Analog simulation of three flavor oscillations in a two neutrino system on a driven superconducting circuit

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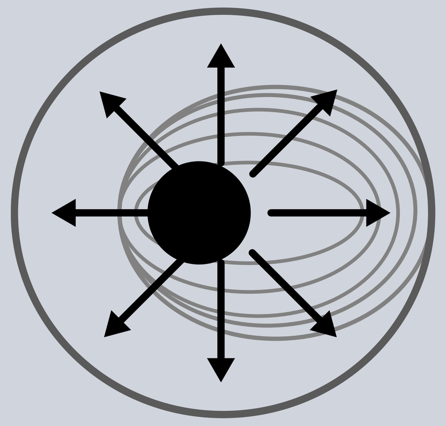
Introduction

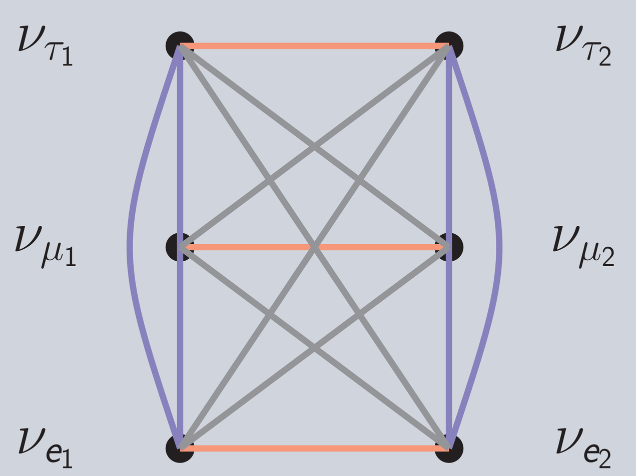
- Quantum computers can simulate quantum systems efficiently, in principle
- In the current noisy intermediate scale quantum (NISQ) digital systems can only perform a few operations without error correction [1]
- Before digital, fault tolerant, error-corrected quantum computers come online, analog quantum emulators may be able to solve difficult problems in physics
- Neutrino flavor dynamics are one such problem worth investigating with superconducting circuit-based analog simulators
- In the process of designing these circuits, we can better understand the physics of these circuits which may be applicable to scaling up digital systems

Neutrinos in supernova explosions

Core collapse supernova [2]



Neutrino flavor interactions



1. Massive star collapses under gravity when fusion ceases
2. Compact object forms and generates a shock wave that stalls
3. $\mathcal{O}(10^{58})$ neutrinos from compact object restart the shock wave

- Always-on, flavor oscillations of each neutrino
- Energy exchange between like flavors of neutrinos
- Two flavor energy exchange between different flavors of neutrinos

Two neutrino Hamiltonian in terms of six qubit operators a_k

$$\mathcal{H}_\nu = \sum_{k\in\{\nu_{\alpha_n}\}} \hbar\omega_k a_k^\dagger a_k + \sum_{kk'} \left(g_{kk'} a_k^\dagger a_{k'} + g_{kk'}^* a_k a_{k'}^\dagger \right) + g_{\mathrm{ZZ},kk'}(t) a_k^\dagger a_k a_{k'}^\dagger a_{k'} + \sum_{k\neq k',\, p\neq p'} \left(g_{4\mathrm{B}\nu,kk'pp'}(t) a_k^\dagger a_{k'} a_p^\dagger a_{p'} + g_{4\mathrm{B}\nu,kk'pp'}^*(t) a_k a_{k'}^\dagger a_p a_{p'}^\dagger \right)$$

References

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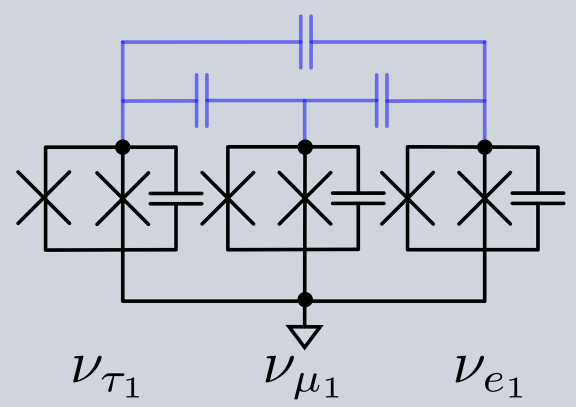
[4]J. D. Strand et al., "First-order sideband transitions with flux-driven asymmetric transmon qubits", Phys. Rev. B **87**, 220505 (2013).

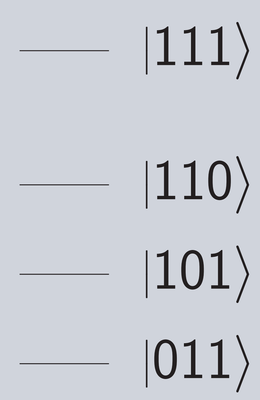
[5]R. K. Naik et al., "Random access quantum information processors using multimode circuit quantum electrodynamics", Nature Communications **8**, 1904 (2017).

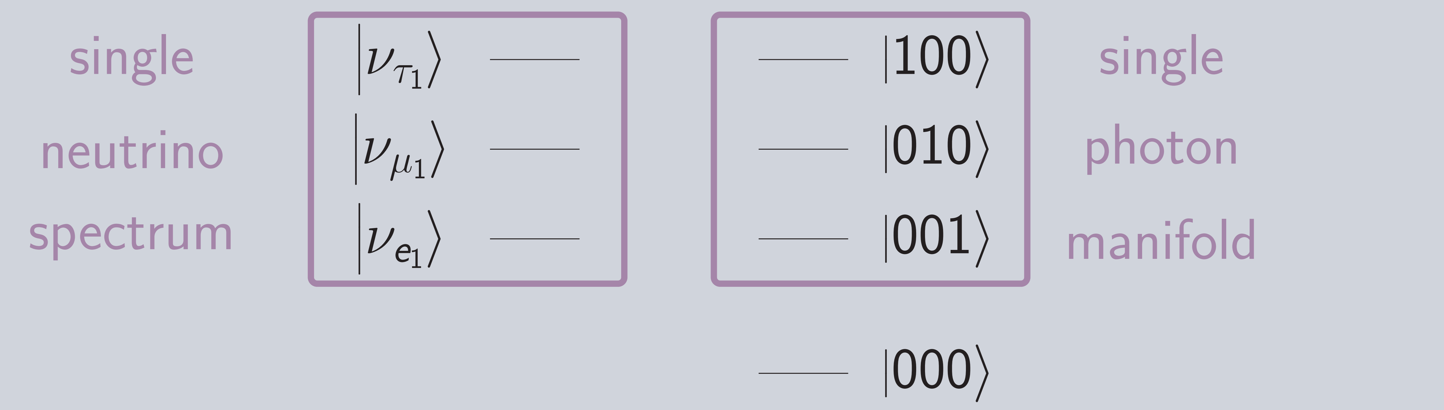
Single neutrino spectrum matching

Single neutrino circuit



Three qubit circuit spectrum

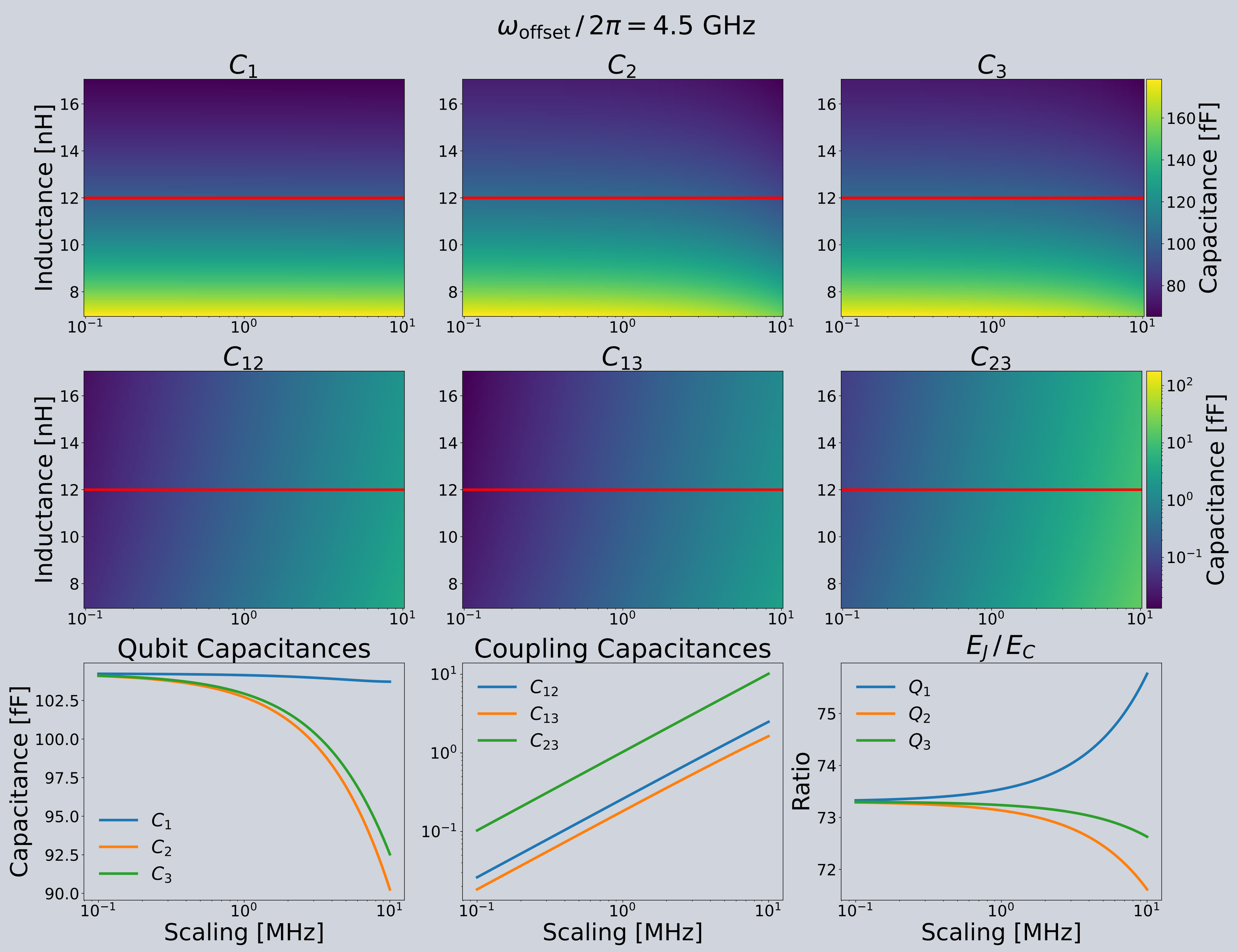




Single neutrino circuit design considerations

- A three level system or qutrit is the natural choice, but transmon level spacings are incompatible with the neutrino spectrum
- Single photon manifold of three qubits gives three levels that are well-understood and tunable with dc flux
- Capacitive coupling is easy to design and fabricate

Single neutrino static circuit parameters



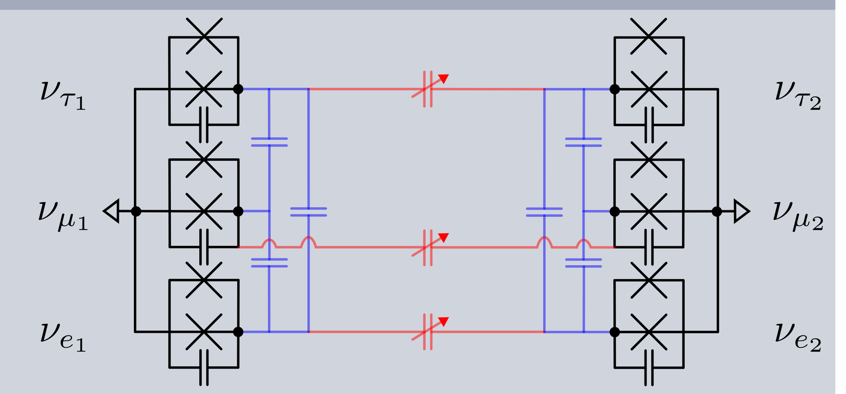
- Qubit capacitances and coupling capacitances in fabricatable range
- Offset frequency set in the range of typical superconducting transmon qubits
- E_J/E_C ratios are firmly in the transmon regime [3]

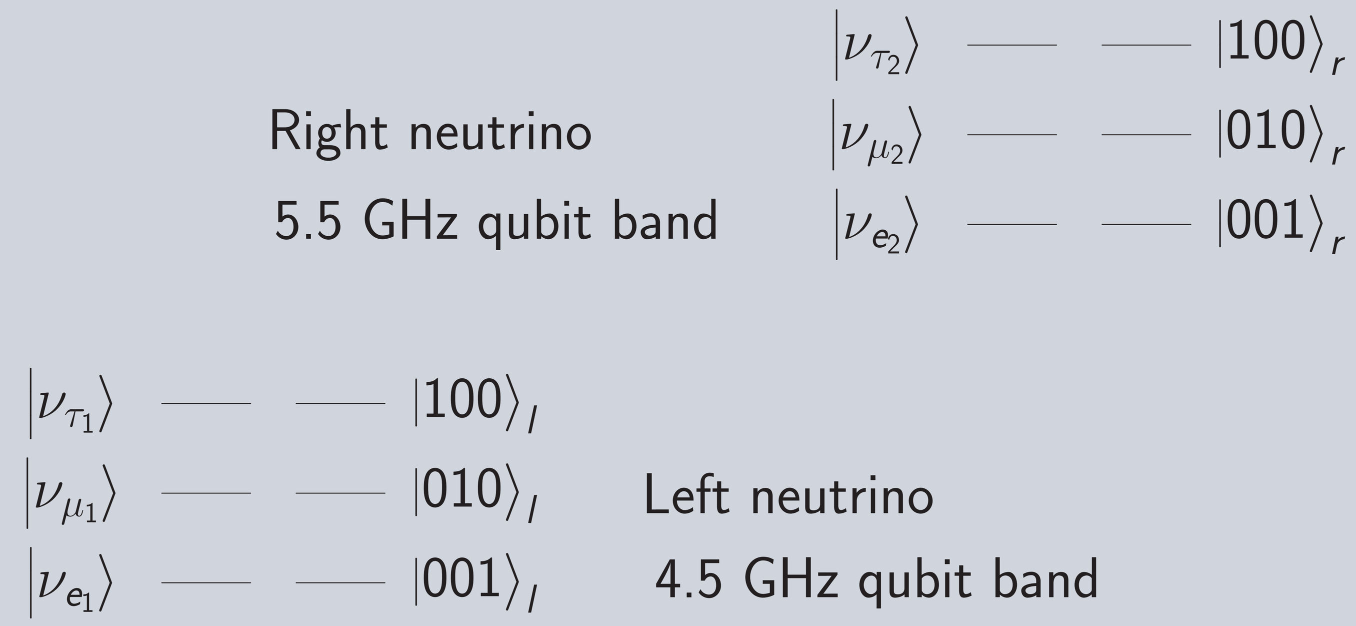
Like flavor energy exchange by dispersive interactions

- Neutrino 1 qubits detuned by ~GHz from neutrino 2

⇒ Dispersive regime, ZZ interactions from Schrieffer–Wolff transformation

- Tunable capacitor–like elements turn on and off ZZ interactions





Two-flavor energy exchange by parametric driving

Rotating frame effective circuit Hamiltonian under coupler flux modulation $\phi(t) = \phi_0 + \delta\phi \sin(\omega_\phi t)$ [4, 5]

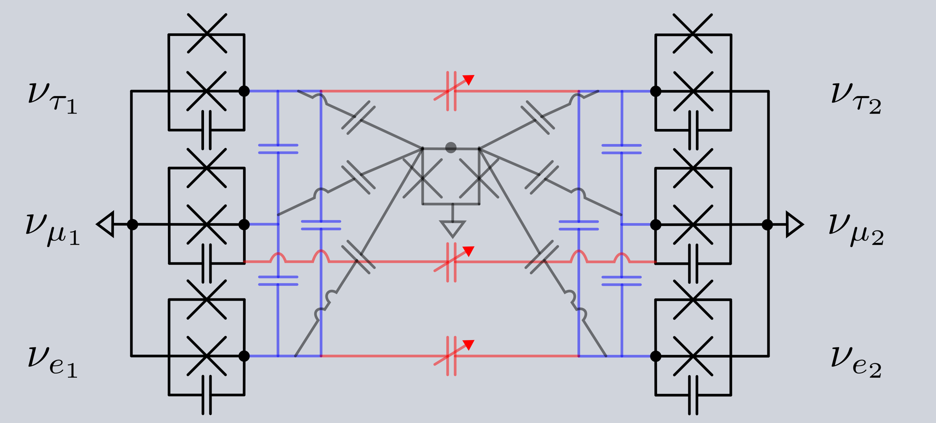
$$\mathcal{H}_{4\mathrm{BC}}^{\mathrm{eff}} = g_{4\mathrm{BC},kk'pp'}^{\mathrm{eff}} a_k^\dagger a_{k'} a_p^\dagger a_{p'} + g_{4\mathrm{BC},kk'pp'}^{\mathrm{eff}*} a_k^\dagger a_{k'} a_p^\dagger a_{p'}$$

$$g_{4\mathrm{BC},kk'pp'}^{\mathrm{eff}} \approx \delta\phi\, g_{4\mathrm{BC},kk'pp'} J_0\left(\frac{\epsilon}{2\omega_\phi}\right) J_0\left(\frac{\epsilon}{2\omega_\phi}\right) J_0\left(\frac{\epsilon}{2\omega_\phi}\right) J_1\left(\frac{\epsilon}{2\omega_\phi}\right)$$

$$\epsilon = \frac{\delta\phi\, \omega_c^0}{2\cos^2\phi_0}, \text{ frequency modulation amplitude}$$

Matching four body terms

- Choose coupler frequency such that $\omega_c \gg \omega_k$
- Drive coupler at ω_ϕ satisfying $2\omega_\phi = \omega_k - \omega_{k'} + \omega_p - \omega_{p'}$
- Adjust $g_{4\mathrm{BC},kk'pp'}$ and $\delta\phi$ to match $\mathcal{H}_{\nu,4\mathrm{B}}$



Future Work: a path to experimental viability

- Perform circuit parameter matching for four body terms
- Comparison of circuit and neutrino time evolution
- Comparison of continuous evolution with Suzuki–Trotter decomposition
- Sensitivity analysis of circuit parameters to quantify required fabrication tolerances to reproduce neutrino spectrum
- Quantify dispersive shifts and mitigate parasitic dispersive couplings

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