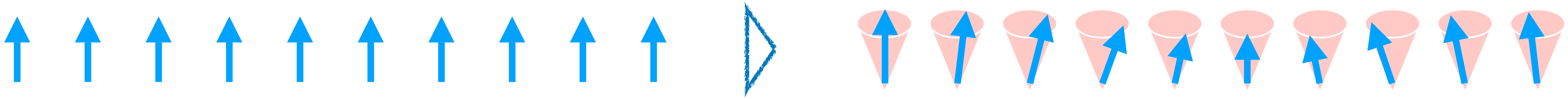




[D. Vollhardt, P. Wölfle and R.B. Hallock (1990)]

Magnon

- Quasiparticle (collective excitation) of the spin structure



- Example: ferromagnet
  - Ground state $\langle S_z \rangle \neq 0$
    $\Leftrightarrow$ spin-rotation symmetries along x, y axes are spontaneously broken
  - Two broken generators S_x and S_y: $\langle [S_x, S_y] \rangle \propto \langle S_z \rangle \neq 0$
  - One "Type-B" Nambu-Goldstone mode = gapless **magnon** mode

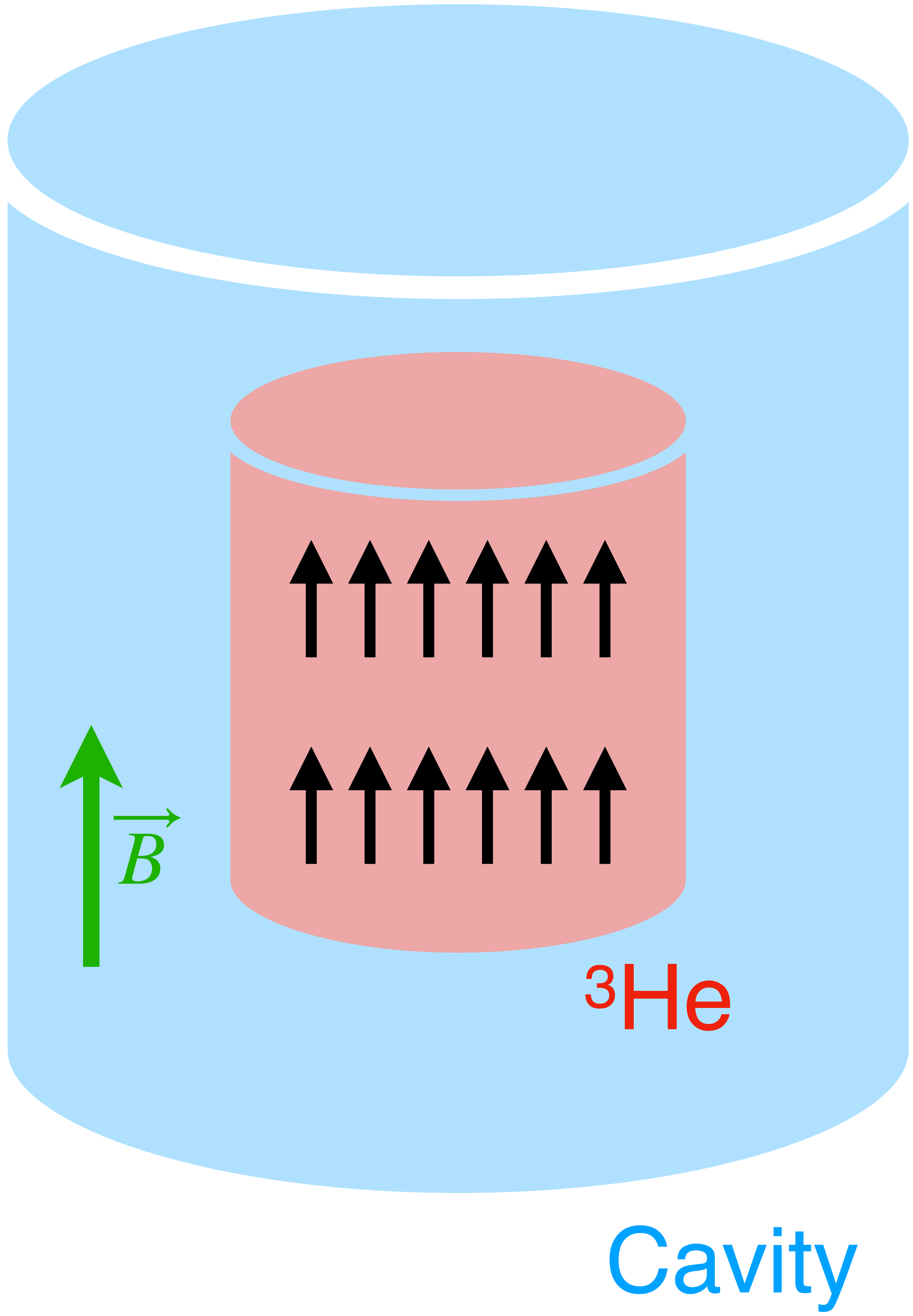
    [Watanabe & Murayama (2012), Hidaka (2013)]
  - External magnetic fields induce energy gap $\omega_L \equiv \gamma B_z$ (Larmor frequency)

Magnon excitation by axions

$$\boxed{\frac{g_{ann}}{m_n}\vec{\nabla}a\cdot\vec{s}_n}$$

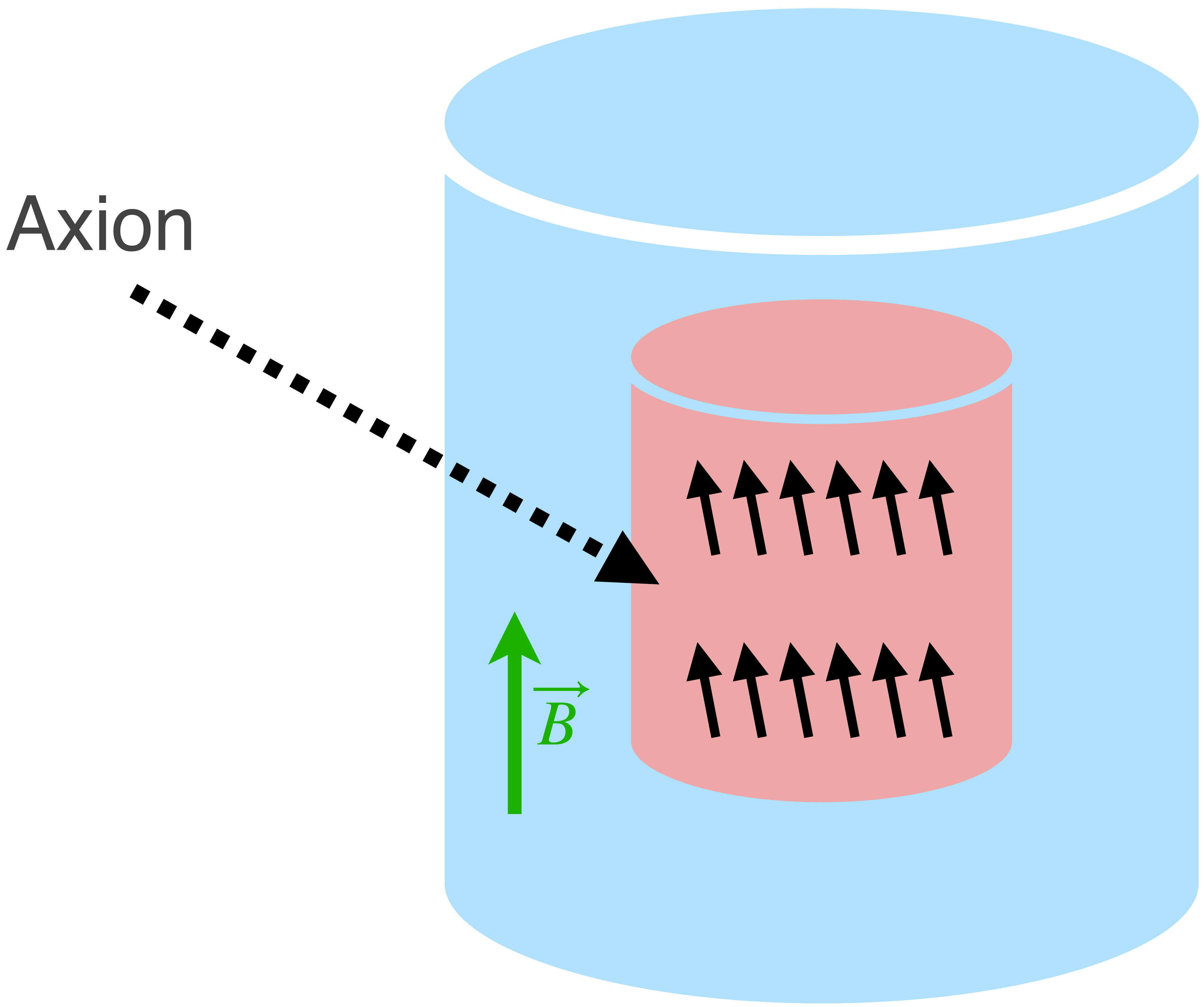
- Axion-neutron interaction induces (homogeneous) **magnon** modes
  - Resonantly enhanced when m_a = **magnon energy gap**
- Larmor frequency of ^{3}He : $\omega_L \simeq 1.3\,\mu\mathrm{eV}\left(\frac{B_z}{10\,\mathrm{T}}\right)$
  - By scanning magnetic fields of $O(10)\,\mathrm{T}$, axions with $\mu\mathrm{eV}$ mass can be probed using the resonance

Experimental setup



1. Put a superfluid ^{3}He sample in a cavity
2. Apply a magnetic field to align nuclear spins

Experimental setup



1. Put a superfluid ^{3}He sample in a cavity
2. Apply a magnetic field to align the nuclear spins
3. Axion excites “magnon” modes

How to detect magnons

$\gamma \vec{s}_n \cdot \vec{B}_{\mathrm{cav}}$

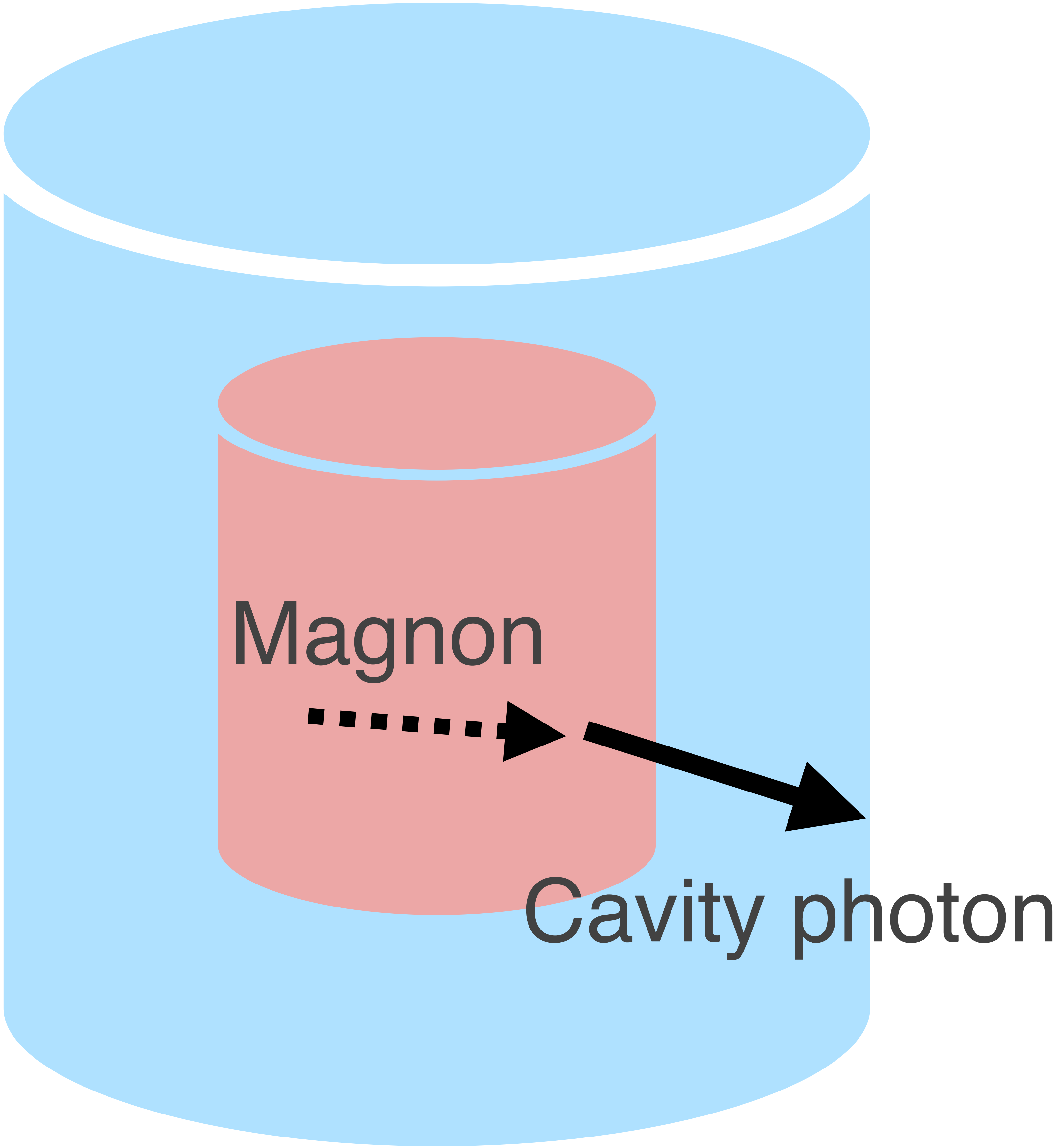
- **Magnon modes** mix with **cavity photons** through interaction between **nuclear spins** and **magnetic fields**
  - "magnon polariton"
- Mixing is maximized when

Larmor frequency ω_L = **cavity frequency** ω_{cav}

  - Scan ω_L and ω_{cav} with $\omega_L = \omega_{\mathrm{cav}} = \mathcal{O}(1)\,\mu\mathrm{eV}$
- Typical size of cavity

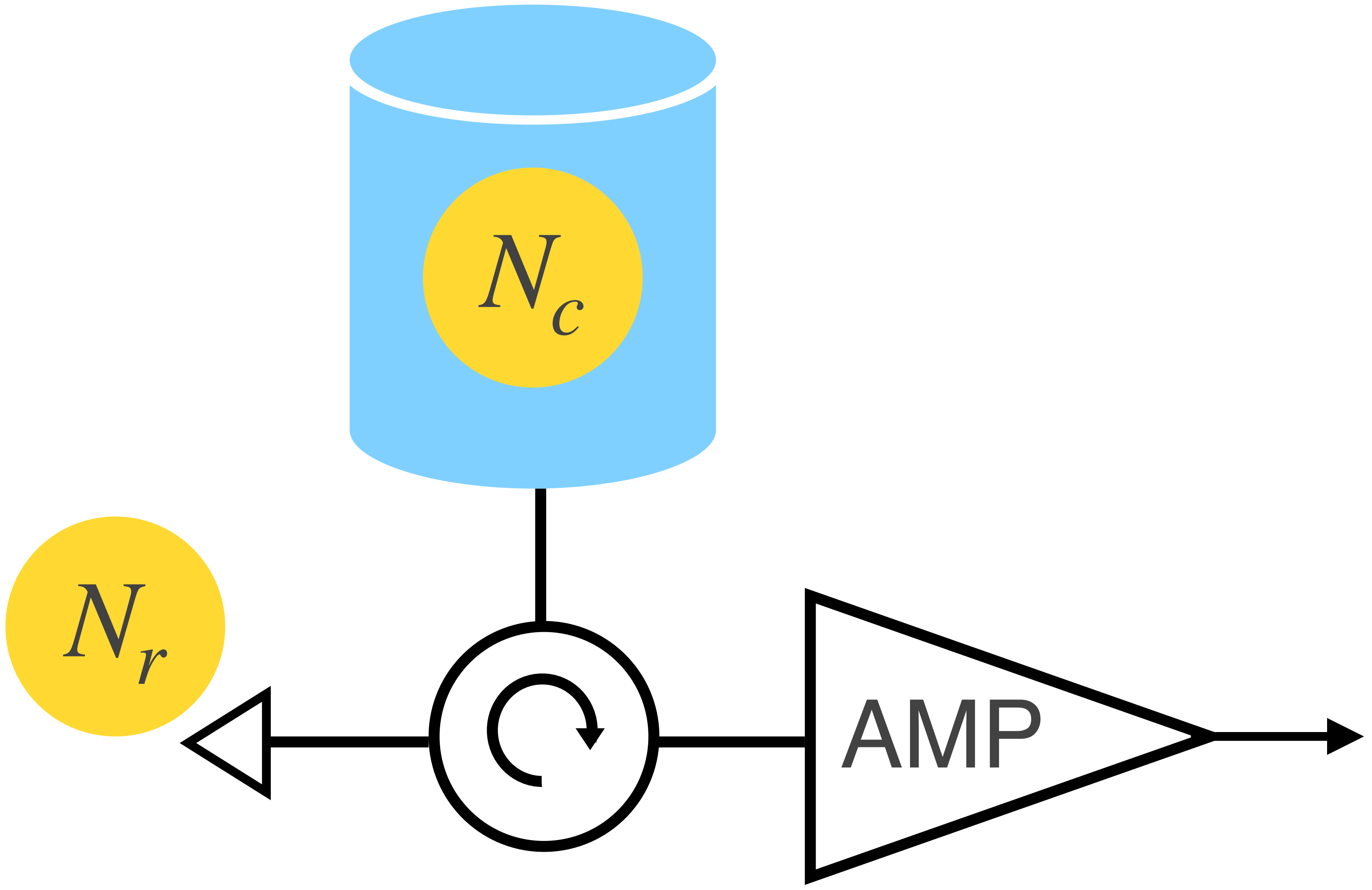
$$2\pi/\omega_{\mathrm{cav}} \simeq 1.2\,\mathrm{m}\,(m_a/\mu\mathrm{eV})^{-1}$$

Experimental setup



1. Put a superfluid ^{3}He sample of the A1 phase in a cavity
2. Apply a magnetic field to align the nuclear spins
3. Axion excites “magnon” modes
4. Magnons mix with cavity photons
5. Amplify and measure the signal (cavity photons)

Thermal noise



- Internal loss of cavity N_c
- From termination resistor N_r

$$N_c, N_r \sim \frac{1}{\exp(\hbar\omega/k_B T) - 1} + \boxed{\frac{1}{2}}$$

Quantum fluctuation

  - For $\hbar\omega = 1\,\mu\mathrm{eV}$, thermal noises N_c and N_r saturate at the quantum fluctuation when $T \lesssim 10\,\mathrm{mK}$ = **quantum limit**
- Typical temperature of our experiment $\sim \mathrm{mK}$
  - Quantum fluctuation dominates thermal noises

Quantum measurement techniques

- Circumvent quantum noise by quantum measurement techniques
- Quadratures

$$\hat{X} = \frac{\hat{a} + \hat{a}^\dagger}{\sqrt{2}}, \quad \hat{Y} = \frac{\hat{a} - \hat{a}^\dagger}{\sqrt{2}i} \quad \triangleright \quad [\hat{X}, \hat{Y}] = i \quad \triangleright \quad (\Delta\hat{X})(\Delta\hat{Y}) \geq \frac{1}{4}$$

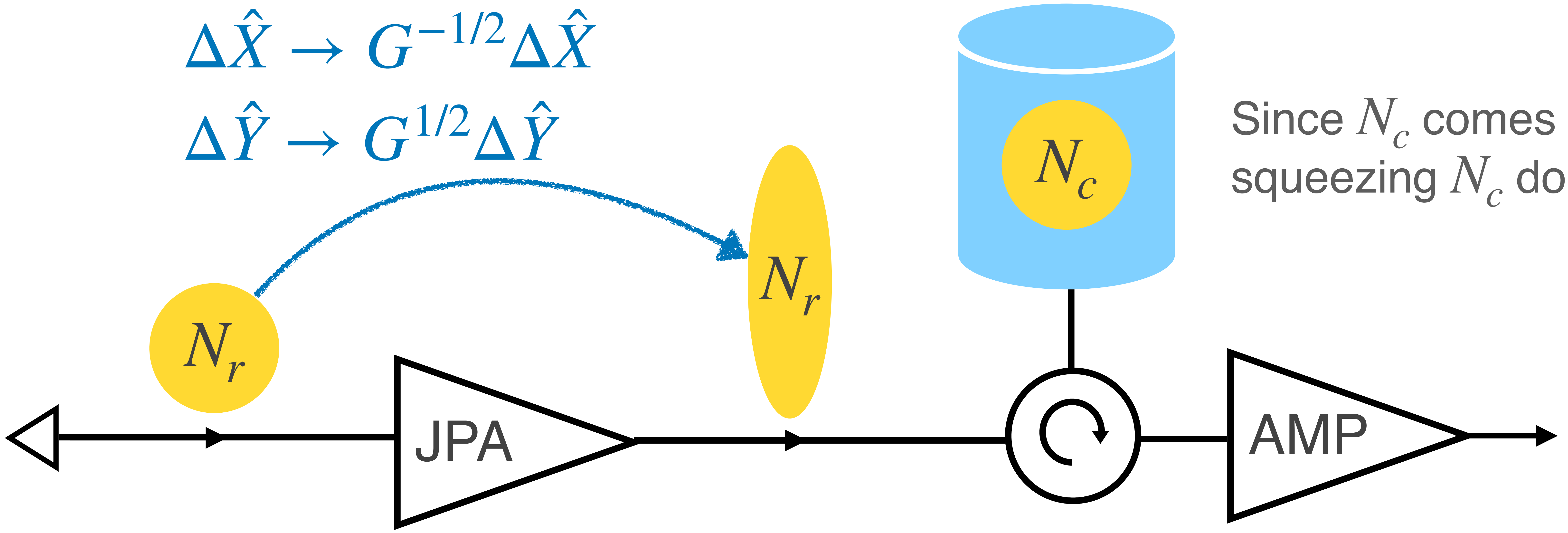
  - Usually, we measure #photons by observing $\hat{X}$ and $\hat{Y}$ simultaneously
  - Quantum noise $\Delta\hat{X} \sim \Delta\hat{Y} \sim 1/2$ becomes dominant in low temperature
- By imposing quantum fluctuation to $\hat{Y}$ and observing only $\hat{X}$,
  we can measure photon signals with quantum fluctuation less than 1/2

Squeezing

Josephson Parametric Amplifier (JPA)

- can reduce quantum fluctuation of one quadrature while maintaining uncertainty relationship

$$\Delta\hat{X} \to G^{-1/2}\Delta\hat{X}$$
$$\Delta\hat{Y} \to G^{1/2}\Delta\hat{Y}$$



Since N_c comes with signals, squeezing N_c does not help to increase SNR

Observe only $\hat{X}$ (**Homodyne measurement**)

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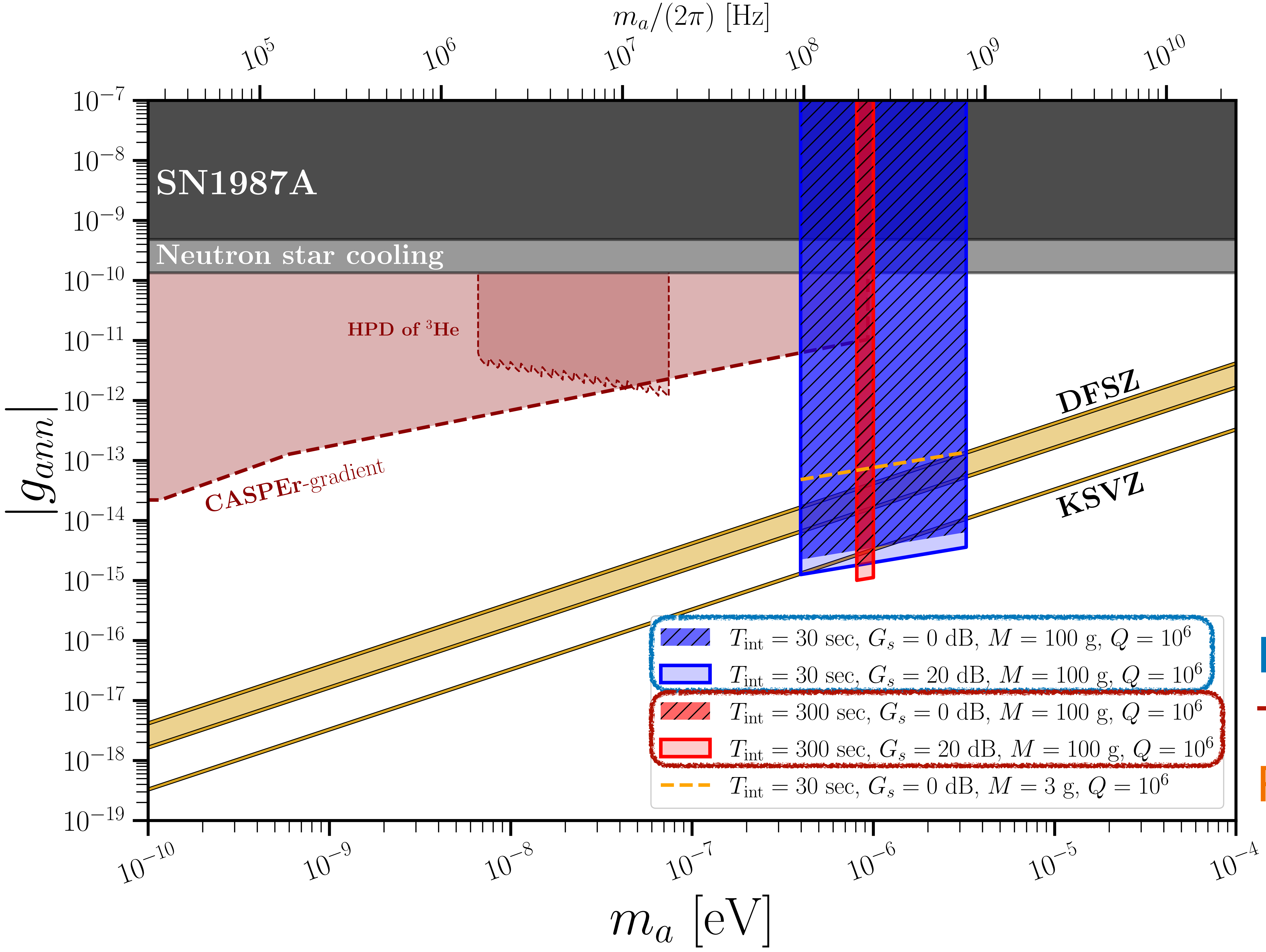
Bench mark setups

- Total observation time: 2 years
- Axion is 100% Dark Matter
- Cavity quality factor: $Q = 10^6$

	Integration time for each scan $T_{\rm int}$	Magnetic field	Squeezing parameter G_s	Helium mass $M_{^3{\rm He}}$
Ideal	30 sec	3.1 - 25 T	0 or 20 dB	100 g
Targeting	300 sec	6.2 - 7.7 T	0 or 20 dB	100g
Realistic	30 sec	3.1 - 25 T	0 dB	3 g

Result: 95% exclusion limit



Ideal w/o & w/ squeezing

Targeting w/o & w/ squeezing

Realistic

Comparison with other axion-neutron coupling experiments

- **CASPEr-gradient**
  - detects spin precession of liquid Xenon-129 induced by axion
  - $\gamma_{^{129}\mathrm{Xe}} \simeq 0.37\,\gamma_{^{3}\mathrm{He}}$ ▷ needs **larger magnetic fields** than ^{3}He case
- **Homogeneous Precession Domain of superfluid ^{3}He** **[Gao et al. (2022)]**
  - uses **B2** phase, which exists for $B \lesssim 0.5\,\mathrm{T}$
  - sensitive only to axion with $m_a \lesssim 0.07\,\mu\mathrm{eV}$

$$\omega_L \simeq 1.3\,\mu\mathrm{eV}\left(\frac{B_z}{10\,\mathrm{T}}\right)$$

- By using **A1** phase of ^{3}He, we can detect $\mu\mathrm{eV}$ axion with realistic magnetic fields!

Summary

- Axion is a fascinating particle since it can solve the strong CP problem and also be a candidate for Dark Matter
- Axion-photon coupling has been well explored, but not for nucleon coupling
- We have shown that axion-neutron coupling can be probed by using magnons in **A1 phase** of **superfluid helium-3**
  - sensitive to $\mu\mathrm{eV}$ axion, which is favored for Dark Matter axion
  - can explore heavier mass regions than experiments which use ^{129}Xe or B2 phase of ^{3}He
- We also quantitatively evaluated enhancement of sensitivity by **squeezing**

Back up

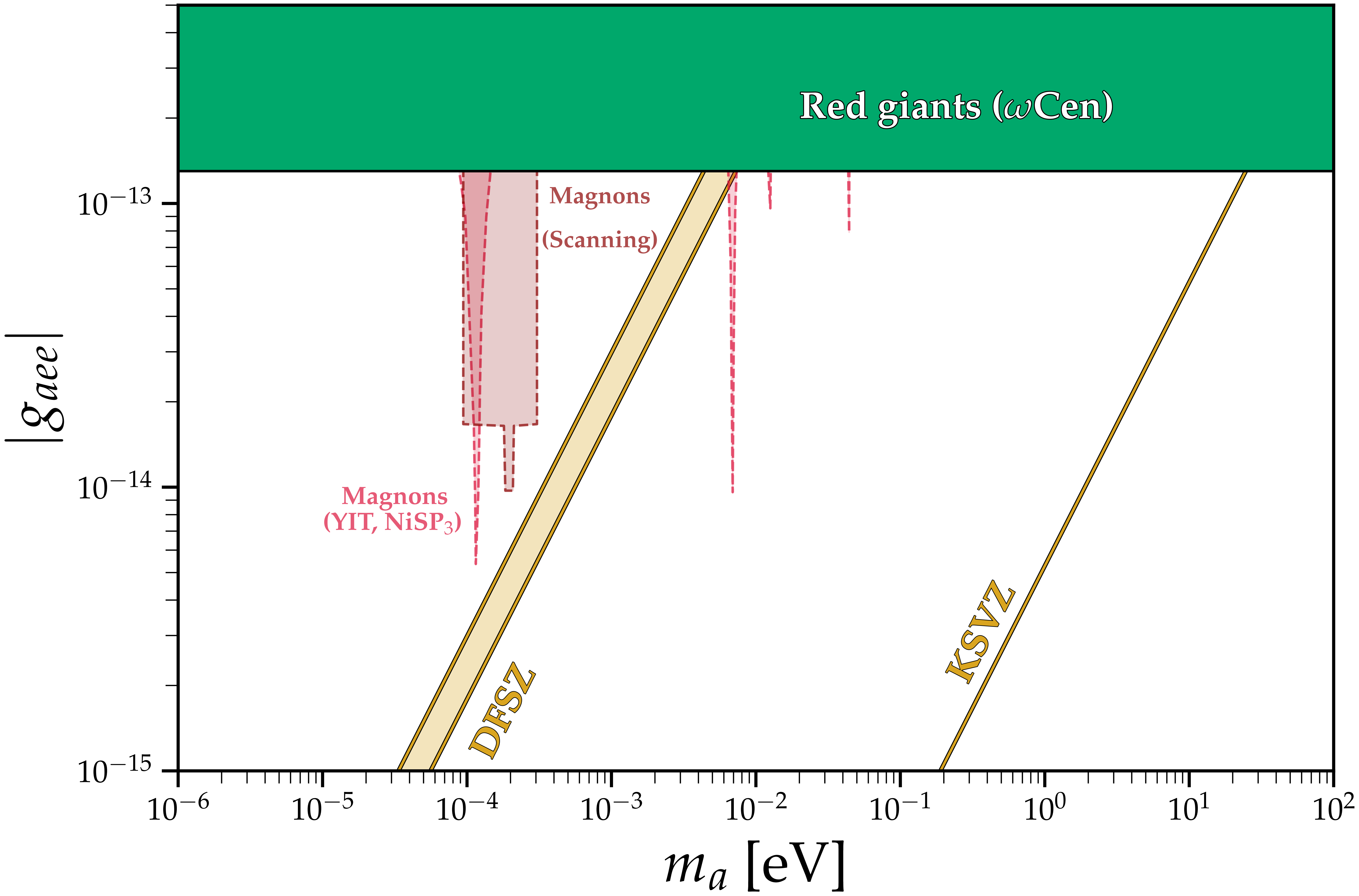
Model dependence of axion-photon coupling

- Axion-photon coupling

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - \frac{2}{3}\frac{4m_d + m_u}{m_d + m_u}\right)$$

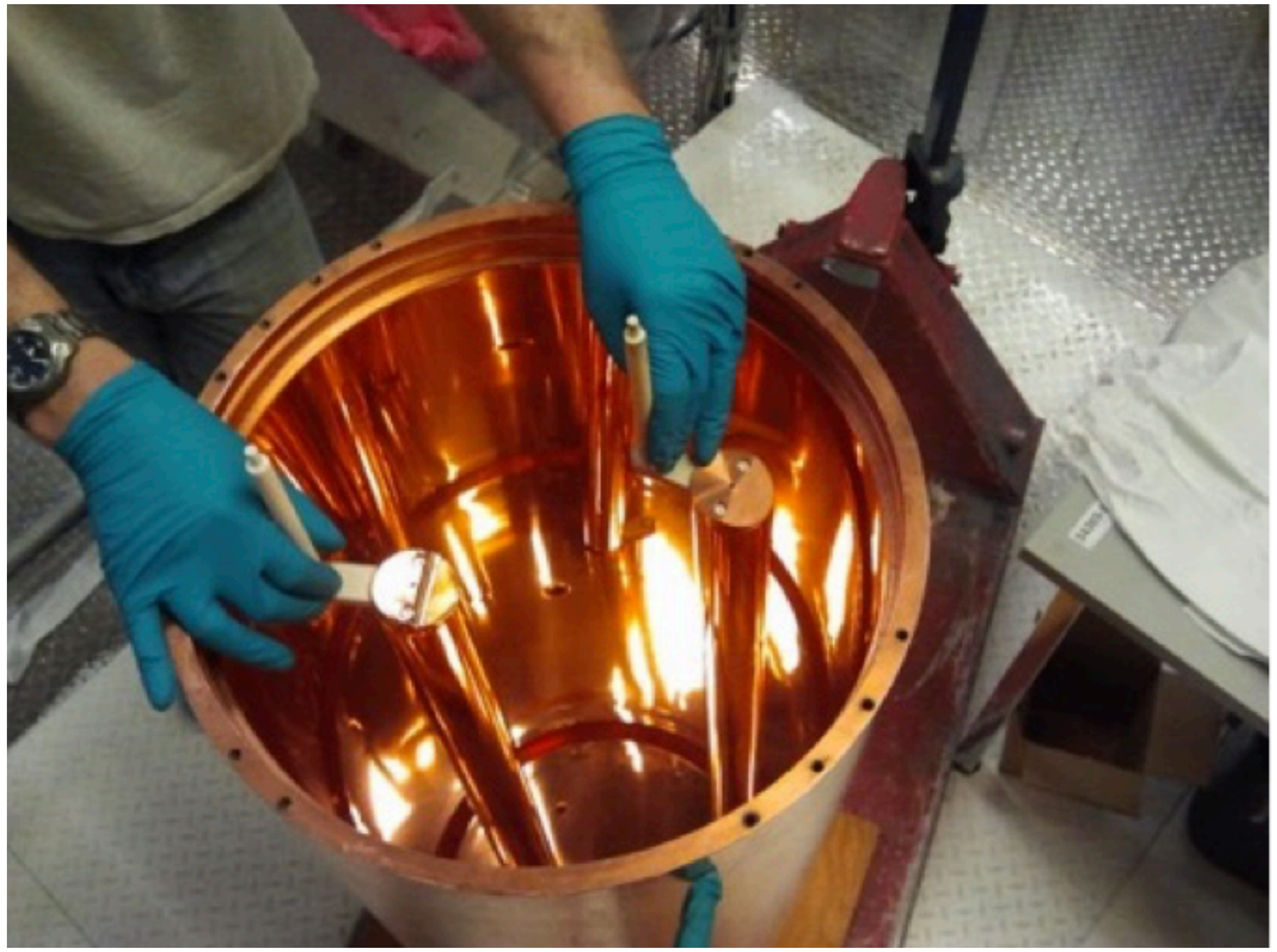
- Highly depends on electromagnetic (color) anomaly coefficient E (N)
  - KSVZ: $E/N = 0$
  - DFSZ: $E/N = 8/3$
  - E/N can take arbitral value in general

Axion-electron coupling



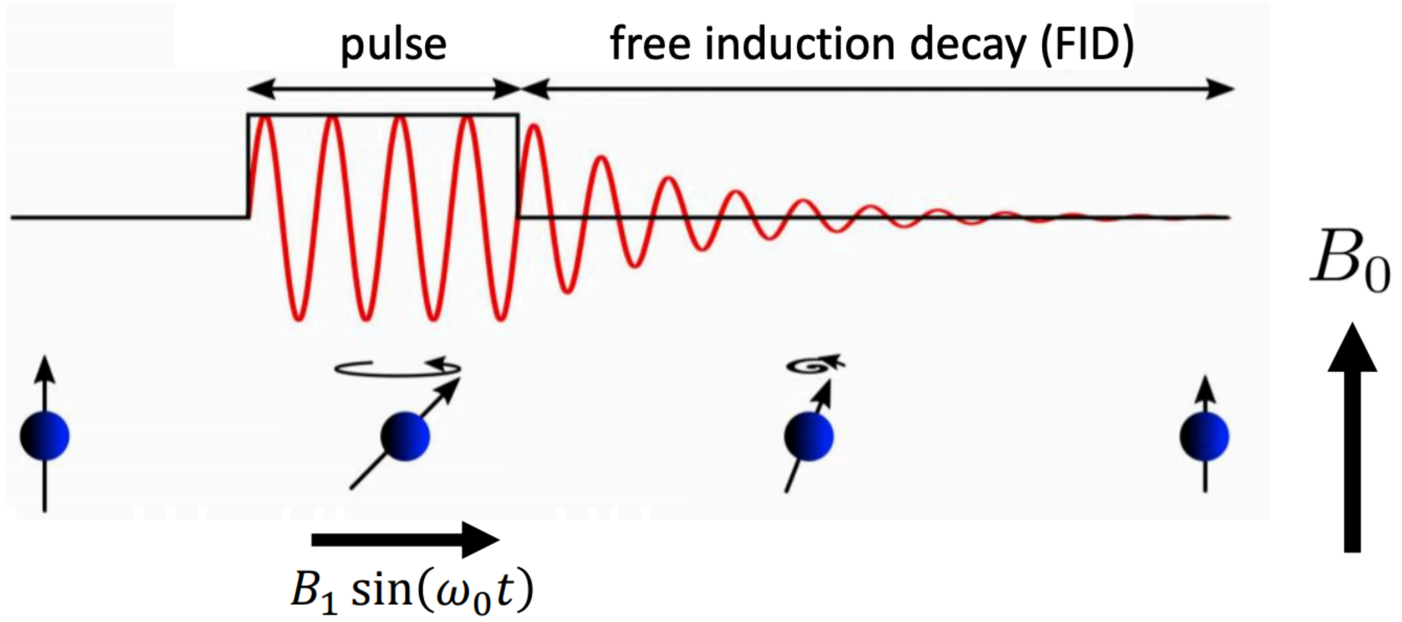
ADMX

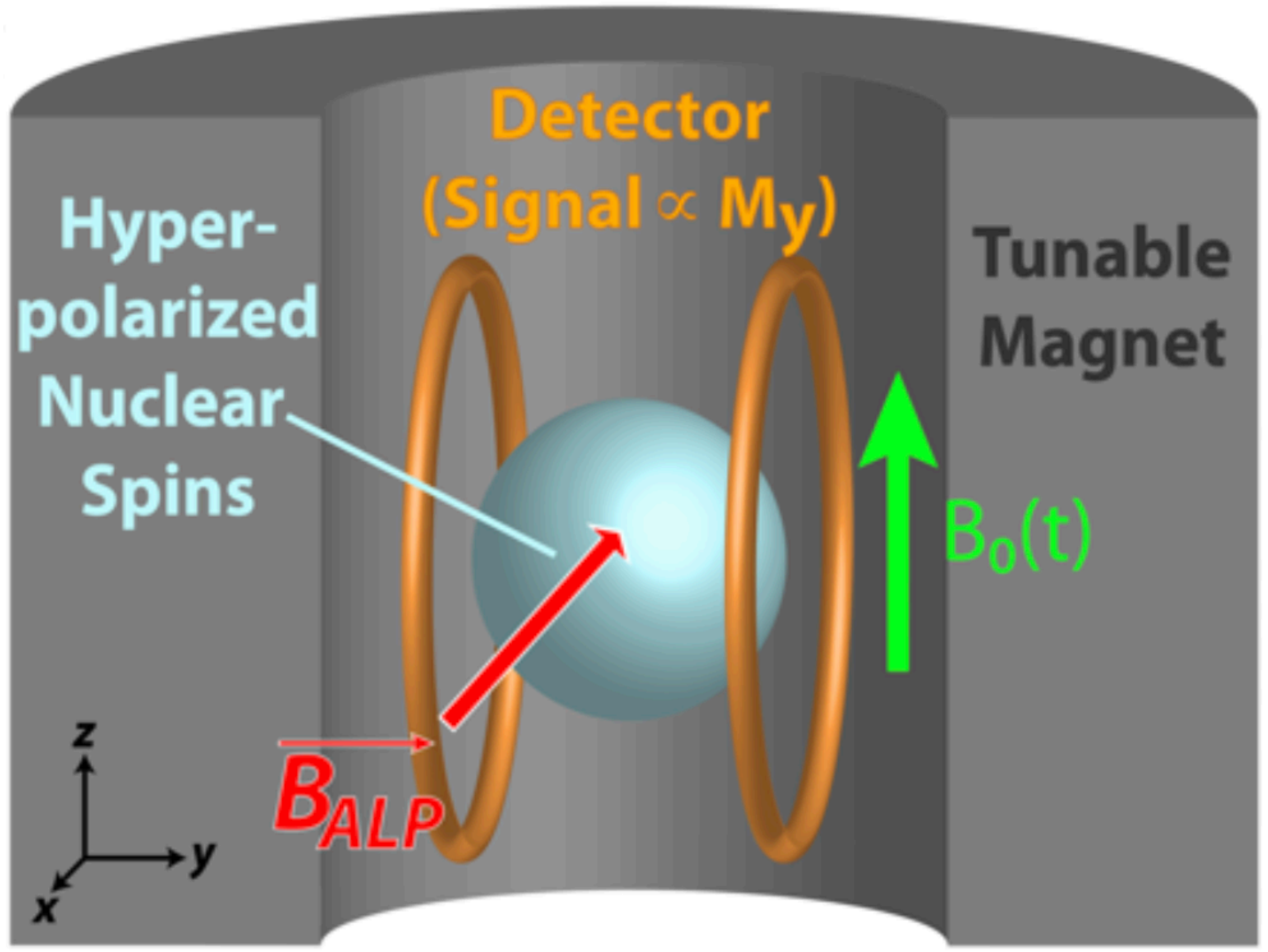
- Temperature inside cavity: 0.1 K
- Superconducting magnet > 7.5 T
- Cavity volume: 140 L
- Cavity quality factor: $\sim 10^5$
- Tune cavity frequency
  by moving “rods” inside cavity



CAPSEr-gradient

- Spin precession induced by axion is measured by magnetic sensor
- Hyperpolarization
  - Increase spin polarization of 129Xe by exchanging electron spins of Rb excited by laser light with nuclear spins of 129Xe
  - Spin polarization ~ 10^{-5} at thermal equilibrium (1 T, 300 K) can be increased to ~ 50%
  - Currently ~11% polarization achieved under 0.2 T magnetic field



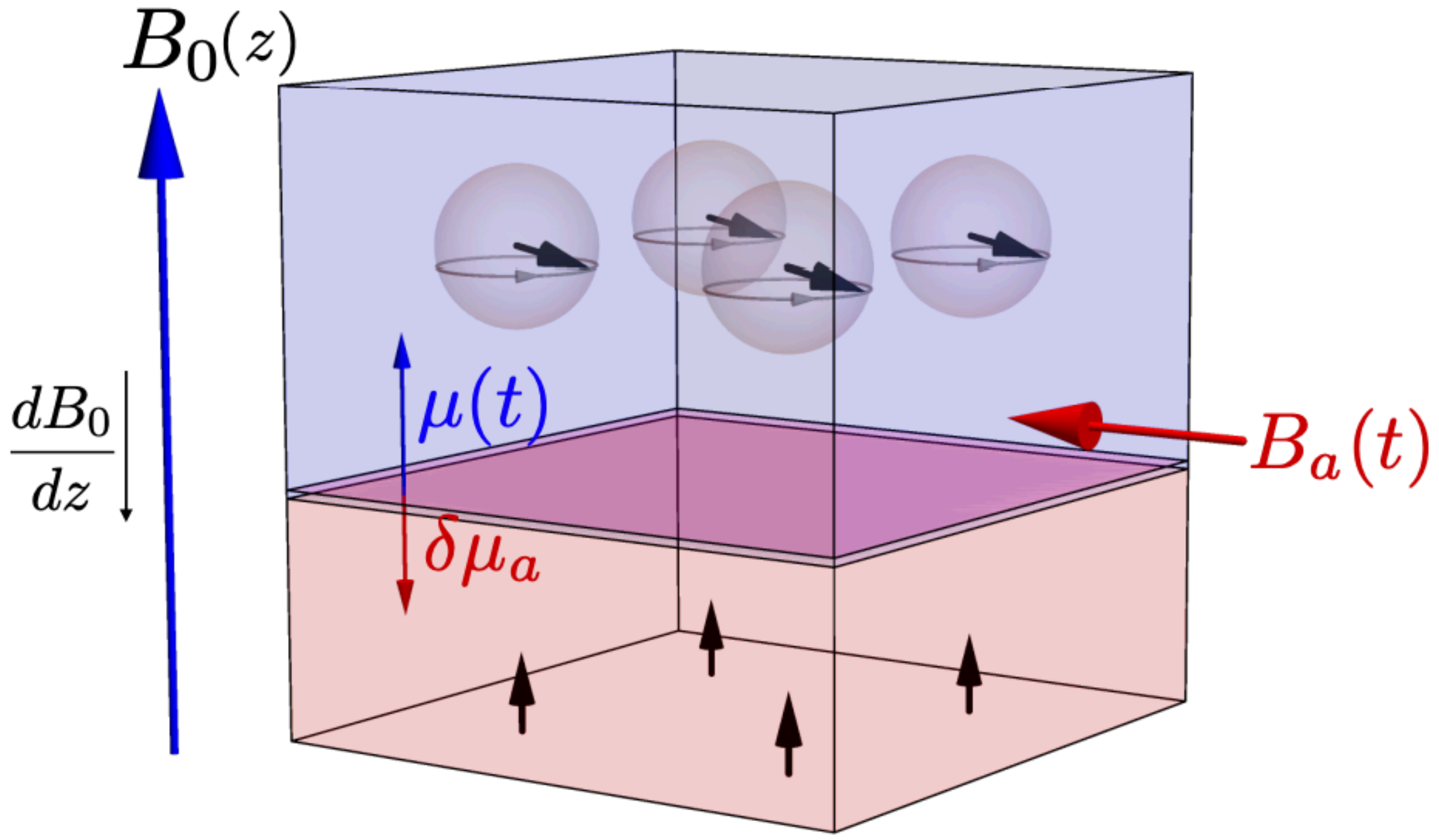


[Budger group]

HPD of Helium-3 [Gao et al. (2022)]

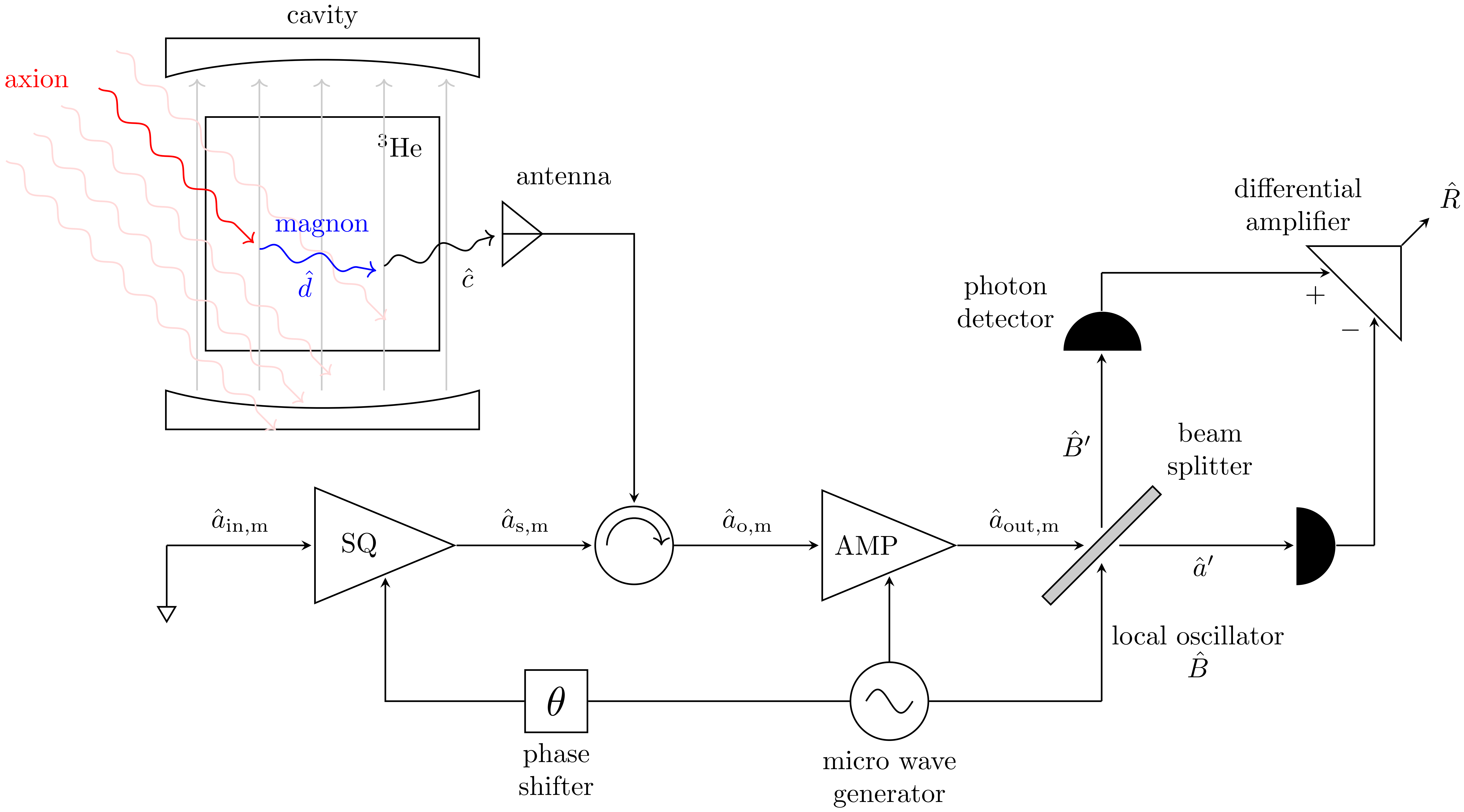
- B2 phase of superfluid ^{3}He = Homogeneous Precession Domain (HPD)
  - Nuclear spins uniformly precess at

$$\omega_L \simeq 1.3\,\mu\mathrm{eV}\left(\frac{B_z}{10\,\mathrm{T}}\right)$$

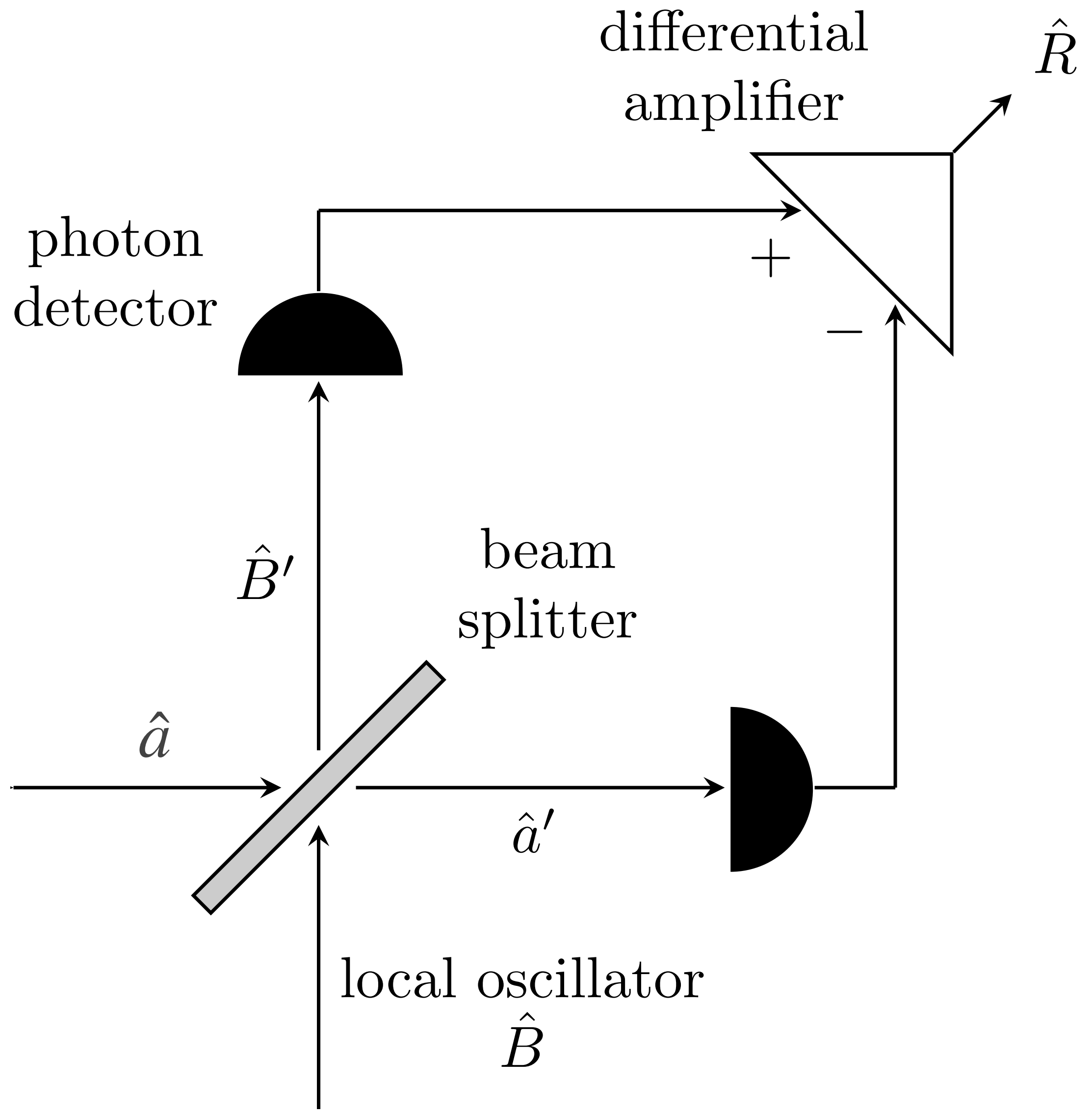


  - Measure a shift of precession frequency induced by axion
  - Since the B2 phase exist only under $B_z \lesssim 0.55\,\mathrm{T}$, this experiment is sensitive to axion with mass $m_a \lesssim 0.07\,\mu\mathrm{eV}$

Experimental configuration



Homodyne measurement



1. Beam splitter $\hat{a}' = \dfrac{\hat{a} - \hat{B}}{\sqrt{2}}, \quad \hat{B}' = \dfrac{\hat{a} + \hat{B}}{\sqrt{2}}$
2. Differential amplifier $\hat{R} = \hat{B}'^{\dagger}\hat{B}' - \hat{a}'^{\dagger}\hat{a}'$

- Assuming that initial state of local oscillator is a coherent state $|\beta\rangle$ ($\beta = |\beta| e^{i\theta}$),

$$\langle \hat{R} \rangle = \sqrt{2}\,|\beta|\,\langle \hat{X}\cos\theta + \hat{Y}\sin\theta \rangle$$

  - In particular, $\langle \hat{R}/\sqrt{2}\,|\beta|\,\rangle = \langle \hat{X} \rangle$ for $\theta = 0$
- The error is proportional to $|\beta|^{-2} = \langle \hat{B}^{\dagger}\hat{B} \rangle^{-2}$
  - We can **measure only $\hat{X}$ precisely** in the limit of large input of local oscillator

Magnon lifetime

- We identify magnon lifetime as **spin relaxation time**
- Two types of spin relaxation time
  - **Longitudinal** spin relaxation time T_1: relaxation of S_z
  - **Transverse** spin relaxation time T_2: relaxation of S_x, S_y
- Since axion couples with transverse components, we should use T_2
- But, due to experimental difficulties,
  there is no measured value of intrinsic T_2 in A1 phase
- T_1 has been measured: $T_1 = O(1\text{-}10)$ sec
- Since $T_2 \lesssim T_1$ typically, we used $T_2 = 1$ sec as magnon lifetime

Log-likelihood ratio test

- Dataset: $\mathscr{D} = \{X_n^{(\mathscr{D})} \equiv X^{(\mathscr{D})}(n\Delta t)\}_{n\in\{0,\cdots,N-1\}}$
  - Fourier transformation: $X_k^{(\mathscr{D})} \equiv \sum_{n=0}^{N-1} X_n^{(\mathscr{D})} e^{-i2\pi kn/N} \quad (k \in \{0,\cdots,N-1\})$
- Power spectral density: $P_k^{(\mathscr{D})} = \frac{\Delta t^2}{T_{\mathrm{int}}} |X_k^{(\mathscr{D})}|^2$
- Log-likelihood: $L(\mathscr{D}\,|\,P_k) = \prod_{k=1}^{N-1} \frac{1}{P_k} e^{-P_k^{(\mathscr{D})}/P_k}$ ($P_k = S_k + B_k$: model of signal and noise output)
- Test statistic:

$$q = 2\sum_{k=1}^{N-1}\left[\ln L(\mathscr{D}_{\mathrm{null}}\,|\,S_k + B_k) - \ln L(\mathscr{D}_{\mathrm{null}}\,|\,B_k)\right] \simeq -\frac{T_{\mathrm{int}}}{2\pi}\int_0^\infty \mathrm{d}\omega \left(\frac{S(\omega)}{B(\omega)}\right)^2$$

  - $q = -2.71$ determines 95% exclusion limit for null axion signal ($\mathscr{D}_{\mathrm{null}}$)

- Amount of Helium-3
  - From natural gas ~ 2 kg / year
  - From decay of Tritium ~ 20 kg / year
- 100g Helium-3 $\simeq 10^3$ cm^3 ~ \$3,000,000
- Cooling of meter-sized cavity
  - CUORE experiment ($0\nu 2\beta$ search) successfully cooled a **~ 1 m** detector to **6 mK** and kept it for 15 days
- CAPP-25T
  - Cavity size 5 L with a magnetic field of 25 T (high-T_c superconducting magnet) planned
- Current highest level of squeezing ~ 15 dB
  - 20 dB will be achieved in a few years

Discussion

- Larger magnetic fields (> 25 T) are needed to explore heavier mass regions
- To explore smaller-g_{ann} regions…

$$g_{ann}^{95\%} \propto m_a^{1/2} \boxed{T_{\rm int}^{-1/4}} \boxed{Q^{-3/8}} \boxed{M_{^3{\rm He}}^{-7/8}} G_s^{-1/8}$$

  - Longer $T_{\rm int}$? … Explored regions become narrower
  - Higher Q ? … State-of-the-art Q is $\sim 10^8$ under 8 T **[Ahn et al. (2024)]**
  - More ^{3}He ? … Typical amount $\sim 1\,\mathrm{mol} \simeq 3\,\mathrm{g}$
- There is no technology that can cool a meter-sized cavity to ~ 2 mK
  - An adiabatic demagnetization refrigerator capable of continuously maintaining sub-mK has recently been developed **[Toda et al. (2018)]**