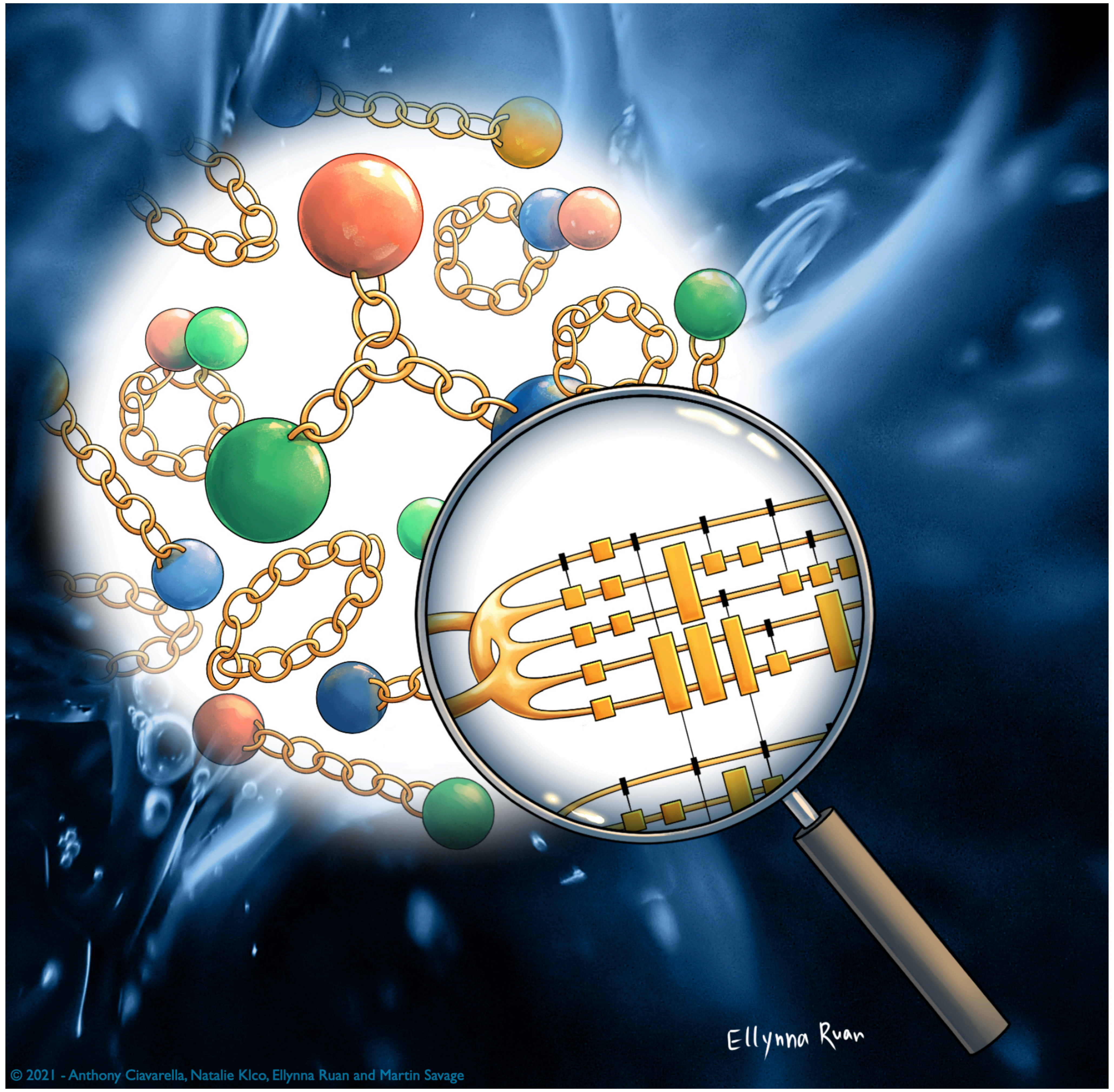


Office of Science
U.S. Department of Energy

QUANTUM SCIENCE CENTER

OAK RIDGE National Laboratory

Fermilab

DOE OFFICE OF NUCLEAR PHYSICS · UW DEPARTMENT OF PHYSICS · UW COLLEGE OF ARTS & SCIENCES

(Thoughts on) Quantum Computation For Quantum Field Theories and Nuclear Physics

My thinking(s) has benefited greatly from many discussions with Silas Beane, Natalie Klco and Alessandro Roggero and others

QuantHEP Seminars, Dec 2021

Martin J Savage

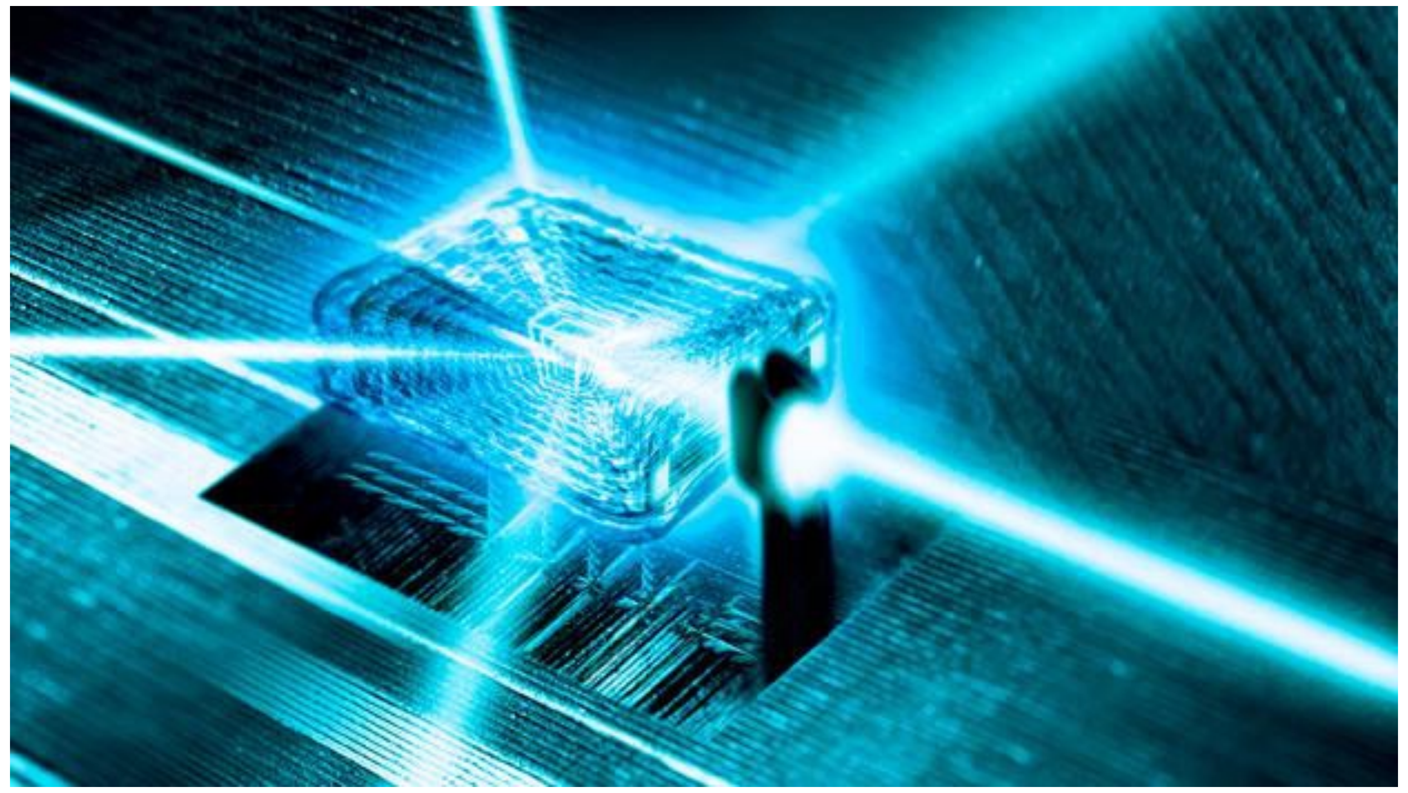
IQuS InQubator for Quantum Simulation

UNIVERSITY of WASHINGTON

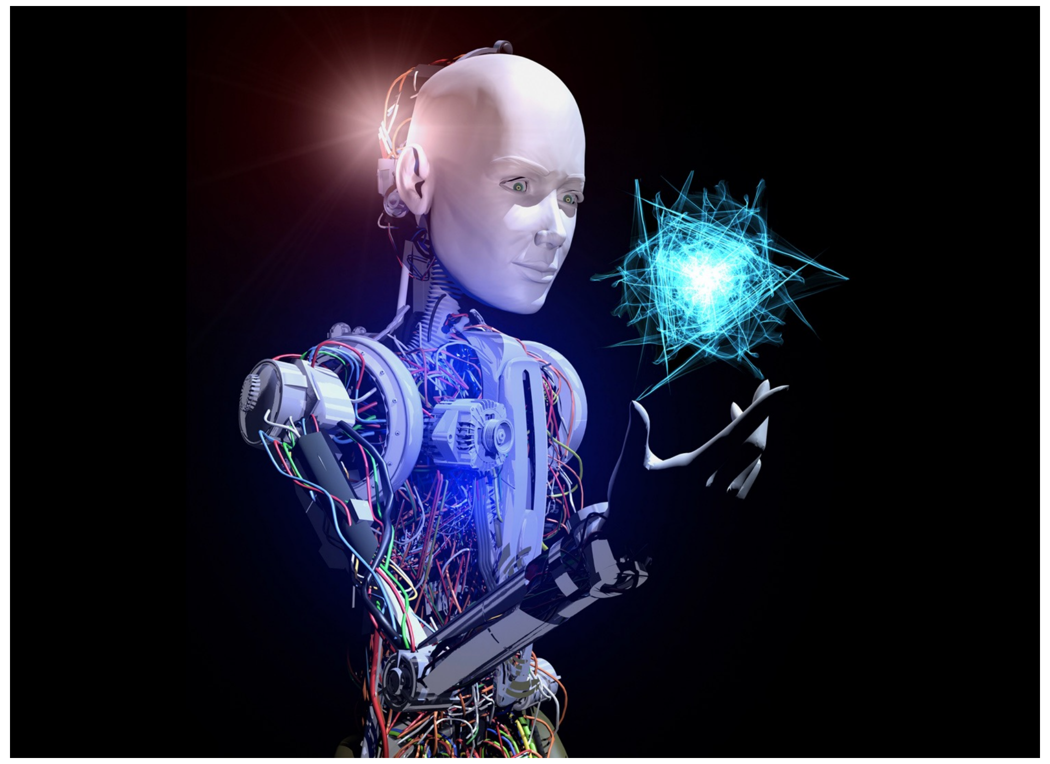
Disruptive Technologies

Quantum Computing/ Simulation

- Entanglement



Machine Learning/ Artificial Intelligence



We are in the Second Quantum “Revolution”

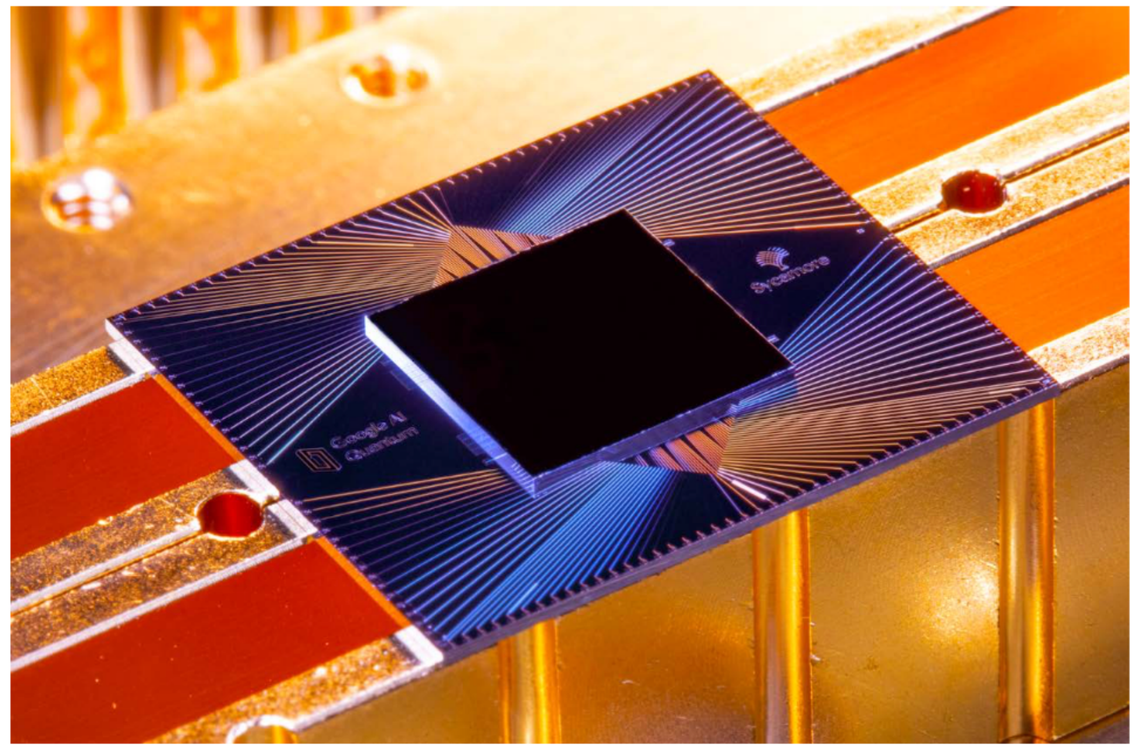
Computing and Simulation

Article *Nature* **574**, pages 505–510 (2019), 23 October 2019

Quantum supremacy using a programmable superconducting processor

https://doi.org/10.1038/s41586-019-1666-5
Received: 22 July 2019
Accepted: 20 September 2019
Published online: 23 October 2019

Frank Arute[1], Kunal Arya[1], Ryan Babbush[1], Dave Bacon[1], Joseph C. Bardin[1,2], Rami Barends[1], Rupak Biswas[3], Sergio Boixo[1], Fernando G. S. L. Brandao[1,4], David A. Buell[1], Brian Burkett[1], Yu Chen[1], Zijun Chen[1], Ben Chiaro[5], Roberto Collins[1], William Courtney[1], Andrew Dunsworth[1], Edward Farhi[1], Brooks Foxen[1,5], Austin Fowler[1], Craig Gidney[1], Marissa Giustina[1], Rob Graff[1], Keith Guerin[1], Steve Habegger[1], Matthew P. Harrigan[1], Michael J. Hartmann[1,6], Alan Ho[1], Markus Hoffmann[1], Trent Huang[1], Travis S. Humble[7], Sergei V. Isakov[1], Evan Jeffrey[1],



Credit: Erik Lucero/Google

In mid-September, the *Financial Times* revealed that Google was preparing to publish a scientific paper showing that it had built a 54-qubit quantum computer that could solve a maths problem in 3 minutes and 20 seconds that would take the world's fastest supercomputer around 10,000 years to solve.

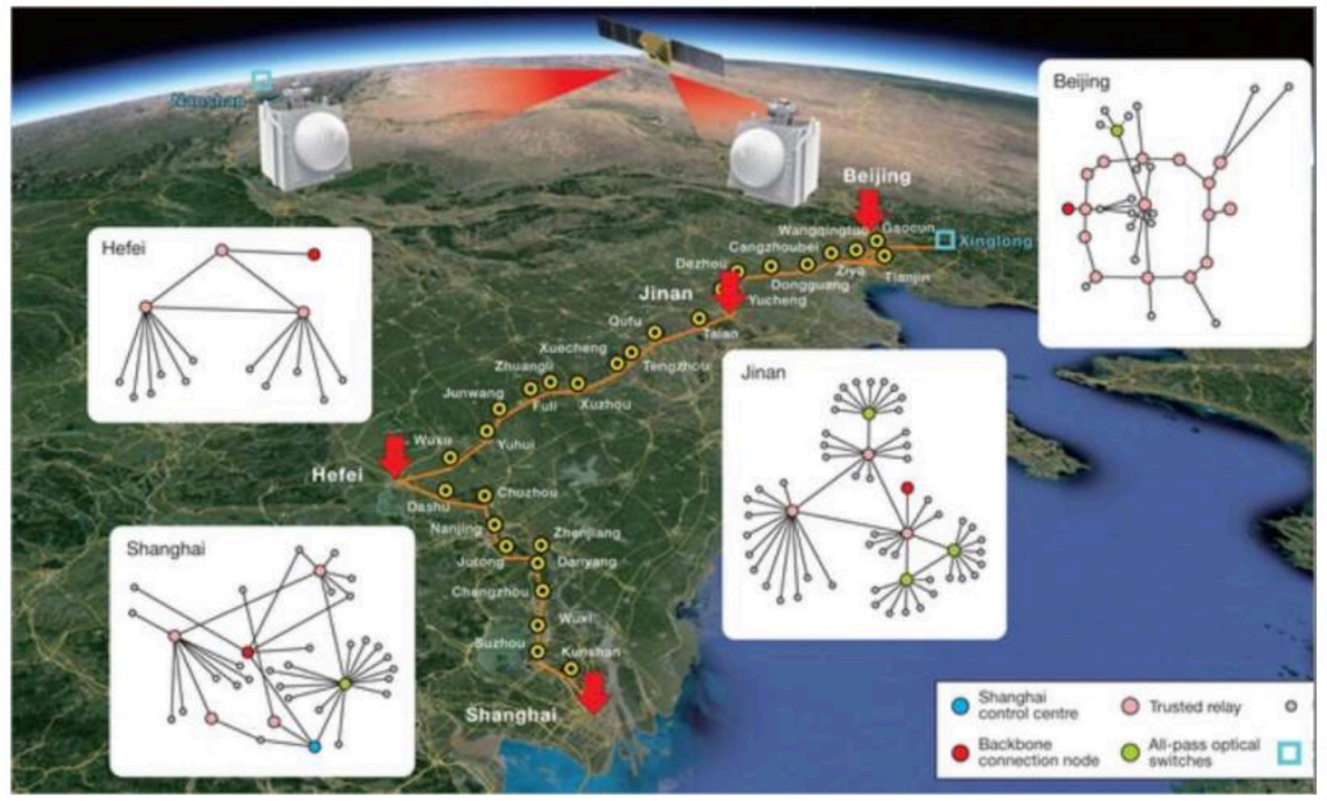
IBM then said ~2 days

Communication

JANUARY 6, 2021

The world's first integrated quantum communication network

by University of Science and Technology of China



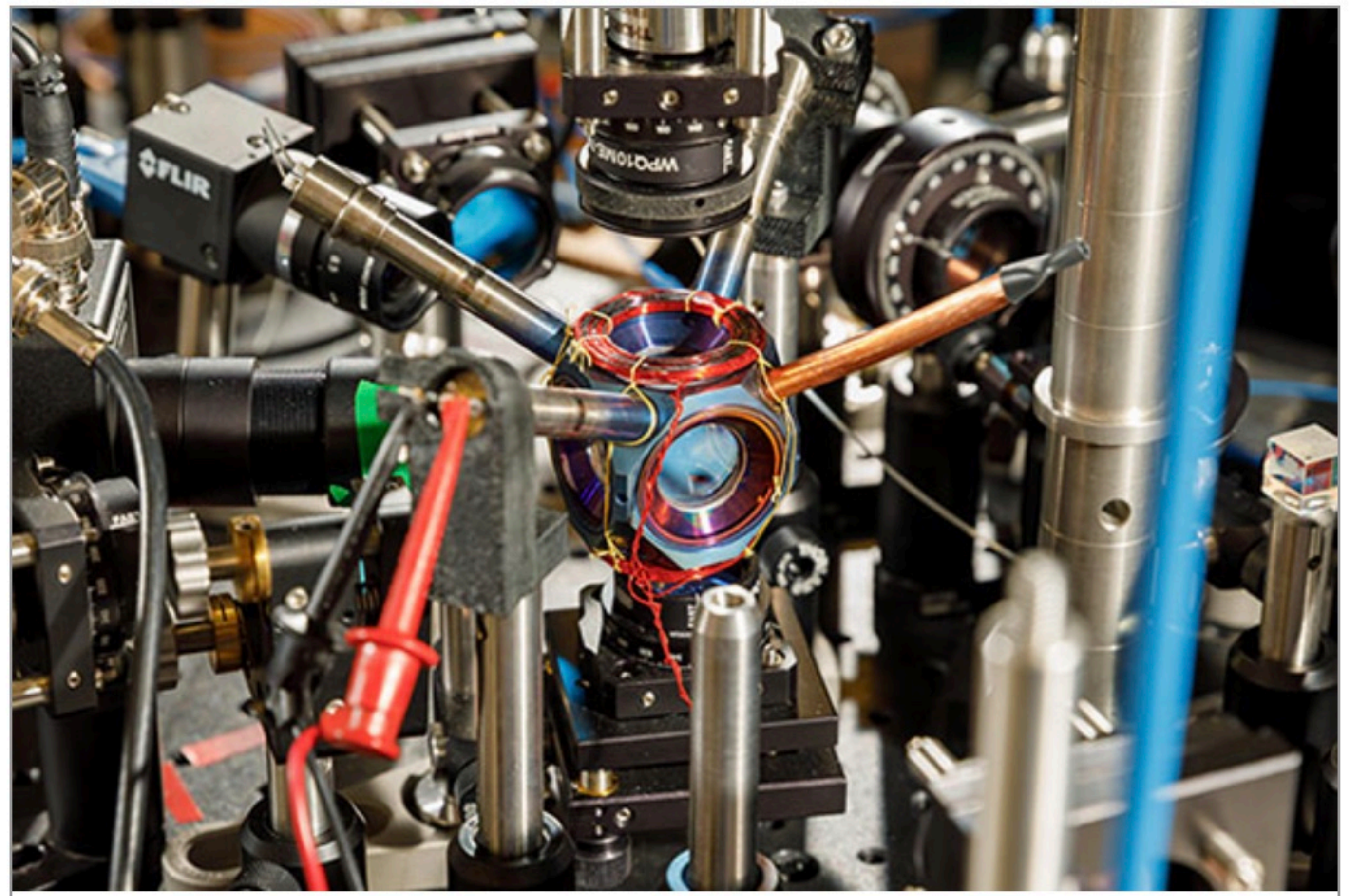
Chinese scientists have established the world's first integrated quantum comm…

Chinese scientists have established the world's first integrated quantum communication network, combining over 700 optical fibers on the ground with two ground-to-satellite links to achieve quantum key distribution over a total distance of 4,600 kilometers for users across the country. The team, led by Jianwei Pan, Yuao Chen, Chengzhi Peng from the University of Science and Technology of China in Hefei, reported in *Nature* their latest advances towards the global, practical application of such a network for future communications.

Sensing

Sandia Labs shows GPS-free quantum-based wayfinding device

October 27, 2021 - By Tracy Cozzens 0 Comments Est. reading time: 2:30



A compact device designed and built at Sandia National Laboratories could become a pivotal component of next-generation navigation systems. (Photo: Bret Latter/Sandia)

Simulating Physics with Computers

4. QUANTUM COMPUTERS—UNIVERSAL QUANTUM SIMULATORS

5. CAN QUANTUM SYSTEMS BE PROBABILISTICALLY SIMULATED BY A CLASSICAL COMPUTER?

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

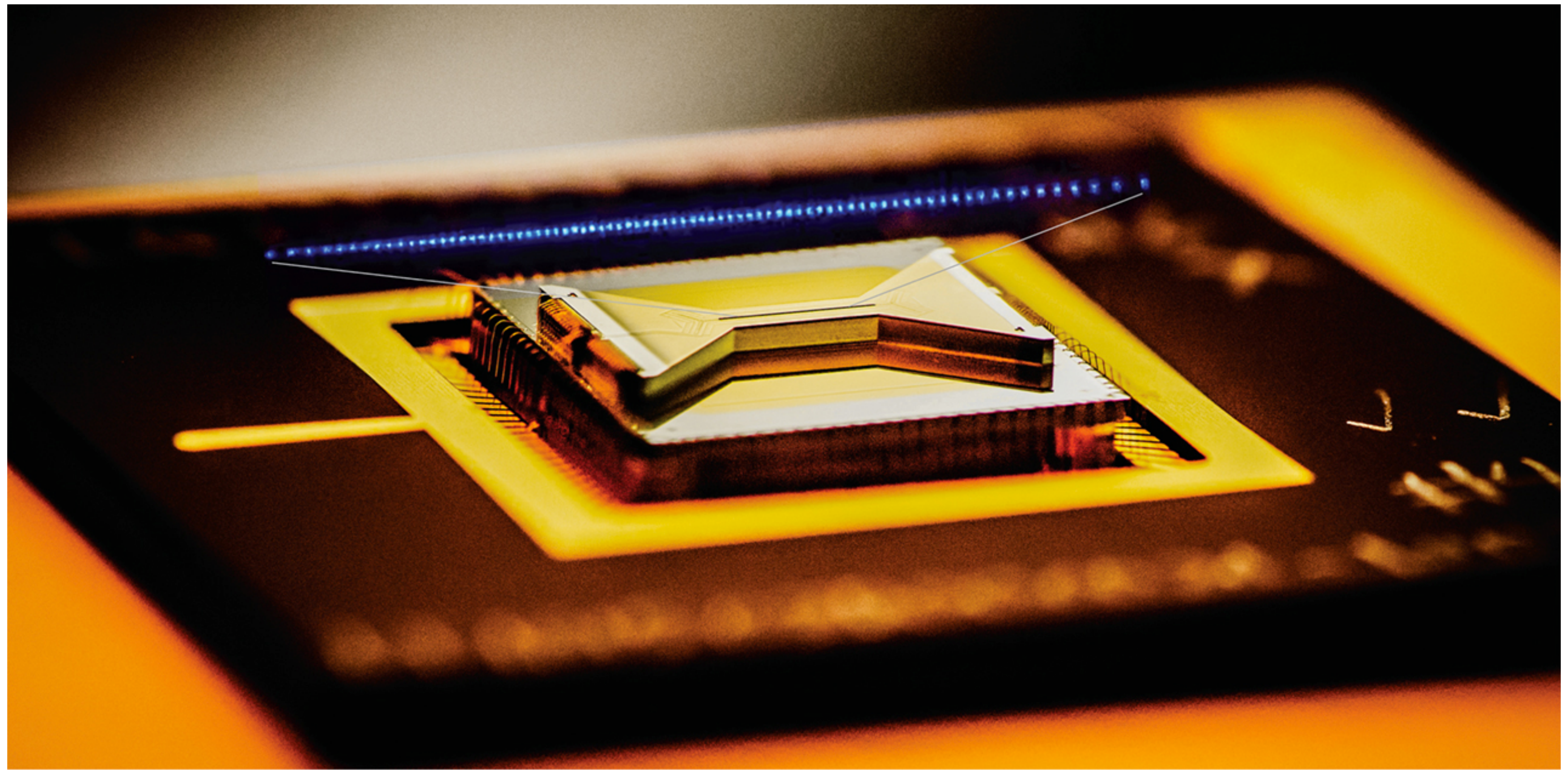
Received May 7, 1981

One cannot describe (all of) more fundamental theories with less fundamental theories

Quantum Mechanics "works the same" at all scales

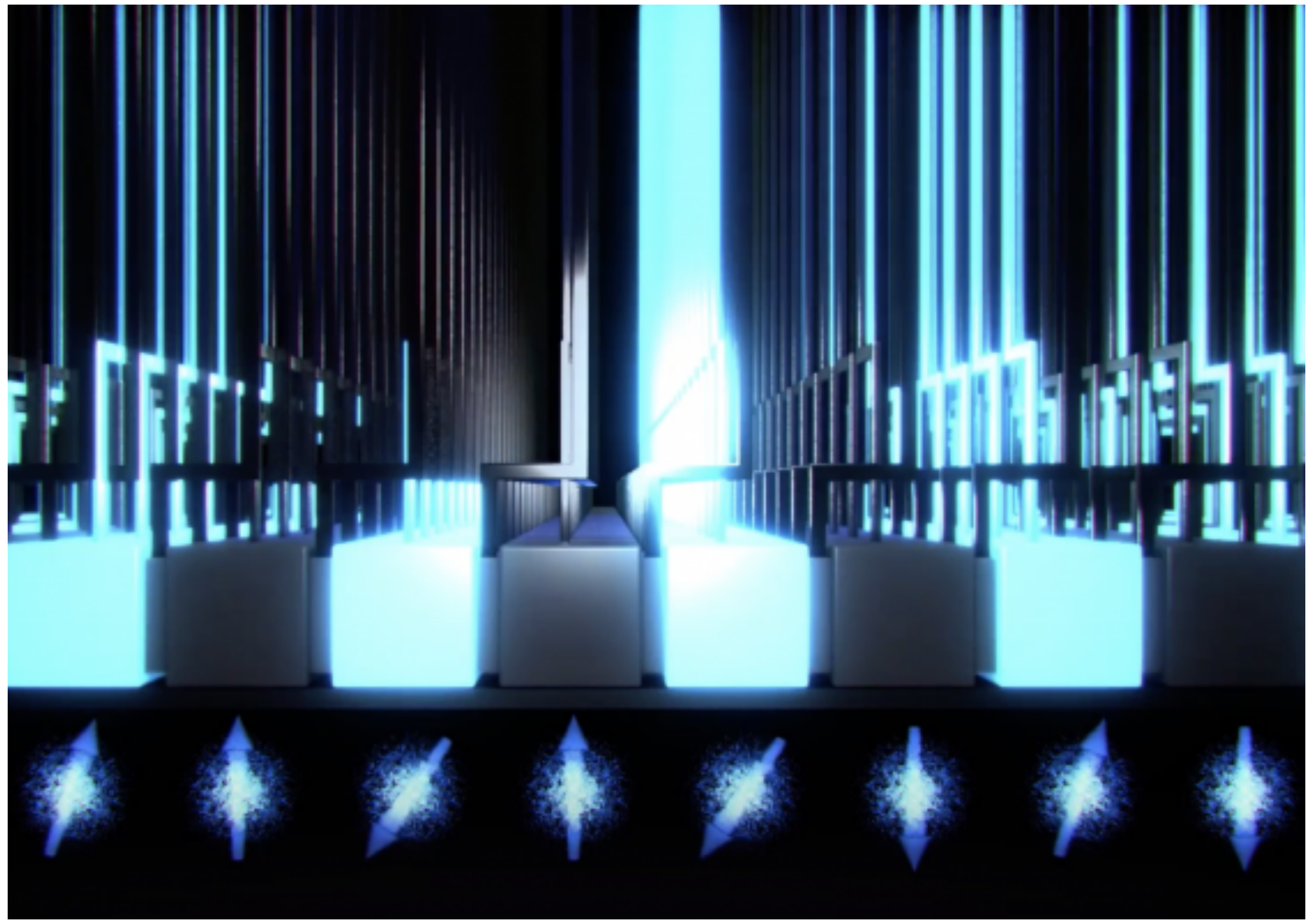
Entanglement and Coherence

How to include into theoretical and numerical frameworks for Standard Model physics?



Where Should We Look For "Quantum Advantages" in Quantum Simulations of Standard Model Physics?

If a classical computer can solve the problem, why "compete" using a quantum device?



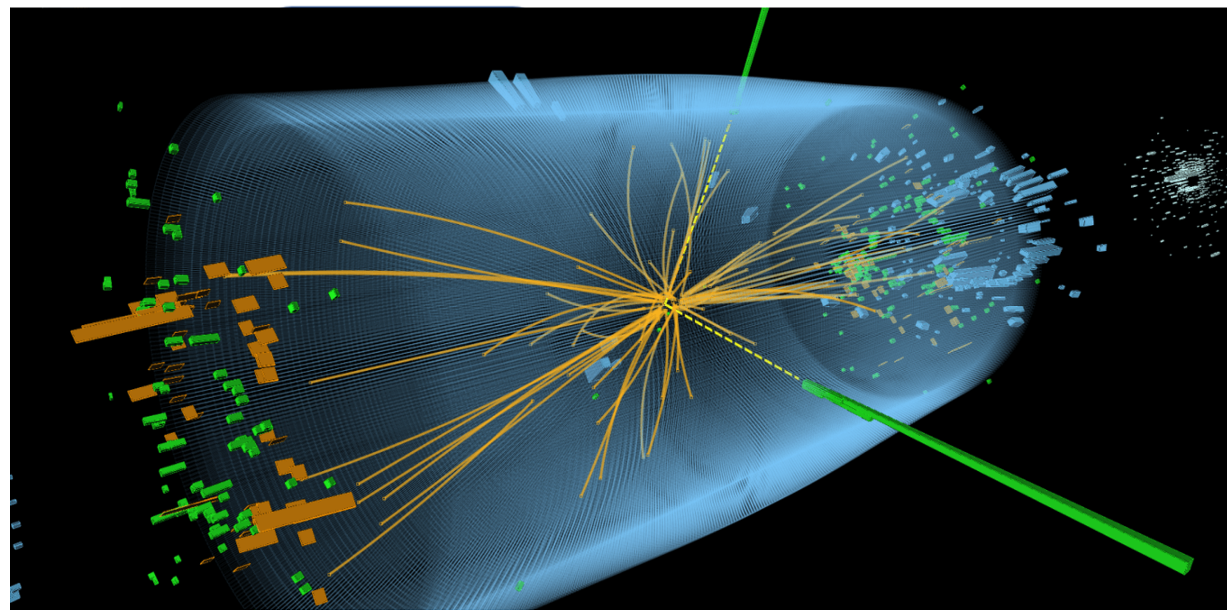
Use quantum devices to solve the (parts of) problems that classical computers can't.

"We have to *know* our problems!"

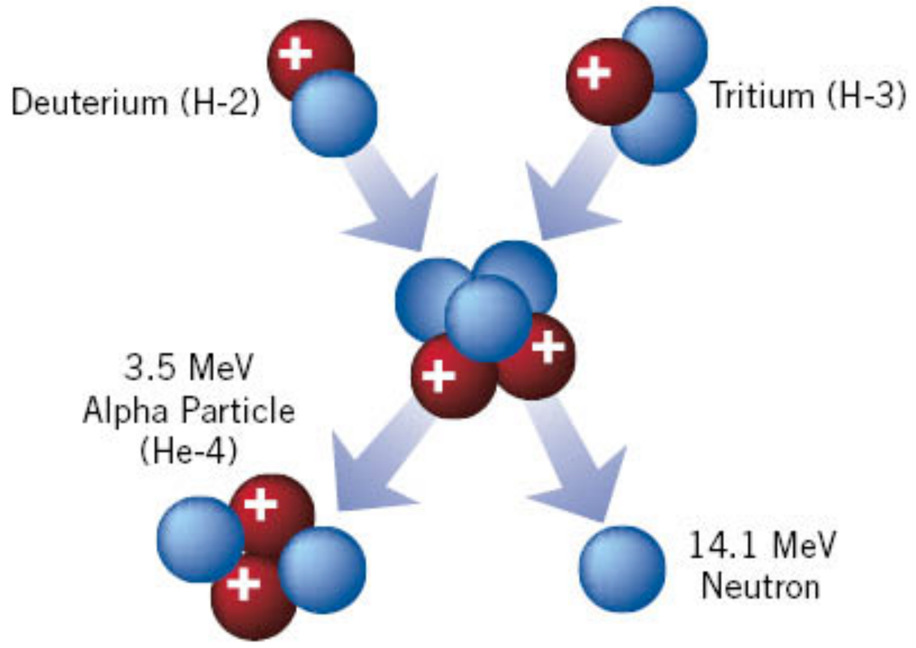
Understand the Entanglement Structures and Dynamics of the systems

Quantum devices are embedded in large classical compute environments

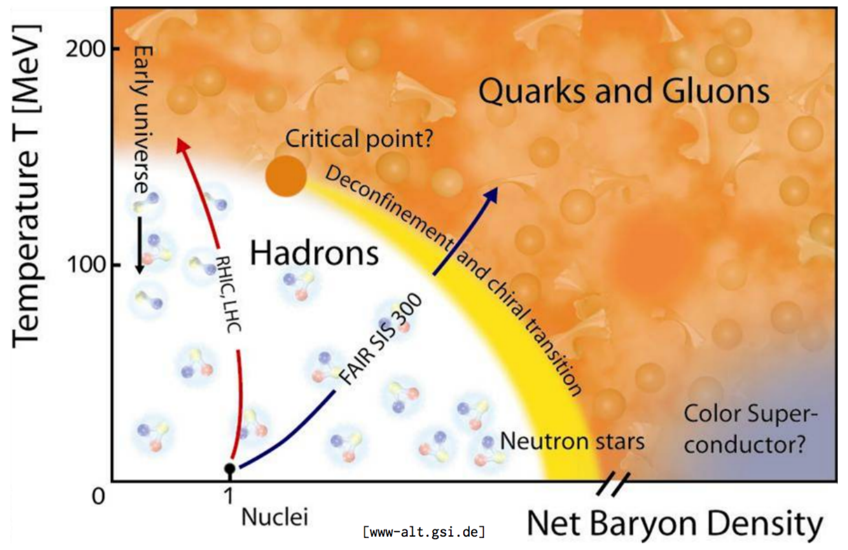
Some Standard Model Objectives



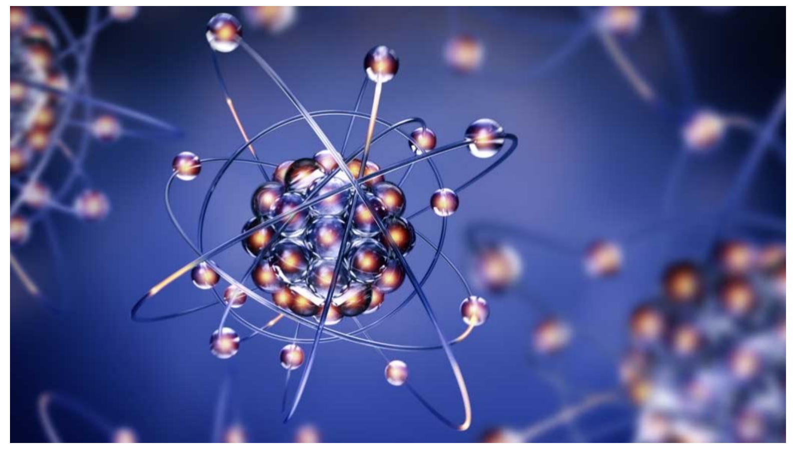
Real-time dynamics, particle production, fragmentation
Lattice quantum field theories, QCD, EFT,…



Low-energy nuclear reactions and fission
Electroweak processes in nucleons and nuclei
Neutrino dynamics in extreme astrophysical environments



Equation of state of dense, hot matter and dynamics
Conquering some “sign problems”



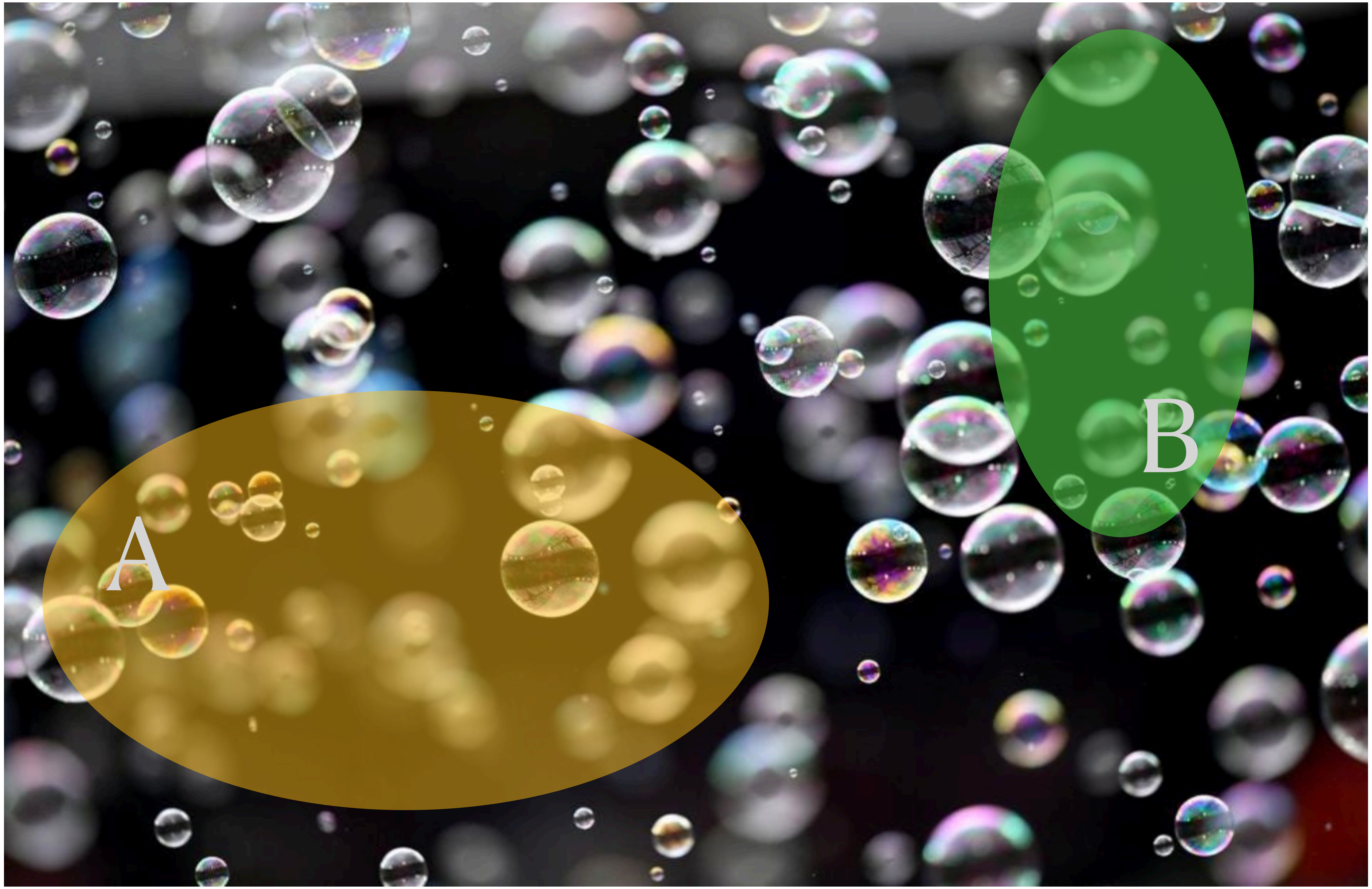
Precision structure and interactions of medium and large nuclei
Exponentially large Hilbert spaces of many-body systems

Entanglement, Separability

If

$$\rho = \sum_k p_k \rho_1^k \otimes \rho_2^k$$

then system is separable



Entanglement, Separability

e.g., 2 qubits

$$\rho(\eta) = \eta\ \rho\left(\frac{|00\rangle + |11\rangle}{\sqrt{2}}\right) + (1-\eta)\frac{\mathbb{I}}{4}$$

Werner State, 1995

$$\rho(\eta) = \frac{\eta}{2}\left[\rho\left(|++\rangle_x\right) + \rho\left(|--\rangle_x\right) + \rho\left(|+-\rangle_y\right) + \rho\left(|-+\rangle_y\right)\right]$$

$$+ \frac{1-\eta}{4}\left[\rho\left(|00\rangle\right) + \rho\left(|11\rangle\right)\right] + \frac{1-3\eta}{4}\left[\rho\left(01\rangle\right) + \rho\left(|10\rangle\right)\right]$$

The latter is a valid density matrix for $\eta \leq 1/3$

Local operations in A do not impact observables in B

- quantum correlations are consistent with classical correlations - the system is separable
- the ensemble contains states that are entangled - but cannot be distilled

Entanglement, Separability

A-B may be separable
A-C may be separable
B-C may be separable

BUT

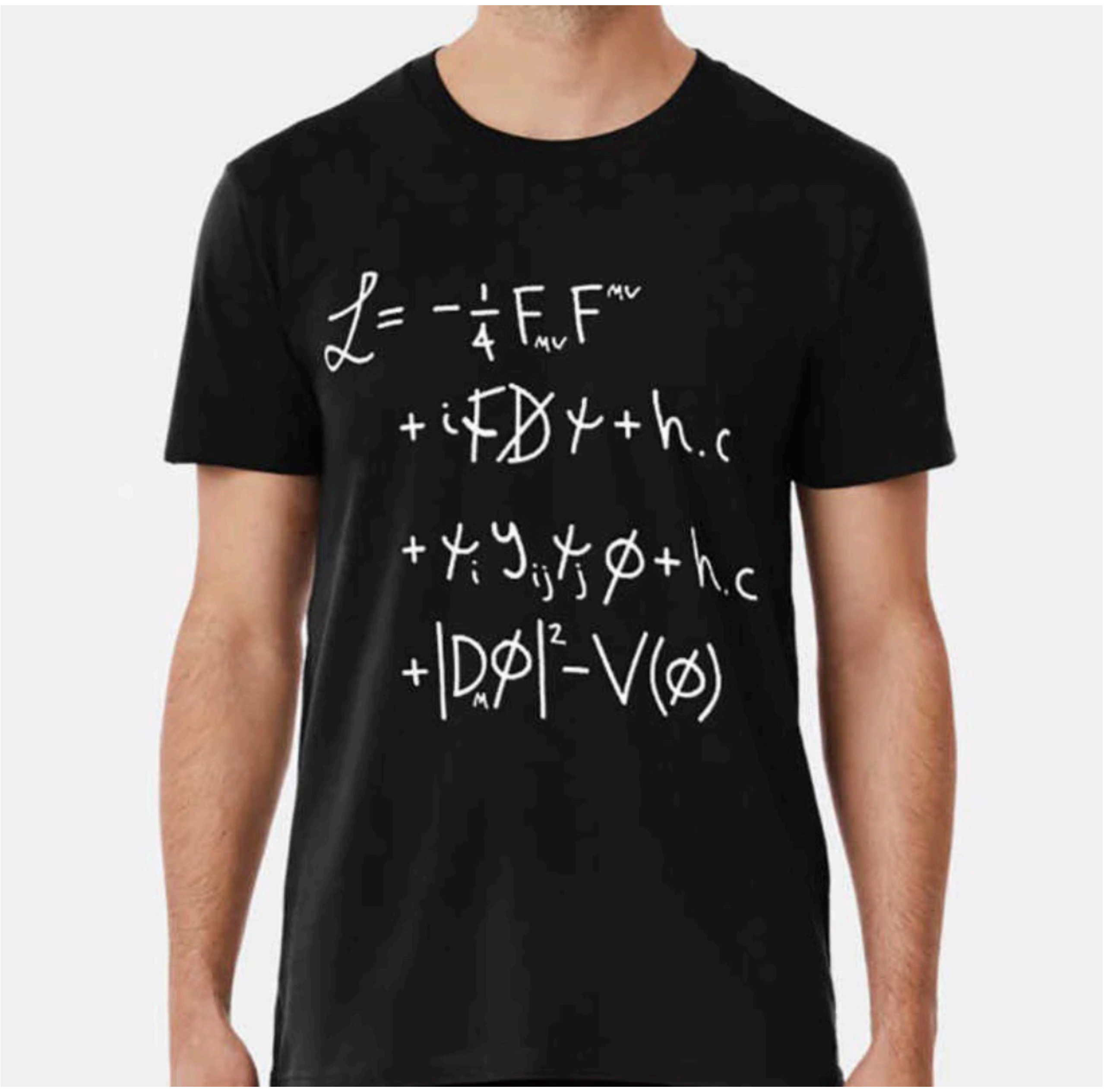
AB-C might **not** be separable

This is a situation (and of course more complex) is found in quantum field theories and quantum many-body systems

One Perspective

20th Century High-Energy Physics - Quantum Field Theories

— identifying short-distance, fundamental interactions - Lagrangians
— non-perturbative lattice QCD using High-Performance Computing (HPC)
— modeling gave way to Effective Field Theories (EFT)
 — typically, leading order is un-entangled
— EFTs were developed specifically to connect lattice QCD simulations to nature
 — systematic error reduction



20th Century Nuclear Physics - Quantum Many-Body systems

— controlling short-distance (phenomenological) interactions
 — initially —- limited progress and was re-invigorated by RG, EFT from HEP, chemistry
— QMB computations using HPC - SciDAC projects, Exascale
— modeling and EFs guided by global symmetries

21st Century HEP+NP - QFT+QMB systems

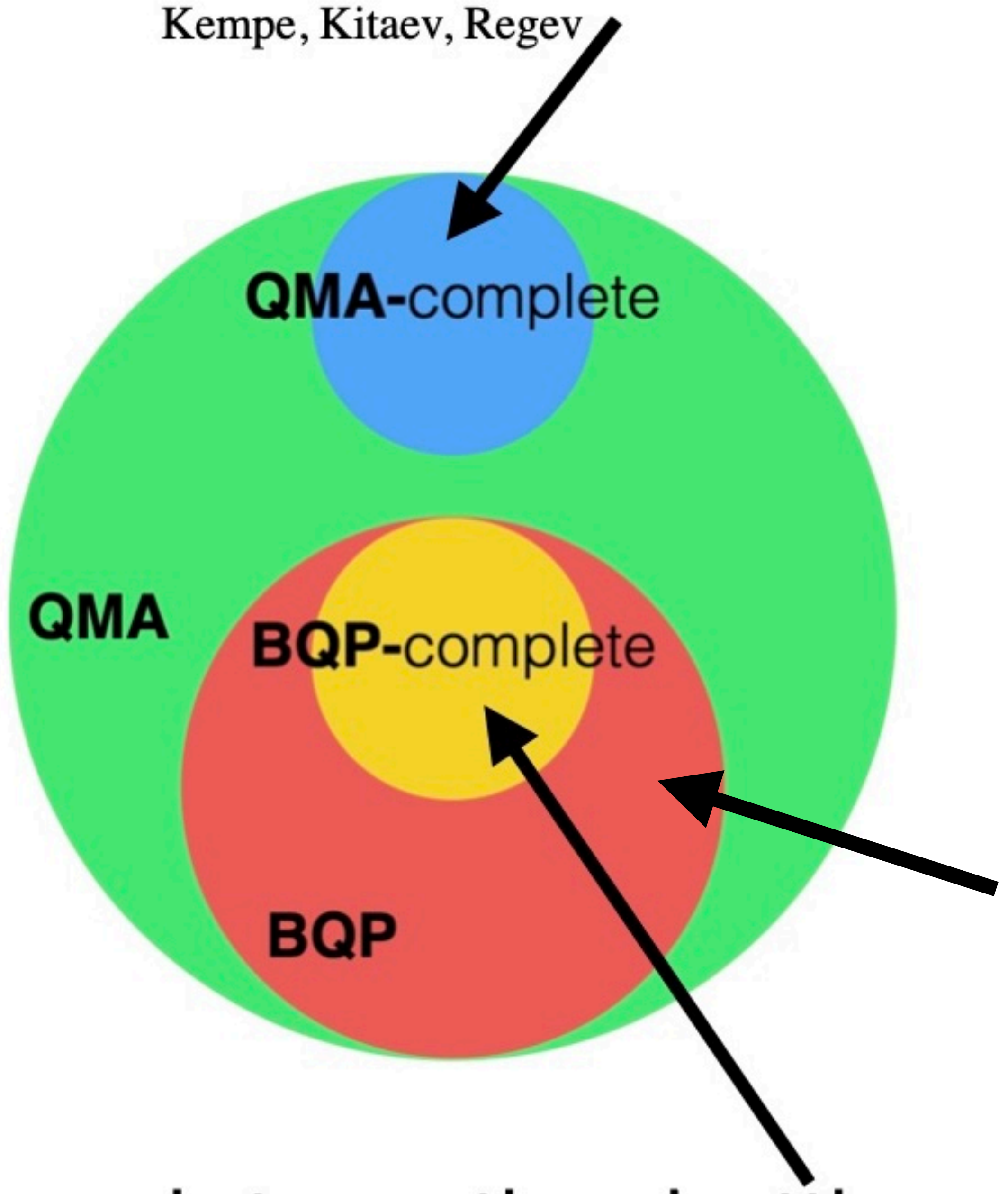
— quantum correlations and non-locality using, and for, quantum simulation, computing and sensing
— requires entanglement-centric analytic, algorithmic, circuit, hybrid, numerical, co-design, … advances

Complexity of Our Systems

Should it be a limitation? …. Not until it is…

K-local Hamiltonian

Kempe, Kitaev, Regev



Time evolution of a quantum system

Interacting Lattice Scalar Field Theory

(Jordan, Lee, Preskill)

We are so far from “asymptotic resources” that all that we can know for sure is the performance of our current circuits on current hardware, and do some limited extrapolations.

X^{10} is worse than $e^{+0.01\,x}$ until $x \sim 9000$

(Highlighted by quantum chemists - what are the coefficients?)

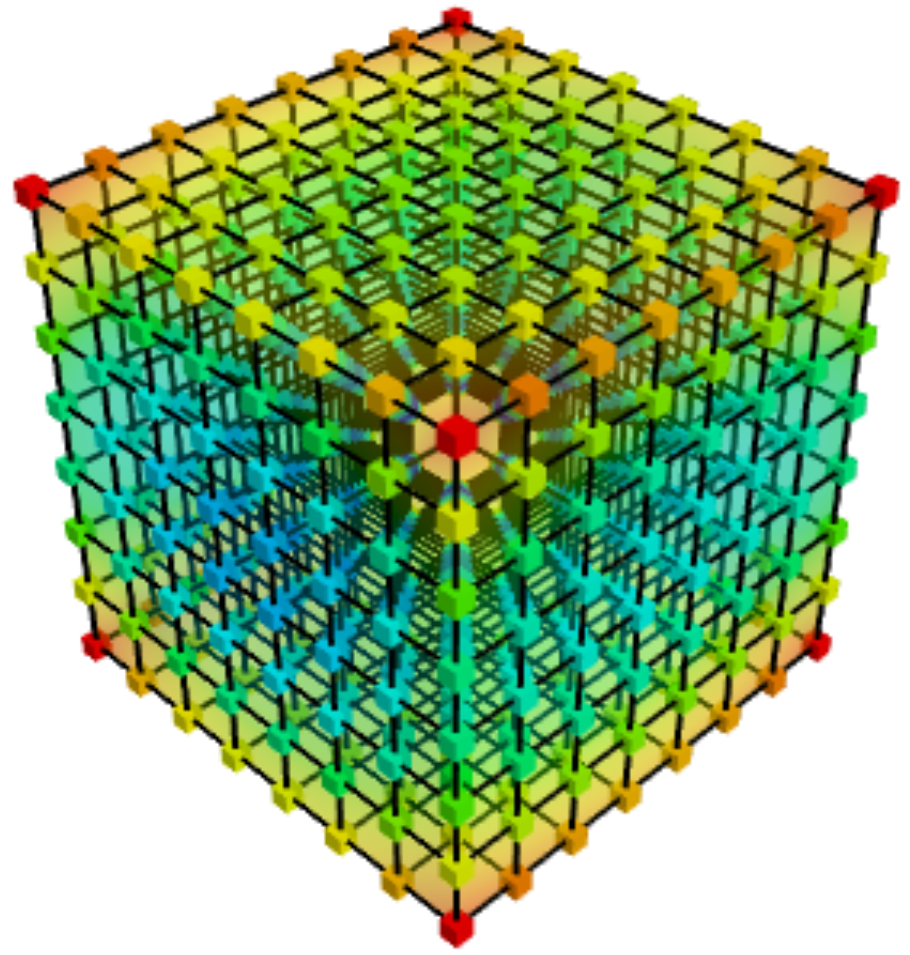
Complexity class indicates worst case - can be much better

The “B” in BQP gives us latitude to change theories “a little”

With a target precision, perturbative expansions can potentially change problem difficulty

Mapping, Scaling, Time-Evolution

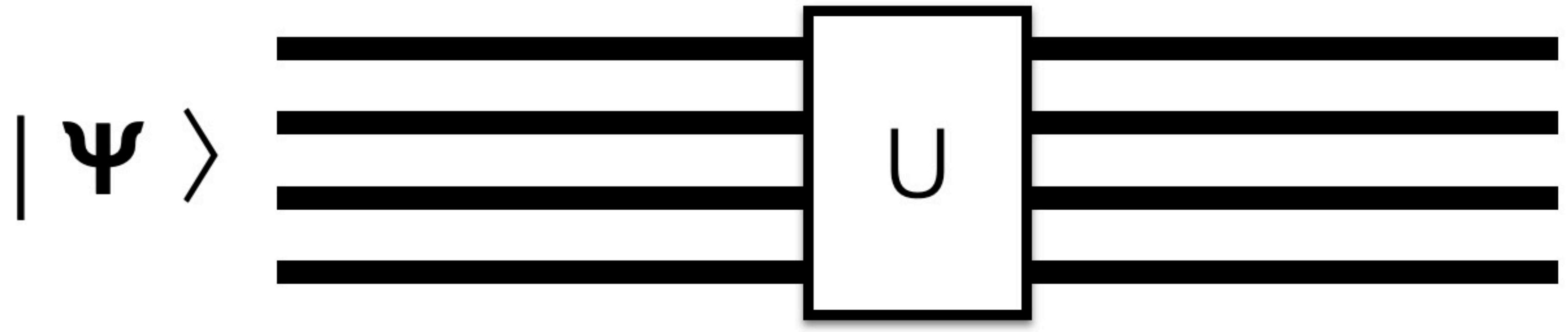
Expect that n-dof locally interacting for time T *requires*
n-dof evolved through ~T time steps for a total of ~ poly(n) T operations.



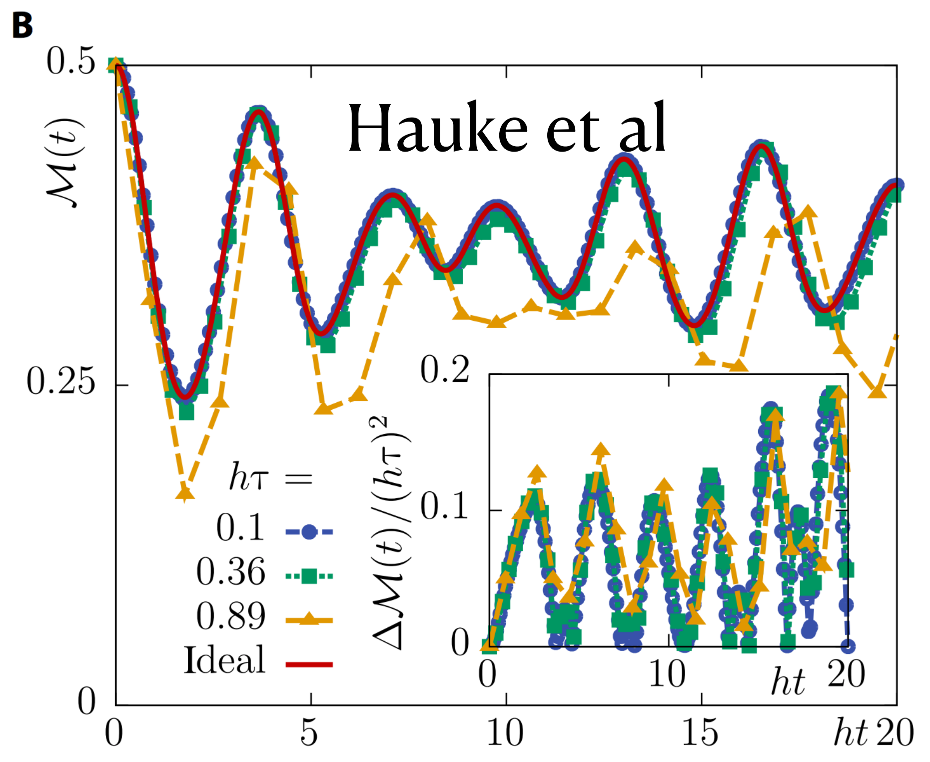
D-dim systems optimally simulated with D-dim systems.
e.g., 2-dim systems will not optimally simulate 3-dim systems

Real-time evolution through small time-steps lies within BQP

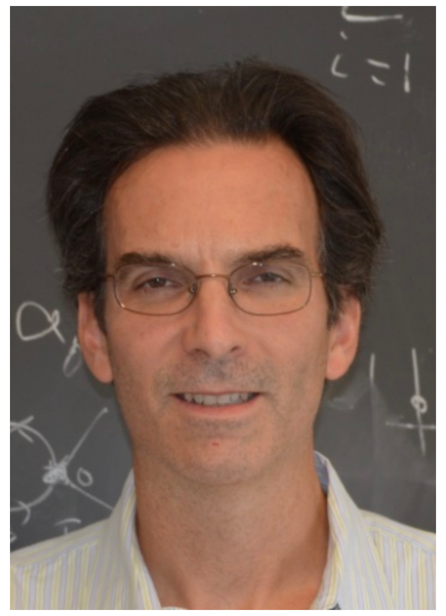
$$e^{-iHT} = \left(\prod_k e^{-ih_k T/n}\right)^n + \mathcal{O}\left(T^2/n\right)$$



Hot algorithmic area: Implementation (mapping dependent)
higher order, linear combinations of unitaries, qDrift, Fast Forwarding



What is efficient on near-term devices? at scale?

Entanglement Suppression and Emergent Symmetries of Strong Interactions

Silas R. Beane, David B. Kaplan, Natalie Klco, and Martin J. Savage

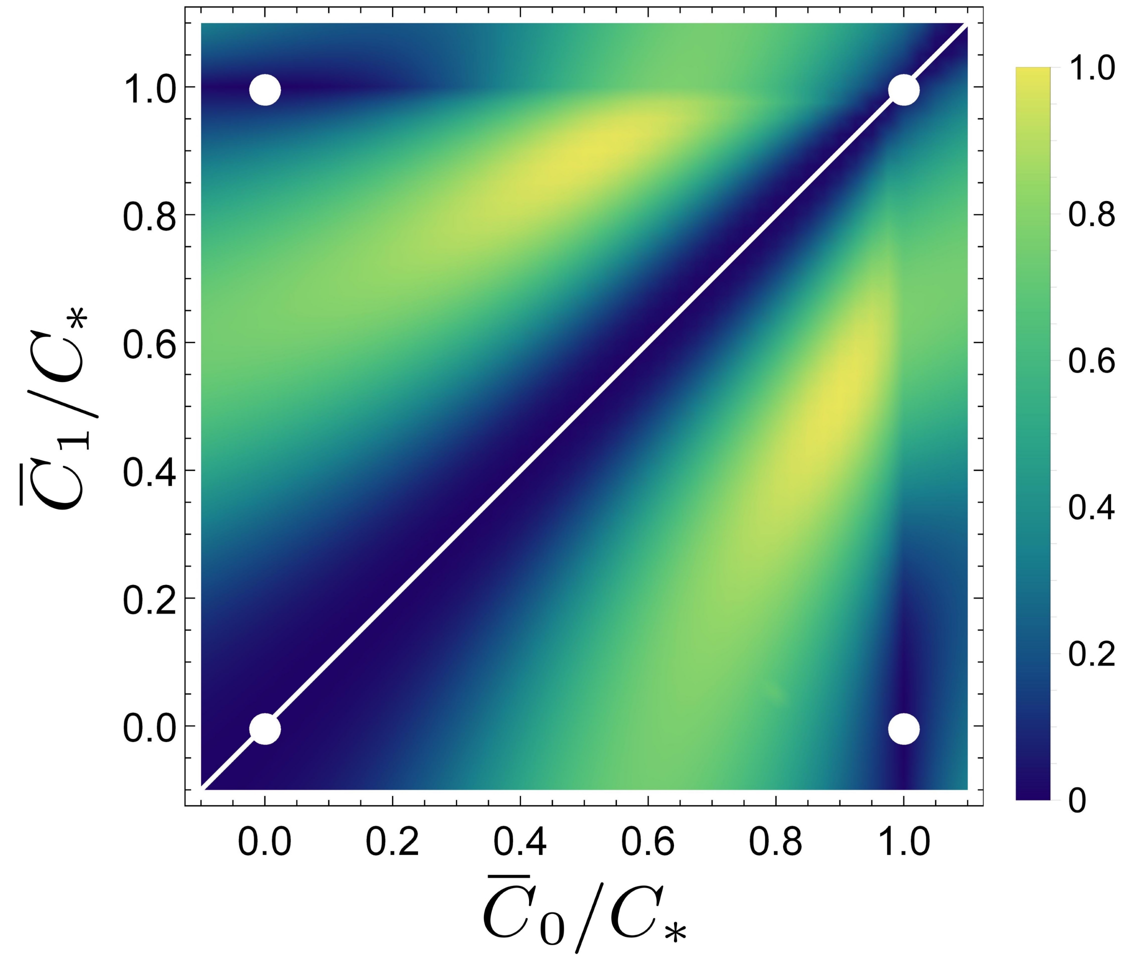
Phys. Rev. Lett. **122**, 102001 – Published 14 March 2019

Finding GS of generic n-body system is **QMA**-complete

$$\hat{\mathbf{S}}_\sigma = \frac{1}{4}\left(3e^{i2\delta_3} + e^{i2\delta_1}\right)\hat{\mathbf{1}} + \frac{1}{4}\left(e^{i2\delta_3} - e^{i2\delta_1}\right)\hat{\boldsymbol{\sigma}}\cdot\hat{\boldsymbol{\sigma}}$$

$$e_p(\hat{A}) \longrightarrow \mathcal{E}(\hat{\mathbf{S}}_\sigma) = \frac{1}{6}\,\sin^2\left(2(\delta_3 - \delta_1)\right)$$

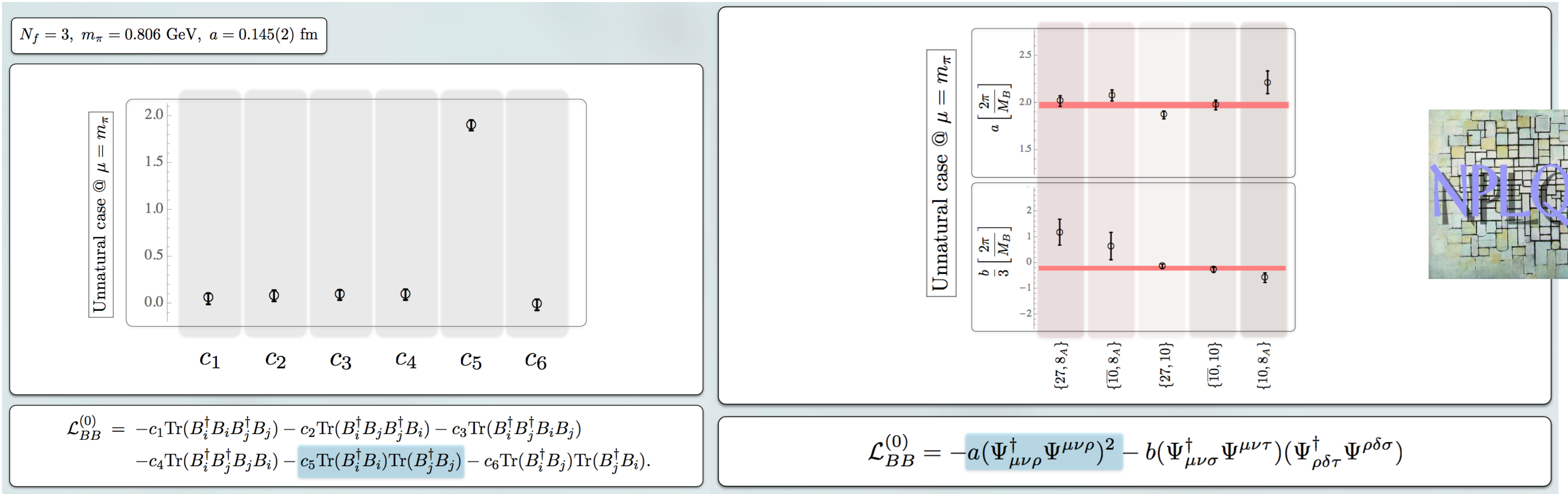
$$\hat{\rho}_{\hat{A};1}(\theta_i,\phi_i) = \mathrm{Tr}_2[\hat{\rho}_{\hat{A};12}(\theta_i,\phi_i)] \qquad E_{\hat{A}}(\theta_i,\phi_i) = 1 - \mathrm{Tr}_1[\,(\hat{\rho}_{\hat{A};1}(\theta_i,\phi_i))^2\,]$$



 conformal points

 Wigner symmetry

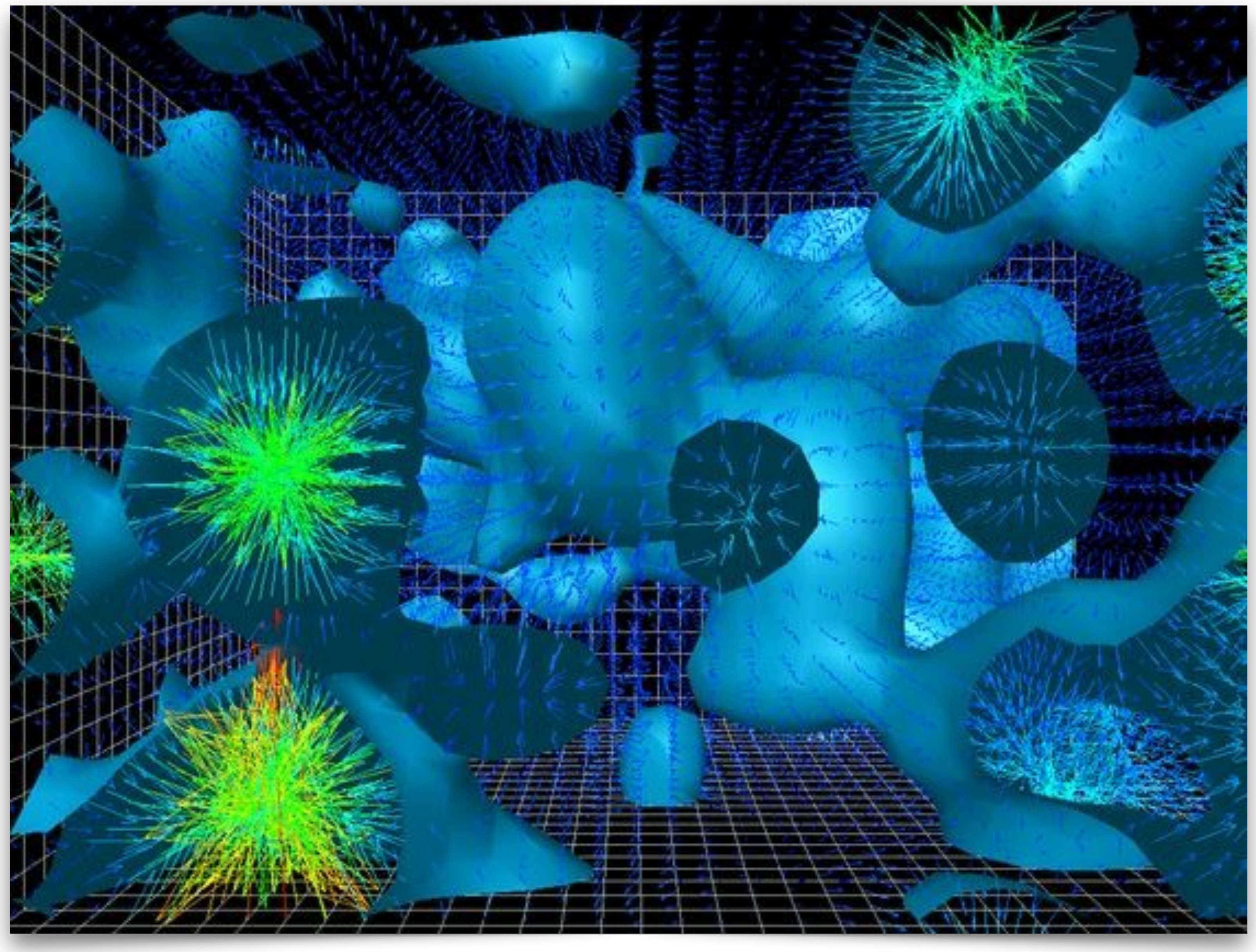
SU(4) for 2 flavors and **SU(16)** for 3 flavors
- more symmetry than large-Nc, [SU(4) and SU(6)]



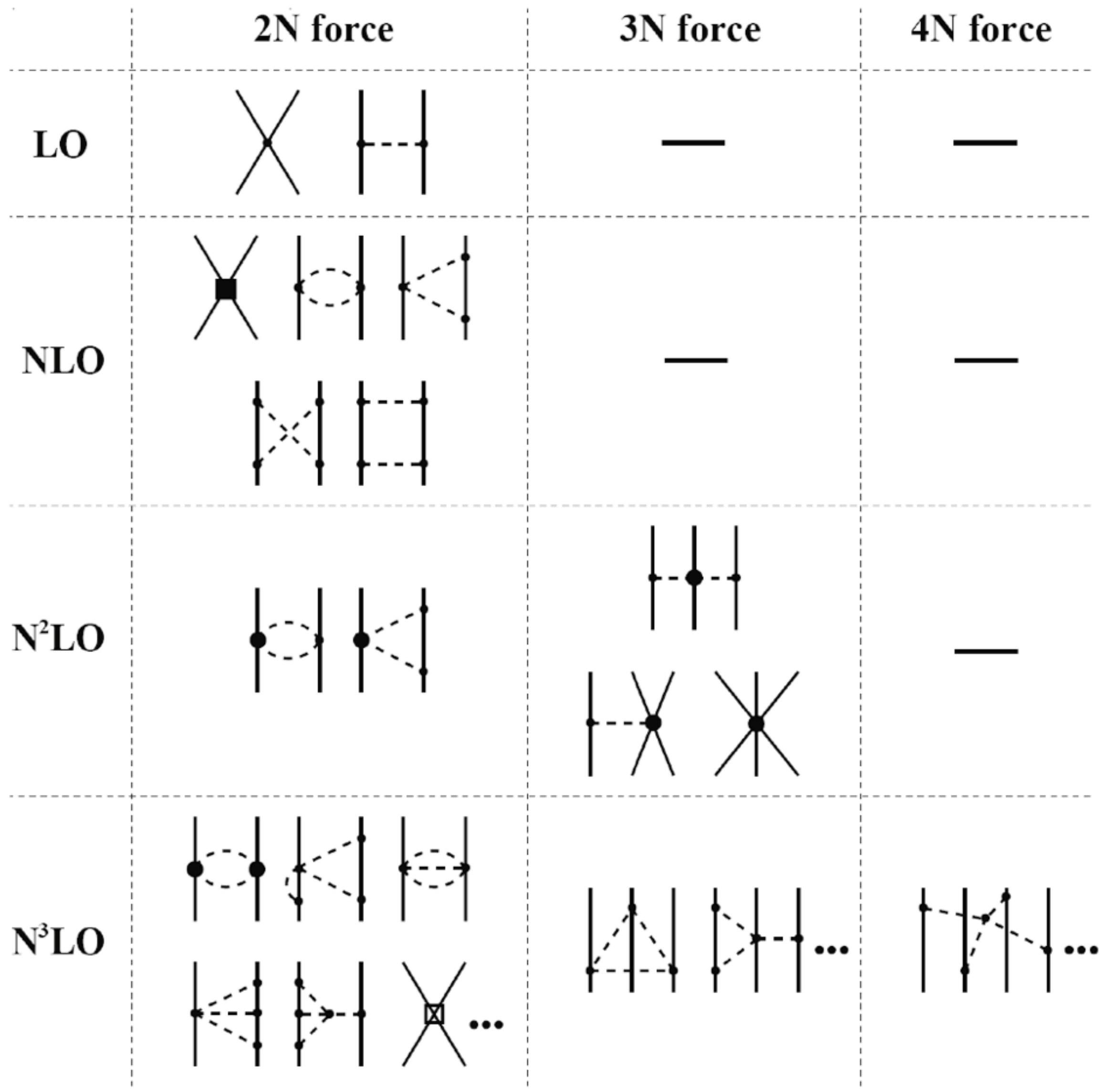
Emergent approximate symmetries in nuclear systems ⟷ Suppressed fluctuations in entanglement

Suppressed sign problems in classical simulations

Strong Interactions at Long and Short Distances



Derek Leinweber



Bira van Kolck

Short Distances

Perturbative QCD and asymptotic freedom
Nearly free quarks and gluons

Long Distances

Perturbative Chiral Perturbation Theory
Nearly free pions

Expansions about free massless or nearly massless fields and long and short distances

Geometric quantum information structure in quantum fields and their lattice simulation

Natalie Klco and Martin J. Savage
Phys. Rev. D **103**, 065007 – Published 22 March 2021

Entanglement Spheres and a UV-IR Connection in Effective Field Theories

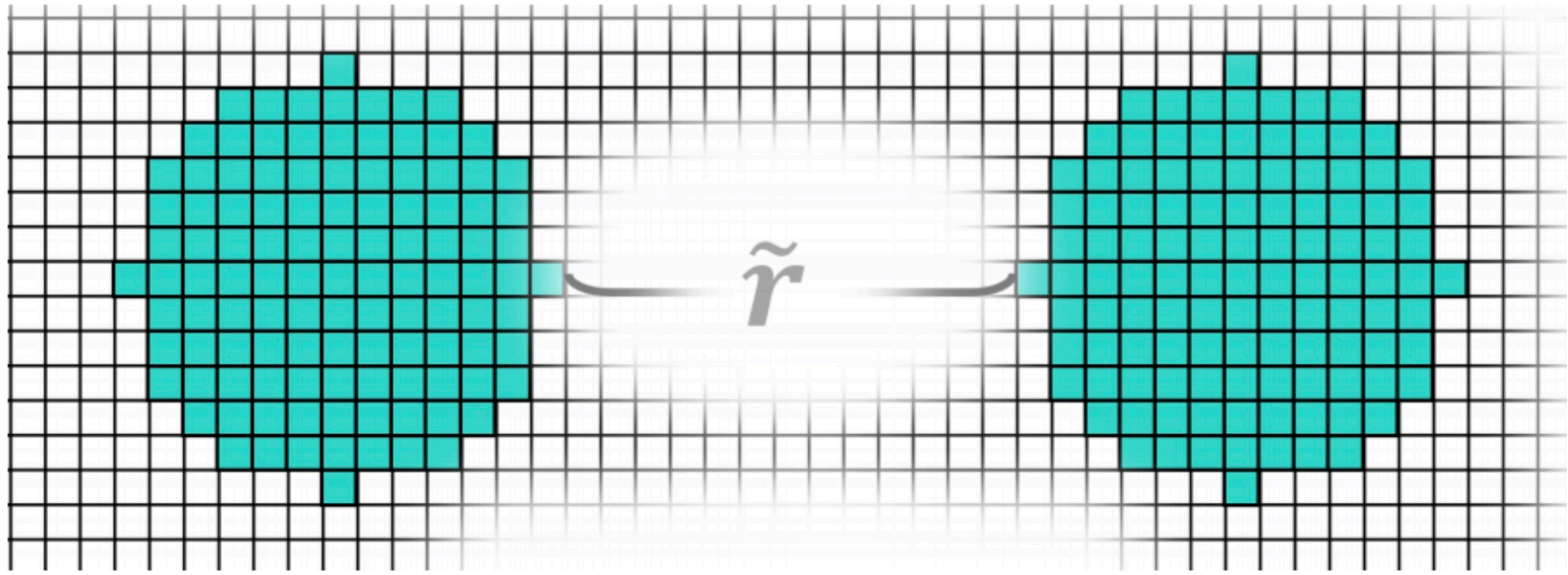
Natalie Klco and Martin J. Savage
Phys. Rev. Lett. **127**, 211602 – Published 16 November 2021

Lattice Scalar Field Theory (= Harmonic Chains)

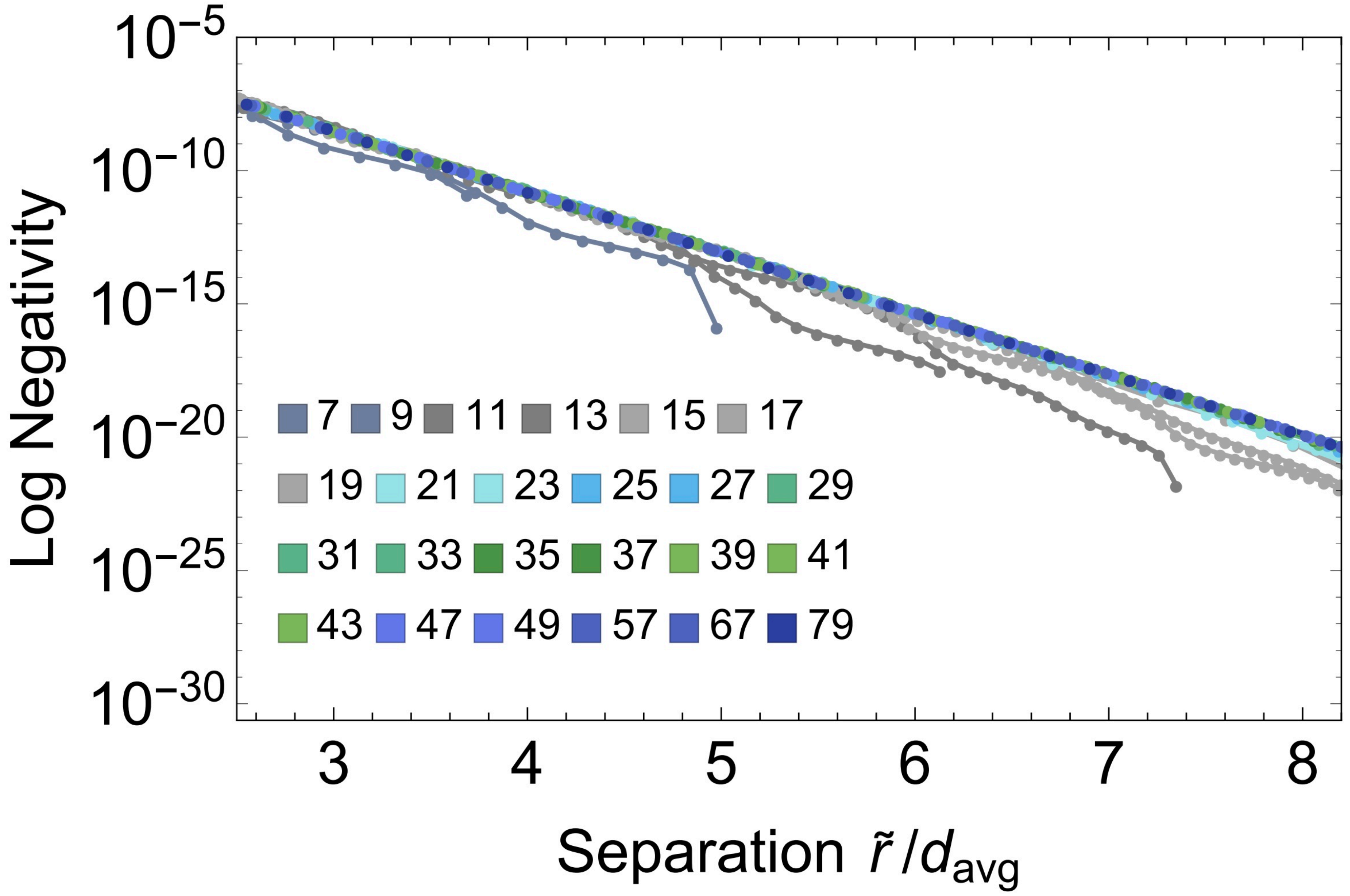
Reznik, Tonni, Cardy, …. many many others

Entanglement Structures in Quantum Field Theories: Negativity Cores and Bound Entanglement in the Vacuum

Natalie Klco,[1,*] D. H. Beck,[2,†] and Martin J. Savage[3,‡]



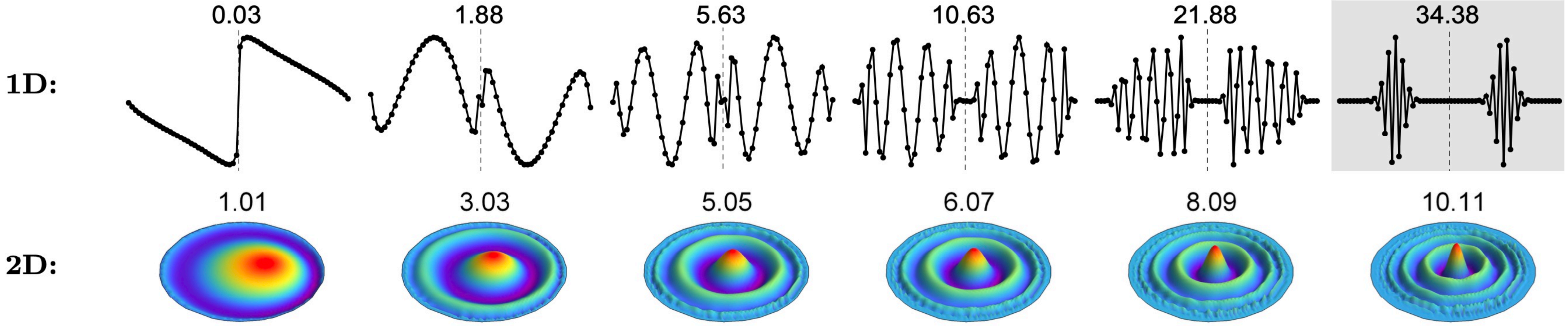
We performed lattice calculations in 1,2,3D



1D: 2.82(3)
2D: 5.29(4)
3D: 7.6(1)

The long-distance structure of entanglement is determined by the UV structure - UV-IR connection

Separable



Entanglement Structures in Quantum Field Theories: Negativity Cores and Bound Entanglement in the Vacuum

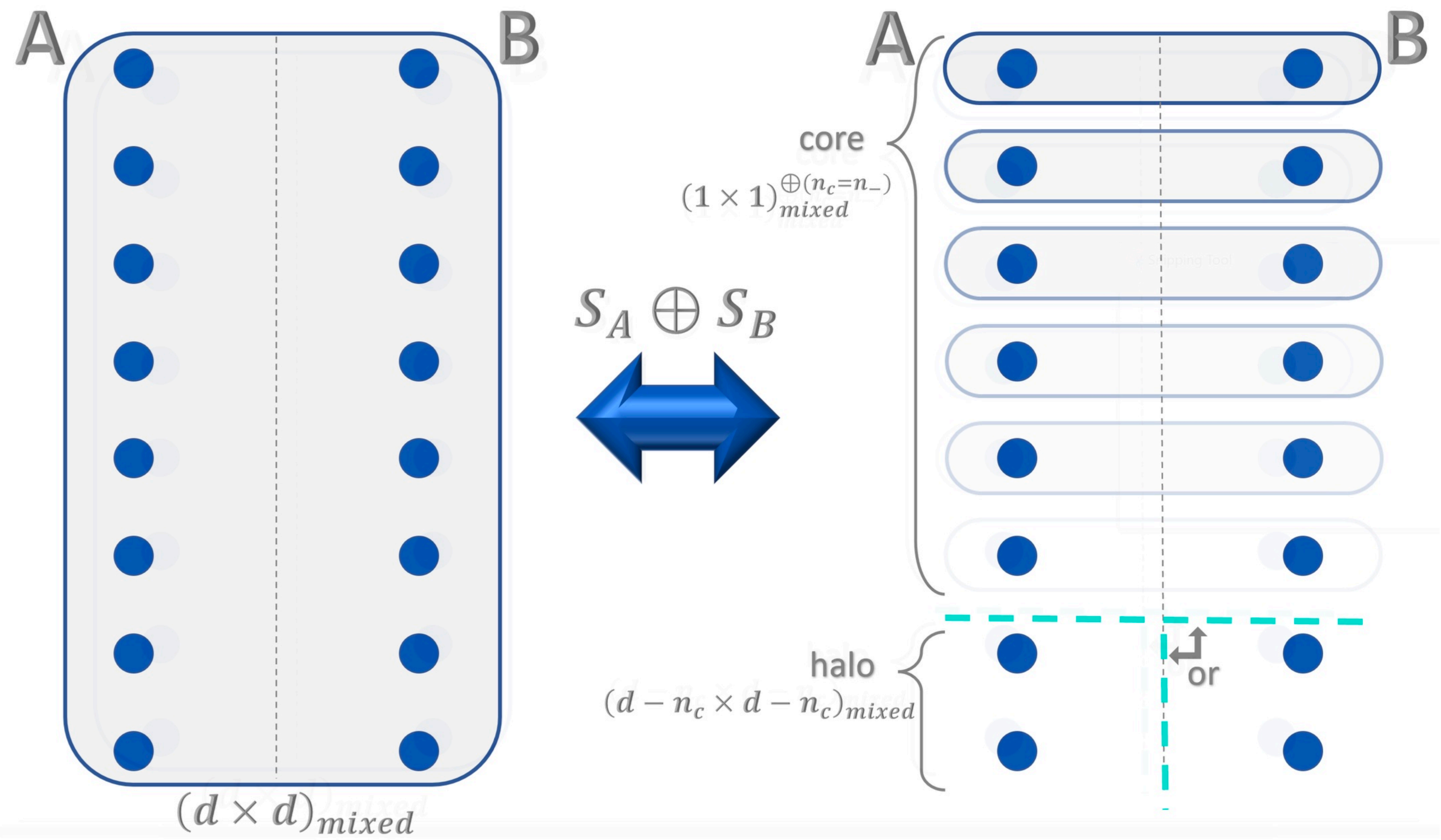
Natalie Klco,[1,*] D. H. Beck,[2,†] and Martin J. Savage[3,‡]

Lattice Scalar Field Theory
Entanglement Cores/Strings

Reznik, Tonni, Cardy, …. many many others

Natalie Klco

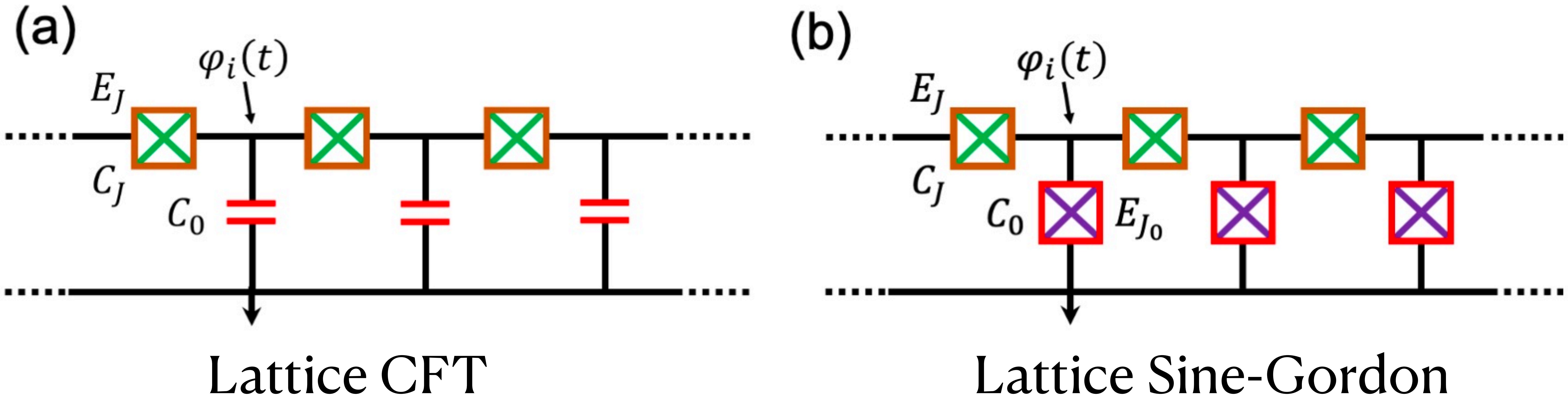
Douglas Beck



Q: Will better understanding structure enable more efficient quantum simulations of quantum field theories?
A: We don't know yet …….

Analog Quantum Simulation with Quantum Circuits

From presentation by Ananda Roy at IQuS



The quantum sine-Gordon model with quantum circuits

Ananda Roy[a], Dirk Schuricht[b], Johannes Hauschild[c], Frank Pollmann[a,d], Hubert Saleur[e]

[a]*Department of Physics, T42, Technische Universität München, 85748 Garching, Germany*
[b]*Institute for Theoretical Physics, Center for Extreme Matter and Emergent Phenomena, Utrecht University, Princetonplein 5, 3584 CE Utrecht, The Netherlands*
[c]*Department of Physics, University of California, Berkeley, CA 94720, USA*
[d]*Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany*
[e]*Institut de Physique Théorique, Paris Saclay University, CEA, CNRS, F-91191 Gif-sur-Yvette*

Entanglement in Heavy-Ion Collisions and Hadron Structure - examples

$\Lambda\Lambda$-entanglement induced by QCD strings

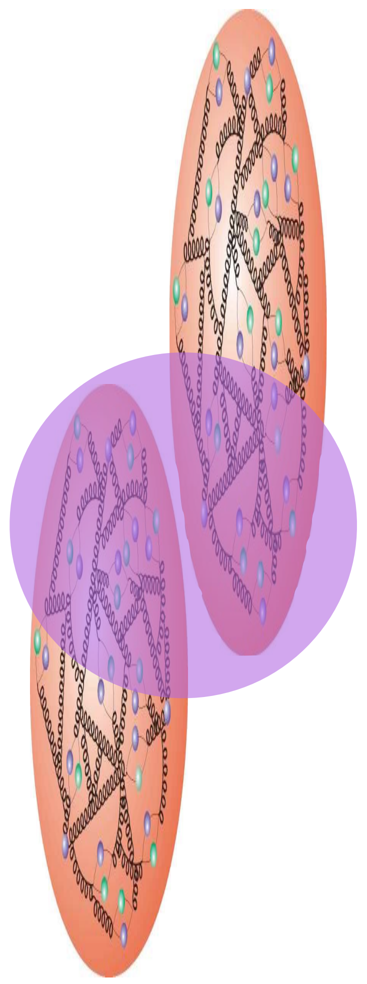
Monte Carlo event generators

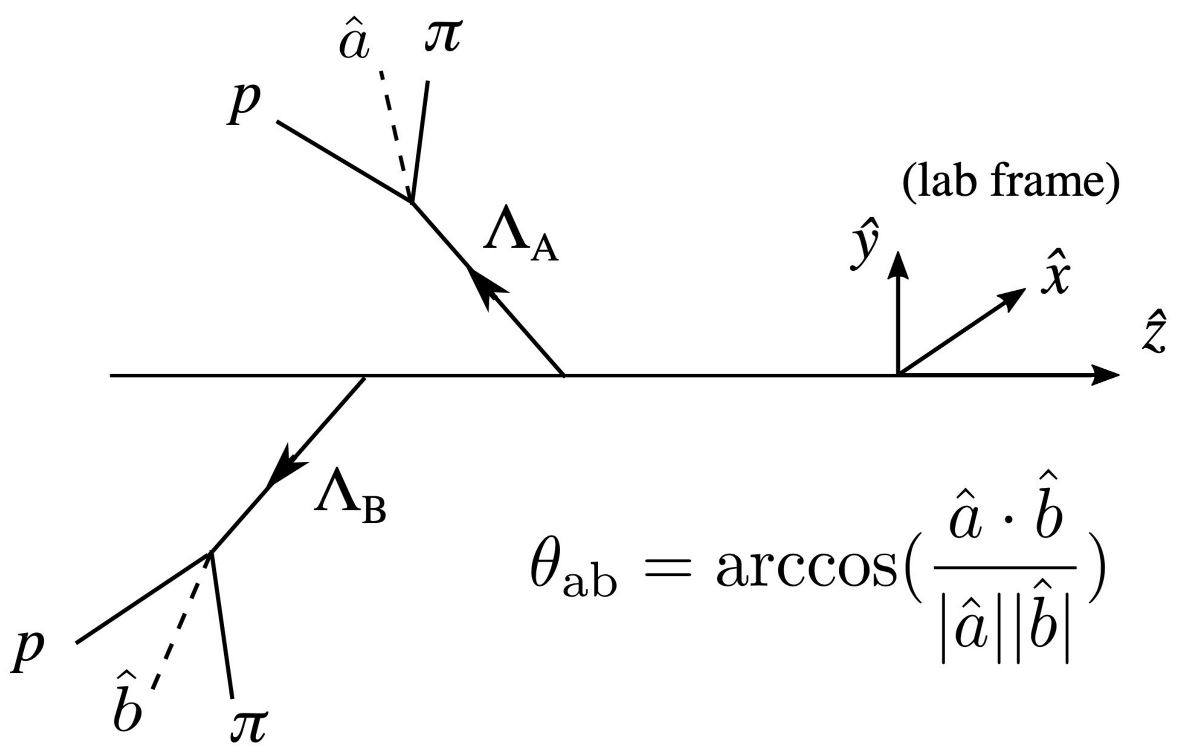
Bell-type inequality tests and quantum entanglement from Λ-hyperon spin correlations at high energy colliders

Wenjie Gong,[1,*] Ganesh Parida,[2,†] Zhoudunming Tu,[3,4,‡] and Raju Venugopalan[3,§]

[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138*
[2]*Department of Physics, University of Wisconsin-Madison, Madison, Wisconsin 53706*
[3]*Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA*
[4]*Center for Frontiers in Nuclear Science, Stony Brook, New York 11794, USA*

(Dated: July 29, 2021)





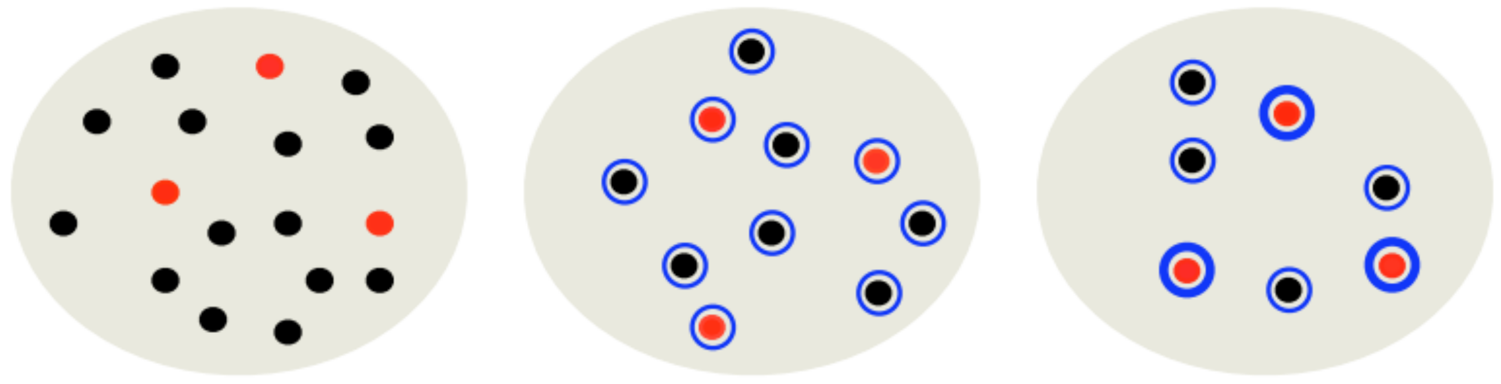
$$\theta_{ab} = \arccos\left(\frac{\hat{a}\cdot\hat{b}}{|\hat{a}||\hat{b}|}\right)$$

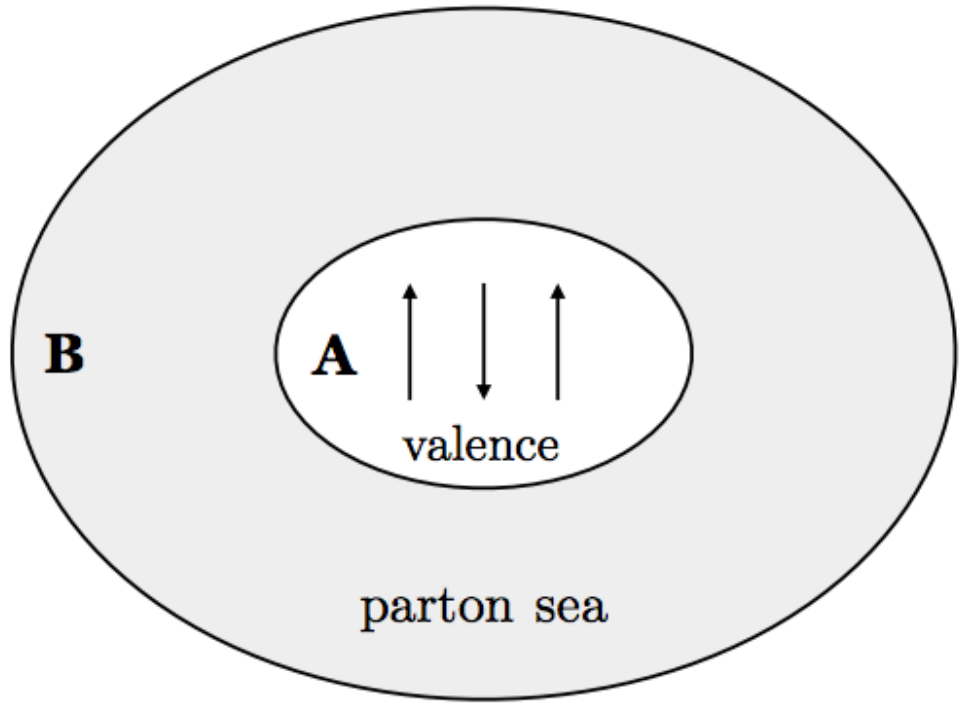
Entanglement as an order-parameter for Chiral Symmetry breaking

Modern Physics Letters A | Vol. 35, No. 08, 2050048 (2020) | Research Papers
No Access

Chiral symmetry breaking, entanglement, and the nucleon spin decomposition

Silas R. Beane and Peter J. Ehlers





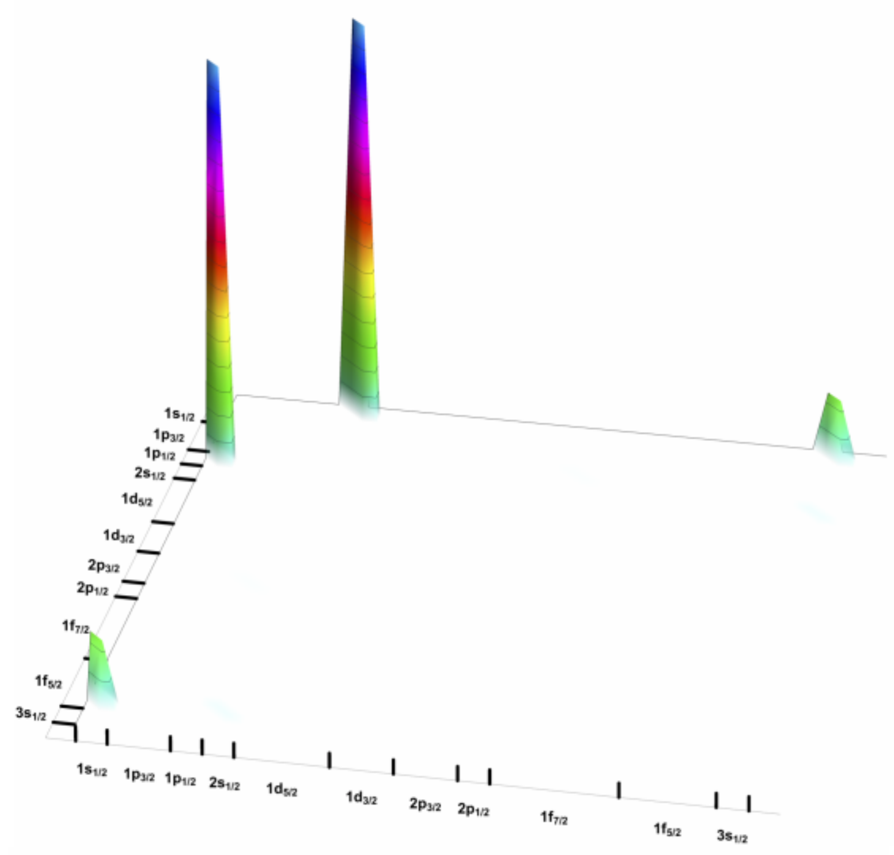
Entanglement as an Organizing Principle in Nuclei
Toward Hybrid QPU-CPU Nuclear Structure

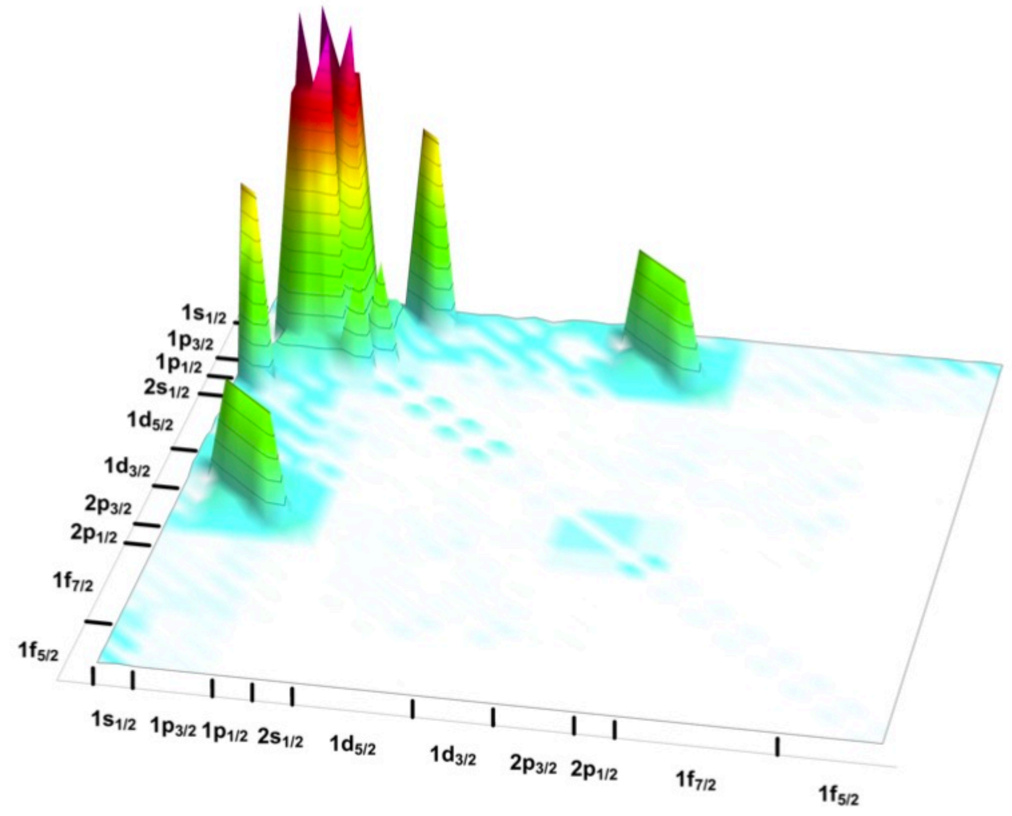
Caroline Robin

2018: Gorton and Johnson [MS thesis, Gorton]

Caroline Robin, Nathalie Pillet, MJS
Phys.Rev.C 103 (2021) 3, 034325

Harmonic Oscillator

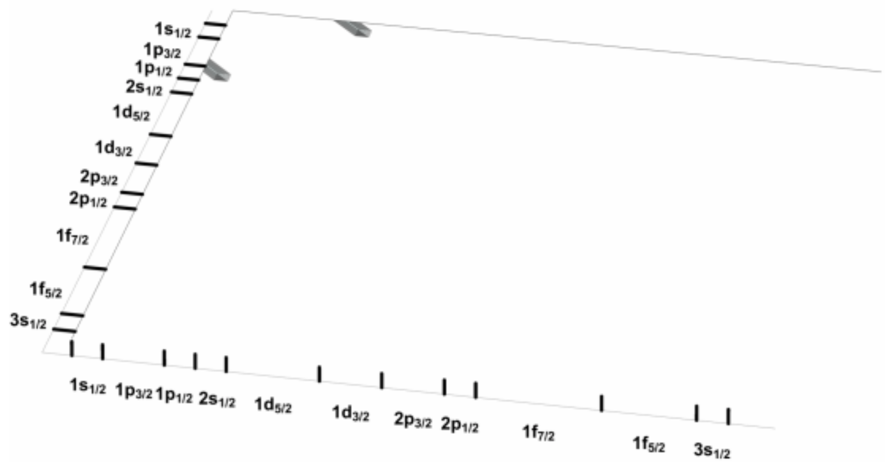


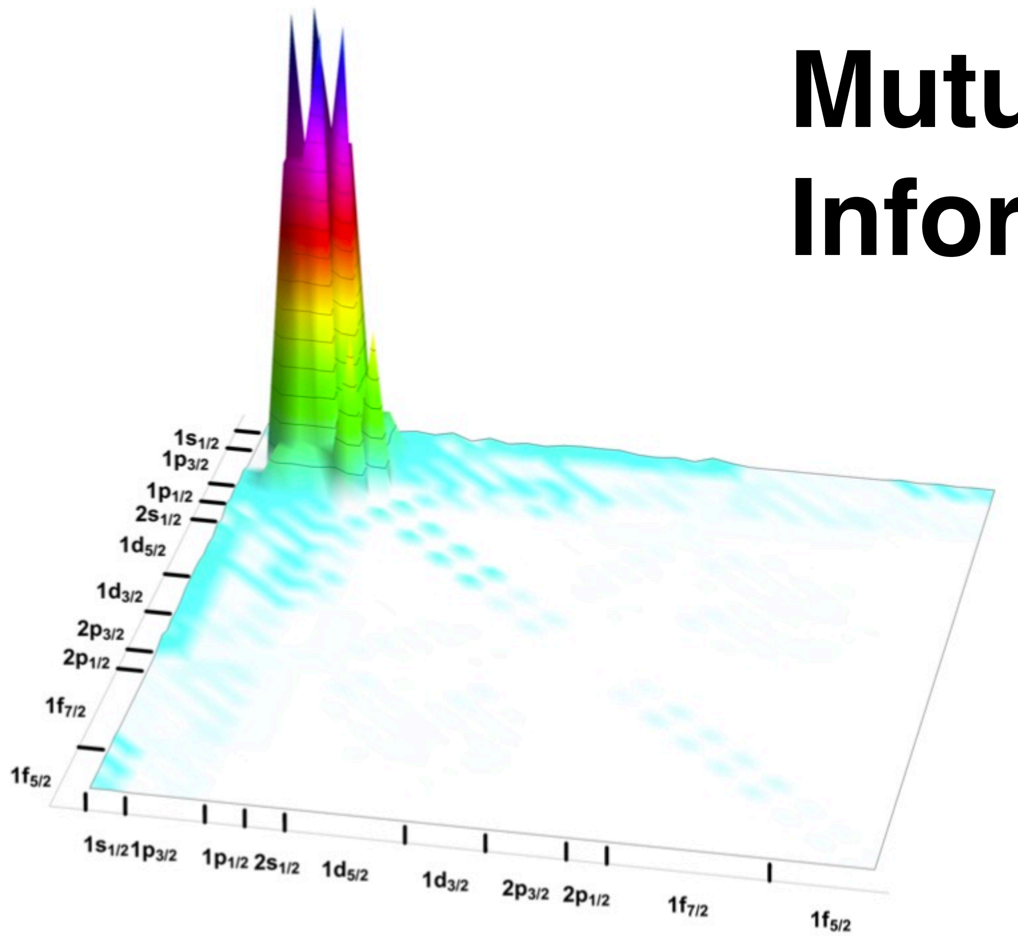


Negativity

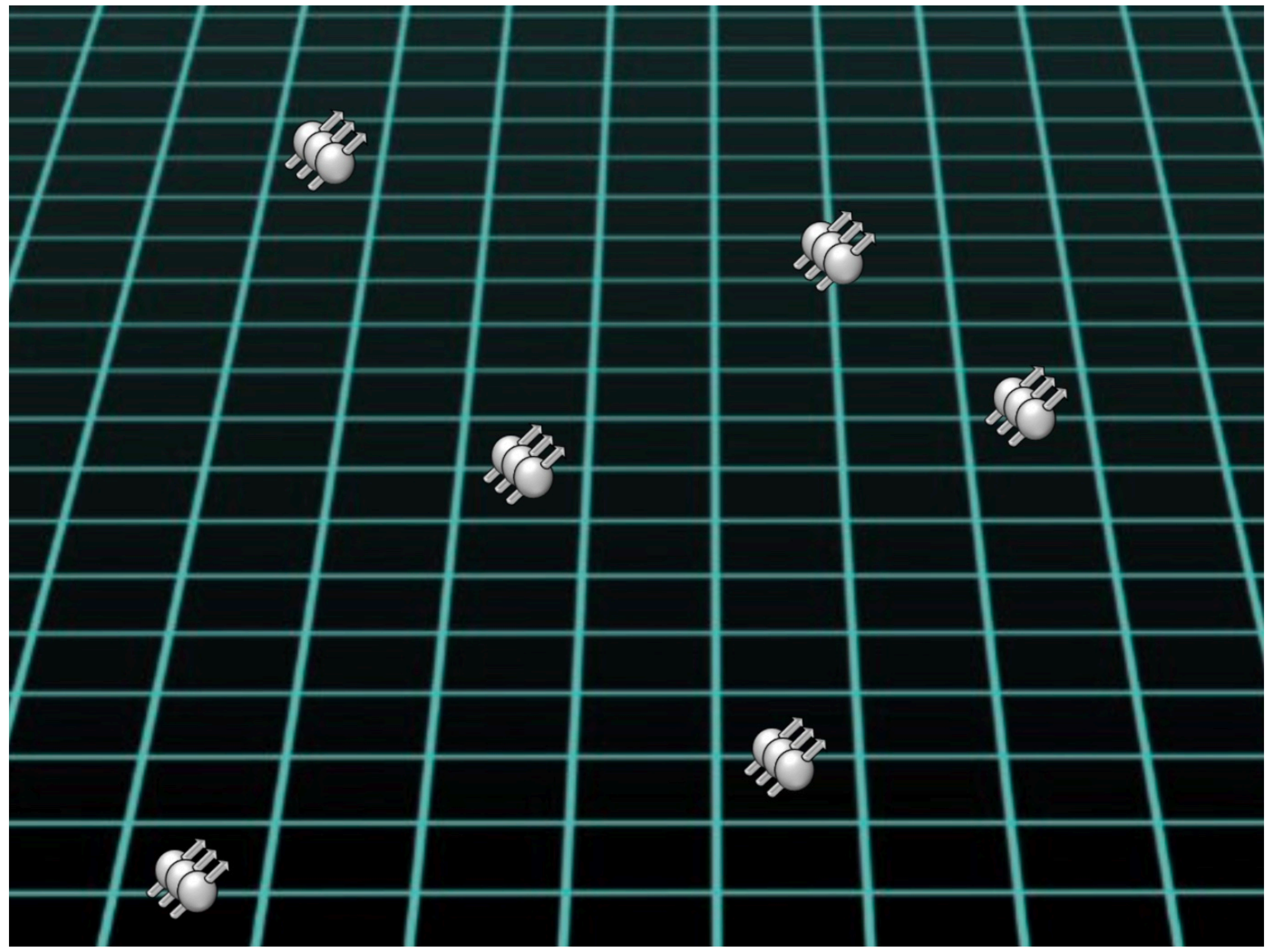
Mutual Information

Self-Consistent, Correlated





Quantum Field Theories - 101



- Finite lattice to support the fields
- 3-dim for 3-dim
- Real-time Hamiltonian evolution
- Fields mapped to qubits/qudits
- BCs
- Hybrid - tasks for QPU?

- Different mappings (most “efficient” path to continuum physics?)
  - “qubits arranged” with fermions on sites and gauge fields on links (KS)
  - or continuum fields de-localized. (e.g. quantum link models)
  - truncations/samplings in gauge rotations or irreps
  - and/or Integrate out gauge freedoms
  - and/or Gauss’s law explicit/implicit, error correction to enforce

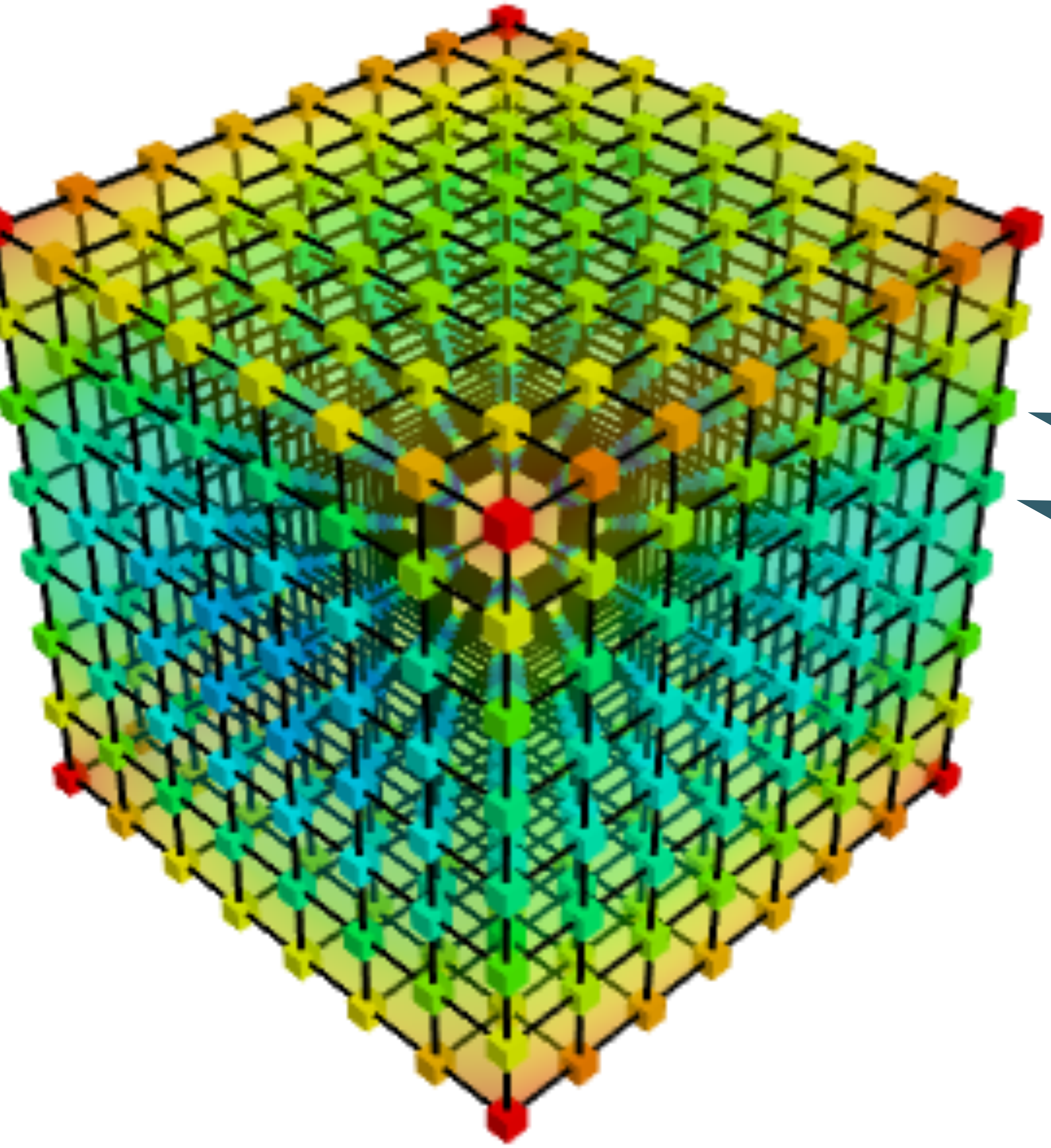
Truncations, convergence and errors (gauge field, spacetime)
Ultimately, we need a complete quantification of uncertainties

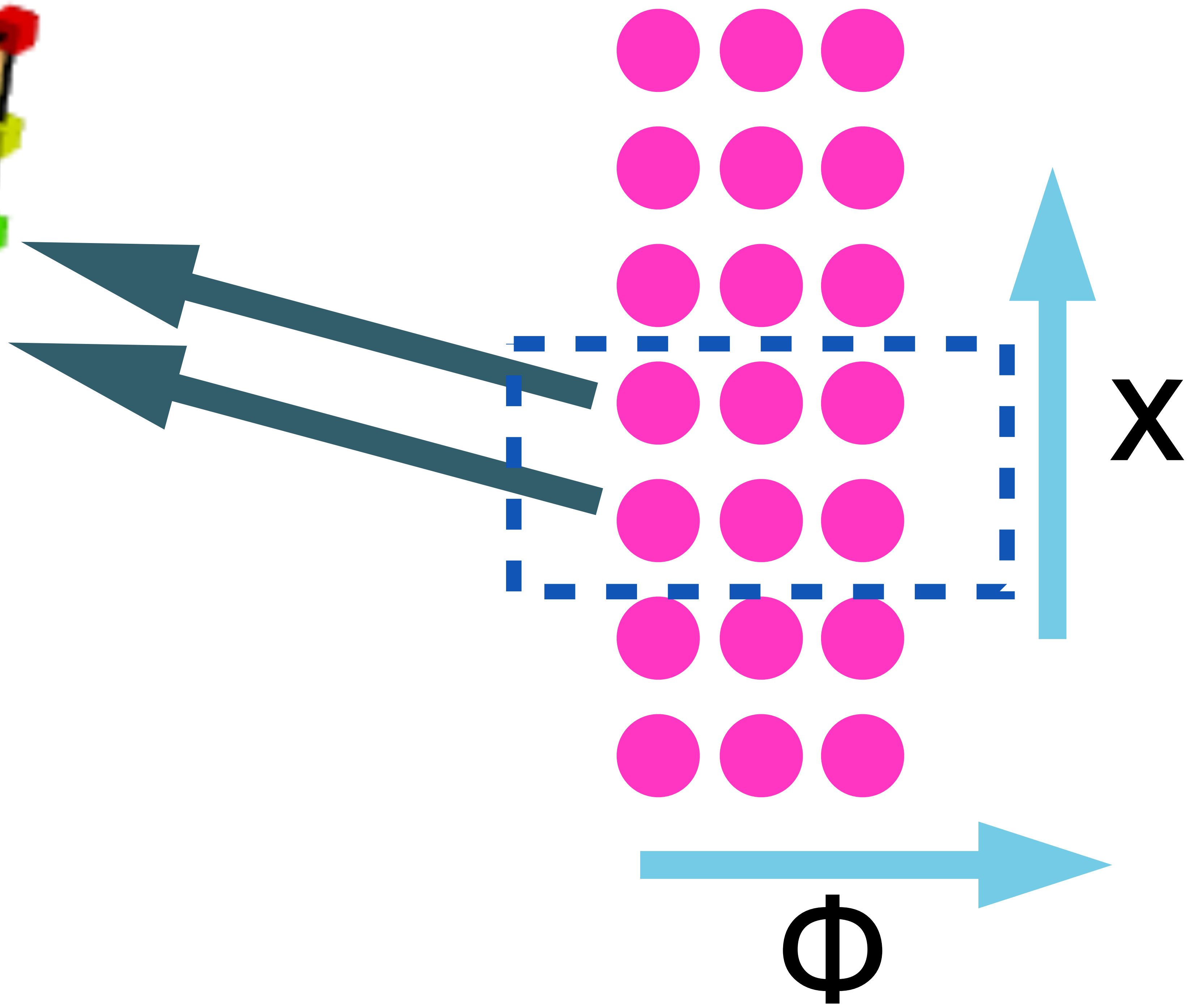
Scalar Field Theory

Jordan, Lee, Preskill

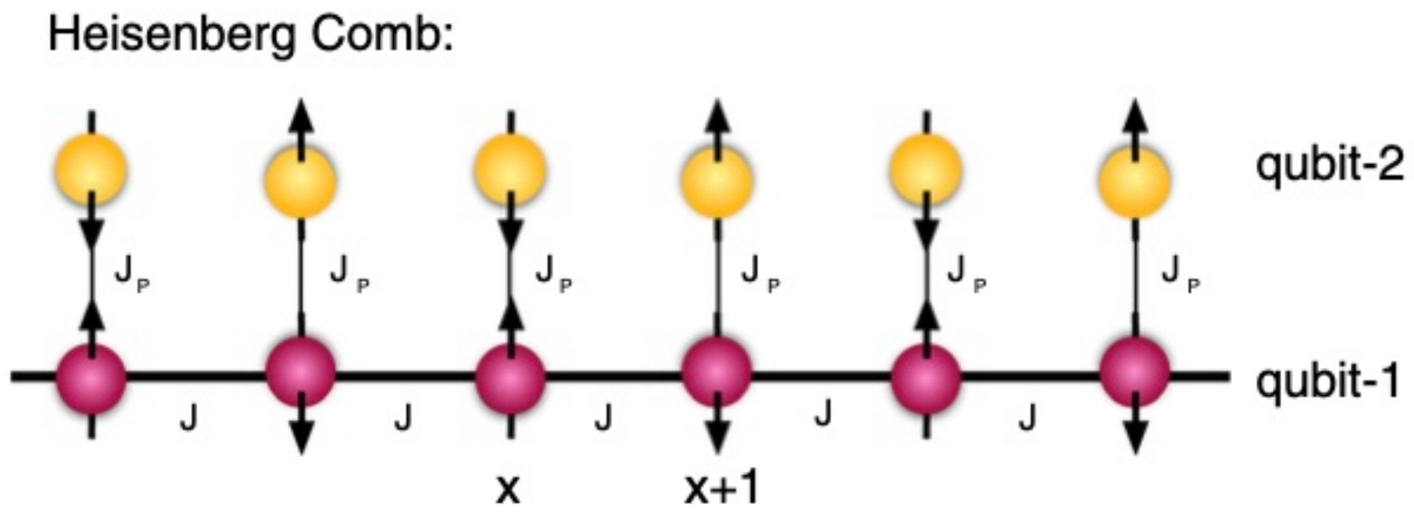
Parallelizes easily at the circuit level

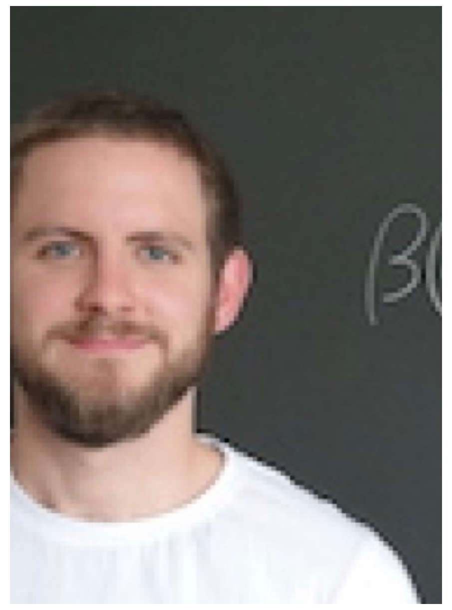
- dual layer application per Trotter step





Mappings to spin-systems





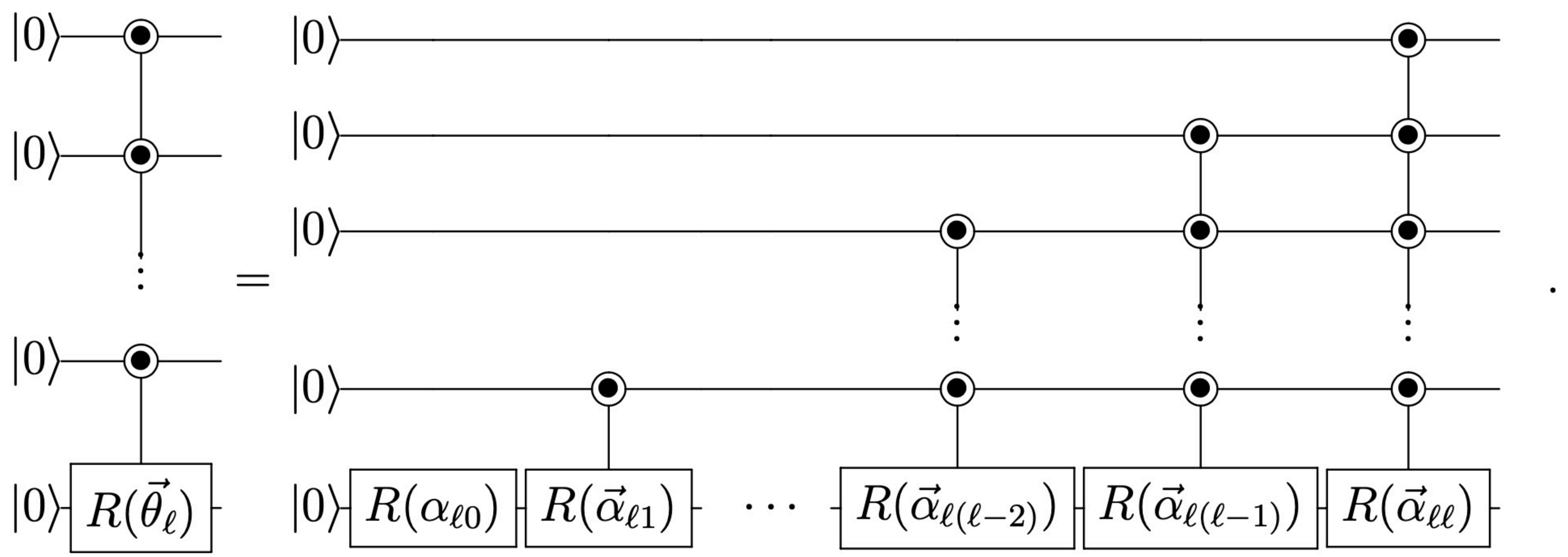
Stephan Caspar

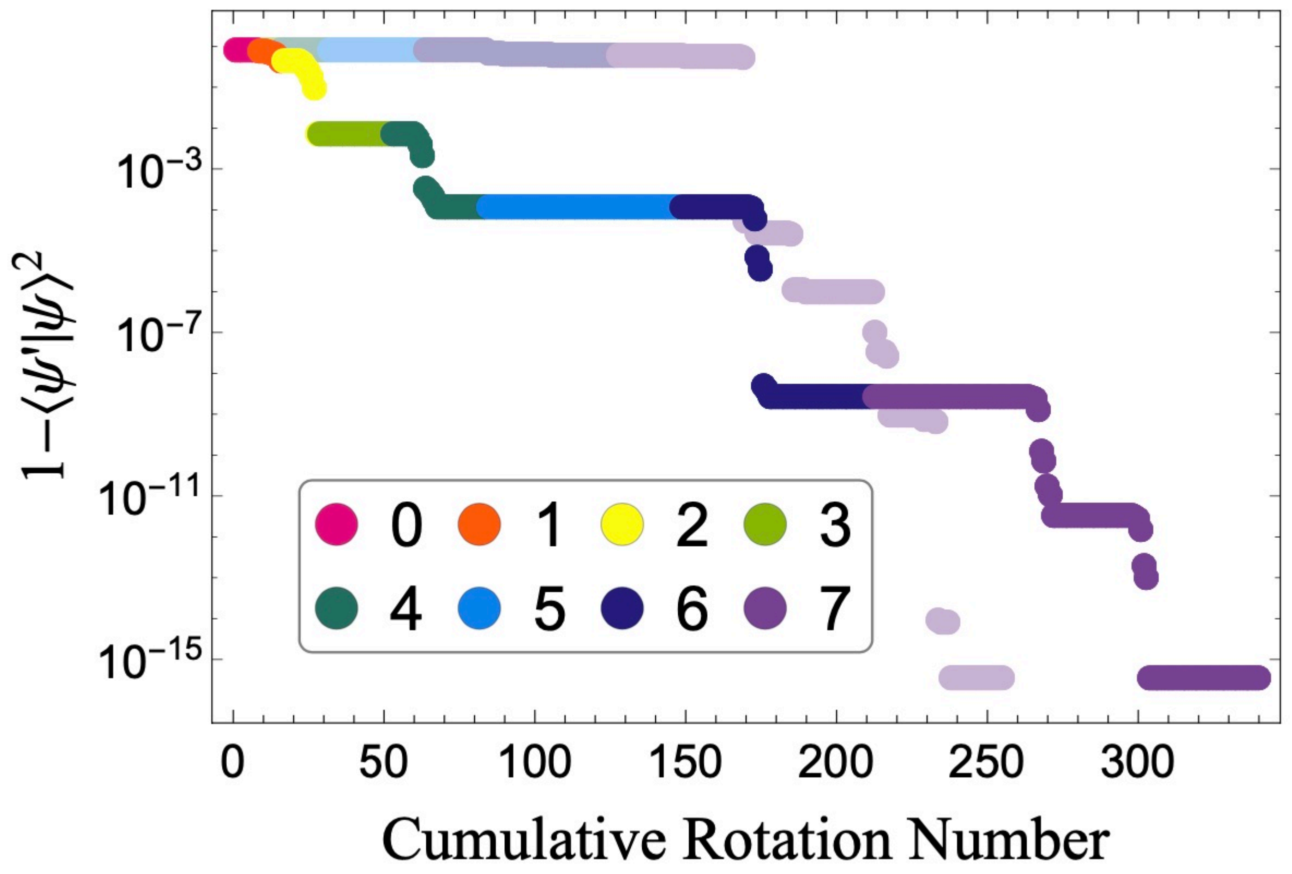
Hersh Singh

Systematically localizable operators for quantum simulations of quantum field theories
Natalie Klco and Martin J. Savage
Phys. Rev. A **102**, 012619 – Published 22 July 2020

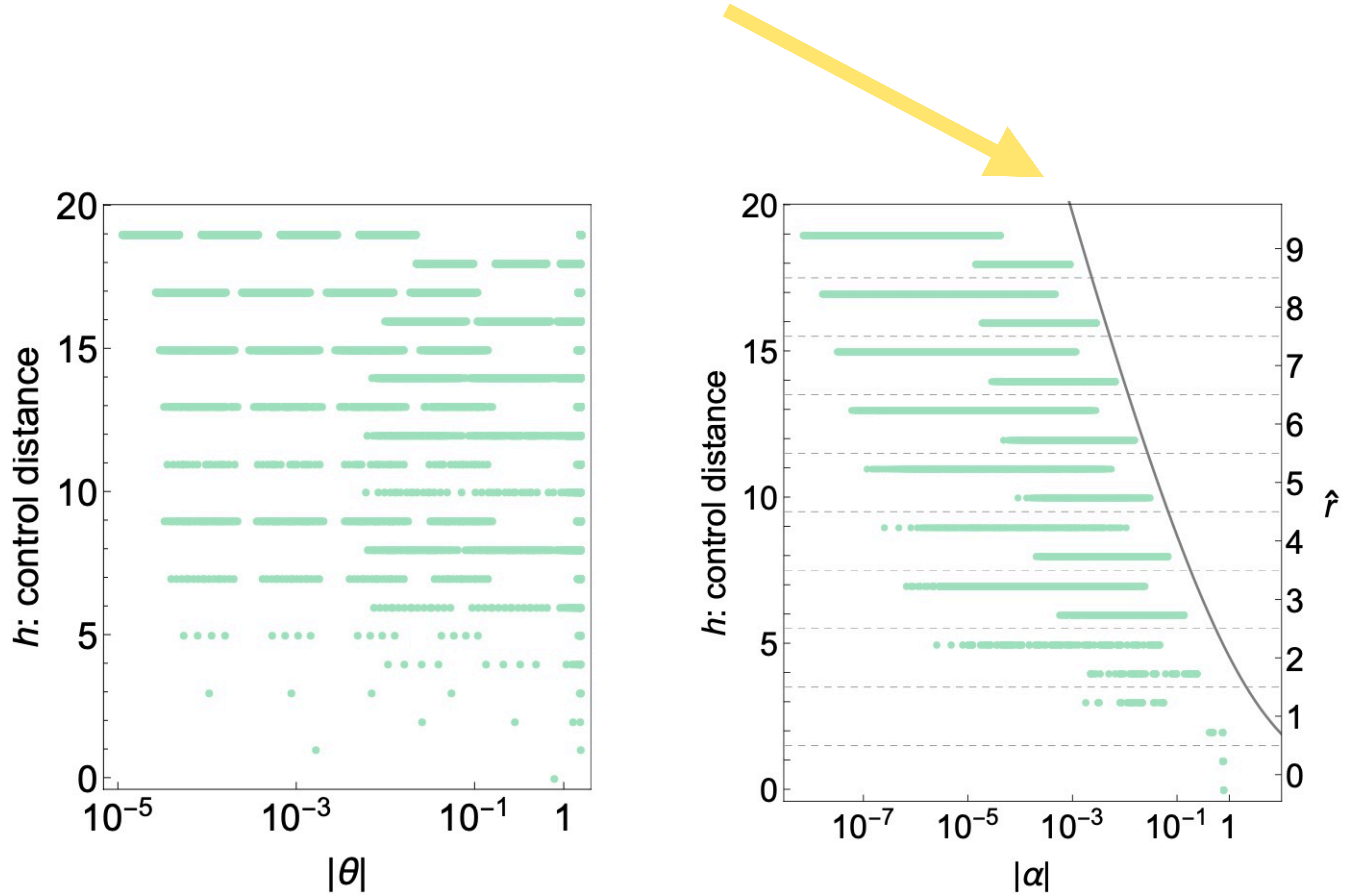
Circuits Reflecting Classical Correlations

Mapping should reflect physical system





Classical correlation
modified Bessel function

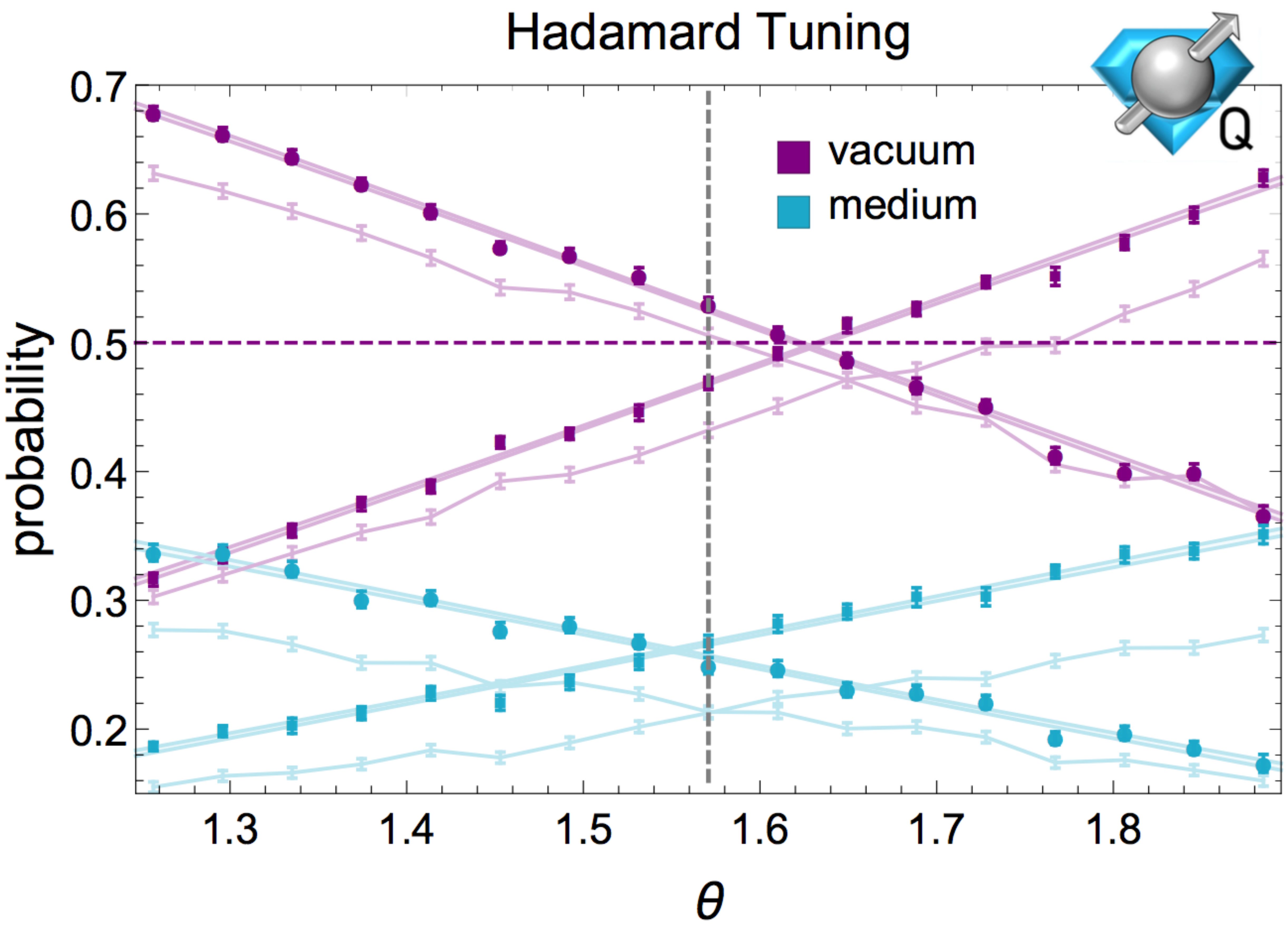


Minimally entangled state preparation of localized wave functions on quantum computers

Natalie Klco and Martin J. Savage

Phys. Rev. A **102**, 012612 – Published 17 July 2020

Calibration - NISQ-Era Lessons - Continually Improving



n_Q=4

Probability of |0> and |8> states

Probability of |7> and |15> states

vacuum: initially all |0>

in-medium: initially n_Q-1are in exponential

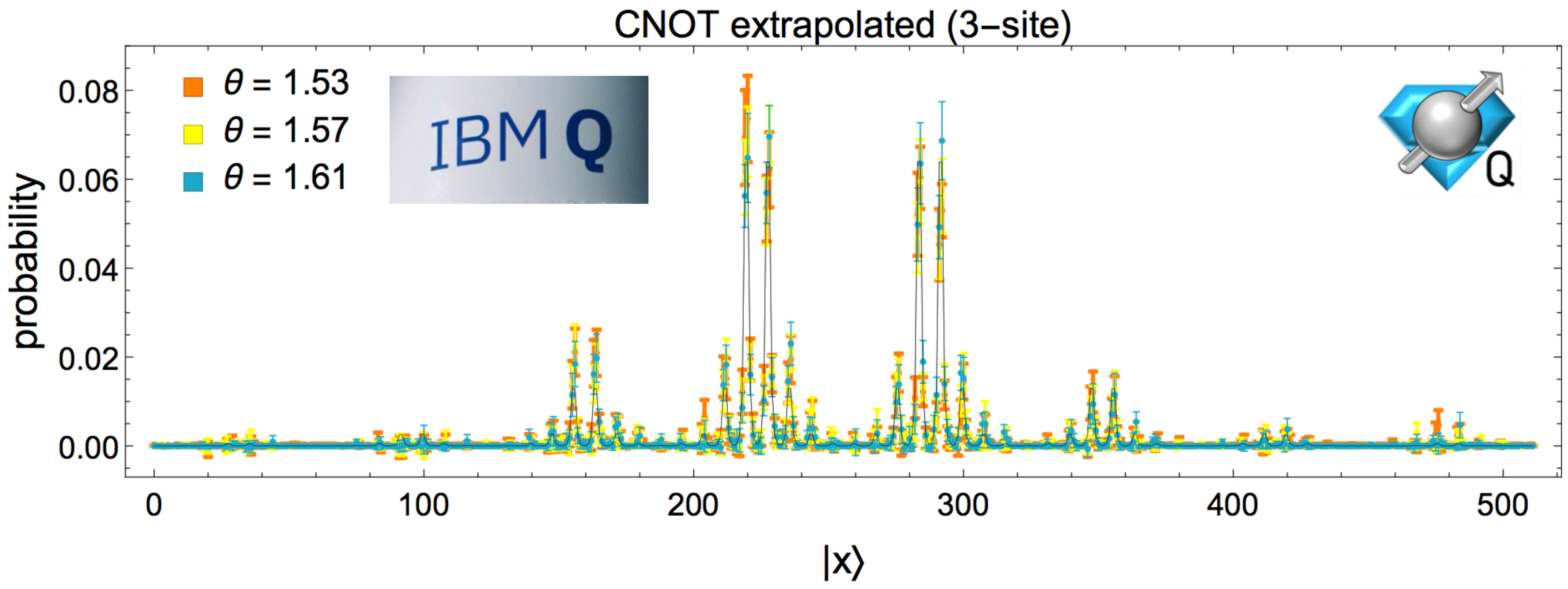
A need:
Integrated workflows for calibration

More Lessons

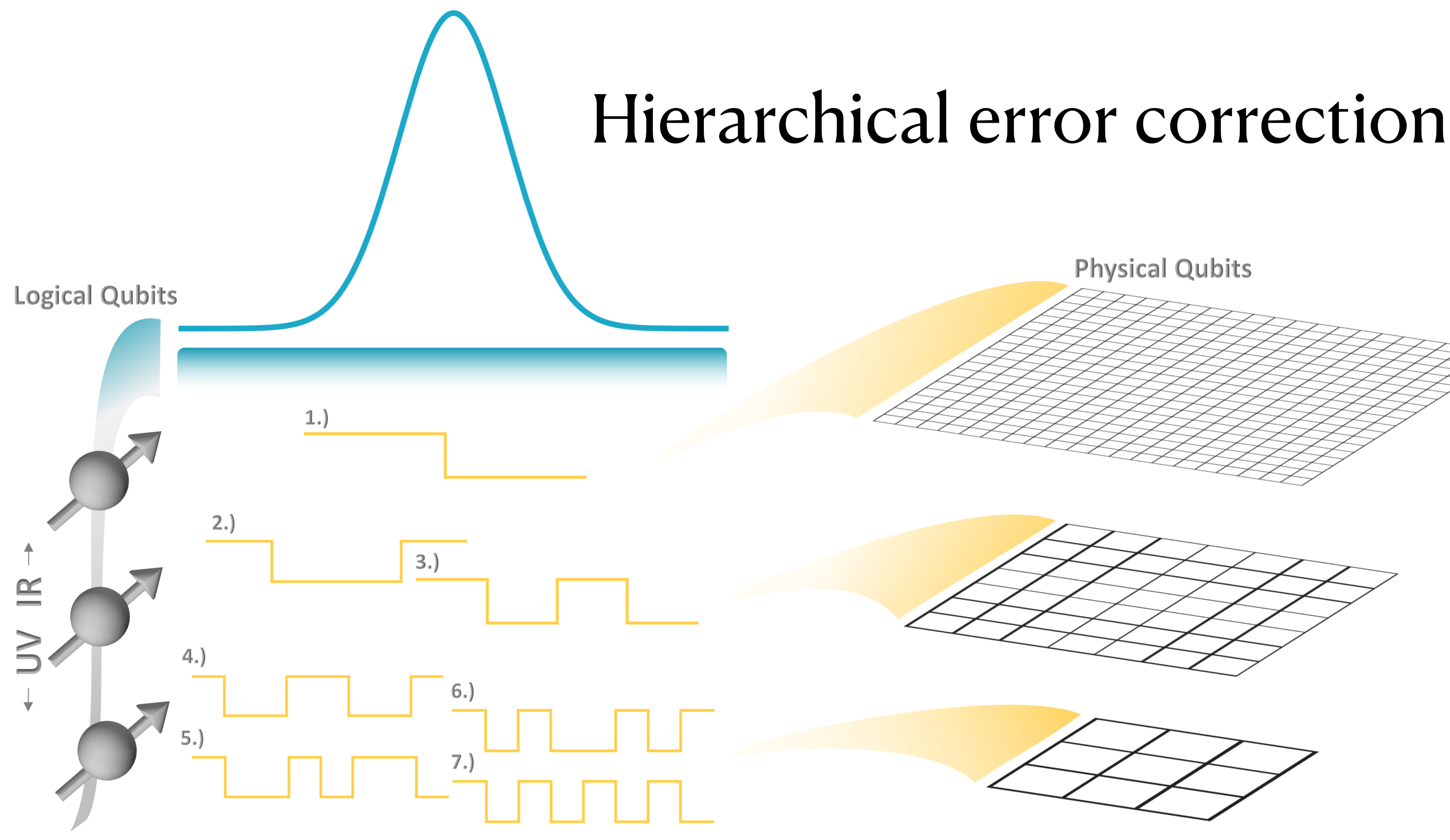
Minimally entangled state preparation of localized wave functions on quantum computers

Natalie Klco and Martin J. Savage
Phys. Rev. A **102**, 012612 – Published 17 July 2020

$n_Q=3 \otimes n_Q=3 \otimes n_Q=3$



Hierarchical error correction



Hierarchical Qubit Maps and Hierarchical Quantum Error Correction

Natalie Klco[1,*] and Martin J. Savage[2,†]
[1] Institute for Quantum Information and Matter and Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena CA 91125, USA
[2] InQubator for Quantum Simulation (IQuS), Department of Physics, University of Washington, Seattle, WA 98195.
(Dated: September 7, 2021 - 0:51)

Scaling of ensemble size — observables considered

~1-cent per circuit — 1 million "shots" = $$$

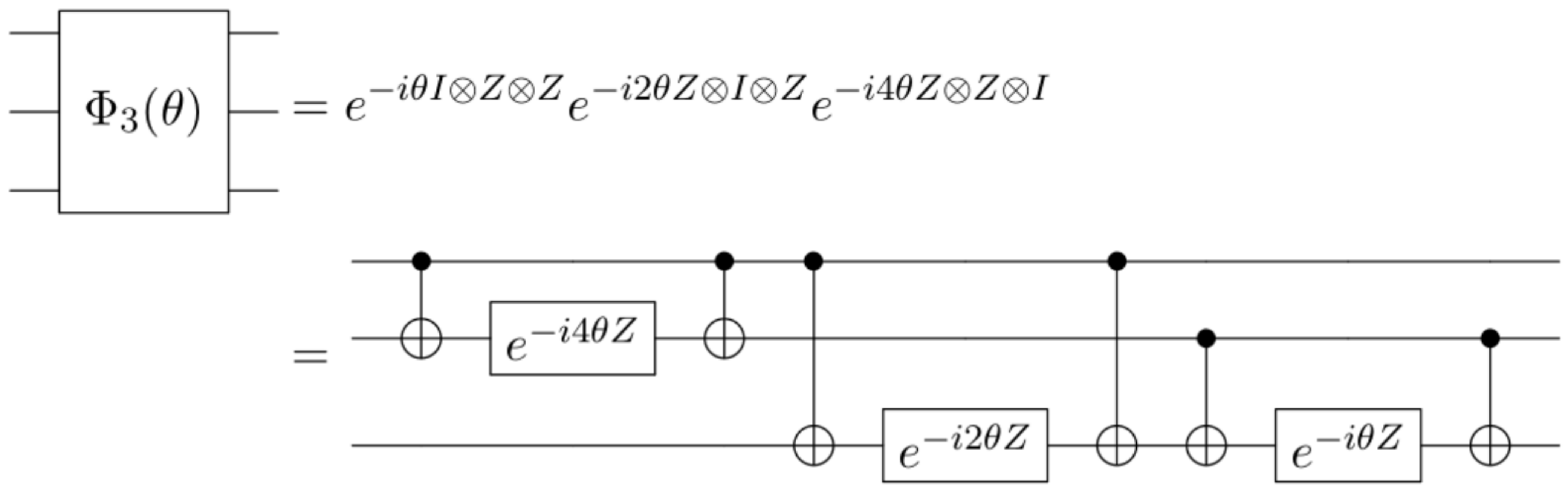
Scalar Field Theory
e.g., Time Evolution

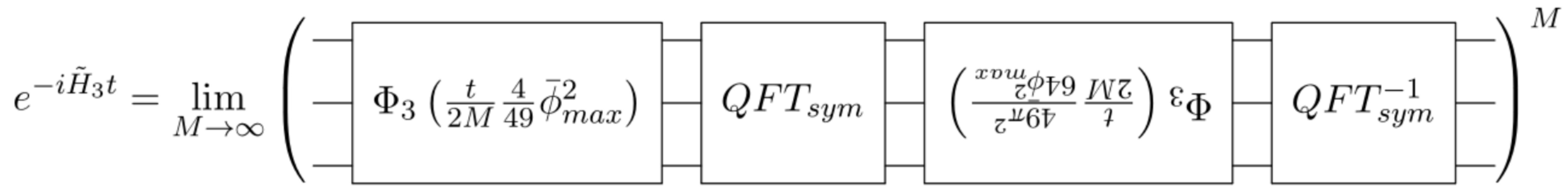
$$\phi = \frac{\bar{\phi}_{\max}}{n_s - 1} \sum_{j=0}^{n_Q - 1} 2^j \sigma_j^z$$

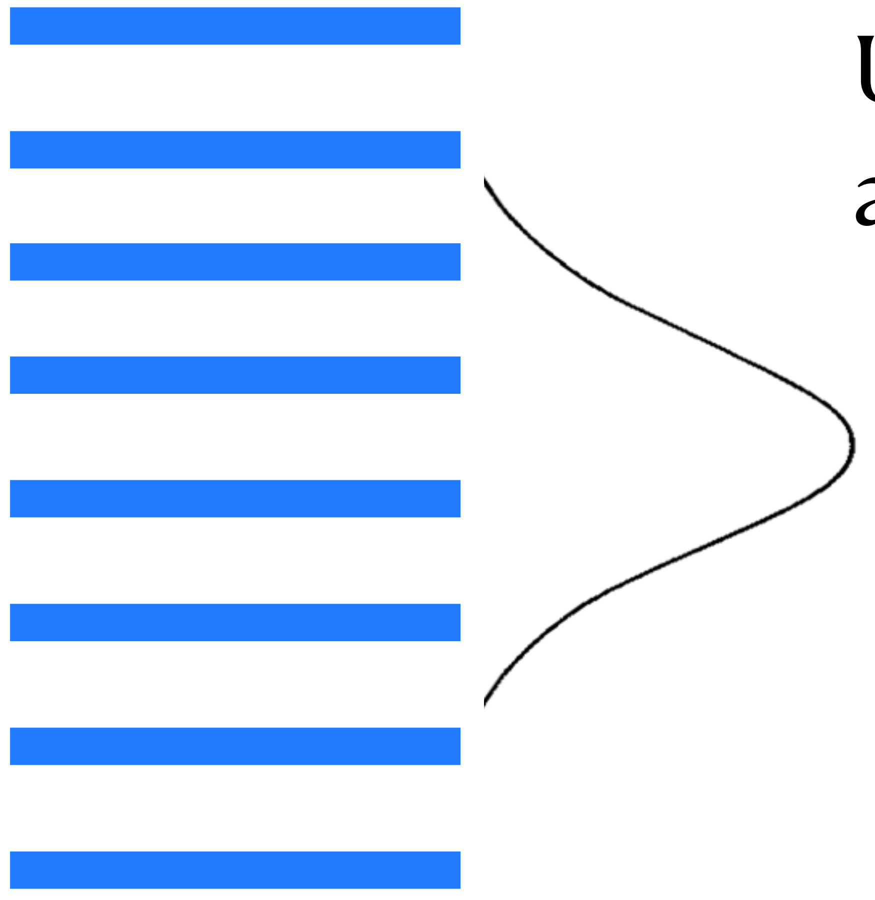
$$\tilde{\phi}^2 = \frac{4}{49}\, \bar{\phi}^2_{\max}\, \mathcal{O}_0^{(n_Q=3)} \quad , \quad \tilde{\Pi}^2 = \frac{49\pi^2}{64\ \bar{\phi}^2_{\max}}\, \mathcal{O}_0^{(n_Q=3)} \quad ,$$

$$\mathcal{O}_0^{(n_Q=3)} = 4\ \sigma^z \otimes \sigma^z \otimes I_2 \ +\ 2\ \sigma^z \otimes I_2 \otimes \sigma^z \ +\ I_2 \otimes \sigma^z \otimes \sigma^z \ +\ \frac{21}{4}\ I$$

$$= \mathcal{O}_{03}^{(n_Q=3)} \ +\ \frac{21}{4}\ I \quad ,$$

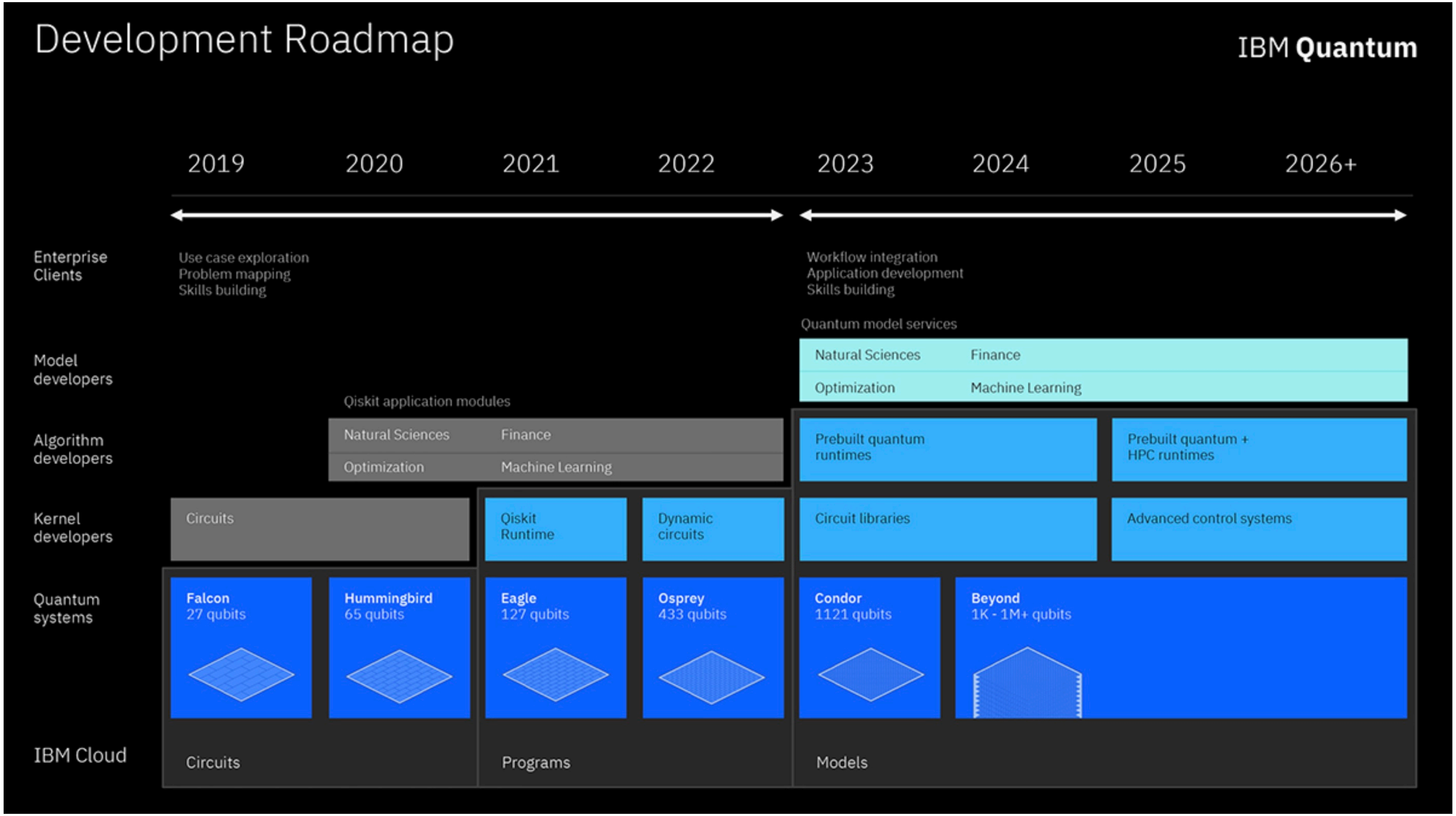






Jordan, Lee and Preskill
Use the exact dispersion relation and not the lattice relation

IBM’s Road Map as an Example



Google’s Demonstration of Repetition Codes
Exponential Suppression of Single Qubit Flips

LETTER

doi:10.1038/nature14270

State preservation by repetitive error detection in a superconducting quantum circuit

J. Kelly[1]*, R. Barends[1]†*, A. G. Fowler[1,2]†*, A. Megrant[1,3], E. Jeffrey[1]†, T. C. White[1], D. Sank[1]†, J. Y. Mutus[1]†, B. Campbell[1], Yu Chen[1]†, Z. Chen[1], B. Chiaro[1], A. Dunsworth[1], I.-C. Hoi[1], C. Neill[1], P. J. J. O’Malley[1], C. Quintana[1], P. Roushan[1]†, A. Vainsencher[1], J. Wenner[1], A. N. Cleland[1] & John M. Martinis[1]†

Article | Open Access | Published: 14 July 2021

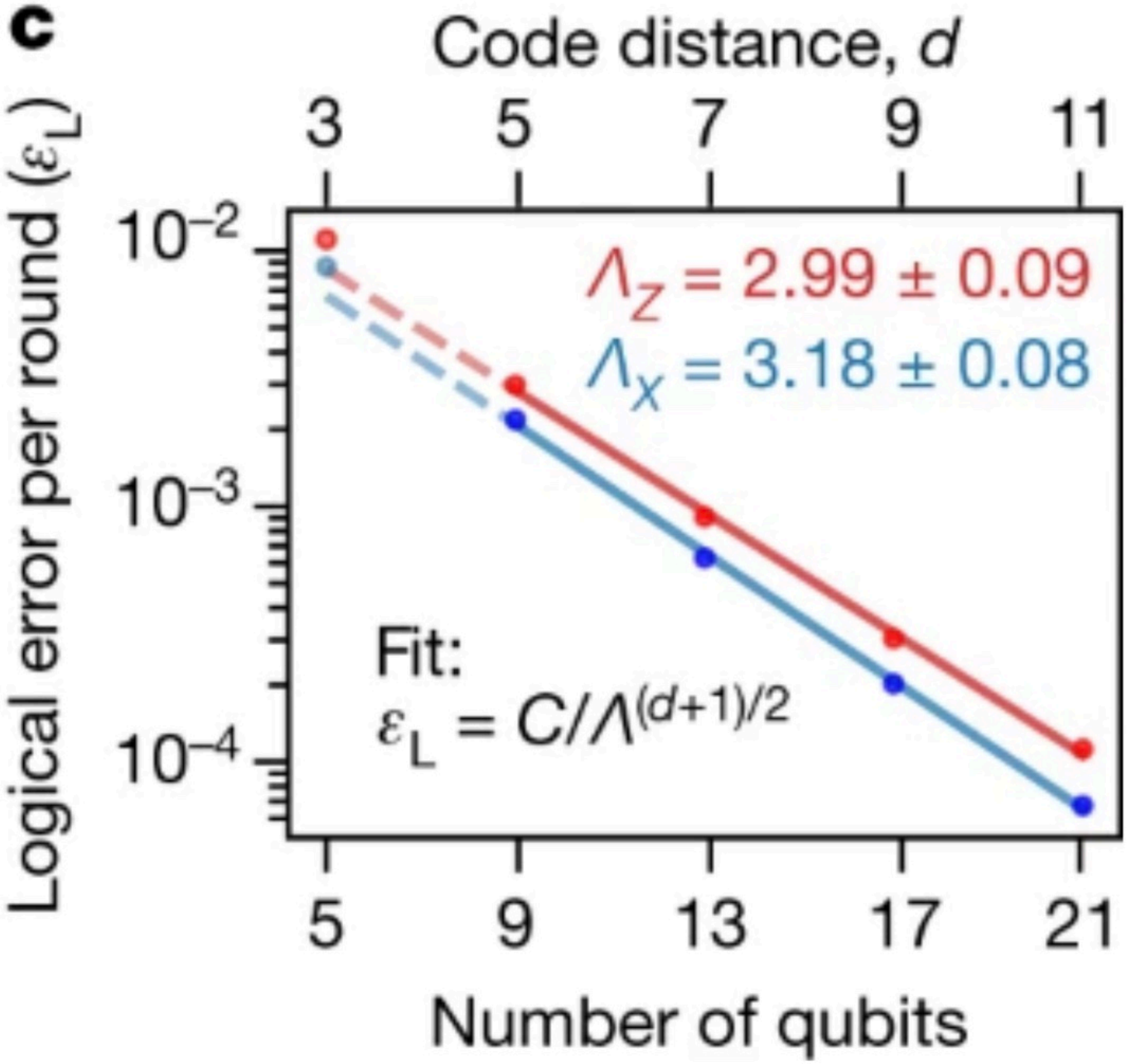
Exponential suppression of bit or phase errors with cyclic error correction

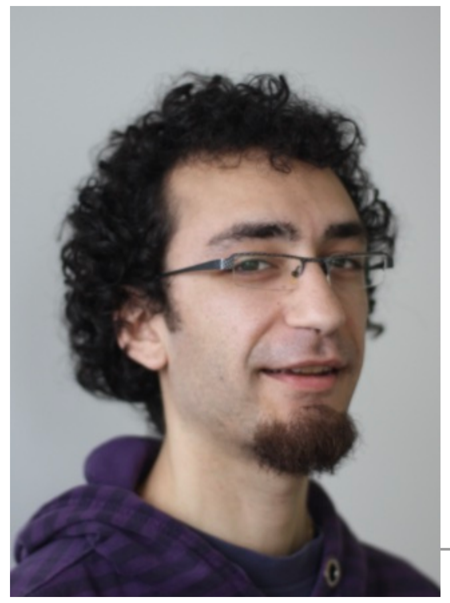
Google Quantum AI

Nature **595**, 383–387 (2021) | Cite this article

$$\varepsilon_L = C/\Lambda^{(d+1)/2}$$

Repetition code using Sycamore QPU

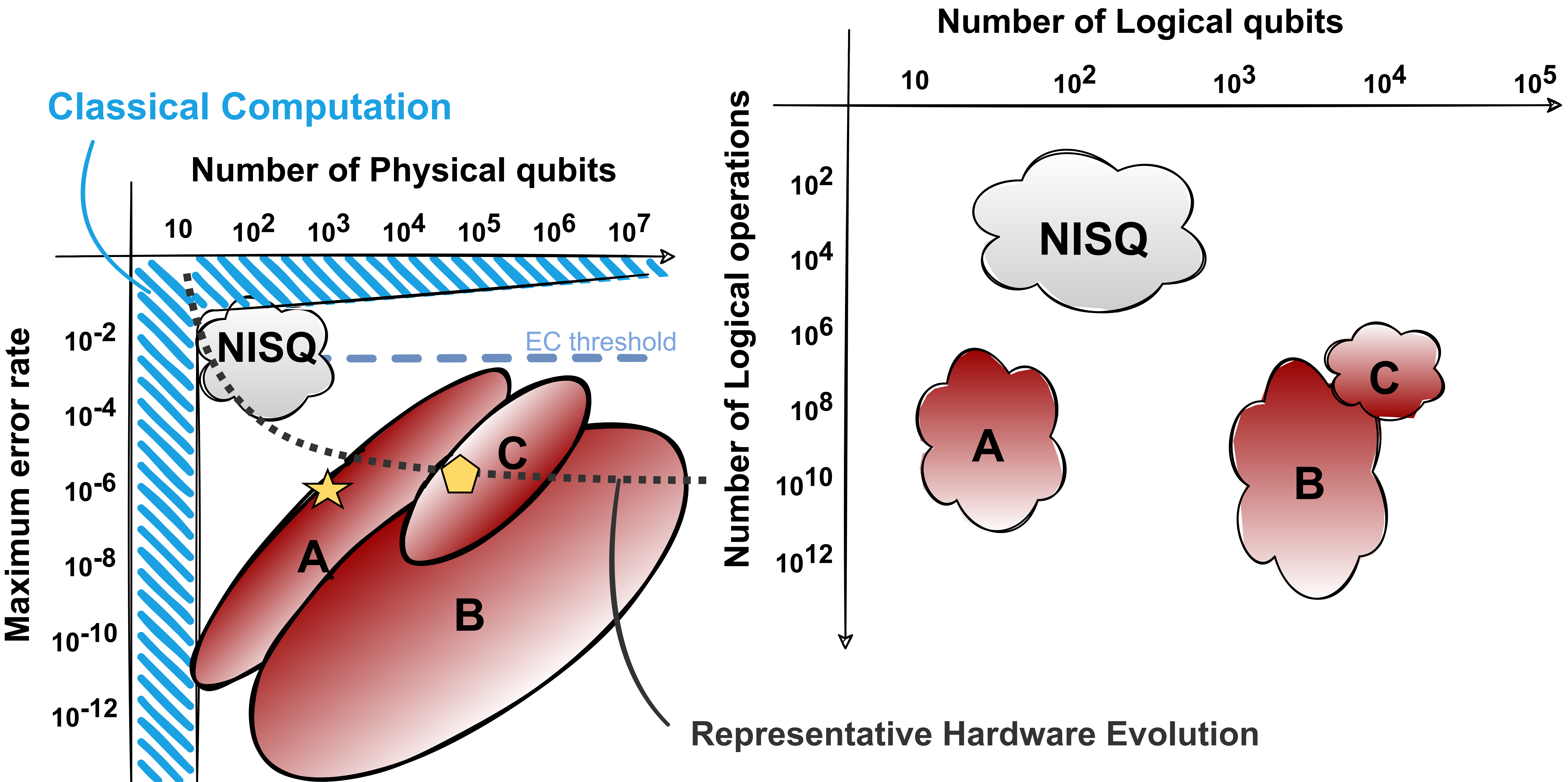


Hardware Evolution(s) and Considerations for Simulations

Standard Model Physics and the Digital Quantum Revolution: Thoughts about the Interface

Natalie Klco,[1,*] Alessandro Roggero,[2,3,†] and Martin J. Savage[2,‡]



Modified from Google figure

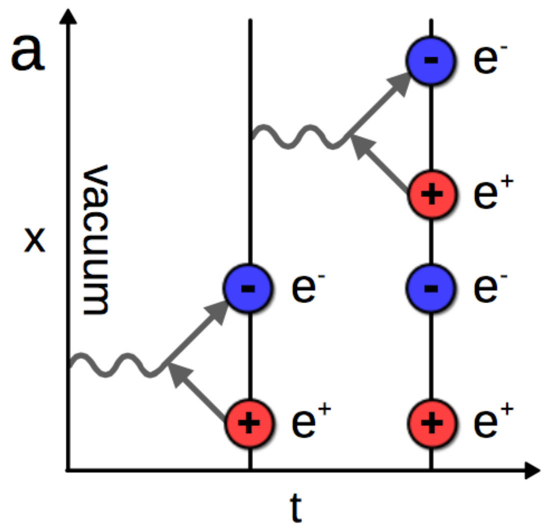
Dynamics in the Schwinger Model - Abelian Gauge Theory
1-dim systems

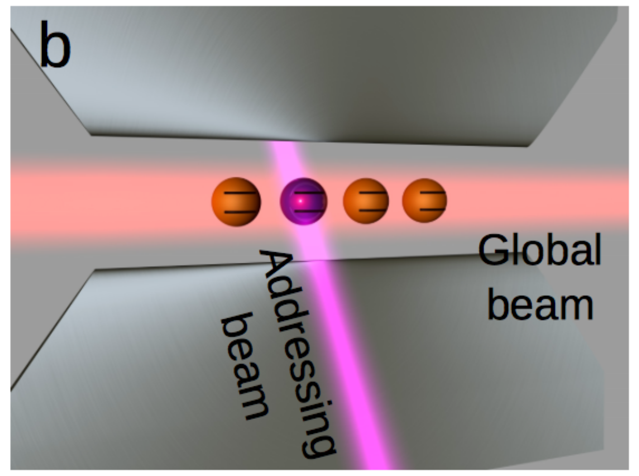
Real-time dynamics of lattice gauge theories with a few-qubit quantum computer

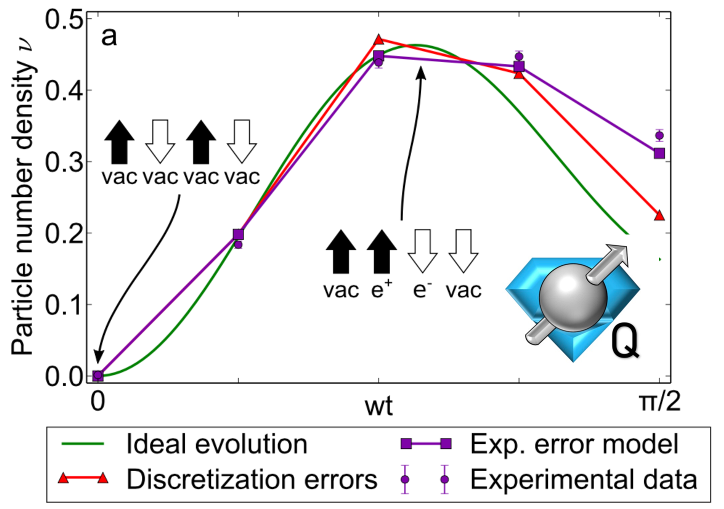
Esteban A. Martinez,[1,*] Christine Muschik,[2,3,*] Philipp Schindler,[1] Daniel Nigg,[1] Alexander Erhard,[1] Markus Heyl,[2,4] Philipp Hauke,[2,3] Marcello Dalmonte,[2,3] Thomas Monz,[1] Peter Zoller,[2,3] and Rainer Blatt[1,2]

(2016)

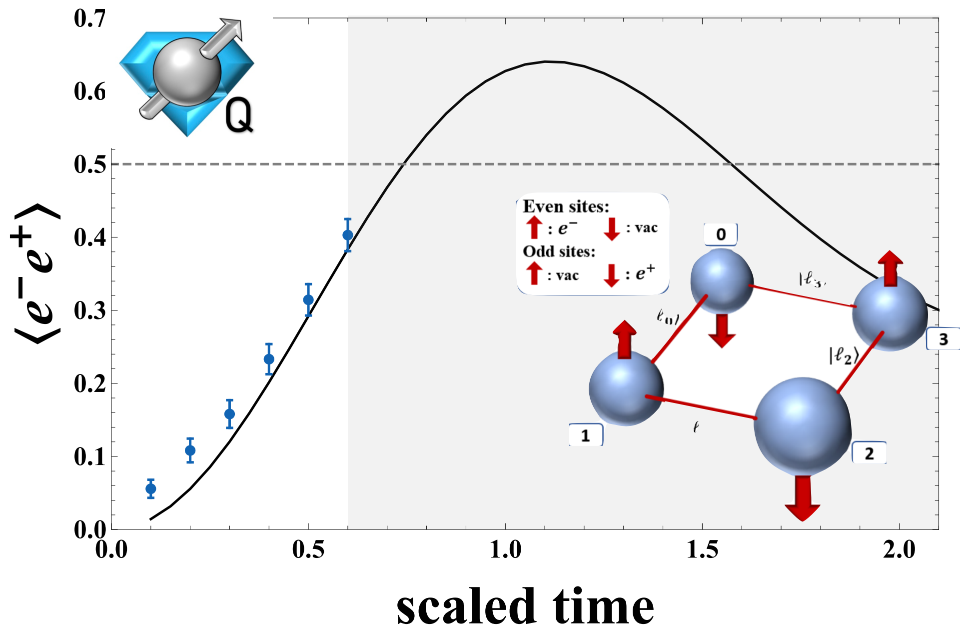
1+1 dim QED



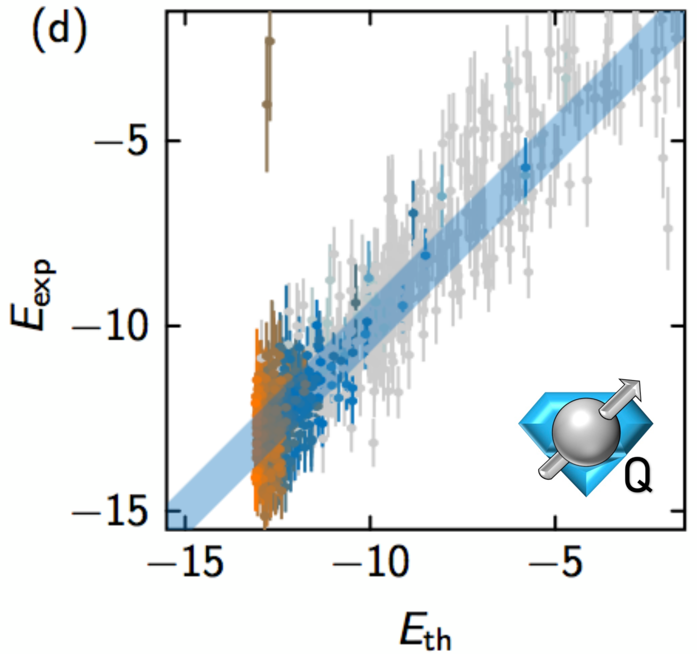




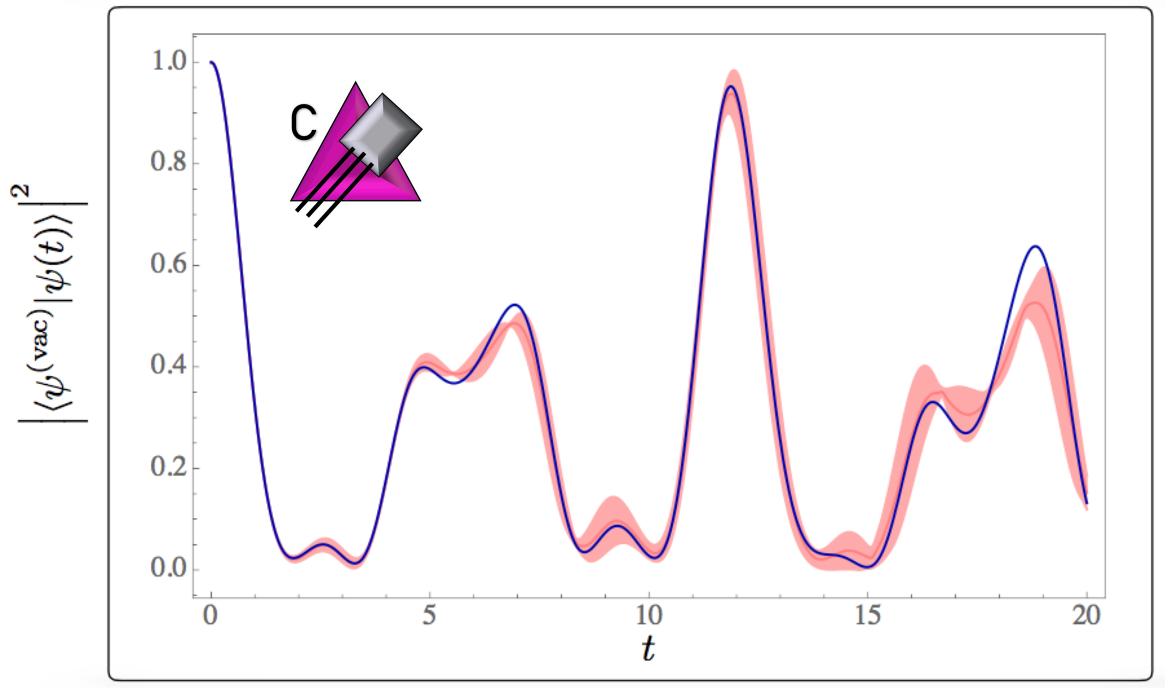
Innesbruck



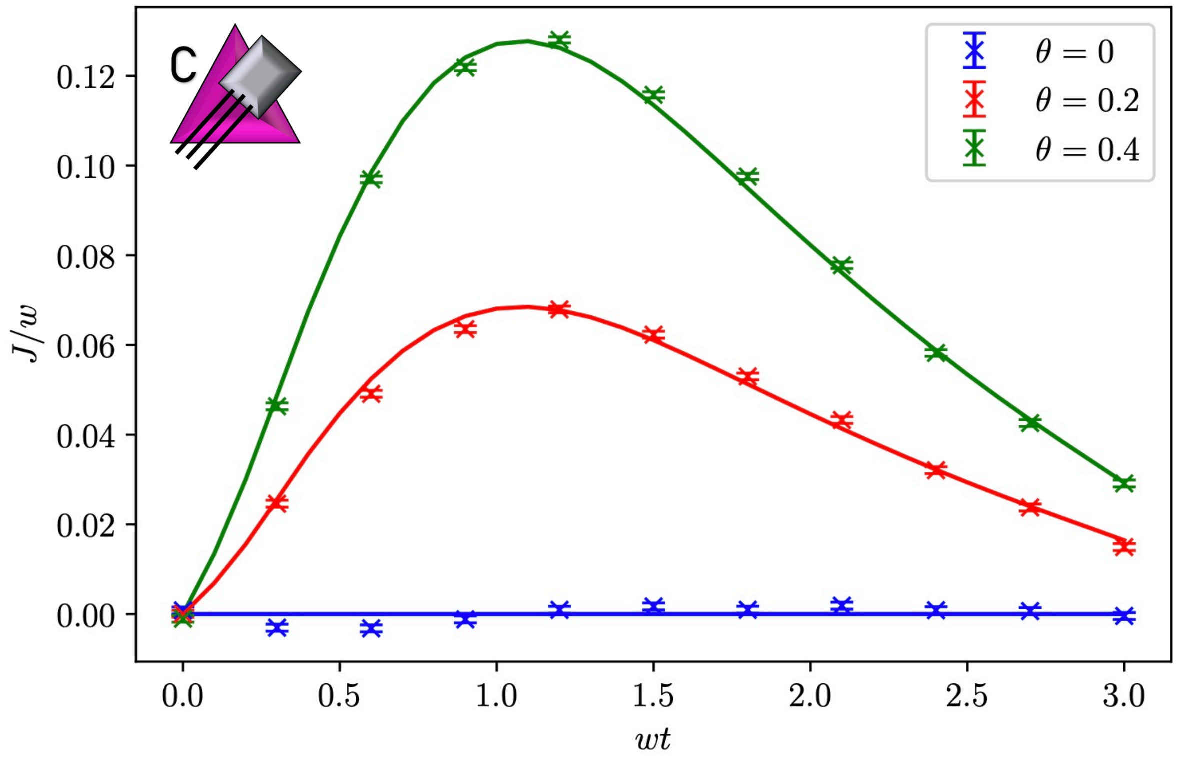
ORNL-Washington-Basque



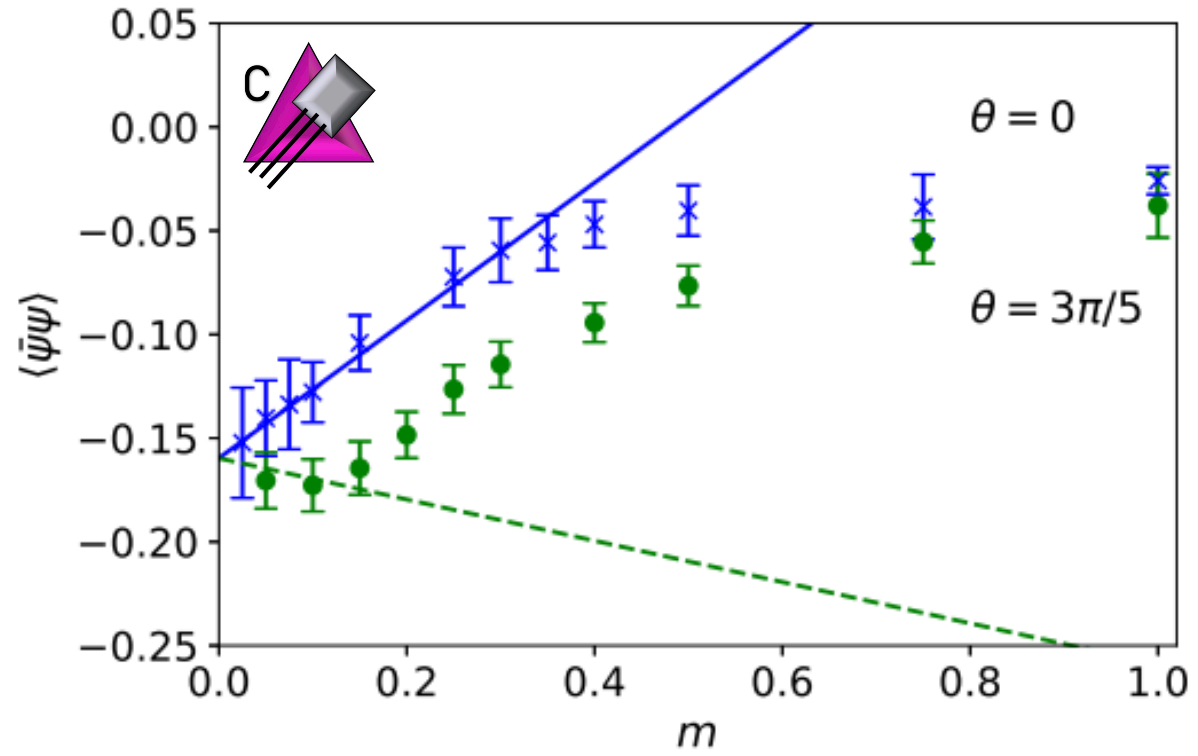
Innesbruck



Maryland



Kharzeev-Kikuchi



Chakraborty, Honda, Izubuchi, Tomiya

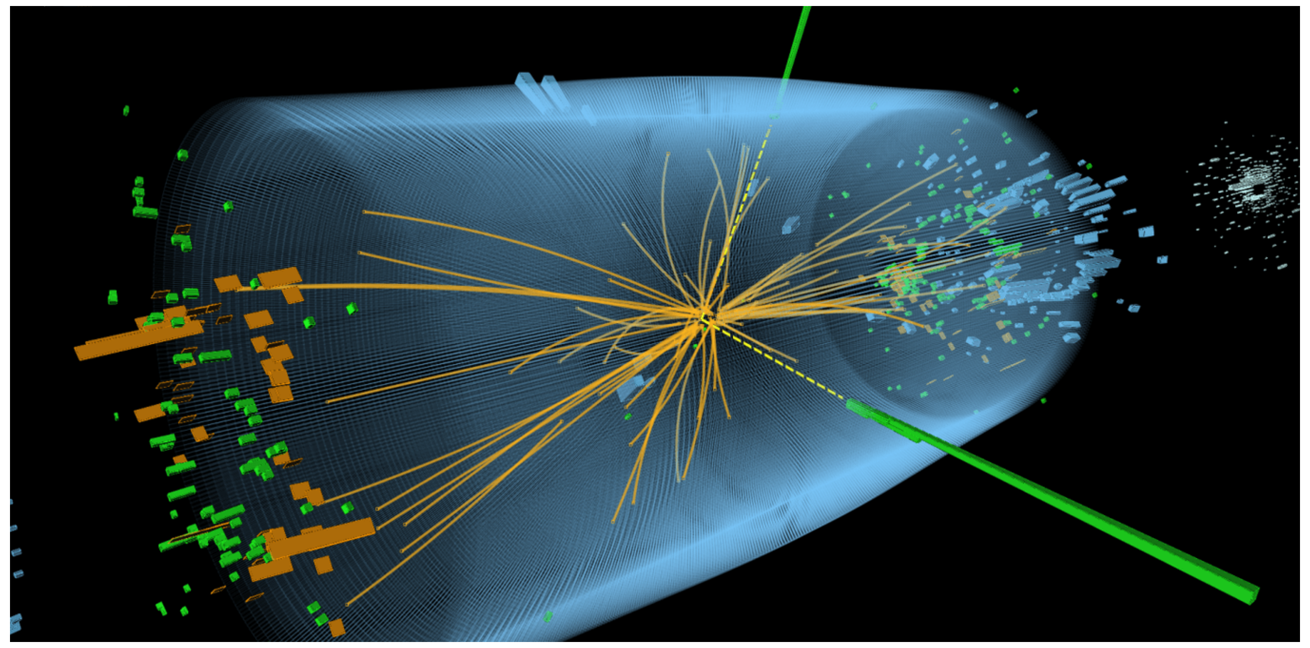
Quantum Algorithms for Simulating the Lattice Schwinger Model

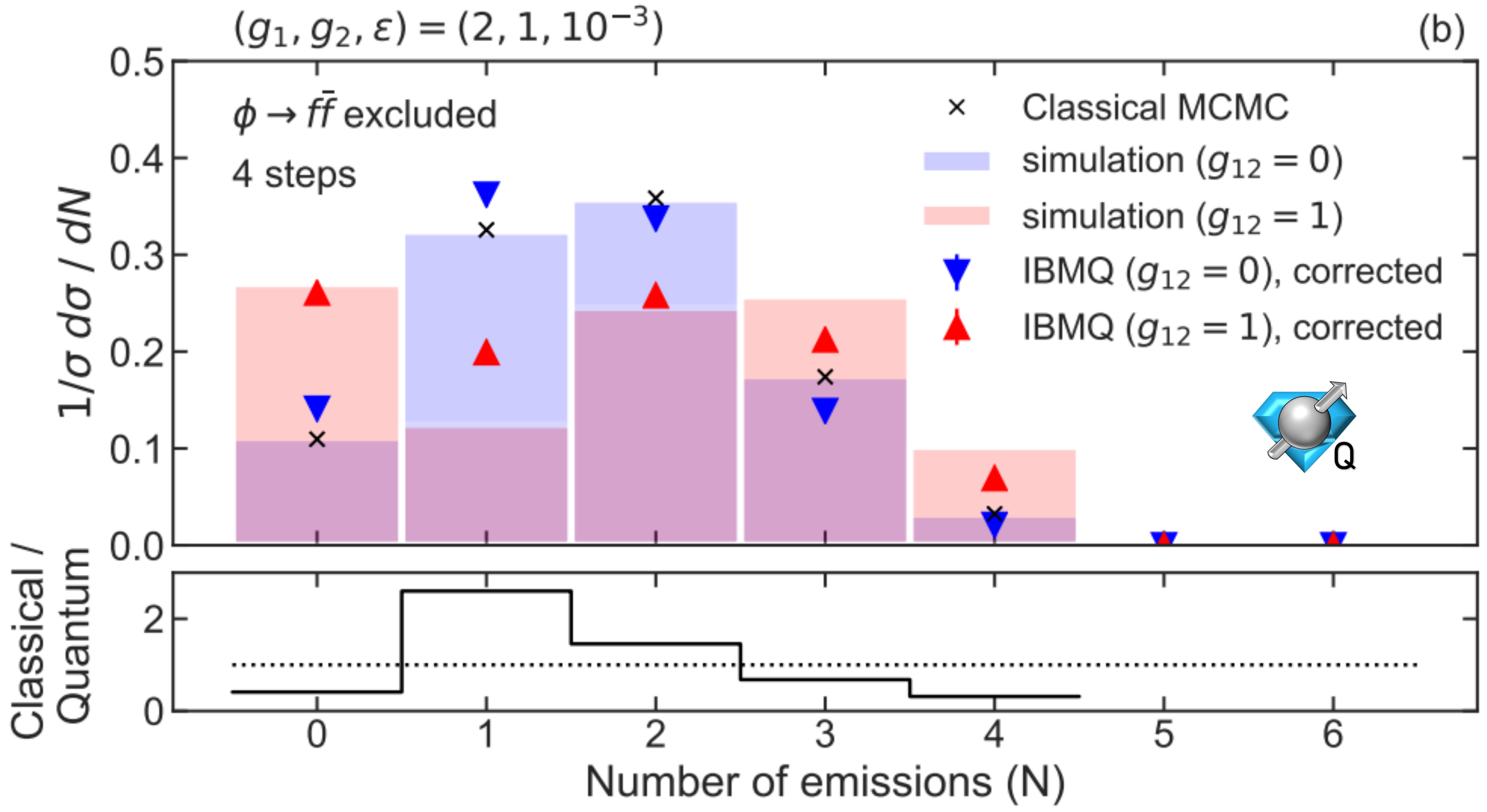
Shaw, Alexander F.[1], Lougovski, Pavel[1], Stryker, Jesse R.[2], and Wiebe, Nathan[3,4]

Quantum 2020-08-10, volume 4, page 306

arXiv:2002.11146v1 [quant-ph]

Fragmentation and Collisions





Deeply inelastic scattering structure functions on a hybrid quantum computer

Niklas Mueller,* Andrey Tarasov,† and Raju Venugopalan‡
Physics Department, Brookhaven National Laboratory, Bldg. 510A, Upton, NY 11973, USA
(Dated: August 21, 2019)

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

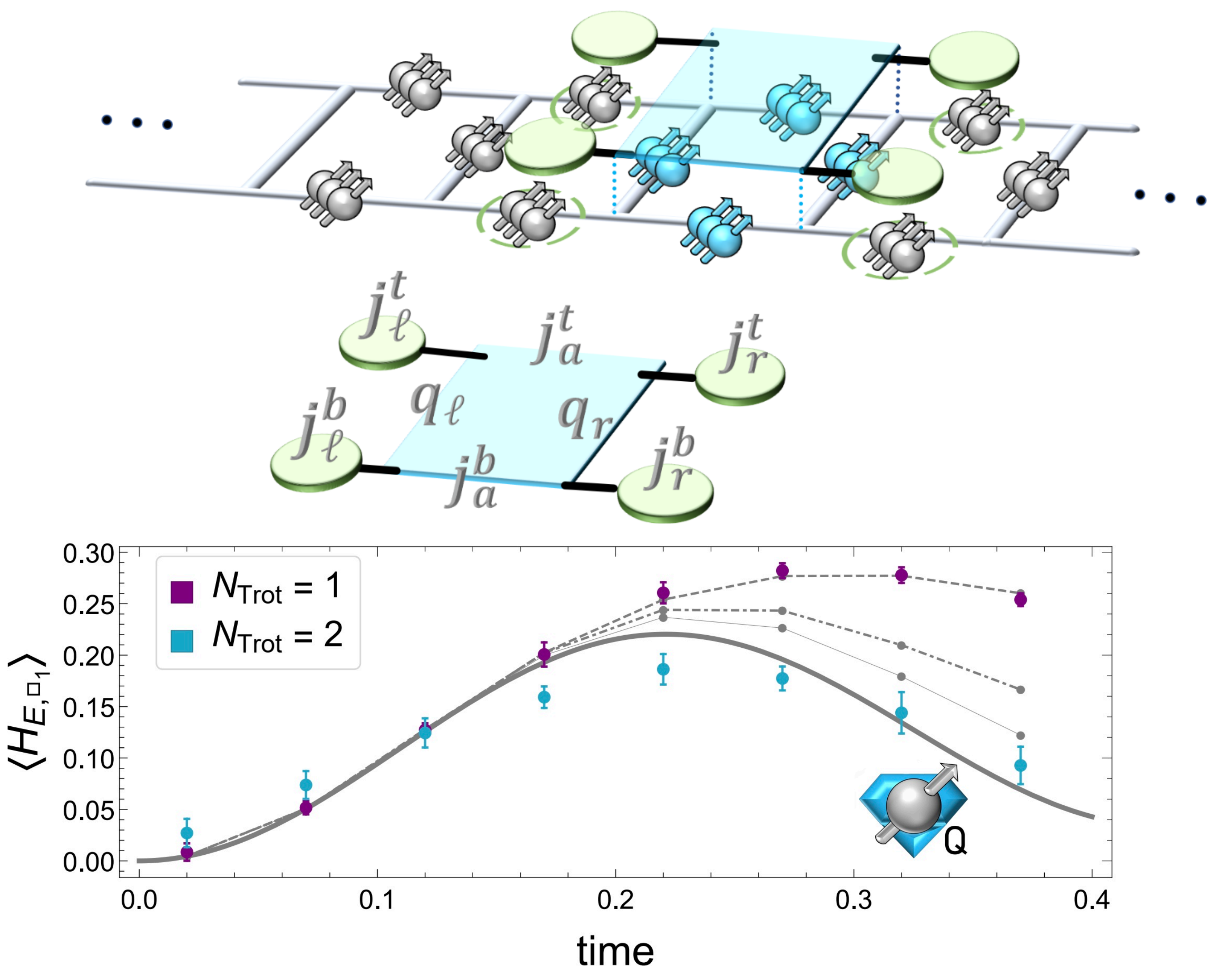
$$\mathcal{L} = \bar{f}_1(i\partial\!\!\!/ + m_1)f_1 + \bar{f}_2(i\partial\!\!\!/ + m_2)f_2 + (\partial_\mu\phi)^2 + g_1\bar{f}_1 f_1\phi + g_2\bar{f}_2 f_2\phi + g_{12}\left[\bar{f}_1 f_2 + \bar{f}_2 f_1\right]\phi\,.$$

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

Parton Physics on a Quantum Computer

Henry Lamm,[1,*] Scott Lawrence,[1,†] and Yukari Yamauchi[1,‡]
(NuQS Collaboration)
[1]*Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
(Dated: February 18, 2020)

SU(2) in low-dimensions



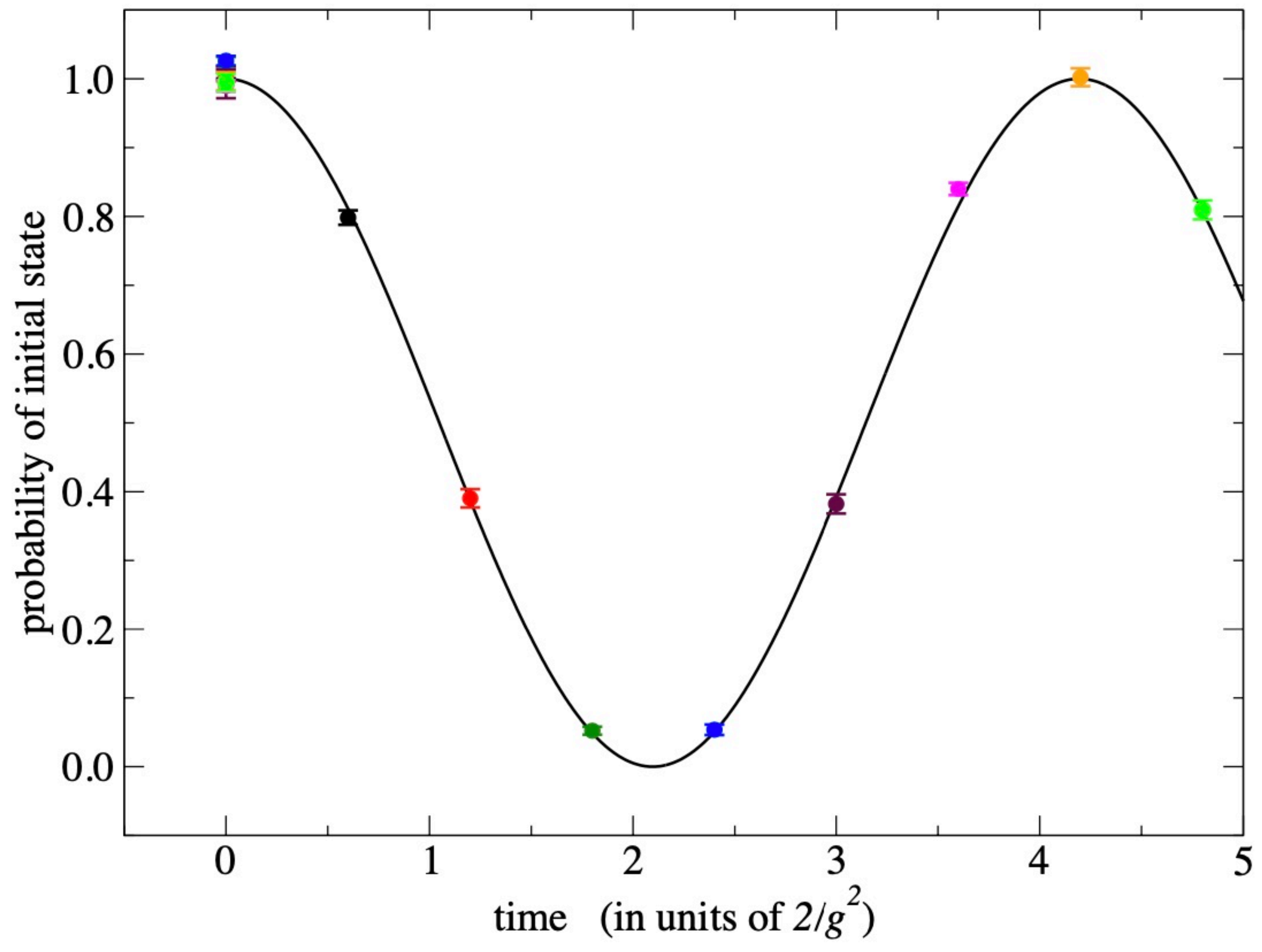
- Only dynamical gauge fields
- Gauge Variant Completions (GVC)
- Severely truncated in field space
- 2D, but really 1D

SU(2) non-Abelian gauge field theory in one dimension on digital quantum computers

Natalie Klco, Jesse R. Stryker and Martin J. Savage[1]

[1] *Institute for Nuclear Theory, University of Washington, Seattle, WA 98195-1550, USA*

(Dated: August 19, 2019 - 13:7)

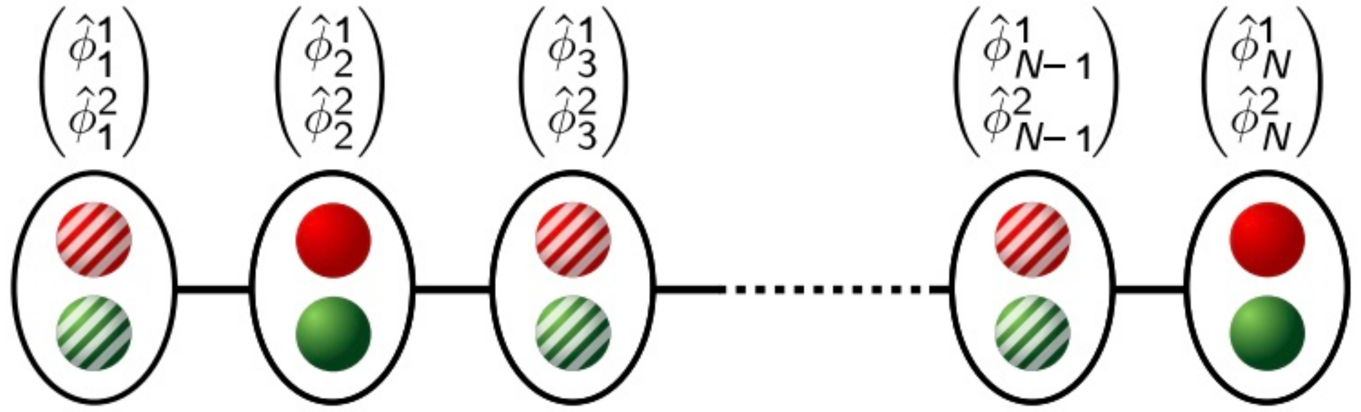


SU(2) lattice gauge theory on a quantum annealer

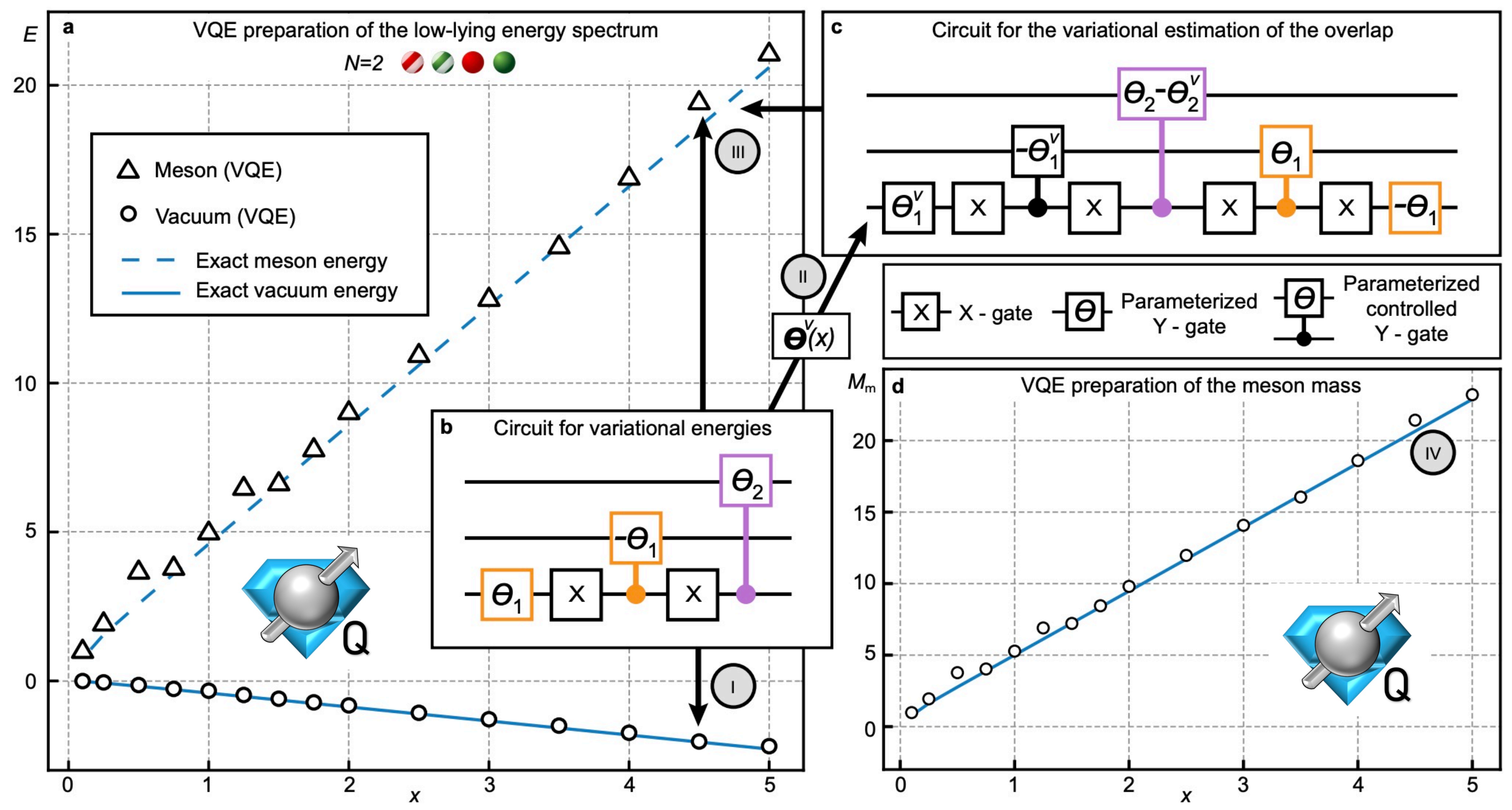
Sarmed A Rahman, Randy Lewis, Emanuele Mendicelli, and Sarah Powell

Department of Physics and Astronomy, York University, Toronto, Ontario, M3J 1P3, Canada

(Dated: August 3, 2021)



- Matter fields
- Non-dynamical gauge fields



SU(2) hadrons on a quantum computer

Yasar Atas *,[1,2,†] Jinglei Zhang *,[1,2,‡] Randy Lewis,[3] Amin Jahanpour,[1,2] Jan F. Haase,[1,2,§] and Christine A. Muschik[1,2,4]

- e-Print: 2102.08920 [quant-ph]

PHYSICAL REVIEW A
covering atomic, molecular, and optical physics and quantum information
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Simulating lattice gauge theories on a quantum computer

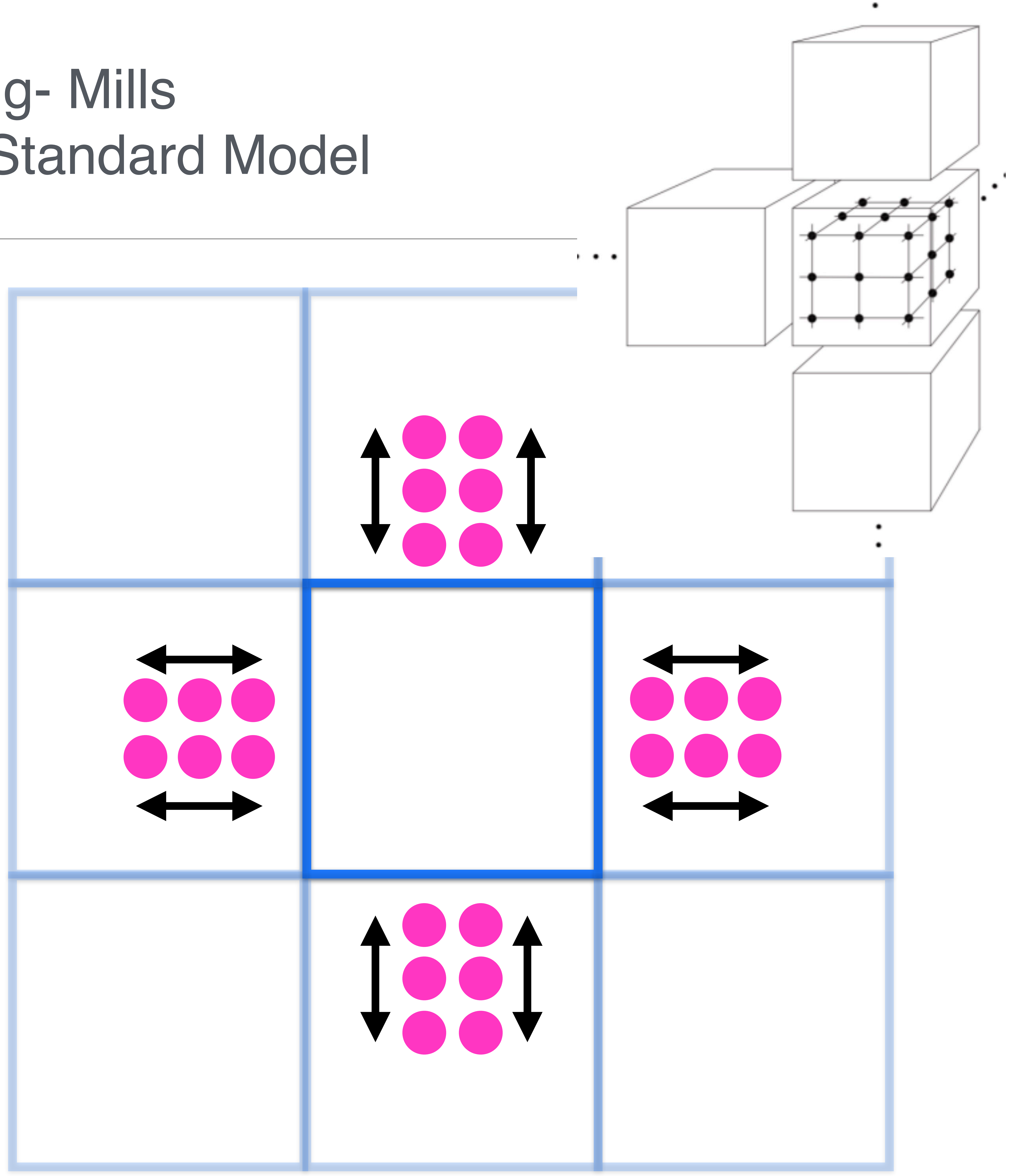
Tim Byrnes and Yoshihisa Yamamoto
Phys. Rev. A **73**, 022328 – Published 17 February 2006

Yang- Mills
Toward the Standard Model

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

$$|p, q, T_L, T^z_L, Y_L, T_R, T^z_R, Y_R\rangle$$

- p and q define the number of up and down indices in a tensor representation of a color irrep.
- T,Y are isospin and hypercharge quantum numbers in left and right hand vertices joined by the link.
- state products (CG) are BQP (Bacon, Chuang, Harrow (06))
- Gauss's Law enforced by the Hamiltonian Structure (and EC)
- Local Gauge Invariance - only p,q, entangled between sites



SU(2) non-Abelian gauge field theory in one dimension on digital quantum computers

Natalie Klco, Martin J. Savage, and Jesse R. Stryker
Phys. Rev. D **101**, 074512 – Published 21 April 2020

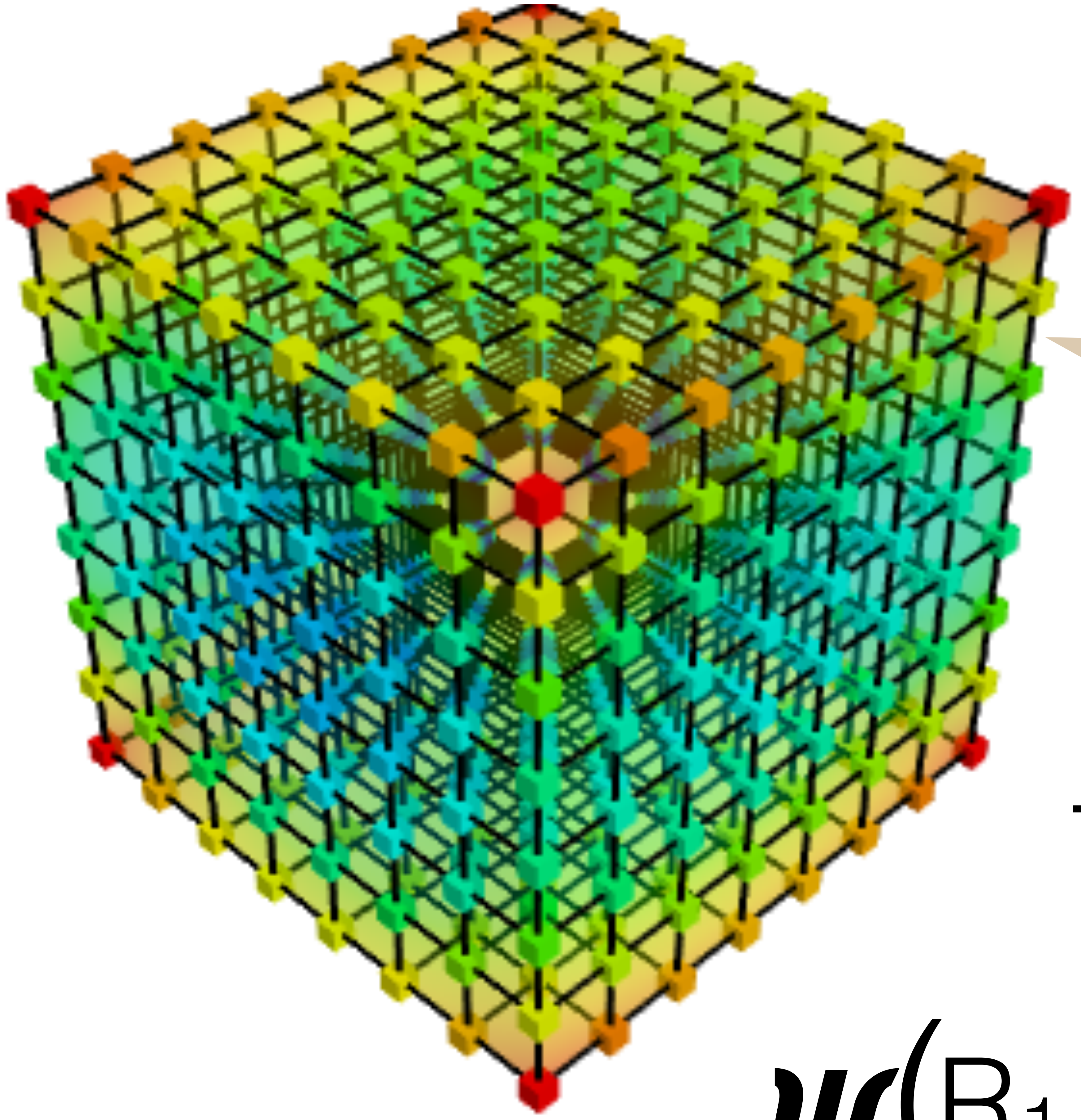
Trailhead for quantum simulation of SU(3) Yang-Mills lattice gauge theory in the local multiplet basis

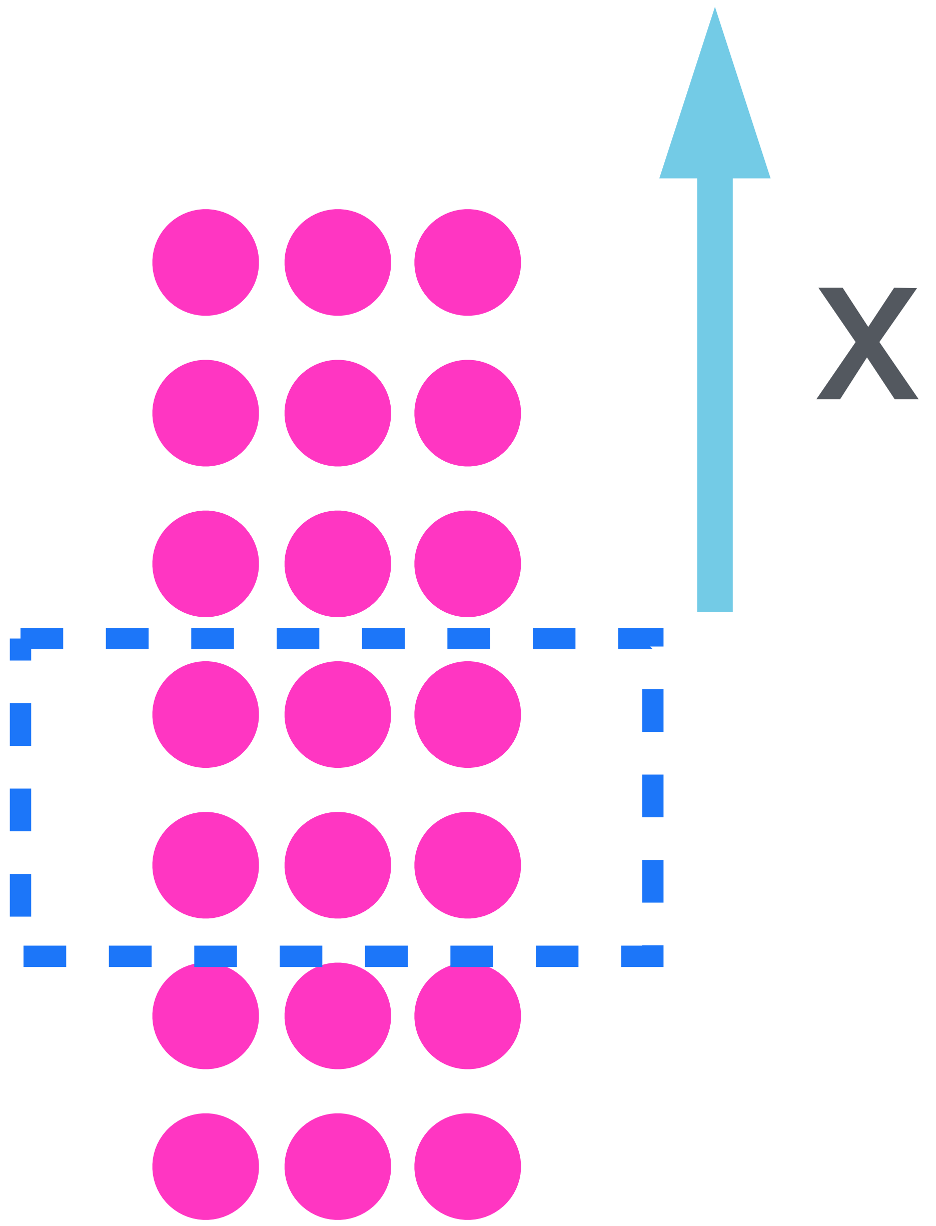
Anthony Ciavarella, Natalie Klco, and Martin J. Savage
Phys. Rev. D **103**, 094501 – Published 4 May 2021

Pure Yang-Mills

Natalie Klco, Jesse Stryker, Anthony Ciavarella

IQuS InQubator for Quantum Simulation





One of a number of frameworks

Color Irrep space truncated

SU(3) links in "angular momentum" space

Kogut-Susskind Hamiltonian

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

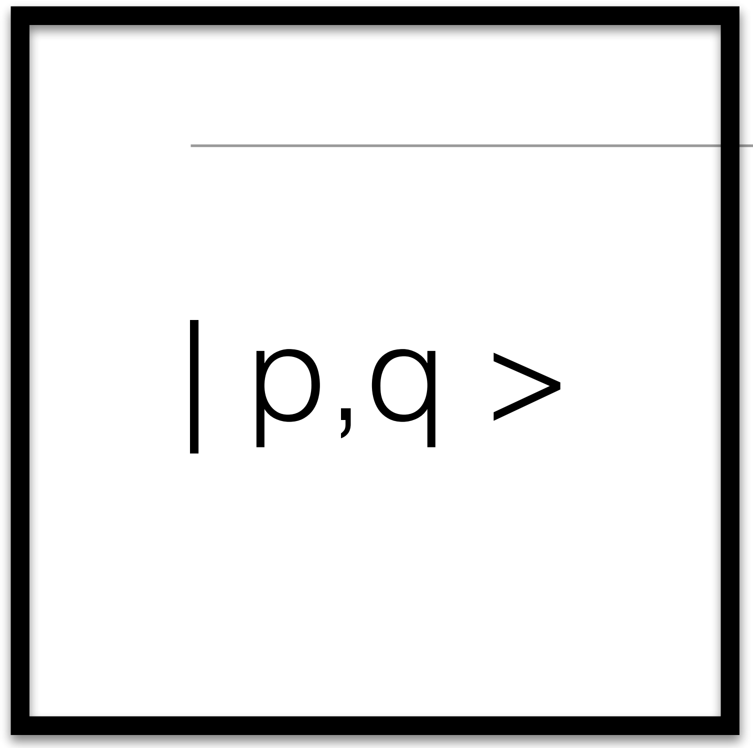
$$T^{a_1\ldots a_p}_{b_1\ldots b_q} \xrightarrow[\text{Gauge Invariance}]{} R(p,q)$$

Also see Mari Carmen Banuls, Karl Jansens et al

$$\psi\left(R_1\,, R_2 \qquad R_{L3}\right)$$

Trailhead for quantum simulation of SU(3) Yang-Mills lattice gauge theory in the local multiplet basis
Anthony Ciavarella, Natalie Klco, and Martin J. Savage
Phys. Rev. D **103**, 094501 – Published 4 May 2021

SU(3) - 1-Plaquette

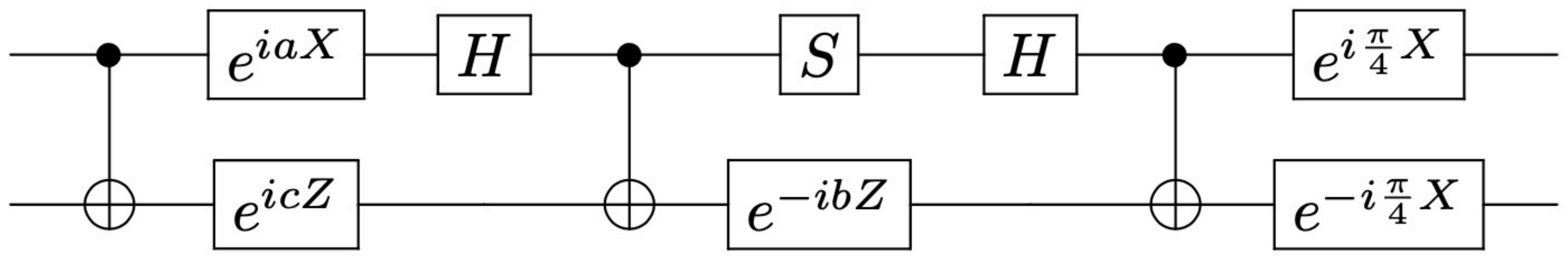


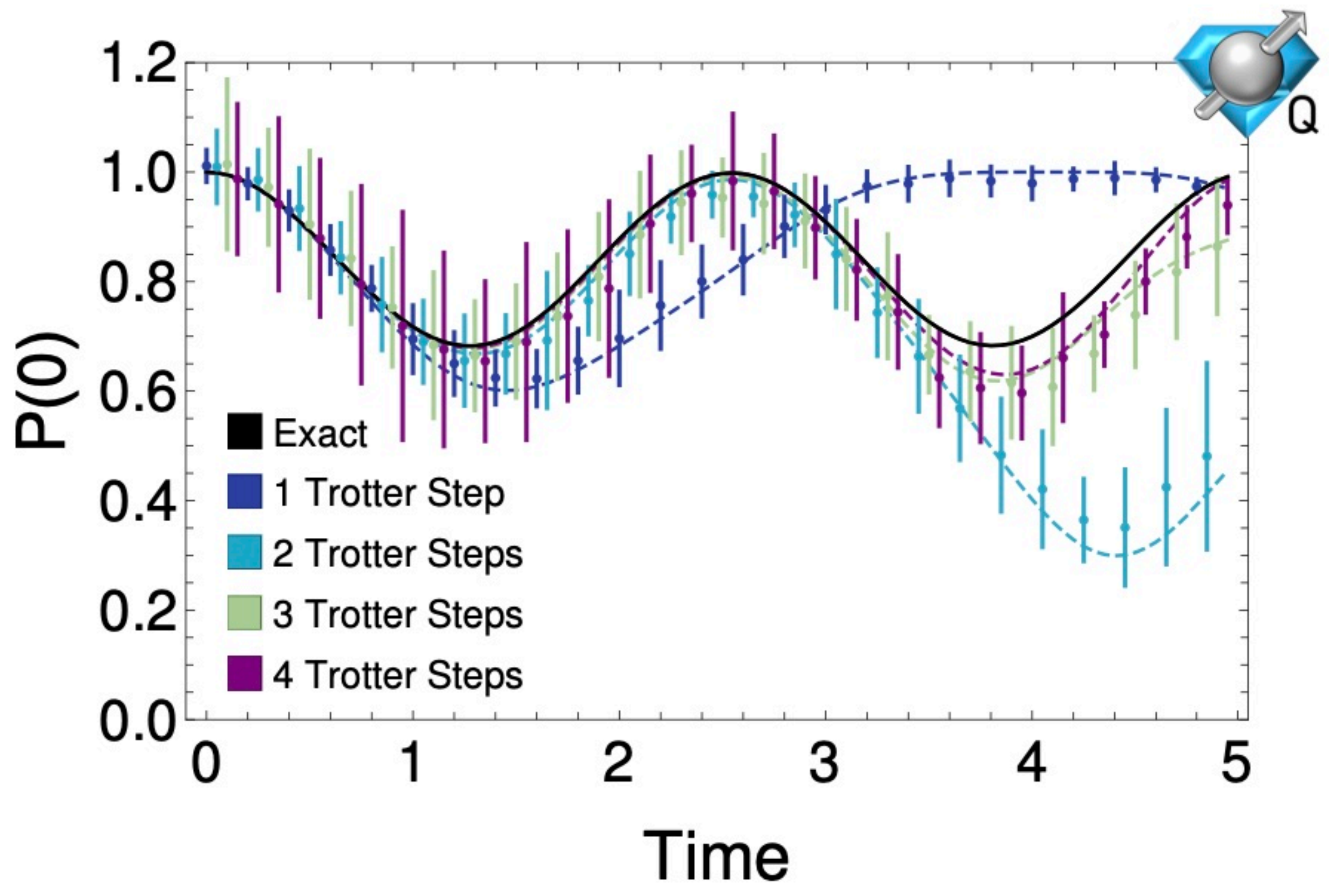
$$\hat{H} = \frac{g^2}{2}\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \frac{16}{3} & 0 & 0 \\ 0 & 0 & \frac{16}{3} & 0 \\ 0 & 0 & 0 & 12 \end{pmatrix} + \frac{1}{g^2}\left(3\,\hat{\mathbb{I}} - \frac{1}{2}\begin{pmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{pmatrix}\right)$$

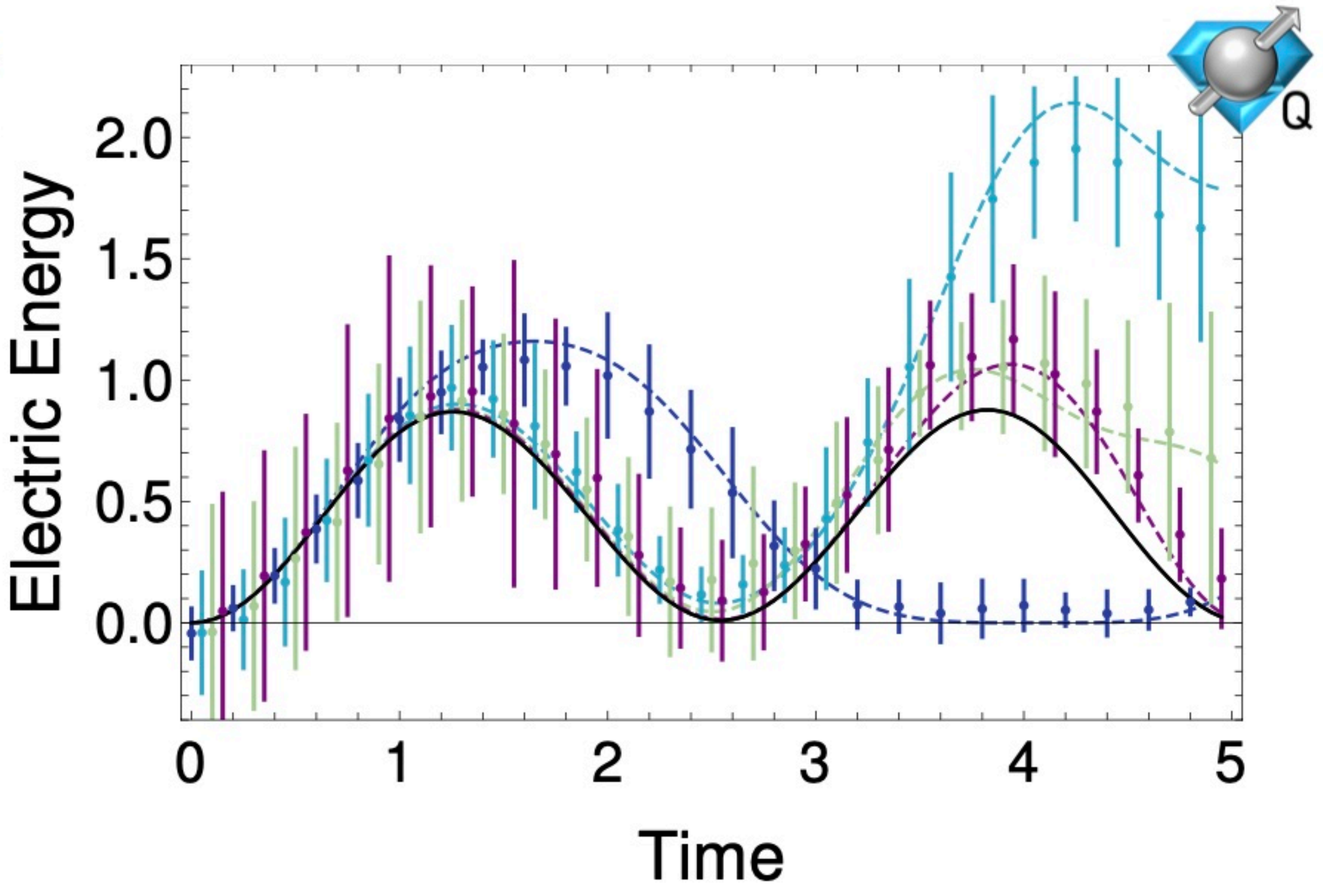
$$\hat{H}_1 = \left(\frac{17g^2}{6} + \frac{3}{g^2}\right)\hat{\mathbb{I}}\otimes\hat{\mathbb{I}} - \frac{g^2}{6}\left(9\ \hat{Z}\otimes\hat{\mathbb{I}} + 9\ \hat{\mathbb{I}}\otimes\hat{Z}\right) - \frac{1}{2g^2}\left(\hat{X}\otimes\hat{\mathbb{I}} + \hat{\mathbb{I}}\otimes\hat{X}\right)$$

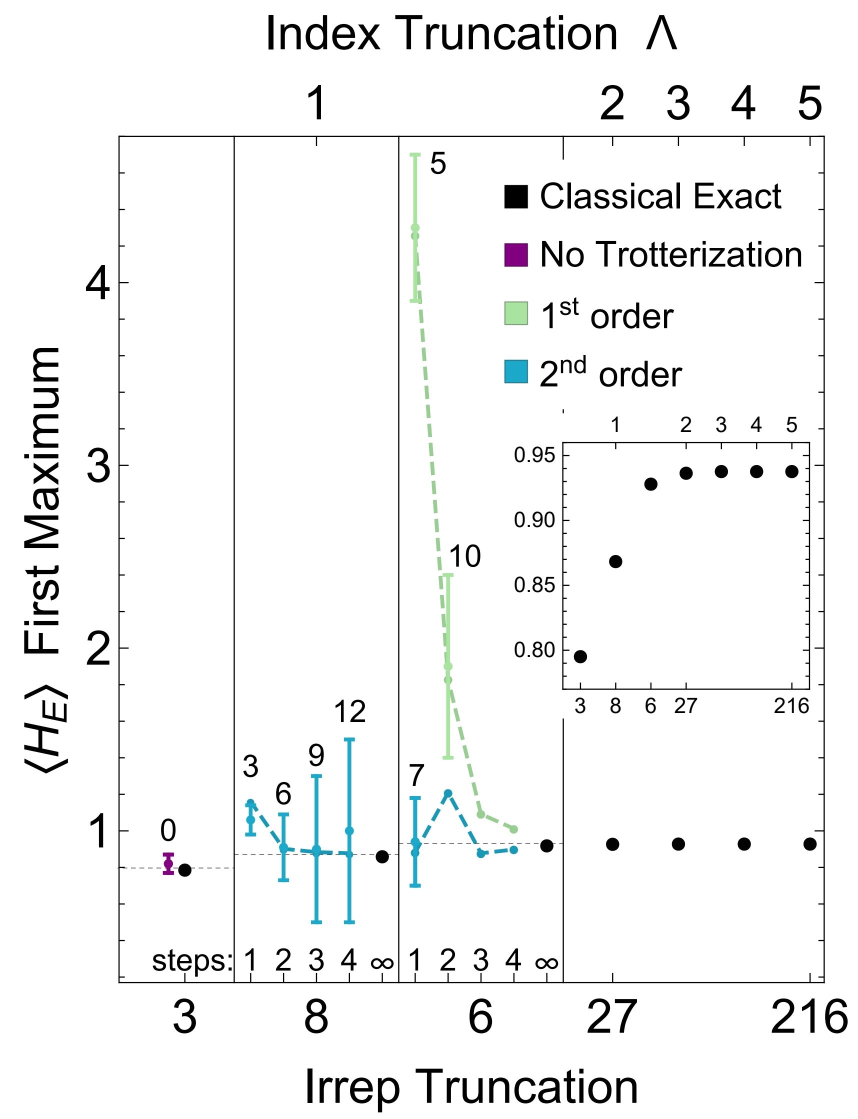
$$\hat{H}_2 = \frac{g^2}{6}\hat{Z}\otimes\hat{Z} - \frac{1}{4g^2}\left(\hat{X}\otimes\hat{X} + \hat{Y}\otimes\hat{Y}\right) \quad .$$

$$e^{i(a\hat{X}\otimes\hat{X}+b\hat{Y}\otimes\hat{Y}+c\hat{Z}\otimes\hat{Z})} =$$





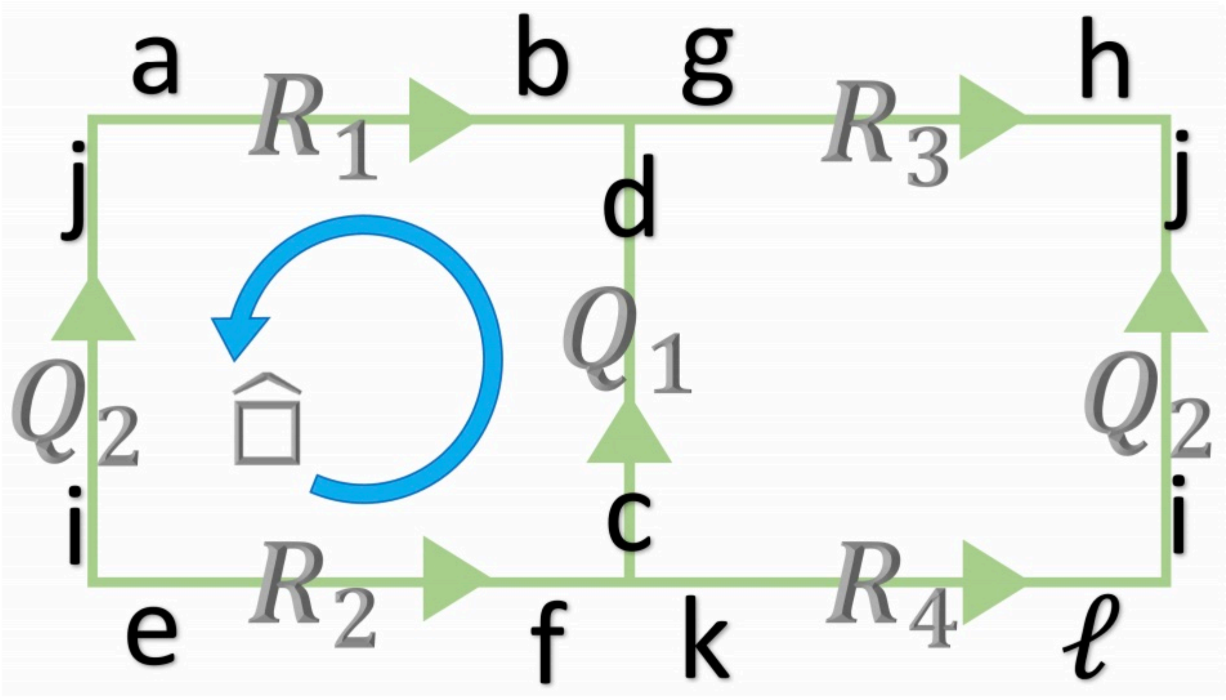




Trailhead for quantum simulation of SU(3) Yang-Mills lattice gauge theory in the local multiplet basis

Anthony Ciavarella, Natalie Klco, and Martin J. Savage
Phys. Rev. D **103**, 094501 – Published 4 May 2021

2-Plaquettes - Global



$|\chi(\mathbf{R_1}, \mathbf{Q_1}, \mathbf{R_2}, \mathbf{R_3}, \mathbf{Q_2}, \mathbf{R_4})\rangle$

Including $\underline{\mathbf{1}}$, $\underline{\mathbf{3}}$, $\underline{\overline{\mathbf{3}}}$, $\underline{\mathbf{8}}$ on each link only

$$|\psi_1^{(\mathbf{13\bar{3}8};+++)}\rangle = |\chi(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})\rangle \quad ,$$

$$|\psi_{2a}^{(\mathbf{13\bar{3}8};+++)}\rangle = \frac{1}{2}\left[\, |\chi(\mathbf{3},\bar{\mathbf{3}},\bar{\mathbf{3}},\mathbf{1},\mathbf{3},\mathbf{1})\rangle + |\chi(\bar{\mathbf{3}},\mathbf{3},\mathbf{3},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})\rangle + |\chi(\mathbf{1},\mathbf{3},\mathbf{1},\mathbf{3},\bar{\mathbf{3}},\bar{\mathbf{3}})\rangle + |\chi(\mathbf{1},\bar{\mathbf{3}},\mathbf{1},\bar{\mathbf{3}},\mathbf{3},\mathbf{3})\rangle \,\right]$$

$$|\psi_{2b}^{(\mathbf{13\bar{3}8};+++)}\rangle = \frac{1}{\sqrt{2}}\left[\, |\chi(\mathbf{3},\mathbf{1},\bar{\mathbf{3}},\mathbf{3},\mathbf{1},\bar{\mathbf{3}})\rangle + |\chi(\bar{\mathbf{3}},\mathbf{1},\mathbf{3},\bar{\mathbf{3}},\mathbf{1},\mathbf{3})\rangle \,\right] \quad ,$$

$$|\psi_3^{(\mathbf{13\bar{3}8};+++)}\rangle = \frac{1}{\sqrt{2}}\left[\, |\chi(\mathbf{8},\mathbf{1},\mathbf{1},\mathbf{8},\mathbf{1},\mathbf{1})\rangle + |\chi(\mathbf{1},\mathbf{1},\mathbf{8},\mathbf{1},\mathbf{1},\mathbf{8})\rangle \,\right] \quad ,$$

$$\vdots$$

$$|\psi_9^{(\mathbf{13\bar{3}8};+++)}\rangle = |\chi(\mathbf{8},\mathbf{8},\mathbf{8},\mathbf{8},\mathbf{8},\mathbf{8})\rangle$$

Keeping states with Casimir above 6-threshold includes only part of that higher-energy space

- 15 basis states (4 qubits)
- Max electric energy ~ 6*3
- 8 ⊗ 8 ⊗ 8

Efficient Representation for Simulating U(1) Gauge Theories on Digital Quantum Computers at All Values of the Coupling

Christian W. Bauer[1,*] and Dorota M. Grabowska[2,†]

[1] *Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[2] *Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland*

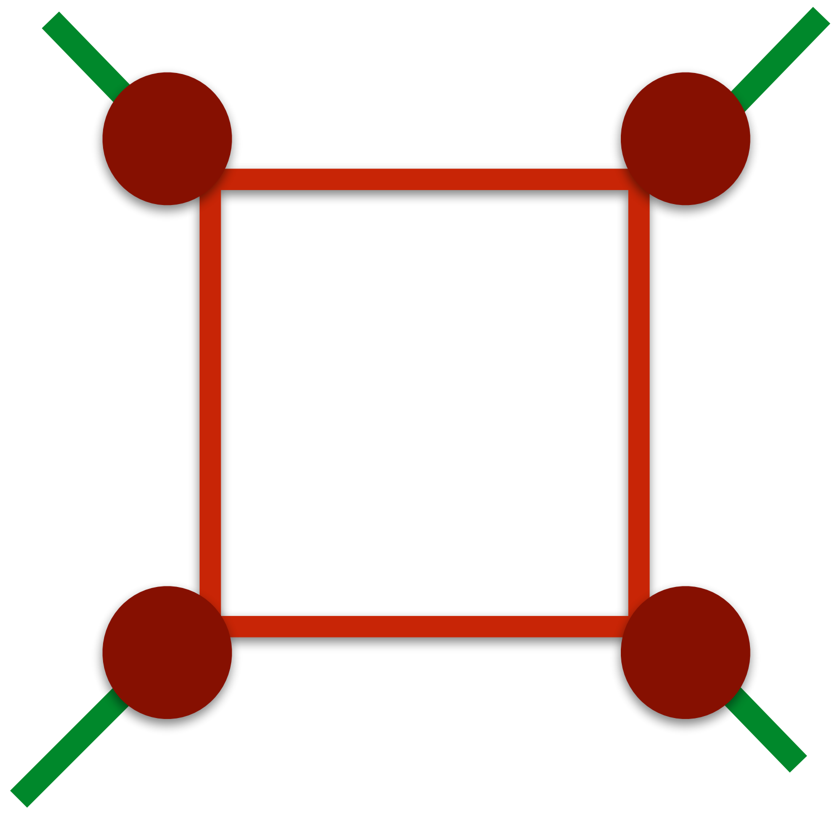
(Dated: November 17, 2021)

Trailhead for quantum simulation of SU(3) Yang-Mills lattice gauge theory in the local multiplet basis

Anthony Ciavarella, Natalie Klco, and Martin J. Savage

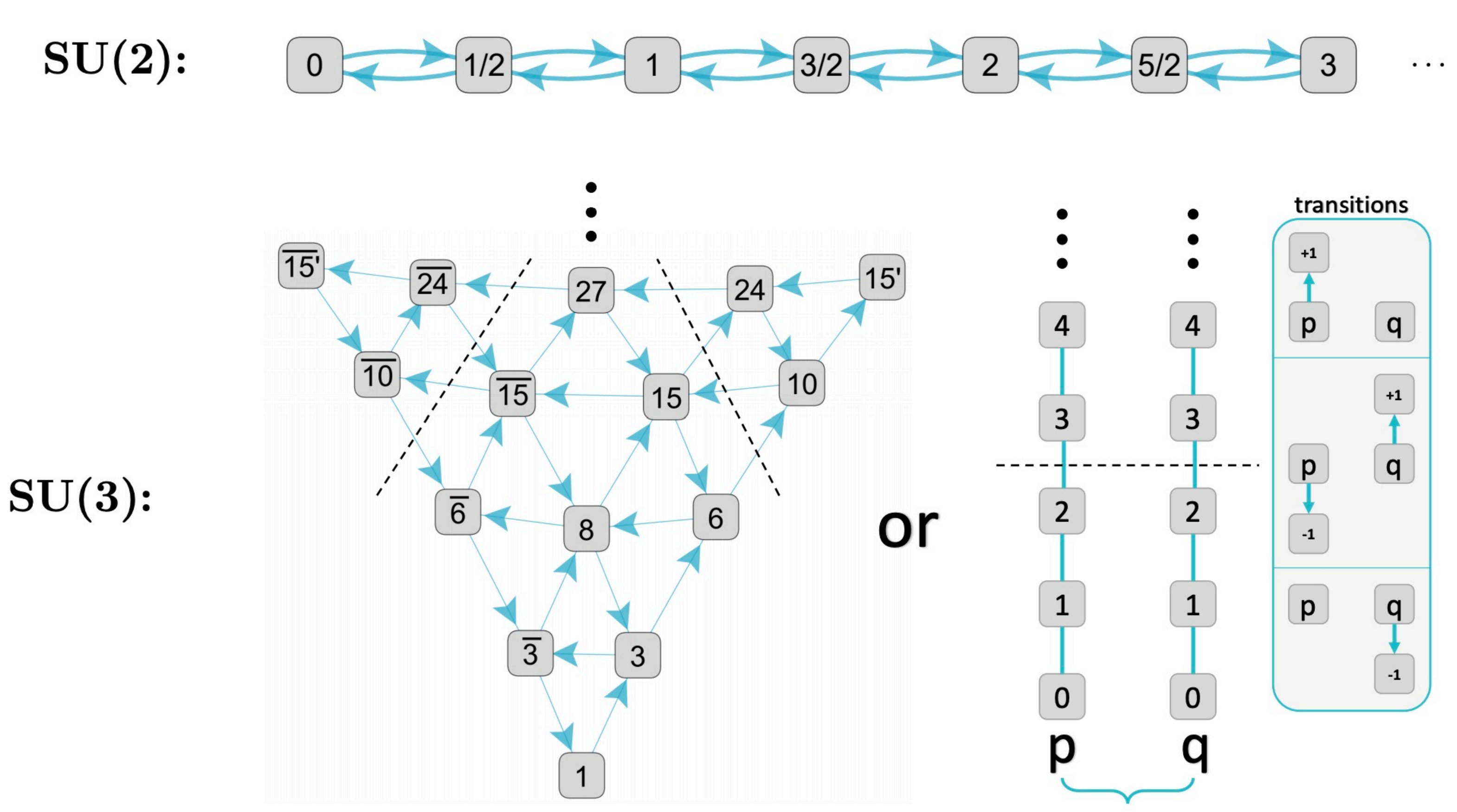
Phys. Rev. D **103**, 094501 – Published 4 May 2021

SU(3) Kogut-Susskind Classical/Quantum Resources



$\Lambda_p = \Lambda_q$	dimensions	physical states	matrix elements	elements/states
1	$(\mathbf{1}, \mathbf{3})$	81	81	1
1	$(\mathbf{1}, \mathbf{3}, \mathbf{8})$	529	1,018	1.92
2	$(\mathbf{1}, \mathbf{3}, \mathbf{8}, \mathbf{6})$	5,937	19,594	3.30
2	$(\mathbf{1}, \mathbf{3}, \mathbf{8}, \mathbf{6}, \mathbf{15})$	59,737	419,316	7.02
2	$(\mathbf{1}, \mathbf{3}, \mathbf{8}, \mathbf{6}, \mathbf{15}, \mathbf{27})$	139,317	1,049,931	7.54
3	$(\mathbf{1}, \mathbf{3}, \mathbf{8}, \mathbf{6}, \mathbf{15}, \mathbf{27}, \mathbf{10})$	509,271	4,001,111	7.86
3	$(\mathbf{1}, \mathbf{3}, \mathbf{8}, \mathbf{6}, \mathbf{15}, \mathbf{27}, \mathbf{10}, \mathbf{24})$	2,008,297	24,648,819	12.27

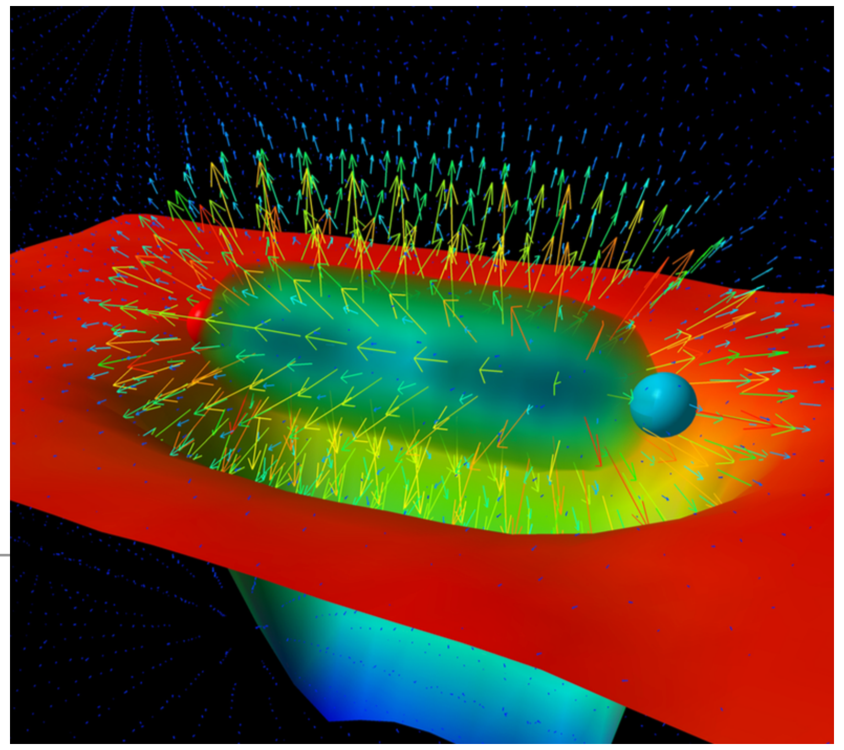
TABLE III. Properties of the plaquette operator truncated in the local index (p, q) basis and at intermediate truncations organized by dimension. The number of physical states constituting the gauge-invariant basis of the plaquette operator, as well as the number of non-zero matrix elements within the physical subspace are presented. The ratio of these two quantities is shown in the right column.



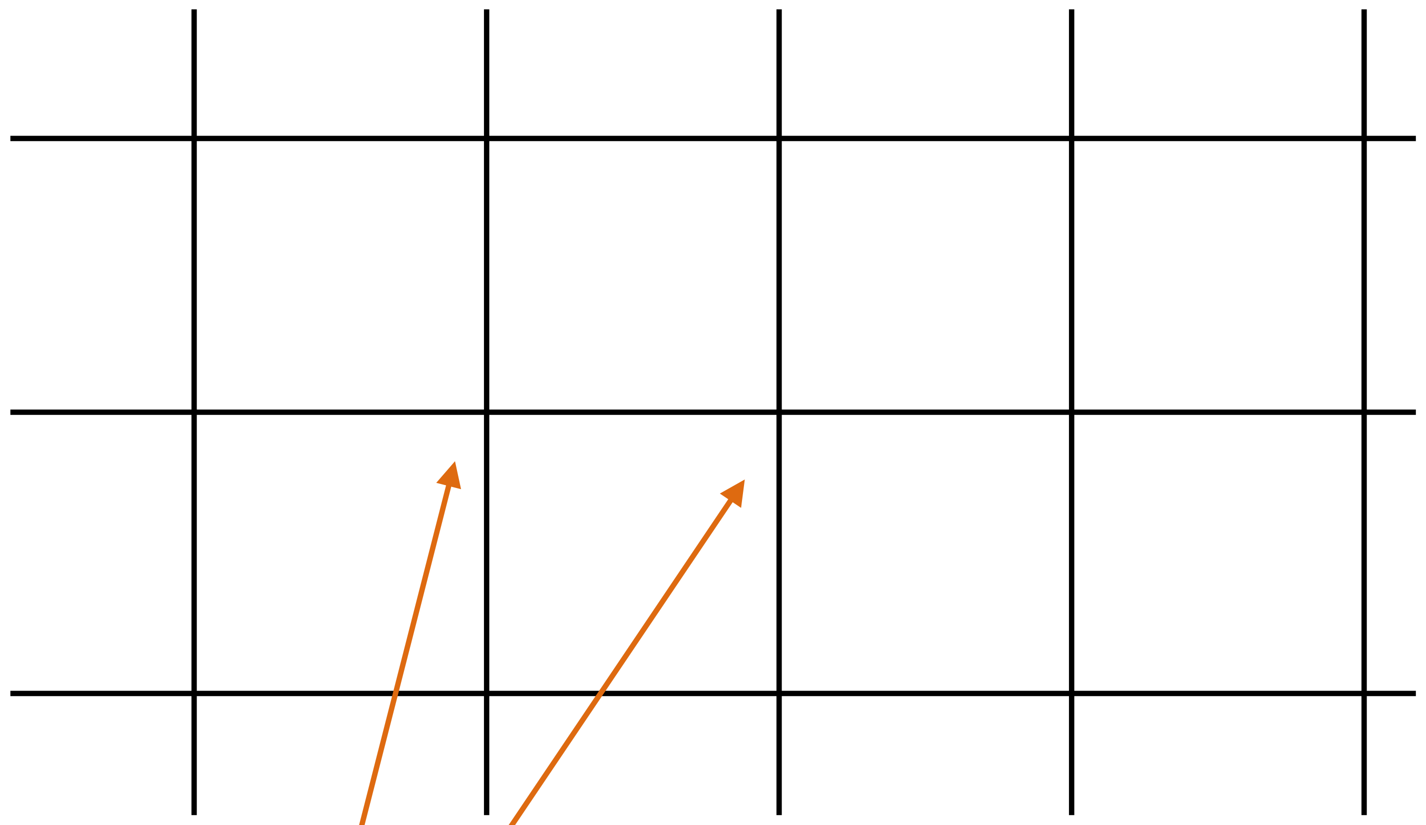
Exponential convergence in field space

Number of singlets ~ Cut-off ^(2 nR)

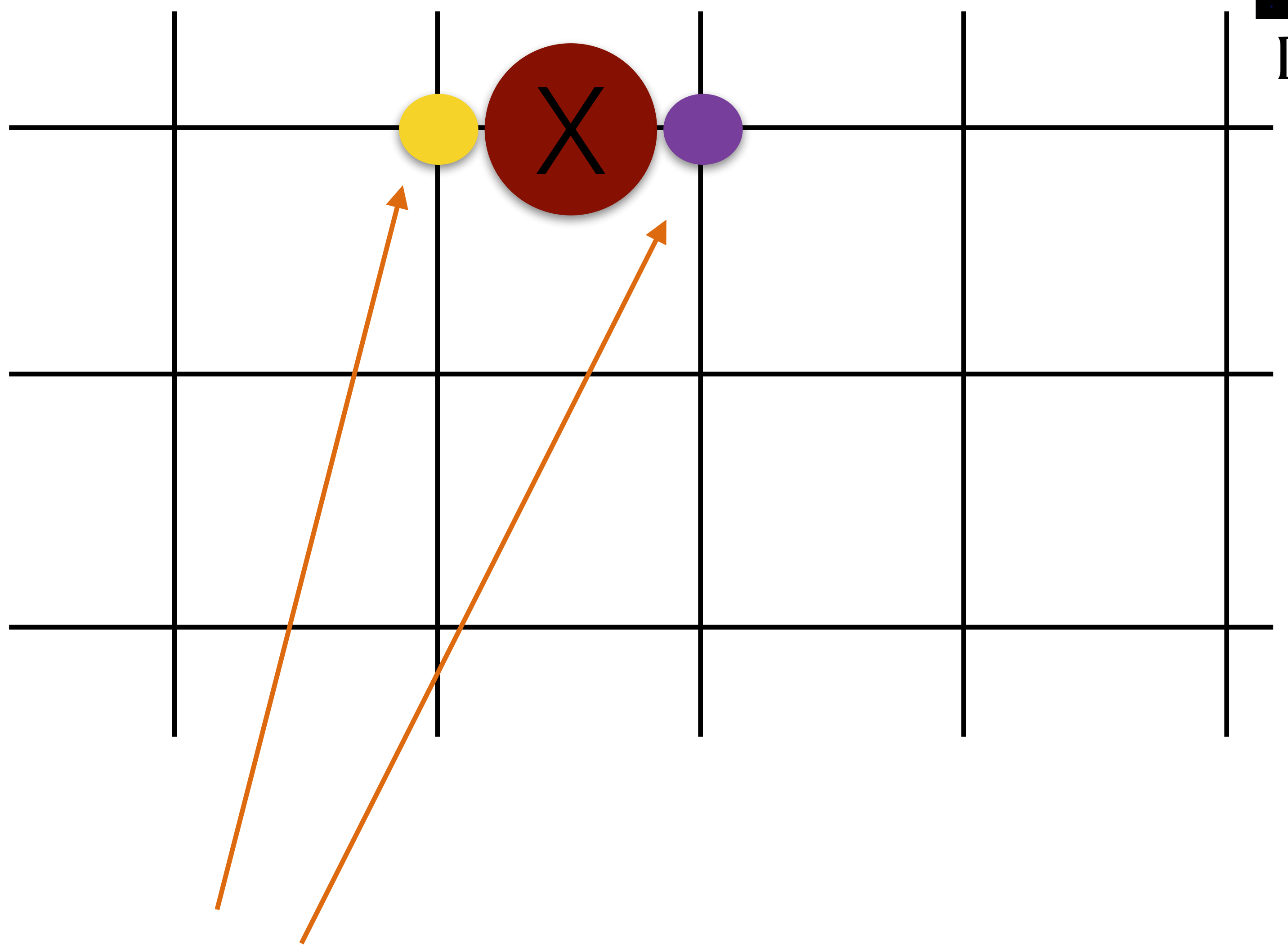
Errors in Standard Model Simulations


Derek Leinweber

Color = **1, 3, $\bar{\mathbf{3}}$, 8, 6, $\bar{\mathbf{6}}$, ...**



Gauss's Law satisfied at each vertex,
Color = **1** (singlet)



Gauss's Law violated

- Confinement will keep color charges "close" during dynamics - naively easier than EC for 3-dim QED

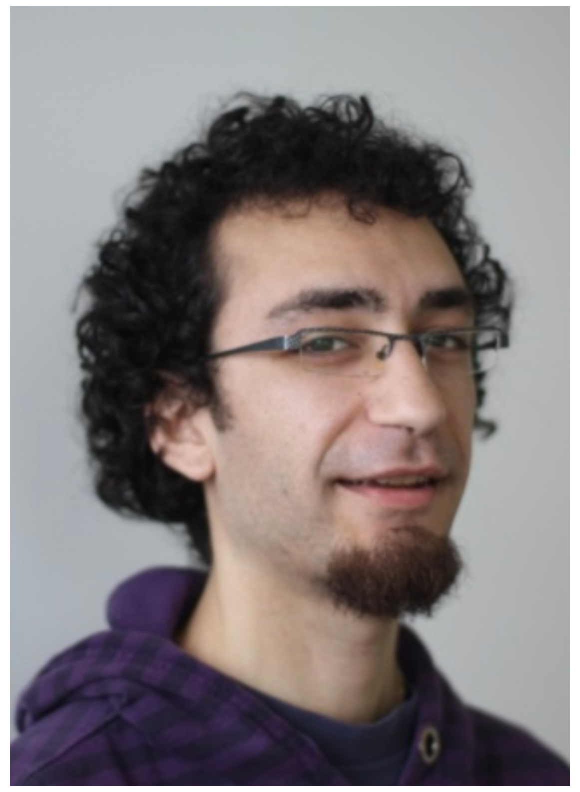
- Single shot EC
- Related to topologically-ordered GSs at finite-T.

PHYSICAL REVIEW X **5,** 031043 (2015)

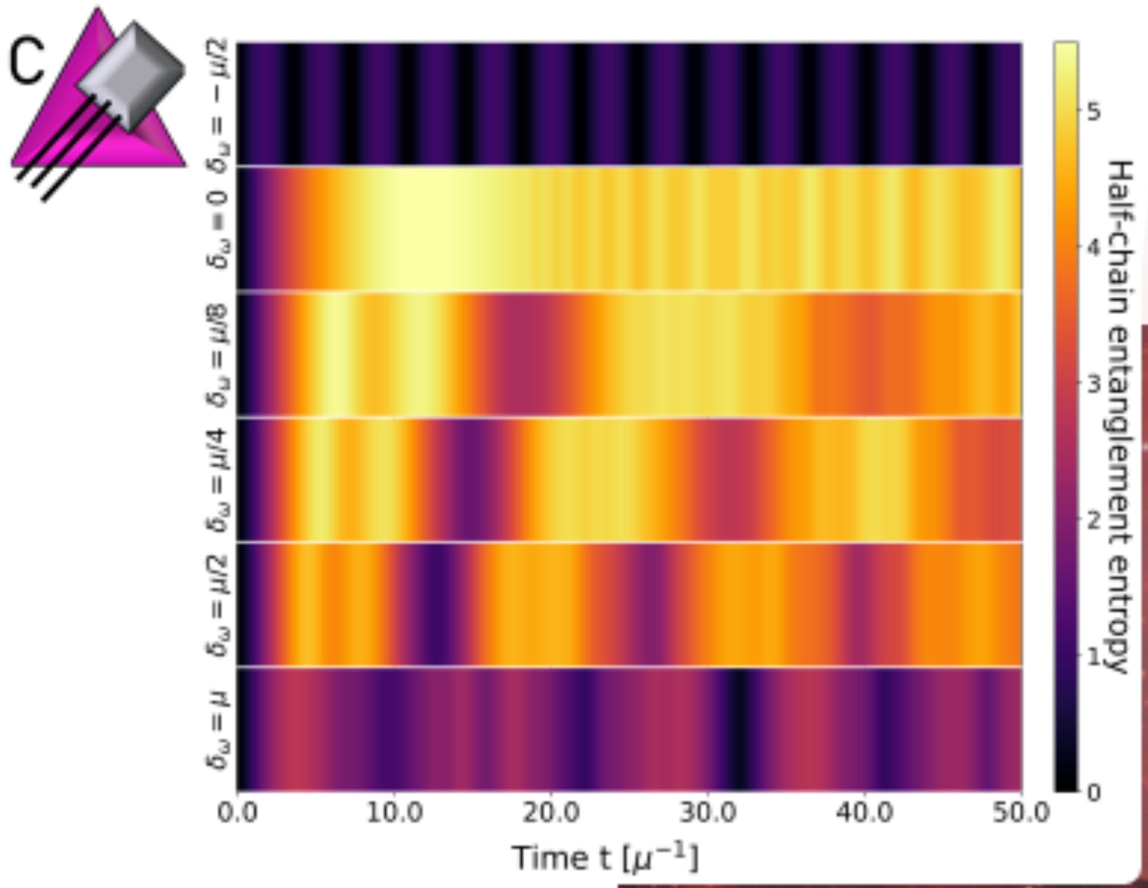
Single-Shot Fault-Tolerant Quantum Error Correction

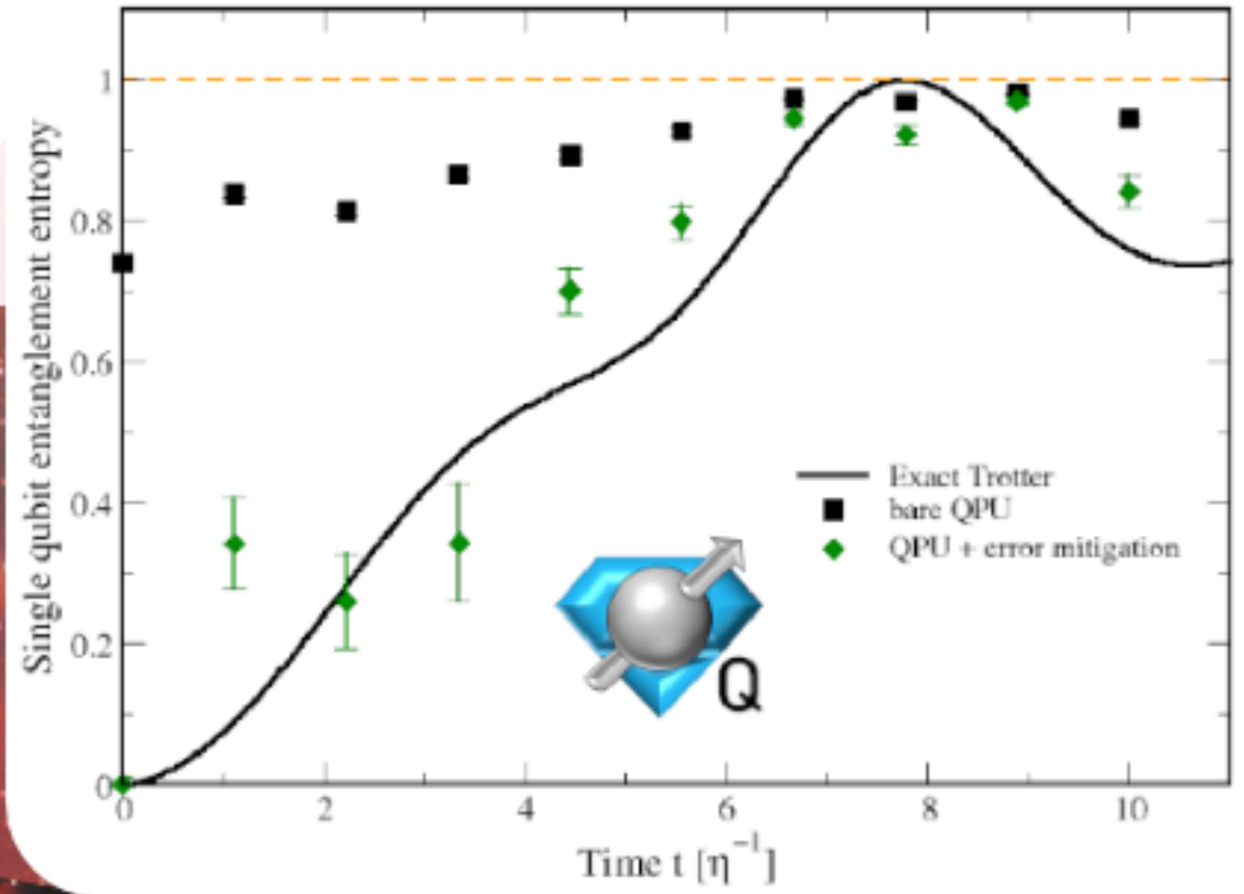
Héctor Bombín

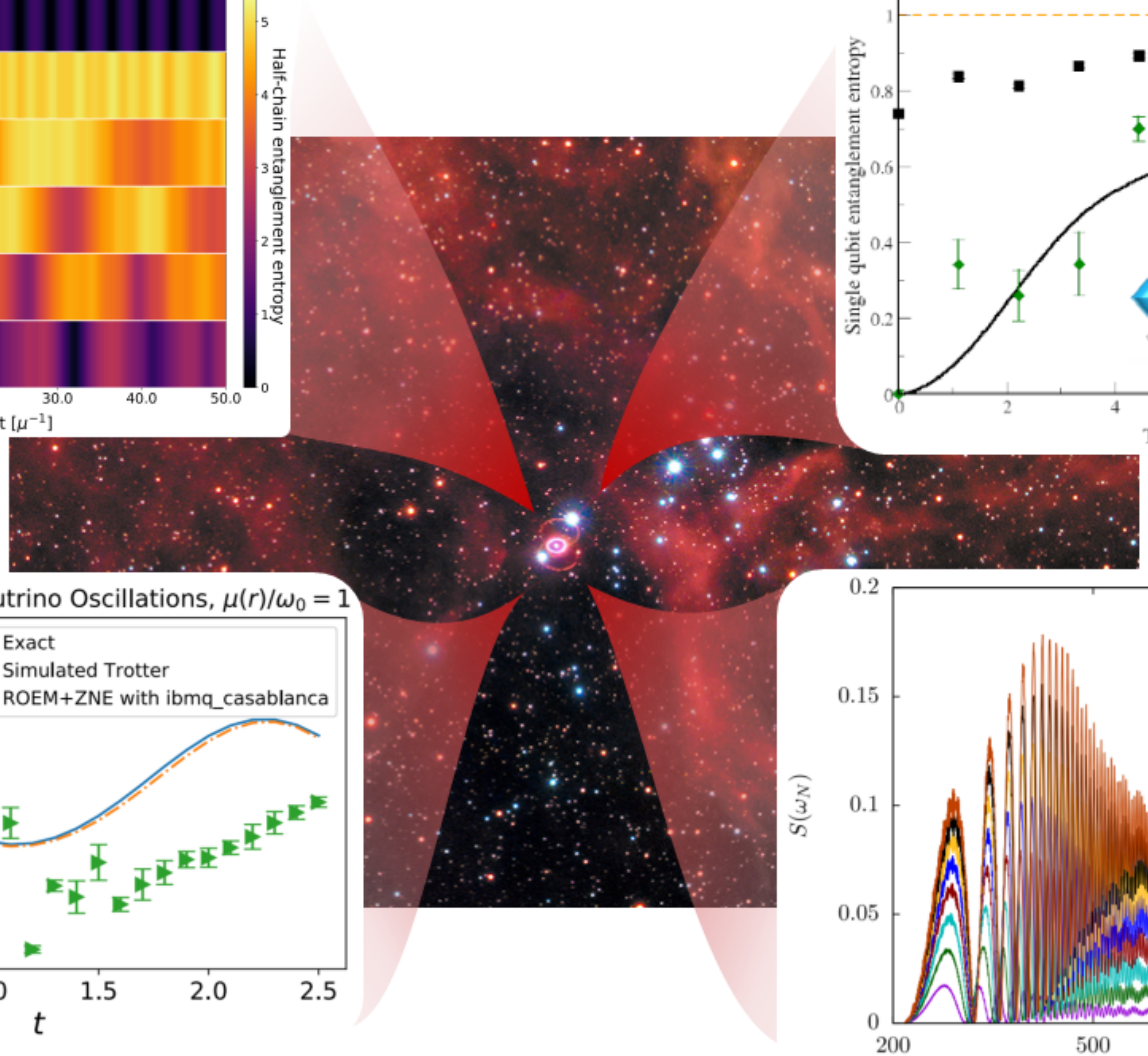
Neutrinos

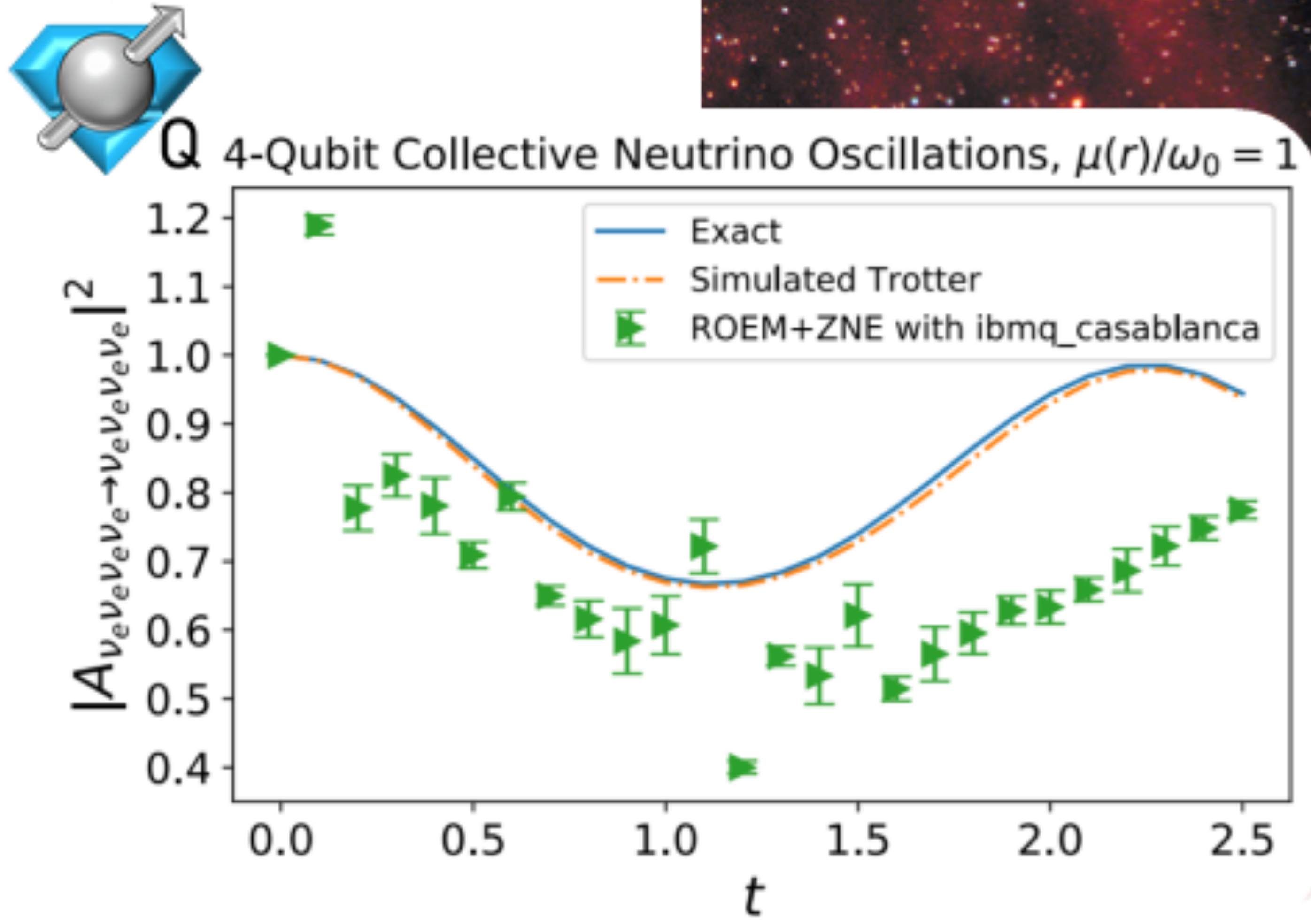


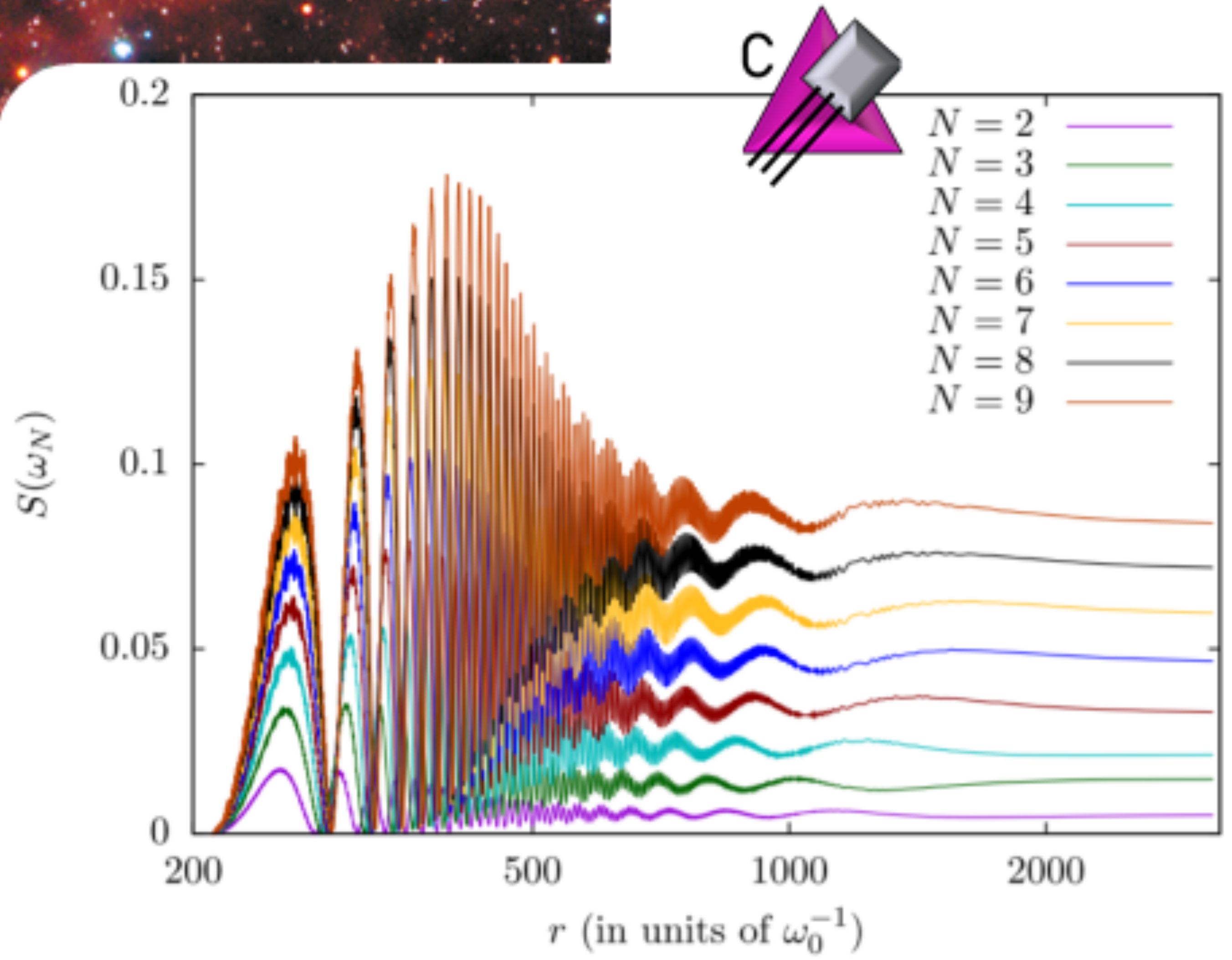
Alessandro Roggero











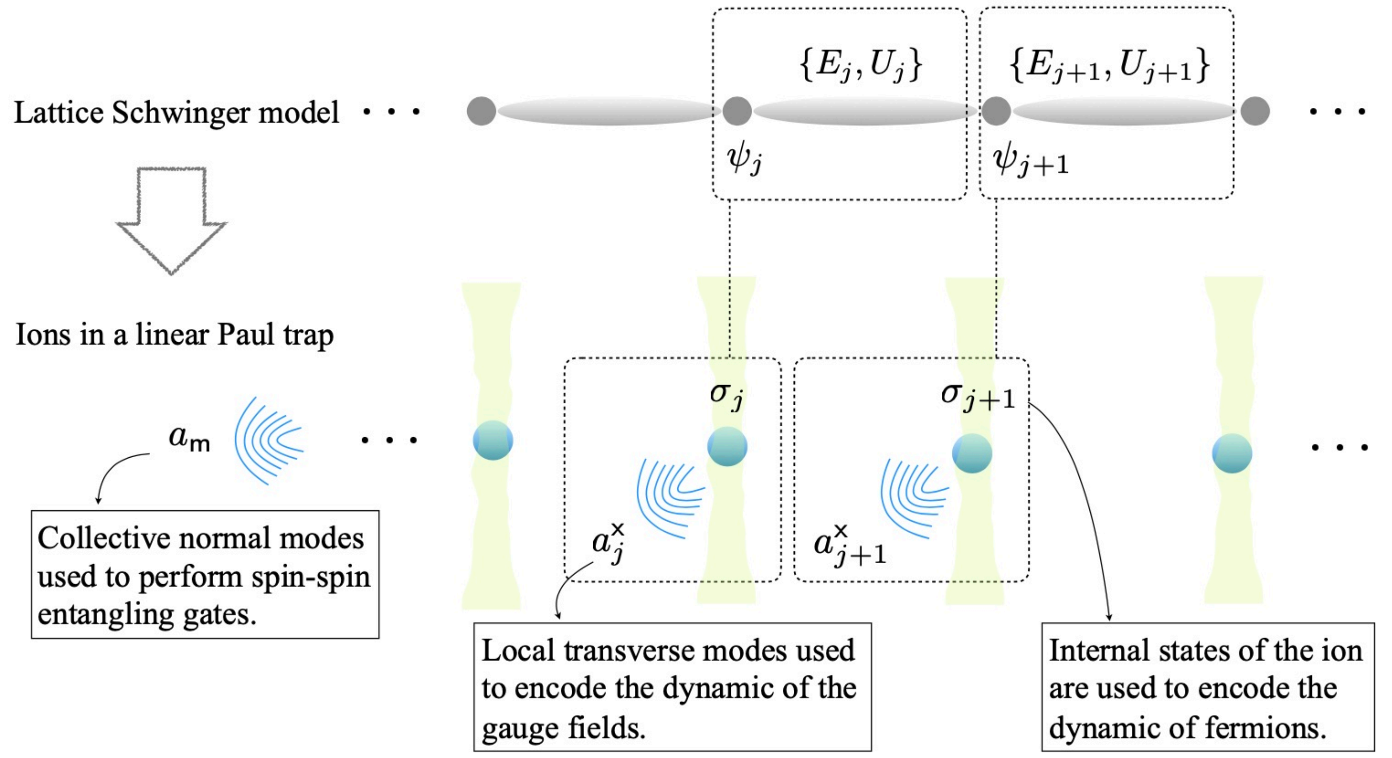
$$H_{FS} = -\sum_{k=1}^{N} \frac{\omega_k}{2} \sigma_k^z + \frac{\mu}{2N} \sum_{i<j}^{N} \mathcal{J}_{ij} \vec{\sigma}_i \cdot \vec{\sigma}_j$$

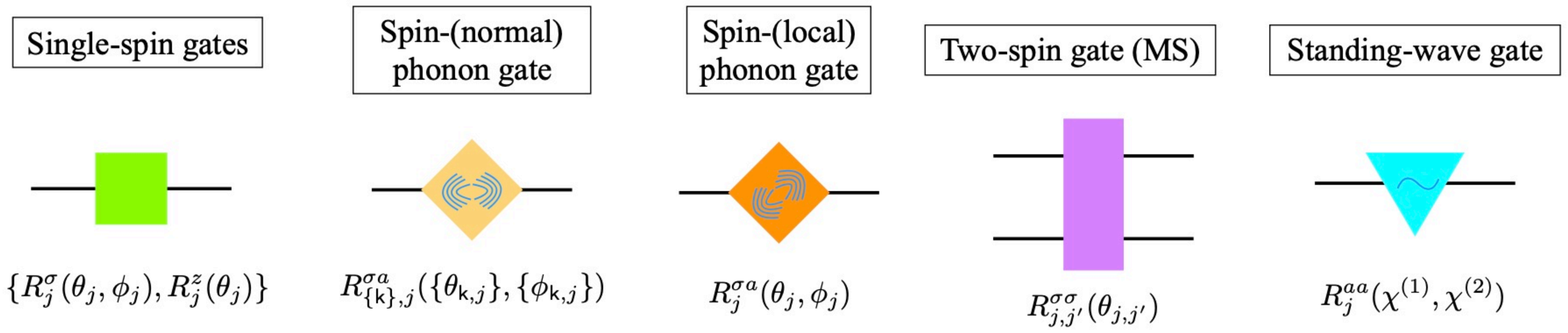
K. Yeter-Aydeniz, S. Bangar, G. Siopsis, and R. C. Pooser, "Collective neutrino oscillations on a quantum computer," (2021), arXiv:2104.03273 [quant-ph].
B. Hall, A. Roggero, A. Baroni, and J. Carlson, "Simulation of collective neutrino oscillations on a quantum computer," (2021), arXiv:2102.12556 [quant-ph].
M. J. Cervia, A. V. Patwardhan, A. B. Balantekin, S. N. Coppersmith, and C. W. Johnson, Phys. Rev. D **100**, 083001 (2019).
A. Roggero, "Dynamical phase transitions in models of collective neutrino oscillations," (2021), arXiv:2103.11497 [hep-ph].

Explosions of New Ideas and Techniques
Just 3 examples of many many

Toward simulating quantum field theories with controlled phonon-ion dynamics: A hybrid analog-digital approach

Zohreh Davoudi,[1,*] Norbert M. Linke,[2] and Guido Pagano[3]
[1] *Maryland Center for Fundamental Physics and Department of Physics, University of Maryland, College Park, MD 20742, USA.*
[2] *Joint Quantum Institute and Department of Physics, University of Maryland, College Park, MD 20742*
[3] *Department of Physics and Astronomy, Rice University, 6100 Main Street, Houston, TX 77005, USA.*
(Dated: April 20, 2021)



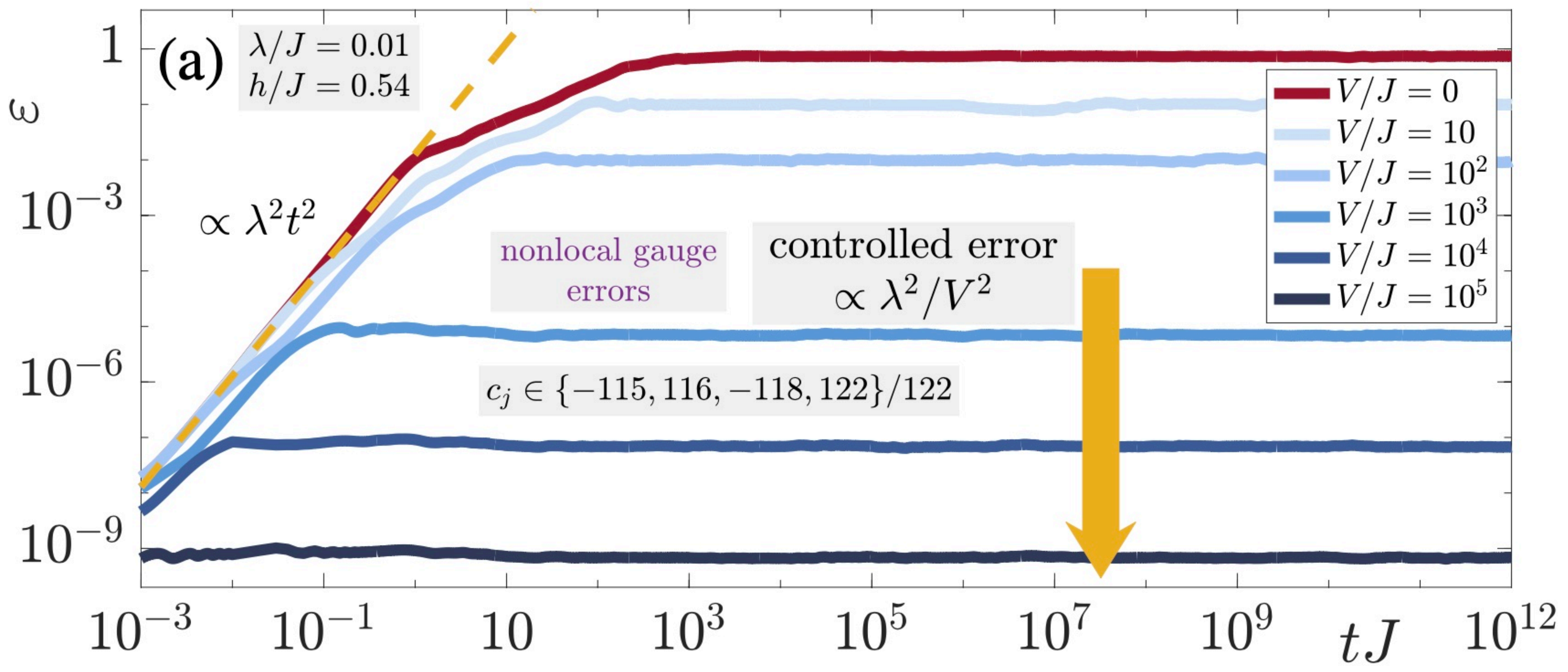


Efficient Representation for Simulating U(1) Gauge Theories on Digital Quantum Computers at All Values of the Coupling

Christian W. Bauer[1,*] and Dorota M. Grabowska[2,†]
[1] *Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[2] *Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland*
(Dated: November 17, 2021)

Stabilizing Lattice Gauge Theories Through Simplified Local Pseudo Generators

Jad C. Halimeh,[1,*] Lukas Homeier,[2,3] Christian Schweizer,[4,5,3] Monika Aidelsburger,[5,3] Philipp Hauke,[1] and Fabian Grusdt[2,3]



InQubator for Quantum Simulation

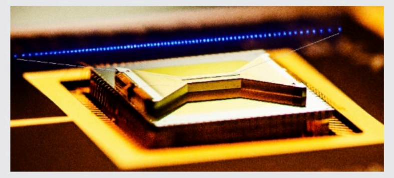
Nuclear physics is expected to advance and be advanced by quantum information science research in quantum many-body systems, quantum field theories and fundamental physics.

https://iqus.uw.edu/

IQuS Workshops

Quantum Simulation of Strong Interactions (QuaSI) Workshop 1 : Theoretical Strategies for Gauge Theories

Organizers: Christian Bauer (LBNL), Zohreh Davoudi (UMD), Natalie Klco (Caltech) and Erez Zohar (Jerusalem).

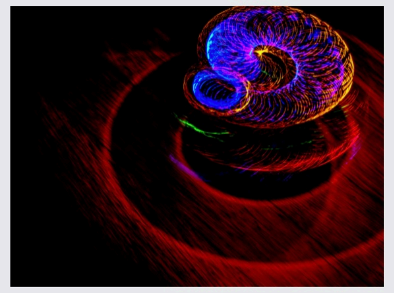


Monday - Friday Nov 08 - 12 2021 All Day

Scientific Quantum Computing and Simulation on Near-Term Devices: Quantum Simulations of Strongly Correlated Systems WORKSHOP

This workshop is jointly sponsored by the Quantum Science Center (QCS) and IQuS. It starts with a 2-day meeting "Quantum computing and the science of strongly correlated systems".
Due to Covid and the safety of our community being of paramount concern, we have decided to hold a virtual workshop during this time period, and are planning for an in-person workshop sometime during early 2022.

Cyber Space



Monday - Tuesday Nov 08 - 09 2021 All Day

Quantum computing and the science of strongly correlated systems WORKSHOP

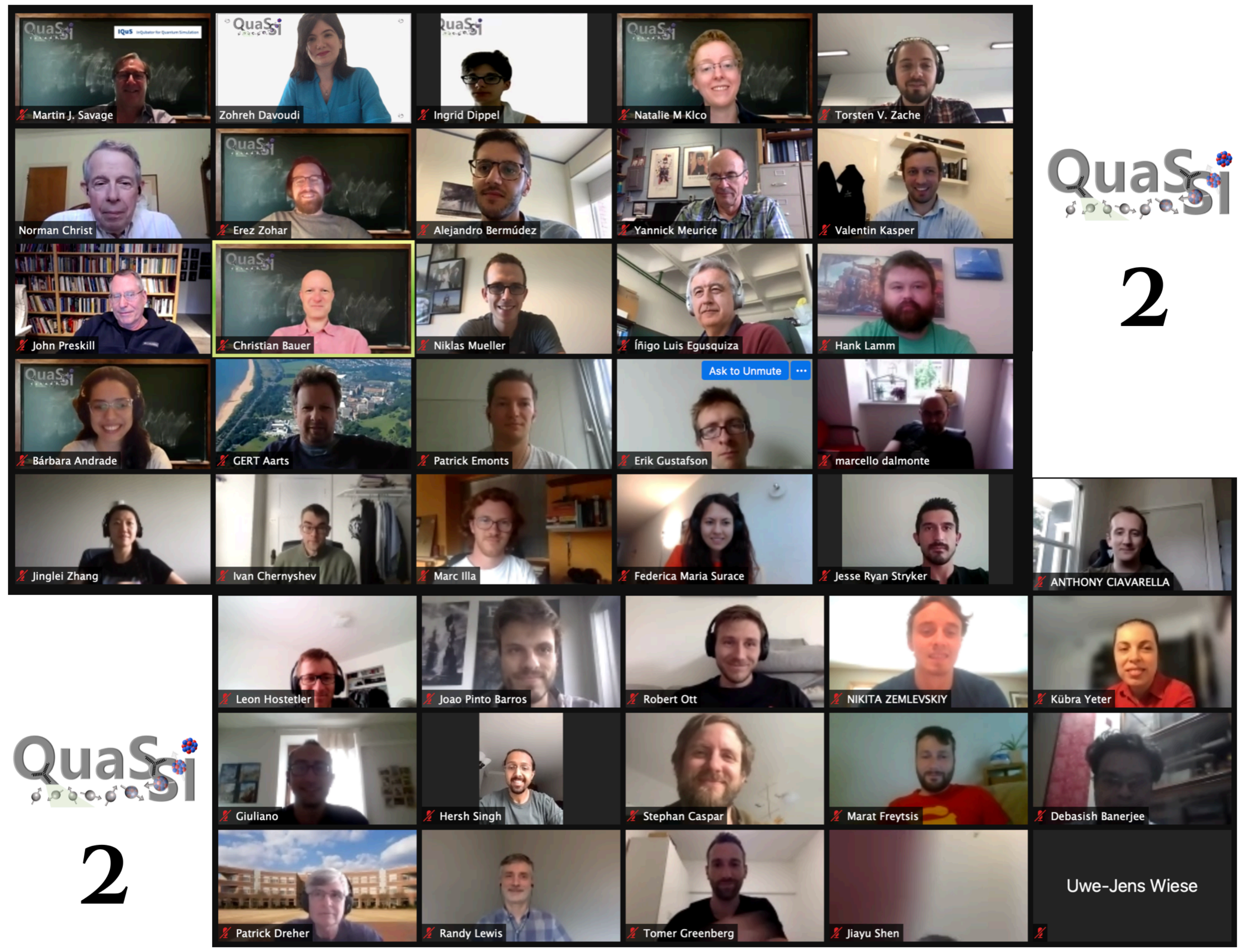
This 2-day meeting is part of the "Scientific Quantum Computing & Simulation on Near-Term Devices: Quantum Simulations of Strongly Correlated Systems" two-week workshop that is jointly sponsored by the Quantum Science Center (QCS) and IQuS.
Due to Covid and the safety of our community being of paramount concern, we have decided to hold a virtual workshop during this time period, and are planning for an in-person workshop sometime during early 2022.

This workshop has been merged with "Scientific Quantum Computing and Simulation on Near-Term Devices: Quantum Simulations of Strongly Correlated Systems"

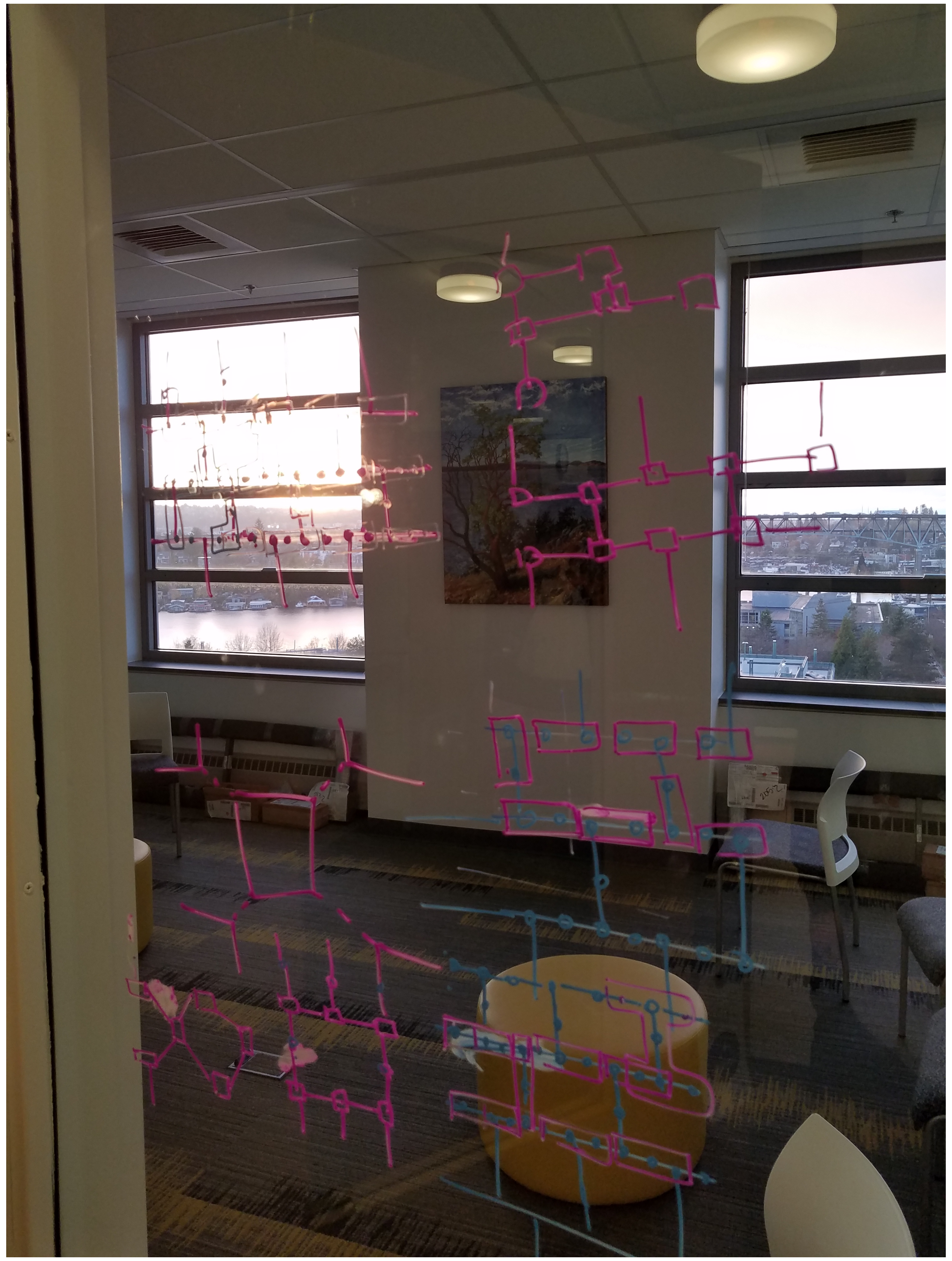
Cyber Space

Quantum Simulation of Strong Interactions (QuaSI) Workshop 2 : Implementation Strategies for Gauge Theories

IQuS InQubator for Quantum Simulation



Parting Comments



Quantum Mechanics 2.0

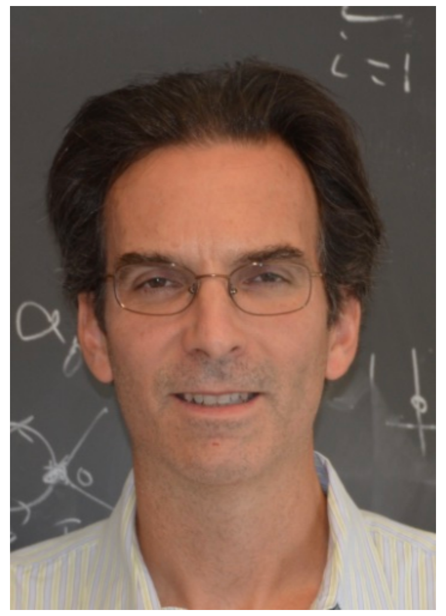
A special time for computing, simulation, communication and sensing

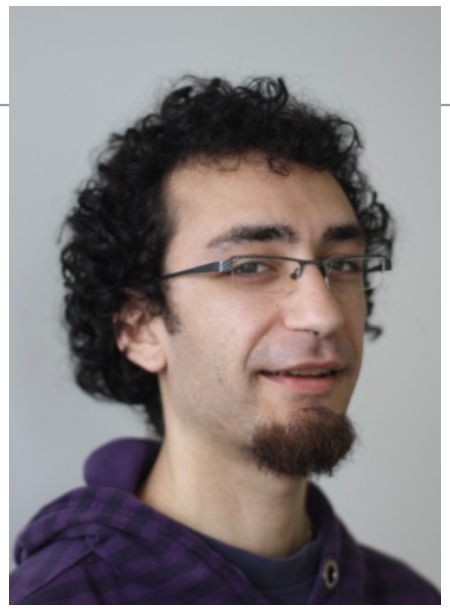
Starting down the road to quantum simulations of Standard Model physics.

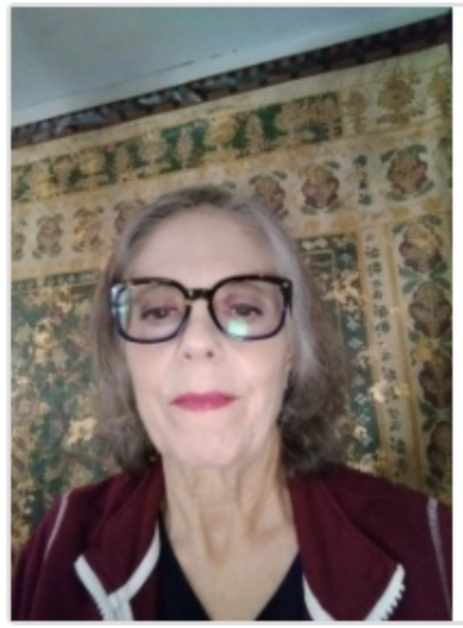
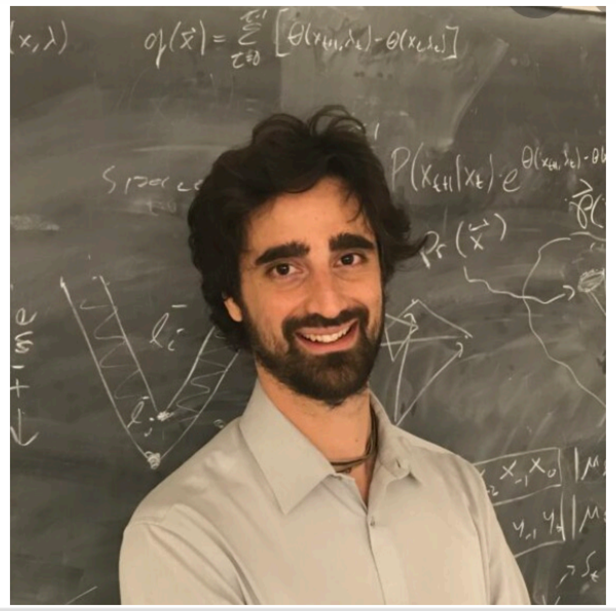
I'm incredibly grateful to my collaborators, colleagues, friends, funding agencies, UW, and more

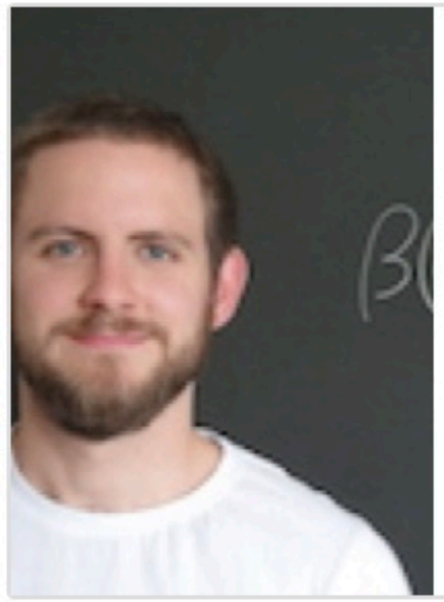
FIN

IQuS People





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FermiLab Quantized Postdoctoral Fellow
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Bose-Einstein condensation
Chern-Simons-Yang-Mills lattice models

FULL PROFILE »

Marc Illa Subina
QSC Postdoctoral Fellow
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Quantum Simulations of the Standard Model
Lattice Gauge Theories
Low-energy nuclear physics with lattice QCD

FULL PROFILE »

Hersh Singh
FermiLab Quantized Postdoctoral Fellow
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Spin Systems
Quantum Algorithms
Quantum Computing

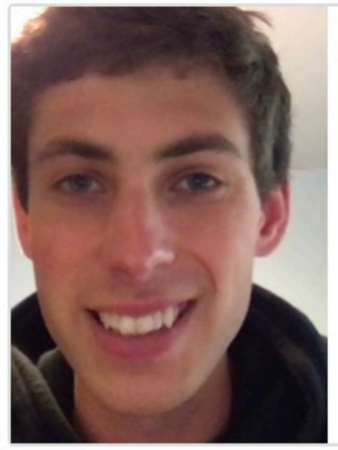
Open positions
Research Assistant Profs
and
Postdoctoral Fellows

Ramya Bhaskar
PhD student
Simulation of Quantum Spin Systems and Field Theories

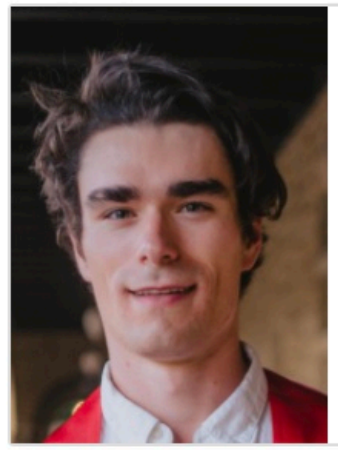
Ivan Chernyshev
PhD student
Quantum Simulation
VQE for QCD Hamiltonian

Anthony Ciavarella
PhD Student
Quantum Simulation of Field Theories

Peter Ehlers
PhD Student
Entanglement in QFT



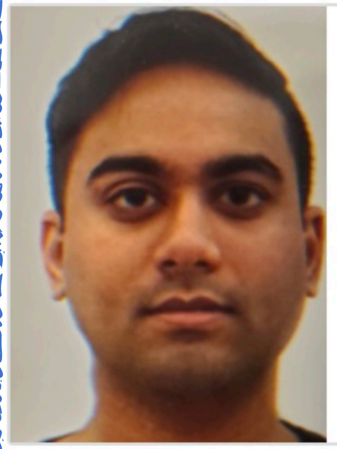
Roland Farrell
PhD Student
Entanglement in QFT



Henry Froland
PhD Student
Entanglement in quantum field theory

Jeremy Hartse
PhD Student
Quantum Information

Zhiyao Li
PhD Student
Quantum Information



Abhishek Rajput
PhD student
Quantum Simulation of field theories

Nikita Zemlevskiy
PhD student
Quantum Information

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U.S. Department of Energy

QUANTUM SCIENCE CENTER

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IQuS Workshops

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INSTITUTE for NUCLEAR THEORY

MAY 2022

May 02 - 13 2022

Quantum Error Mitigation for Particle and Nuclear Physics (22-1b)

Organizers: Benjamin Nachman (LBNL), Christian Bauer (LBNL) , Wibe de Jong (LBNL), Kristan Temme (IBM), Abhinav Kandala (IBM) and Raphael Pooser (ORNL).

Institute for Nuclear Theory

NOVEMBER 2022

Nov 07 - 18 2022

At the Interface of Sensors and Simulations (22-3b)

Organizers: Doug Beck (UIUC), Natalie Klco (Caltech), Crystal Noel (UMD) and Joel Ullom (NIST)

Institute for Nuclear Theory

Call for 2022 – 2023 IQuS Workshop Proposals

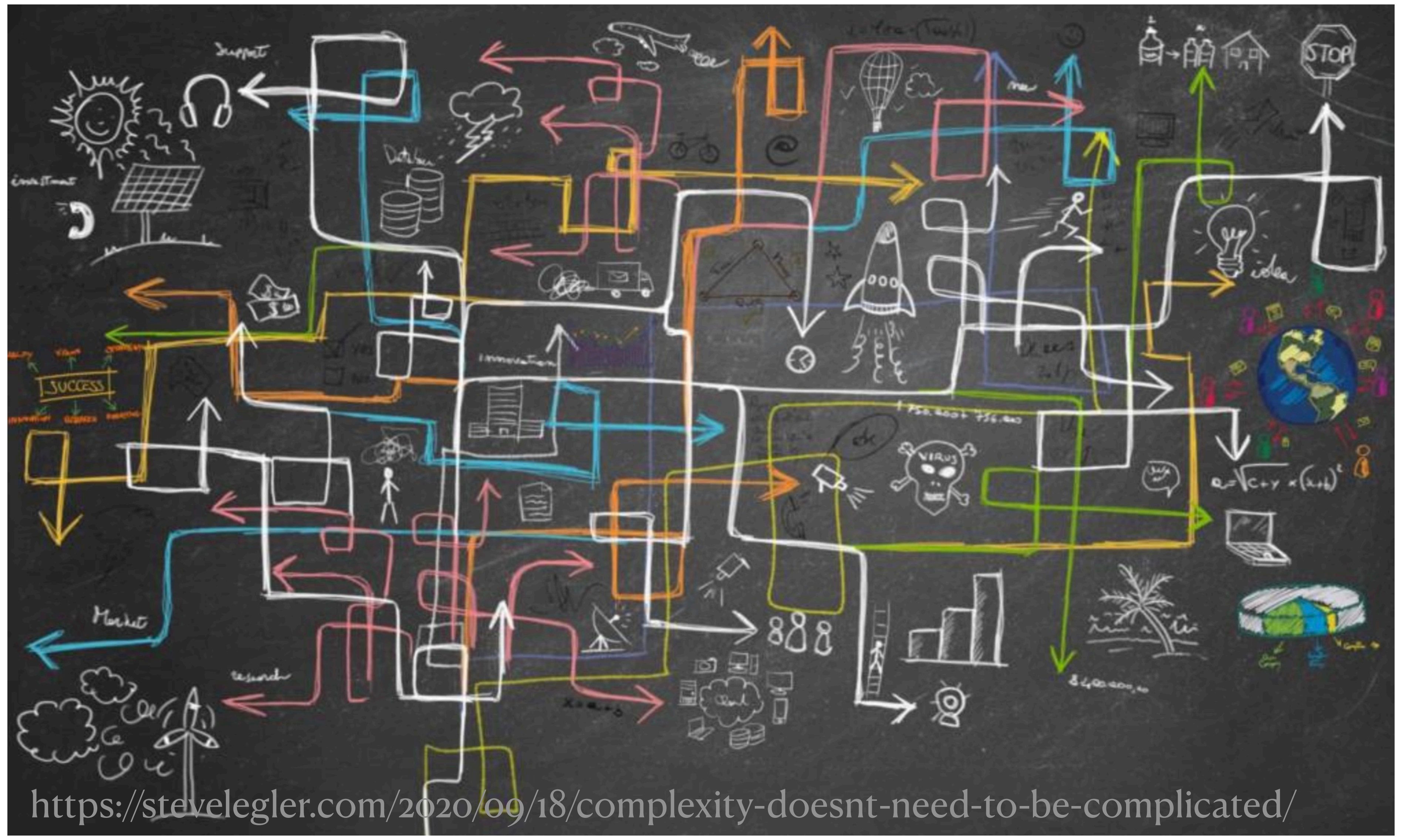
We welcome proposals for in-person IQuS workshops in the Institute for Nuclear Theory (INT) of one or two week duration during 2022 and 2023 to focus on topics at the interface of nuclear physics, quantum simulation and more generally quantum information science. IQuS workshops are intended to bring together a cross-disciplinary group of approximately 20 researchers from diverse backgrounds and career stages to address immediate challenges that require "collective brainstorming" in an immersive environment. Of particular interest are topics and structures that have the potential to lead to disruptive advances in the simulation of quantum many-body systems and are likely to enable knowledge transfer within and between diverse communities and career stages. Proposals will be selected based upon evaluations by the Scientific Advisory Board in coordination with IQuS scientists.

Workshops
Upcoming Workshops
Past Workshops
Submit a Workshop Proposal

NEED HELP?

For questions, or help in submitting proposals or preprints, please contact Katie Hennessey.

Complexity



A statement about the scaling of required computing resources to solve a given problem as the size of the system becomes asymptotically large.

e.g., what are the scalings of computing resources required to compute ....

- the vacuum energy-density of a lattice theory with n-body interactions,
- S-matrix elements (scattering amplitudes) in a given theory