

Supplementary Notes: Quantum enhancement and Doppler-induced suppression in a Kasevich–Chu atom interferometer with motional squeezed states

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To compare the sensitivity enhancement and the corresponding Doppler-induced suppression for the two measurement protocols, we examine their maximum CFIs relative to the corresponding QFIs. Because the sensitivity gain $\mathcal{G} \propto \sqrt{F_C/F_{\text{SCL}}}$, the CFIs and QFIs determine the sensitivity gains of the chosen measurement protocol and the ultimate sensitivity set by the QCRB, respectively. We choose four typical diagonal directions in the Poincaré disk (the black dashed radial lines in subsection of *population measurement* and *joint population-position measurement*) and vary β from 0 to 4.2. To clearly display their QCRBs, the explicit dependence on β is suppressed in each panel of Fig. 1.

Around $\theta = 0$, the Doppler effects are negligible, the differences between scenarios are minimal, and the atomic coherence length is so large that the CFI gains of the two protocols converge as β increases, see Fig. 1(a1). However, around $\theta = \pi$, the strongest momentum fluctuations not only strongly suppress the quantum enhancement in the “Ideal” scenario ($F_C^{\mathcal{I}}(\{\hat{S}_z\}) \approx F_C^{\mathcal{I}}(\{\hat{z}, \hat{S}_z\}) \approx$

F_{SCL} , see the red lines), but also induce large Doppler effects which further suppress the remaining measurement gain below the SCL ($F_C^{\mathcal{D}}(\{\hat{S}_z\}) \approx F_C^{\mathcal{D}}(\{\hat{z}, \hat{S}_z\}) \ll F_{\text{SCL}}$), see Fig. 1(a2).

As the squeezing angle θ moves away from these two points, the difference between the two measurement protocols becomes increasingly pronounced, see Fig. 1. In the “Ideal” scenario, the MSS only introduces a negligible enhancement under population measurement (red dashed lines in Fig. 1), whereas it brings a much larger enhancement under joint population–position measurement (blue dashed lines in Fig. 1). In the “Doppler” scenario where Doppler effects are fully taken into account, although Doppler effects reduce the CFI, and hence the sensitivity gain for both protocols, joint population–position measurement is substantially more robust than population measurement. In the quantum-enhancement-dominated regime, the MSS-induced gain for joint population–position measurement can outweigh the Doppler-induced reduction (Fig. 1 (c2,d2)), a behavior absent for population measurement.

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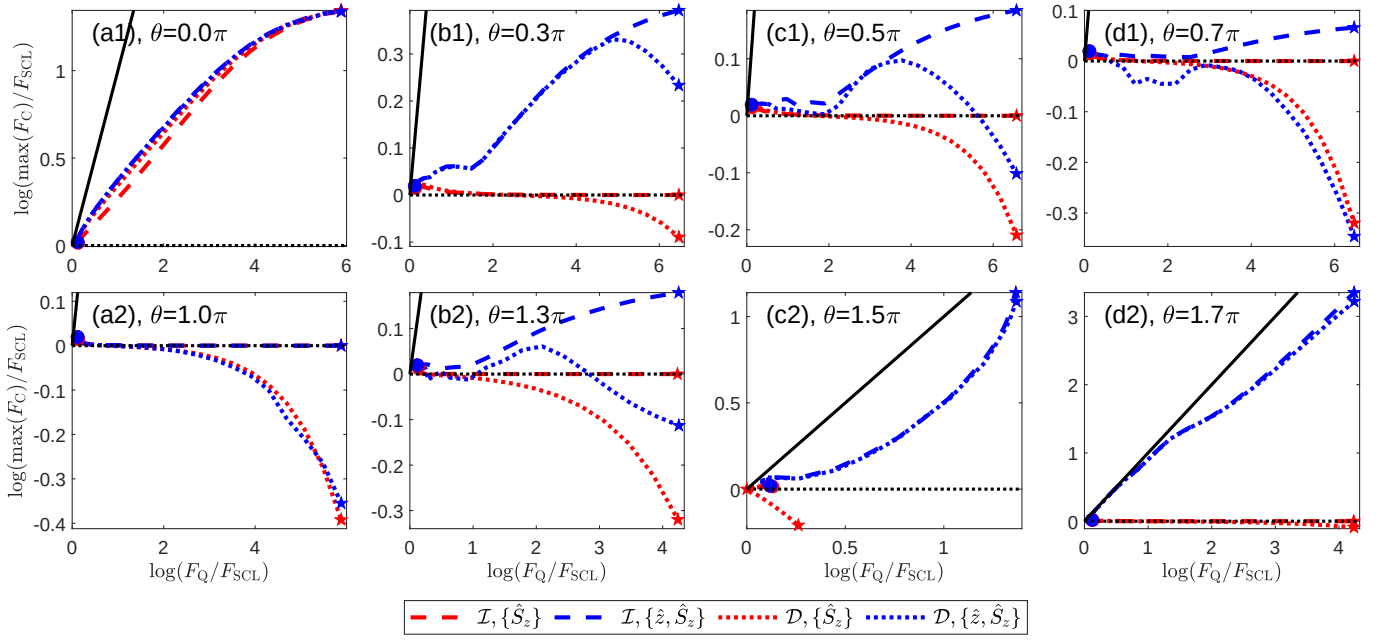


FIG. 1. (color online) The maximum CFIs (vertical axis, log scale) versus the corresponding QFIs (horizontal axis, log scale) for two measurement protocols and two scenarios along four diagonal directions (see the black dashed radial lines in Fig. ?? and Fig. ??) with β varying from 0 (filled circles) to 4.2 (pentagrams). The explicit dependence of all CFIs and QFIs on the squeezing-parameter β is suppressed in each panel. The dashed (dotted) curves correspond to the “Ideal” (“Doppler”) scenario, while the red (blue) lines denote the population measurement $\{\hat{S}_z\}$ (joint population–position measurement $\{\hat{z}, \hat{S}_z\}$). The black dotted and solid lines indicate the SCL and the QCRB, respectively. Other parameters are identical to those in Fig. ??.