Massachusetts Institute of Technology

NEW IDEAS FOR AXION SEARCHES IN SUPERFLUID HELIUM

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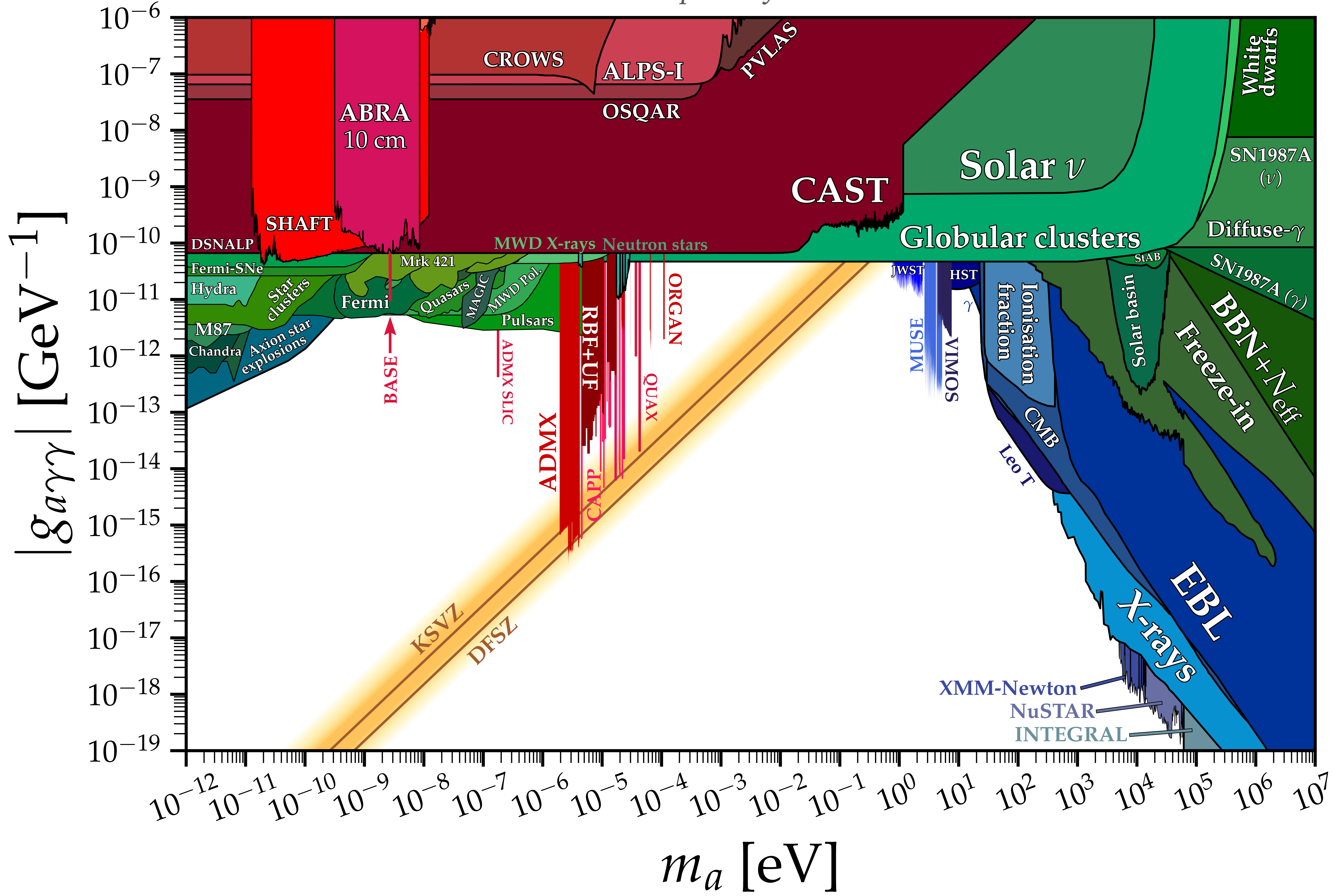
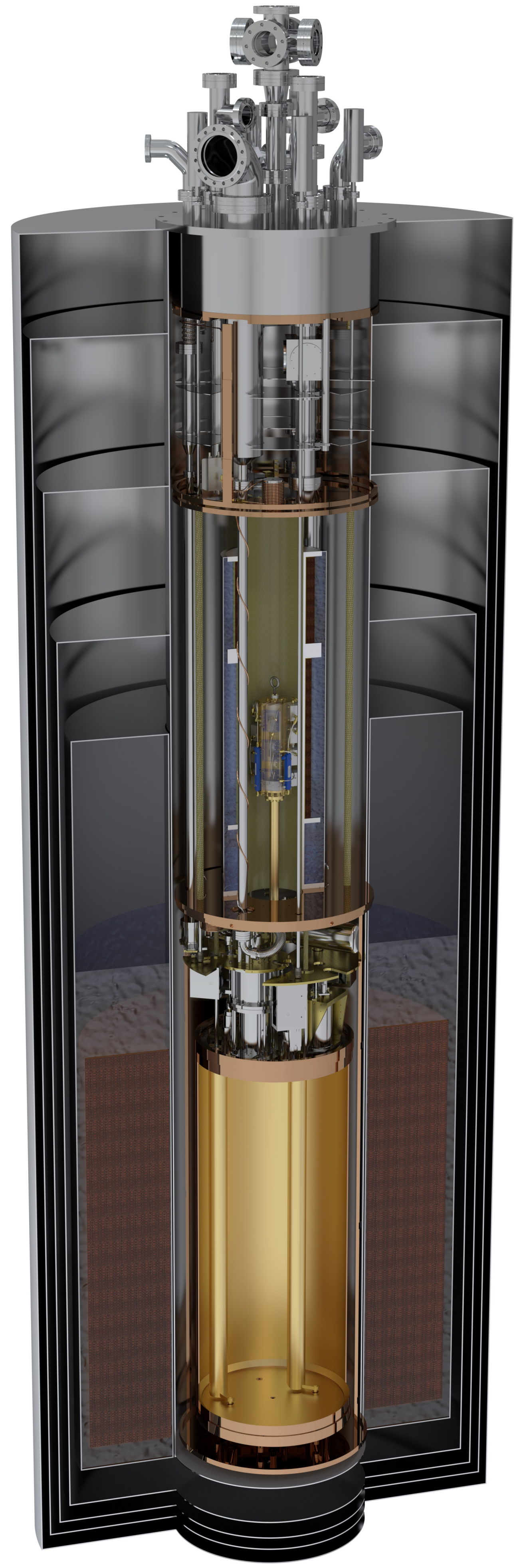
Based on arXiv:2310.07791

AXION PARAMETER SPACE AND SEARCH EFFORTS

Ciaran O'Hare. Axion Limits Github Repository





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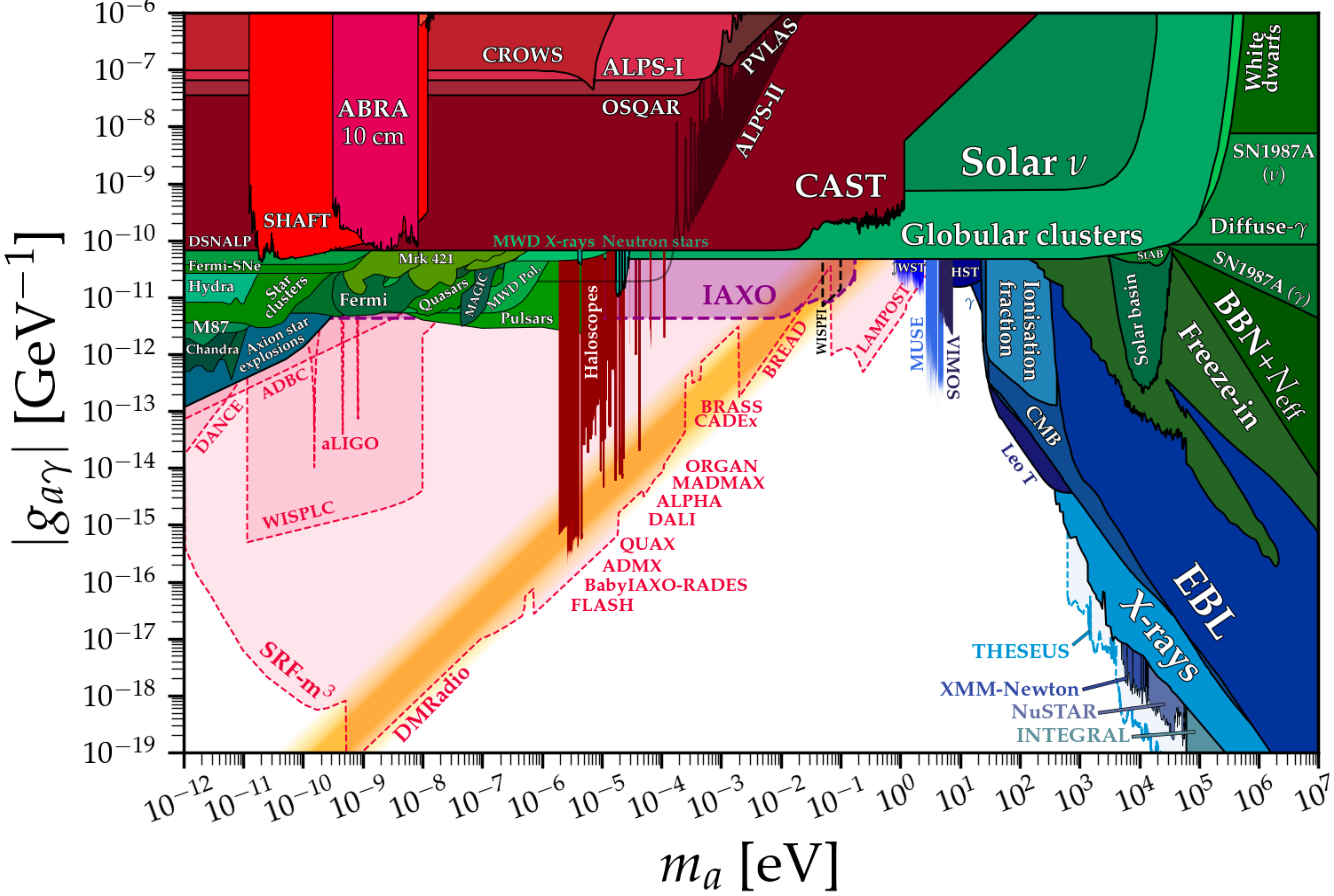

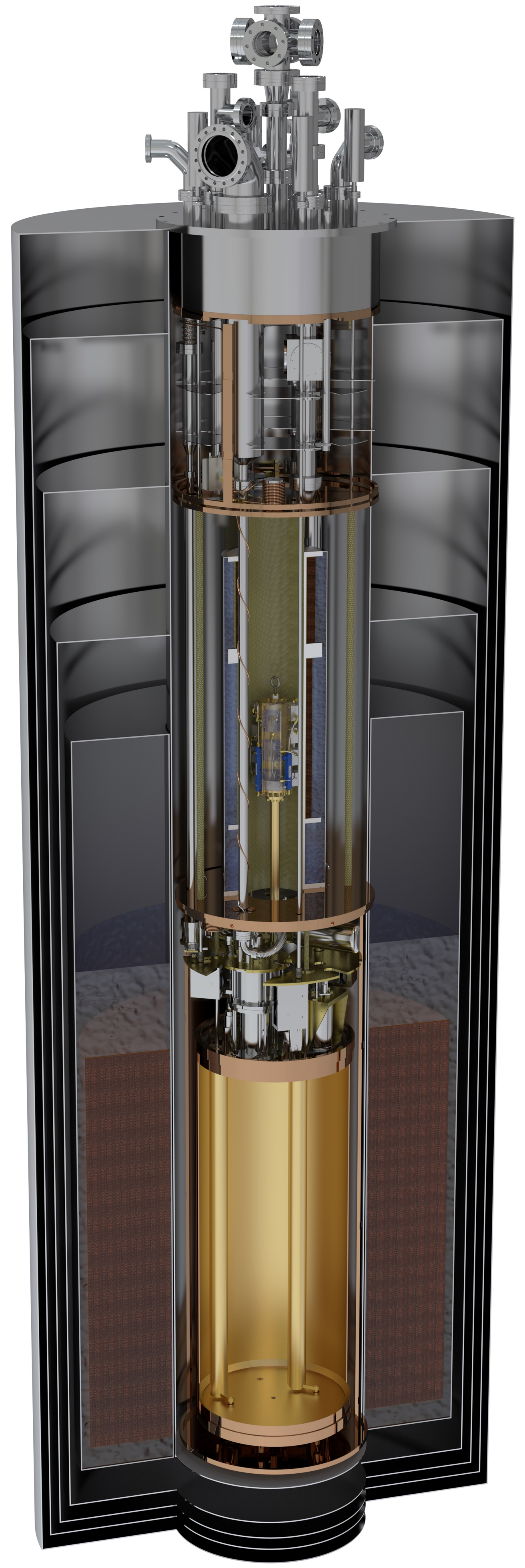

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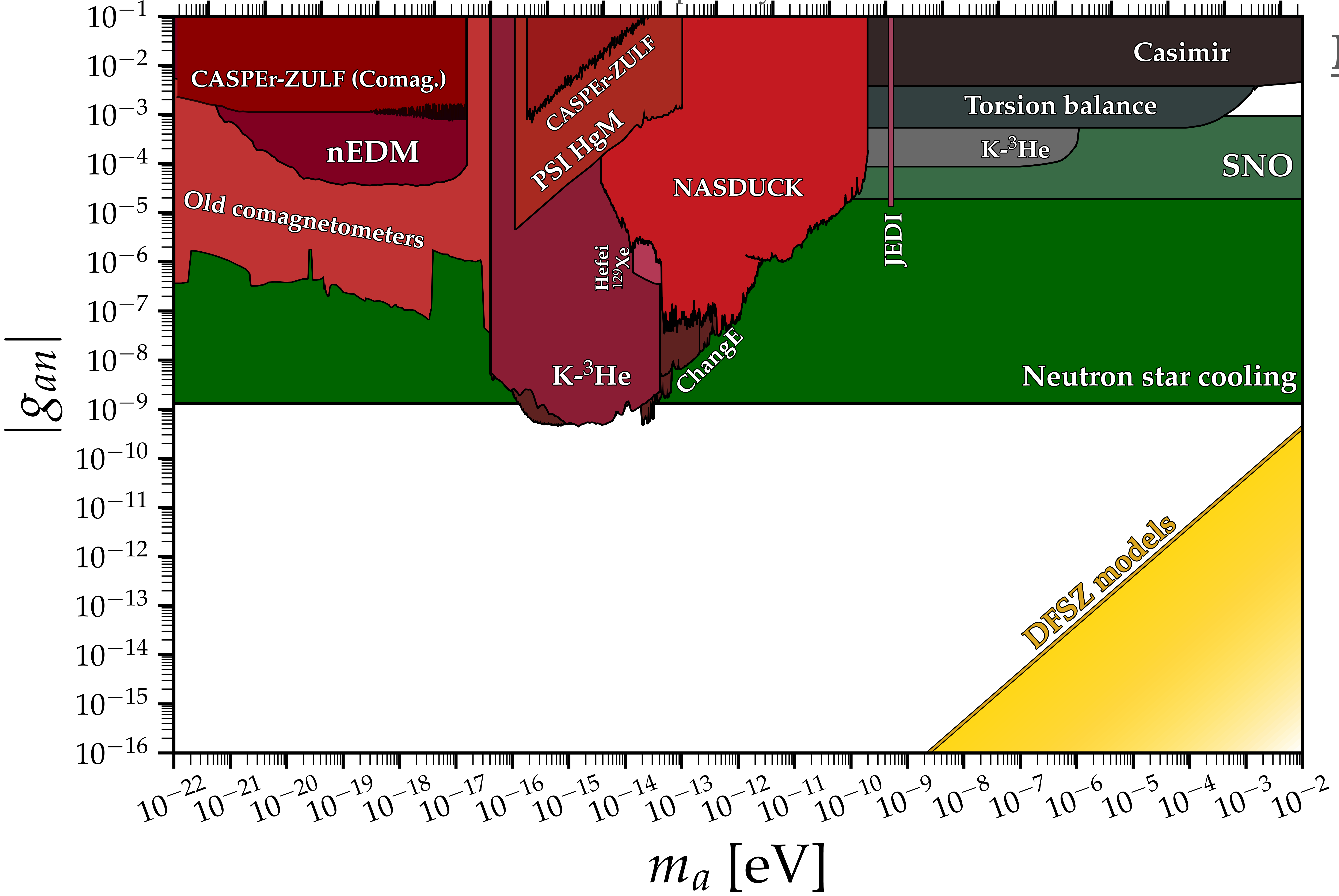


Nuclear spin couplings to axion

$$H \supset g_{aNN} \nabla a \cdot \sigma_n$$

Axion Effective Magnetic Field

$$\mathbf{B}_\mathrm{a} \equiv \frac{g_{aNN}}{\gamma} \nabla a$$

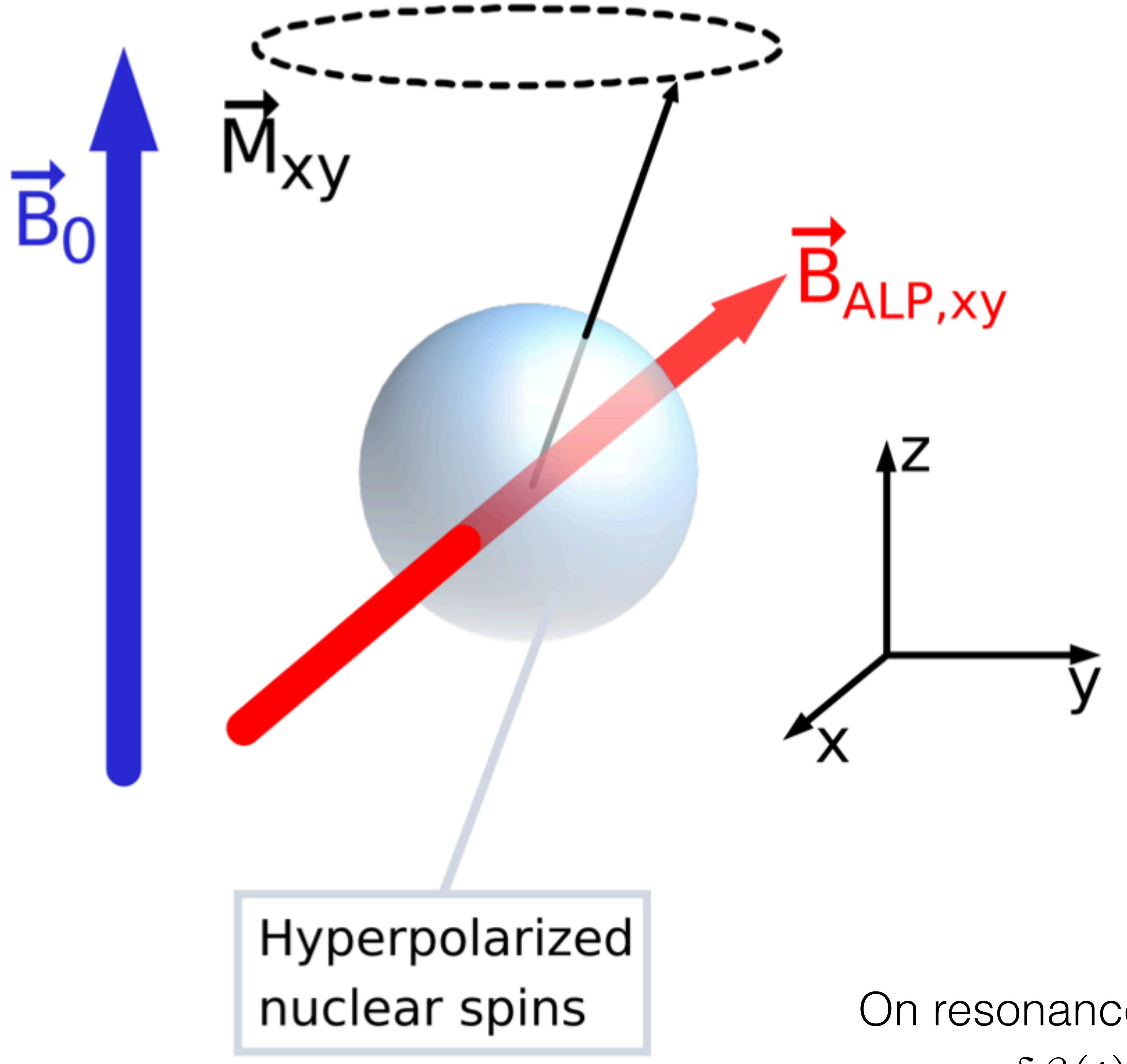
$$\approx g_{aNN} \frac{\sqrt{2\rho_\mathrm{DM}}}{\gamma} \cos(m_a t) \mathbf{v}_a$$

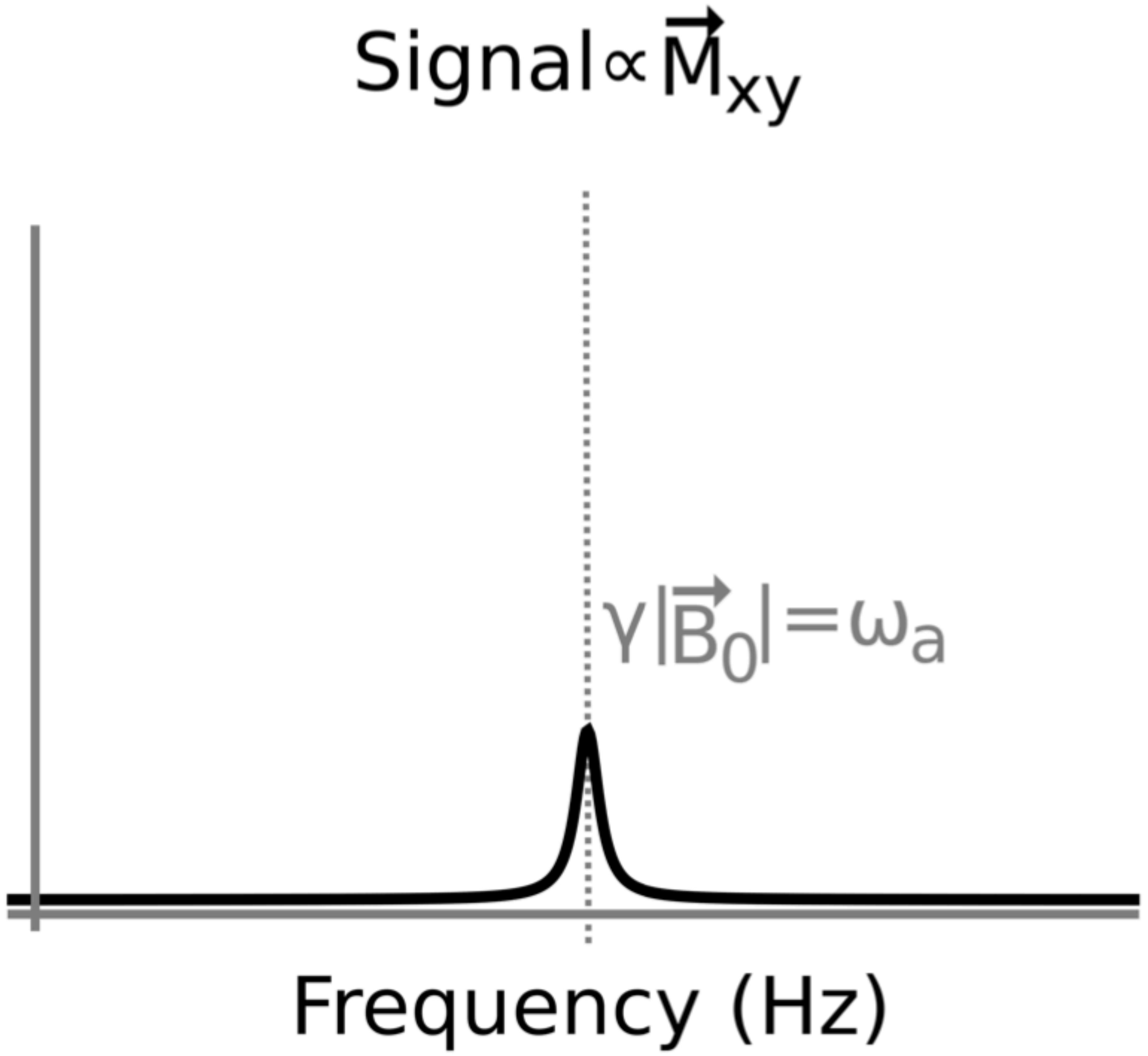
$$|\mathbf{B}_a| \approx 5 \times 10^{-23}\,\mathrm{T} \times \left(\frac{10^{-7}\,\mathrm{eV}}{m_a}\right)$$

QCD Axion DM

CONVENTIONAL AXION WIND DETECTION

[CASPEr collab; Garcon et al. arXiv:1707.05312]





On resonance, $\gamma B_0 = m_a$,linearly growing tip angle:

$$\delta\beta(t) \;=\; \gamma B_a t \quad \text{for } \; t < \min[\tau_a, T_2]$$

HOMOGENEOUS PRECESSION DOMAIN OF HE-3

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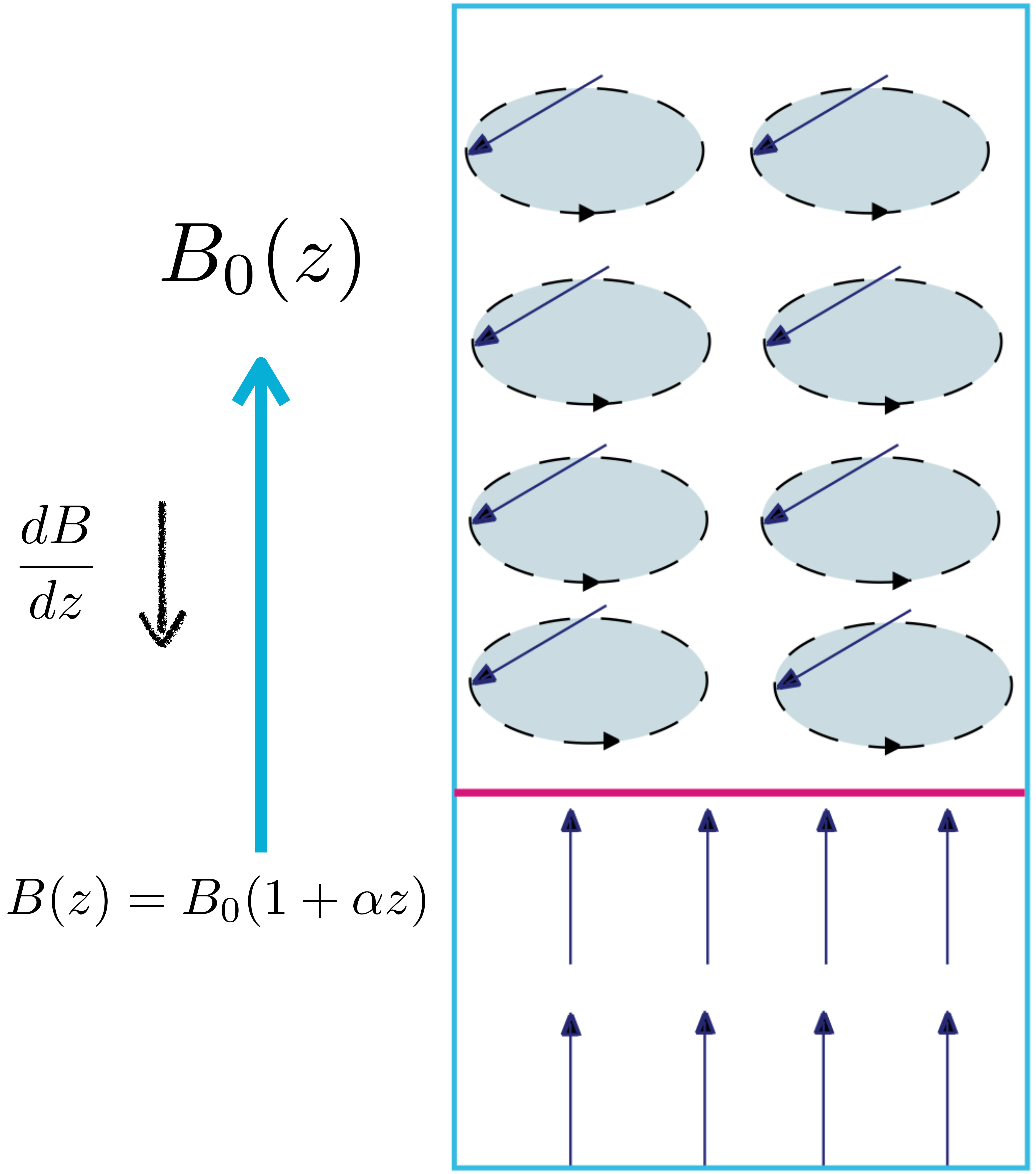


HPD Properties Specified by Domain Wall Location

$$N = \frac{5}{4}\frac{\chi B(z)}{\gamma} V_{\mathrm{HPD}} \qquad \omega_L = \gamma B(z)$$

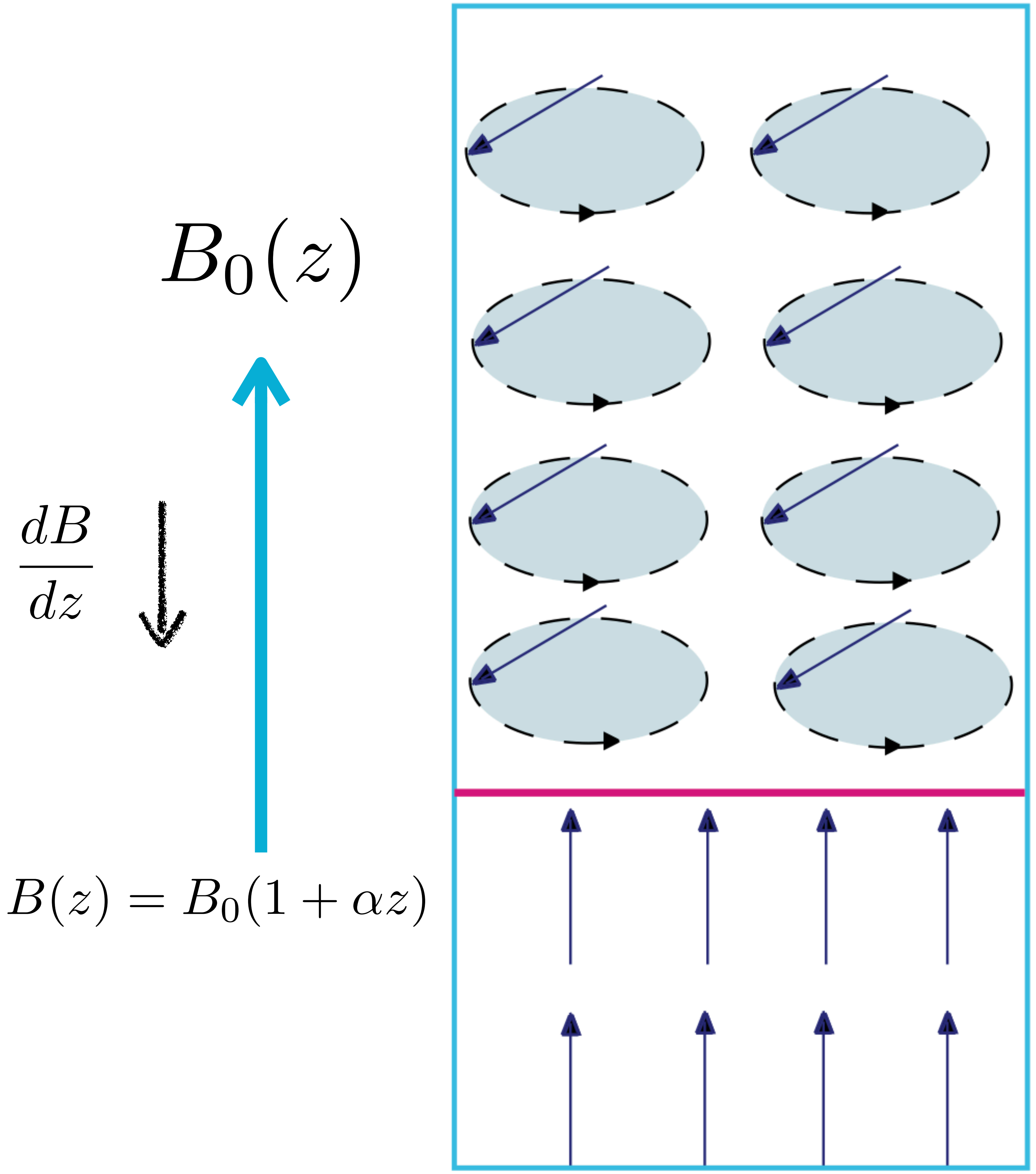
Effective Bloch System (No Perturbations)

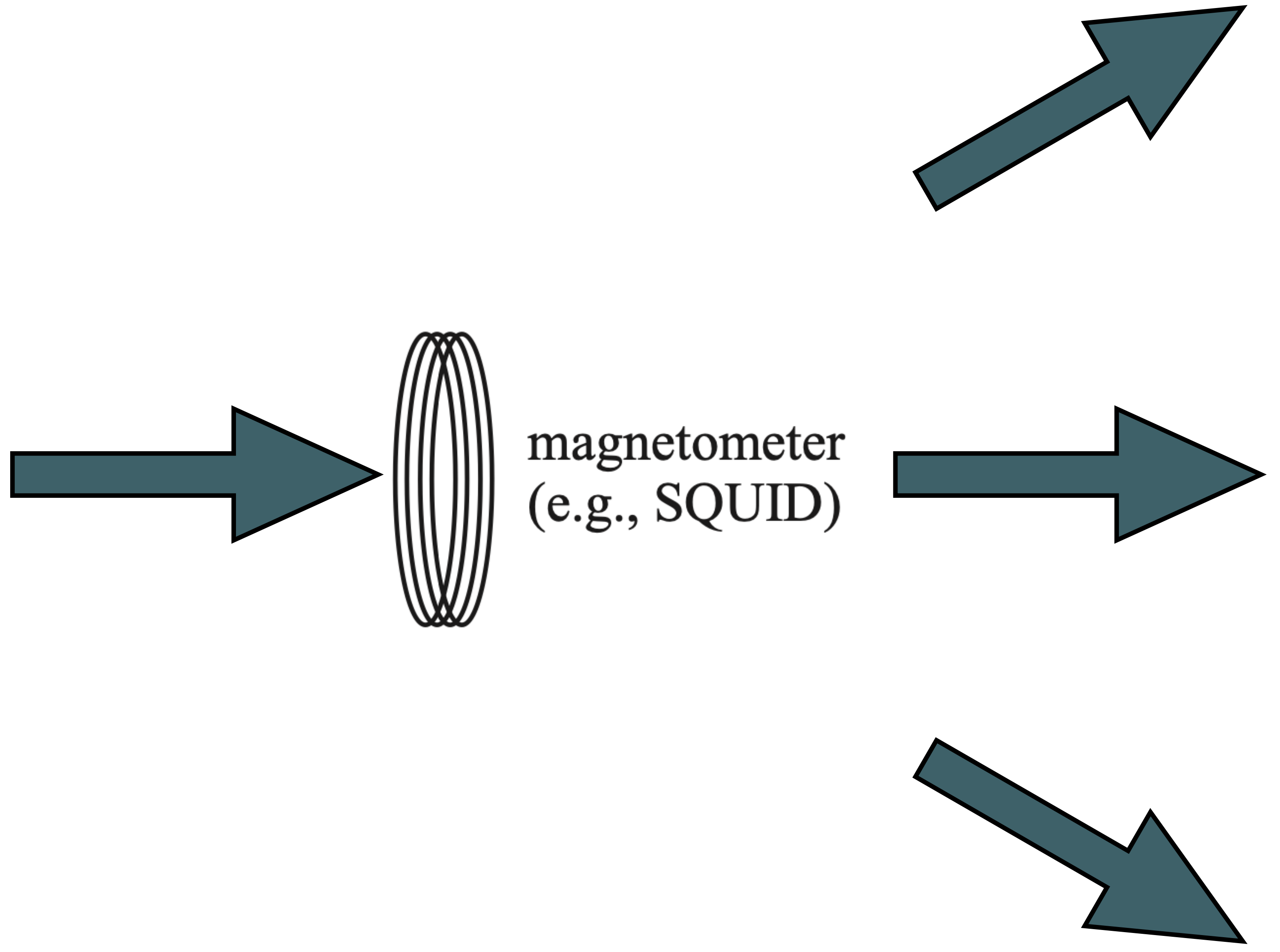
$$\dot{M}_z = -\frac{M_z - \widetilde{M}_0}{5T_1} \qquad \dot{M}_{xy} = -i\gamma M_{xy} B_z - \frac{M_{xy}}{T_1}$$

Equations of Motion for Precession Phase

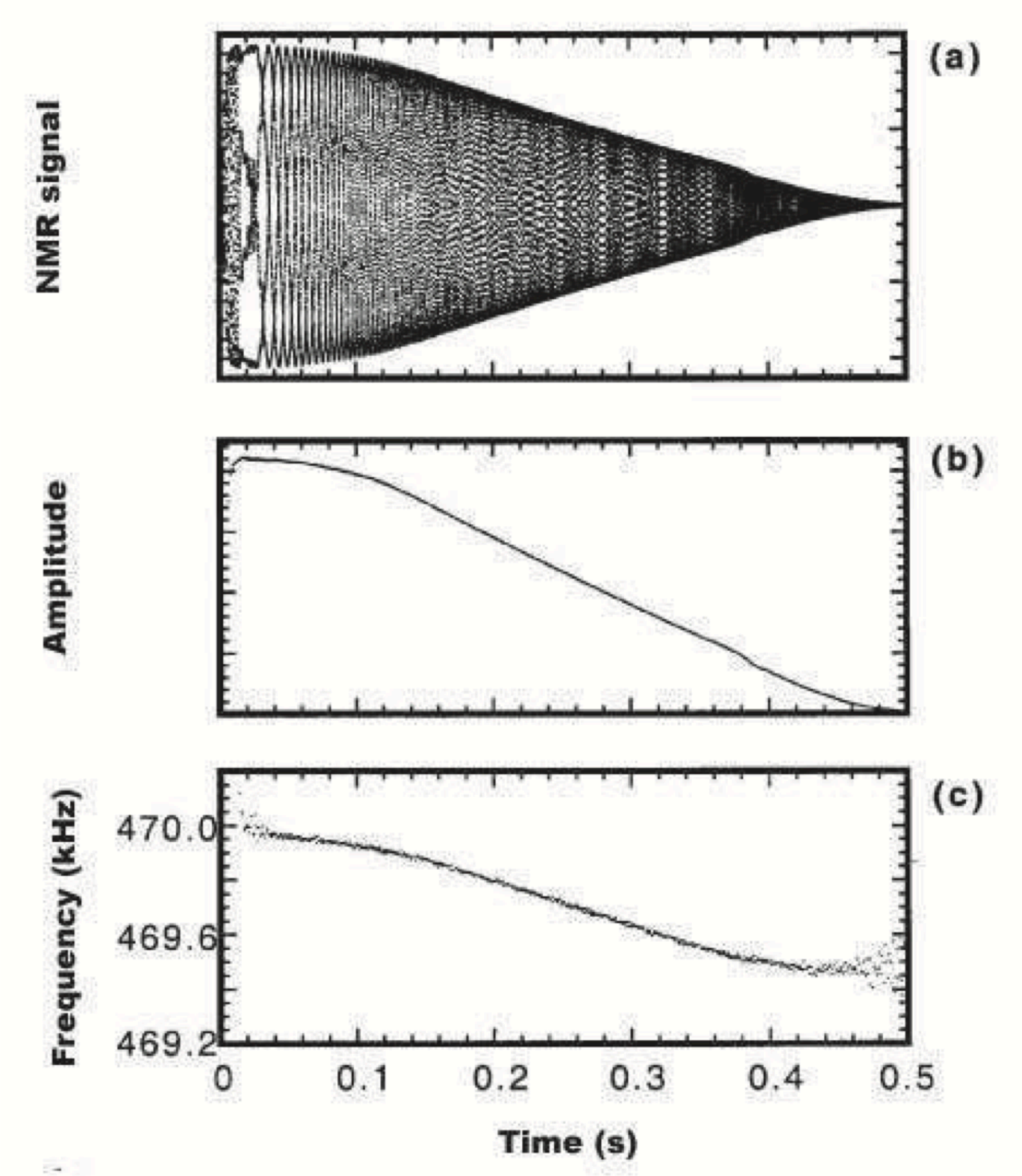
$$\dot{z}_0(t) = -\frac{z_0(t)\,(\alpha z_0(t) + 1)}{T_1\,(2\alpha z_0(t) + 1)} \qquad \dot{\theta}_0(t) = \gamma B_0\,[1 + \alpha z_0(t)]$$

HOMOGENEOUS PRECESSION DOMAIN OF HE-3





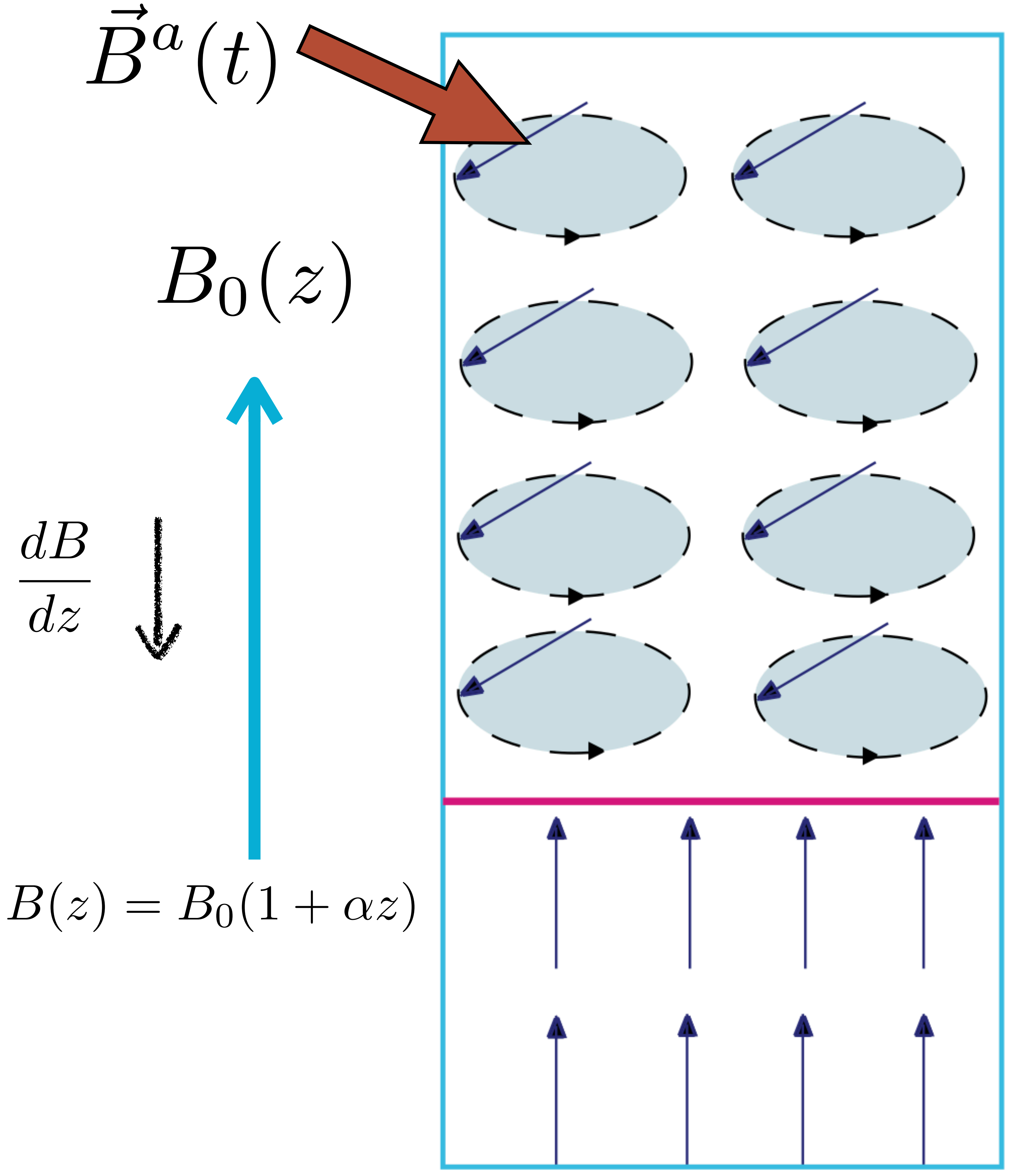
[Bunkov and Volovik, arXiv:0904.3889, arXiv:1003.4889, arXiv:0708.0663]



$$\dot{z}_0(t) = -\frac{z_0(t)\,(\alpha z_0(t)+1)}{T_1\,(2\alpha z_0(t)+1)}$$

$$\dot{\theta}_0(t) = \gamma B_0\,[1+\alpha z_0(t)]$$

HOMOGENEOUS PRECESSION DOMAIN OF HE-3



Effective Bloch System with Axion Perturbations

$$\dot{M}_z = \frac{i\gamma}{2}\left(M_{xy}\bar{B}^a_{xy} - \bar{M}_{xy}B^a_{xy}\right) - \frac{M_z - \widetilde{M}_0}{5T_1}$$

$$\dot{M}_{xy} = -i\gamma(M_{xy}B_z - M_z B^a_{xy}) - \frac{M_{xy}}{T_1}$$

Axion-Induced Shift in Domain-Wall Location

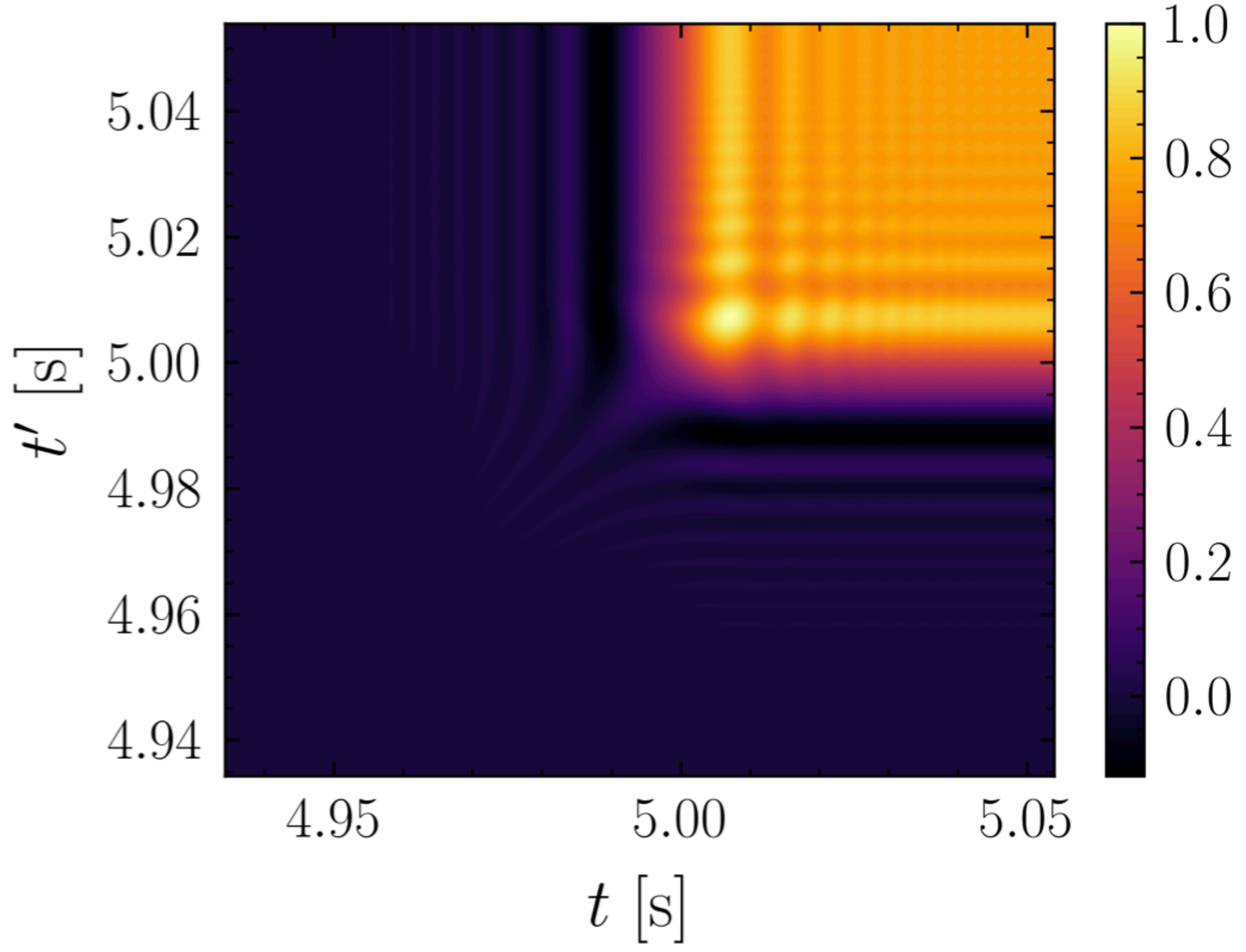
$$\dot{z}_a(t) = -\sqrt{15}\gamma\left(\frac{1+\alpha z_0(t)}{1+2\alpha z_0(t)}\right)\left[B^a_x(t)\sin\left[\theta_0(t)\right] + B^a_y(t)\cos\left[\theta_0(t)\right]\right]$$

Axion-Induced Shift in Precession Rate

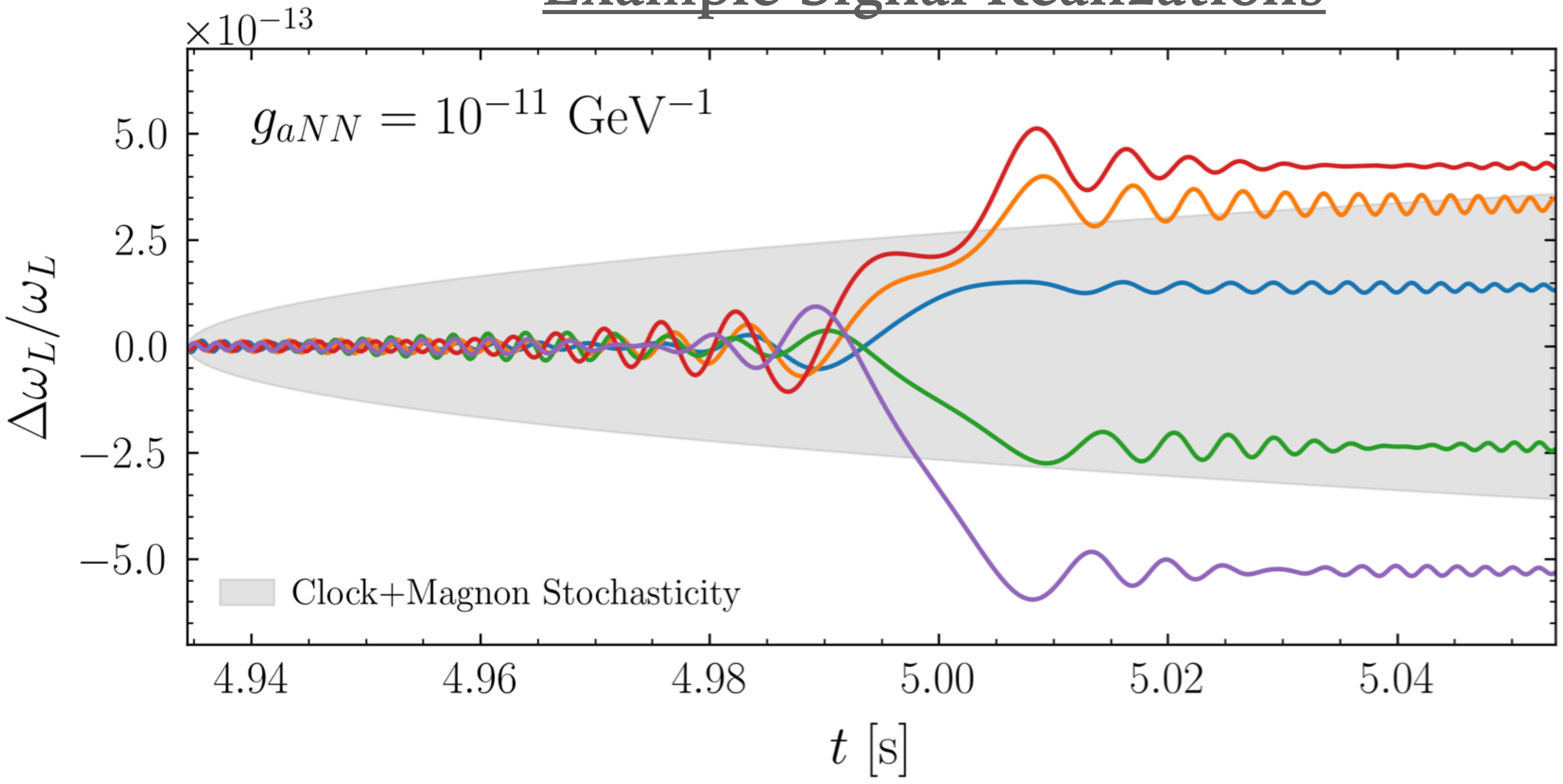
$$\dot{\theta}_a(t) = \alpha\gamma B_0 z_0(t) z_a(t)$$

AXION SIGNAL

Time-Domain Covariance Matrix



Example Signal Realizations

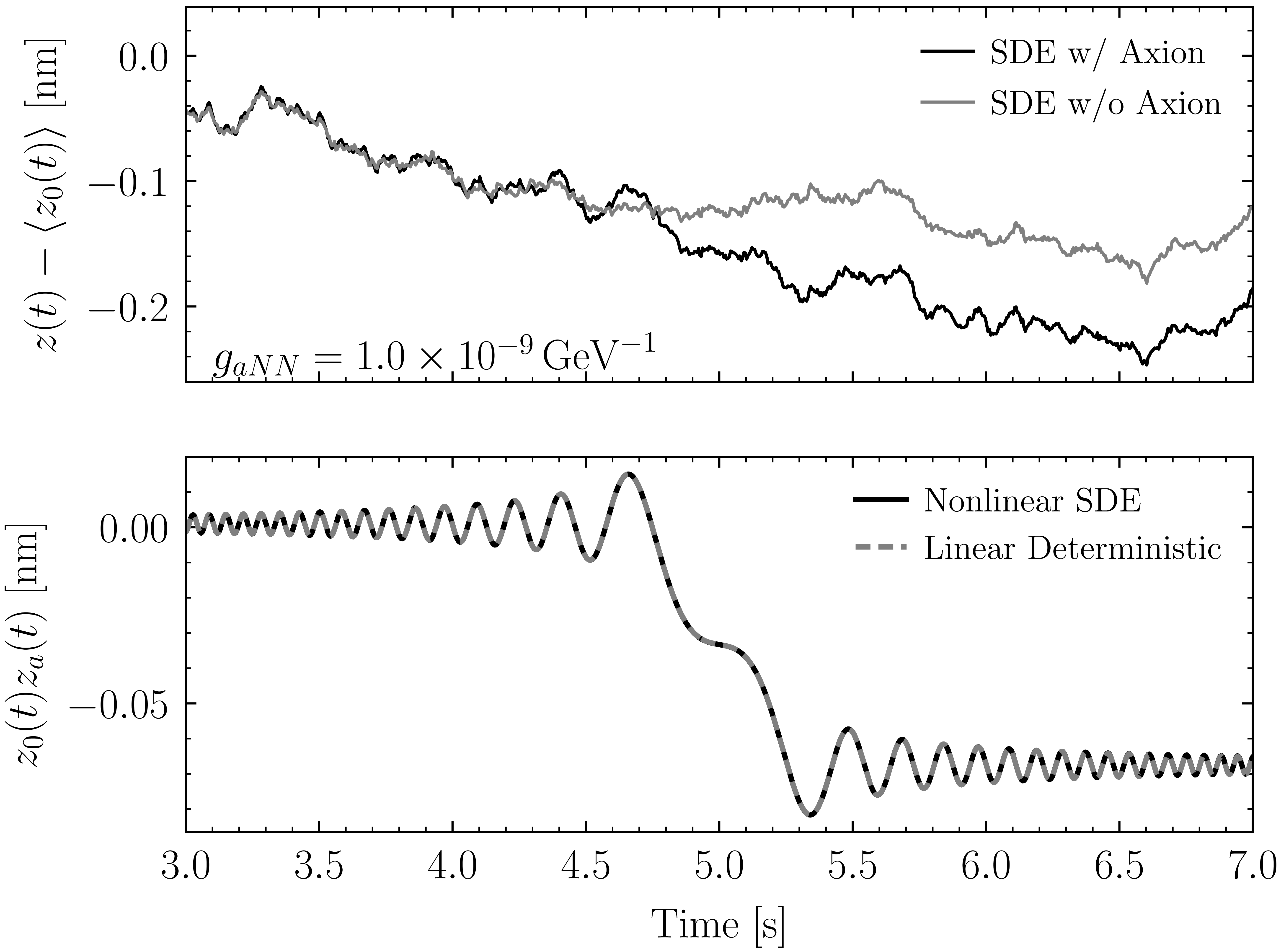


- Dynamics fully characterized as a non-stationary gaussian process
  - Depends on HPD relaxation time + axion coherence
- Searches for signals are searches for excess covariance

AXION SIGNAL IN A STOCHASTIC SYSTEM

- Bloch treatment is "zeroth order"
- Coarse-grained properties of the HPD depend on magnon number
  - **Background**: uncorrelated magnon decay
  - **Signal**: correlated magnon pumping by axion field
- Background accumulates at all times
- Signal accumulates only during resonance
- Require rapid, high-precision frequency measurement

$$dN(t) = -\Gamma N(t)dt + [\Gamma N(t)]^{1/2}\, dW_t + dN_a(t)$$



MEASURING AN AXION SIGNAL IN A STOCHASTIC BACKGROUND

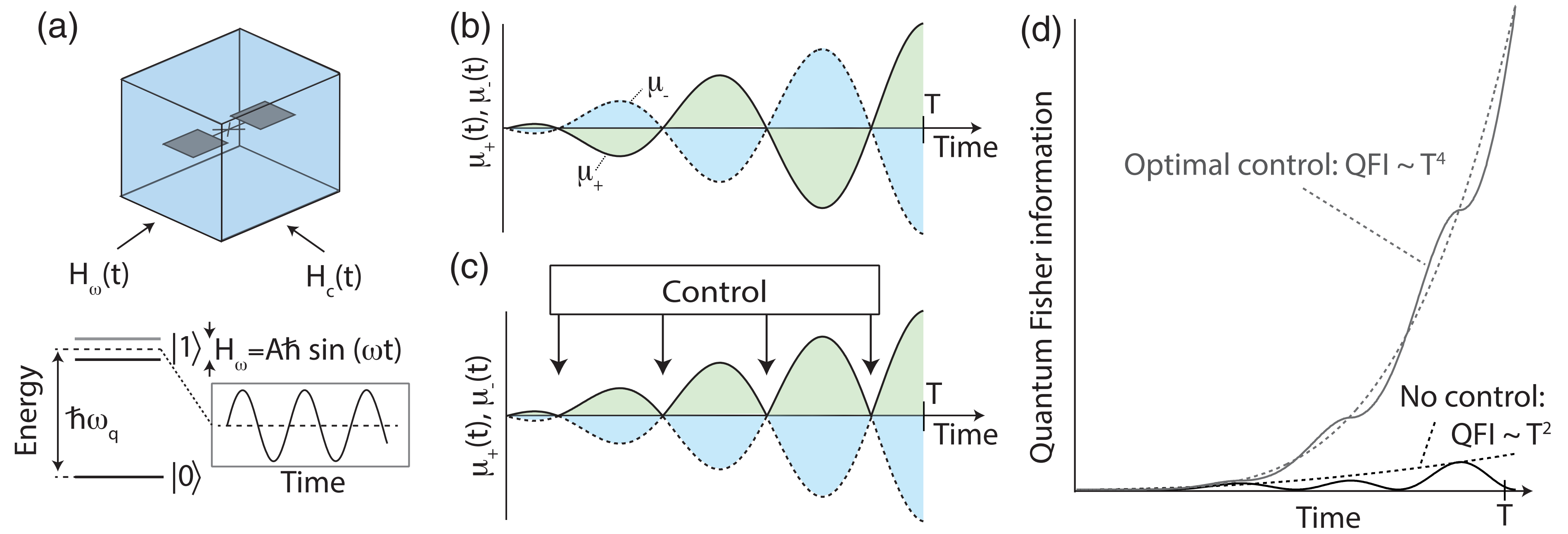
- Read out HPD precession rate with a flux-sensitive transom qubit

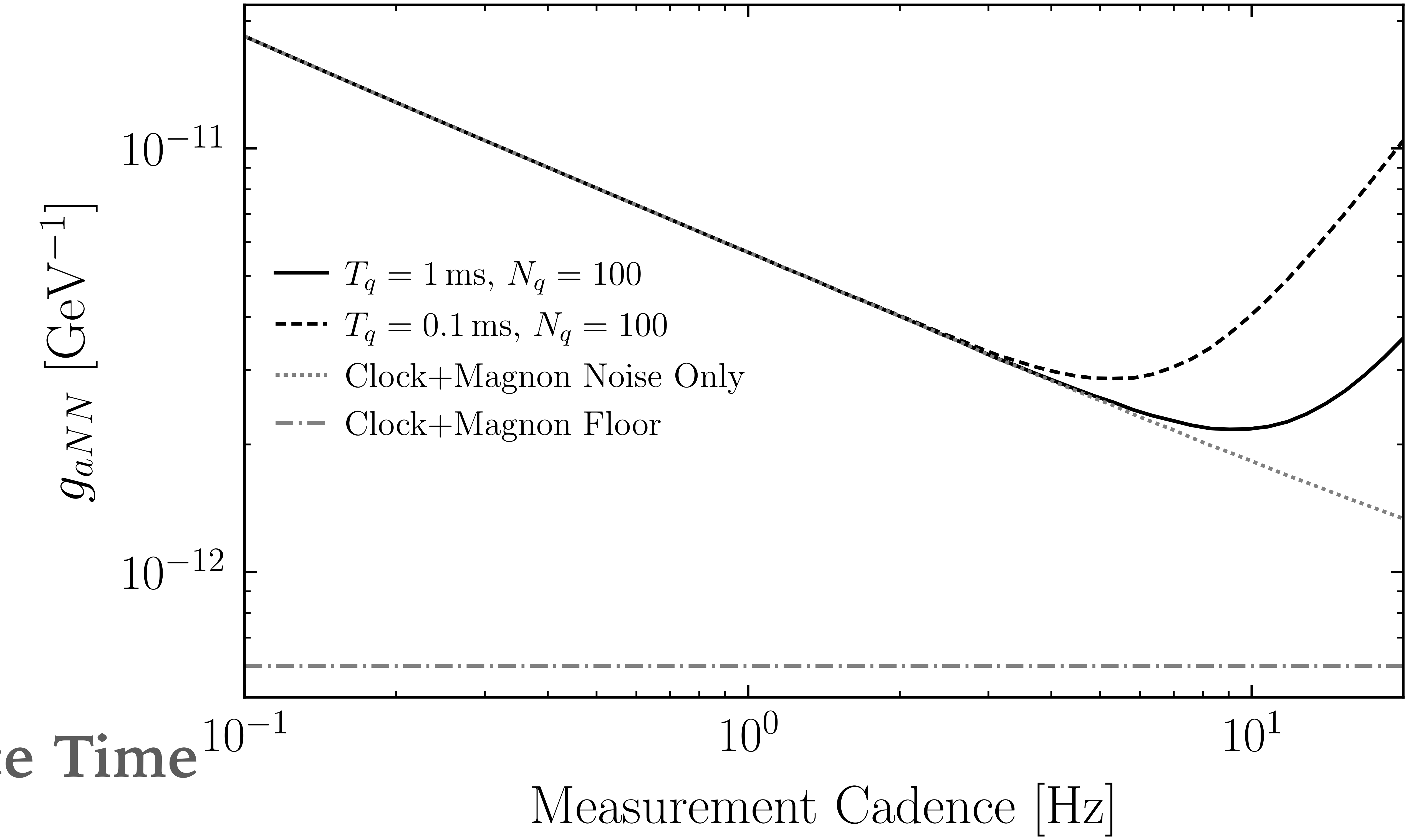
$$H_{\dot\omega}(t) = A \sin(\omega_L t + \dot\omega t^2/2)\frac{\sigma_z}{2}$$

- Applying time-dependent control pulses allows for optimal estimate of evolution of precession rate

$$\delta\dot\omega \sim T^{-5/2} T_q^{-1/2}$$

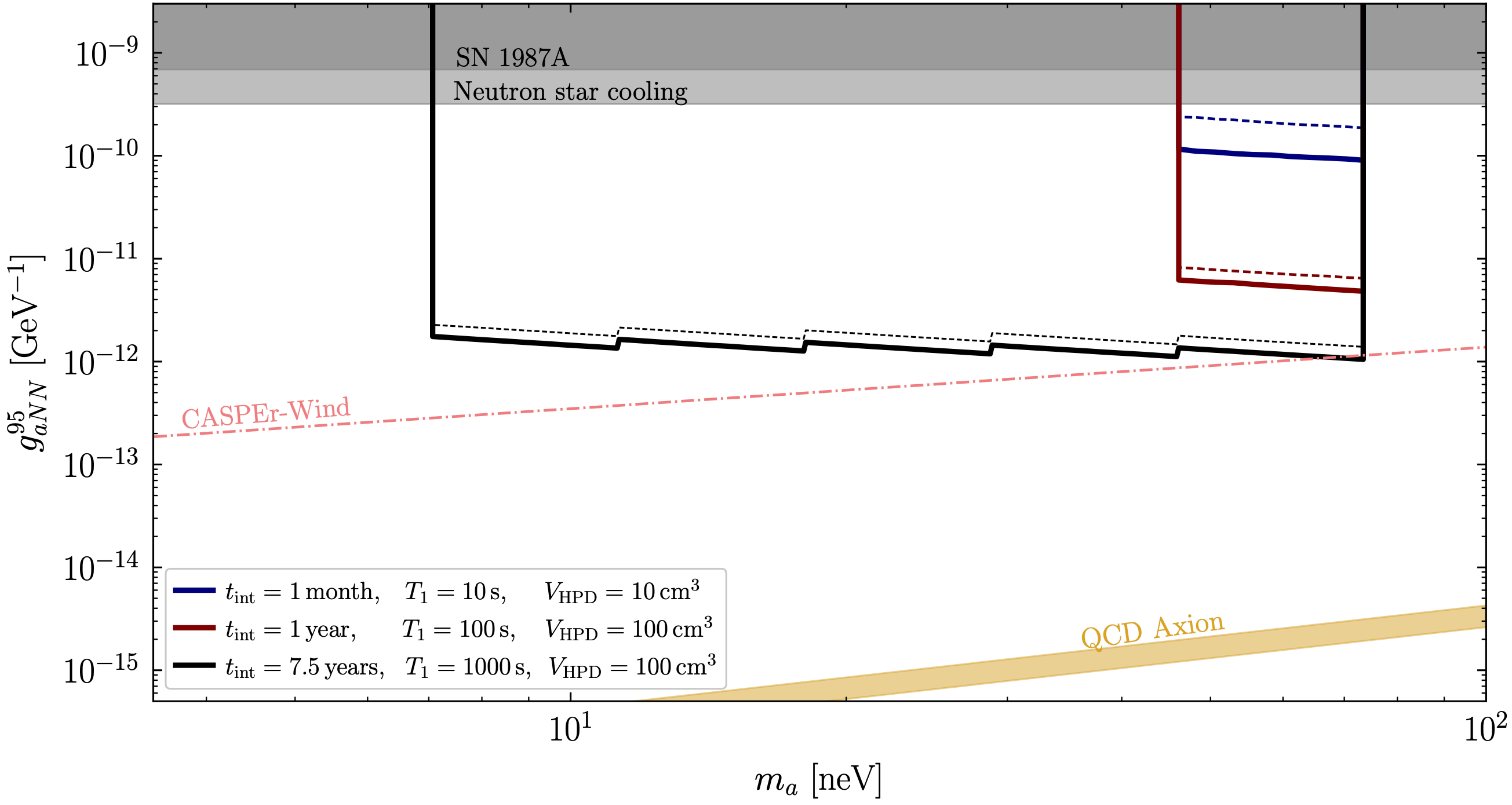
Measurement Interval **Qubit Coherence Time**





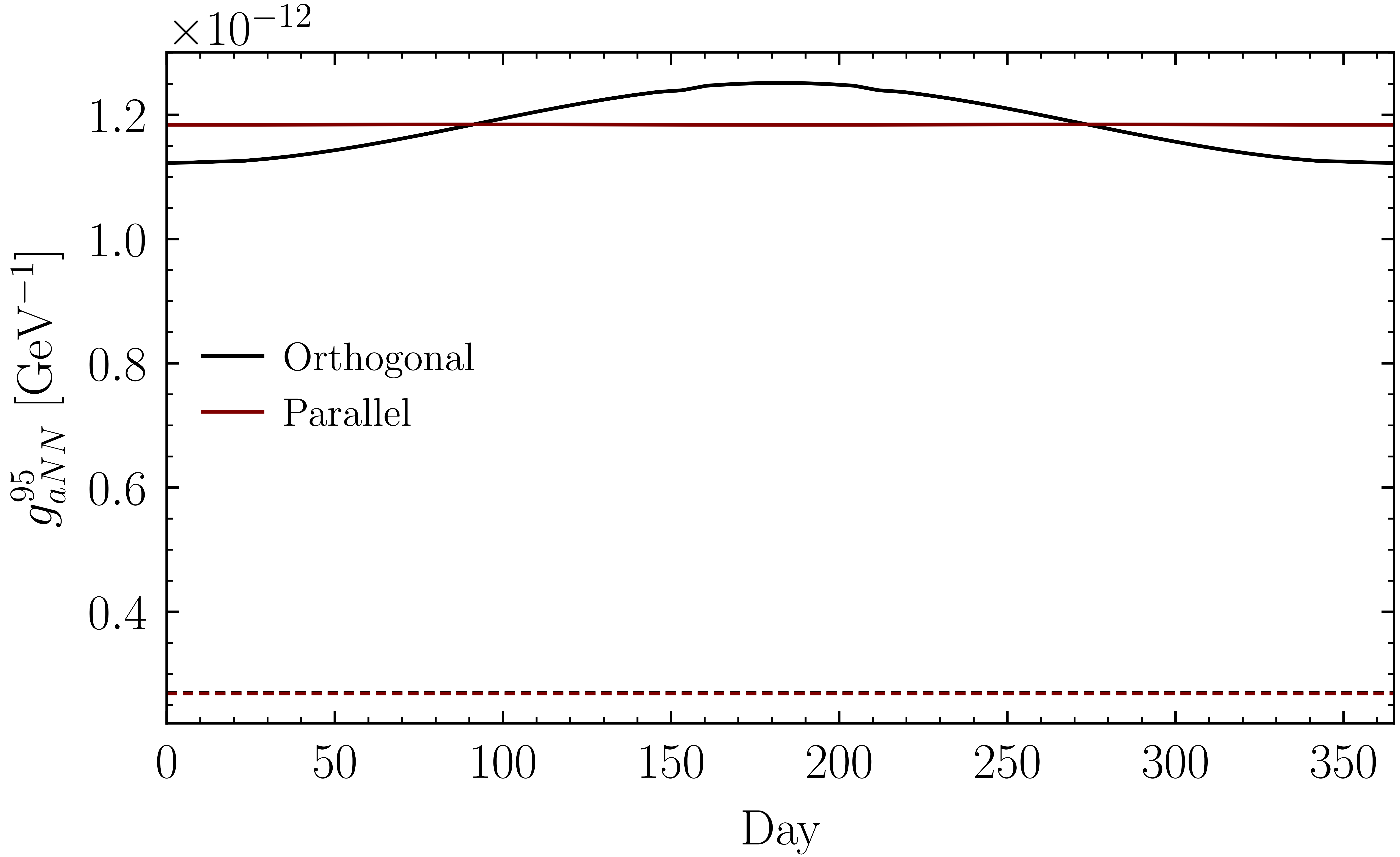
[Naghiloo, Jordan, Murch, PRL 2017; Schmitt et al., Science 2017]

PROJECTED HPD SENSITIVITY

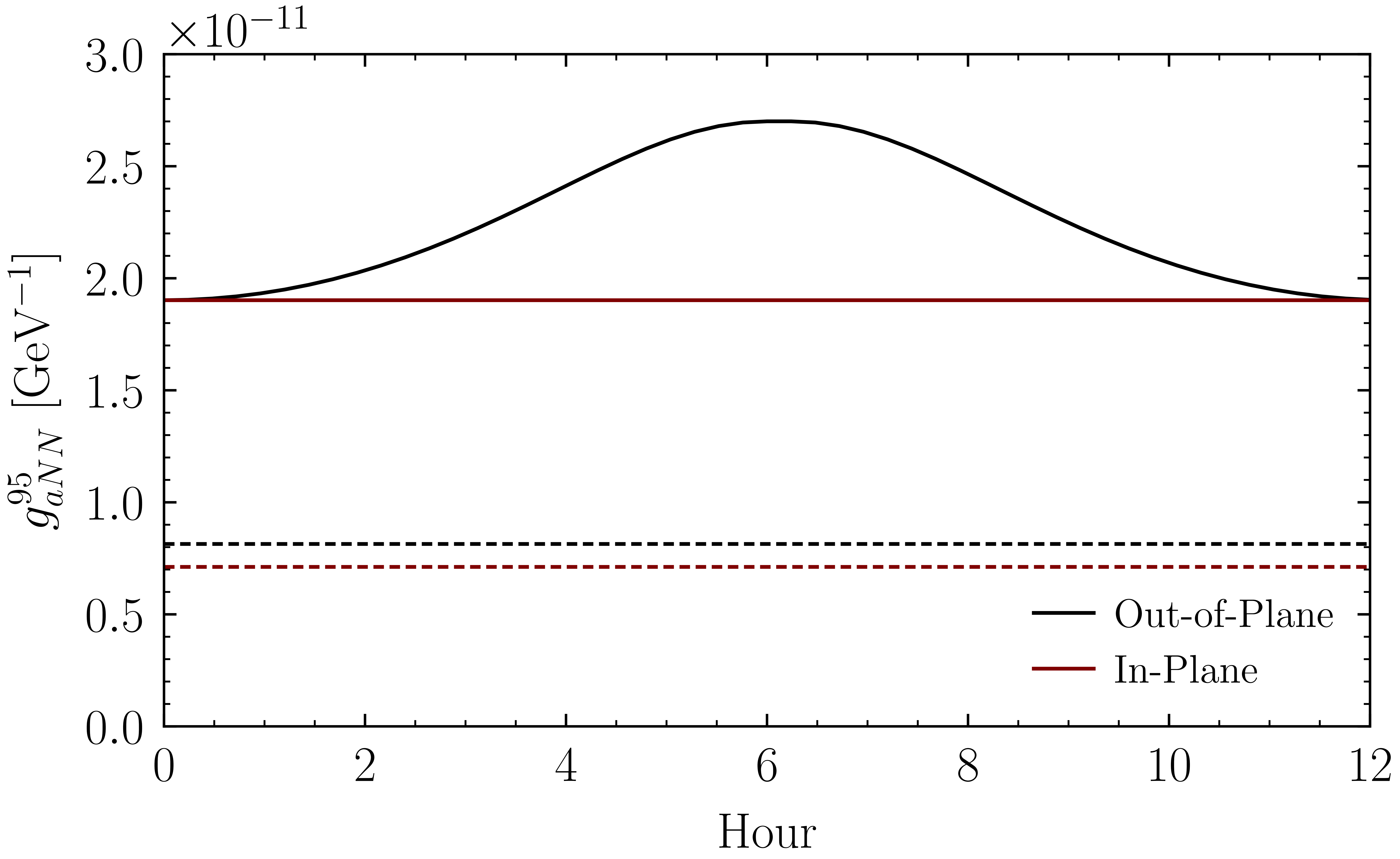


BACKUP SLIDES

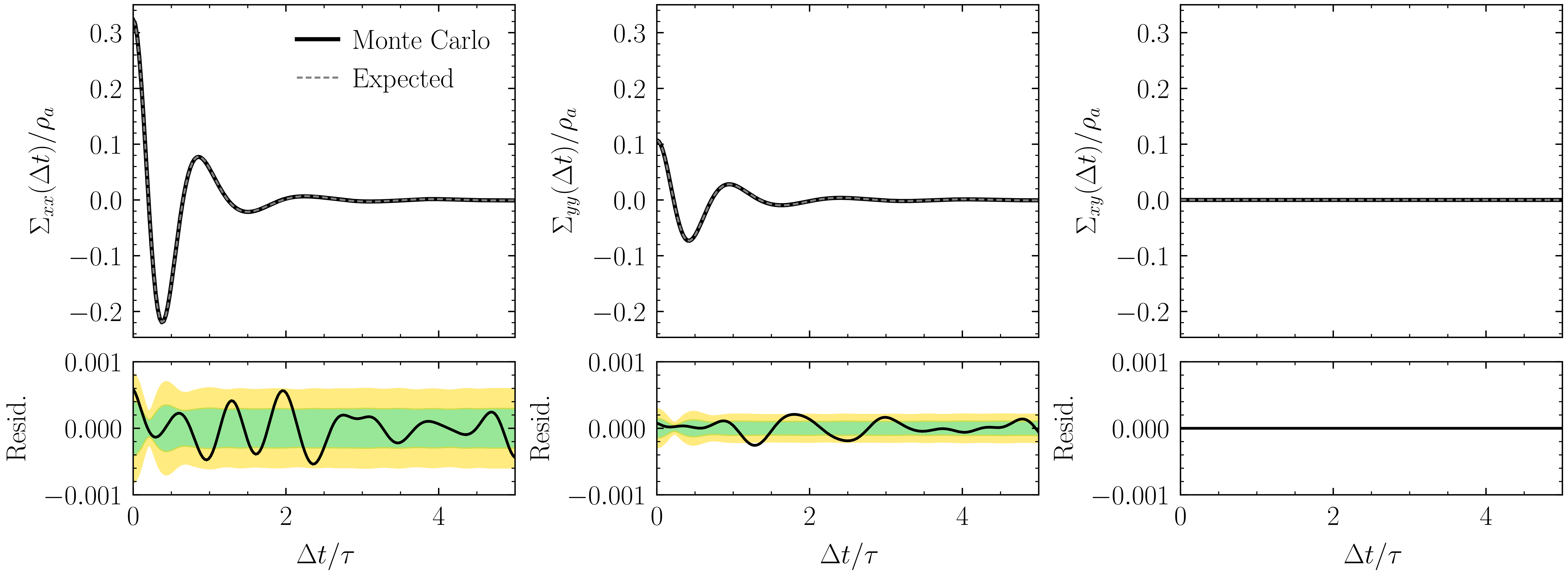
ANNUAL MODULATION



DAILY MODULATION



VALIDATING THE TIME-DOMAIN STATISTICS



VALIDATING THE STOCHASTIC DYNAMICS