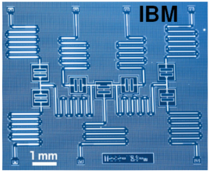
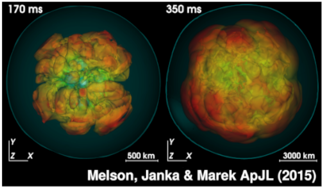
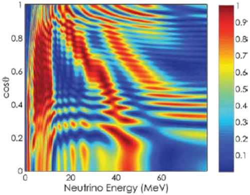
Quantum Simulation of Collective Neutrino Oscillations

Alessandro Roggero





Melson, Janka & Marek ApJL (2015)



Duan et al. (2006)

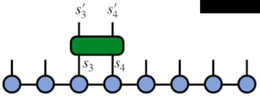
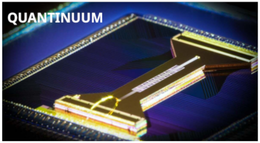
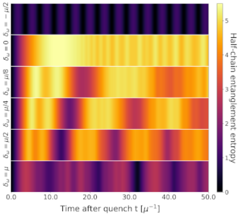


image from itensor.org





QUANTHEP @ London
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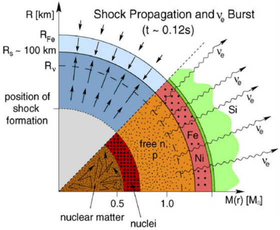
MOdeling Nuclear STructure and REactions

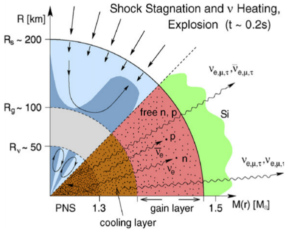
Neutrino's roles in supernovae

figures from Janka et al. (2007)

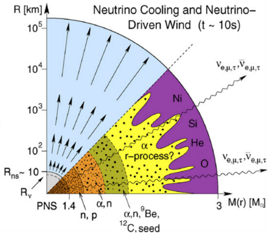
- efficient energy transport away from the shock region (burst)



- energy deposition to revive the stalled shock (explosion)



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



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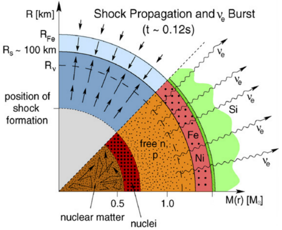

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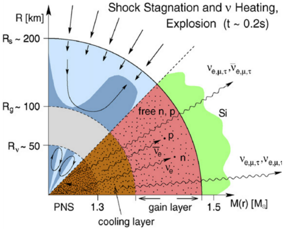

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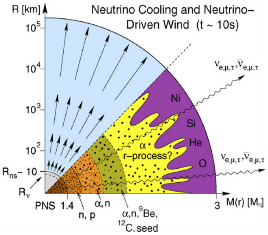
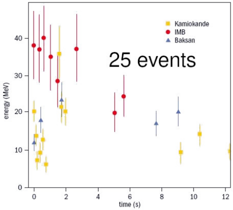
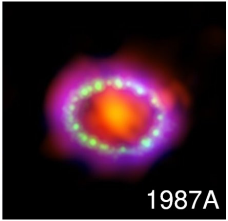


$\approx 10^{58}$ neutrinos emitted in few sec.





Two flavor neutrinos and the Heisenberg model

For neutrinos with only two flavors, we can use qubits to encode flavor as

$$|0\rangle = |\uparrow\rangle = |\nu_e\rangle \qquad |1\rangle = |\downarrow\rangle = |\nu_x\rangle$$

Vacuum oscillations drive rotations around the mass basis

$$H_{vac} = \sum_i \frac{\Delta m^2}{4E_i} \vec{B} \cdot \vec{\sigma}_i \qquad \vec{B} = (\sin(\theta_{mix}), 0, -\cos(\theta_{mix}))$$

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In CCSN or BNS merger we have incredibly large ν fluxes

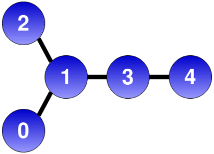
Forward scattering through neutral currents give $\nu\nu$ interaction

$$H_{int} = \frac{\sqrt{2} G_F \rho}{N} \sum_{i<j} J_{ij} \vec{\sigma}_i \cdot \vec{\sigma}_j \ ,$$

where ρ is the number density, N the number of neutrinos in the system and the coefficients J_{ij} encode the geometry. see also J.Kopp's talk

Quantum simulation of collective neutrino oscillations

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



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- all-to-all interactions are difficult with reduced connectivity

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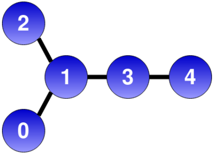

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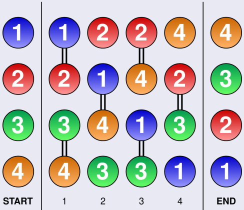
SWAP network



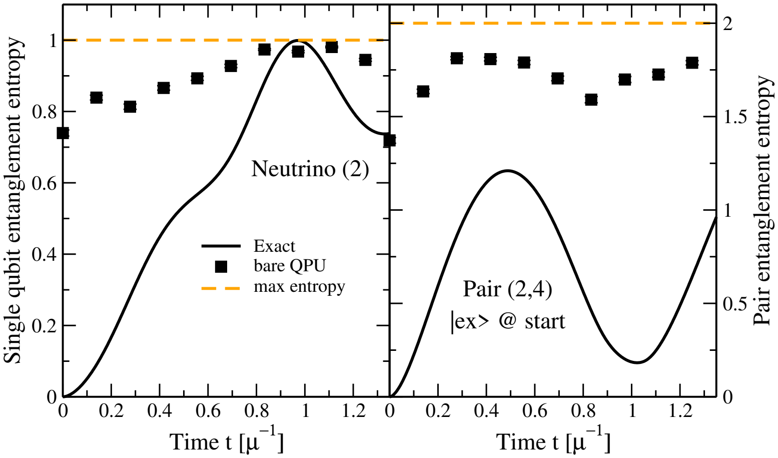
- SWAP qubits every time we apply time-evolution to neighboring terms
- in N steps we perform full evolution using only $\binom{N}{2}$ two qubit gates
  - NOTE: final order will be reversed

Kivlichan et al. PRL (2018)

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

Entanglement evolution and error mitigation with $N = 4$

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



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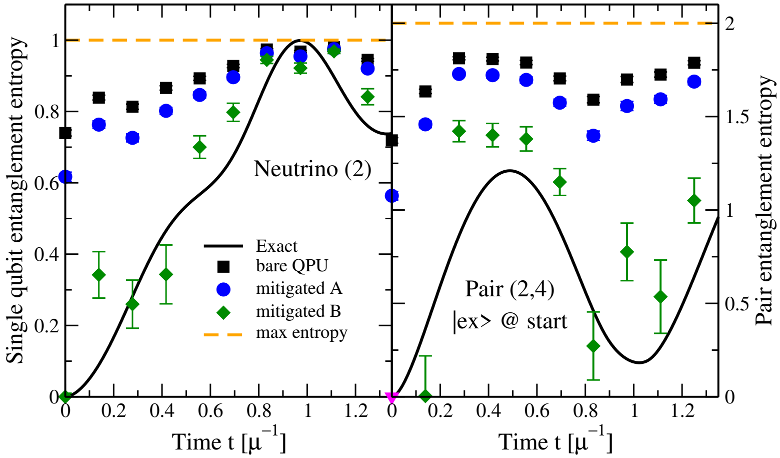
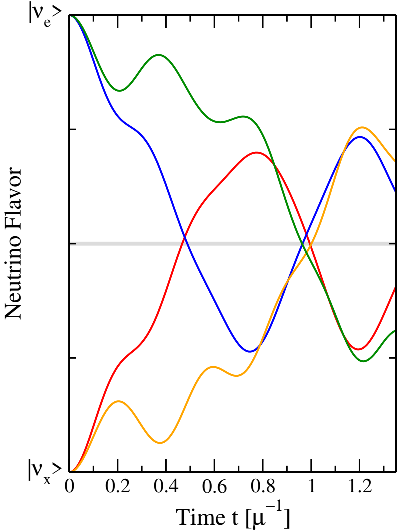


- Dechoerence with environment leads to increase in measured entropy
- Noise impact on observables can be modeled and effect mitigated

Accuracy in flavor evolution

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



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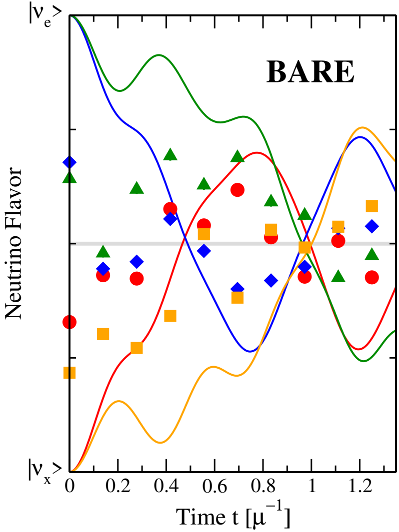

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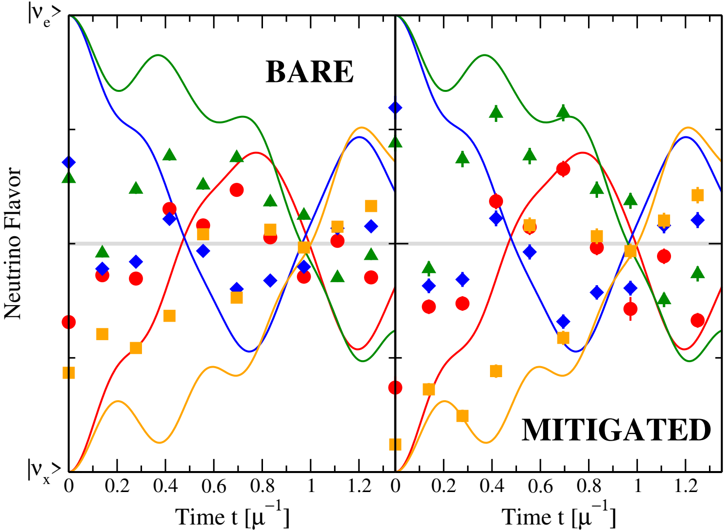

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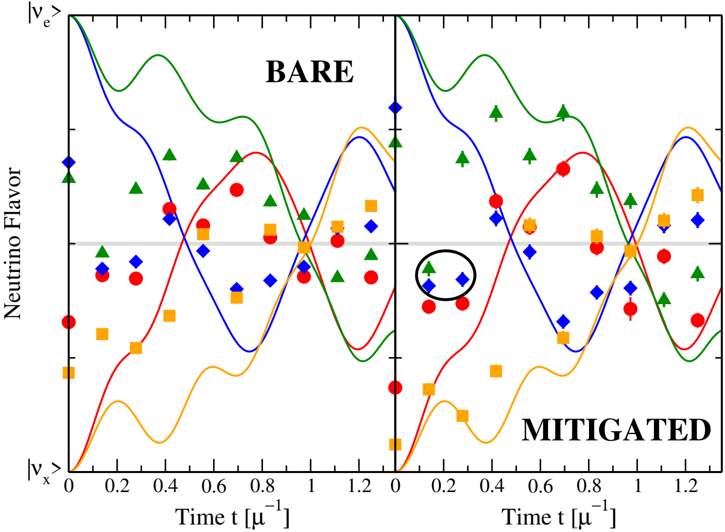
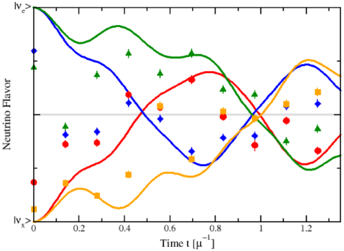


N=4 on IBM (2021)



B.Hall et al. PRD(2021)

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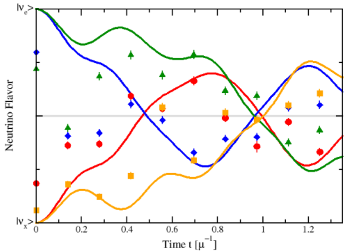

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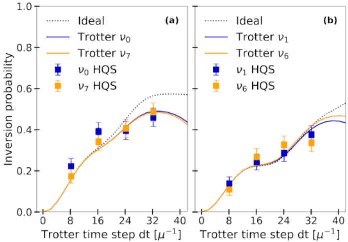
N=8 on Quantinuum (2023)



V.Amitrano et al. PRD(2023)

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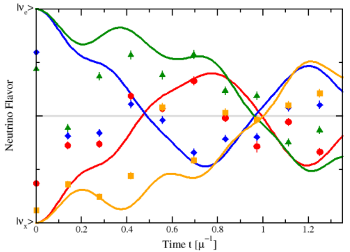

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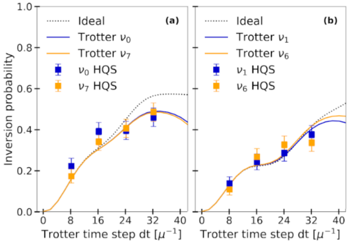

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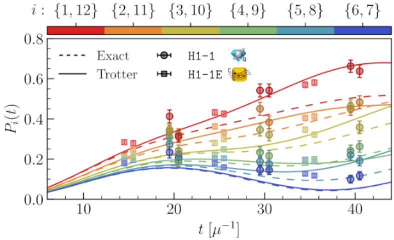

Illa & Savage PRL(2023)

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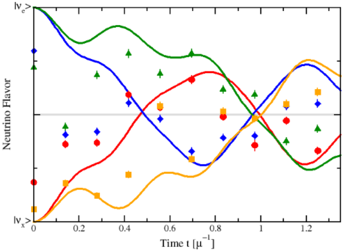

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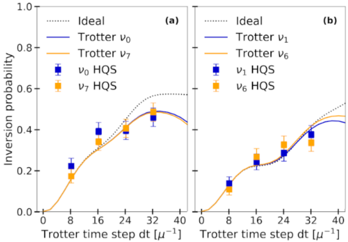

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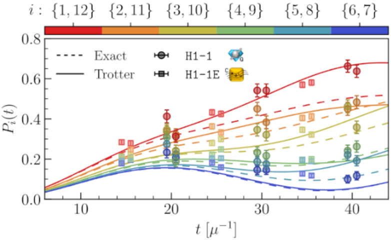

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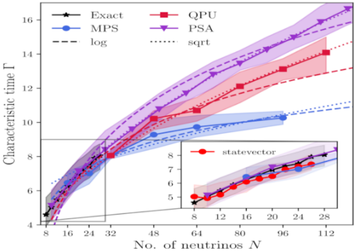
N=112 on IBM (2025)



O. Kiss et al. Comm. Phys. (2026)

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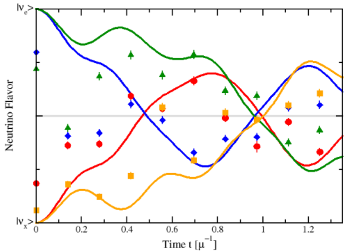
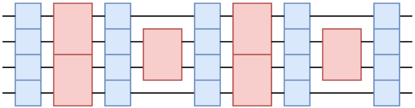


B.Hall et al. PRD(2021)

18 CNOT on **4** qubits



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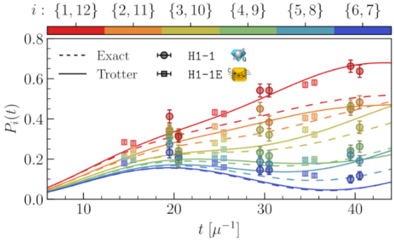

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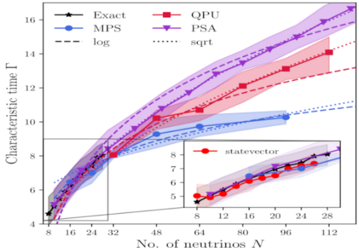

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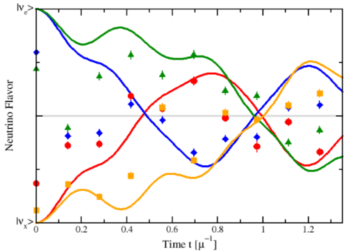

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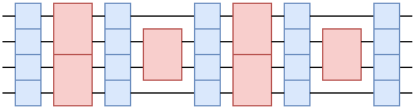
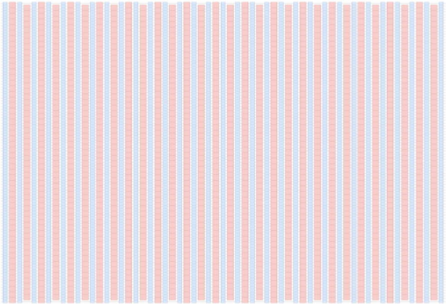


B.Hall et al. PRD(2021)

4995 CNOT on **112** qubits



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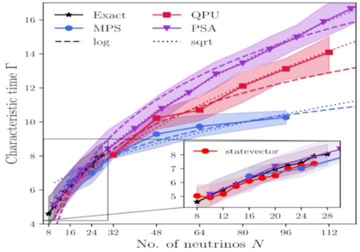

O. Kiss et al. Comm. Phys. (2026)

The secret sauce

* Rahman, Lewis, Mendicelli, Powell, PRD (2022)

The most recent result was possible thanks to 3 main ingredients

- better quantum devices (thanks IBM)
- better error mitigation (thanks Emanuele*)
- physical intuition

The neutrino flavor Hamiltonian leads to thermalization (satisfies ETH)
Can we track average single qubit thermalization in a cheaper way?

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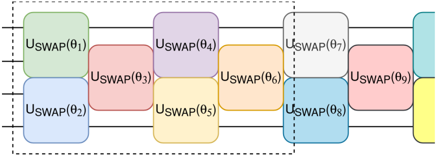
$$H_{\nu\nu} \propto \vec{\sigma}_i \cdot \vec{\sigma}_j \propto \mathrm{SWAP}_{ij} + \mathrm{const.}$$

Time evolution consists of random partial SWAPs between neighbors. One full Trotter step has angles $\theta \approx (\pi/2 + \Delta t \xi / N)$ on N layers



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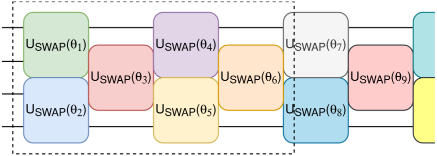
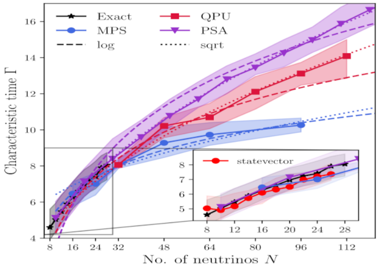


Idea: can we replace this instead with angles $\theta \approx (\pi/2 + \alpha\xi/L)$ on L layers and constrain α to match timescale?



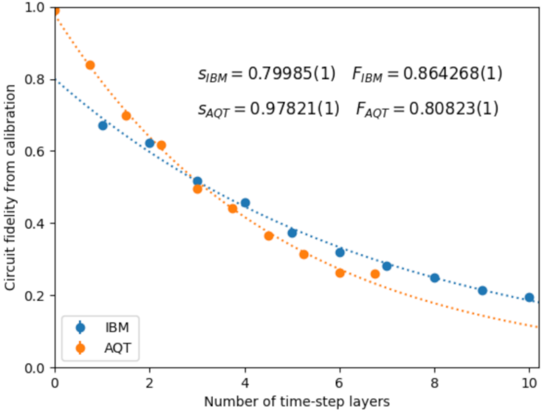
Going to the full 3 flavors

L.Spagnoli, N. Goss, et al. PRD (2025)

$$H_{\nu\nu} = \frac{\mu}{2N} \sum_{i<j} J_{ij} \vec{\lambda}_i \cdot \vec{\lambda}_j$$

We can proceed in two ways

- we encode the 3 flavor states into 2 qubits (4 total)
- we directly use 2 qutrits



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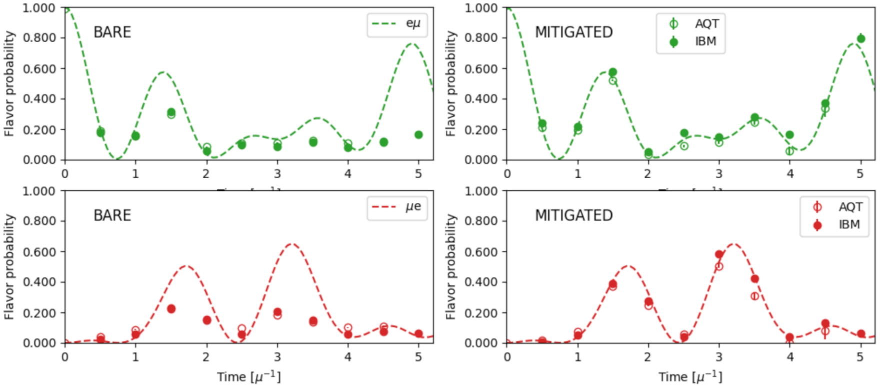

Summary and perspectives

- collective neutrino oscillations are an interesting **strongly coupled** many-body system driven by the **weak interaction** with possible important impact on flavor dynamics in extreme environments
- even the basic 2-flavor model for collective oscillations poses a challenging many-body problem well suited to quantum technologies
  - Hamiltonian is two-local and all-to-all $\rightarrow$ doable on all connectivities
- first calculations on small scale digital devices show promise in studying flavor evolution and achievable fidelity is advancing rapidly
- error mitigation is critical to push the ability to extract useful information out of current quantum devices
  - superconducting QPU's short time per shot is a great advantage here
  - can perform 90 layers on 112 qubits on devices with QV=512 (n=9)
- qudit platforms can be used to study 3-flavor oscillations efficiently
- More realistic models for neutrino evolution in the supernova environment will require spatial degrees of freedom to become dynamical $\rightarrow$ naive implementations require beyond NISQ resources

Thanks to my collaborators

- L. Spagnoli (Trento)
- V. Amitrano (Trento)
- L. Vespucci (Trento)
- P. Luchi (Trento)
- F. Turro (Trento)
- F. Pederiva (Trento)
- A. Baroni (ORNL)
- J. Carlson (LANL)
- B. Hall (MSU)
- N. Goss (UCB)
- R. Naik (LBL/UCB)
- E. Rrapaj (LBL)
- O. Kiss (CERN)
- I. Tavernelli (IBM)
- F. Tacchino (IBM)
- D. Lacroix (IJCLab)

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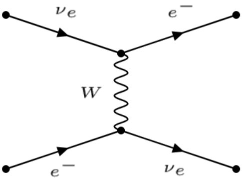
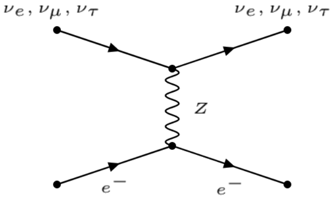
Thank you for your attention!

Neutrino oscillations in astrophysical environments

We know that neutrinos can display flavor oscillations in vacuum, does it matter in a core-collapse supernova?

- energy deposition behind shock and in the wind proceeds through charge-current reactions (large differences in $\nu_e - \nu_{\mu/\tau}$)
- neutrino oscillation rates can get enhanced through elastic forward scattering with high density external matter (MSW effect)

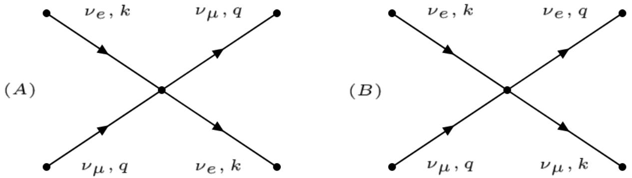




In a supernova scattering of neutrinos off each other becomes important

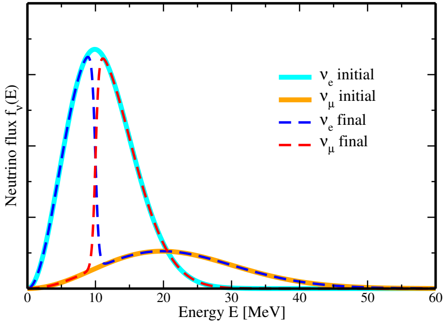
Neutrino-neutrino forward scattering

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
  - total flavor is conserved

Important effect if initial distributions are strongly flavor dependent



Error mitigation with zero-noise extrapolation

Li & Benjamin PRX(2017), Temme, Bravy, Gambetta PRL(2017), Endo,Benjamin,Li PRX(2018)

Zero noise extrapolation

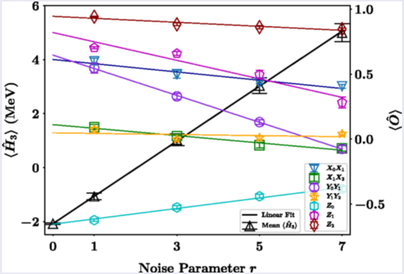
For small enough noise we can write

$$M(\epsilon) = M_0 + \epsilon M_1 + \frac{\epsilon^2}{2} M_2 + \dots$$

Using two points $\epsilon_2 = \eta \epsilon_1$ we have

$$M_0 \approx M(\epsilon_1) - \frac{M(\epsilon_1) - M(\epsilon_2)}{\eta - 1}$$

picture from Dumitrescu et al. PRL(2018)



- for moderate ϵ other parametrizations (like exp) might be more useful

$$M(\epsilon) = M_0 e^{-\alpha\epsilon} \Rightarrow M_0 \approx M(\epsilon_1) \left(\frac{M(\epsilon_2)}{M(\epsilon_1)} \right)^{\frac{\epsilon_1}{\epsilon_1 - \epsilon_2}}$$

In that case it is very beneficial to ensure $M(\epsilon \to \infty) \to 0$ (mitigated B)

Stochastic compilation for flavor evolution

- continuous line corresponds to average over exact distribution

$$\mathbb{E}_k[O_k(t)] = \mathbb{E}_k\left[\exp(it\hat{H}^{(k)}_{\nu\nu})O(0)\exp(-it\hat{H}^{(k)}_{\nu\nu})\right]$$

- dashed line corresponds to evolution under average Hamiltonian

$$\overline{O}(t) = \exp(it\mathbb{E}_k[\hat{H}^{(k)}_{\nu\nu}])O(0)\exp(-it\mathbb{E}_k[\hat{H}^{(k)}_{\nu\nu}])$$