Quantum sensing applied to dark matter detection: squeezing, entanglement, error correction and quantum machine learning

PRX Quantum **3**, 030333 (2022)
npj Quantum Inf. **9**, 27 (2023)
Nat. Photon. **17**, 470 (2023)
In preparation (2023)

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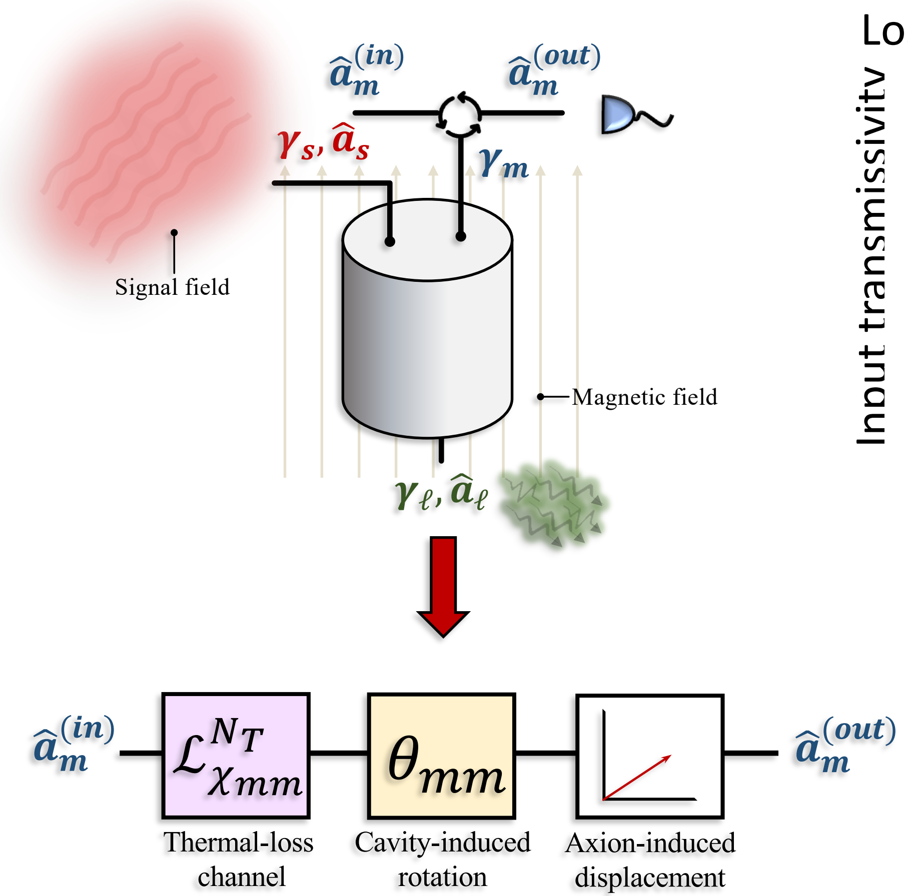
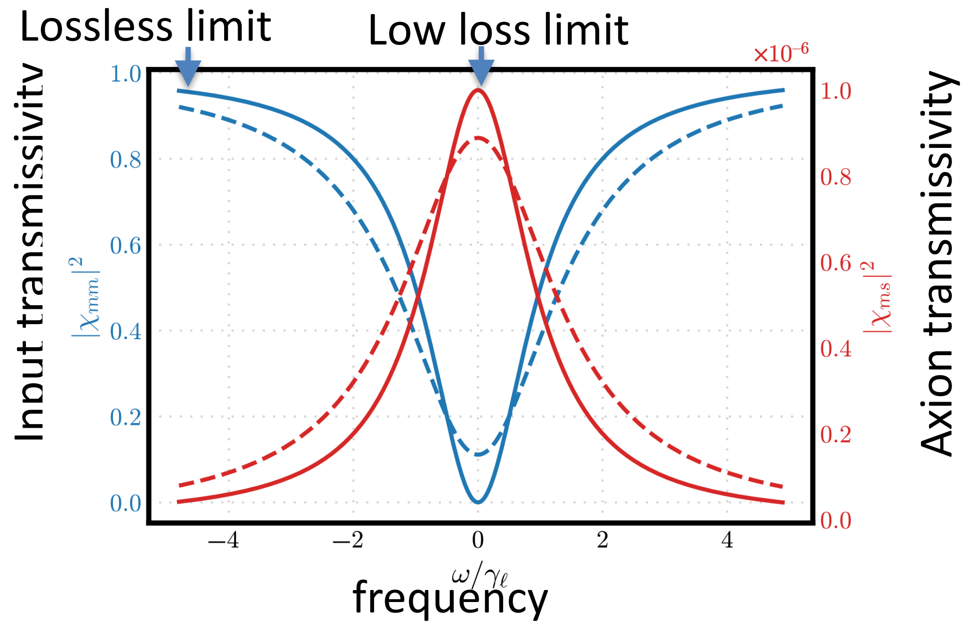
Quantum Technologies for Fundamental Physics
Sep 4 2023, Erice, Italy

Detecting axion dark matter: microwave cavities

AJB, CG, RH, ZL, ZZ, QZ, PRX Quantum **3**, 030333 (2022)





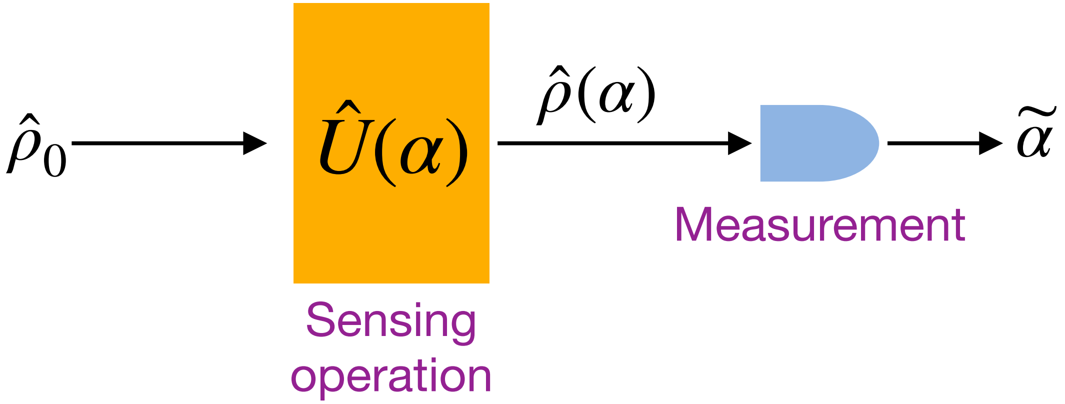
$$|\chi_{mm}|^2 \approx \frac{(\gamma_m - \gamma_\ell)^2/4 + \omega^2}{(\gamma/2)^2 + \omega^2},$$

$$|\chi_{ms}|^2 = \frac{\gamma_m \gamma_s}{(\gamma/2)^2 + \omega^2}$$

Quantum channel modeling: like a beamsplitter with noise/coherent state injection

- Displacement: random and Gaussian in long time
- DM detection reduced to sensing of random displacements---noise sensing

Quantum sensing---parameter estimation



$$\text{mean squared error } \delta\alpha^2 = \left\langle (\tilde{\alpha} - \alpha)^2 \right\rangle$$

$$\geq 1/\mathrm{QFI}$$

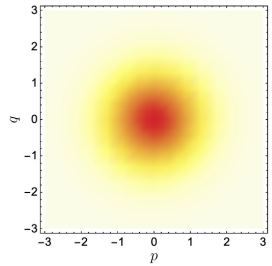
Unbiased estimator
Cramer-Rao bound

QFI: quantum Fisher information

$$\text{Scan rate} \propto \int_{-\infty}^{\infty} \text{power SNR } d\omega$$

$$\propto \int_{-\infty}^{\infty} \mathrm{QFI} \; d\omega$$

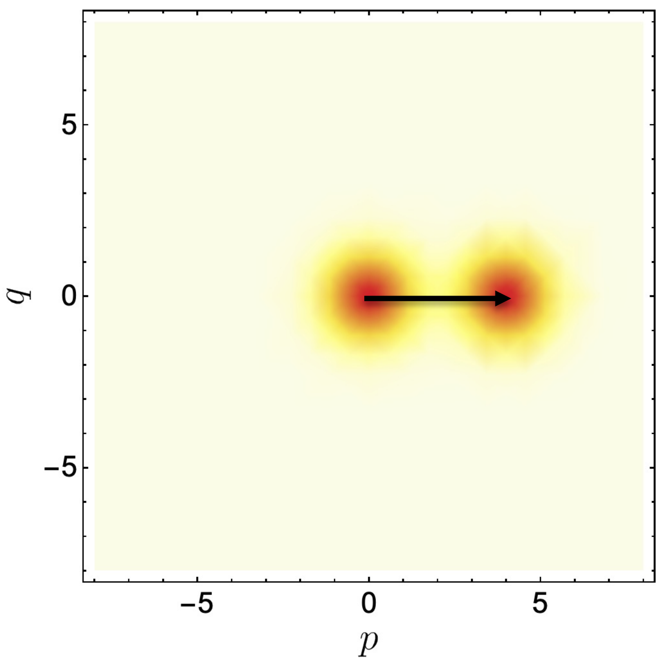
DM detection modeled as displacement sensing



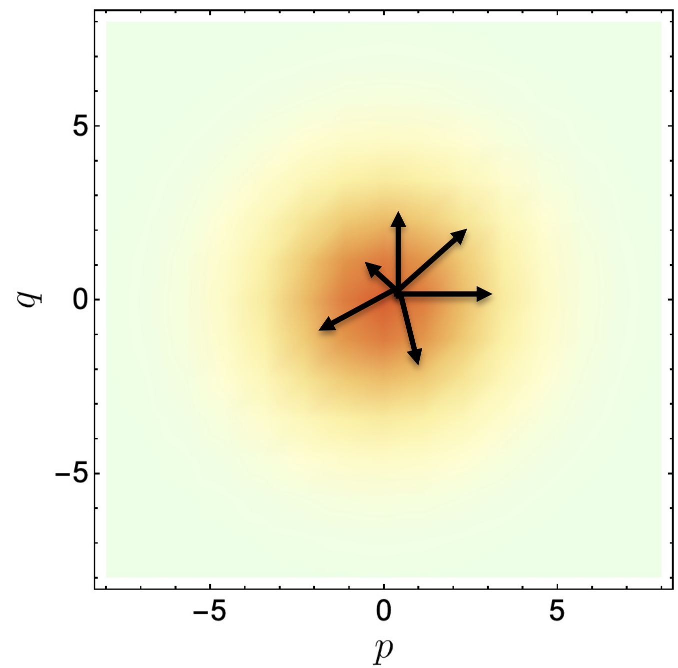
Consider harmonic oscillator,
The ground state |0> in phase space

A fixed displacement

$$\hat{D}(\alpha) = \exp\left(\alpha \hat{a}^\dagger - \alpha^* \hat{a}\right) \qquad \hat{a} \to \hat{a} + \alpha$$



Random displacements = noise



Wigner function of the optical mode (a harmonic oscillator)

How can quantum effects help---Advantage from squeezing

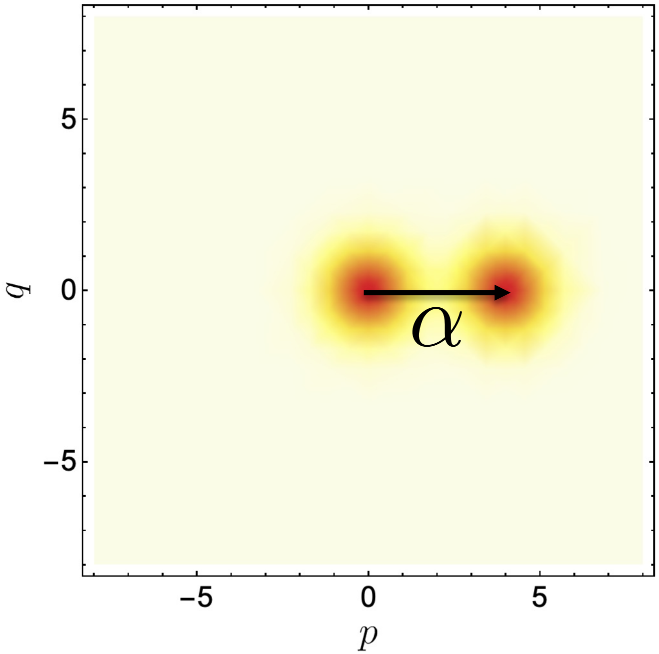
Walls, Caves, Shapiro and others (1990s)

$$\delta p^2 \cdot \delta q^2 \geq 1$$

vacuum noise

Covariance matrix

$$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

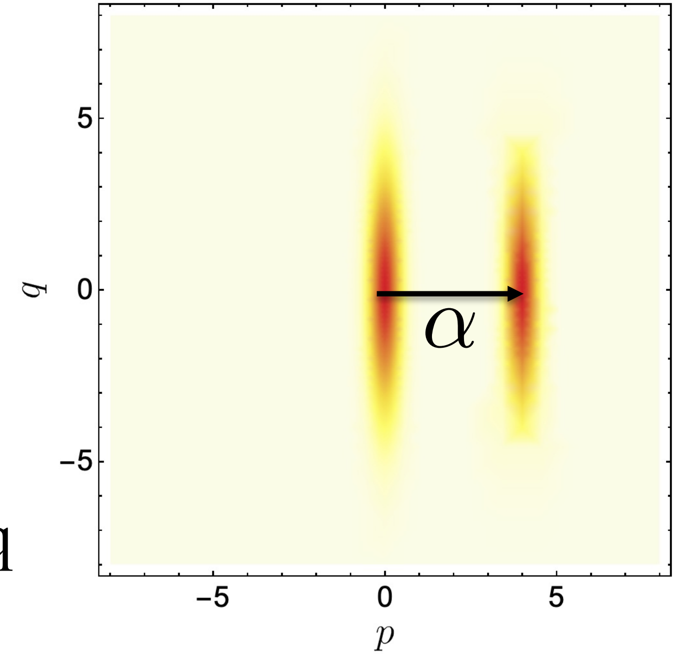


$$\delta\alpha \sim 1$$

squeezed vacuum

Covariance m

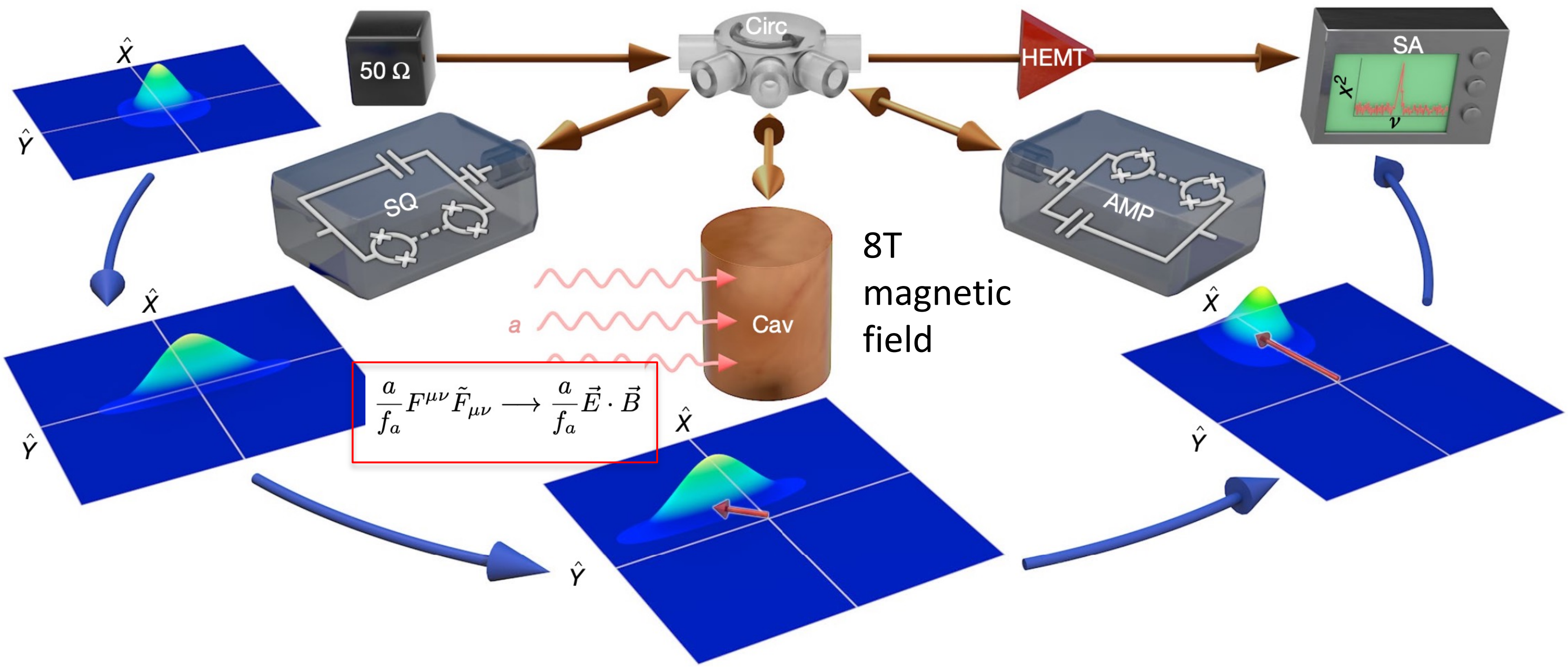
$$\begin{pmatrix} e^{2r} & 0 \\ 0 & e^{-2r} \end{pmatrix}$$



q

$$\delta\alpha \sim \frac{1}{\sqrt{\text{energy}}}$$

How can quantum effects help---Advantage from squeezing



Malnou *et al.*, Phys. Rev. X 9, 021023 (2019)
Backes *et al.* (HAYSTAC), Nature **590**, 238 (2021)

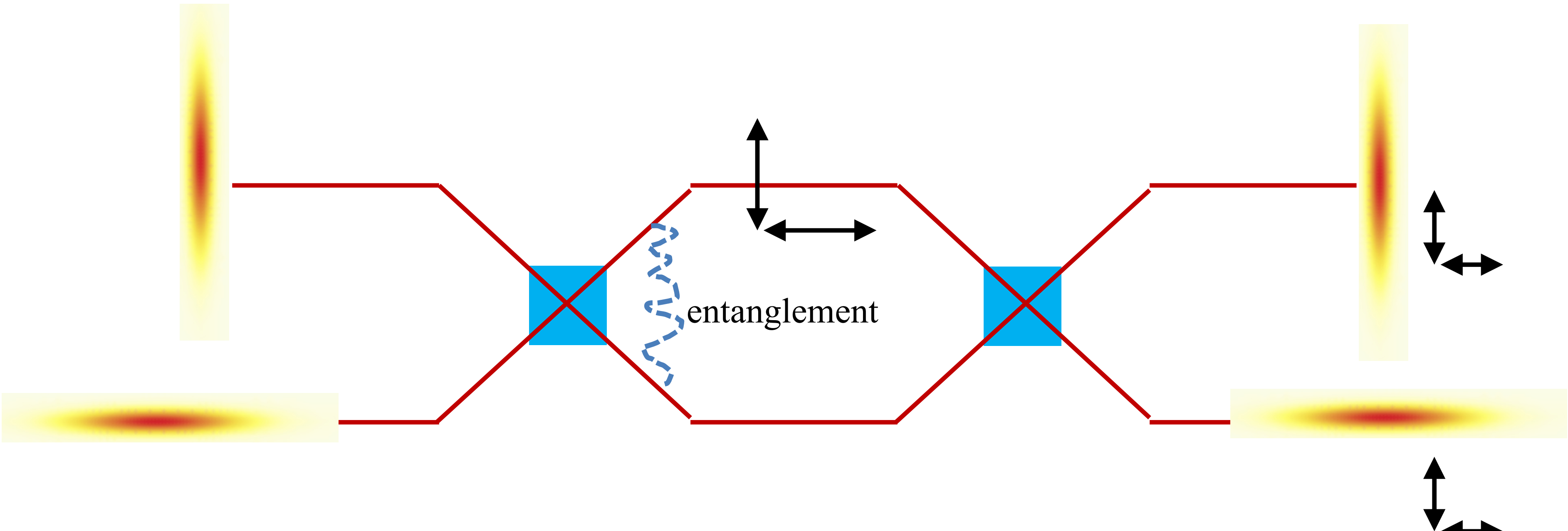
- Injecting squeezing into the cavity suppresses the shot noise to improve the scan-rate

Possibly generating squeezing inside cavity:
PRX QUANTUM 4, 010322 (2023)

How can quantum effects help---advantage from entanglement

Circumventing $\delta p^2 \cdot \delta q^2 \geq 1$

Dense metrology [Nat. Photon. 7 626 (2013)]



$$\delta p, \delta q \sim \frac{1}{\sqrt{\text{energy}}}$$

See also:

A71.00002 : Fulfilling entanglement's optimal advantage via converting correlation to coherence

Talk by Haowei Shi, earlier

Time delay---range
Frequency shift---velocity

QZ, ZZ and JHS, Phys. Rev. A **96**, 040304(R) (2017)
ZH, CL, PK, PRX Quantum 2, 030303 (2021)

More example: quantum reading, quantum illumination (quantum radar)……

Ultimate limit of noise sensing

HS and QZ, npj Quantum Inf. 9, 27 (2023)

- Derived lower bound on sensitivity of noise sensing for all possible quantum input states and measurements

Theorem 1 *The quantum Fisher information per mode for energy constrained additive noise sensing of a phase-covariant Bosonic Gaussian channel* $\mathcal{N}_{\kappa,n_B}$ *has the following upper bound:*

$$\mathcal{J}_{\mathrm{UB,UE}} = \frac{1}{n_B(n_B+1)} + \frac{\kappa N_S(2n_B-\kappa+1)}{n_B(n_B+1)^2(n_B-\kappa+1)}, \quad (11)$$

where N_S is the input mean photon number per mode. Furthermore, the upper bound is additive: $\mathcal{J}[\hat{\rho}(n_B)] \leq M\mathcal{J}_{\mathrm{UB,UE}}$ for any $2M$-mode input-ancilla state subject to mean photon number constraint MN_S.

- Additive
- Ultimate limit achieved by an entangled strategy

From Quantum Fisher information to scan-rate

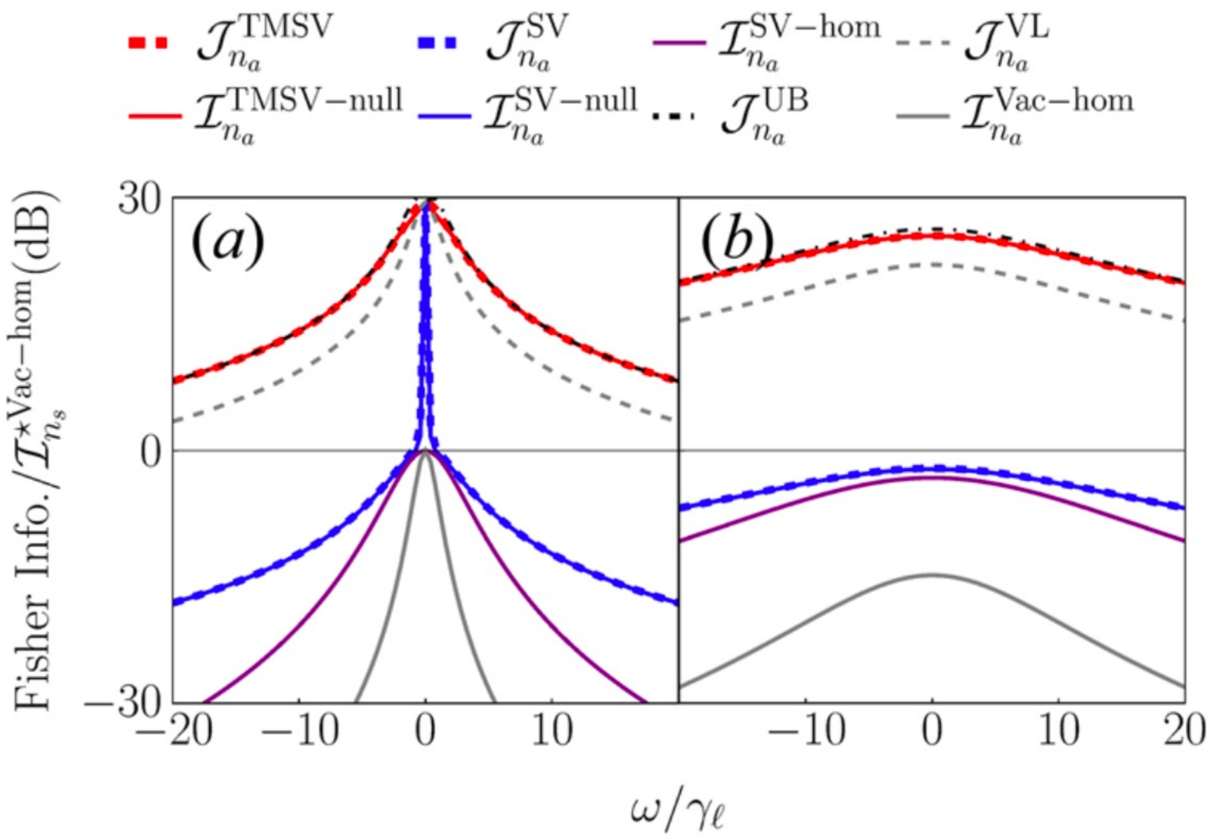


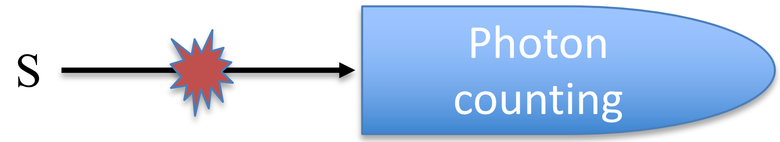
Fig. 8 Frequency spectrum of the Fisher information with respect to the axion occupation number n_a. The values are normalized by the optimized peak value of vacuum-homodyne Fisher $\mathcal{I}^{\star\,\mathrm{Vac-hom}}_{n_a}$ and plotted in decibel unit. **a** $\gamma_m/\gamma_\ell = 1$; **b** $\gamma_m/\gamma_\ell = 2G$. Temperature $T = 61$ mK, cavity resonant frequency $\omega_c = 2\pi \cdot 10$ GHz, squeezing strength $G = 10$ dB, $\gamma_a/\gamma_\ell = 10^{-12}$.

Ultimate limit of noise sensing

HS and QZ, npj Quantum Inf. 9, 27 (2023)

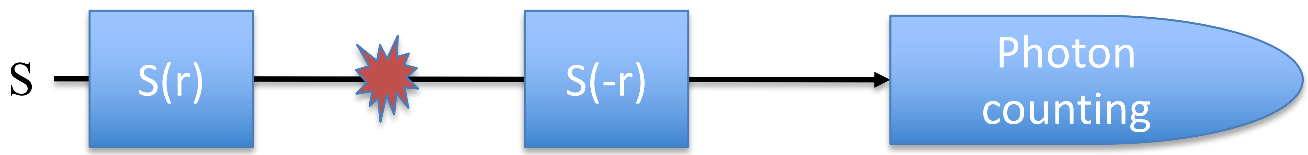
Vacuum + homodyne

Vacuum + photon counting



Squeezing + homodyne

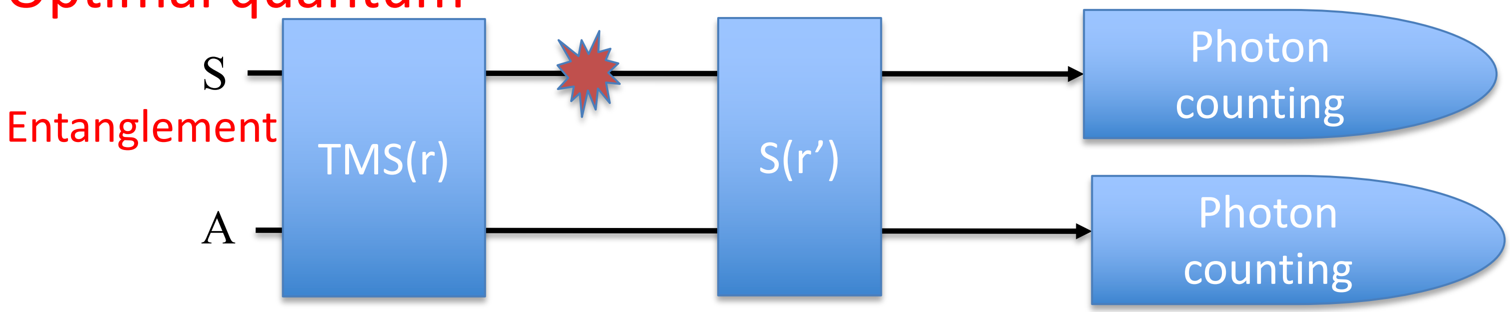
Squeezing + photon counting



See L. Maccone's talk in the noiseless case Phys. Rev. Lett. 129, 240503 (2022)

Optimal quantum

Joint detection



From Quantum Fisher information to scan-rate

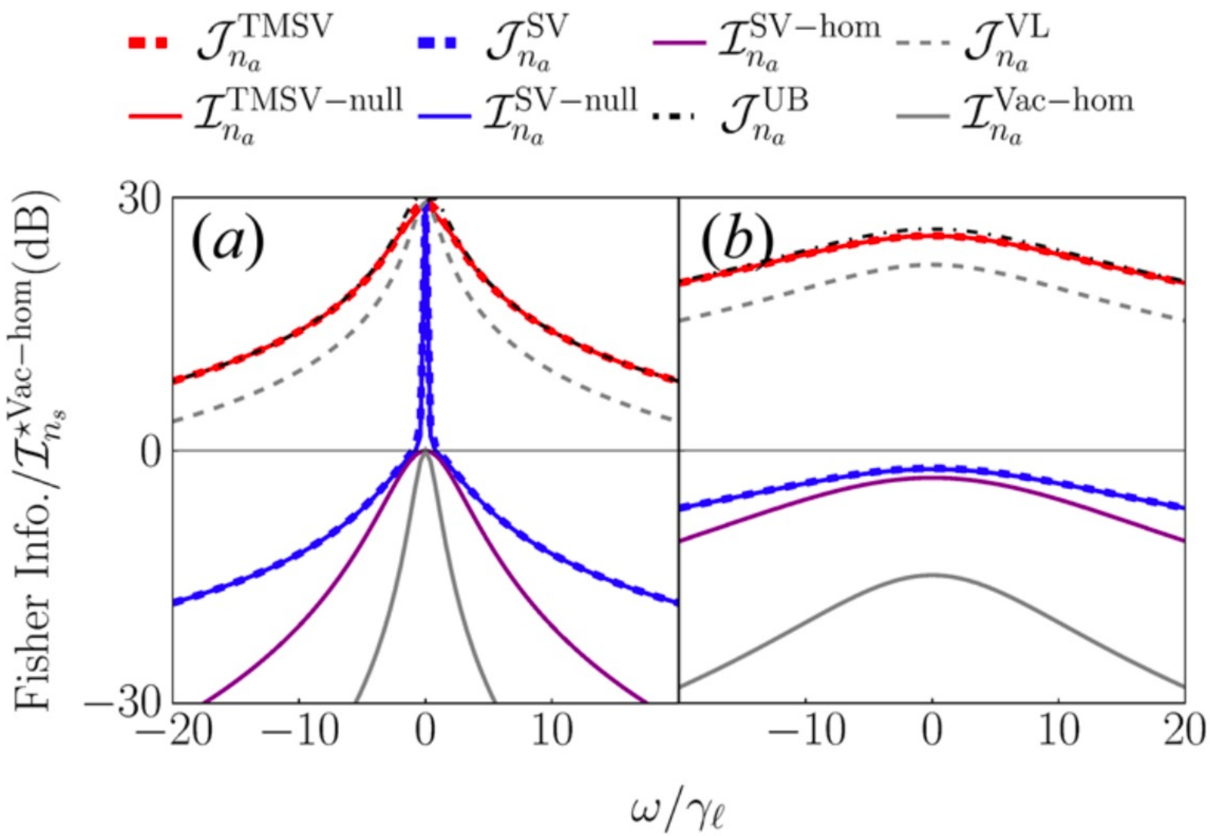
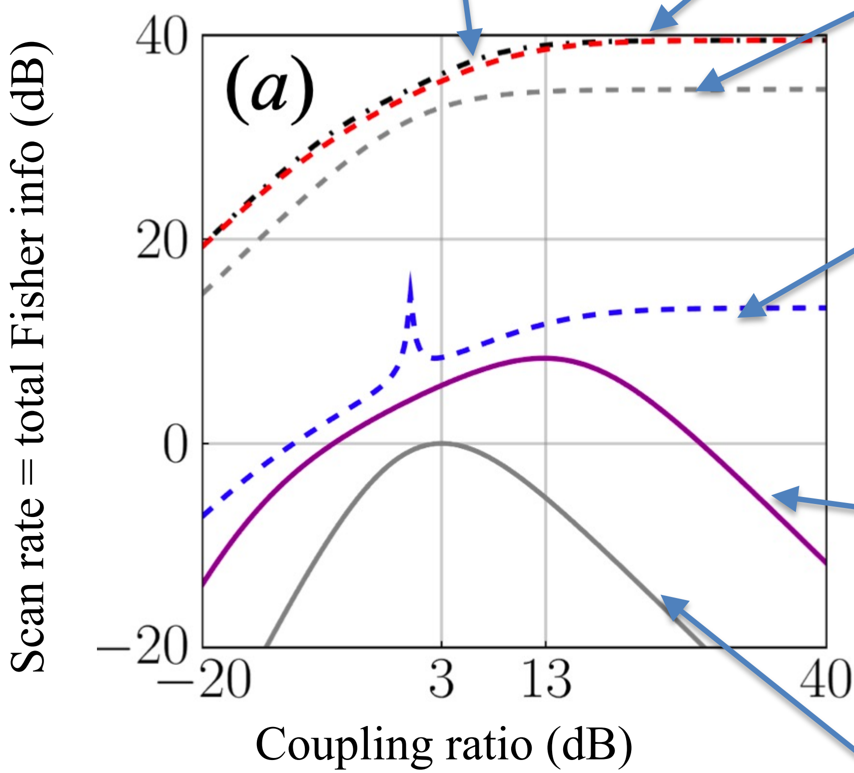


Fig. 8 Frequency spectrum of the Fisher information with respect to the axion occupation number n_a. The values are normalized by the optimized peak value of vacuum-homodyne Fisher $\mathcal{I}^{\star\,\rm Vac-hom}_{n_a}$ and plotted in decibel unit. **a** $\gamma_m/\gamma_\ell = 1$; **b** $\gamma_m/\gamma_\ell = 2G$. Temperature $T = 61$ mK, cavity resonant frequency $\omega_c = 2\pi \cdot 10$ GHz, squeezing strength $G = 10$ dB, $\gamma_a/\gamma_\ell = 10^{-12}$.

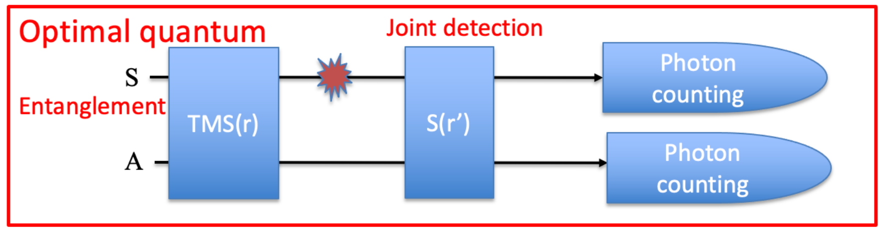
Note: this is for axion, not dark photon

HS and QZ, npj Quantum Inf. 9, 27 (2023)

Ultimate upper bound (single sensor)

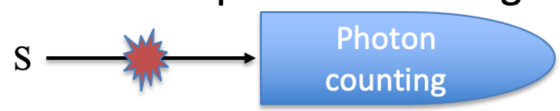


entangled



Vacuum limit

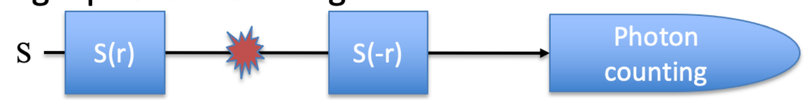
Vacuum + photon counting



Squeezing limit **~ using photon number state**

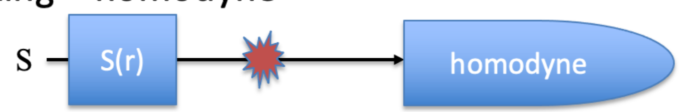
See Phys. Rev. Lett. 129, 240503 (2022)

Squeezing + photon counting



HAYSTAC theoretical

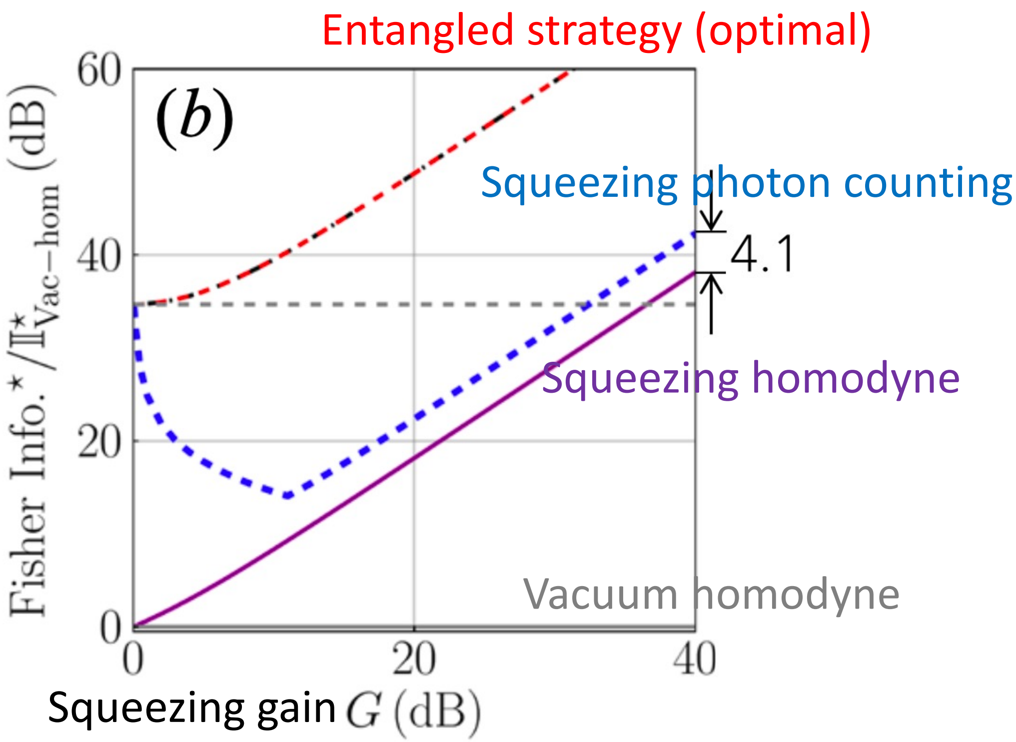
Squeezing + homodyne



Vacuum + homodyne

Interpret the ultimate limit to DM search scan rate

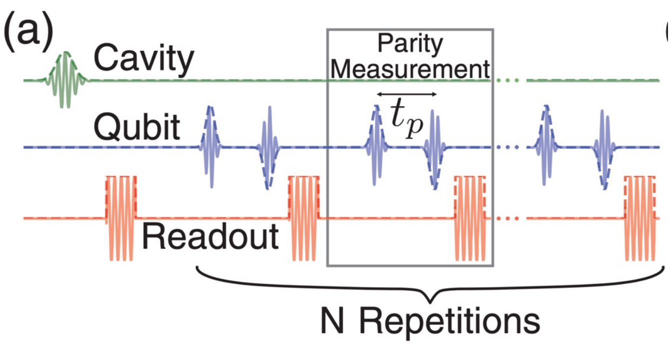
HS and QZ, npj Quantum Inf. 9, 27 (2023)



- Entangled ancilla is important for DM search.
- Single-mode squeezing/number state are not good for scan
- Microwave photon detection is important, although challenging.

e.g. implemented by qubit-qumode coupling:
Phys. Rev. Lett. 126, 141302 (2021);

arXiv:2307.03614



Why squeezing/number state are not that useful:
Story is different when there is loss

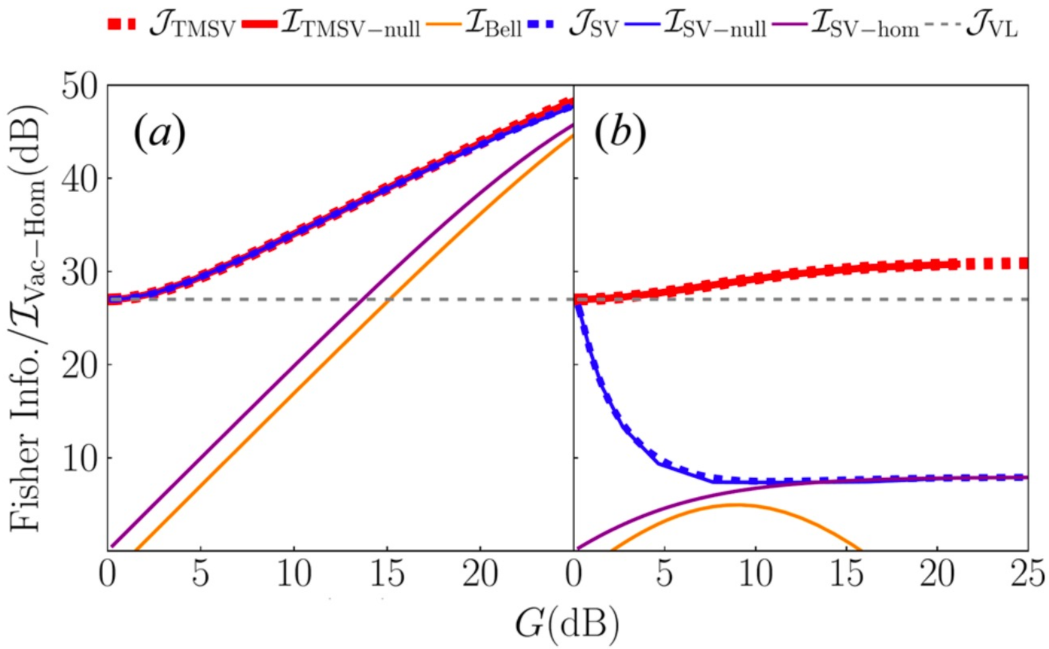
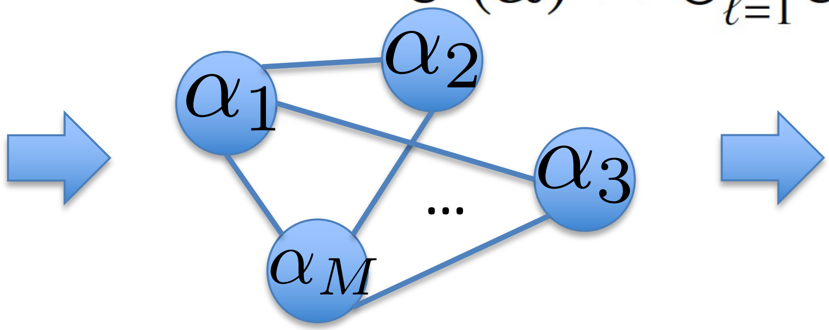


Fig. 7 Comparison of the Fisher information of practical measurements (solid) with the quantum limits (dashed). The Fisher information is normalized by the standard Fisher information of homodyne on vacuum input. **a** $\kappa = 1$. **b** $\kappa = 0.6$. Both axes are plotted in the decibel (dB) unit. $n_B = 10^{-3}$. As a reminder, $G = e^{2r} = \exp\{2\sinh^{-1}\sqrt{N_S}\}$.

How can quantum effects help---advantage from multi-partite entanglement

Distributed sensing $\hat{U}(\boldsymbol{\alpha}) \equiv \otimes_{\ell=1}^{M} \hat{U}(\alpha_\ell)$

$\hat{\rho}_M$  $\hat{\rho}_M(\boldsymbol{\alpha}) = \hat{U}(\boldsymbol{\alpha})\,\hat{\rho}_M \hat{U}^\dagger(\boldsymbol{\alpha})$

Unknown parameters $\boldsymbol{\alpha} = \{\alpha_m\}_{m=1}^{M}$

Goal---estimate a weighted average: $\bar{\alpha} = \boldsymbol{w}\cdot\boldsymbol{\alpha} \equiv \sum_{\ell=1}^{M} w_\ell \alpha_\ell$

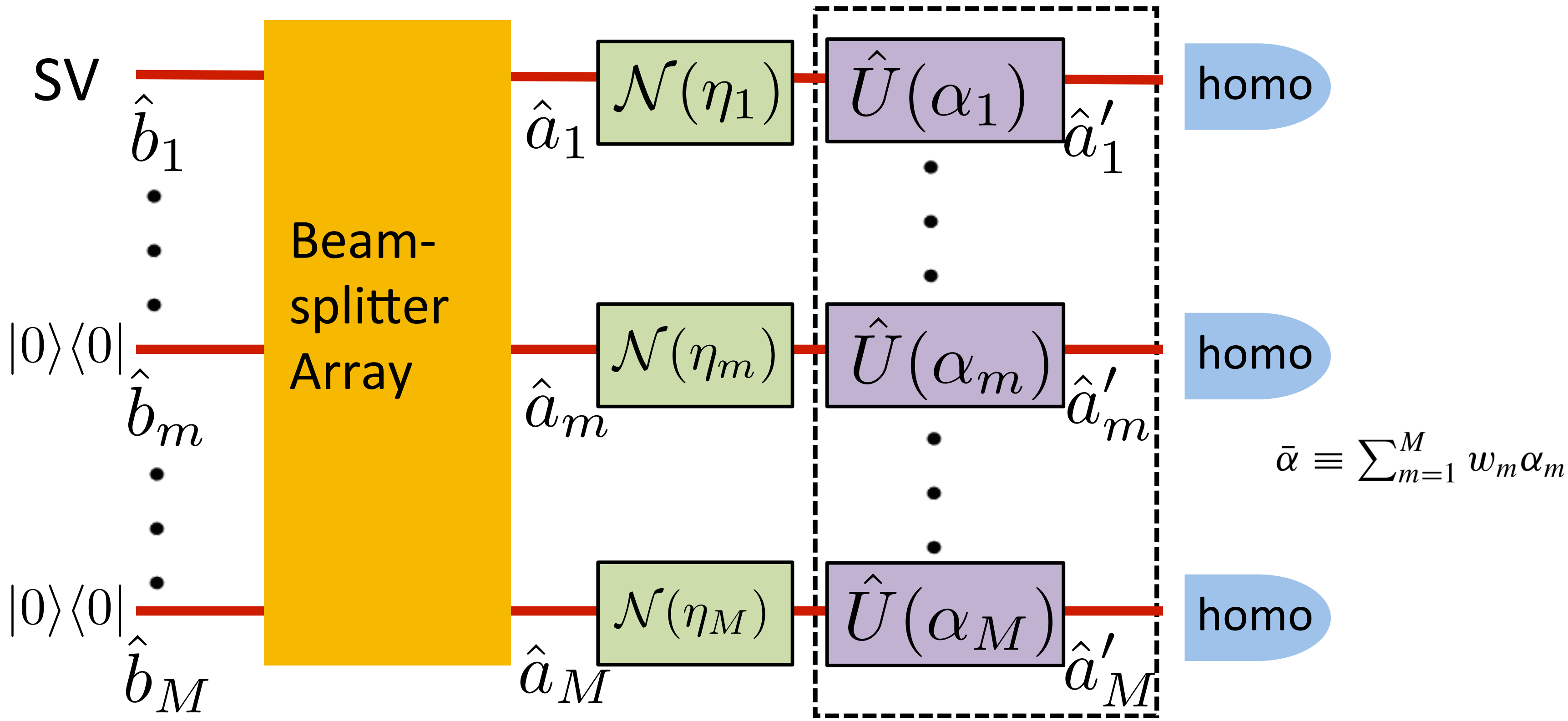
How about analytical function?

$$f(\boldsymbol{\alpha}) \simeq f(\tilde{\boldsymbol{\alpha}}) + \sum_\ell \partial_{\alpha_\ell} f(\tilde{\boldsymbol{\alpha}})(\alpha_\ell - \tilde{\alpha}_\ell)$$

Qian K, Eldredge Z, Ge W, Pagano G, Monroe C, Porto J V and Gorshkov A V 2019 *Phys. Rev. A* **100** 042304

Distributed displacement sensing scheme

QZ, ZZ, JHS, Phys. Rev. A 97, 032329 (2018)

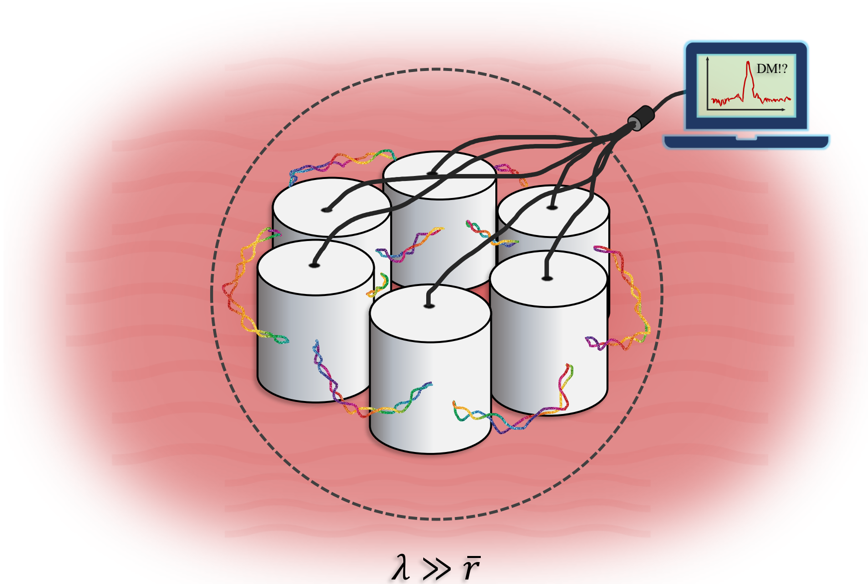


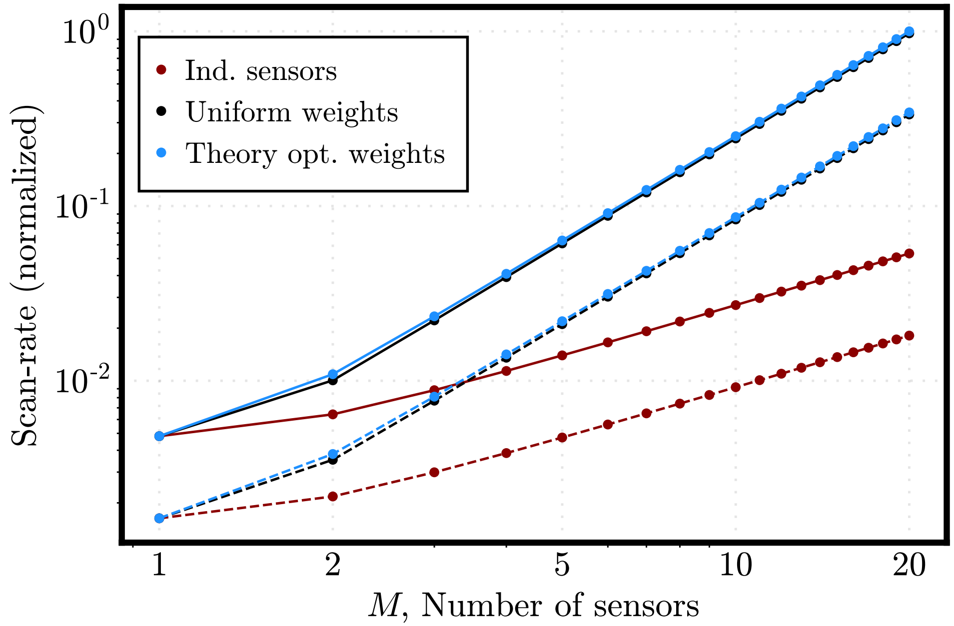
- Optimality: in absence of loss, it's the optimum. Phys. Rev. A **99**, 012328 (2019)
  fixed homodyne detection, it's always the optimum state.
  in presence of loss, optimum Gaussian scheme.
- Heisenberg scaling measurement of quadrature displacement
  with only basic components in linear optics!

Application: distributed sensing for dark matter search

AJB, CG, RH, ZL, ZZ, QZ, PRX Quantum **3**, 030333 (2022)

- Local microwave cavity sensor network for dark matter detection.





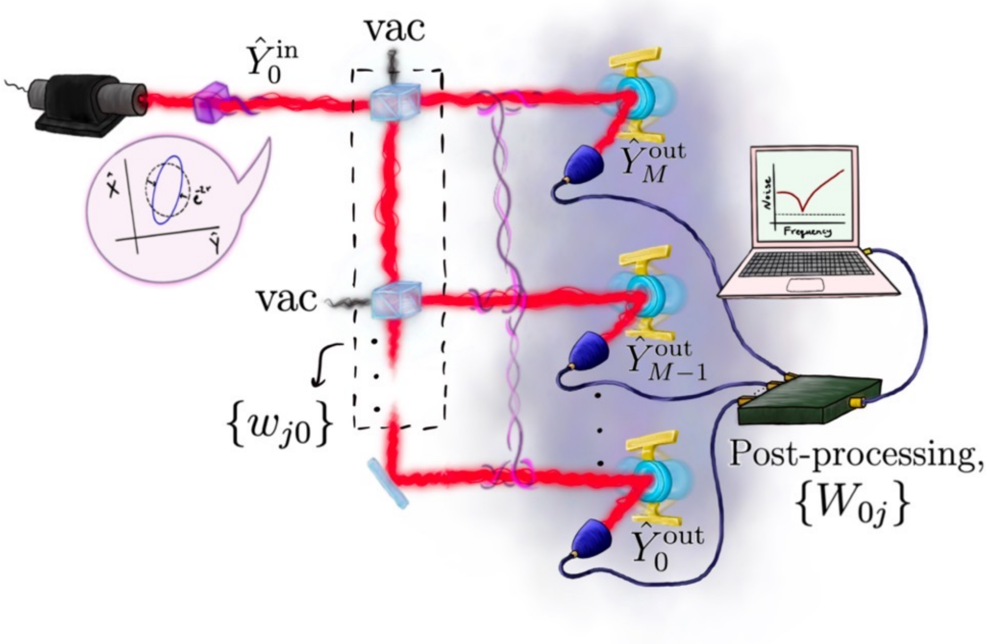
- Coherence of axion field
- Entanglement suppresses noise
- Performance characterized by scan-rate: how fast you build up signal-to-noise-ratio (SNR)

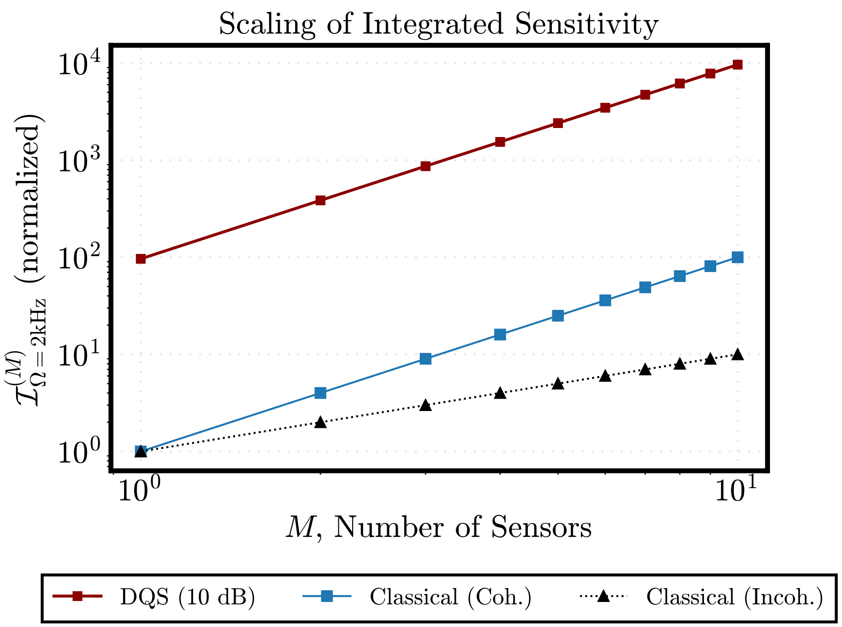
Application: distributed sensing for dark matter search

AJB, XC, KX, YX, JM, MDC, ZL, RH, DJW, ZZ, QZ, Commun. Phys. **6**, 237 (2023)

Fermilab SQMS NSF C-Accel

- Local opto-mechanical sensor network for dark matter detection.





Including dark matter models:

vector Baryon-Lepton (B-L) model, Force ∝ B-L charge

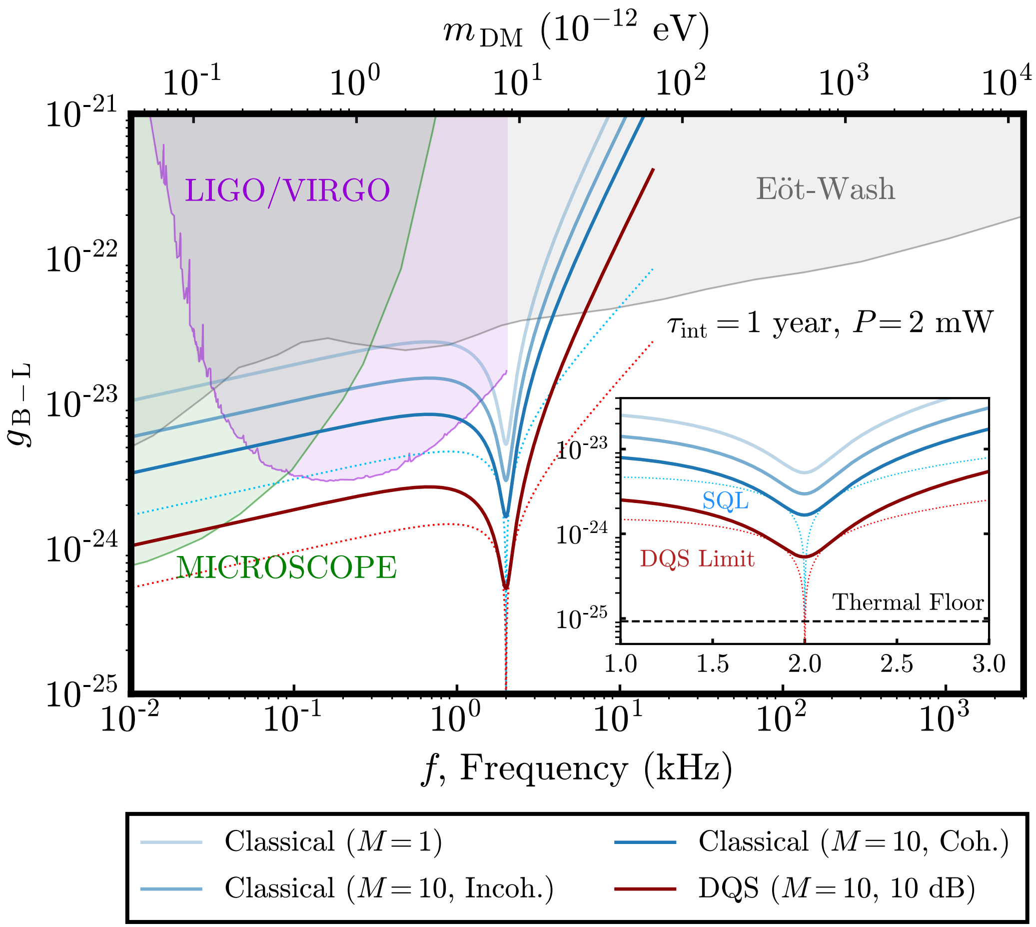
scalar coupling to neutrons Force ∝ neutron #

Application: distributed sensing for dark matter search

AJB, XC, KX, YX, JM, MDC, ZL, RH, DJW, ZZ, QZ, to appear in Commun. Phys.

Fermilab SQMS NSF C-Accel

- Local opto-mechanical sensor network for dark matter detection.



Projected minimum detectable coupling strength for B−L DM

Prior prediction: Phys. Rev. Lett. 126, 061301 (2021)

MICROSCOPE:
Phys. Rev. Lett. 119, 231101 (2017)
Phys. Rev. Lett. 120, 141101 (2018)

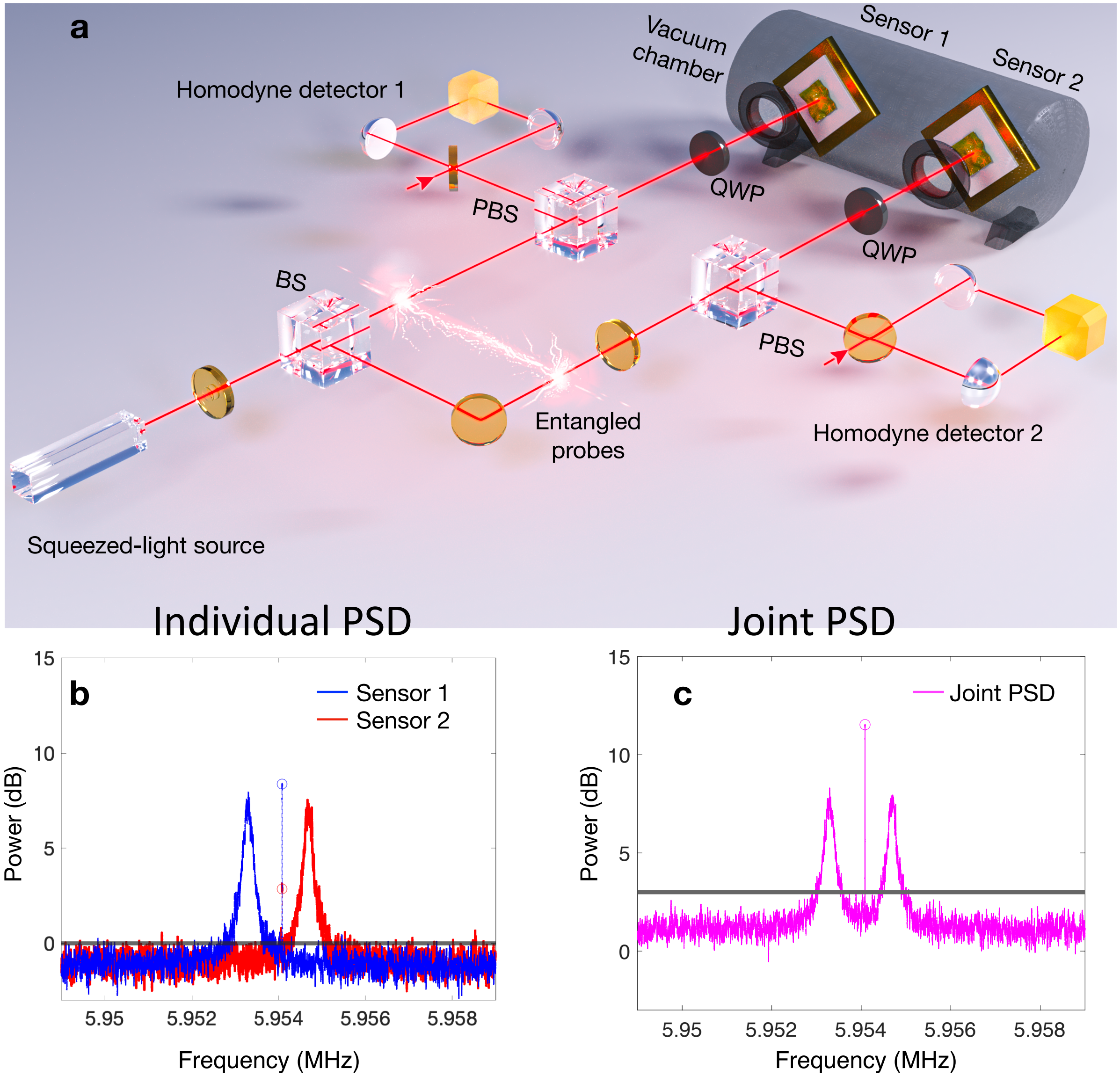
Eöt-Wash
Class. Quant. Grav. 29, 184002 (2012)

LIGO/VIRGO
Phys. Rev. D 105, 063030 (2022)

Application: distributed sensing for dark matter search

proof-of-principle experiment of opto-mechanical sensor network

YX, ARA, CMP, AJB, ZL, QZ, DJW, ZZ, Nat. Photon. **17**, 470 (2023)



Experimental led by Zheshen Zhang

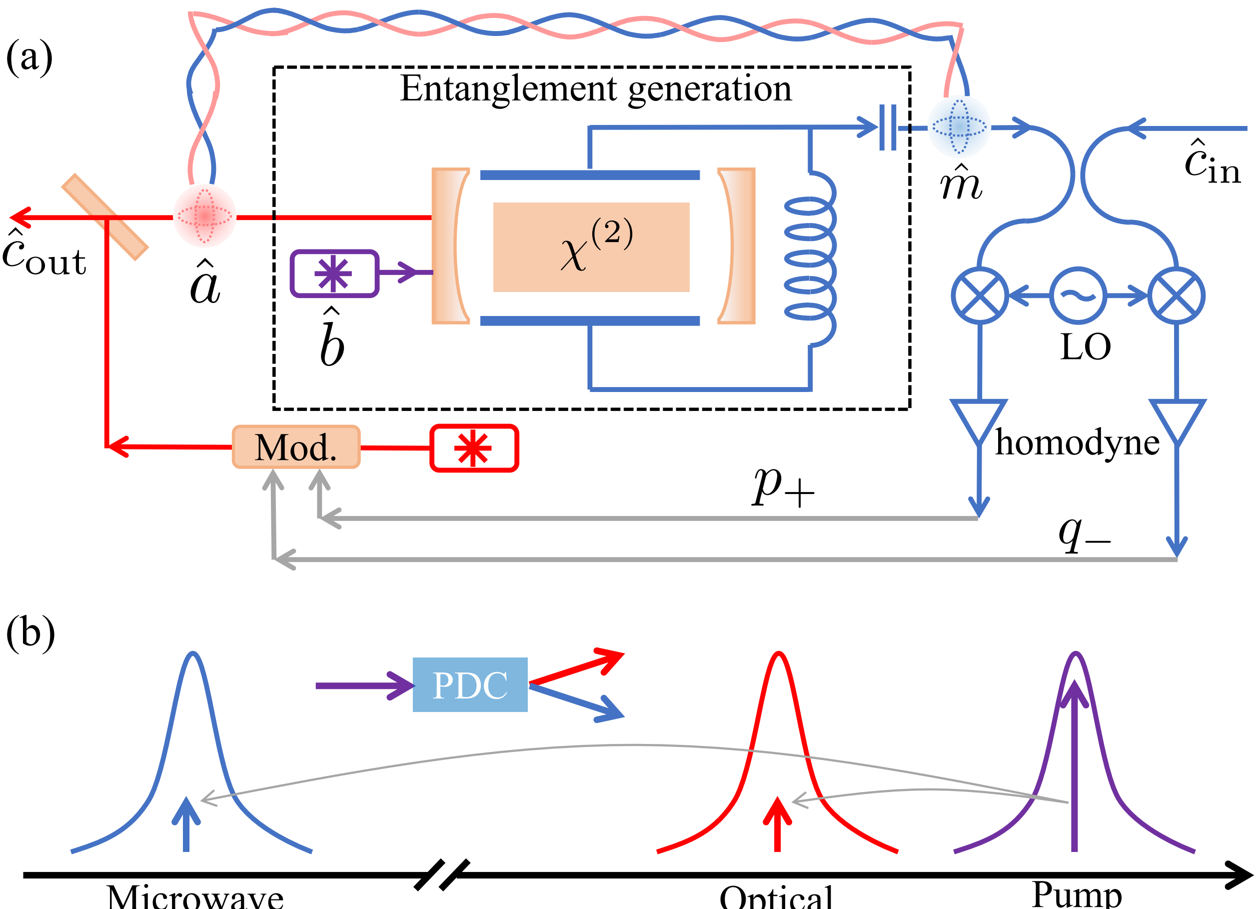
Fermilab SQMS

NSF C-Accel

How can quantum effects help---quantum transduction

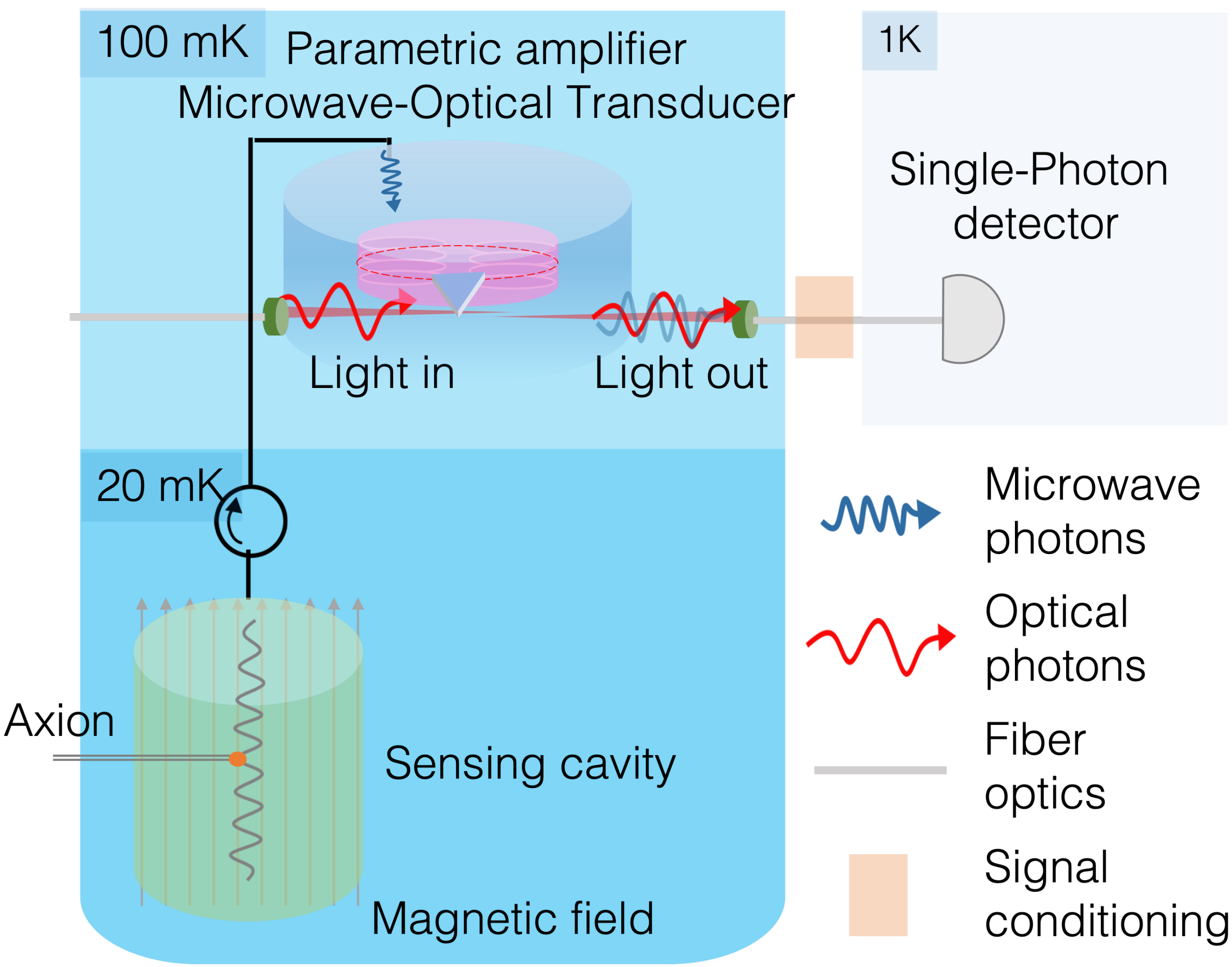
JW, CC, LF, QZ, Phys. Rev. Applied **16**, 064044 (2021)

- Teleportation-based transduction between microwave and optical
- Enhancement from squeezing
- VQC for quantum transduction



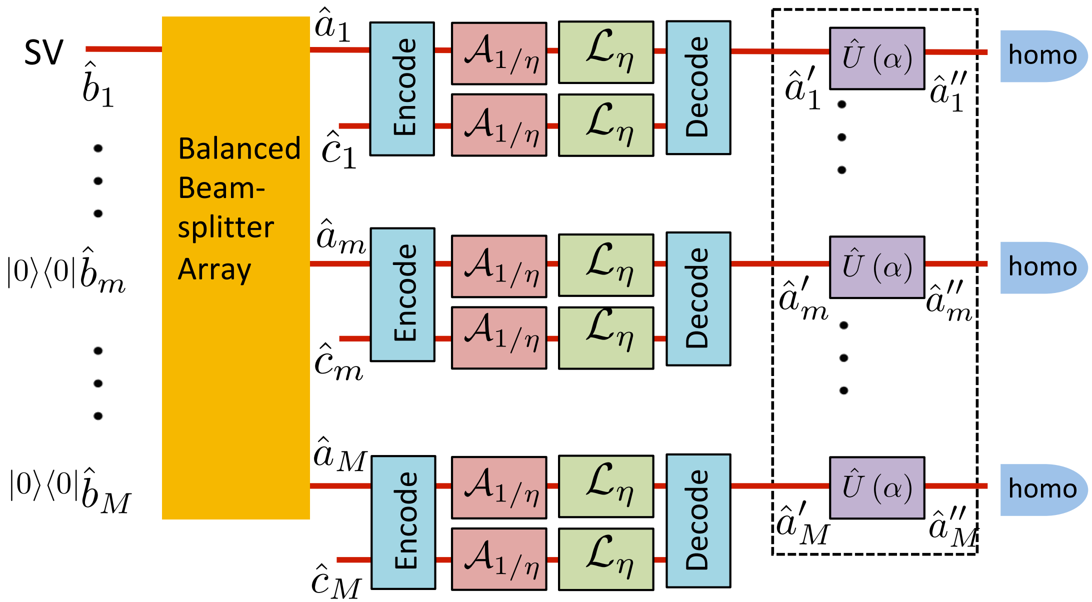
Quantum transduction enabled photon counting

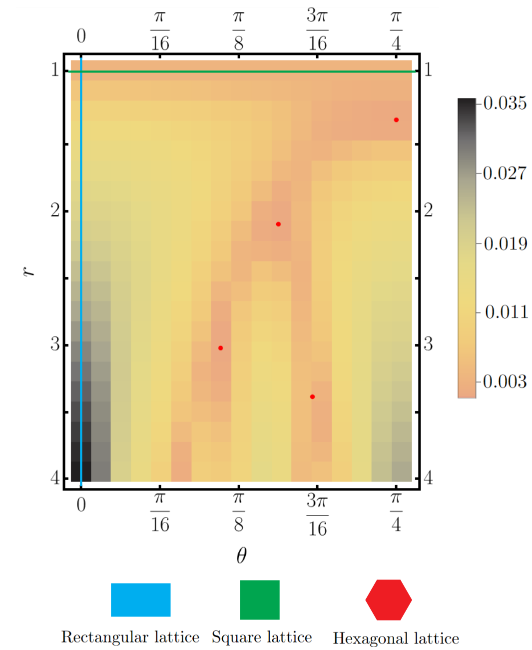
AJB, HS, CW, JW, SZ and QZ, in preparation (2023)

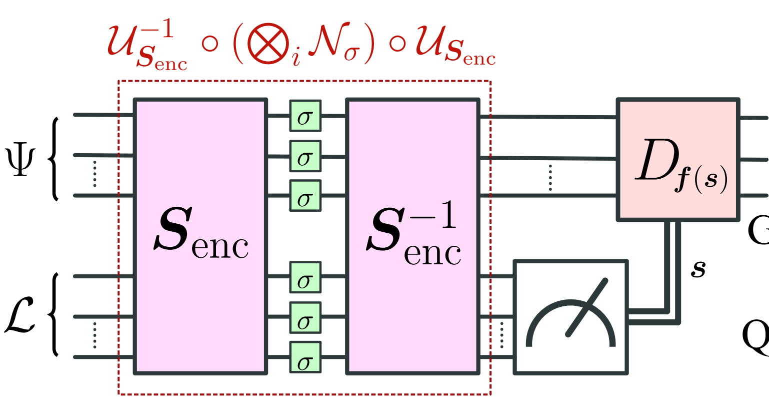


Quantum technology enabling DQS: error correction

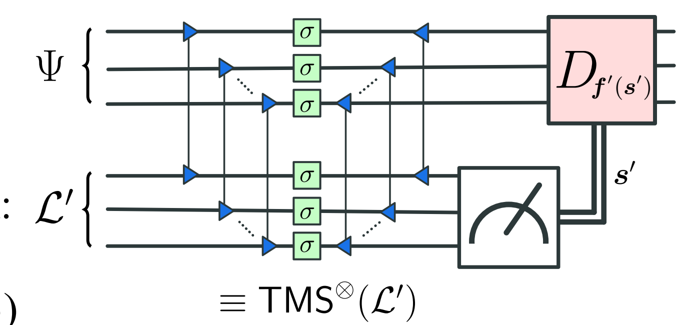
JW and QZ, Phys. Rev. Applied **15**, 034073 (2021)
QZ, JP, and LJ, New J. Phys. **22**, 022001 (2020)
BZ, AJB, QZ, Phys. Rev. A 106, 012404 (2022)







General code reduction:
JW, AJB, QZ,
Quantum 7, 1082 (2023)

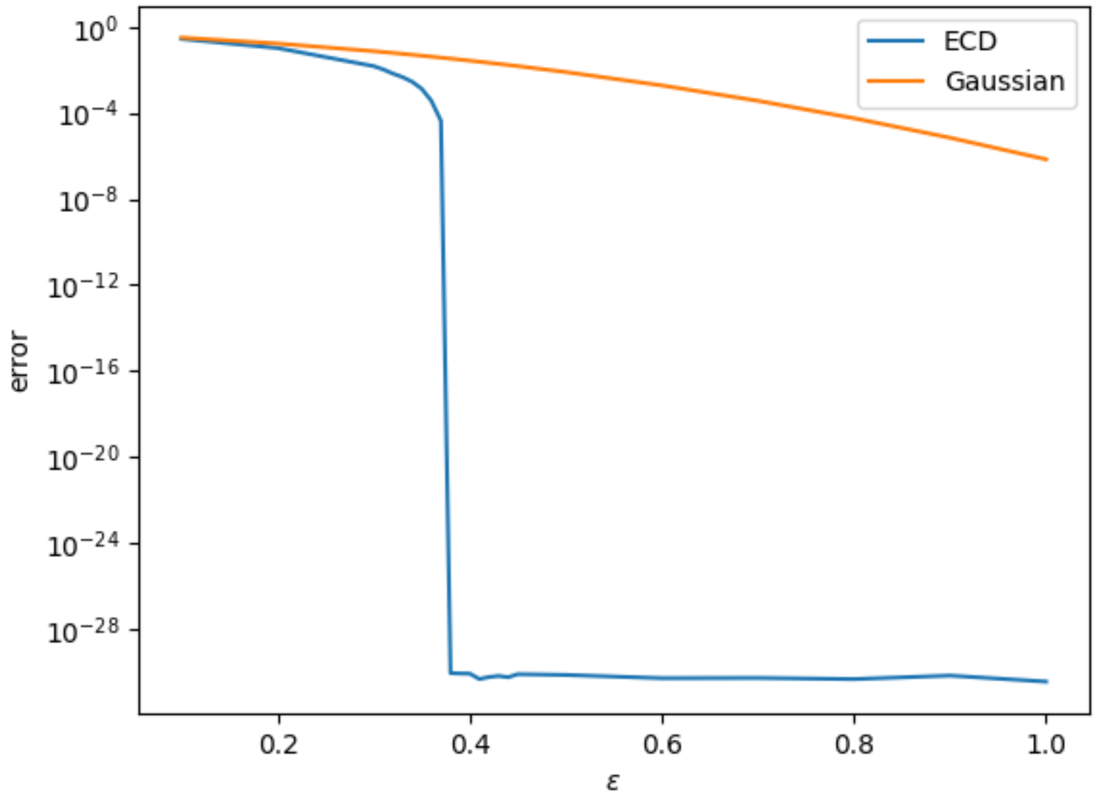


DARPA YFA

How can quantum effects help---quantum machine learning

PL, BZ and QZ, in preparation (2023)

Quantum machine learning for quantum hypothesis testing



USC University of Southern California

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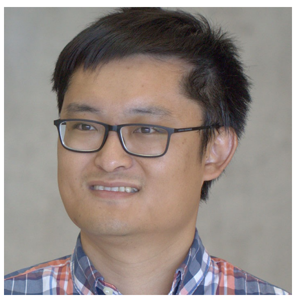
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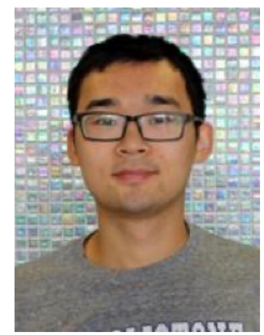
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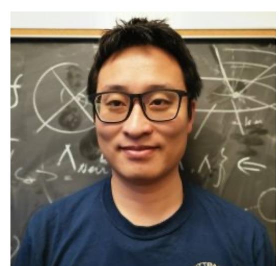
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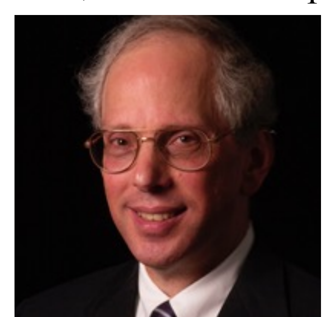
Jeffrey Shapiro
MIT