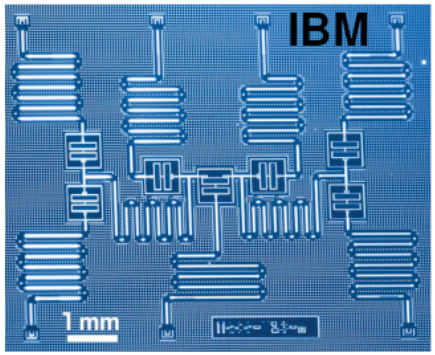
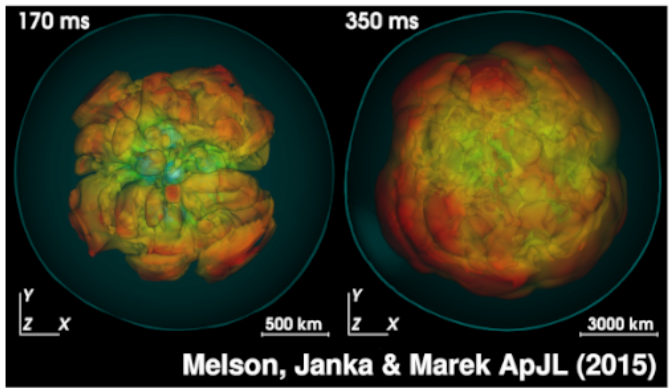
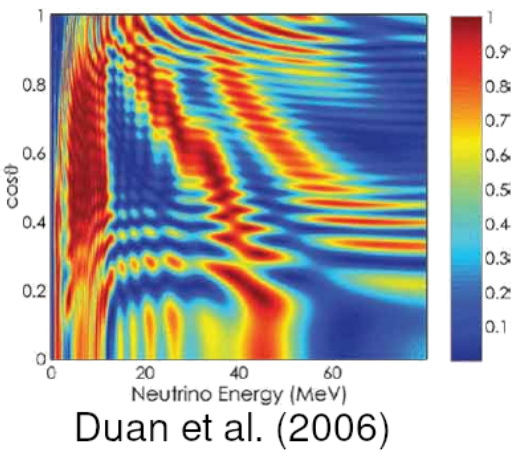
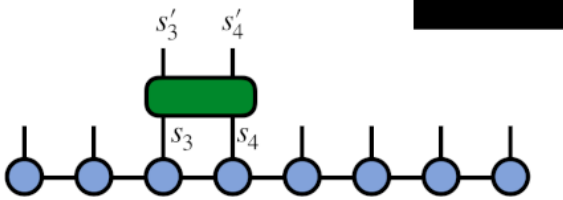
Quantum Simulations of collective neutrino oscillations

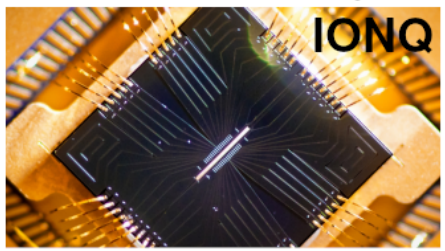
Alessandro Roggero

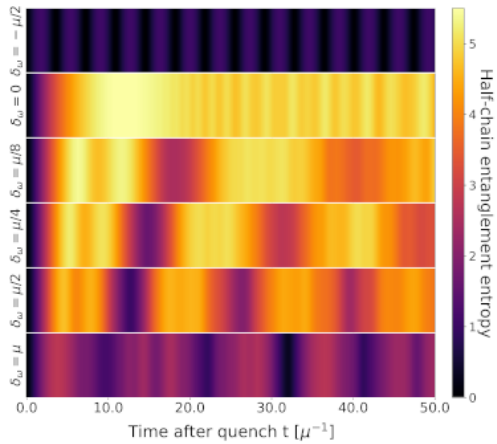












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Quantum Computing with IBM Q
01 July, 2022

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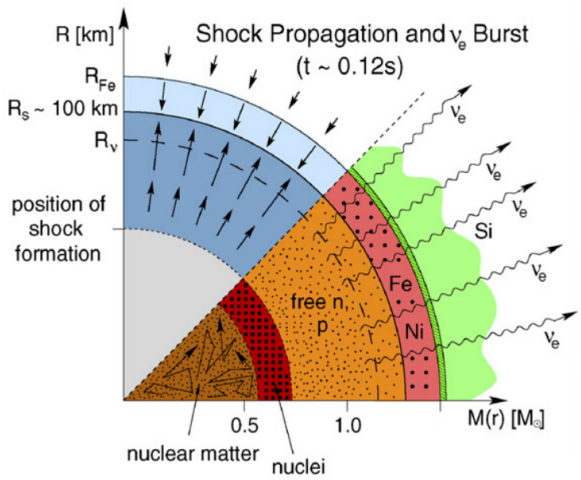
Neutrino's roles in supernovae

figures from Janka et al. (2007)

- efficient energy transport away from the shock region (burst)



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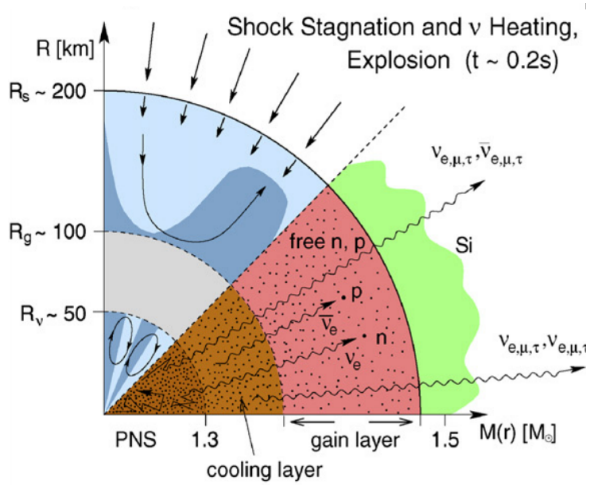
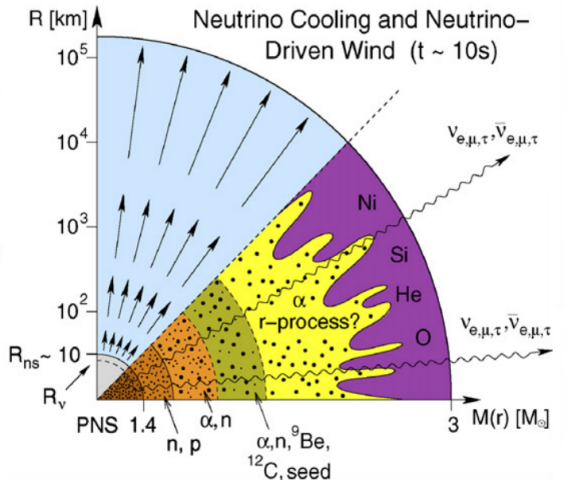


- regulation of electron fraction in ν-driven wind (nucleosynthesis)



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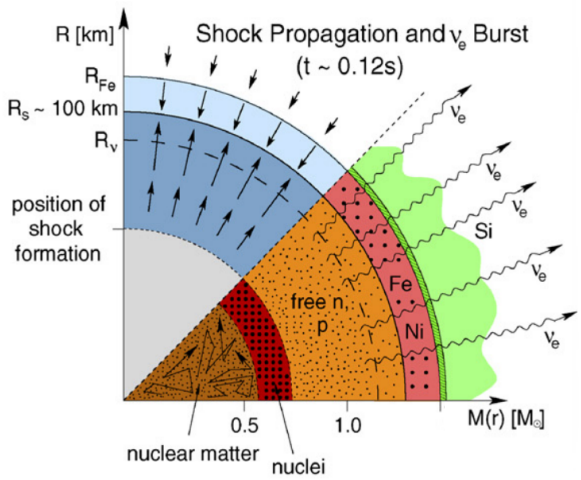

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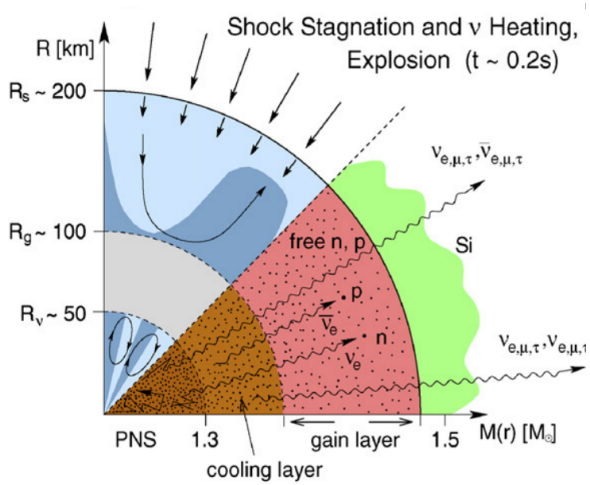

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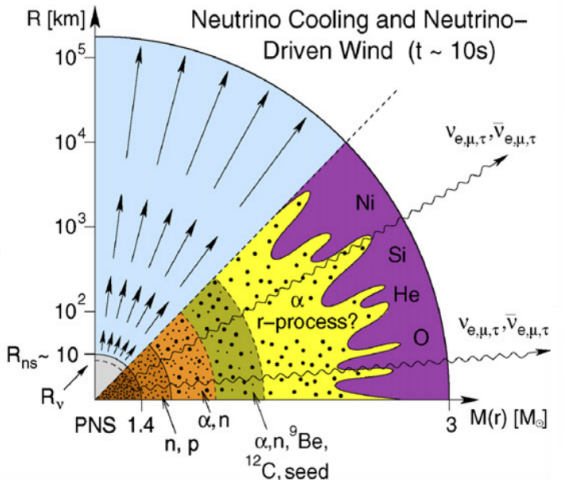
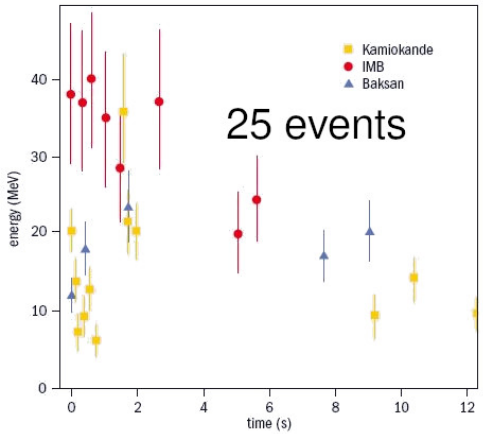
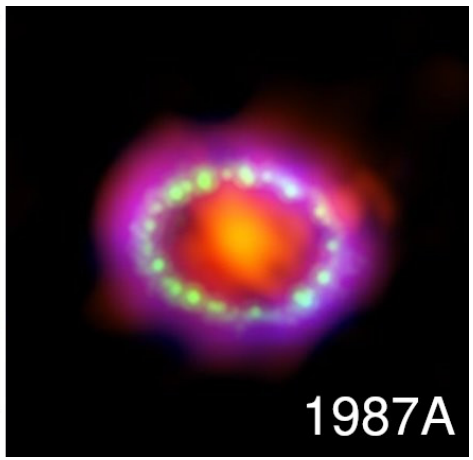


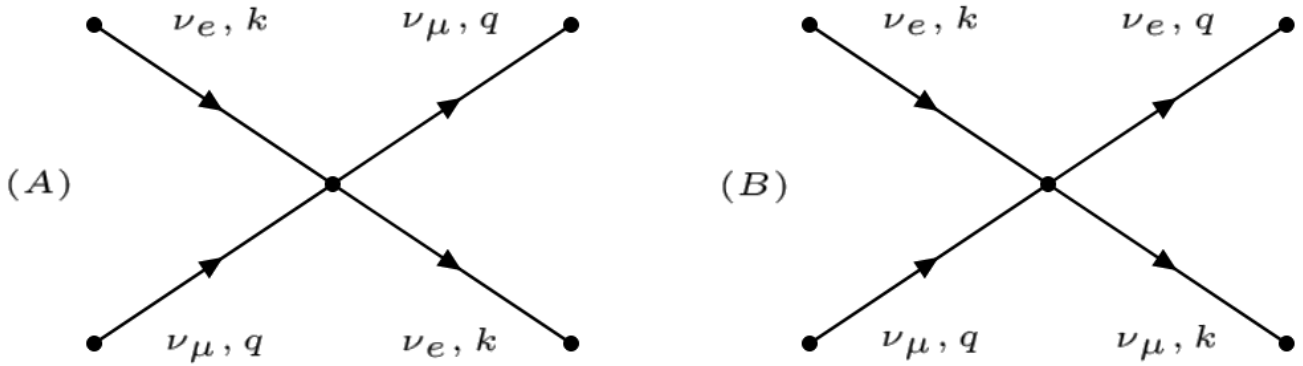
$\approx 10^{58}$ neutrinos emitted in few sec.





Neutrino-neutrino forward scattering

Fuller, Qian, Pantaleone, Sigl, Raffelt, Sawyer, Carlson, Duan, . . .



- diagonal contribution (A) does not impact flavor mixing
- off-diagonal term (B) equivalent to flavor/momentum exchange between two neutrinos
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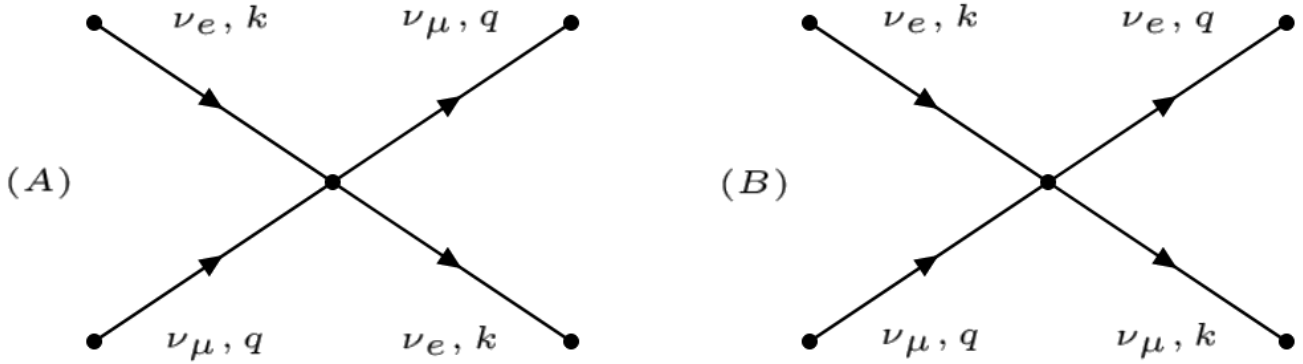

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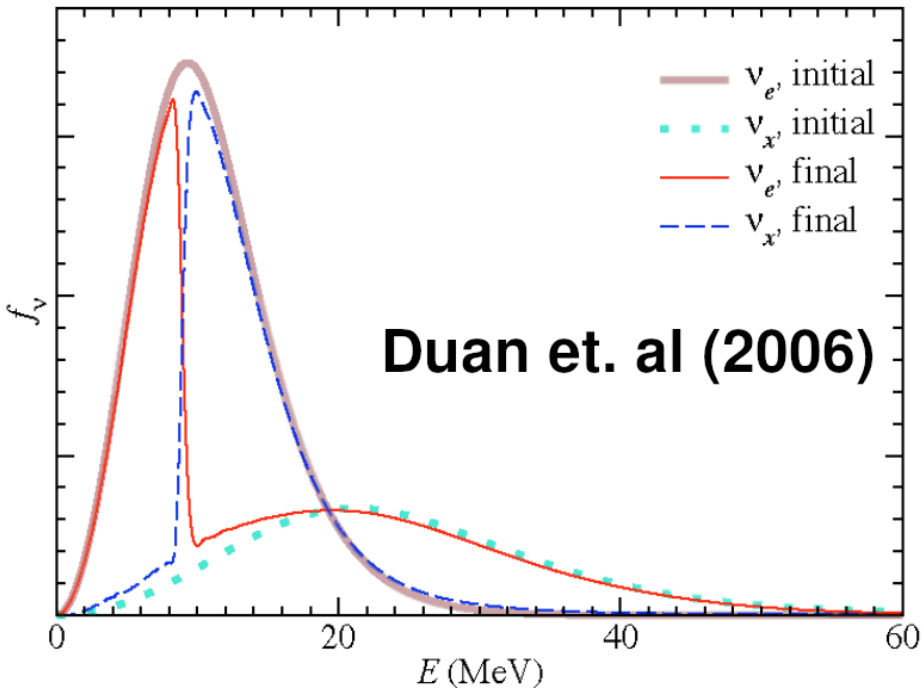
Important effect if initial distributions are strongly flavor dependent



Two-flavor approximation and the iso-spin Hamiltonian

Consider two active flavors (ν_e,ν_x) and encode flavor amplitudes for a neutrino with momentum p_i into an $SU(2)$ iso-spin:

$$|\Phi_i\rangle = \cos(\eta_i)|\nu_e\rangle + \sin(\eta_i)|\nu_x\rangle \equiv \cos(\eta_i)|\uparrow\rangle + \sin(\eta_i)|\downarrow\rangle$$

A system of N interacting neutrinos is then described by the Hamiltonian

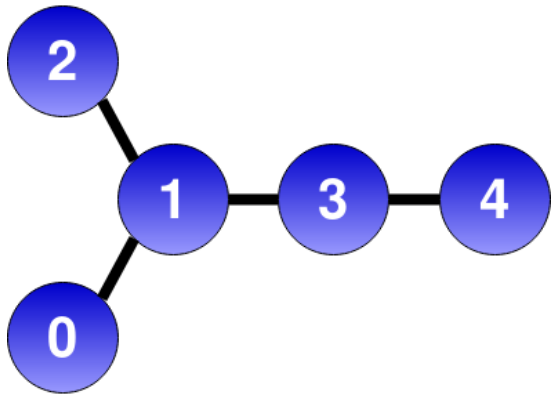
$$H = \sum_i \frac{\Delta m^2}{4E_i}\vec{B}\cdot\vec{\sigma}_i + \lambda\sum_i \sigma_i^z + \frac{\mu}{2N}\sum_{i<j}\big(1-\cos(\phi_{ij})\big)\vec{\sigma}_i\cdot\vec{\sigma}_j$$

- vacuum oscillations: $\vec{B} = (\sin(2\theta_{mix}), 0, -\cos(2\theta_{mix}))$
- interaction with matter: $\lambda = \sqrt{2}G_F\rho_e$
- neutrino-neutrino interaction: $\mu = \sqrt{2}G_F\rho_\nu$
  - dependence on momentum direction: $\cos(\phi_{ij}) = \frac{\vec{p}_i}{\|\vec{p}_i\|}\cdot\frac{\vec{p}_j}{\|\vec{p}_j\|}$

for a full derivation, see e.g. Pehlivan et al. PRD(2011)

Quantum simulation of collective neutrino oscillations

$$H_\nu = \sum_i \omega_i \vec{B} \cdot \vec{\sigma}_i + \frac{\mu}{2N} \sum_{i<j} J_{ij} \vec{\sigma}_i \cdot \vec{\sigma}_j$$



- with only 2 flavors direct map to spin 1/2 degrees of freedom (qubits)
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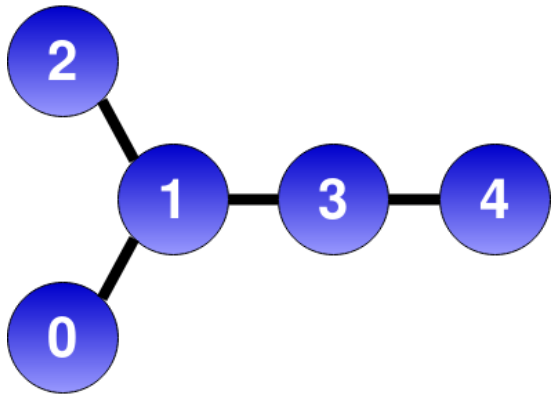

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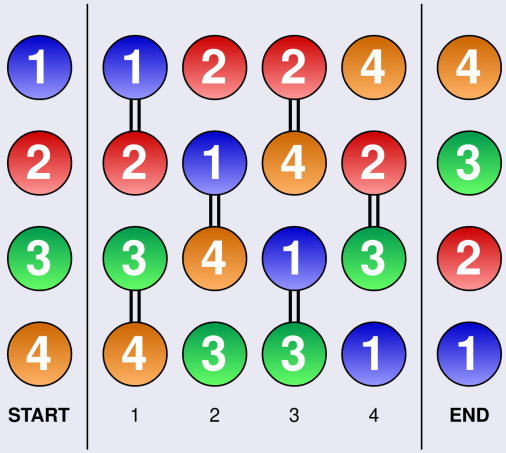
SWAP network



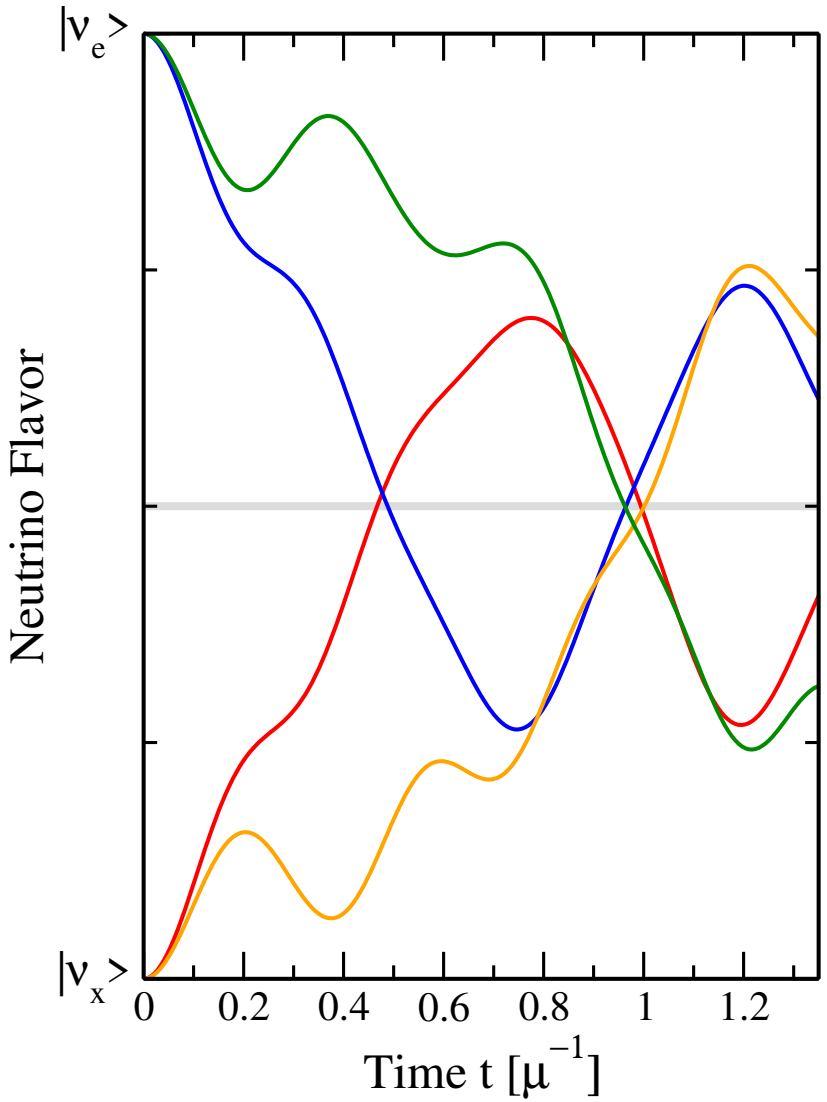
- SWAP qubits every time we apply time-evolution for neighboring terms
- in N steps we perform full evolution using only $\binom{N}{2}$ two qubit gates
  - NOTE: final order will be reversed

Kivlichan et al. PRL (2018)

B.Hall, AR, A.Baroni, J.Carlson (2021), AR (2021)

Accuracy in flavor evolution

How's the current (≈Fall 2020) accuracy in predicting flavor evolution?



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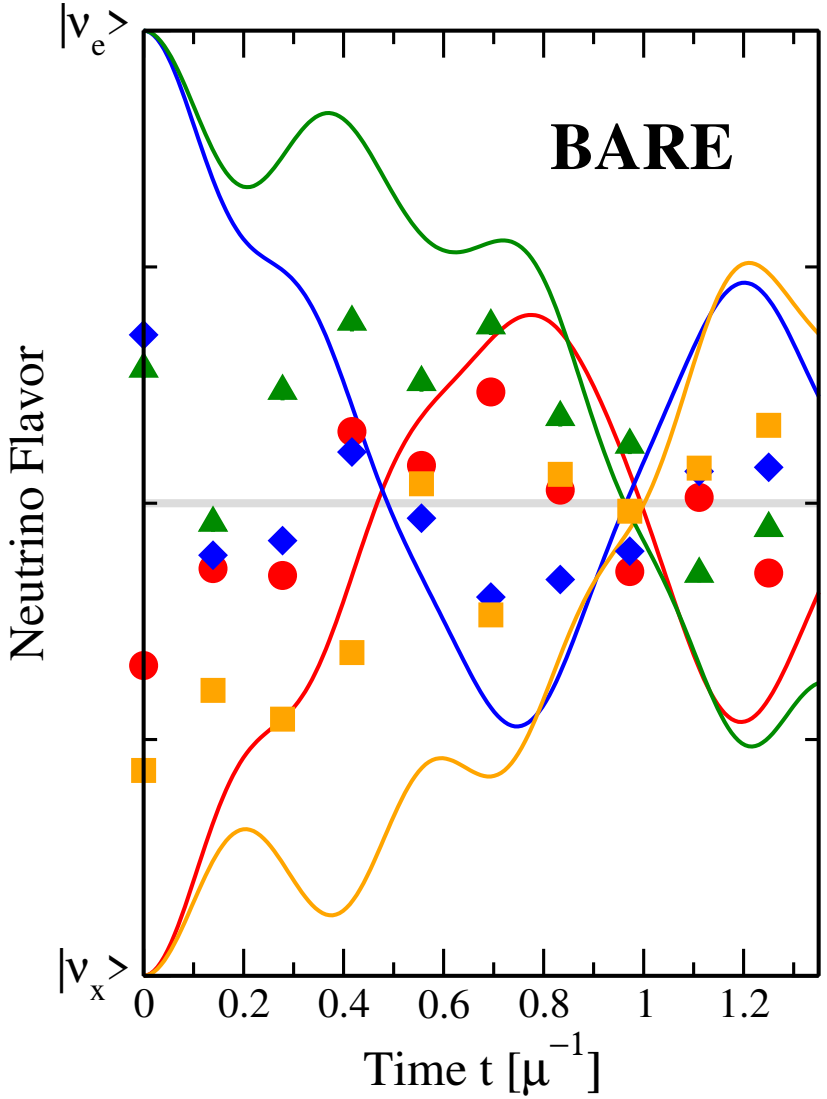

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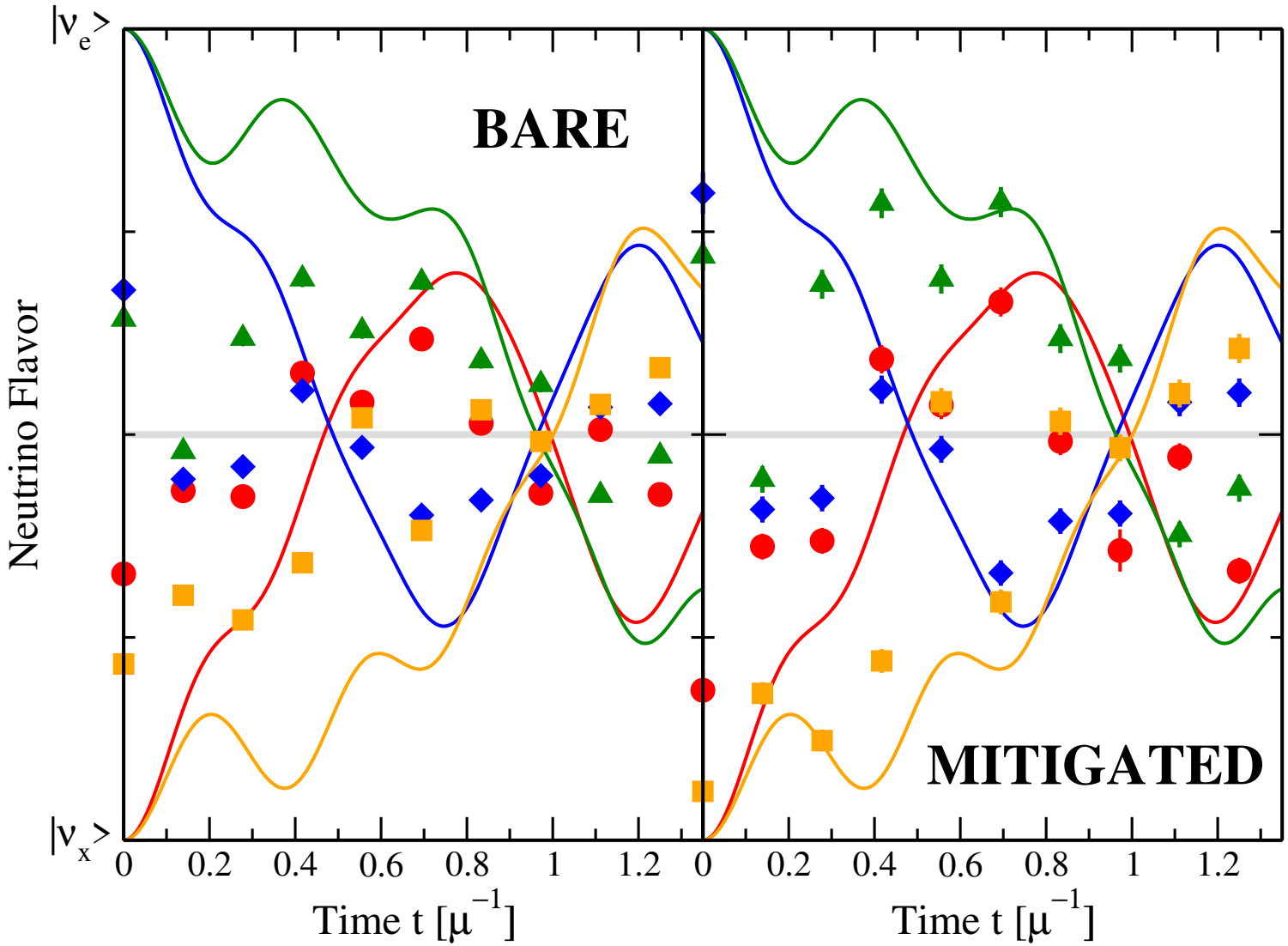

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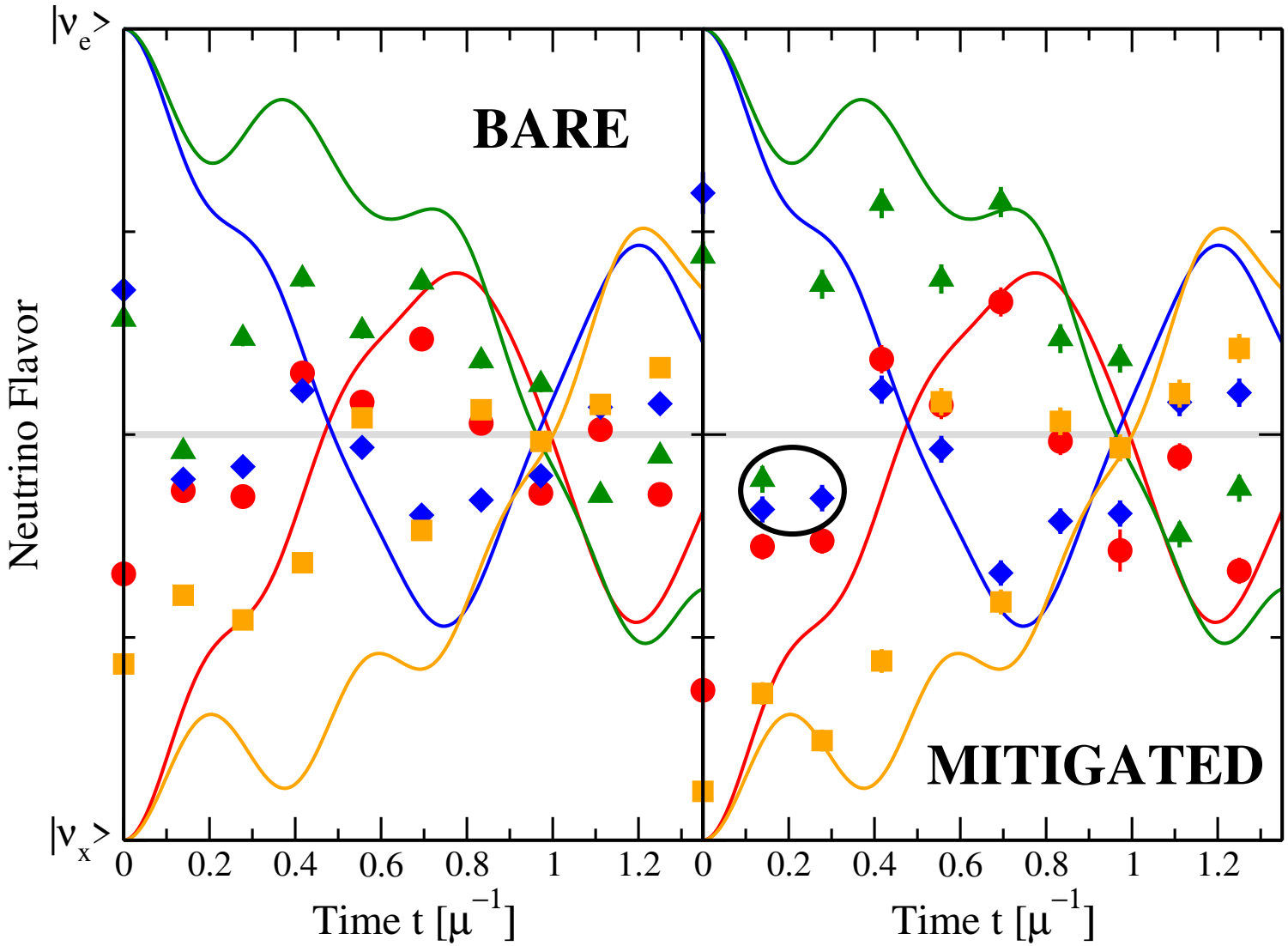
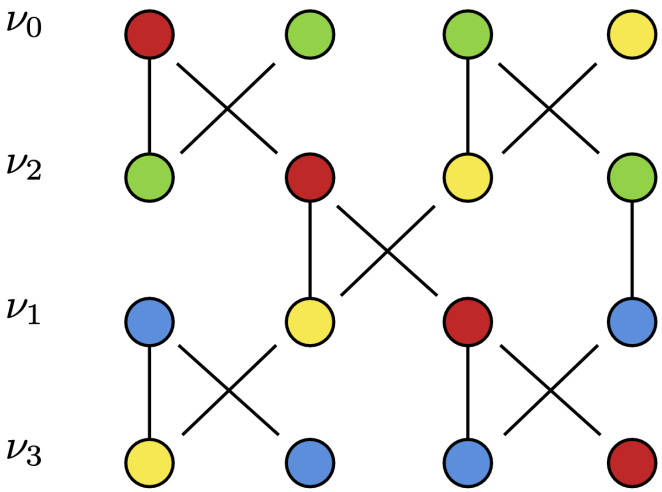
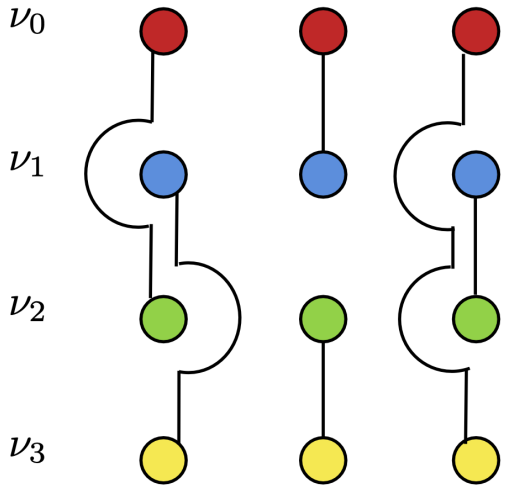


Recent progress in porting the scheme to trapped ions

V.Amitrano, AR, P.Luchi, F.Turro, L.Vespucci, F.Pederiva, arXiv:2207.xxxx (2022)

- all-to-all connectivity allows a reduction in circuit depth and the possibility of exploring different orderings for the decomposition





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- very low infidelities: $\approx 5 \times 10^{-5}$ one-qubit, $\approx 3 \times 10^{-3}$ two-qubit

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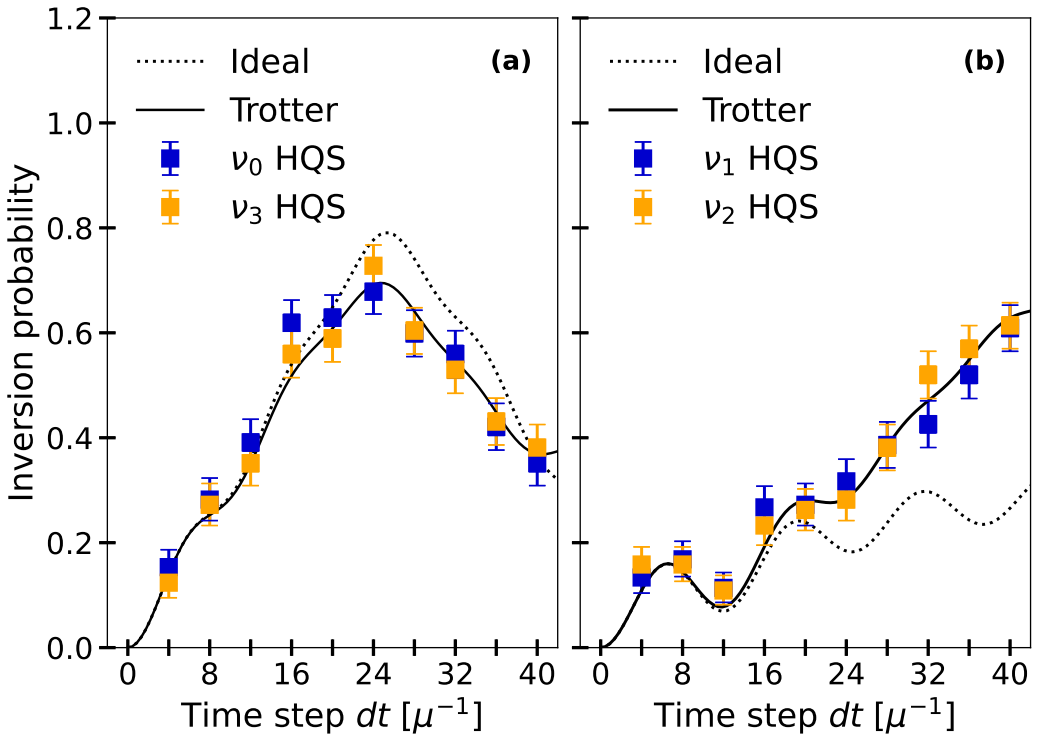

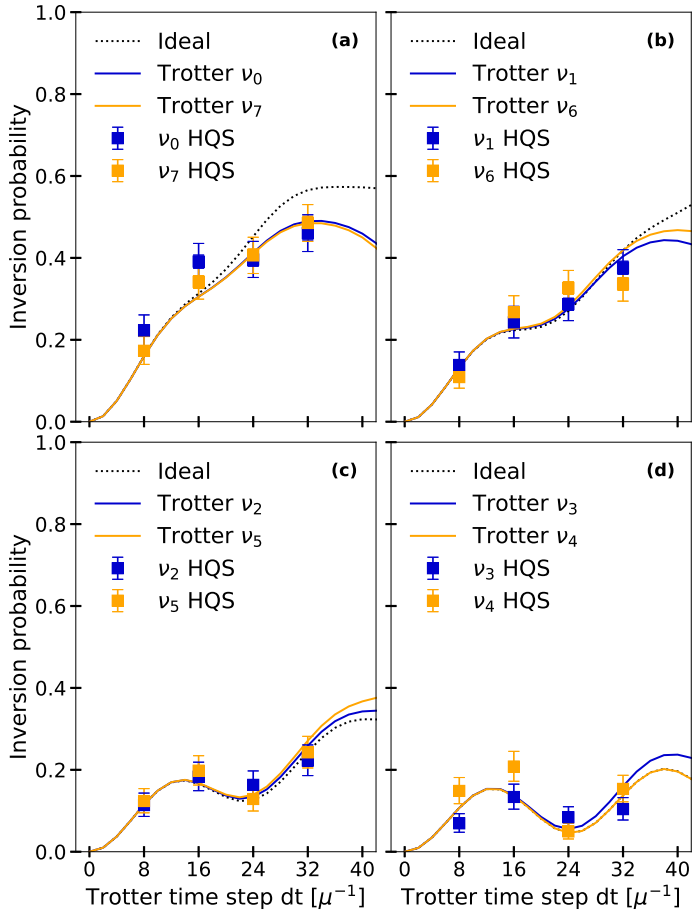

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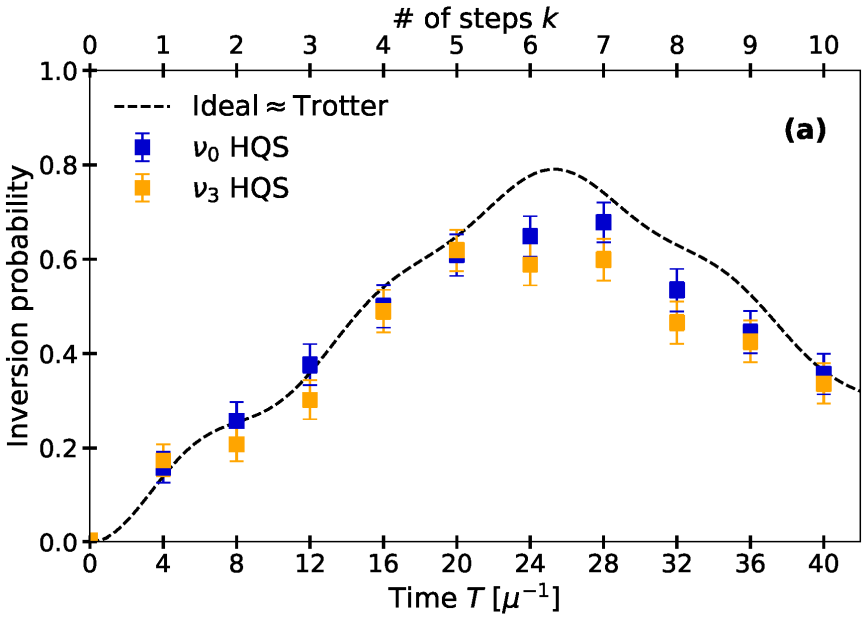

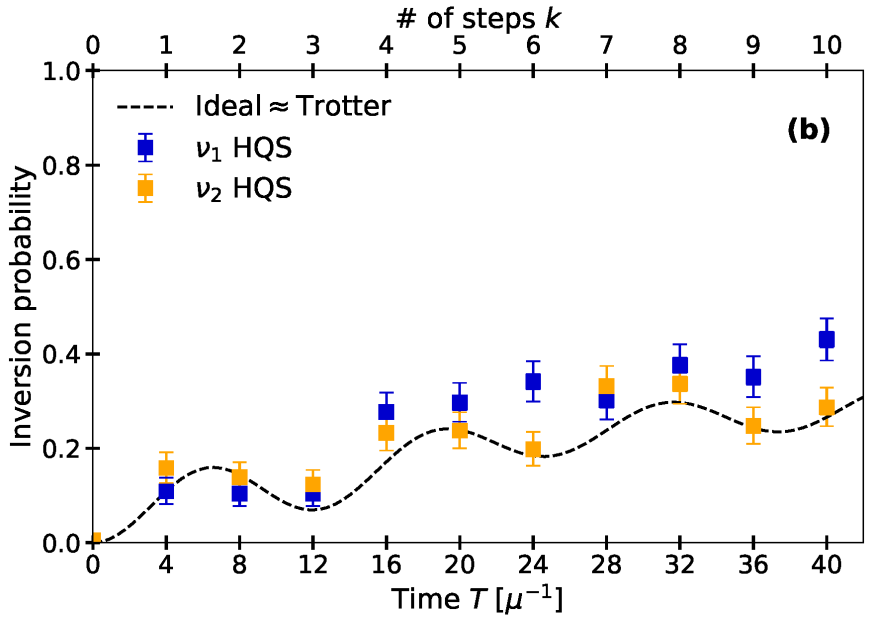

Last two points required: ≈ 350 two-qubit gates over 8 qubits

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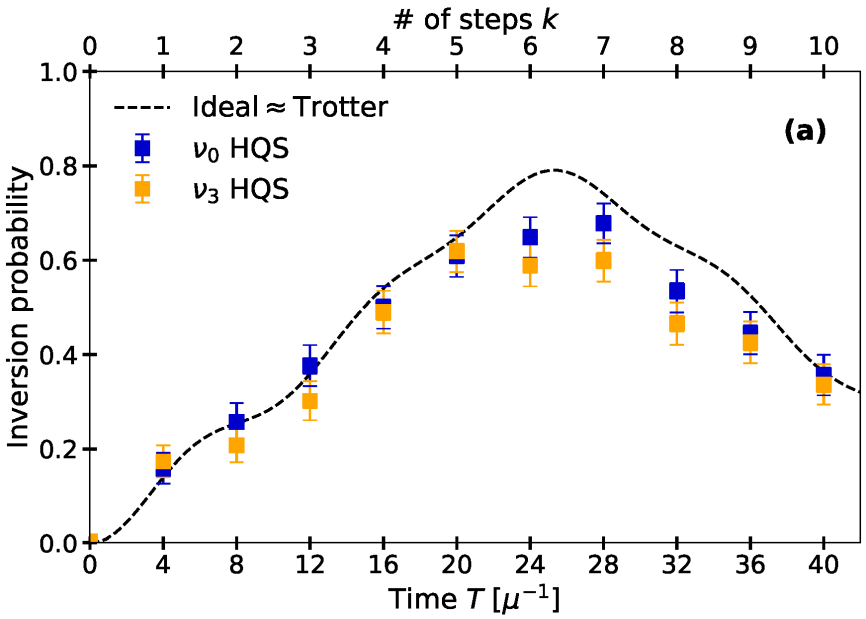

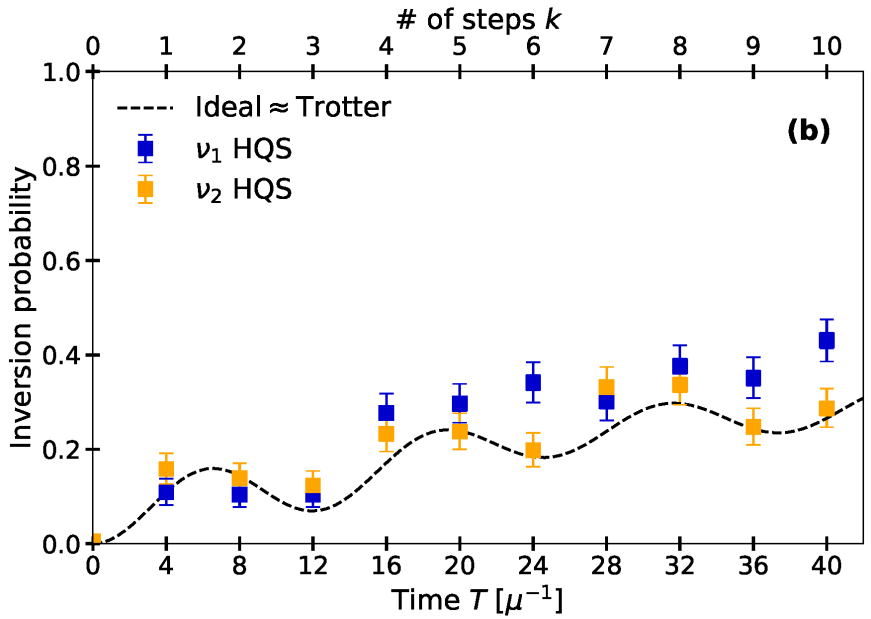

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Exploring pulse design for neutrino problems

Can we get higher fidelities using pulse level control?

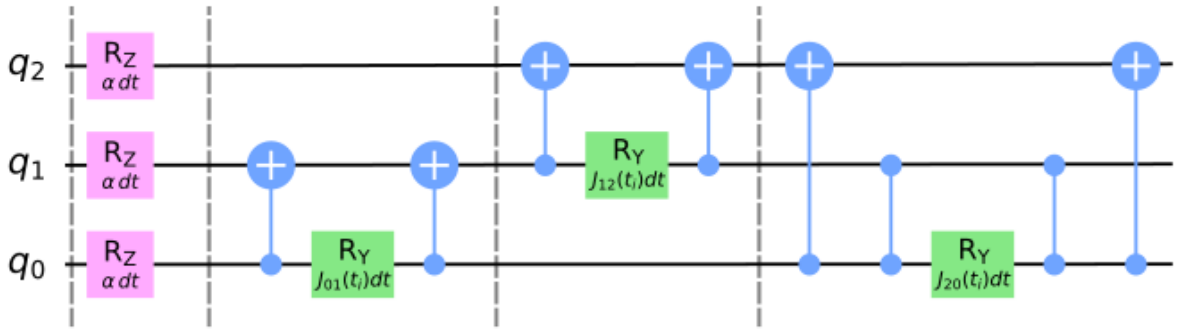

image modified from Stenger et al. 2021