# Axion detection using a ferromagnetic phase of superfluid Helium-3

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Based on *JHEP* **09 (2024) 191**
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Hitoshi Fest, 17th Dec. 2024

# Hitoshi and condensed matter physics

**Hitoshi is expert not only in particle physics but also in condensed matter physics.**


Let's start some project combining
**particle physics** &
**condensed matter physics**!

**Axion detection**
**using superfluid Helium-3**

**My master thesis**

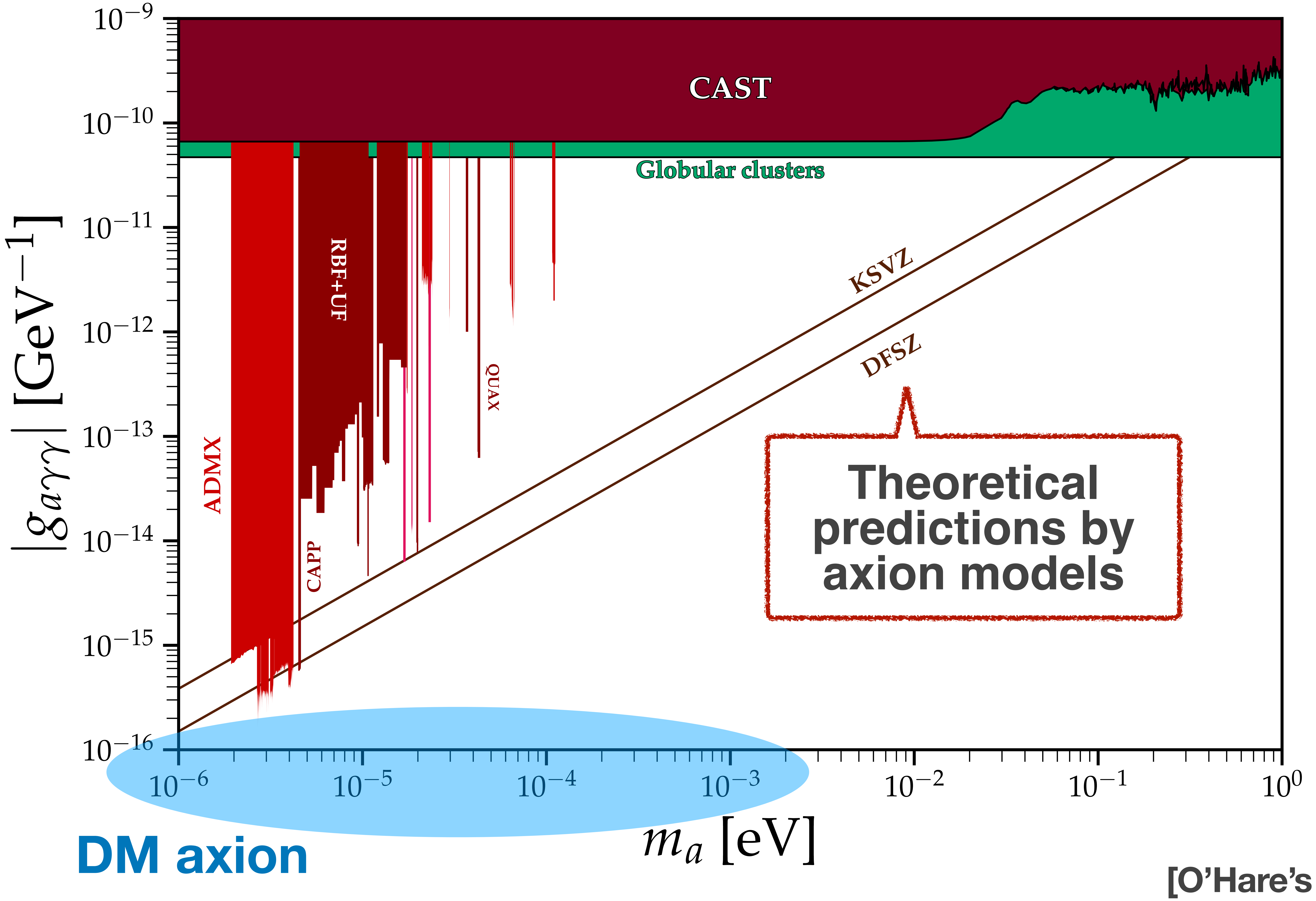
1. arXiv:2309.09160 [pdf, other] hep-ph cond-mat.supr-con hep-ex doi 10.1007/JHEP09(2024)191
   Axion detection via superfluid $^3$He ferromagnetic phase and quantum measurement techniques
   **Authors:** So Chigusa, Dan Kondo, Hitoshi Murayama, Risshin Okabe, Hiroyuki Sudo
   **Submitted** 1 November, 2024; **v1** submitted 17 September, 2023; **originally announced** September 2023.
   **Comments:** v3: 41 pages, 7 figures, accepted version for JHEP, estimated sensitivity has been improved
   **Journal ref:** JHEP 09 (2024) 191
2. arXiv:1405.0997 [pdf, ps, other] hep-th cond-mat.other cond-mat.quant-gas cond-mat.supr-con hep-ph doi 10.1103/PhysRevD.90.121703
   Englert-Brout-Higgs Mechanism in Nonrelativistic Systems
   **Authors:** Haruki Watanabe, Hitoshi Murayama
   **Submitted** 25 July, 2014; **v1** submitted 5 May, 2014; **originally announced** May 2014.
   **Comments:** 5 + 2 pages, including Supplemental Materials; v3: discussions clarified
   **Report number:** IPMU14-0109, UCB-PTH-14/30
   **Journal ref:** Phys. Rev. D 90, 121703(R) (2014)
3. arXiv:1403.3365 [pdf, ps, other] hep-th cond-mat.other hep-ph doi 10.1103/PhysRevD.89.101701
   Nambu-Goldstone bosons with fractional-power dispersion relations
   **Authors:** Haruki Watanabe, Hitoshi Murayama
   **Submitted** 1 May, 2014; **v1** submitted 13 March, 2014; **originally announced** March 2014.
   **Comments:** 5 pages, 1 figure. v2: references added; published version
   **Report number:** IPMU14-0058,UCB-PTH14/05
   **Journal ref:** Phys. Rev. D 89, 101701(R) (2014)
4. arXiv:1402.7066 [pdf, ps, other] hep-th cond-mat.other cond-mat.quant-gas cond-mat.str-el hep-ph doi 10.1103/PhysRevX.4.031057
   Effective Lagrangian for Nonrelativistic Systems
   **Authors:** Haruki Watanabe, Hitoshi Murayama
   **Submitted** 19 September, 2014; **v1** submitted 27 February, 2014; **originally announced** February 2014.
   **Comments:** 34 pages, 5 tables, 2 figures; v2: published version (to appear in Physical Review X)
   **Report number:** IPMU14-0043, UCB-PTH14/03
   **Journal ref:** Phys. Rev. X 4, 031057 (2014)
5. arXiv:1401.8139 [pdf, ps, other] hep-th cond-mat.other cond-mat.quant-gas hep-ph doi 10.1103/PhysRevLett.112.191804
   Noncommuting Momenta of Topological Solitons
   **Authors:** Haruki Watanabe, Hitoshi Murayama
   **Submitted** 14 May, 2014; **v1** submitted 31 January, 2014; **originally announced** January 2014.
   **Comments:** 5 +1 pages, including Supplemental Material; v4: new references added, published version
   **Report number:** UCB-PTH 14/02, IPMU14-0019
   **Journal ref:** Phys. Rev. Lett. 112, 191804 (2014)
6. arXiv:1303.1527 [pdf, ps, other] hep-th cond-mat.quant-gas cond-mat.stat-mech hep-ph doi 10.1103/PhysRevLett.111.021601
   Massive Nambu-Goldstone Bosons
   **Authors:** Haruki Watanabe, Tomáš Brauner, Hitoshi Murayama
   **Submitted** 2 July, 2013; **v1** submitted 6 March, 2013; **originally announced** March 2013.
   **Comments:** 5 pages, REVTeX 4.1; v2: text length reduced upon editor's request, the effective Lagrangian section largely rewritten, other minor changes throughout the text; version accepted to PRL
   **Report number:** BI-TP 2013/02, IPMU13-0056
   **Journal ref:** Phys.Rev.Lett.111:021601(2013)
7. arXiv:1302.4800 [pdf, ps, other] cond-mat.other hep-th quant-ph doi 10.1103/PhysRevLett.110.181601
   Redundancies in Nambu-Goldstone Bosons
   **Authors:** Haruki Watanabe, Hitoshi Murayama
   **Submitted** 5 April, 2013; **v1** submitted 19 February, 2013; **originally announced** February 2013.
   **Comments:** 4 pages; discussion improved, new references added
   **Report number:** IPMU13-0046
   **Journal ref:** Phys. Rev. Lett. 110, 181601 (2013)
8. arXiv:1203.0609 [pdf, ps, other] hep-th cond-mat.other hep-ph doi 10.1103/PhysRevLett.108.251602
   Unified Description of Nambu-Goldstone Bosons without Lorentz Invariance
   **Authors:** Haruki Watanabe, Hitoshi Murayama
   **Submitted** 12 June, 2012; **v1** submitted 3 March, 2012; **originally announced** March 2012.
   **Comments:** 5 pages, REVTeX 4.1; v3: published version
   **Journal ref:** Phys. Rev. Lett. 108, 251602 (2012)

**[Hitoshi's papers in cond-mat]**

# Axion: in a nutshell

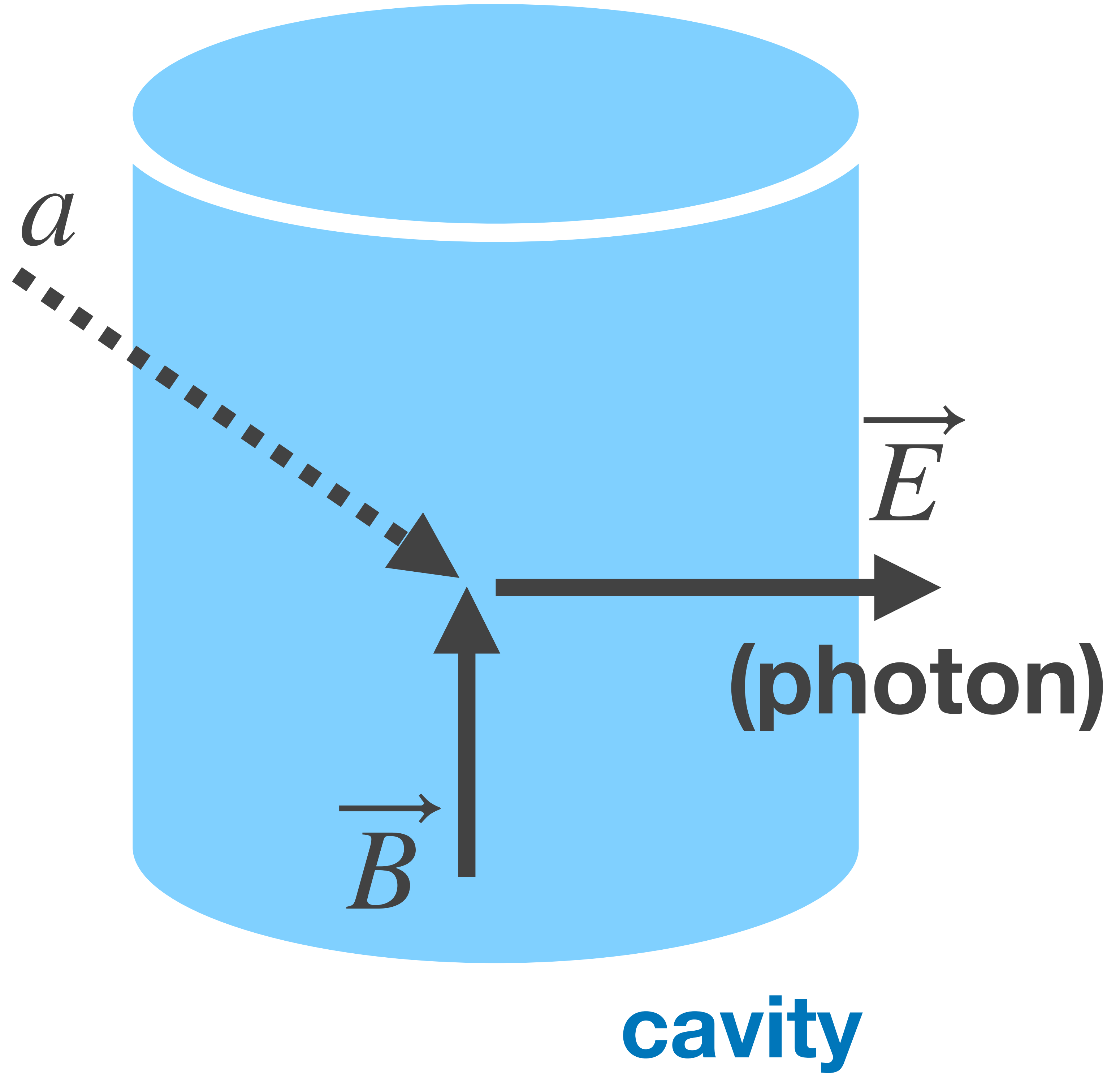
- **Strong CP problem**
  - A CP-breaking in Quantum ChromoDynamics is **unnaturally tiny**.
- **This can be solved by Peccei—Quinn mechanism.**
  - introduce **an additional global symmetry** $\mathrm{U}(1)_{\mathrm{PQ}}$
  - spontaneous symmetry breaking of $\mathrm{U}(1)_{\mathrm{PQ}}$
    generates a (pseudo-)Nambu—Goldstone boson = **Axion**
- **Axion can be Dark Matter (DM)**
  - preferred mass region: $m_a \sim 10^{-6} - 10^{-3}\,\mathrm{eV}$

# Constraints on axion-photon coupling

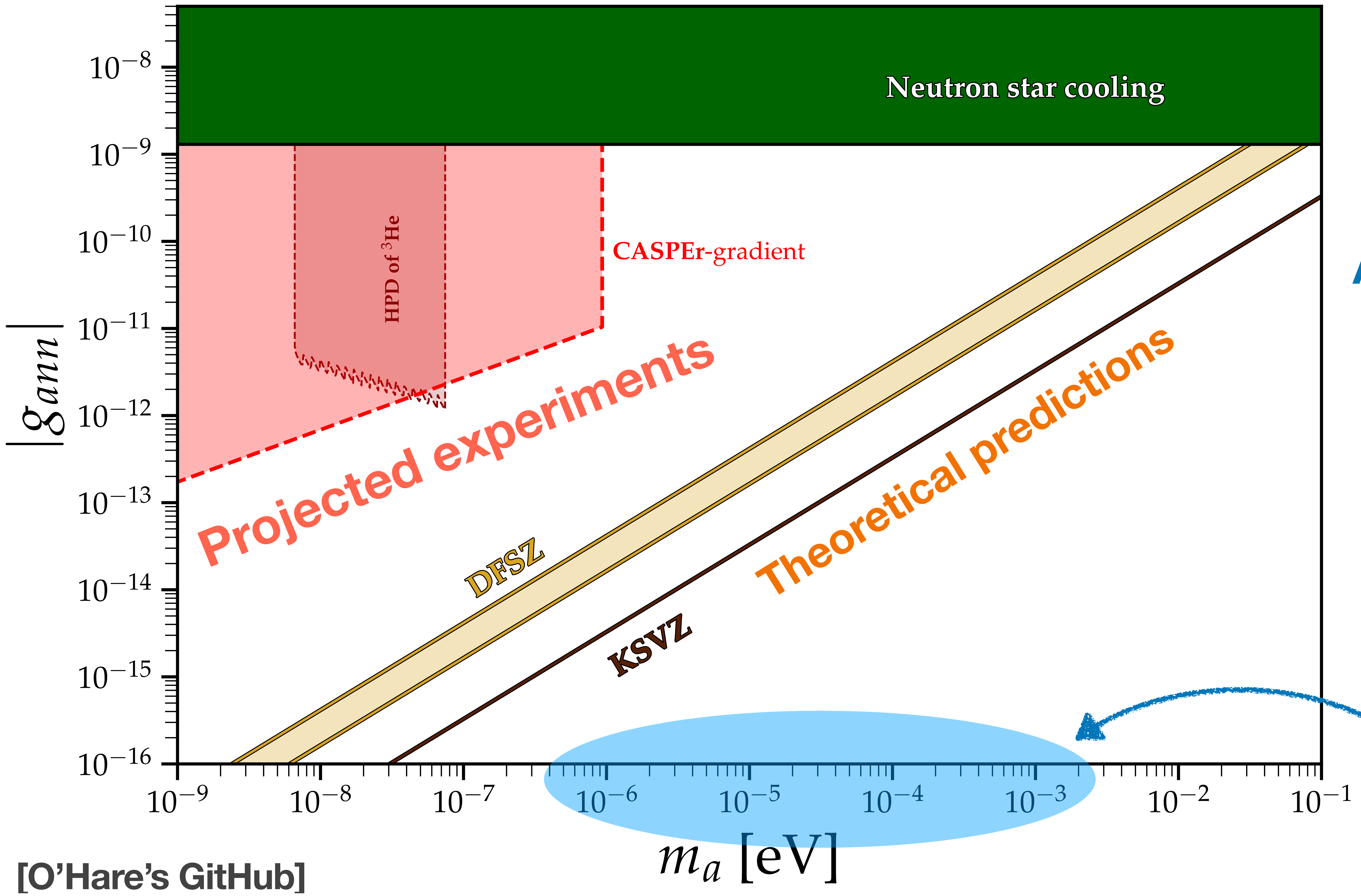



[O'Hare's GitHub]

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

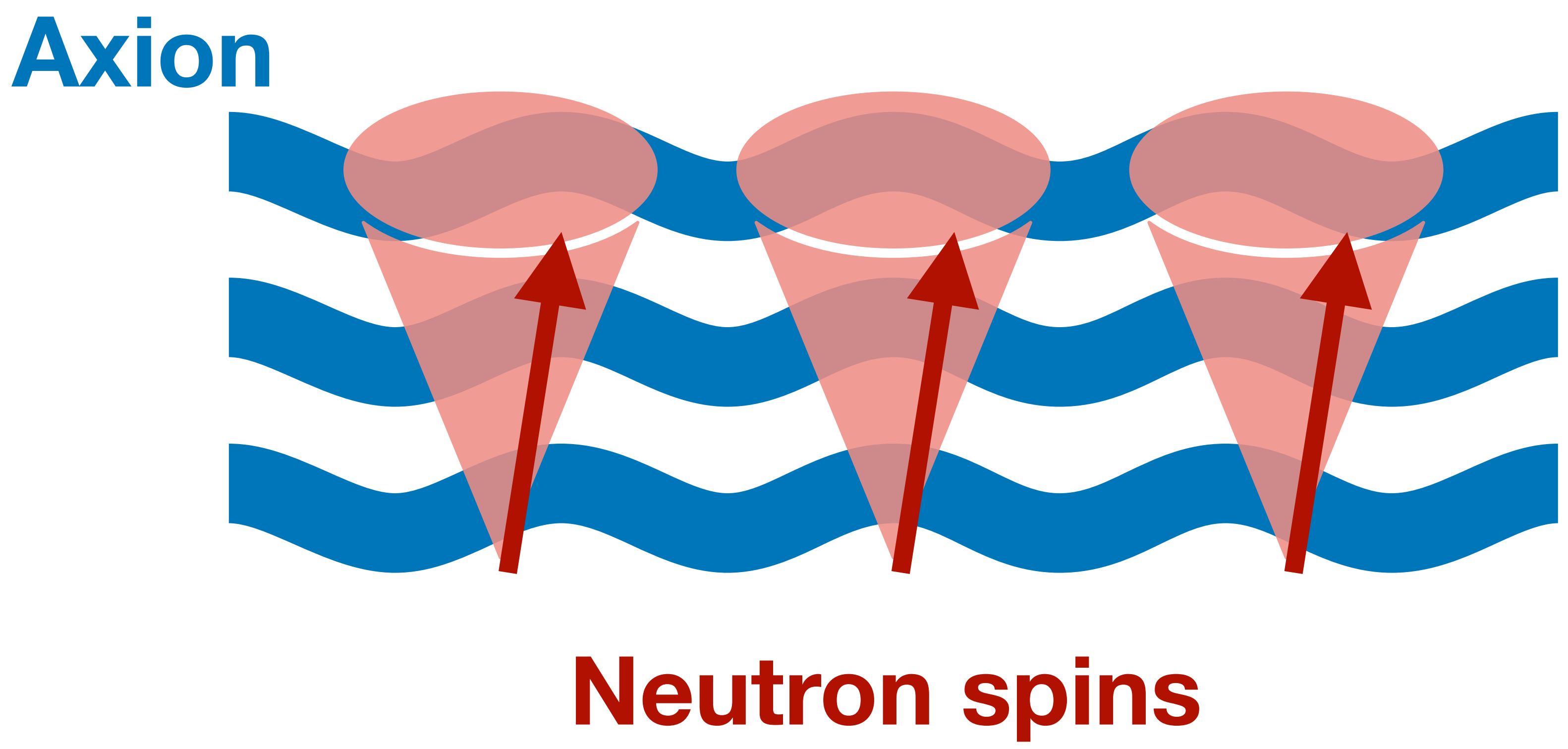


# Constraints on axion-neutron coupling




[O'Hare's GitHub]

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



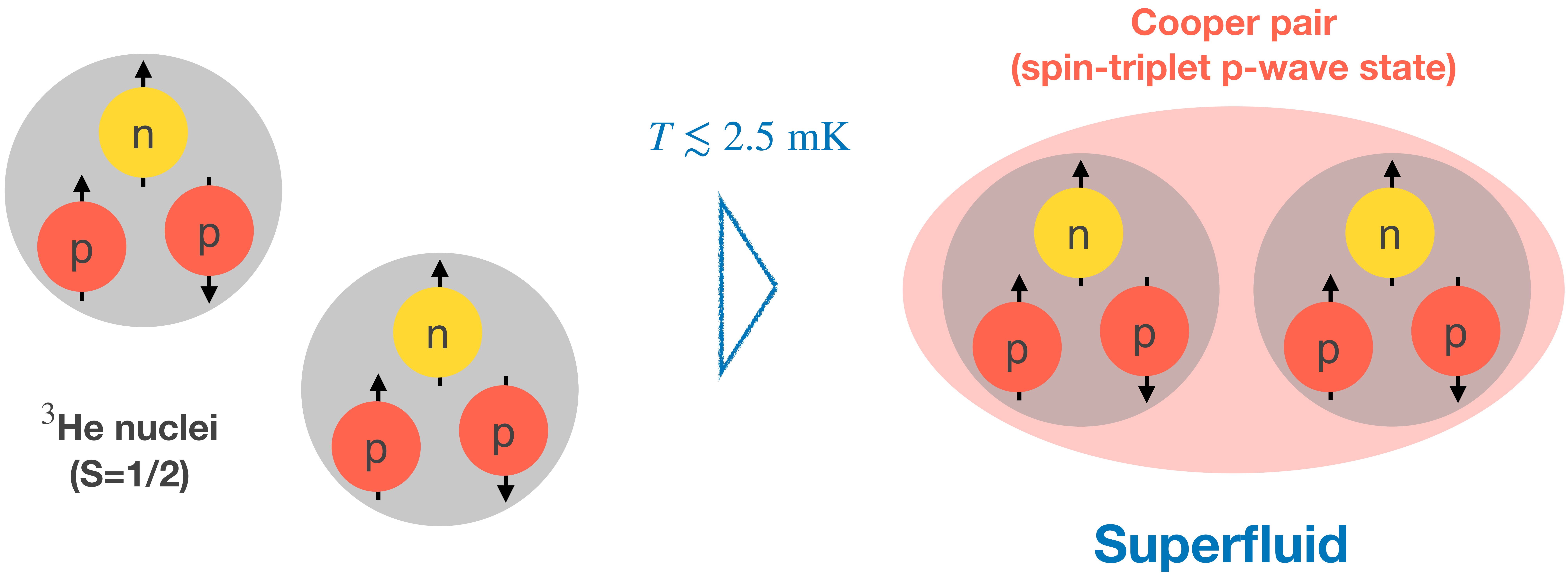

**No projected experiments for DM axion region**

**We propose a novel experiment**

**to explore axion-neutron coupling**

**using superfluid Helium-3**

# Superfluid Helium-3



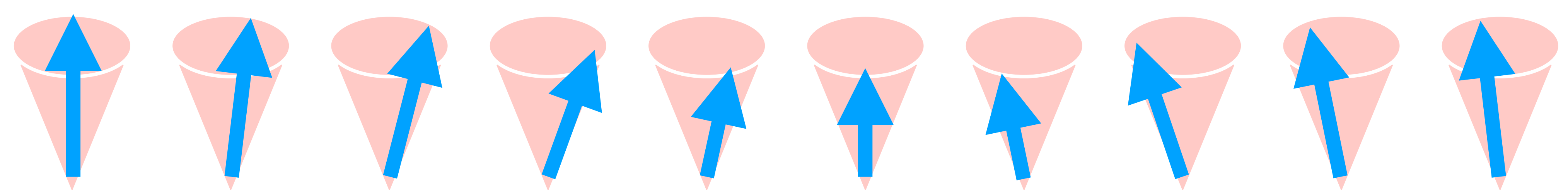

## Spins of protons and electrons are canceled

- Interaction between axion & $^3$He = Interaction between axion & **neutron**

# Superfluid phases of Helium-3

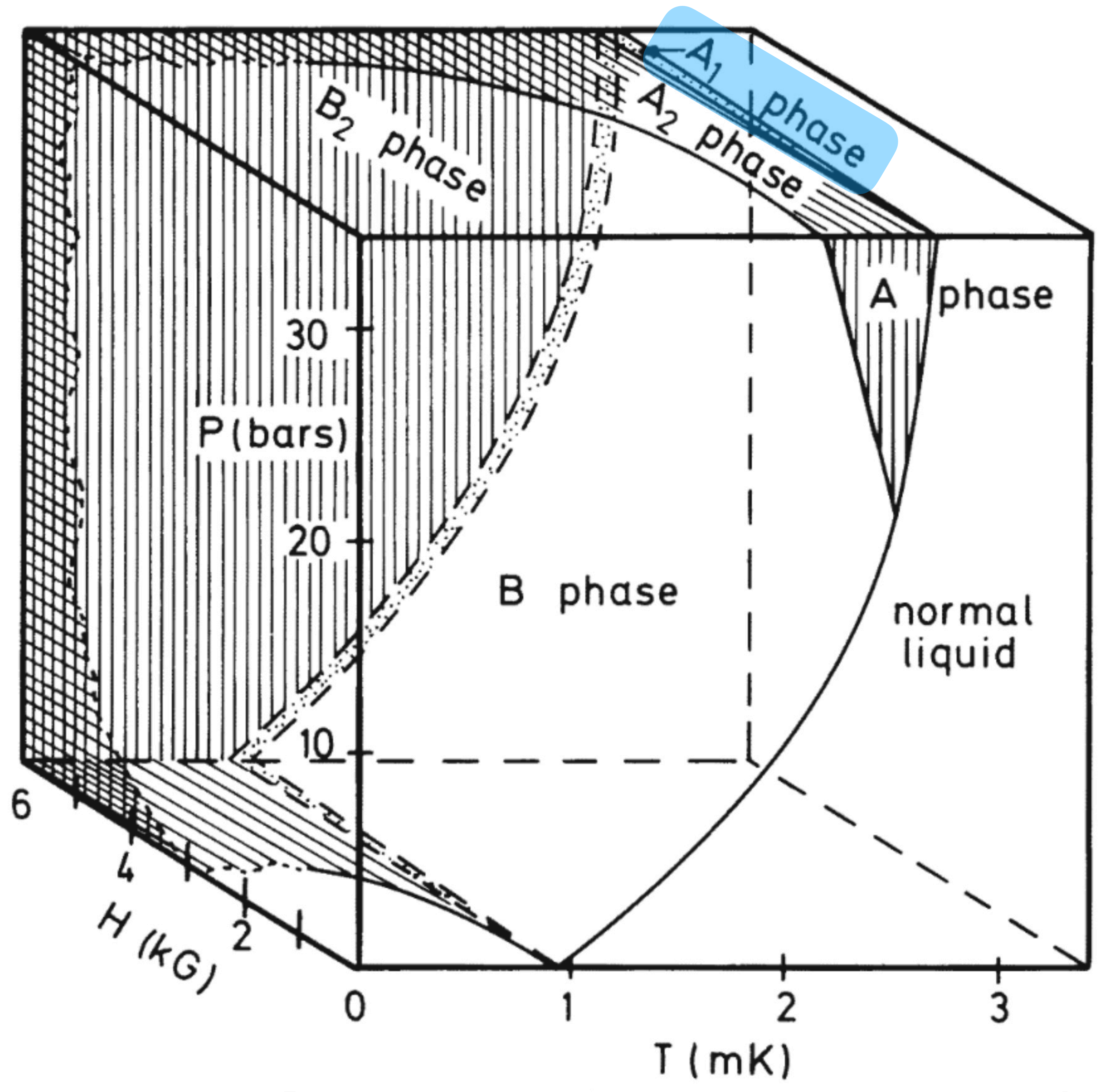
## A1-phase

- **Ferromagnetic** phase for nuclear spin
- has a **magnon** mode (= collective excitation of spins)



Type-B Nambu—Goldstone mode

[Watanabe & Murayama (2012), Hidaka (2013)]




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

# Magnon excitation by axions

**Axion-neutron interaction induces (homogeneous) magnon modes**

- Resonantly enhanced when

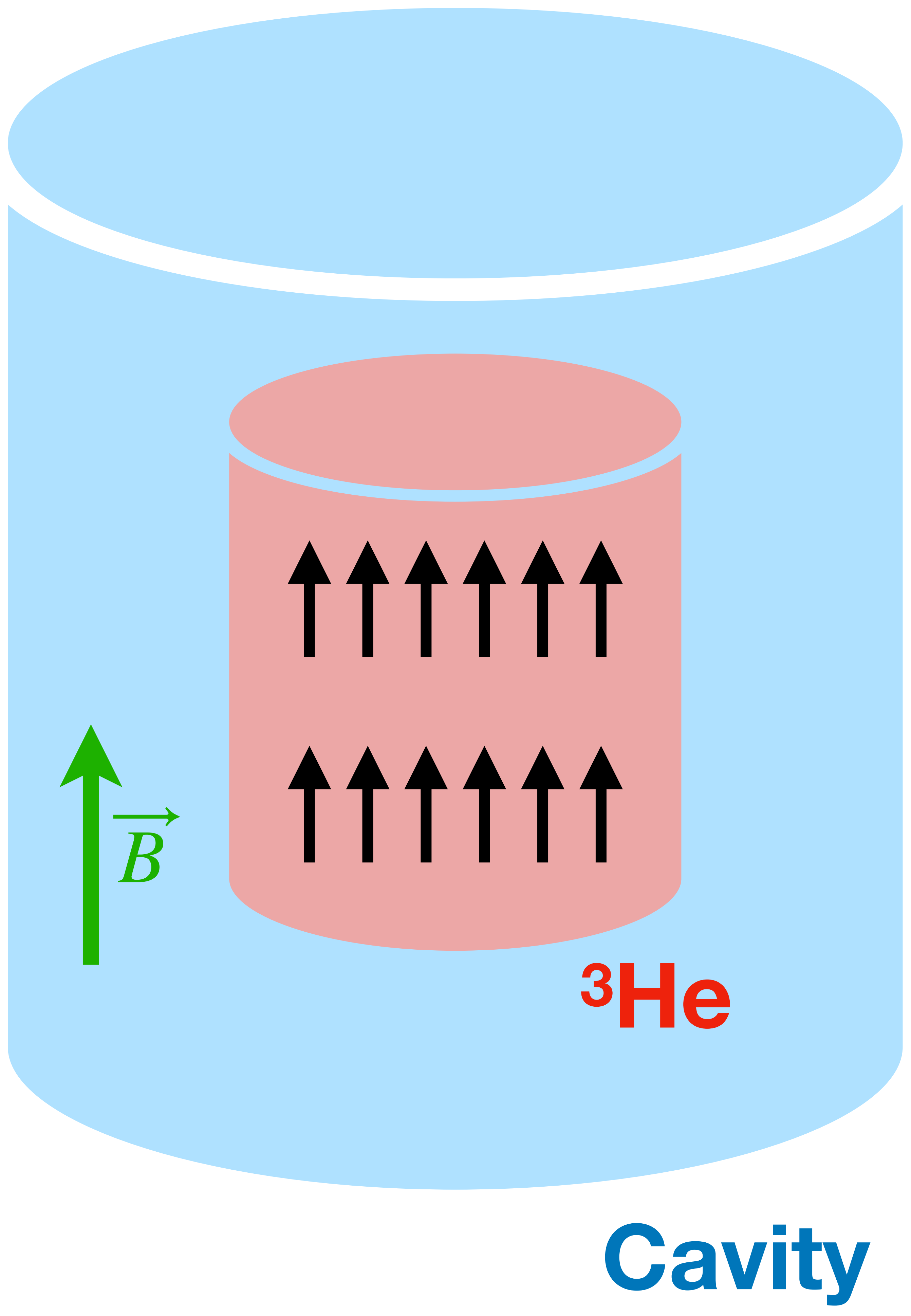
$$\frac{g_{ann}}{m_n}\vec{\nabla} a \cdot \vec{s}_n$$

$$m_a = \textbf{magnon energy gap } \omega_L$$

$$= \gamma_{^3\mathrm{He}} B_z \simeq 1.3\,\mu\mathrm{eV}\left(\frac{B_z}{10\,\mathrm{T}}\right)$$

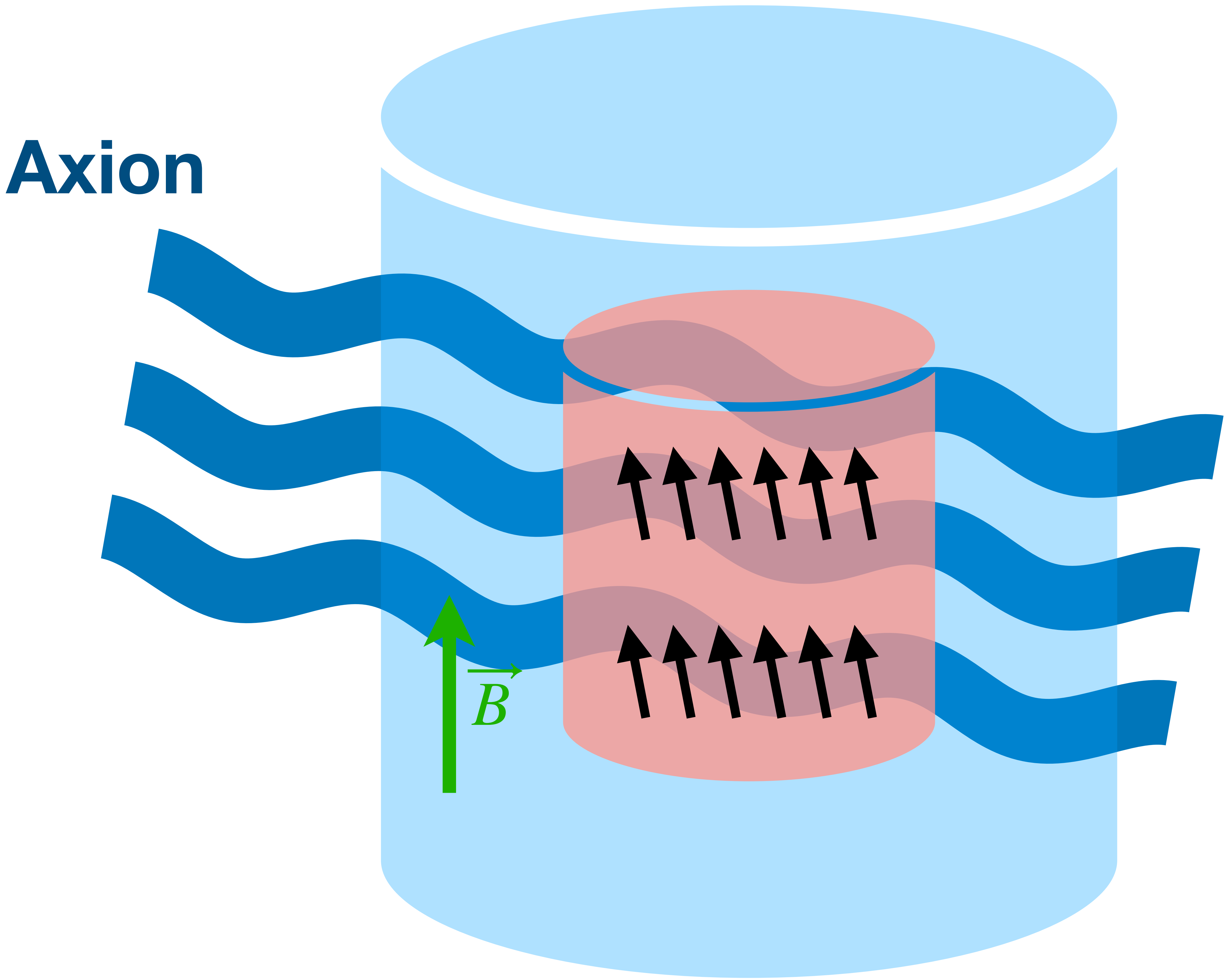
**By applying magnetic fields of $O(10)\,\mathrm{T}$ ,**
**$\mu\mathrm{eV}$ axions can be probed using this resonance**

# Experimental setup




1. Put **superfluid 3He sample** in a **cavity**
2. Apply **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" mode**

# How to detect magnons

- **Magnon modes mix with cavity photons through interaction** $\gamma \vec{s}_n \cdot \overrightarrow{B}_{\rm cav}$
  - "magnon polariton"
  - Mixing is maximized when

**Magnon energy gap** $\omega_L$ **= cavity frequency** $\omega_{\rm cav}$

- **Typical size of cavity :** $$\frac{2\pi}{\omega_{\rm cav}} \simeq 1.2\,\mathrm{m}\,\left(\frac{m_a}{\mu\mathrm{eV}}\right)^{-1}$$

# Scan strategy

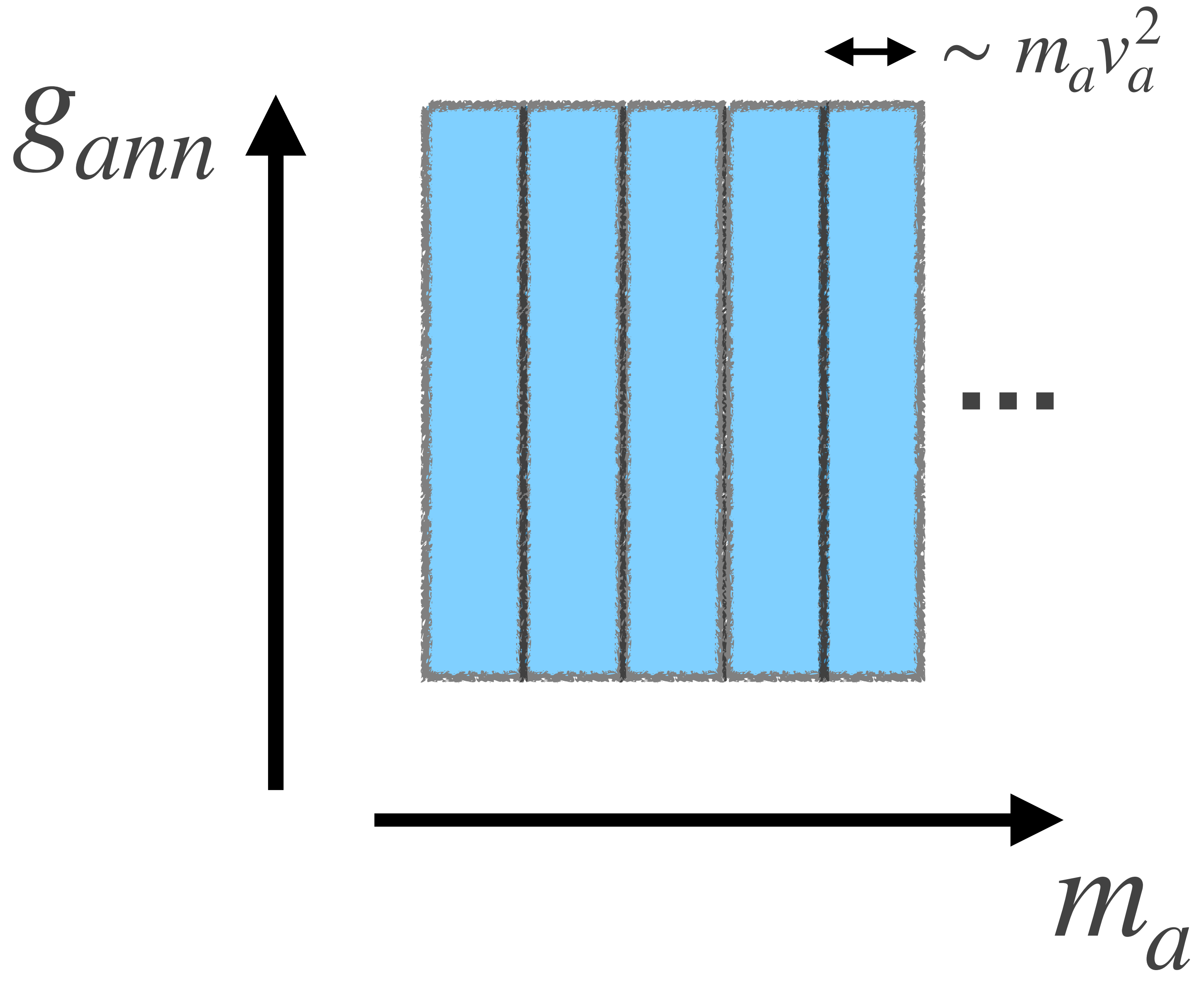
**Finite mass region can be explored by gradually scanning small regions.**

- The targeted axion mass $m_a$ can be scanned by varying $\vec{B}$ and $\omega_{\mathrm{cav}}$ while keeping

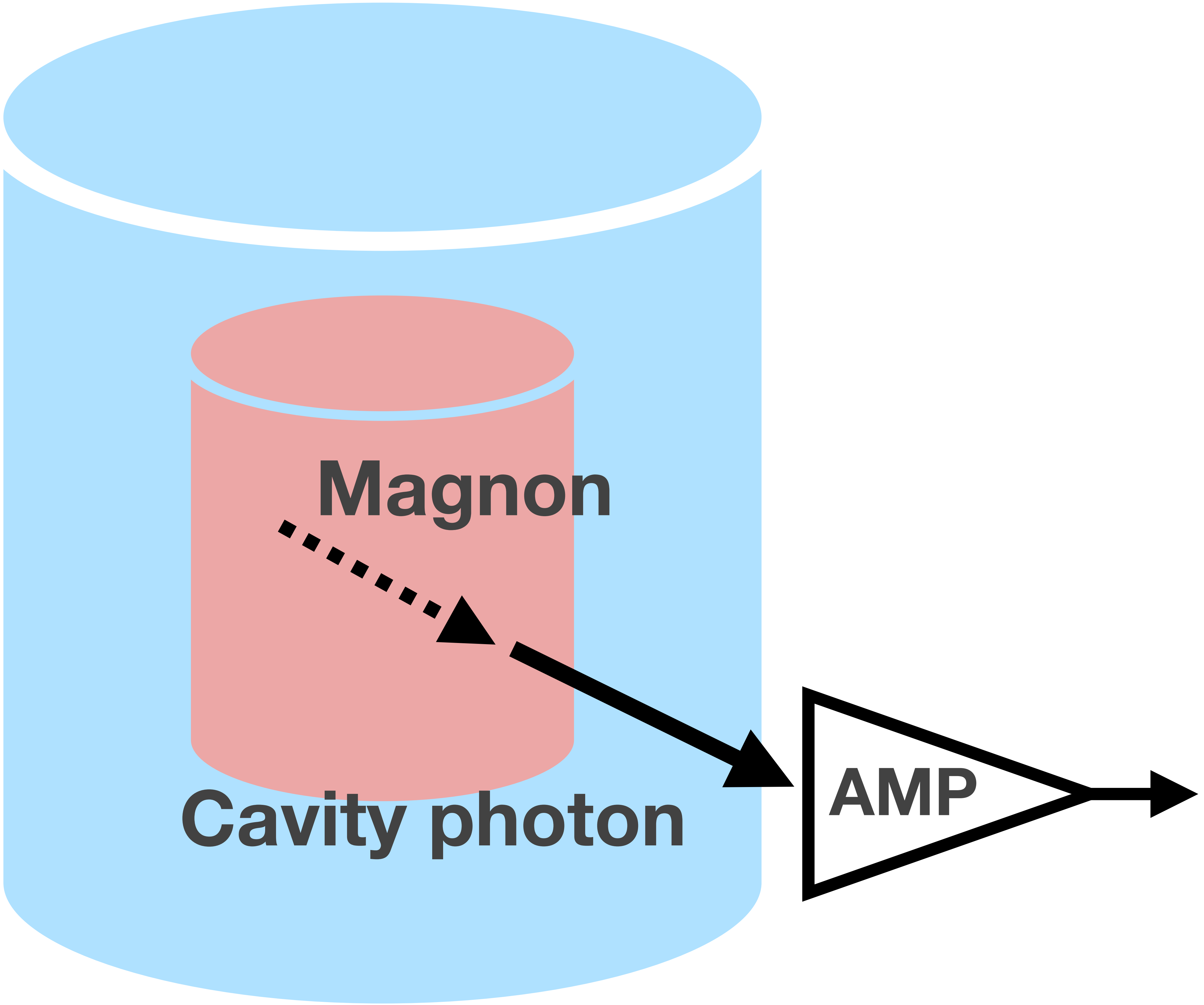
$$\omega_{\mathrm{cav}} = \omega_L = m_a$$

Resonance of magnon-photon mixing

Resonance of axion-magnon convergion



# 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 of cavity photons**

# Thermal noise

$$N = \frac{1}{\exp(\hbar\omega/k_B T) - 1} + \boxed{\frac{1}{2}}$$

Quantum fluctuation

- For $\hbar\omega/k_B T \gtrsim \mathcal{O}(1)$, quantum fluctuation dominates thermal noises

  = ***Quantum limit***

- Our experiment: $\hbar\omega \sim \mu\mathrm{eV}\,,\, T \sim \mathrm{mK}$ ▷ $N \simeq 1/2$

**But, quantum measurement techniques can circumvent quantum noise!**

# Quantum measurement techniques

[Today's talk by Lindley Winslow]

## *Quadratures*

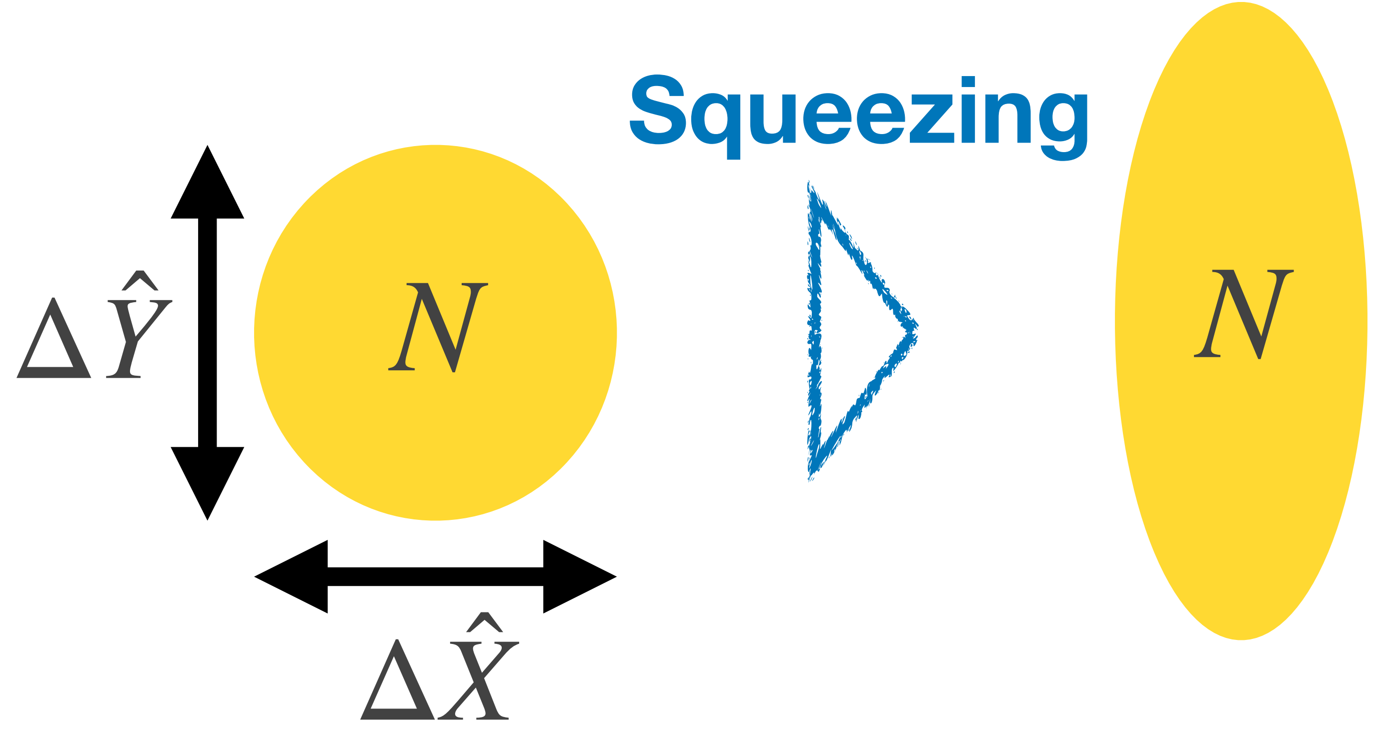
$$\hat{X} = \frac{\hat{a} + \hat{a}^\dagger}{\sqrt{2}}, \quad \hat{Y} = \frac{\hat{a} - \hat{a}^\dagger}{\sqrt{2}i} \quad \triangleright \quad [\hat{X}, \hat{Y}] = i \quad \triangleright \quad (\Delta\hat{X})(\Delta\hat{Y}) \geq \frac{1}{4}$$

- Usually, we measure #photons $\propto \hat{X}^2 + \hat{Y}^2$ by observing $\hat{X}$ & $\hat{Y}$ simultaneously
- Quantum fluctuation $\Delta\hat{X} \sim \Delta\hat{Y} \sim 1/2$ becomes dominant in low $T$

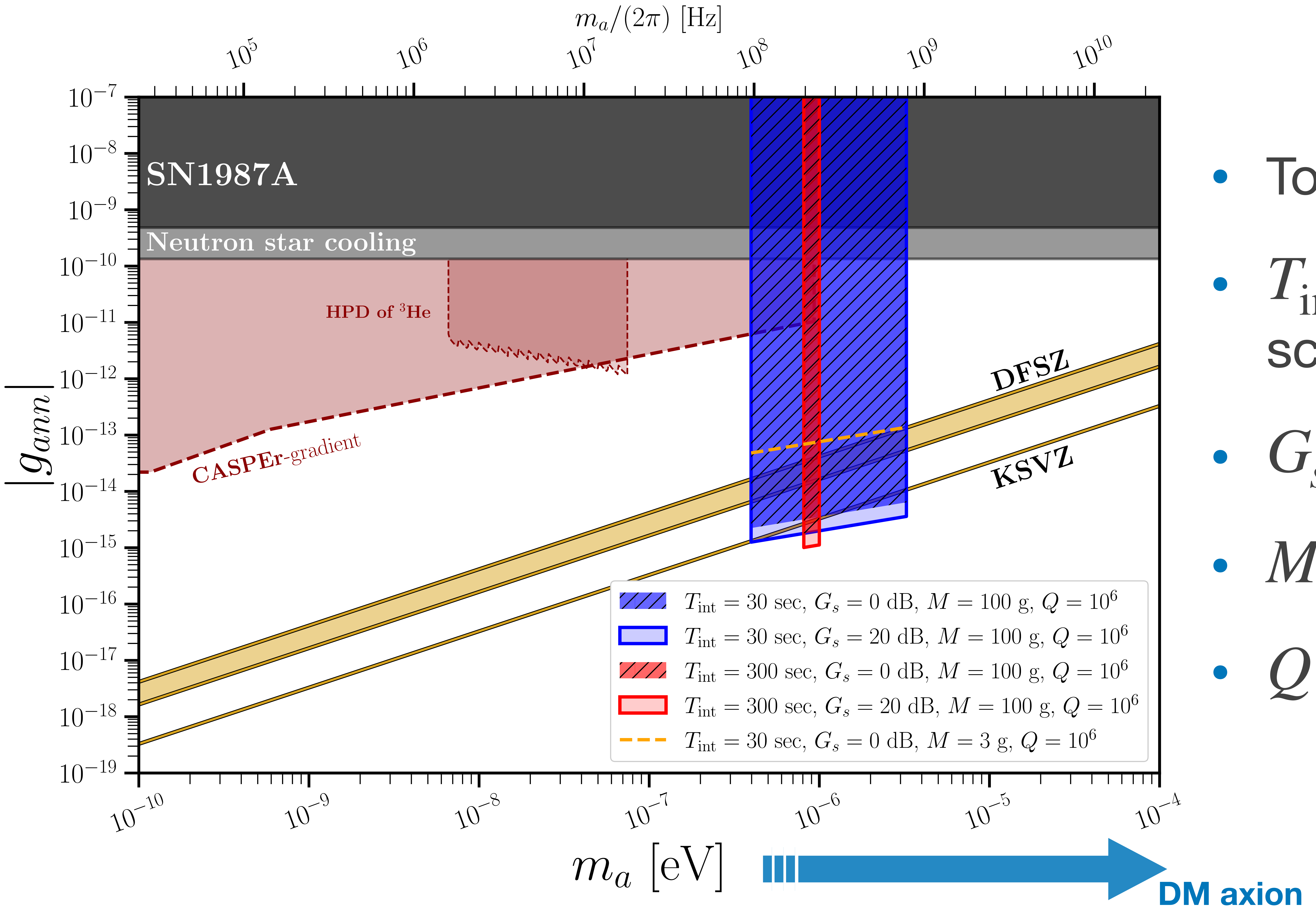
**Imposing quantum fluctuation to $\hat{Y}$ (squeezing) &**

**observing only $\hat{X}$ (homodyne measurement),**

can reduce **quantum noise less than 1/2**



# Result: expected sentivity for DM axion




- Total observation time: 2 years
- $T_{\rm int}$ : measuring time for one scanning
- $G_s$ : squeezing parameter
- $M$ : total amount of Helium-3
- $Q$ : cavity quality factor

# Summary

- Hitoshi is also knowledgeable about condensed matter physics.
- Axion-photon coupling has been well explored, but NOT for **nucleon** coupling.
- We have shown that **axion-neutron coupling can be probed by using (nuclear) magnons in A1 phase of superfluid $^3$He.**
    - sensitive to $\mu\mathrm{eV}$ axion, which is favored for DM axion
    - can explore **heavier mass regions** than other projected experiments
- We also quantitatively evaluated enhancement of sensitivity by **quantum measurements.**

**Happy birthday!!**