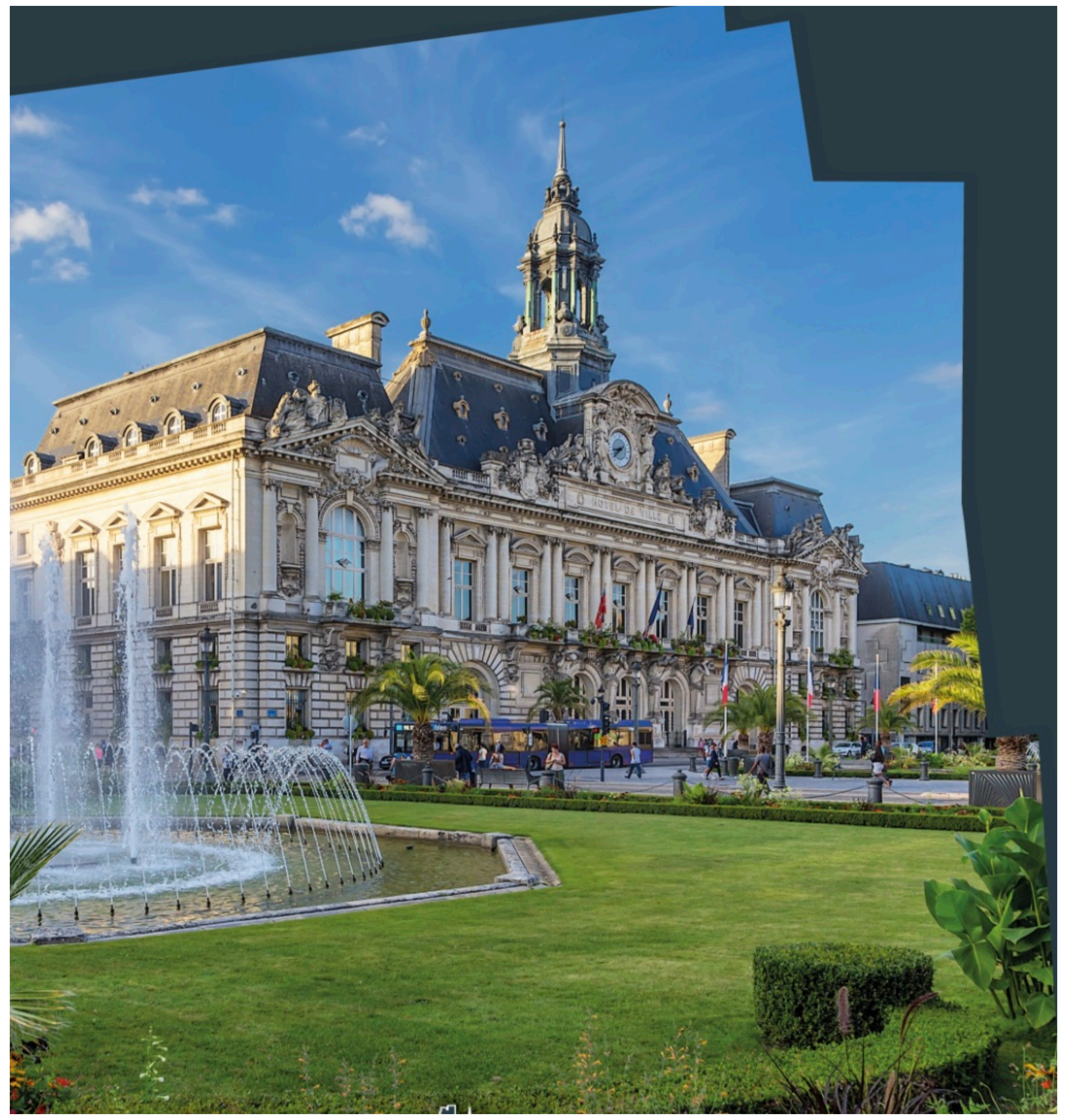
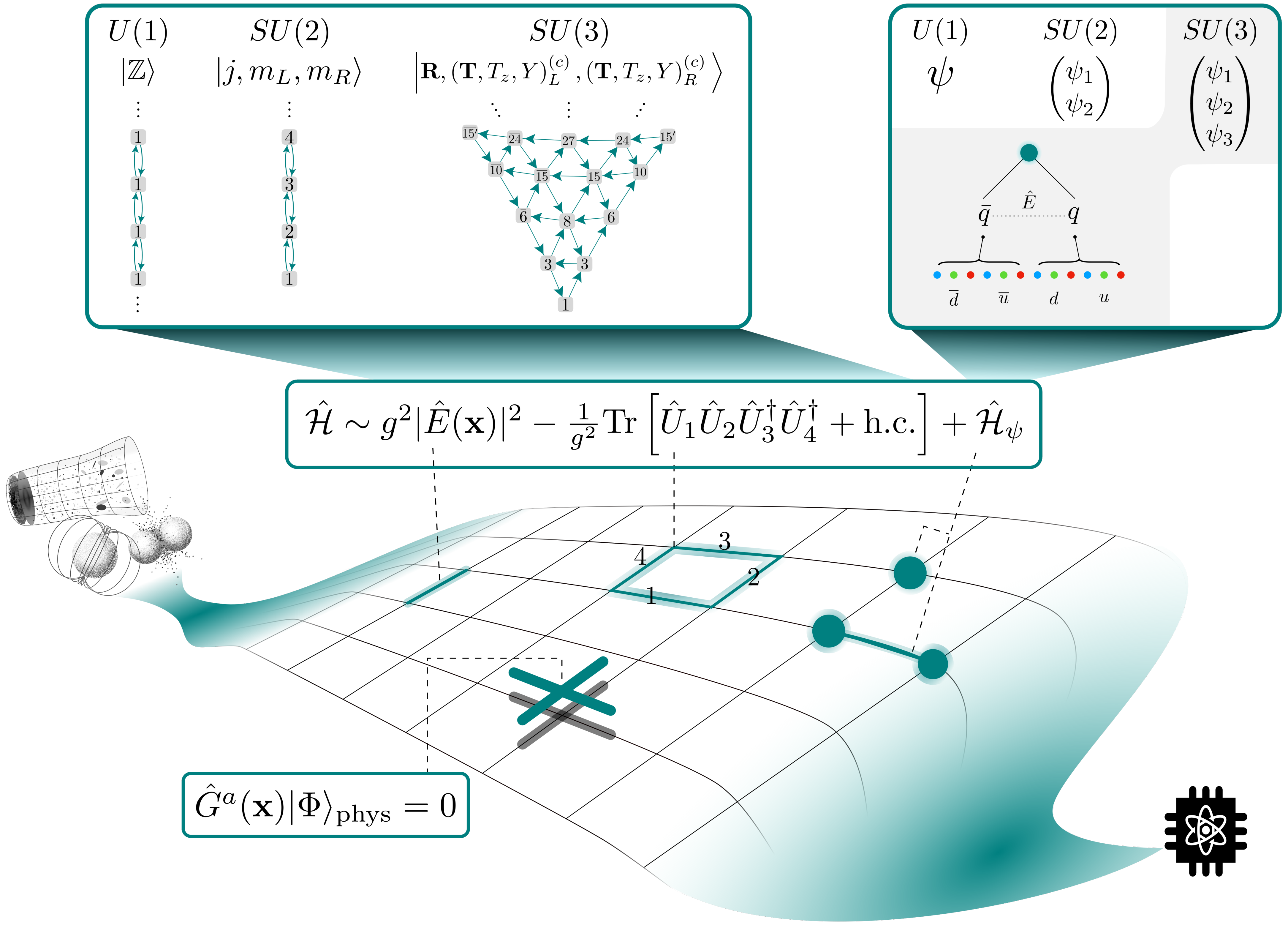
Toward Digital Quantum Simulations of Standard Model Physics
- a look from my path

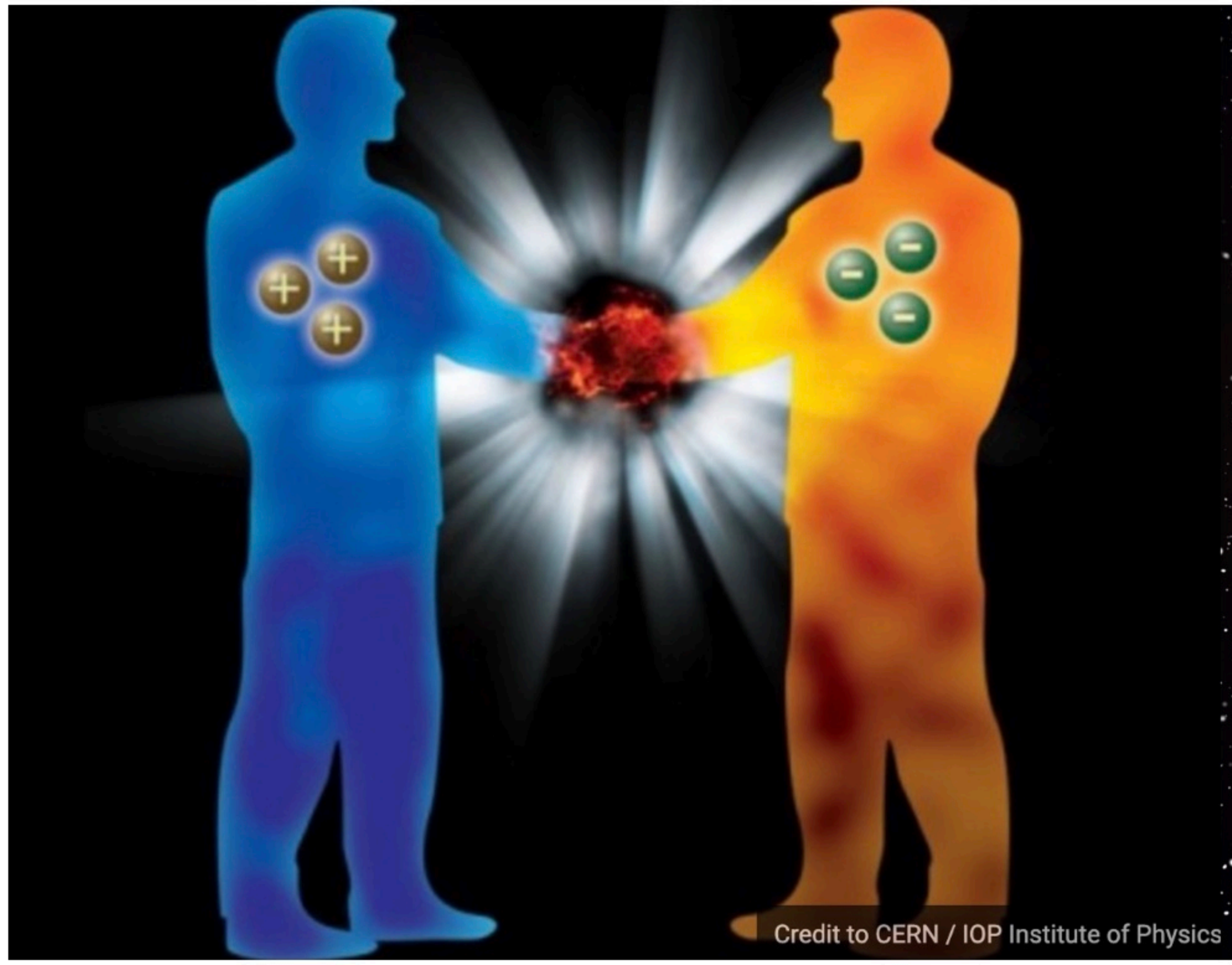


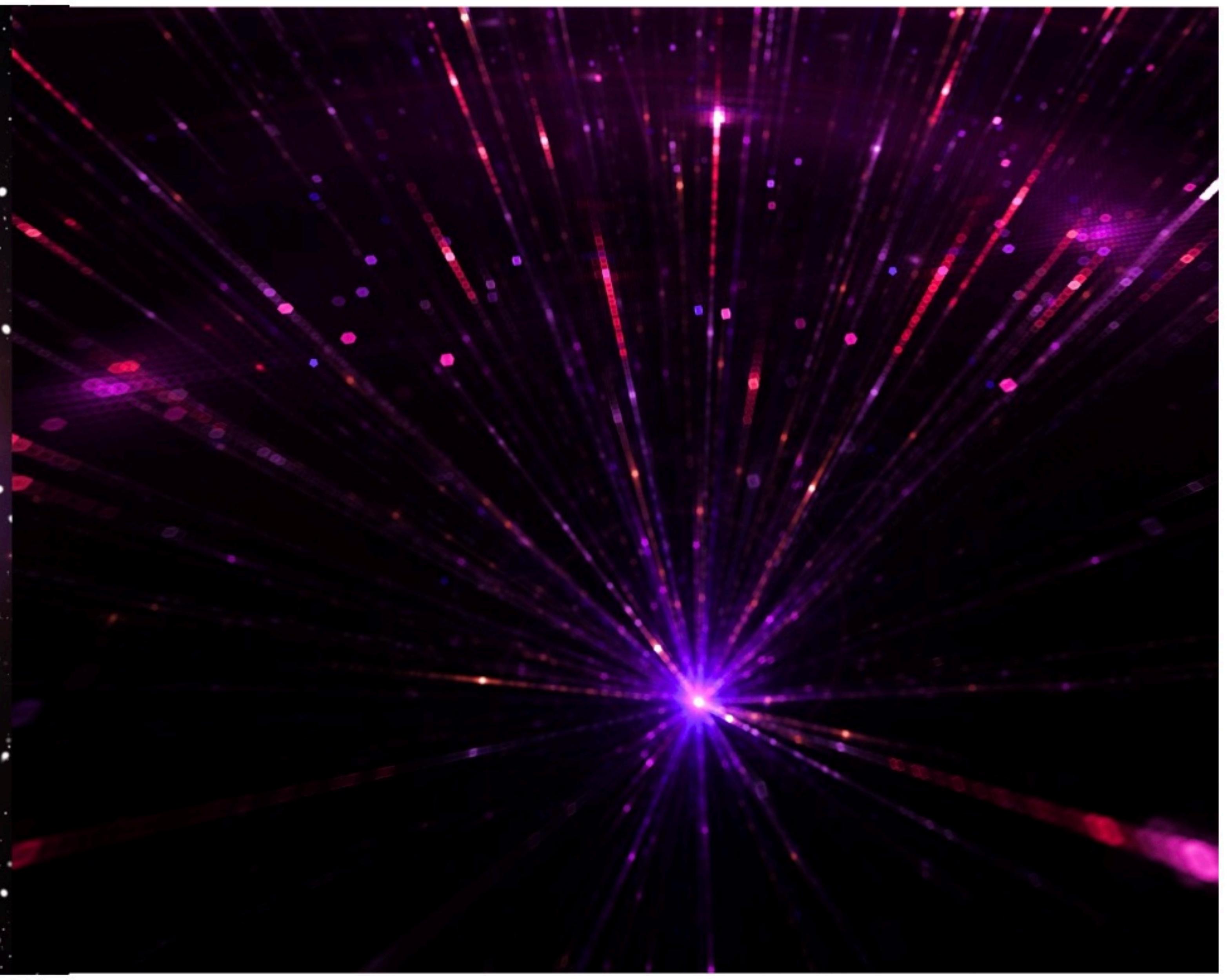
Martin Savage
InQubator for Quantum Simulation
University of Washington

Chiral Matter
Tours, July 05, 2023



Matter in Extreme ``Situations”





The Matter-Antimatter Asymmetry

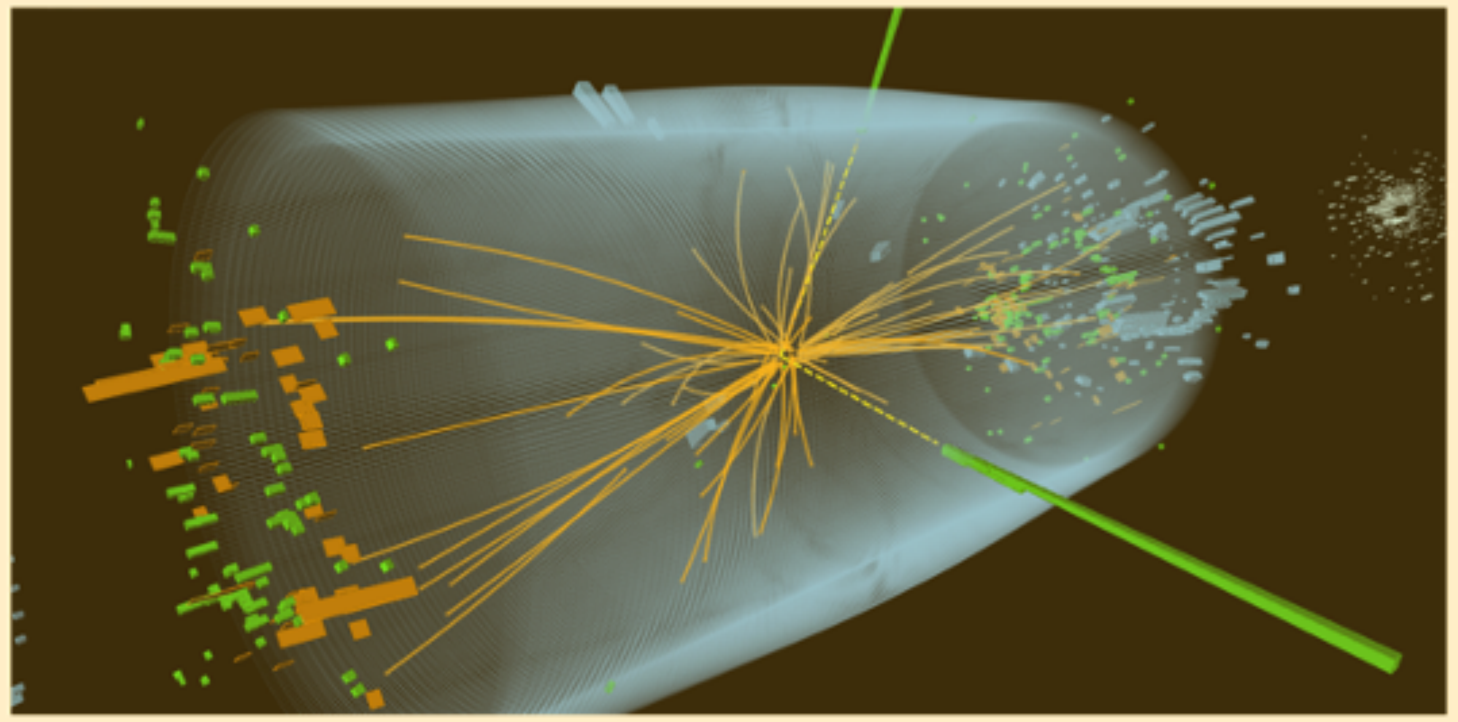
Astrophysical Environments

Collisions and Reactions

Particles & Interactions
Simulation
Phases & Dynamics of Matter
Quarks
Leptons
Gauge Bosons
Higgs Boson
c s d t u b g γ H Z^0 $W^{\pm}$ e ν_τ μ ν_μ τ ν_e
0100
0011
Classic Computing
Quantum Computing
Quantum Entanglement
Early Universe
High-energy Particle Collisions
Neutron Star Core
Standard Model
Bauer, Davoudi, Klco, Savage

Simulation Objectives for the Standard Model and Beyond

Gauge Theories and Descendent Effective Field Theories and Models



Real-time dynamics
particle production, fragmentation
vacuum and in medium

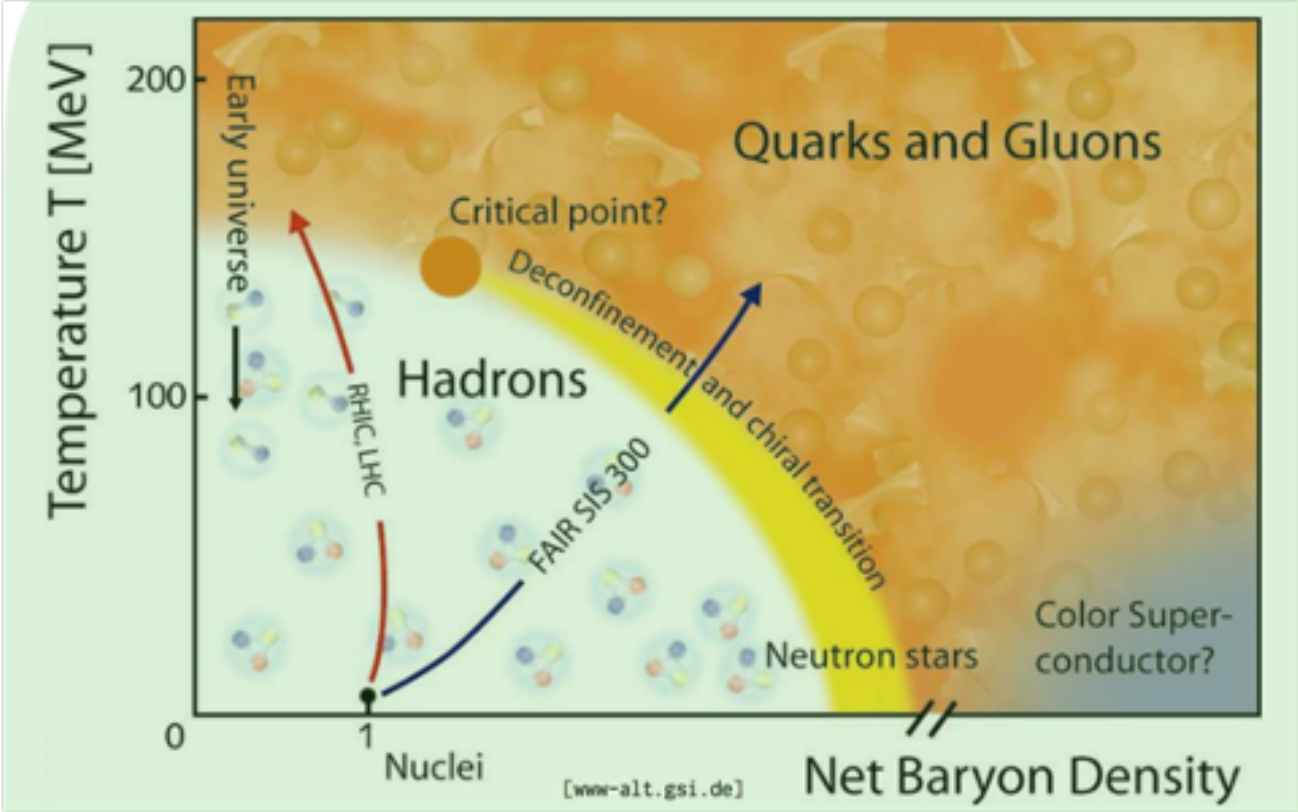
Low-energy reactions

Electroweak processes (e.g., nu-A)

Neutrino dynamics

Matter-antimatter asymmetry

BQP

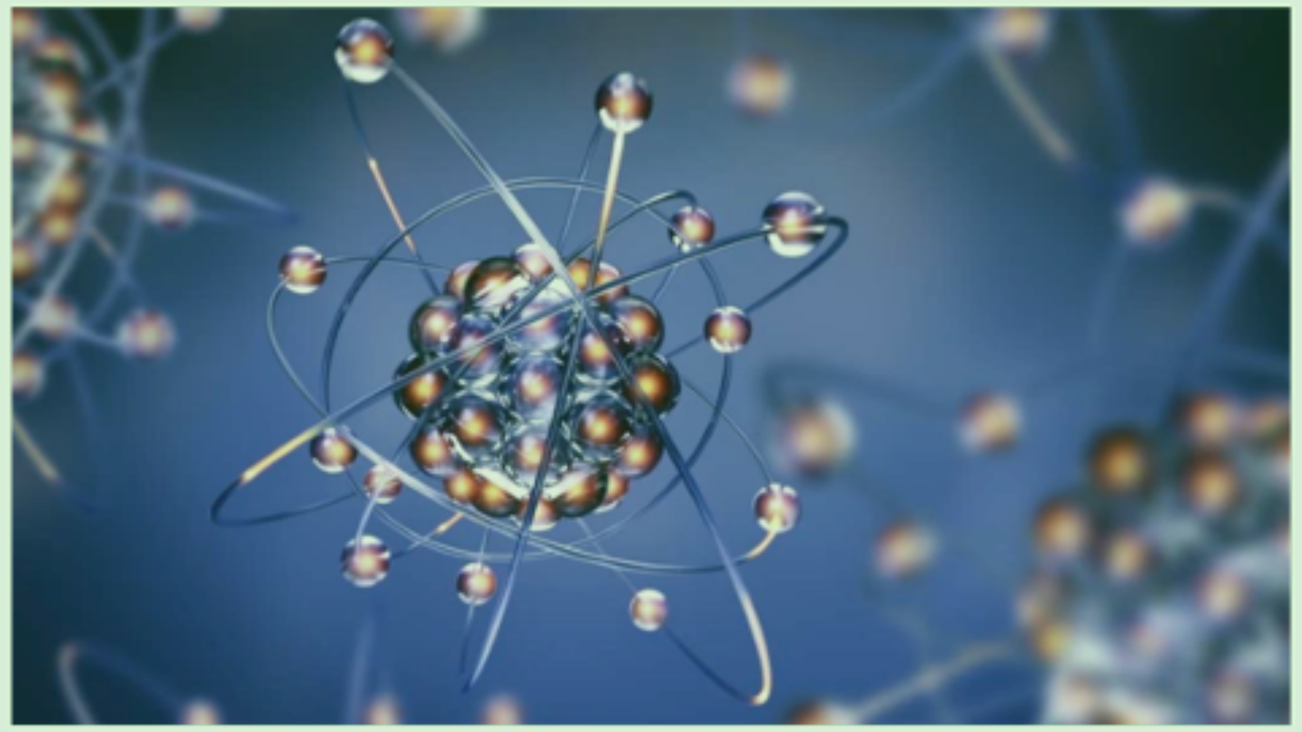


Equation of state of dense
hot matter and dynamics
viscosity, etc

Conquering some "sign problems"

The early universe

Supernova/Neutron stars



Precision structure and interactions
of nuclei

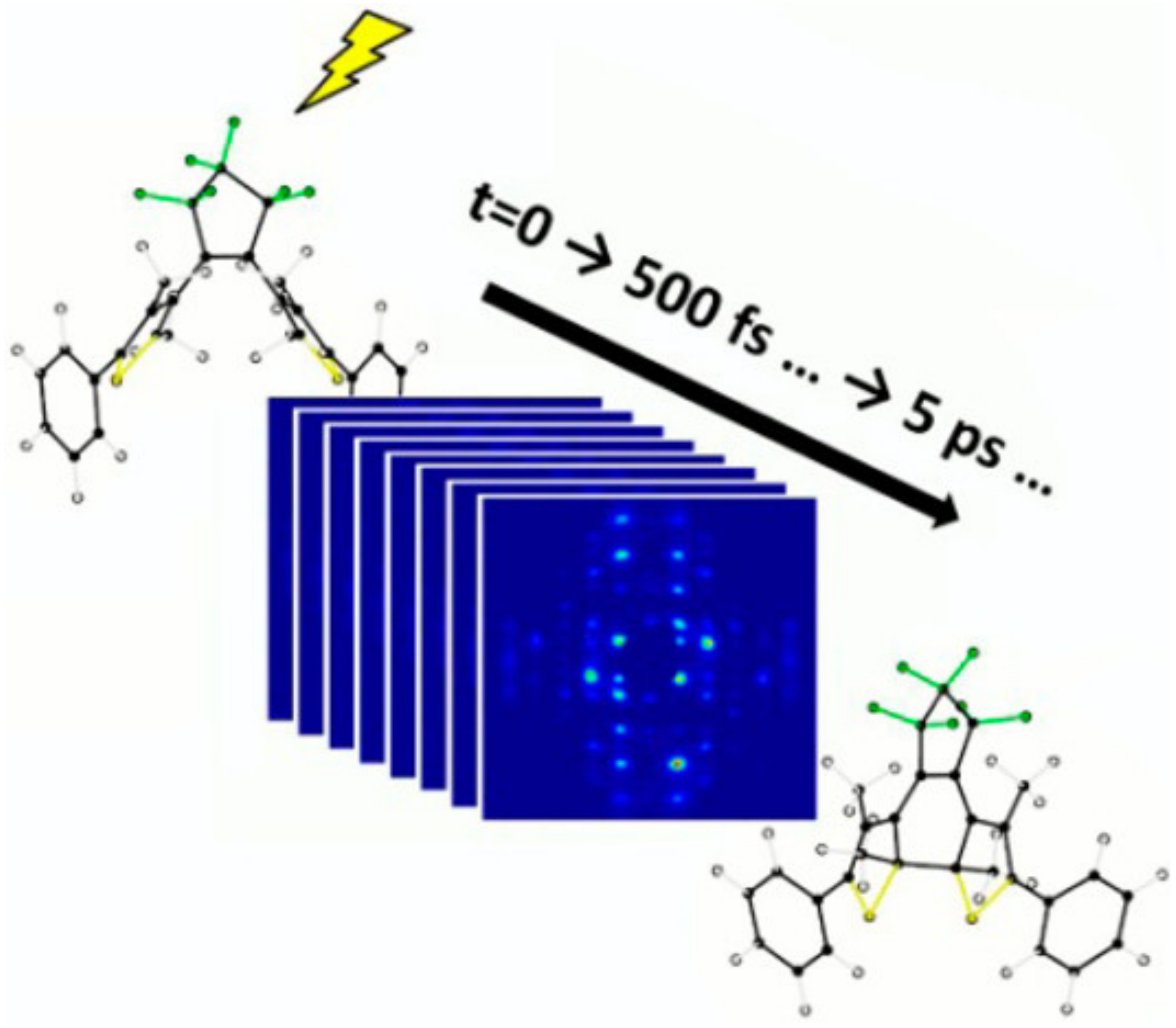
Many-body systems

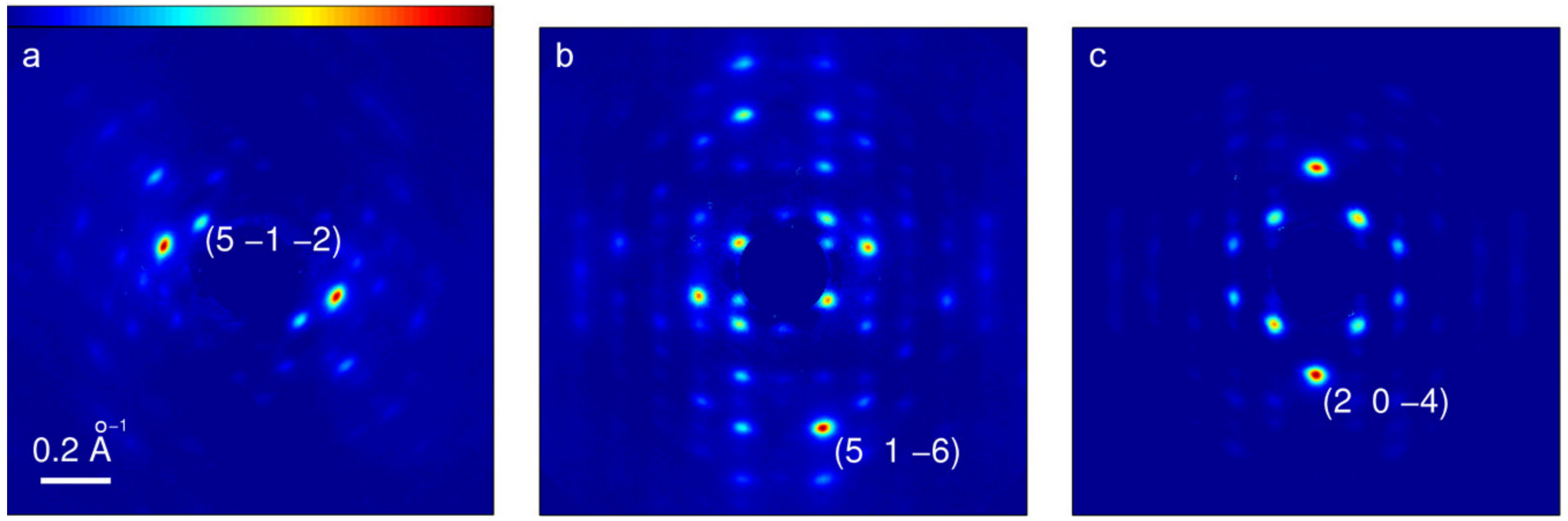
Rare processes, double-beta decay

QMA

– symmetries

Real-Time Dynamics and
Improved Modeling of Reaction Pathways





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

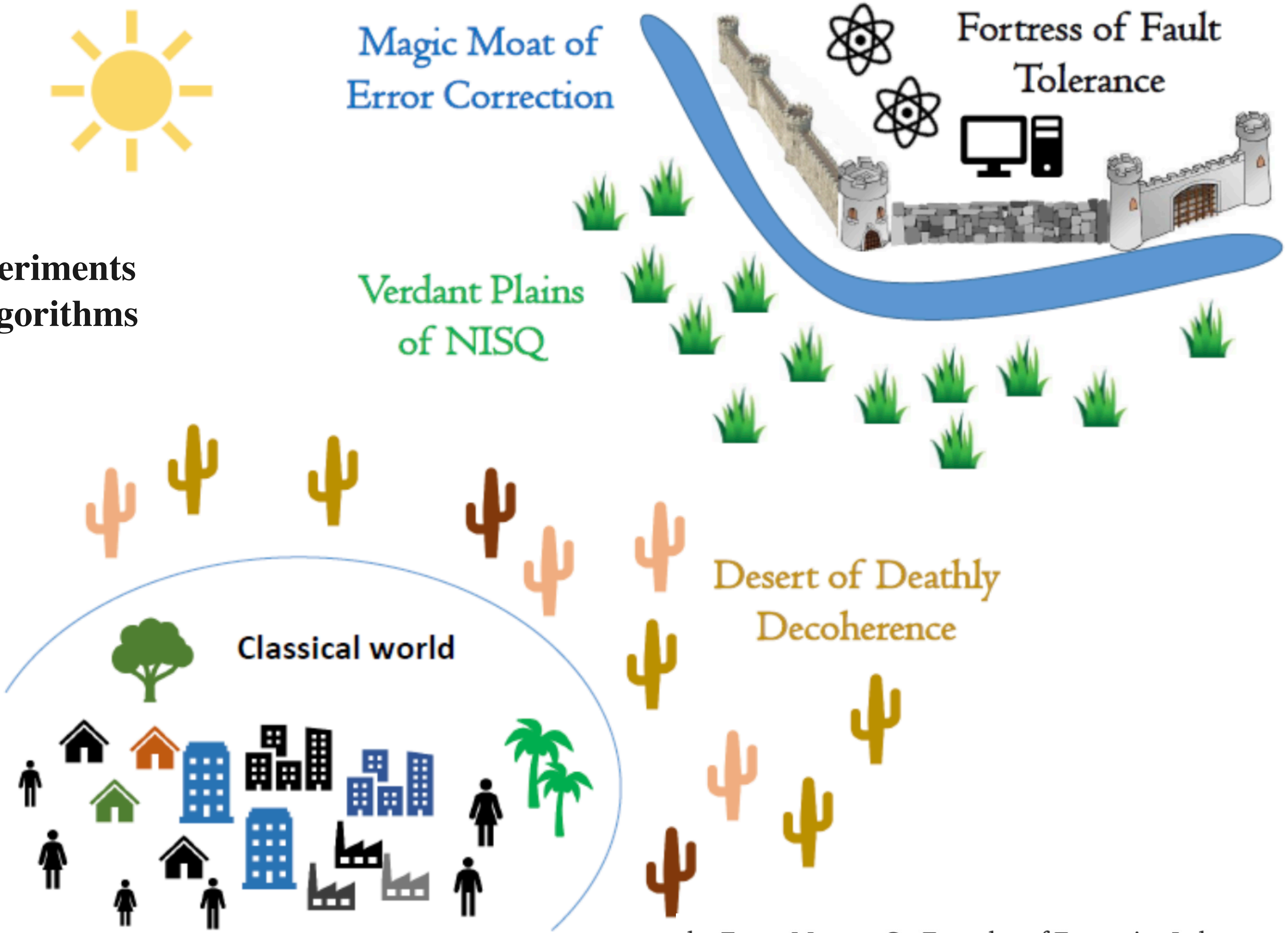
Femto-second chemistry reveals reaction mechanisms
Quantum simulations will reveal the reactions pathways of QCD

Quantum Simulation in the NISQ Era

Today: Error Mitigation and Dreaming of Correction

Precision simulations to compare with experiments and make reliable predictions

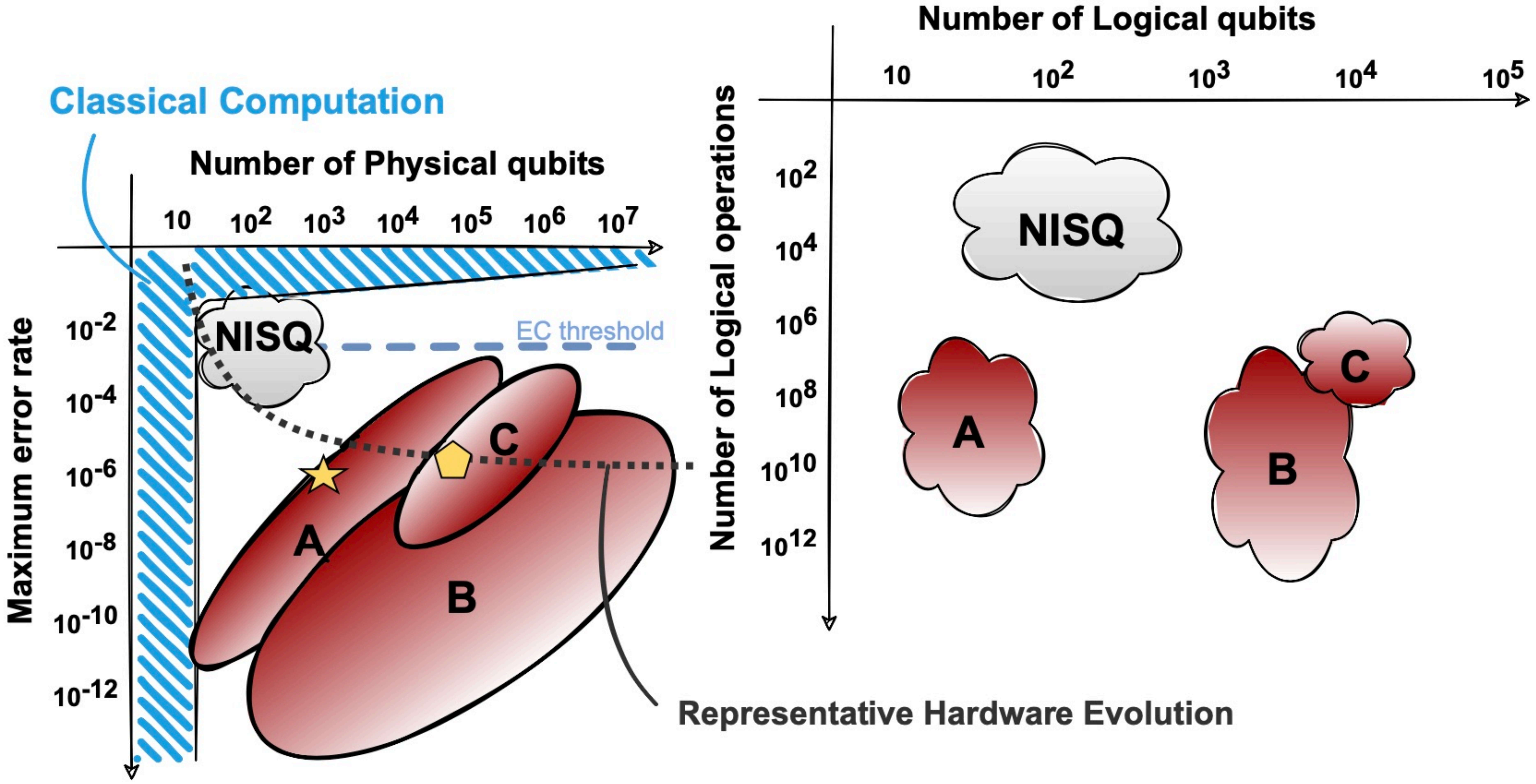
QIS motivates new experiments and observables and algorithms



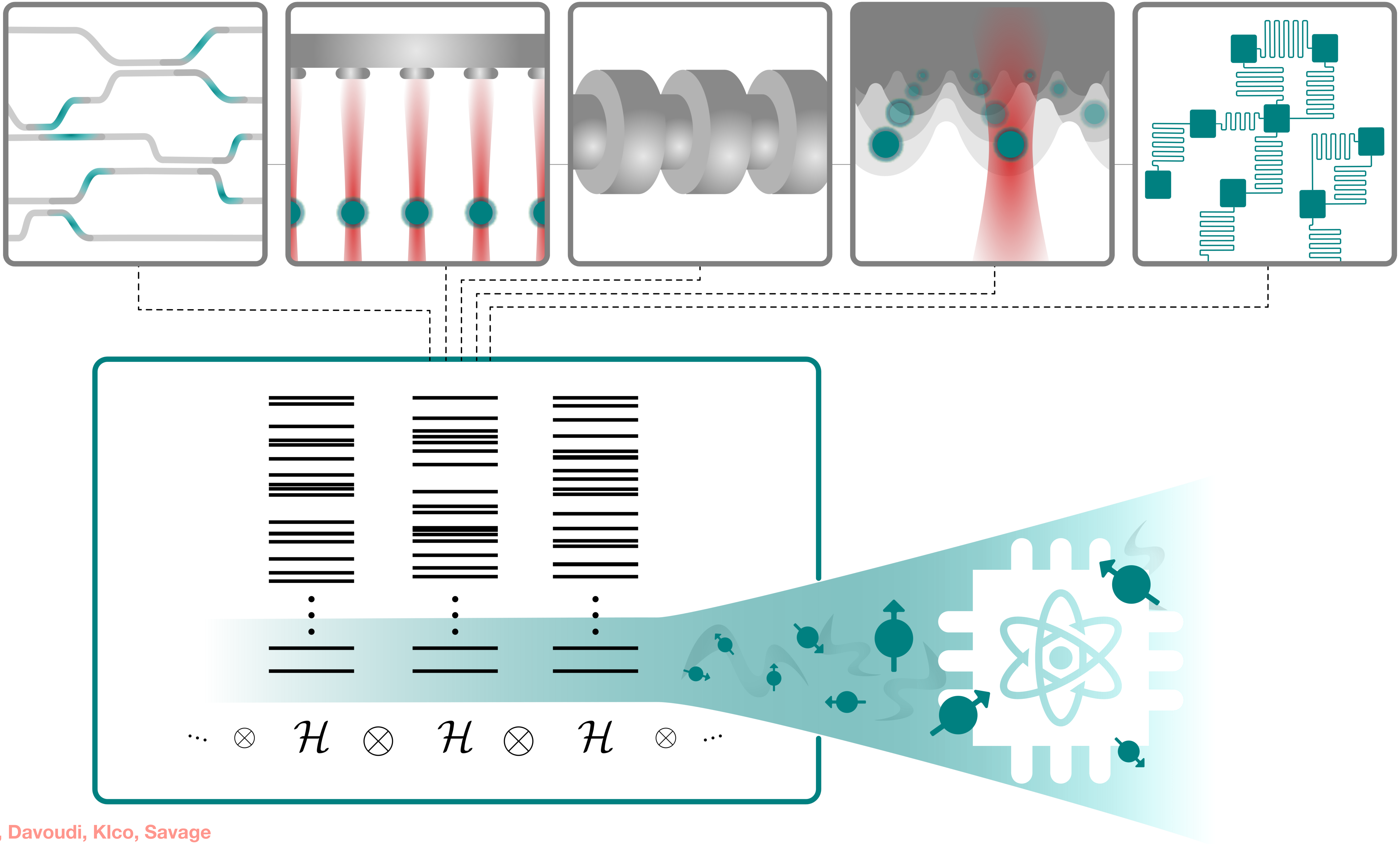
by Ewan Munro, Co-Founder of Entropica Labs.

Landscape of quantum computing from an error correction perspective. Inspired by a figure by Daniel Gottesman.

Quantum Simulation in the NISQ Era



Klco, Roggero, Savage

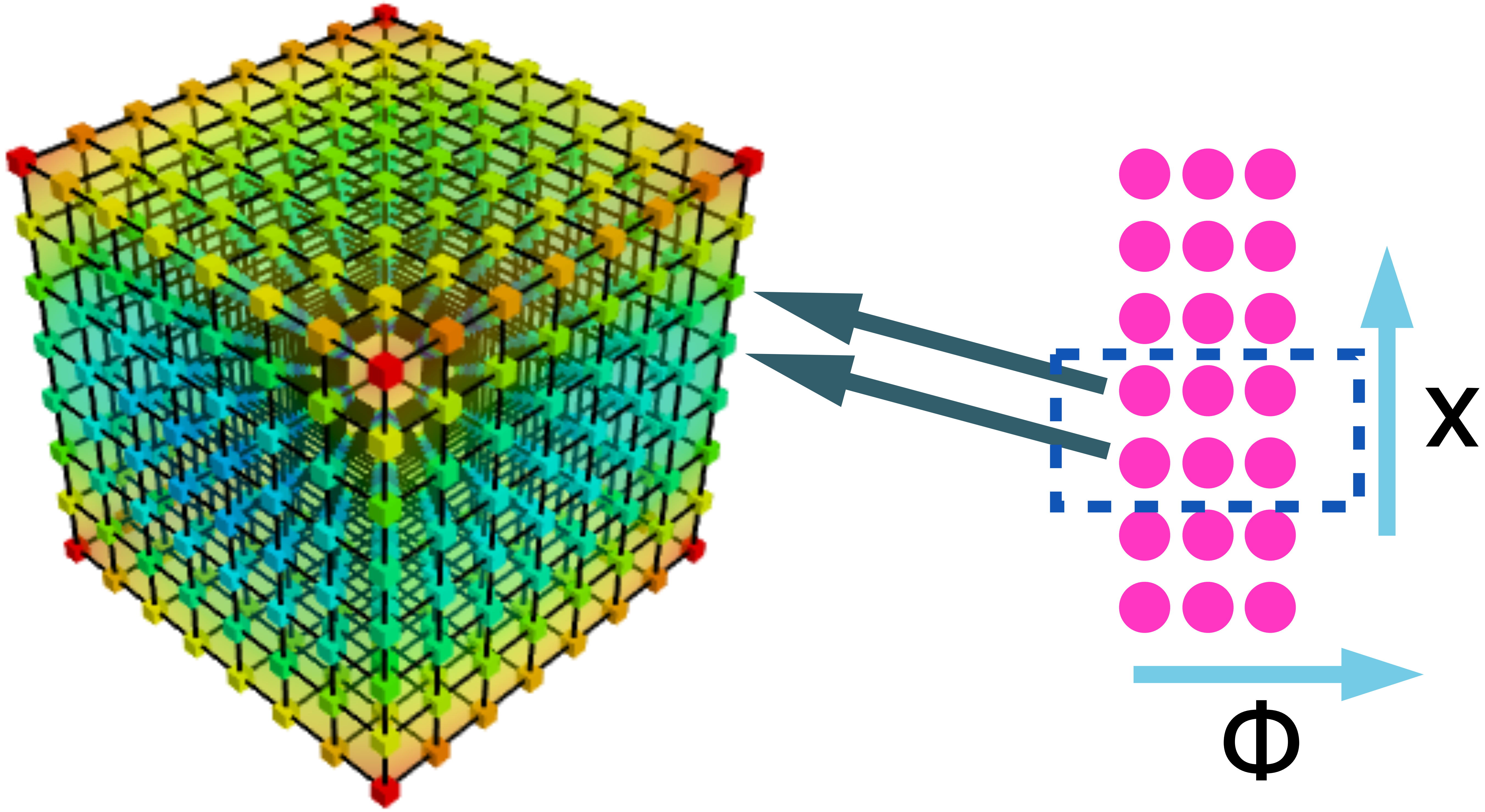


Bauer, Davoudi, Klco, Savage

Gold-Standard for QFT
Could it be done better ?
Can Entanglement be used Strategically?

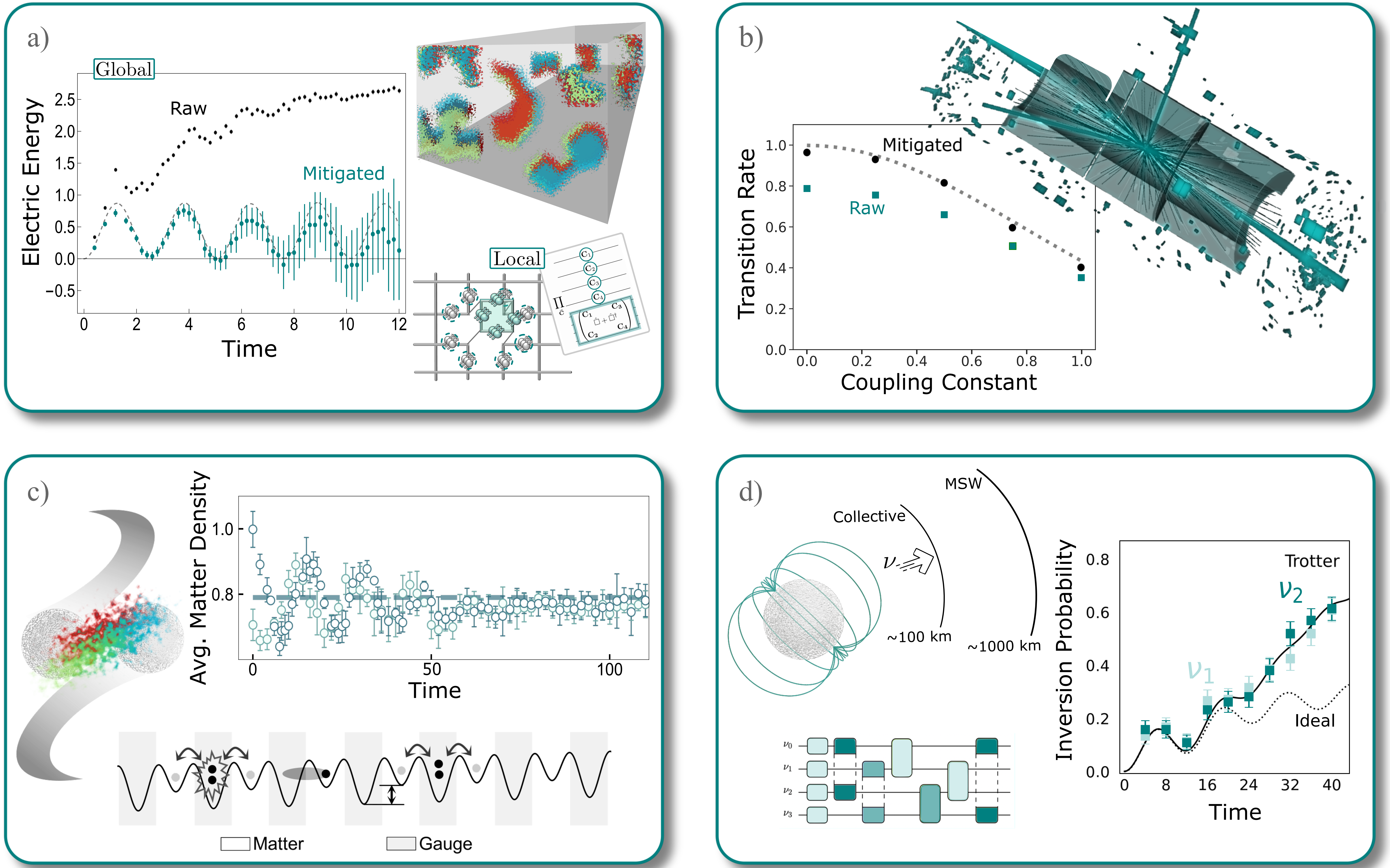
Jordan, Lee, Preskill

Parallelizes easily at the circuit level



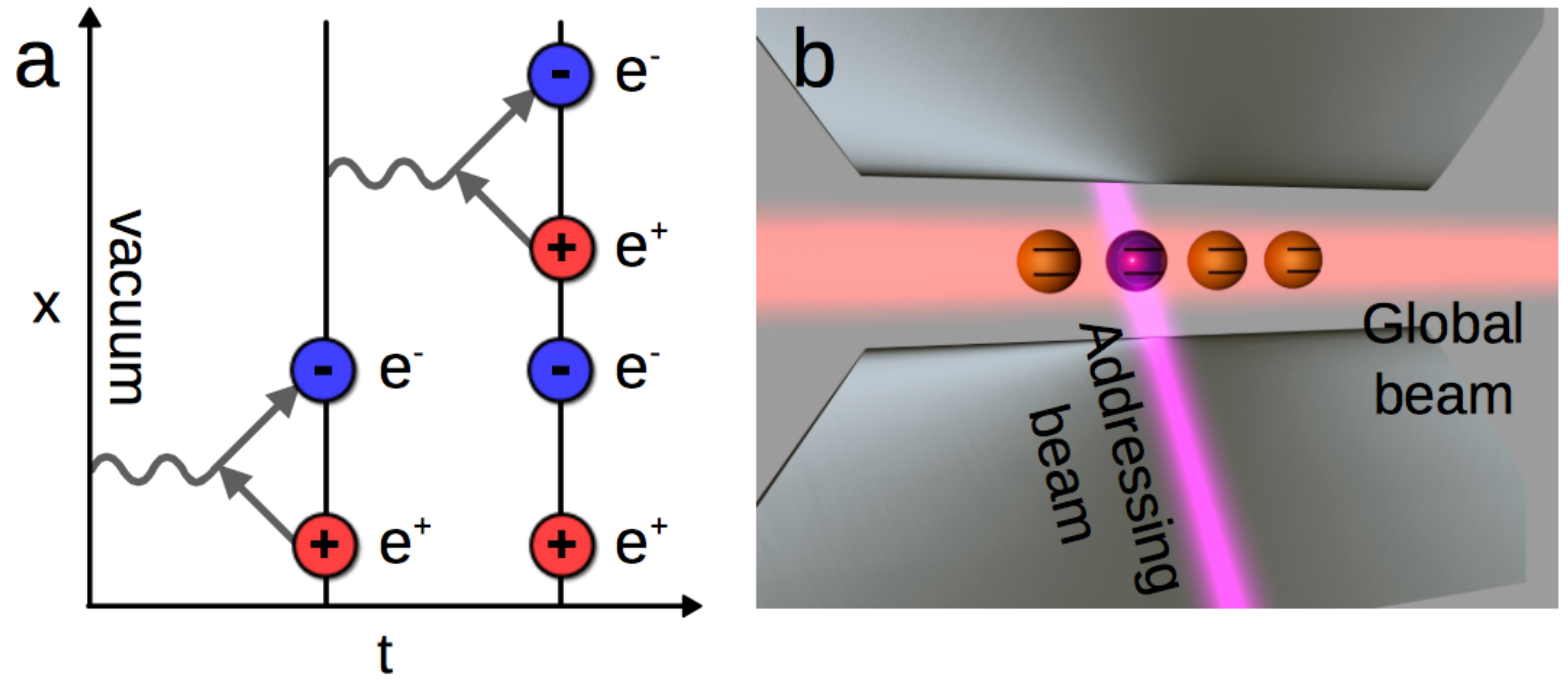
Double exponential convergence of field digitization

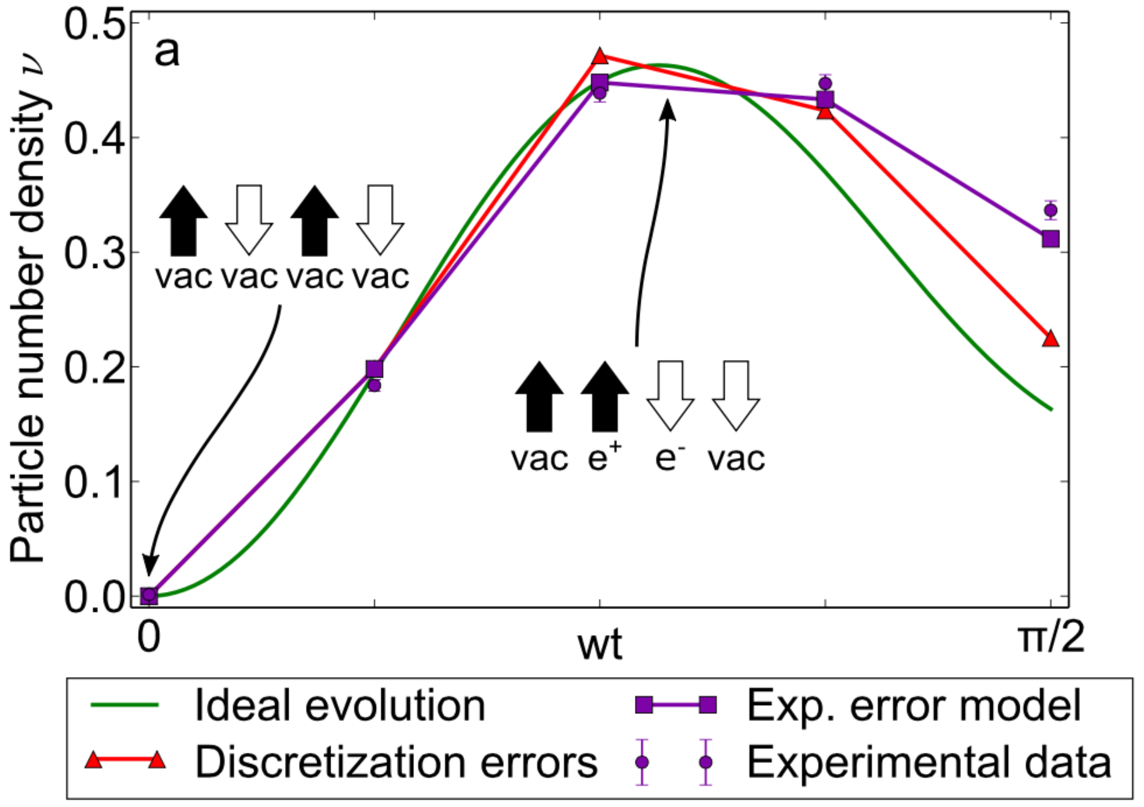
Some of the Areas of Development For Quantum Simulation



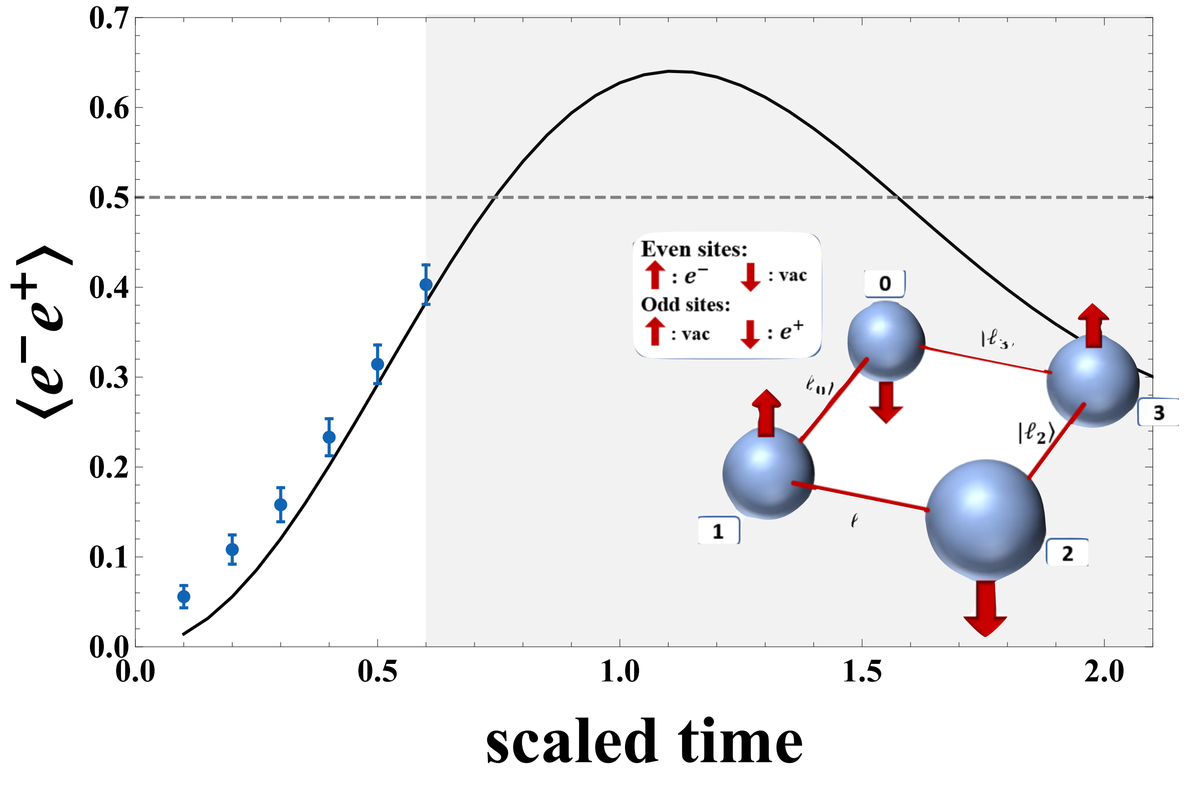
Bauer, Davoudi, Klco, Savage

Dynamics in the Schwinger Model

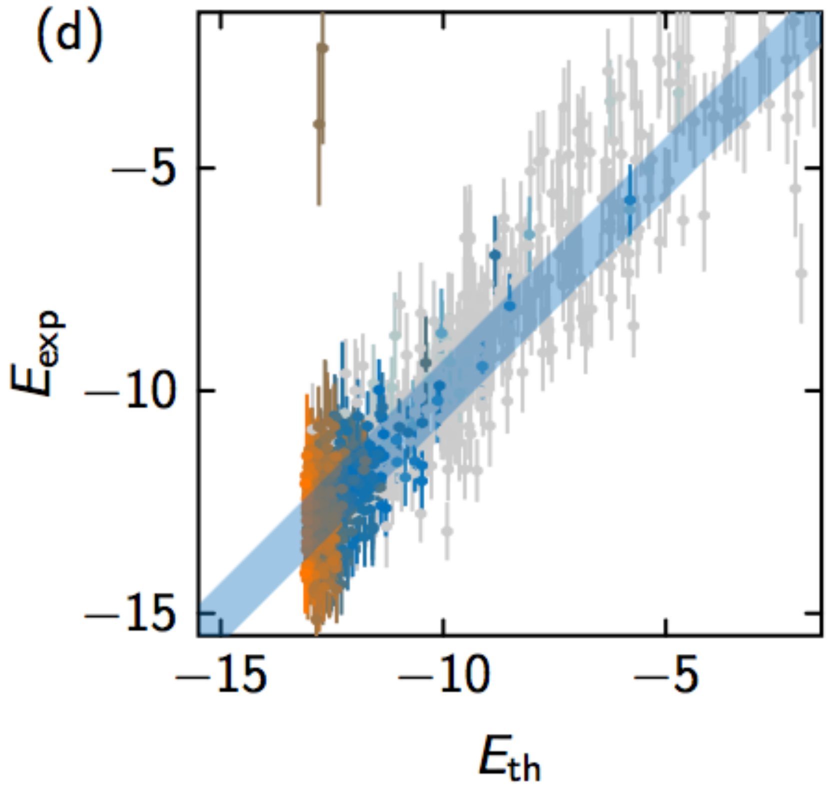




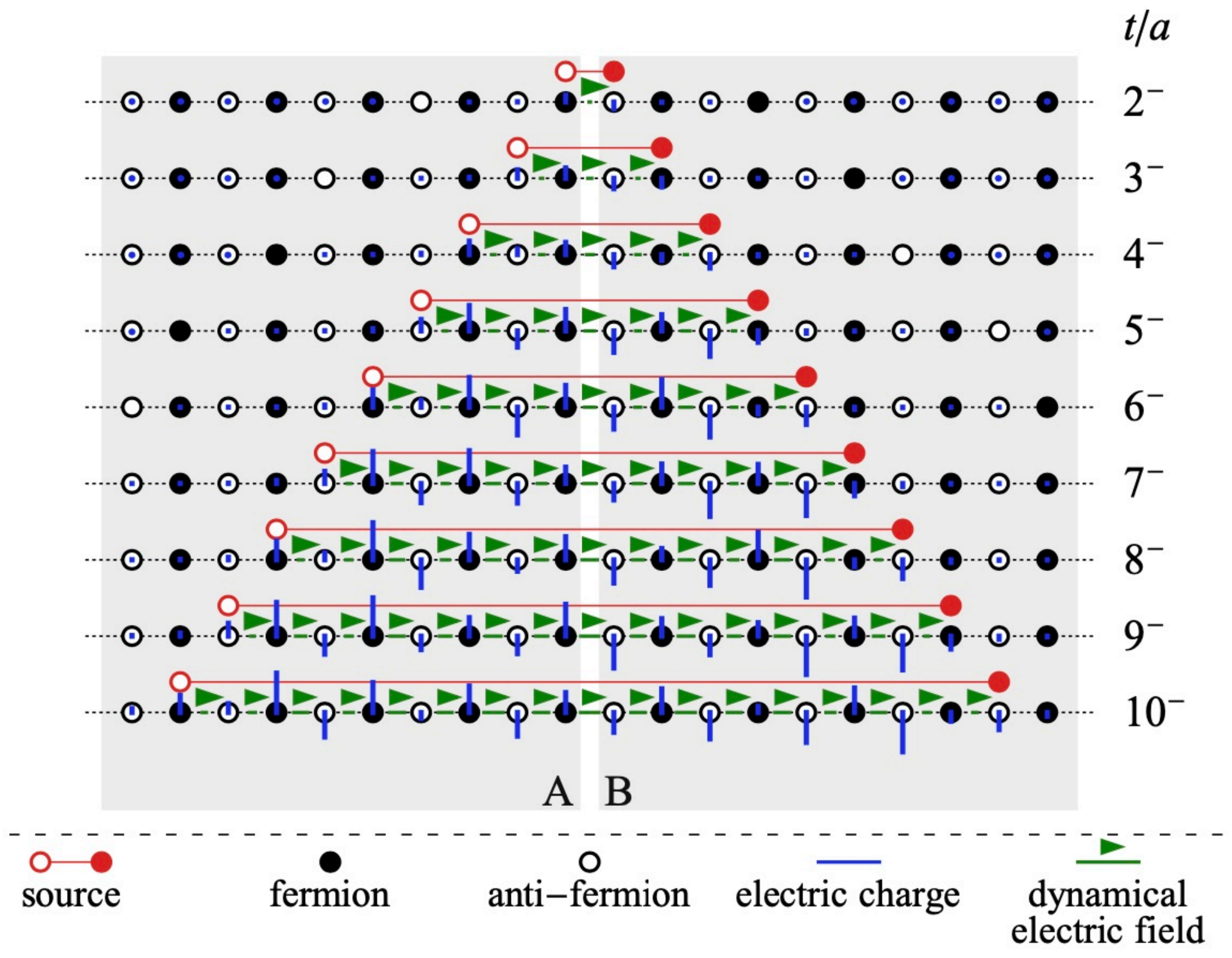
Innesbruck

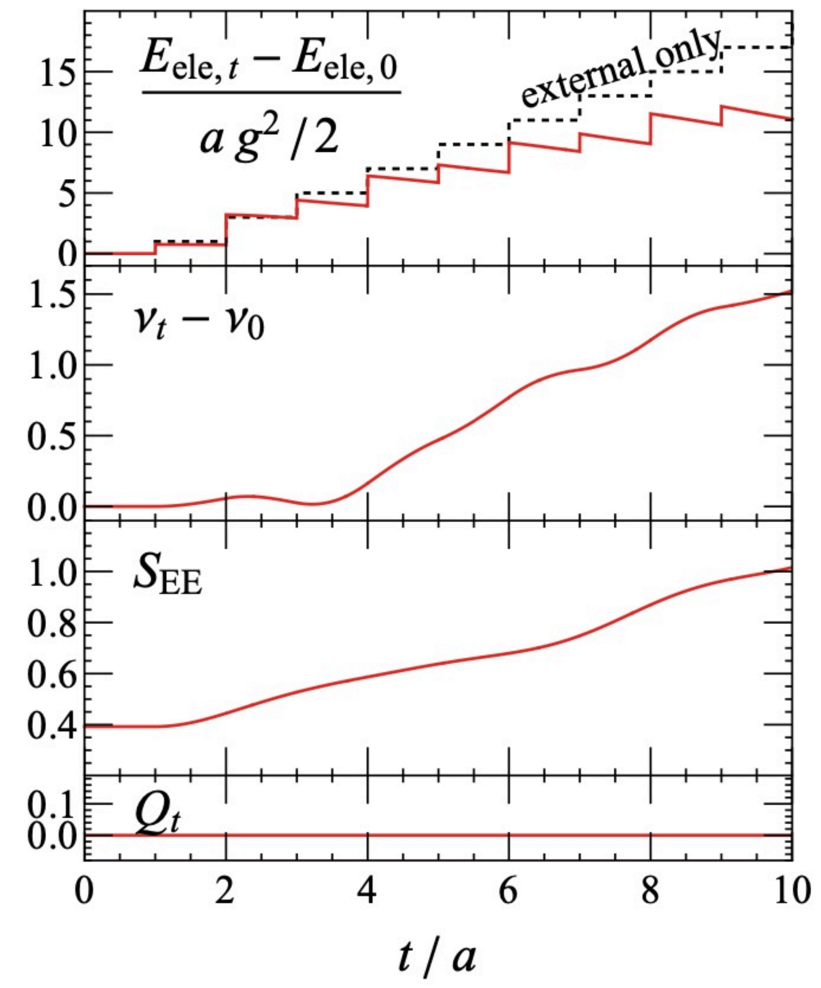


ORNL-Washington-Basque



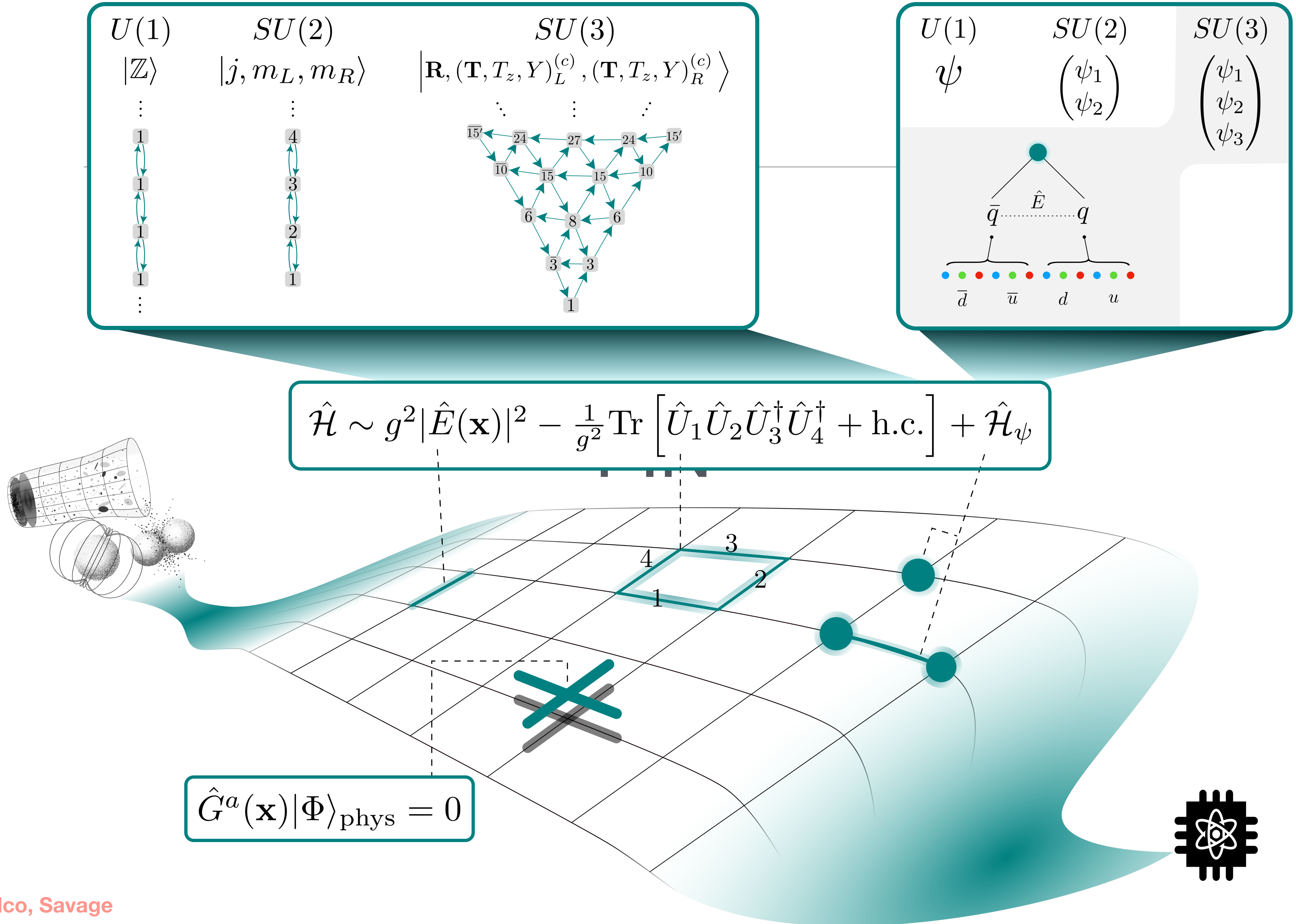
Innesbruck





Florio, Kharzeev et al
2023

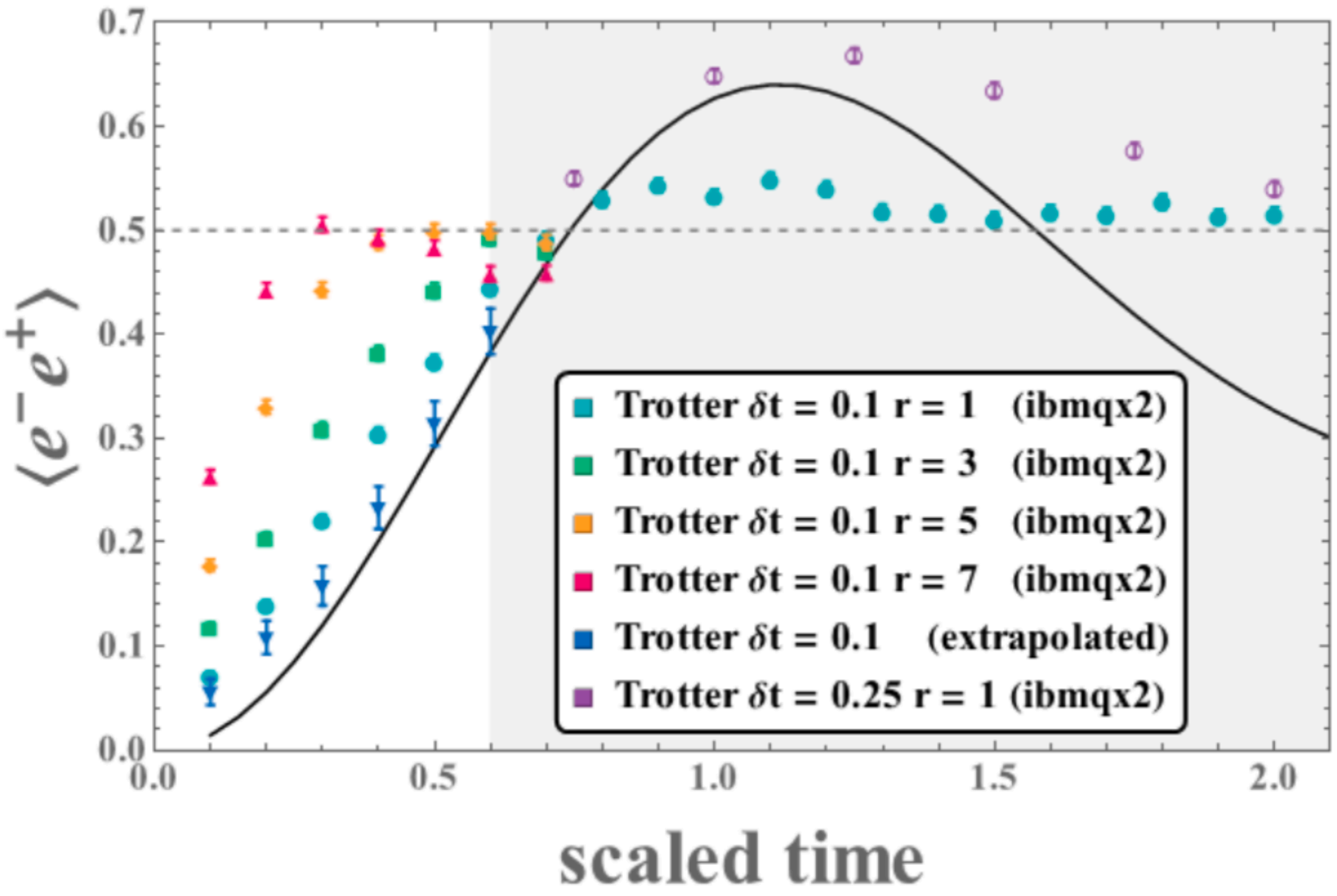
Algorithmic resource requirement estimates: Lougovski, Wiebe Stryker, et al.



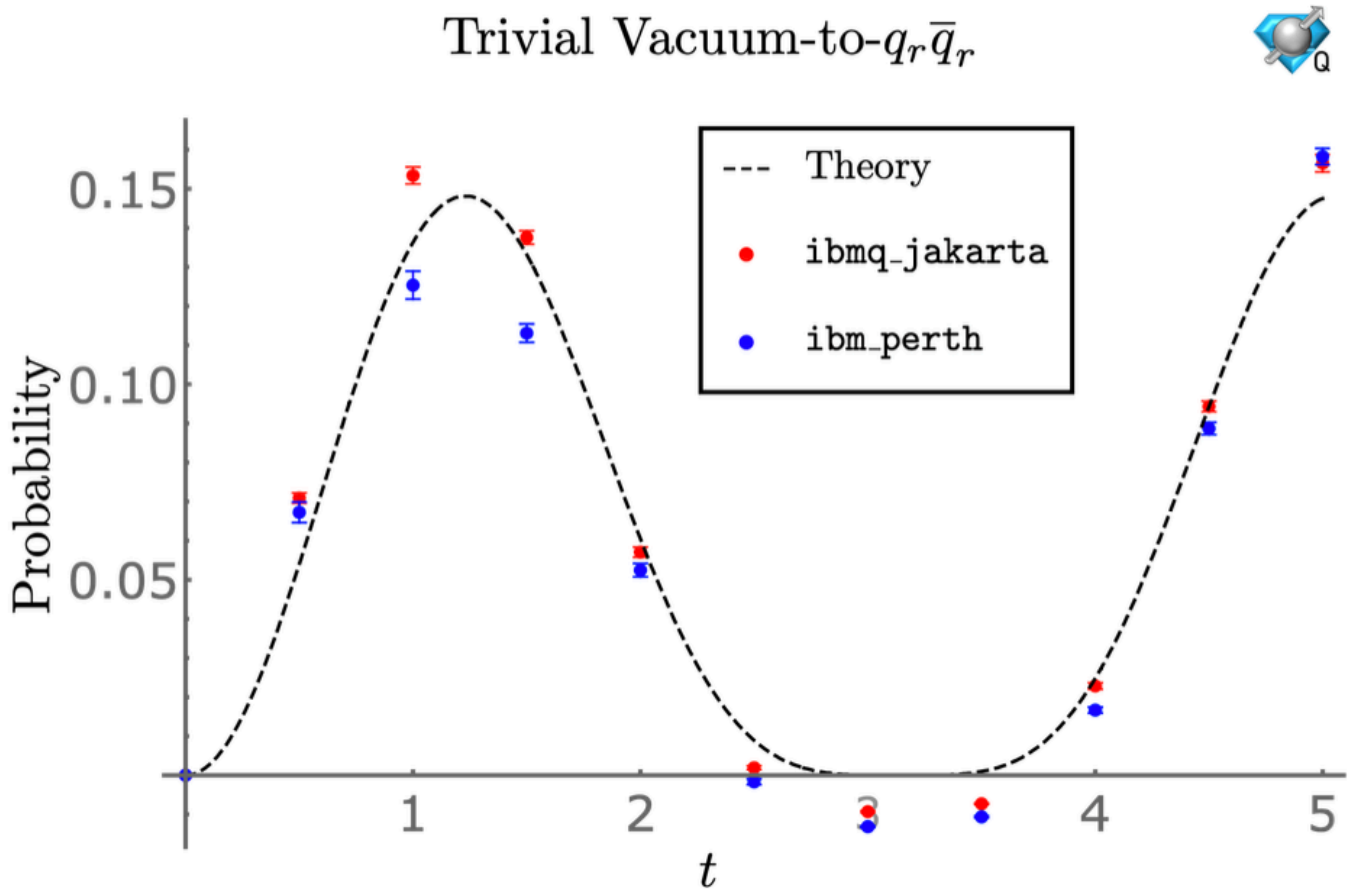
Bauer, Davoudi, Klco, Savage

The Difference 5 Years Makes

2017-8

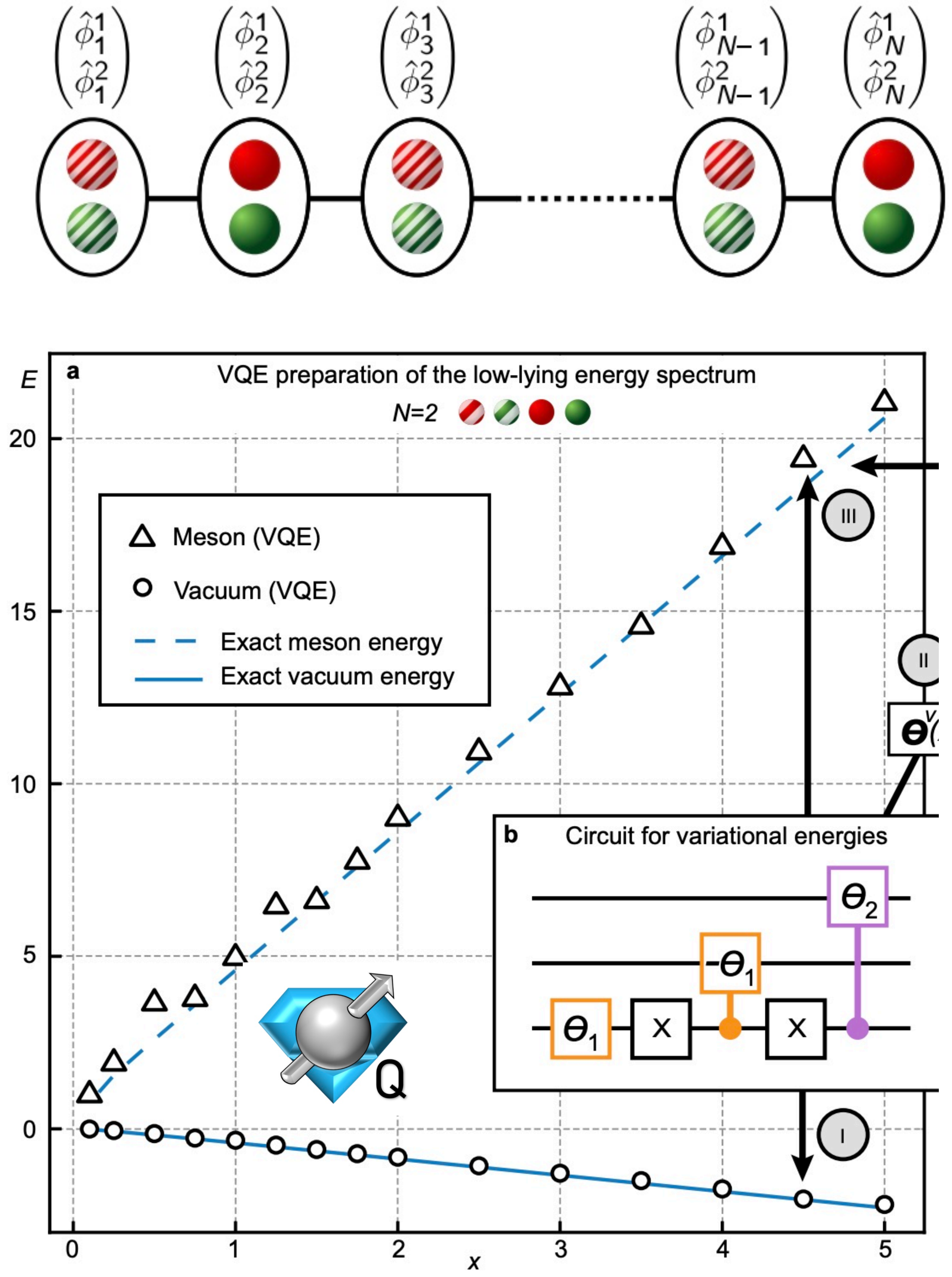


2022

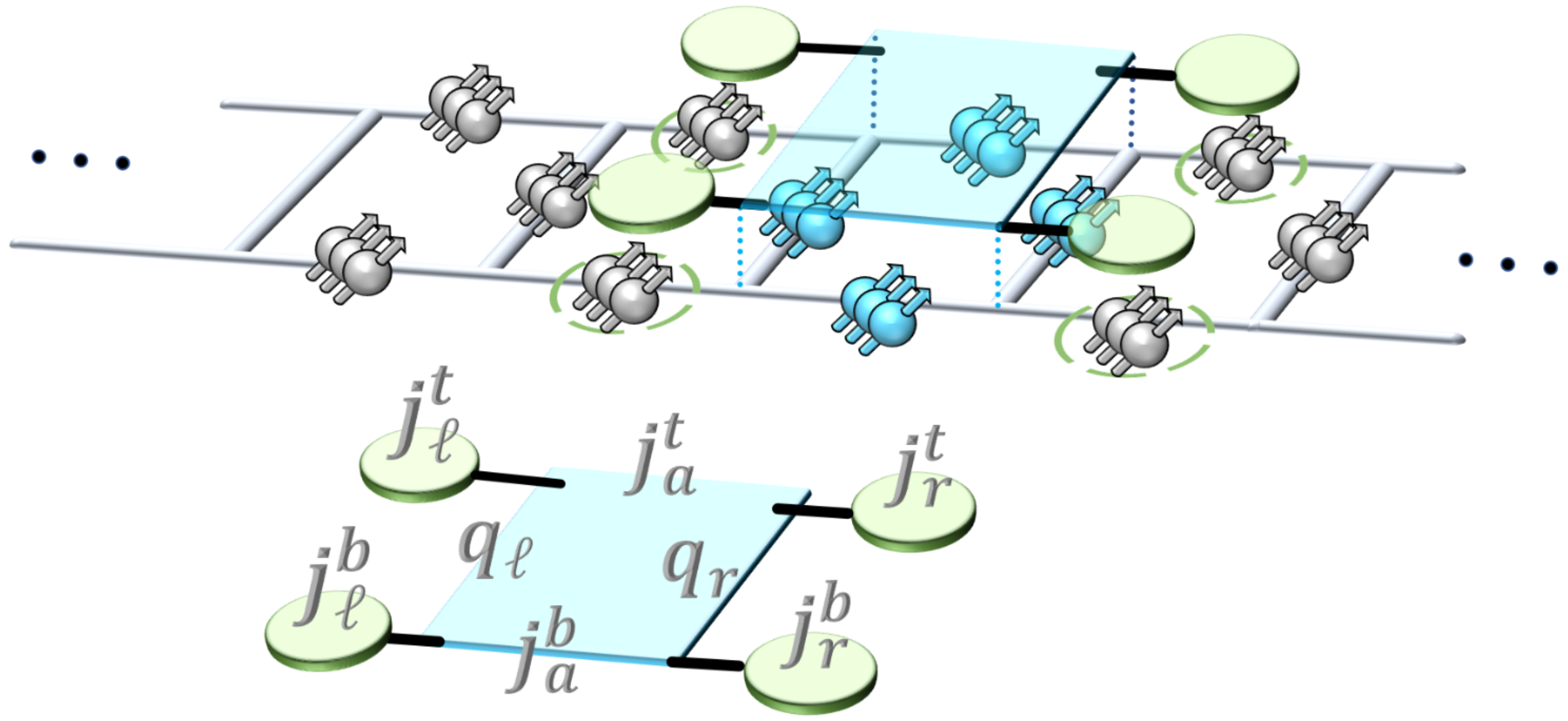


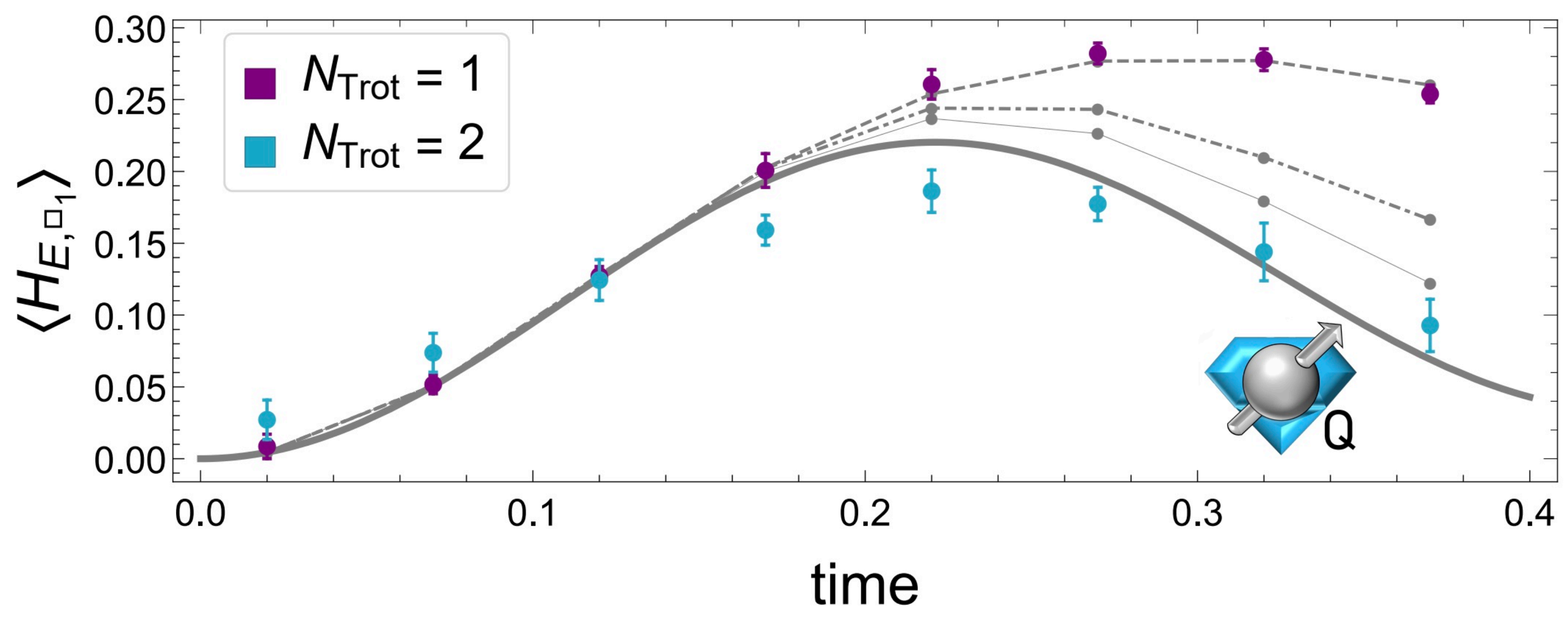
SU(2) Yang-Mills - First Efforts

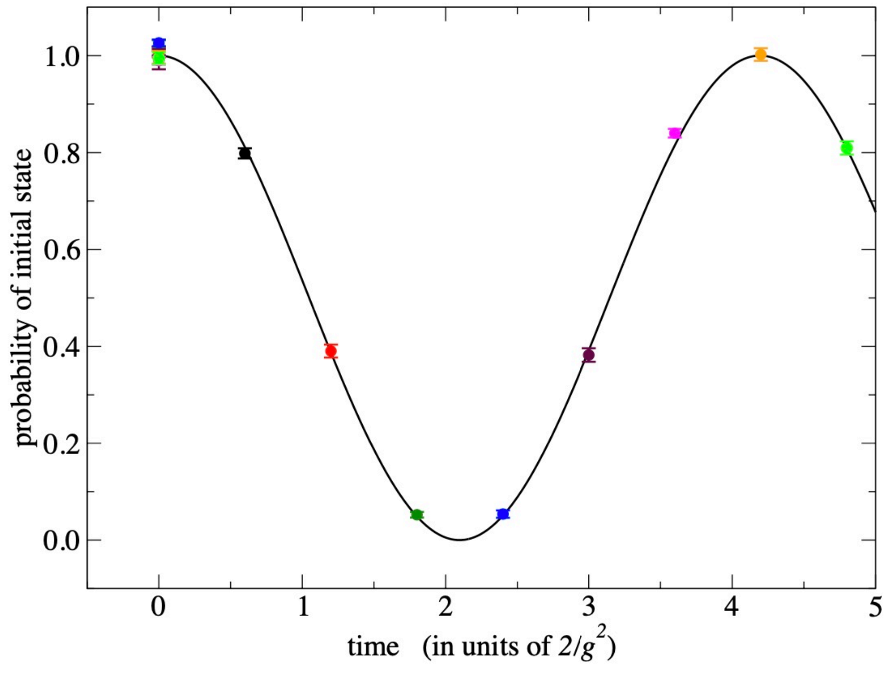
Also see Mari Carmen Banuls, Karl Jansen et al



Muschik, Lewis, et al (2021)





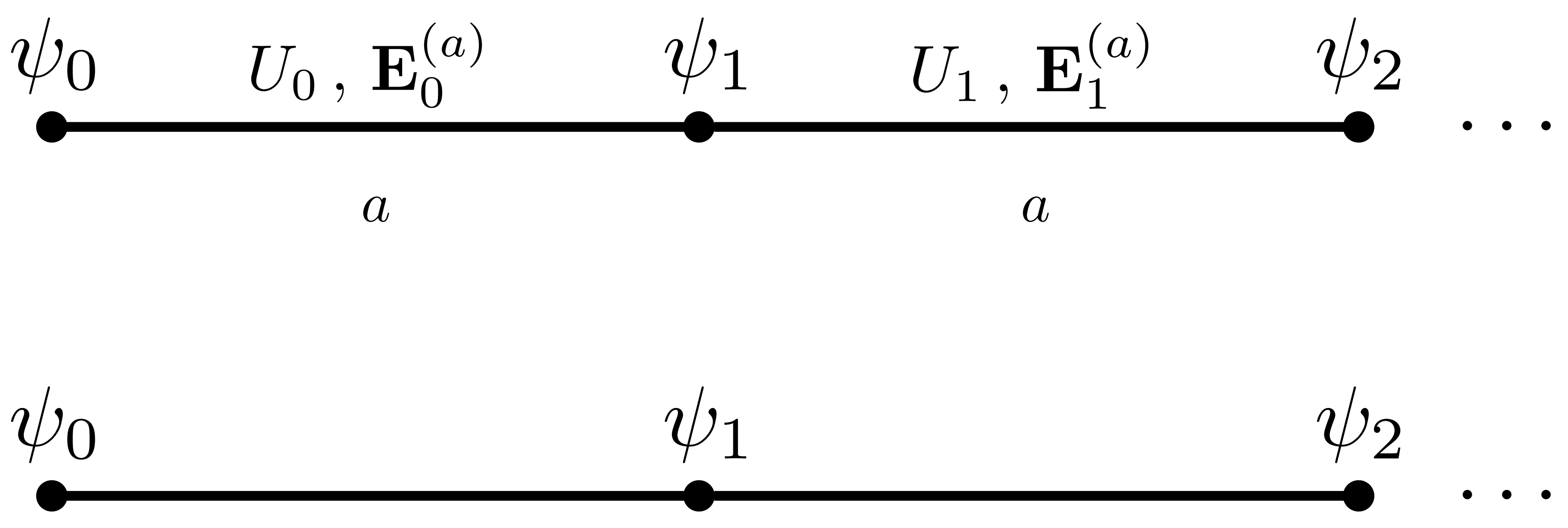


Klco, Stryker, MJS (2019), A Rahman et al (2021)

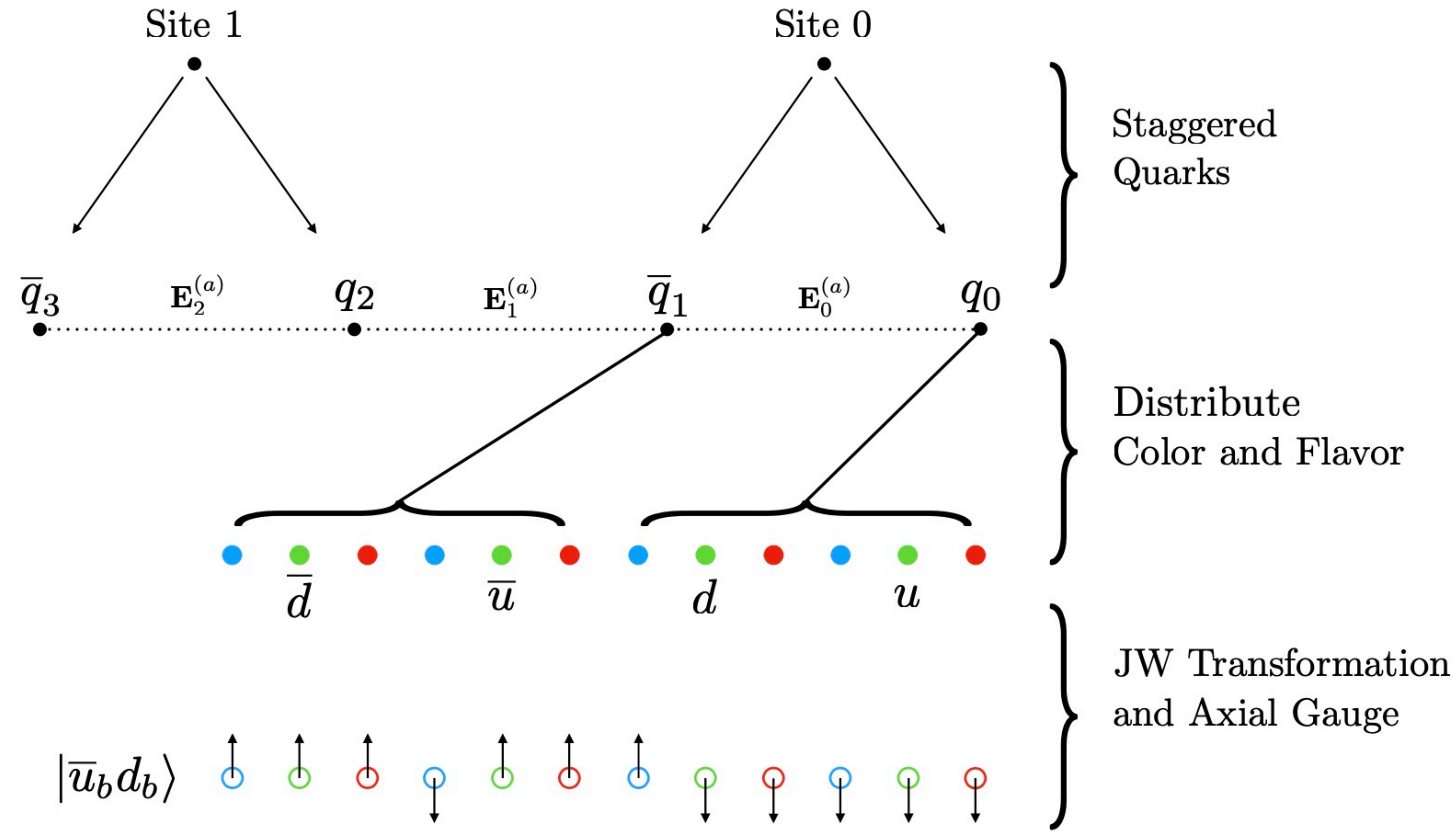
1+1Dimensional SU(3) [toward QCD]

Building on the works of others, Banuls, Dirac, Jansen, Muschik, Lewis, ….

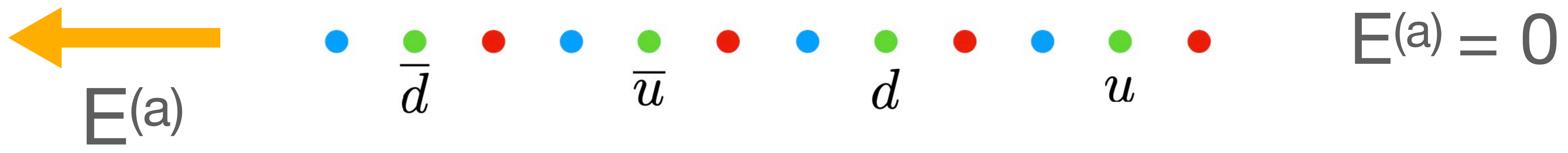
Gauge Choice : Axial Gauge Vs Weyl Gauge



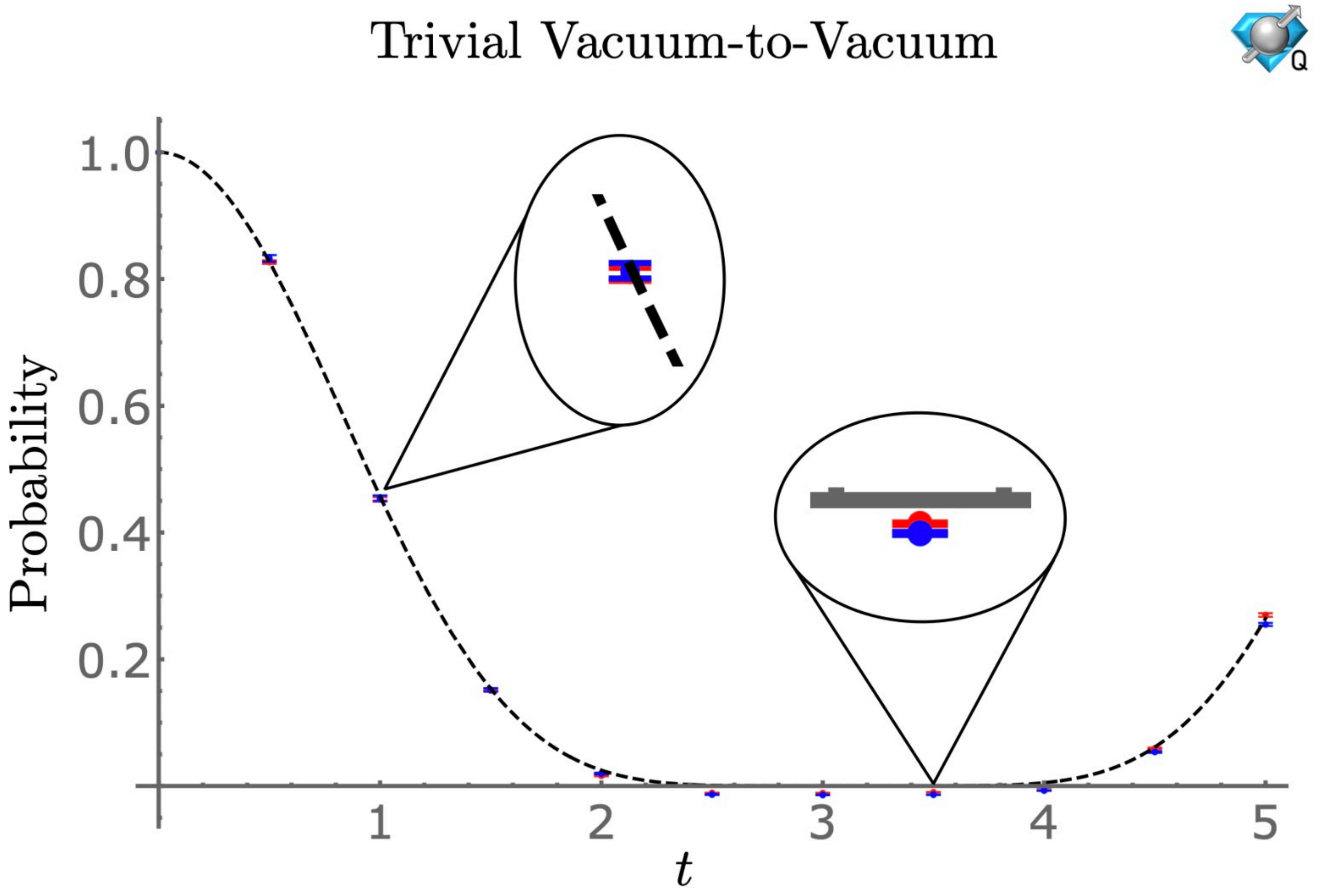
Found time-evolution requirements to be approx independent of gauge choice

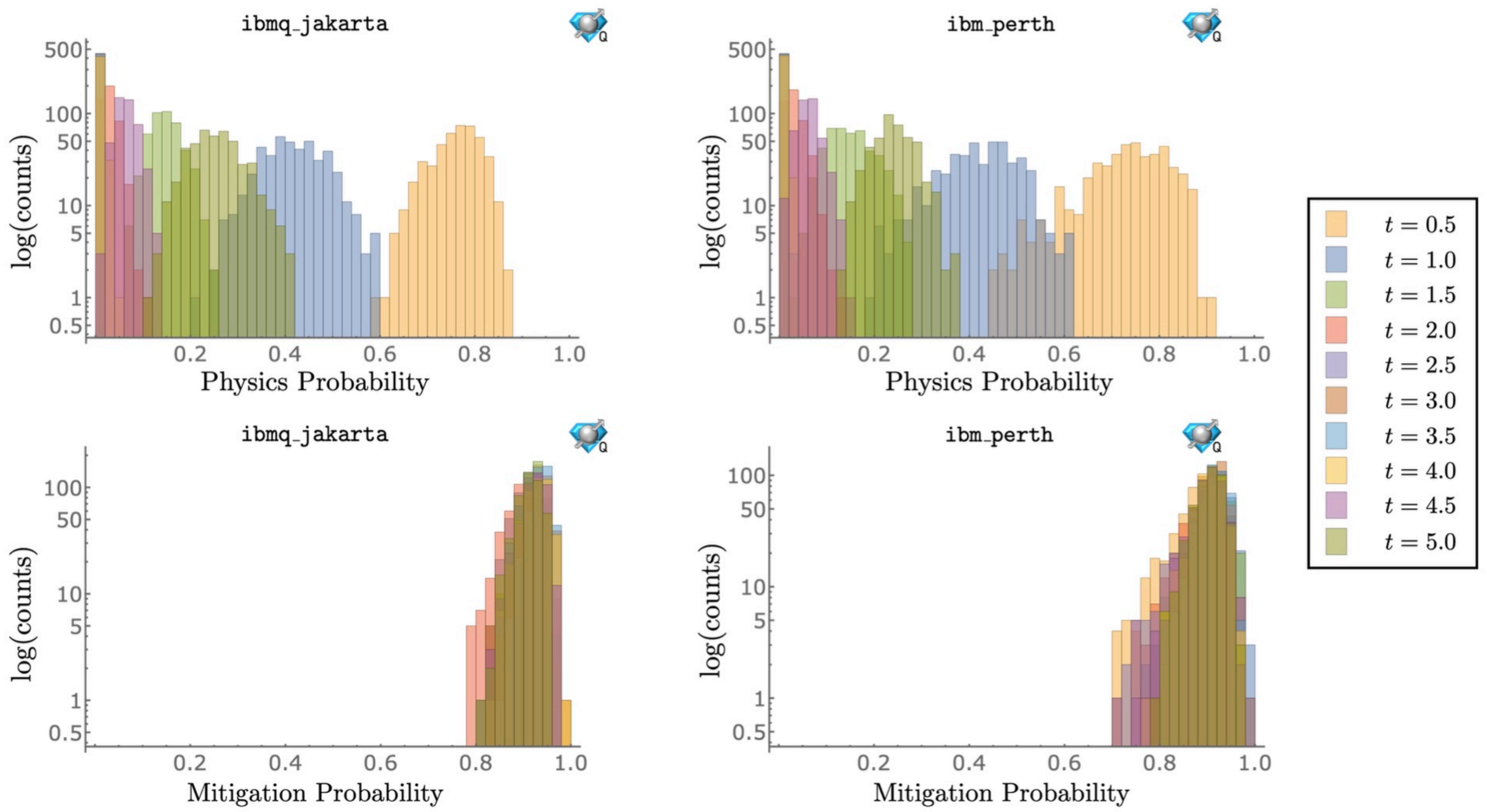


Color edge states



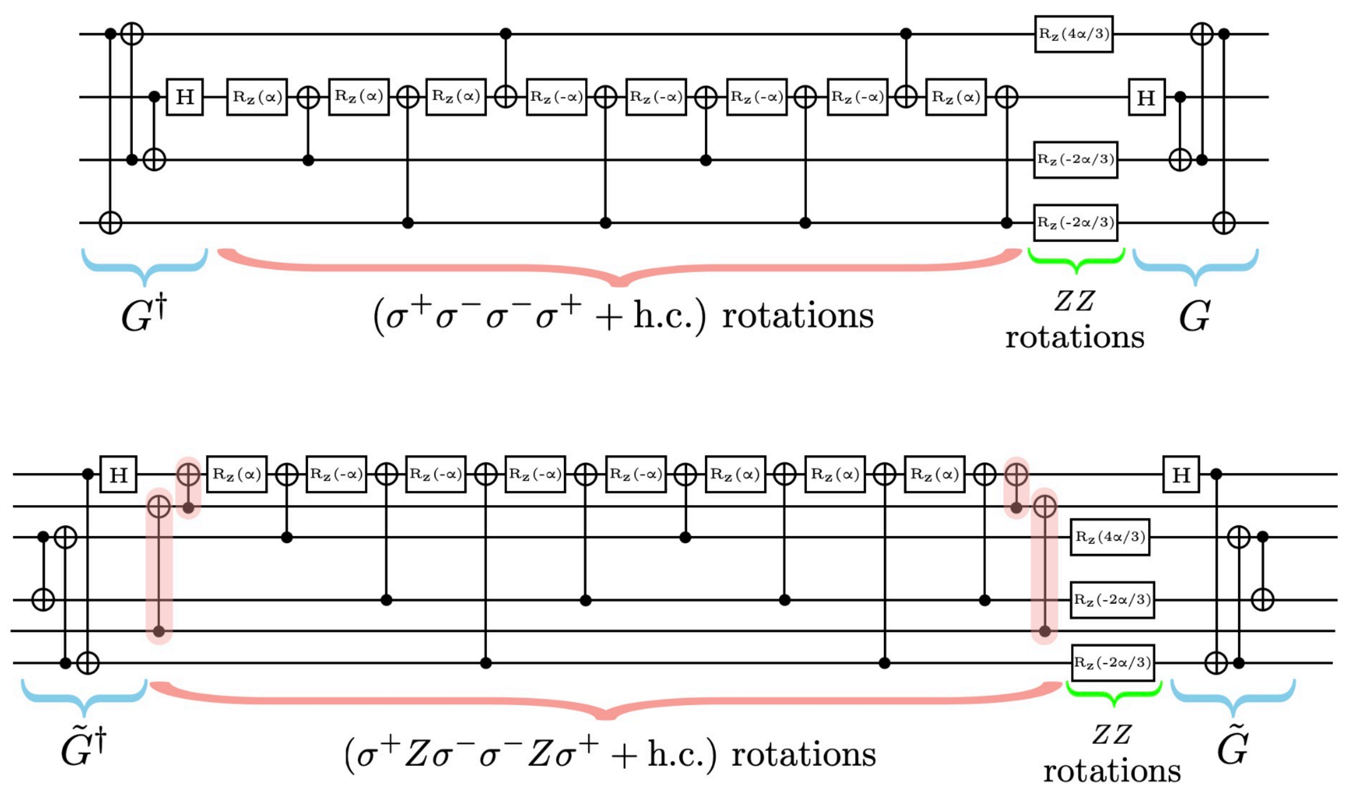
Simulations using IBM's Quantum Computers
1-site, 3 colors, 1 flavor





IBM 7 qubit Perth and Jakarta

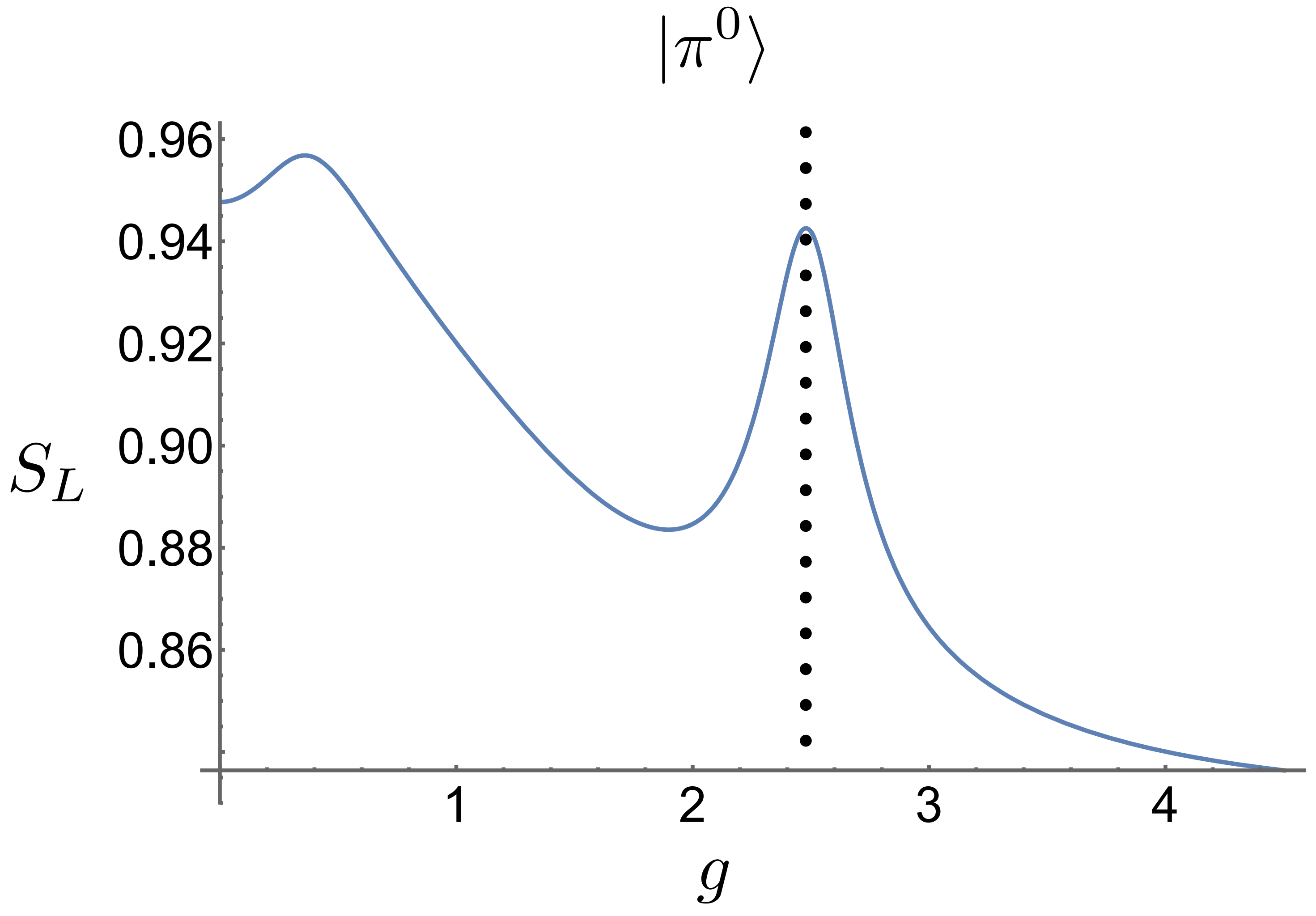
34 CNOTs per step
447 Pauli-Twirled circuits
1000 shots per circuits

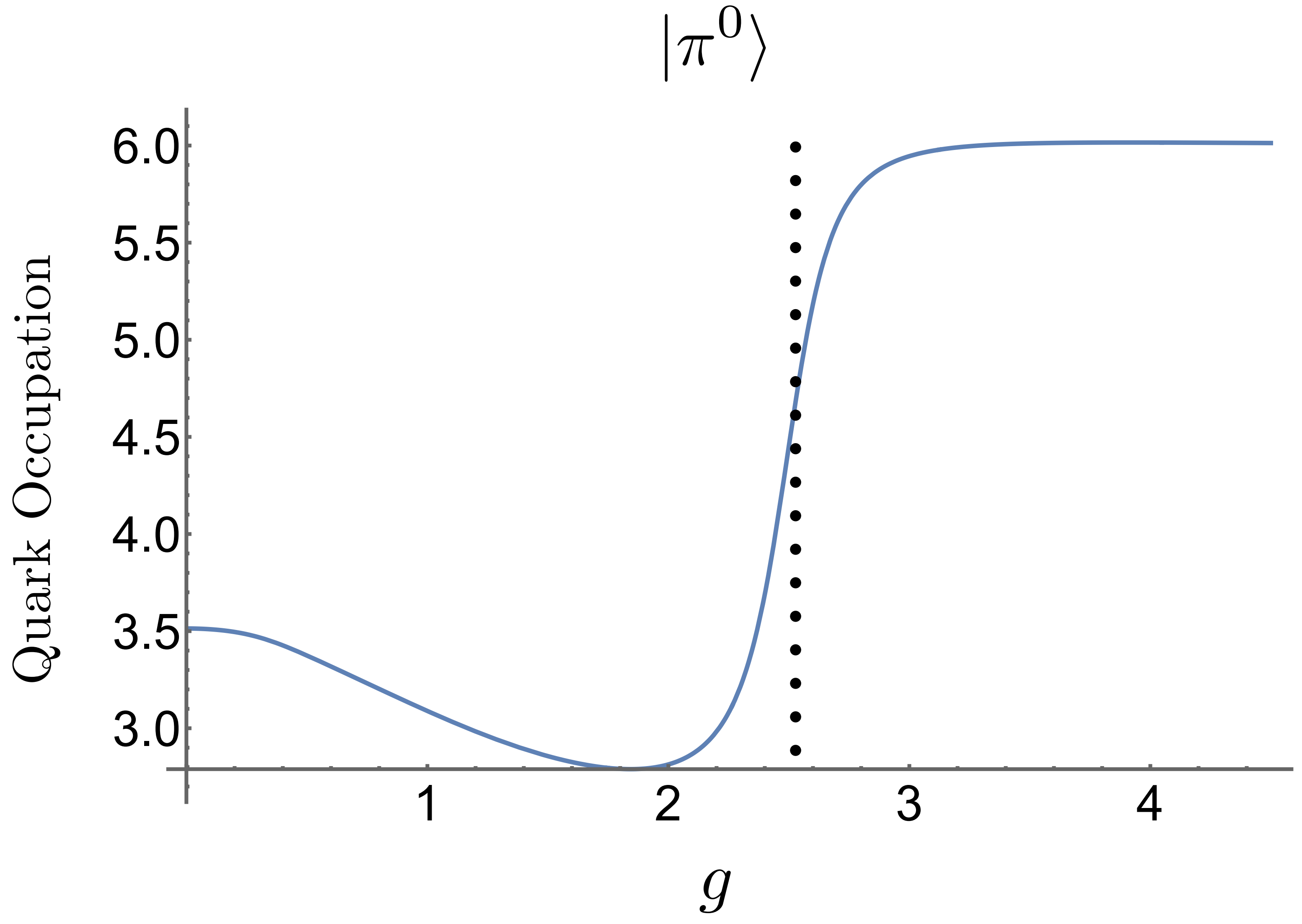


Dynamic Decoupling
Pauli-Twirling
Post selection
De-coherence renormalization (Bauer et al, Lewis et al)

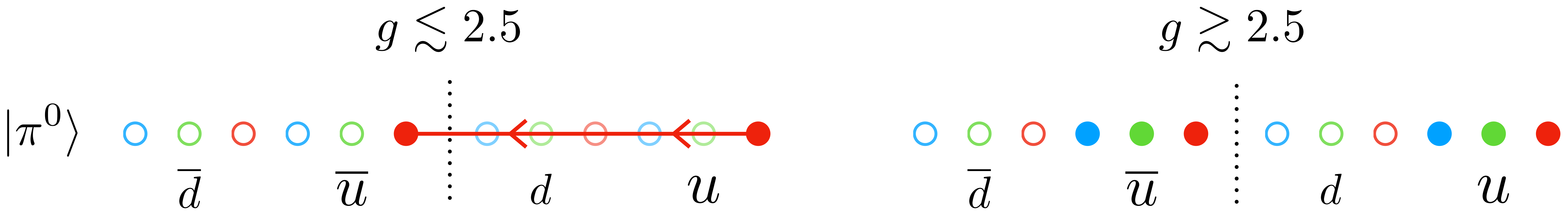
Number of CNOT gates for one Trotter step of $SU(3)$			
L	$N_f = 1$	$N_f = 2$	$N_f = 3$
1	30	114	242
2	228	878	1,940
5	1,926	7,586	16,970
10	8,436	33,486	75,140
100	912,216	3,646,086	8,201,600

Entanglement structure in the mesons for $L = 2$



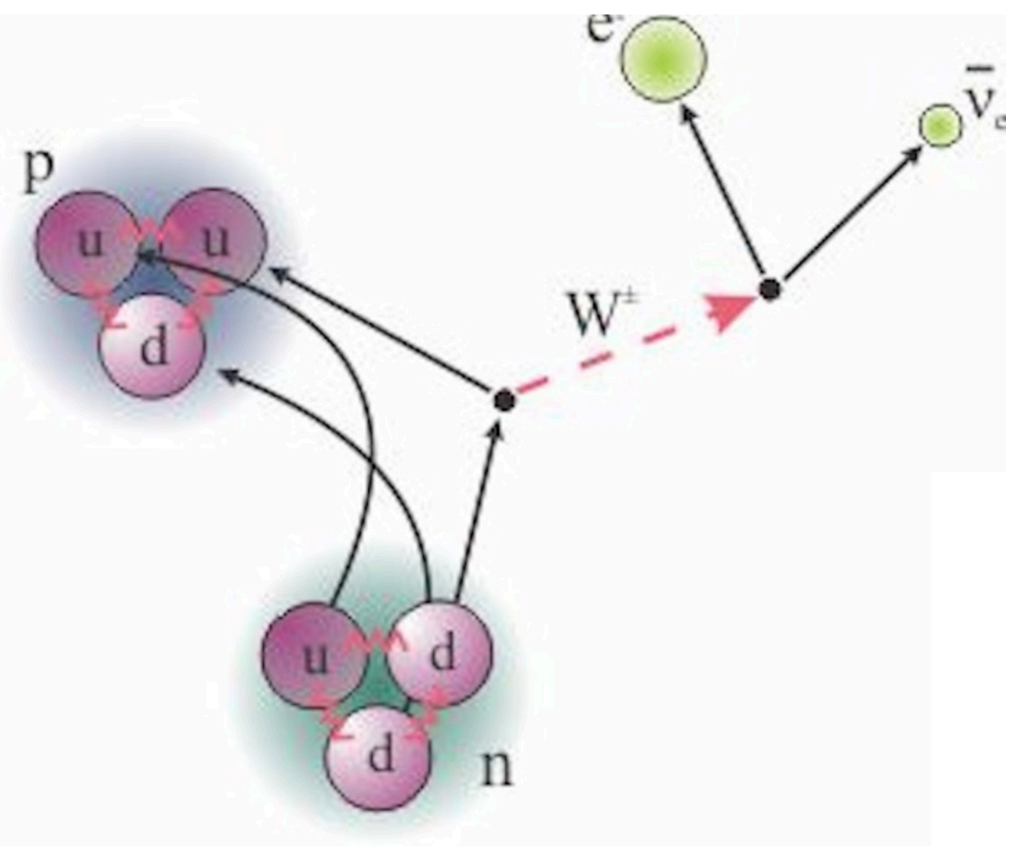


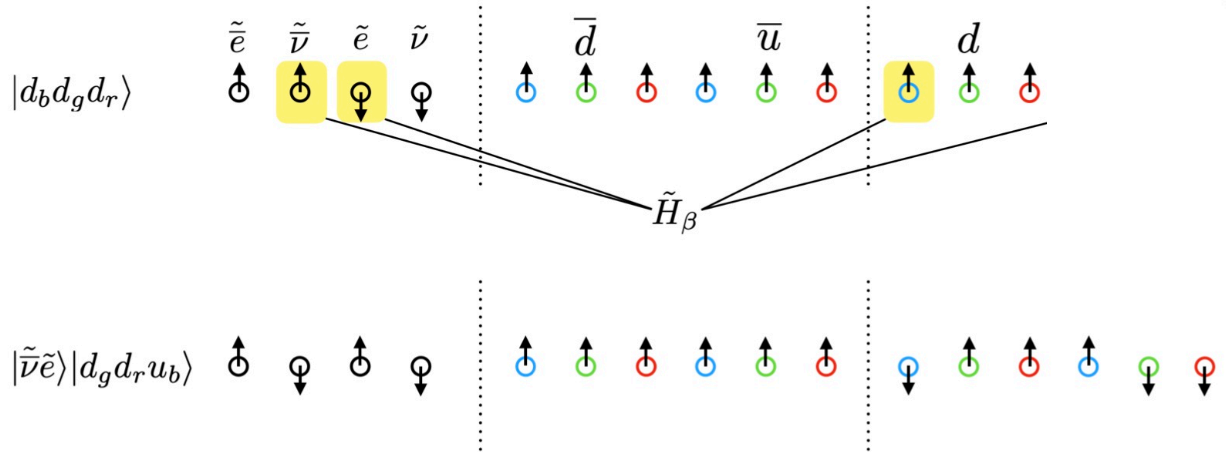
Peak in entanglement coincides with transition from quark-antiquark to baryon-anti-baryon structure

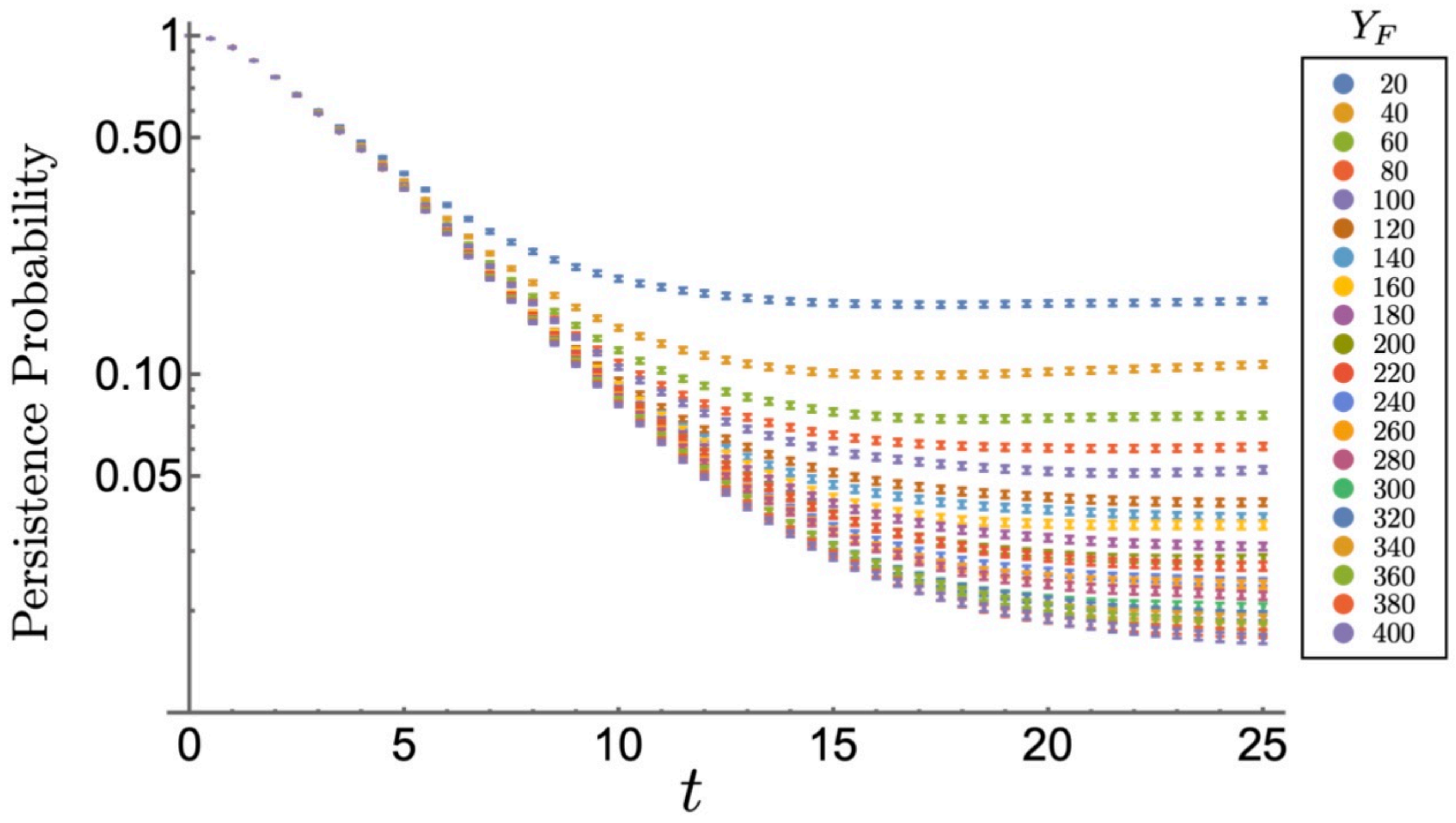


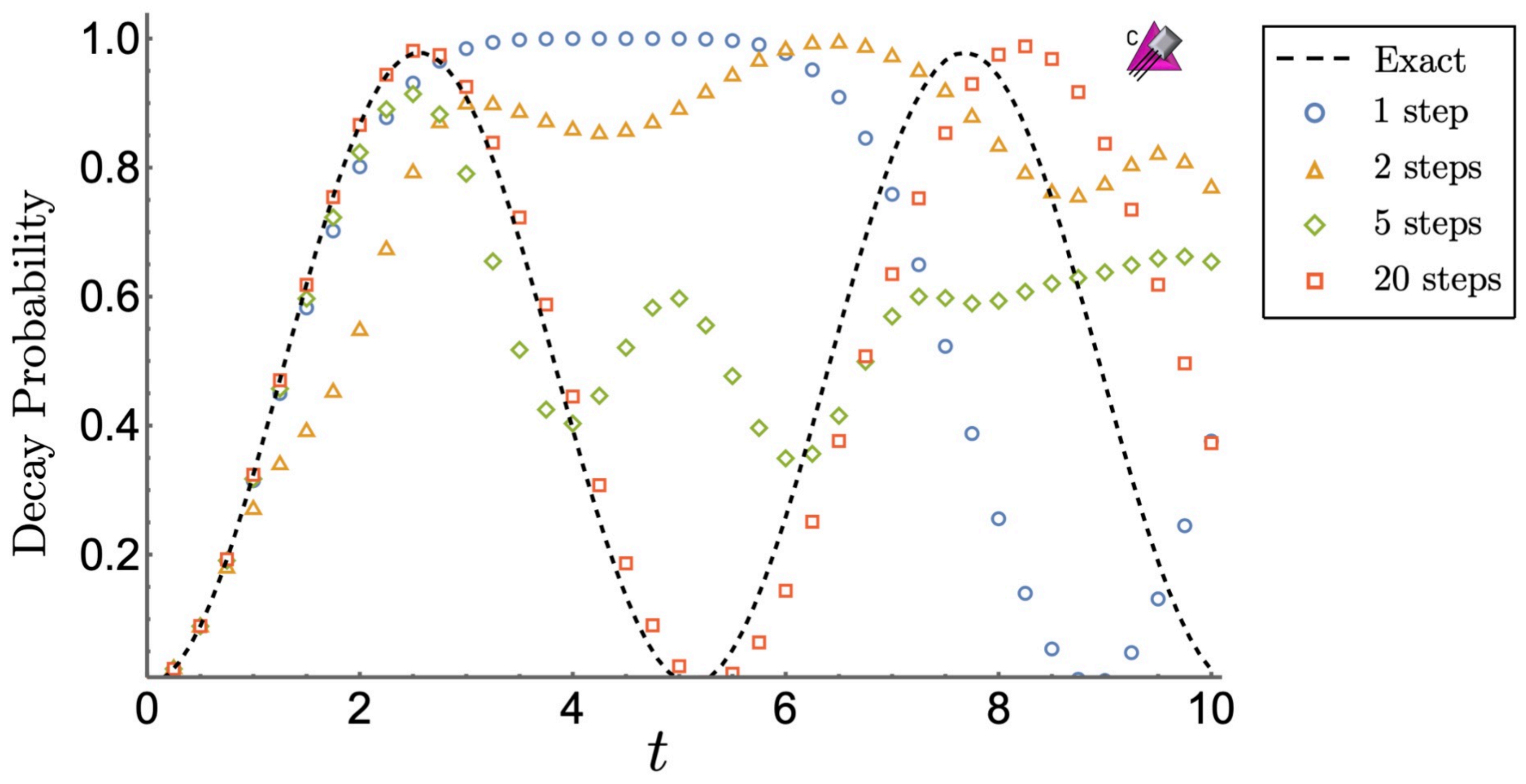
Balance between mass and gauge-field energies

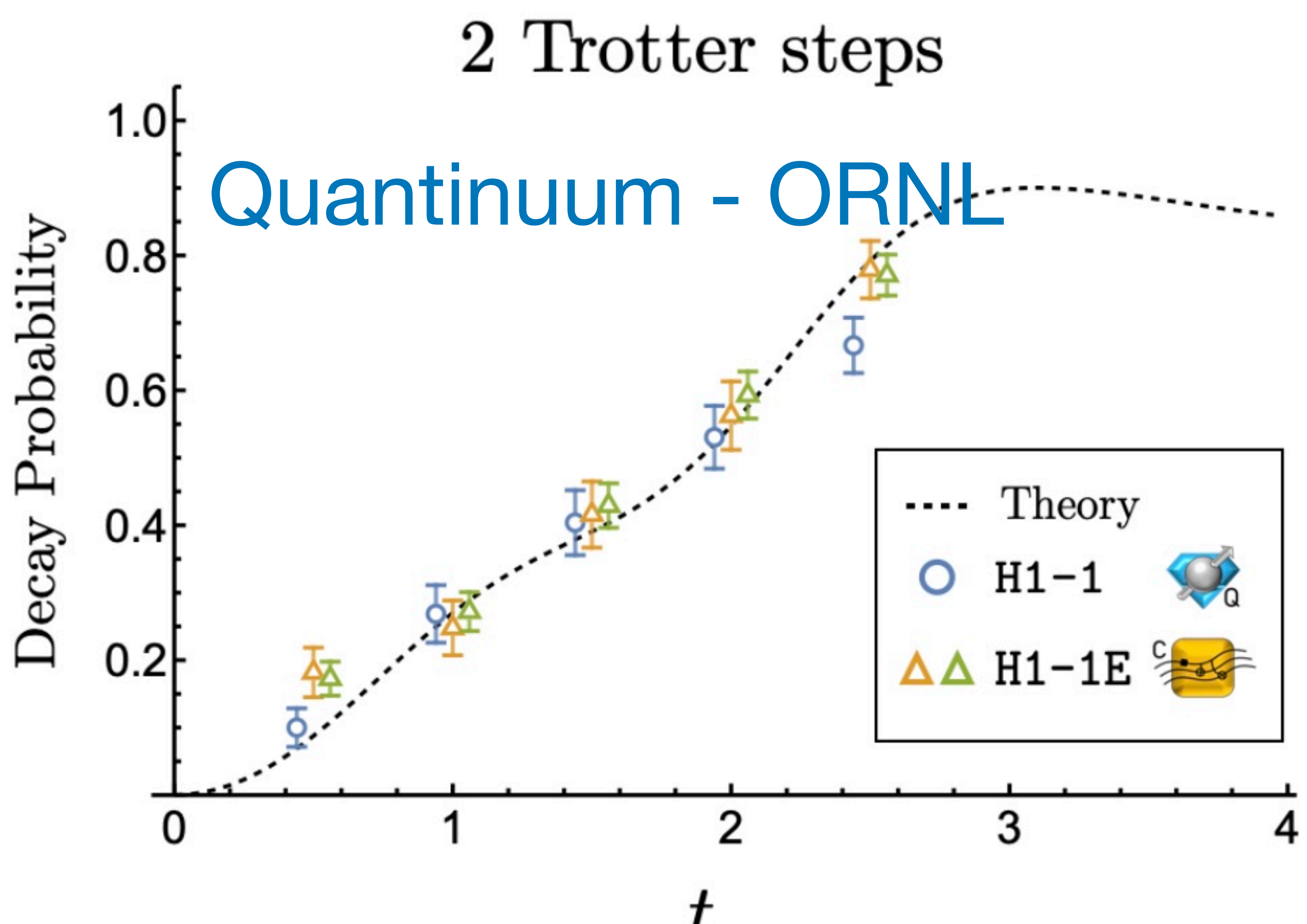
Real-time Exponential-Decay Weak Interactions









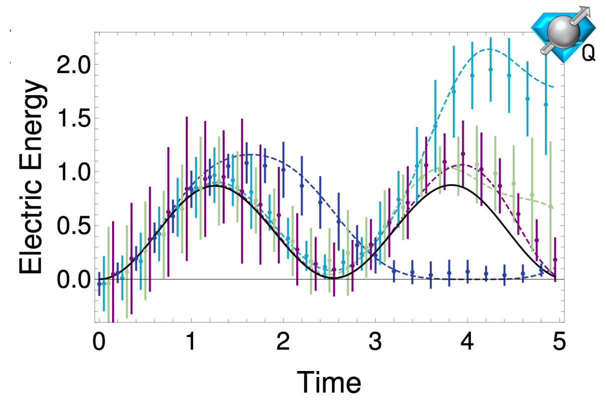


Decoherence Renormalization
The Difference 1 Year Can Make!

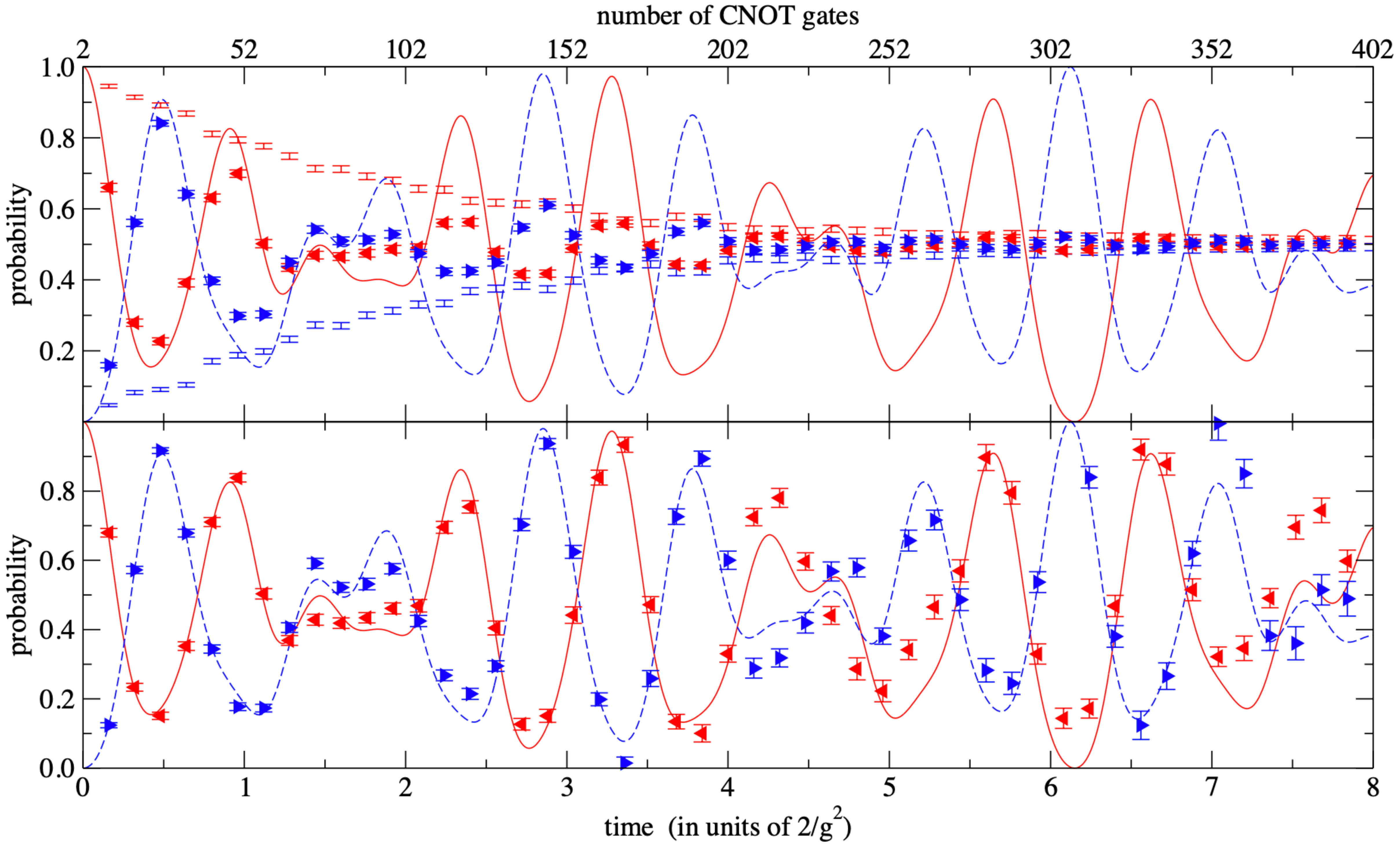
Self-mitigating Trotter circuits for SU(2) lattice gauge theory on a quantum computer

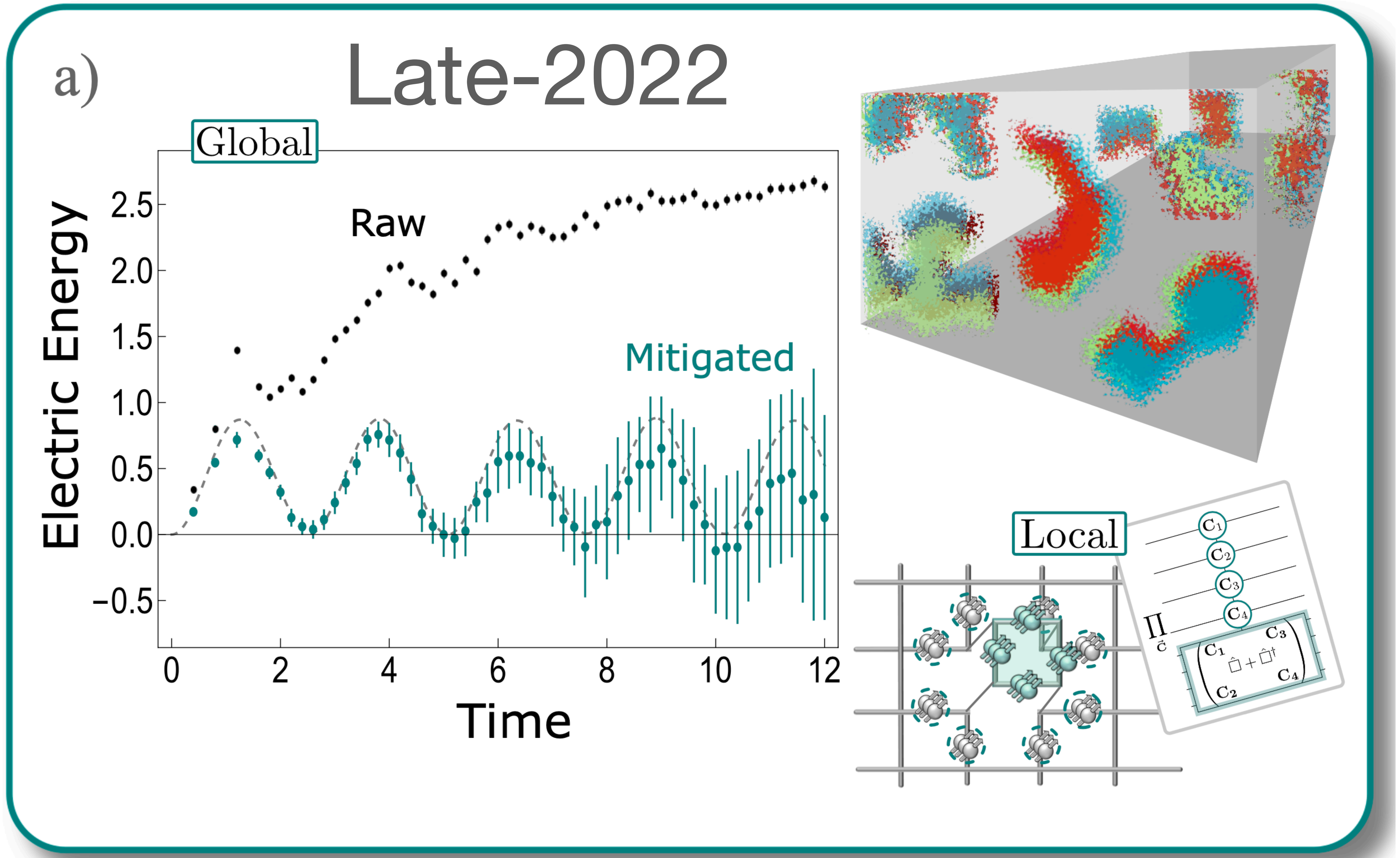
Sarmed A Rahman, Randy Lewis, Emanuele Mendicelli, and Sarah Powell
Department of Physics and Astronomy, York University, Toronto, Ontario, Canada, M3J 1P3

(Dated: May 2022. Updated: October 2022.)

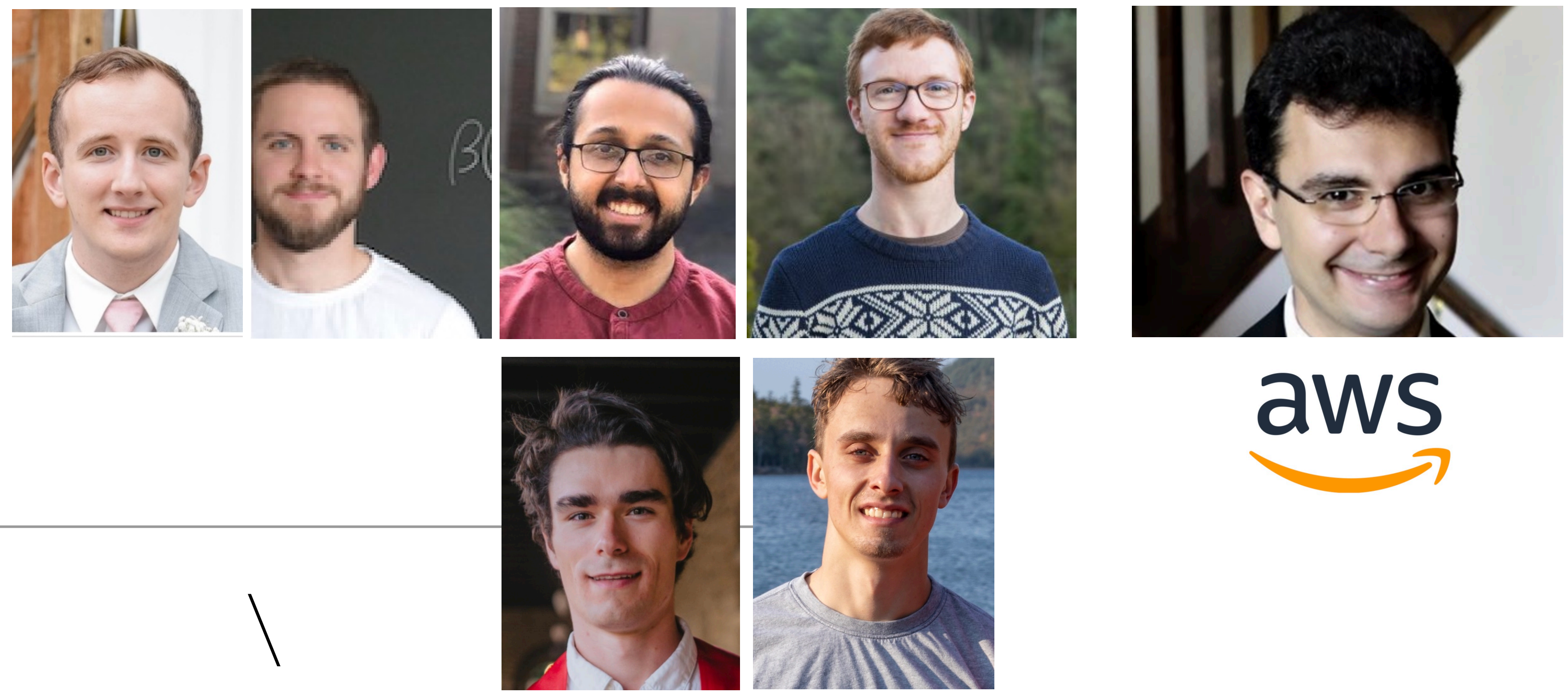


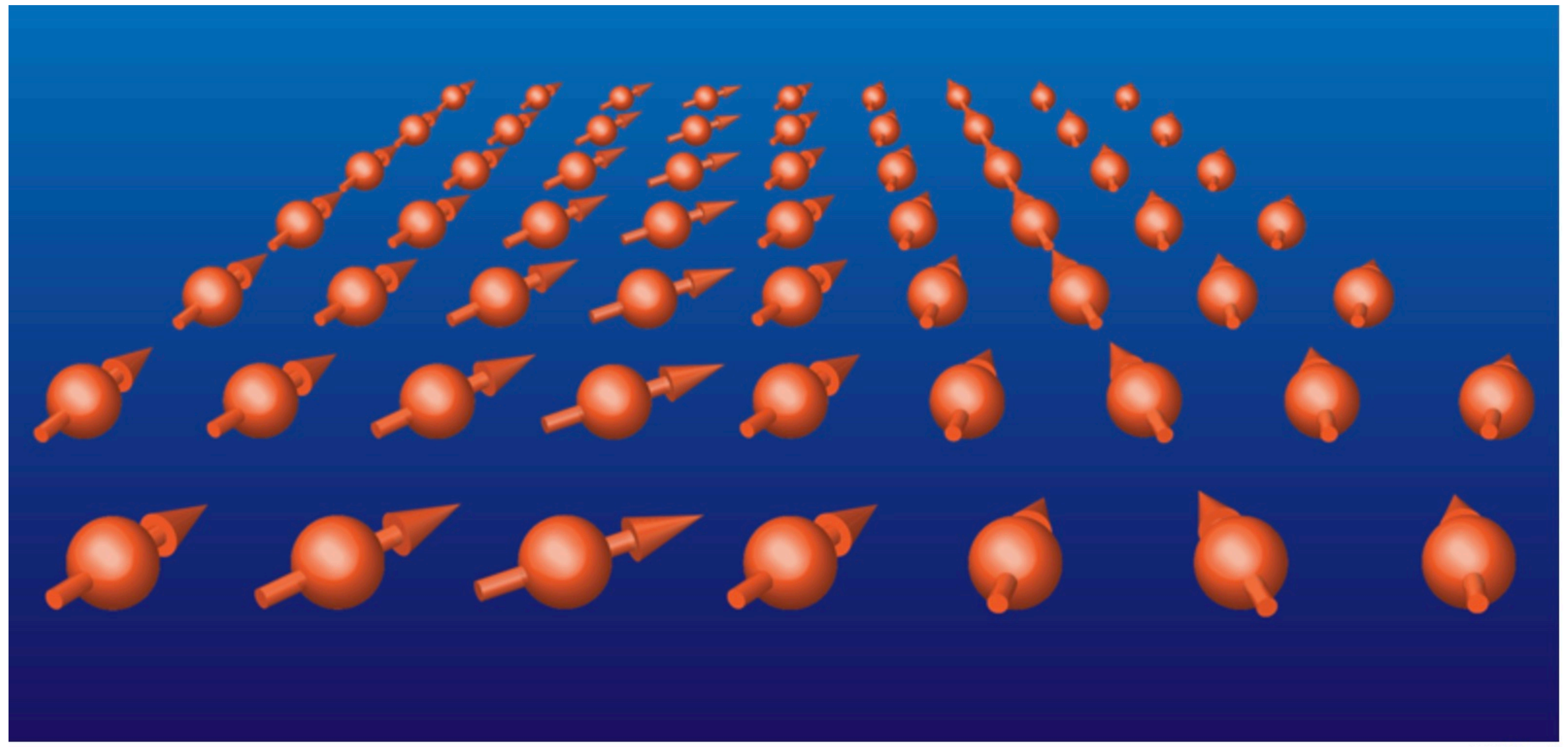
Early-2022



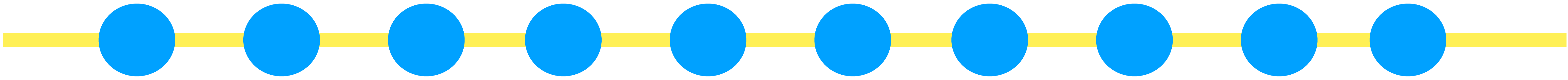


For Cold-Atom Systems
Dimensional Reduction





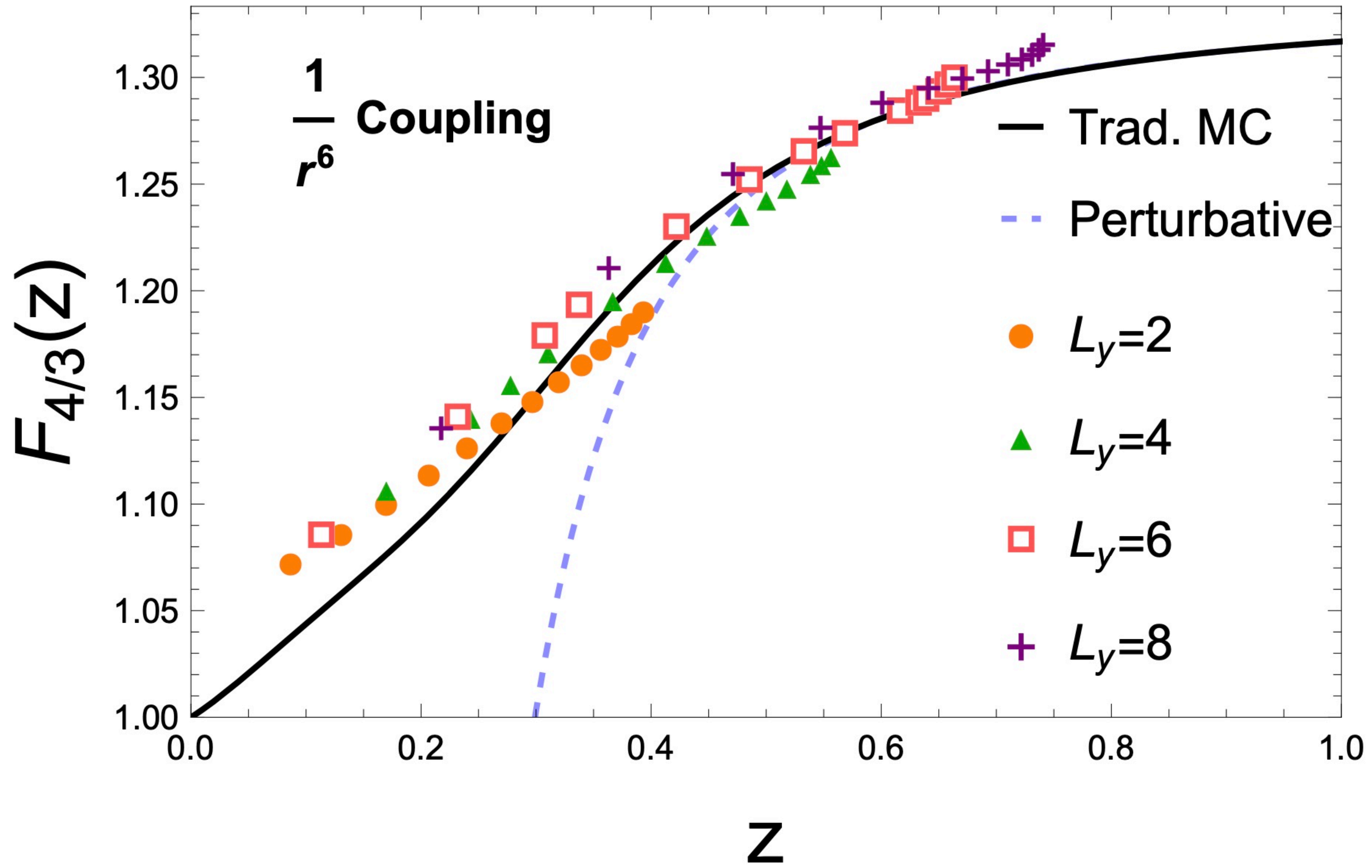
APS/Alan Stonebraker



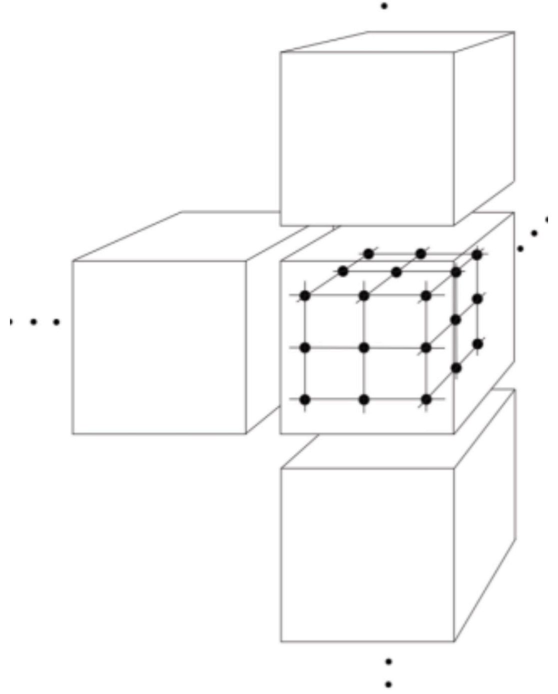
$$S = \frac{1}{2g} \int dt\, dx\, \partial_\mu \vec{\phi}(x,t) \cdot \partial^\mu \vec{\phi}(x,t)$$

2+1D → **1+1D**

$$\hat{H}^D = J_x \sum_{x,y} \vec{S}_{x,y} \cdot \vec{S}_{x+1,y} + J_y \sum_{x,y} \vec{S}_{x,y} \cdot \vec{S}_{x,y+1}$$



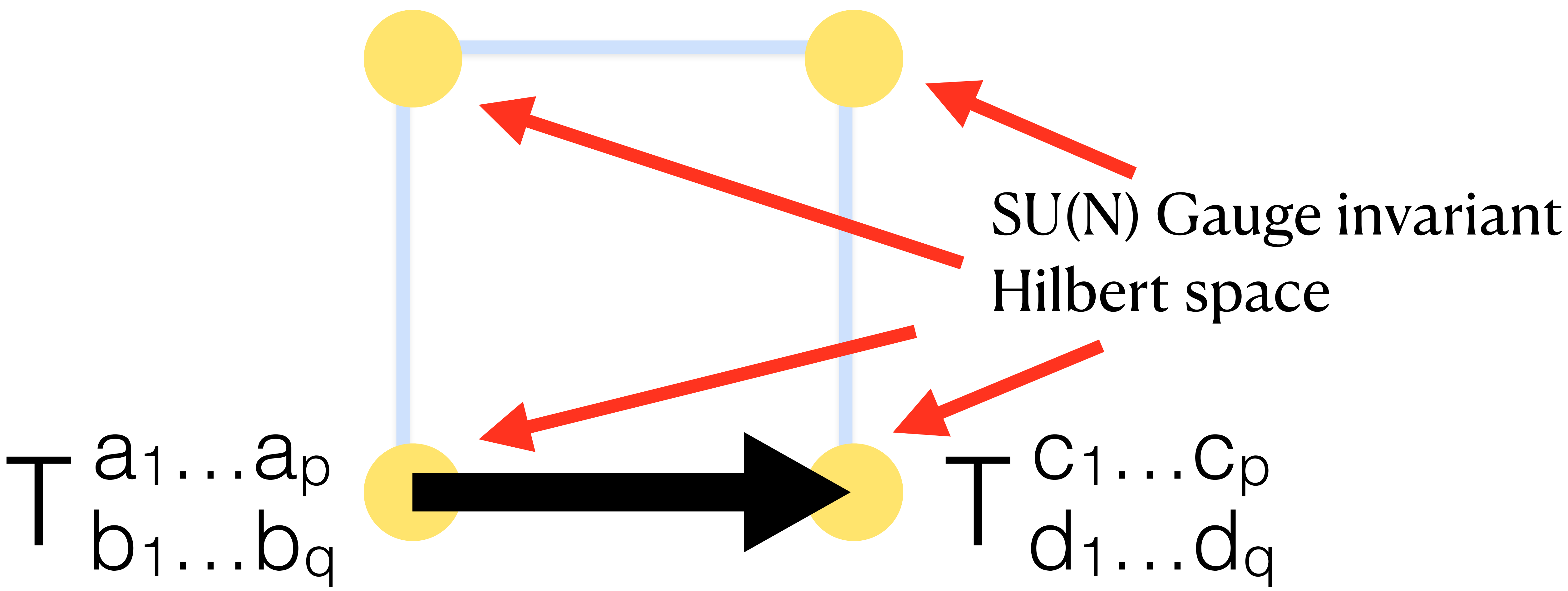
Yang-Mills
Byrnes-Yamamoto — Kogut-Susskind

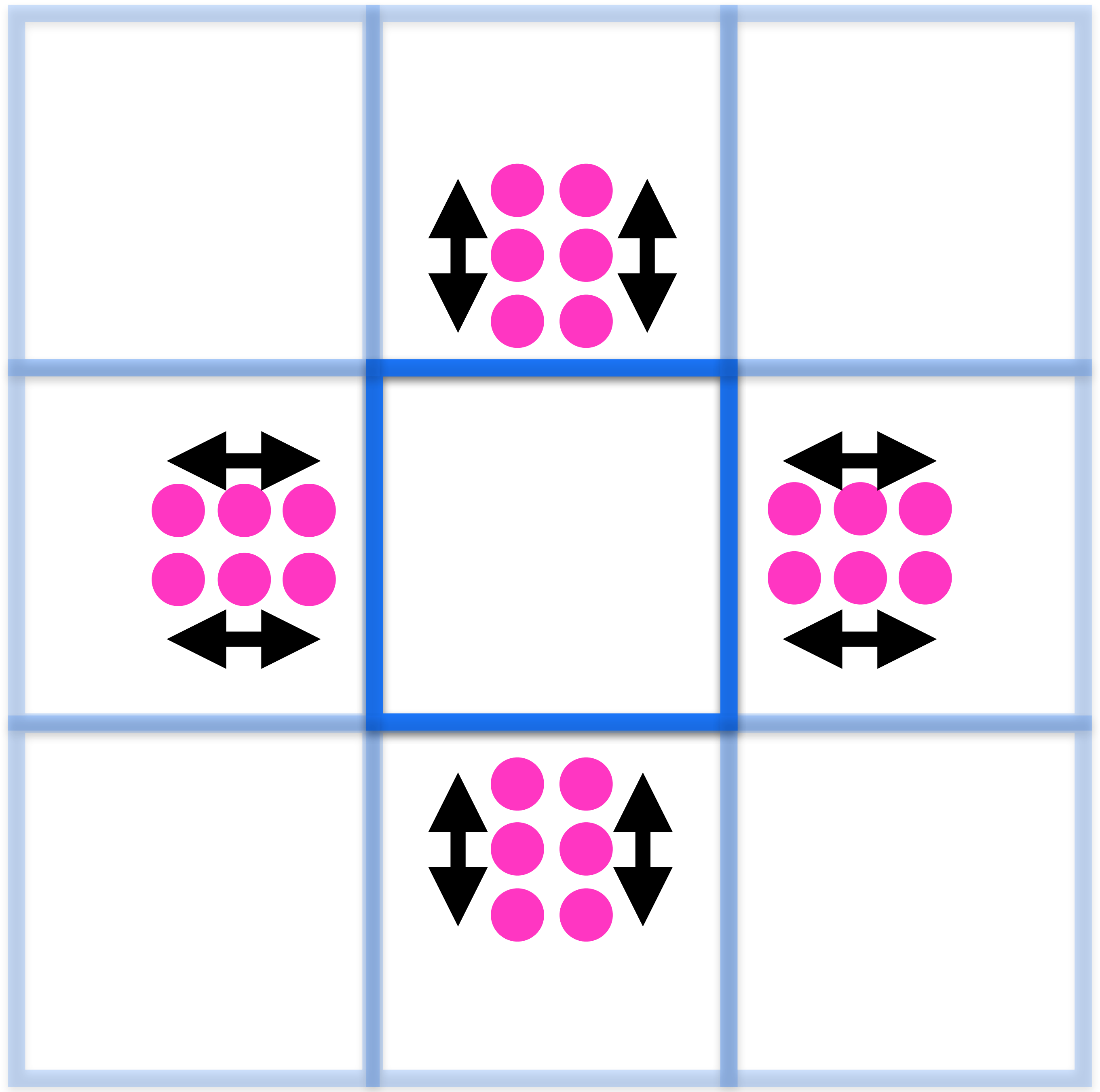


Kogut-Susskind basis = electric basis ....

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

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





Truncate field

Continuum limit

Conjecture ....

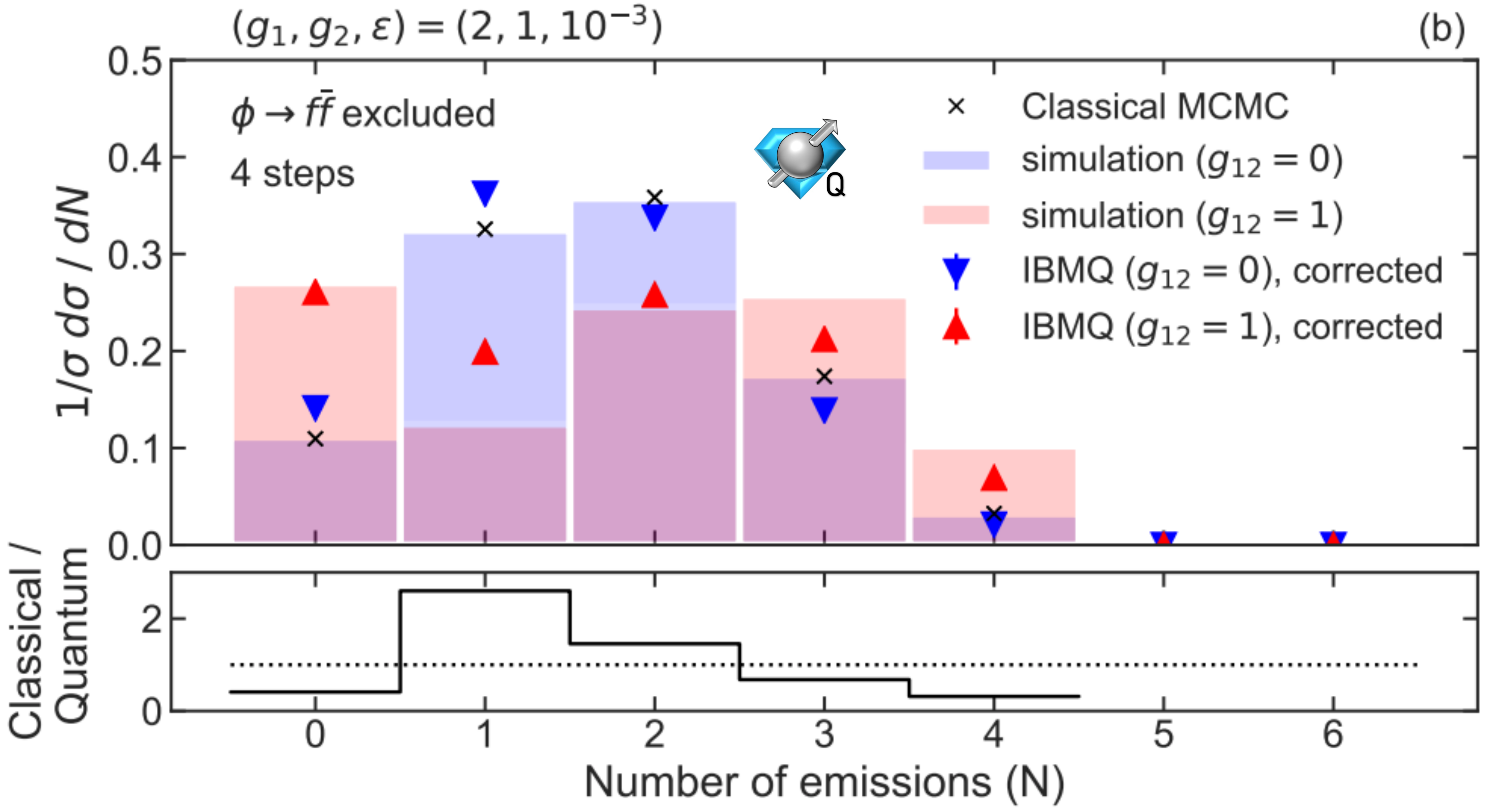
ECT*, Trento, June 2023

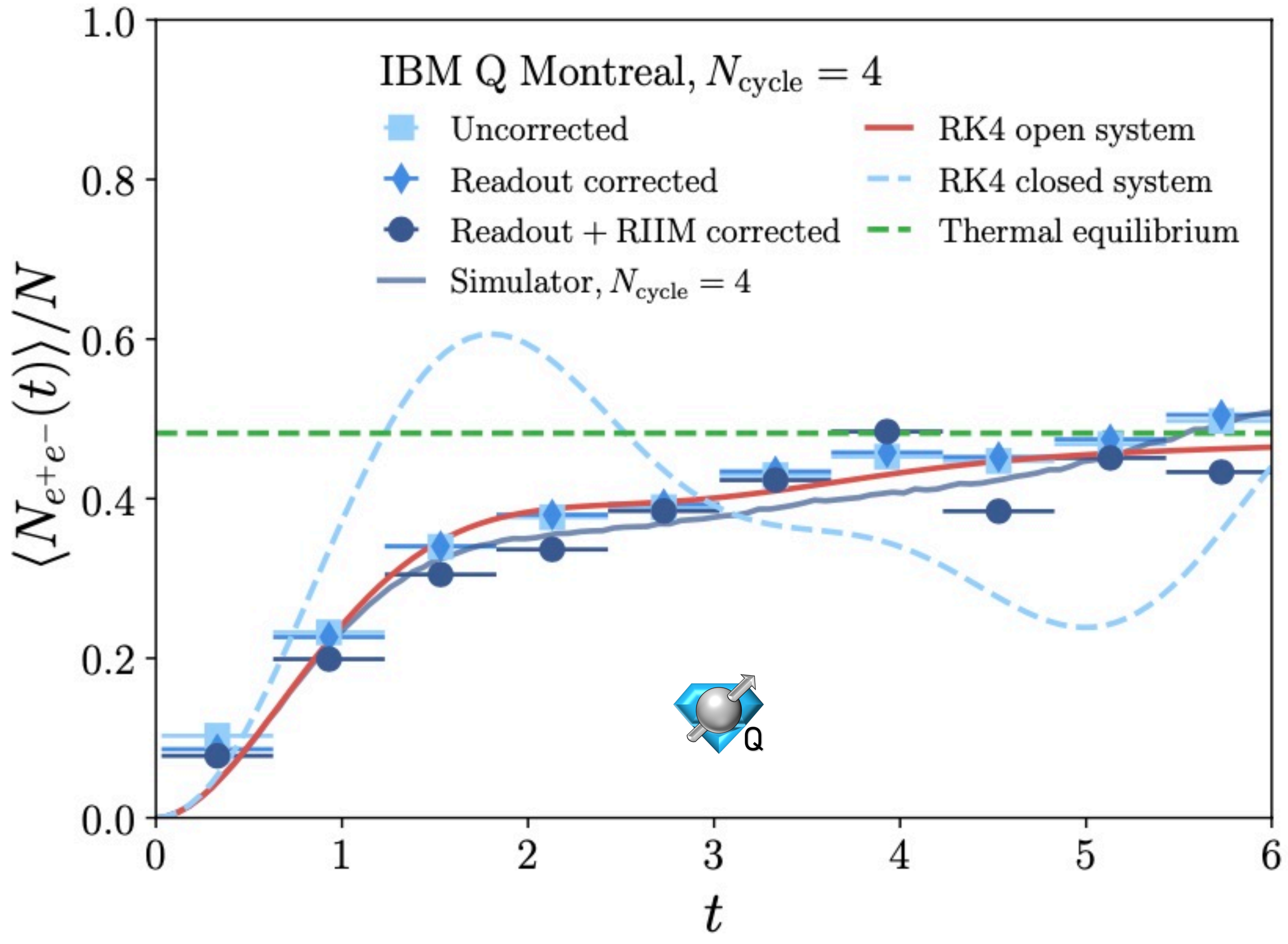
We are likely missing an important ingredient so far:

- all of the “power” of computation - the gates - are being applied at the scale of the (unphysical) lattice spacing

Conjecture: efficient digital quantum circuits exist for Standard Model simulations where the gate-structure, or power, is dominantly focused at the scale of the physics/observable(s).
i.e., EFTs can manifest at the quantum circuit level.

Fragmentation and Collisions
Vacuum and In-Medium





$$\mathcal{L} = \bar{f}_1(i\not{\partial} + m_1)f_1 + \bar{f}_2(i\not{\partial} + m_2)f_2 + (\partial_\mu\phi)^2 + g_1\bar{f}_1 f_1\phi + g_2\bar{f}_2 f_2\phi + g_{12}\left[\bar{f}_1 f_2 + \bar{f}_2 f_1\right]\phi\,.$$

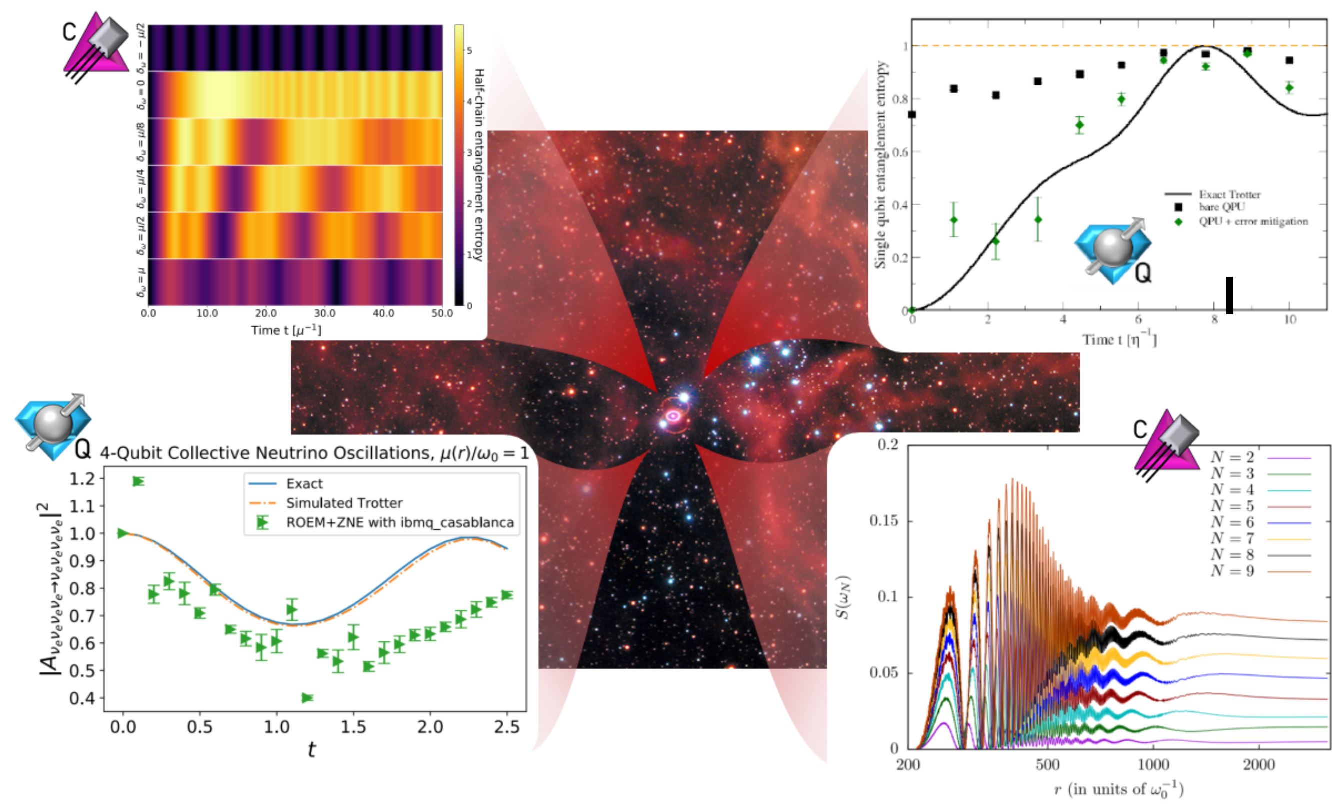
Fragmentation

A quantum algorithm for high energy physics simulations
Christian W. Bauer, Wibe A. de Jong, Benjamin Nachman, Davide Provasoli, arXiv:1904.03196 [hep-ph]

Simulating Collider Physics on Quantum Computers using Effective Field Theories
Christian W. Bauer, Benjamin Nachman, Marat Freytsis, arXiv:2102.05044 [hep-ph]

QQbar moving in medium

Quantum simulation of non-equilibrium dynamics and thermalization in the Schwinger model, Wibe A. de Jong, Kyle Lee, James Mulligan, Mateusz Płoskoń, Felix Ringer et al. e-Print: 2106.08394 [quant-ph]

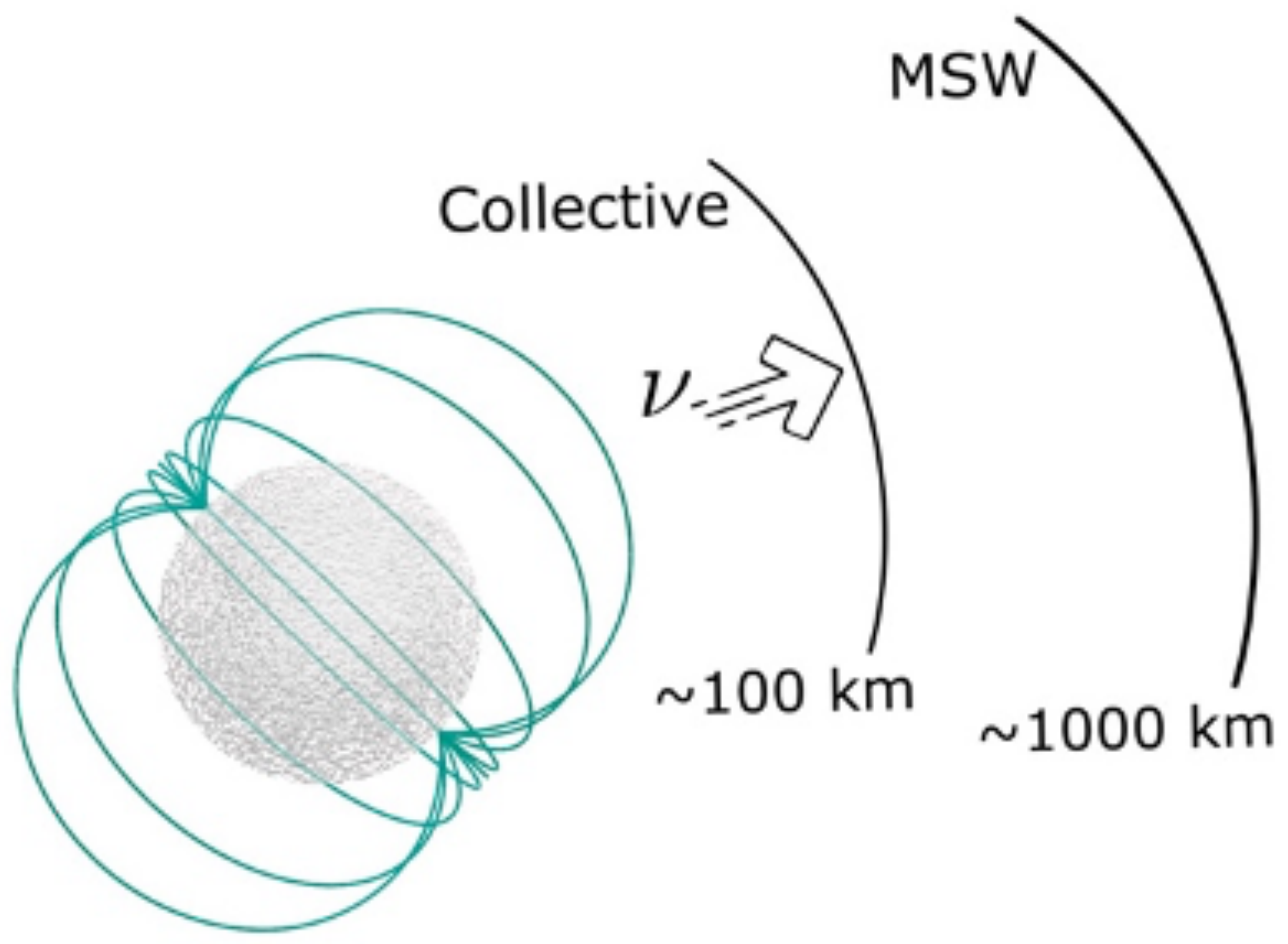


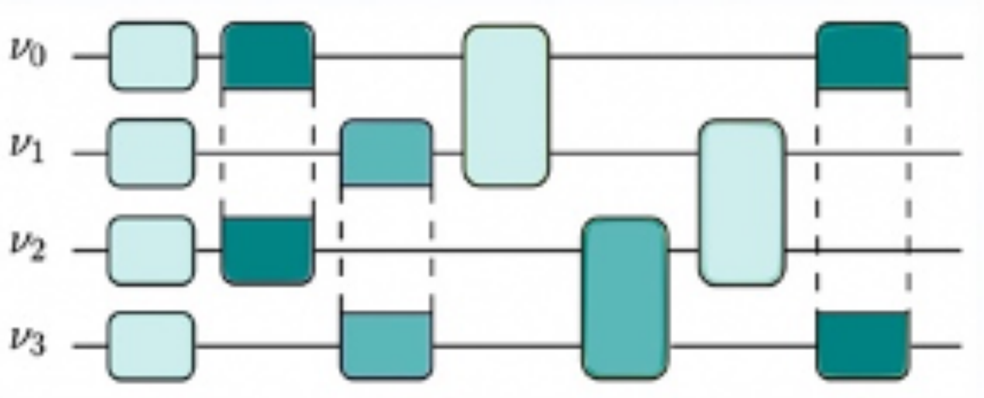
Balantekin, Pooser, Roggero, Siopsis, Pederiva,.....

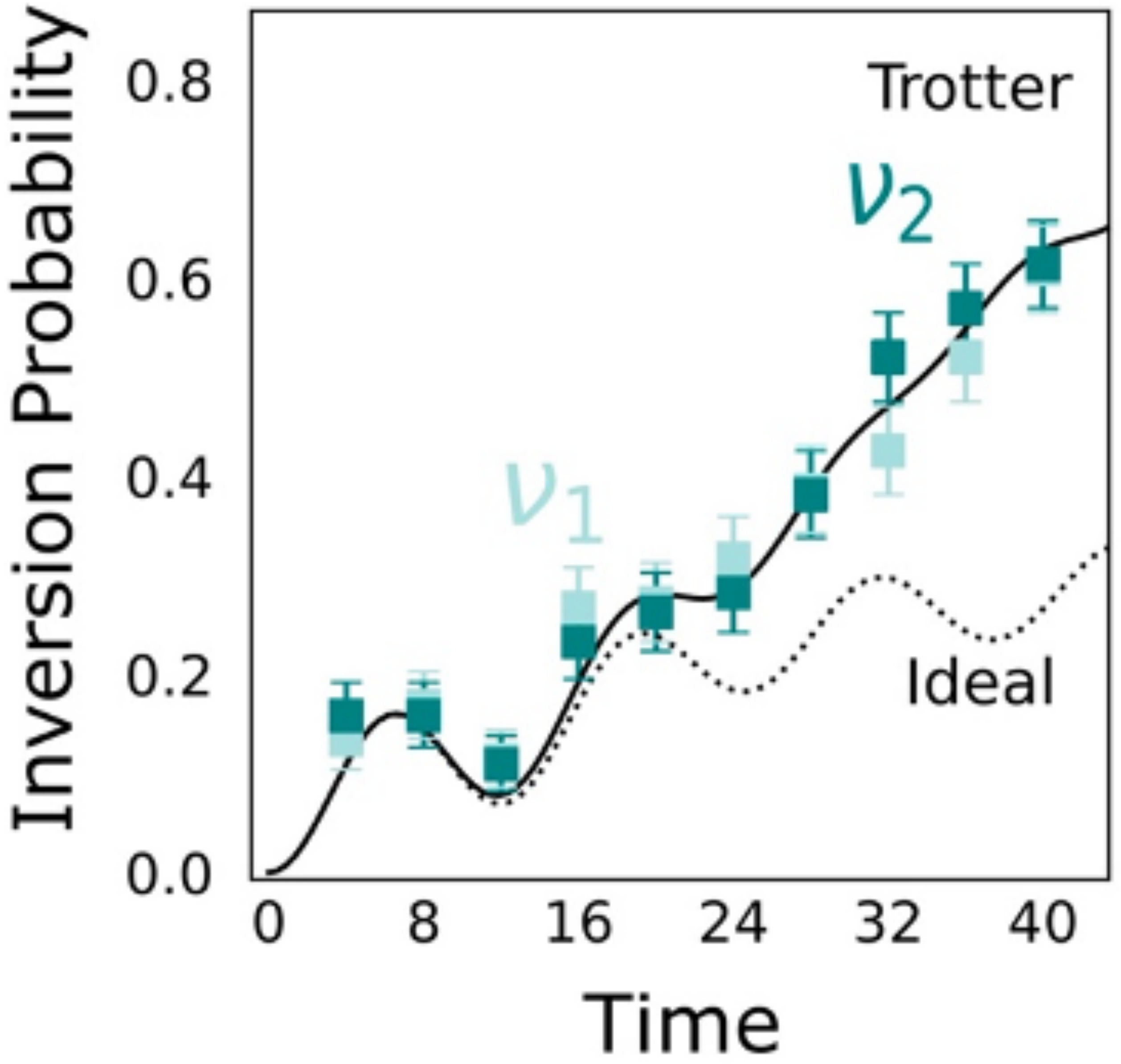
Neutrino Flavor Dynamics in Supernova

LANL,..

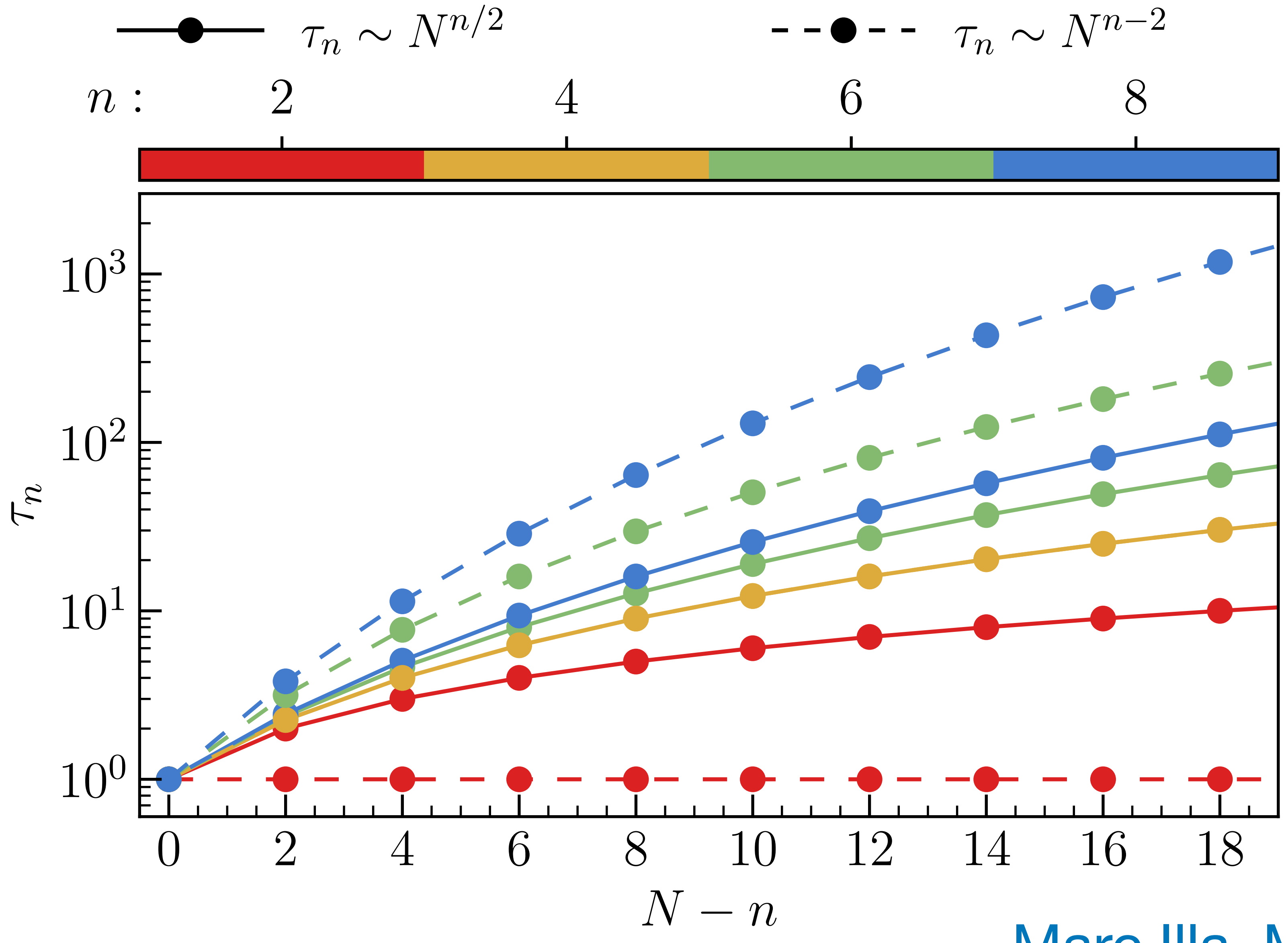
$$H_{FS} = -\sum_{k=1}^{N} \frac{\omega_k}{2}\sigma_k^z + \frac{\mu}{2N}\sum_{i<j}^{N} \mathcal{J}_{ij}\vec{\sigma}_i \cdot \vec{\sigma}_j$$







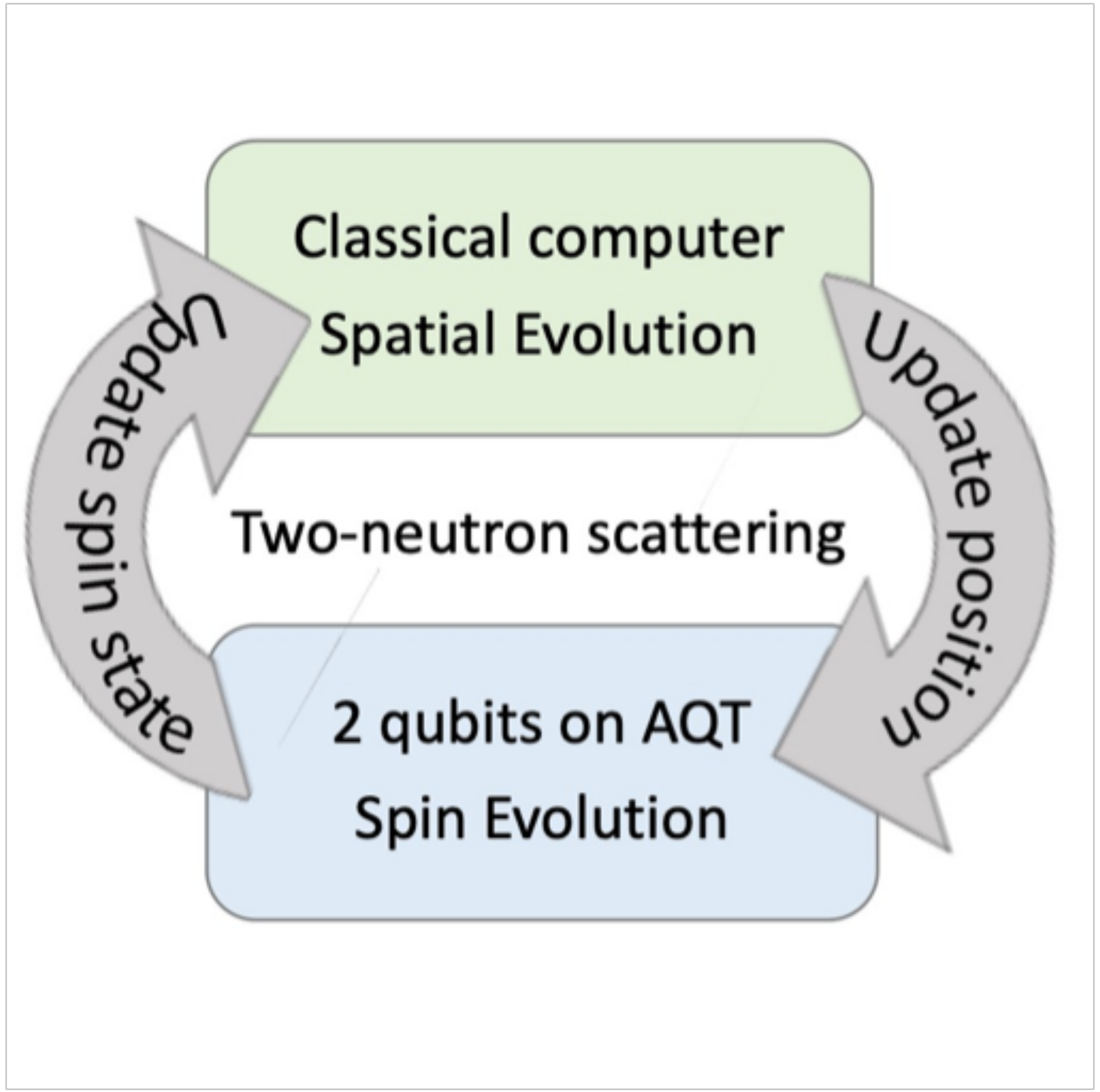
Multi-Neutrino Entanglement

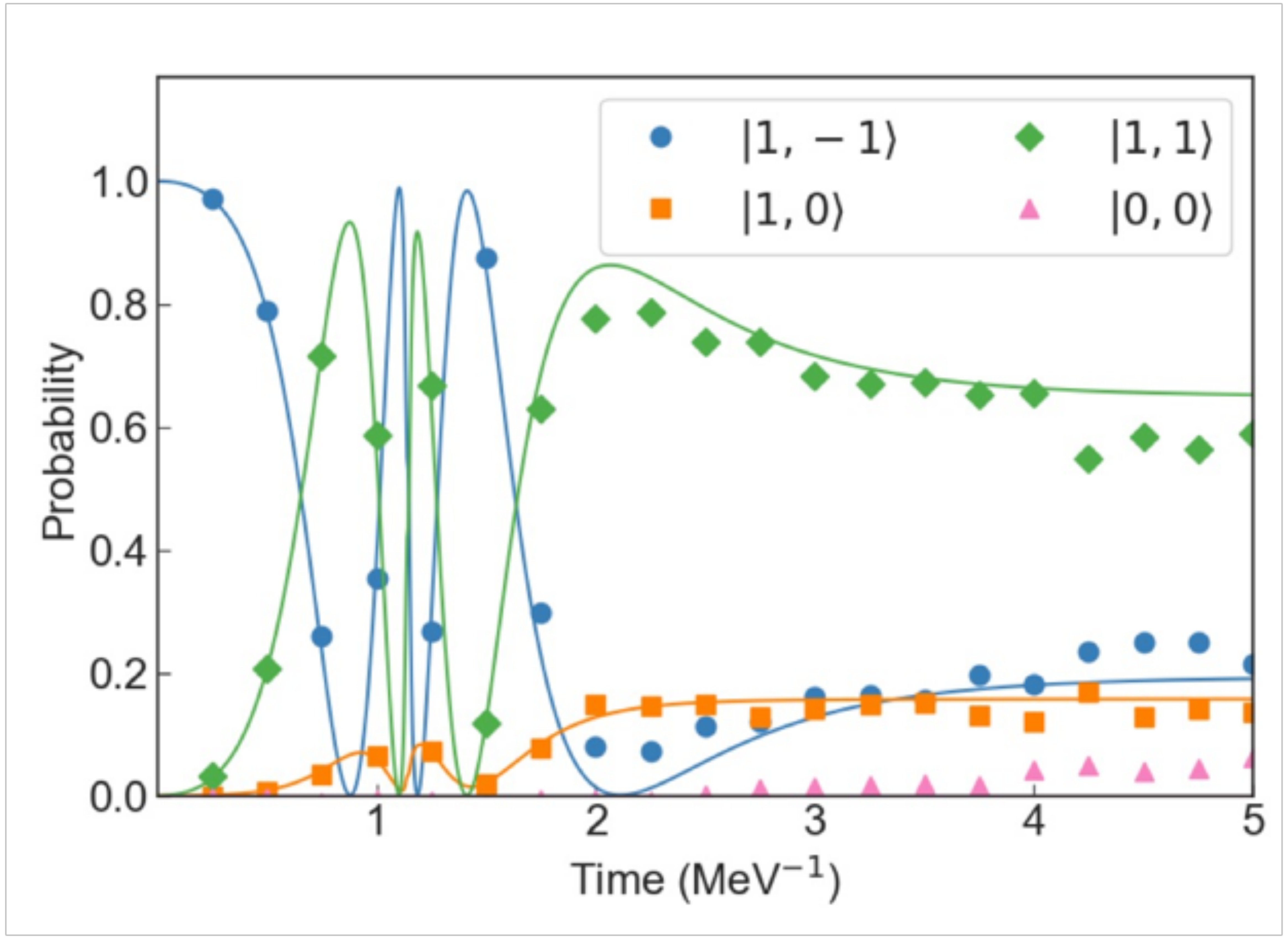


Marc Illa, MJS

Neutron Scattering with Hybrid Quantum Simulation

LLNL+Trento

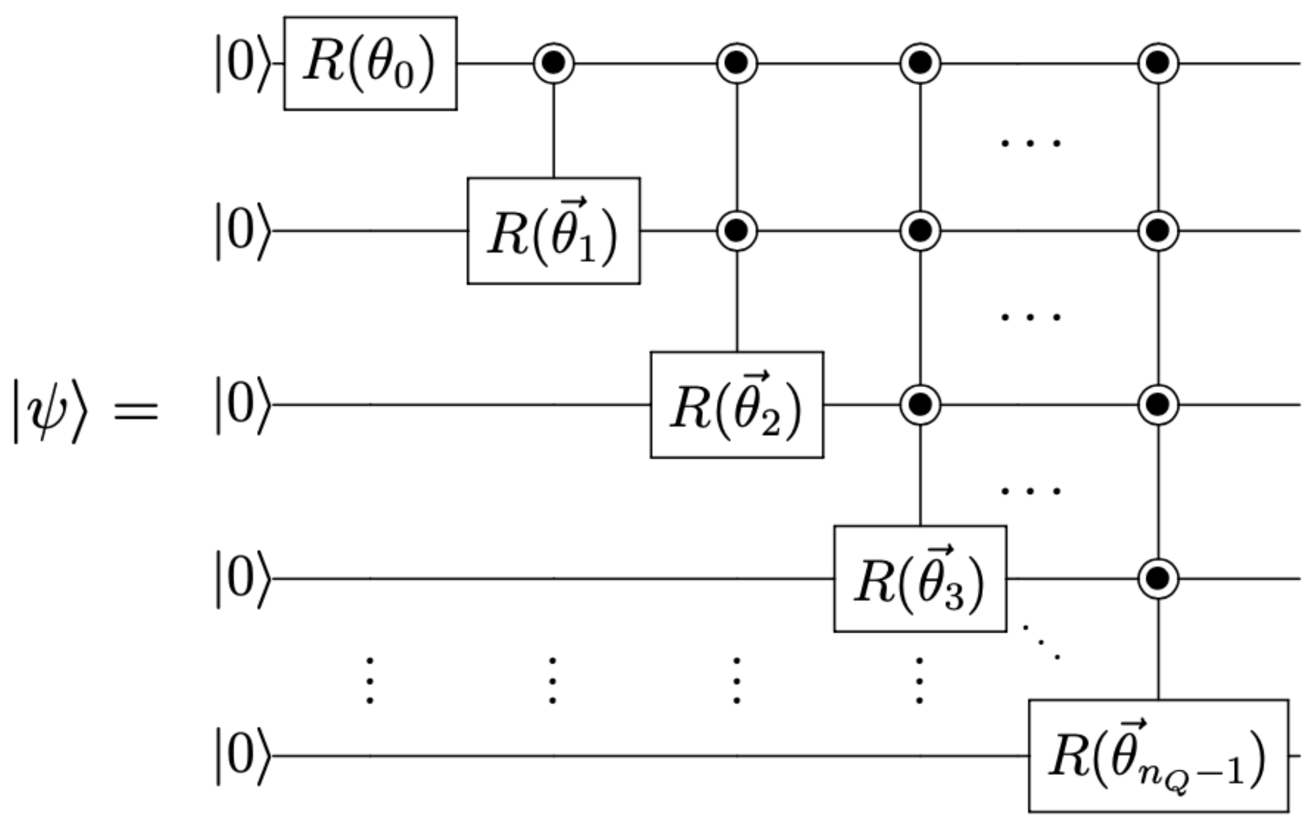


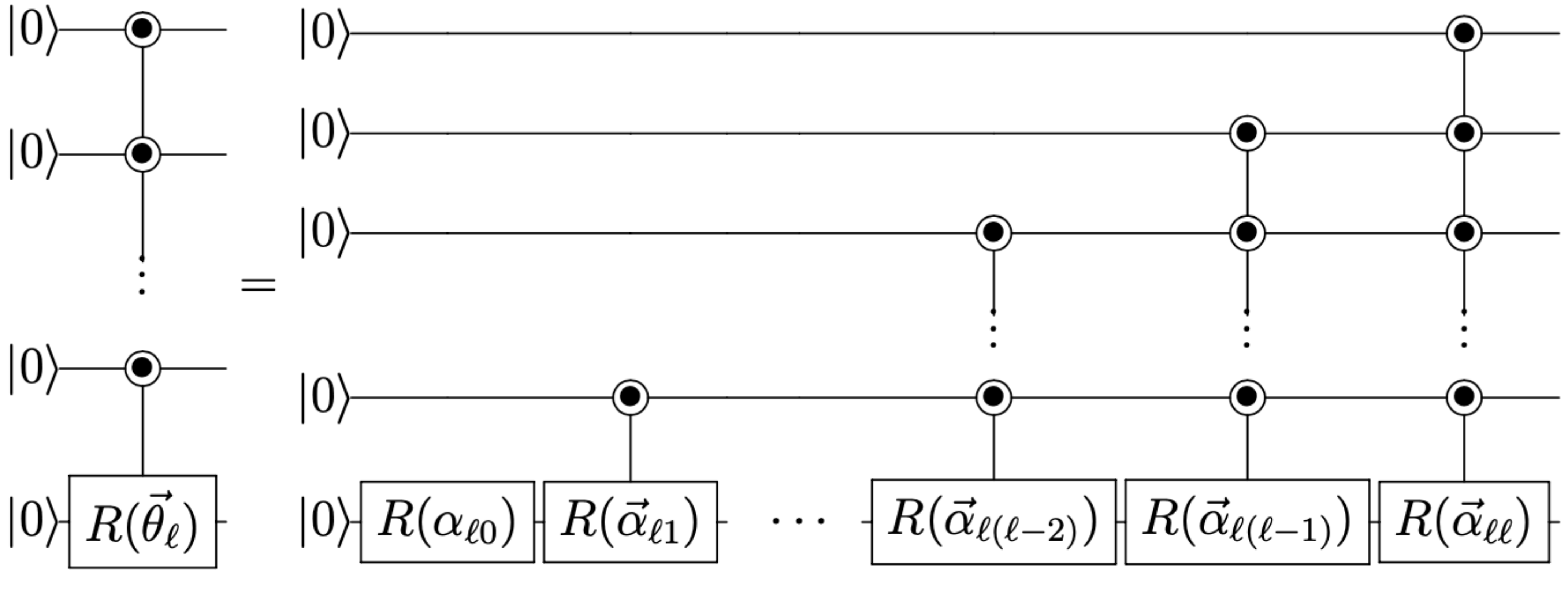


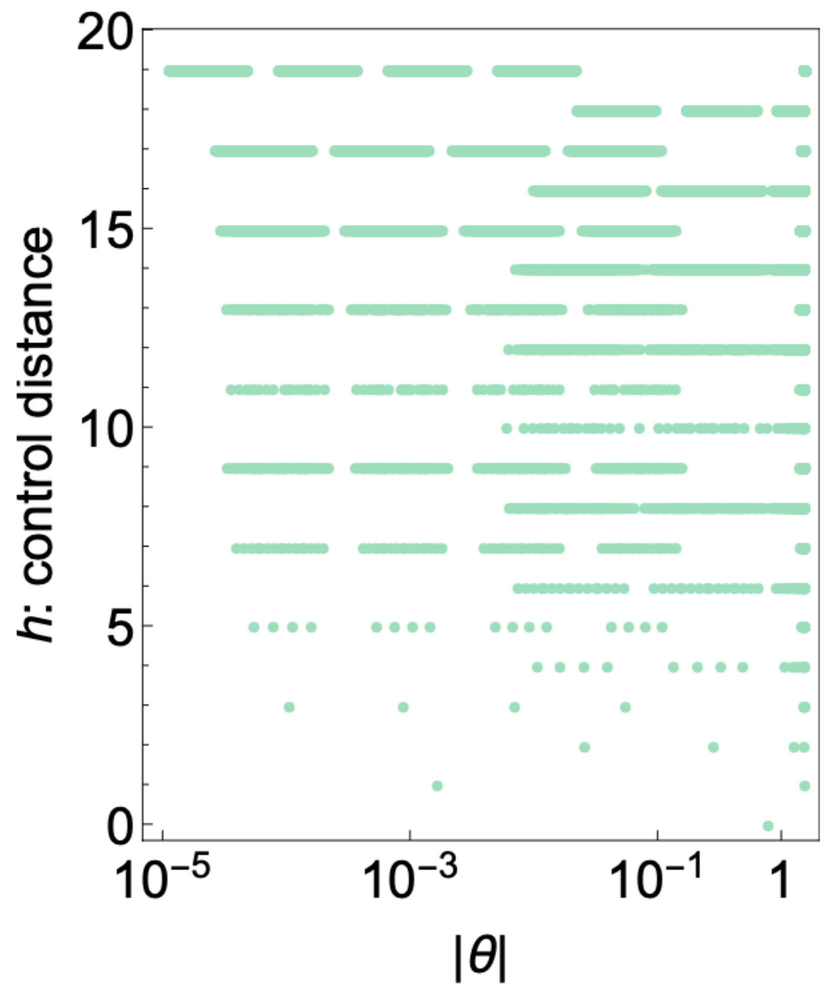
State Preparation with Localizable or **Physics-Aware** Quantum Circuits

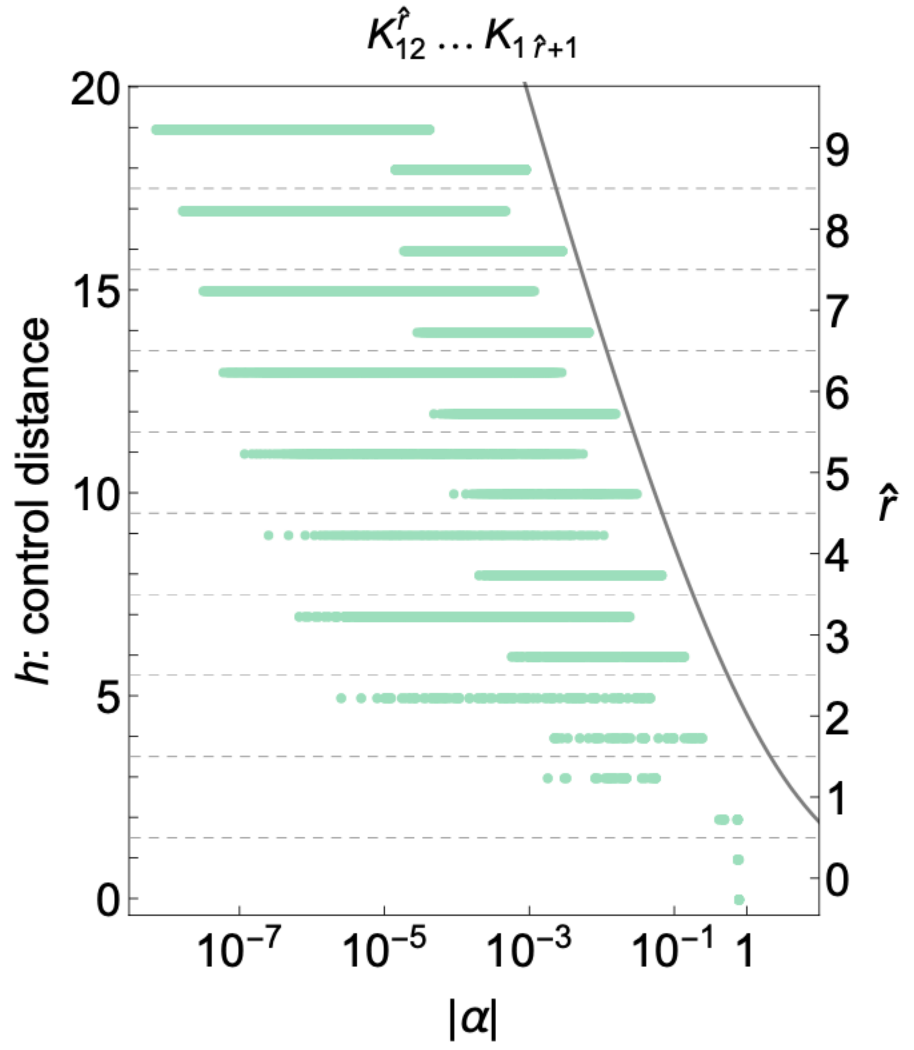
Systematically Localizable Operators for Quantum Simulations of Quantum Field Theories

Natalie Klco* and Martin J. Savage†





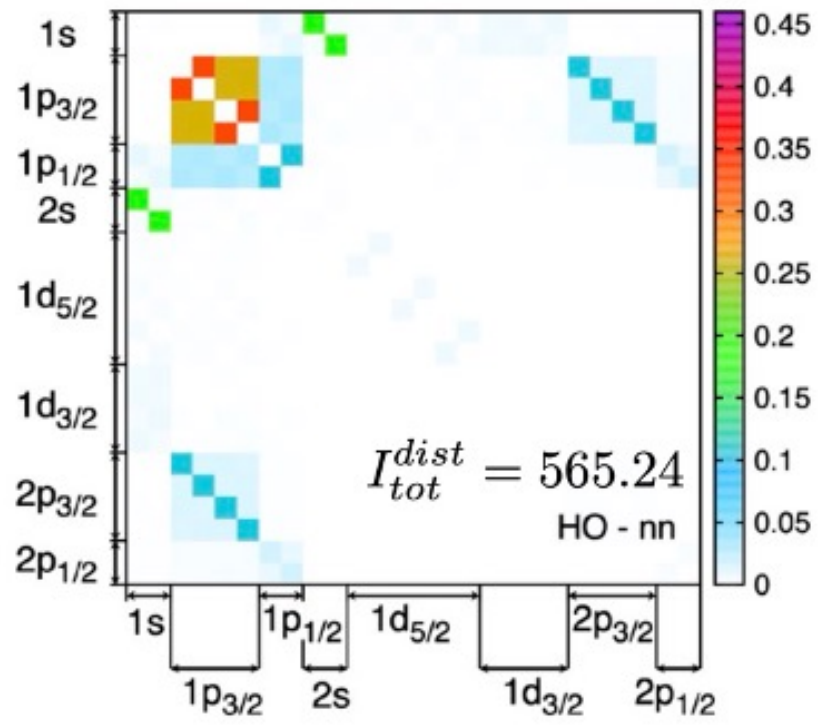


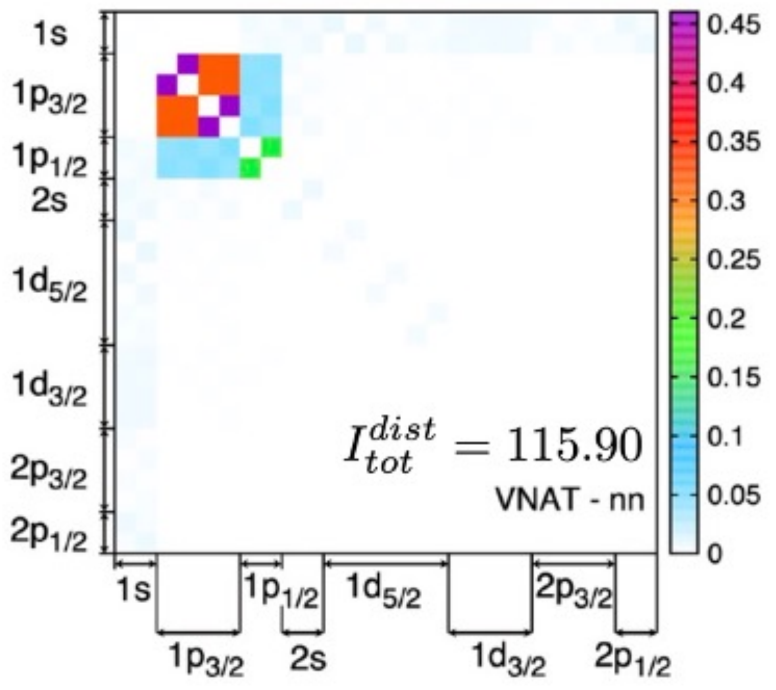


Correlation length allows for fixed-point angles to be determined exponentially well with small-scale simulations

Entanglement Rearrangement and Hamiltonian Learning in Nuclei and Spin Systems

Caroline Robin





state preparation $\Psi(\boldsymbol{\theta}^{(k)})$

Measurement of cost function and derivatives

$$E(\beta^{(k)}, \boldsymbol{\theta}^{(k)})$$

$$\frac{\partial E(\beta^{(k)}, \boldsymbol{\theta}^{(k)})}{\partial \theta_i^{(k)}} \qquad \frac{\partial E(\beta^{(k)}, \boldsymbol{\theta}^{(k)})}{\partial \beta^{(k)}}$$

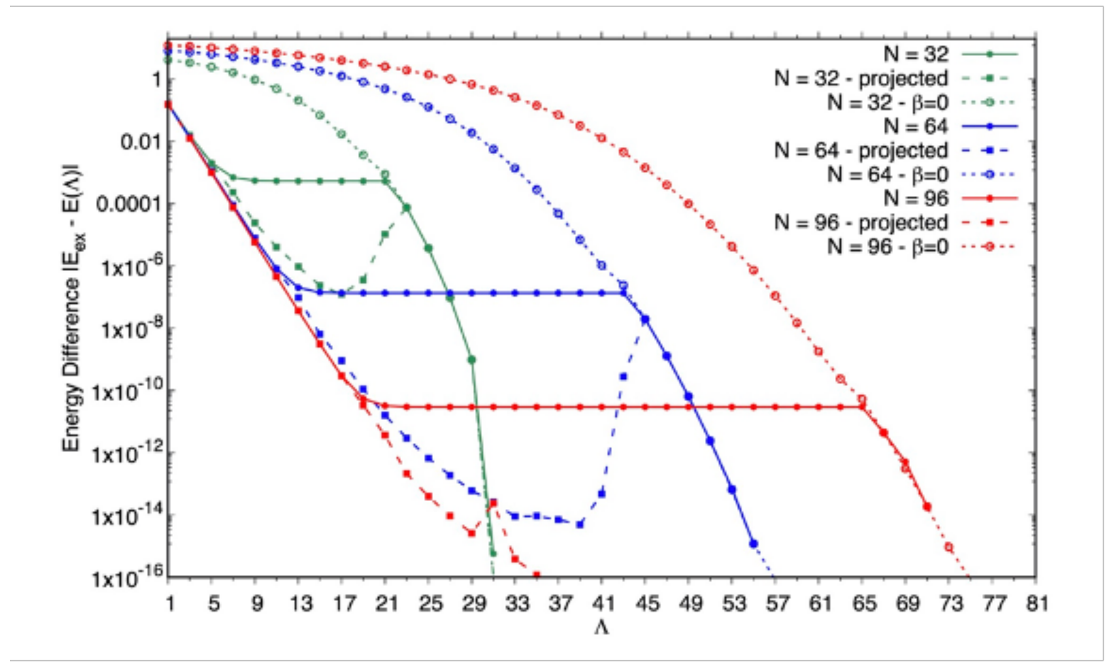
k=k+1

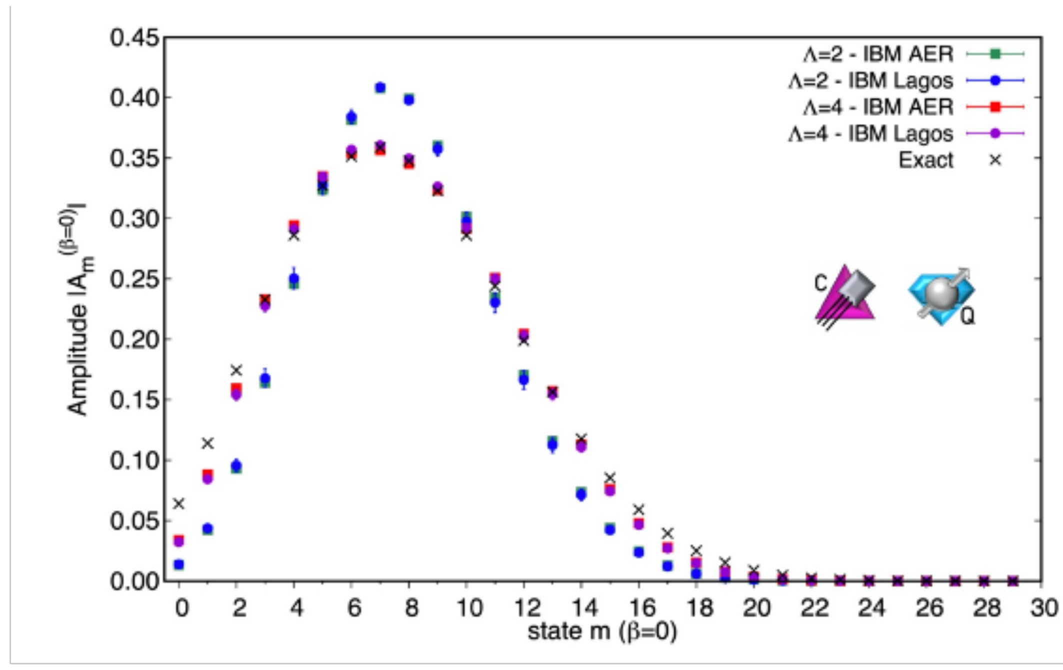
classical optimization of

$$\left(\boldsymbol{\theta}^{(k)}, \beta^{(k)}\right)$$

(gradient descent)

Non-commutivity of symmetries and cut off

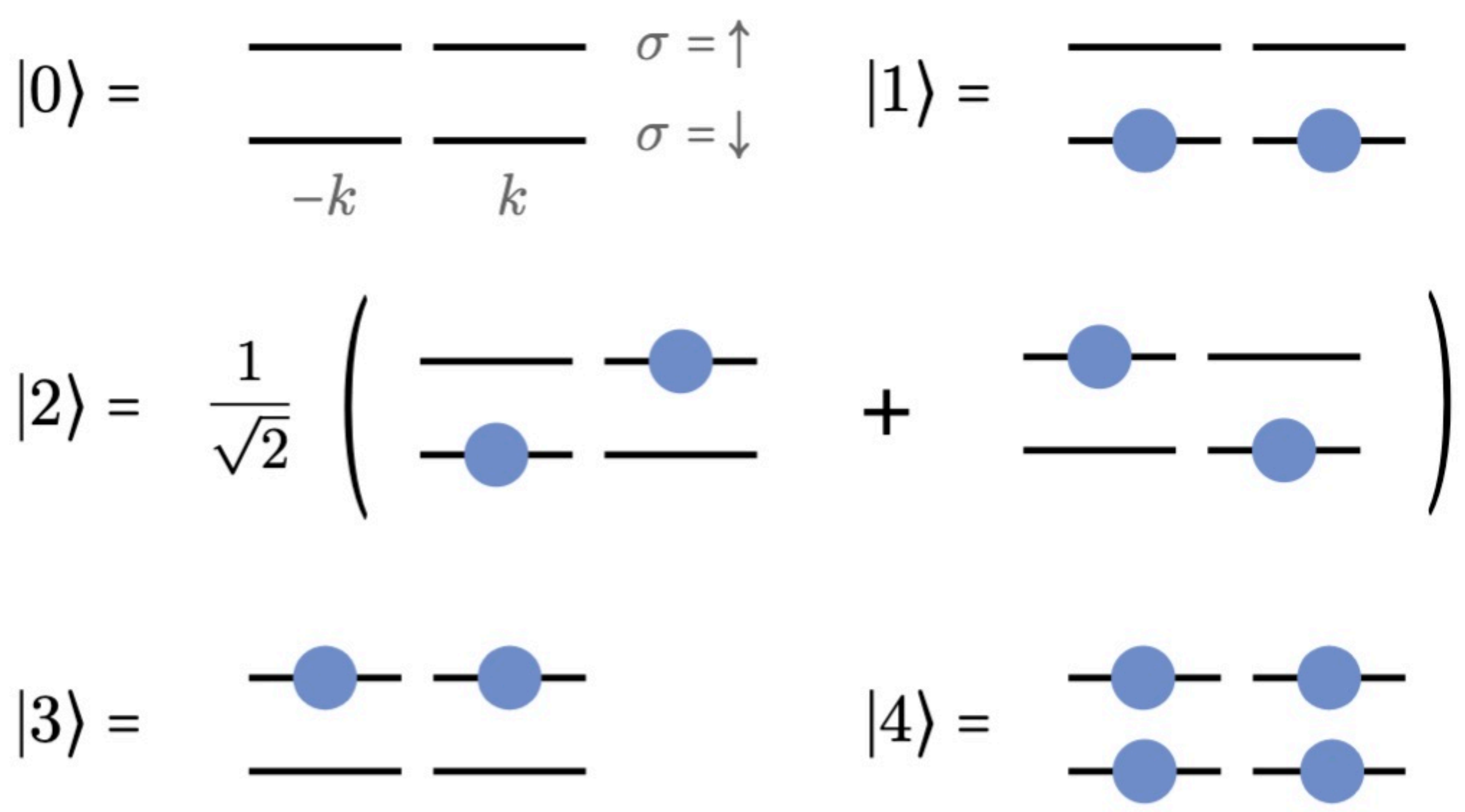




Lipkin-Meshkov-Glick Model with Pairing

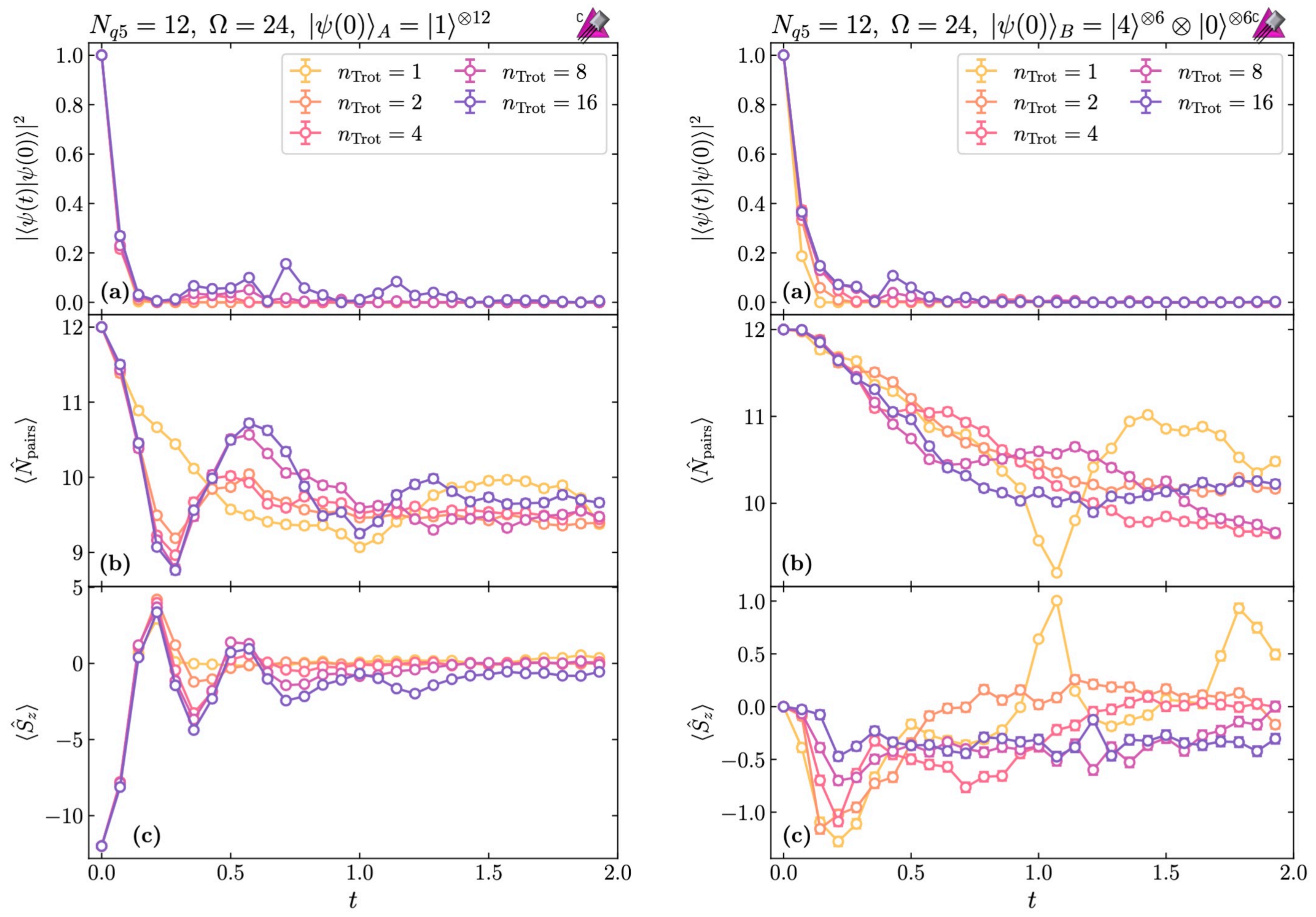
Quantum Simulations of SO(5) Many-Fermion Systems using Qudits

Marc Illa[1,*] Caroline E. P. Robin[2,3,†] and Martin J. Savage[1,‡]



Low in spectrum

High in spectrum

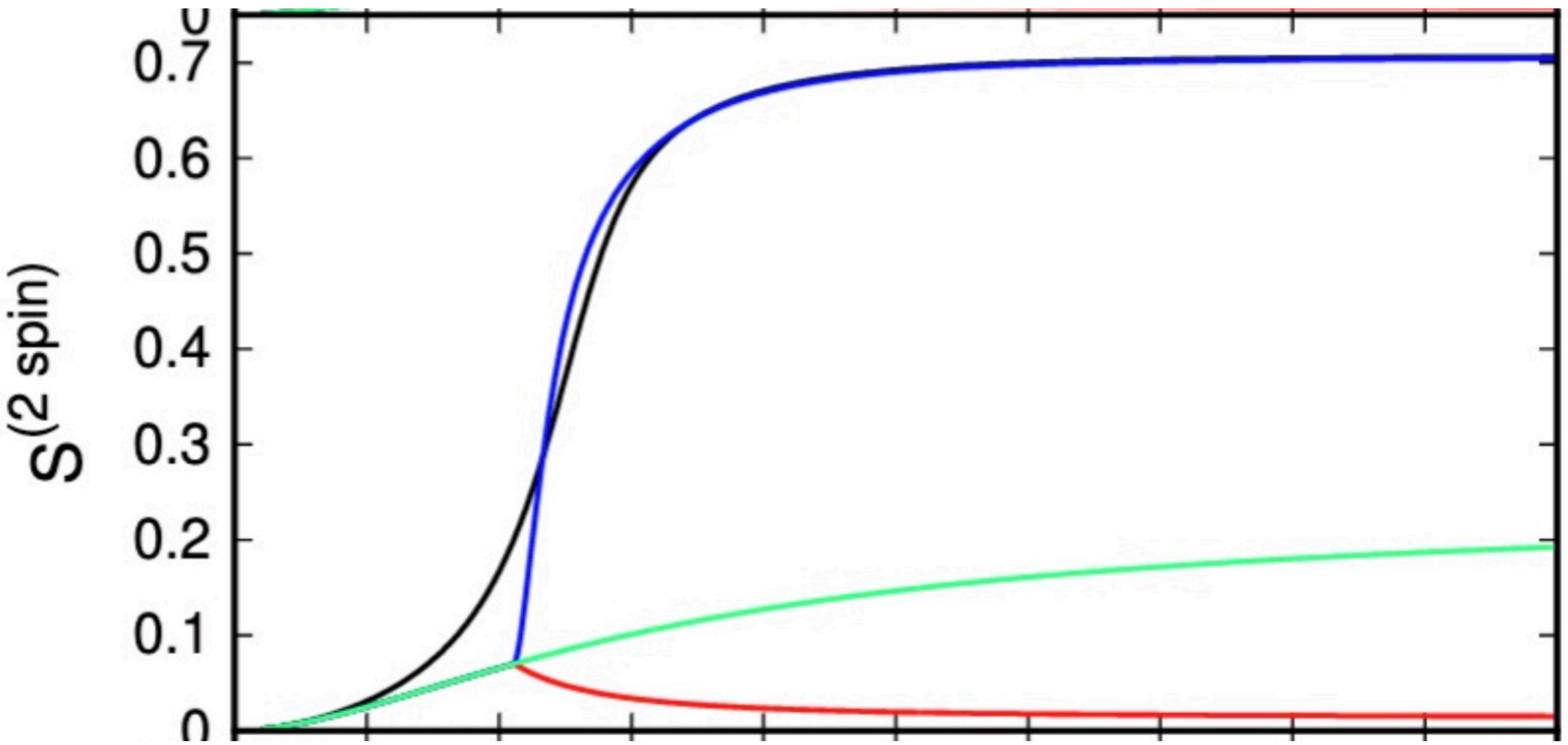


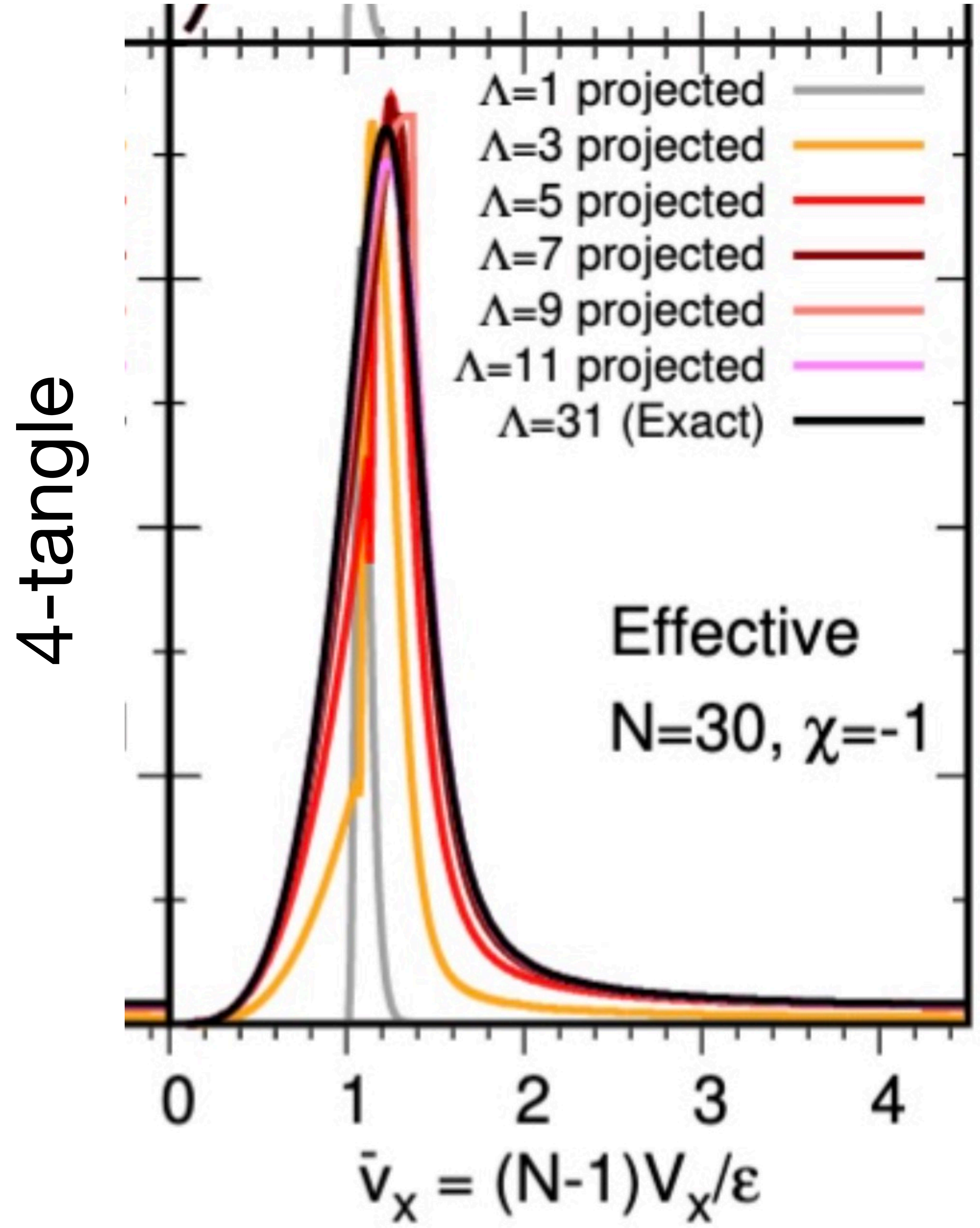
Lipkin-Meshkov-Glick Model Generalized

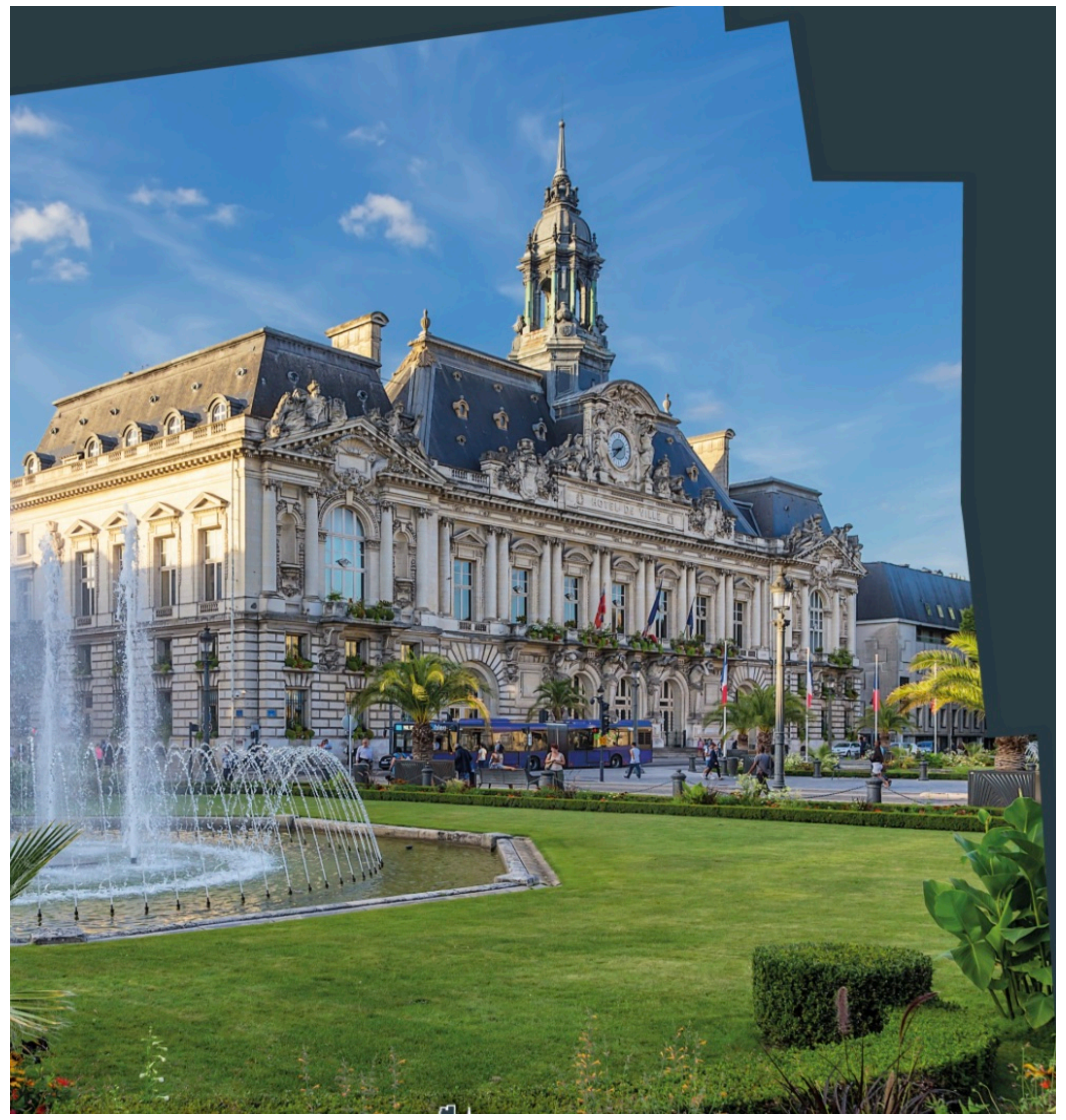
Multi-Body Entanglement and Information Rearrangement in Nuclear Many-Body Systems

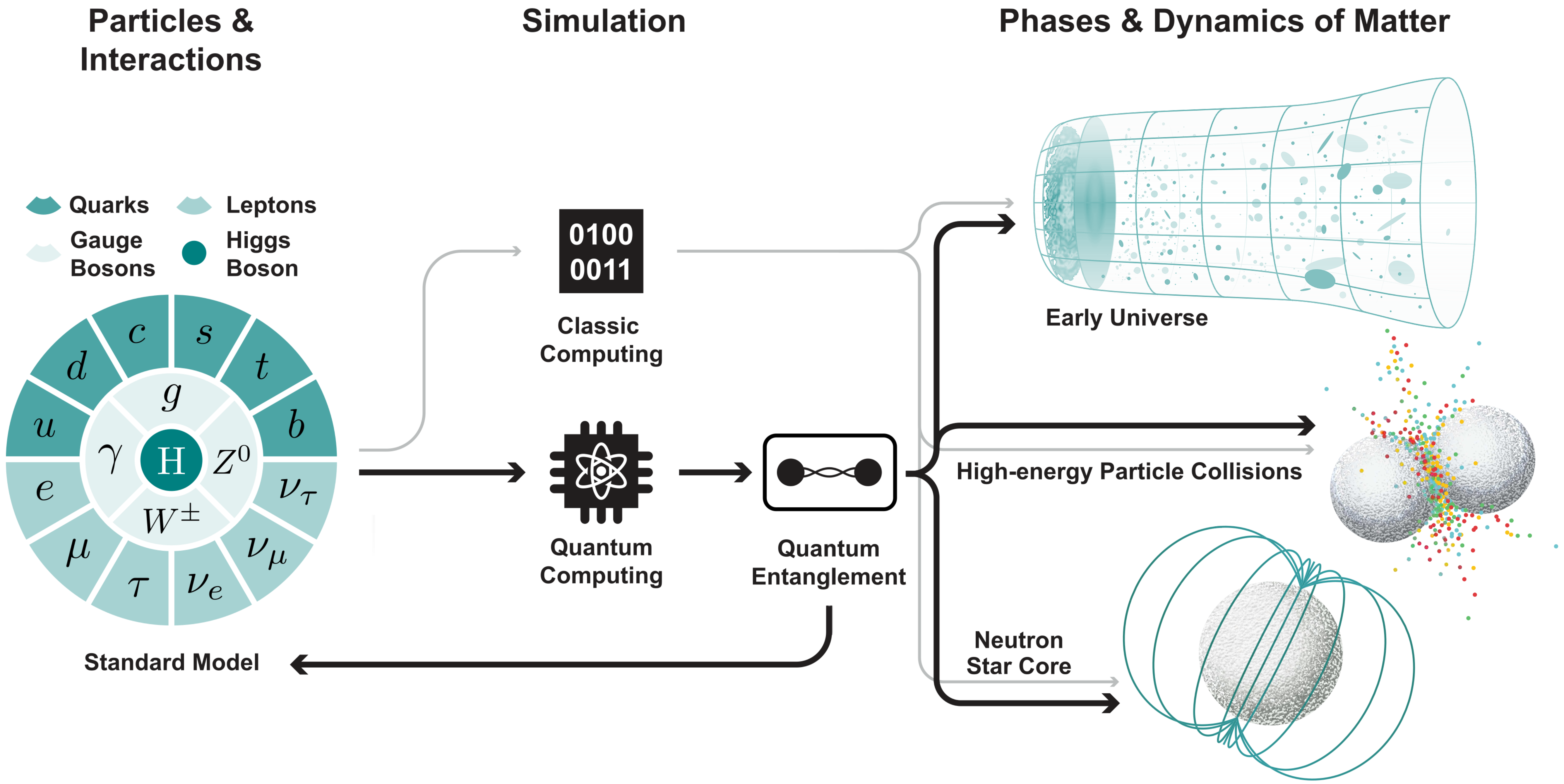
S. Momme Hengstenberg[1a], Caroline E. P. Robin[1,2 b], and Martin J. Savage[3c]

$$\hat{H} = \varepsilon \hat{J}_z - V_x(\hat{J}_x^2 + \chi \hat{J}_y^2) + V_x \frac{1+\chi}{4}\hat{N}$$









Summary

- Standard Model dynamics requires quantum simulations
- Early stages in assessing requirements. Significant obstacles remain.
- Encouraging progress in quantum simulations in low-dimensional systems.
- Efforts toward 2+1 and 3+1 simulations.
- Connections within nuclear many-body systems are emerging
- Thank You Organizers!

FIN