Theoretical Physics Colloquium

hosted by Prof. Igor Shovkovy at the Arizona State University

Towards Quantum Simulations for Nuclear and Particle Physics

Martin J Savage

InQubator for Quantum Simulation (IQuS)

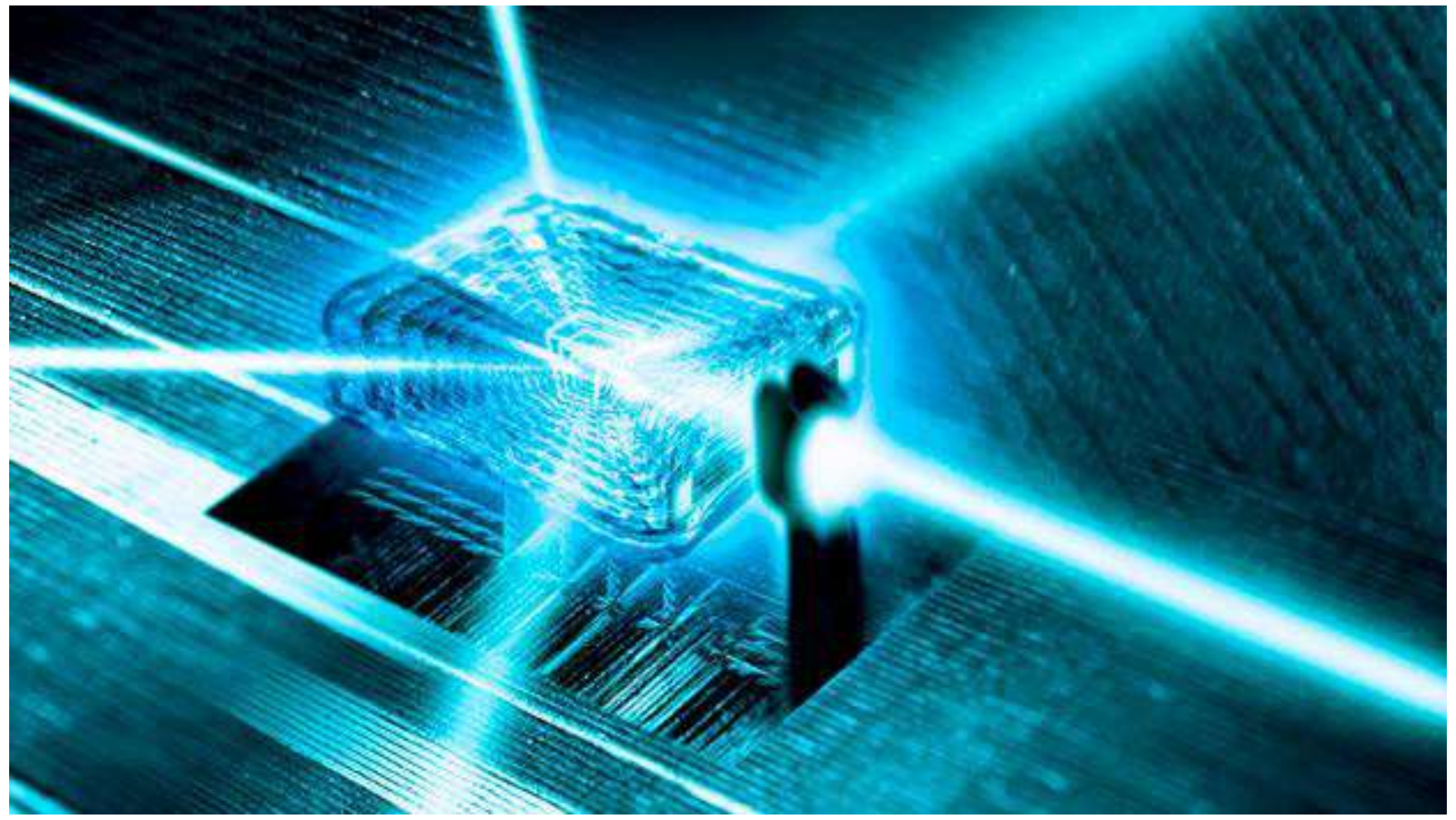
UNIVERSITY *of*
WASHINGTON

virtual-ASU August 25, 2021

Two Disruptive Computing Technologies for the Standard Model

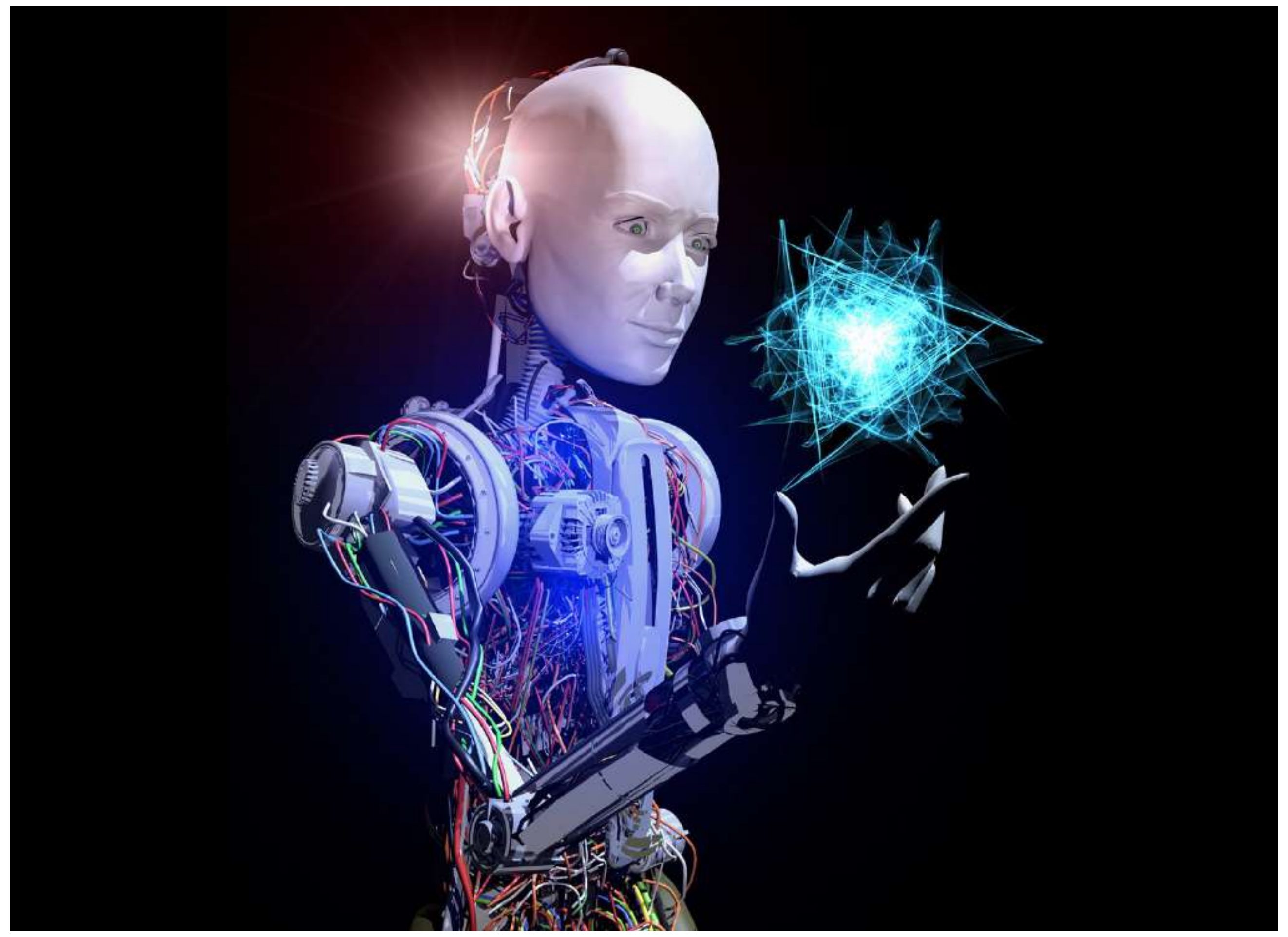
Quantum Computing

- Computations inaccessible to classical computing
- Entanglement and coherence for computing



Machine Learning

- Predictions from learned correlations



2019 : Quantum Advantage in Computing

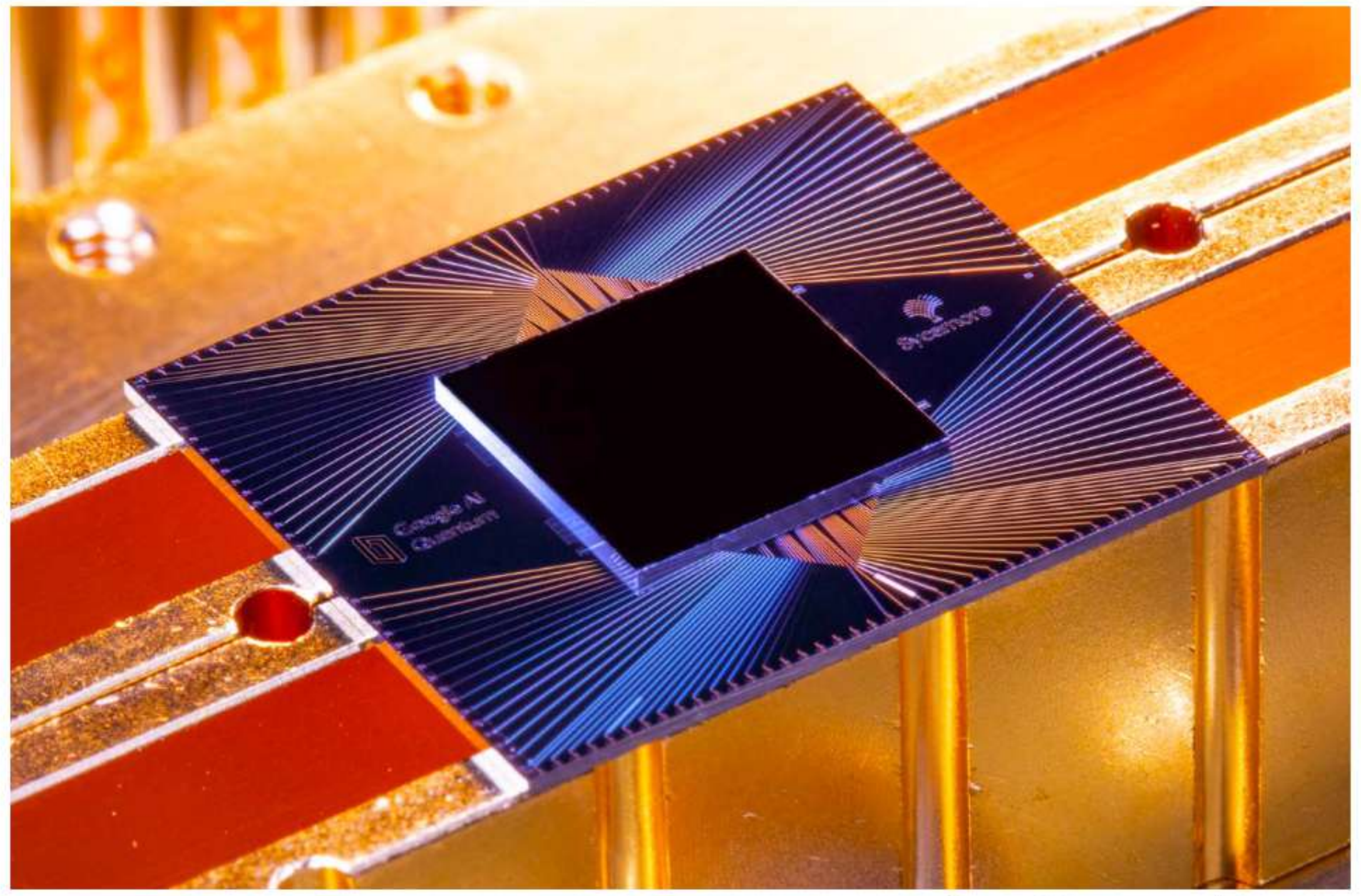
Nature **574**, pages 505–510 (2019), 23 October 2019

Article

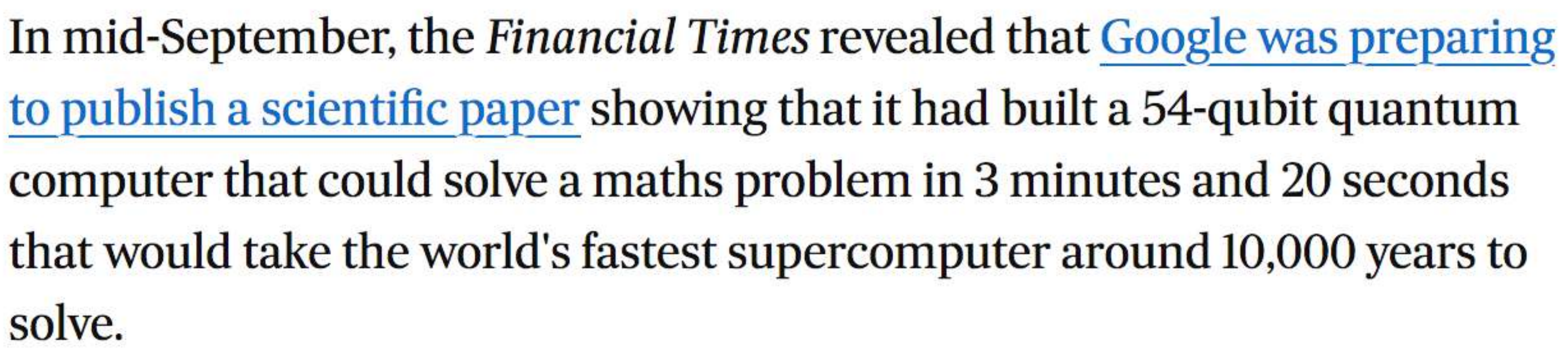
Quantum supremacy using a programmable superconducting processor

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

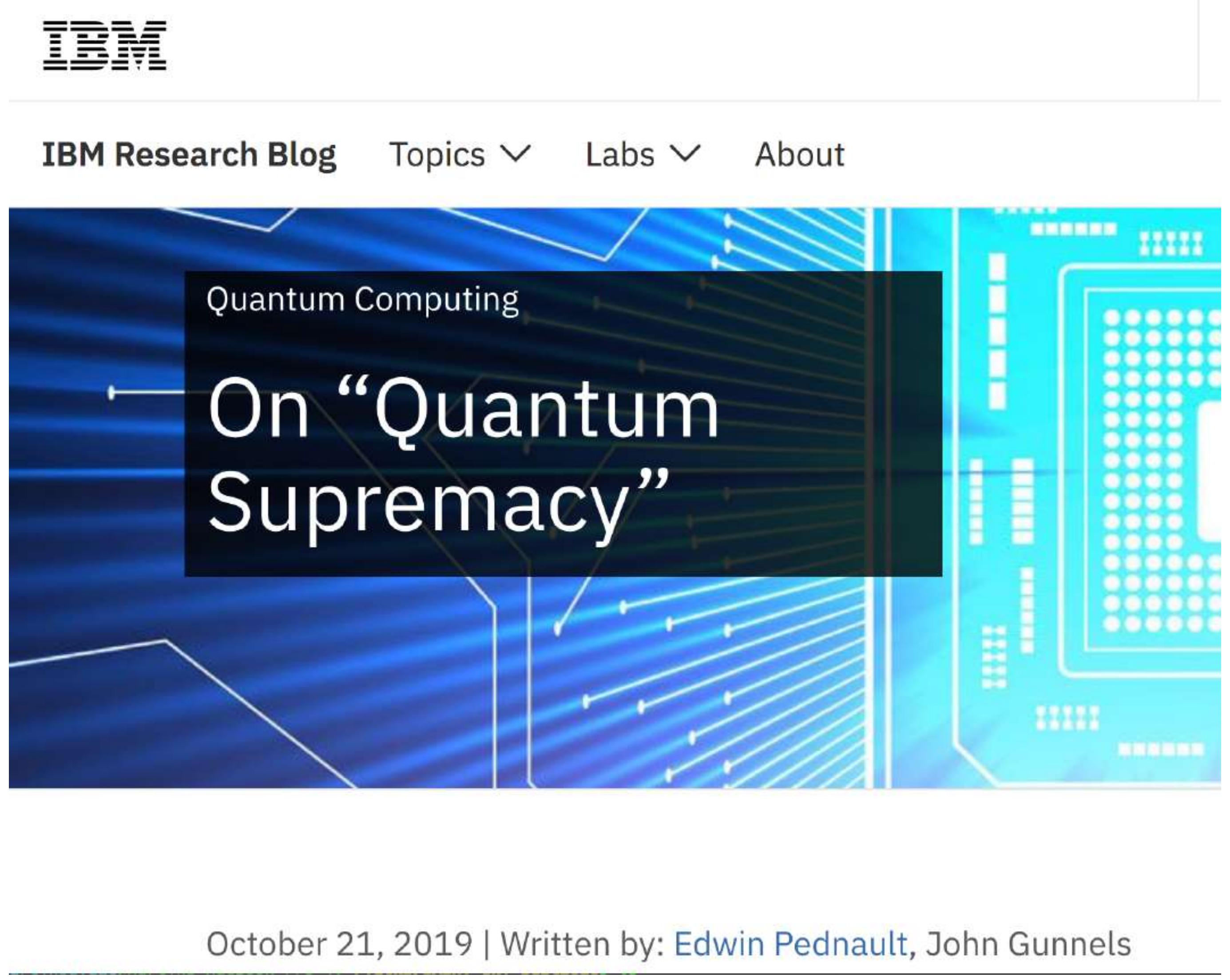
Frank Arute[1], Kunal Arya[1], Ryan Babbush[1], Dave Bacon[1], Joseph C. Bardin[1,2], Rami Barends[1], Rupak Biswas[3], Sergio Boixo[1], Fernando G. S. L. Brandao[1,4], David A. Buell[1], Brian Burkett[1], Yu Chen[1], Zijun Chen[1], Ben Chiaro[5], Roberto Collins[1], William Courtney[1], Andrew Dunsworth[1], 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

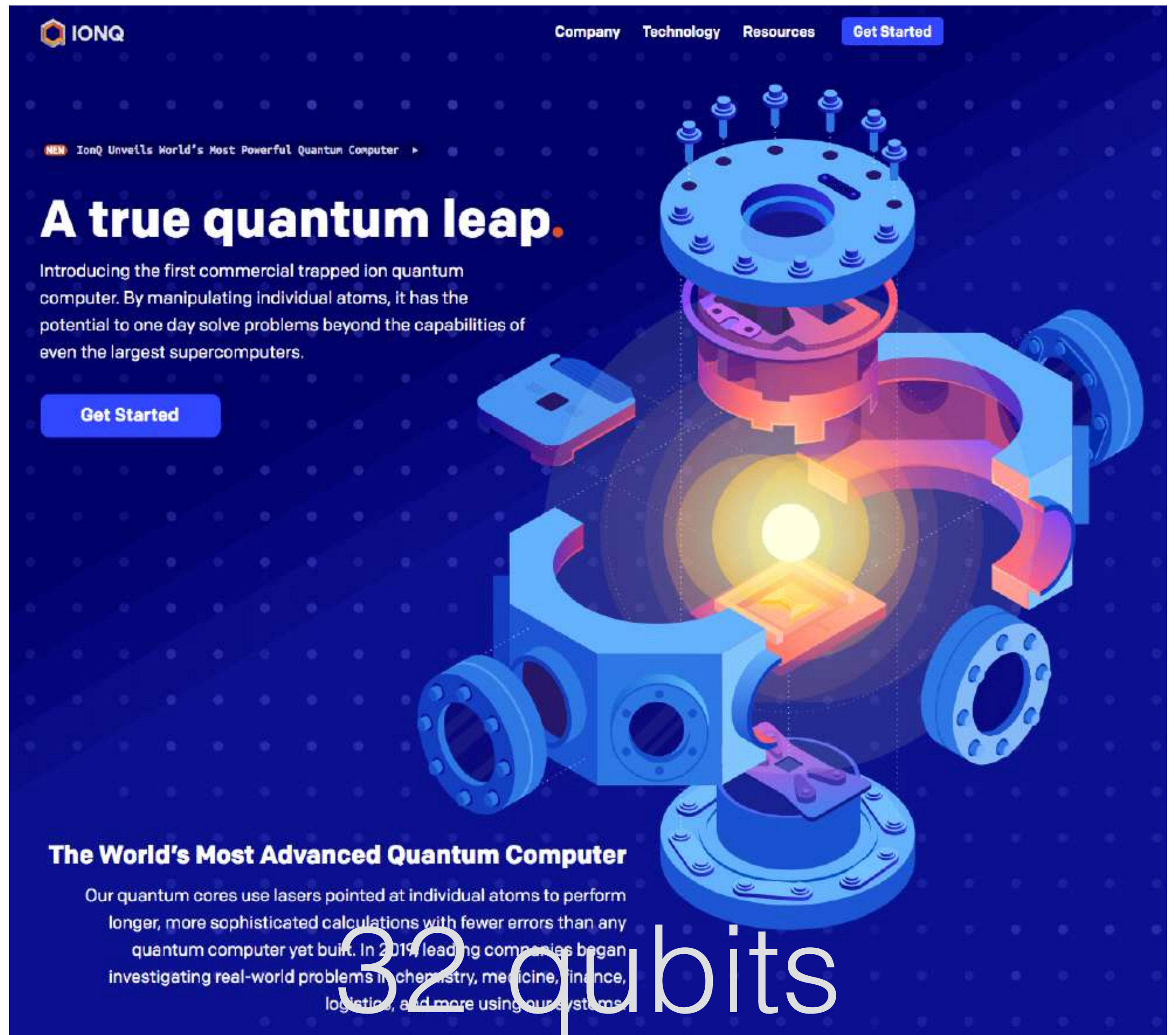


In mid-September, the *Financial Times* revealed that Google was preparing to publish a scientific paper showing that it had built a 54-qubit quantum computer that could solve a maths problem in 3 minutes and 20 seconds that would take the world's fastest supercomputer around 10,000 years to solve.



On "Quantum Supremacy"

October 21, 2019 | Written by: Edwin Pednault, John Gunnels



A true quantum leap.

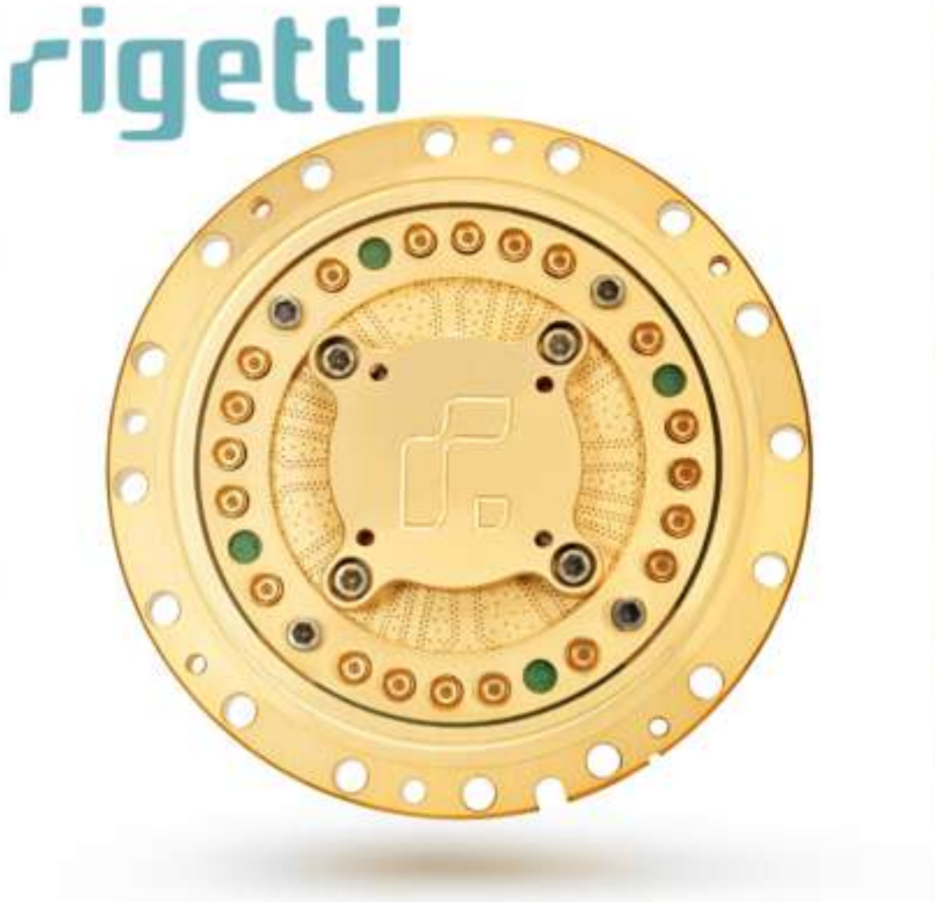
Introducing the first commercial trapped ion quantum computer. By manipulating individual atoms, it has the potential to one day solve problems beyond the capabilities of even the largest supercomputers.

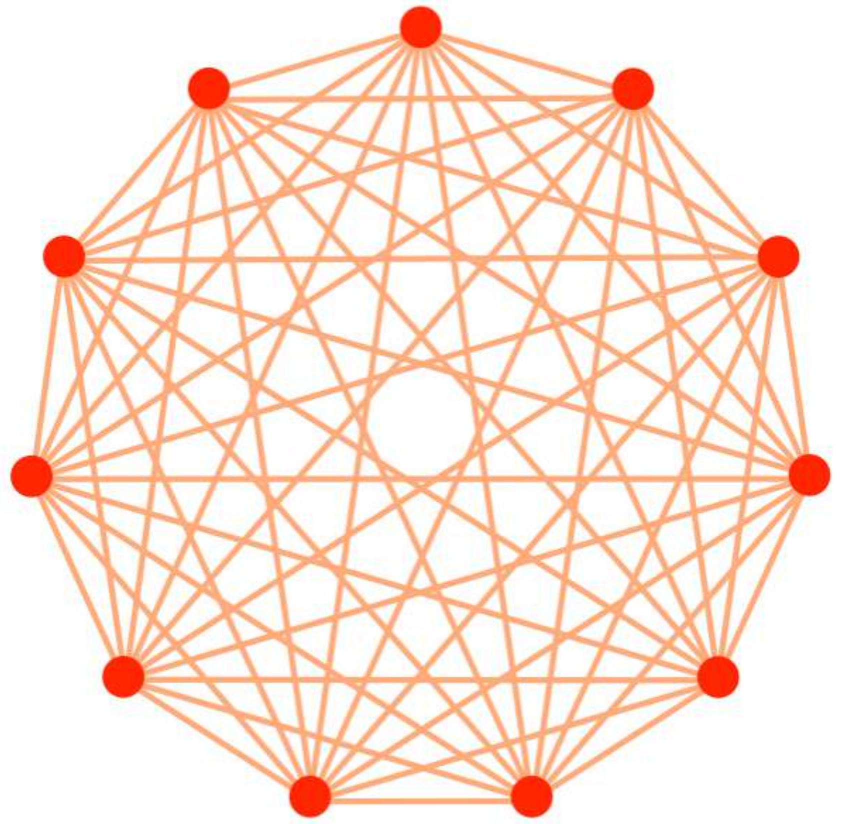
The World's Most Advanced Quantum Computer

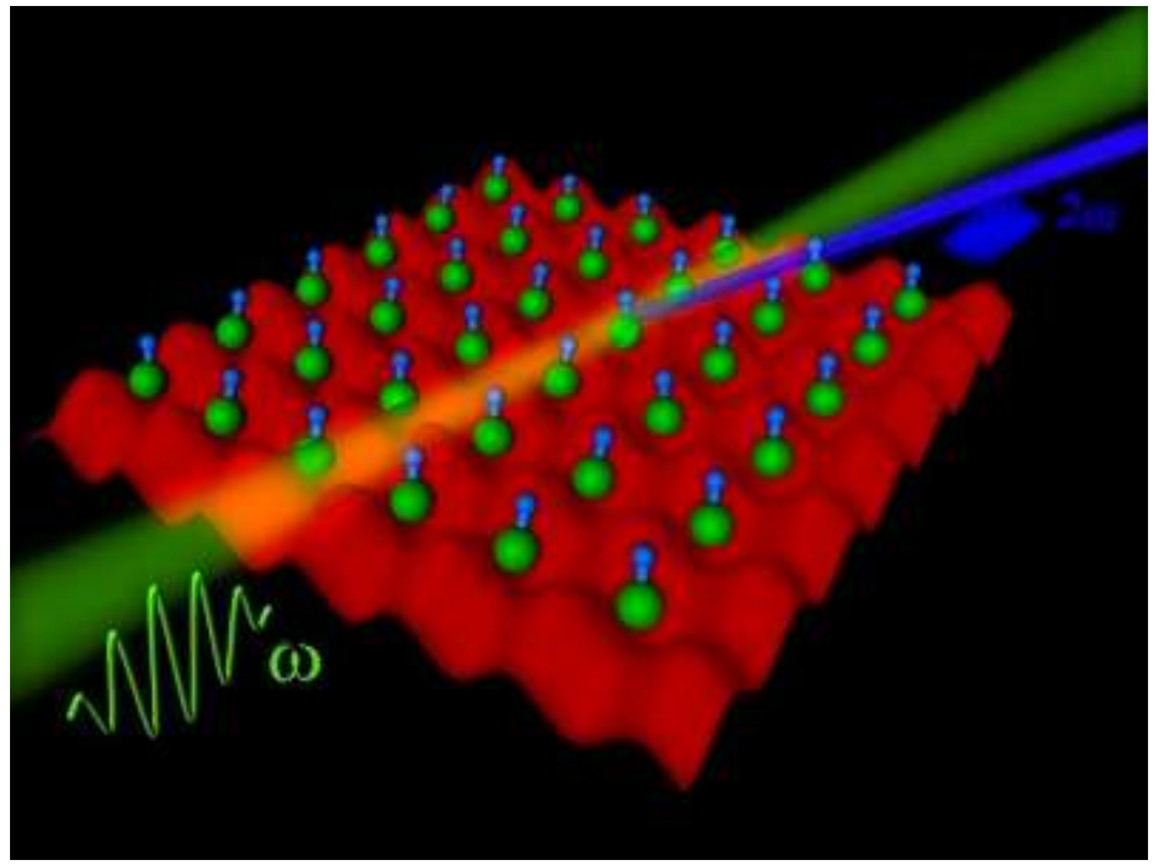
Our quantum cores use lasers pointed at individual atoms to perform longer, more sophisticated calculations with fewer errors than any quantum computer yet built. In 2019 leading companies began investigating real-world problems in chemistry, medicine, finance, logistics, and more using our systems.

32 qubits

2017 : First Quantum Devices for Scientific Applications







Hemmerling, Cornel, https://www.photonics.com/Article.aspx?AID=64150

NISQ-era quantum devices for applications

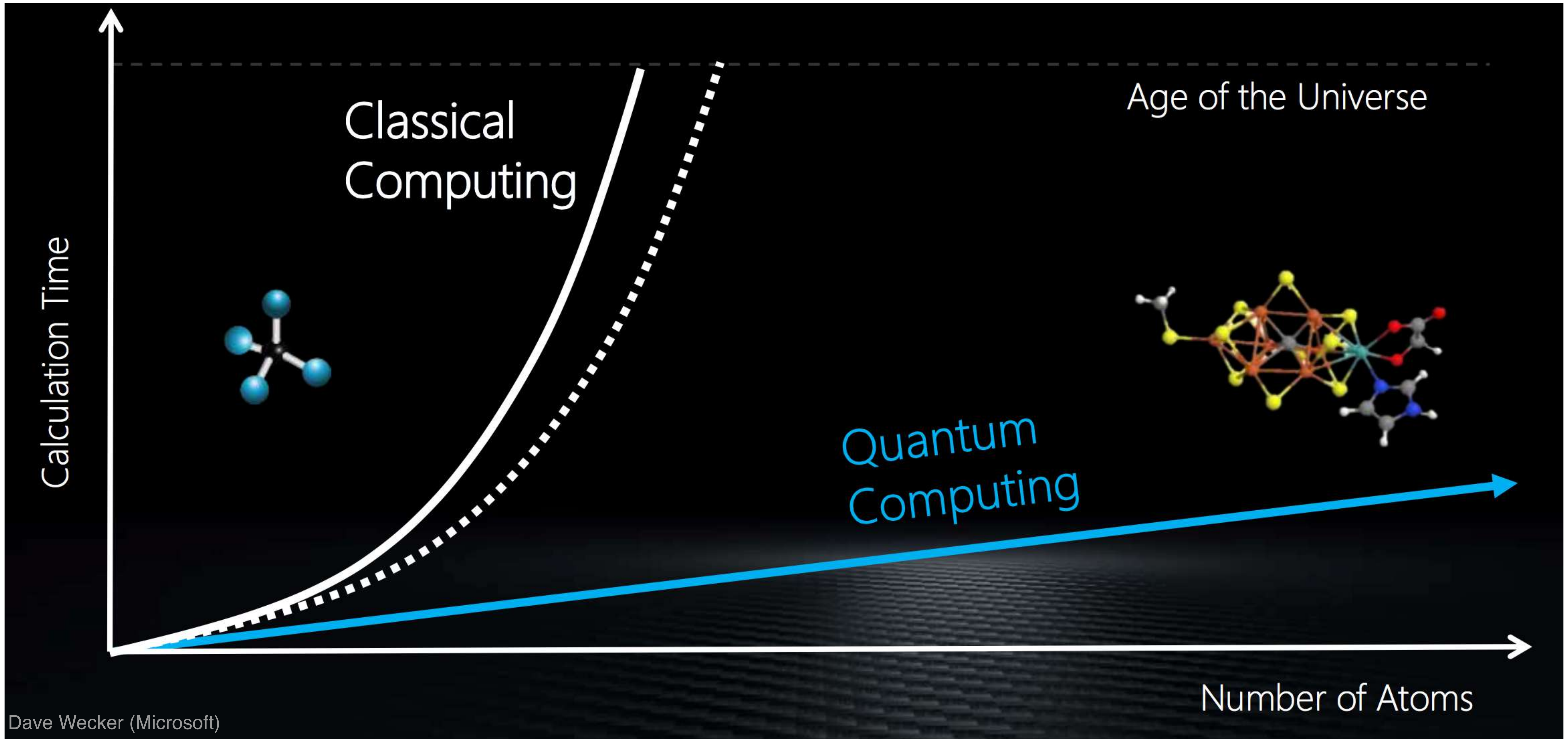
Quantum Systems for Quantum Systems

Quantum mechanics “works the same” at all scales we have probed so far

- The promise to simulate systems at one scale with systems at another with fidelity
  (Feynman, Benioff, Manin and others)

-

The Potential of Quantum Computing



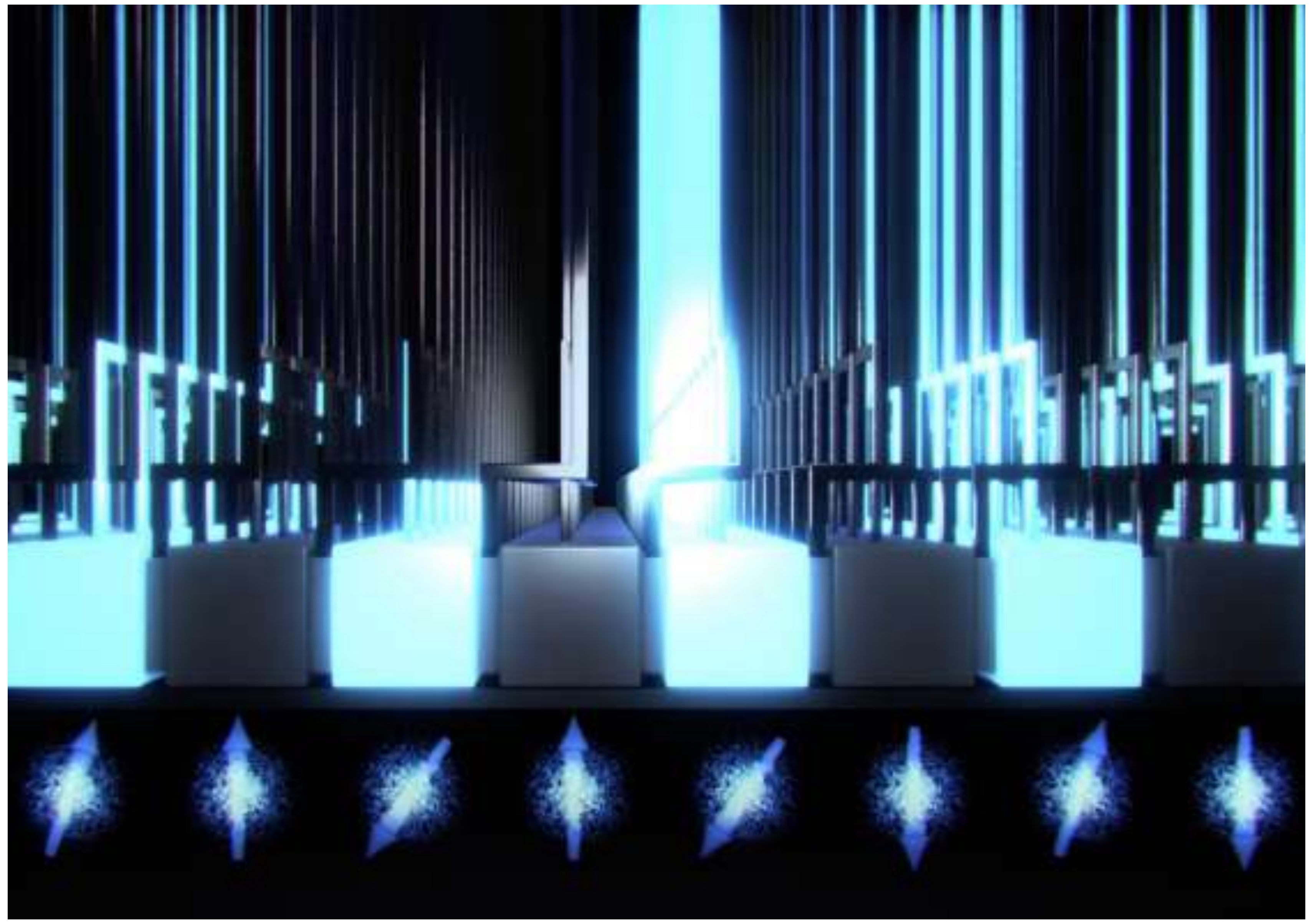
Dave Wecker (Microsoft)

~ 100 qubit devices can address problems in chemistry that are beyond classical computing

50 qubits : ~ 20 petabytes ~ Leadership-Class HPC facility

300 qubits : more states [10^{90}] than atoms in universe [10^{86}]

Where to look for a quantum advantage

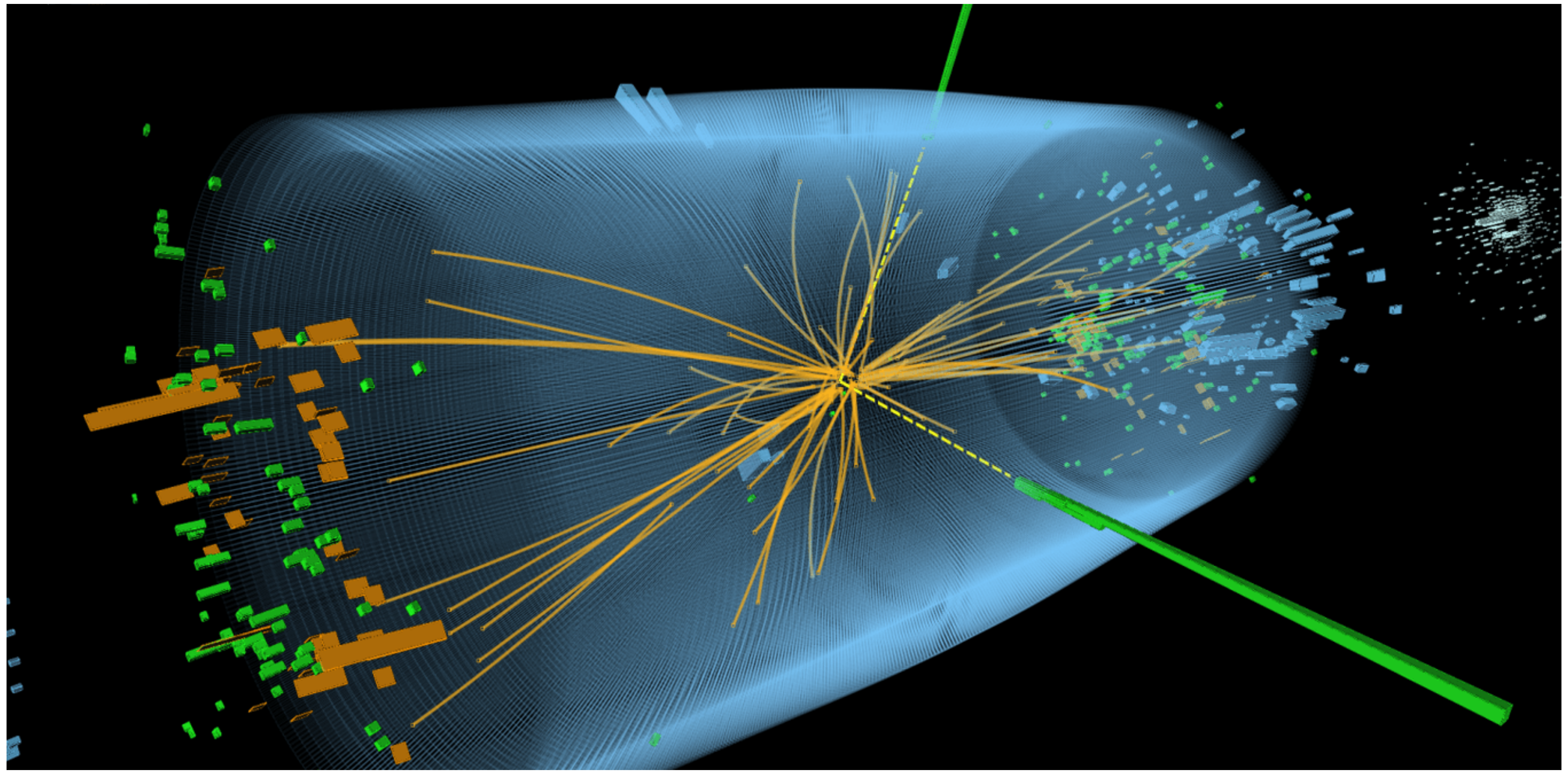


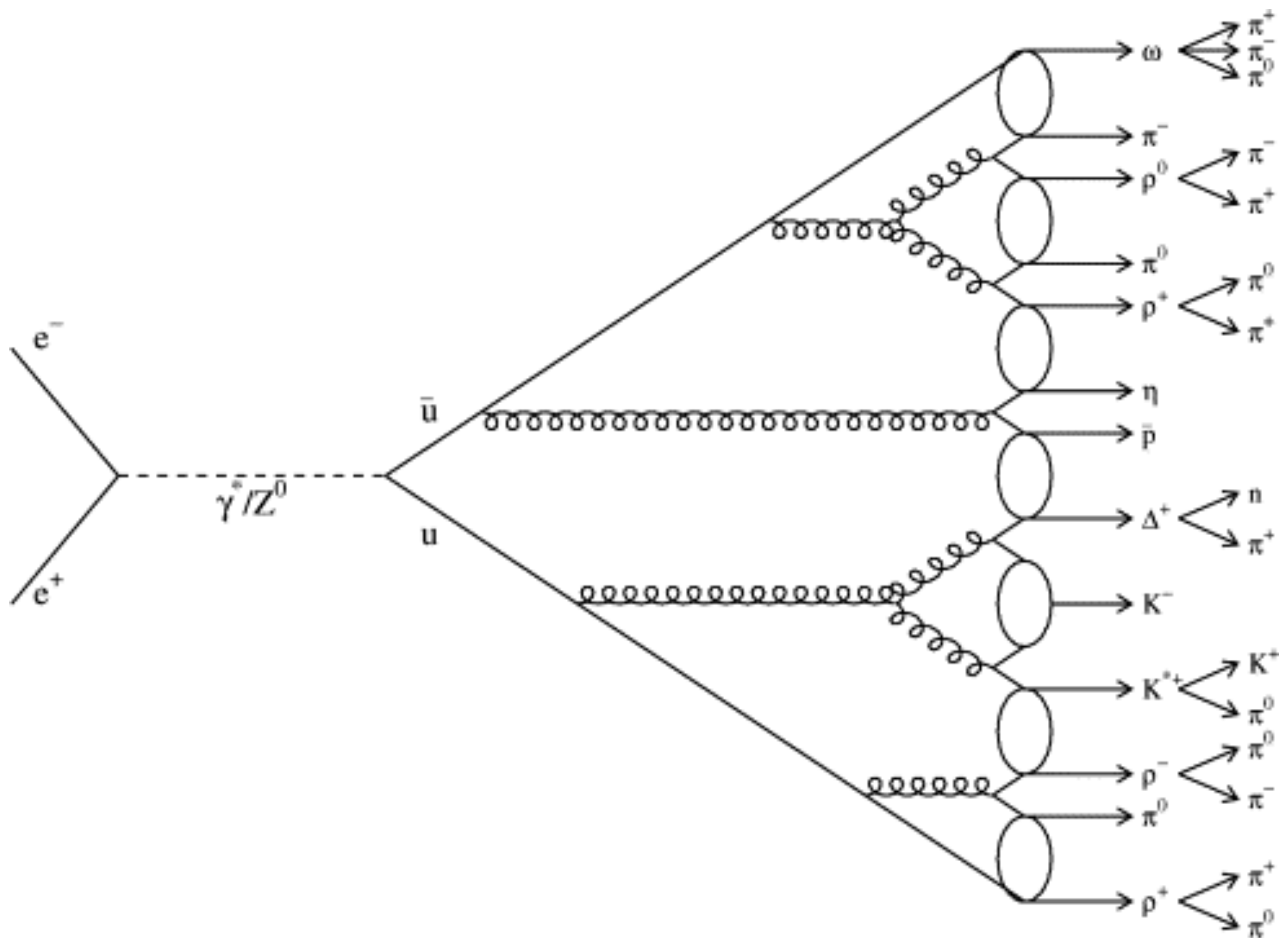
If a classical computer can solve the problem,
why “compete” using a quantum device?

Use quantum devices to solve the problems (or parts of problems!) that classical computers can’t solve “at scale”

“ Gotta *know* your problems!”

Potential for Impact of Quantum Simulations



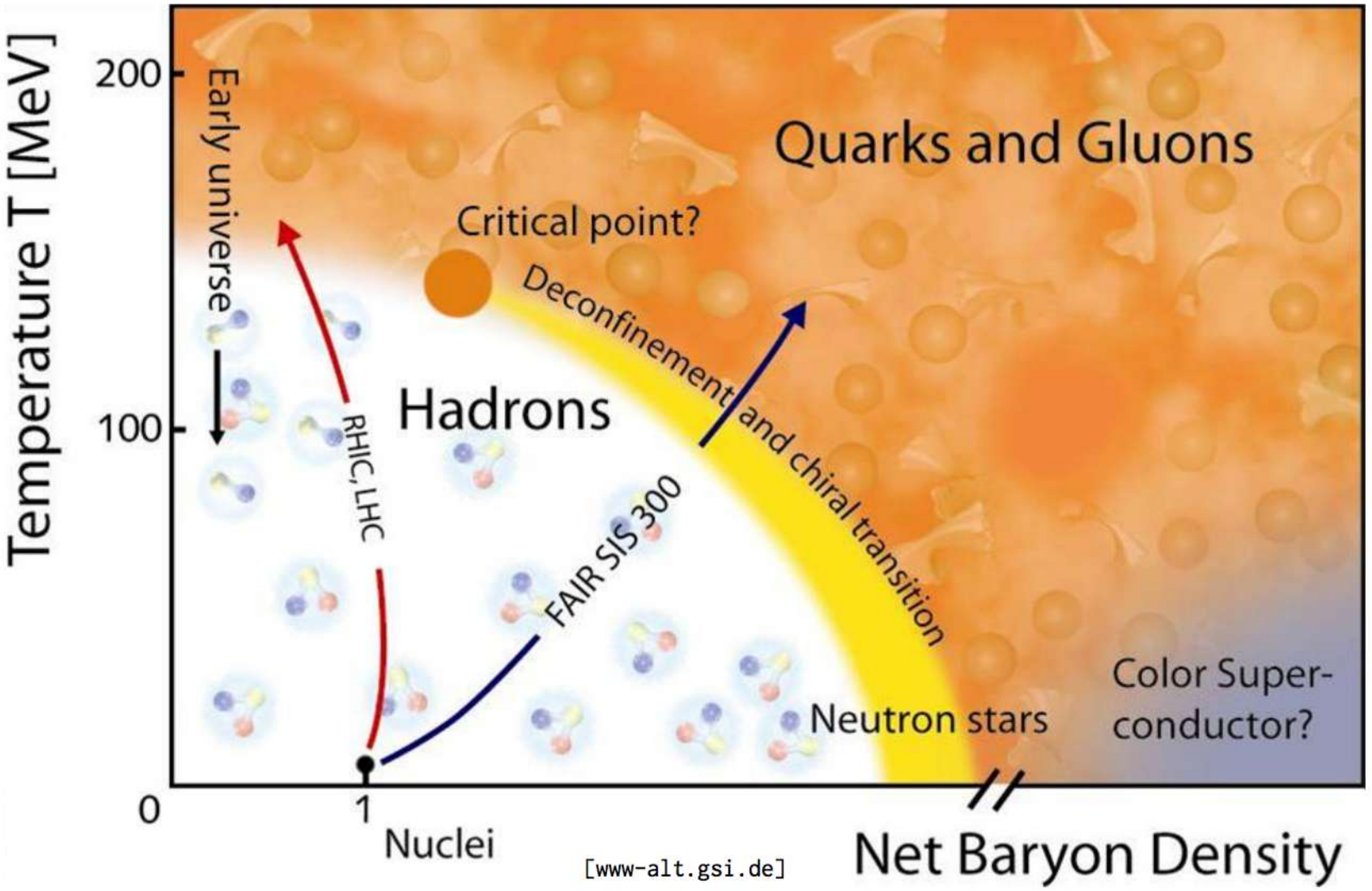


Real-time dynamics and particle production

Lattice quantum field theories - Quantum Chromodynamics and Electroweak, Effective Field Theories

Fragmentation and highly inelastic processes

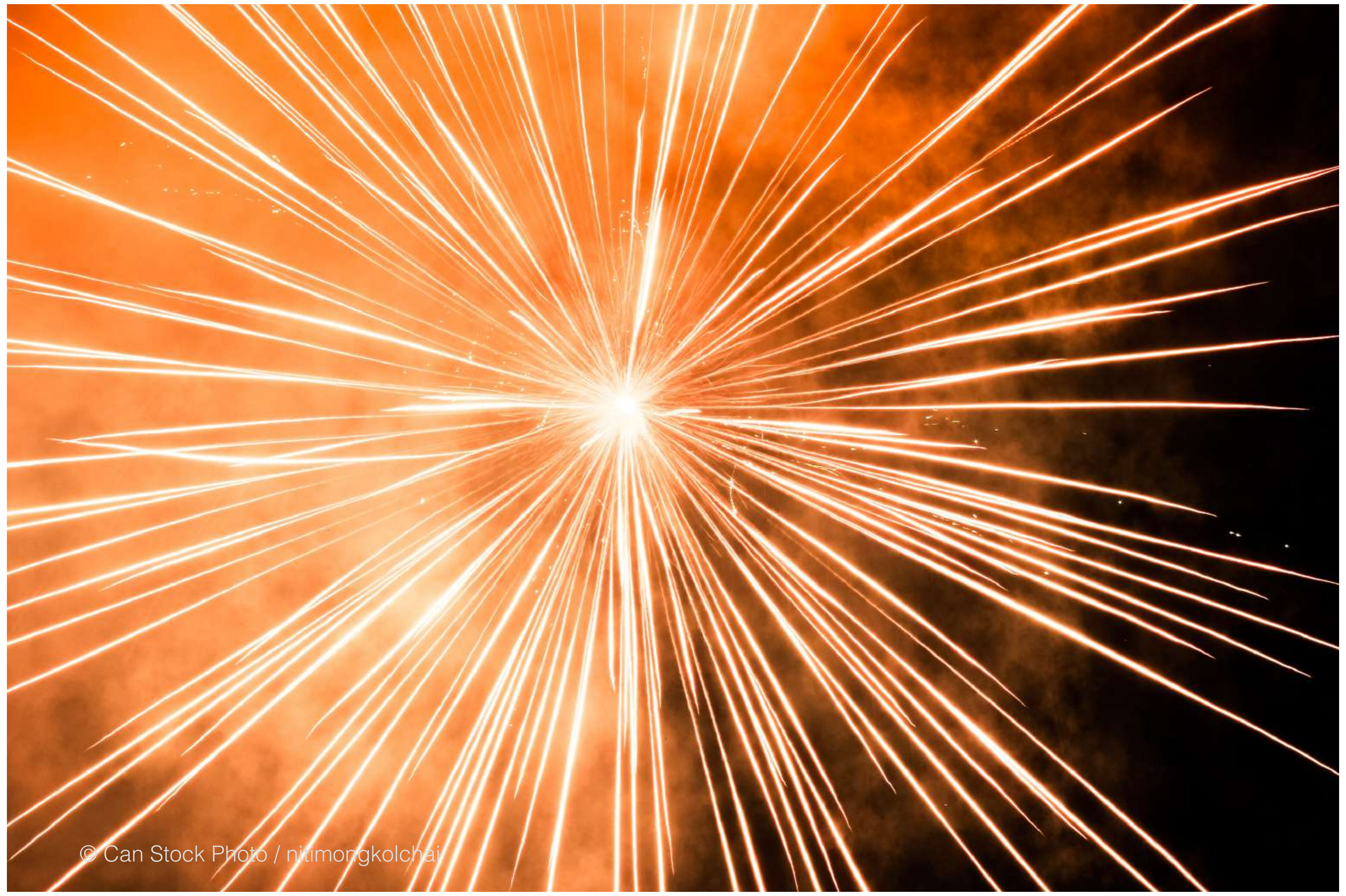
Potential for Impact of Quantum Simulations



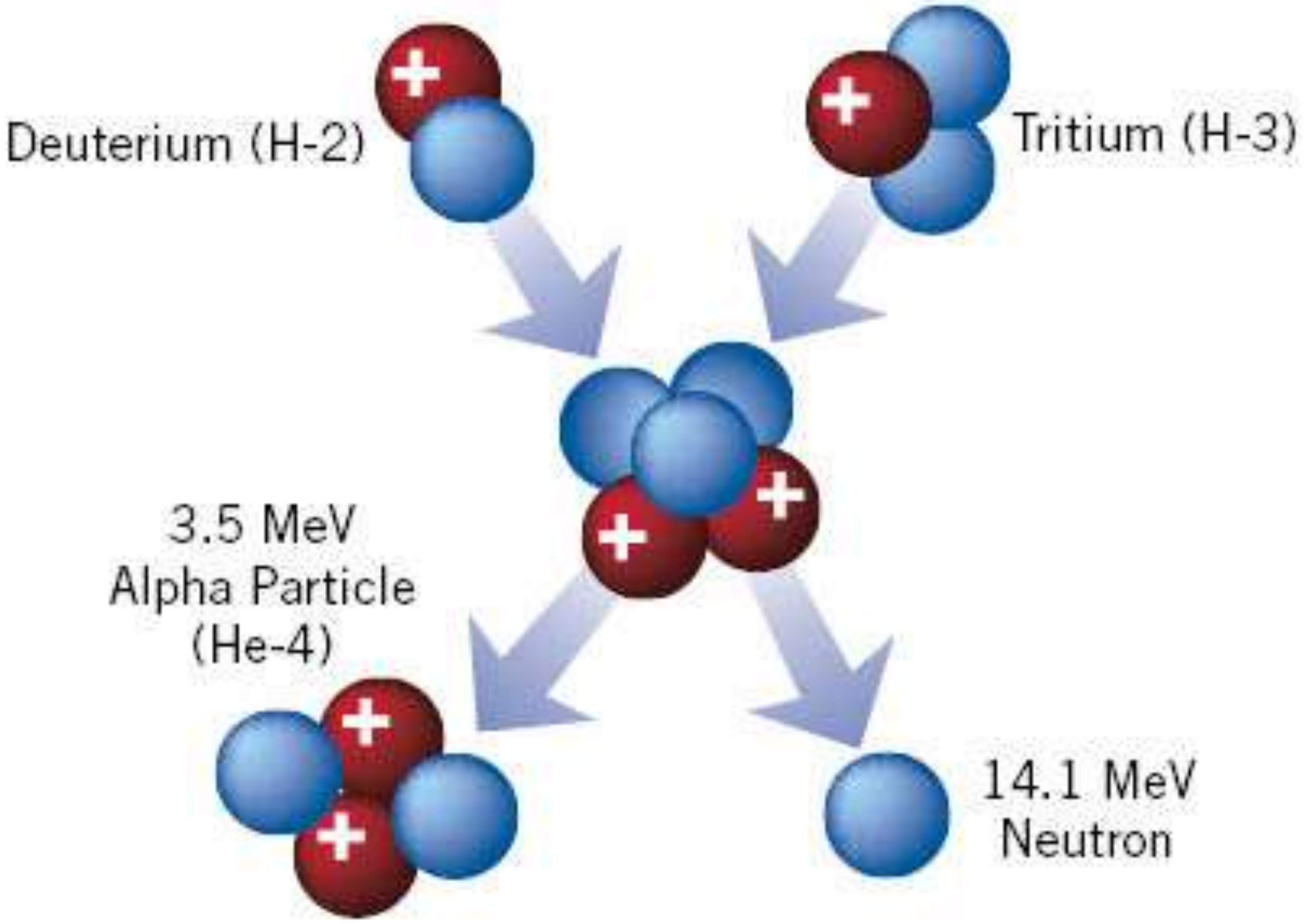
[www-alt.gsi.de]

Equation of state and non-equilibrium dynamics of dense and/or hot matter
Early universe phase transitions - baryogensis
Conquering “sign problems”

Potential for Impact of Quantum Simulations



© Can Stock Photo / nitimongkolchai

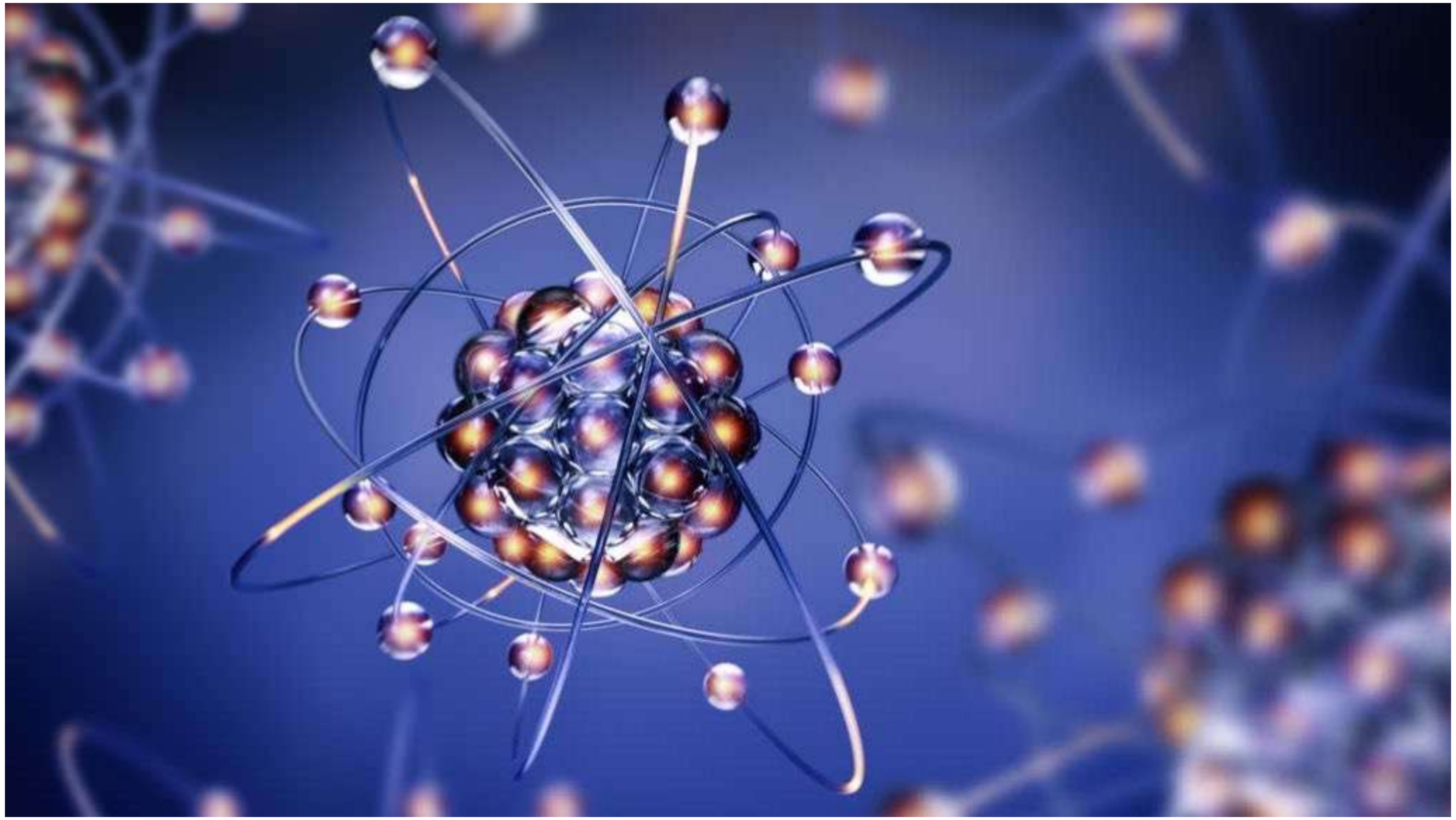


Neutrino dynamics in extreme astrophysical environments

Electroweak processes in nucleons and nuclei

Low-energy nuclear reactions and fission

Potential for Impact of Quantum Simulations



Precision structure and interactions of medium and large nuclei
Exponentially large Hilbert spaces

Entanglement - Perspective

In part:

20th Century HEP - QFT

—“chasing” short-distance fundamental interactions
— nonperturbative lattice QCD using HPC
— modeling gave way to EFTs - leading order separable

20th Century NP - QMB systems

— “handling” short-distance (phenomenological) repulsion
  — ended NT for a few years! Re-invigorated by RG and EFT from HEP, chemistry
— quantum many-body computations using HPC
— modeling gave way to EFTs

21st Century HEP+NP - QFT+QMB systems

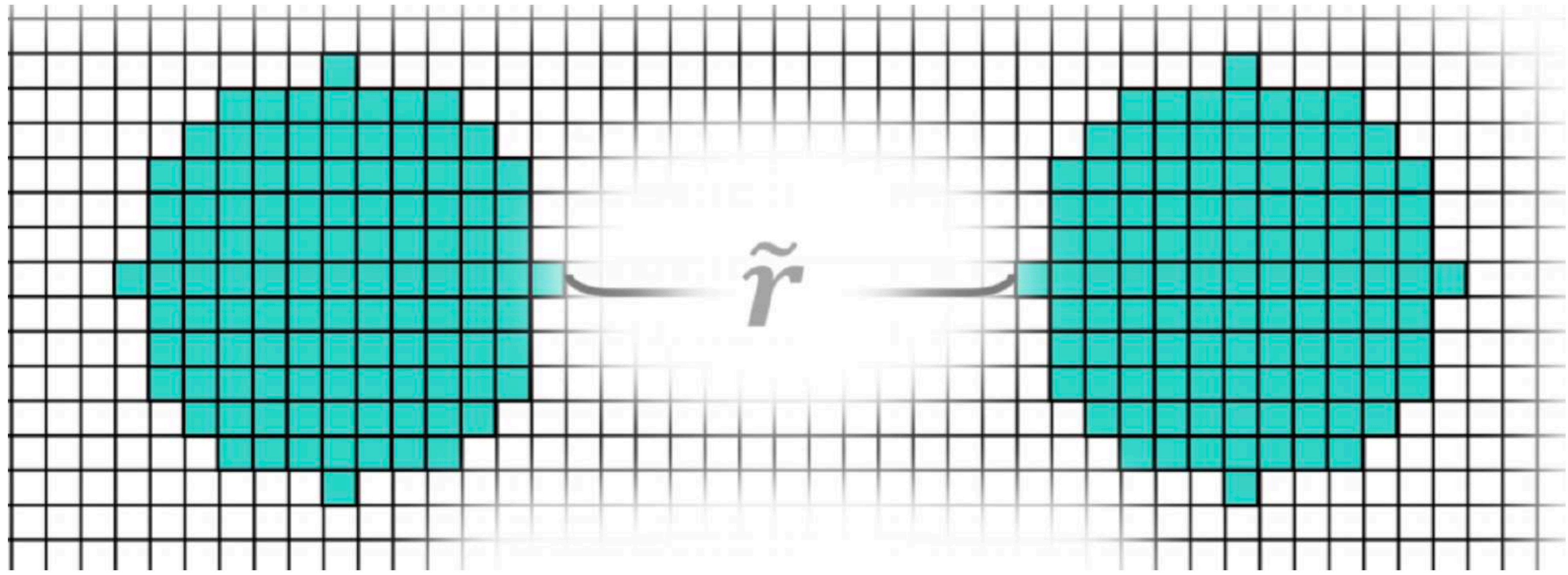
— quantum correlations and non-locality using/for quantum simulation and quantum computing

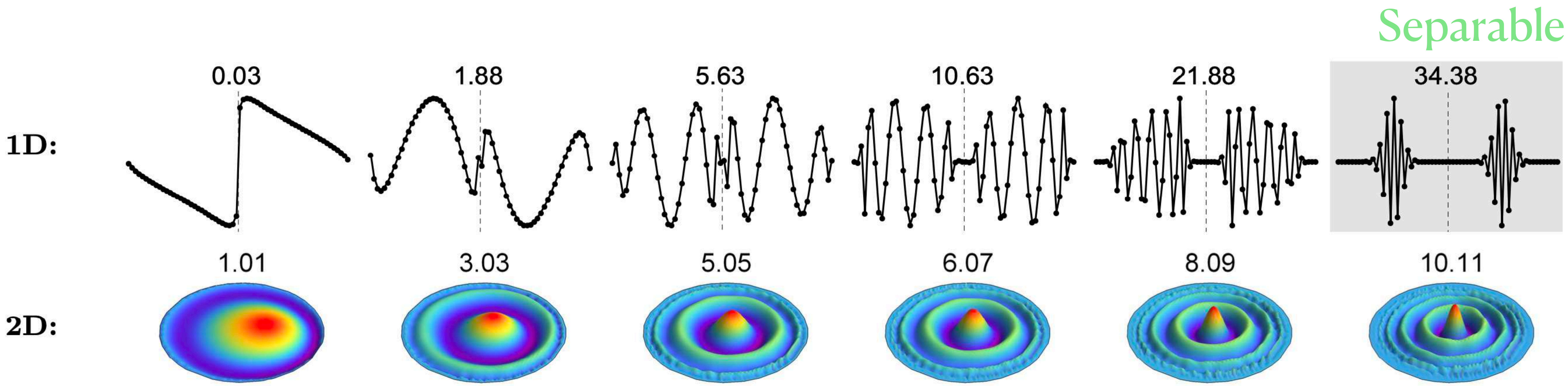
Natalie Klco, MJS

Vacuum Negativity and Separability in 1D, 2D, 3D

Massless, noninteracting scalar field theory … short-distance strong interactions

Entanglement in harmonic chains - Reznik and many others





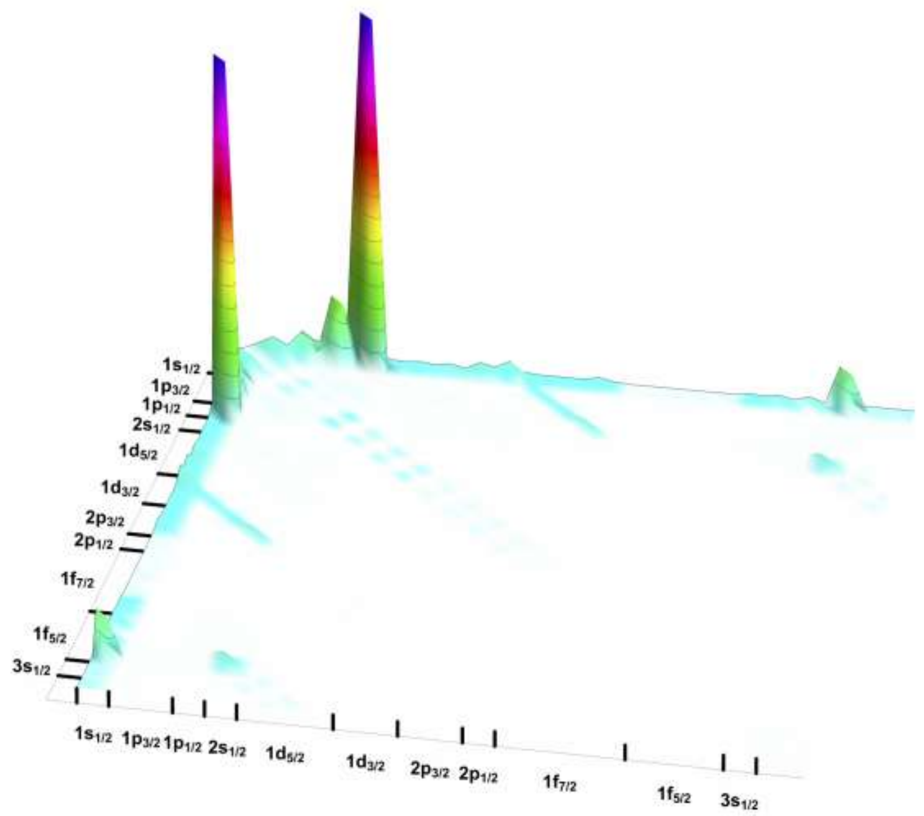
The long-distance structure of entanglement is determined by the UV structure of the theory - UV-IR connection

Entanglement in Nuclei

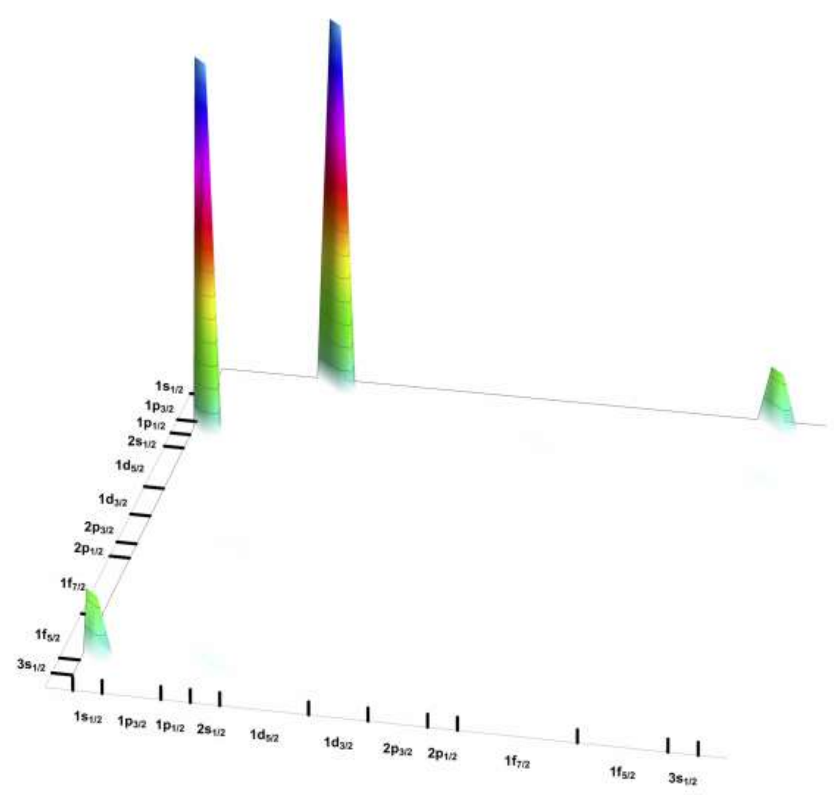
Toward Hybrid QPU-CPU Nuclear Structure

Caroline Robin, MJS, Nathalie Pillet

2018: Entanglement Entropy as an organizing principle
Gorton and Johnson [MS thesis, Gorton]

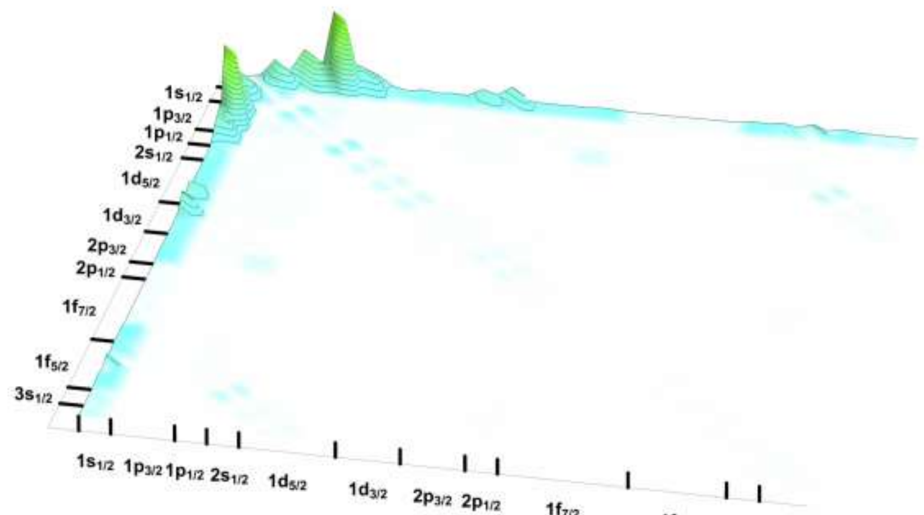


Harmonic Oscillator basis

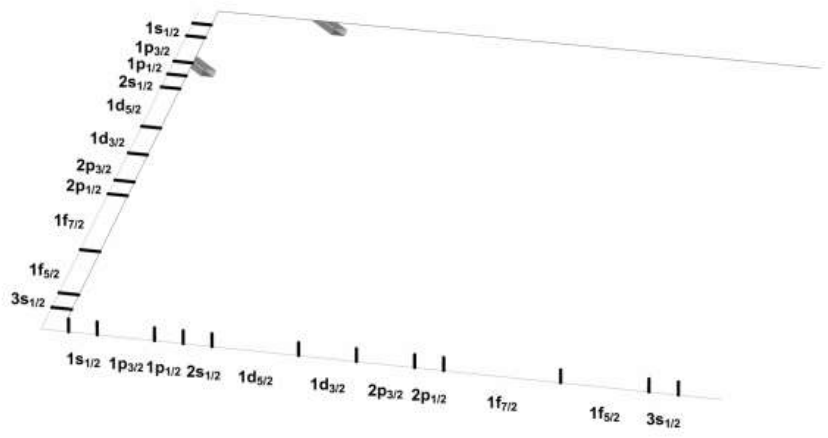


Negativity

Mututal Information



Self-Consistent, Correlated

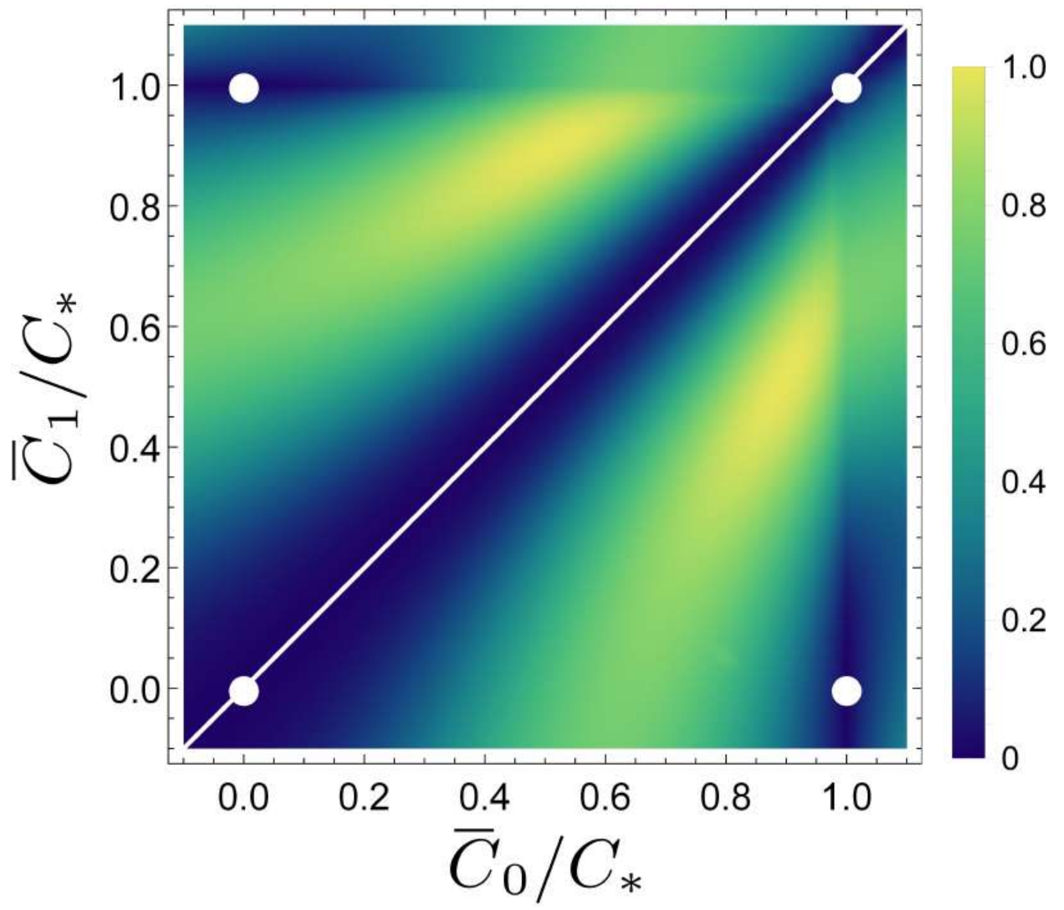


Beane, Kaplan, Klco, MJS

Entanglement - Emergent Symmetries

$$\hat{\mathbf{S}}_\sigma = \frac{1}{4}\left(3e^{i2\delta_3} + e^{i2\delta_1}\right)\hat{\mathbf{1}} \; + \; \frac{1}{4}\left(e^{i2\delta_3} - e^{i2\delta_1}\right)\hat{\boldsymbol{\sigma}}\cdot\hat{\boldsymbol{\sigma}} \qquad \mathcal{E}(\hat{\mathbf{S}}_\sigma) = \frac{1}{6}\; \sin^2\left(2(\delta_3 - \delta_1)\right)$$

Finding GS of n-body system is in **QMA**-complete - generally beyond QC



● conformal points

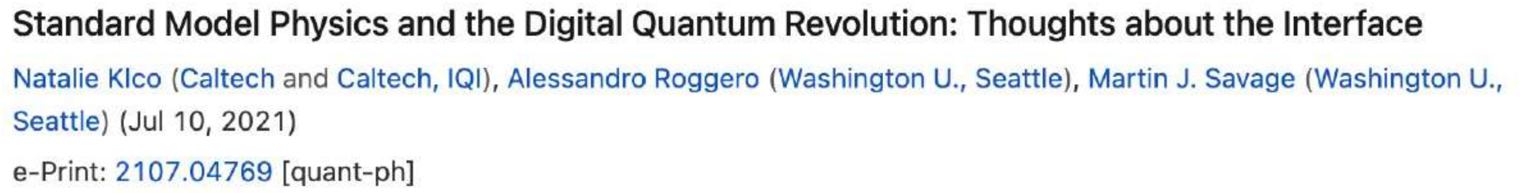
╱ Wigner symmetry

SU(4) for 2 flavors and **SU(16)** for 3 flavors (seen in LQCD calculations)
- 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

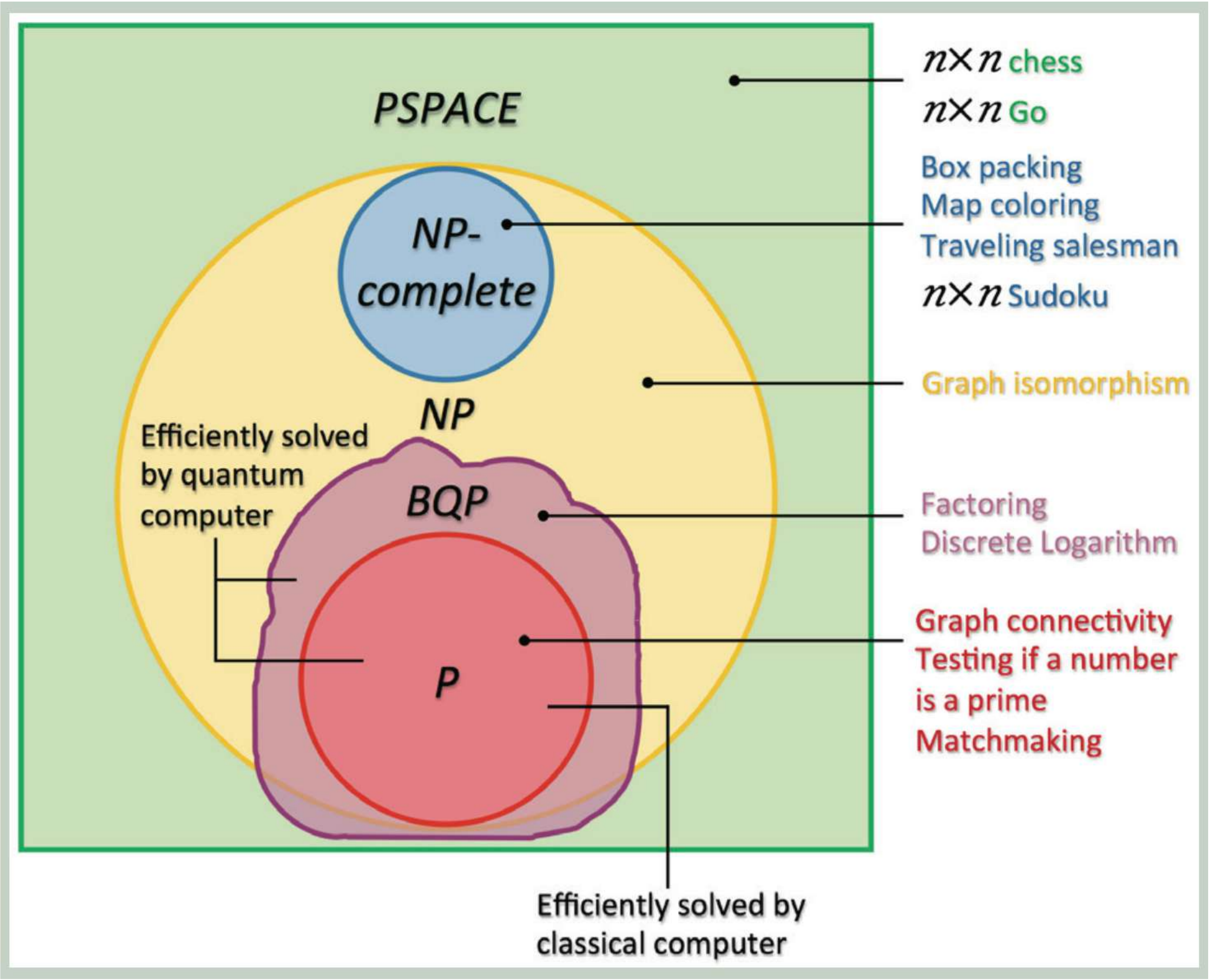
Dean Lee, et al



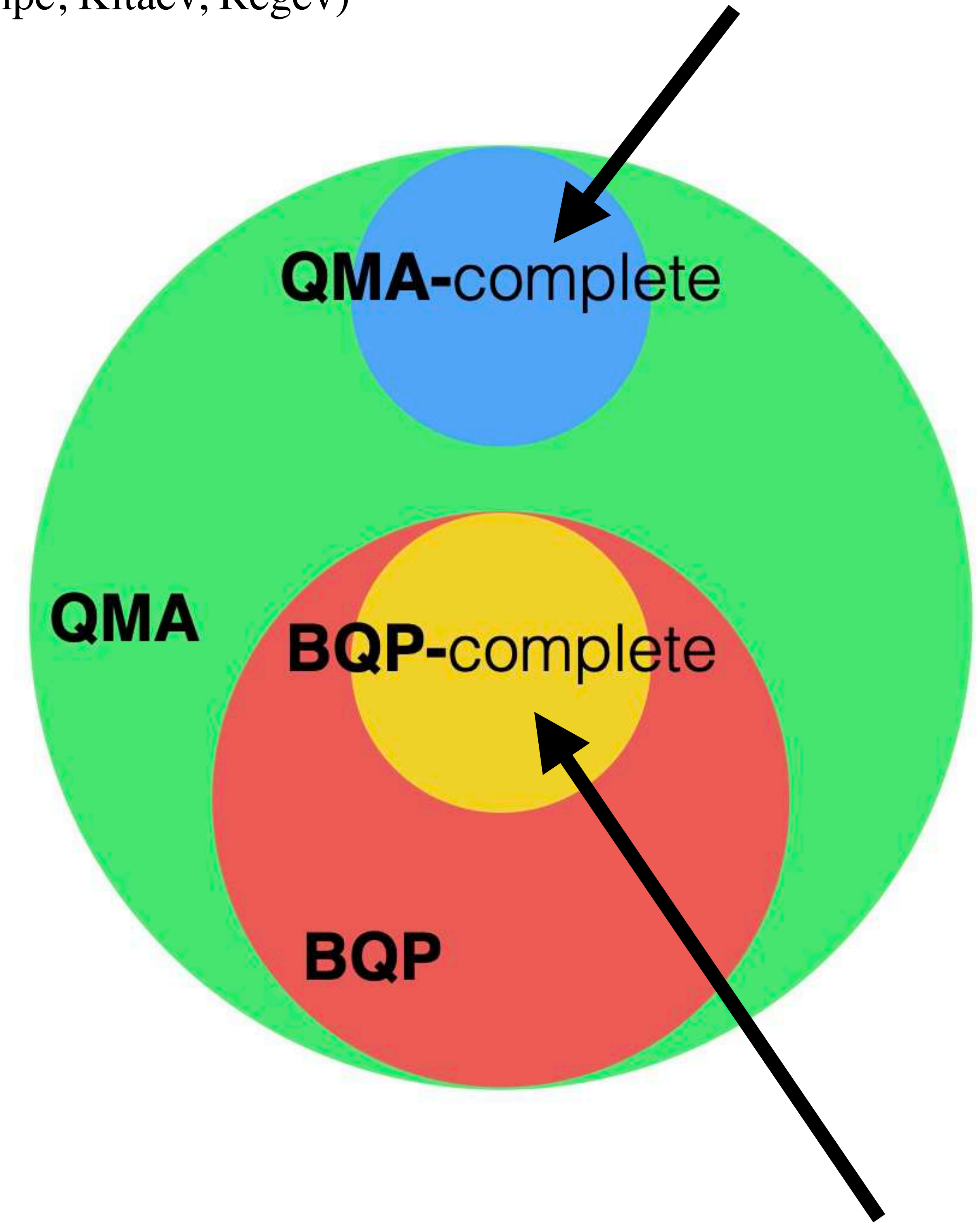
Standard Model Physics and the Digital Quantum Revolution: Thoughts about the Interface
Natalie Klco (Caltech and Caltech, IQI), Alessandro Roggero (Washington U., Seattle), Martin J. Savage (Washington U., Seattle) (Jul 10, 2021)
e-Print: 2107.04769 [quant-ph]

Complexity
The scaling of resources required to solve a problem

Scott Aaronson, Sci. Am.



g.s. of k-local Hamiltonian
(Kempe, Kitaev, Regev)



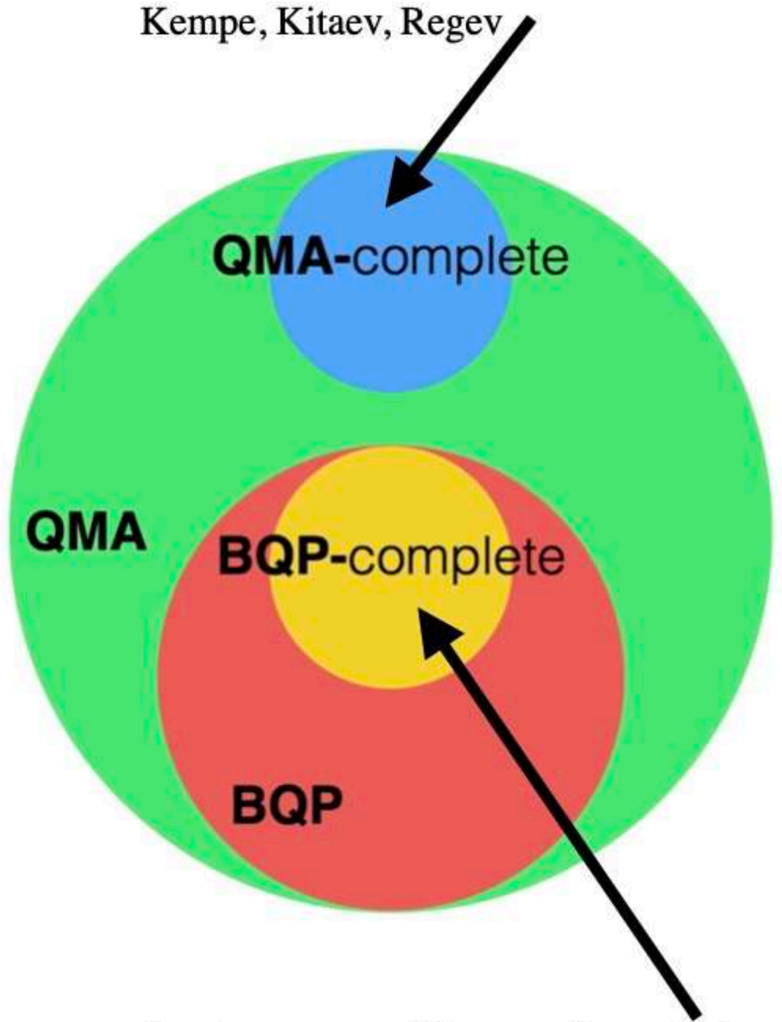
Interacting Lattice
Scalar Field Theory
(Jordan, Krovi, Lee, Preskill)

BQP = Polynomial scaling quantum resources to achieve a given precision (Bounded Error)
BPP (Bounded Probabilistic Polynomial) in BQP

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

K-local Hamiltonian

Kempe, Kitaev, Regev



Interacting Lattice Scalar Field Theory

(Jordan, Lee, Preskill)

Finite resources are not asymptotic.

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

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

Complexity class indicates worst case

- can be much easier

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

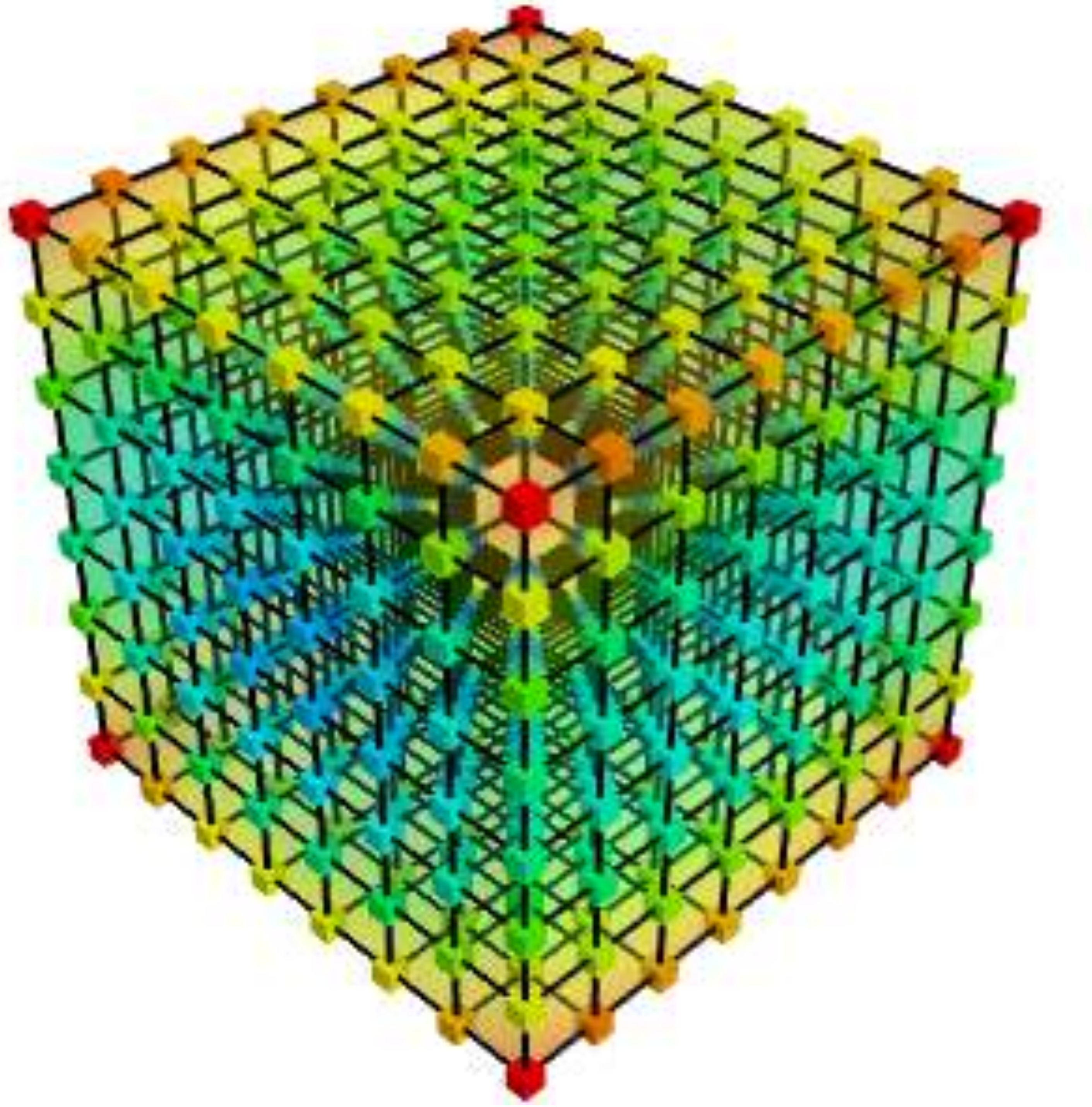
With a target precision, can use pertubative expansions to potentially change problem difficulty at (tractible) LO.

Mapping and Scaling

Seth Lloyd - Time-evolution within BQP

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

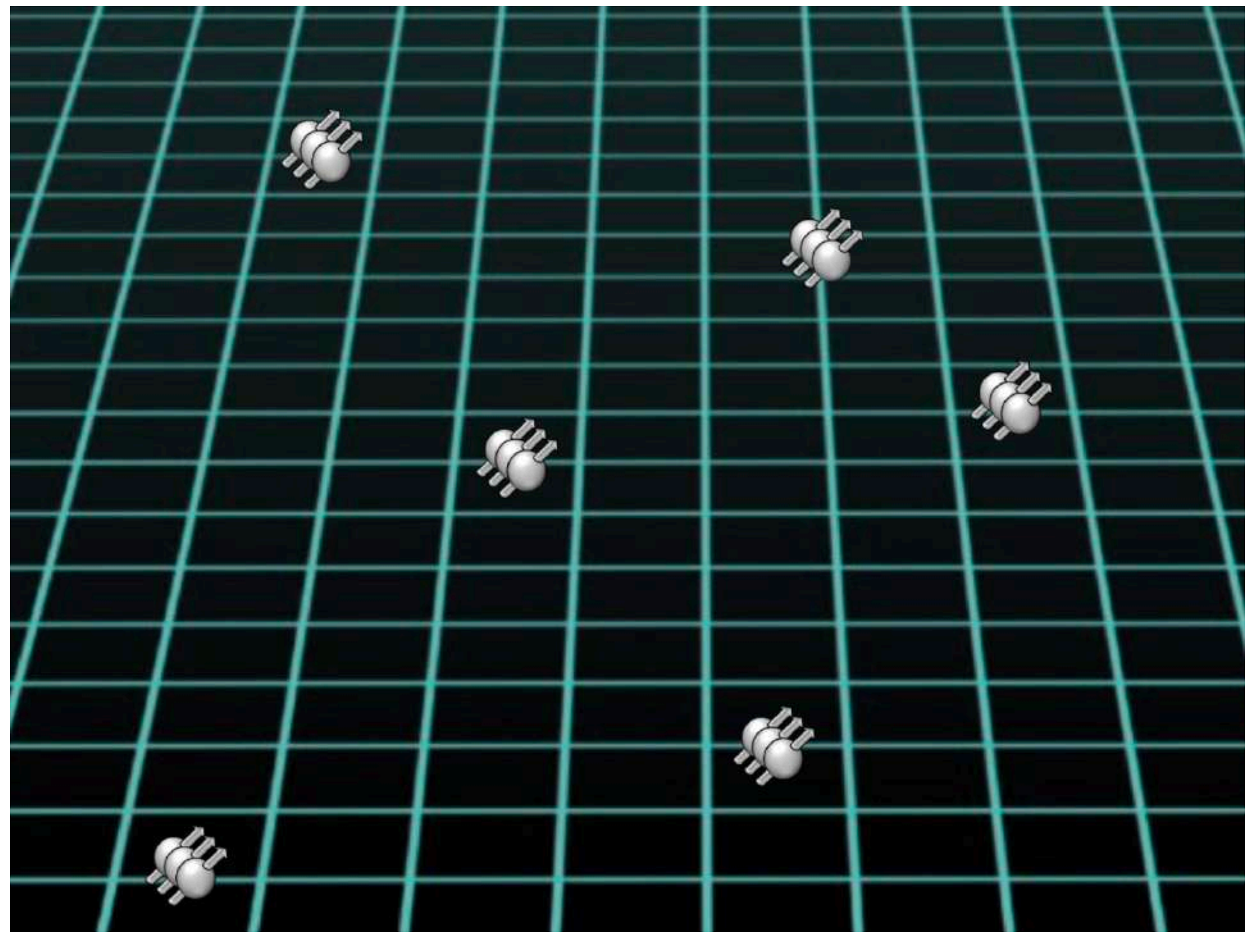
D-dim systems optimally simulated with D-dim systems.



e.g., a 2-dim systems of spins will not optimally simulate a 3-dim system of locally interacting dof.

Implications for 3-d QFT and QMBs …. co-design
i.e., understand how to “simply” scale between system and device

Quantum Field Theories



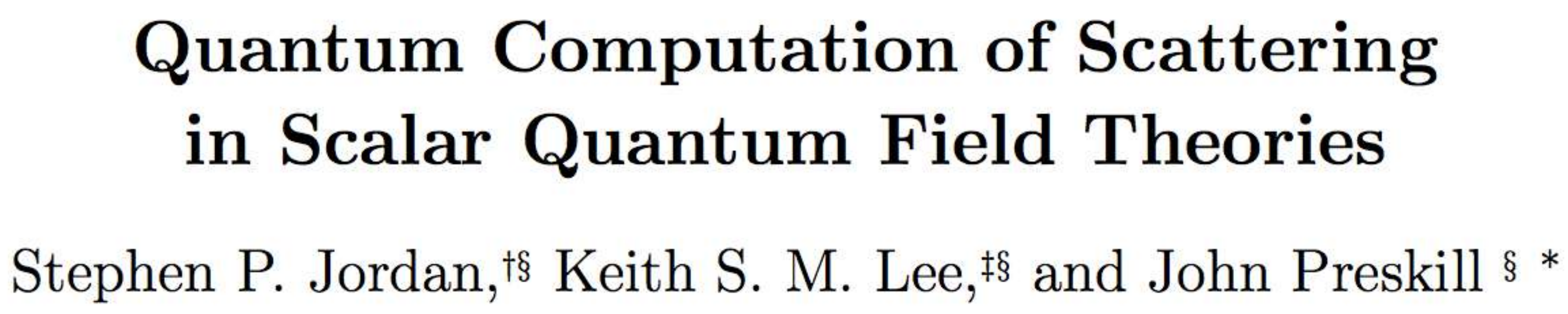
- Finite lattice to support the fields
- 3-dim
- Real-time Hamiltonian evolution
- Fields mapped to qubits/qudits
- BCs
- Hybrid - tasks for QPU?

- 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)

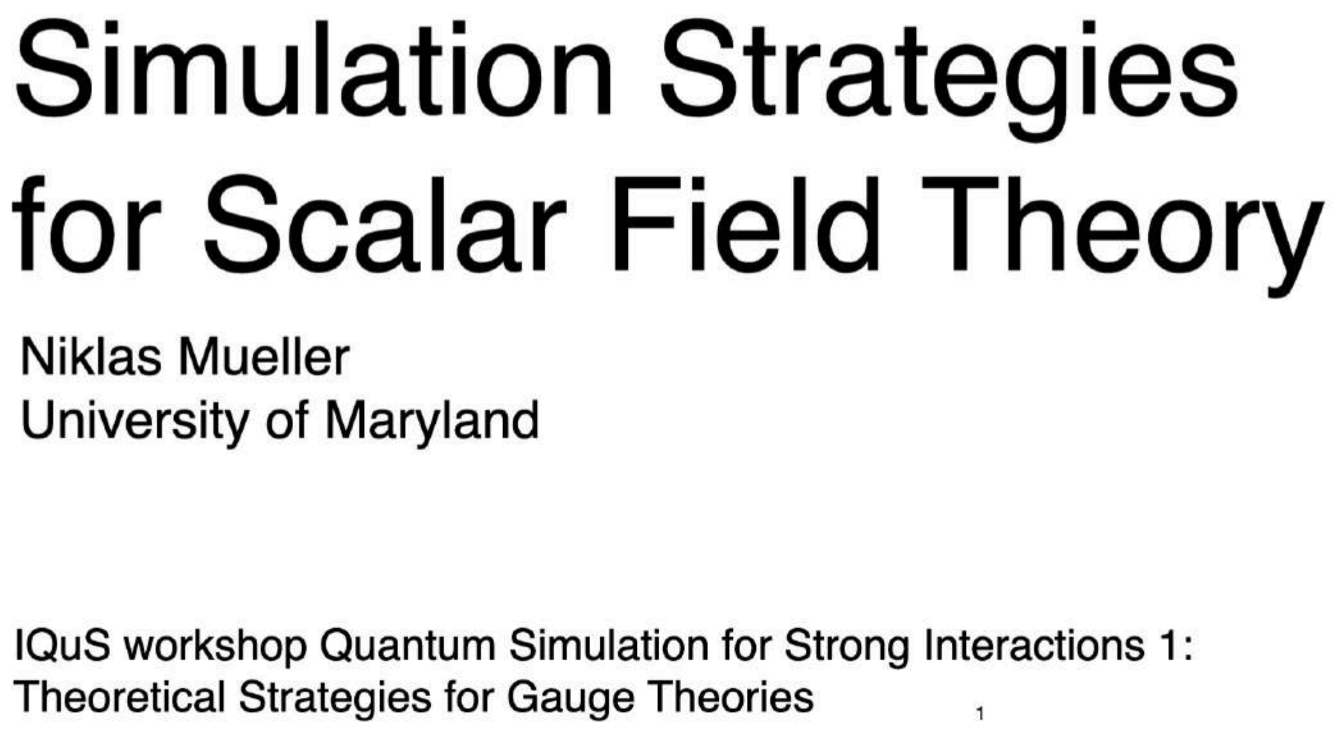
Ultimately, we will need to establish a complete quantification of uncertainties.

Scattering in Scalar Field Theory
-Gold Standard for Algorithmic Design for SM



Quantum Computation of Scattering in Scalar Quantum Field Theories

Stephen P. Jordan,[†§] Keith S. M. Lee,[‡§] and John Preskill [§] [*]



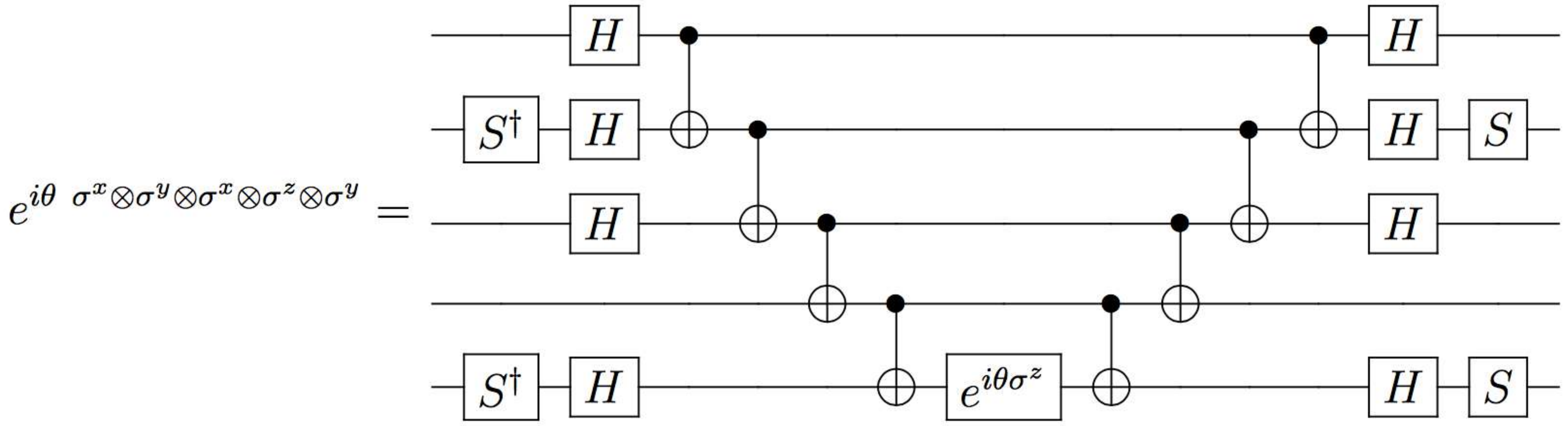
Simulation Strategies for Scalar Field Theory

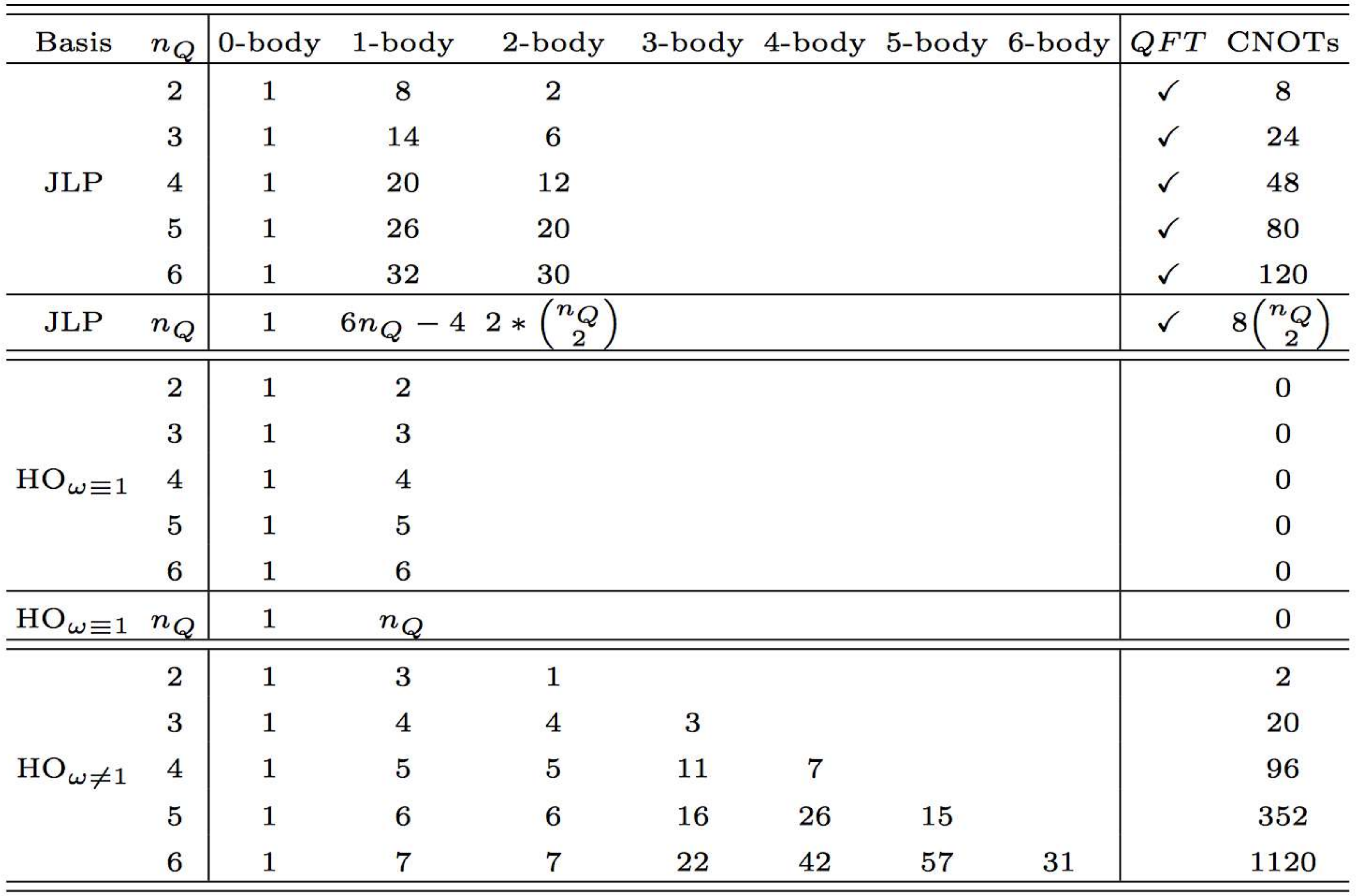
Niklas Mueller
University of Maryland

IQuS workshop Quantum Simulation for Strong Interactions 1:
Theoretical Strategies for Gauge Theories

1

Scalar Field Theory

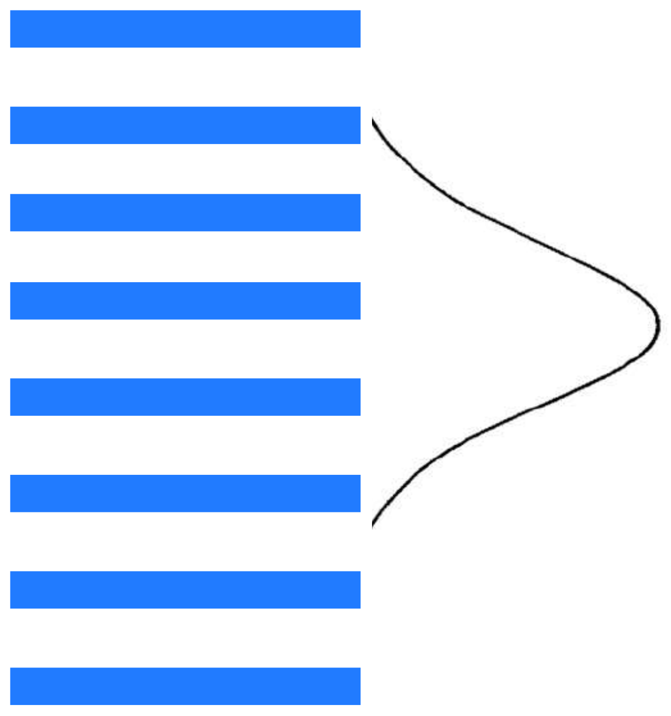


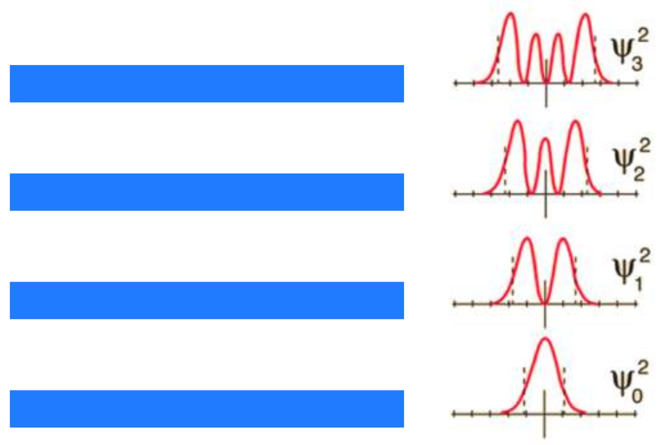


Basis	n_Q	0-body	1-body	2-body	3-body	4-body	5-body	6-body	QFT	CNOTs
JLP	2	1	8	2					✓	8
	3	1	14	6					✓	24
	4	1	20	12					✓	48
	5	1	26	20					✓	80
	6	1	32	30					✓	120
JLP	n_Q	1	$6n_Q - 4$	$2 * \binom{n_Q}{2}$					✓	$8\binom{n_Q}{2}$
$\text{HO}_{\omega\equiv1}$	2	1	2							0
	3	1	3							0
	4	1	4							0
	5	1	5							0
	6	1	6							0
$\text{HO}_{\omega\equiv1}$	n_Q	1	n_Q							0
$\text{HO}_{\omega\neq1}$	2	1	3	1						2
	3	1	4	4	3					20
	4	1	5	5	11	7				96
	5	1	6	6	16	26	15			352
	6	1	7	7	22	42	57	31		1120

Particle basis also explored
Siopsis et al

PRA 103, 042410, arXiv:2012.00020 [hep-th]
Barata, NM, Tarasov, Venugopalan





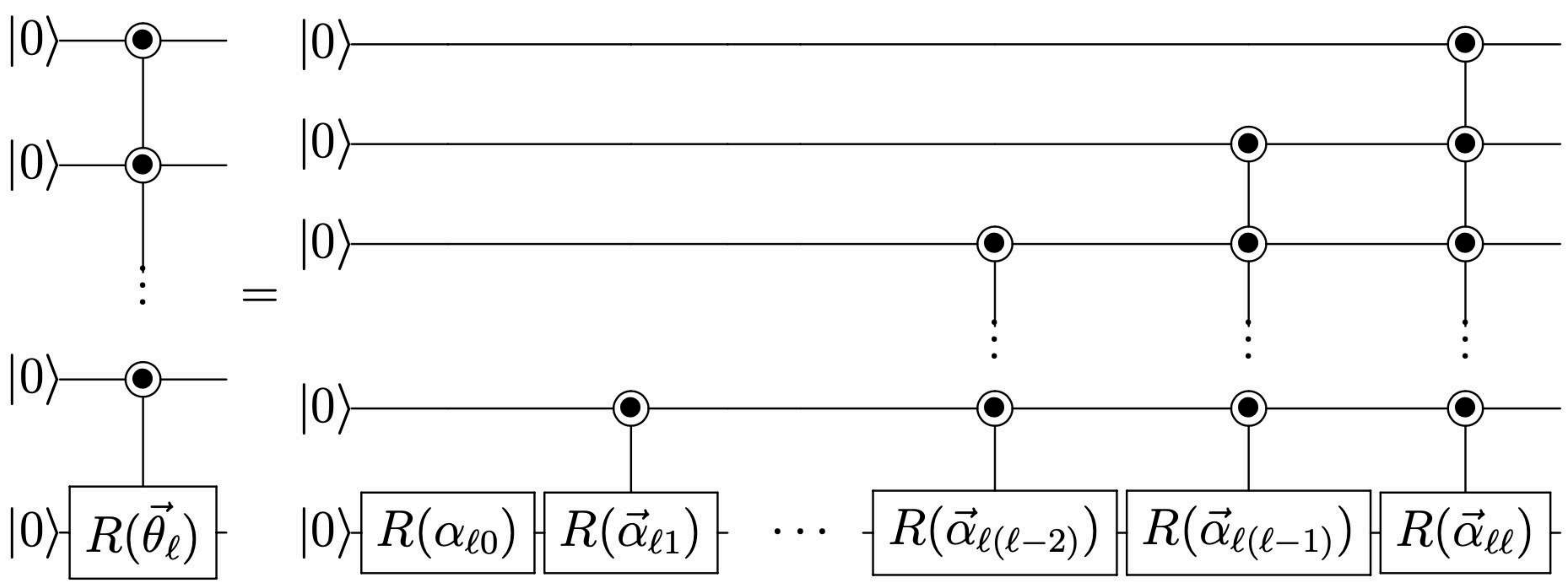
Systematically Localizable Operators for Quantum Simulations of Quantum Field Theories

Natalie Klco (Washington U., Seattle), Martin J. Savage (Dec 7, 2019)

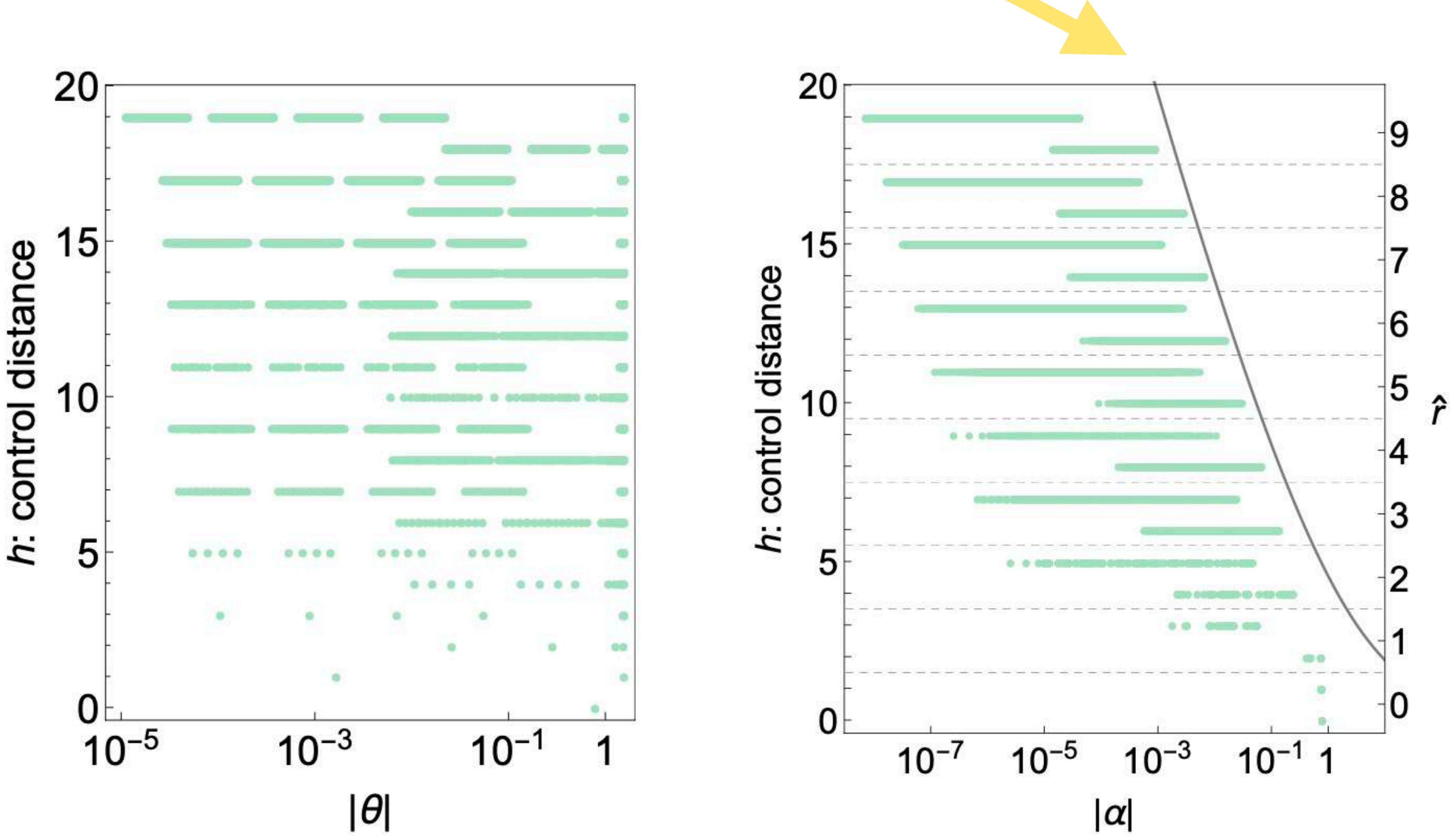
Published in: *Phys.Rev.A* 102 (2020) 1, 012619 • e-Print: 1912.03577 [quant-ph]

Scalar Field Theory

If mapping reflects physical system - as it must for optimal simulation - build in physical correlation lengths into state preparation circuit design



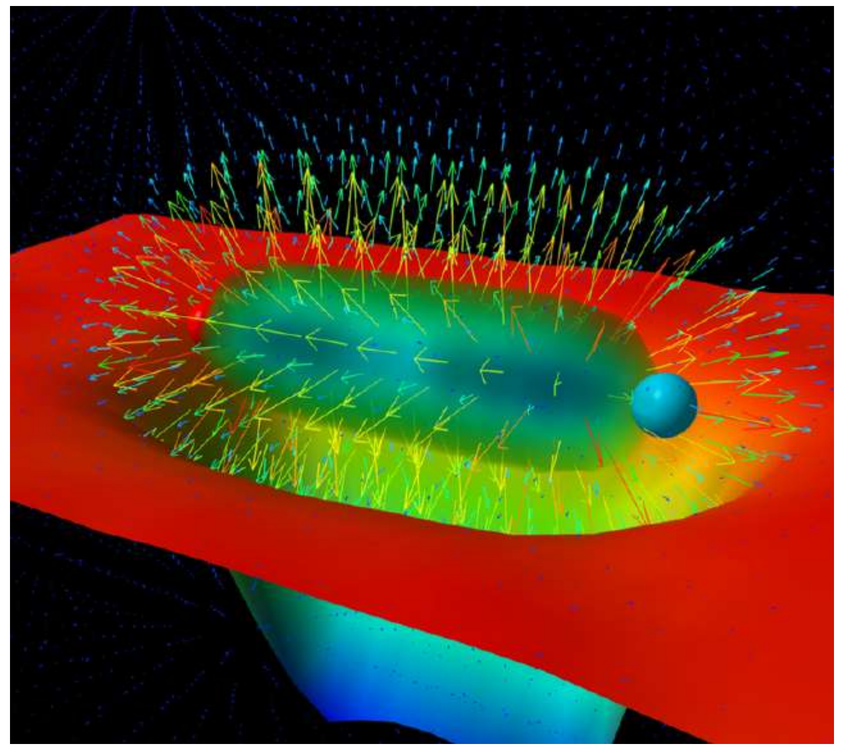
Classical correlation
modified Bessel function

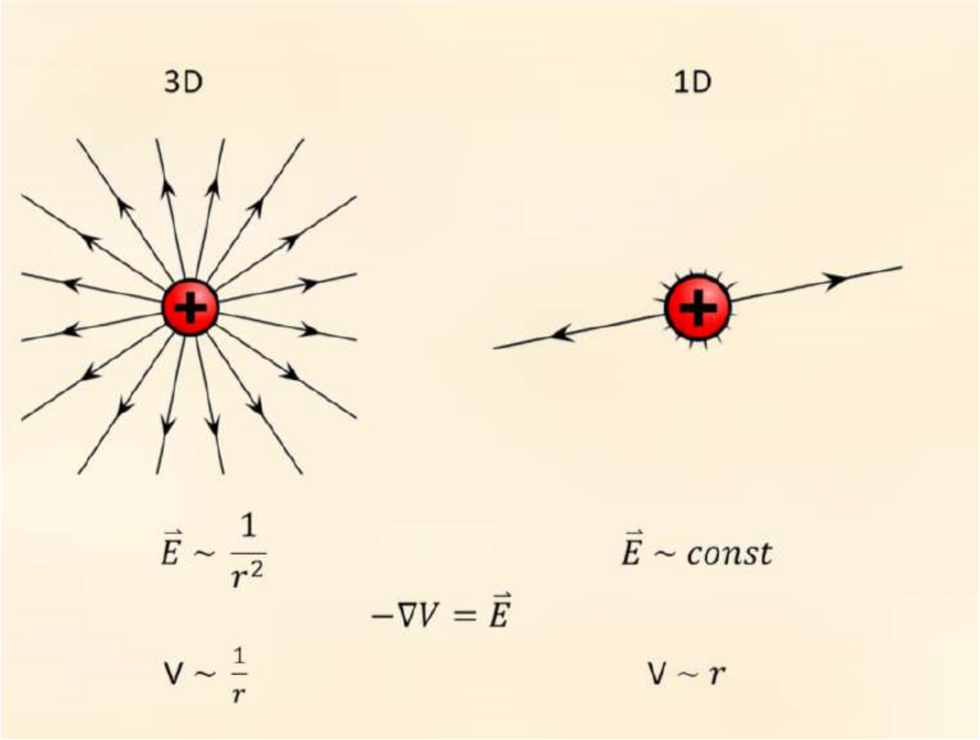


Schwinger Model

$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - gA\!\!\!/ - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{g\theta}{4\pi}\varepsilon^{\mu\nu}F_{\mu\nu}$$

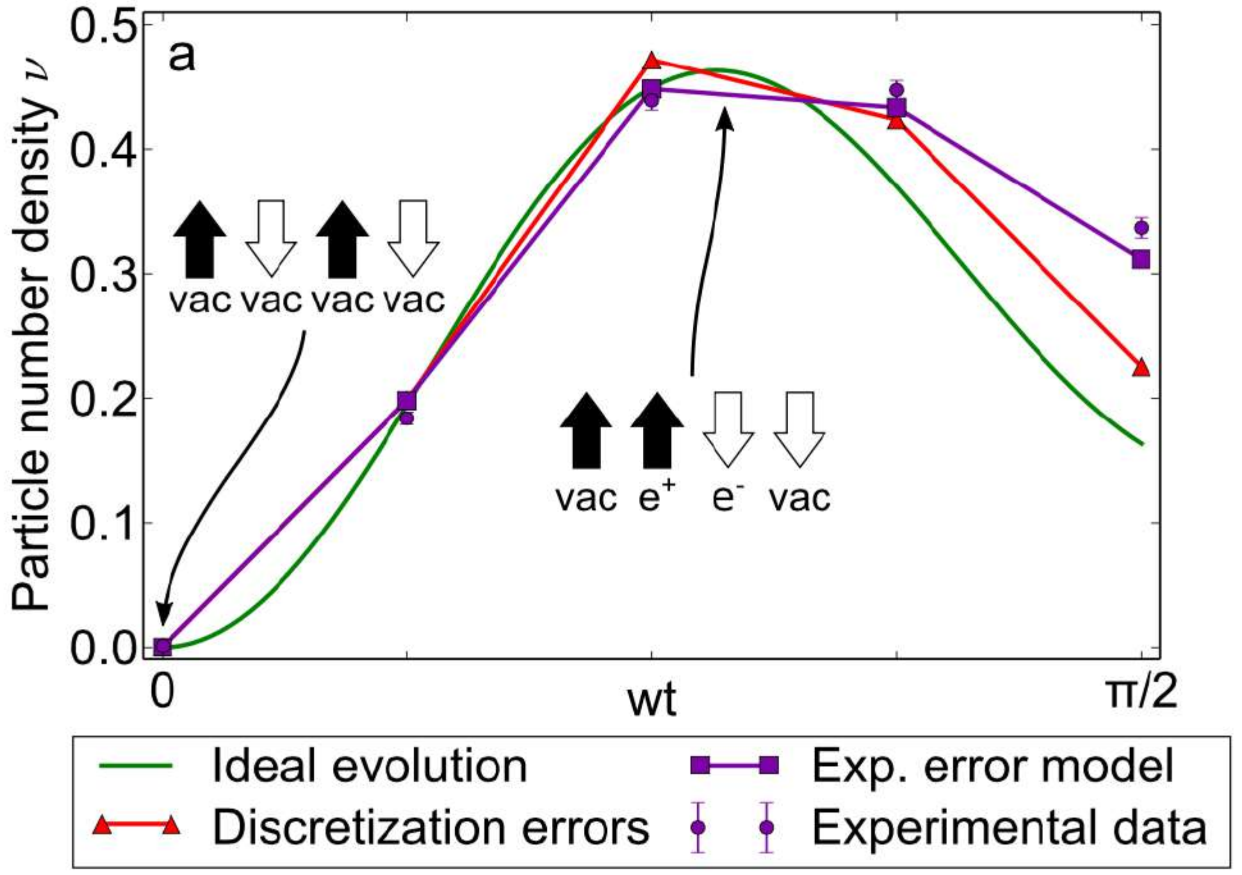
- Charge screening, confinement
- fermion condensate

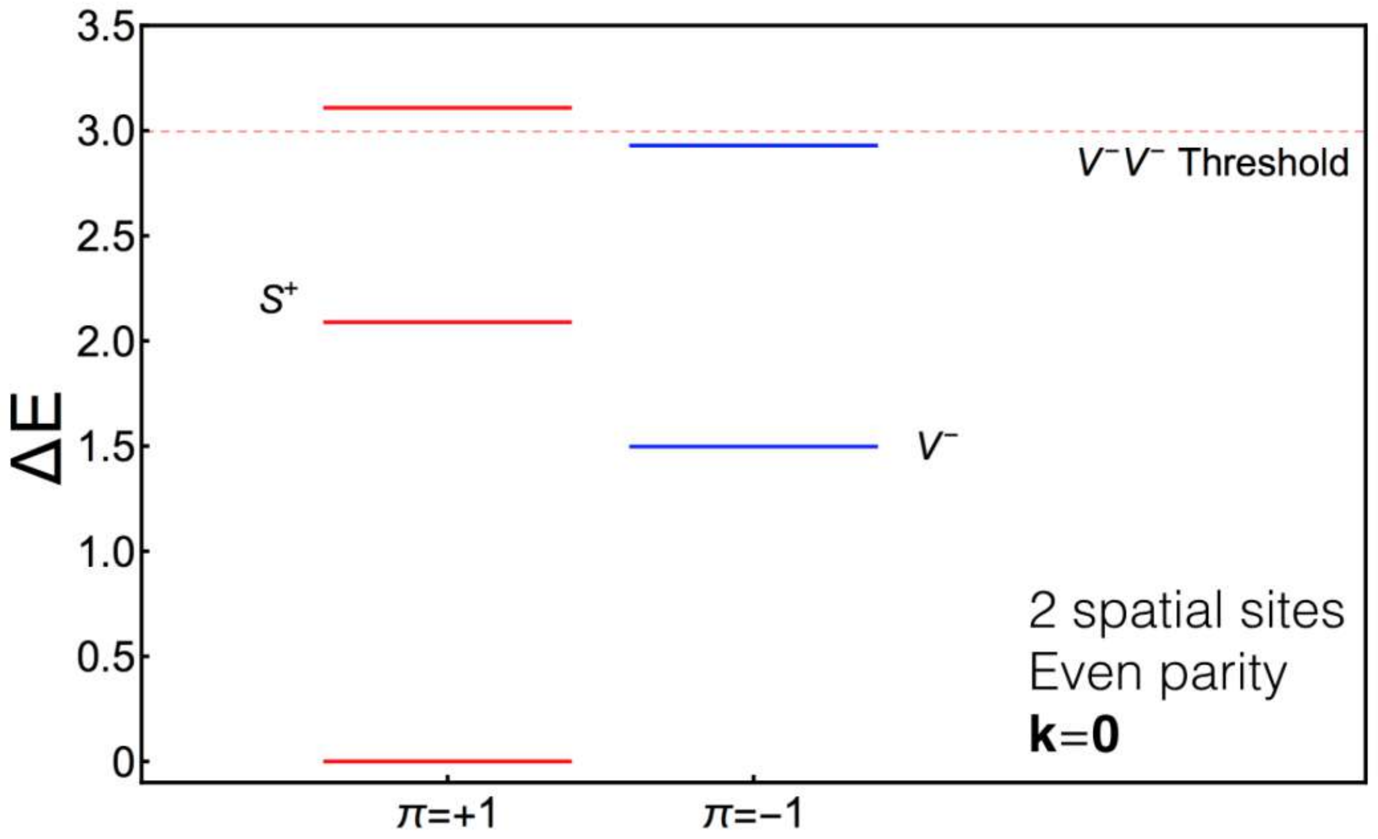

Derek Leinweber



Natalie Klco

$$\hat{H} = x \sum_{n=0}^{N_{fs}-1} \left(\sigma_n^+ L_n^- \sigma_{n+1}^- + \sigma_{n+1}^+ L_n^+ \sigma_n^-\right) + \sum_{n=0}^{N_{fs}-1} \left(l_n^2 + \frac{\mu}{2}(-)^n \sigma_n^z\right) .$$





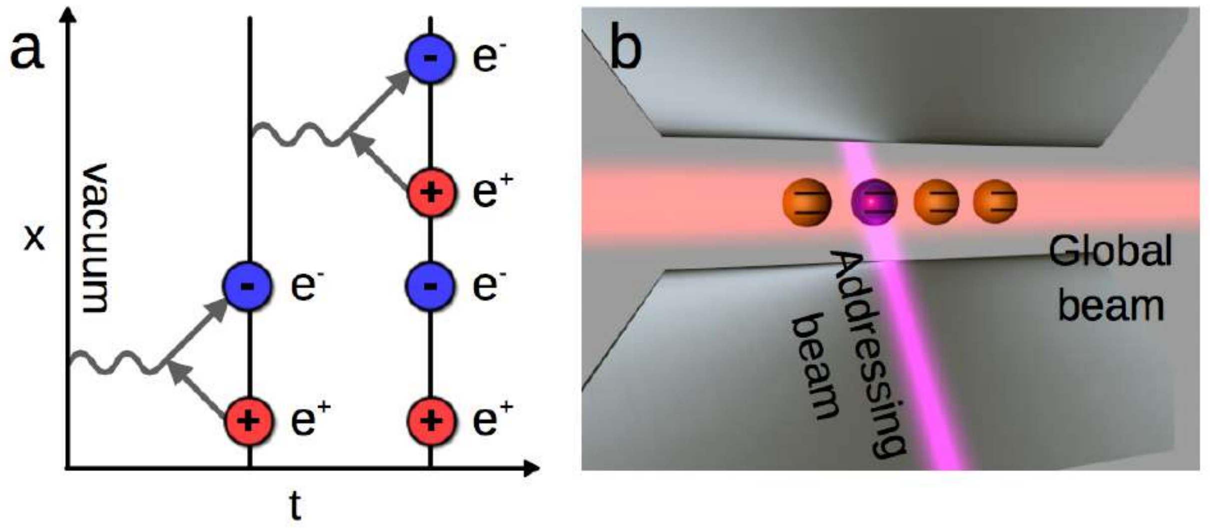
Dynamics in the Schwinger Model
1-dim systems

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

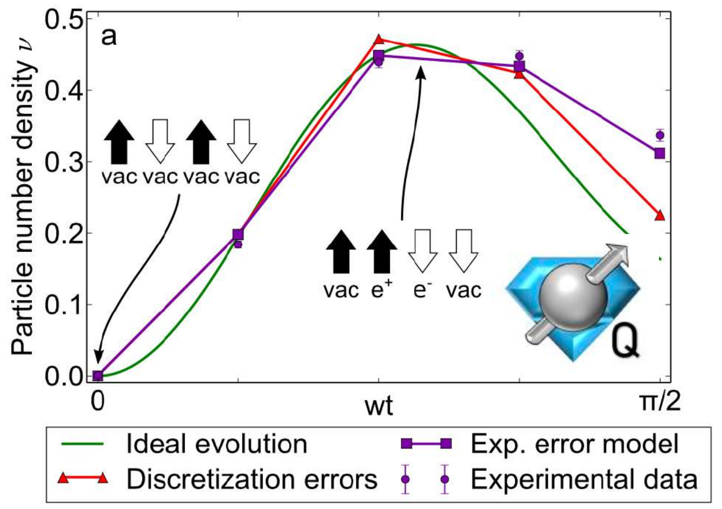
Esteban A. Martinez,[1,*] Christine Muschik,[2,3,*] Philipp Schindler,[1] Daniel Nigg,[1] Alexander Erhard,[1] Markus Heyl,[2,4] Philipp Hauke,[2,3] Marcello Dalmonte,[2,3] Thomas Monz,[1] Peter Zoller,[2,3] and Rainer Blatt[1,2]

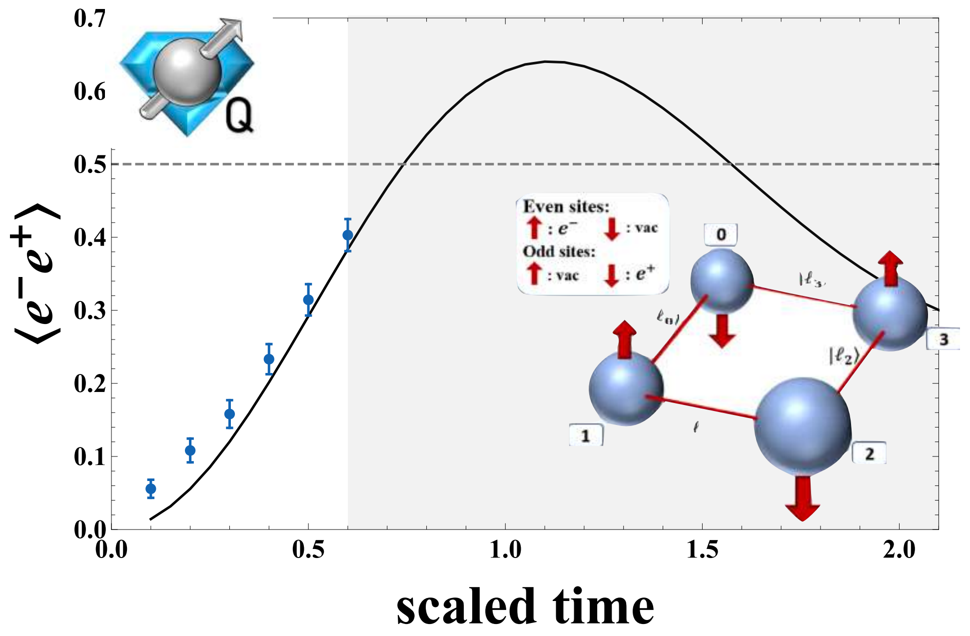
1+1 dim QED

(2016)

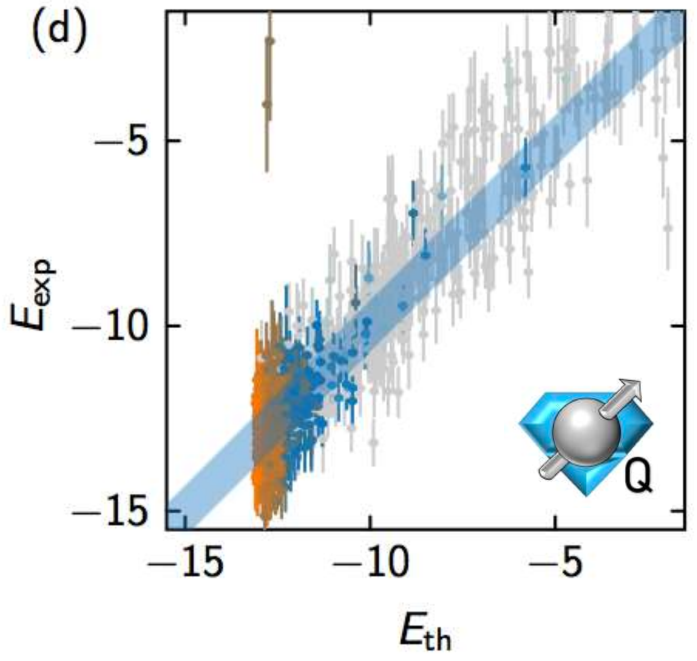


Innesbruck

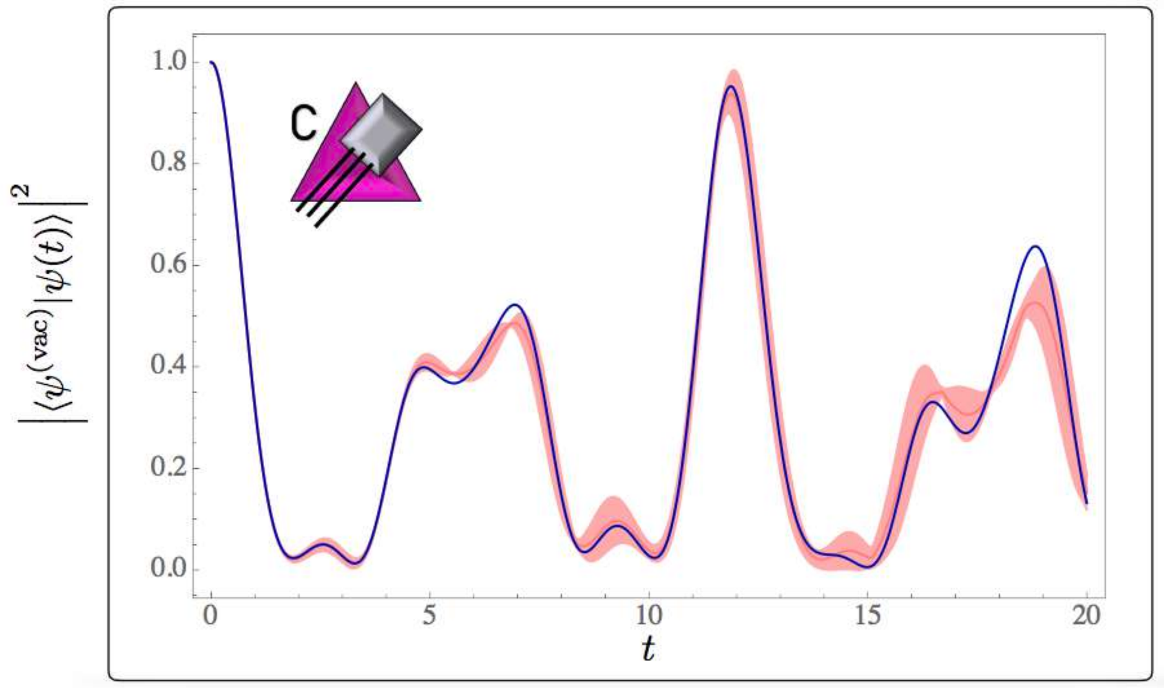




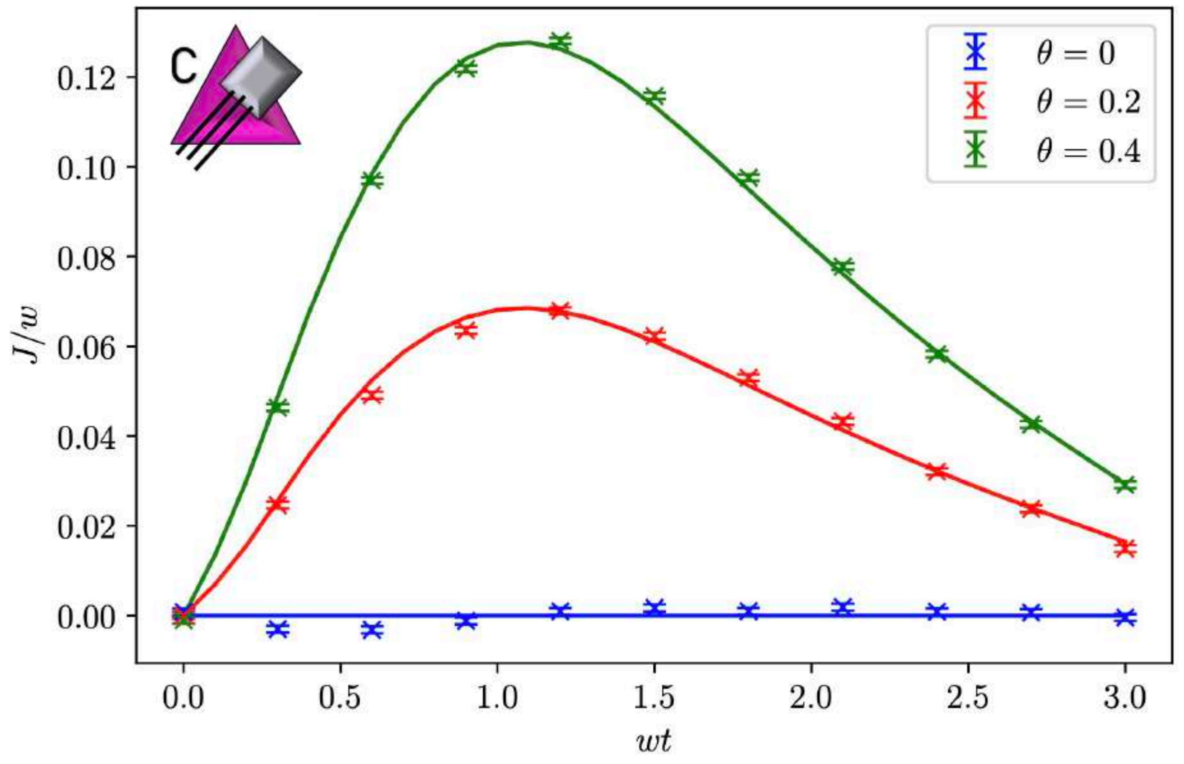
ORNL-Washington-Basque



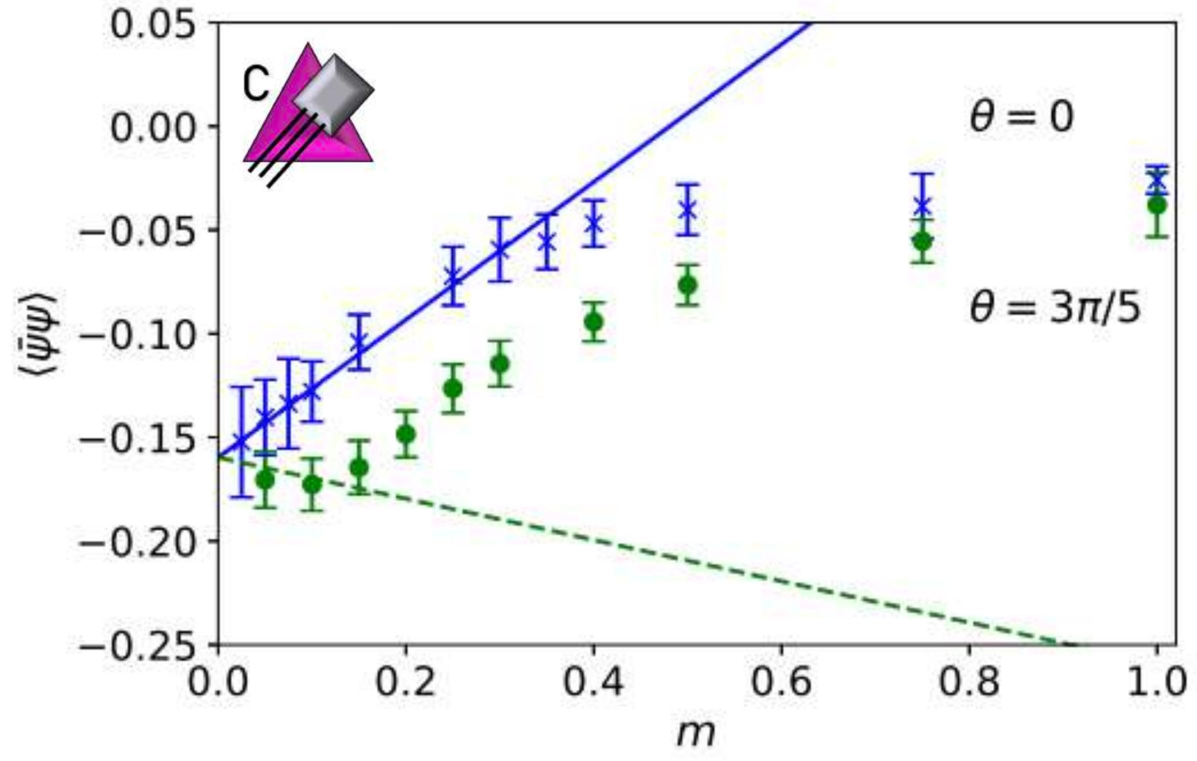
Innesbruck



Davoudi et al - Maryland



Kharzeev-Kikuchi



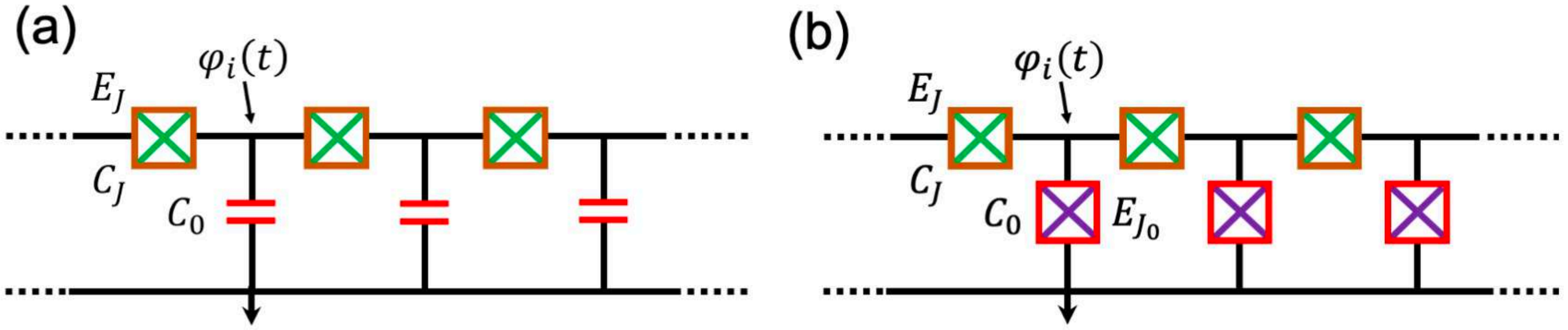
Chakraborty, Honda, Izubuchi, Tomiya

Quantum Algorithms for Simulating the Lattice Schwinger Model

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

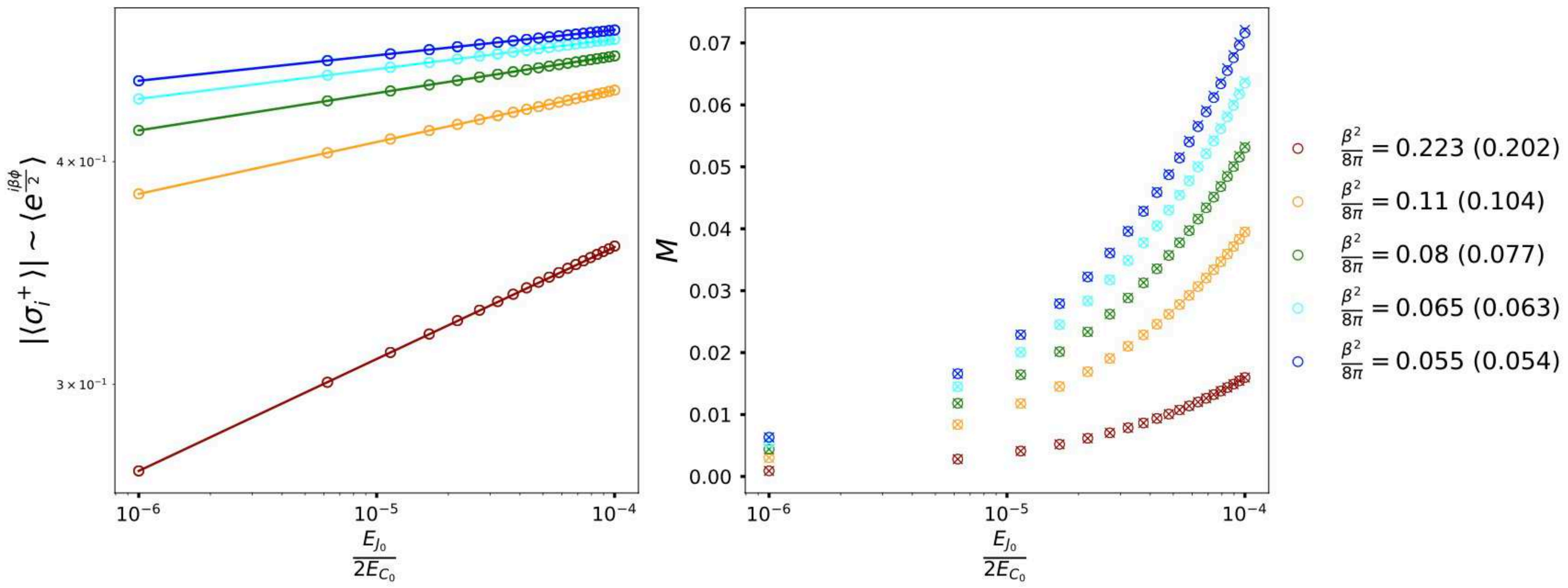
Analog Quantum Simulation with Quantum Circuits

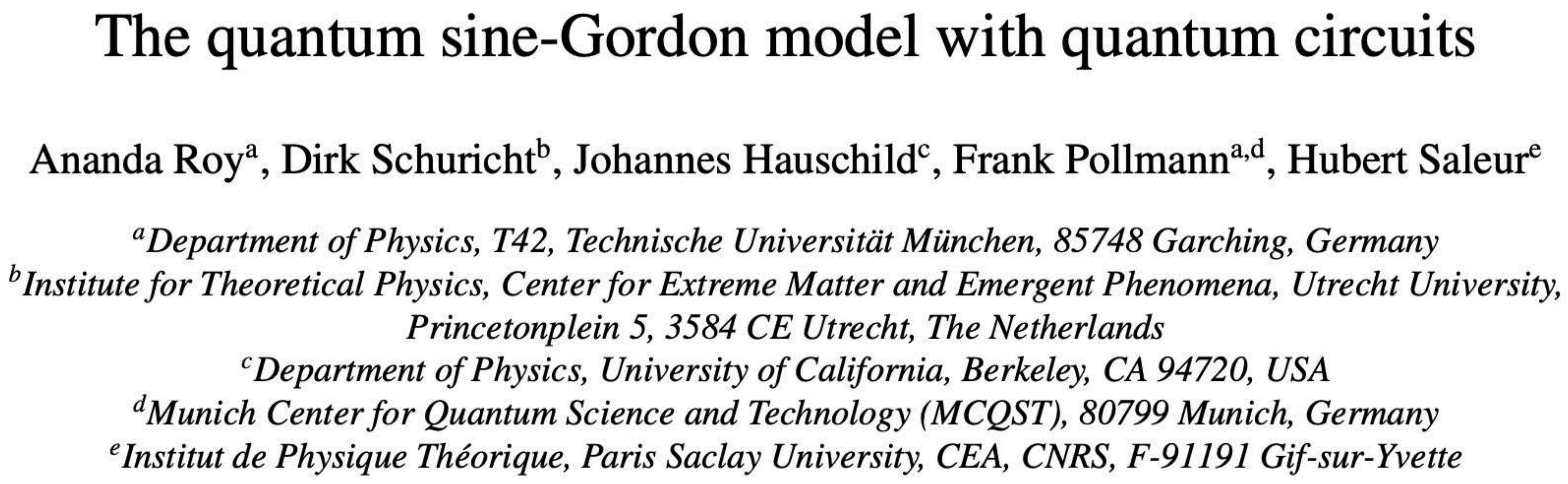
From presentation by Ananda Roy at IQuS



Lattice CFT

Lattice Sine-Gordon





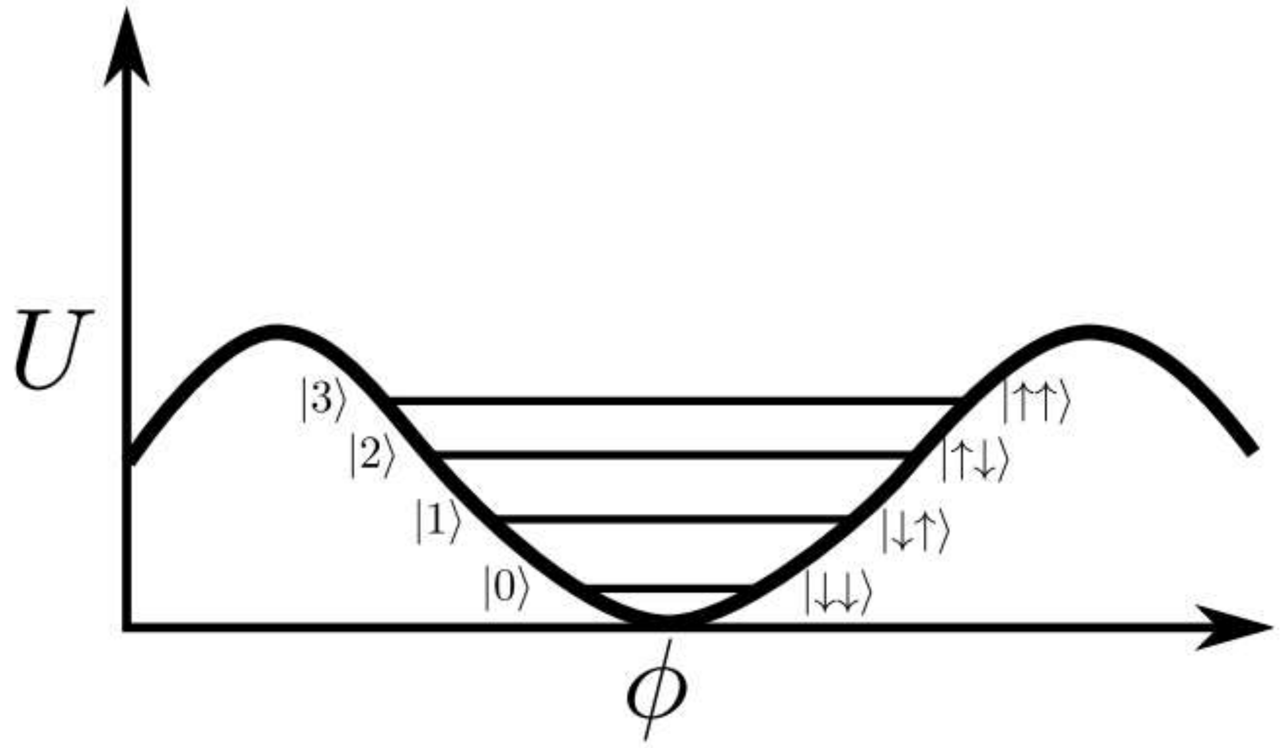
The quantum sine-Gordon model with quantum circuits

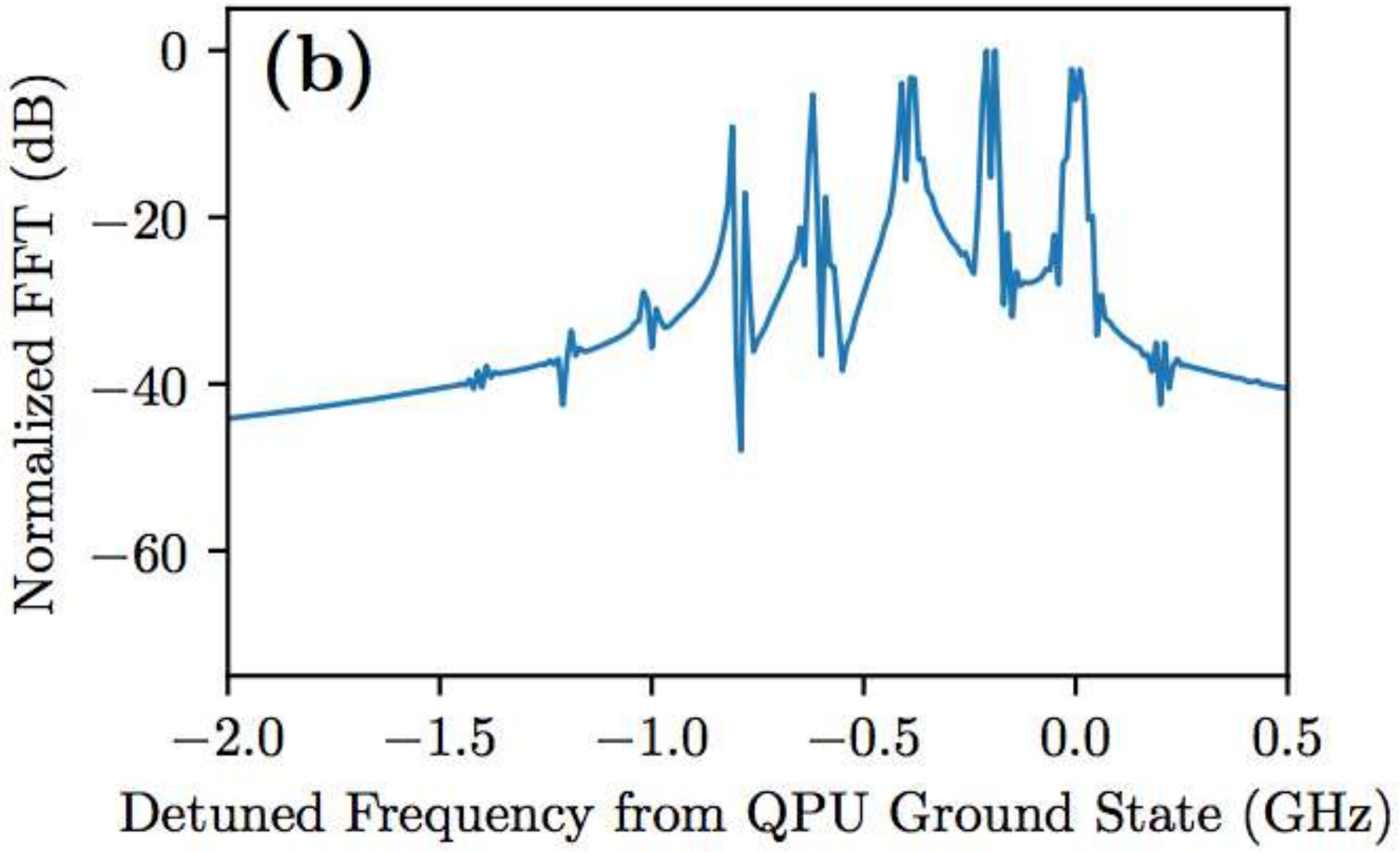
Ananda Roy[a], Dirk Schuricht[b], Johannes Hauschild[c], Frank Pollmann[a,d], Hubert Saleur[e]

[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*

Analog Quantum Simulation with SRF Cavities

LLNL-Trento and FermiLab





Toward nuclear reactions and quantum field theories

Published: 14 March 2010

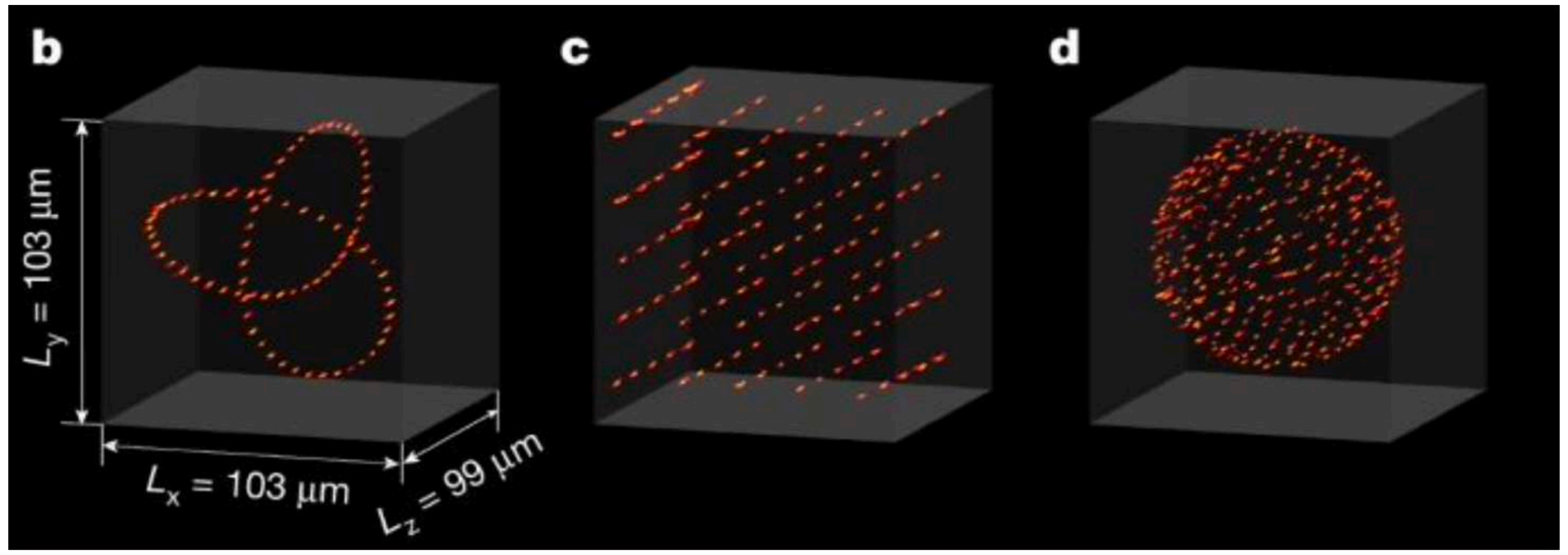
A Rydberg quantum simulator

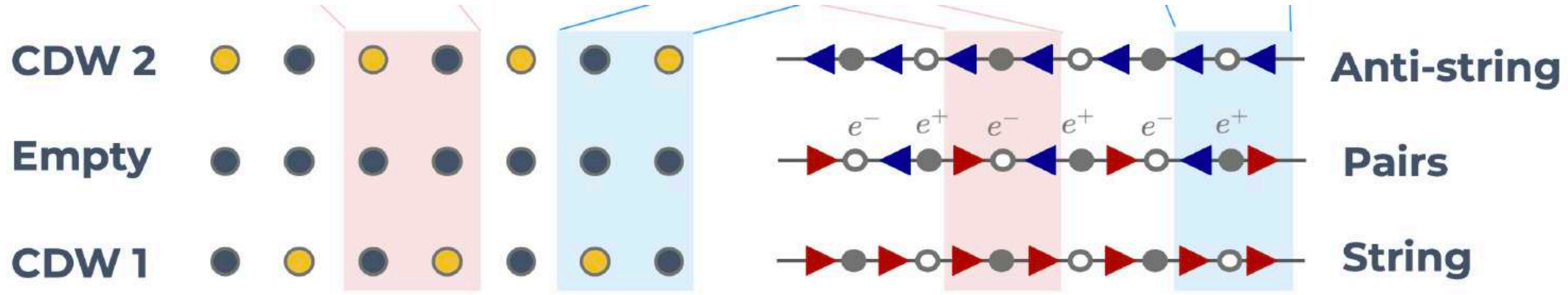
Hendrik Weimer, Markus Müller, Igor Lesanovsky, Peter Zoller & Hans Peter Büchler

Nature Physics **6**, 382–388 (2010) | Cite this article

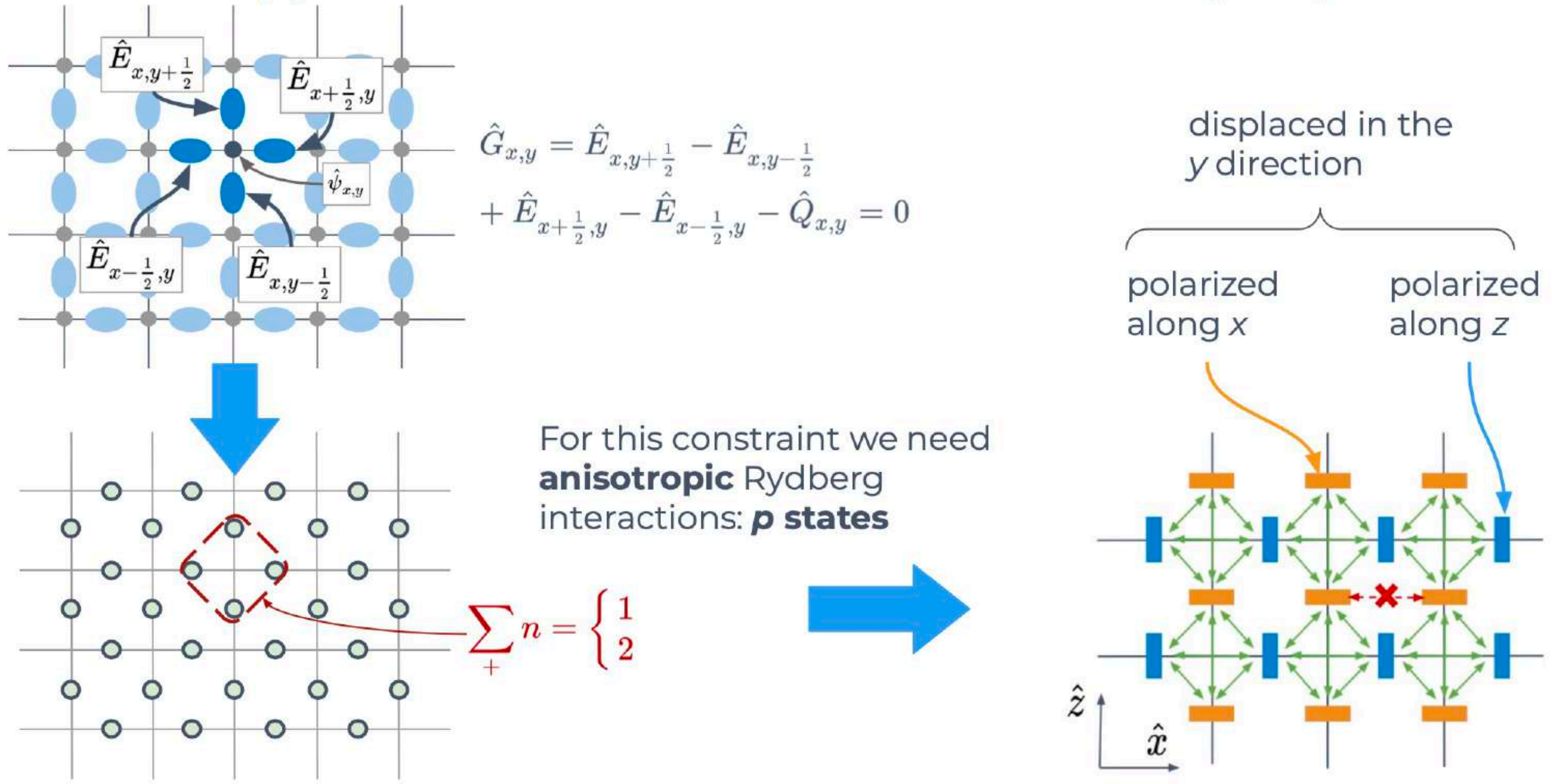
Simulations with Rydberg Atoms
Link Models and Gauge Theories

From presentation by
Federica Surace at IQuS





U(1) LATTICE GAUGE THEORY IN (2+1)D

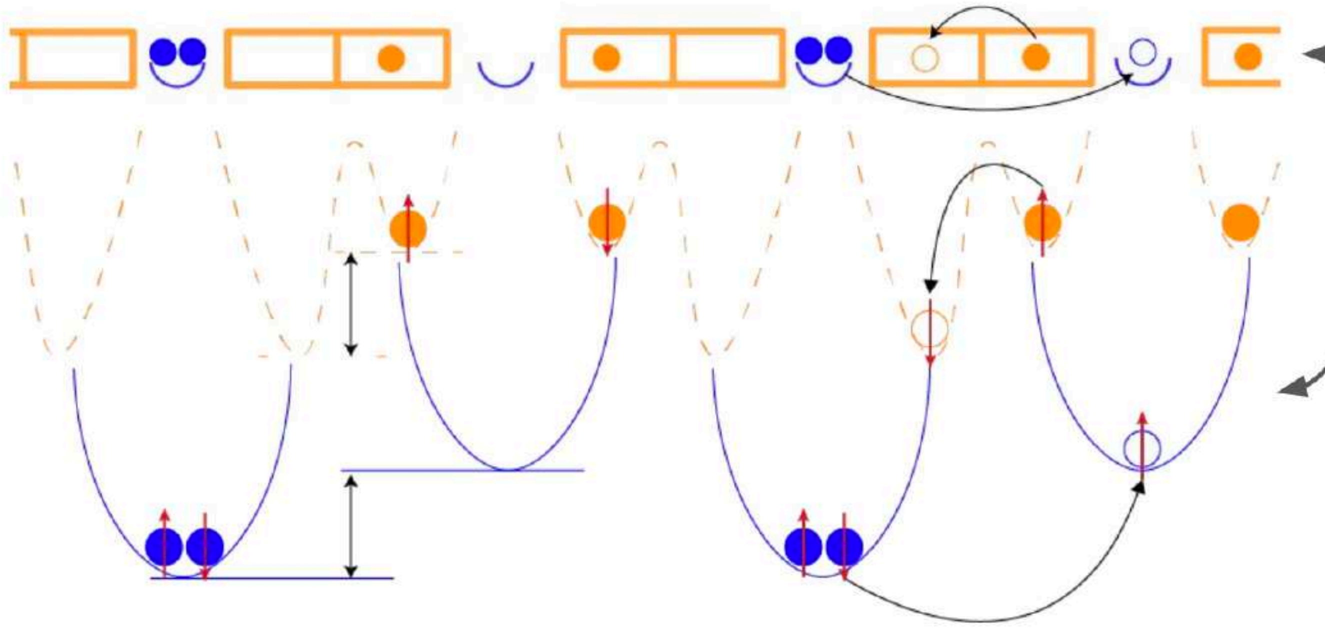


$$\hat{G}_{x,y} = \hat{E}_{x,y+\frac{1}{2}} - \hat{E}_{x,y-\frac{1}{2}} + \hat{E}_{x+\frac{1}{2},y} - \hat{E}_{x-\frac{1}{2},y} - \hat{Q}_{x,y} = 0$$

For this constraint we need **anisotropic** Rydberg interactions: ***p* states**

RESONANT GAUGE-INVARIANT SUBSPACE

SU(N)xU(1) Quantum link models



U(N) QLM with $\mathcal{N} = 1$ rishon per link

^{173}Yb in an optical lattice
- 2 orbitals
  - g ↔ ψ
  - e ↔ U
- SU(N) symmetry
- strong interorbital interactions

$$H = H_0 + V \qquad [H_0, G_x^a] = 0$$

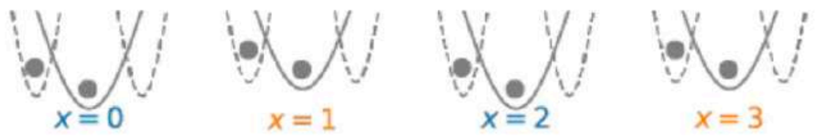
$$\mathcal{P}_{res} H \mathcal{P}_{res}^{-1} = H_{QLM}$$

AB INITIO PREDICTIONS

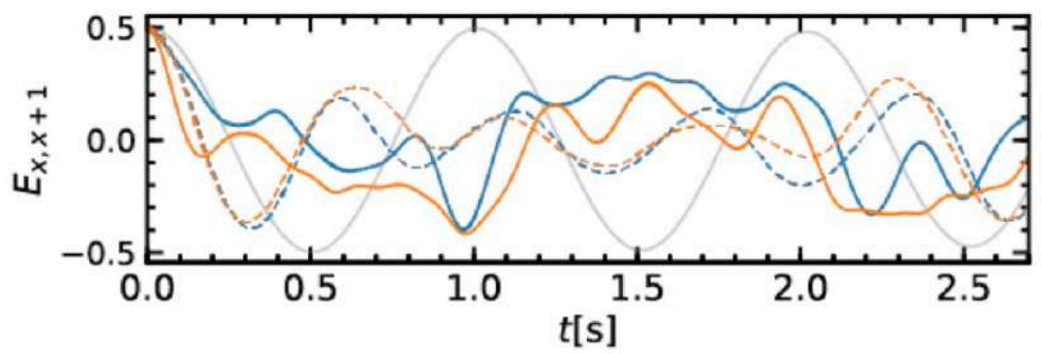
simulations for N=2

4 matter + 8 gauge sites, PBC

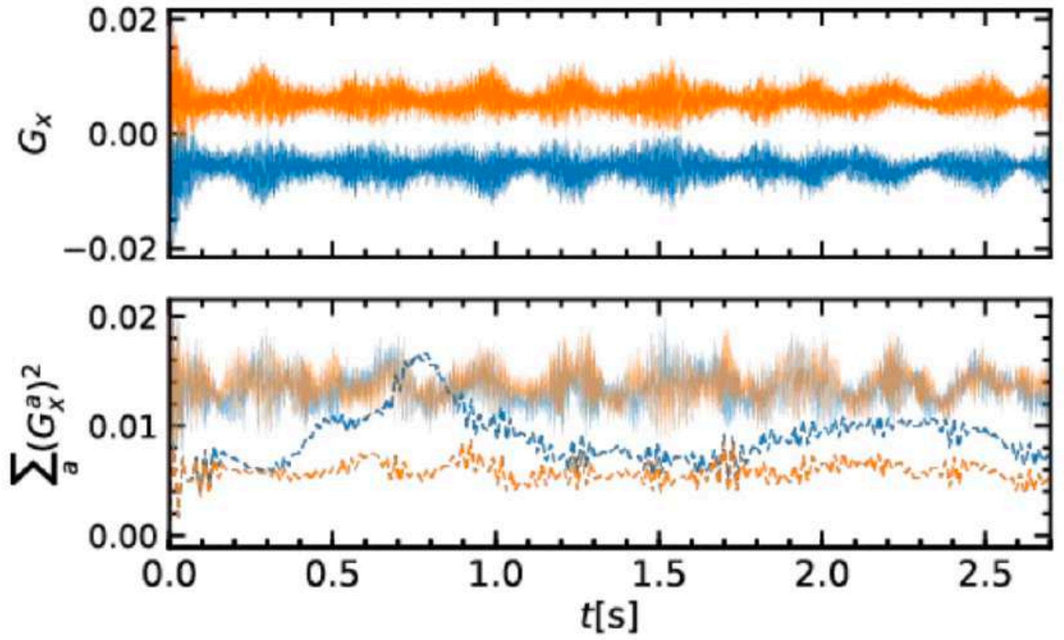
Initial state

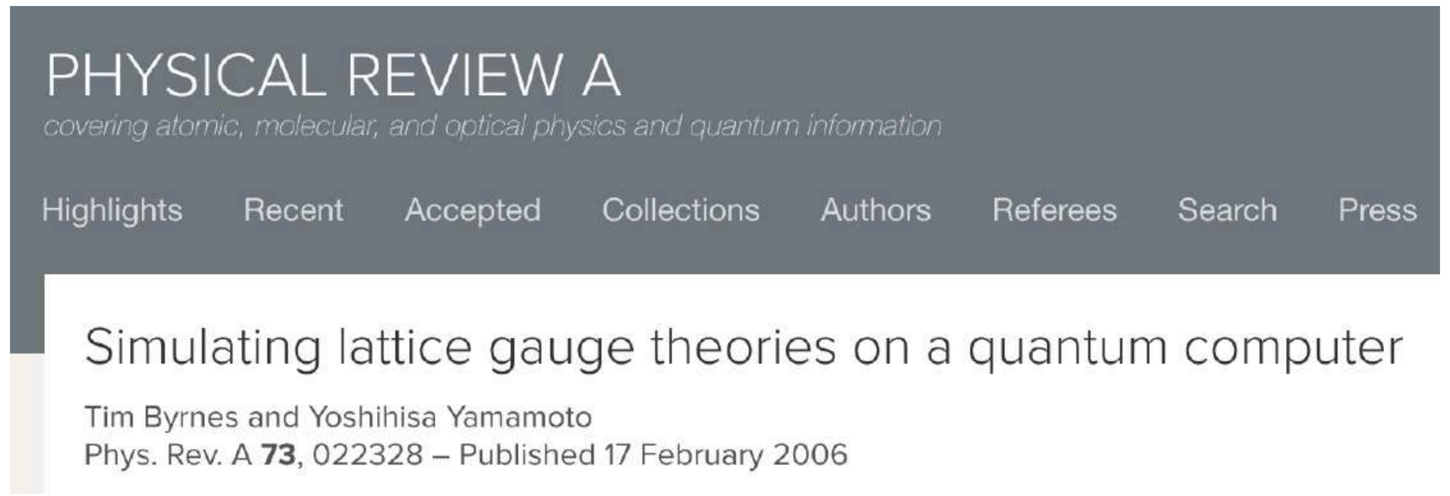


Time evolution



Conservation laws




PHYSICAL REVIEW A

covering atomic, molecular, and optical physics and quantum information

Highlights Recent Accepted Collections Authors Referees Search Press

Simulating lattice gauge theories on a quantum computer

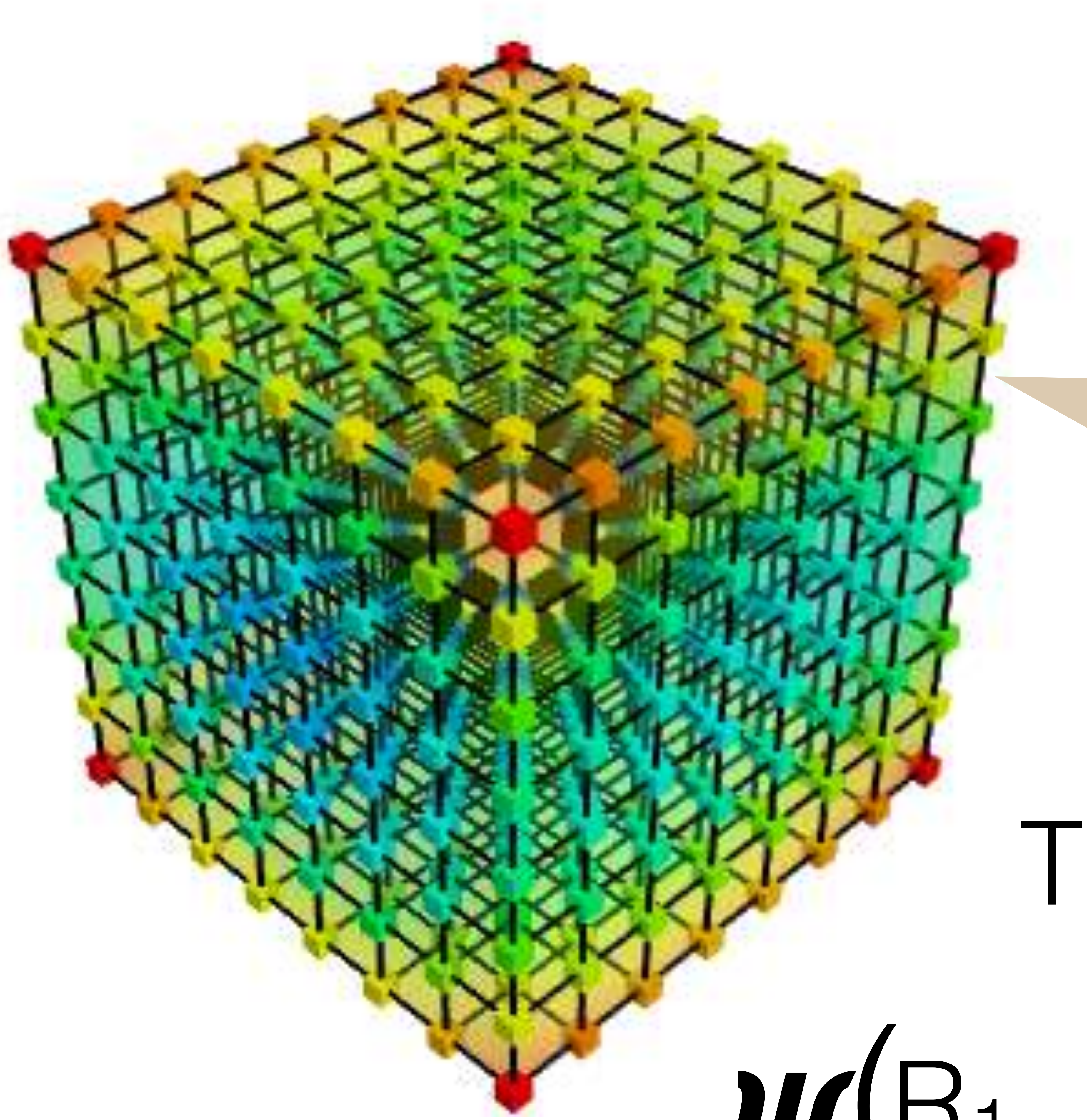
Tim Byrnes and Yoshihisa Yamamoto

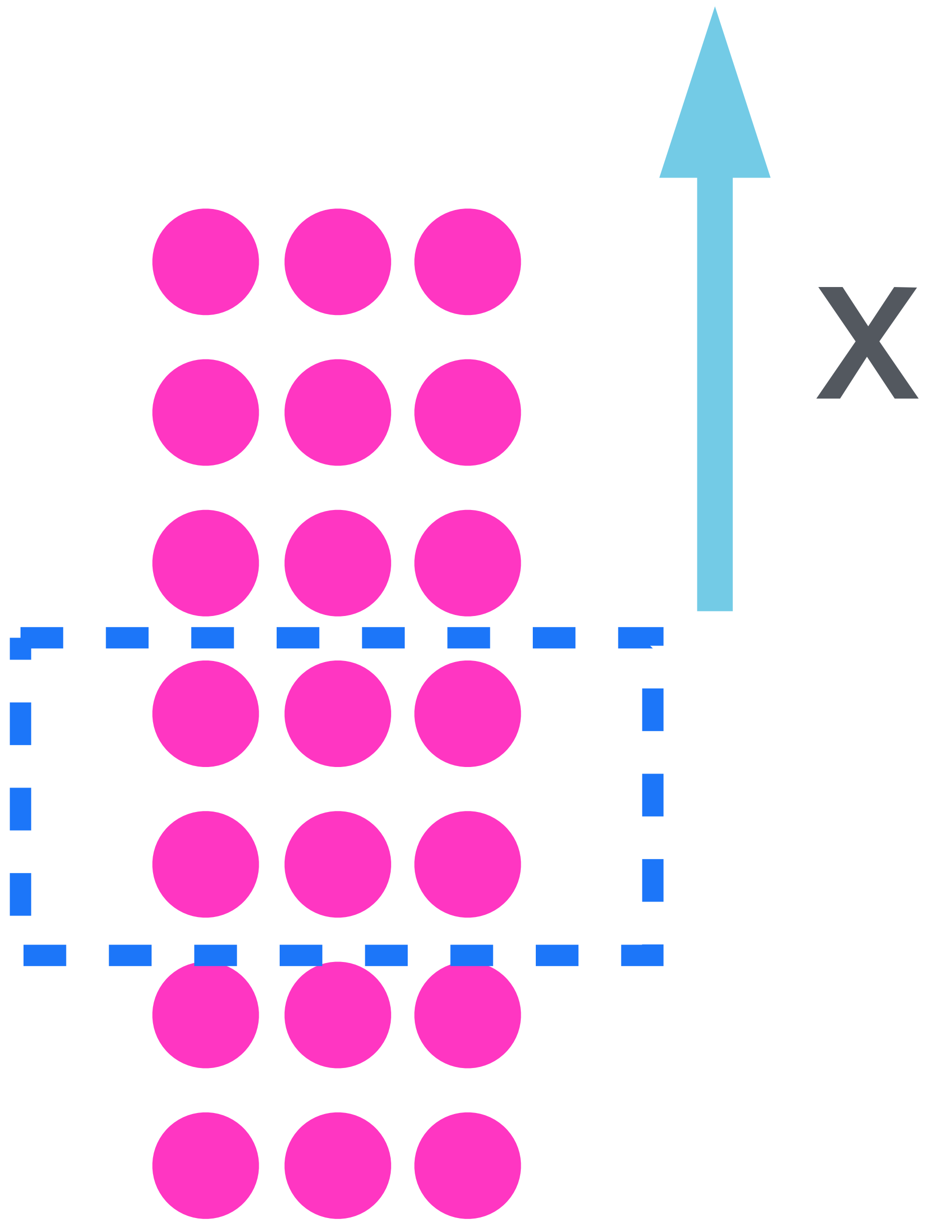
Phys. Rev. A **73**, 022328 – Published 17 February 2006

Toward Quantum Chromodynamics

Zohar, Cirac, Resnik - How to impliment

One of a number of frameworks





Color Irrep space truncated

SU(3) links in
“angular momentum” space

Kogut-Susskind Hamiltonian

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

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

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

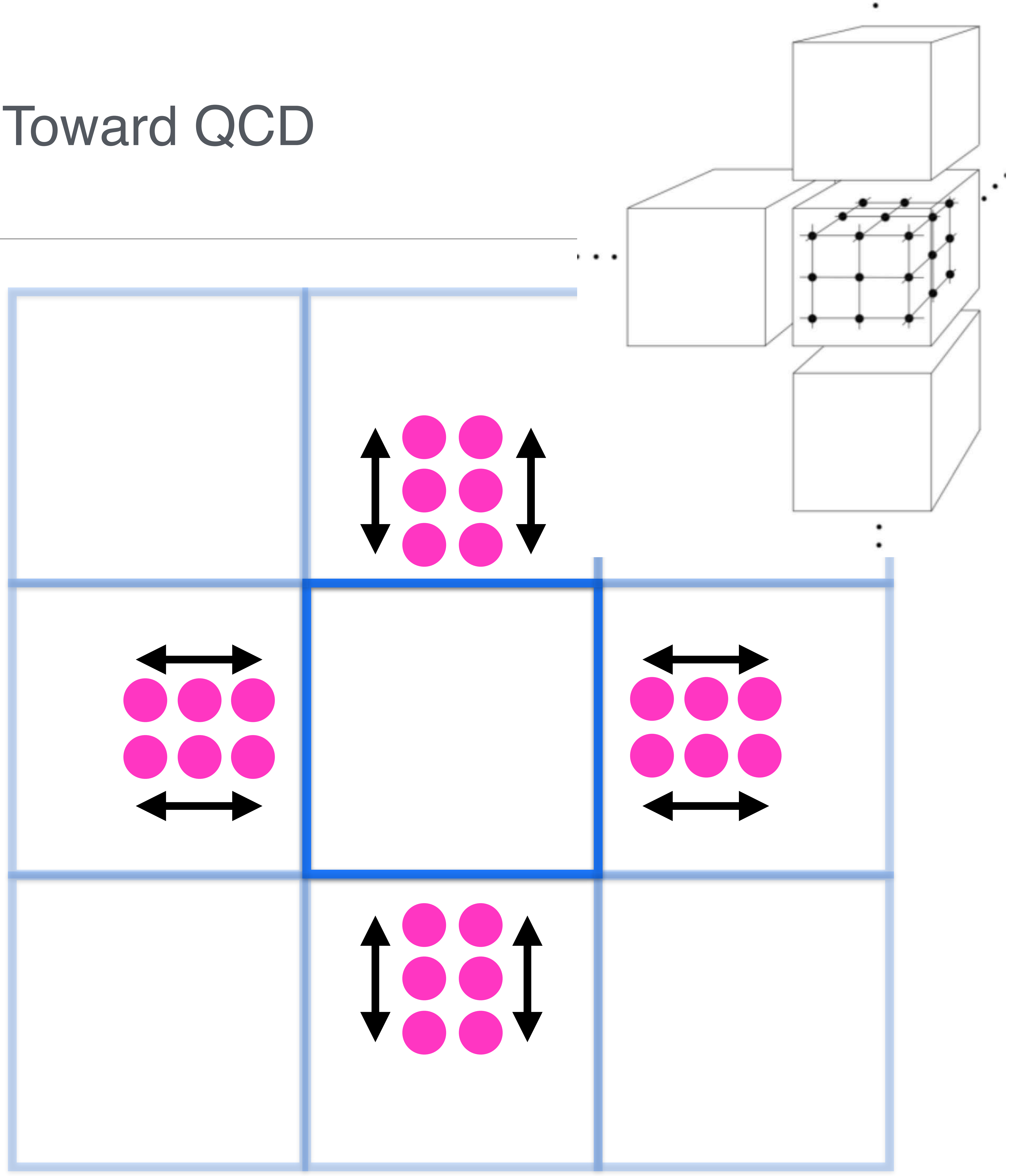
Yang- Mills - Toward QCD

Local Basis Scales

Link ket

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

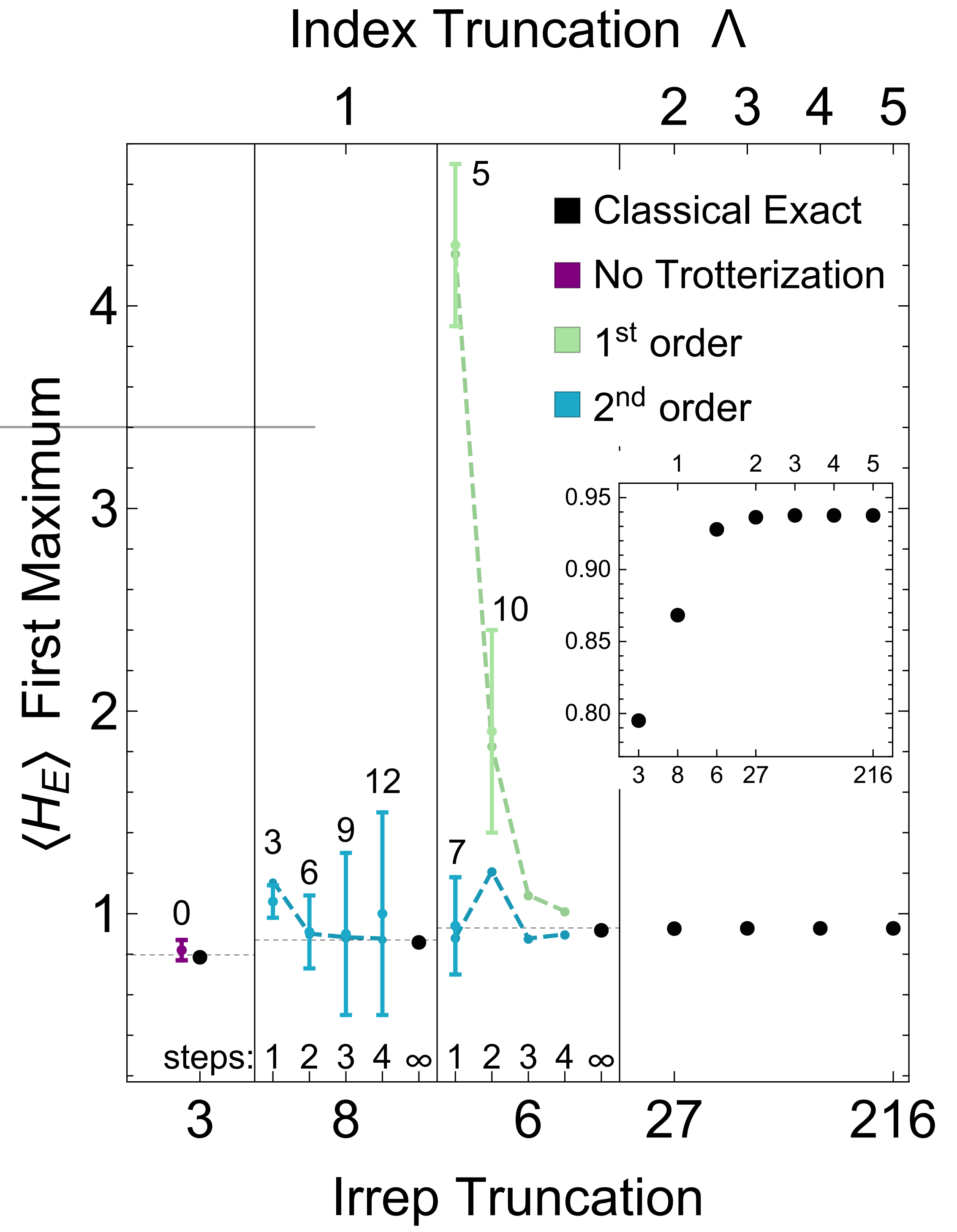
- p and q define the number of up and down indices in a tensor representation of a color irrep.
- T,Y are isospin and hypercharge quantum numbers in left and right hand vertices joined by the link.
- state products (CG) are BQP (Bacon, Chuang, Harrow (06))
- Gauss's Law enforced "by hand"

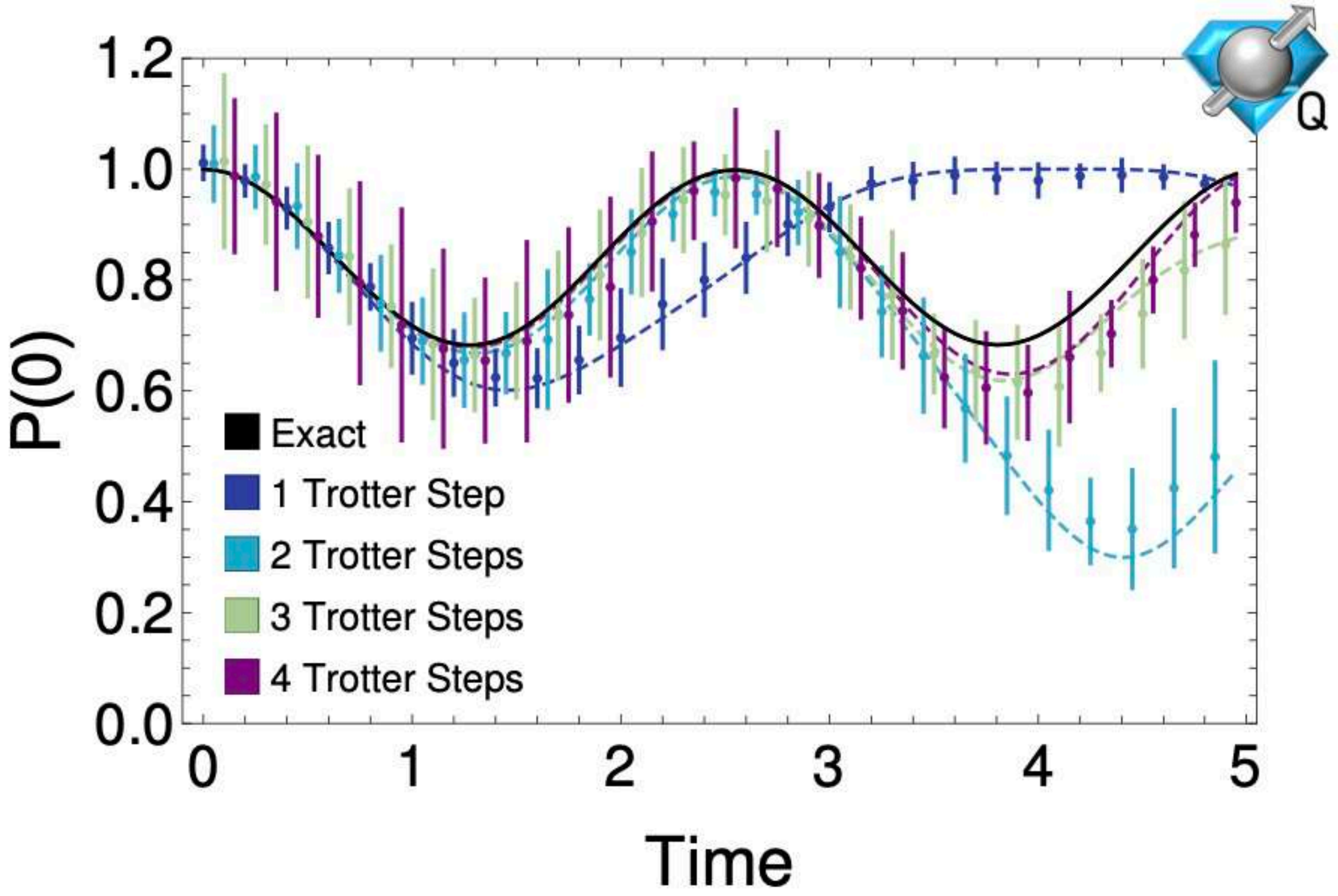


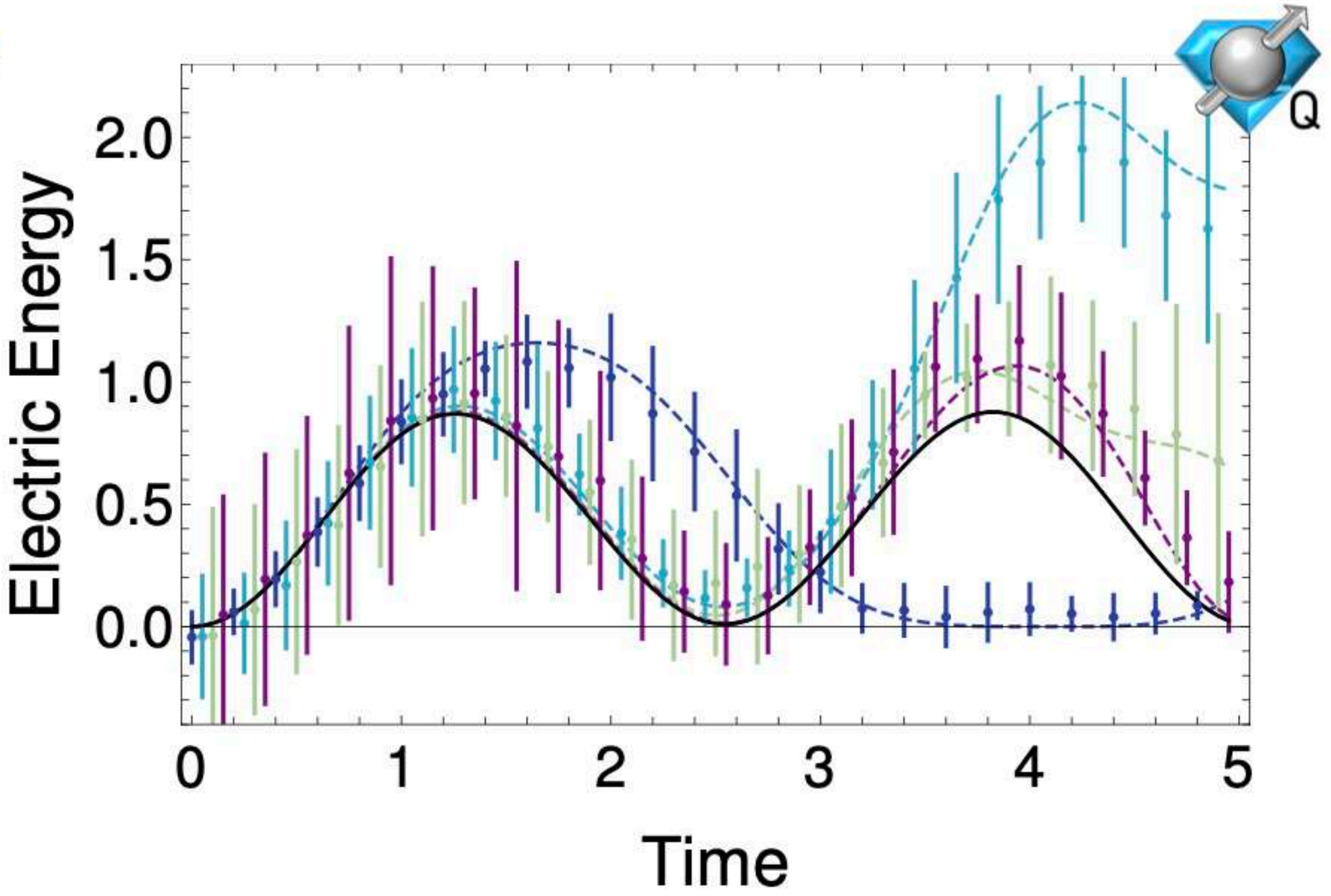
Trailhead for quantum simulation of SU(3) Yang-Mills lattice gauge theory in the local multiplet basis
Anthony Ciavarella, Natalie Klco, MJS
Phys.Rev.D 103 (2021) 9, 094501 • e-Print: 2101.10227 [quant-ph]

Yang-Mills - first steps

| p,q >

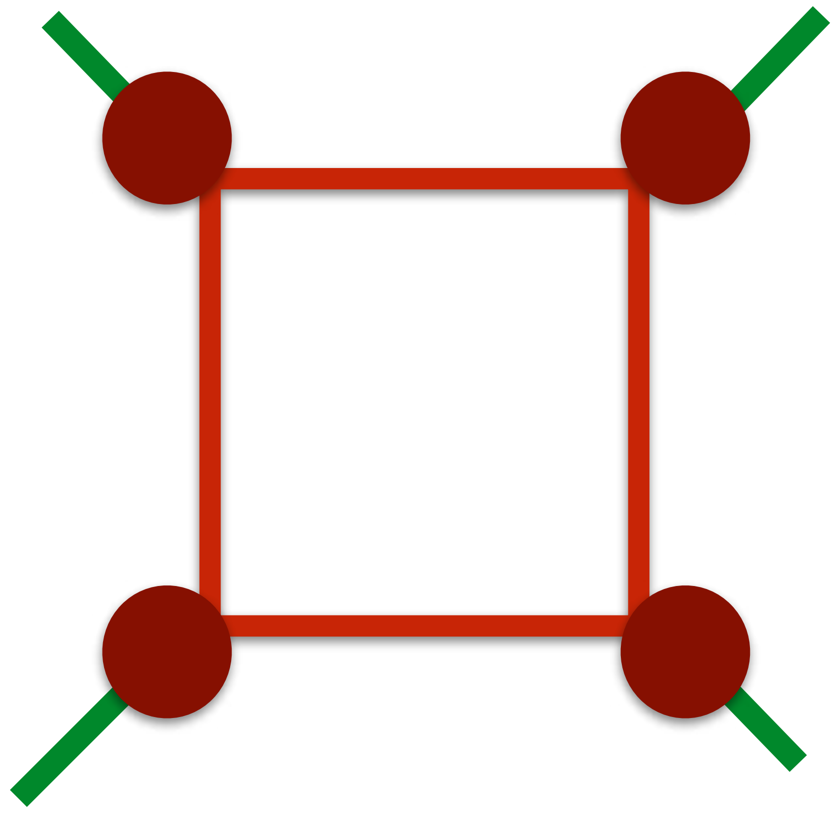


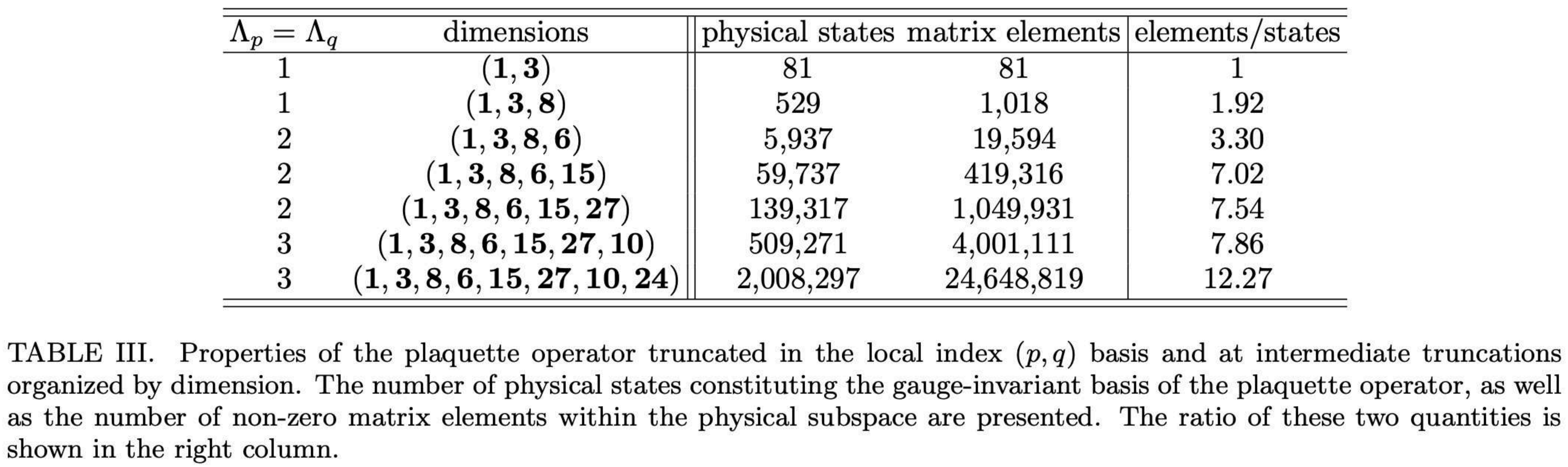




{1,3,3bar,8}

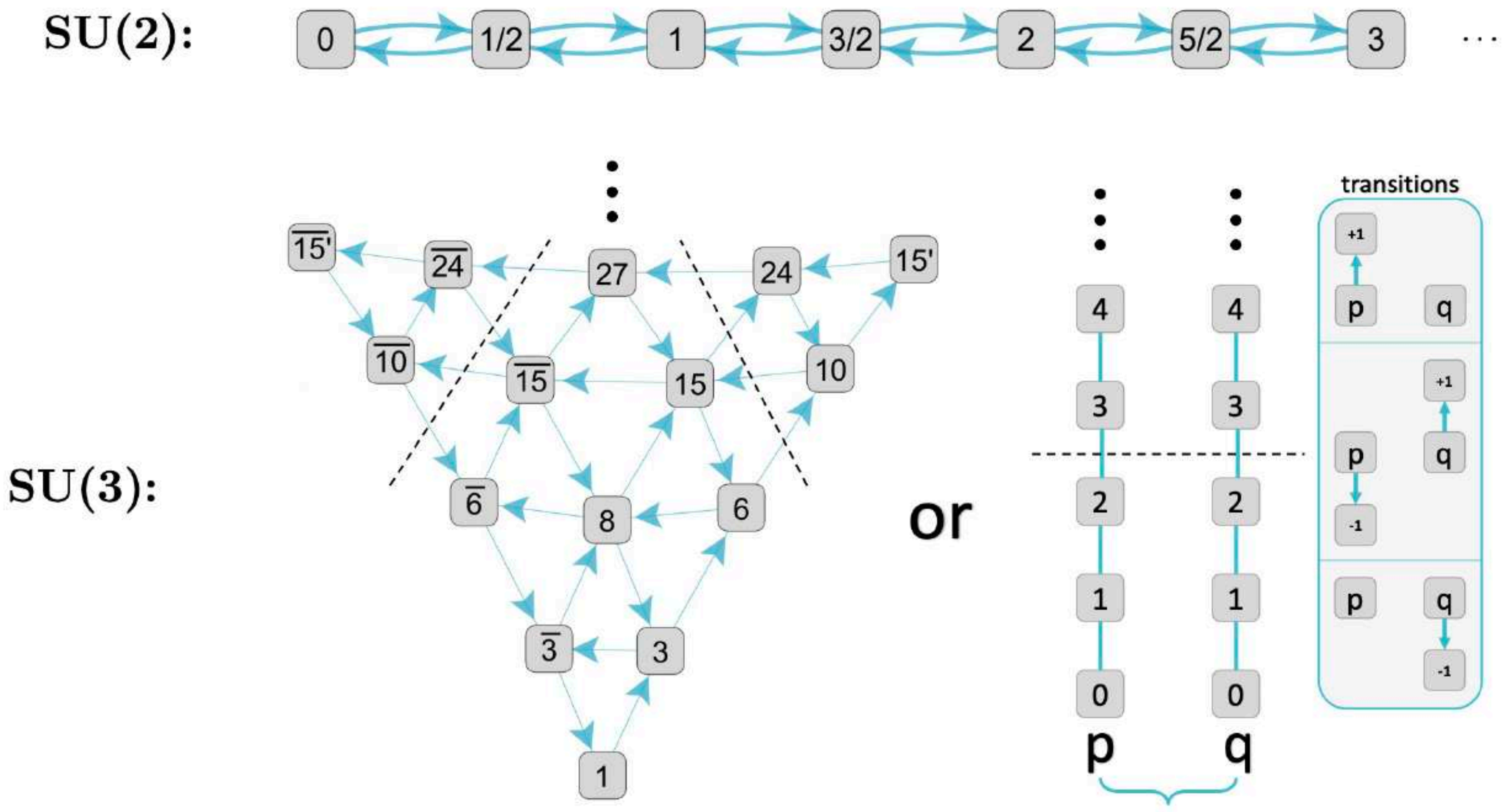
SU(3) Kogut-Susskind - Classical/Quantum Resources





$\Lambda_p = \Lambda_q$	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

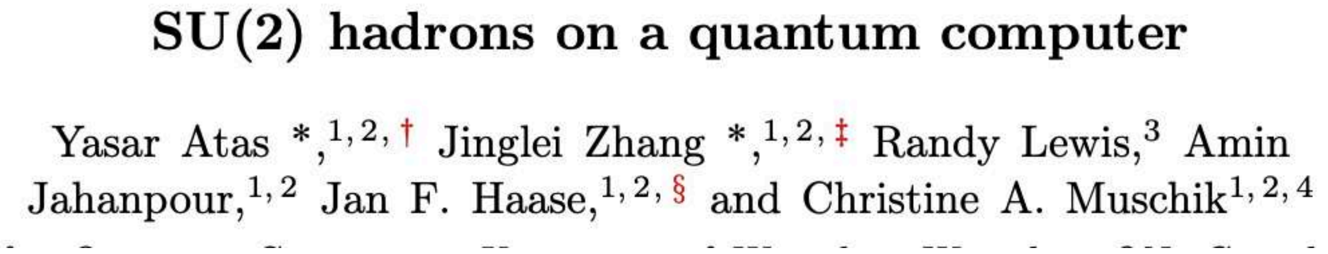
TABLE III. Properties of the plaquette operator truncated in the local index (p,q) basis and at intermediate truncations organized by dimension. The number of physical states constituting the gauge-invariant basis of the plaquette operator, as well as the number of non-zero matrix elements within the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



Require a 3-dim resource costing
Exponential convergence in field space

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

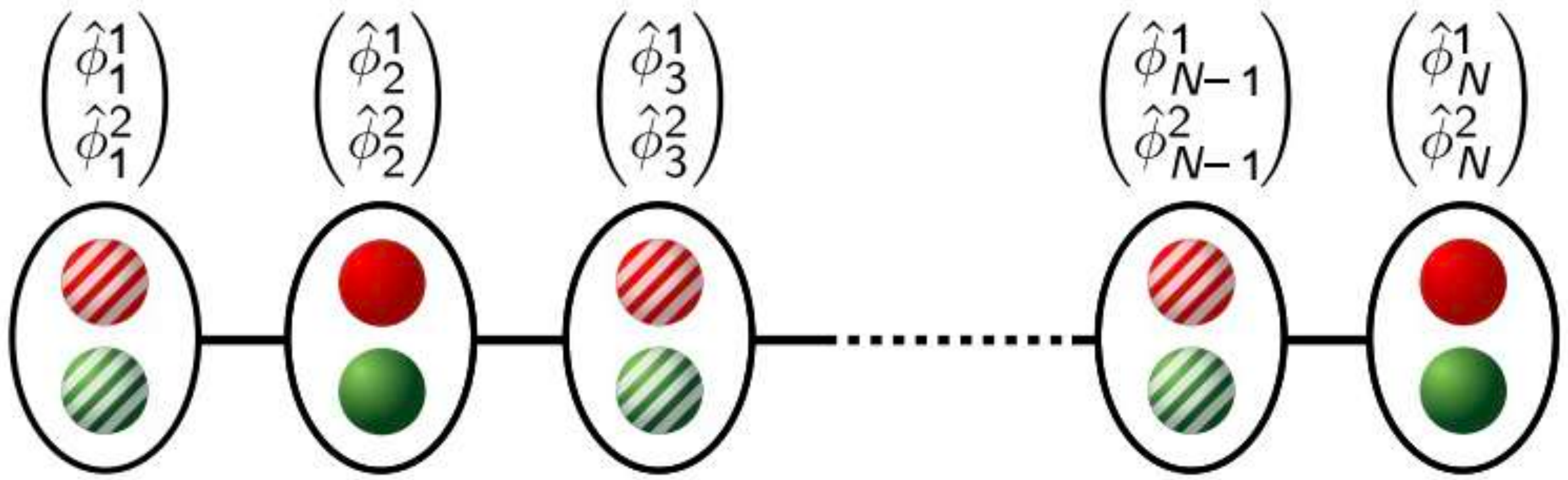
SU(2) in low-dimensions

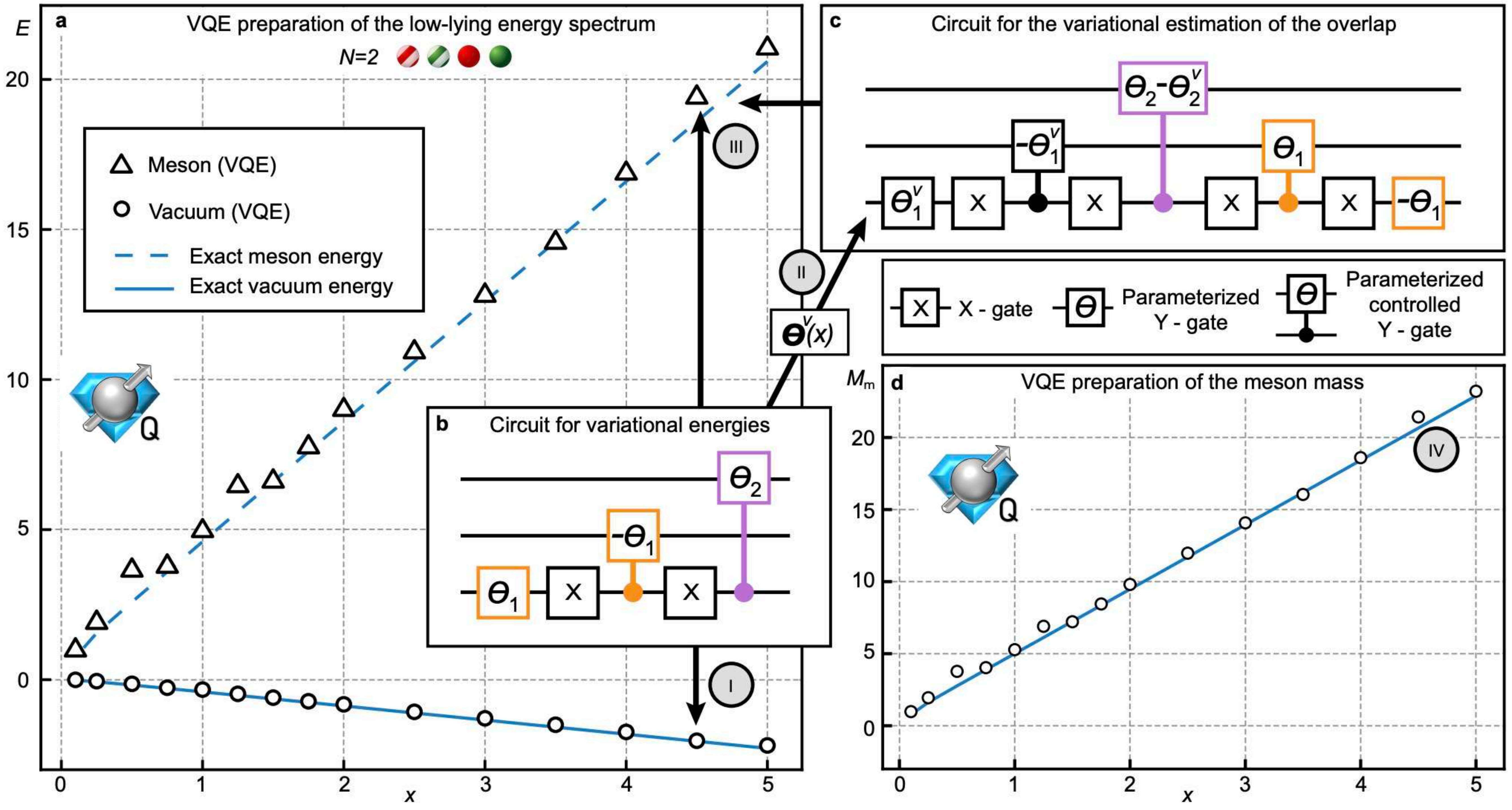


SU(2) hadrons on a quantum computer

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]





- Matter fields
- Non-dynamical gauge fields

Kink Scattering in Spin Models
-Elastic and Inelastic

arXiv.org > quant-ph > arXiv:2012.07243

Quantum Physics

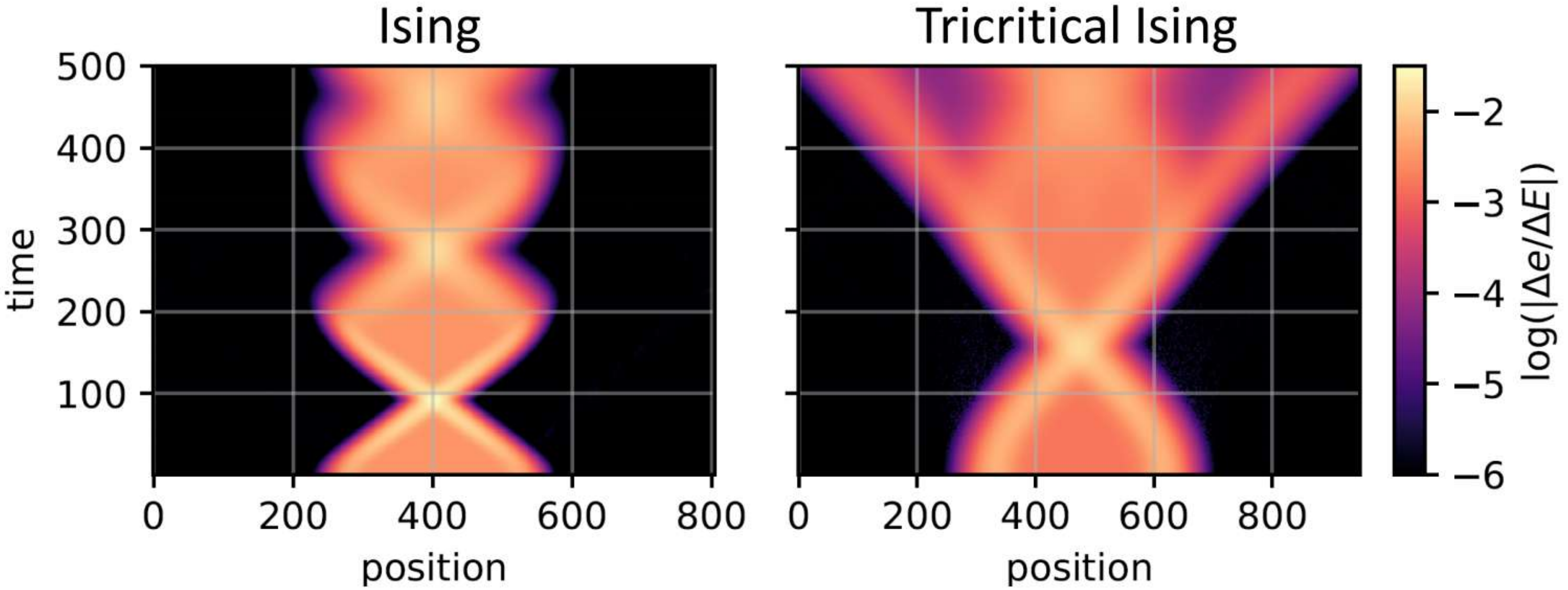
[Submitted on 14 Dec 2020 (v1), last revised 9 Mar 2021 (this version, v2)]

Collisions of false-vacuum bubble walls in a quantum spin chain

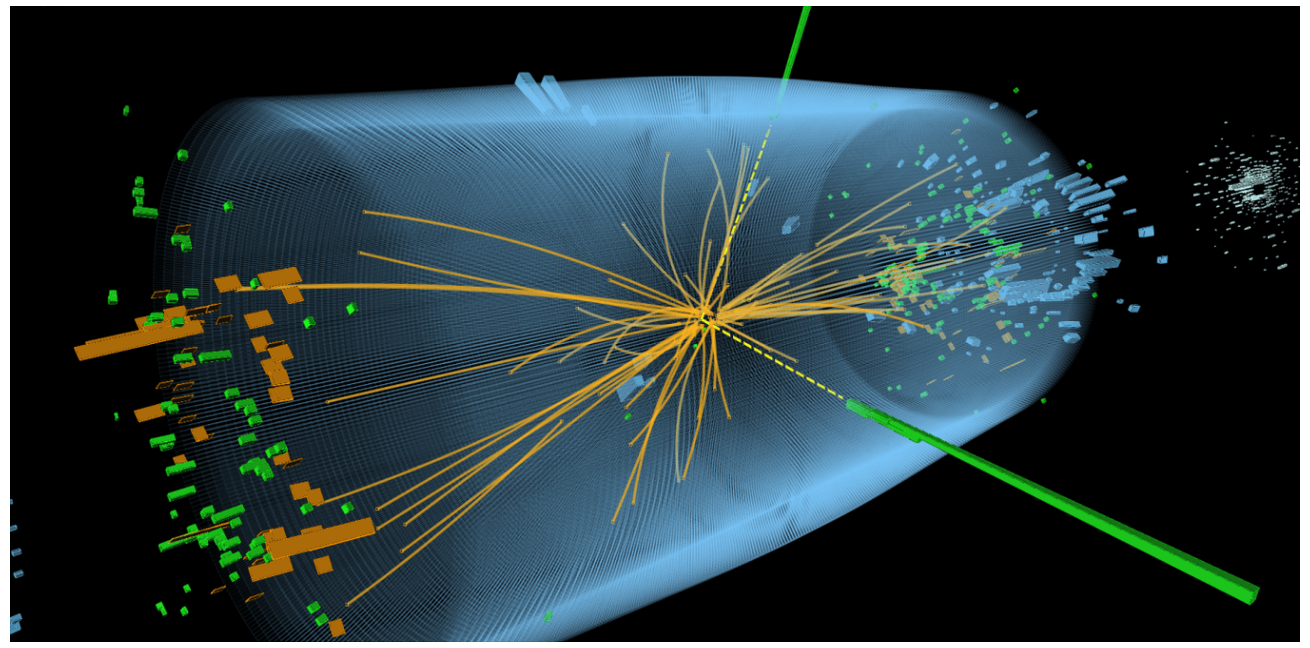
Ashley Milsted, Junyu Liu, John Preskill, Guifre Vidal

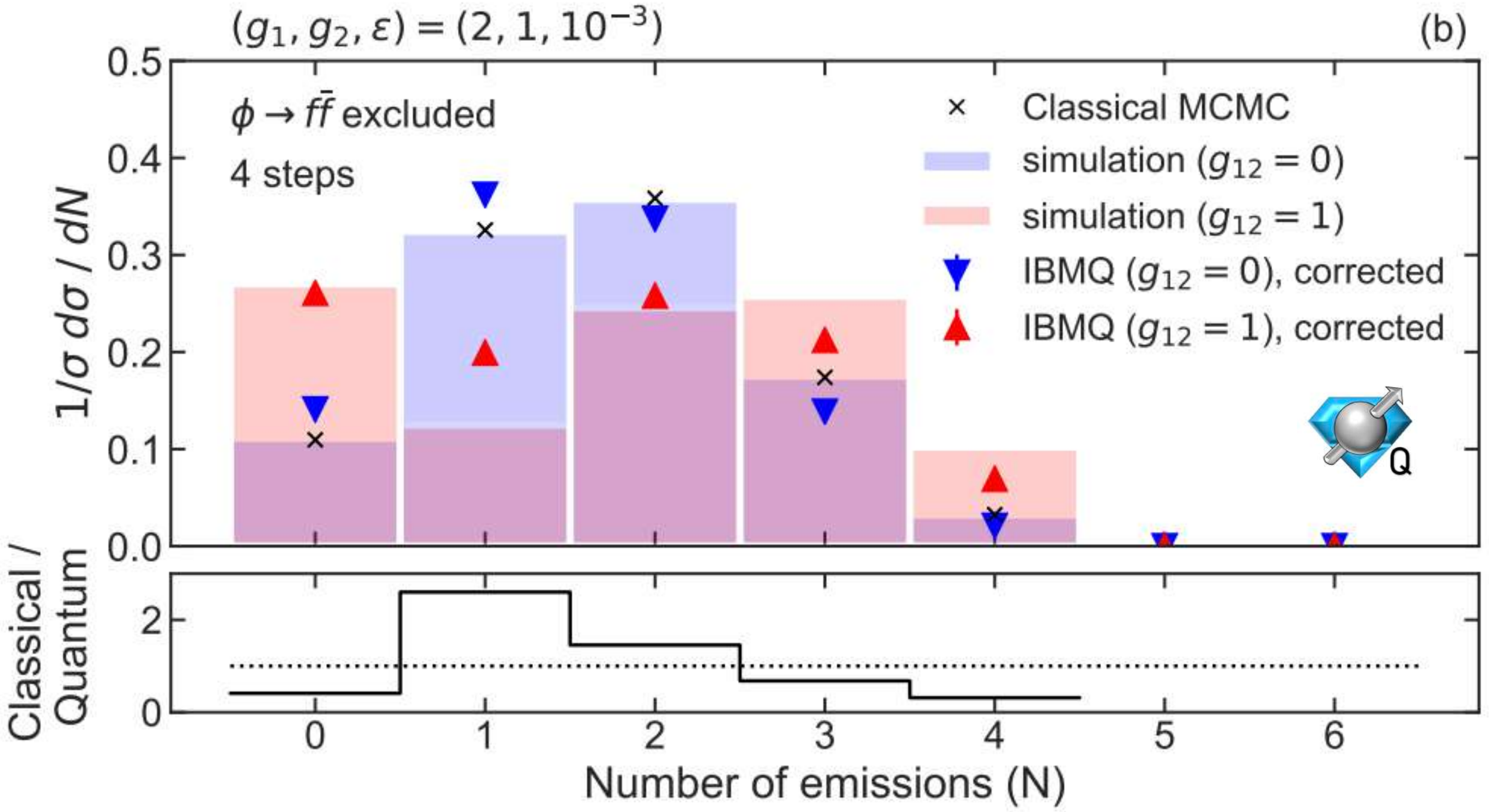
Explicit symmetry breaking (false vacuum)

$$H = \sum_{j=1}^{N}\left[-Z_j Z_{j+1} - gX_j - hZ_j + \lambda\left(X_j Z_{j+1} Z_{j+2} + Z_j Z_{j+1} X_{j+2}\right)\right]$$



Fragmentation and Collisions



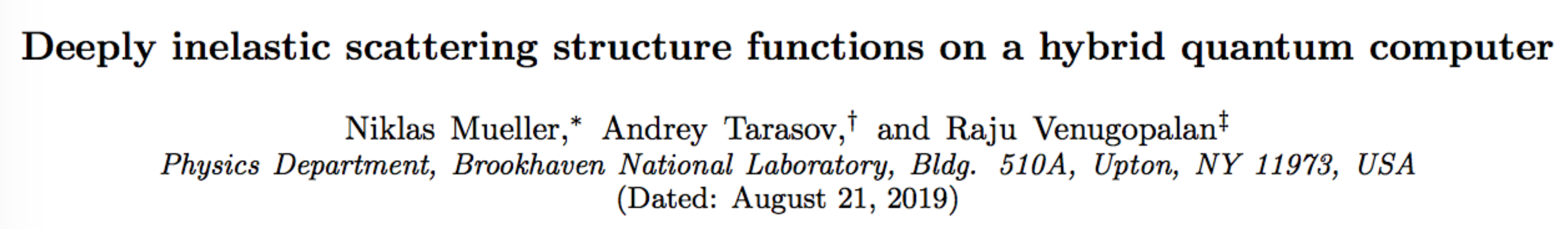


A quantum algorithm for high energy physics simulations
Christian W. Bauer, Wibe A. de Jong, Benjamin Nachman, Davide Provasoli, arXiv:1904.03196 [hep-ph]

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

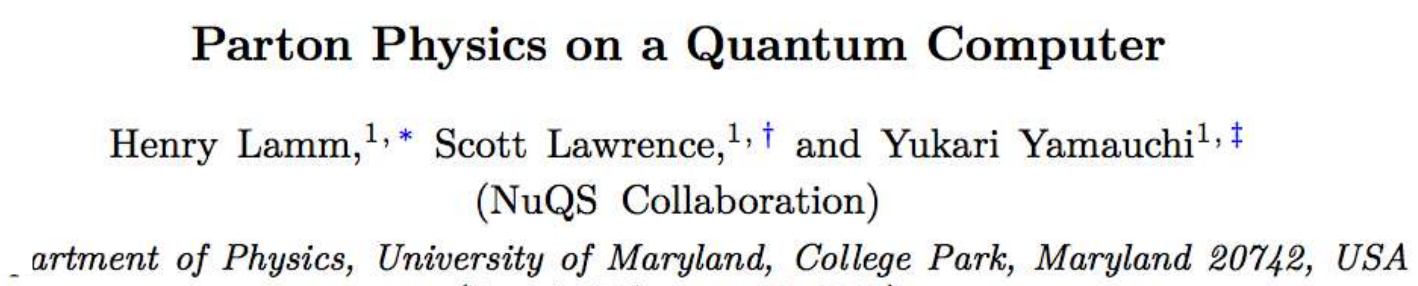
Simulating Collider Physics on Quantum Computers using Effective Field Theories
Christian W. Bauer, Benjamin Nachman, Marat Freytsis, arXiv:2102.05044 [hep-ph]

The utility of EFTs, such as SCET, in organizing calculation strategies and observables



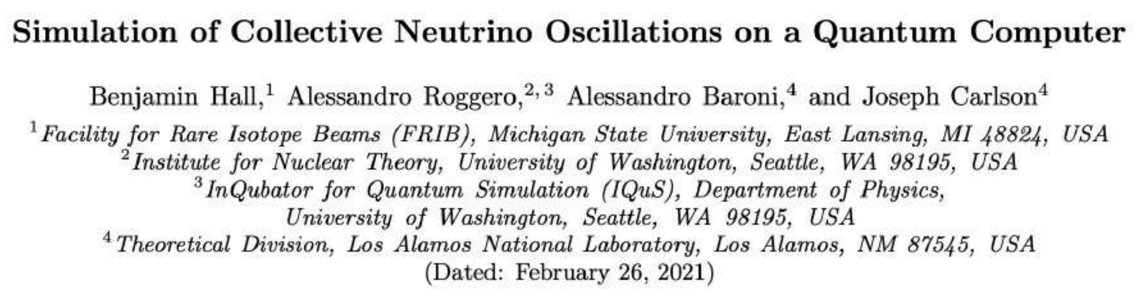
Deeply inelastic scattering structure functions on a hybrid quantum computer

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



Parton Physics on a Quantum Computer

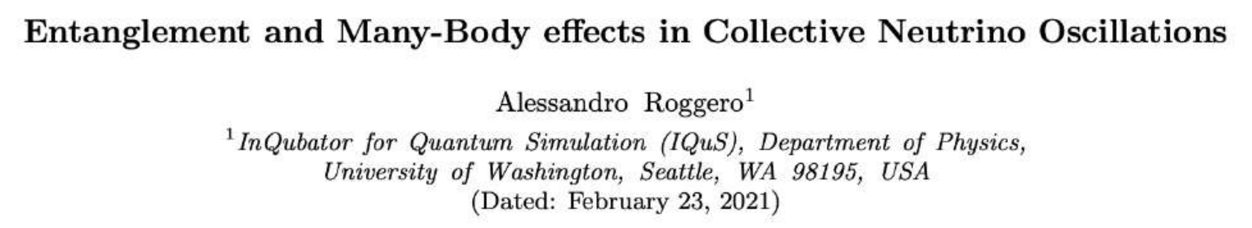
Henry Lamm,[1,*] Scott Lawrence,[1,†] and Yukari Yamauchi[1,‡]
(NuQS Collaboration)
artment of Physics, University of Maryland, College Park, Maryland 20742, USA



Simulation of Collective Neutrino Oscillations on a Quantum Computer

Benjamin Hall,[1] Alessandro Roggero,[2,3] Alessandro Baroni,[4] and Joseph Carlson[4]
[1] *Facility for Rare Isotope Beams (FRIB), Michigan State University, East Lansing, MI 48824, USA*
[2] *Institute for Nuclear Theory, University of Washington, Seattle, WA 98195, USA*
[3] *InQubator for Quantum Simulation (IQuS), Department of Physics,*
University of Washington, Seattle, WA 98195, USA
[4] *Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
(Dated: February 26, 2021)

Neutrino Evolution



Entanglement and Many-Body effects in Collective Neutrino Oscillations

Alessandro Roggero[1]
[1] *InQubator for Quantum Simulation (IQuS), Department of Physics,*
University of Washington, Seattle, WA 98195, USA
(Dated: February 23, 2021)

First simulations, entanglement using a quantum devices

© Can Stock Photo / nitimongkolchai

$$H = \sum_{k=1}^{N} \vec{b} \cdot \vec{\sigma}_k + \sum_{p<q}^{N} J_{pq} \vec{\sigma}_p \cdot \vec{\sigma}_q$$

$$J_{pq} = (1 - \cos(\theta_{pq}))$$

Pauli matrices in neutrino flavor space

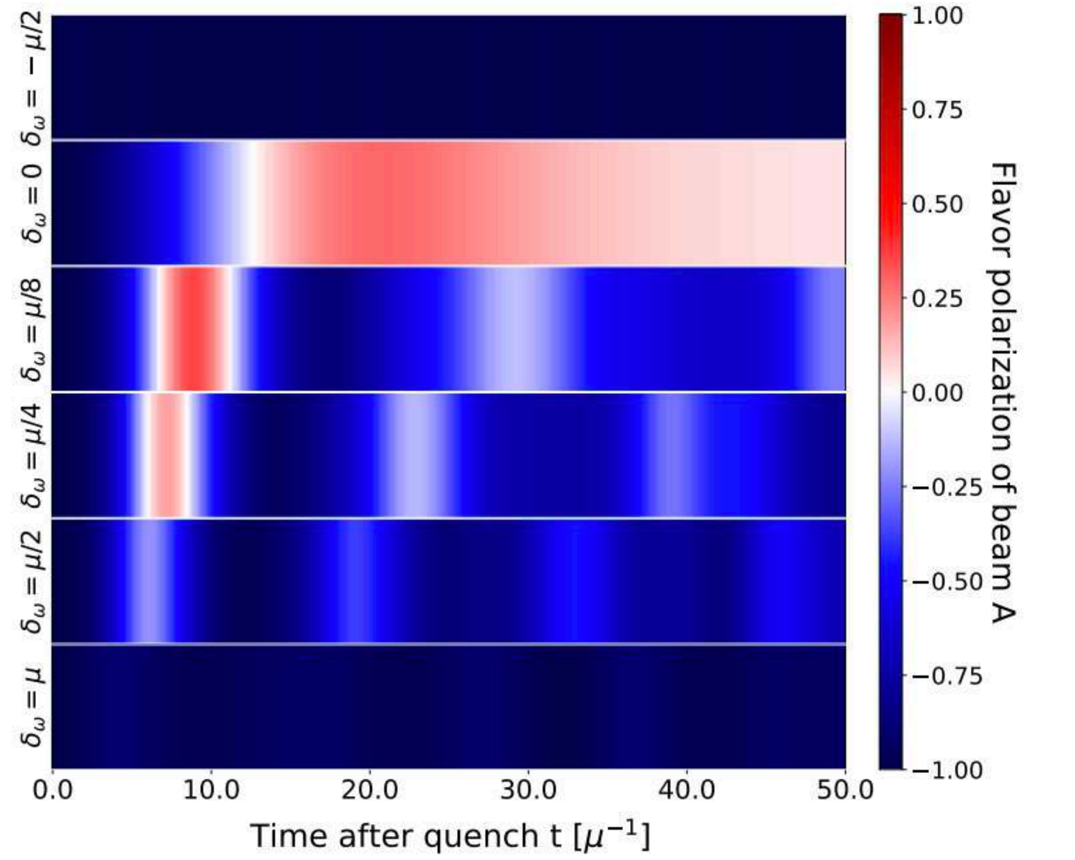
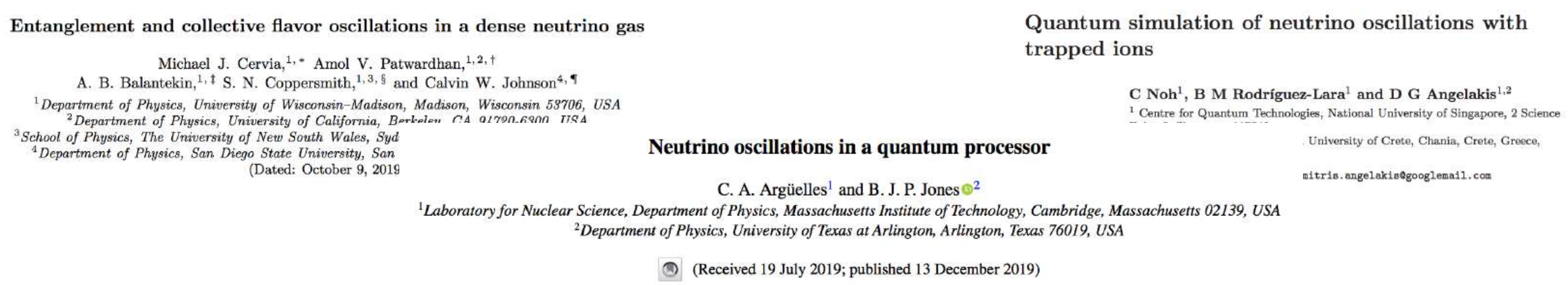


FIG. 1. (Color online) Flavor polarization per particle $\langle J_z^A(t)\rangle/(N/4)$ of neutrinos in the A beam as a function of time for six values of the energy asymmetry parameter δ_ω/μ (from top to bottom): $-0.5, 0.0, 0.125, 0.25, 0.5, 1.0$.



Entanglement and collective flavor oscillations in a dense neutrino gas

Michael J. Cervia,[1,*] Amol V. Patwardhan,[1,2,†]
A. B. Balantekin,[1,‡] S. N. Coppersmith,[1,3,§] and Calvin W. Johnson[4,¶]
[1] *Department of Physics, University of Wisconsin–Madison, Madison, Wisconsin 53706, USA*
[2] *Department of Physics, University of California, Berkeley, CA 94720-6300, USA*
[3] *School of Physics, The University of New South Wales, Syd*
[4] *Department of Physics, San Diego State University, San*
(Dated: October 9, 2019

Quantum simulation of neutrino oscillations with trapped ions

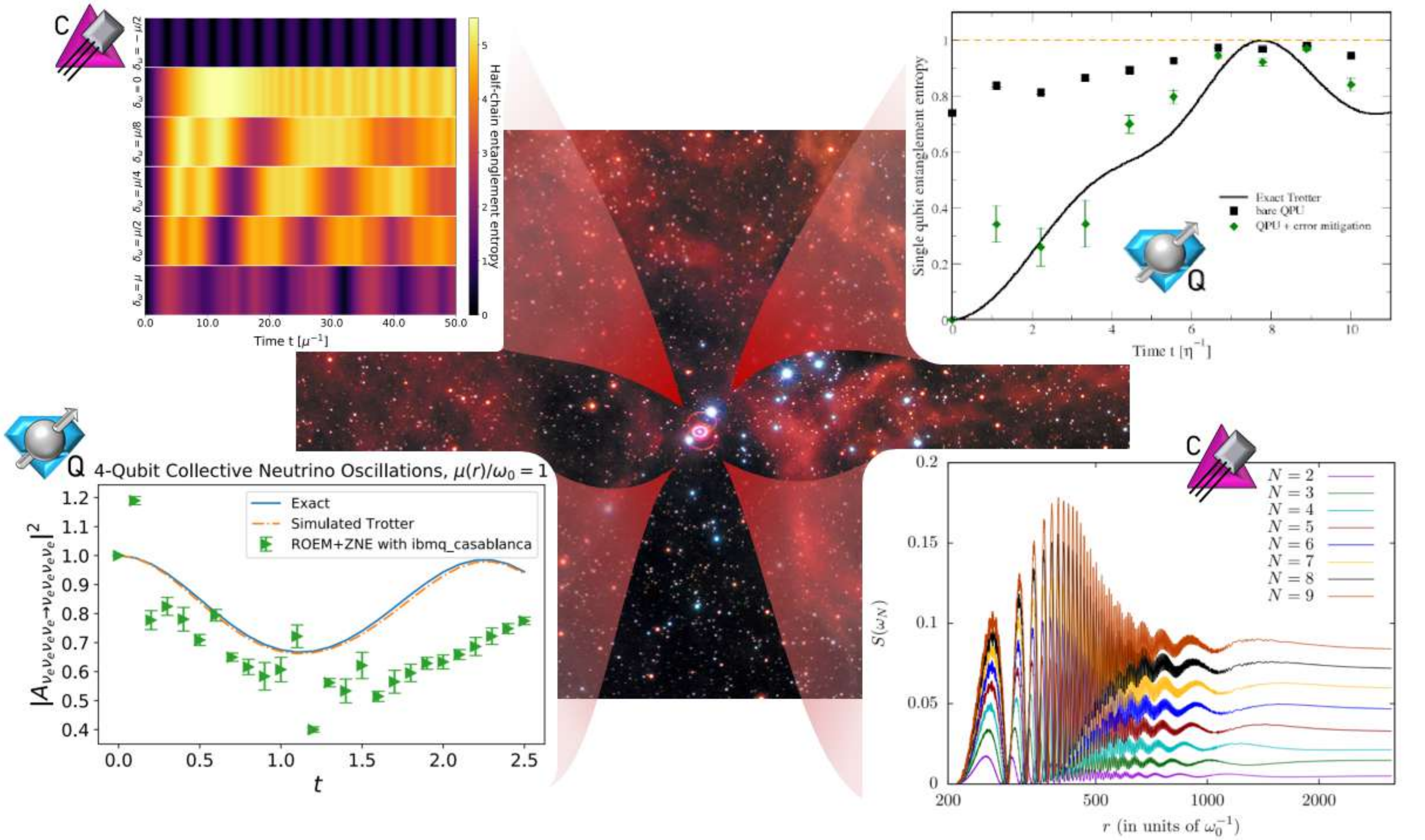
C Noh[1], B M Rodríguez-Lara[1] and D G Angelakis[1,2]
[1] Centre for Quantum Technologies, National University of Singapore, 2 Science
University of Crete, Chania, Crete, Greece,
mitris.angelakis@googlemail.com

Neutrino oscillations in a quantum processor

C. A. Argüelles[1] and B. J. P. Jones[2]
[1] *Laboratory for Nuclear Science, Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[2] *Department of Physics, University of Texas at Arlington, Arlington, Texas 76019, USA*

(Received 19 July 2019; published 13 December 2019)

e.g., Neutrinos



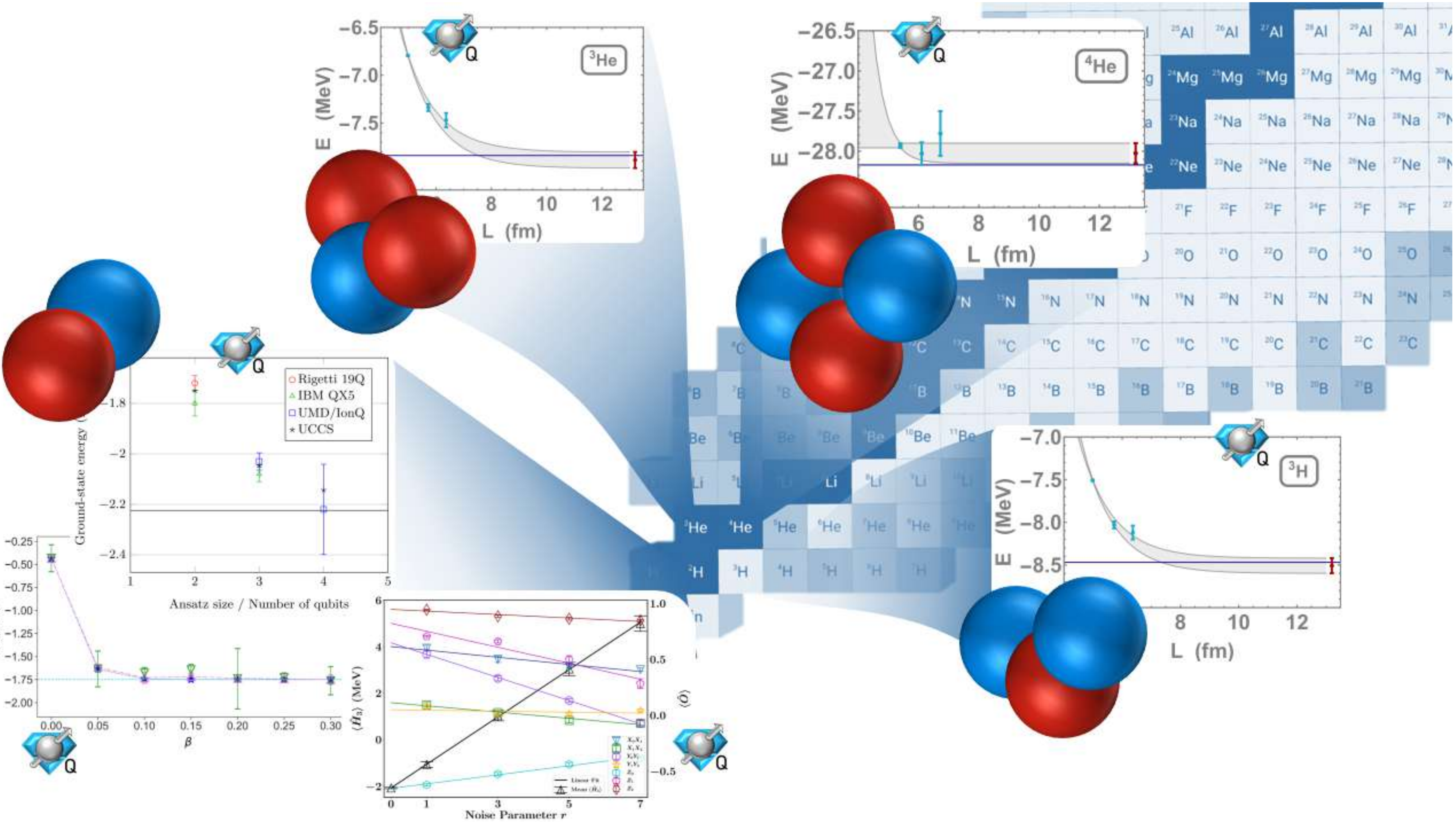
K. Yeter-Aydeniz, S. Bangar, G. Siopsis, and R. C. Pooser, "Collective neutrino oscillations on a quantum computer," (2021), arXiv:2104.03273 [quant-ph].

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).

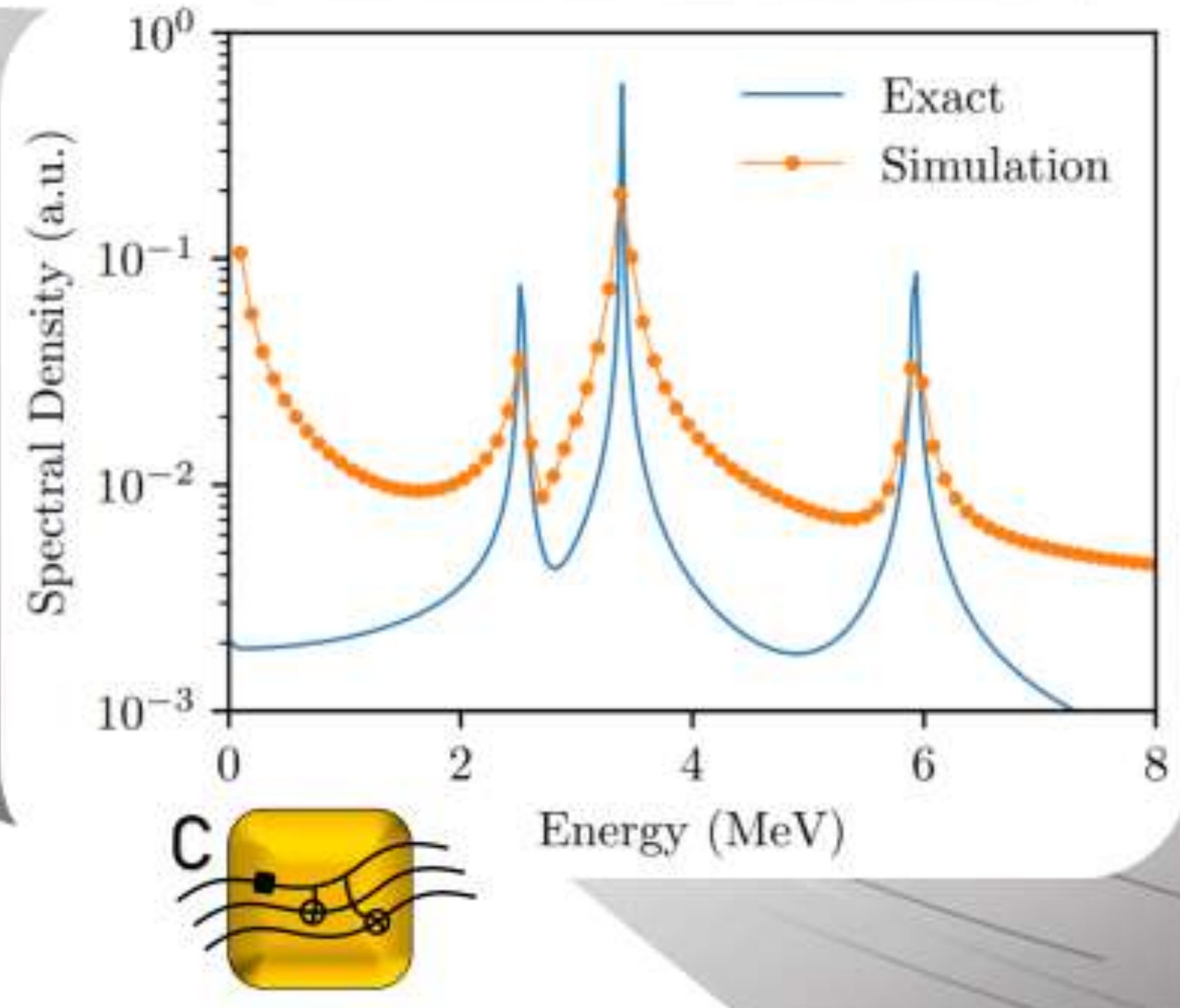
A. Roggero, "Dynamical phase transitions in models of collective neutrino oscillations," (2021), arXiv:2103.11497 [hep-ph].

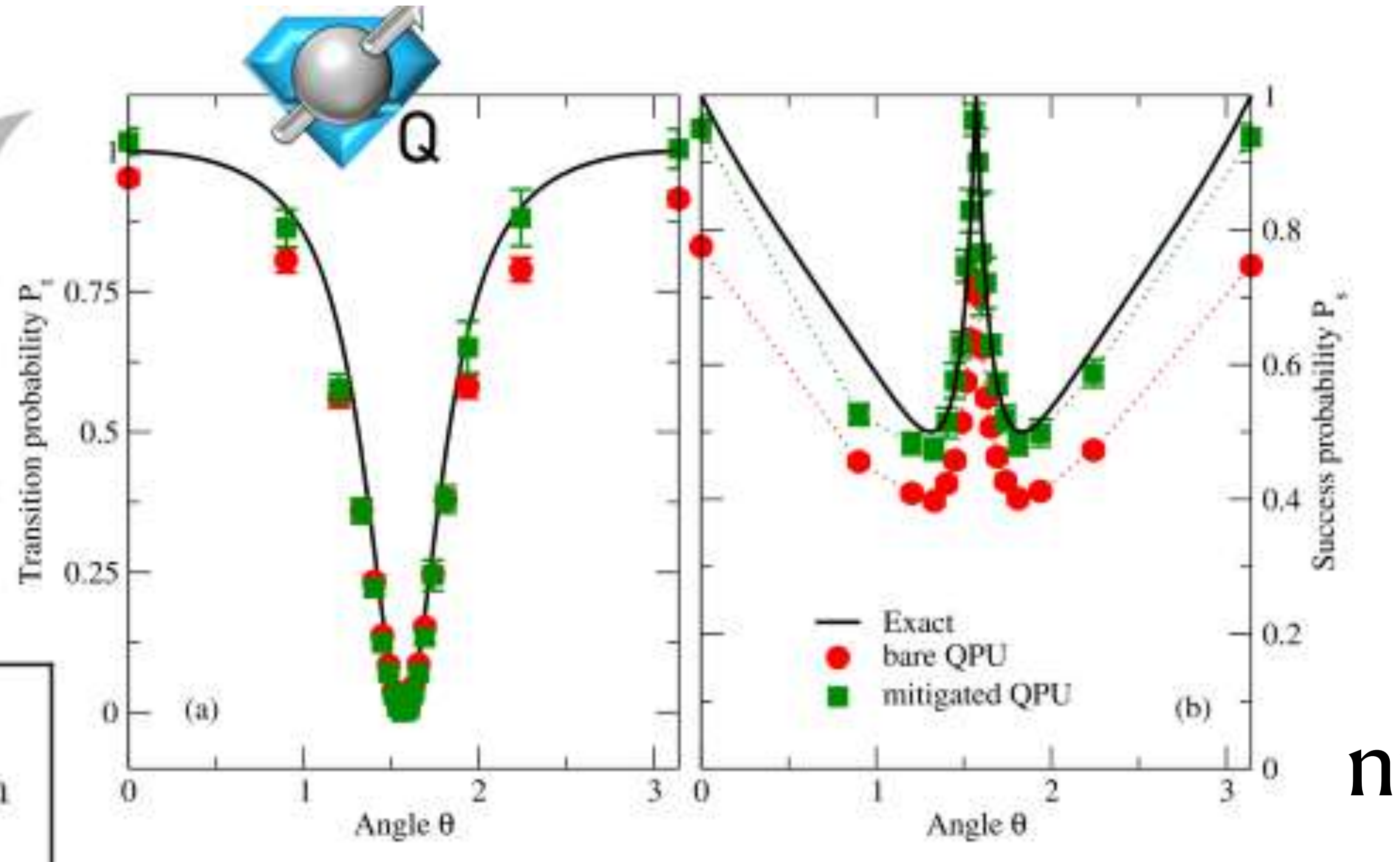
Nuclear Structure



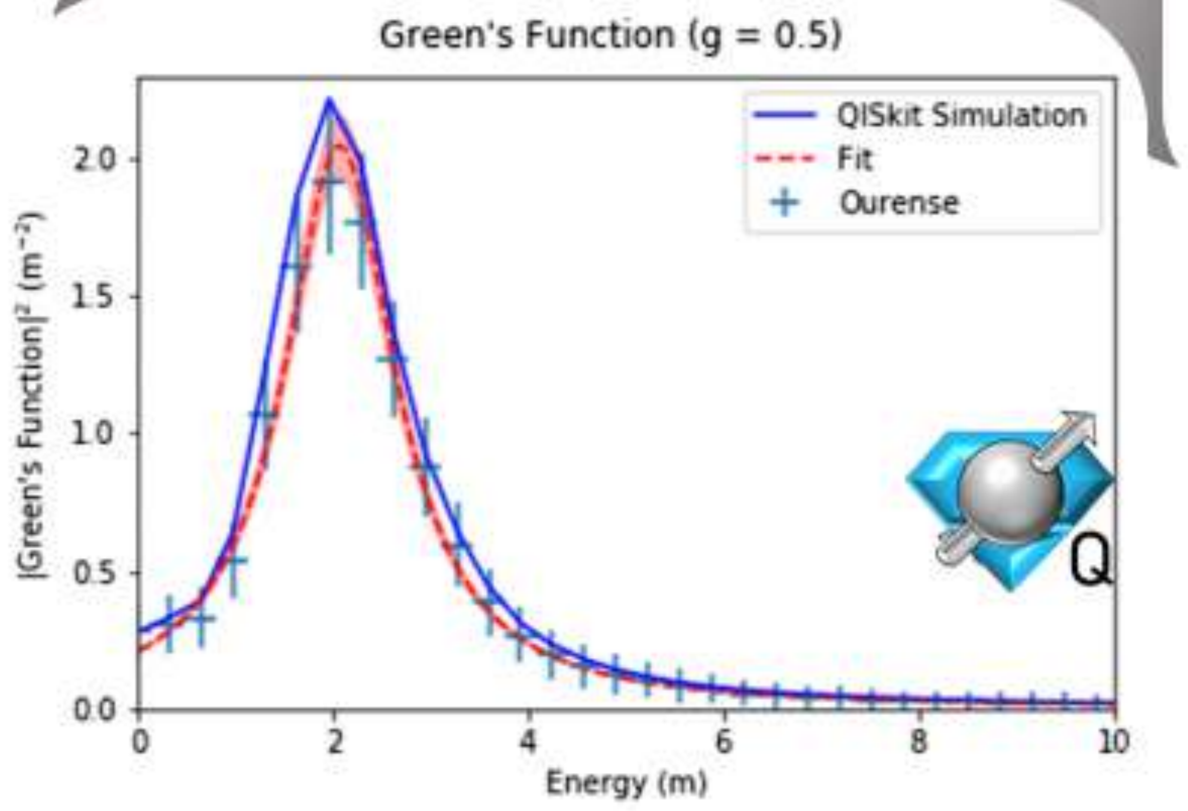
Reactions

nn with SRF

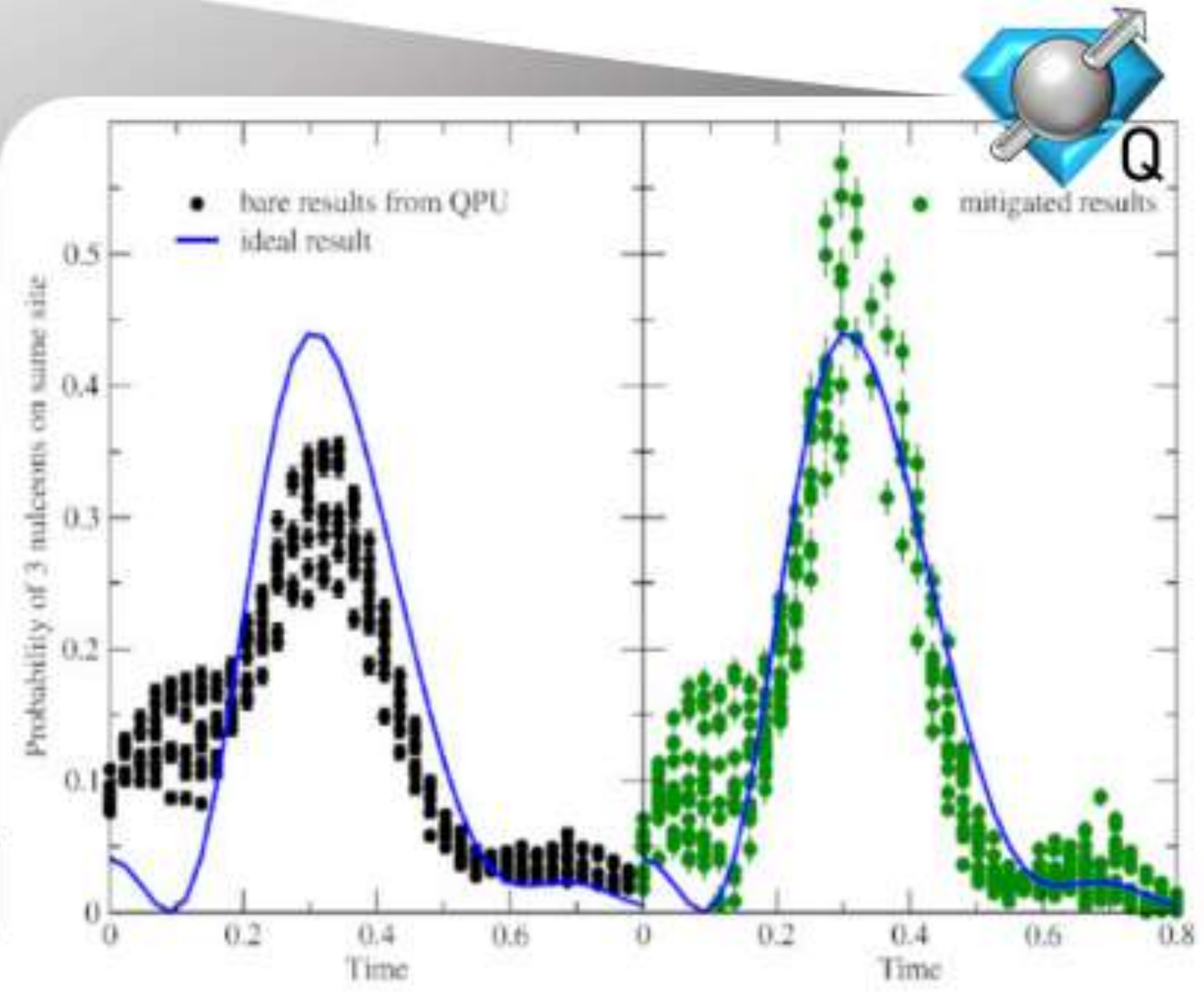




np to dγ

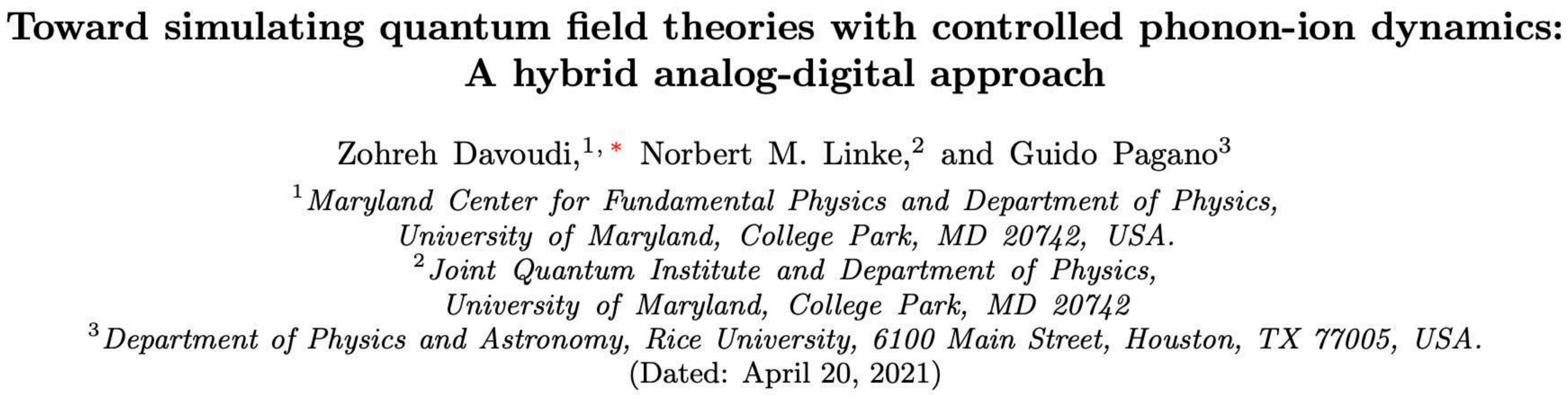


x to yz



nnn

Hybrid Analogue-Digital using Trapped Ions

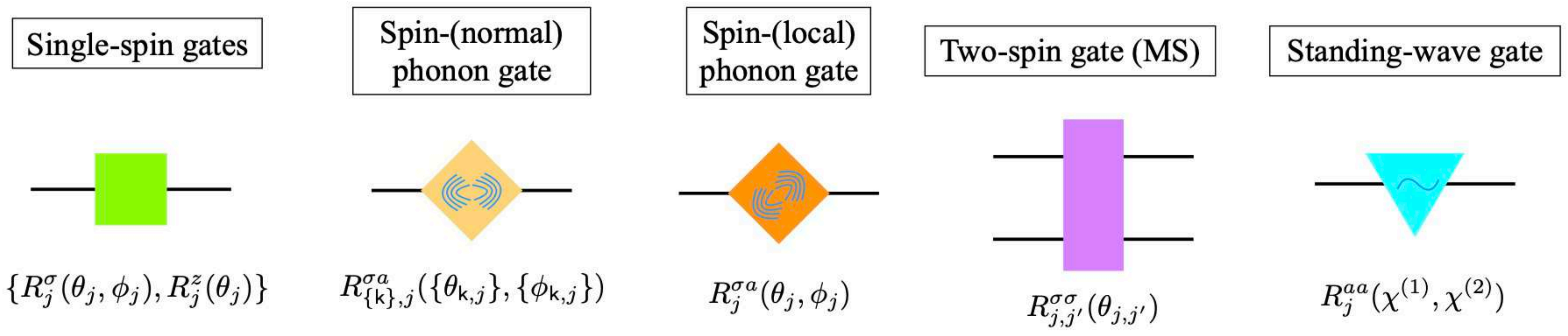


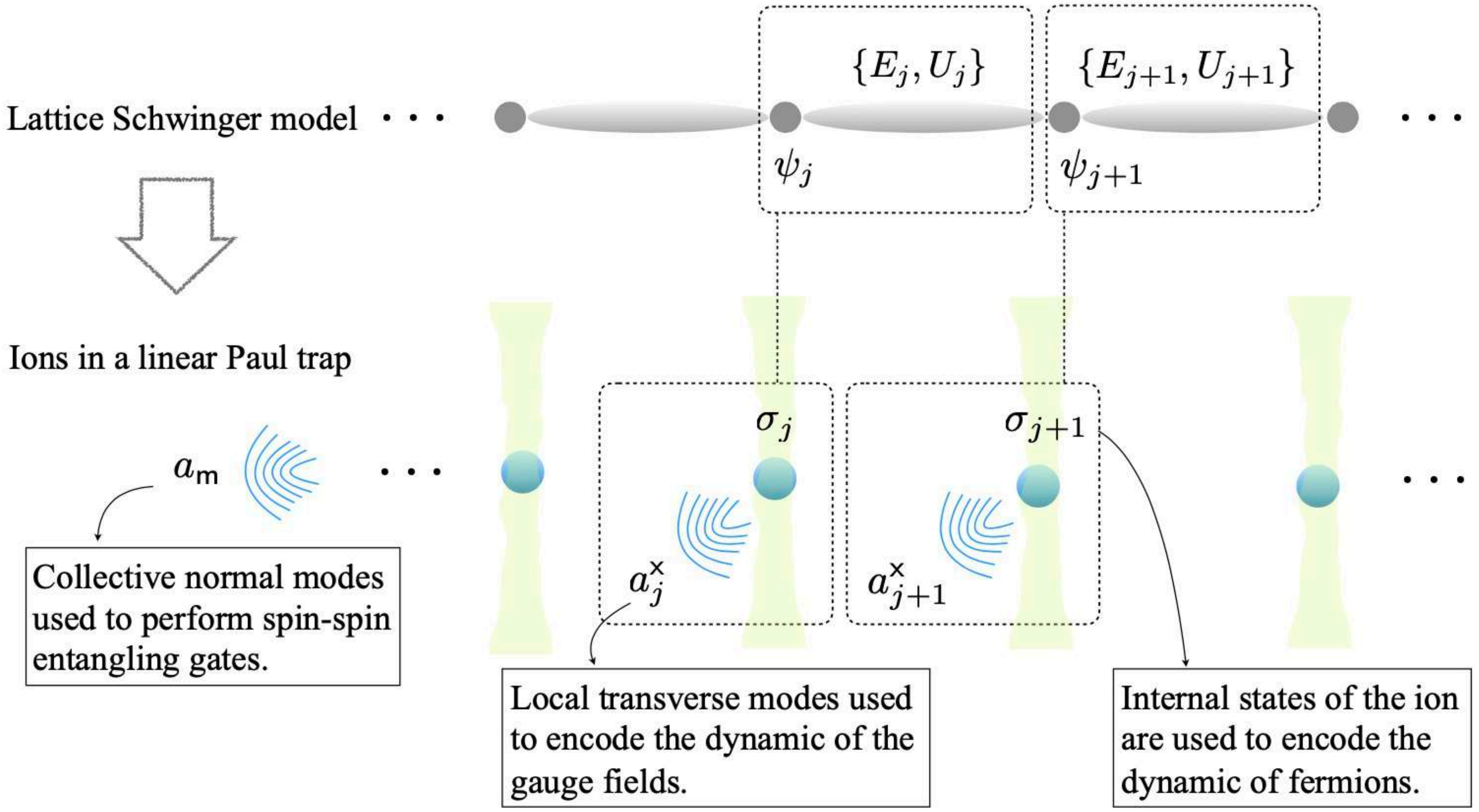
Toward simulating quantum field theories with controlled phonon-ion dynamics: A hybrid analog-digital approach

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)

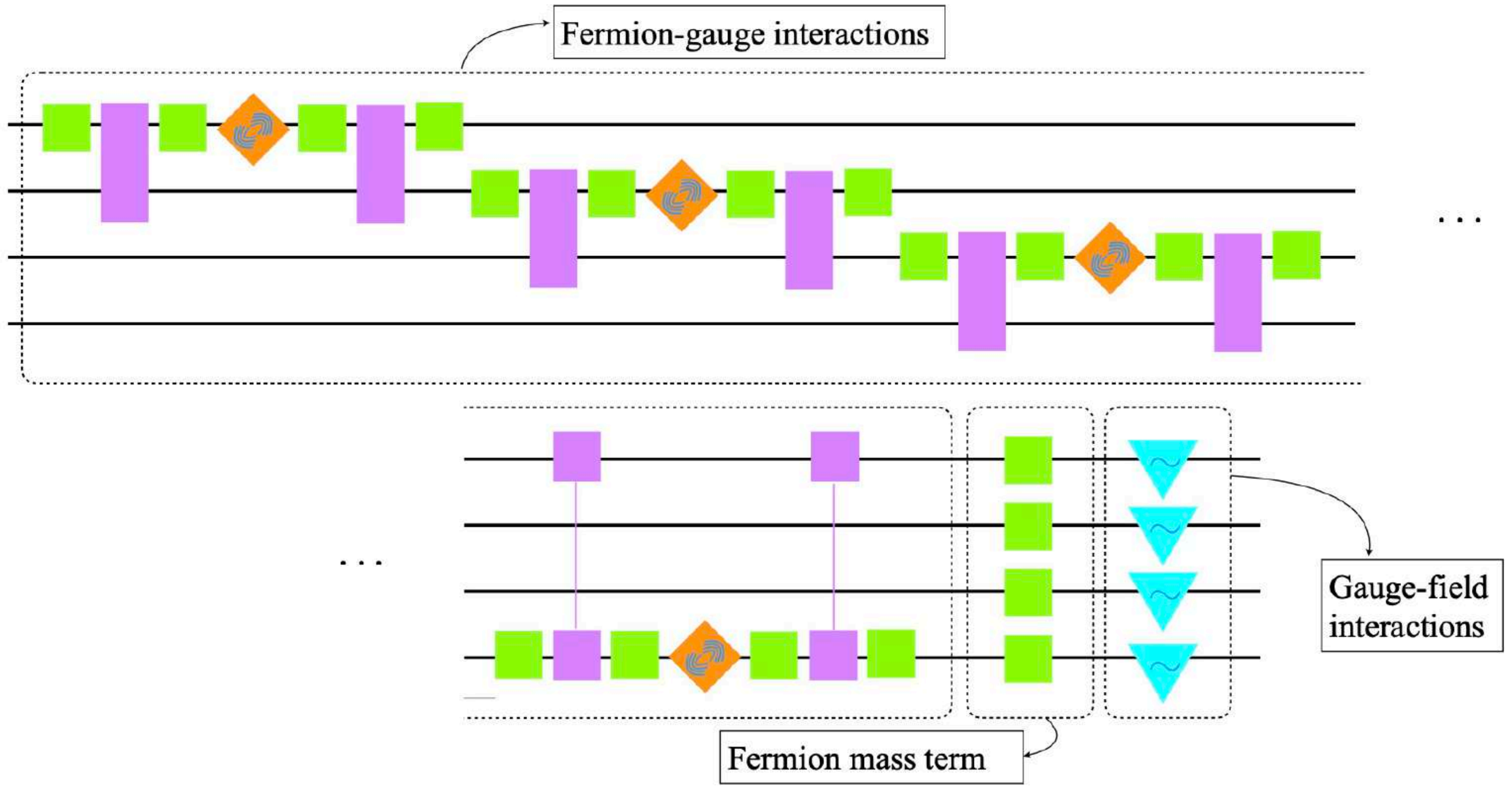




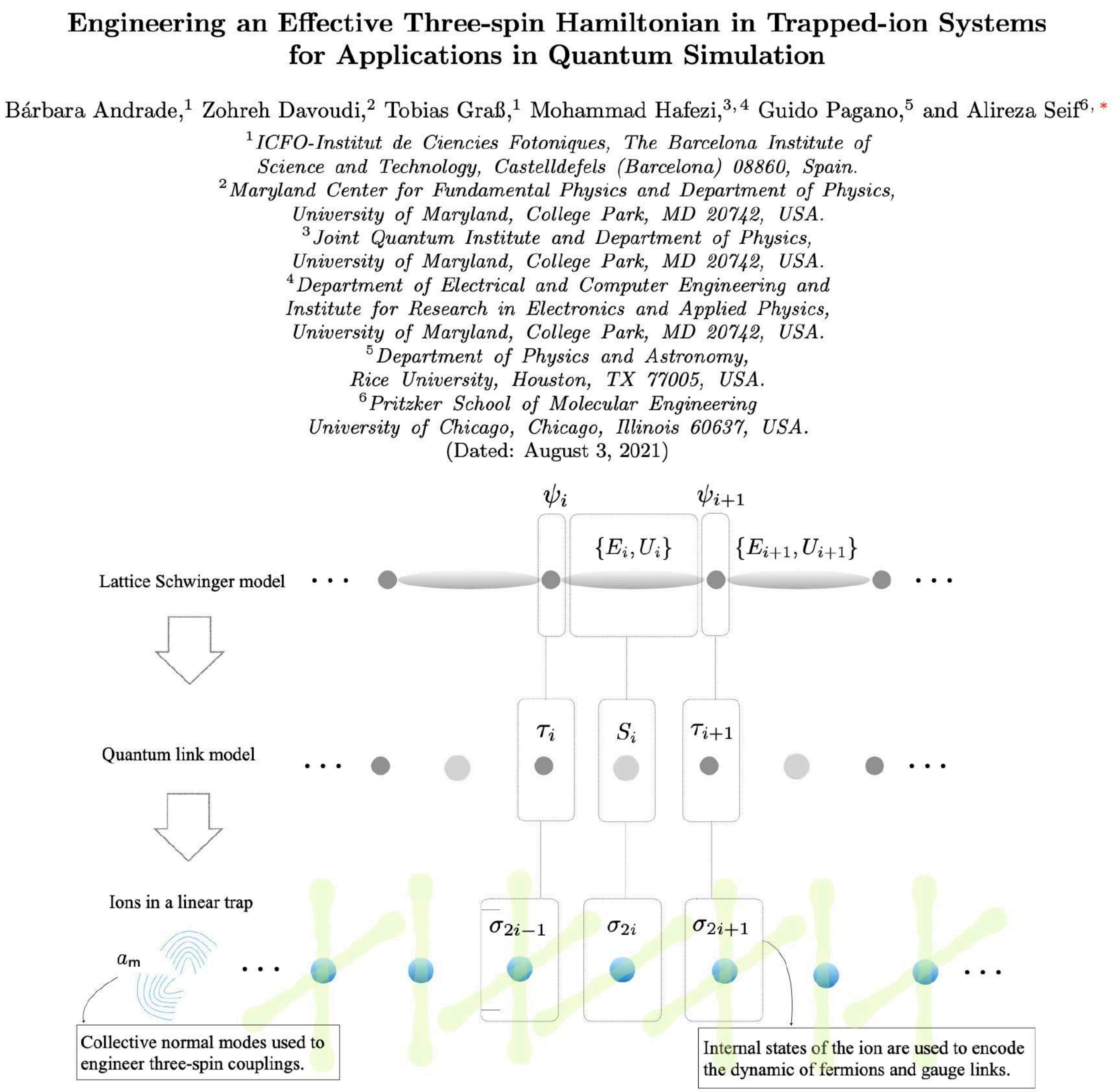
Collective normal modes used to perform spin-spin entangling gates.

Local transverse modes used to encode the dynamic of the gauge fields.

Internal states of the ion are used to encode the dynamic of fermions.



Three-Body Forces on Trapped-Ion Systems



Engineering an Effective Three-spin Hamiltonian in Trapped-ion Systems for Applications in Quantum Simulation

Bárbara Andrade,[1] Zohreh Davoudi,[2] Tobias Graß,[1] Mohammad Hafezi,[3,4] Guido Pagano,[5] and Alireza Seif[6,*]

[1] *ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, Castelldefels (Barcelona) 08860, Spain.*
[2] *Maryland Center for Fundamental Physics and Department of Physics, University of Maryland, College Park, MD 20742, USA.*
[3] *Joint Quantum Institute and Department of Physics, University of Maryland, College Park, MD 20742, USA.*
[4] *Department of Electrical and Computer Engineering and Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, MD 20742, USA.*
[5] *Department of Physics and Astronomy, Rice University, Houston, TX 77005, USA.*
[6] *Pritzker School of Molecular Engineering University of Chicago, Chicago, Illinois 60637, USA.*

(Dated: August 3, 2021)

Collective normal modes used to engineer three-spin couplings.

Internal states of the ion are used to encode the dynamic of fermions and gauge links.

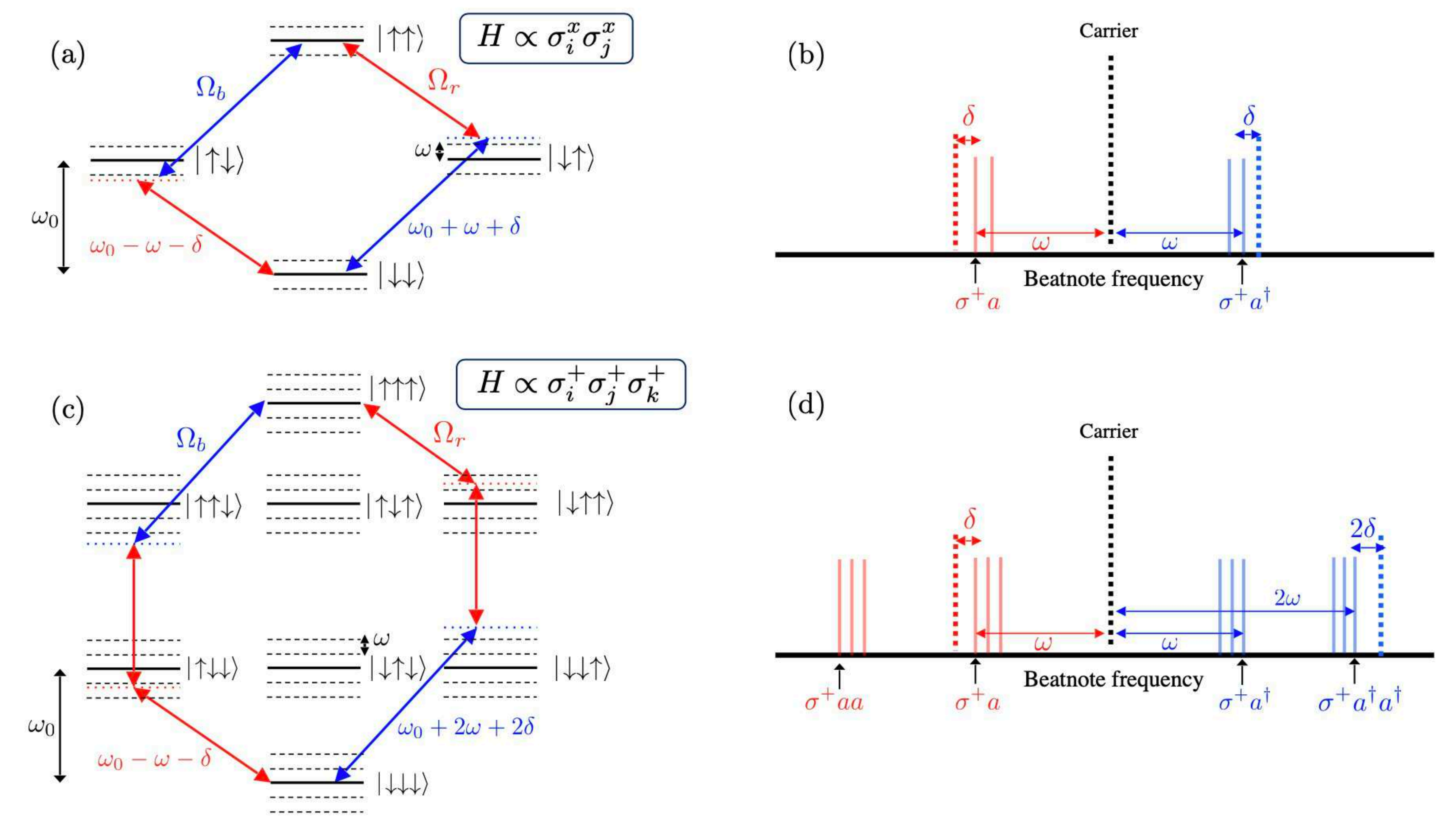


FIG. 1. (a,b) Traditional Mølmer-Sørensen scheme based on a pair of bichromatic laser beatnotes off-resonantly driving first-order spin-phonon couplings with symmetric detuning ($\pm\delta$), giving rise to an effective spin-spin interaction. The two-ion case is shown for simplicity. (c,d) Generalized Mølmer-Sørensen scheme to generate an effective three-spin coupling. A second-order blue sideband is driven with twice the detuning (2δ) as the first-order red ($-\delta$) sideband. As shown in (c), this process creates two virtual phonons with a second-order process and annihilates the same number of phonons through two first-order processes. Note that only two out of several possibilities are depicted. In all subfigures, Ω_r and Ω_b are the Rabi frequencies of the red and blue beatnotes, respectively. ω_0 is the qubit frequency, and $\omega\,[\equiv \omega_{\rm com}]$ is the transverse center-of-mass frequency.

Accessibility

Light-weight codes from Tech companies have been important to bring the field to where it is today

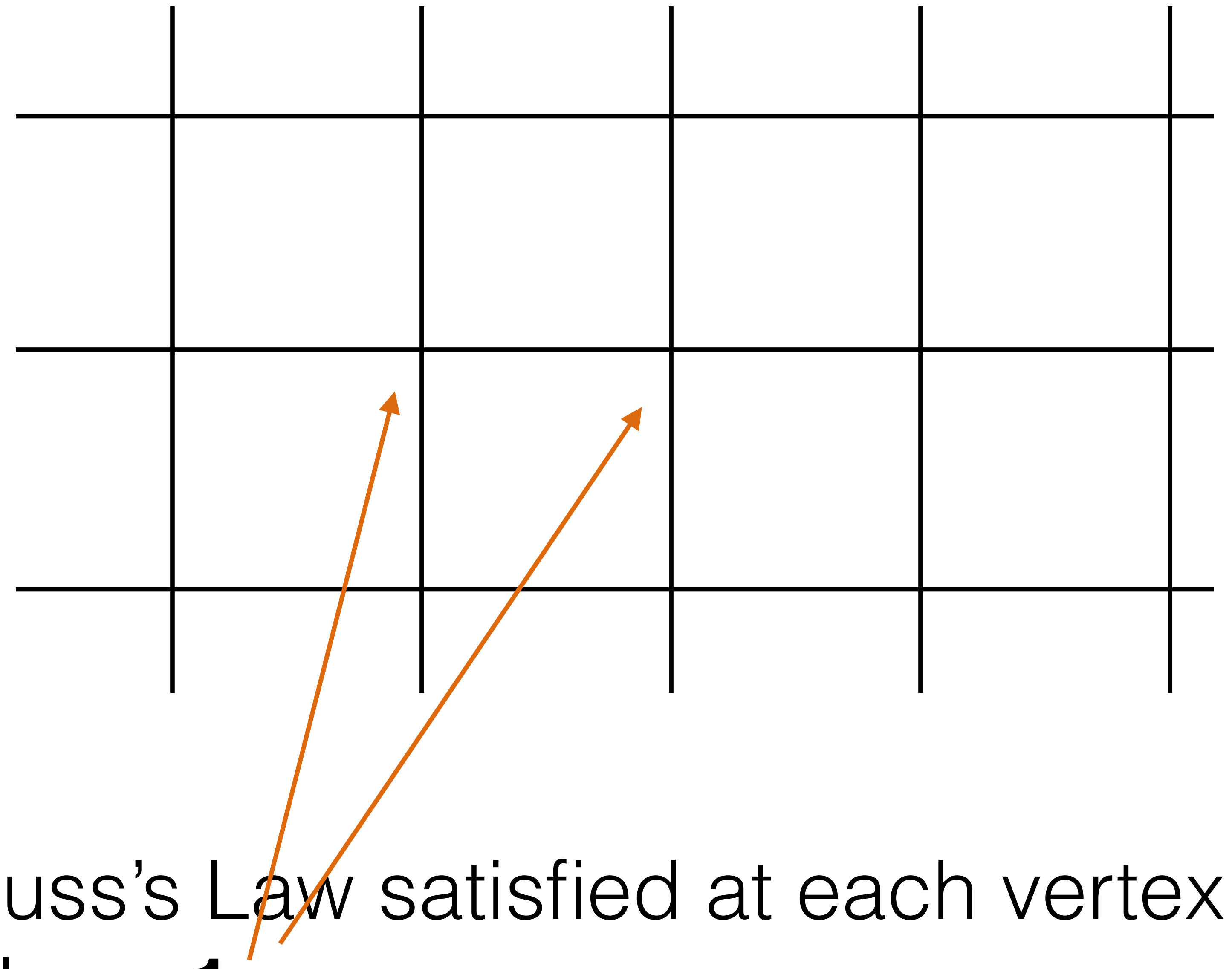
```
In [13]: #
         # Checking
         # specific values of g and t
         #

         g0=1.0
         t0=0.25

         Bccirctest=Bctest(g0,t0)

         # Display it.
         print("Circuit to decompose:\n")
         print(Bccirctest )
         # Decompose the circuit.
         ion_device_Bccirctest = ion_device.decompose_circuit(Bccirctest)
         # Display the decomposed circuit.
         print("\nIonDevice circuit:\n")
         print(ion_device_Bccirctest)
```

```
IonDevice circuit:

0: ───S───────────────MS(-0.25π)───MS(-0.25π)───────MS(-0.25π)───────MS(-0.25π)───────MS(-0.25π)───MS(-0.25π)───MS(-
0.25π)───Z^-0.08───MS(0.25π)───MS(0.25π)───MS(0.25π)───MS(0.25π)───MS(0.25π)───MS(0.25π)───MS(0.25π)───PhX(0)^0.5───
S────────MS(-0.25π)───MS(-0.25π)───MS(-0.25π)───MS(-0.25π)───MS(-0.25π)───MS(-0.25π)───MS(-0.25π)───MS(-0.25π)───Z^0.
08───MS(0.25π)───MS(0.25π)───MS(0.25π)───MS(0.25π)───MS(0.25π)───MS(0.25π)───MS(0.25π)────────────────MS(0.25π)───
───────────────PhX(-0.5)^0.5───Z──────────────────────────────────────────────────────────────────────────────M('r
esult')───

1: ───────────────────MS(-0.25π)───┼────────────┼────────────┼────────────┼─────────┼─────────┼───
──────────────────MS(0.25π)───┼──────┼──────┼──────┼──────┼──────┼───
```

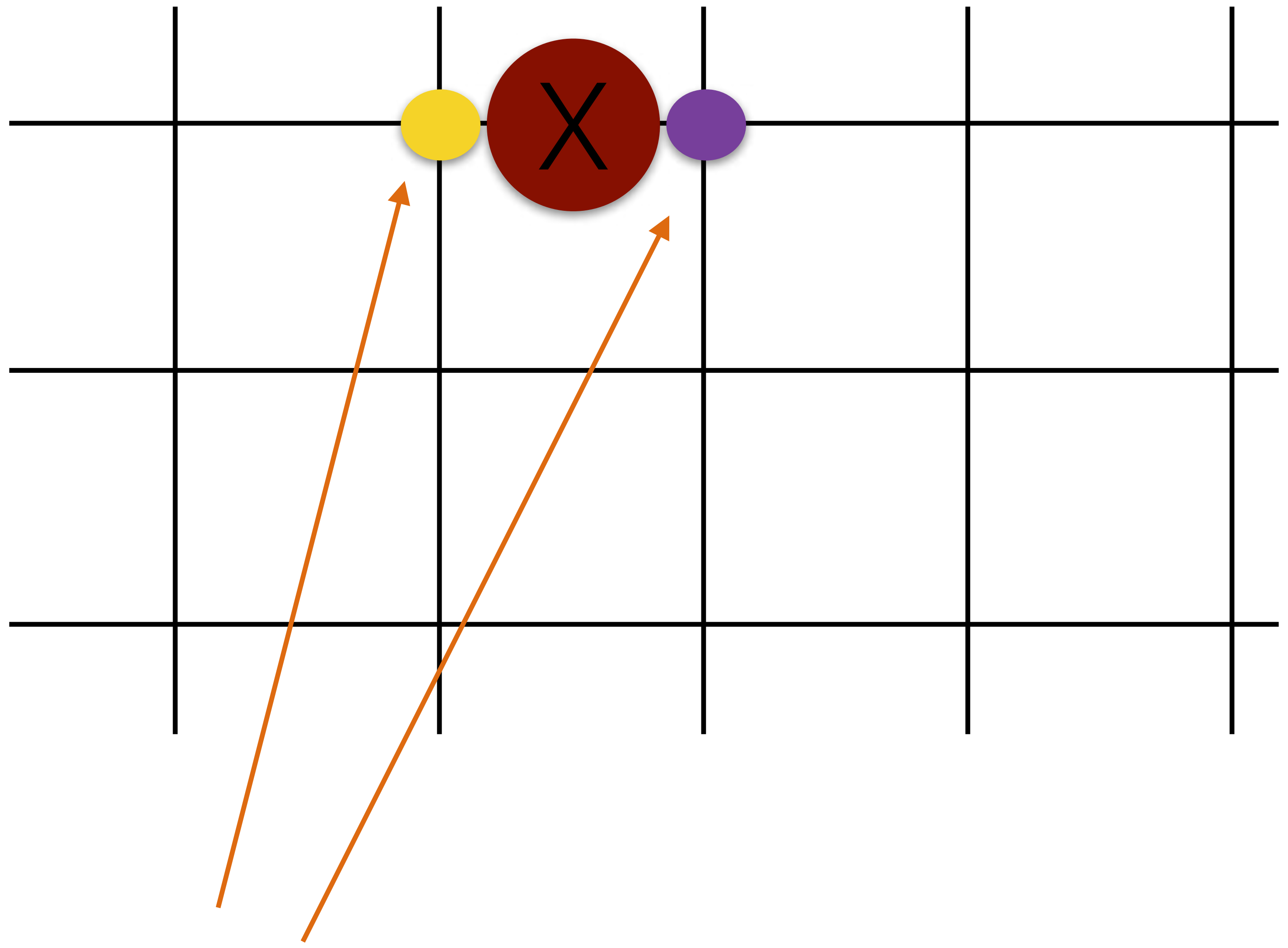
SM Quantum Fields - Errors in QFT

e.g., Yang-Mills, Kogut-Susskind formulation

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



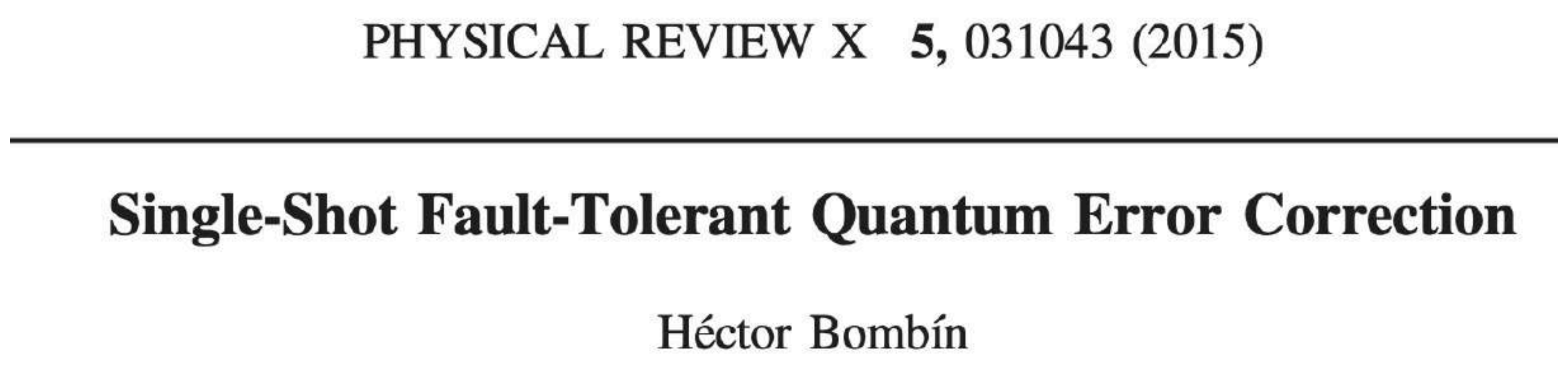
Gauss's Law satisfied at each vertex,
Color = **1**



Gauss's Law violated

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

- Single shot EC in color codes
- Related to self-correcting topologically-ordered GS at finite-T.

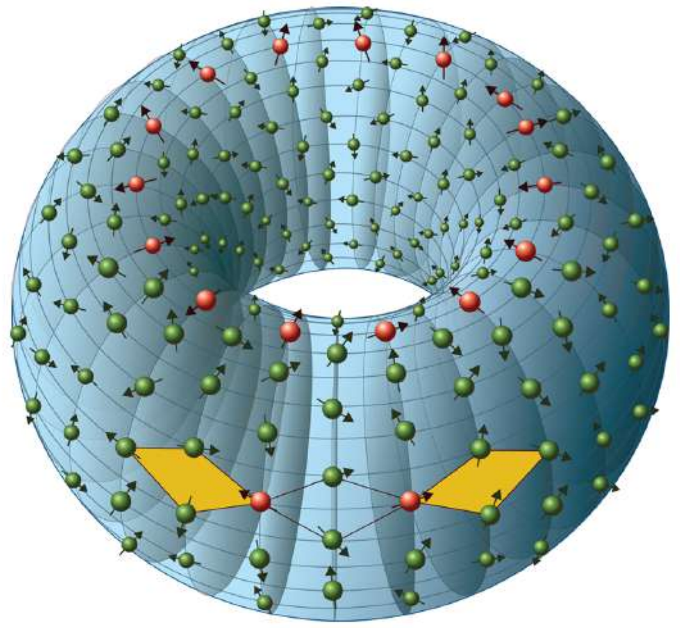


PHYSICAL REVIEW X **5,** 031043 (2015)

Single-Shot Fault-Tolerant Quantum Error Correction

Héctor Bombín

Quantum Fields for EC



Stabilization of information against errors — the discovery of EC in 1995 (Shor, Knill+Laflamme+Zurek,Aharonv+Ben-Or)

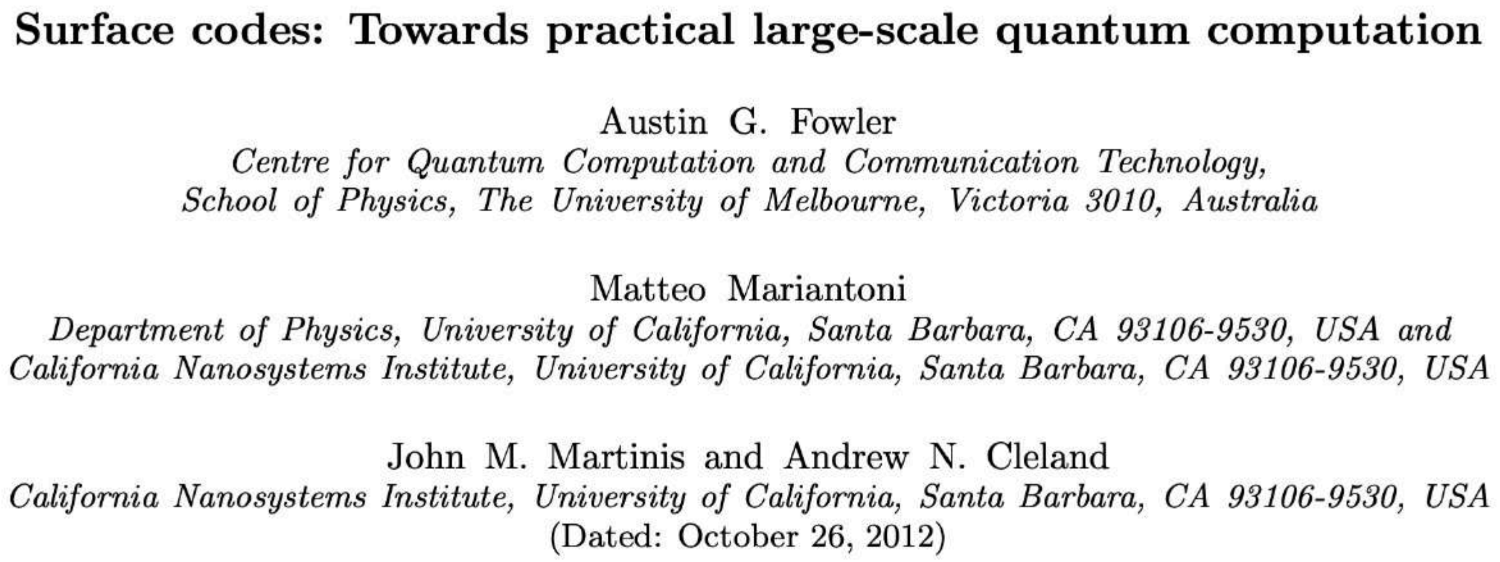
Toric Code (Kitaev)

— both hardware and algorithmic advances

— entangled, topologically ordered ground states of spin systems, with ancillars and (repeated…) application of stabilizers.

— e.g. toric, surface codes, color codes,….

— threshold error rate, below which exponential reduction in logical qubit error rate from increasing number of physical qubits.

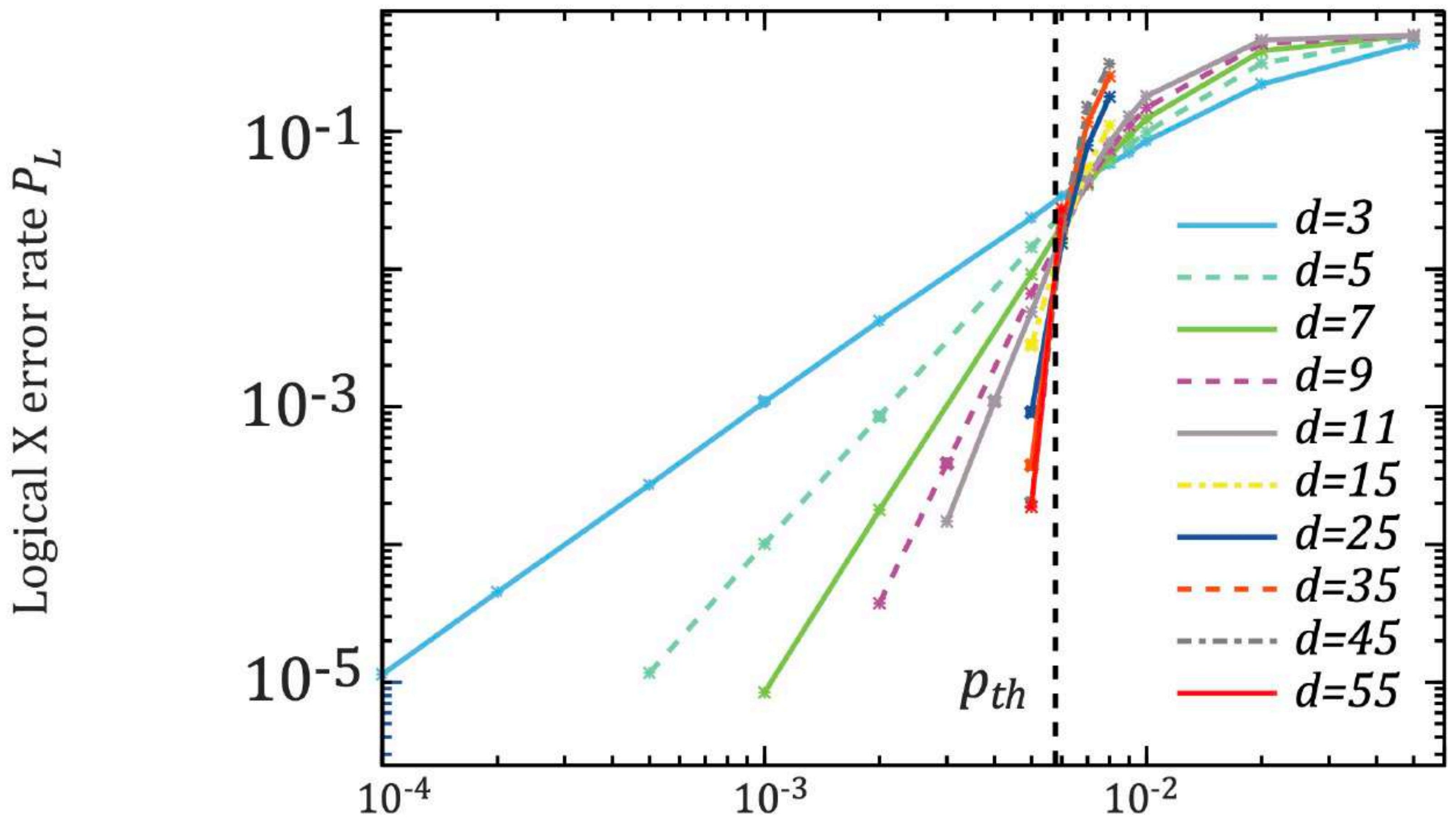


Surface codes: Towards practical large-scale quantum computation

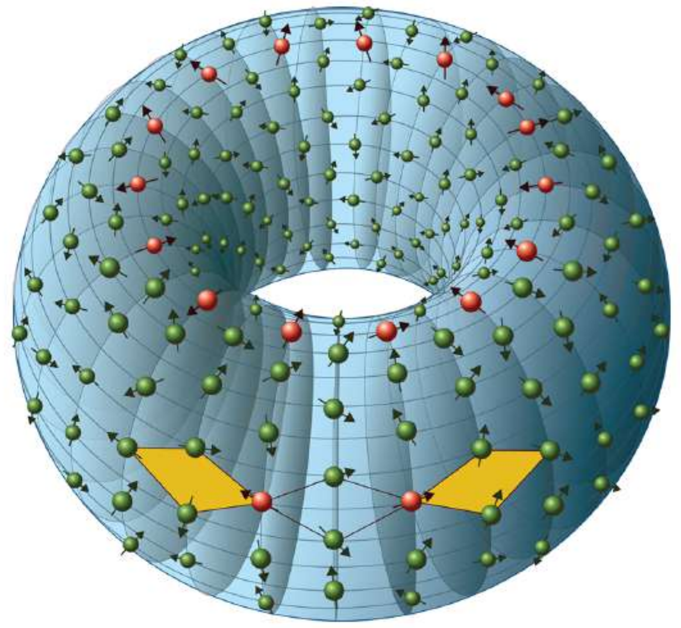
Austin G. Fowler
Centre for Quantum Computation and Communication Technology,
School of Physics, The University of Melbourne, Victoria 3010, Australia

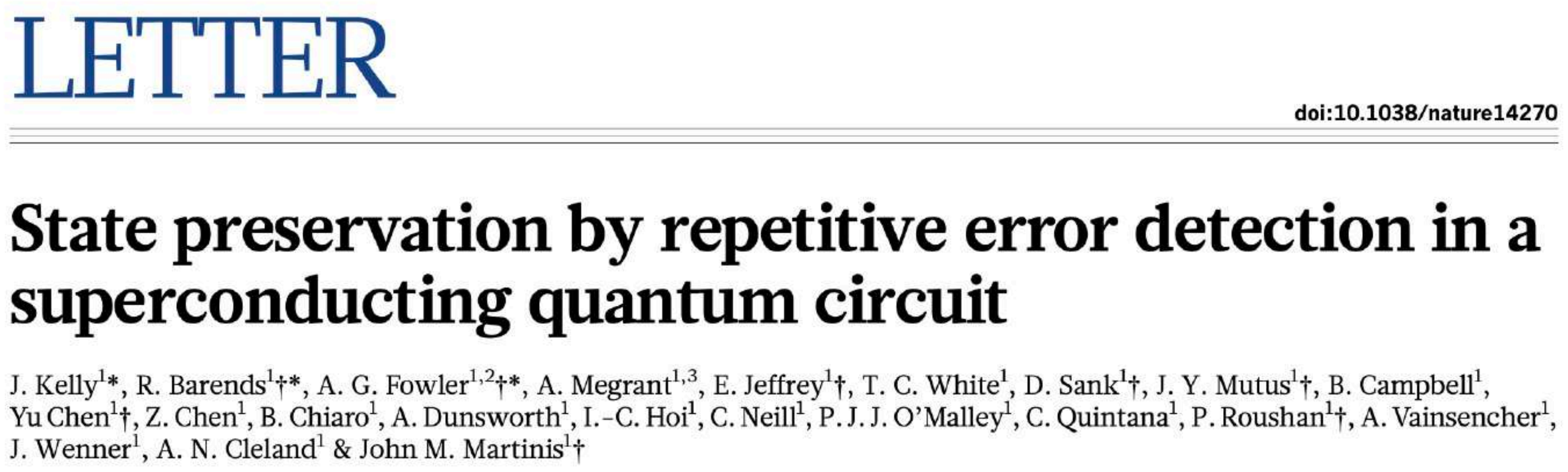
Matteo Mariantoni
Department of Physics, University of California, Santa Barbara, CA 93106-9530, USA and
California Nanosystems Institute, University of California, Santa Barbara, CA 93106-9530, USA

John M. Martinis and Andrew N. Cleland
California Nanosystems Institute, University of California, Santa Barbara, CA 93106-9530, USA
(Dated: October 26, 2012)



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



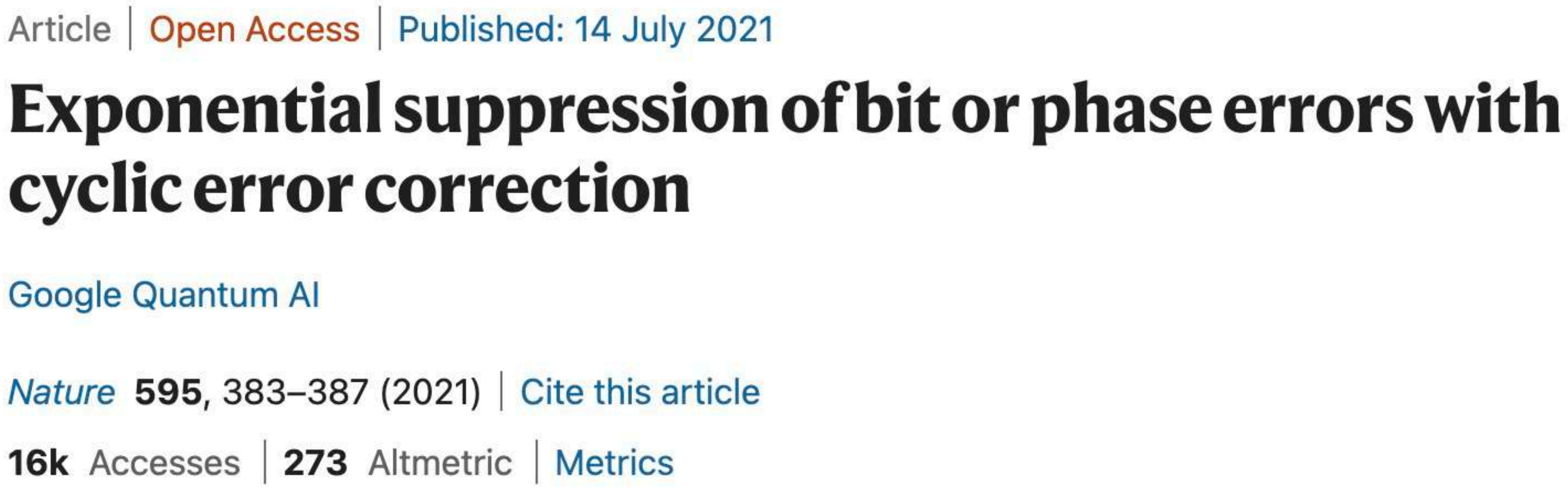


LETTER

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

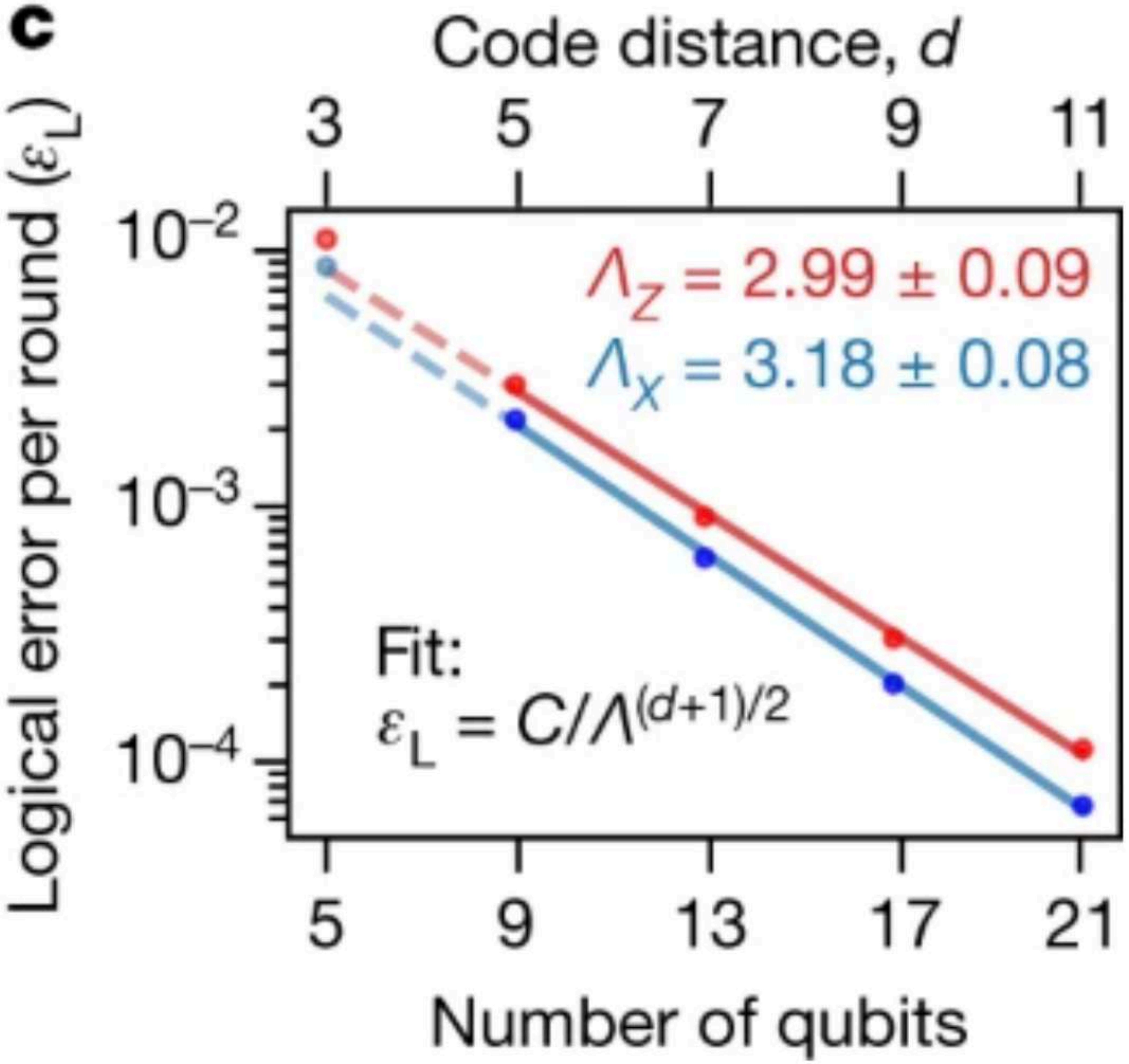
Google Quantum AI

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

16k Accesses | **273** Altmetric | Metrics

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

Repetition code using Sycamore QPU



Honeywell's Color Code Building Blocks
Single Logical Qubit

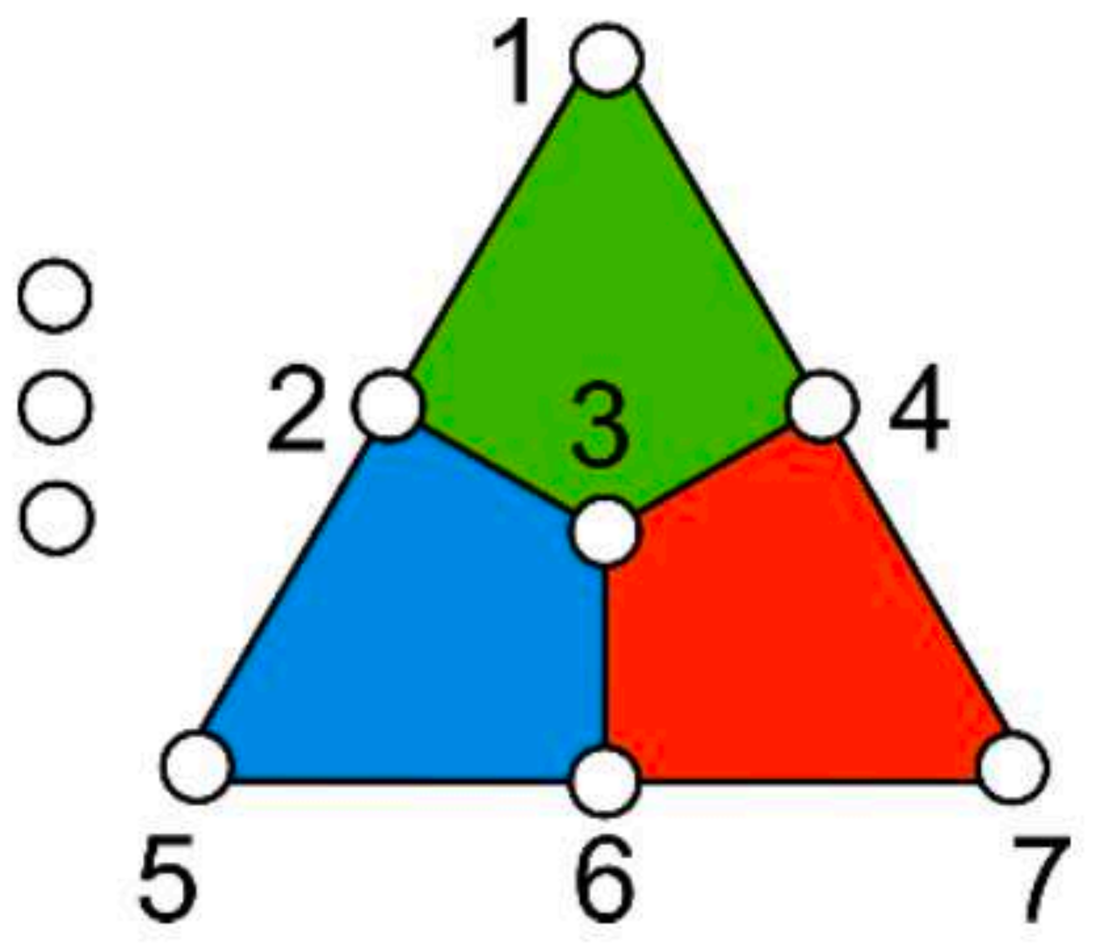
Realization of real-time fault-tolerant quantum error correction

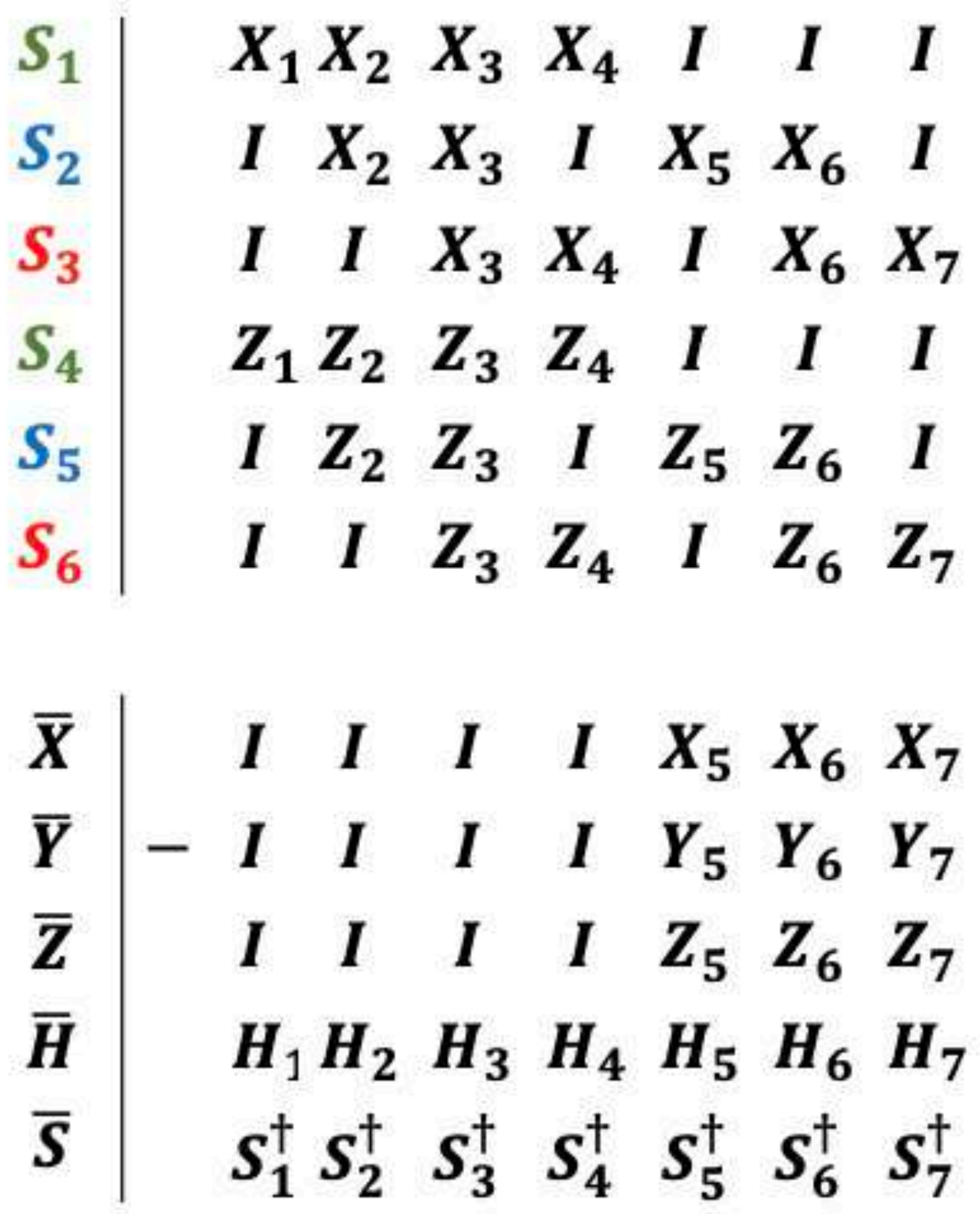
C. Ryan-Anderson, J. G. Bohnet, K. Lee, D. Gresh, A. Hankin, J. P. Gaebler, D. Francois, A. Chernoguzov, D. Lucchetti, N. C. Brown, T. M. Gatterman, S. K. Halit, K. Gilmore, J. Gerber, B. Neyenhuis, D. Hayes, and R. P. Stutz[1]

[1] *Honeywell Quantum Solutions, Broomfield, CO*

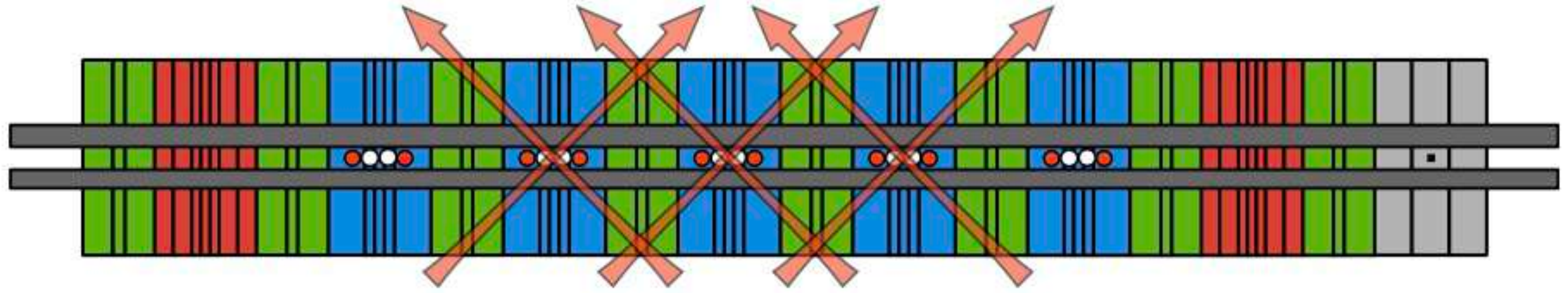
(Dated: July 16, 2021)

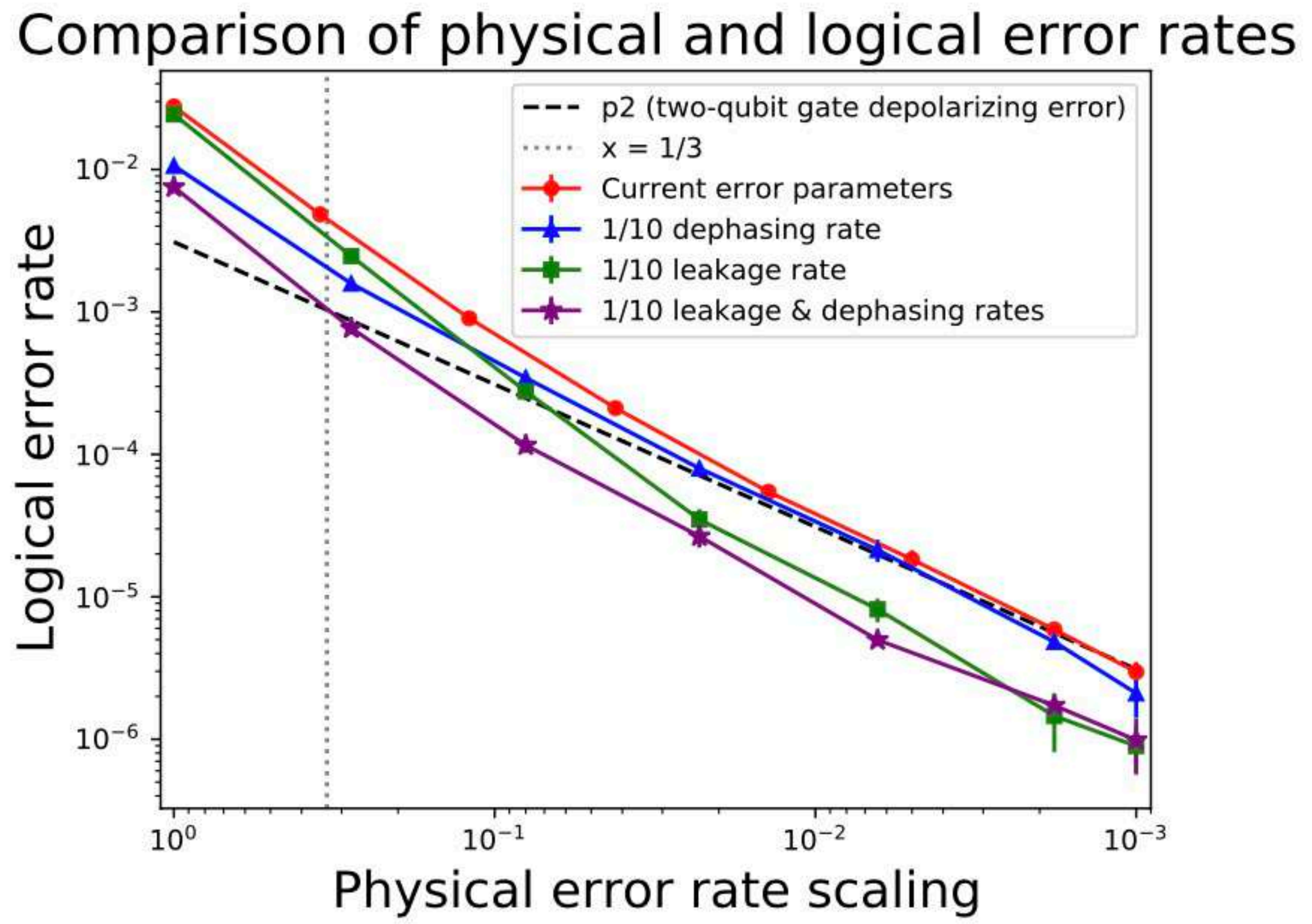
[[7,1,3]] Steane Code





S_1		X_1	X_2	X_3	X_4	I	I	I
S_2		I	X_2	X_3	I	X_5	X_6	I
S_3		I	I	X_3	X_4	I	X_6	X_7
S_4		Z_1	Z_2	Z_3	Z_4	I	I	I
S_5		I	Z_2	Z_3	I	Z_5	Z_6	I
S_6		I	I	Z_3	Z_4	I	Z_6	Z_7
$\bar{X}$		I	I	I	I	X_5	X_6	X_7
$\bar{Y}$	$-$	I	I	I	I	Y_5	Y_6	Y_7
$\bar{Z}$		I	I	I	I	Z_5	Z_6	Z_7
$\bar{H}$		H_1	H_2	H_3	H_4	H_5	H_6	H_7
$\bar{S}$		$S_1^\dagger$	$S_2^\dagger$	$S_3^\dagger$	$S_4^\dagger$	$S_5^\dagger$	$S_6^\dagger$	$S_7^\dagger$





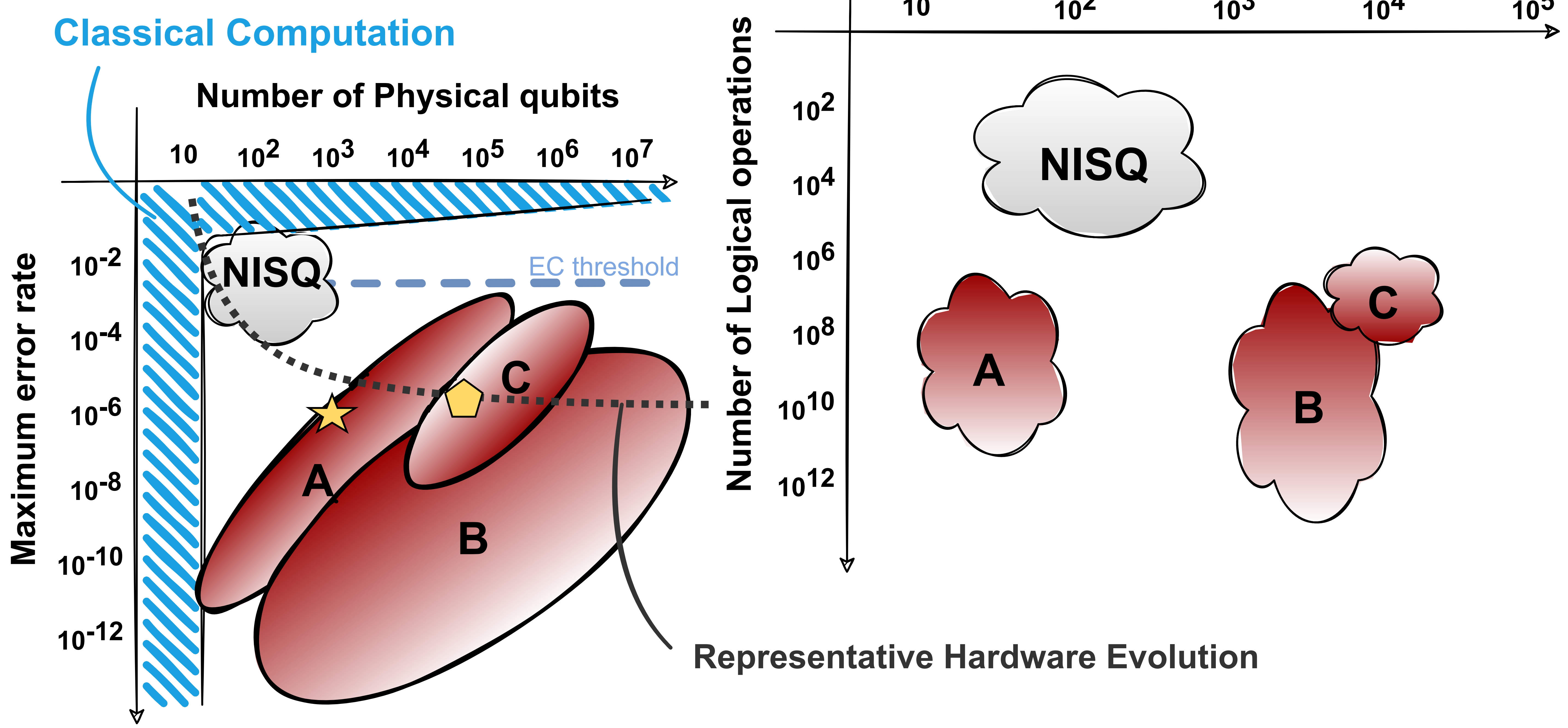
CONCLUSION

In this work, we demonstrated the primitives needed for quantum error correction restricted to a single logical qubit, including high fidelity state-preparation and readout of logical basis states and a magic state, logical single-qubit gates, and repeatable error correction cycles. By establishing the necessary hardware capabilities along with detailed simulations of the processes, we can now begin developing a QCCD system architecture that is optimized for computations at the logical level.

Standard Model Physics and the Digital Quantum Revolution: Thoughts about the Interface
Natalie Klco (Caltech and Caltech, IQI), Alessandro Roggero (Washington U., Seattle), Martin J. Savage (Washington U., Seattle) (Jul 10, 2021)
e-Print: 2107.04769 [quant-ph]

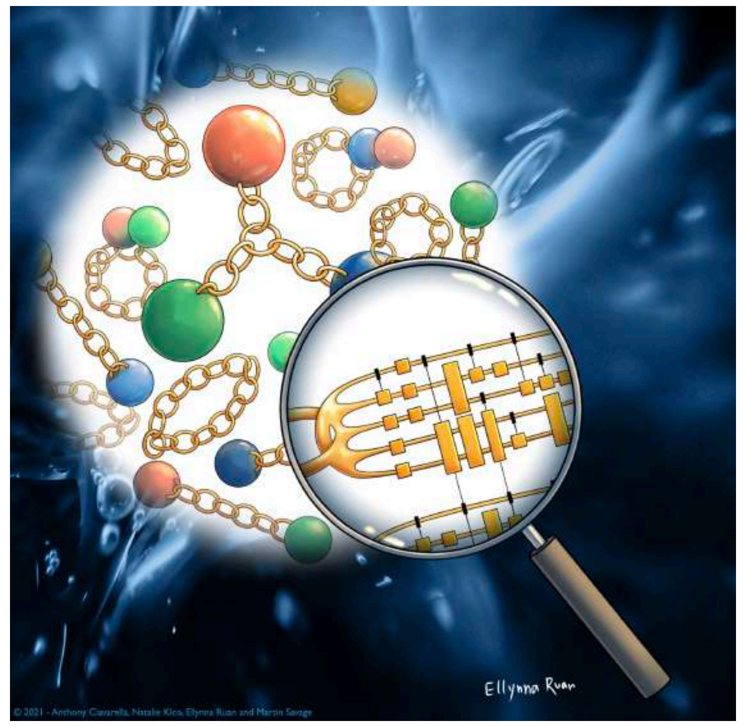
Some Considerations for Simulations

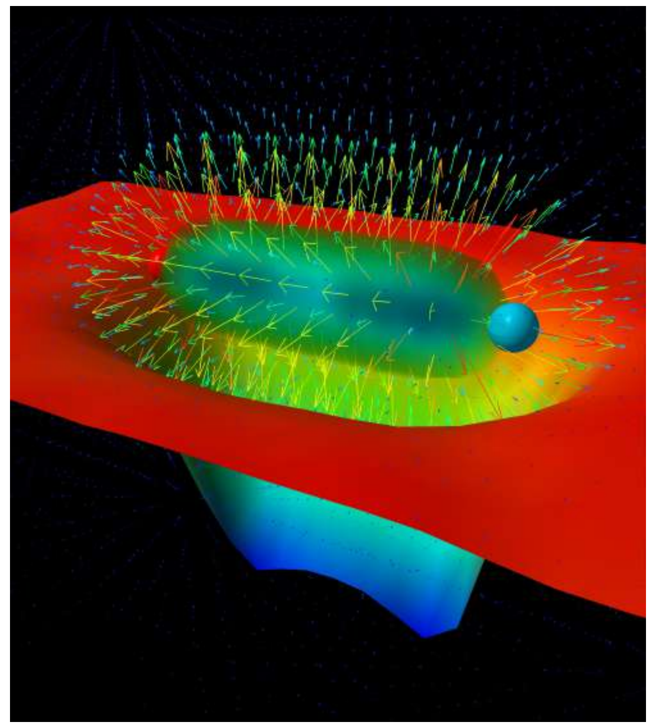
Modified from Google figure

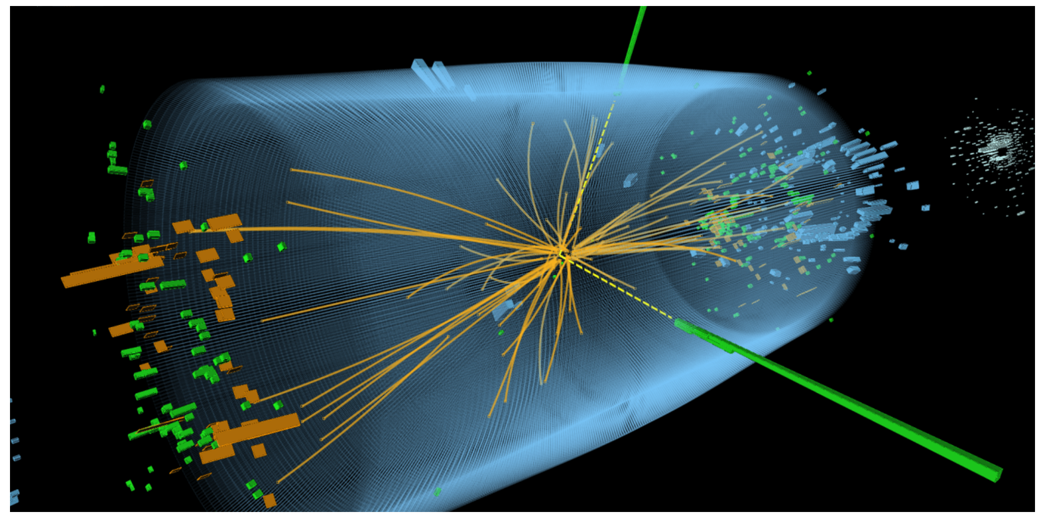


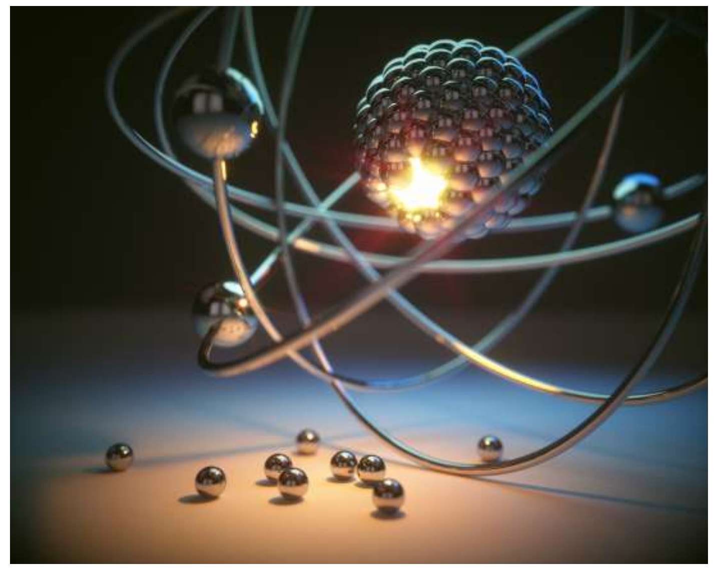
- EC thresholds for surface code around 0.5%
- Different problems have different "ε", and different circuits depths
- Can be mapped differently onto hardware
  - A given hardware configuration (device) of physical qubits may be able to address multiple problems
- Co-developed hardware may be required for given problems

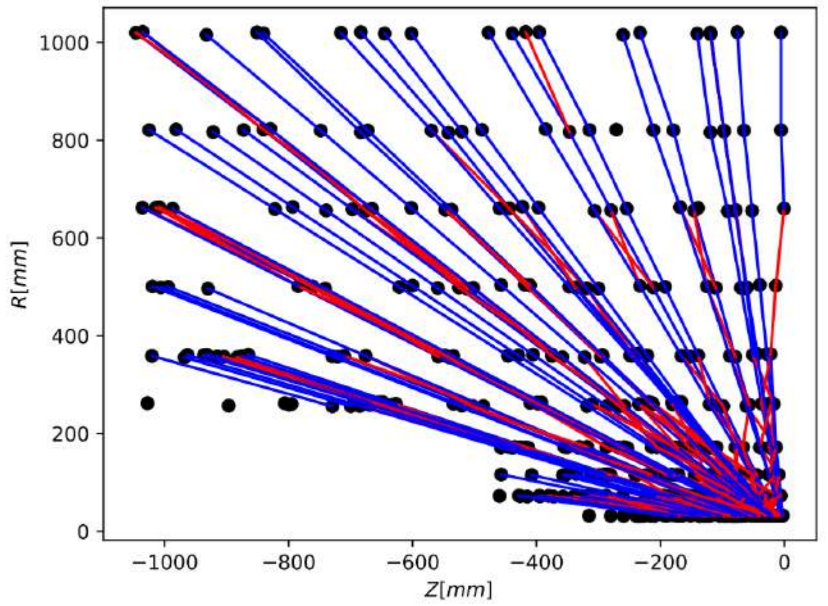
Close











It is a remarkable period in the development of quantum simulations for Standard Model physics - quantum field theories and quantum many-body systems

Non-equilibrium dynamics, highly-inelastic processes, structure of large nuclei, neutrinos in dense systems, …..

Co-design and development

Quantum correlations, entanglement and simulation = New Frontier

FIN

2020 : DOE and NSF : Funding for Quantum Centers

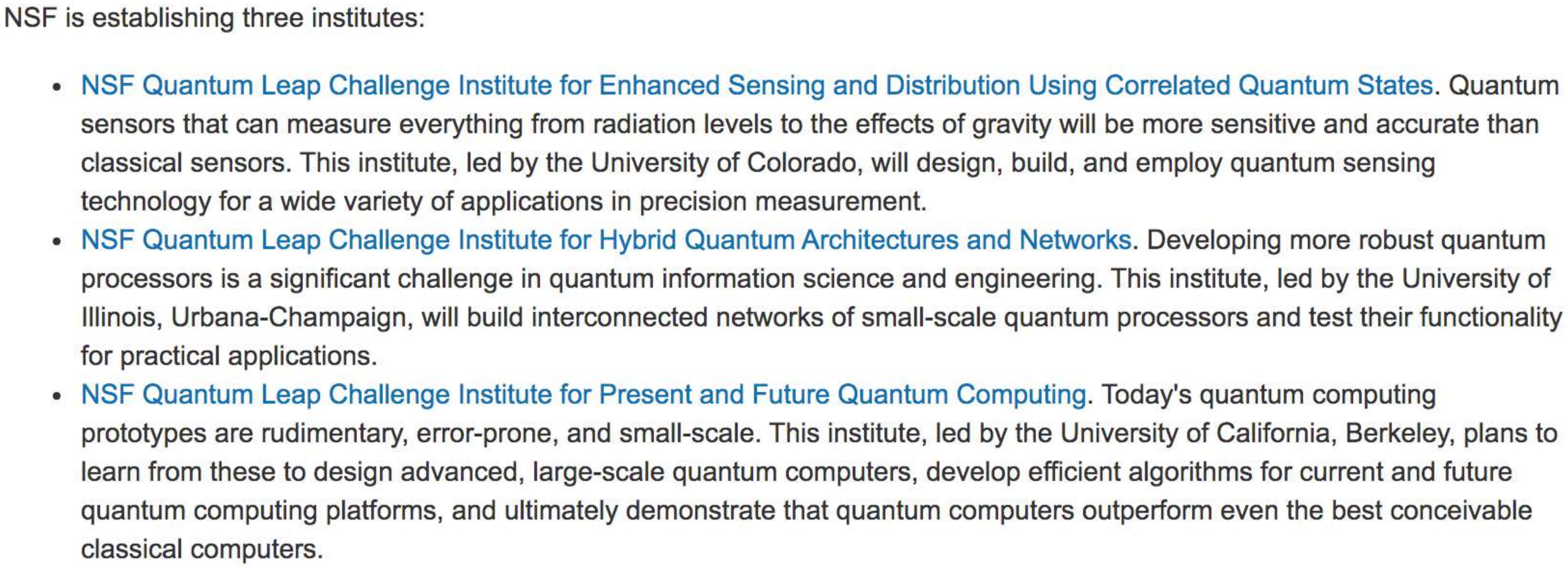
C^2QA
Co-design Center for
Quantum Advantage

QUANTUM
SCIENCE
CENTER

QUANTUM SYSTEMS ACCELERATOR
Catalyzing the Quantum Ecosystem

Q-NEXT
NEXT GENERATION QUANTUM
SCIENCE AND ENGINEERING


Superconducting Quantum Materials and Systems Center
A national center for advancing quantum science and technology


NSF is establishing three institutes:

- NSF Quantum Leap Challenge Institute for Enhanced Sensing and Distribution Using Correlated Quantum States. Quantum sensors that can measure everything from radiation levels to the effects of gravity will be more sensitive and accurate than classical sensors. This institute, led by the University of Colorado, will design, build, and employ quantum sensing technology for a wide variety of applications in precision measurement.
- NSF Quantum Leap Challenge Institute for Hybrid Quantum Architectures and Networks. Developing more robust quantum processors is a significant challenge in quantum information science and engineering. This institute, led by the University of Illinois, Urbana-Champaign, will build interconnected networks of small-scale quantum processors and test their functionality for practical applications.
- NSF Quantum Leap Challenge Institute for Present and Future Quantum Computing. Today's quantum computing prototypes are rudimentary, error-prone, and small-scale. This institute, led by the University of California, Berkeley, plans to learn from these to design advanced, large-scale quantum computers, develop efficient algorithms for current and future quantum computing platforms, and ultimately demonstrate that quantum computers outperform even the best conceivable classical computers.