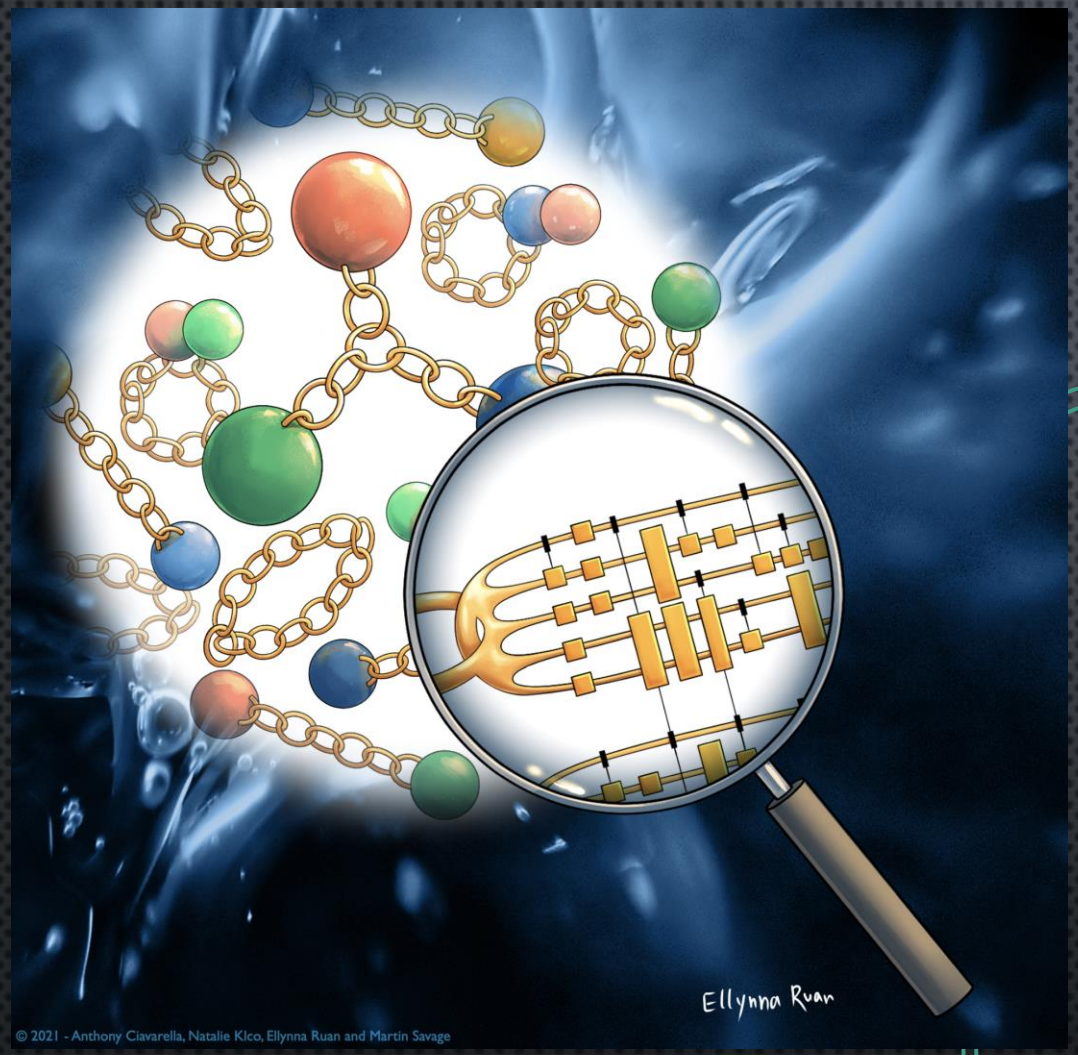
Quantum Simulation for High Energy Physics

Snowmass Community Summer Study Meeting

Seattle. Washington
July 23, 2022

Duke University
Duke Quantum Center

Natalie Klco



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

Question: If quantum mechanical degrees of freedom are incorporated into computational frameworks, is that enough to create a computationally efficient description of nature?

Beyond theoretically, how can we do it?

community Achievements

relevant to broad 21st century progress

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1 Realized impact of turning off natural processes on ambitions to represent and explore the complexity of nature

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J. Bell (1964), Freedman and Clauser (1972), Aspect and Grainger (1982)

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community Achievements

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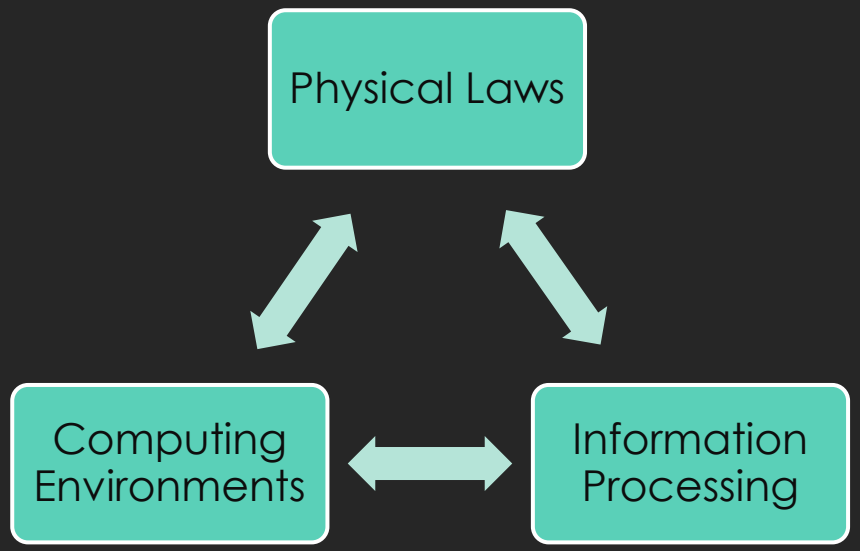
The rule of simulation that I would like to have is that the **number of computer elements** required to simulate a large physical system is only to **be proportional to the space-time volume** of the physical system. I don't want to have an explosion. …. If doubling the volume of space and time means I'll need an exponentially larger computer, I consider that against the rules

Feynman, 1982



Bennet, Fredkin, Toffoli, …

community Achievements

1

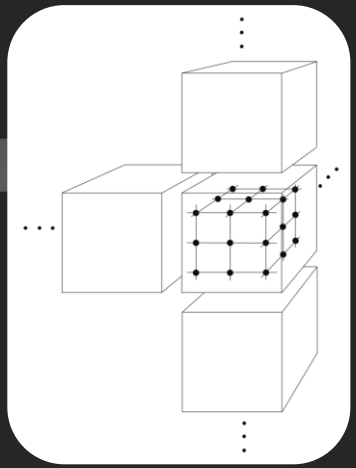
Simulating lattice gauge theories on a quantum computer

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

low-energy initialization
Variational trial wf

Digitization of Hilbert Space

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



Time Evolution
CGs through poly-overhead
Operator construction

Bacon, Chuang, Harrow (2006)

Operators ~ V^α

$1 \leq \alpha \leq 2$

community Achievements

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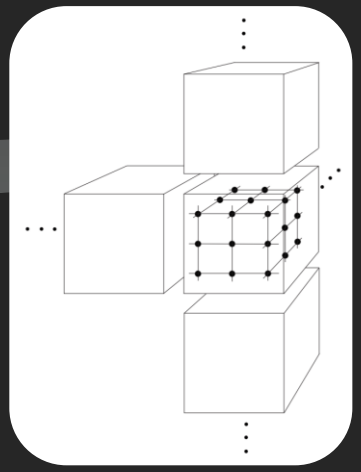

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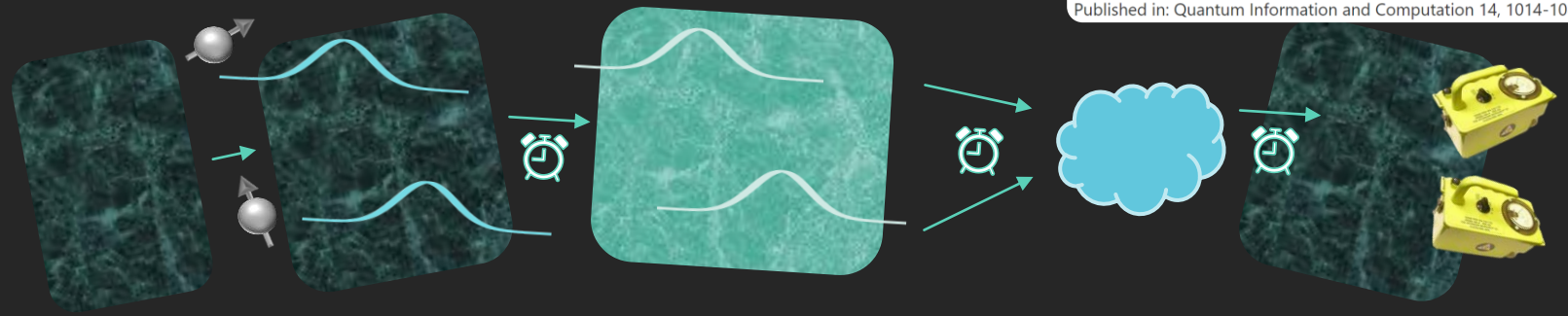
Quantum Computation of Scattering in Scalar Quantum Field Theories

Stephen P. Jordan (NIST, Wash., D.C. and Caltech), Keith S.M. Lee (Pittsburgh U. and Caltech), John Preskill (Caltech)
Published in: Quantum Information and Computation 14, 1014-1080 (2014), *Quant.Inf.Comput.* 14 (2014) 1014-1080



(bounded error)
probability sampling

- Efficient - precision, energy, particle #, coupling strength

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  e.g., collective neutrino oscillations

  Patwardhan, Cervia, Balantekin (2021) Martin, Roggero, Duan, Carlson, Cirigliano (2022) …

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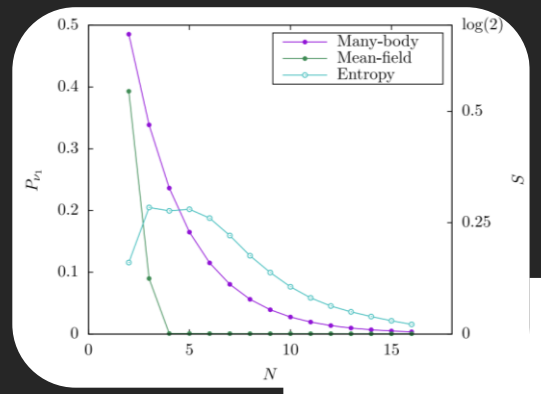
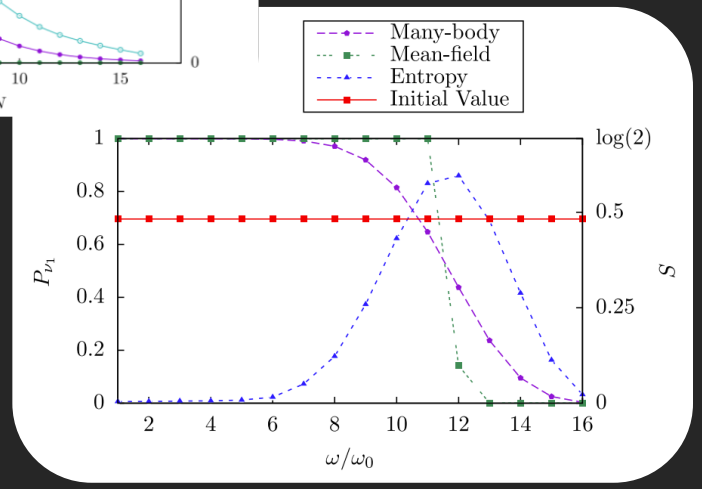
$$|\nu_e \ldots \nu_e\rangle \rightarrow |\nu_1\rangle_{\omega_{max}}$$



Deviations from mean-field correlate with single-particle entanglement entropy



entanglement entropy peaks ~ spectral split frequencies

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  e.g., lattice artifacts

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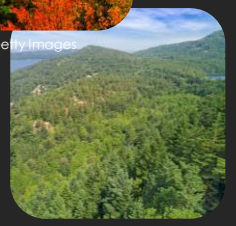
Field Pixelation, finite bandwidth
(reduced complexity)

Chris Murray/Aurora/Getty Images



Ecosystem
De-coherence

community Achievements

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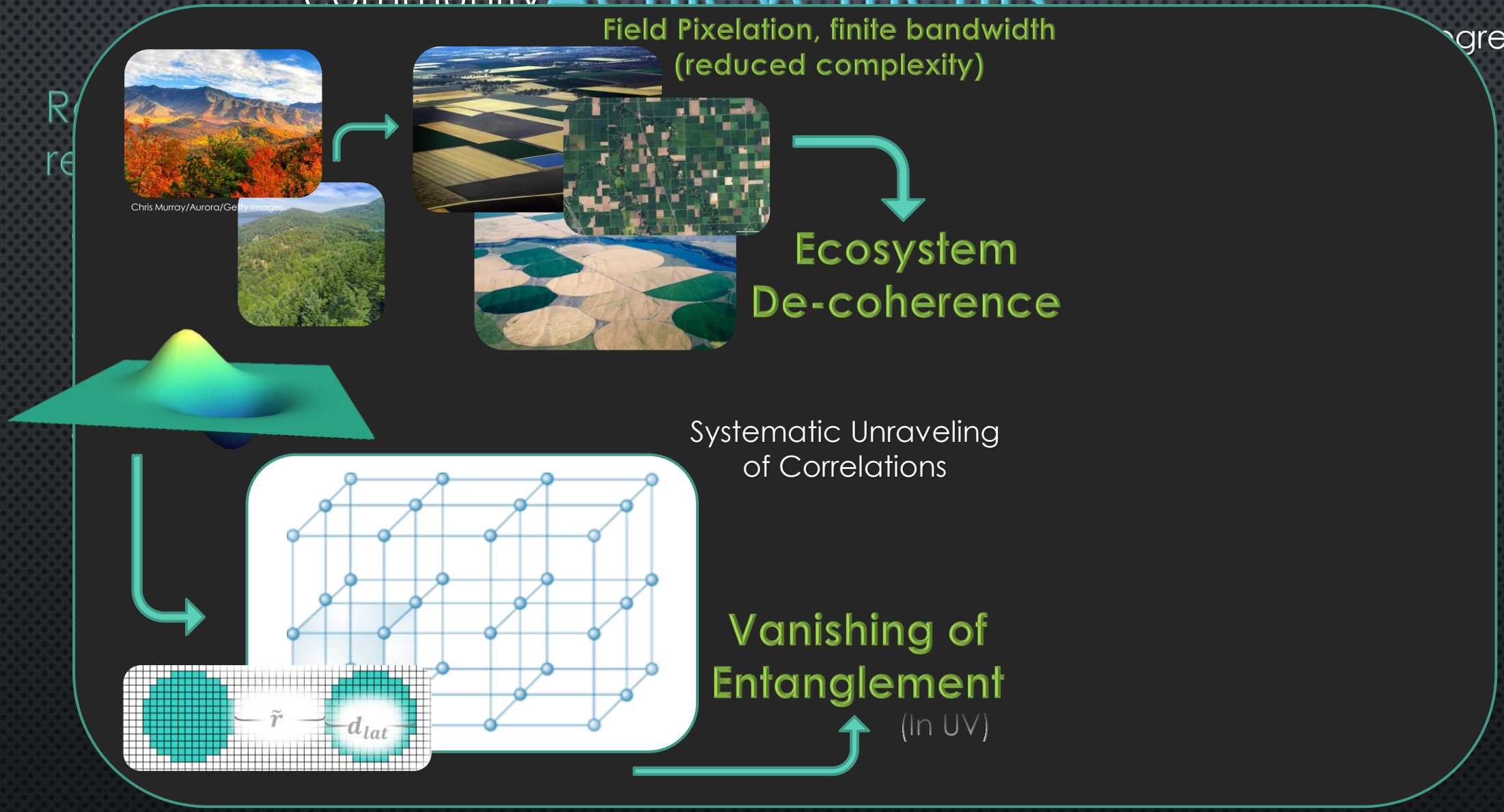

community Achievements

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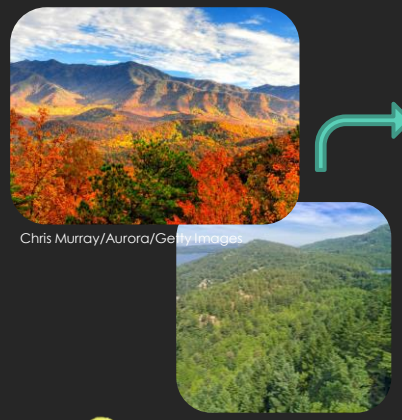
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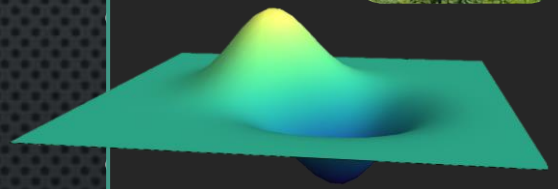
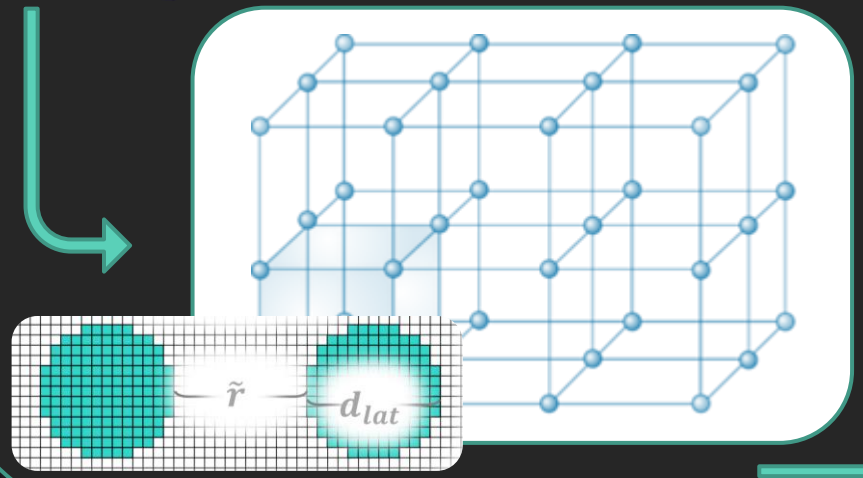
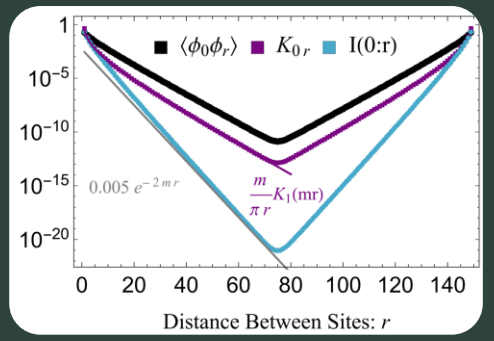


Systematic Unraveling
of Correlations



Vanishing of
Entanglement
(In UV)

Classically
dominated
correlations
persist



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  e.g., collective neutrino oscillations

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  e.g., many-body thermalization

  Deutsch (1991) Srednicki (1994) Ho, Hsu (2016) Baker, Kharzeev (2018) Berges, Floerchinger, Venugopalan (2018)

community Achievements

rogress

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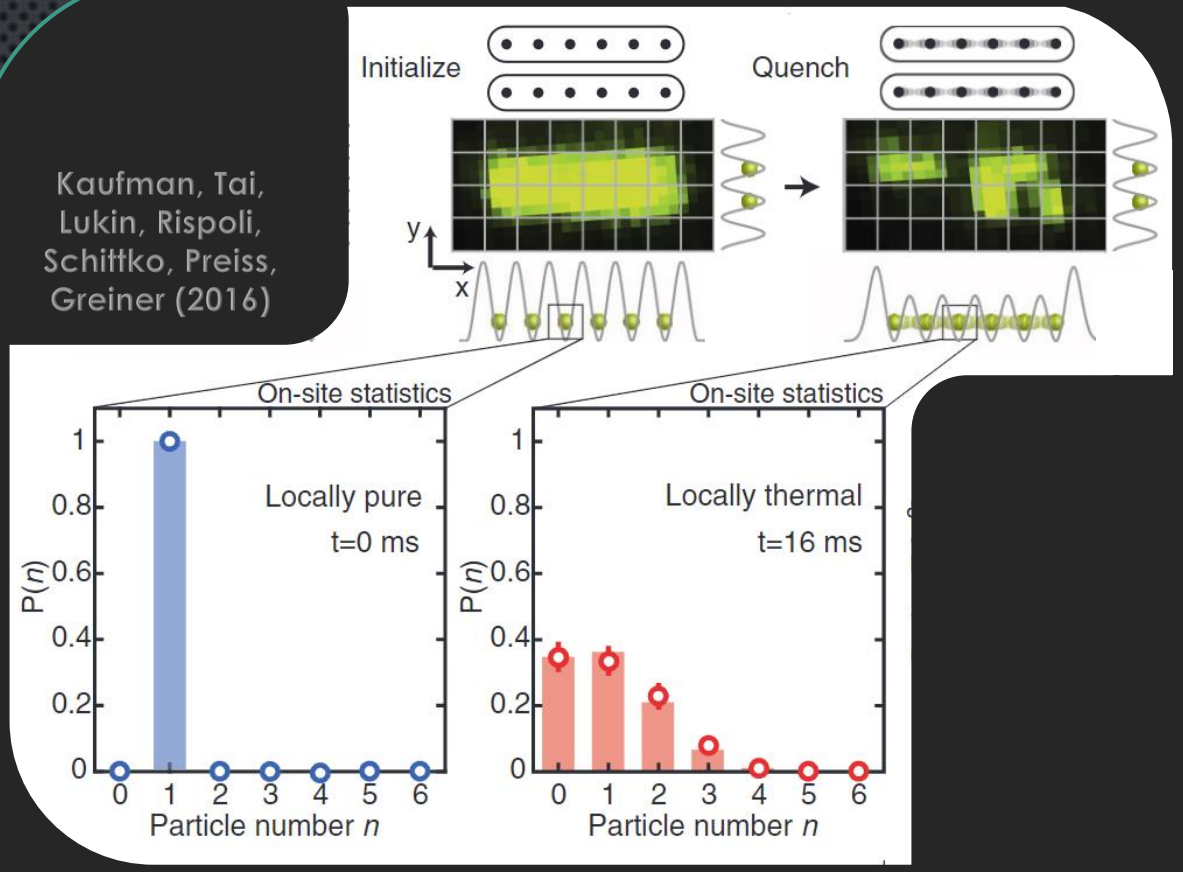
Kaufman, Tai, Lukin, Rispoli, Schittko, Preiss, Greiner (2016)



Microscopic origins for thermalization

gopalan (2018)

Local Thermalization

~

propagation of entanglement

× scattering

community Achievements

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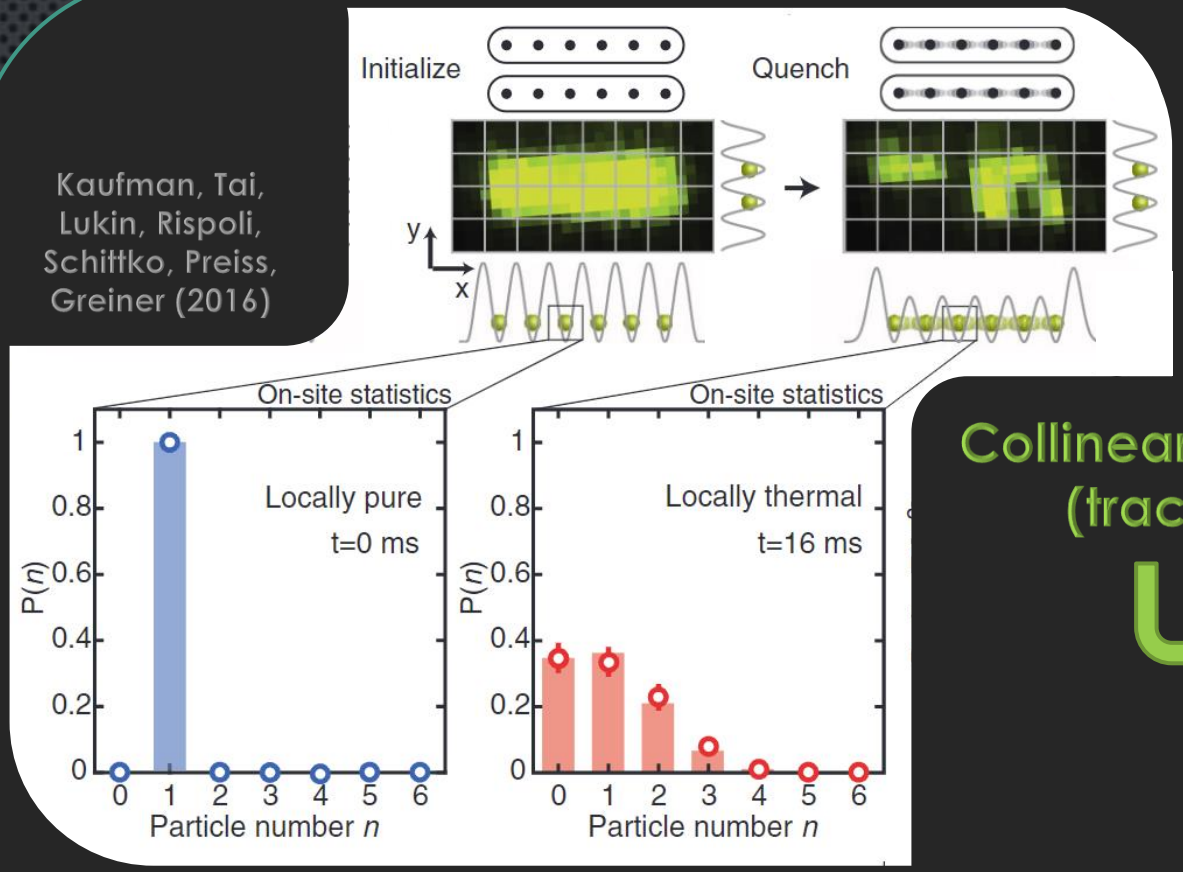
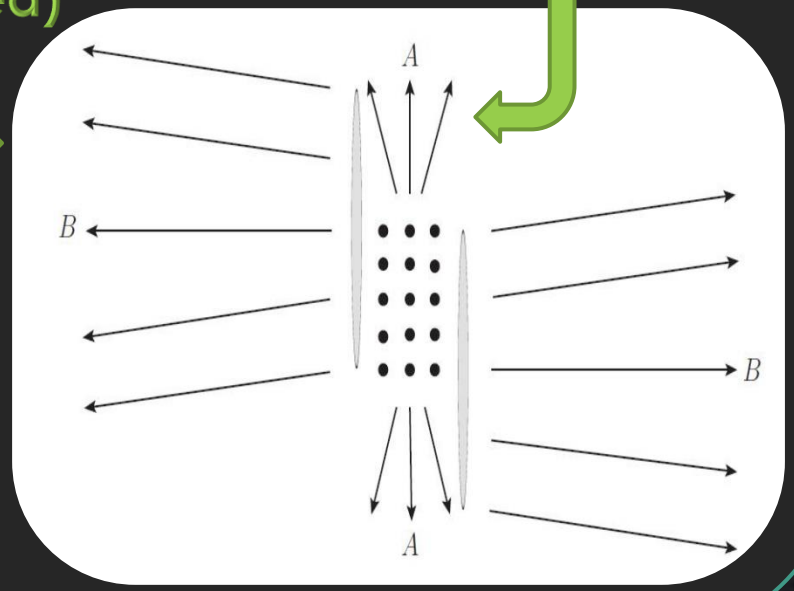


Microscopic origins for thermalization

Soft/central modes (locally thermal)

Collinear modes (traced)



Ho, Hsu (2016)

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2 Demonstrated commitment to non-perturbative restoration

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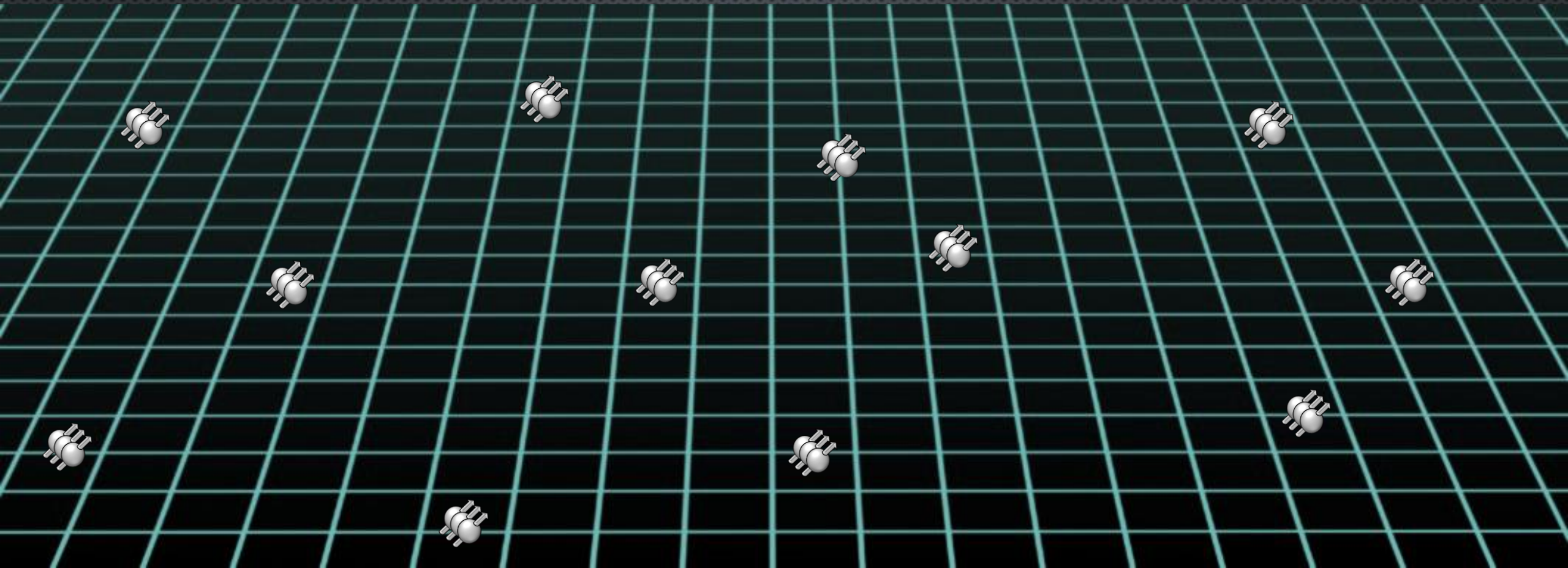
2 Demonstrated commitment to non-perturbative restoration

- Long-range vision of natural realignment
- Developing quantum simulation ecosystem

  e.g., hardware-software co-design, workforce development, academia-government-industry partnership



Digitizing continuous fields to finite dimensional hardware Hilbert spaces

- Explicit quantum resources
- Resulting entanglement structure
- Impact of broken symmetries

Underlying Simulations Grill

Language

Electric Basis, Magnetic Basis, purely fermionic, Free-field eigenstates, position space lattice, discrete subgroups, light front formulation, momentum mode lattice, link models and qubit regularization, orbifold lattices, loop string hadron, global bases, purely bosonic

Architecture

Cold neutral atoms, trapped ions, superconducting quantum circuits, SRF cavities, photonics, solid state defects, annealers, dipolar molecules

Style

Digital, Analog, Digital-Analog Hybrid, Quantum-Classical Hybrid

Error Mitigation

Physical subspace projection, dynamical symmetry protection, measure inversion/voting, conservation laws

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Geometrically Local Interactions

Non-Abelian Gauss Law free

Gauge-variant-subspace free

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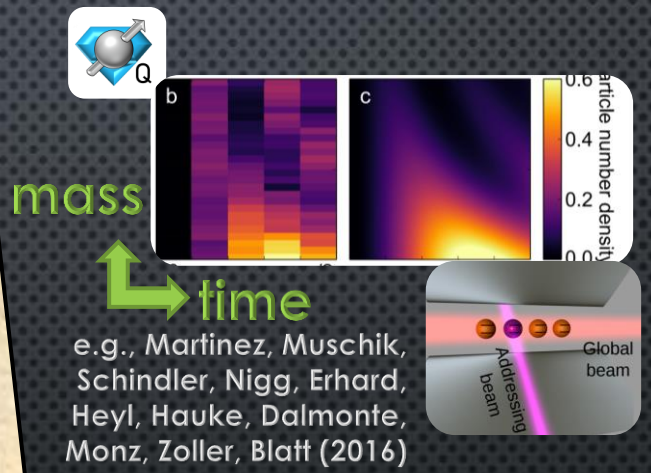

e.g., Martinez, Muschik, Schindler, Nigg, Erhard, Heyl, Hauke, Dalmonte, Monz, Zoller, Blatt (2016)

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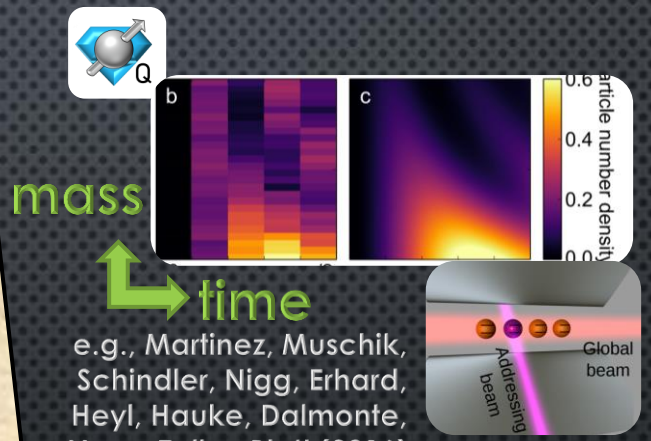

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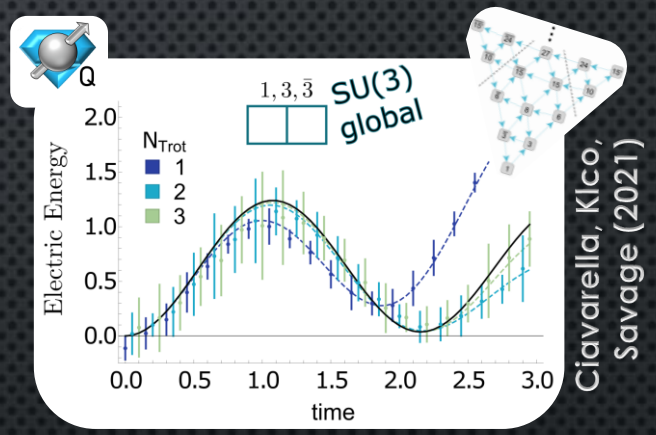

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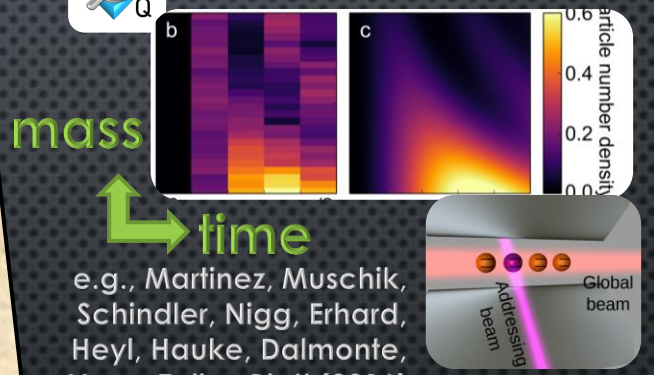

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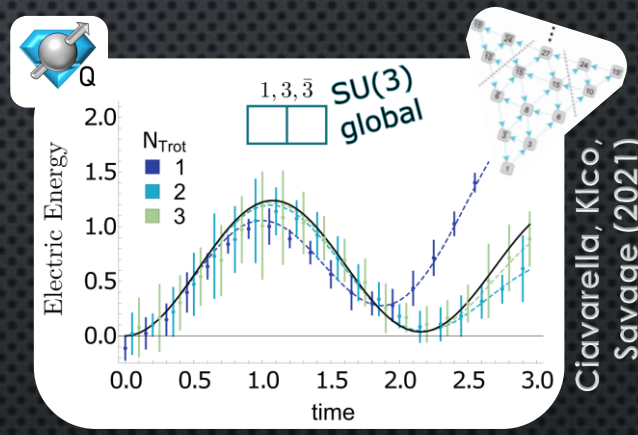

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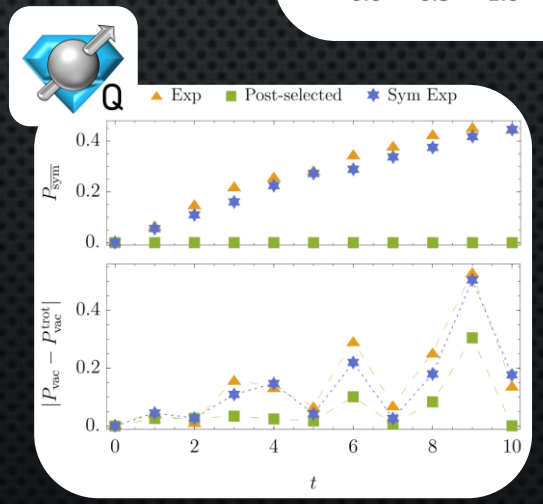

Dynamical Symm. Protect. Tran, Su, Carney, Taylor (2021)

N = 4
Trapped ions
U(1) Schwinger

Nguyen, Tran, Zhu, Green, Huerta Alderete, Davoudi, Linke (2022)

"Nature hacking" complexity

Long history with EFTs **focusing on physics of interest**

Now: "BQP Leading Order" and Entanglement Hierarchies

KIco, Roggero, Savage (2021)

"Nature hacking" complexity

Long history with EFTs **focusing on physics of interest**

Now: "BQP Leading Order" and Entanglement Hierarchies

Klco, Roggero, Savage (2021)

- Diffusion coefficients
- Exclusive decay rates Ciavarella (2020)
- Parton distribution functions Lamm, Lawrence, Yamauchi (2020)
  Echevarria, Egusquiza, Rico, Schnell (2021)
  Kreshchuk, Jia, Kirby, Goldstein, Vary, Love (2021)
  Perez-Salinas, Cruz-Martinez, Alhajri, Carrazza (2021)
- Hadronic tensors Lamm, Lawrence, Yamauchi (2020)
- Transport coefficients Cohen, Lamm, Lawrence, Yamauchi (2020)
  Kan, Nam (2022)
- Low dimensional
  - Confinement and string breaking Banerjee, Dalmonte, Muller, Rico, Stebler, Wiese, Zoller (2012)
    Verdel, Liu, Whitsitt, Gorshkov, Heyl (2020)
    de Jong, Lee, Mulligan, Płoskoń, Ringer, Yao
  - Hadronization
  - Jet Functions Wei, Naik, Harrow, Thaler (2020)
    Pires, Bargassa, Seixas, Omar (2021)
  - Parton showers Nachman, Provasoli, de Jong, Bauer (2021)

"Nature hacking" complexity

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    Pires, Bargassa, Seixas, Omar (2021)
  - Parton showers Nachman, Provasoli, de Jong, Bauer (2021)

Avoiding:

volume scale state preparations

propagations to/from asymptotic times

Precision across separated scales

"Nature hacking" complexity

Long history with EFTs **focusing on physics of interest**

Now: "BQP Leading Order" and Entanglement Hierarchies

Klco, Roggero, Savage (2021)

- Diffusion coefficients
- Exclusive decay rates Ciavarella (2020)
- Parton distribution functions Lamm, Lawrence, Yamauchi (2020)
  Echevarria, Egusquiza, Rico, Schnell (2021)
  Kreshchuk, Jia, Kirby, Goldstein, Vary, Love (2021)
  Perez-Salinas, Cruz-Martinez, Alhajri, Carrazza (2021)
- Hadronic tensors Lamm, Lawrence, Yamauchi (2020)
- Transport coefficients Cohen, Lamm, Lawrence, Yamauchi (2020)
  Kan, Nam (2022)
- Low dimensional
  - Confinement and string breaking Banerjee, Dalmonte, Muller, Rico, Stebler, Wiese, Zoller (2012)
    Verdel, Liu, Whitsitt, Gorshkov, Heyl (2020)
    de Jong, Lee, Mulligan, Płoskoń, Ringer, Yao
  - Hadronization
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Avoiding:

volume scale state preparations

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Precision across separated scales

Balance computational precision among components

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PHYSICAL REVIEW LETTERS **127,** 212001 (2021)

Simulating Collider Physics on Quantum Computers Using Effective Field Theories

Christian W. Bauer[*] and Benjamin Nachman[†]
Marat Freytsis[‡]

Soft-Collinear Effective Theory (SCET)

UV: Lattice Spacing $E \lesssim \frac{1}{a}$ IR: Volume $E \gtrsim \frac{1}{N\,a}$

MeV to TeV ~ 10^{18} sites in 3D volume

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$$\sigma = H \otimes J_1 \otimes \cdots \otimes J_n \otimes S$$

Soft Function

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Treat short-distance perturbatively, integrate out collinear energetic d.o.f.

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$$\langle X | \mathrm{T}[Y_n \, Y_{\bar{n}}^\dagger] | \Omega \rangle$$

Wilson Line in Gauge Field

Soft Function

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-GeV ~ 10^6 sites in 3D volume

Soft matrix elements: Jet dynamics ⟶ fixed Wilson line in soft bath

Techniques for full theory simulation naturally port

Leveraging dynamical QC techniques designed for micro-descriptions

Non-perturbative Quantum Gravity

gravity Bulk ↔ strongly interacting boundary

- Holographic Correspondence: Bulk geometry emerges from boundary entanglement

  Maldacena (1999) Ryu, Takayanagi (2006)

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    Almheiri, Dong, Harlow (2015) Pastawski, Beni Yoshida, Daniel Harlow, and John Preskill (2015)

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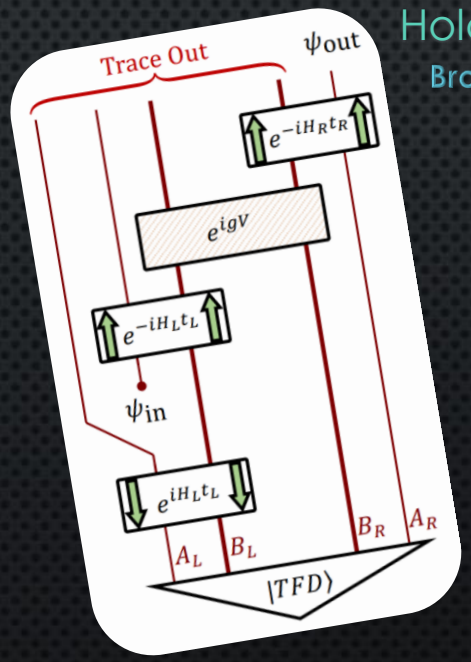
Quantum Gravity in the Lab

Holographic teleportation protocols

Brown, Gharibyan, Leichenauer, Lin, Nezami, Salton, Susskind, Swingle, Walter (2019)



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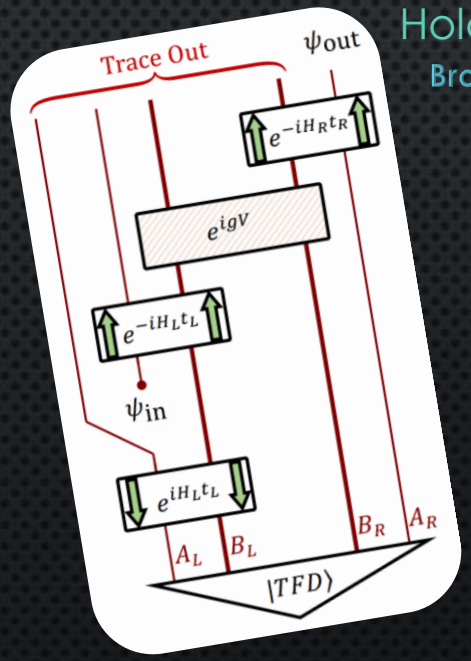
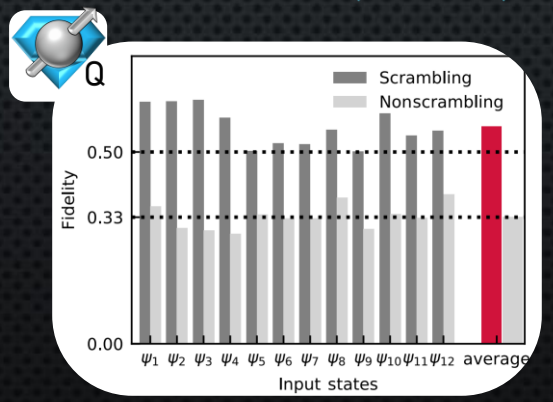
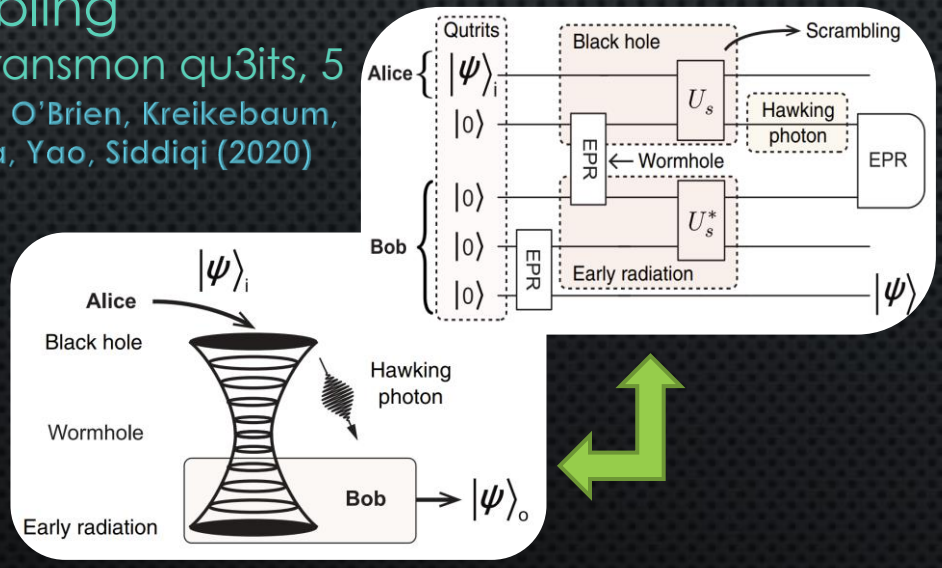


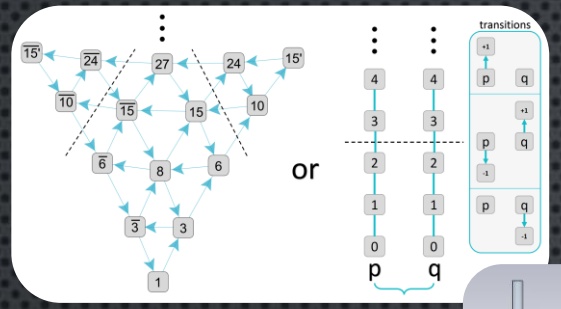
Teleportation-heralded Scrambling

Superconducting transmon qu3its, 5

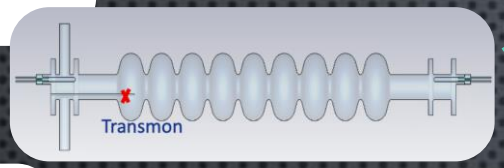
Blok , Ramasesh , Schuster, O'Brien, Kreikebaum, Dahlen, Morvan , Yoshida, Yao, Siddiqi (2020)



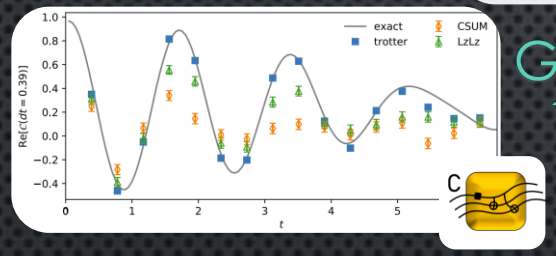




Givens Rotations
SU(3)
Ciavarella, Klco, Savage (2021)



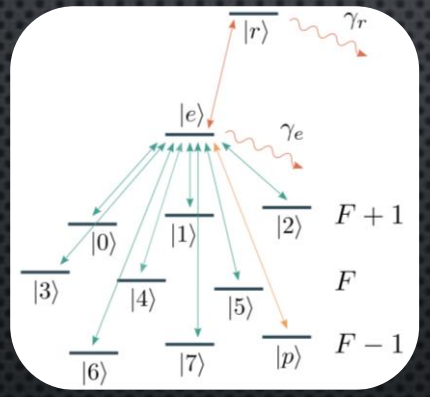
SRF Cavities
e.g., 2204.08605

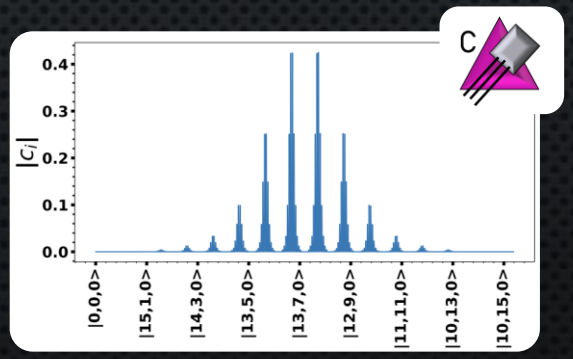


Gate costs and Prospects
1D scalar QED/Abelian Higgs
Gustafson (2021)

Rydberg tweezer arrays
Native holonomic gates
$Q_8 \subset SU(2)$

Gonzalez-Cuadra, Zache, Carrasco, Kraus, Zoller (2022)



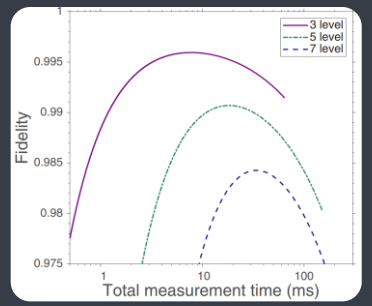


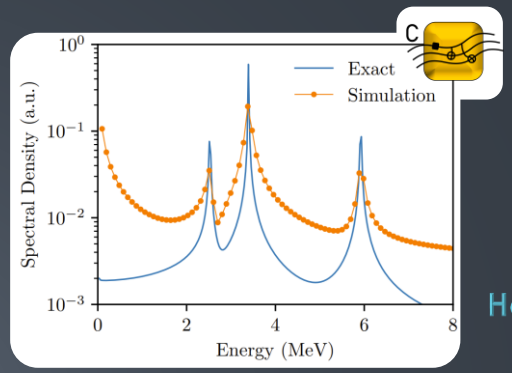
Photon number, 3 cavities

PRA 92, 040303(R) (2015)

SNAP and displacement gates
Scalar ϕ^4
Kurkcuoglu, Alam, Job, Li, Macridin, Perdue, Providence (2022)

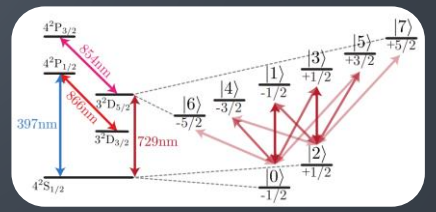
Design of 1,2-qudit gates Experimentally informed
Trapped ions
Low, White, Cox, Day, Senko (2019)



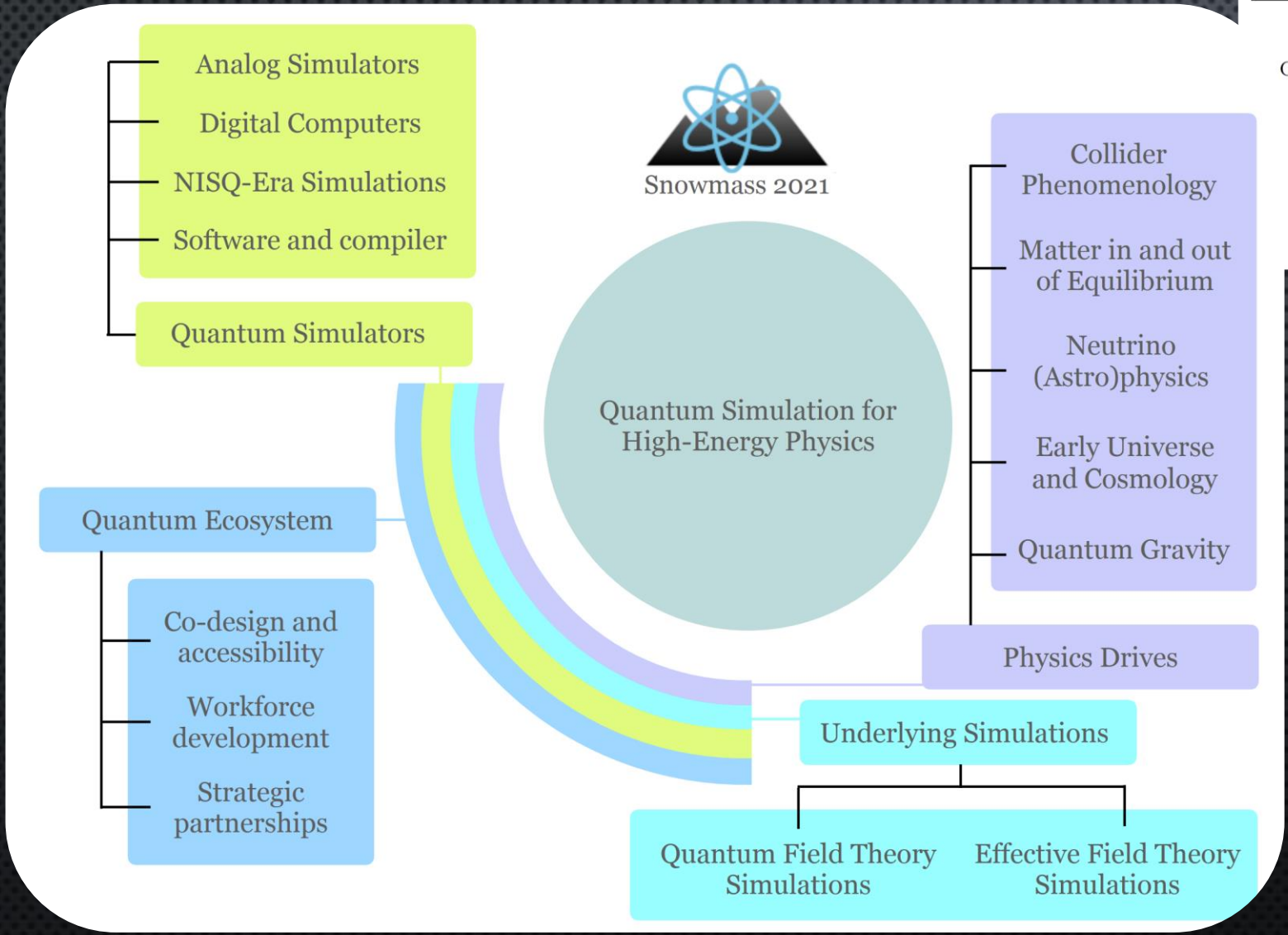


Optimized pulses for NN dynamics in chiral EFT
Superconducting transmon qu4it
Holland, Wendt, Kravvaris, Wu, Ormand, DuBois, Quaglioni, Pederiva (2019)

Design 1,2-qudit gates
Trapped ion qu7its
Ringbauer, Meth, Postler, Stricker, Blatt, Schindler, Monz (2021)



Rise of the QuDit



Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

Quantum Simulation for High Energy Physics

Christian W. Bauer,[1,a] Zohreh Davoudi,[2,b] A. Baha Balantekin,[3] Tanmoy Bhattacharya,[4] Marcela Carena,[5,6,7,8] Wibe A. de Jong,[1] Patrick Draper,[9] Aida El-Khadra,[9] Nate Gemelke,[10] Masanori Hanada,[11] Dmitri Kharzeev,[12,13] Henry Lamm,[5] Ying-Ying Li,[5] Junyu Liu,[14,15] Mikhail Lukin,[16] Yannick Meurice,[17] Christopher Monroe,[18,19,20,21] Benjamin Nachman,[1] Guido Pagano,[22] John Preskill,[23] Enrico Rinaldi,[24,25,26] Alessandro Roggero,[27,28] David I. Santiago,[29,30] Martin J. Savage,[31] Irfan Siddiqi,[29,30,32] George Siopsis,[33] David Van Zanten,[5] Nathan Wiebe,[34,35] Yukari Yamauchi,[2] Kübra Yeter-Aydeniz,[36] and Silvia Zorzetti[5]

Recurring Features

- Non-perterbative Interference effects
  - intermediate states (flavor, spin, color)
- Increased access to large Hilbert space/particle number
  - High-multiplicity final states, coherent neutrinos, etc.

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