Quantum Sensing Enhanced by Squeezing and Non-Hermitian Physics

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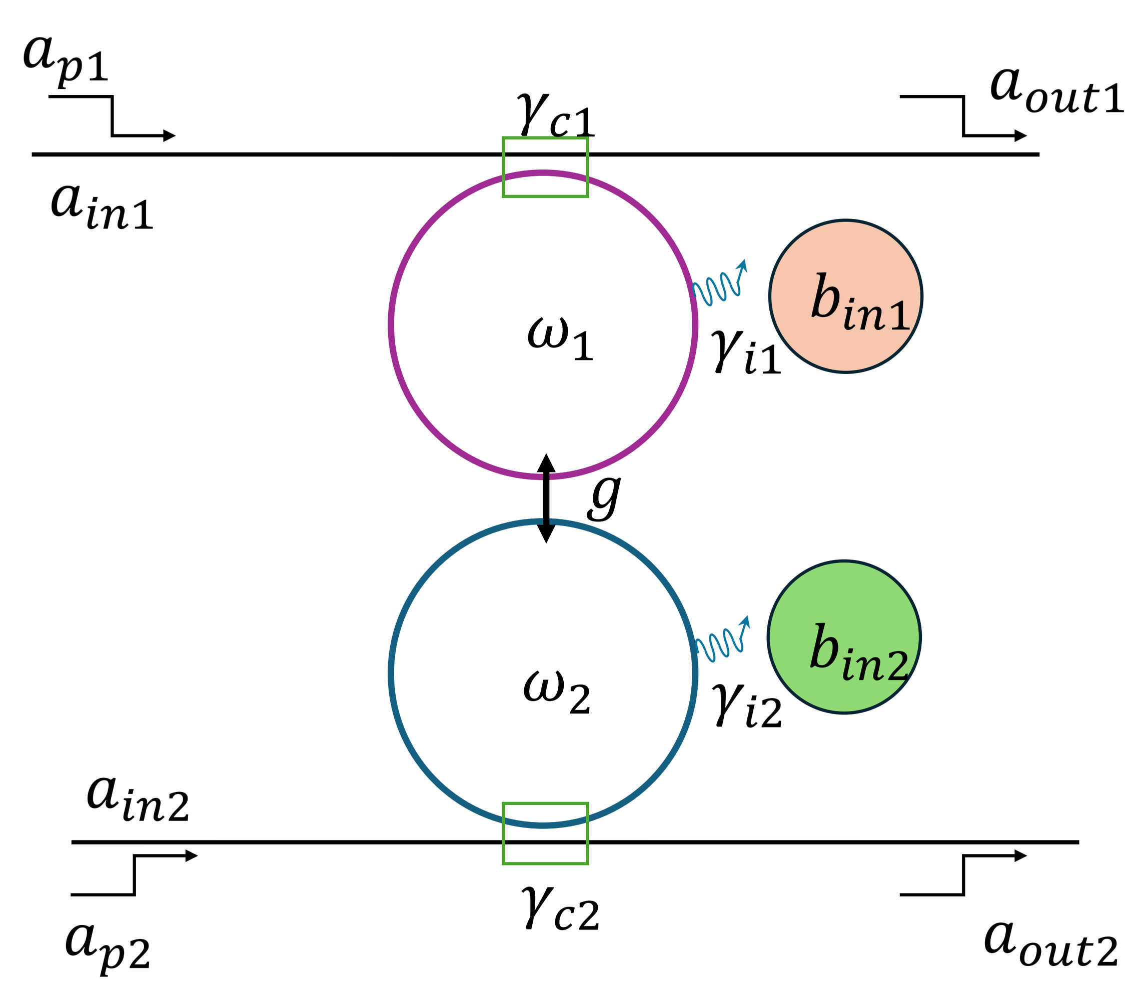
Abstract

We find extraordinary enhancement of sensitivity by integrating non-Hermitian and squeezing effects in a general framework for quantum sensing. When a bosonic-mode sensor operates at the parametric oscillation (PO) threshold and an exceptional point (EP), the sensing precision exhibits a quartic scaling with the perturbation strength, leading to ultrahigh sensitivity. The result generalizes to multimode squeezed-state sensors with higher-order EPs, with potential applicability across a wide range of quantum sensing platforms.

Quantum noise theory for bosonic-mode sensors

A bosonic-mode sensor consists of two harmonic oscillators coupled to input-output channels. The squeezing is concurrently generated by parametric-down conversion or Kerr nonlinearity. Perturbation, which shifts the resonance frequencies ($\omega_{1,2} \to \omega_{1,2} + \theta$), is estimated via the scattering from the input to the output.



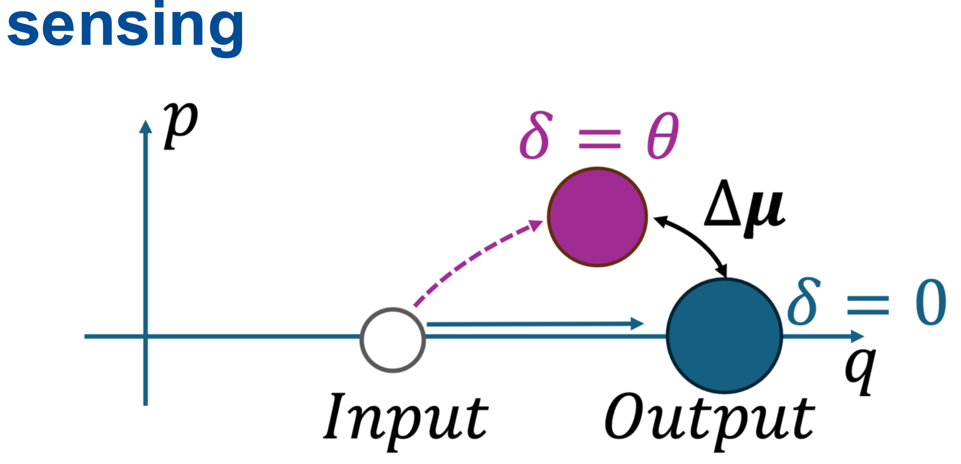
The precision lower bound is determined by quantum Fisher information (QFI) of a noisy Gaussian state:

$$I(\theta) = \left(\frac{d\mu}{d\theta}\right)^T V^{-1} \frac{d\mu}{d\theta} + \frac{1}{2} Tr\left(V^{-1} \frac{dV}{d\theta} V^{-1} \frac{dV}{d\theta}\right)$$

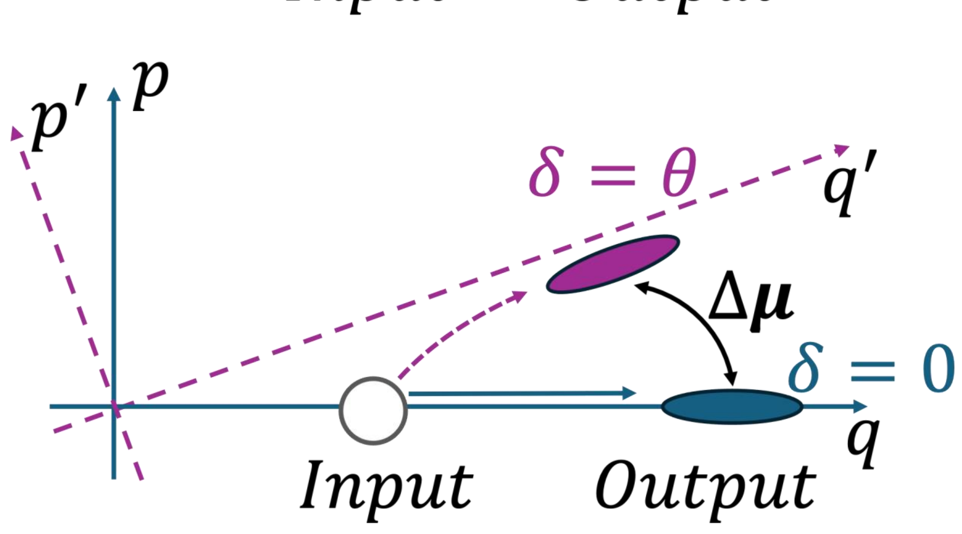
The Cramér-Rao bound sets the precision limit $\delta\theta_{CMR} = \frac{1}{\sqrt{I(\theta)}}$.

Squeezing enhanced sensing

Sensing near the lasing threshold. $\delta\theta_{CMR} \sim \theta$.

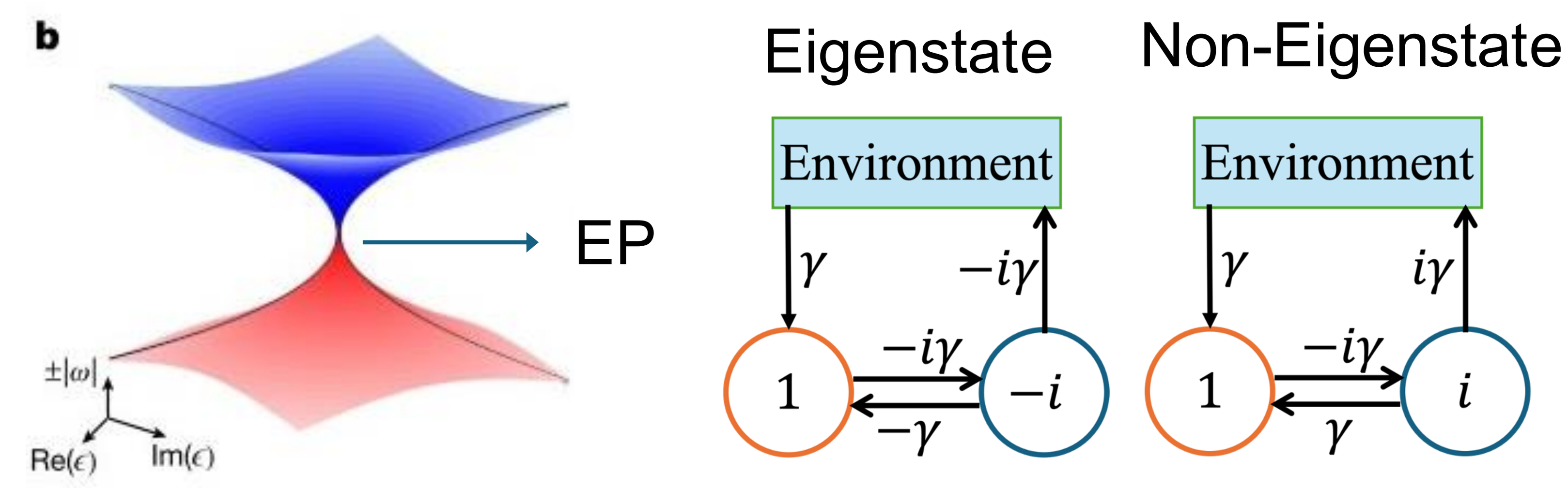


Sensing near the parametric oscillation (PO) threshold. $\delta\theta_{CMR} \sim \theta^2$.



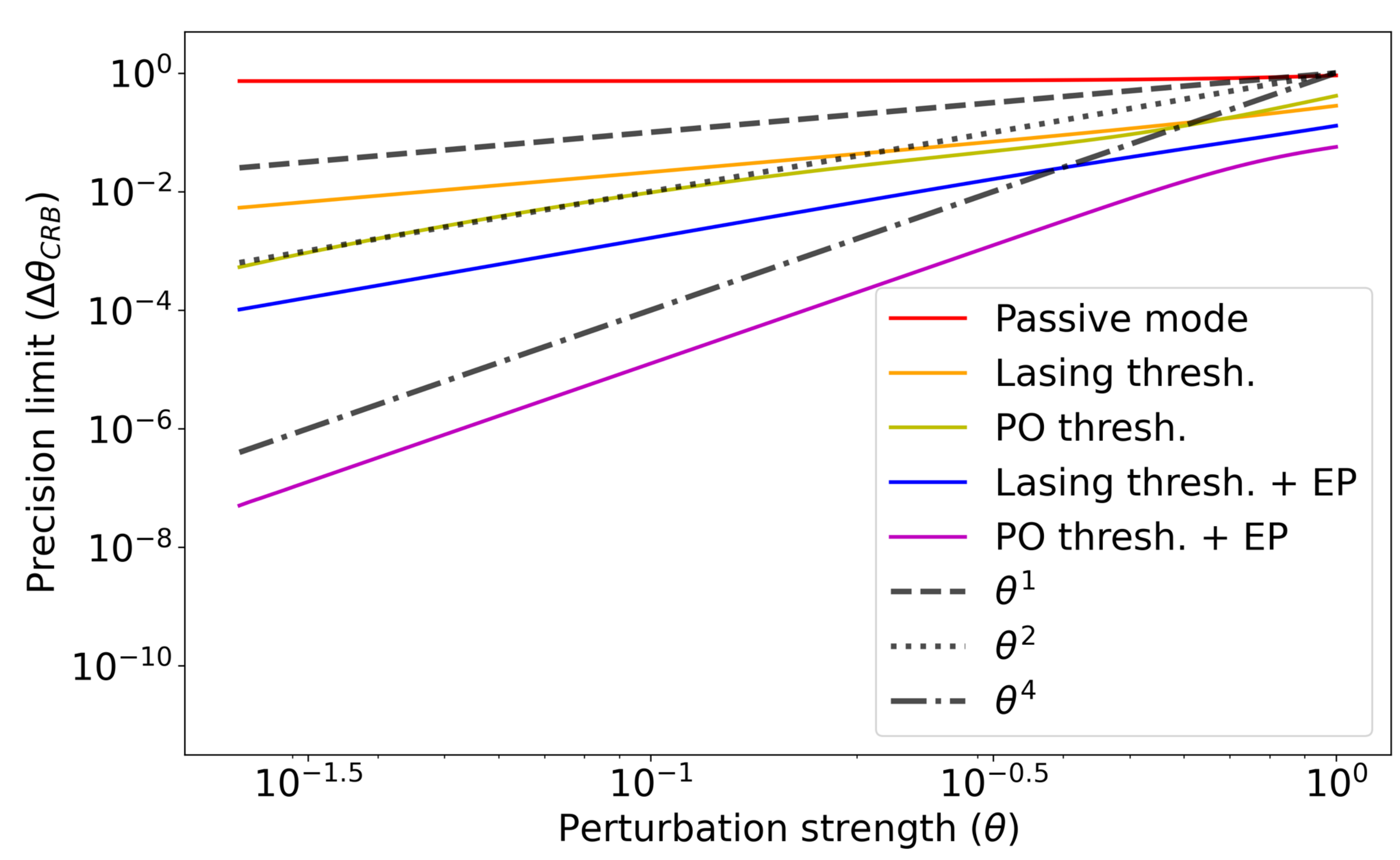
Sensing at an exceptional point (EP)

EPs are singularities in the parameter space of non-Hermitian systems, where eigenvalues and eigenstates become degenerate. Driving the non-eigenstate leads to field amplification as it evolves towards the eigenstate, leading to enhanced sensitivity to external perturbation.

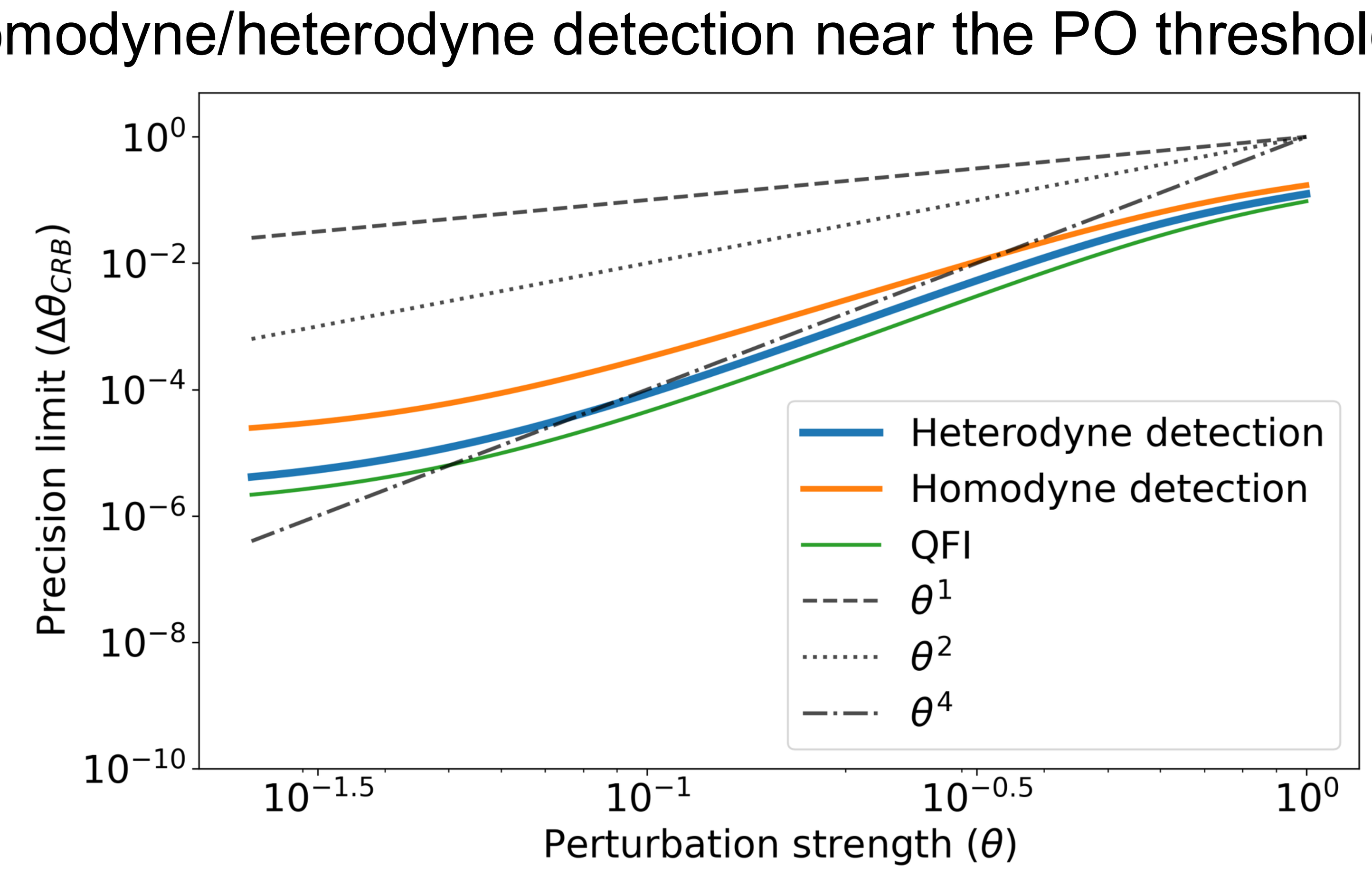


Squeezing-enhanced sensor at an EP

Precision limit exhibits a quartic scaling with perturbation ($\delta\theta_{CMR} \sim \theta^2$) for a second-order EP sensor at PO threshold.



The precision with quartic scaling can be approached using homodyne/heterodyne detection near the PO threshold.



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References

arXiv:2507.17961 (2025)

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