A photonic which-path entangler

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CAP Congress
University of Western Ontario, London, ON
2024 May 27

More information: Z. M. McIntyre and WAC, Phys. Rev. Lett. **132**, 093603 (2024) [entanglement]
Z. M. McIntyre and WAC, arXiv:2405.13265 [sensing]

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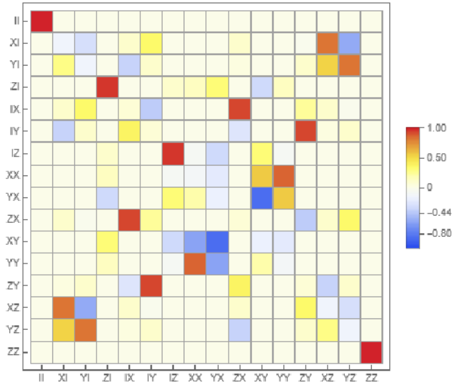
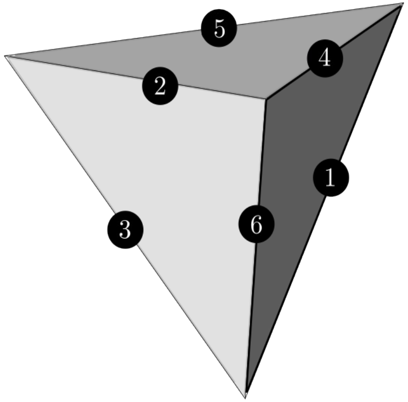


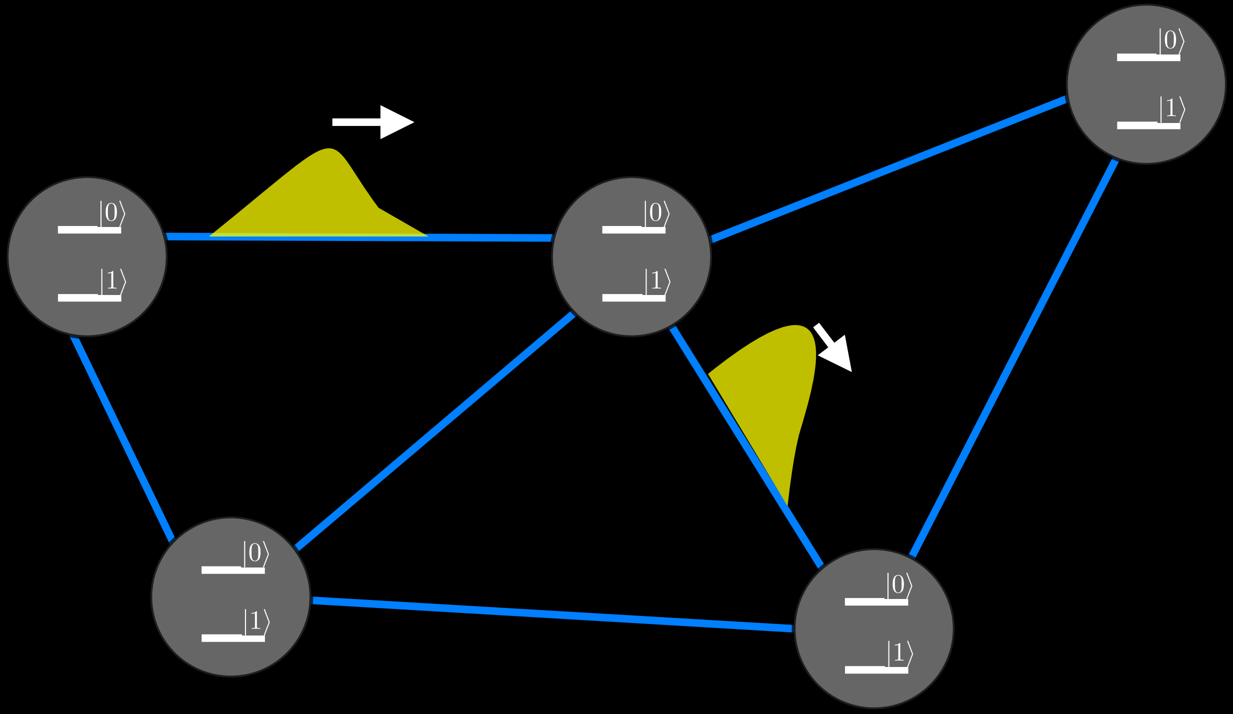
Noah Pinkney

Today @ 11:00-11:15 (SSC 2020)
Entropy-based Bayesian approach to multi-parameter estimation



Zoé McIntyre

Today @ 16:45-17:00 (PAB 150)
Flying-cat parity checks for quantum error correction and quantum communication



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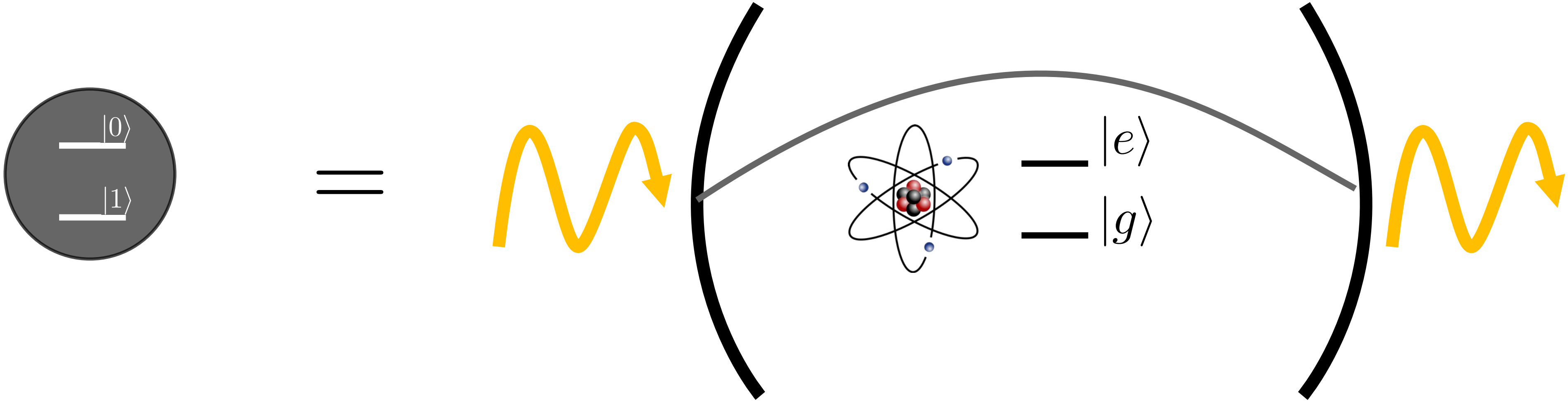

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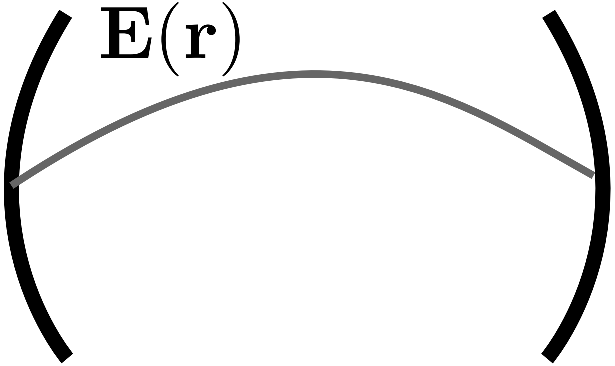
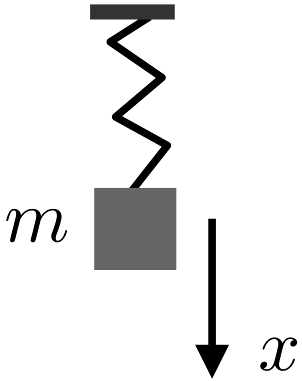
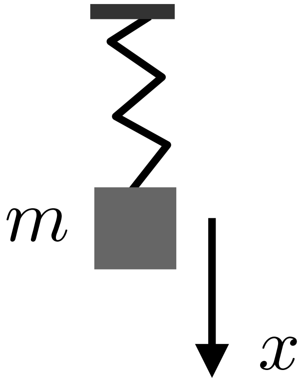


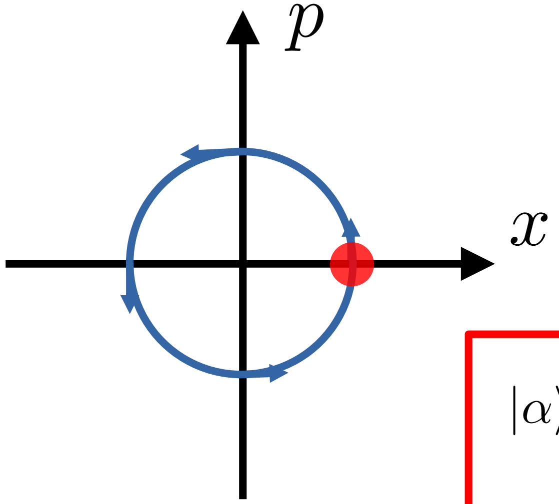
$$\text{Energy} \sim \frac{1}{2}\int d^3r \left(\epsilon_0 E^2(\mathbf{r}) + \frac{1}{\mu_0}B^2(\mathbf{r})\right)$$



$$\text{Energy} = \frac{p^2}{2m} + \frac{1}{2}m\omega^2 x^2$$

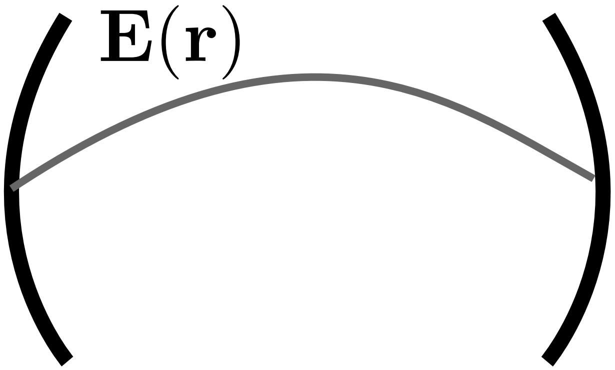
$$H = \hbar\omega\left(n + \frac{1}{2}\right); \quad n = 0, 1, 2, \ldots$$

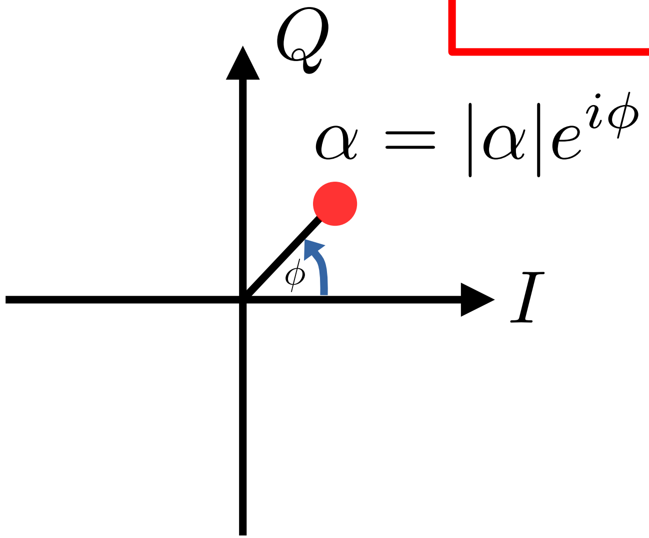


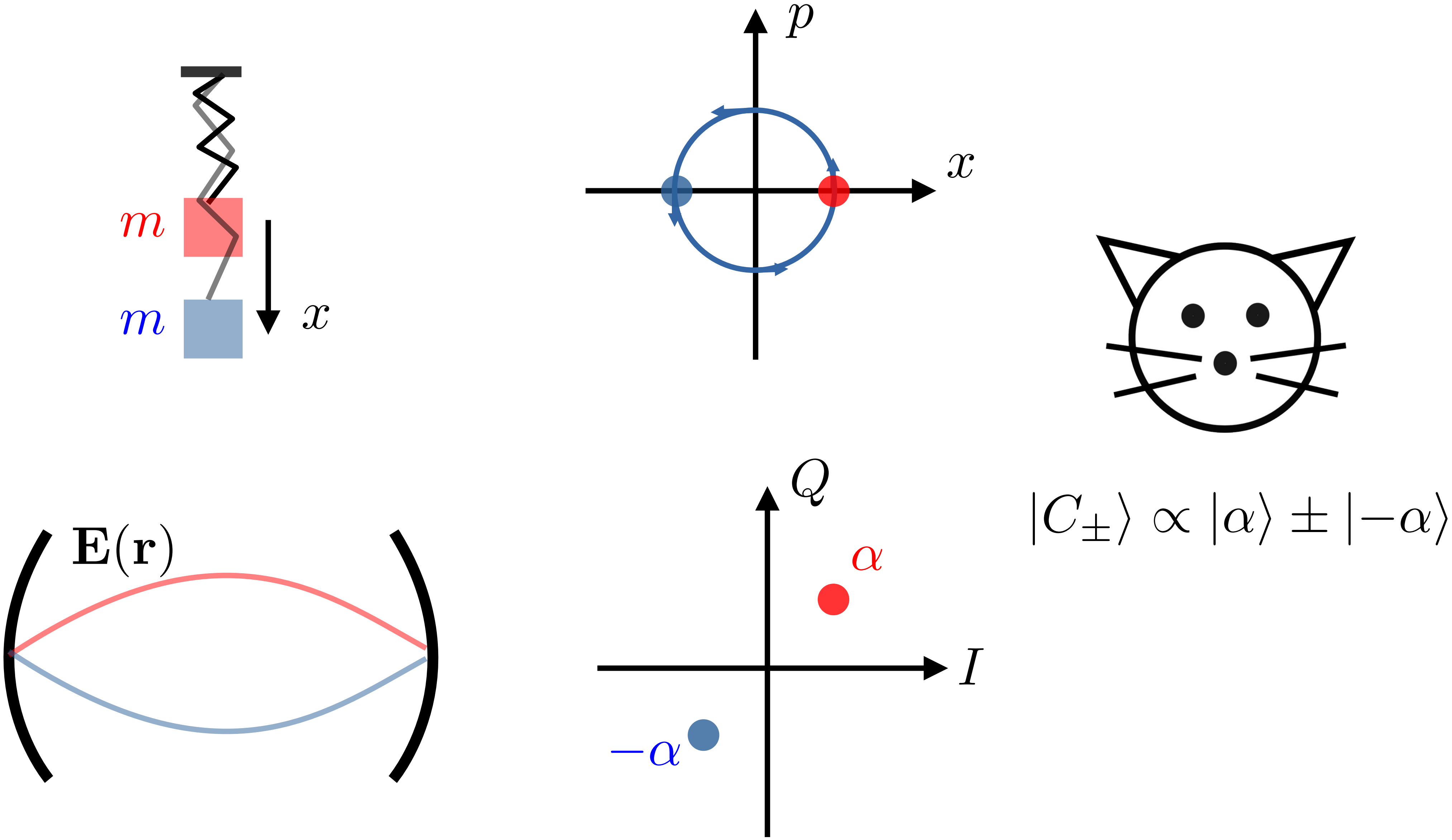


$$|\alpha\rangle = e^{-|\alpha|^2/2} \sum_n \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

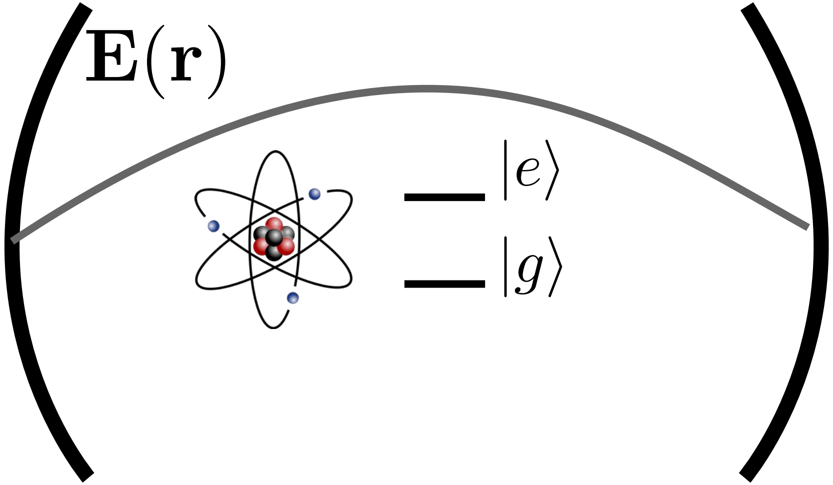
$$a\,|\alpha\rangle = \alpha\,|\alpha\rangle$$







m
m
x
p
x
$\mathbf{E}(\mathbf{r})$
Q
α
I
$-\alpha$
$|C_{\pm}\rangle \propto |\alpha\rangle \pm |-\alpha\rangle$



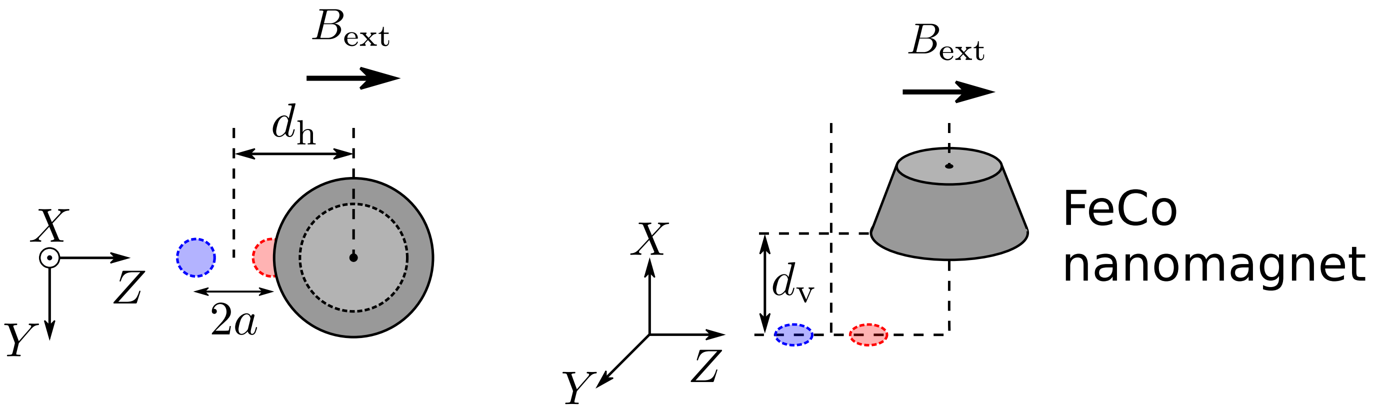
$$H_{\text{dip.}} = e\mathbf{E}(\mathbf{r_0}) \cdot \mathbf{r}$$

$$\mathbf{E}(\mathbf{r_0}) \sim a + a^\dagger$$

$$\sigma_z = |e\rangle\langle e| - |g\rangle\langle g| \qquad \sigma_x = |e\rangle\langle g| + |g\rangle\langle e|$$

$$H_{\text{eff}} = g_z \sigma_z (a + a^\dagger) + g_x (a\sigma_+ + a^\dagger \sigma_-)$$

$$g_z \propto \langle e| \mathbf{r} |e\rangle - \langle g| \mathbf{r} |g\rangle \qquad g_x \propto \langle e| \mathbf{r} |g\rangle$$



$$H_{\text{eff}} \simeq \boxed{g_z\left(a^\dagger + a\right)\sigma_z} + \boxed{g_x(a^\dagger\sigma_- + \sigma_+ a)}$$

Longitudinal   Transverse

F. Beaudoin, D. Lachance-Quirion, WAC, and M. Pioro-Ladrière, Nanotechnology (2016)

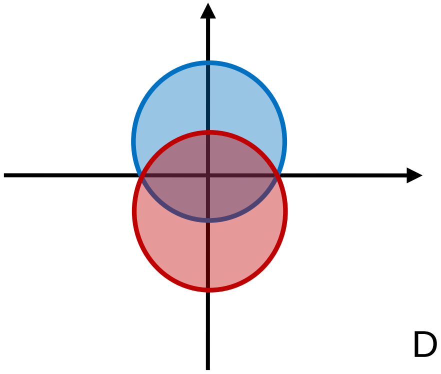
Longitudinal parametric readout

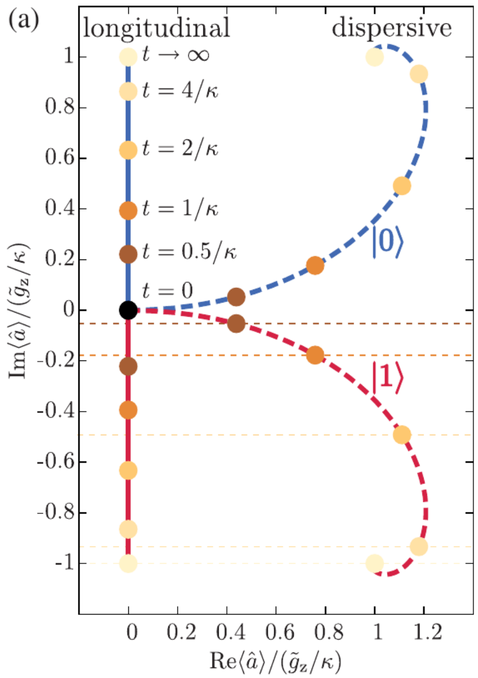
$$H(t) = \omega_c a^\dagger a + g_z(t)\left(a + a^\dagger\right)\sigma_z$$

$$g_z(t) = \bar{g}_z + \tilde{g}_z \cos\left(\omega_c t\right)$$

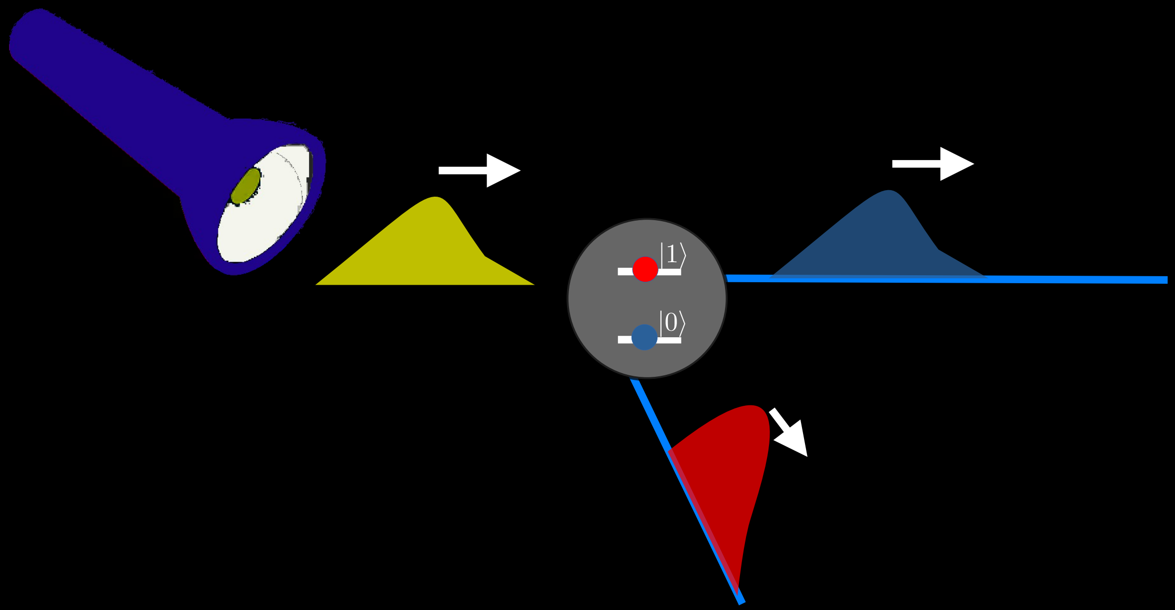
Qubit-state-dependent displacement:

$$H_{\mathrm{RWA}} = \tilde{g}_z(a + a^\dagger)\sigma_z$$





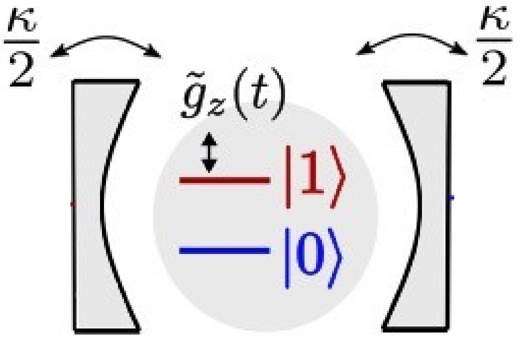
Didier, Bourassa, Blais, PRL **115**, 203601 (2015)



Z. M. McIntyre and WAC, PRL (2024)

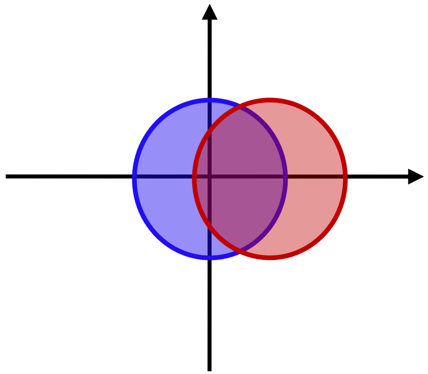
Modulated longitudinal coupling

$$g_z(t) = \bar{g}_z + \tilde{g}_z(t)\cos(\omega_c t)$$



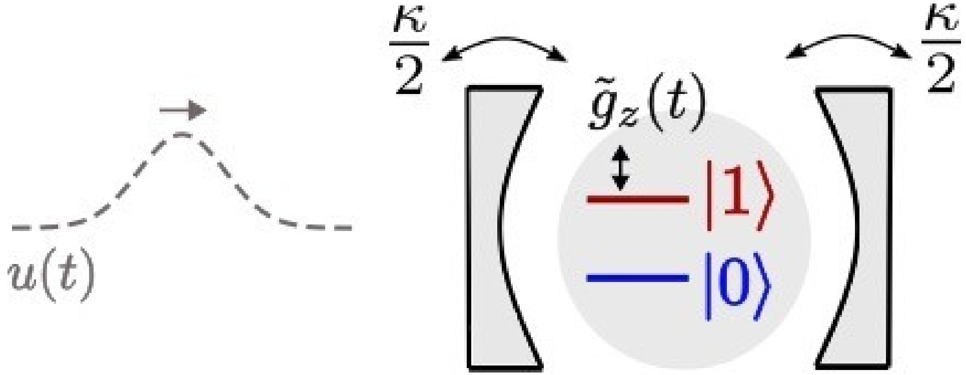
Rotating frame:

$$H(t) = i\tilde{g}_z(t)\,|1\rangle\langle 1|\,(a - a^\dagger)$$



Z. M. McIntyre and WAC, PRL (2024)

$$\langle r_{\text{in}} \rangle_t = \alpha_0 u(t)$$



Quantum Langevin equation:

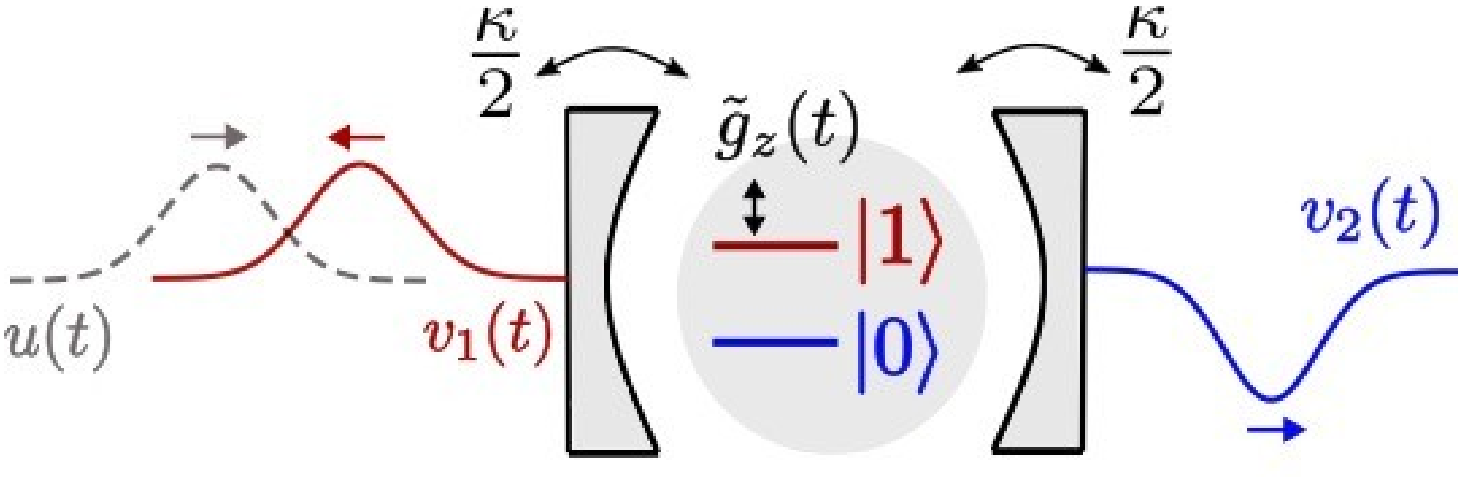
$$\langle \dot{a} \rangle_t = -\frac{\kappa}{2} \langle a \rangle_t + \tilde{g}_z(t) s - \sqrt{\frac{\kappa}{2}} \alpha_0 u(t)$$

$s = 0, 1$ (qubit state)

Z. M. McIntyre and WAC, PRL (2024)

A which-path entangler

Qubit-state-conditioned transmission: $\tilde{g}_z(t) \propto \alpha_0 u(t)$



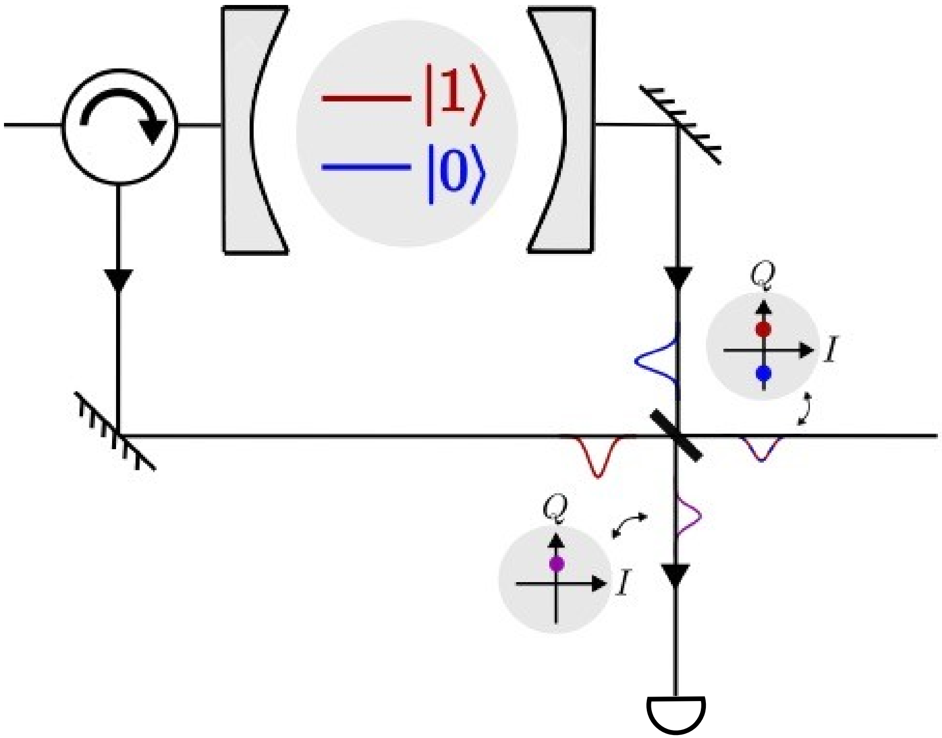
Qubit—Which-Path state

$$|\mathrm{QWP}\rangle = \frac{1}{\sqrt{2}}\left(|1\rangle\,|\alpha,0\rangle + |0\rangle\,|0,\alpha\rangle\right)$$

Similar interference measured experimentally in Corrigan et al., Phys. Rev. Applied (2023)

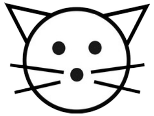
Z. M. McIntyre and WAC, PRL (2024)

Re-encoding the which-path qubit



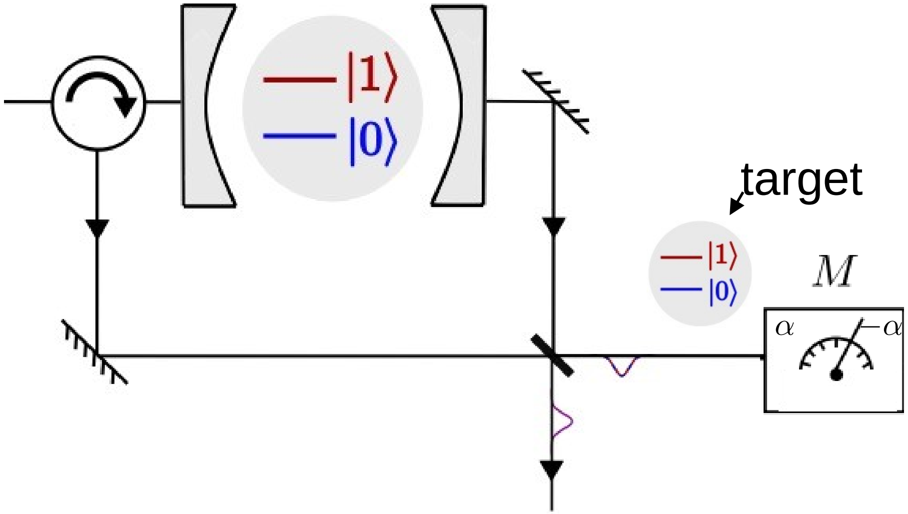
Post-measurement state:

$$|\Psi\rangle = \frac{1}{2} \sum_{\lambda=\pm} N_\lambda \, |\lambda, C_\lambda\rangle$$

“Flying” cat states: 

$$|C_\pm\rangle = \frac{1}{N_\pm} \left(|+\alpha\rangle \pm |-\alpha\rangle\right)$$

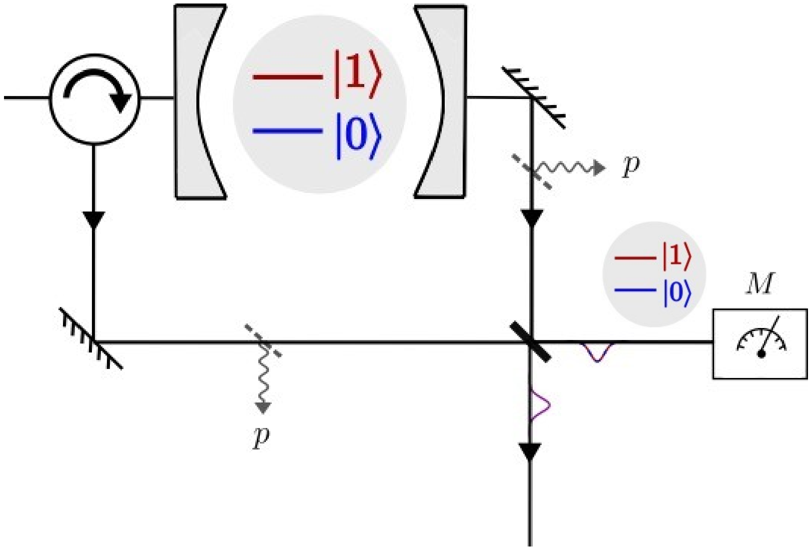
Distributed Bell/GHZ states



Measure: $|\pm\alpha\rangle \Rightarrow \quad |\Psi_{\mathrm{Bell}}\rangle = \frac{1}{2}\left(|++\rangle \pm |--\rangle\right)$

Parity-dependent qubit phase flip: Kono et al., Nature Physics **14**, 546-549 (2018); Besse et al., PRX **8**, 021003 (2018);
Hacker et al., Nature Photonics **13**, 110-115 (2019); Besse et al., PRX **10**, 011046 (2020)

Entanglement: two-qubit concurrence

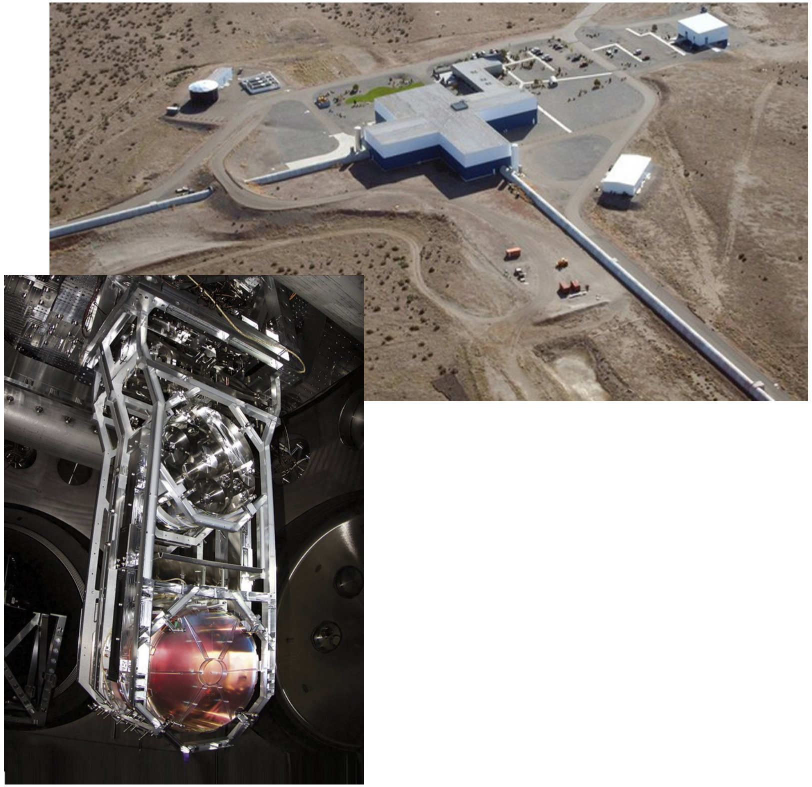


$$C = \max\left\{0, \mathrm{erf}\left(\sqrt{N_{\mathrm{det}}}\right) e^{-N_{\mathrm{lost}}} - \mathrm{erfc}\left(\sqrt{N_{\mathrm{det}}}\right)\right\}$$

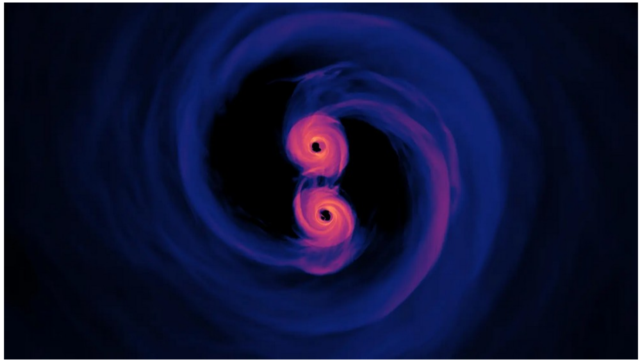
$$N_{\mathrm{det}} = p(1-p)|\alpha|^2$$

$$N_{\mathrm{lost}} = p|\alpha|^2$$

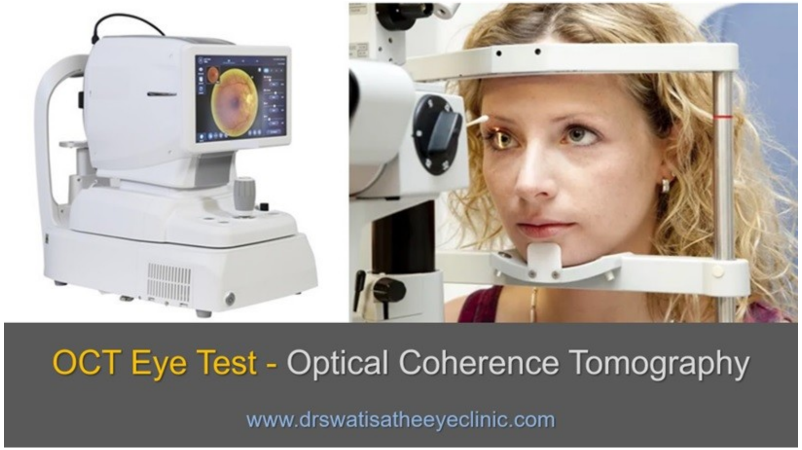
Precision sensing/interferometry?



https://www.ligo.caltech.edu/news/ligo20231023



https://bigthink.com/starts-with-a-bang/merging-supermassive-black-holes/

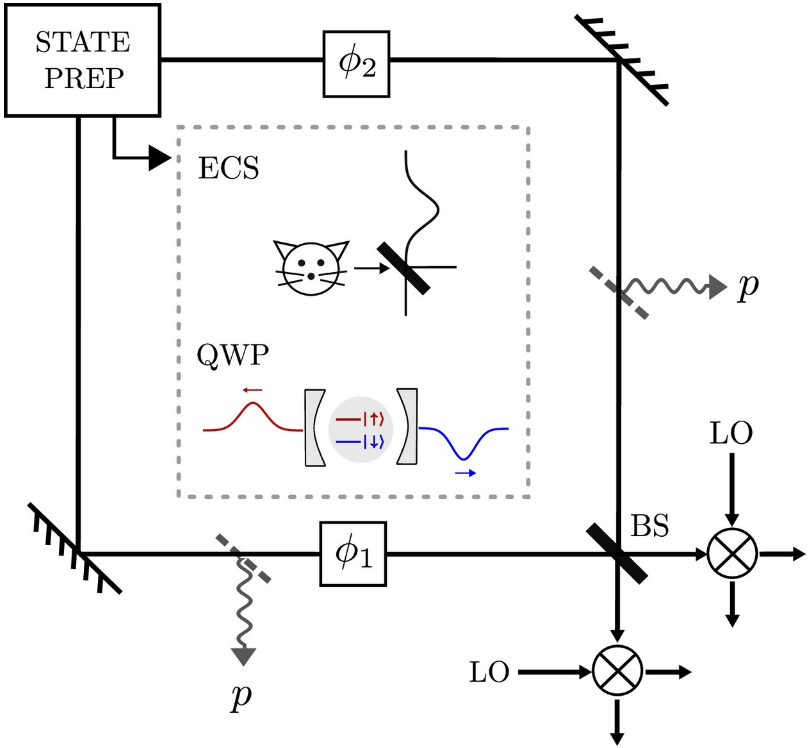


Precision phase measurements with path-entangled states

$$|\mathrm{ECS}\rangle = \mathcal{N}_\alpha \left(|\alpha, 0\rangle + |0, \alpha\rangle\right)$$

$$|\mathrm{QWP}\rangle = \frac{1}{\sqrt{2}} \left(|\uparrow, \alpha, 0\rangle + |\downarrow, 0, \alpha\rangle\right)$$

$$\phi = \phi_1 - \phi_2 = ?$$



Quantum Cramér-Rao bound:

$$\delta\phi_{\min} = \frac{1}{\sqrt{M I_{\mathrm{Q}}(\rho_\phi)}}$$

$$\rho_\phi = U_\phi \rho(0) U_\phi^\dagger, \quad U_\phi = \prod_{i=1,2} e^{-i\phi_i n_i}$$

Z. M. McIntyre and WAC, arXiv:2405.13265

$$I_Q(|\alpha\rangle_\phi) = \bar{n} \longrightarrow \delta\phi_{\min} \sim \frac{1}{\sqrt{\bar{n}}}$$

SQL
(shot noise)

$$I_{\mathrm{Q}}(|N00N_\phi\rangle) = N^2 \longrightarrow \delta\phi_{\min} \sim \frac{1}{N}$$

Heisenberg

$$I_{\mathrm{Q}}(|\mathrm{ECS}_\phi\rangle) = \bar{n}^2 + \bar{n} + O(\bar{n}^2 e^{-\bar{n}})$$

$$I_{\mathrm{Q}}(|\mathrm{QWP}_\phi\rangle) = \bar{n}^2 + \bar{n}$$

Heisenberg

SQL
(shot noise)

Optimal measurements

Classical Cramér-Rao bound: $$\delta\phi = \frac{1}{\sqrt{M I_{\mathrm{C}}(\phi)}}$$

$$I_{\mathrm{C}}(\phi) = \int dx\, (\partial_\phi \ln p(x|\phi))^2 p(x|\phi)$$

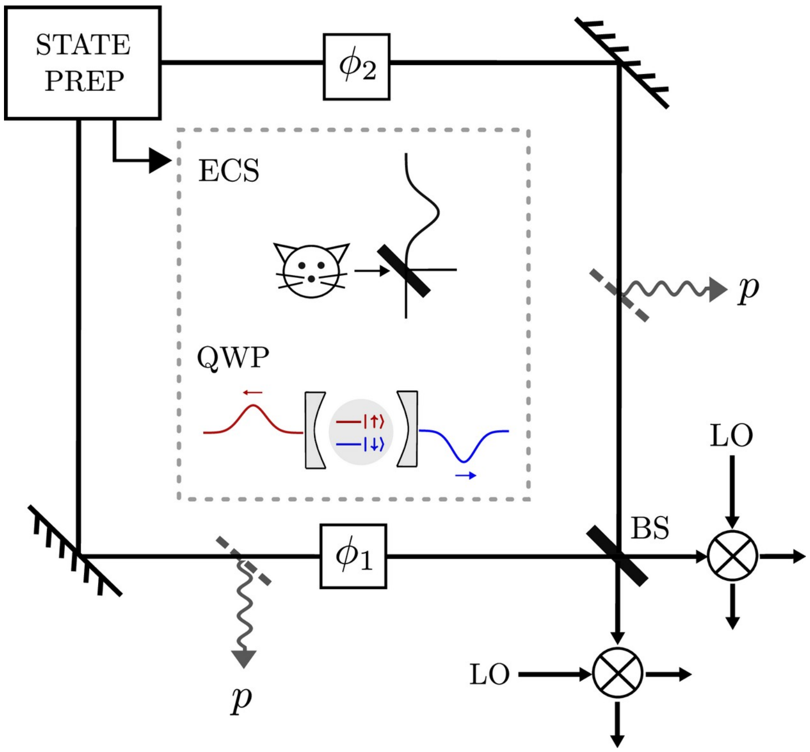
$$p(x|\phi) = \mathrm{Tr}\{\hat{\Pi}_x \rho_\phi\}$$

$$I_{\mathrm{C}}(\phi) = I_{\mathrm{Q}}(\rho_\phi)$$

$$\delta\phi = \delta\phi_{\mathrm{min}}$$

e.g. photon counting [Hofman, PRA (2009)]

An optimal homodyning scheme



$$\varphi_+ = \frac{\pi}{2} + \bar{\phi} \qquad \bar{\phi} = \frac{1}{2}(\phi_1 + \phi_2)$$

$$\varphi_- = \bar{\phi}$$

+ X-basis readout for QWP

$$\hat{\Pi}_x = |X\rangle\langle X| \bigotimes_{\sigma=\pm} |x_{\varphi_\sigma}\rangle\langle x_{\varphi_\sigma}|$$

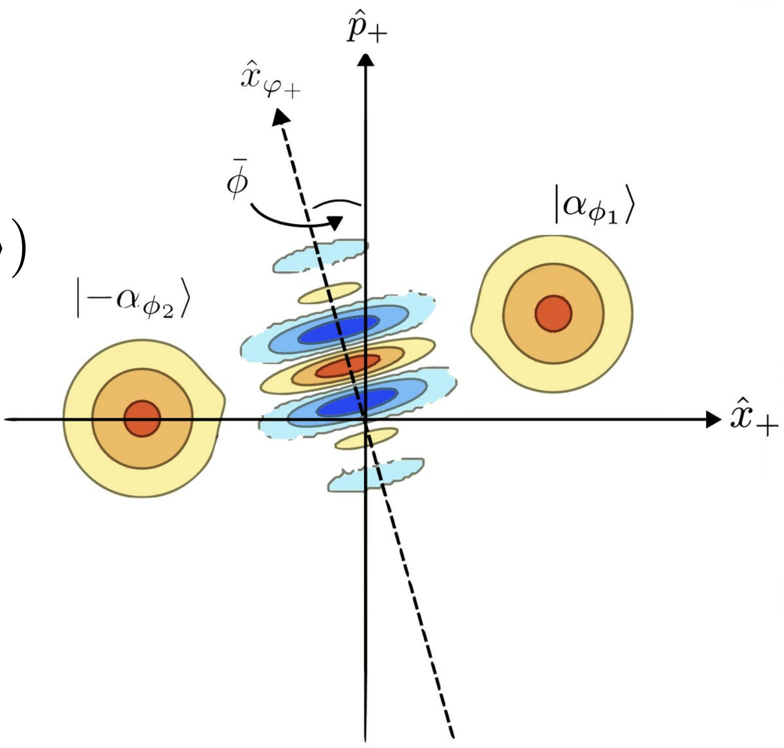
$$I_{\mathrm{C}}(\phi) = I_{\mathrm{Q}}(\rho_\phi)$$ ✓

Heisenberg scaling is due to phase-space interference

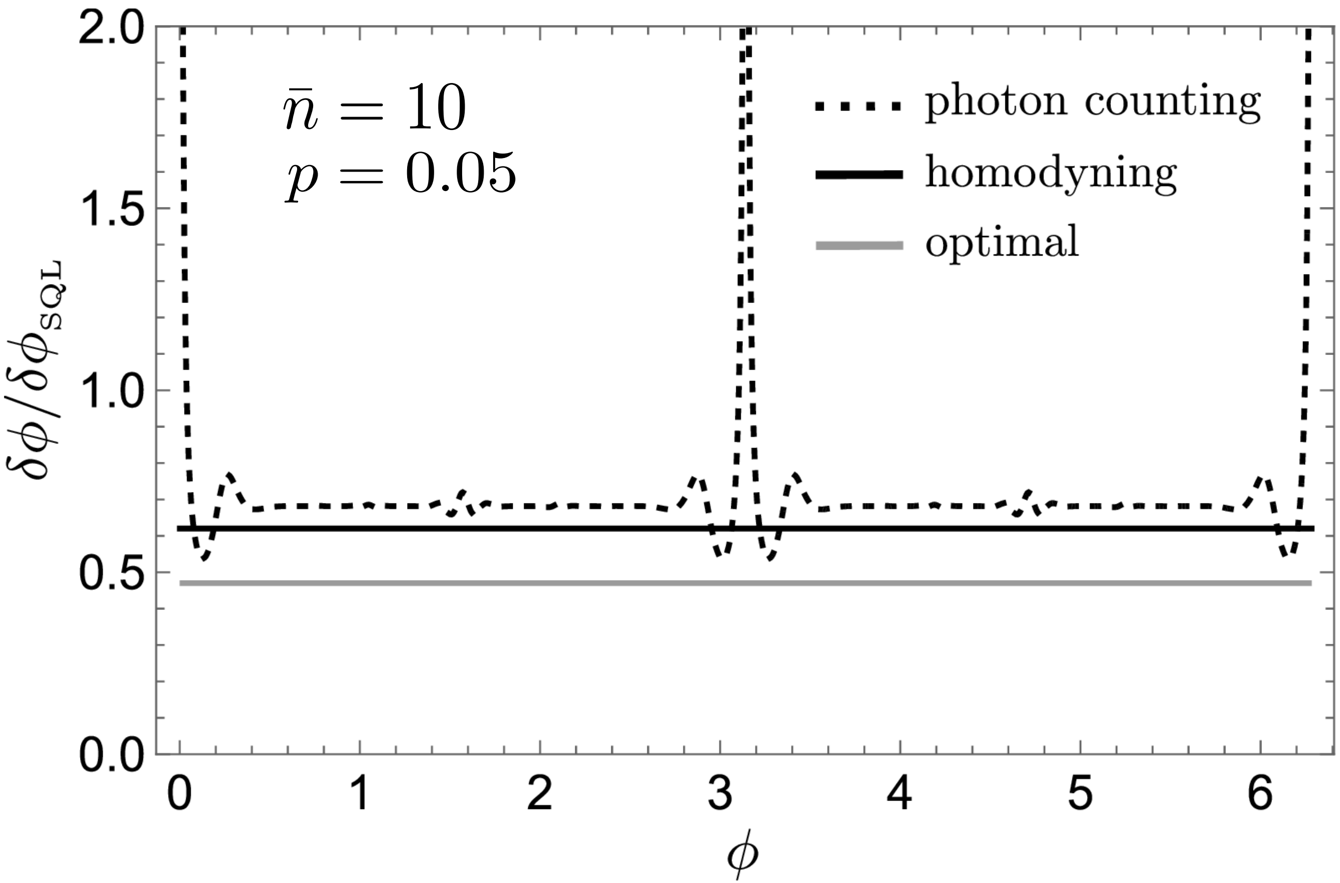
$$|\widetilde{\mathrm{ECS}_\phi}\rangle = \mathcal{N}_\alpha \left(|\alpha_{\phi_1}, \alpha_{\phi_1}\rangle + |-\alpha_{\phi_2}, \alpha_{\phi_2}\rangle\right)$$

$$|\widetilde{\mathrm{QWP}_\phi}\rangle = \frac{1}{\sqrt{2}} \left(|\uparrow, \alpha_{\phi_1}, \alpha_{\phi_1}\rangle + |\downarrow, -\alpha_{\phi_2}, \alpha_{\phi_2}\rangle\right)$$

$$\alpha_{\phi_j} = e^{i\phi_j} \frac{\alpha}{\sqrt{2}}$$



No prior knowledge of ϕ required



Thanks: Group/Collaborators

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