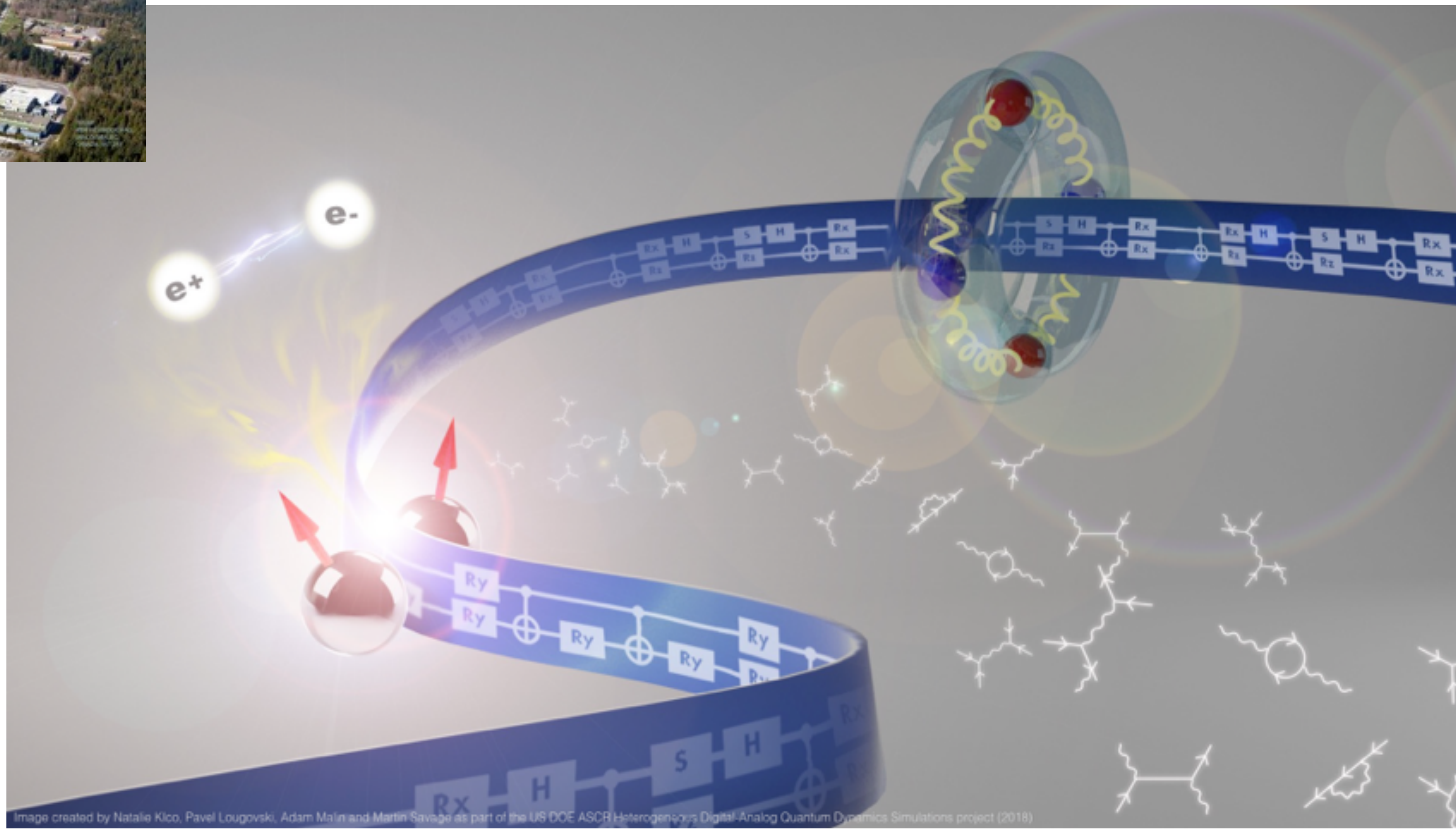


Pursuing a Quantum Advantage for QCD

Data Science and Quantum Computing Workshop
TRIUMF, June 26-28, 2018

Martin J Savage

INSTITUTE for NUCLEAR THEORY

Feynman's Vision

Simulating Physics with Computers

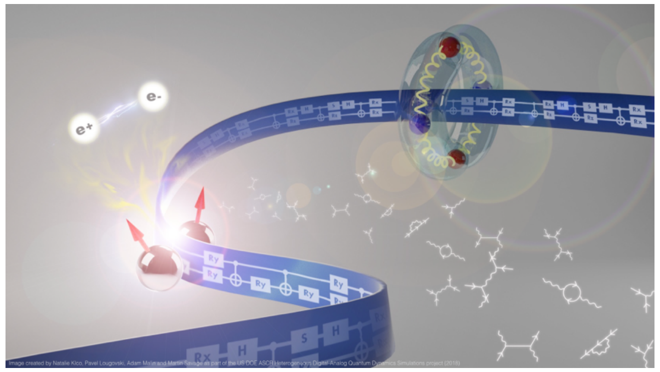
Richard P. Feynman

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

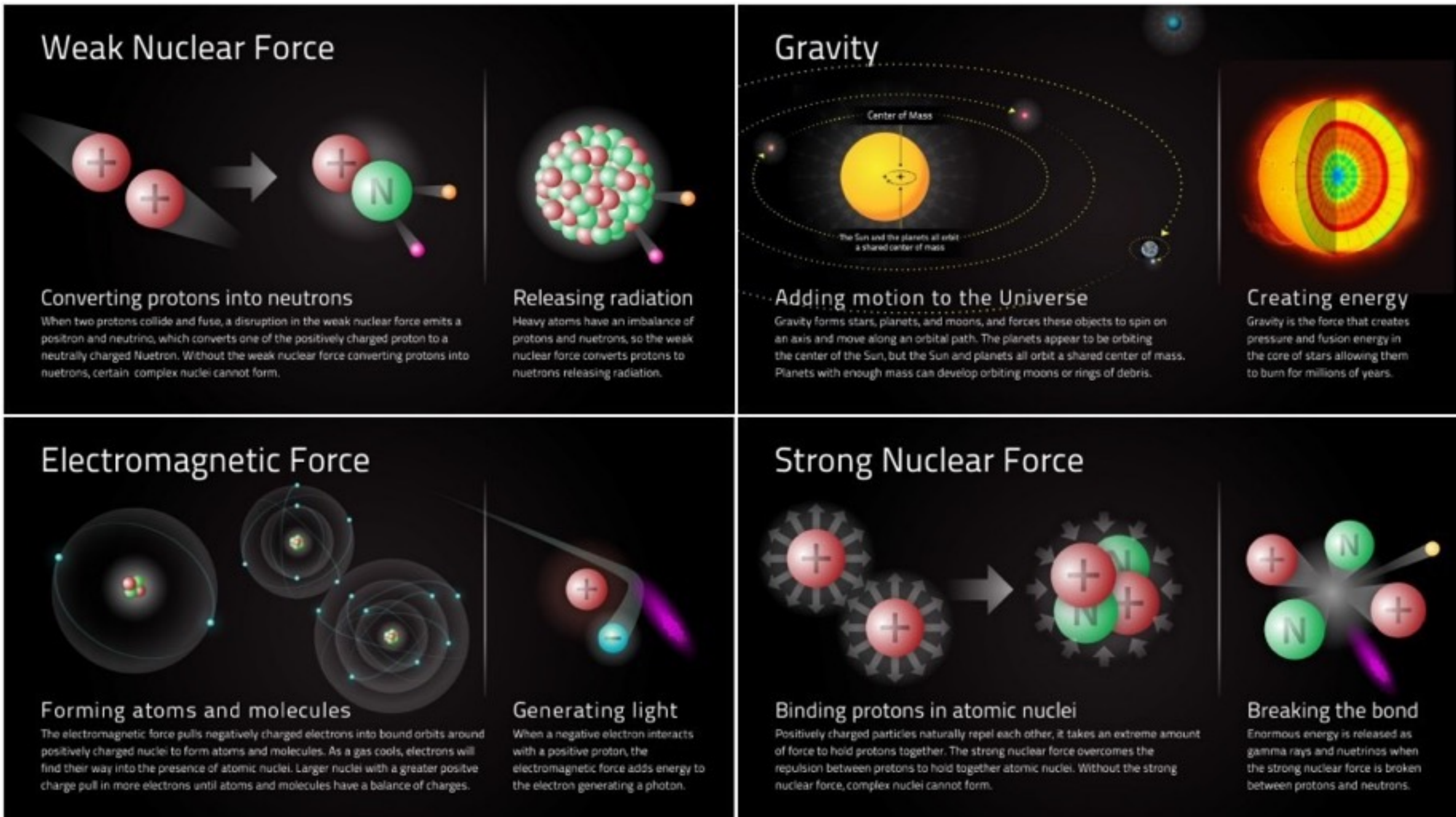
Received May 7, 1981

4. QUANTUM COMPUTERS—UNIVERSAL QUANTUM SIMULATORS

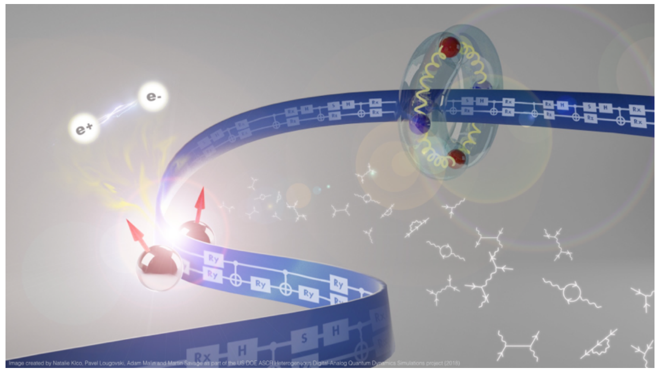
5. CAN QUANTUM SYSTEMS BE PROBABILISTICALLY SIMULATED BY A CLASSICAL COMPUTER?



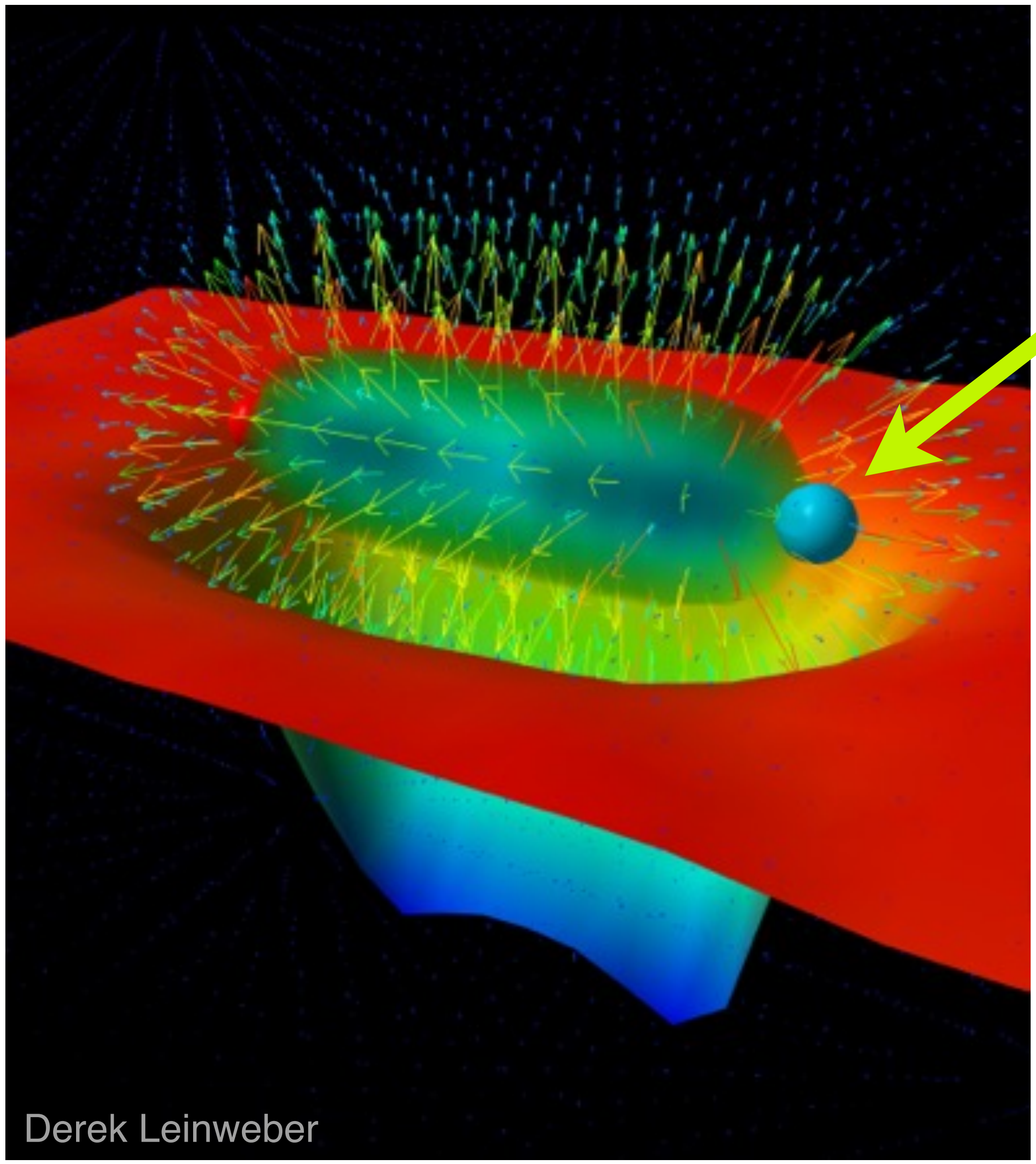
Fundamental Forces of Nature



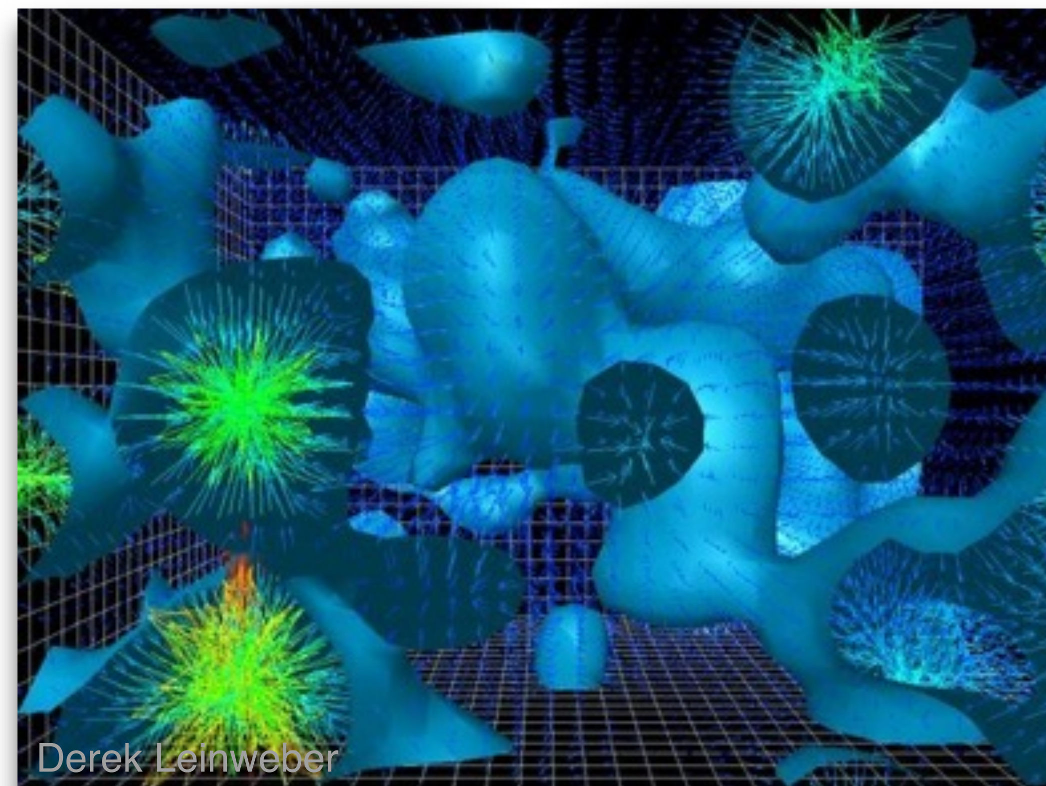
https://rootofscience.com



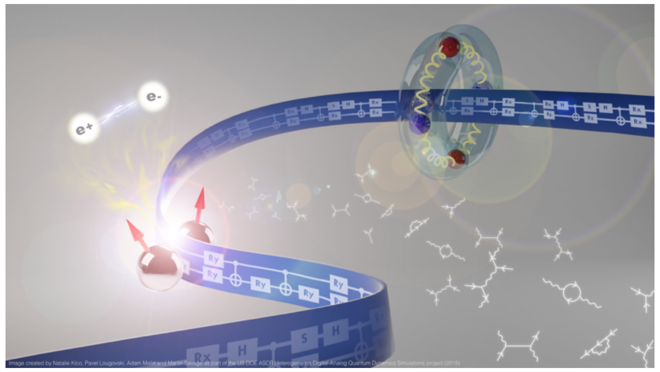
Quantum Chromodynamics



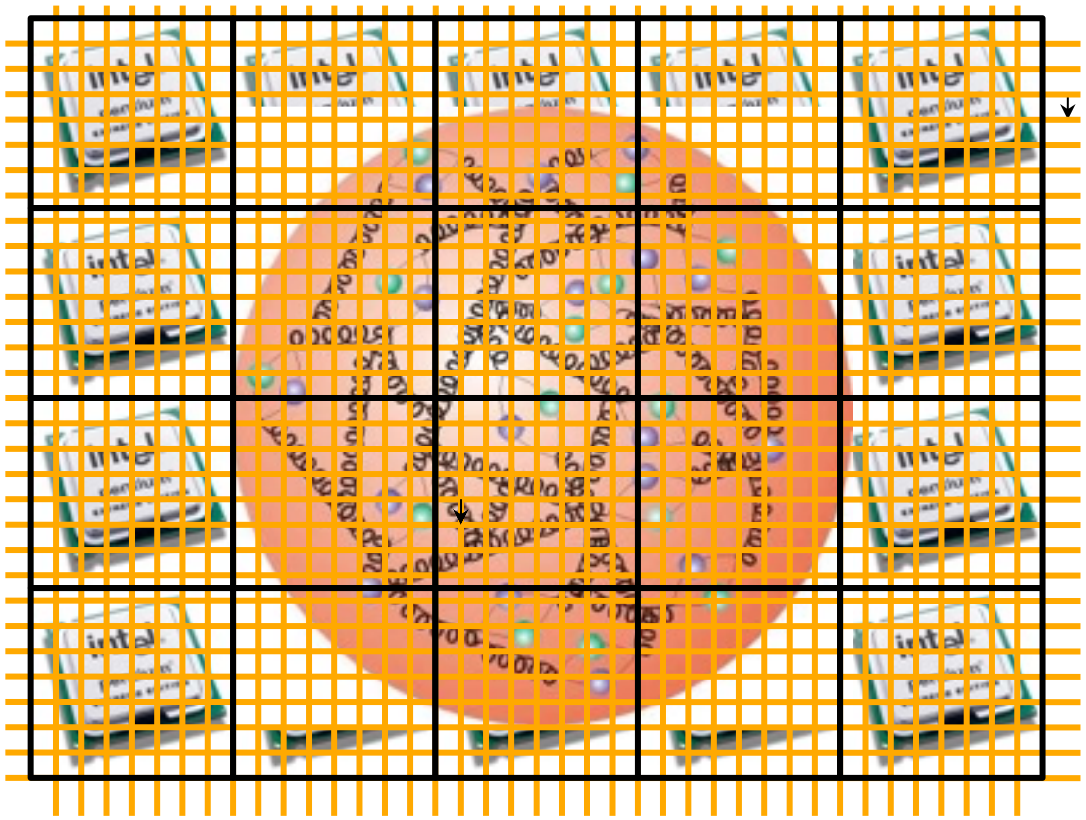
$F \sim 2 \times 10^5$ N



- Analytic techniques fail to converge
- The vacuum is non-trivial with a quark condensate
- Lattice QCD enables reliable calculations - HEP and NP



Lattice Quantum Chromodynamics - Discretized Euclidean Spacetime

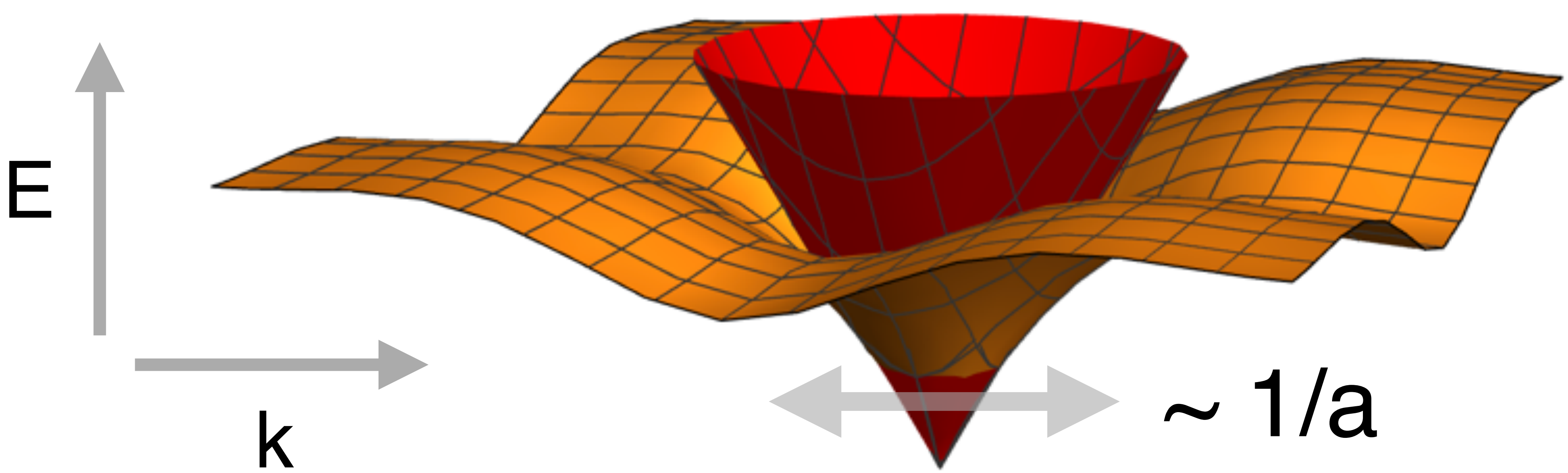


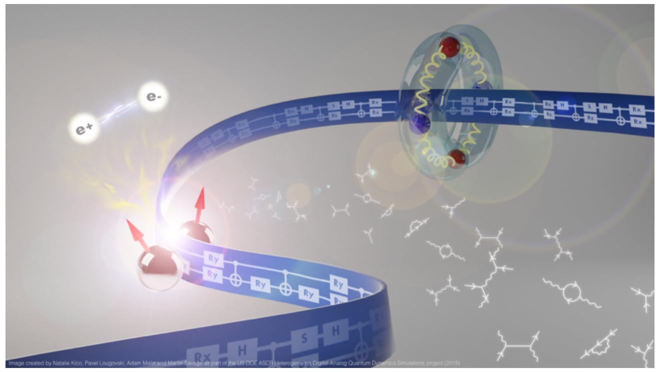
Lattice Spacing :
$a << 1/\Lambda\chi$
(Nearly Continuum)

Lattice Volume :
$m_\pi L >> 2\pi$
(Nearly Infinite Volume)

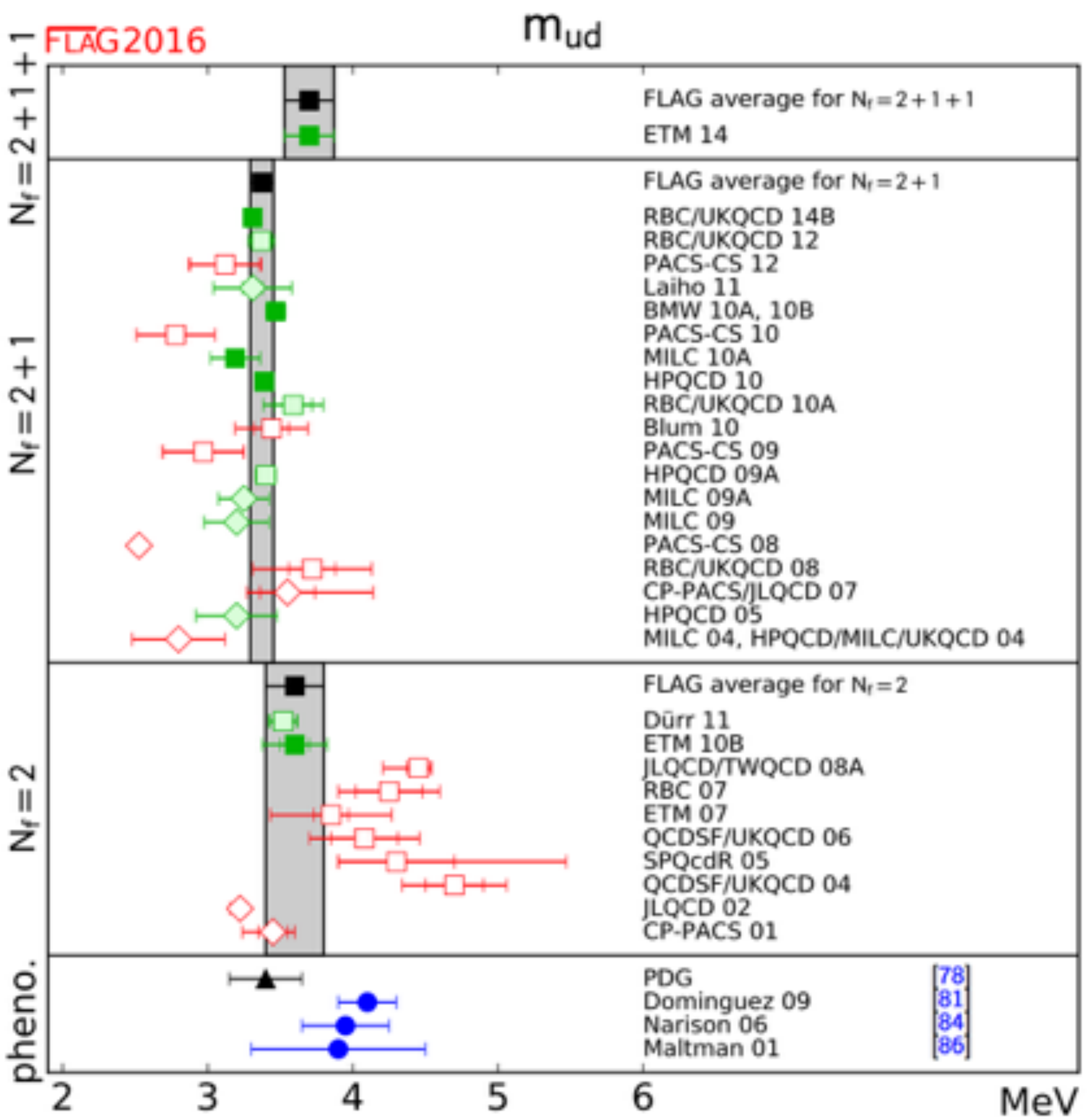
Reliable extrapolation to
$a = 0 \quad \text{and} \quad L = \infty$

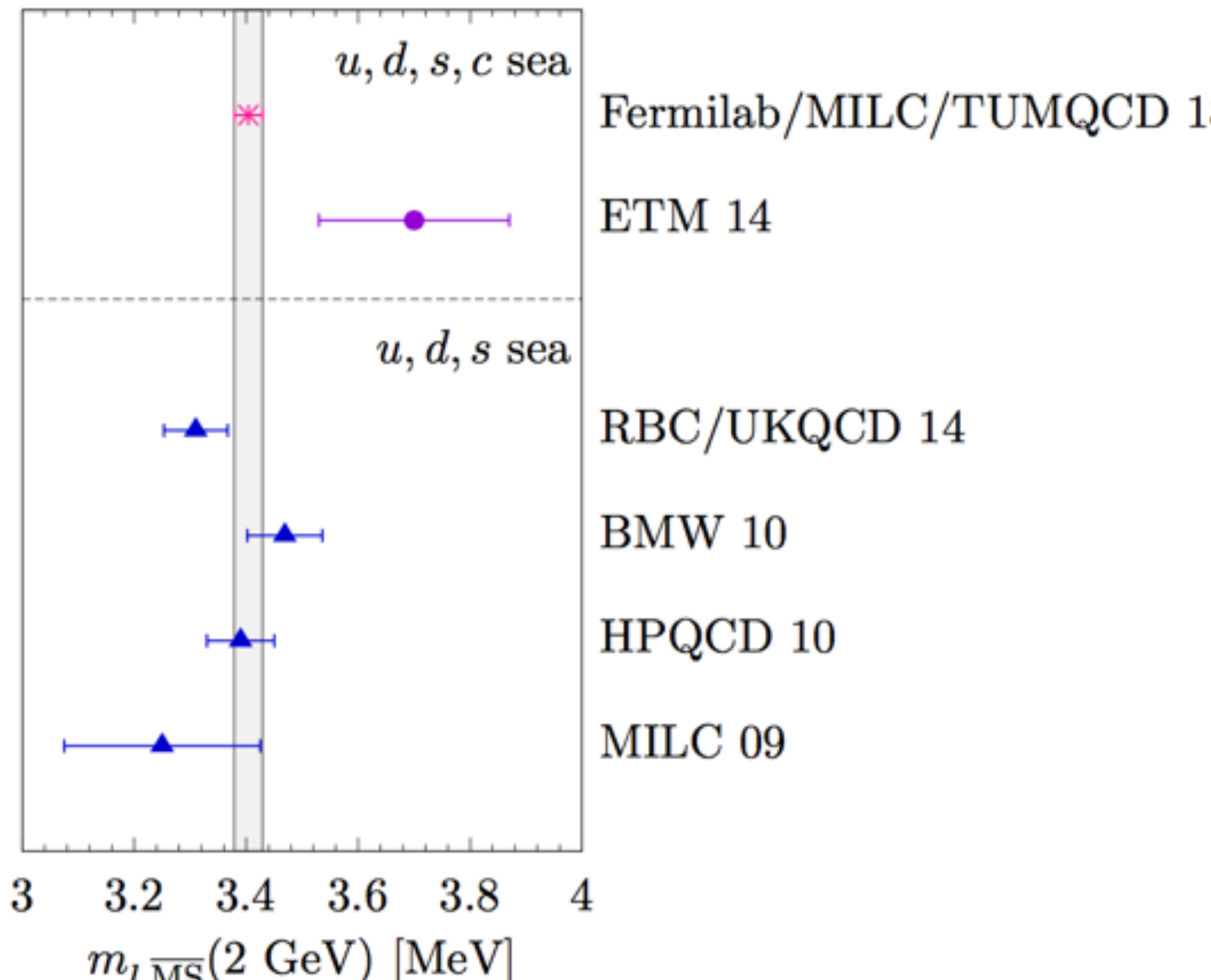
Systematically remove non-QCD parts of calculation through effective field theories





Lattice QCD
The Quark Masses





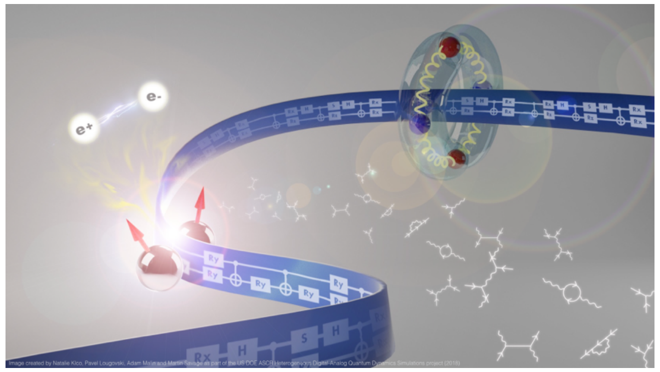
Up-, down-, strange-, charm-, and bottom-quark masses from four-flavor lattice QCD

A. Bazavov,[1] C. Bernard,[2,*] N. Brambilla,[3,4,†] N. Brown,[2] C. DeTar,[5] A.X. El-Khadra,[6,7] E. Gámiz,[8] Steven Gottlieb,[9] U.M. Heller,[10] J. Komijani,[3,4,11,‡] A.S. Kronfeld,[7,4,§] J. Laiho,[12] P.B. Mackenzie,[7] E.T. Neil,[13,14] J.N. Simone,[7] R.L. Sugar,[15] D. Toussaint,[16,¶] A. Vairo,[3,**] and R.S. Van de Water[7]

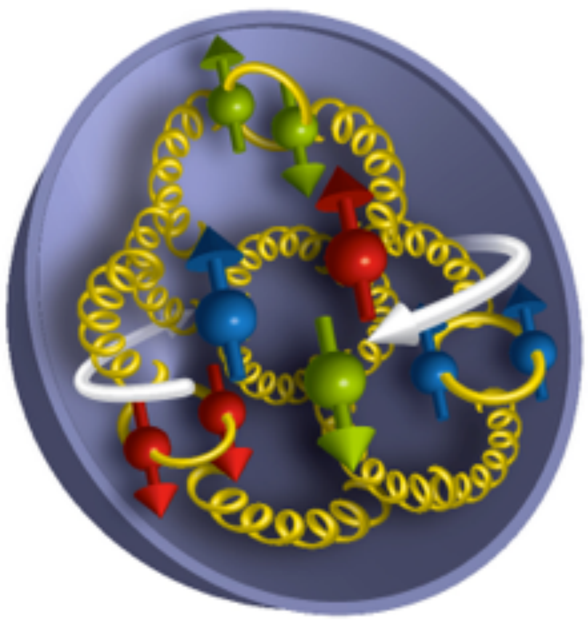
(Fermilab Lattice, MILC, and TUMQCD Collaborations)

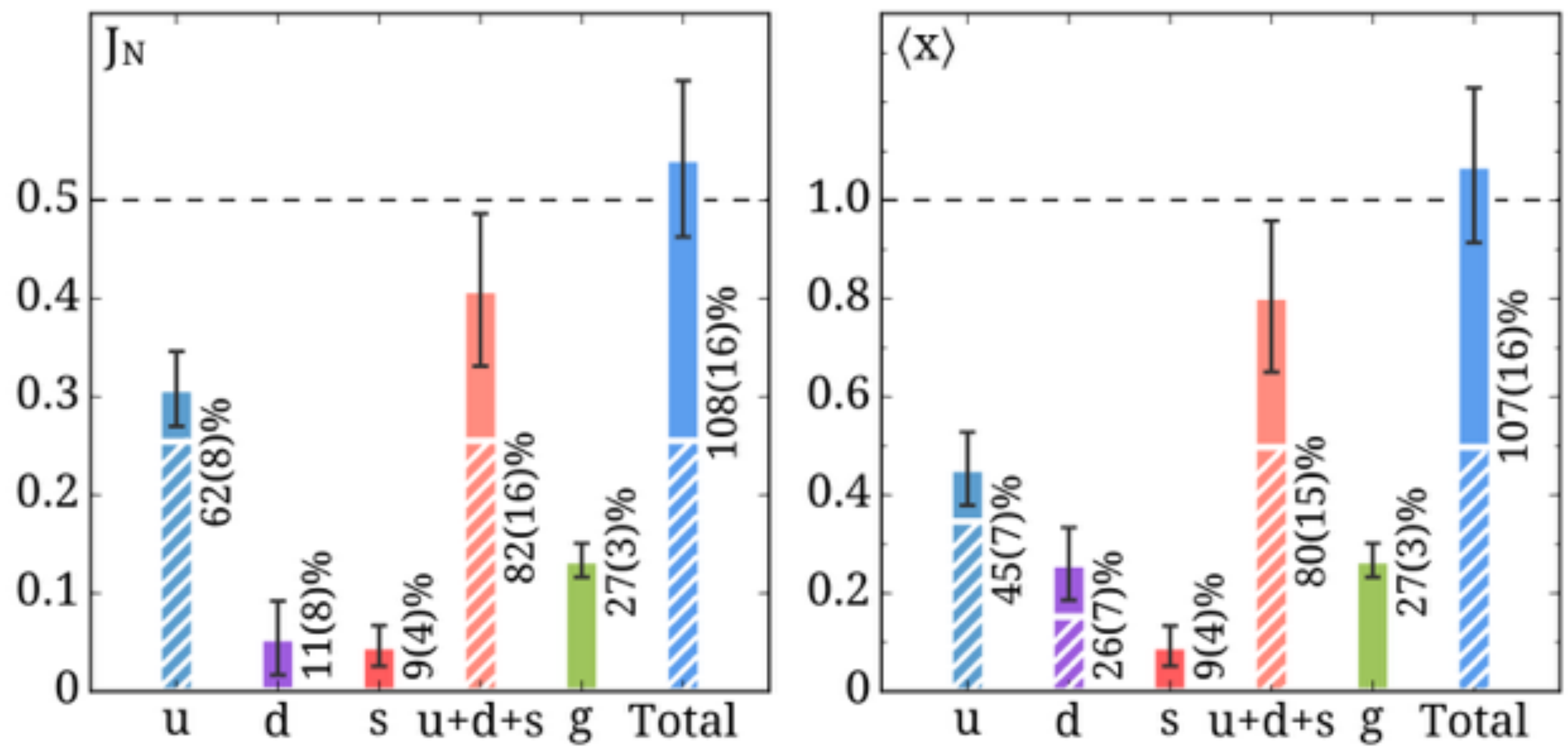
e-Print: arXiv:1802.04248 [hep-lat]

$$m_{l,\overline{\text{MS}}}(3\text{ GeV}) = 3.073(13)_{\text{stat}}(07)_{\text{syst}}(10)_{\alpha_s}(04)_{f_\pi,\text{PDG}}\text{ MeV},$$
$$m_{u,\overline{\text{MS}}}(3\text{ GeV}) = 1.912(16)_{\text{stat}}(29)_{\text{syst}}(06)_{\alpha_s}(03)_{f_\pi,\text{PDG}}\text{ MeV},$$
$$m_{d,\overline{\text{MS}}}(3\text{ GeV}) = 4.234(27)_{\text{stat}}(32)_{\text{syst}}(14)_{\alpha_s}(05)_{f_\pi,\text{PDG}}\text{ MeV},$$
$$m_{s,\overline{\text{MS}}}(3\text{ GeV}) = 83.53(36)_{\text{stat}}(16)_{\text{syst}}(27)_{\alpha_s}(11)_{f_\pi,\text{PDG}}\text{ MeV},$$
$$m_{c,\overline{\text{MS}}}(3\text{ GeV}) = 984.3(4.2)_{\text{stat}}(1.6)_{\text{syst}}(3.2)_{\alpha_s}(0.6)_{f_\pi,\text{PDG}}\text{ MeV}.$$

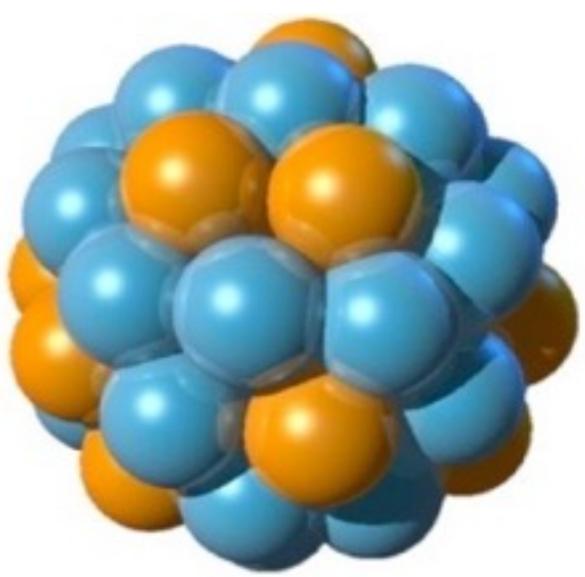


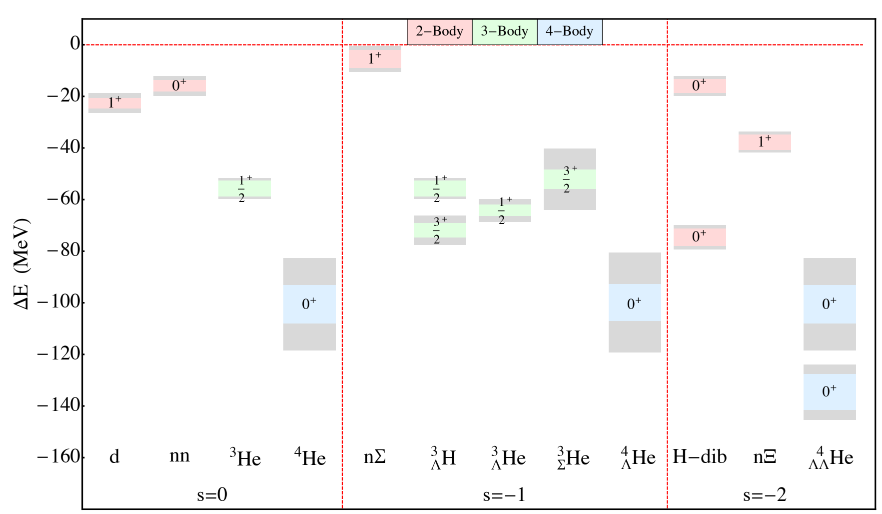
NP - Hadrons and Nuclei



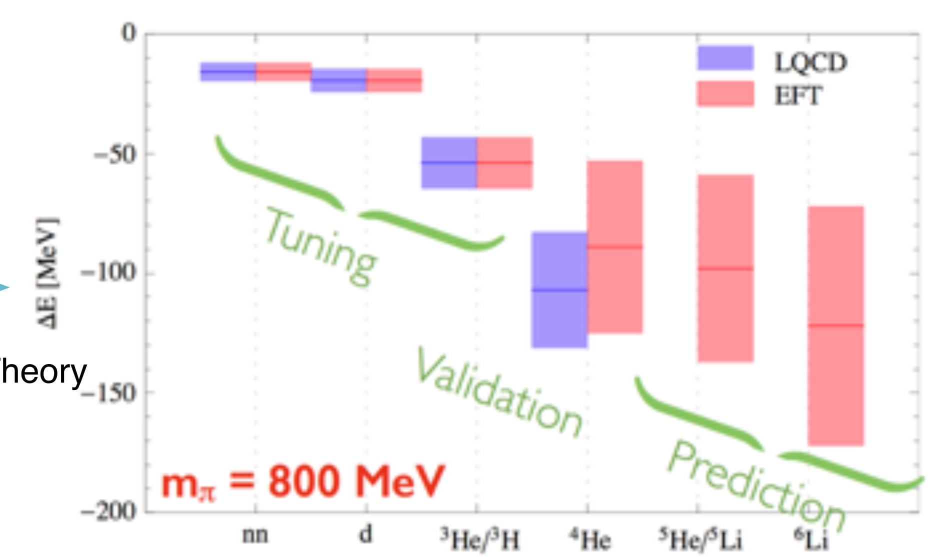


Nucleon Spin and Momentum Decomposition Using Lattice QCD Simulations
C. Alexandrou, M. Constantinou, K. Hadjiyiannakou, K. Jansen, C. Kallidonis, G. Koutsou, A. Vaquero Avilés-Casco, C. Wiese, Phys.Rev.Lett. 119 (2017) no.14, 142002



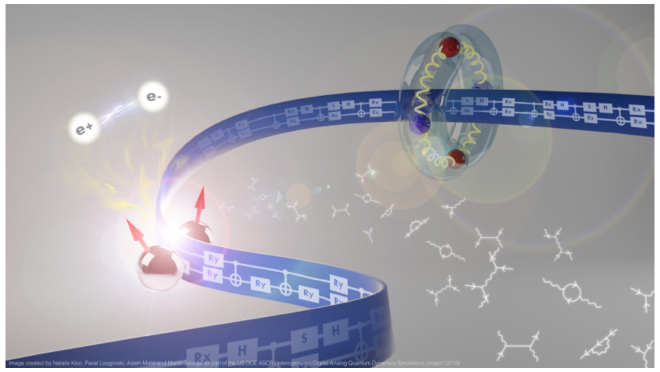


Effective Field Theory



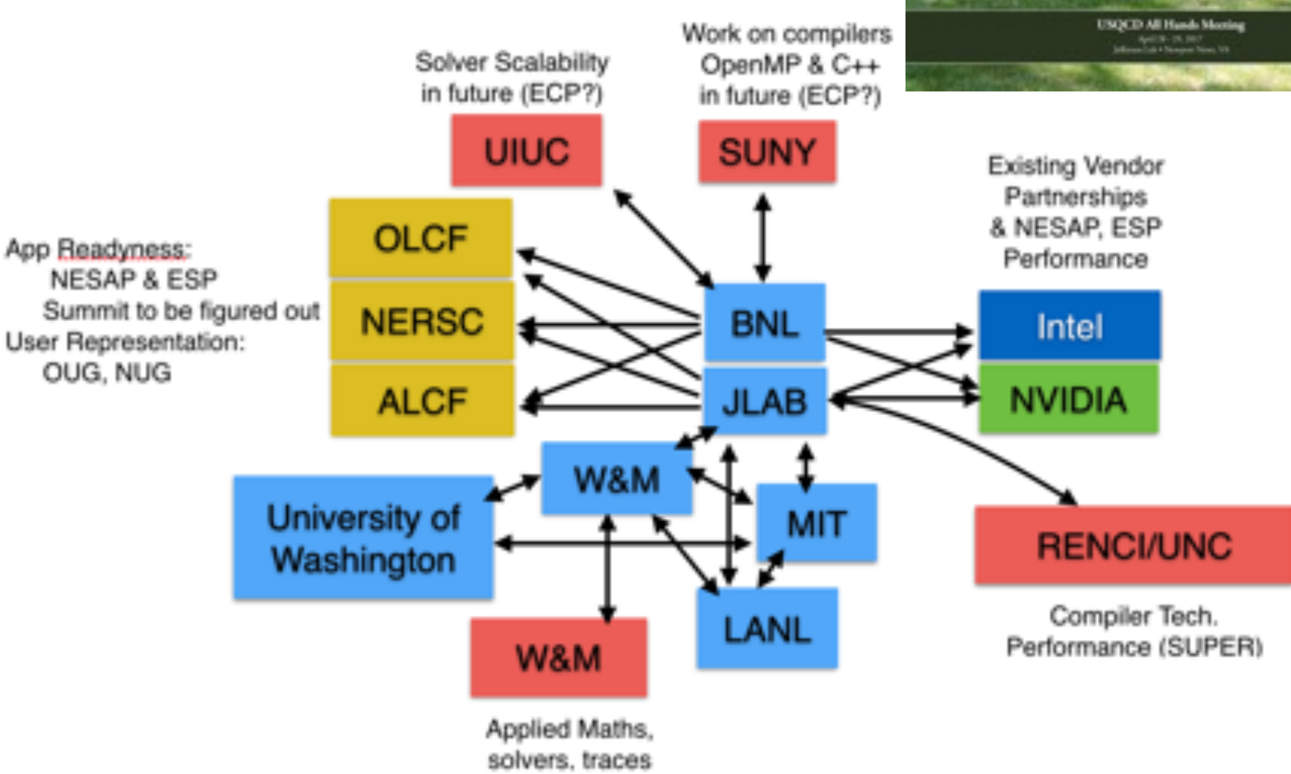
NPLQCD (2013)

Barnea et al (2015), Contessi et al, Bansal et al

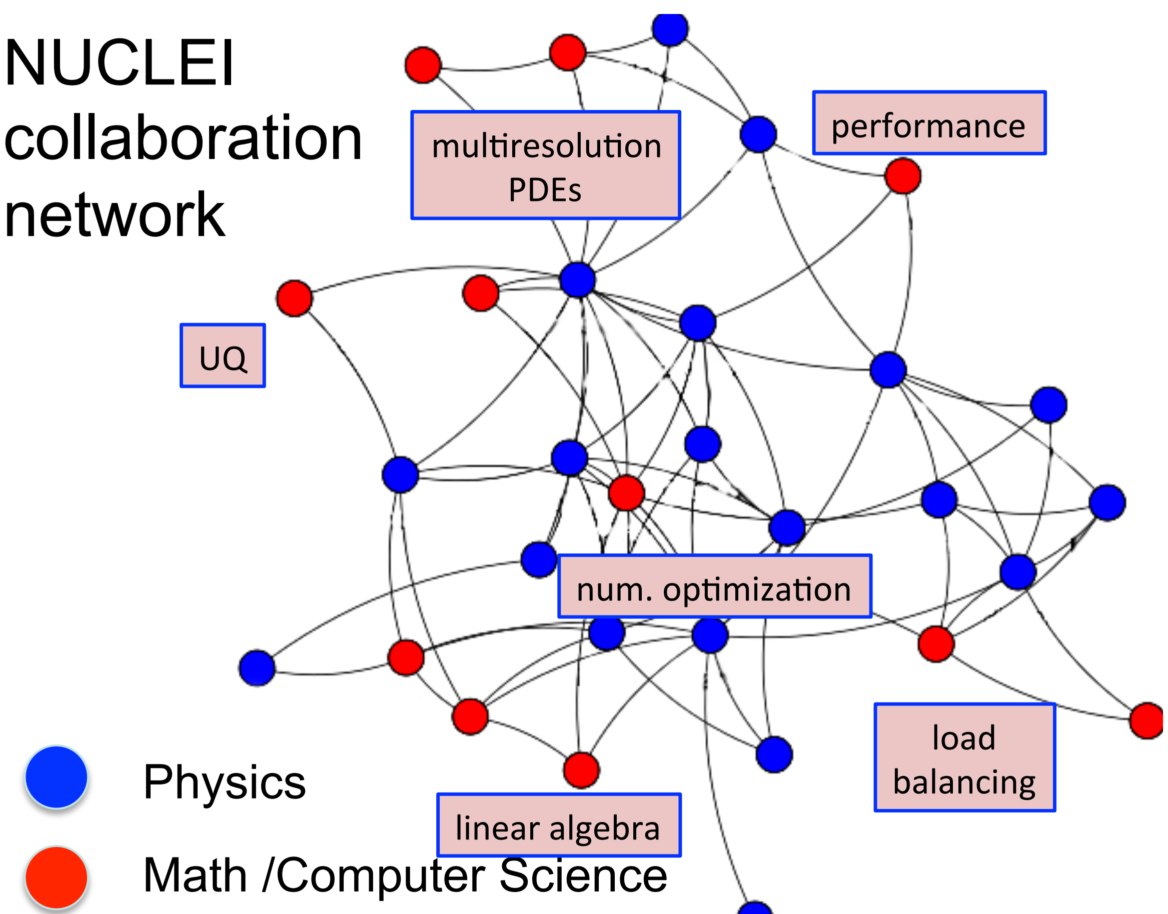


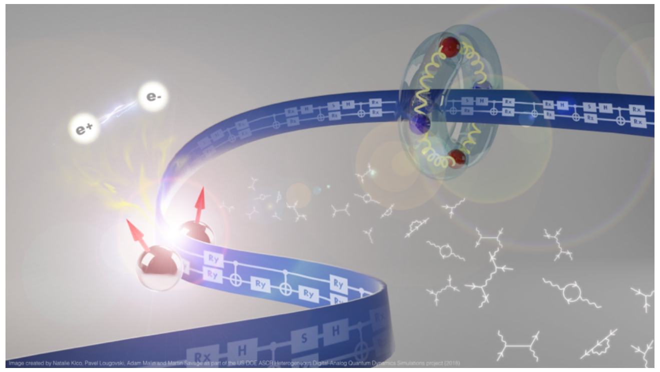
Essential, Extensive Collaboration

USQCD-Joint NP-HEP

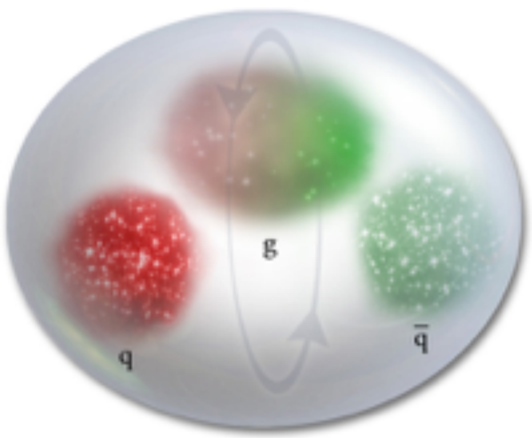


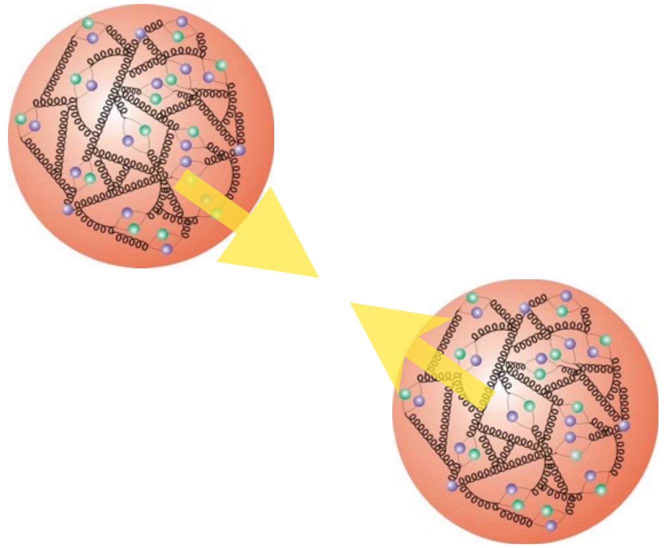
NUCLEI collaboration network

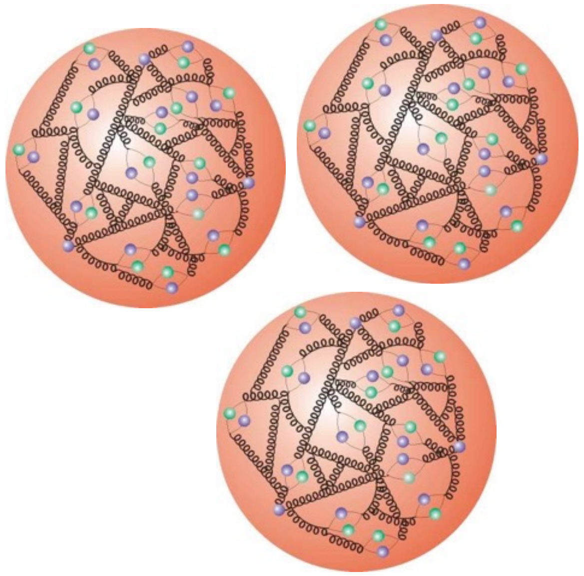




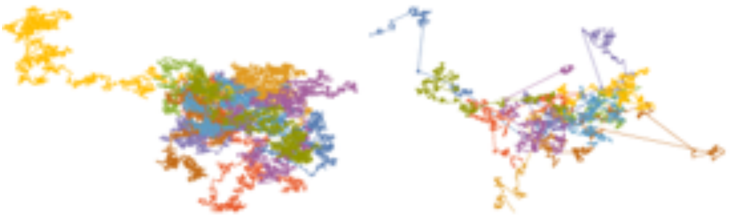
“ Features “

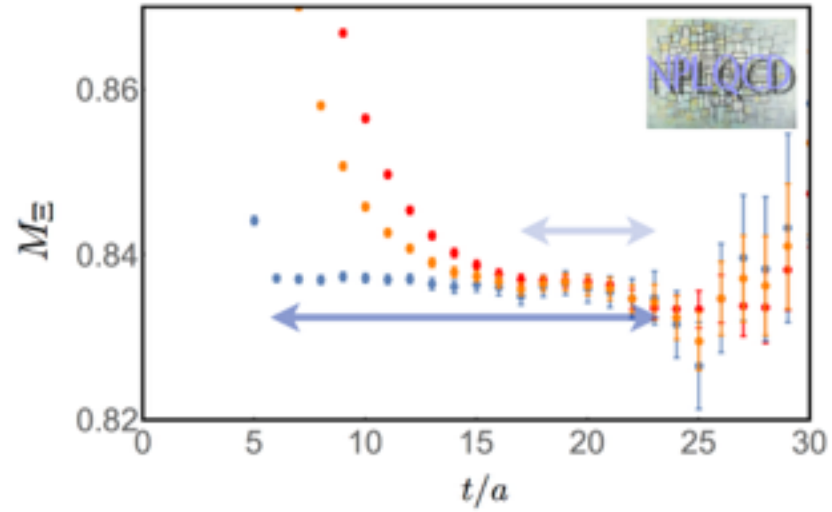


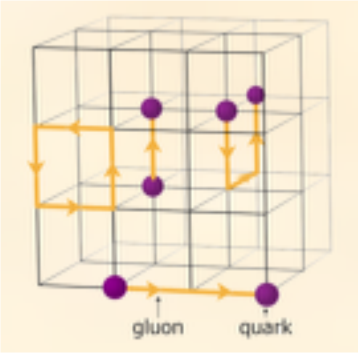




Signal to Noise Problem [Sign Problem]

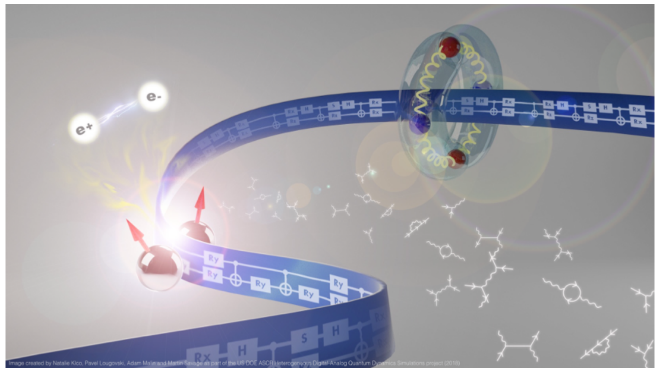






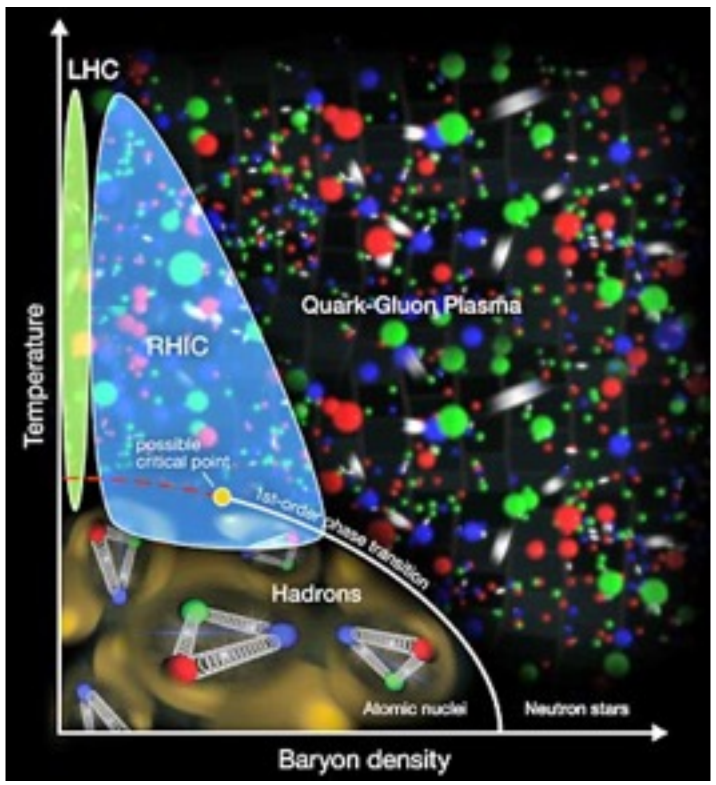
Michael Wagman, PhD Thesis

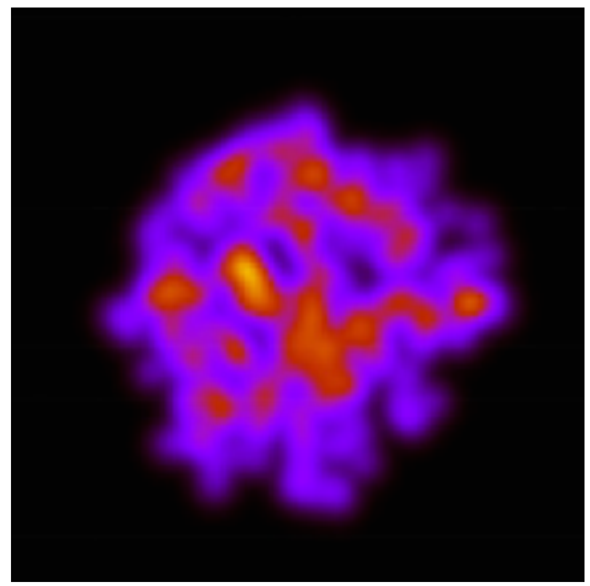
Statistical sampling of the path integral is the limiting element

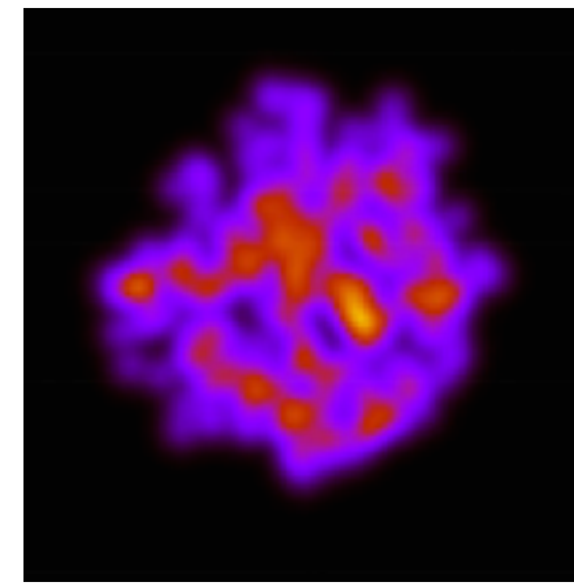


" Features - Finite Density "

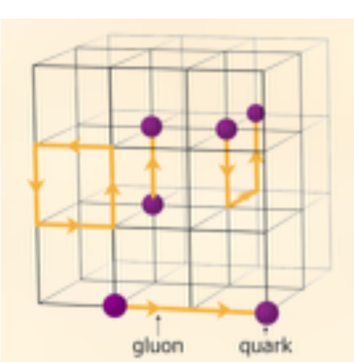
Time evolution of system with baryon number, isospin, electric charge, strangeness, ...
Currents, viscosity, non-equilibrium dynamics - real-time evolution





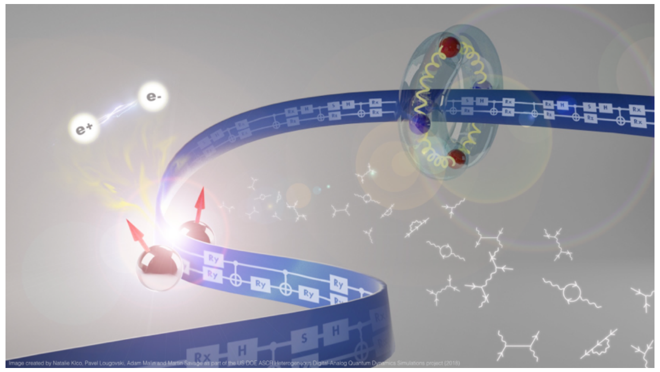


Sign Problem

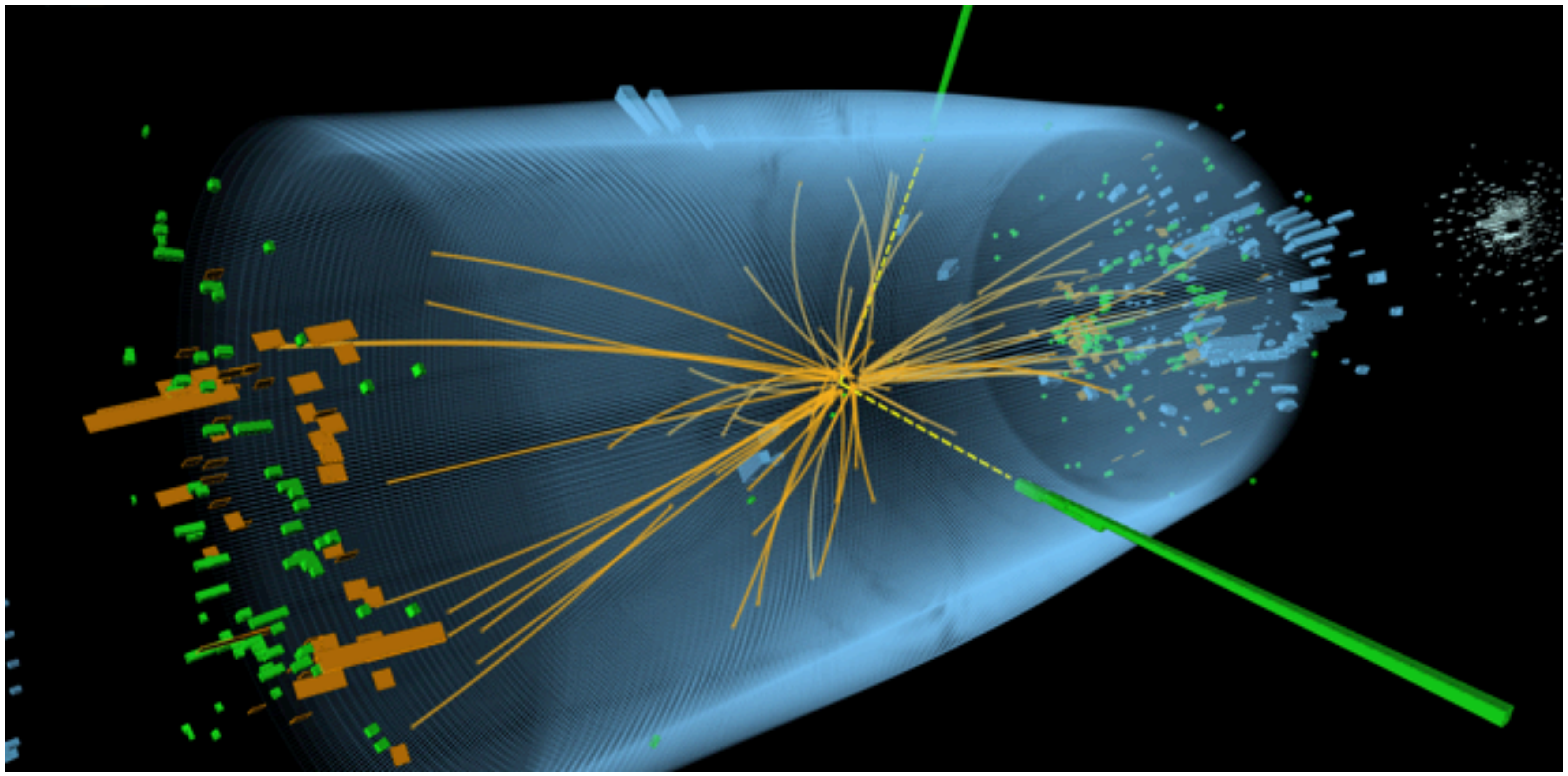


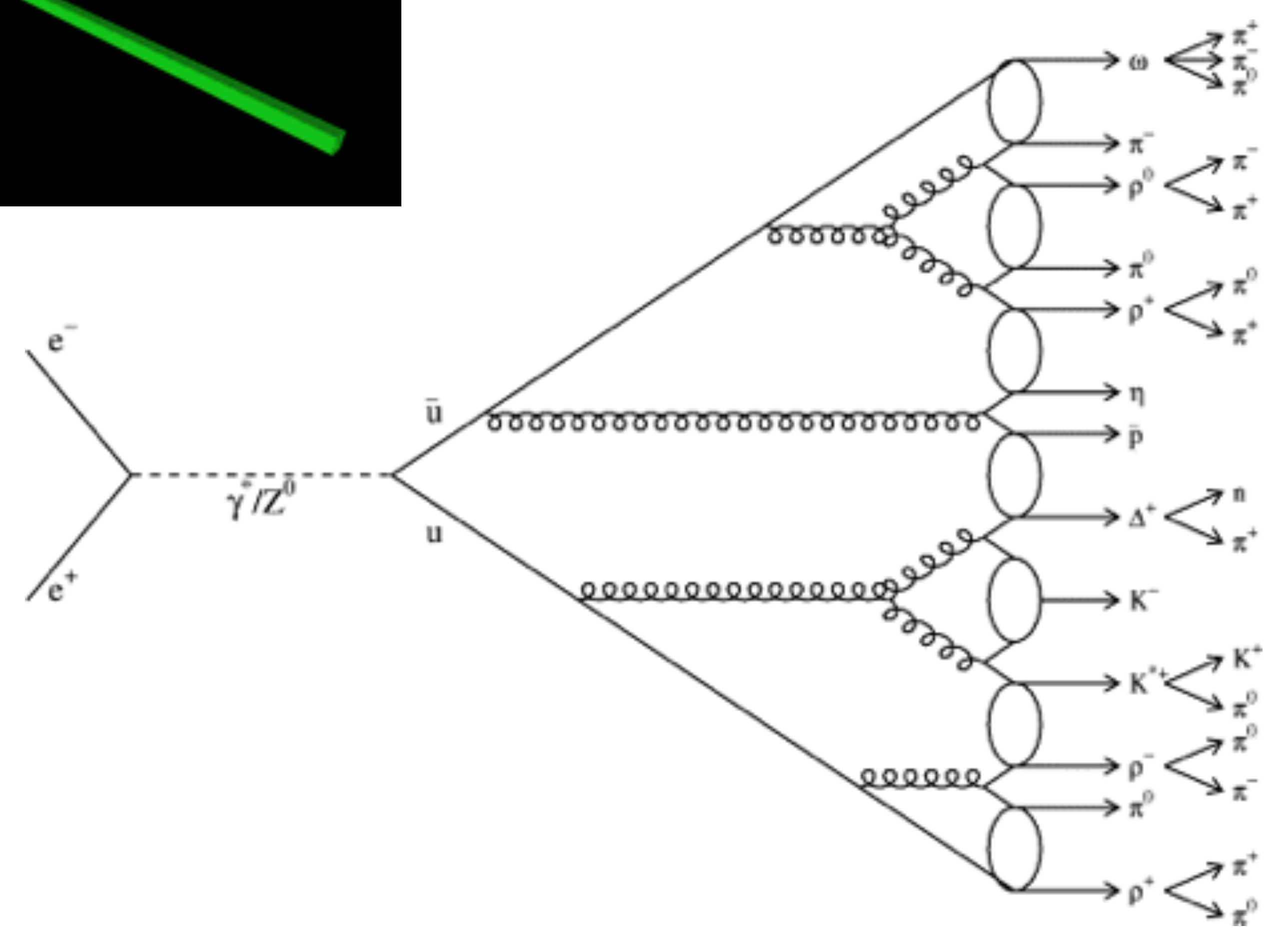
$$\langle\hat{\theta}\rangle \sim \int \mathcal{D}\mathcal{U}_\mu\ \hat{\theta}[\mathcal{U}_\mu]\ \det[\kappa[\mathcal{U}_\mu]]\ e^{-S_{YM}}$$

Complex for non-zero chemical potential



Fragmentation
Vacuum and In-Medium

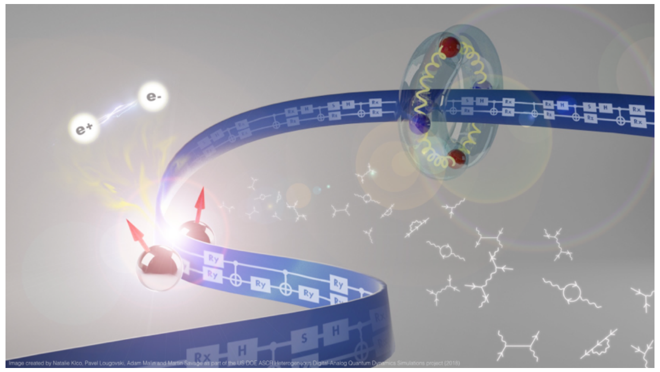




Free-space and in-medium

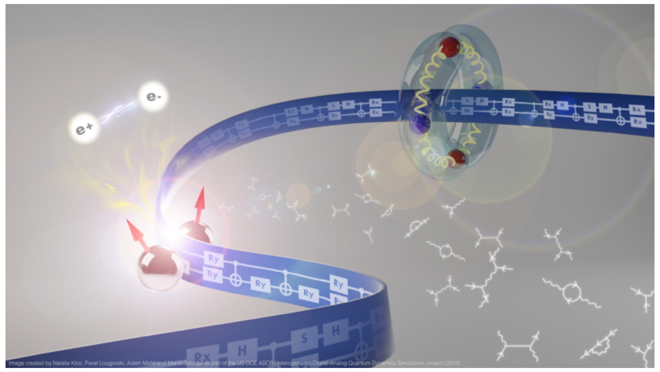
Diagnostic of state of dense and hot matter
- heavy-ion collisions (e.g., jet quenching)
- finite density and time evolution

Highly-tuned phenomenology and pQCD calculations



Quantum Computing
- We are now Entering the NISQ Era

rigetti



Quantum Field Theory with Quantum Computers - Foundational Works

Simulating lattice gauge theories on a quantum computer

Tim Byrnes*
National Institute of Informatics, 2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan

Yoshihisa Yamamoto
E. L. Ginzton Laboratory, Stanford University, Stanford, CA 94305 and
National Institute of Informatics, 2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan
(Dated: February 1, 2008)

We examine the problem of simulating lattice gauge theories on a universal quantum computer. The basic strategy of our approach is to transcribe lattice gauge theories in the Hamiltonian formulation into a Hamiltonian involving only Pauli spin operators such that the simulation can be performed on a quantum computer using only one and two qubit manipulations. We examine three models, the U(1), SU(2), and SU(3) lattice gauge theories which are transcribed into a spin Hamiltonian up to a cutoff in the Hilbert space of the gauge fields on the lattice. The number of qubits required for storing a particular state is found to have a linear dependence with the total number of lattice sites. The number of qubit operations required for performing the time evolution corresponding to the Hamiltonian is found to be between a linear to quadratic function of the number of lattice sites, depending on the arrangement of qubits in the quantum computer. We remark that our results may also be easily generalized to higher SU(N) gauge theories.

Phys.Rev. A73 (2006) 022328

Quantum Computation of Scattering in Scalar Quantum Field Theories

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

[†] *National Institute of Standards and Technology, Gaithersburg, MD 20899*

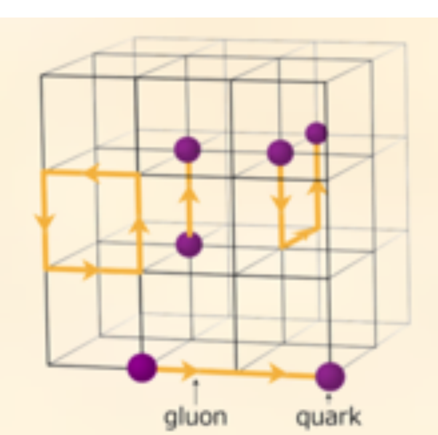
[‡] *University of Pittsburgh, Pittsburgh, PA 15260*

[§] *California Institute of Technology, Pasadena, CA 91125*

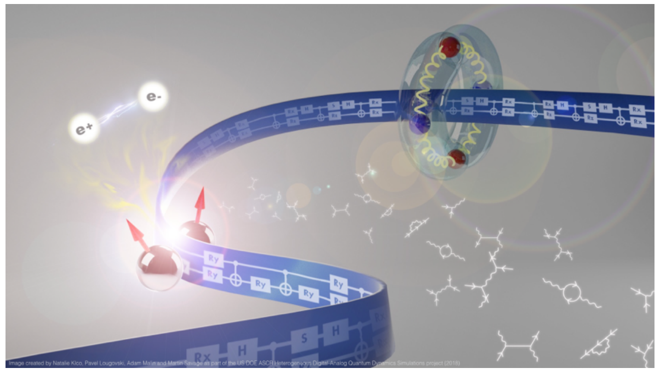
Abstract

Quantum field theory provides the framework for the most fundamental physical theories to be confirmed experimentally, and has enabled predictions of unprecedented precision. However, calculations of physical observables often require great computational complexity and can generally be performed only when the interaction strength is weak. A full understanding of the foundations and rich consequences of quantum field theory remains an outstanding challenge. We develop a quantum algorithm to compute relativistic scattering amplitudes in massive ϕ^4 theory in spacetime of four and fewer dimensions. The algorithm runs in a time that is polynomial in the number of particles, their energy, and the desired precision, and applies at both weak and strong coupling. Thus, it offers exponential speedup over existing classical methods at high precision or strong coupling.

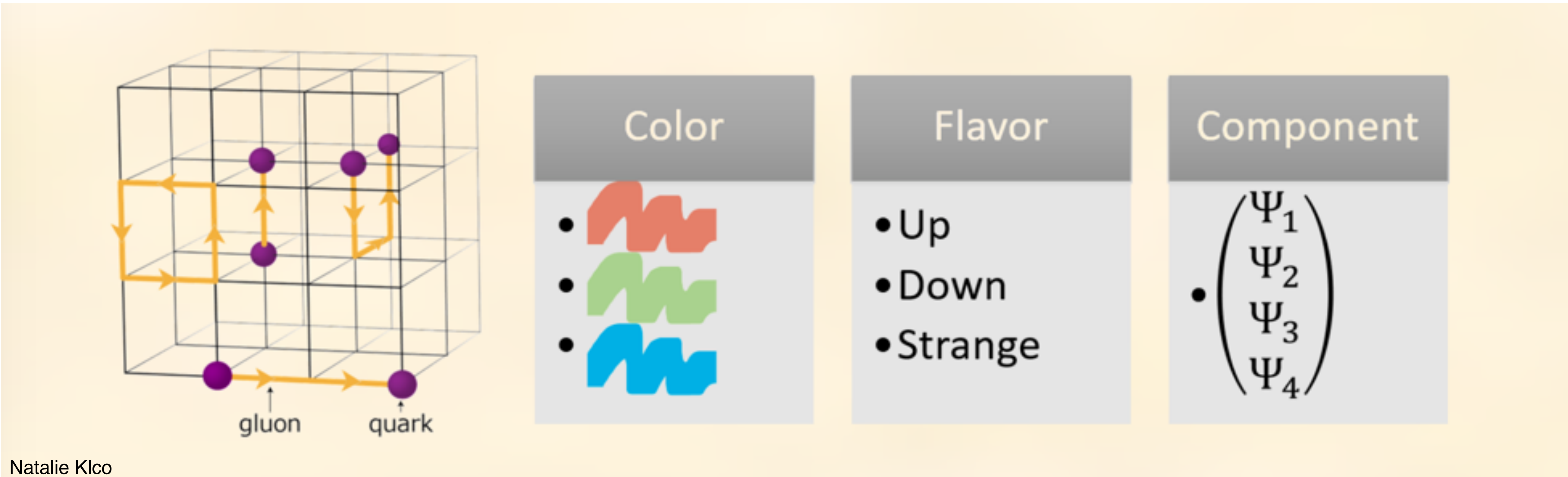
Quantum Information and Computation 14, 1014-1080 (2014)



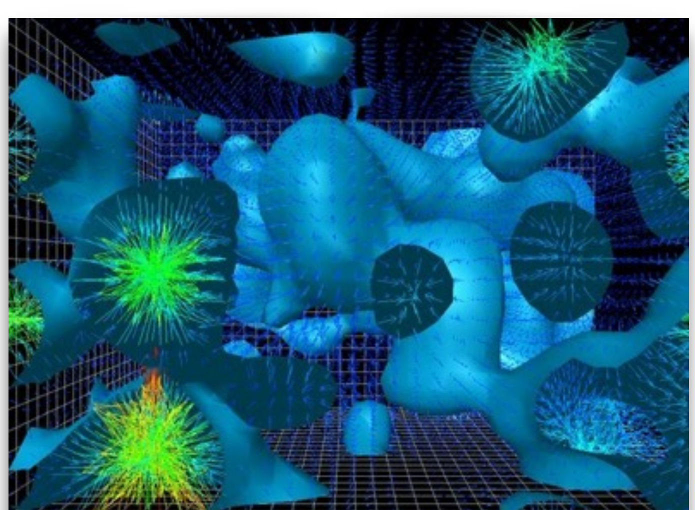
Detailed formalism for 3+1 quenched Hamiltonian Gauge Theory



Gauge Field Theories
e.g. QCD



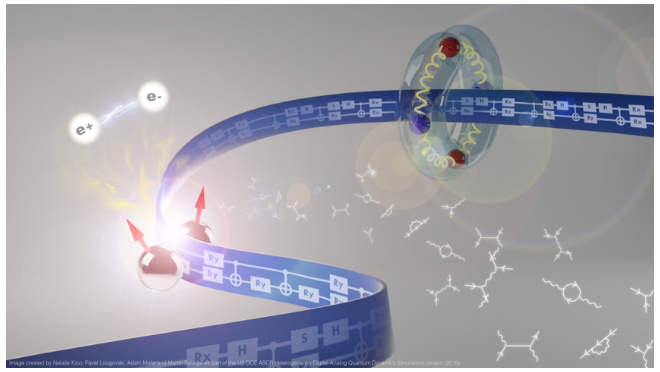
32^3 lattice requires naively > 4 million qubits !



State Preparation - a critical element

| random > = a |0> + b |(pi pi)> + c | (pi pi pi pi) > + …. + d | (GG) > + ….

Conventional lattice QCD likely to play a key role in QFT on QC

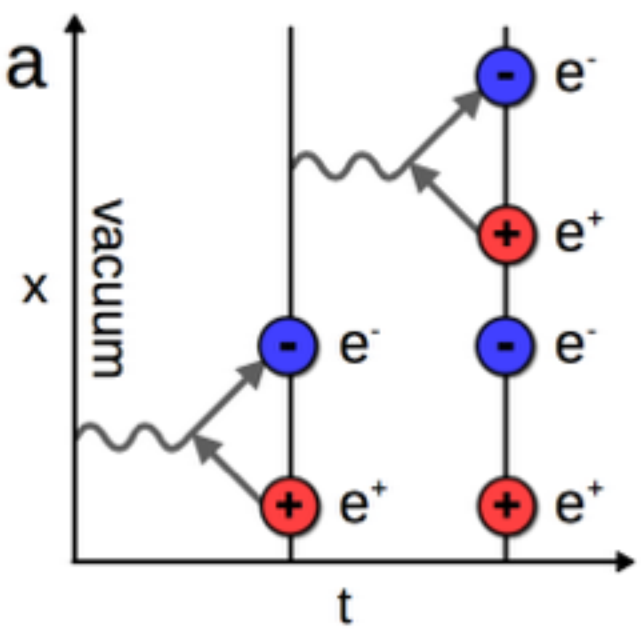


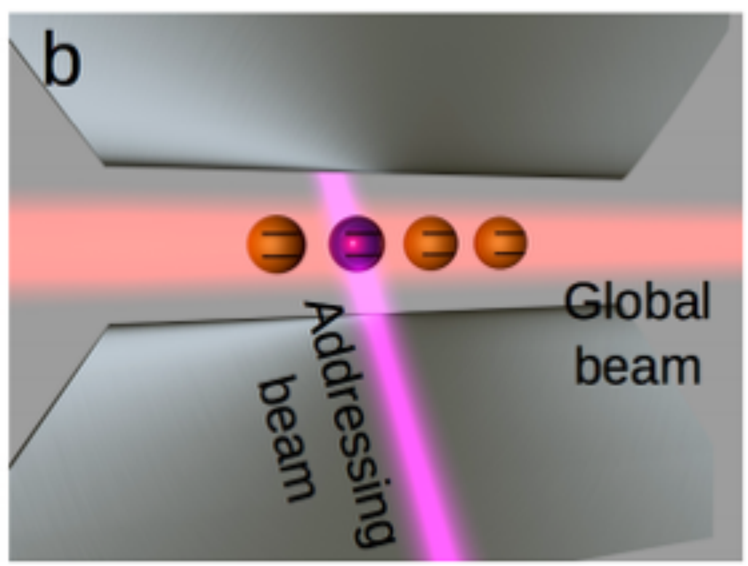
Starting Simple 1+1 Dim QED - Pivotal Paper

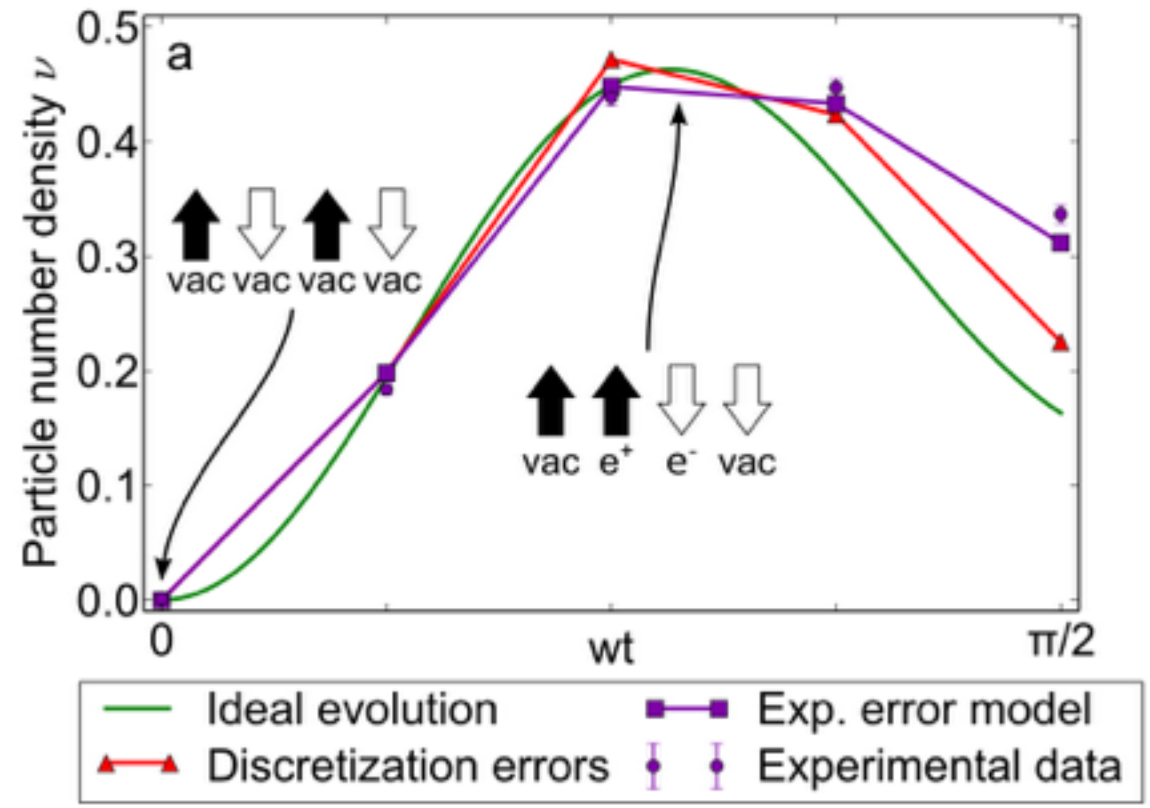
Real-time dynamics of lattice gauge theories with a few-qubit quantum computer

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]

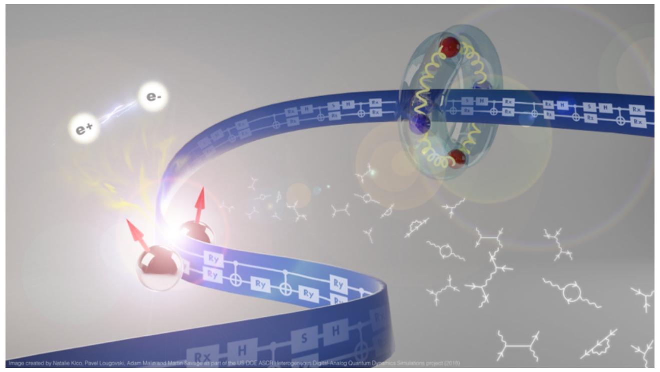
(2016)







Based upon a string of $^{40}Ca^{+}$ trapped-ion quantum system
Simulates 4 qubit system with long-range couplings = 2-spatial-site Schwinger Model
> 200 gates per Trotter step



Quantum Field Theory - recent examples

Quantum sensors for the generating functional of interacting quantum field theories

A. Bermudez,[1,2,*] G. Aarts,[1] and M. Müller[1]
[1]*Department of Physics, College of Science, Swansea University, Singleton Park, Swansea SA2 8PP*
[2]*Instituto de Física Fundamental, IFF-CSIC, Madrid E-28006, Spain*

Difficult problems described in terms of interacting quantum fields evolving in real time or out
are abound in condensed-matter and high-energy physics. Addressing such problems via controll
in atomic, molecular, and optical physics would be a breakthrough in the field of quantum simu
work, we present a quantum-sensing protocol to measure the generating functional of an intera
field theory and, with it, all the relevant information about its in or out of equilibrium phenomena
can be understood as a collective interferometric scheme based on a generalization of the notion
sources in quantum field theories, which make it possible to probe the generating functional. We

Quantum Simulation of the Abelian-Higgs Lattice Gauge Theory with Ultracold Atoms

Daniel González-Cuadra[1,2], Erez Zohar[2] and J. Ignacio Cirac[2]
[1] ICFO – The Institute of Photonic Sciences, Av. C.F. Gauss 3, E-08860, Castelldefels (Barcelona), Spain
[2] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, D-85748 Garching, Germany

Dynamics of entanglement in expanding quantum fields

Jürgen Berges,[a] Stefan Floerchinger[a] and Raju Venugopalan[b]

Electron-Phonon Systems on a Universal Quantum Computer

Alexandru Macridin, Panagiotis Spentzouris, James Amundson, Roni Harnik
Batavia, Illinois 60510, USA

Quantum simulation of the universal features of the Polyakov loop

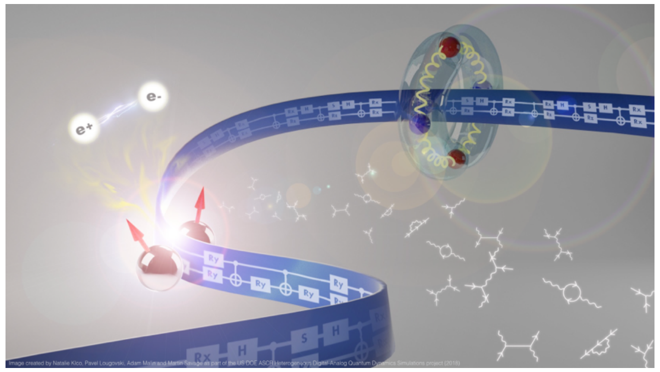
Jin Zhang[1], J. Unmuth-Yockey[2], A. Bazavov[3], S.-W. Tsai[1], and Y. Meurice[4]
[1] *Department of Physics and Astronomy, University of California, Riv*
[2]*Department of Physics, Syracuse University, Syracuse, New Y*
[3], *Department of Physics and Astronomy, Michigan State University, East Lan*
[4] *Department of Physics and Astronomy, The University of Iowa, Iow*
(Dated: March 30, 2018)

U(1) Wilson lattice gauge theories in digital quantum simulators

Christine Muschik[1,2], Markus Heyl[2,3], Esteban Martinez[4], Thomas Monz[4], Philipp Schindler[4], Berit Vogell[1,2], Marcello Dalmonte[1,5], Philipp Hauke[1,2], Rainer Blatt[4,6], Peter Zoller[1,6]

Eliminating fermionic matter fields in lattice gauge theories

Erez Zohar and J. Ignacio Cirac
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany.
(Dated: May 16, 2018)



Scalar Field Theory

Jordan, Lee and Preskill - several works

$$\hat{H} = \hat{H}_{\Pi} + \hat{H}_{\phi}$$

$$\hat{\mathcal{H}}_{\Pi} = \frac{1}{2}\Pi^2 \ , \quad \hat{\mathcal{H}}_{\phi} = \frac{1}{2}(\nabla\phi)^2 + \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4!}\phi^4$$

$$\hat{H}_{\phi_j} = b\sum_x \left(\frac{1}{2}\phi_j\phi_{j+1} + \frac{1}{2}\phi_j\phi_{j-1} - \phi_j^2 + \frac{1}{2}m^2\phi_j^2 + \frac{\lambda}{4!}\phi_j^4 \right)$$

$$q = -\frac{2\pi}{N_\phi}N^{\mathrm{max}}, -\frac{2\pi}{N_\phi}(N^{\mathrm{max}} - 1), .., 0, ..., \frac{2\pi}{N_\phi}N^{\mathrm{max}}$$

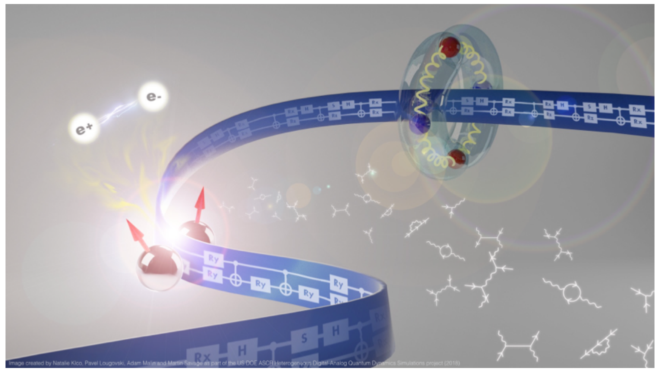
$$\left[\hat{\phi}_n \ , \ \hat{\Pi}_j \right] = i\delta_{nj}$$

$$\phi = j\ \delta\phi$$

$$e^{-iHt} = e^{-i\sum_j H_j t} = \lim_{N_{\mathrm{Trot.}}\to\infty} \left(\prod_j e^{-iH_j\delta t} \right)^{N_{\mathrm{Trot.}}}$$

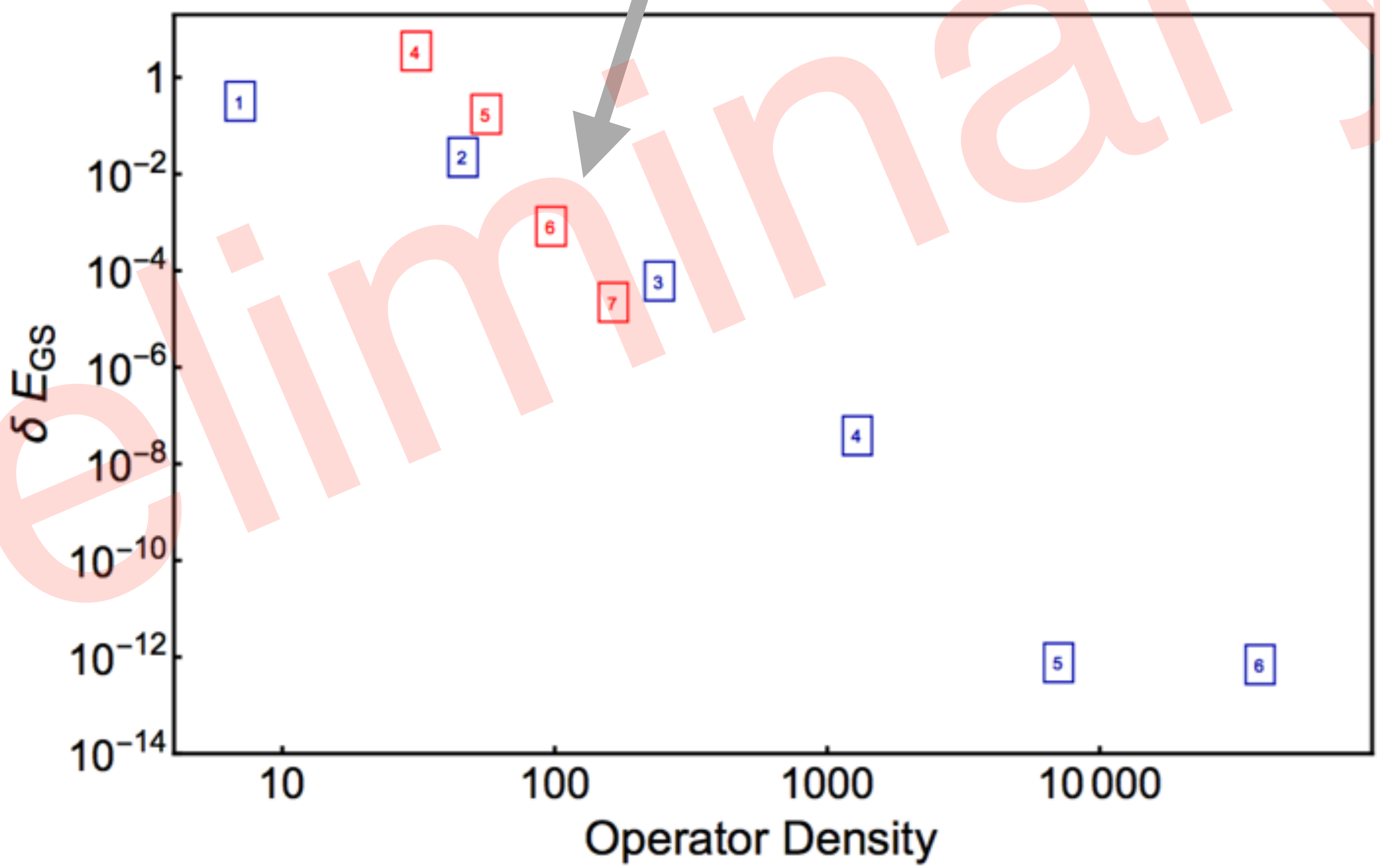
Natalie Klco and MJS - work in progress

Preliminary

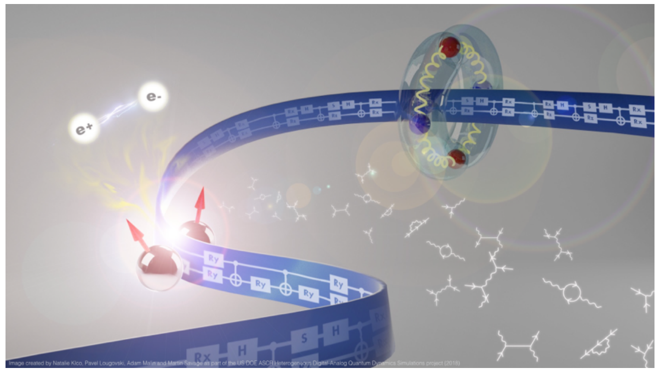


Scalar Field Theory Digitization

Jordan, Lee and Preskill - several works



Natalie Klco and MJS - work in progress



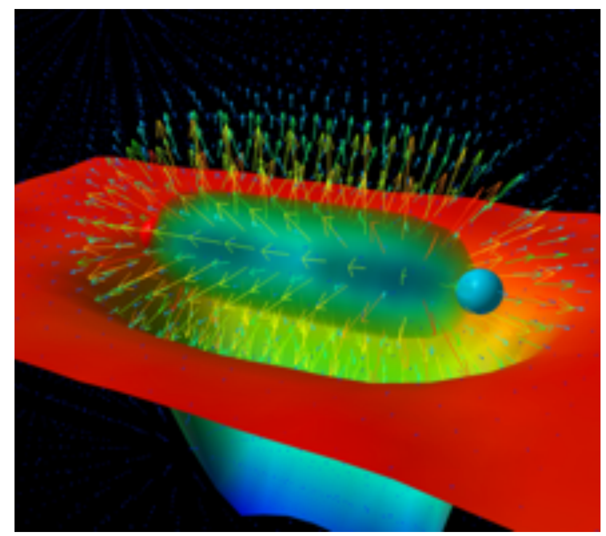
Starting Simple 1+1 Dim QED Construction

Two ORNL-led research teams receive $10.5 million to advance quantum computing for scientific applications

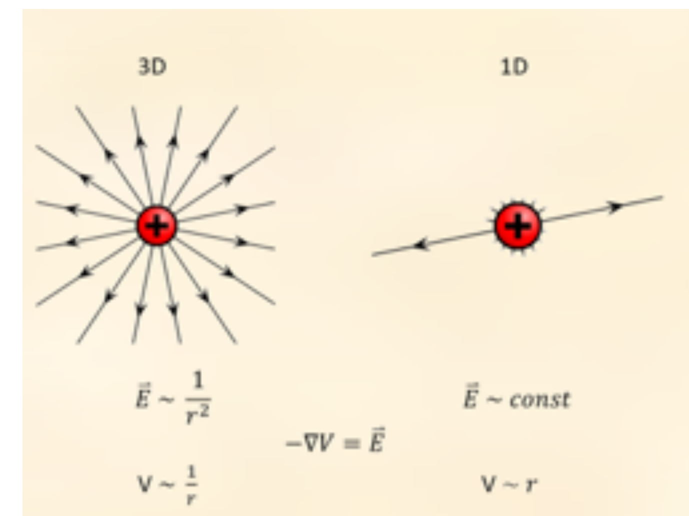
"Quantum computing makes you think about your calculations very differently than programming a classical computer," says Natalie Klco.
// MEDIA CREDIT: WHITNEY SANCHEZ

$$\mathcal{L} = \overline{\psi}\left(i\not{D} - m\right)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

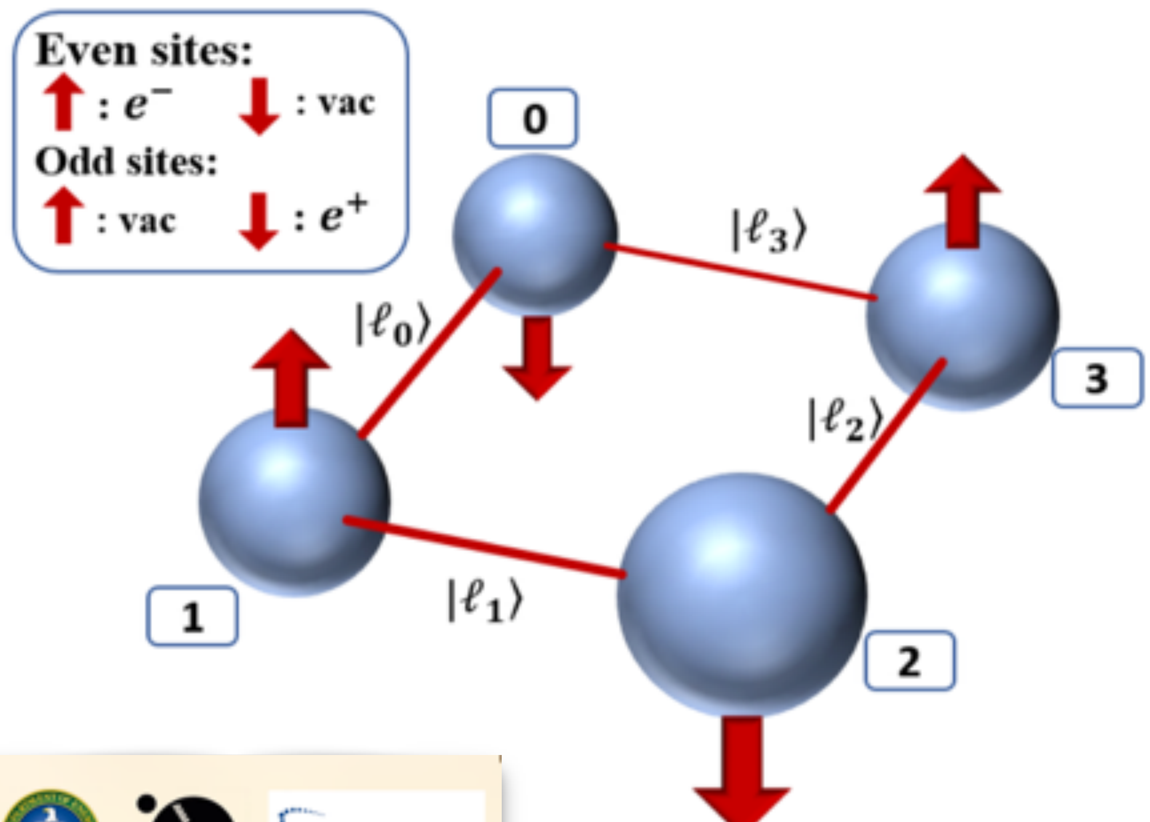
- Charge screening, confinement
- fermion condensate



Derek Leinweber



Natalie Klco

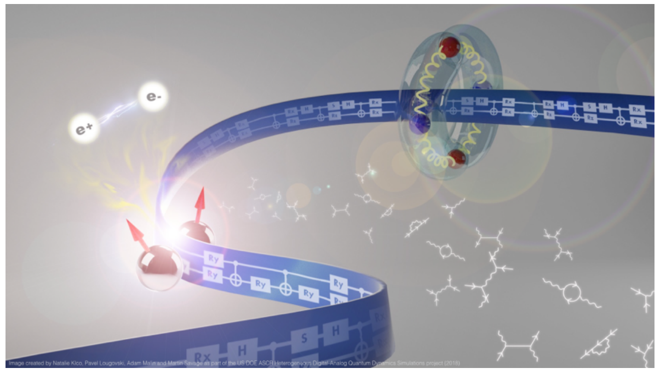


$$\hat{H} = x \sum_{n=0}^{N_{fs}-1}\left(\sigma_n^+ L_n^- \sigma_{n+1}^- + \sigma_{n+1}^+ L_n^+ \sigma_n^-\right) + \sum_{n=0}^{N_{fs}-1}\left(l_n^2 + \frac{\mu}{2}(-)^n \sigma_n^z\right) .$$

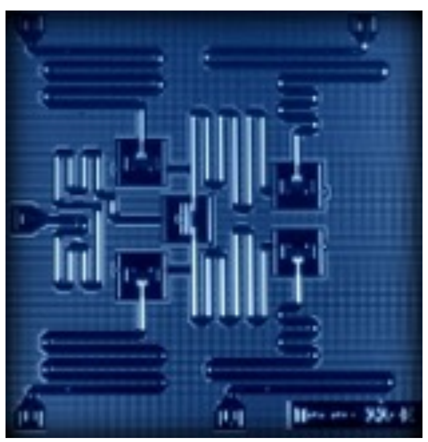
Quantum-Classical Dynamical Calculations of the Schwinger Model using Quantum Computers

N. Klco, E.F. Dumitrescu, A.J. McCaskey, T.D. Morris, R.C. Pooser, M. Sanz, E. Solano, P. Lougovski, M.J. Savage.

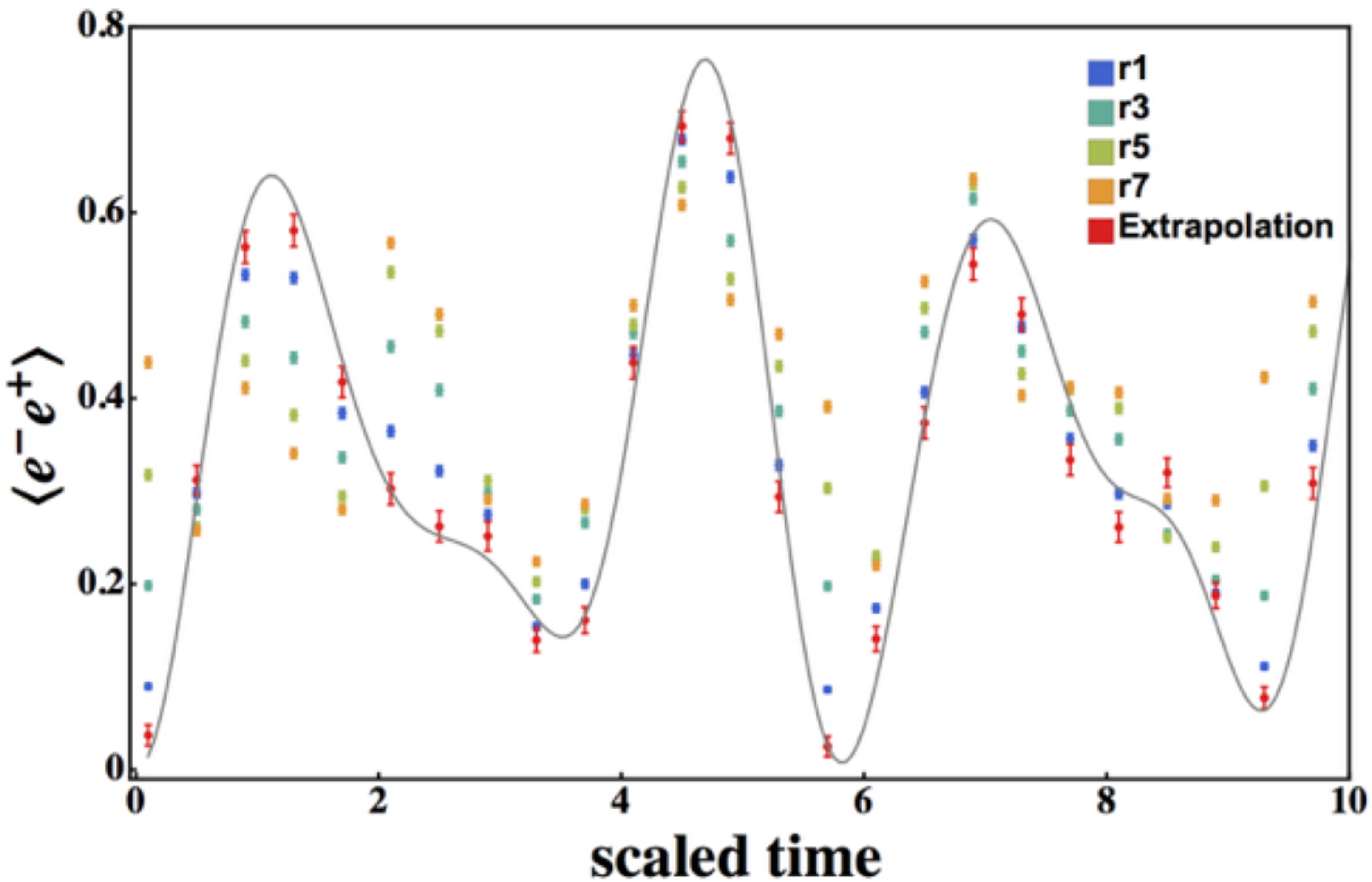
arXiv:1803.03326 [quant-ph]

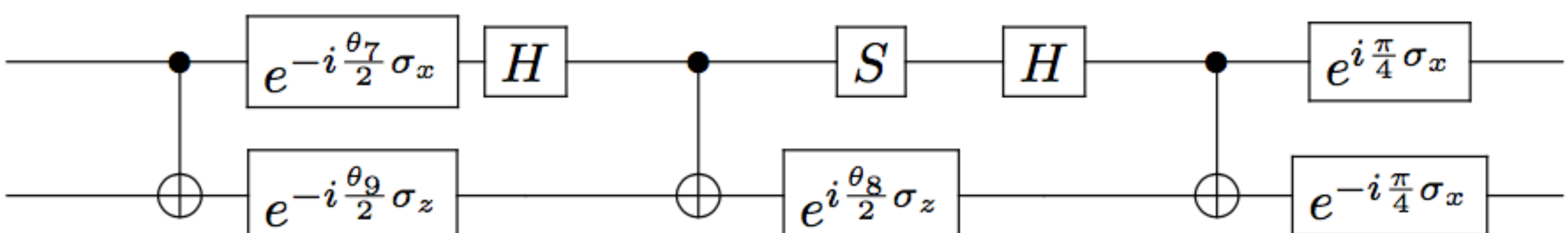


Starting Simple 1+1 Dim QED
Living NISQ - IBM
Classically Computed U(t)

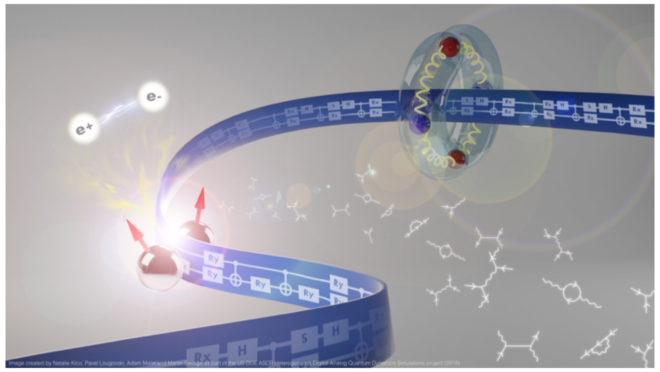


ibmqx2 - cloud-access
8K shots per point

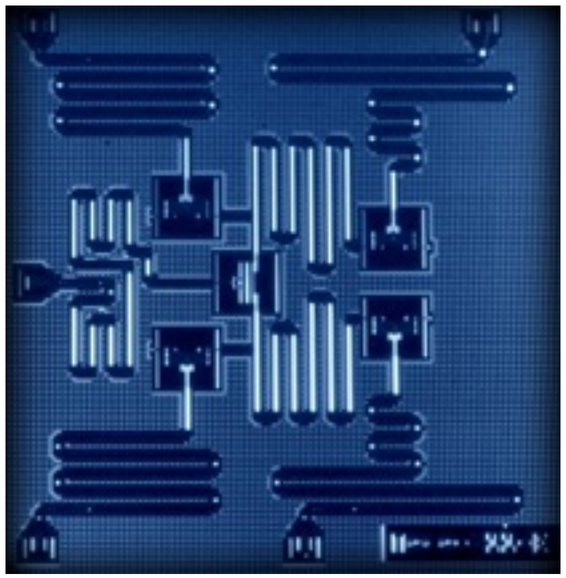




Cartan sub-algebra

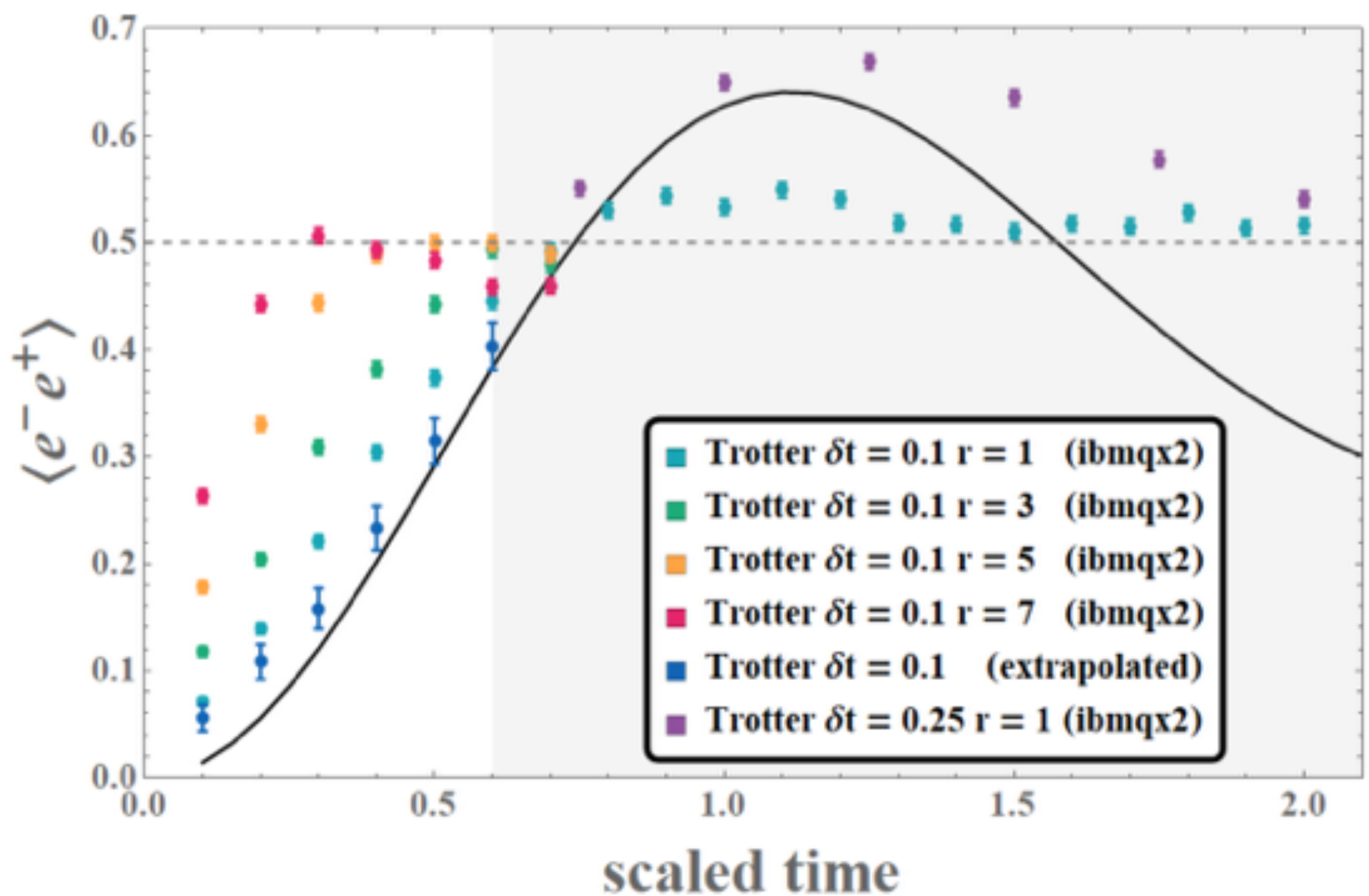


Starting Simple 1+1 Dim QED
Living NISQ - IBM
Trotter U(t)



$$e^{-iHt} = e^{-i\sum_j H_j t} = \lim_{N_{\text{Trot.}}\to\infty} \left(\prod_j e^{-iH_j \delta t} \right)^{N_{\text{Trot.}}}$$

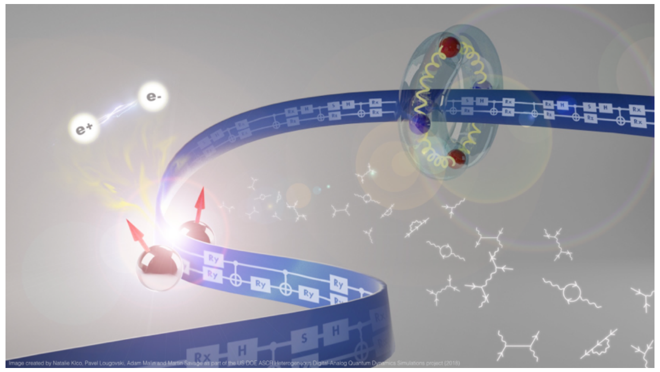
T2 (μs)	55.20	65.10	47.00	35.10	37.60



$$\mathrm{H} = \frac{x}{\sqrt{2}}\,\sigma_x \otimes \sigma_x + \frac{x}{\sqrt{2}}\,\sigma_y \otimes \sigma_y - \mu\,\sigma_z \otimes \sigma_z + x\left(1 + \frac{1}{\sqrt{2}}\right) I \otimes \sigma_x - \frac{1}{2}\, I \otimes \sigma_z - (1+\mu)\,\sigma_z \otimes I + x\left(1 - \frac{1}{\sqrt{2}}\right) \sigma_z \otimes \sigma_x$$

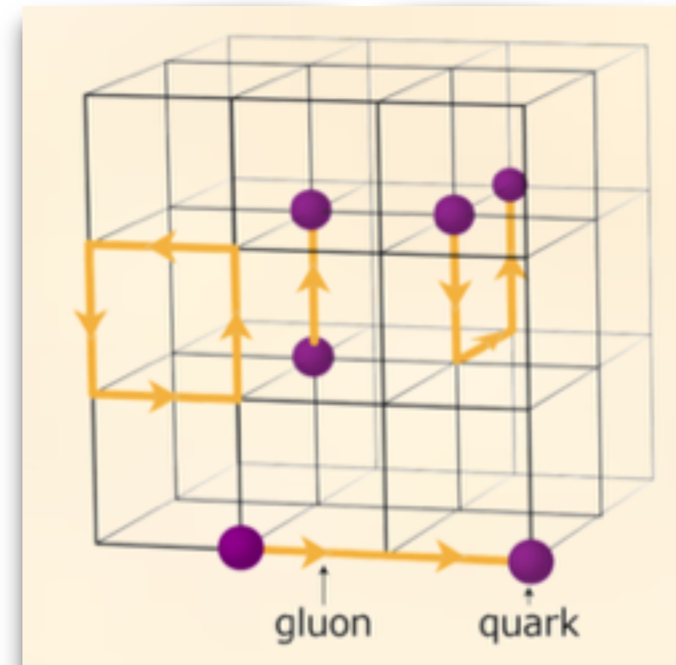
3.6 QPU-s and 260 IBM units

[``Capacity computing” - required only 2 of the 5 qubits on the chip]

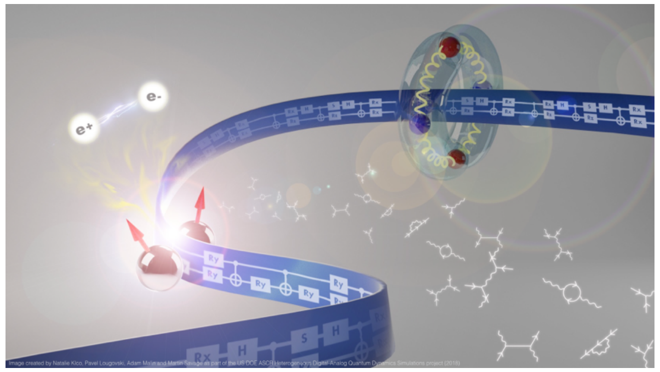


Summary

- Quantum Computing and QIS offer the possibility of a Quantum Advantage in QFTs (and other quantum many-body systems). Required to address Grand Challenge problems in NP and HEP.
- Essential collaborations between universities, national laboratories and technology companies forming around QIS, QC and the domain sciences.
- Algorithm and circuit designing is critical - fundamental change in thinking - will surely benefit others areas.



FIN



The promise of Quantum Computing

Parallel Processing of quantum states and information

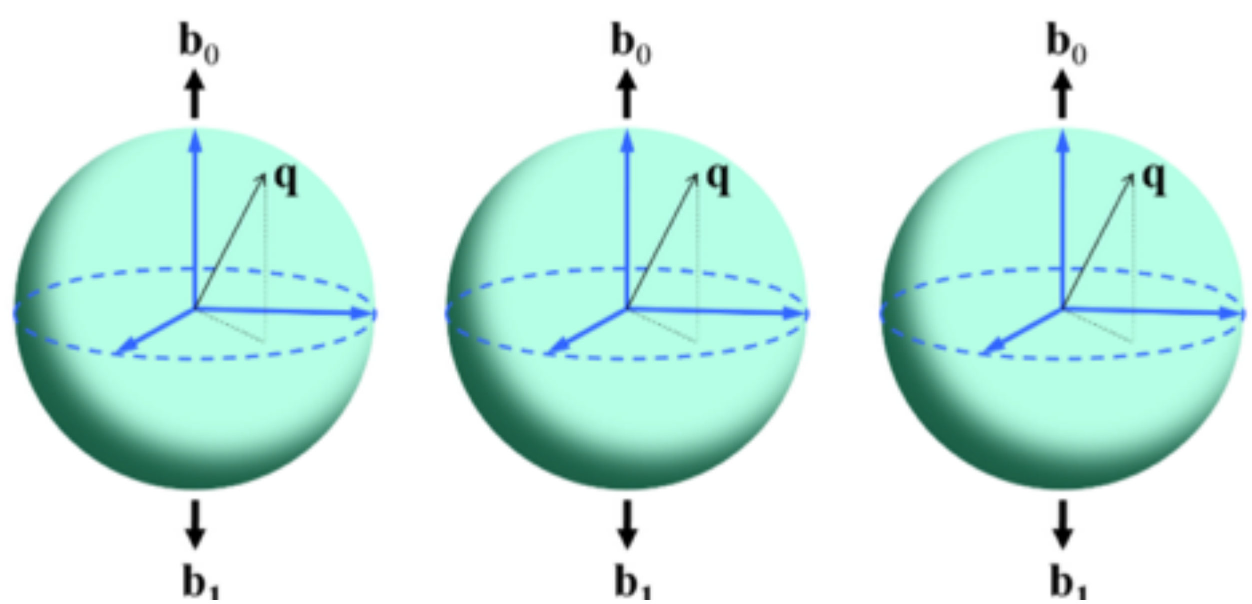
e.g., for a 3-bit computer (2^3 states)

Classical computer in 1 of 8 possible states

$$|\psi\rangle \;=\; |000\rangle \text{ or } |001\rangle \text{ or } |010\rangle \text{ or } |100\rangle \text{ or } |011\rangle \text{ or } |101\rangle \text{ or } |110\rangle \text{ or } |111\rangle$$

Quantum computer could be in all states at once!

$$|\psi\rangle = \alpha_1\,|000\rangle + \alpha_2\,|001\rangle + \alpha_3\,|010\rangle + \alpha_4\,|100\rangle + \alpha_5\,|011\rangle + \alpha_6\,|101\rangle + \alpha_7\,|110\rangle + \alpha_8\,|111\rangle$$



$$H^{\otimes 3}|000\rangle \;=\; \frac{1}{\sqrt{2}}\left[|0\rangle + |1\rangle\right] \otimes \frac{1}{\sqrt{2}}\left[|0\rangle + |1\rangle\right] \otimes \frac{1}{\sqrt{2}}\left[|0\rangle + |1\rangle\right]$$