

How to Reconstruct the Axion Velocity from CASPEr

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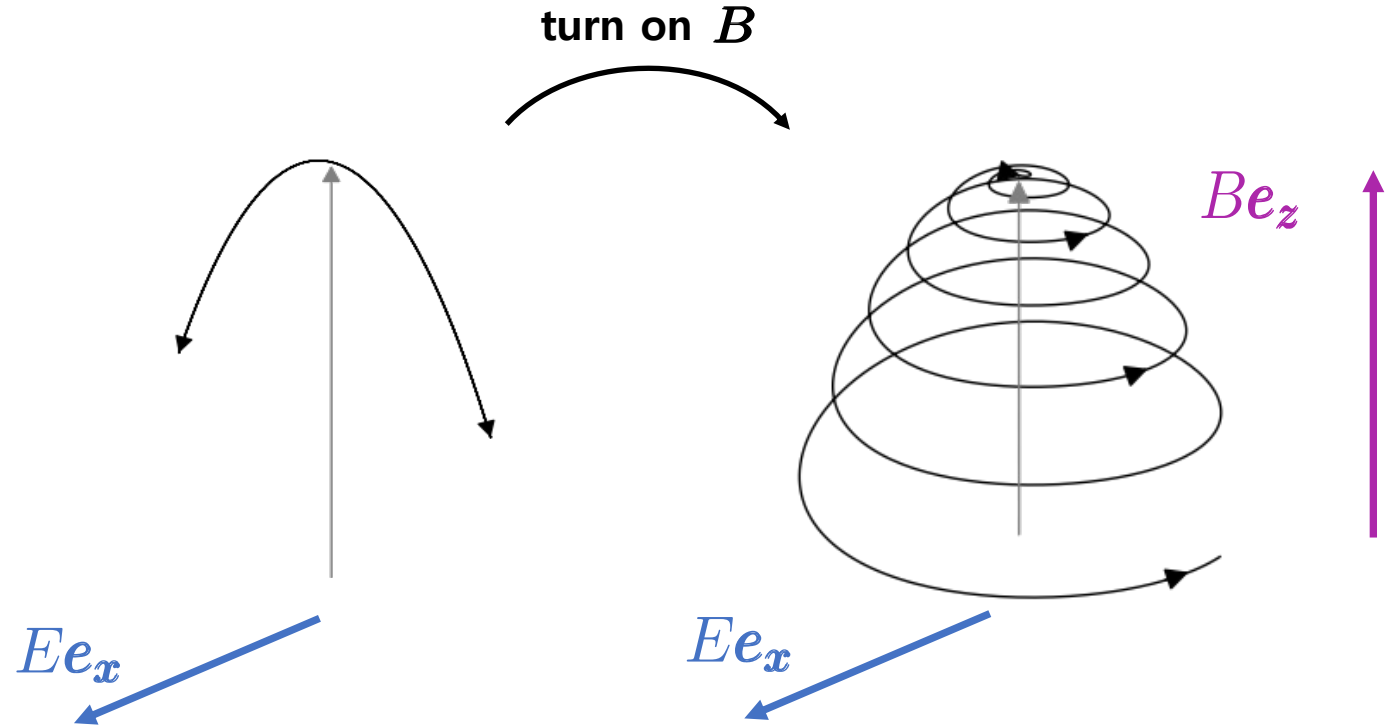
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Investigating the Axion-EDM coupling using NMR

$$H_{\text{int}} \sim g_d a(t) \cdot d_n$$

Resonantly enhance axion

$$a(t) \sim \cos(m_a t)$$



Oscillation frequency of axion

$$m_a$$

Hierarchy of scales

$$\frac{\omega_c}{m_a} \ll 1$$

Coupling frequency

$$\omega_c$$

Larmor frequency

$$\omega_L \sim B$$

But what about velocities?

$$m_a \longrightarrow m_a(1 + v^2/2)$$

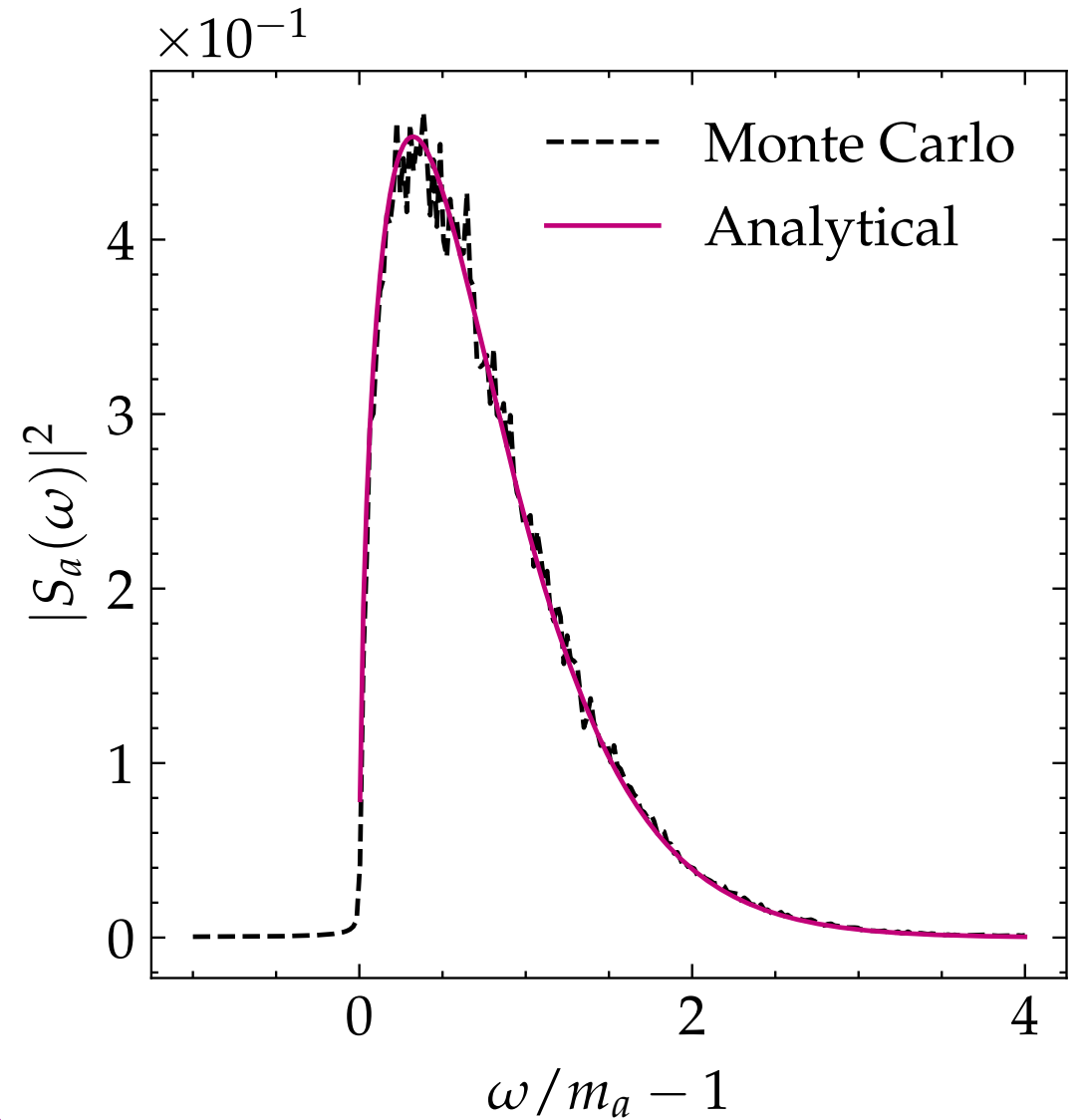
Broadening of the Axion PSD

$$a(t) \sim \sum_i a_i(t, v_i)$$

Velocities distributed via SHM

$$f(v) \sim e^{-\alpha v^2}$$

Can we measure this with CASPER?



Dynamics governed by Bloch equations

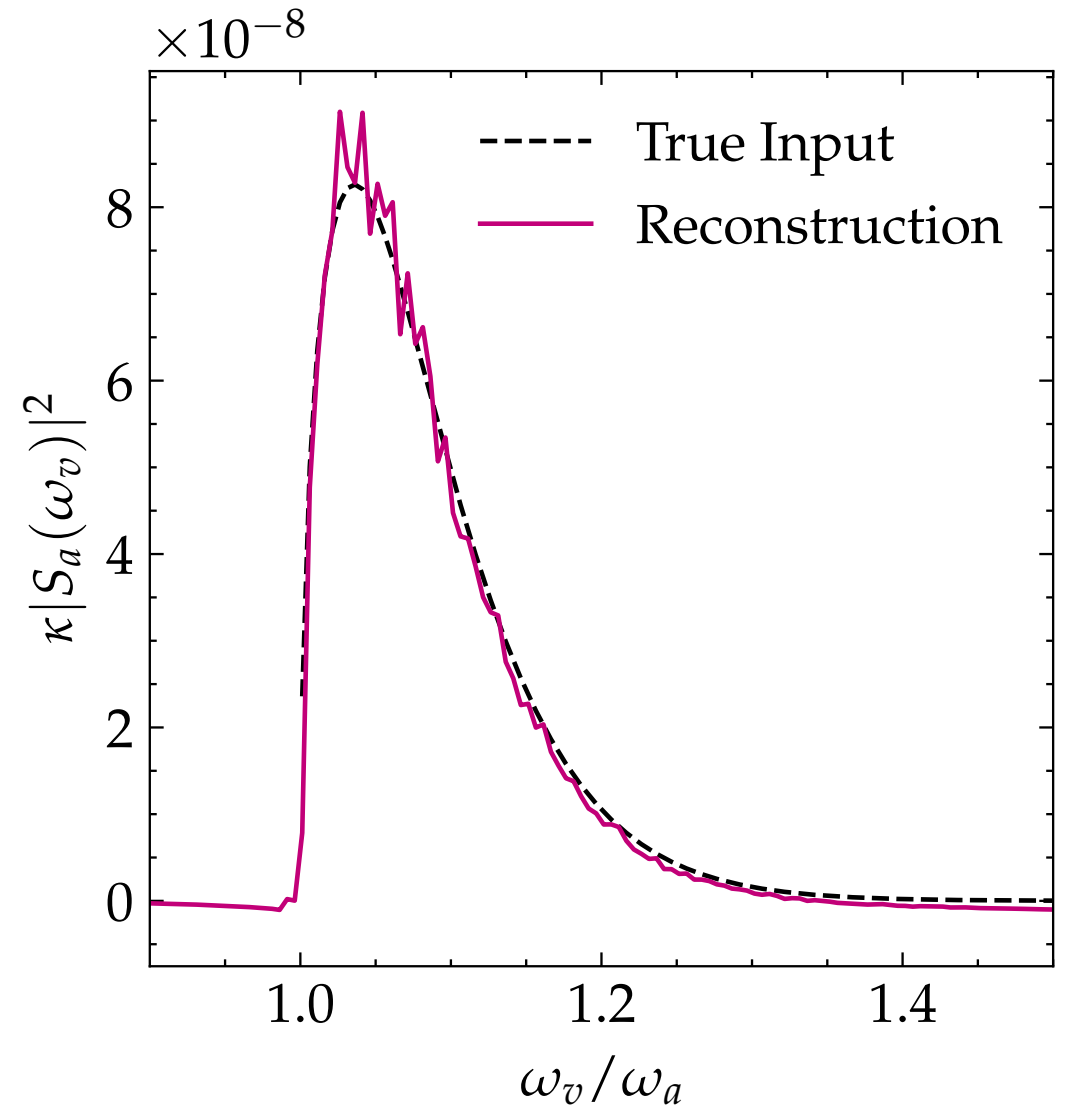
$$\dot{\mathbf{M}}(t) = \mathbf{A}(t) \cdot \mathbf{M}(t)$$

Linearize by using ω_c/m_a

$$\mathbf{M}(t) \approx (1 + \int_0^t \mathbf{A}(t') dt') \cdot \mathbf{M}_0$$

Result is a linear inverse Problem

$$|S_{meas}(\omega_m)|^2 = K_{m,n} \cdot \kappa |S_a(\omega_n)|^2$$



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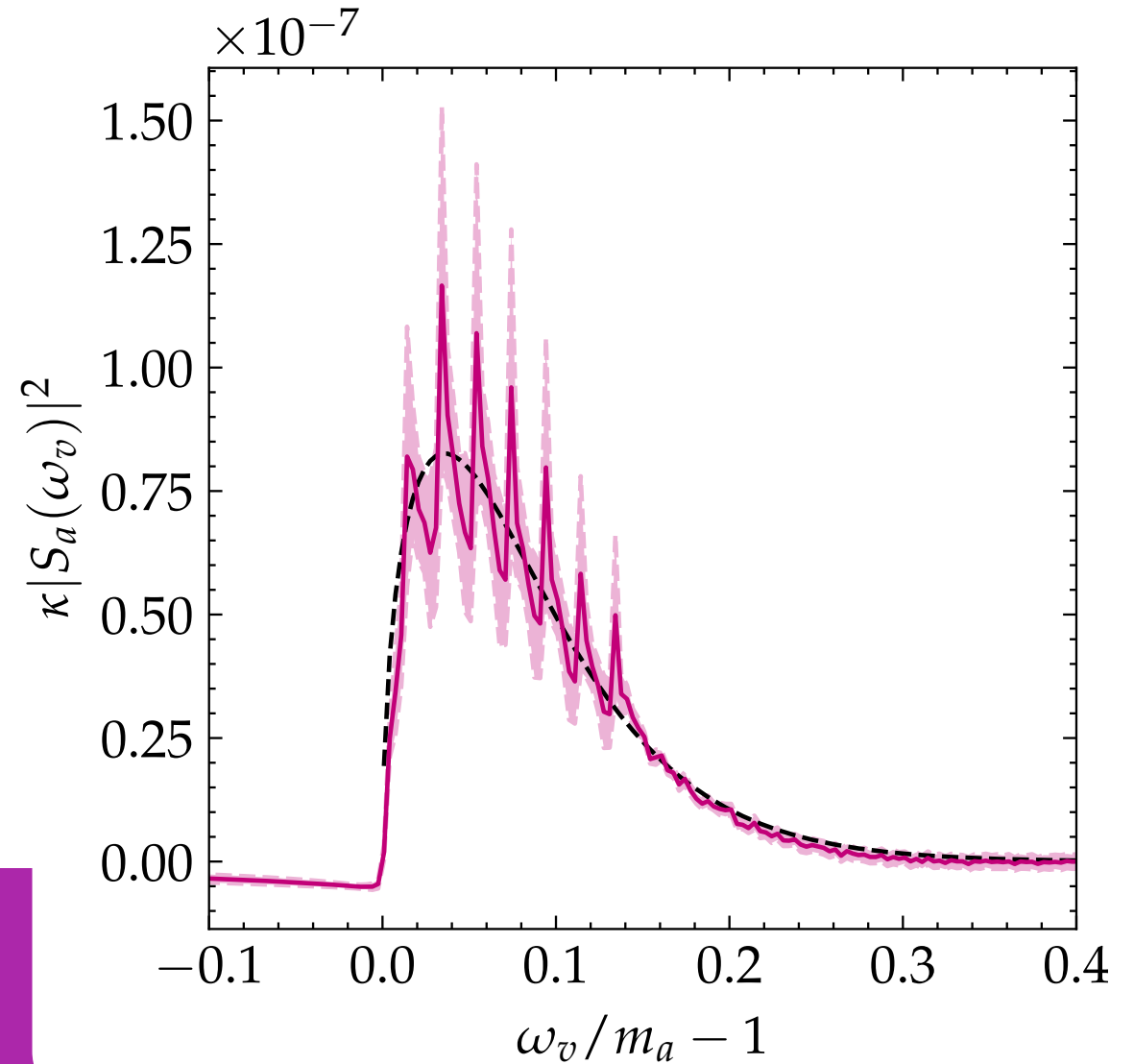
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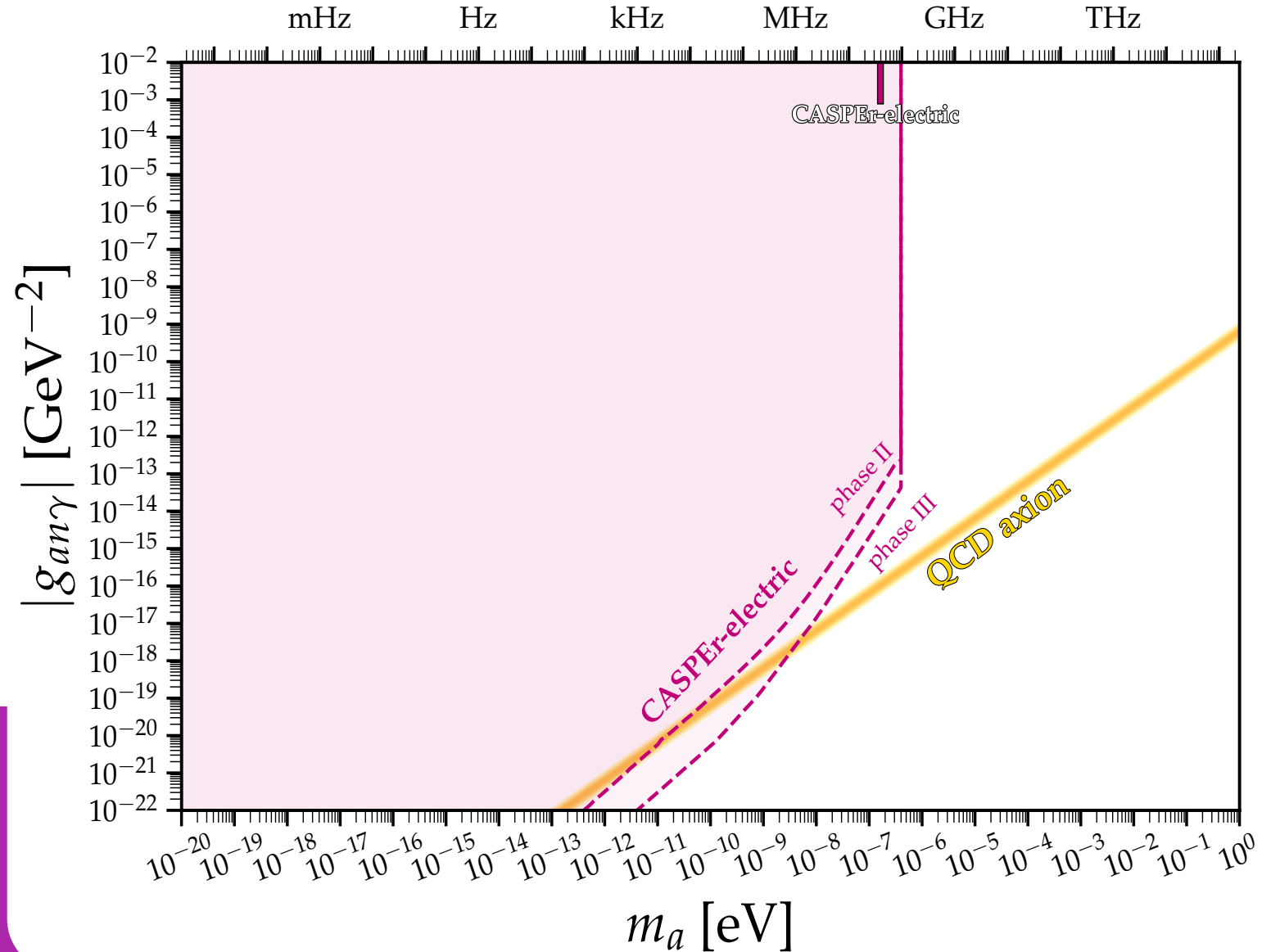


Now to reality...

- For which masses?
- What about noise?

$$\tau_a \sim m_a^{-1} \ll T_{meas}$$

Analysis w.r.t noise
will yield g_d sensitivity

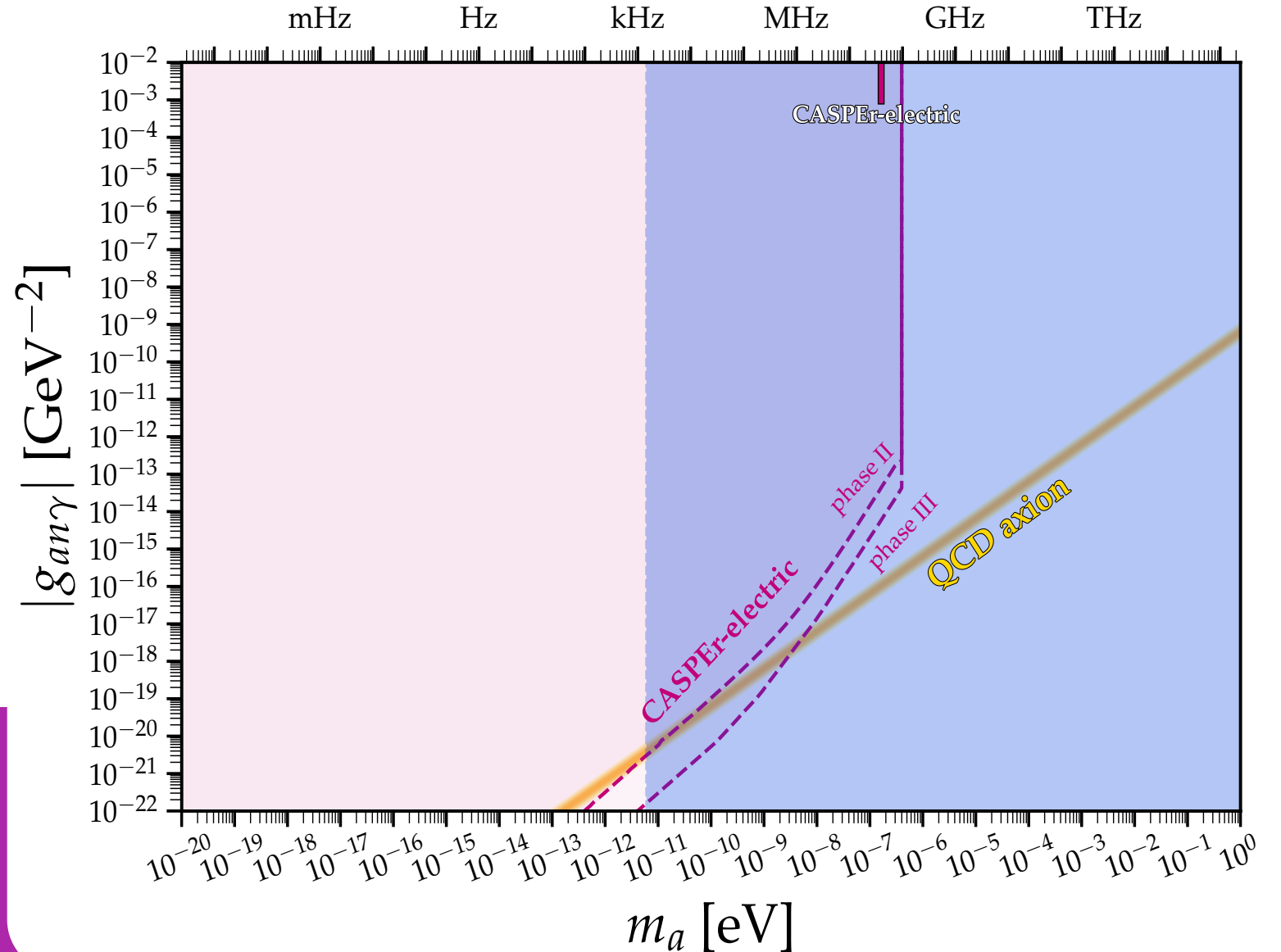


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The Takeaway:



One can measure the axion DM velocity with CASPER

(In principle)

TODO:

Include experimental noise

Ask me about oscillations

How to Reconstruct the Axion Velocity from CASPER

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Motivation

- Axion DM originates from solution to strong CP problem
- (QCD) Axion DM naturally couples to neutron electric dipole moment (EDM)
- Axion presumed to oscillate coherently $a(t) \sim \cos(m_a t)$
 \Rightarrow Investigate coupling using NMR techniques

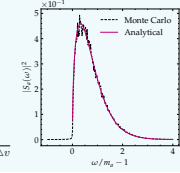
$$H_{\text{int}} = 2g_a a(t) \mathbf{E} \cdot \mathbf{S} \quad a(t) = a_0 \cos(m_a t)$$

$$\mathbf{E} = E \mathbf{e}_x$$

- The goal is measuring an oscillating neutron EDM
- This is done using NMR techniques \Rightarrow we want to induce resonant enhancement of the axion's oscillation
- Done in the cosmic axion spin precession experiment (CASPER)

The Stochastic Axion & Objectives

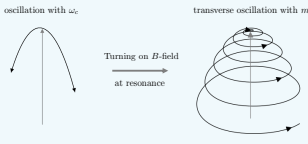
- Investigating the axion for $T \gg \tau_a$ resolves its velocity spectrum \Rightarrow can we measure it with CASPER?
- Velocity spectrum can be modeled using the **standard halo model**
- Monte Carlo:
 $a(t) = \sum_{i=1}^{N_c} a_0 \cos(\omega_i t + \phi_i)$
 $\omega_i = m_a(1 + v_i^2/2)$
- Analytical:
 - Fixed velocity interval
 - Occupation no. $\sqrt{f(v_i)} \Delta v$



Resonance & Scales

- Introduce magnetic field $\mathbf{B} = B \mathbf{e}_z \Rightarrow$ Larmor freq. $\omega_L = \gamma_n B$
- Amplitude of the axion induced oscillation: $\omega_c = g_a E a_0 \ll 1$
- Matching ω_L to $m_a \Rightarrow$ Resonance

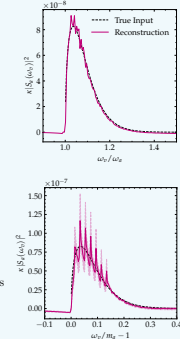
Nuclear Magnetic Resonance (NMR)



Axion freq.	$m_a \gtrsim 10^{-20} \text{ eV}$
Coupling freq.	$\omega_c \lesssim 10^{-49} [m_a]$
Axion coherence time	$\tau_a \sim 10^8 m_a^{-1}$

Results

- Linear Inverse Problem**
 Linearized time evolution leads to a linear inverse problem for the axion velocity spectrum
 $|S_{\text{meas}}(\omega_n)|^2 = K_{n,m} \cdot \kappa |S_a(\omega_m)|^2$
- Off-Resonance**
 Good agreement with the input spectrum
 Reconstructed via simple SVD
- On-Resonance**
 Peaked deviations at Larmor frequencies
 Position of error is given by experimental input \Rightarrow average over multiple runs
 Enough statistics give good agreement



Linearized Time Evolution

- Dynamics of the Magnetization governed by Bloch equations

$$\dot{\mathbf{M}}(t) = \mathbf{A}(t) \cdot \mathbf{M}(t)$$

\swarrow magnetization vector

- Hierarchy of scales & smallness of coupling frequency \Rightarrow linearized time evolution (in rotating frame!)

$$\mathbf{M}(t) \approx (1 + \int_0^t \mathbf{A}(\tau) d\tau) \cdot M_0 \mathbf{e}_z$$

Conclusion

We can reconstruct the velocity spectrum! (without noise)

References

[1] J. Jaeckel, V. Montoya and C. Quint, A Quantum Perspective on Oscillation Frequencies in Axion Dark Matter Experiments, 2023, arXiv: 2304.02523
 [2] A. V. Gramolin et al., Spectral Signatures of Axionlike Dark Matter, 2022, PhysRevD 105
 [3] A. Garcon et al., Constraints on Bosonic Dark Matter from Ultralow-Field Nuclear Magnetic Resonance, 2019, Science Advances 5