Imaging stars with quantum error correction

Zixin Huang[1], Gavin K. Brennen[1], Yingkai Ouyang[2]

1. Centre for Engineered Quantum Systems, Macquarie University
2. Centre of Quantum Technologies, National University of Singapore

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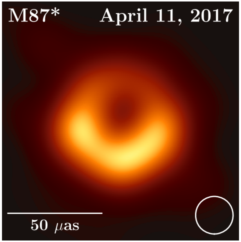
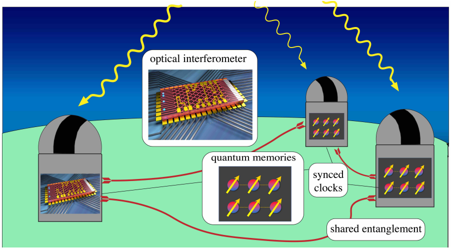
Large-baseline optical quantum imaging





- Imaging requires measuring amplitude and phase information
- Current large-baseline interferometers operate in radio/microwave
- Optical frequencies can increase resolution by $\lambda_{\text{radio}}/\lambda_{\text{optical}}$, a factor $10^3 - 10^5$
- Noise and transmission losses

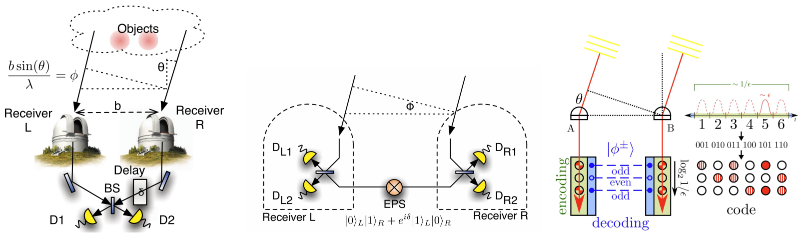
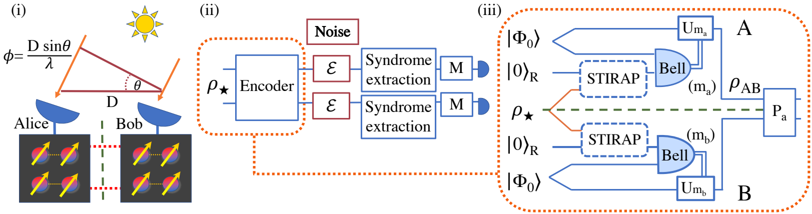


Figure: Taken from [1],[2]

Outstanding problem: spontaneous emission, accommodating errors while processing signal, multiphoton events

[1] D Gottesman et al., Phys. Rev. Lett. 109, 070503 (2012)
[2] E. T. Khabiboulline et al., Phys. Rev. Lett. 123, 070504 (2019)

The protocol



- Collect light from astronomical sources into distant sites
- Absorb the state into memory qubits into a non-radiative atomic level via STIRAP, encode into QECC
- Filter our vacuum and two-photon component
- Quantum error correction and extraction of signal

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In the weak-photon limit,

$$\rho_\star \approx (1-\epsilon)\,|\mathsf{vac},\mathsf{vac}\rangle\langle \mathsf{vac},\mathsf{vac}|_{AB} + \epsilon\left(\frac{1+\gamma}{2}\right)|\psi_+^\phi\rangle\langle\psi_+^\phi| + \epsilon\left(\frac{1-\gamma}{2}\right)|\psi_-^\phi\rangle\langle\psi_-^\phi| \quad (1)$$

where $|\psi_\pm^\phi\rangle = (|1\rangle_A|\mathsf{vac}\rangle_B \pm e^{i\phi}|\mathsf{vac}\rangle_A|1\rangle_B)/\sqrt{2}$.

Parameters to be estimated:

- $\gamma \in [0,1]$ (spatial distribution)
- $\phi \in [0,2\pi)$ (location)

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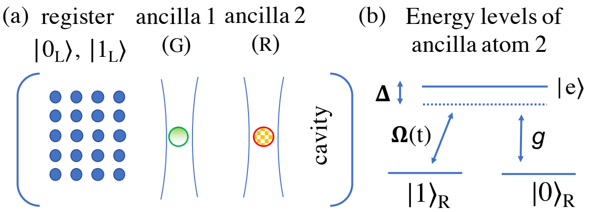
Stimulated Raman Adiabatic Passage

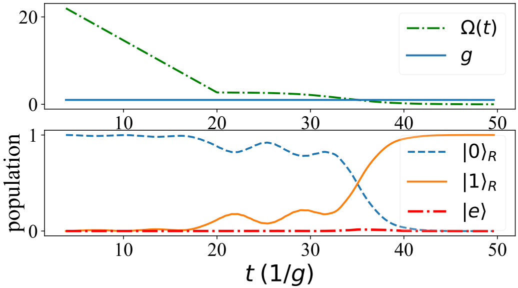


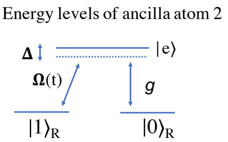
Rotating wave approximation, $\{|1_R, n-1\rangle, |e, n-1\rangle, |0_R, n\rangle\}$,

$$H^{(n)}(t) = \begin{pmatrix} 0 & \Omega(t)^* & 0 \\ \Omega(t) & -\Delta & g\sqrt{n} \\ 0 & g^*\sqrt{n} & 0 \end{pmatrix} \qquad (2)$$

$$|\psi_0(t)\rangle \propto \left(-\frac{g\sqrt{n}}{\Omega(t)}\,|1\rangle_R\,|n-1\rangle + |0\rangle_R\,|n\rangle\right) \qquad (3)$$

STIRAP





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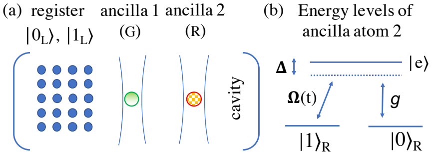


We prepare the register and the green ancilla in the Bell state

$$|\Phi_0\rangle = \frac{1}{\sqrt{2}}(|0_L\rangle\,|0_G\rangle + |1_L\rangle\,|1_G\rangle) \otimes |0\rangle_R \tag{4}$$

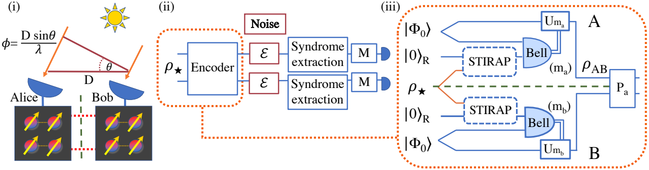
In the presence of the star photon, $|0\rangle_R \to |1\rangle_R$. They share

$$\frac{1}{\sqrt{2}}(|1_p\rangle_A\,|\text{vac}\rangle_B \pm e^{i\phi}\,|\text{vac}\rangle_A\,|1_p\rangle_B) \tag{5}$$

After the Bell measurement

$$\frac{1}{\sqrt{2}}\left(|1_L, 0_L\rangle_{AB} \pm e^{i\phi}\,|0_L, 1_L\rangle_{AB}\right) \tag{6}$$

Removing the vacuum



Pre-shared logical Bell pairs $|\Phi^{\pm}\rangle = (|0_L, 0_L\rangle \pm |1_L, 1_L\rangle)/\sqrt{2}$

Use CZ gates to project out the vacuum:

$$\rho_{AB} \otimes |\Phi^+\rangle \overset{2\times\mathrm{CZ}}{\to} |0_L, 0_L\rangle \langle 0_L, 0_L|_{AB} \otimes |\Phi^+\rangle \langle \Phi^+| + \epsilon \left(\frac{1+\gamma}{2}\right) |\psi^{\phi}_{+,L}\rangle \langle \psi^{\phi}_{+,L}| \otimes |\Phi^-\rangle \langle \Phi^-| + \epsilon \left(\frac{1-\gamma}{2}\right) |\psi^{\phi}_{-,L}\rangle \langle \psi^{\phi}_{-,L}| \otimes |\Phi^-\rangle \langle \Phi^-| \qquad (7)$$

Performance with QEC

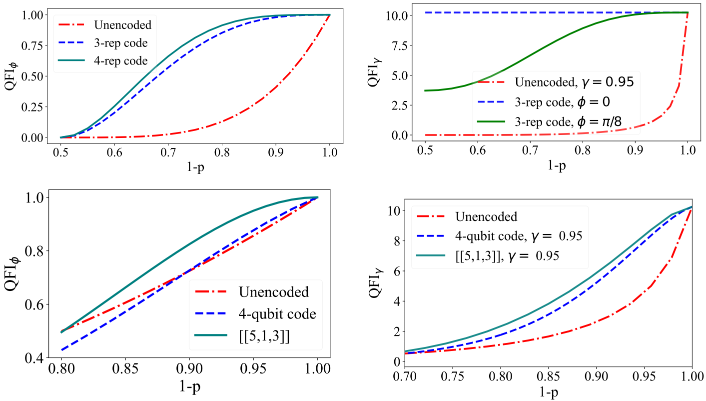


Figure: (Top) dephasing. (Bottom) depolarising

$$\mathcal{E}_{\text{dephase}}[\rho] \to (1 - p/2)\,\rho + p/2\sigma_z \rho \sigma_z^\dagger$$
$$\mathcal{E}_{\text{depol}}(\rho) = (1 - p)\rho + p\mathbb{1}/2$$

Large quantum codes

Let ϵ_{fail} denote the probability of having an uncorrectable state, ϵ_{fail} is at most the probability of having at least $d/2$ errors [6],

$$\epsilon_{\text{fail}} \leq e^{-D(p\|d/2n)n}, \tag{8}$$

where $D(x\|y) = x\ln(x/y) + (1-x)\ln[(1-x)/(1-y)]$, $p < d/2n$.

- For our scheme such QEC codes can tolerate noise afflicting up to 9.4% of the qubits while preserving the QFI.

[6] Chernoff et al., The Annals of Mathematical Statistics 23, 493 (1952)

Huang, Brennen, Ouyang, Phys. Rev. Lett. 129, 210502 (2022)

- We proposed a general framework for applying QEC to an imaging task, where the experimenter did not prepare the probe.
- We have proposed an application for a NISQ device for imaging.
- A significant advantage, even for a small repetition code (for dephasing, we tolerate error rates up to 50%).

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"I DON'T CARE IF YOU HAVE A F*CKING NOBEL PRIZE, FRIENDSHIP IS FOREVER!" – Jonathan P. Dowling, August 2018

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