Modeling Many-Body Quantum Noise in a Spinor BEC Comagnetometer for Dark Matter Searches

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We present a quantum noise model for a comagnetometer based on a ^{87}Rb spinor Bose-Einstein condensate (sBEC), and project its sensitivity to spin-dependent forces mediated by axion-like particles (ALPs). The platform builds upon a magnetometry demonstration with record energy resolution $E_R = 0.075(16)\,\hbar$ [1]. In comagnetometer mode, the $F=1$ and $F=2$ hyperfine manifolds provide 44 dB common-mode magnetic rejection while retaining sensitivity to nuclear spin couplings [2].

The sensitivity of the comagnetometer is ultimately limited by many-body quantum dynamics within the condensate. To predict performance beyond the standard quantum limit (SQL), we model these dynamics using the truncated Wigner approximation (TWA), incorporating the full $F = 1 \oplus F = 2$ single-mode Hamiltonian in a dual rotating frame: quadratic Zeeman shifts, intra- and inter-manifold spin-exchange collisions, and two-body losses—all parametrized from experimentally measured scattering lengths [3].

Using the TWA-predicted noise, we project constraints on ALP-mediated monopole-dipole couplings to protons [4], with Earth and a nearby tungsten mass as unpolarized sources (Fig. 1). Depending on the assumed sensitivity—demonstrated single-shot (72 fT) [1], projected SQL (31 fT/$\sqrt{\text{Hz}}$) [2], or TWA-simulated—the sBEC comagnetometer can improve existing laboratory limits [5] by up to six orders of magnitude at interaction ranges $\sim 10\,\mu$m–1 m.

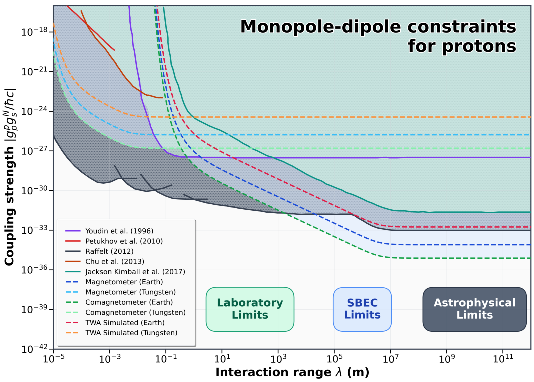

Fig. 1: Projected ALP-proton monopole-dipole constraints. Existing laboratory limits from [5]; dashed curves show sBEC projections for Earth and tungsten sources.

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