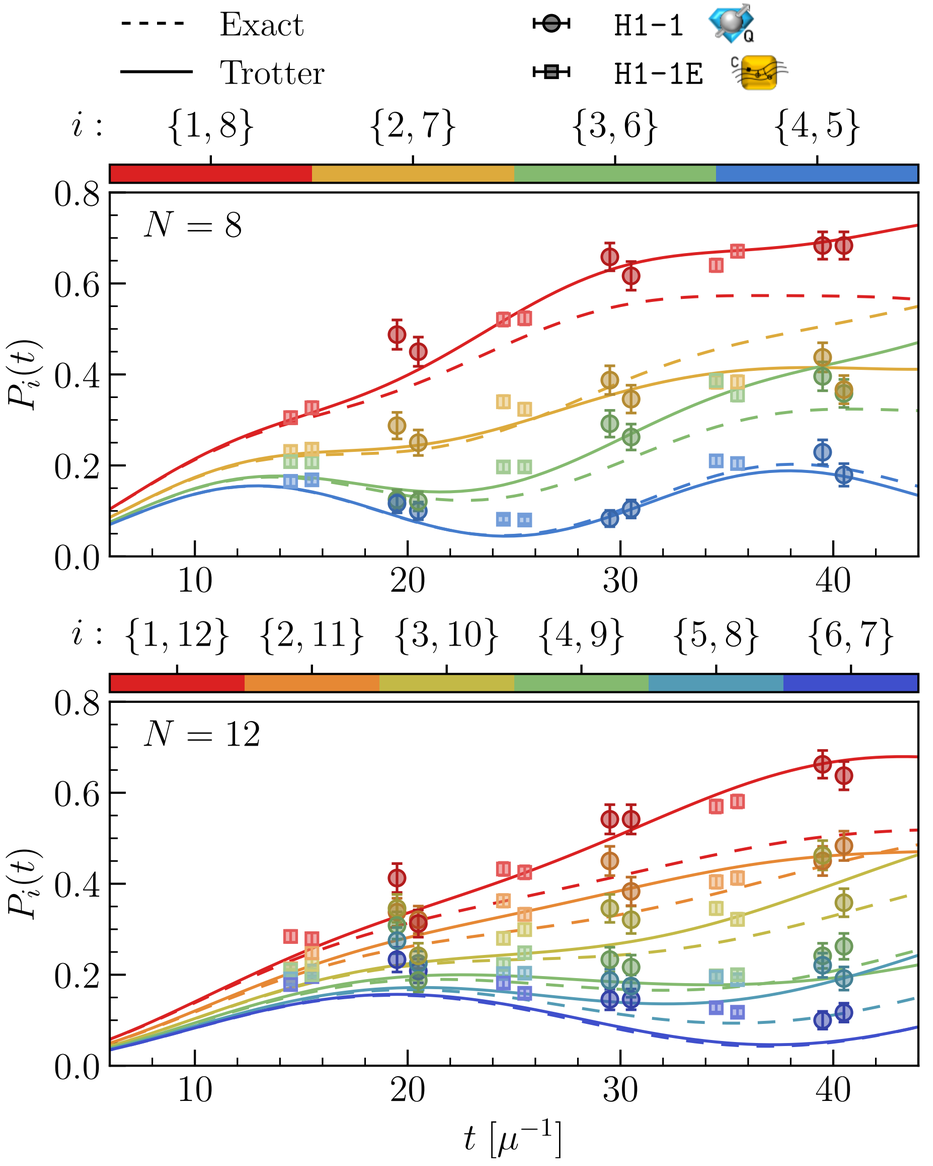
Some of Our Recent Progress in Digital Quantum Simulations for Nuclear Physics

Martin Savage
InQubator for Quantum Simulation
University of Washington

BNL
November 29, 2022



Four Quantum Simulation Projects

- **1+1D QCD and Weak Decays**

Preparations for Quantum Simulations of Quantum Chromodynamics in 1+1 Dimensions: (I) Axial Gauge
- e-Print: 2207.01731 [quant-ph]
(II) Single-Baryon Beta-Decay in Real Time
- e-Print: 2209.10781 [quant-ph]

Roland Farrell

Nikita Zemlevskiy

Sarah Powell
Ugrad at York University

Marc Illa

Ivan Chernyshev

- **Entanglement in Dense Systems of Neutrinos**

Multi-Neutrino Entanglement and Correlations in Dense Neutrino Systems - e-Print: 2210.08656 [nucl-th]

Marc Illa

- **HL-VQE for Effective Model Spaces of the Lipkin-Meshkov-Glick Model**

Quantum Simulations of the Lipkin-Meshkov-Glick Model utilizing Effective Model Spaces (1): Hamiltonian Learning-VQE using Digital Quantum Computers
- arrival in December

Caroline Robin - U of Bielefeld and GSI

Chapter 1

1+1D QCD and Weak decays

Roland Farrell

Nikita Zemlevskiy

Sarah Powell
Ugrad at York University

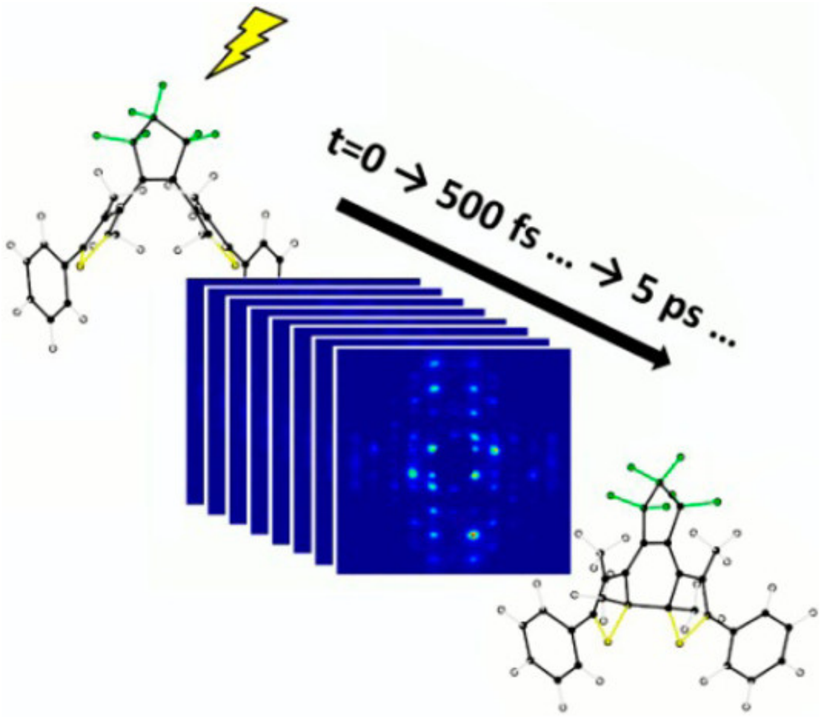
Marc Illa

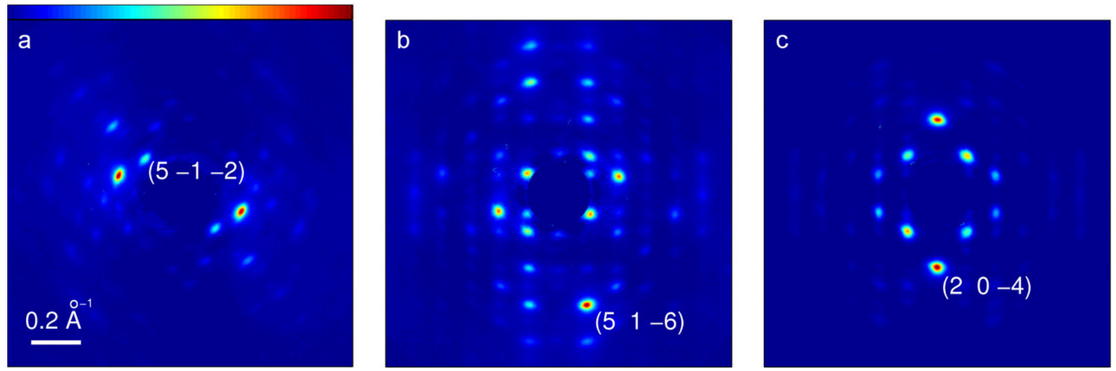
Ivan Chernyshev

Builds upon many previous works, including recent simulations of SU(2) 1+1D lattice gauge theory, Atas, Lewis, Muschik et al, *Nature Commun.* 12 (2021) 1, 6499 . e-Print: 2102.08920 [quant-ph]

And followed within days by Atas , Lewis, Muschik et al, e-Print: 2207.03473 [quant-ph]

Real-Time Dynamics and Reaction Pathways





J. Phys. Chem. B 2013, 117, 49, 15894-15902

Femto-second chemistry reveals reaction mechanisms
Quantum simulations will reveal the reactions pathways of QCD

Quantum Chromodynamics

$$\mathcal{L} = \sum_{i=u,d,s,c,b,t} \bar{q}_i \left[i \not{D} - m_i \right] q_i - \frac{1}{4} \sum_{a=1,\ldots,8} G^a_{\mu\nu} G^{\mu\nu,a}$$

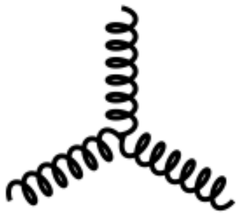
quark kinetic term
left and right fields uncoupled

quark mass term
(Higgs mechanism)

gluon kinetic
Yang-Mills action
Chromo-electric and chromo-magnetic terms

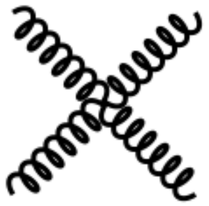
$$D_\mu q(x) = \partial_\mu q(x) + ig \sum_{a=1,\ldots,8} A^a_\mu(x) T^a q(x)$$

covariant derivative



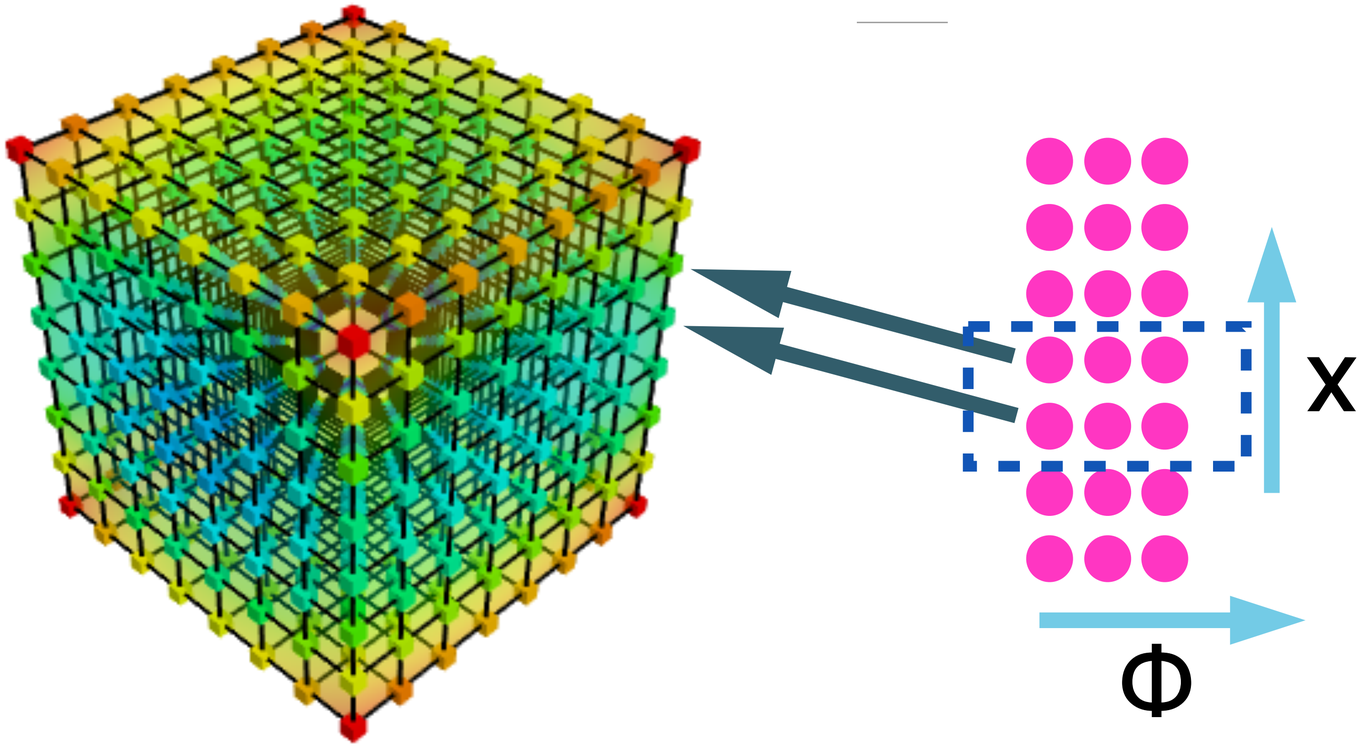
$$G_{\mu\nu}(x) = \frac{1}{ig} \left[D_\mu, D_\nu \right] = \sum_{a=1,\ldots,8} T^a G^a_{\mu\nu}(x)$$

gluon field strength



Digital To-Do List for Quantum Chromodynamics

1. **Map quarks and gluons on a quantum register of qubits, qutrits, …**



2. **Develop unitary operators to evolve initial wavefunctions forward in time**

$$e^{-iHt} = \left(e^{-iH_1 t/N} e^{-iH_2 t/N} e^{-iH_3 t/N} e^{-iH_1 t/N} e^{-iH_2 t/N} e^{-iH_3 t/N} \cdots\right)$$

N steps

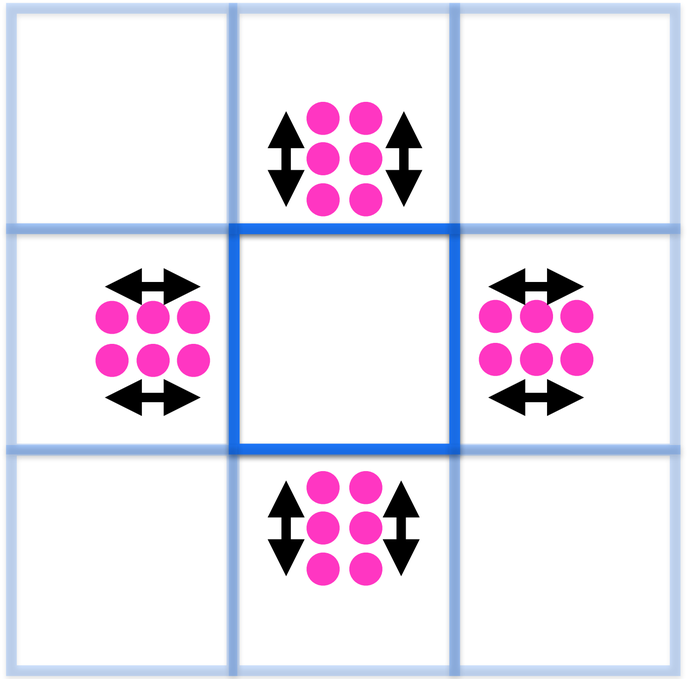
Yang-Mills in 2+1D and 3+1D

Many ways to map/distribute the field(s) in the UV (lattice spacing)
Kogut-Susskind basis = electric basis ….

$$\hat{H} = \frac{g^2}{2} \sum_{\text{links}} \hat{E}^2 - \frac{1}{2g^2} \sum_{\square} \left(\hat{\square} + \hat{\square}^\dagger \right)$$

Electric Field Casimir operator

Magnetic Field operator
Off-diagonal on electric basis



$$|p, q, T_L, T_L^z, Y_L, T_R, T_R^z, Y_R\rangle$$

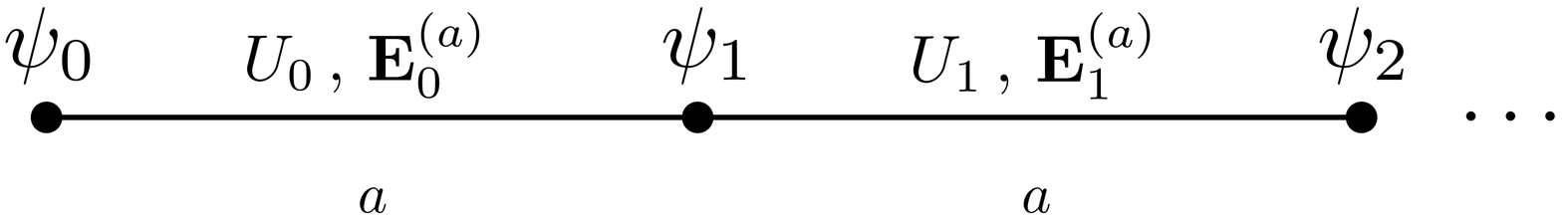
Left-space Right-space

Entangled left-right spaces around the plaquette

Lattice Hamiltonian for two-flavor QCD in 1+1D
A_0=0 Weyl Gauge

Lattice spacing = a

Formal : Banuls, Cirac, Jansen, ….



Staggered Lattice of size $2L$ with (anti)quarks on (odd) even numbered sites

$$H_{\rm KS} = \sum_{f=u,d}\left[\frac{1}{2a}\sum_{n=0}^{2L-2}\left(\psi_n^{(f)\dagger}U_n\psi_{n+1}^{(f)} \;+\; \text{h.c.}\right) \;+\; m_f\sum_{n=0}^{2L-1}(-1)^n\psi_n^{(f)\dagger}\psi_n^{(f)}\right] \;+\; \frac{ag^2}{2}\sum_{n=0}^{2L-2}\sum_{a=1}^{8}|\mathbf{E}_n^{(a)}|^2$$

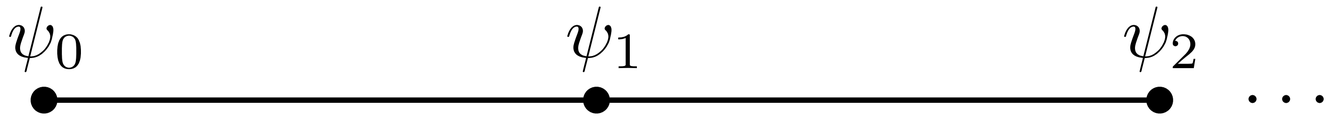
Quark Kinetic Term (Hopping) — Quark Mass Term — Chromo-electric energy

A_0=0 Weyl gauge is explicit

Explicit degrees of freedom (qubits) for gauge fields
- constrained completely by Gauss's law

Lattice Hamiltonian for two-flavor QCD in 1+1D
A_x=0 Axial Gauge

$$V_{\rm QCD} \sim g^2 \sum_{a=1}^{8} Q_0^{(a)} Q_2^{(a)}$$



Staggered Lattice of size $2L$ with (anti)quarks on (odd) even numbered sites

$$H_{\rm KS} = \sum_{f=u,d} \left[\frac{1}{2} \sum_{n=0}^{2L-2} \left(\psi_n^{(f)\dagger} \psi_{n+1}^{(f)} \; + \; \text{h.c.} \right) \; + \; m_f \sum_{n=0}^{2L-1} (-1)^n \psi_n^{(f)\dagger} \psi_n^{(f)} \right] + \frac{g^2}{2} \sum_{n=0}^{2L-2} \sum_{a=1}^{8} \left(\sum_{m \le n} Q_m^{(a)} \right)^2$$

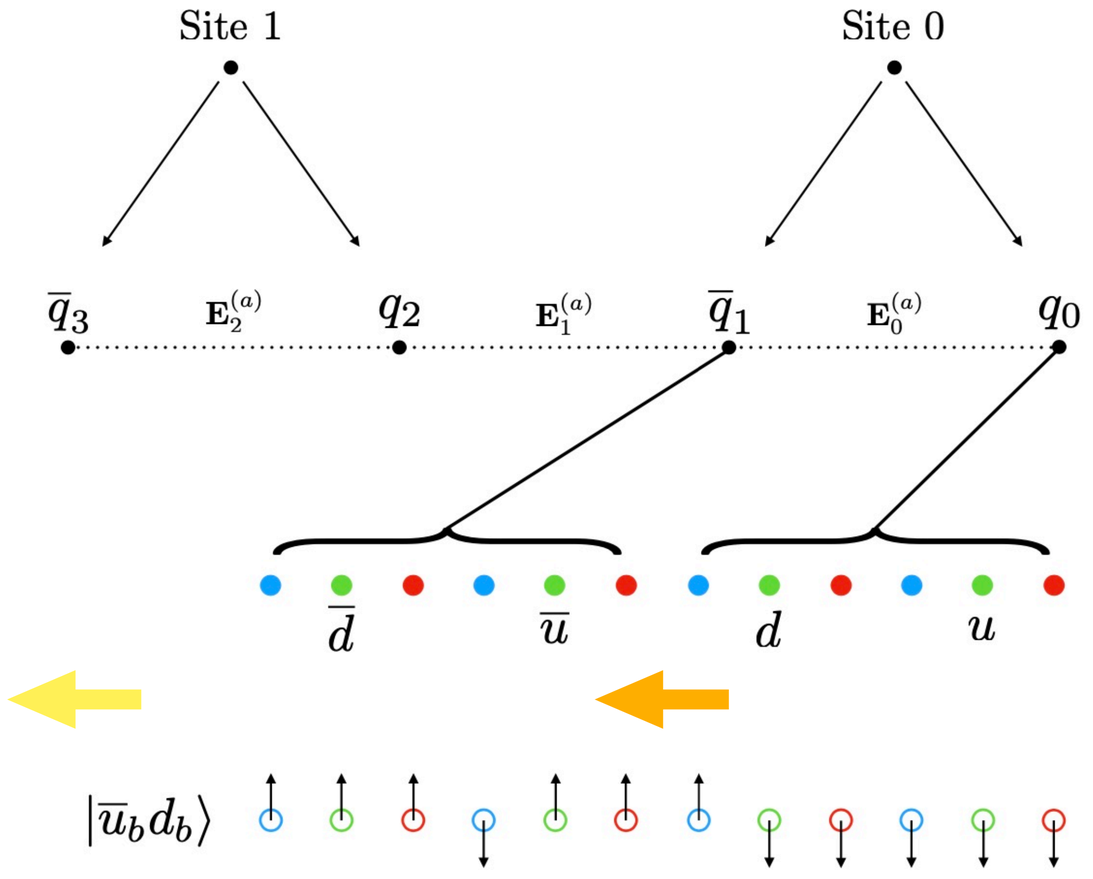
Quark Kinetic Term (Hopping) | Quark Mass Term | Chromo-electric energy

A_x=0 Axial gauge is explicit

$Q^{(a)}$ have diagonal and also off-diagonal action in color space

Mapping two-flavor 1+1D Axial Gauge QCD to qubits - Jordan-Wigner

$$H_{kin} = -\frac{1}{2}\sum_{n=0}^{2L-2}\sum_{f=0}^{1}\sum_{c=0}^{2}\left[\sigma^{+}_{6n+3f+c}\left(\bigotimes_{i=1}^{5}\sigma^{z}_{6n+3f+c+i}\right)\sigma^{-}_{6(n+1)+3f+c} + \text{h.c.}\right]$$



Staggered Quarks

$$H_m = \frac{1}{2}\sum_{n=0}^{2L-1}\sum_{f=0}^{1}\sum_{c=0}^{2} m_f\left[(-1)^n\sigma^{z}_{6n+3f+c} + 1\right]$$

Distribute Color and Flavor

$$H_{el} = \frac{g^2}{2}\sum_{n=0}^{2L-2}(2L-1-n)\left(\sum_{f=0}^{1}Q^{(a)}_{n,f}\,Q^{(a)}_{n,f} \;+\; 2Q^{(a)}_{n,0}\,Q^{(a)}_{n,1}\right)$$

JW Transformation and Axial Gauge

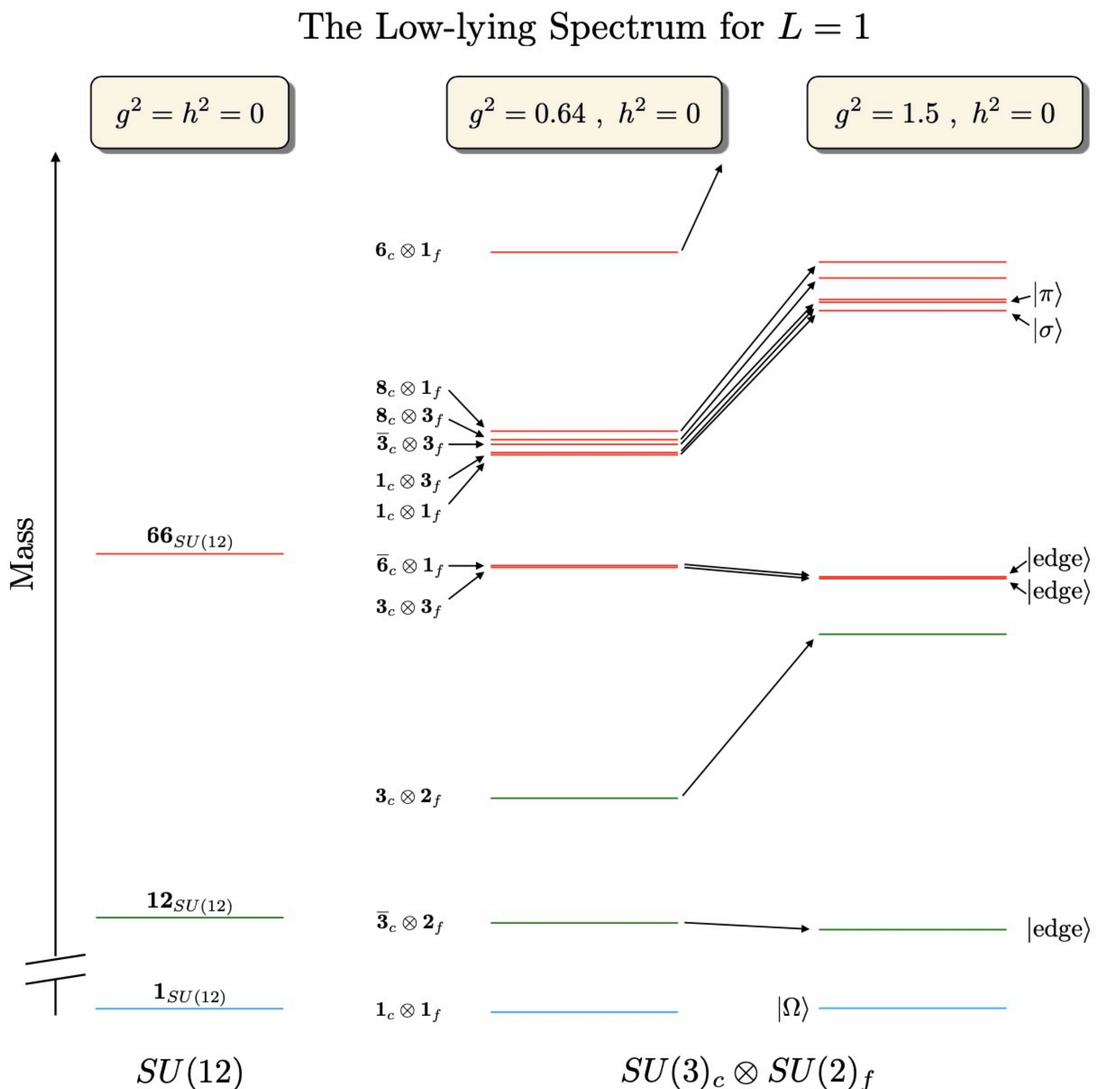
$$+\,g^2\sum_{n=0}^{2L-3}\sum_{m=n+1}^{2L-2}(2L-1-m)\sum_{f=0}^{1}\sum_{f'=0}^{1}Q^{(a)}_{n,f}\,Q^{(a)}_{m,f'}\,,$$

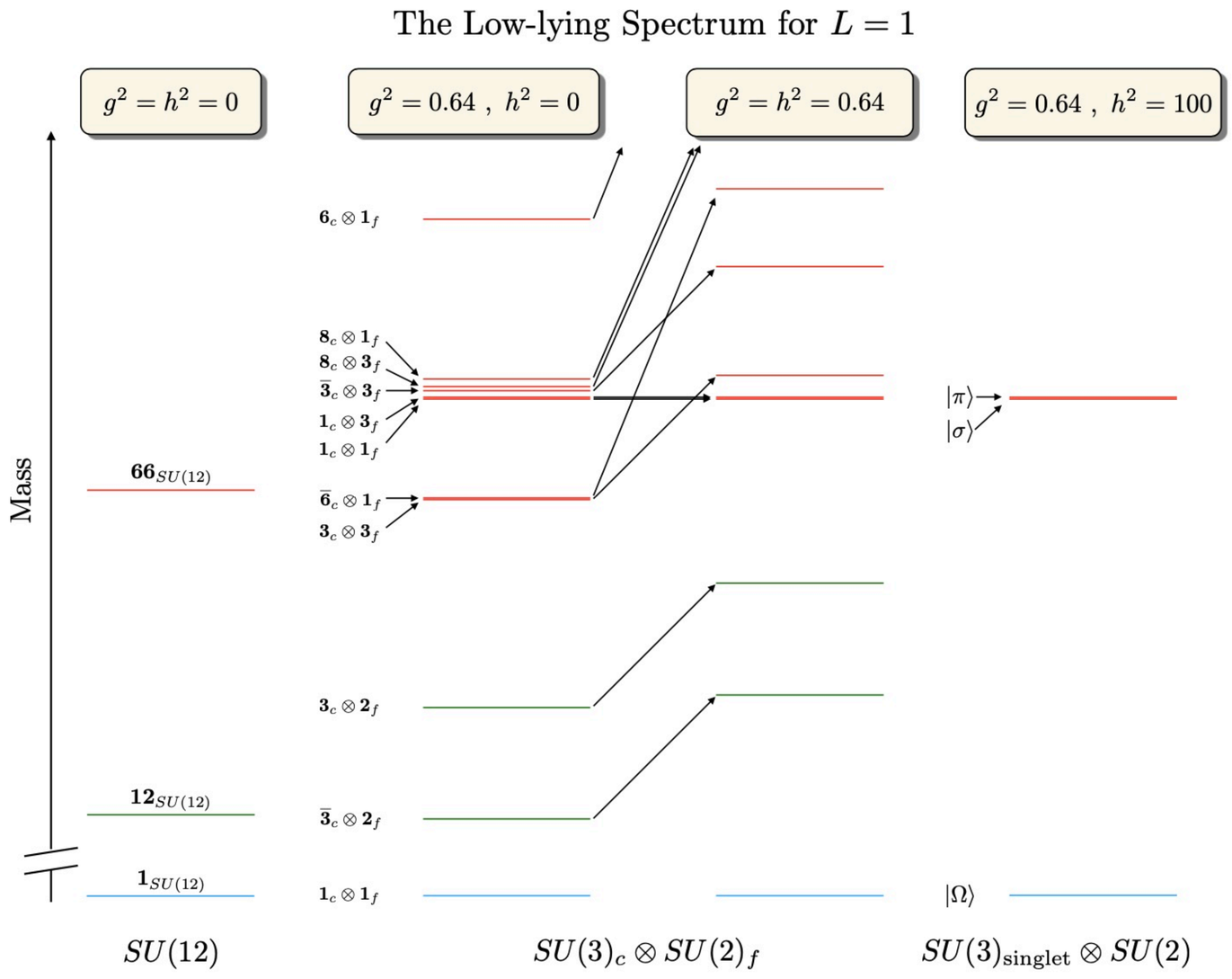
Color Edge States

OBCs support color-edge states

$$H_1 = \frac{h^2}{2} \sum_{n=0}^{2L-1} \left(\sum_{f=0}^{1} Q_{n,f}^{(a)} Q_{n,f}^{(a)} + 2 Q_{n,0}^{(a)} Q_{n,1}^{(a)} \right) + h^2 \sum_{n=0}^{2L-2} \sum_{m=n+1}^{2L-1} \sum_{f=0}^{1} \sum_{f'=0}^{1} Q_{n,f}^{(a)} Q_{m,f'}^{(a)}$$

Low-Lying Spectra





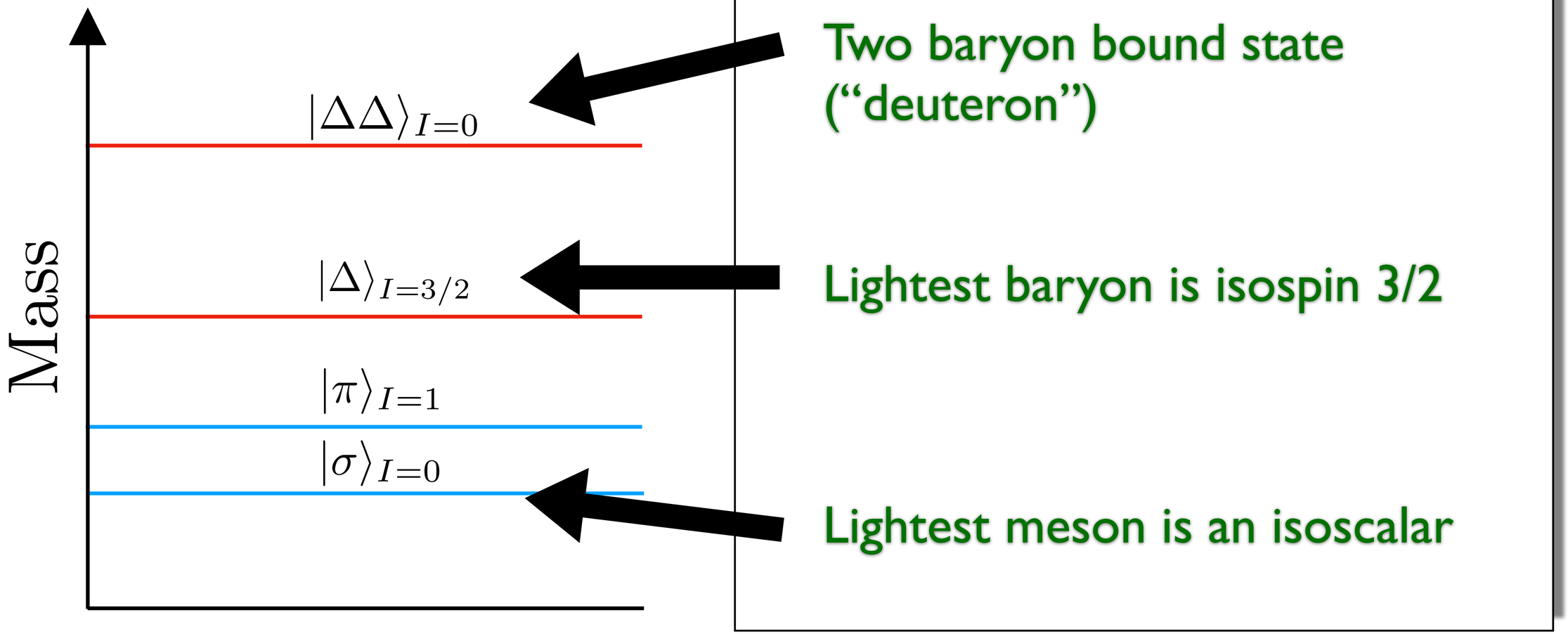
Solving for the spectrum

Hamiltonian is a sum of tensor products

$$H = (\sigma^x \otimes \sigma^y \otimes I \otimes \cdots) + (I \otimes \sigma^y \otimes \sigma^x \otimes \cdots) + \cdots$$

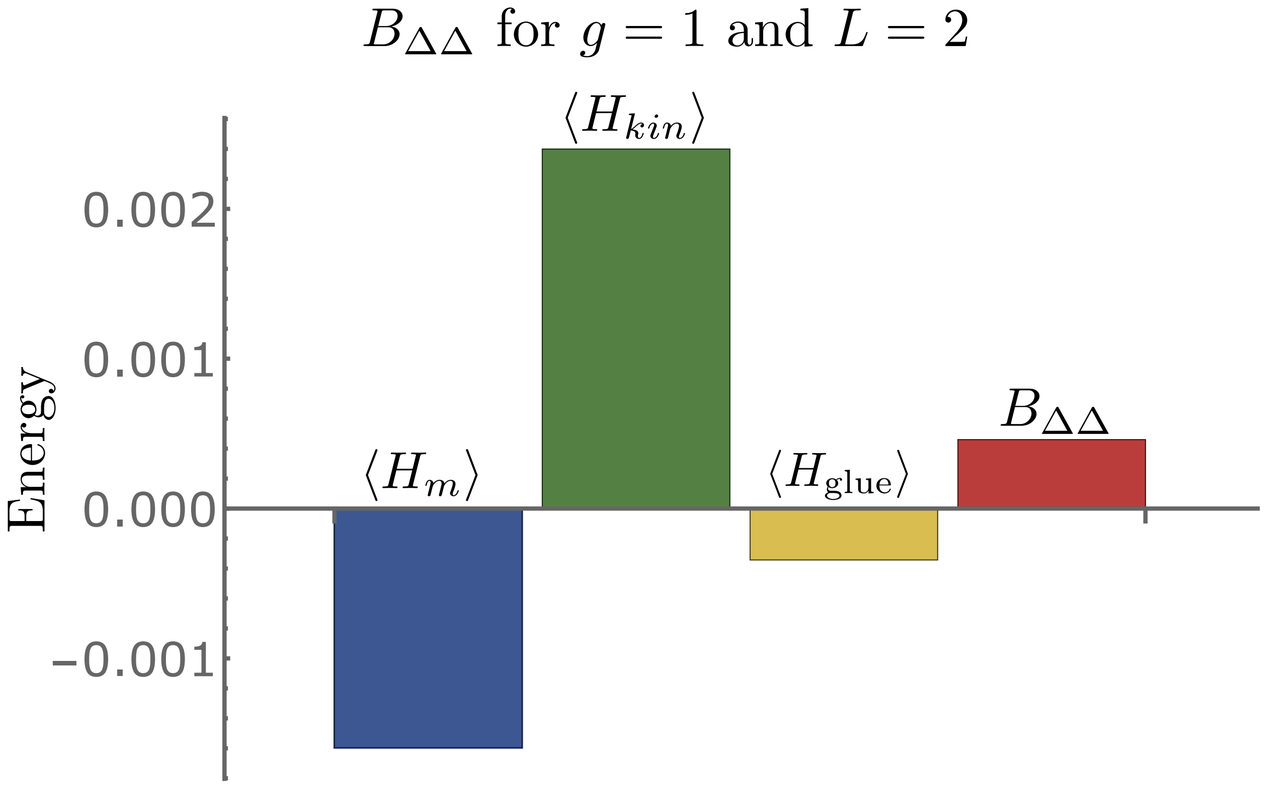
L	# of qubits	Matrix size
1	12	88
2	24	103,704
3	36	199,645,000

The hadronic spectrum



Deuteron Binding

$$B_{\Delta\Delta} = 2M_{\Delta} - M_{\Delta\Delta}$$

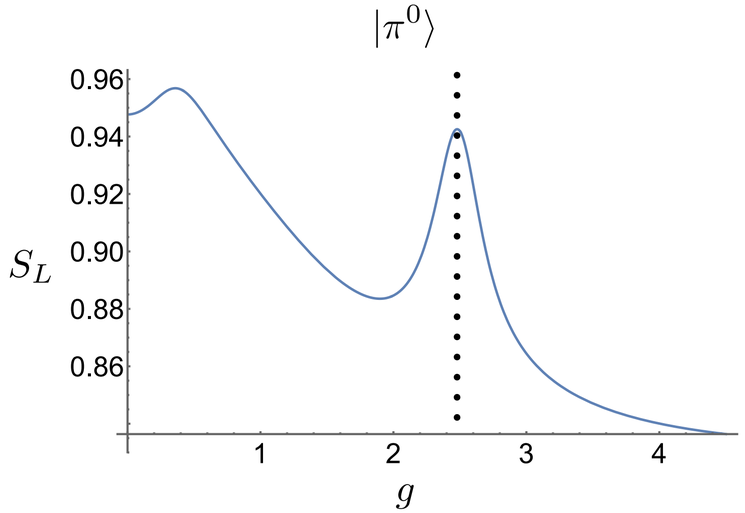


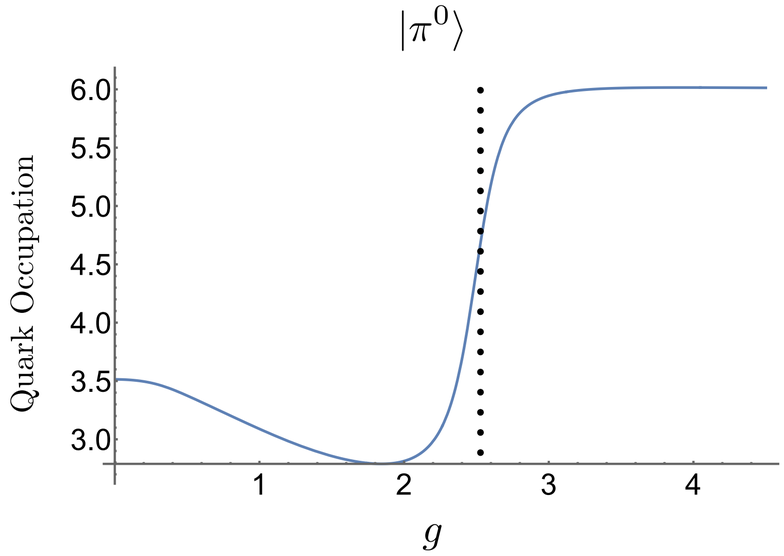
Dominated by $H_{\text{kin}} \sim \psi_n^\dagger \psi_{n+1}$

which creates $q\bar{q}$ pairs; looks

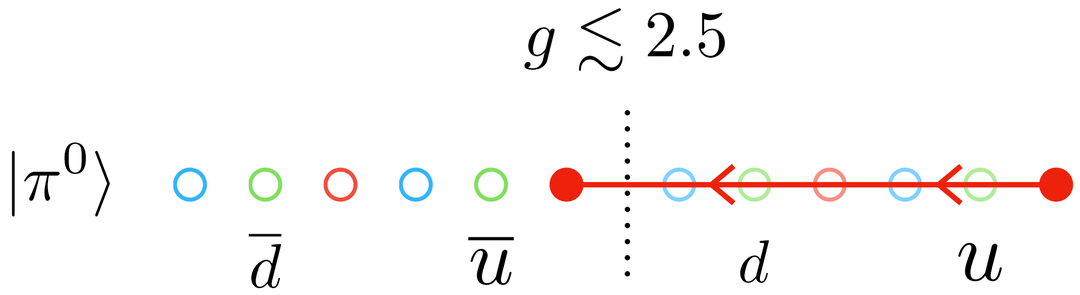
like meson exchange

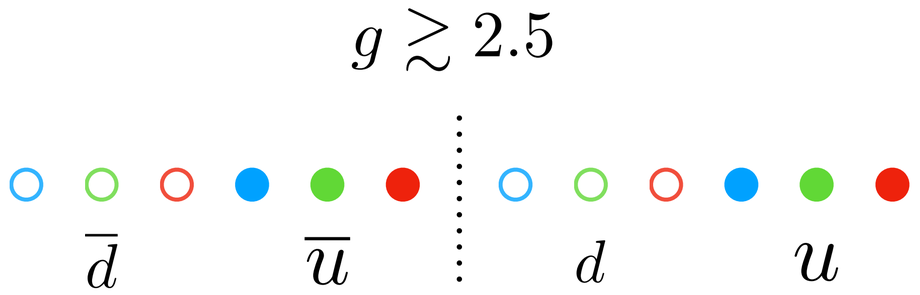
Entanglement structure in the mesons for $L = 2$





Peak in entanglement coincides with transition from quark-antiquark to baryon-anti-baryon structure

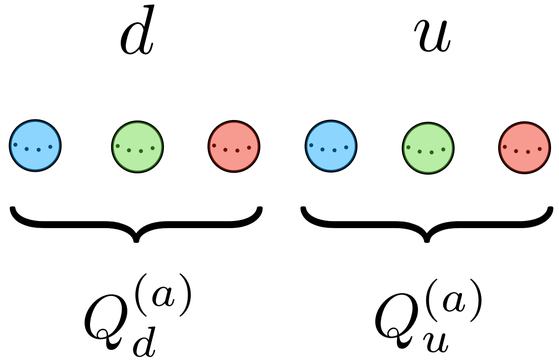




Balance between mass and gauge-field energies

Naive Trotterization Breaks SU(3)

$$H_{\text{glue}} = \frac{g^2}{2} \sum_{a=1}^{8} \left(Q_u^{(a)} Q_u^{(a)} + Q_d^{(a)} Q_d^{(a)} + 2 Q_u^{(a)} Q_d^{(a)} \right)$$



Mutually commuting terms that can be Trotterized together

$$\left(Q_u^{(1)} Q_d^{(1)}, Q_u^{(2)} Q_d^{(2)}, Q_u^{(3)} Q_d^{(3)}, Q_u^{(8)} Q_d^{(8)} \right) \qquad \left(Q_u^{(4)} Q_d^{(4)}, Q_u^{(5)} Q_d^{(5)} \right) \qquad \left(Q_u^{(6)} Q_d^{(6)}, Q_u^{(7)} Q_d^{(7)} \right)$$

Trotterized gauge-term is not SU(3) color singlet
…… it is for SU(2) and U(1), but not SU(3)…..

e.g. $\left[Q_u^{(1)} + Q_d^{(1)} \ , \ e^{-i\left(Q_u^6 Q_d^6 + Q_u^7 Q_d^7 \right)} \right] \neq 0$

Thoughts about Error Mitigation

Physical states are color singlets; “twirl” the errors

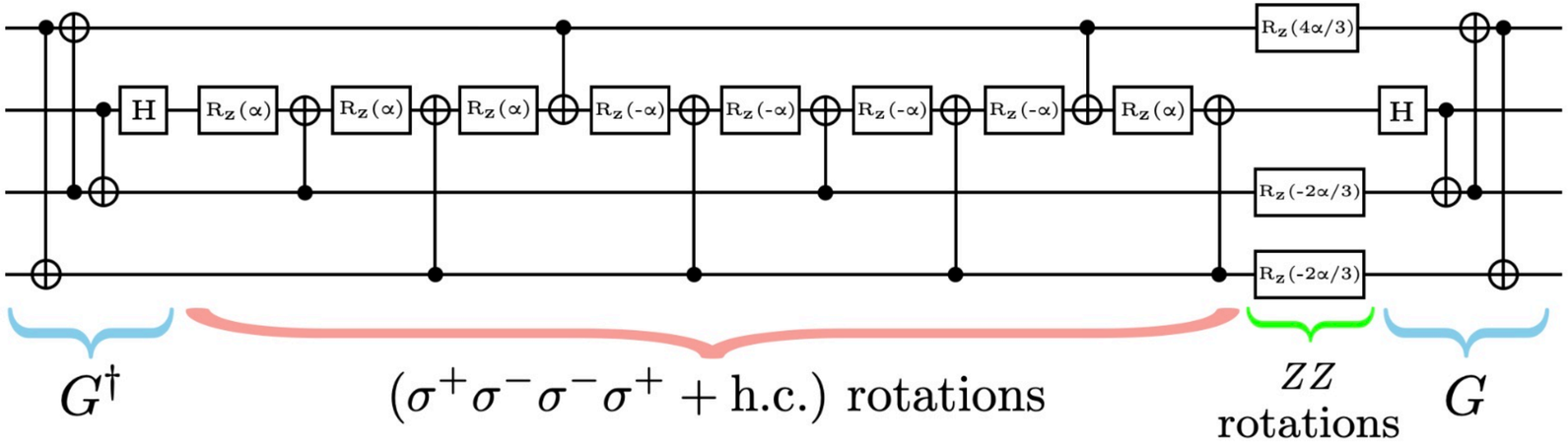
$$\langle\psi(t)|O|\psi(t)\rangle \;\rightarrow \langle\psi(t)|U(\theta)^\dagger\, O\, U(\theta)|\psi(t)\rangle \qquad U(\theta) = e^{-i\theta_a \sum_{n,f} Q^{(a)}_{n,f}}$$

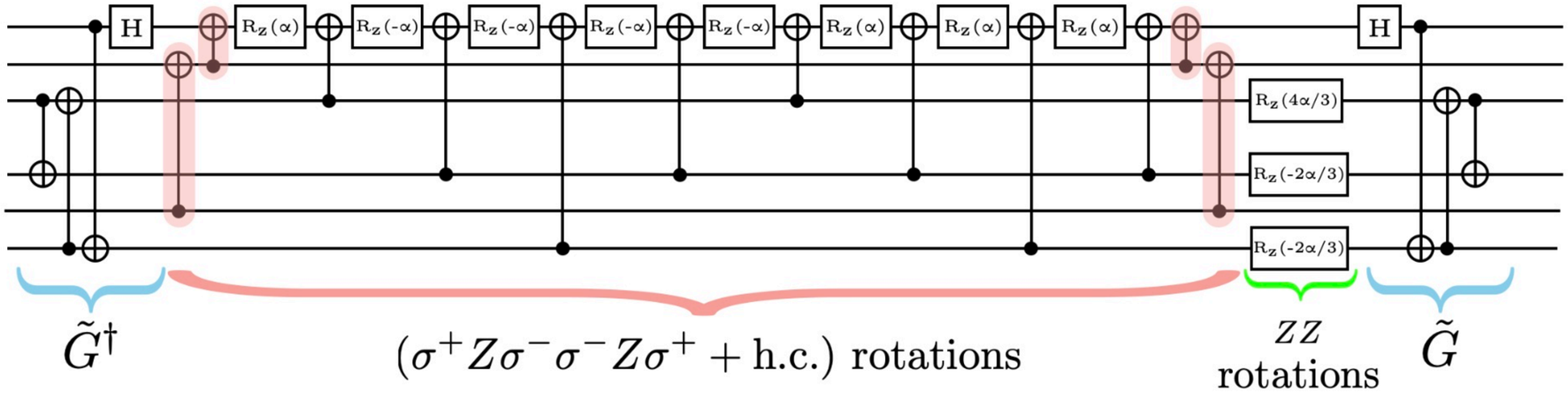
Commutator forms a closed algebra; use an “improved” Hamiltonian

e.g. $$H^{\rm eff}_{\rm glue} = H_{\rm glue} + c_1 \left[Q^{(1)}_u + Q^{(1)}_d \;,\; Q^{(6)}_u Q^{(6)}_d + Q^{(7)}_u Q^{(7)}_d \right] + \ldots$$

Simulations using IBM's Quantum Computers
1-site, 3 colors, 1 flavor: m=g=L=1

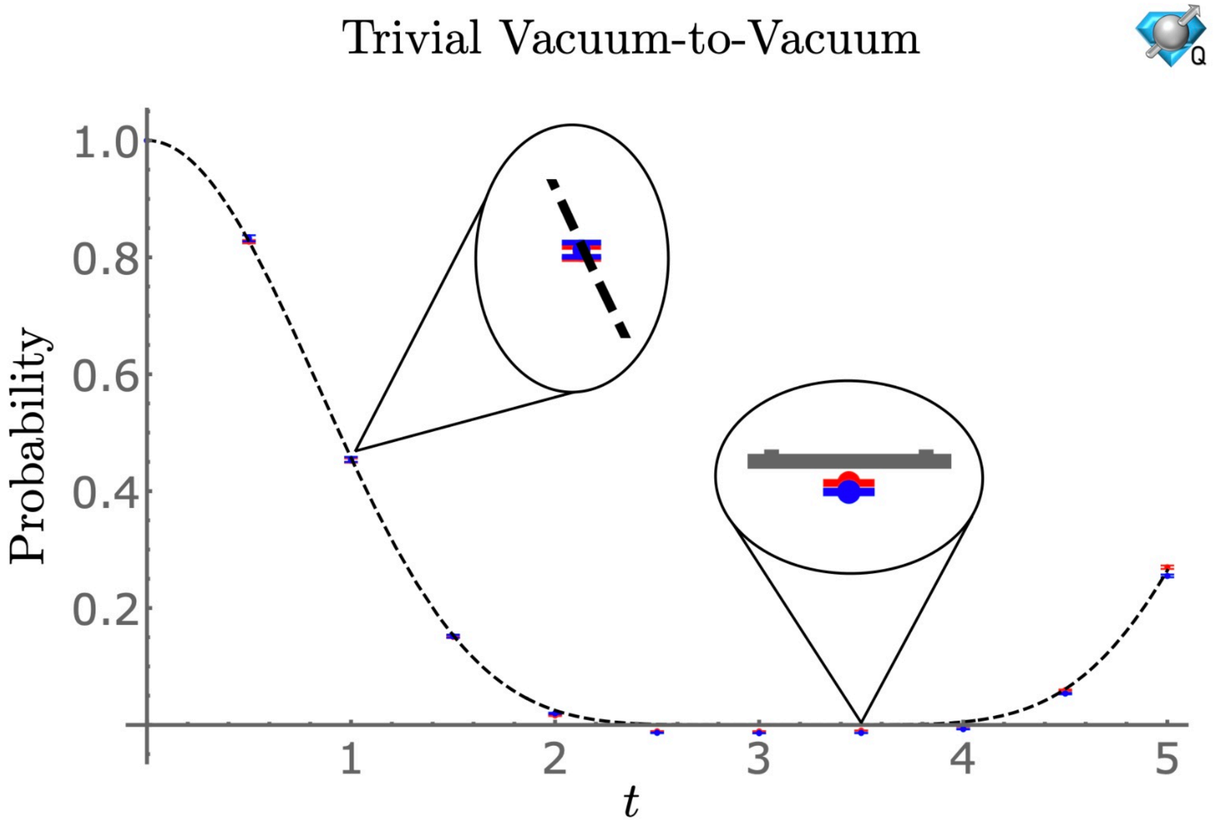
Circuits to implement Trotterized Gauge term





Simulations using IBM's Quantum Computers
1-site, 3 colors, 1 flavor: m=g=L=1

IBM 7 qubit Perth and Jakarta



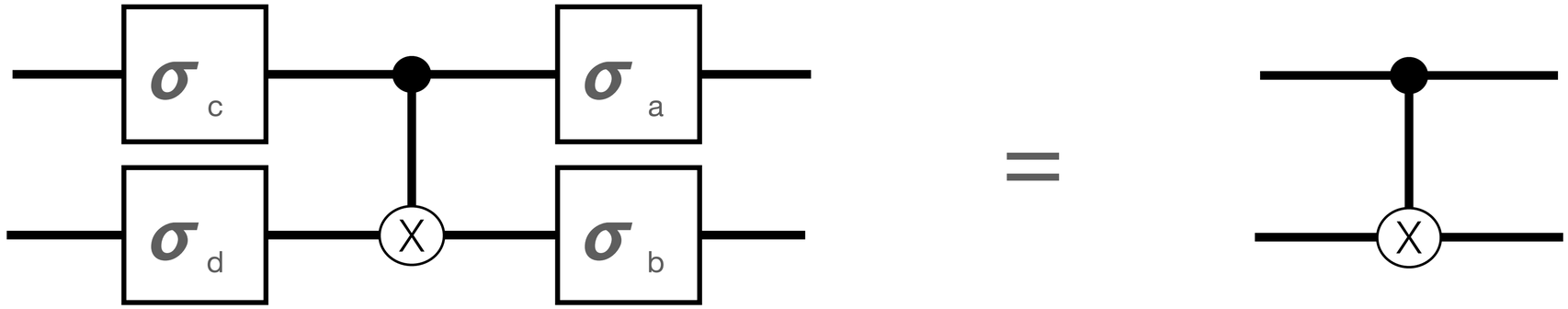
34 CNOTs per step
447 Pauli-Twirled circuits
1000 shots per circuits

Dynamic Decoupling
Pauli-Twirling
Post selection
De-coherence renormalization

Number of CNOT gates for one Trotter step of $SU(3)$			
L	$N_f = 1$	$N_f = 2$	$N_f = 3$
1	30	114	242
2	228	878	1,940
5	1,926	7,586	16,970
10	8,436	33,486	75,140
100	912,216	3,646,086	8,201,600

Error Mitigation - NISQ-Life

Pauli-Twirling



Coherent errors from errors on control and target transformed to incoherent, averaged over all channels

Mitigating depolarizing noise on quantum computers with noise-estimation circuits

Miroslav Urbanek,[1,*] Benjamin Nachman,[2] Vincent R. Pascuzzi,[2]
Andre He,[2,†] Christian W. Bauer,[2] and Wibe A. de Jong[1,‡]

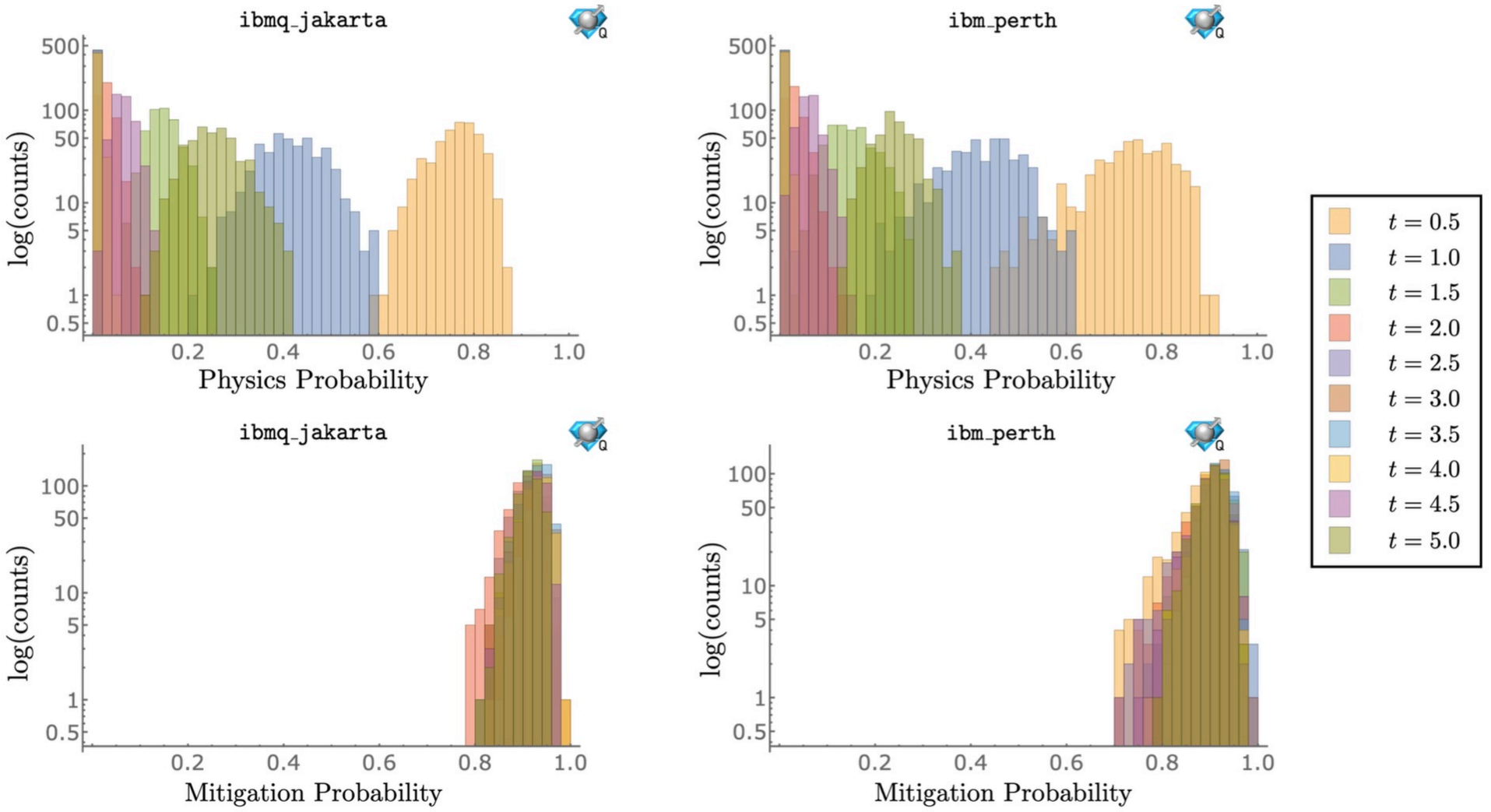
Self-mitigating Trotter circuits for SU(2) lattice gauge theory on a quantum computer

Sarmed A Rahman, Randy Lewis, Emanuele Mendicelli, and Sarah Powell
Department of Physics and Astronomy, York University, Toronto, Ontario, Canada, M3J 1P3
(Dated: May 18, 2022)

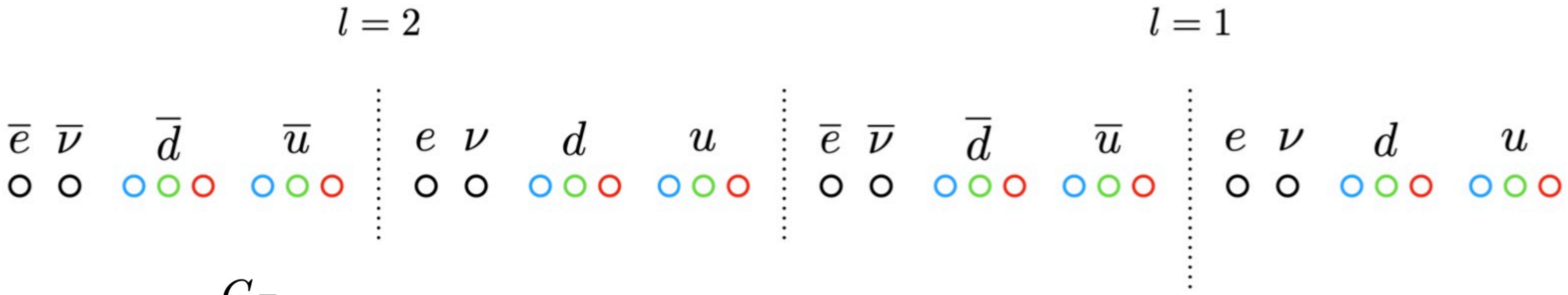
Post-Selection

Device Hilbert space >>> Physical Hilbert space
Select only members of measurement ensemble entirely in Physical space
Eliminates order-p errors.

Twirling and Mitigation



Weak Decays



$$\mathcal{H}_\beta = \frac{G_F}{\sqrt{2}} V_{ud}\, \overline{\psi}_u \gamma^\mu (1-\gamma_5)\psi_d\, \overline{\psi}_e \gamma_\mu (1-\gamma_5)\psi_{\nu_e} \;+\; \text{h.c.}$$

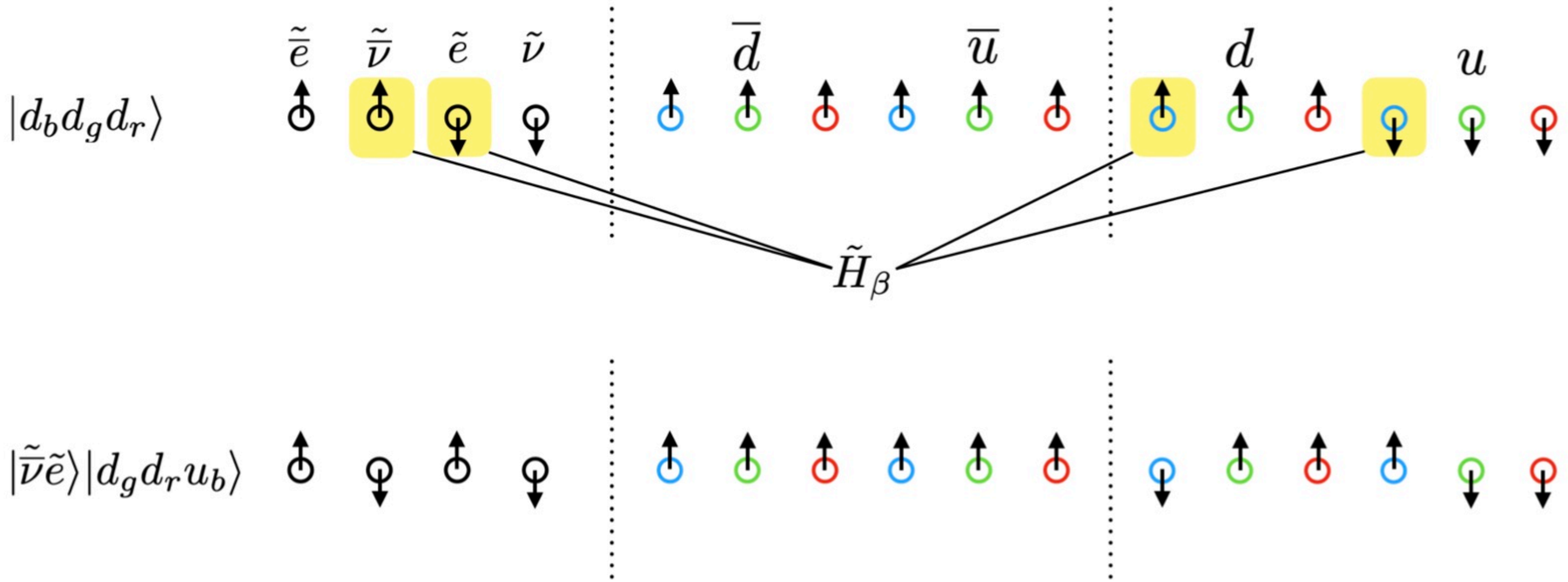
Nature

$$\mathcal{H}_\beta^{1+1} = \frac{G}{\sqrt{2}}\, \overline{\psi}_u \gamma^\mu \psi_d\, \overline{\psi}_e \gamma_\mu \mathcal{C} \psi_\nu \;+\; \text{h.c.}$$

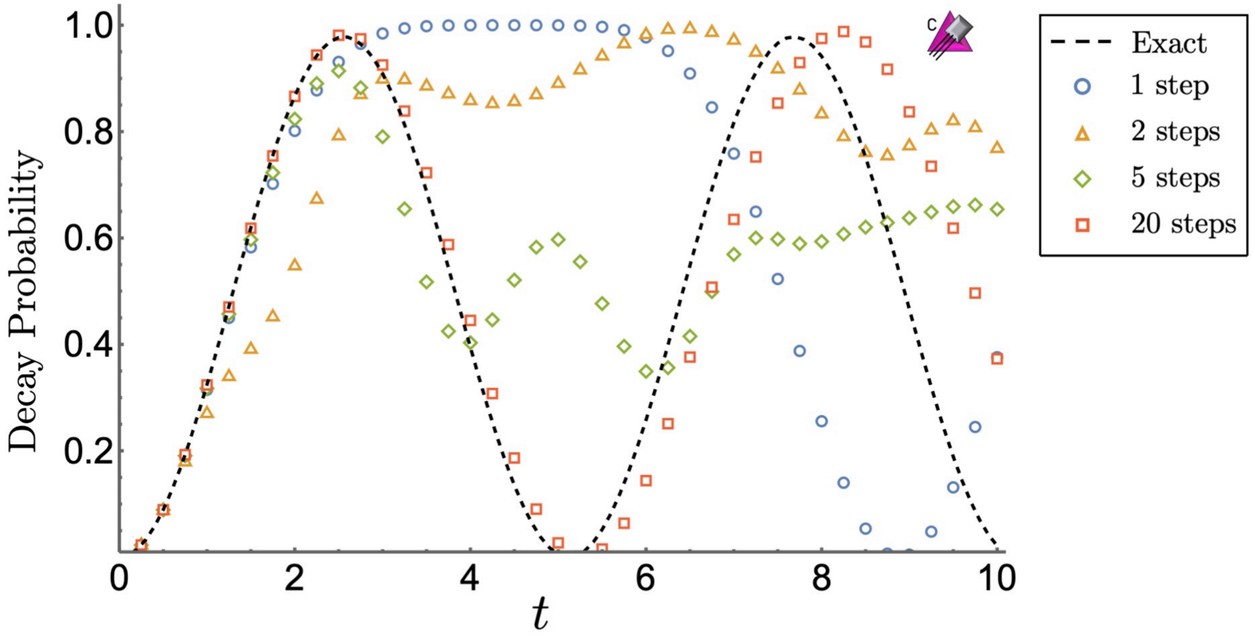
Chosen for simplicity and demonstration

$$\begin{aligned} H_\beta \to \frac{G}{\sqrt{2}} \sum_{l=0}^{L-1} \sum_{c=0}^{2} \Big(& \sigma^-_{l,\overline{\nu}} Z^6 \sigma^+_{l,e} \sigma^-_{l,d,c} Z^2 \sigma^+_{l,u,c} - \sigma^+_{l,\overline{e}} Z^8 \sigma^-_{l,\nu} \sigma^-_{l,d,c} Z^2 \sigma^+_{l,u,c} - \sigma^-_{l,\overline{\nu}} Z^{2-c} \sigma^-_{l,\overline{d},c} \sigma^+_{l,\overline{u},c} Z^c \sigma^+_{l,e} \\ & + \sigma^+_{l,\overline{e}} Z^{3-c} \sigma^-_{l,\overline{d},c} \sigma^+_{l,\overline{u},c} Z^{1+c} \sigma^-_{l,\nu} - \sigma^-_{l,\overline{d},c} Z^{3+c} \sigma^+_{l,e} \sigma^-_{l,\nu} Z^{5-c} \sigma^+_{l,u,c} - \sigma^+_{l,\overline{e}} \sigma^-_{l,\overline{\nu}} \sigma^-_{l,\overline{d},c} Z^{10} \sigma^+_{l,u,c} \\ & - \sigma^+_{l,\overline{u},c} Z^c \sigma^+_{l,e} \sigma^-_{l,\nu} Z^{2-c} \sigma^-_{l,d,c} - \sigma^+_{l,\overline{e}} \sigma^-_{l,\overline{\nu}} \sigma^+_{l,\overline{u},c} Z^4 \sigma^-_{l,d,c} + \text{h.c.} \Big) \,, \end{aligned}$$

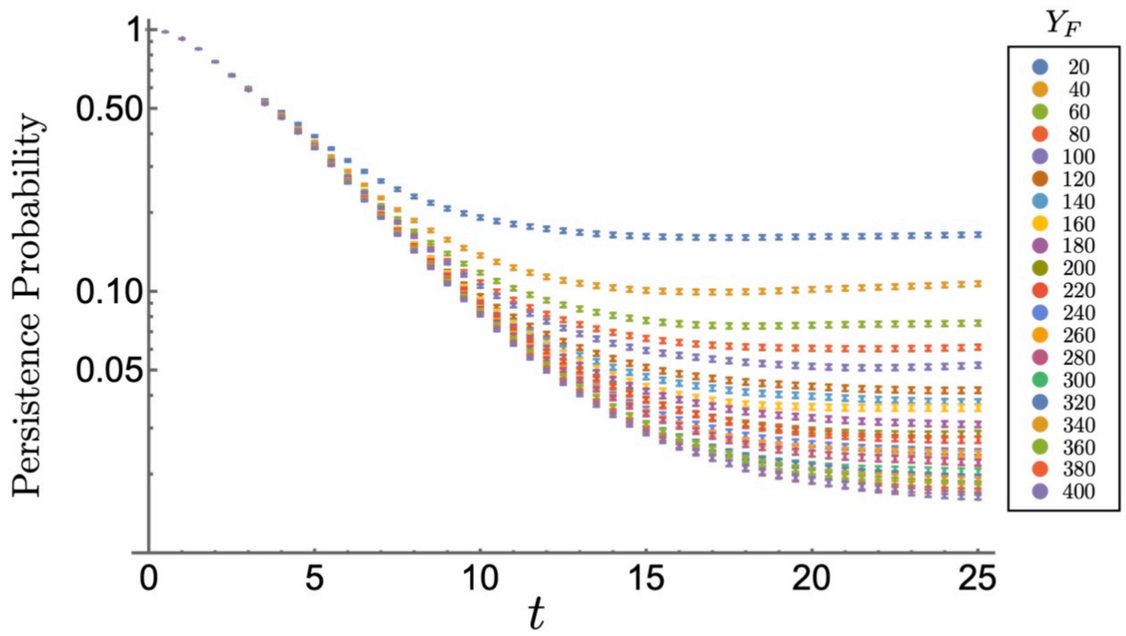
Weak Decays : 1-spatial site



Weak Decays : Expectations
—Recovering Real-time Exponential-Decay

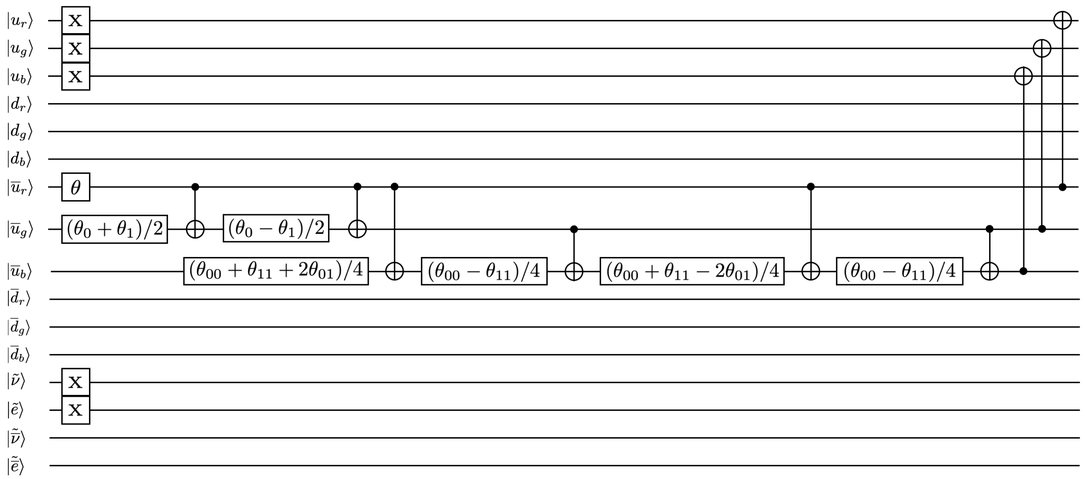


One available final state



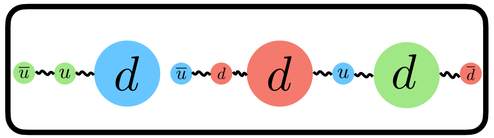
Y_F available final states

Weak Decays : Single Baryon Decay Quantum Circuits



Preparing the “ddd”-baryon state - VQE

=

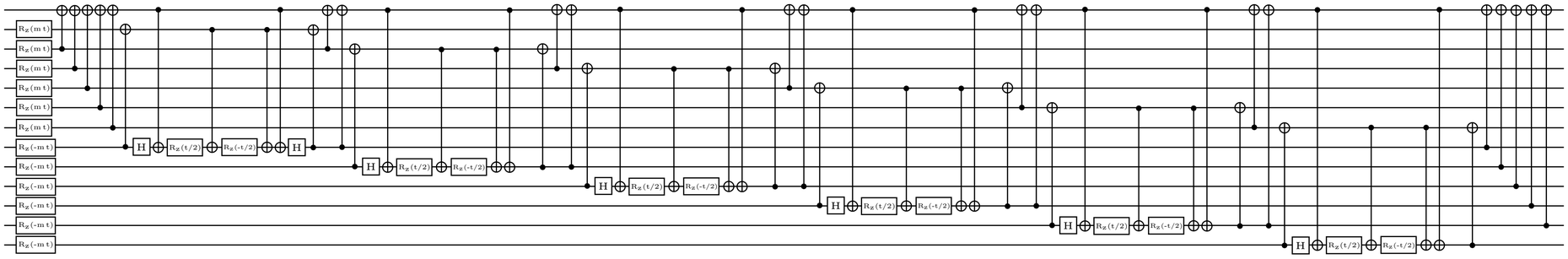


$$|\Delta^-\rangle = |d_r d_g d_b\rangle |\text{up vac}\rangle$$

$$|\text{up vac}\rangle = c_0|0\rangle + c_1(|u_r\bar{u}_r\rangle - |u_g\bar{u}_g\rangle + |u_b\bar{u}_b\rangle)$$
$$+c_2(|u_r\bar{u}_r u_g\bar{u}_g\rangle - |u_r\bar{u}_r u_b\bar{u}_b\rangle + |u_g\bar{u}_g u_b\bar{u}_b\rangle) + c_3|u_r\bar{u}_r u_g\bar{u}_g u_b\bar{u}_b\rangle$$

Apply weak+strong evolution operator

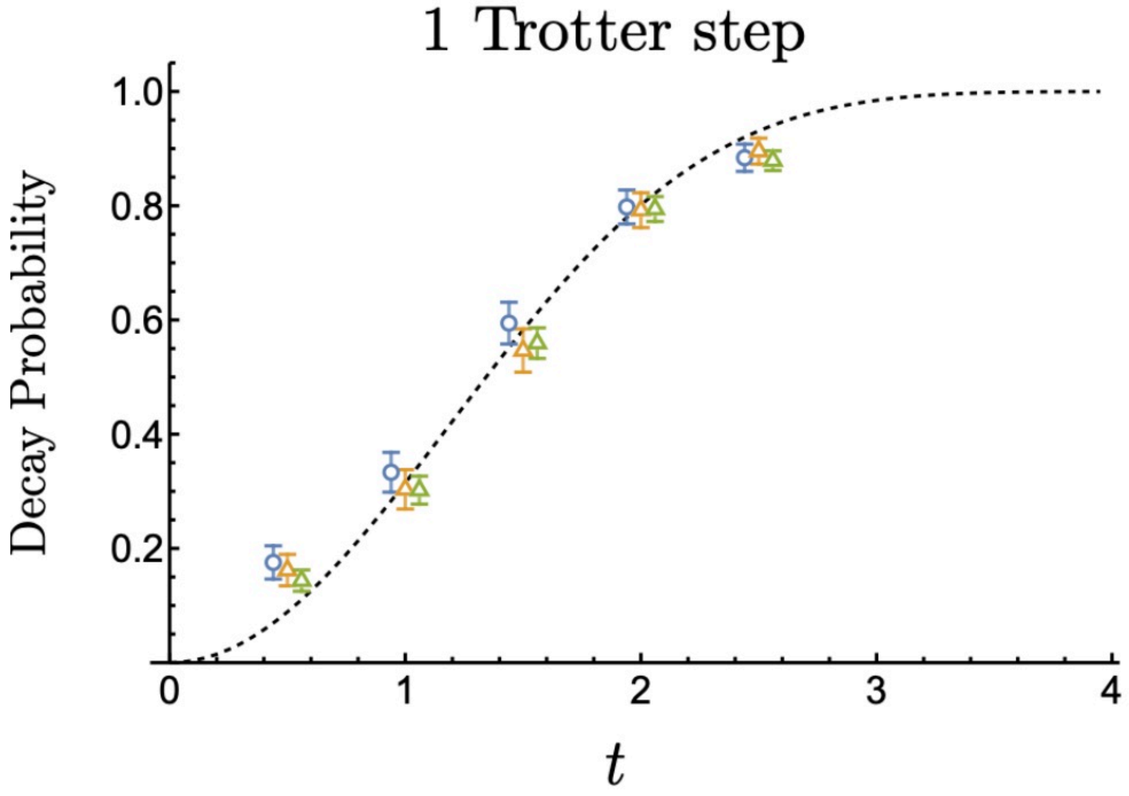
$U(t)_2 =$

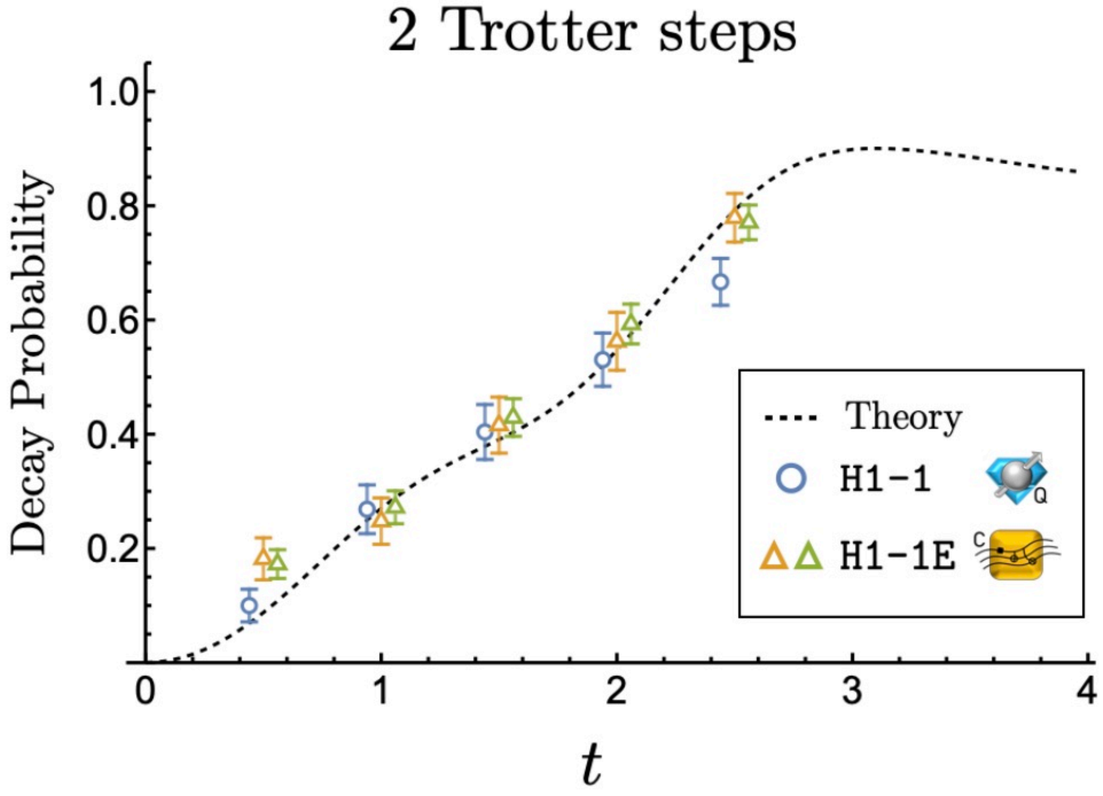


$\cdots$

Measure probability of finding an electron and anti-neutrino

Weak Decays : Quantum Simulation
Single Baryon Decay





1-step: 59 ZZ

2-steps: 212 ZZ gates

Weak Decays : Single Baryon Decay Resource Requirements

For 1 Trotter step

L	# of qubits	CNOTs
5	80	9,874
10	160	38,074
50	800	926,074
100	1600	3,692,074

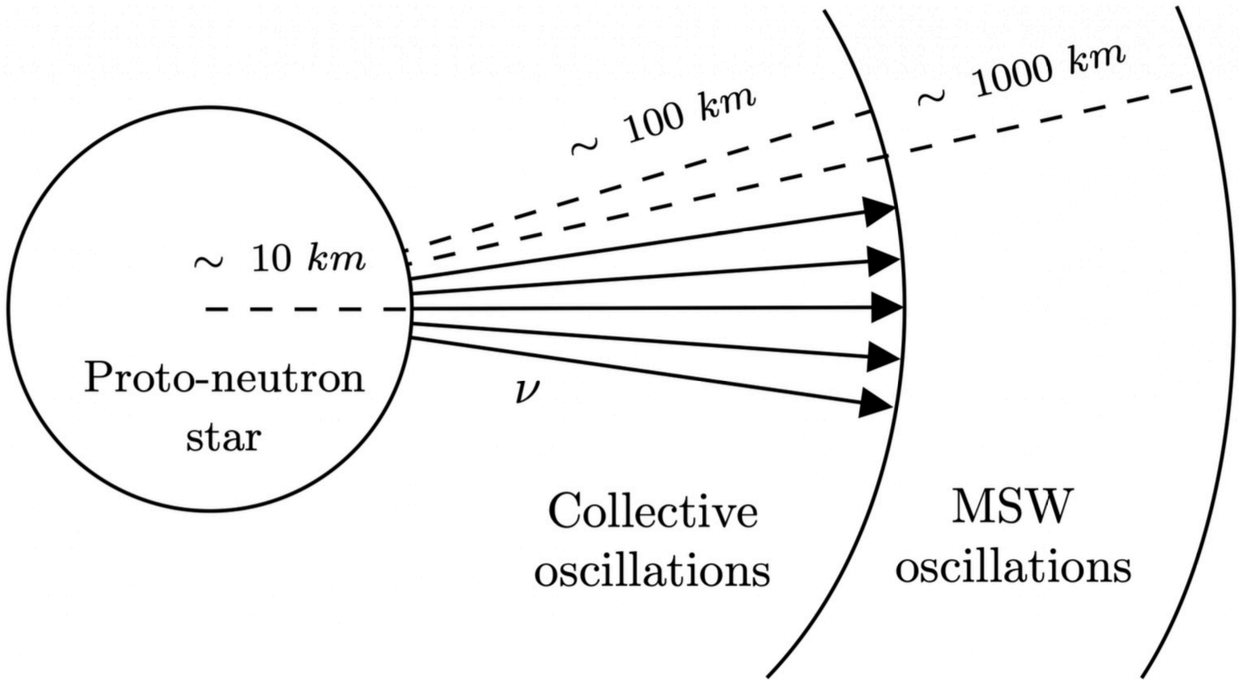
$$H_{\text{glue}} \sim L^2$$

Chapter 2

Entanglement in Dense Systems of Neutrinos

Marc Illa

Neutrino Flavor Dynamics in Supernova



$$|\Psi\rangle = \alpha\,|\nu_e\rangle + \beta\,|\nu_x\rangle$$

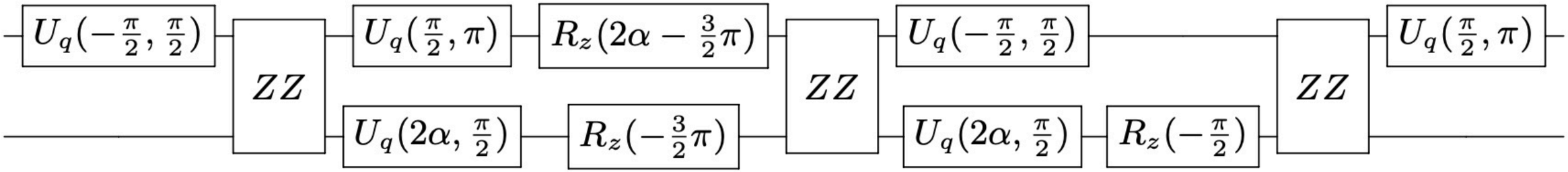
$$H = H^{(1)} + H^{(2)} = \sum_{i=0}^{N-1} h_i + \sum_{i<j}^{N-1} h_{ij}$$

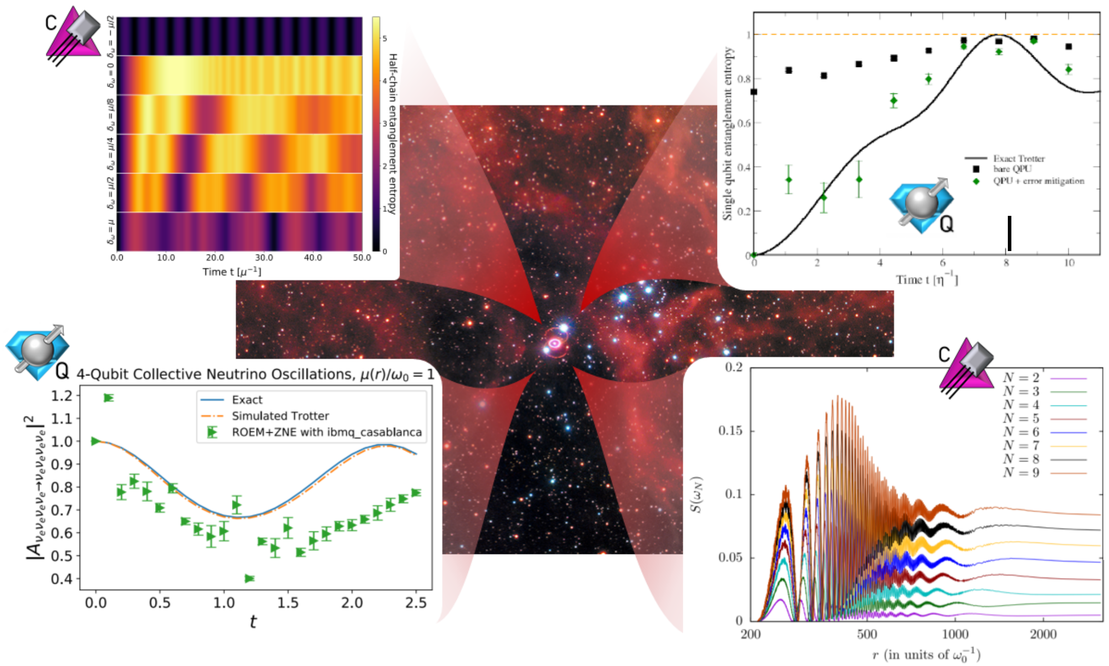
$$= \sum_{i=0}^{N-1} \boldsymbol{b}\cdot\boldsymbol{\sigma}_i + \sum_{i<j}^{N-1} J_{ij}\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j\,,$$

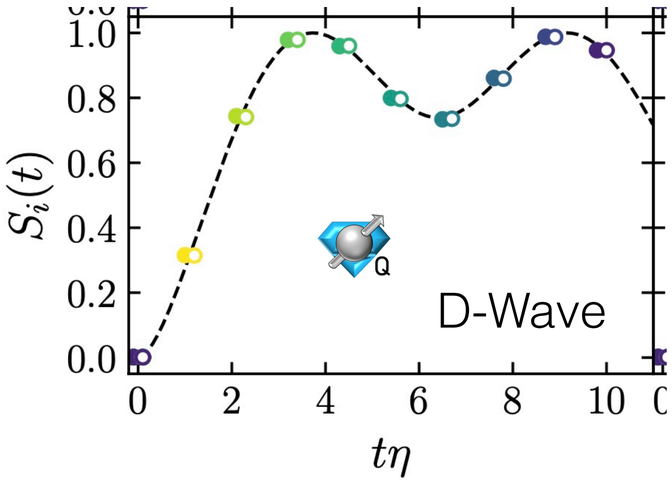
Trapped-Ion Quantum Simulation of Collective Neutrino Oscillations

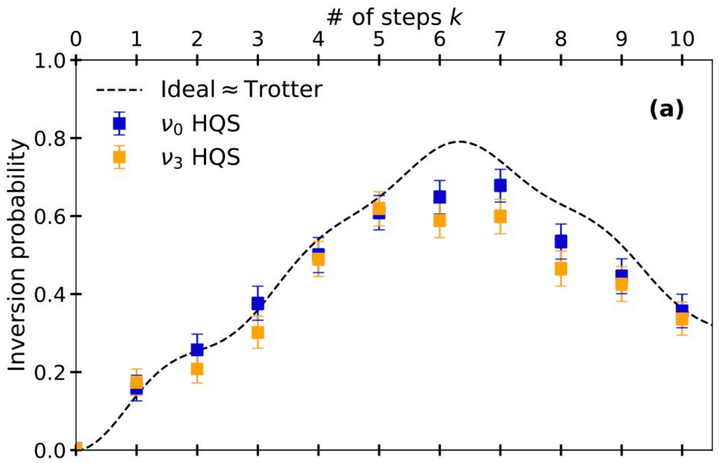
Valentina Amitrano,[1,2] Alessandro Roggero,[1,2] Piero Luchi,[1,2]
Francesco Turro,[1,2] Luca Vespucci,[1,3] and Francesco Pederiva[1,2]

Neutrino Flavor Dynamics in Supernova









18 CNOTS per step
Quantinuum H1-2

A number of independent teams are pursuing these systems

Trapped-Ion Quantum Simulation of Collective Neutrino Oscillations

Valentina Amitrano,[1,2] Alessandro Roggero,[1,2] Piero Luchi,[1,2]
Francesco Turro,[1,2] Luca Vespucci,[1,3] and Francesco Pederiva[1,2]

Coherent Neutrino Systems

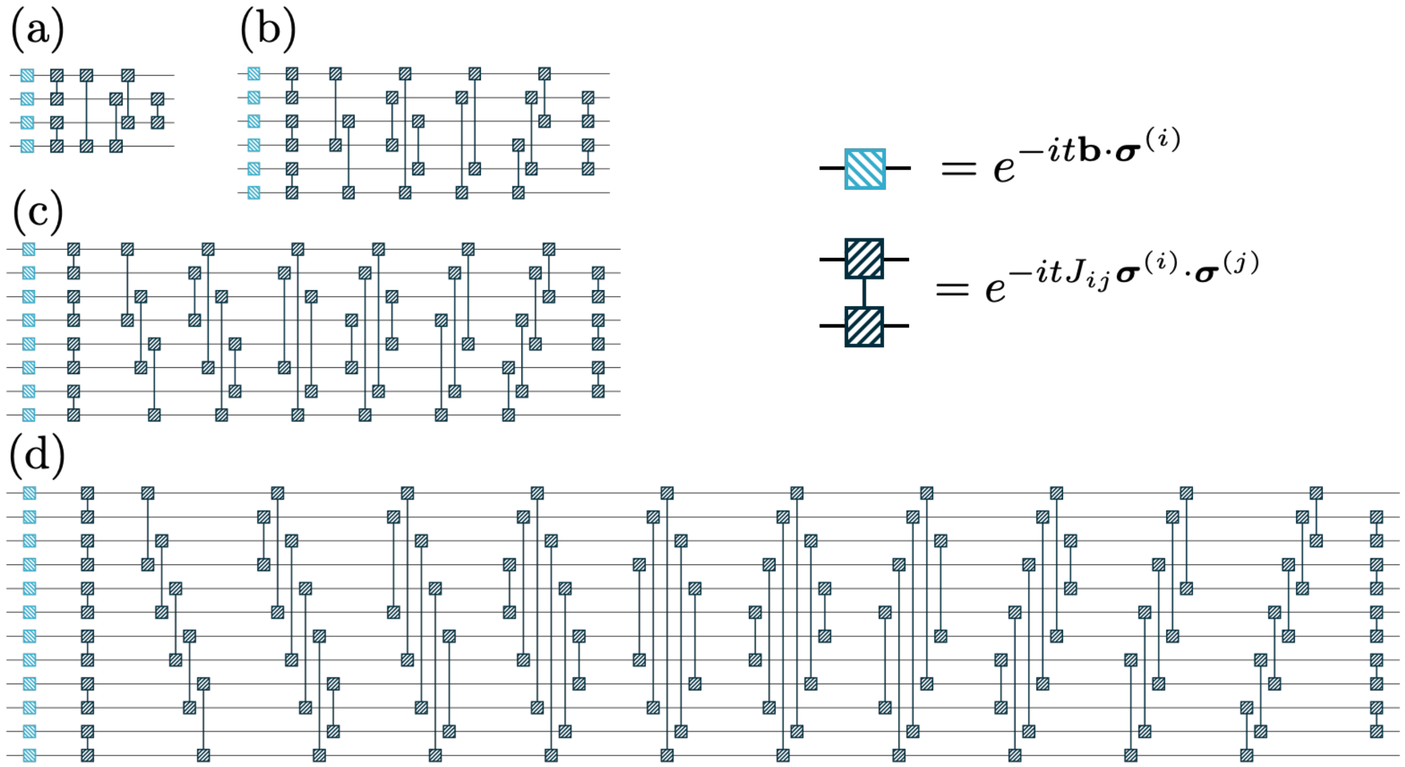
$$H = H^{\nu} + H^{\nu\nu} = \sum_i \mathbf{b}\cdot\boldsymbol{\sigma}^{(i)} + \frac{1}{N}\sum_{i<j} J_{ij}\boldsymbol{\sigma}^{(i)}\cdot\boldsymbol{\sigma}^{(j)}$$

$$\mathbf{b} = \frac{\Delta m^2}{4E}(\sin(2\theta_v), 0, -\cos(2\theta_v))$$

$$J_{ij} = \sqrt{2}G_F\rho_\nu(1-\cos\theta_{ij})$$

$$\theta_{ij} = \arccos(0.9)\times|i-j|/(N-1)$$

$$|\Psi_0\rangle = |\nu_e\rangle^{\otimes N/2}\otimes|\nu_x\rangle^{\otimes N/2}$$

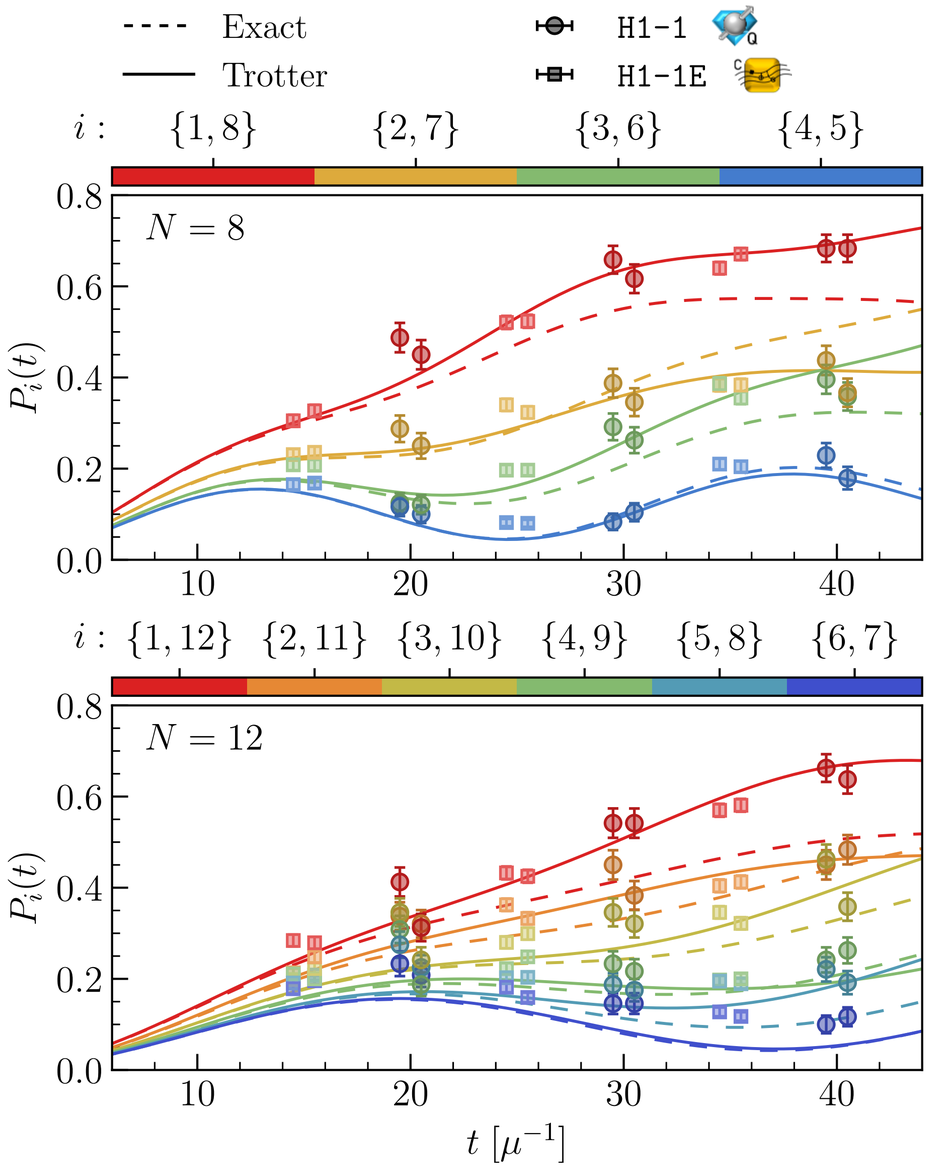


Coherent Neutrino Systems

Quantinuum's H1-1, H1-1E 20 qubit trapped ion quantum computer and emulator

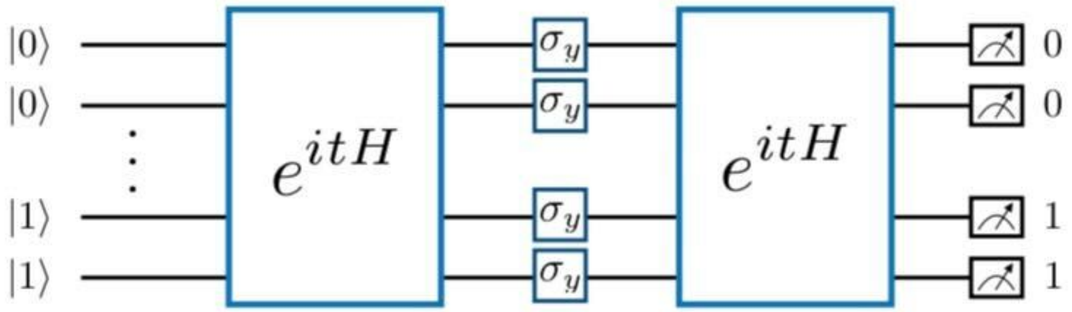
N=4,6,8,12 neutrinos

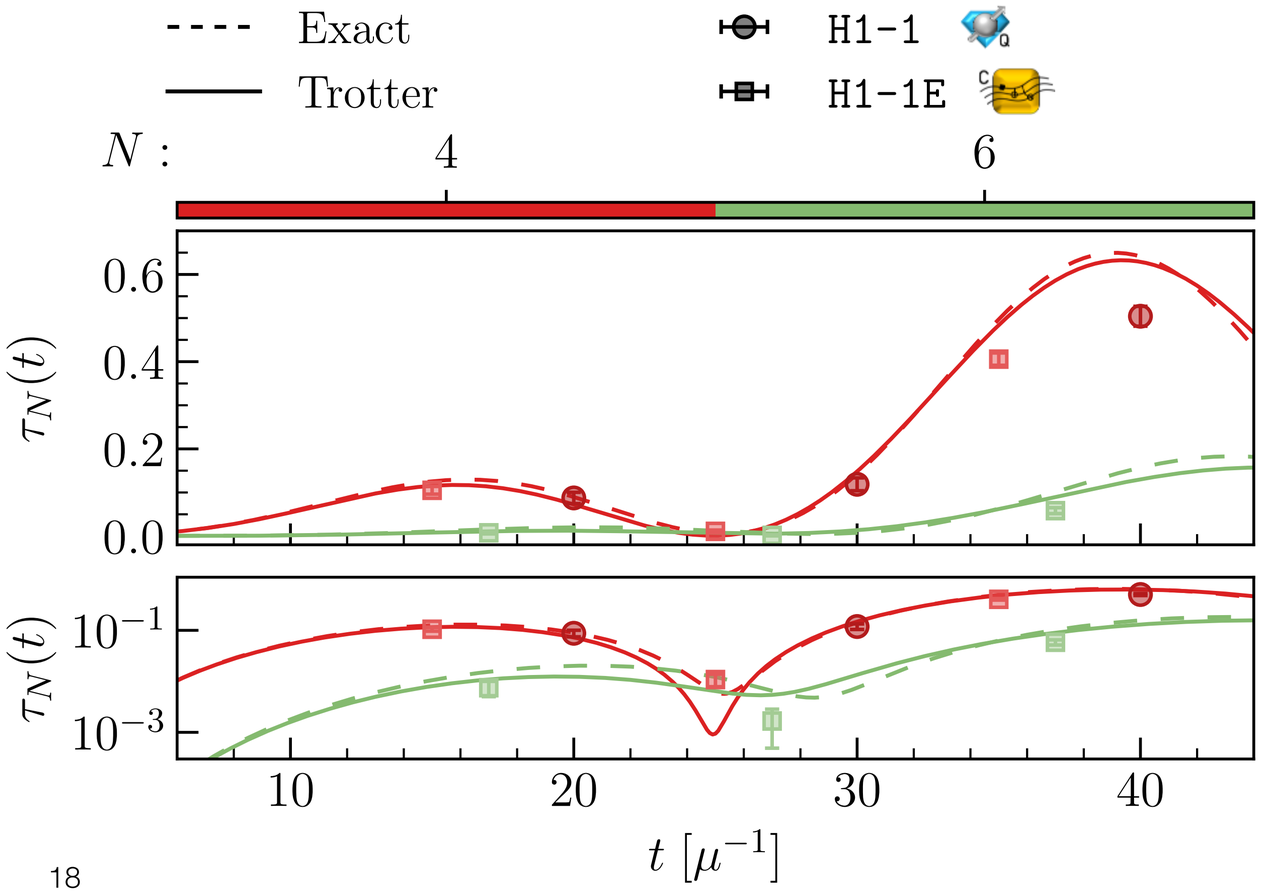
Time evolution
compute state probabilities
correlations
n-tangles



Coherent Neutrino Systems

$$\tau_N(t) = |\langle \Psi_t | \sigma_y^{\otimes N} | \Psi_t^* \rangle|^2 = |\langle \Psi_0 | e^{itH} \sigma_y^{\otimes N} e^{itH} | \Psi_0 \rangle|^2$$



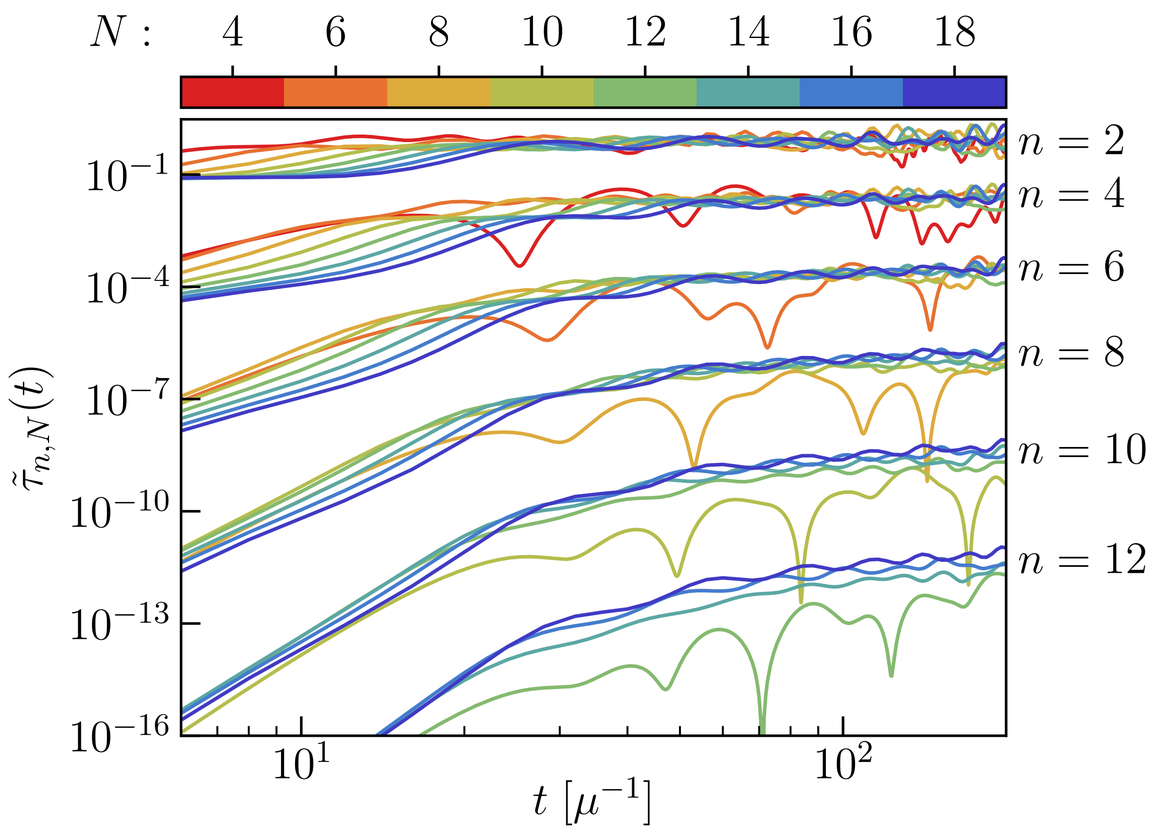


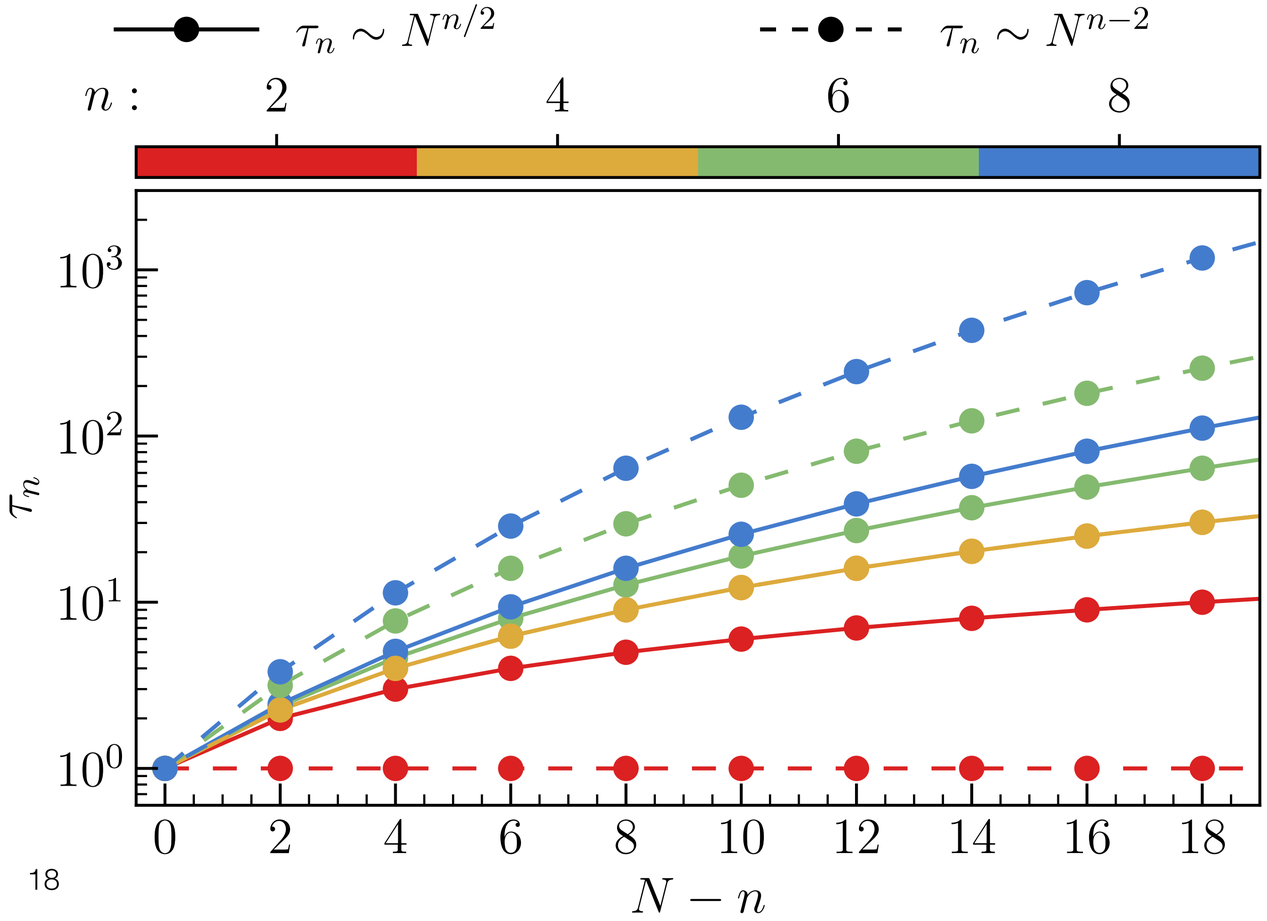
Coherent Neutrino Systems

$$\tilde{\tau}_{n,N} = \frac{1}{N^{n-2}} \sum_i \tau_n^{(i)}$$

$$\tau_n = \binom{N/2}{N/2-n/2} \sim N^{n/2}$$

Bell pairs only

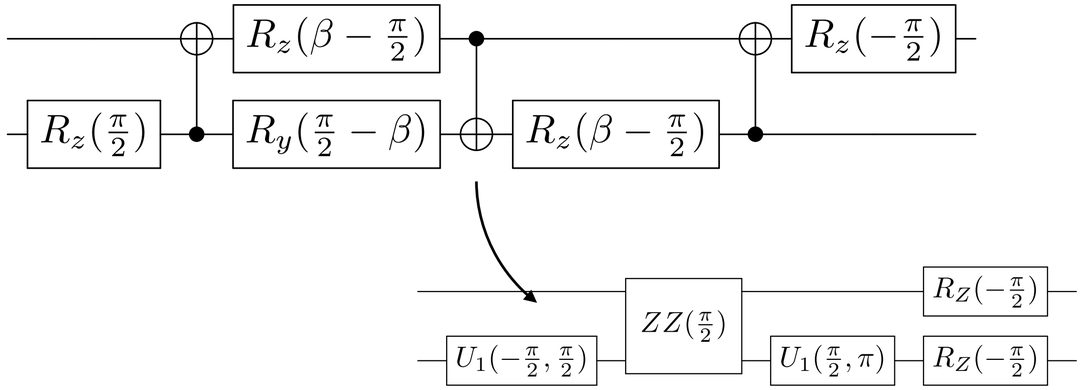




Next Generation Simulations

We have implemented the 2-neutrino term with the SU(4) decomposition:

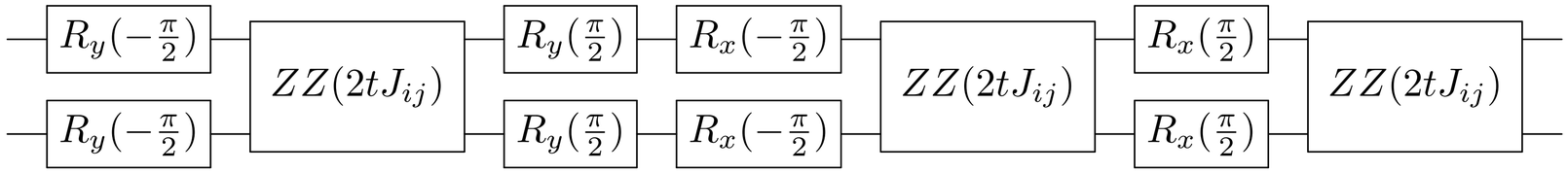
$$e^{-itJ_{ij}\boldsymbol{\sigma}^{(i)}\cdot\boldsymbol{\sigma}^{(j)}} =$$



Quantinuum operation

But it is not the only way to do it…

$$e^{-itJ_{ij}\boldsymbol{\sigma}^{(i)}\cdot\boldsymbol{\sigma}^{(j)}} = e^{-itJ_{ij}\sigma_x^{(i)}\sigma_x^{(j)}}\, e^{-itJ_{ij}\sigma_y^{(i)}\sigma_y^{(j)}}\, e^{-itJ_{ij}\sigma_z^{(i)}\sigma_z^{(j)}}$$



New Quantinuum gate: $ZZ(\theta) \quad \forall\theta \qquad \mathrm{err}[ZZ(\theta)] \propto \sqrt{\theta}$

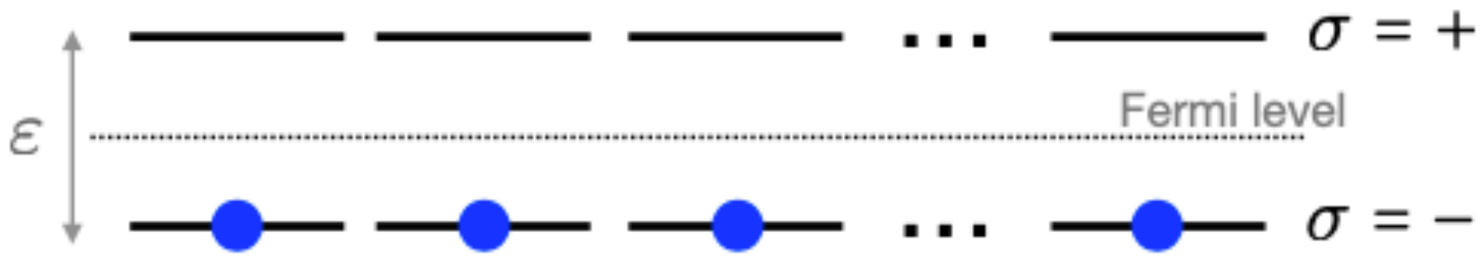
(as of October)

Chapter 3

Hamiltonian Learning-VQE for Effective Model Spaces of the Lipkin-Meshkov-Glick Model

Caroline Robin - U of Bielefeld and GSI

Lipkin-Meshkov-Click Model
Nuclear Surface



N particles distributed on two N-fold degenerate levels

$$H = \frac{\varepsilon}{2}\sum_{\sigma p}\sigma c^{\dagger}_{p\sigma}c_{p\sigma} - \frac{V}{2}\sum_{pq\sigma} c^{\dagger}_{p\sigma}c^{\dagger}_{q\sigma}c_{q-\sigma}c_{p-\sigma}$$

$$= \varepsilon J_z - \frac{V}{2}\left(J_+^2 + J_-^2\right)$$

$$J_z = \frac{1}{2}\sum_{p\sigma}\sigma c^{\dagger}_{p\sigma}c_{p\sigma}$$

$$J_+ = \sum_{p}\sigma c^{\dagger}_{p+}c_{p-}\ , \qquad J_- = \left(J_+\right)^{\dagger}$$

exact solutions: $$|\Psi^{(J)}_{ex}\rangle = \sum_{M=-J}^{J} A_{J,M}|J,M\rangle \equiv \sum_{n=0}^{2J} A_n|n\rangle$$

↘ *np-nh* excitation

Lipkin-Meshkov-Click Model
Transformation and Truncation

$$\begin{pmatrix} c_{p+}(\beta) \\ c_{p-}(\beta) \end{pmatrix} = \begin{pmatrix} \cos(\beta/2) & -\sin(\beta/2) \\ \sin(\beta/2) & \cos(\beta/2) \end{pmatrix} \begin{pmatrix} c_{p+} \\ c_{p-} \end{pmatrix}$$

$$\begin{aligned} H(\beta) =& \varepsilon\Big[\cos\beta J_z(\beta) + \frac{1}{2}\sin\beta\big(J_+(\beta) + J_-(\beta)\big)\Big] \\ & - \frac{V}{4}\Big[\sin^2\beta\big(4J_z(\beta)^2 - \{J_+(\beta), J_-(\beta)\}\big) + (1+\cos^2\beta)\big(J_+(\beta)^2 + J_-(\beta)^2\big) \\ & \quad - 2\sin\beta\cos\beta\big(\{J_z(\beta), J_+(\beta)\} + \{J_z(\beta), J_-(\beta)\}\big)\Big] \end{aligned}$$

Λ Cut off defining an effective model space

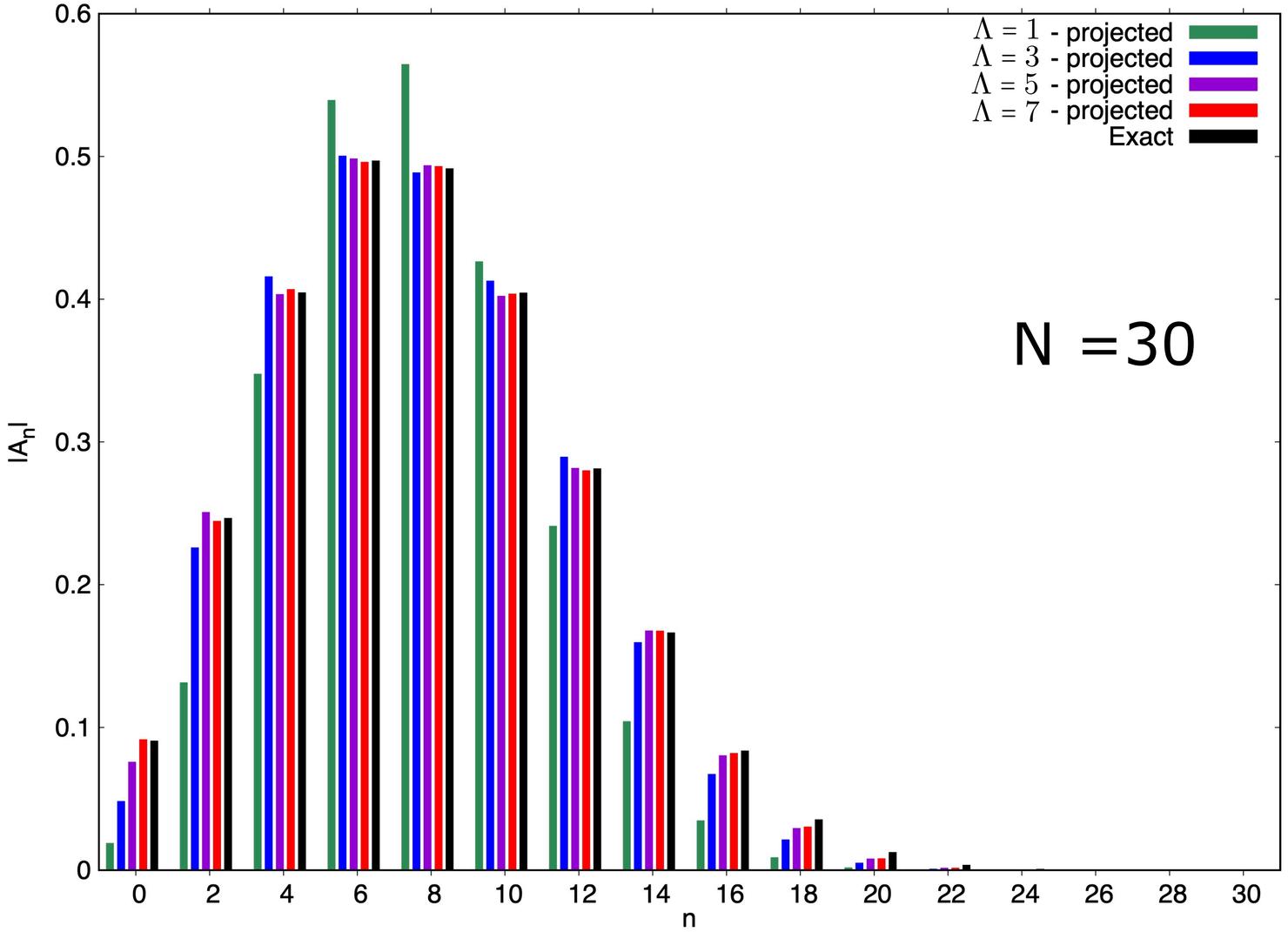
$$|\Psi\rangle = \sum_{n=0}^{\Lambda-1} A_n^{(\beta)} |n,\beta\rangle$$ Effective wave function

$$\langle \Psi(\{A_n^{(\beta)}\}) | H(\beta) | \Psi(\{A_n^{(\beta)}\}) \rangle$$

What are its convergence properties and of other observables?

We need to learn H in each truncated space

Lipkin-Meshkov-Click Model
Convergence in Truncation



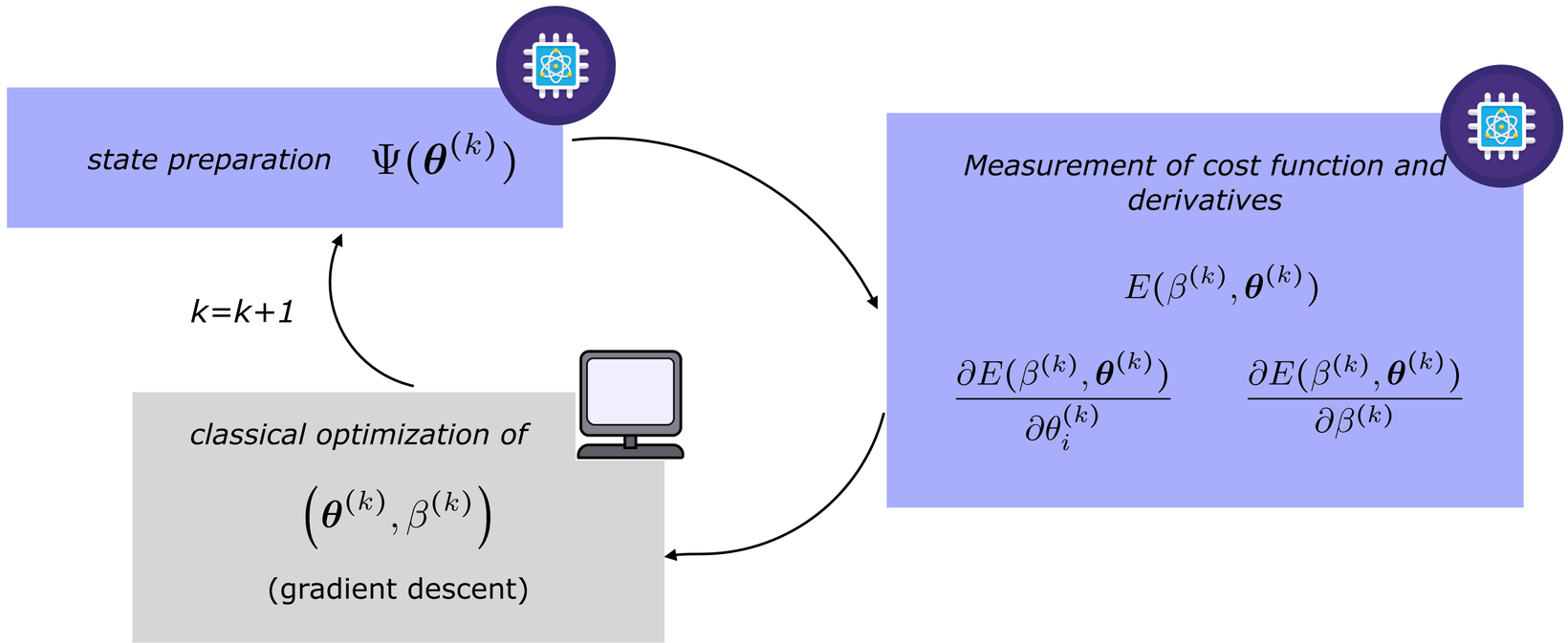
Lipkin-Meshkov-Click Model
Iterative Hamiltonian Learning and VQE

★*Hamiltonian-Learning-VQE:*

$$\overline{\sigma} = \{\hat{I}, \hat{X}, \hat{Y}, \hat{Z}\}$$

Cost function to minimize: $E(\beta, \boldsymbol{\theta}) = \langle \Psi(\boldsymbol{\theta}) | \hat{H}(\beta) | \Psi(\boldsymbol{\theta}) \rangle$

$$= \sum_{i_1,..,i_{n_q}} h_{i_i,..,i_{n_q}}(\beta) \, \langle \Psi(\boldsymbol{\theta}) | \overline{\sigma}_{i_1} \otimes \ ... \otimes \overline{\sigma}_{i_{n_q}} | \Psi(\boldsymbol{\theta}) \rangle$$

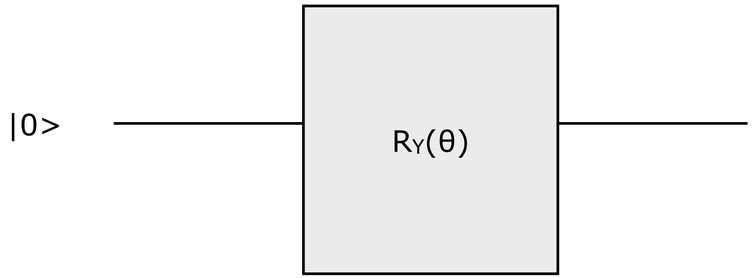


⇒ learns the effective Hamiltonian and identifies the associated ground state simultaneously

Lipkin-Meshkov-Click Model
(Simple) Quantum Circuits for State Preparation

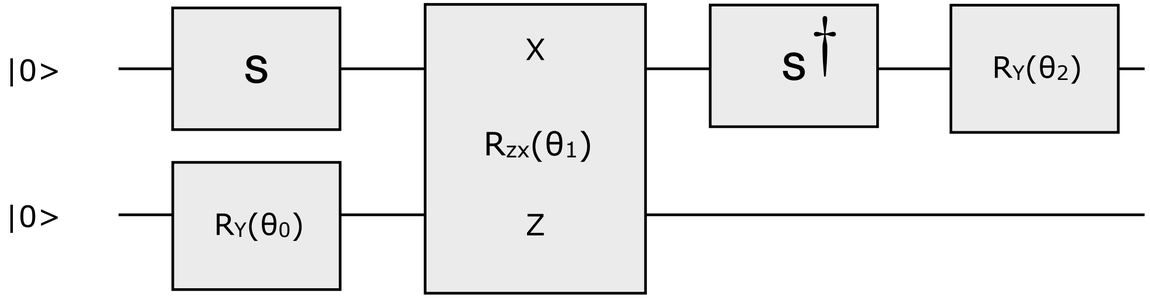
✳1 qubit (Λ = 2):

$$|\Psi(\theta)\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + \sin\left(\frac{\theta}{2}\right)|1\rangle$$



✳2 qubits (Λ = 4):

$$|\Psi(\theta_0, \theta_1, \theta_2)\rangle$$

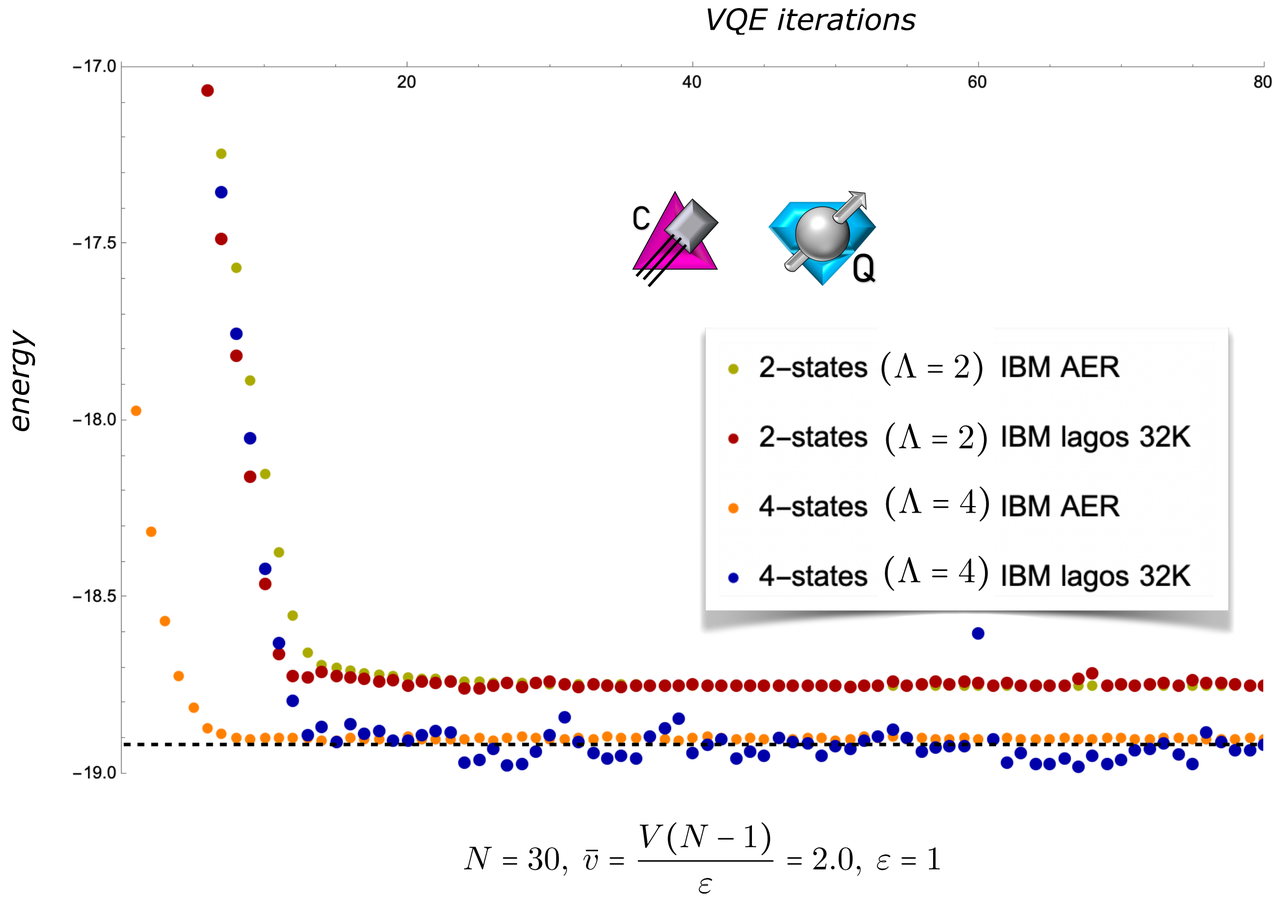


$$R_{ZX}(\theta) = e^{-i\frac{\theta}{2}\hat{X}\otimes\hat{Z}}$$

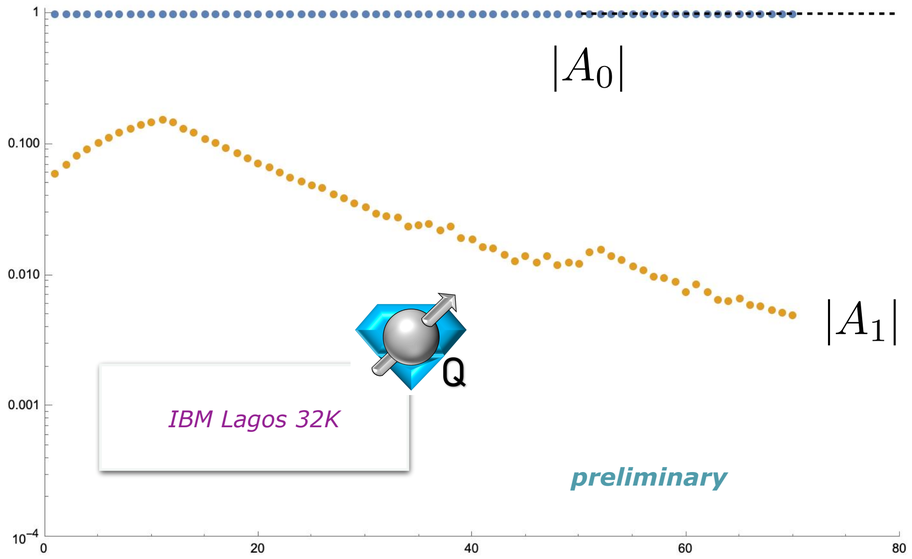
Lipkin-Meshkov-Click Model
Results from IBM's Simulators and Quantum Computers

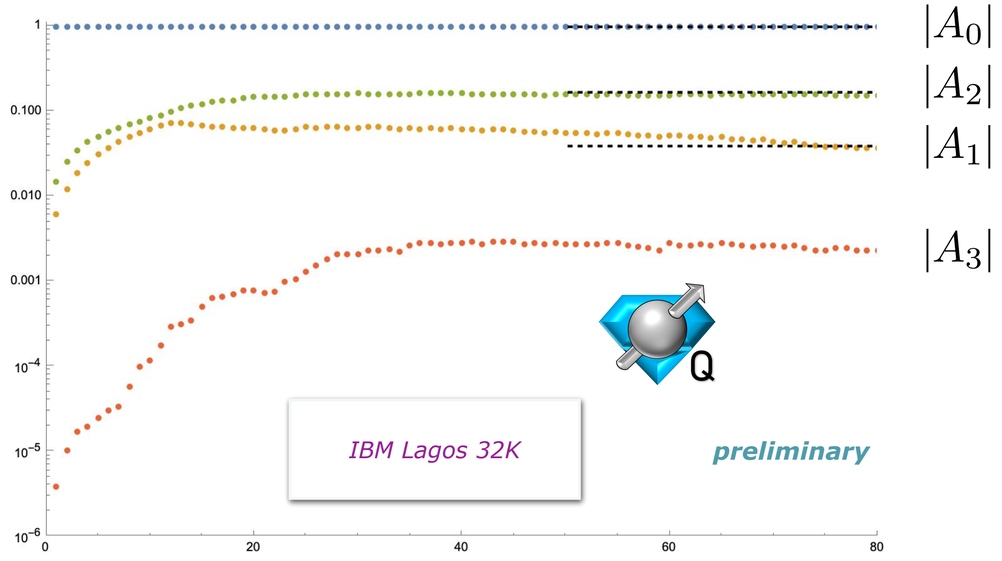
✳1 qubit ($\Lambda = 2$):

✳2 qubits ($\Lambda = 4$):

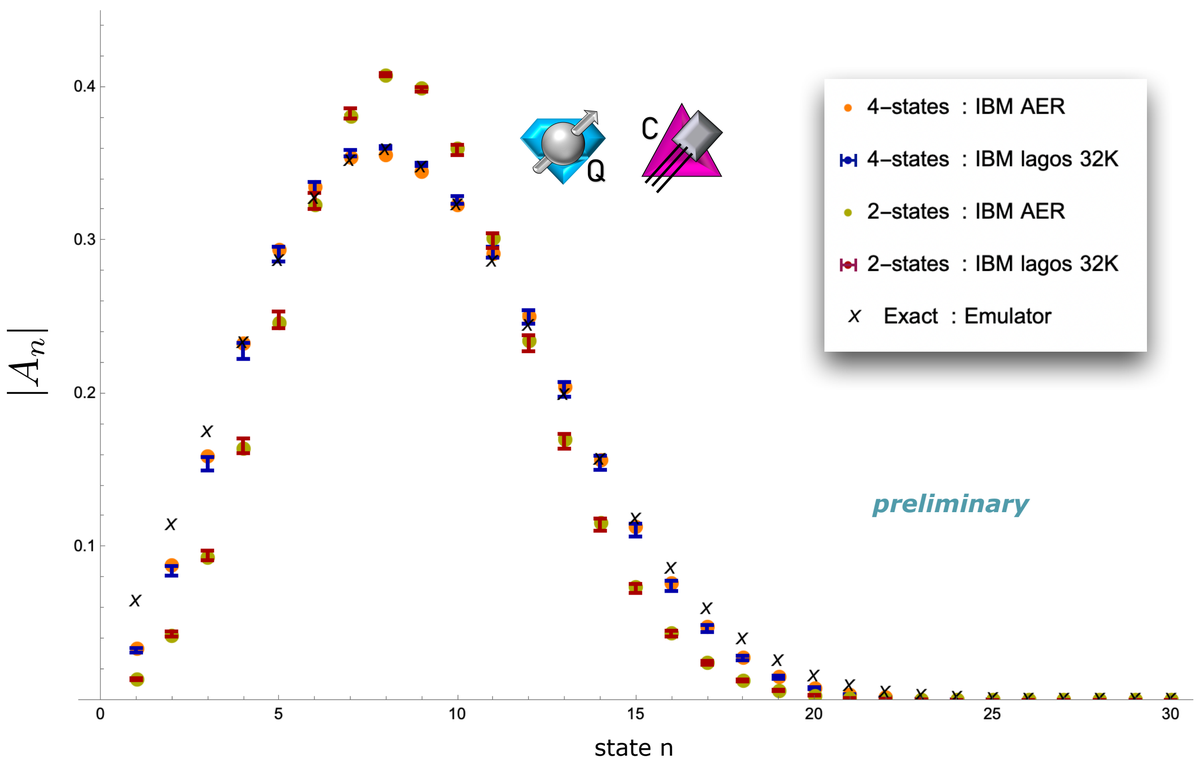


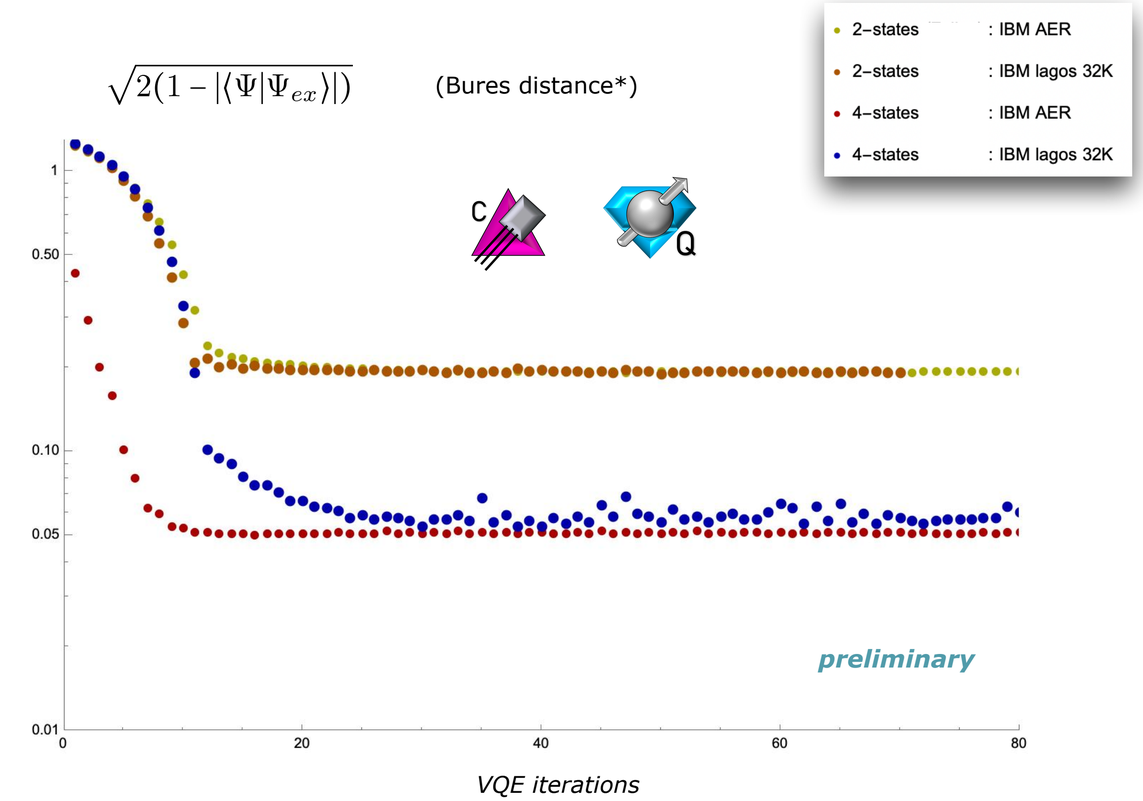
$$N = 30,\ \bar{v} = \frac{V(N-1)}{\varepsilon} = 2.0,\ \varepsilon = 1$$

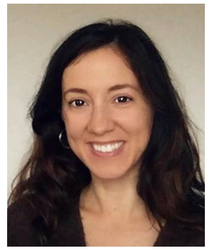


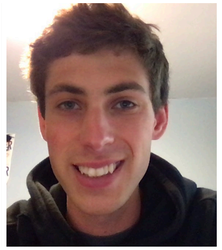


Lipkin-Meshkov-Click Model
Reconstruction the Full-Space Wavefunction

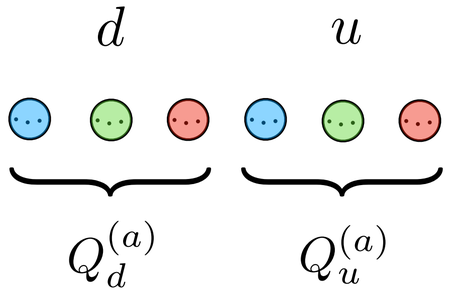


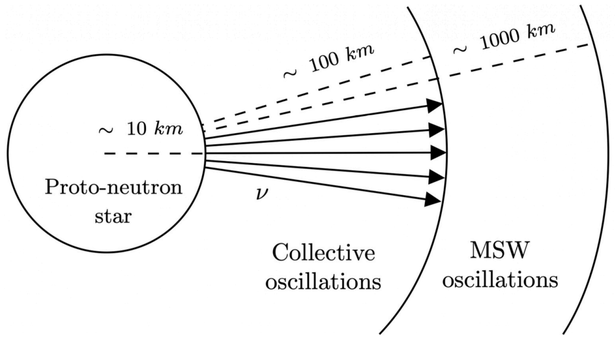


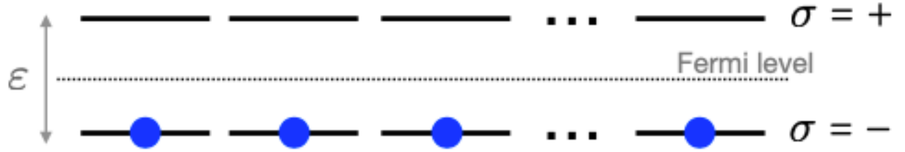




Summary







- Progress in 3 digital quantum simulation projects
  - lattice QCD + weak decays , coherent neutrino evolution , and Lipkin-Meshkov-Glick model
- We are gaining insight into systems relevant to nuclear physics and estimating quantum resources
- Algorithms

Office of Science
U.S. Department of Energy

QUANTUM SCIENCE CENTER

OAK RIDGE National Laboratory

I am very grateful to my collaborators, colleagues, friends, funding agencies, UW, and more

FIN