Axion Production and Detection using NMR

DESY Theory Workshop
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Content

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- Axion production
- Experimental sensitivity

Introduction

- Axion is a well-motivated hypothetical pseudoscalar in the extension of the Standard Model.

- Axion dark matter searches through axion-nucleon coupling g_{aN} using NMR techniques, e.g., CASPEr. [Budker et al., 2014]

- Non-relic axion search: production and detection in the lab.
  - Light-shinning-through-wall experiments [Bibber et al., 1987;…]
  - ARIADNE [Arvanitaki & Geraci, 2014; Geraci et al., 2018]
  - Ferroaxionic force [Arvanitaki et al., 2024]
  - …

Resonant cavity

mechanical oscillators or rotators + NMR

Axion Precession Experiment

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

$a(t, \mathbf{x})$

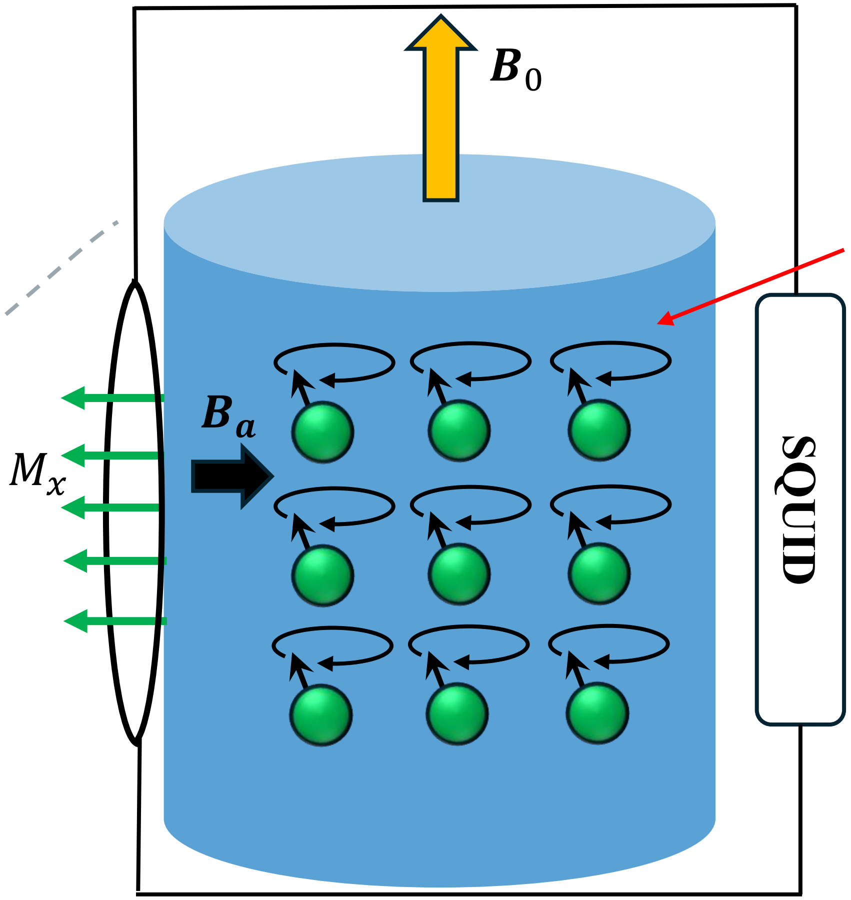
Non-relativistic nucleus:

$$H_{\text{int}} = -2 g_{aN} \nabla a(t, \mathbf{x}) \cdot \mathbf{S}$$

$$\mathbf{B}_a(t, \mathbf{x}) = -\frac{2 g_{aN}}{\gamma} \nabla a(t, \mathbf{x})$$

γ: gyromagnetic ratio of nucleus

On-resonance condition: $\omega_0 = m_a$



Spin sensor

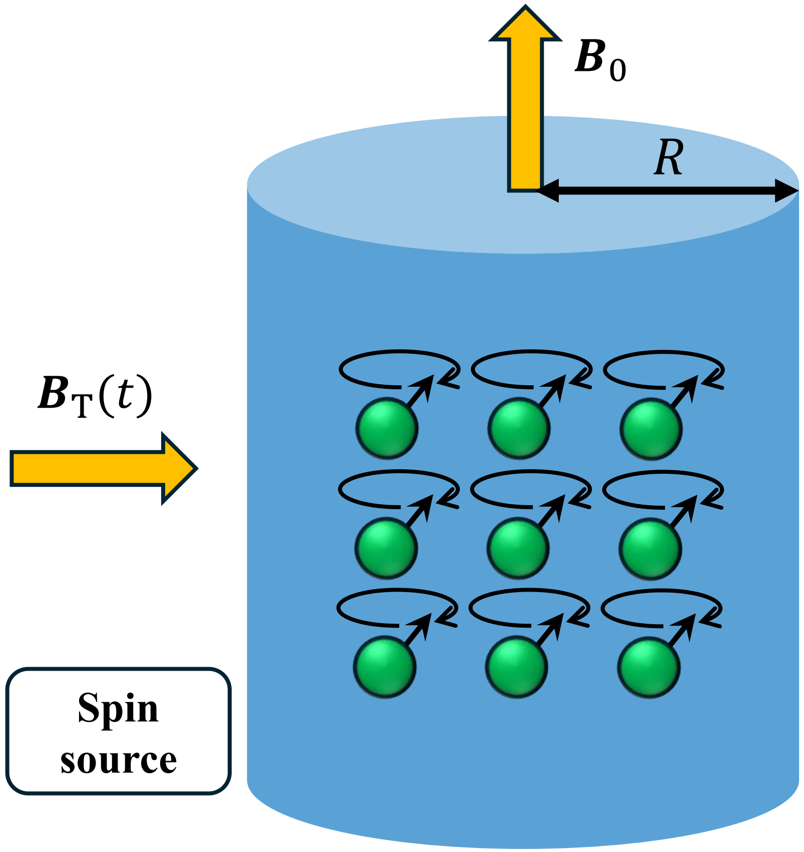
Ambient axion DM field induced AC magnetic field drives the spin precession and produces detectable (transverse) magnetization.

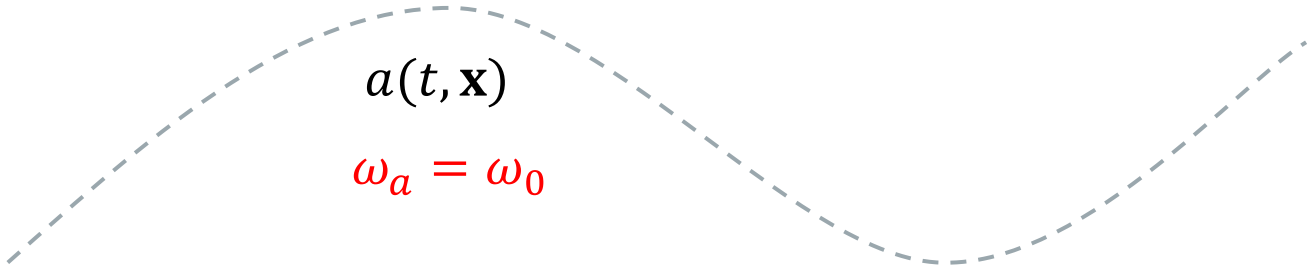
Axion Production

$$(\partial^2 + m_a^2)a(\mathbf{x}, t) = \boxed{-g_{aN}\partial_\mu j^{5\mu}(t, \mathbf{x})} \rightarrow \text{spin density}$$

$$j^{5i}(t, \mathbf{x}) \simeq n_N \sigma^i(t)$$

N.R. limit for nucleus





Near zone ($R \simeq r \ll \lambda$):

$$a(\mathbf{x}) = g_{aN} n_N \int d^3\mathbf{x}' \frac{(\mathbf{x} - \mathbf{x}') \cdot \boldsymbol{\sigma}}{4\pi|\mathbf{x} - \mathbf{x}'|^3}.$$

AC magnetic field drives the spin precession and produces axion fields.

Maximum axion mass

- Full-form axion field profile:

$$a(\mathbf{x}) = g_{aN} n_N \int d^3x' \frac{(\mathbf{x}-\mathbf{x}')\cdot\boldsymbol{\sigma}}{4\pi|\mathbf{x}-\mathbf{x}'|^3}(1 - ik_0|\mathbf{x}-\mathbf{x}'|)\, e^{ik_0|\mathbf{x}-\mathbf{x}'|}$$

$$k_0 \equiv \sqrt{\omega_0^2 - m_a^2}\ (\text{if } \omega_0 \geq m_a)\ \text{ or } i\kappa_0\ (\text{if } \omega_0 < m_a)$$

- When the axion mass is too large,

$$e^{-\kappa_0|\mathbf{x}-\mathbf{x}'|} \rightarrow e^{-m_a r} \ll \mathbf{1}$$

when $m_a R \gg 1$

Near-zone profile

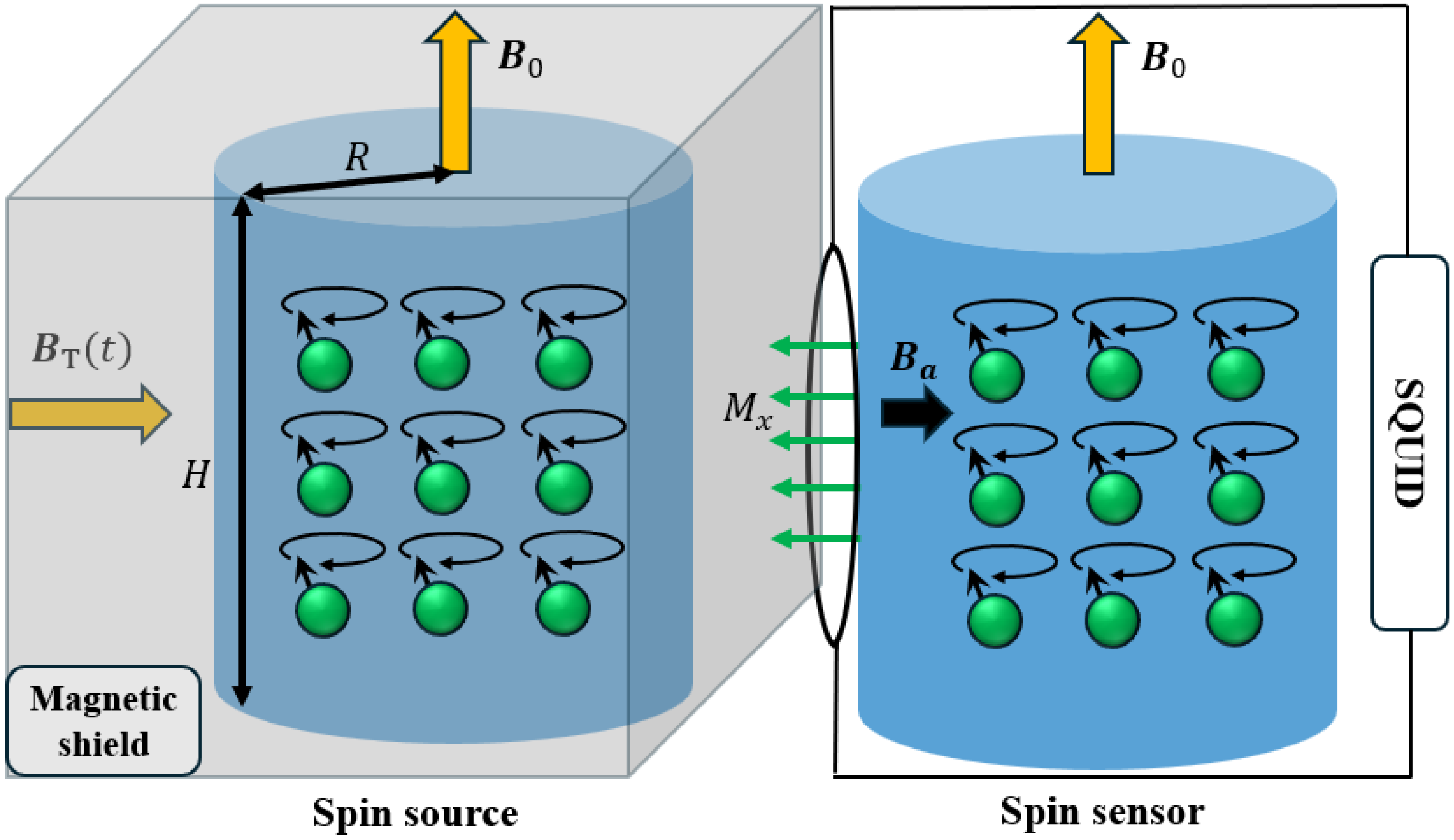
- Axion field generated by spin source:

$$|\partial_x a/a| \sim 1/R$$

- Axion DM field:

$$\frac{\nabla a}{a} \sim m_a \mathrm{v}_0 \sim 10^{-3} m_a \ll R^{-1}$$

Experimental setup



On-resonance condition is always satisfied: $\omega_0 = \omega_0$

Larmor freq. of nucleus in spin sensor

The sourced axion field freq.

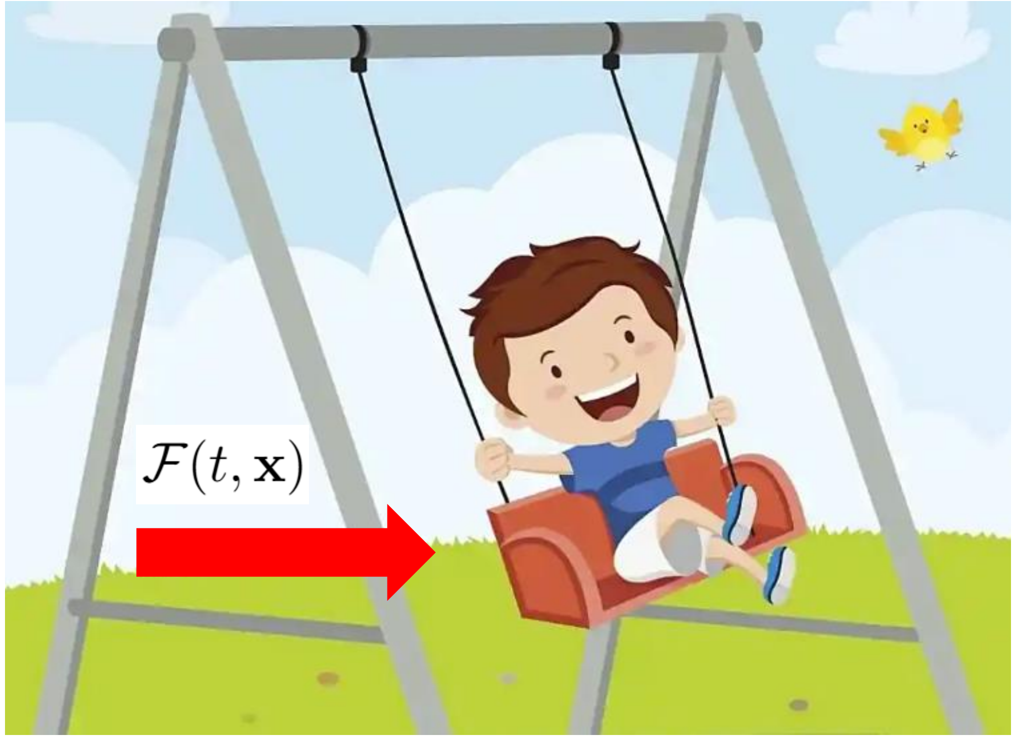
Growth of transverse magnetization

- Driven harmonics of the transverse magnetization M_x:

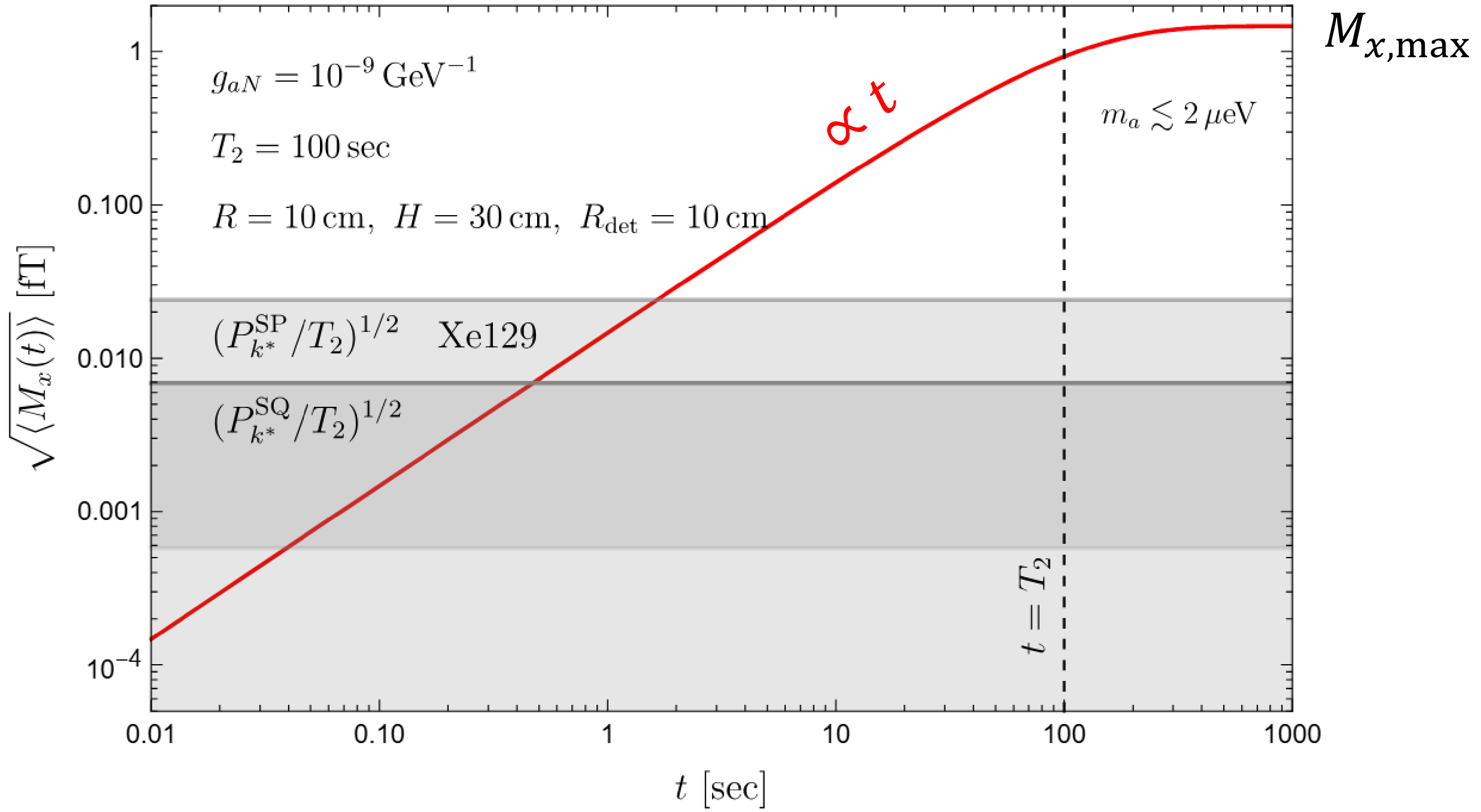
$$\ddot{M}_x + \frac{2}{T_2}\dot{M}_x + \omega_0^2 M_x \simeq \gamma M_0(\omega_0 B_{ax} - \dot{B}_{ay}) \qquad \mathcal{F}(t, \mathbf{x})$$

Transverse relaxation time

driving force

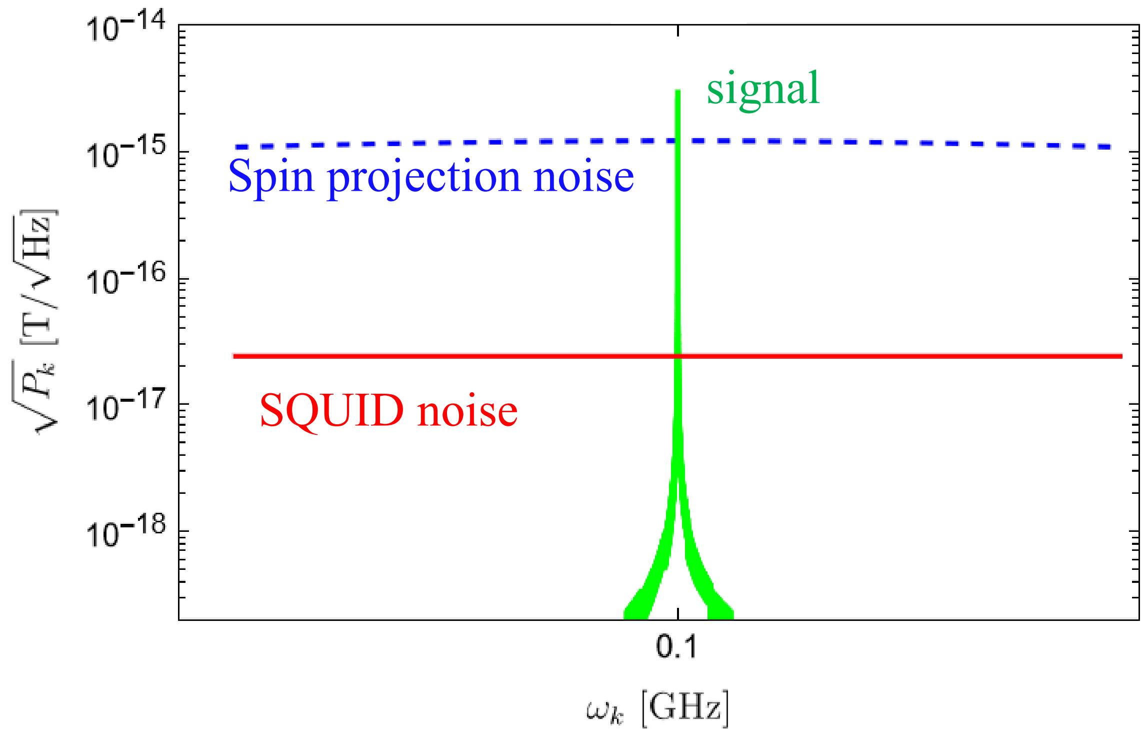


Transverse Magnetization

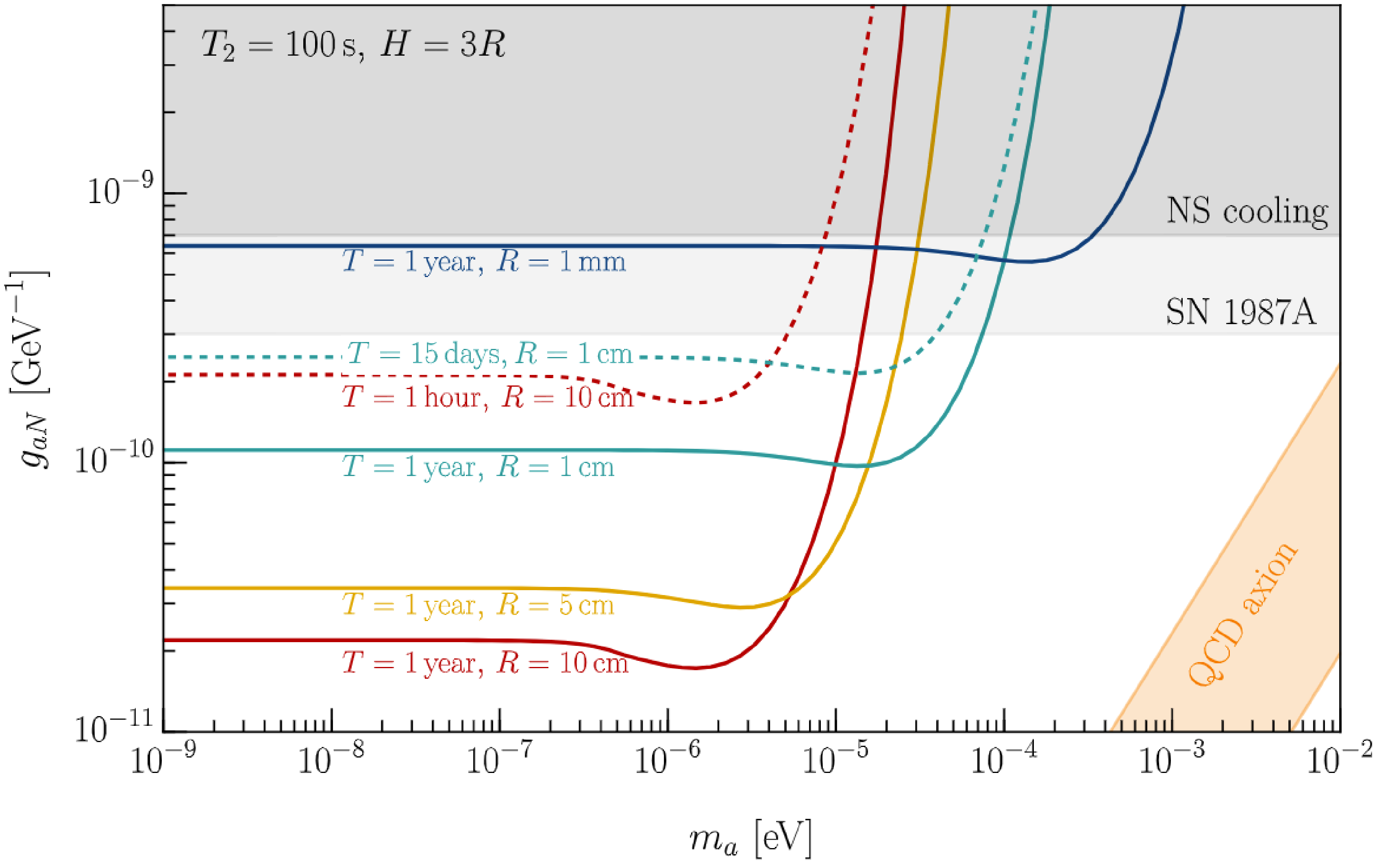


Noise source

- Thermal noise → cool down the apparatus
- SQUID noise → high-precision magnetometer
- Spin projection noise → limited and fundamental
- Transverse AC magnetic field → magnetic shielding



Sensitivity



Scaling of model parameters

- In the plateau region

$$g_{aN}^{(\mathrm{UL})} \simeq 2 \times 10^{-11}\,\mathrm{GeV}^{-1} \left(\frac{n_N}{1.3 \times 10^{22}\,\mathrm{cm}^{-3}} \right)^{-3/4} \times \left(\frac{T_2}{100\,\mathrm{s}} \right)^{-1/4} \left(\frac{T}{1\,\mathrm{yr}} \right)^{-1/4} \left(\frac{V}{0.01\,\mathrm{m}^3} \right)^{-1/4}$$

Advantage

- A broad-band search with large axion mass $m_a \sim R^{-1}$ beyond the Larmor frequency ω_0 of the NMR device.
- The sourced axion field is coherent, with a known frequency ω_0.
  - Can always set the detector intrinsic frequency to satisfy on-resonance condition
  - Can measure for a long observation time
- The sensitivity of a continuous experiment for T_{obs} is equivalent to that of N multiple experiments with a time T_{obs}/N.
  - the experiment is more applicable and reliable since one can calibrate the apparatus daily or hourly.
  - conduct multiple experiments simultaneously with multiple sets of devices.

Conclusion

- 1. Axion production and detection through pure g_{aN} is studied.
- 2. The dual NMR setup can probe the non-relic axion up to $m_a \leq R^{-1}$.
- 3. The sensitivity can surpass the astrophysical constraint within days' observation time and centimeter-scale NMR device.

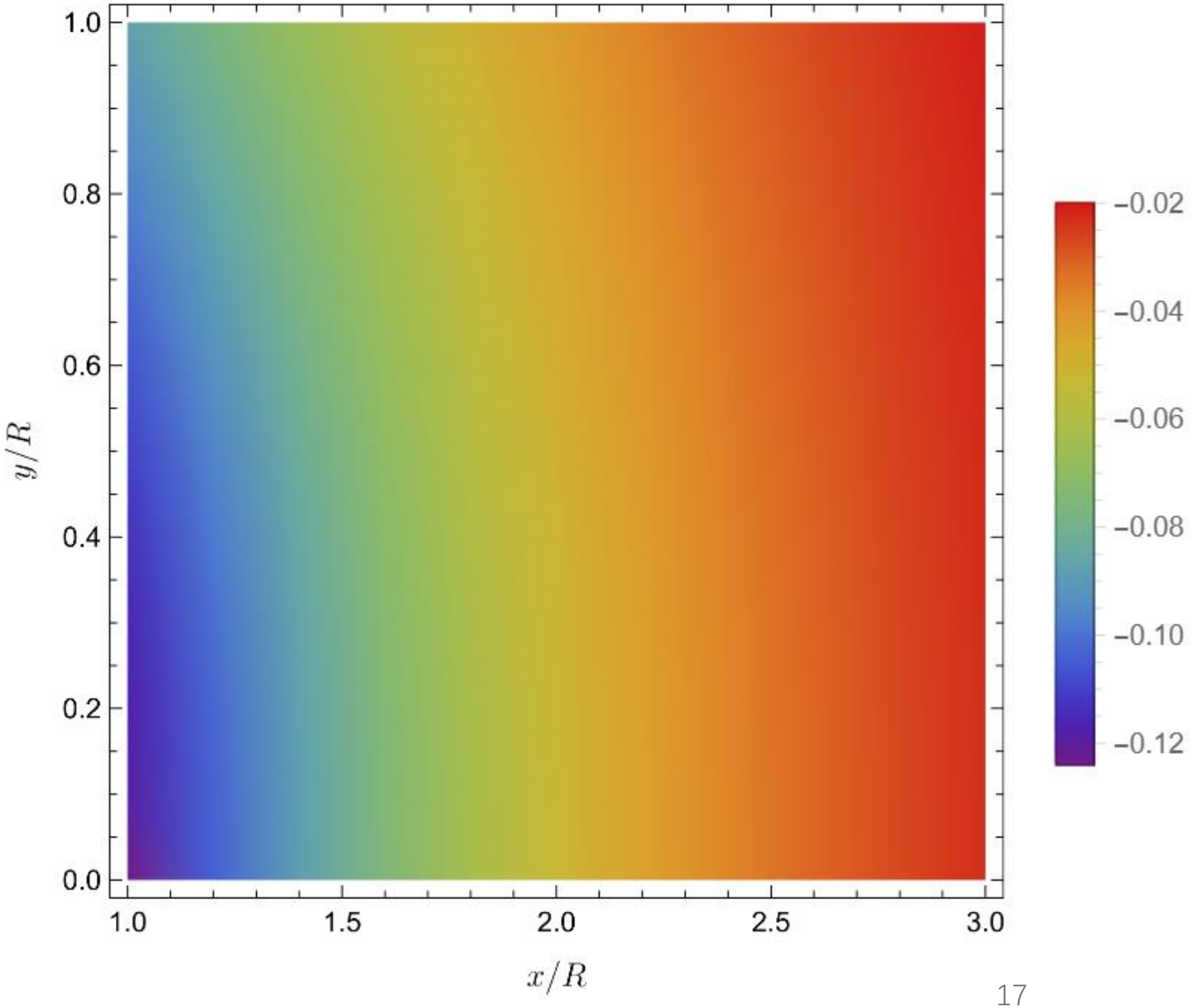
Backup slides

Near-zone profile

- The profile of ∇a in near zone:

$$a(\mathbf{x} = x\hat{x}) \simeq 2.4 \times 10^{-7}\mathrm{eV} \left(\frac{x}{R}\right)^{-1.6} \times \left(\frac{g_{aN}}{10^{-10}\mathrm{GeV}^{-1}}\right)\left(\frac{n_N}{1.3\times 10^{22}\mathrm{cm}^{-3}}\right)\left(\frac{R}{1\mathrm{cm}}\right)$$

$$\partial_x a(\mathbf{x} = x\hat{x}) \simeq -7.6 \times 10^{-12}\mathrm{eV}^2 \left(\frac{x}{R}\right)^{-2.6} \times \left(\frac{g_{aN}}{10^{-10}\mathrm{GeV}^{-1}}\right)\left(\frac{n_N}{1.3\times 10^{22}\mathrm{cm}^{-3}}\right).$$



Axion Production

- *Far zone: $e^{ik_0|\mathbf{x}-\mathbf{x}'|}$ oscillating