

Towards experimentally relevant quantum simulations

Christian Bauer

Theory Group Leader
PI Quantum Computing
Physics Division LBNL

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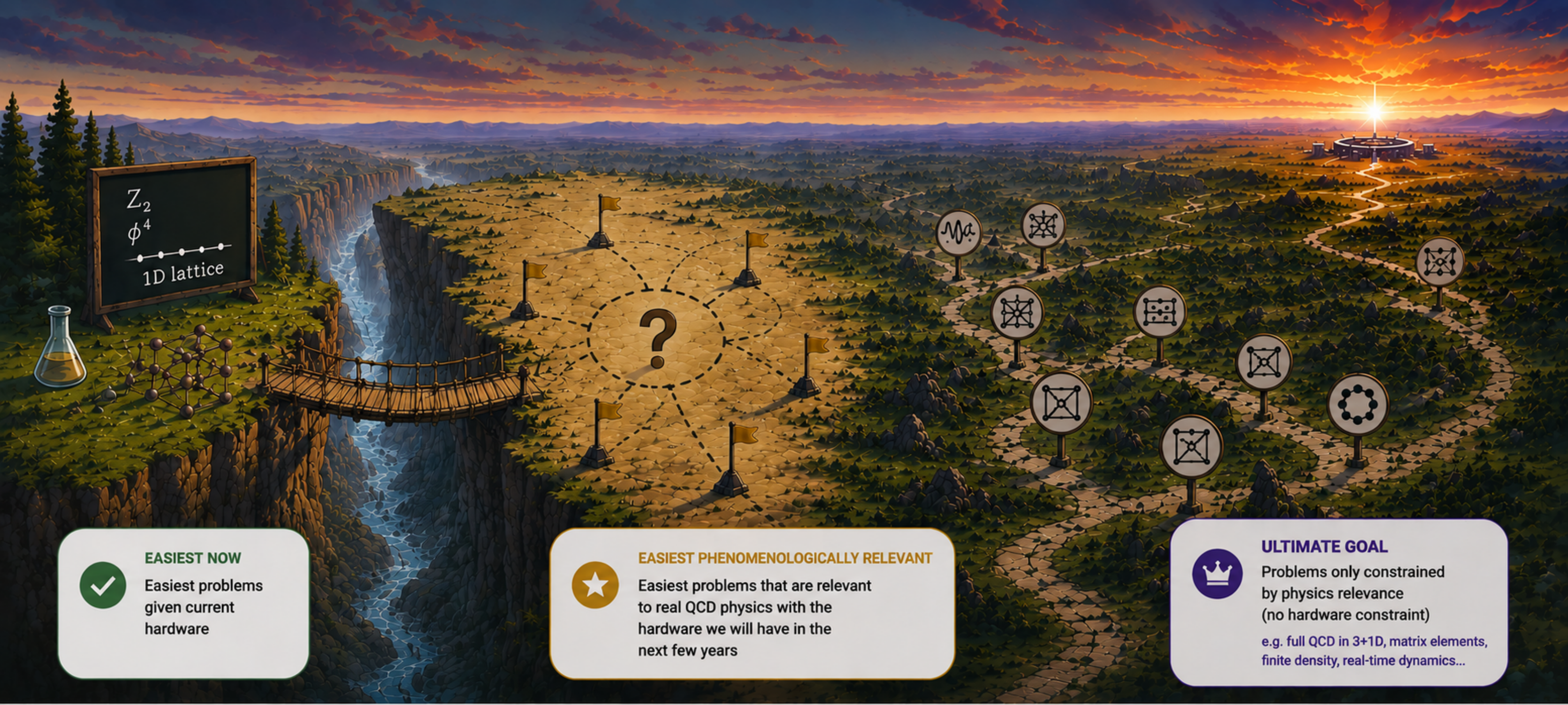
Towards experimentally relevant quantum simulations



When do you think our community will have results that will impact the experimental HEP community?

POLL

					
Already have them now	In 2 years	In 5–10 years	In 10–30 years	In 30+ years	Never
☐	☐	☐	☐	☐	☐



 **EASIEST NOW**
Easiest problems given current hardware

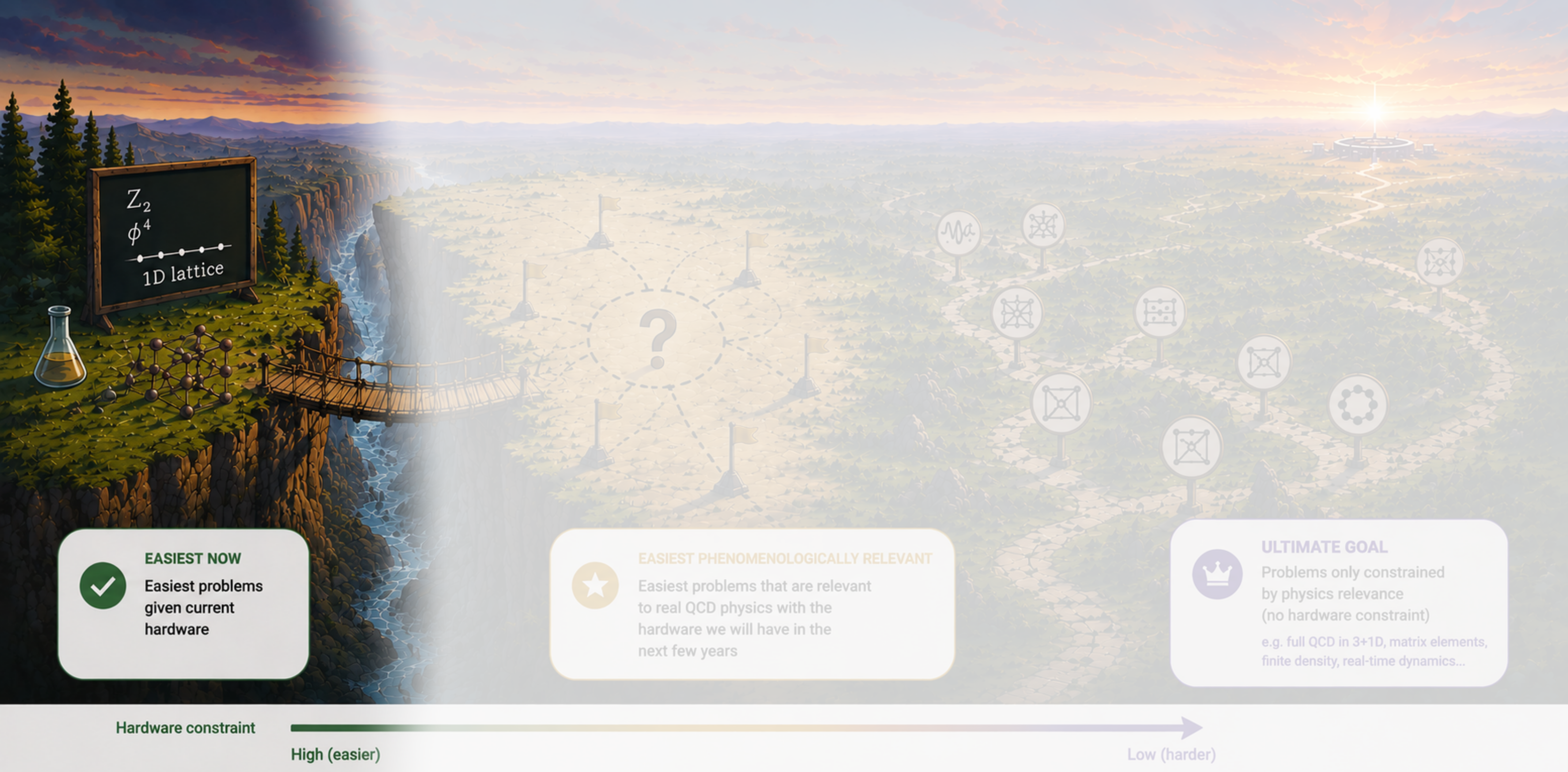
 **EASIEST PHENOMENOLOGICALLY RELEVANT**
Easiest problems that are relevant to real QCD physics with the hardware we will have in the next few years

 **ULTIMATE GOAL**
Problems only constrained by physics relevance (no hardware constraint)
e.g. full QCD in 3+1D, matrix elements, finite density, real-time dynamics...

Hardware constraint

High (easier)

Low (harder)



USHERING IN THE NEXT FRONTIER OF QUANTUM INNOVATION

Executive Orders | June 22, 2026

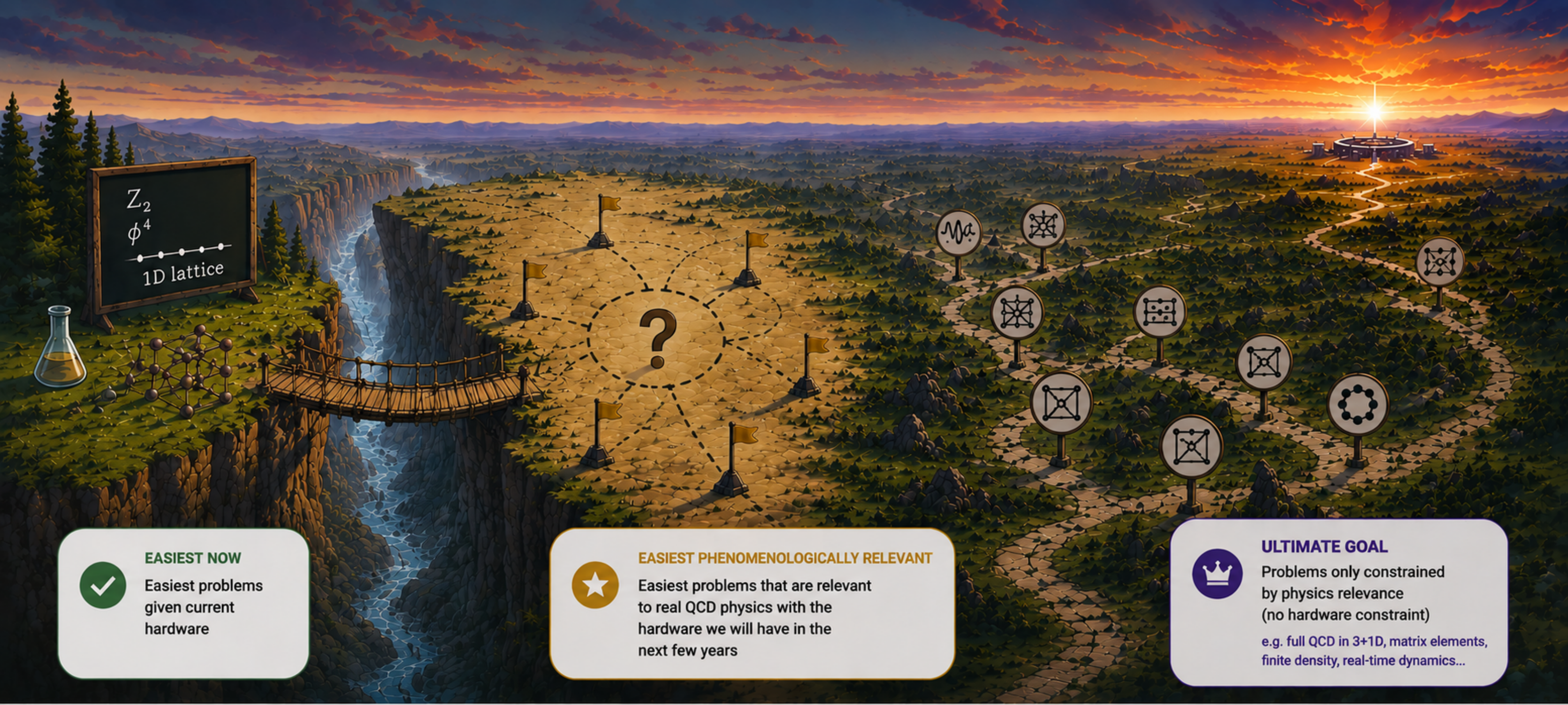
This national effort shall pursue development of a quantum computer at a scale intended to initiate the era of quantum-enabled scientific discovery, with the intent to deliver at least one such computer to a Department of Energy facility (...).

Within 90 days of the date of this order, the Secretary of Energy (...) shall identify the technical specifications required to perform transformative scientific applications that are (...) beyond current classical computer capabilities,

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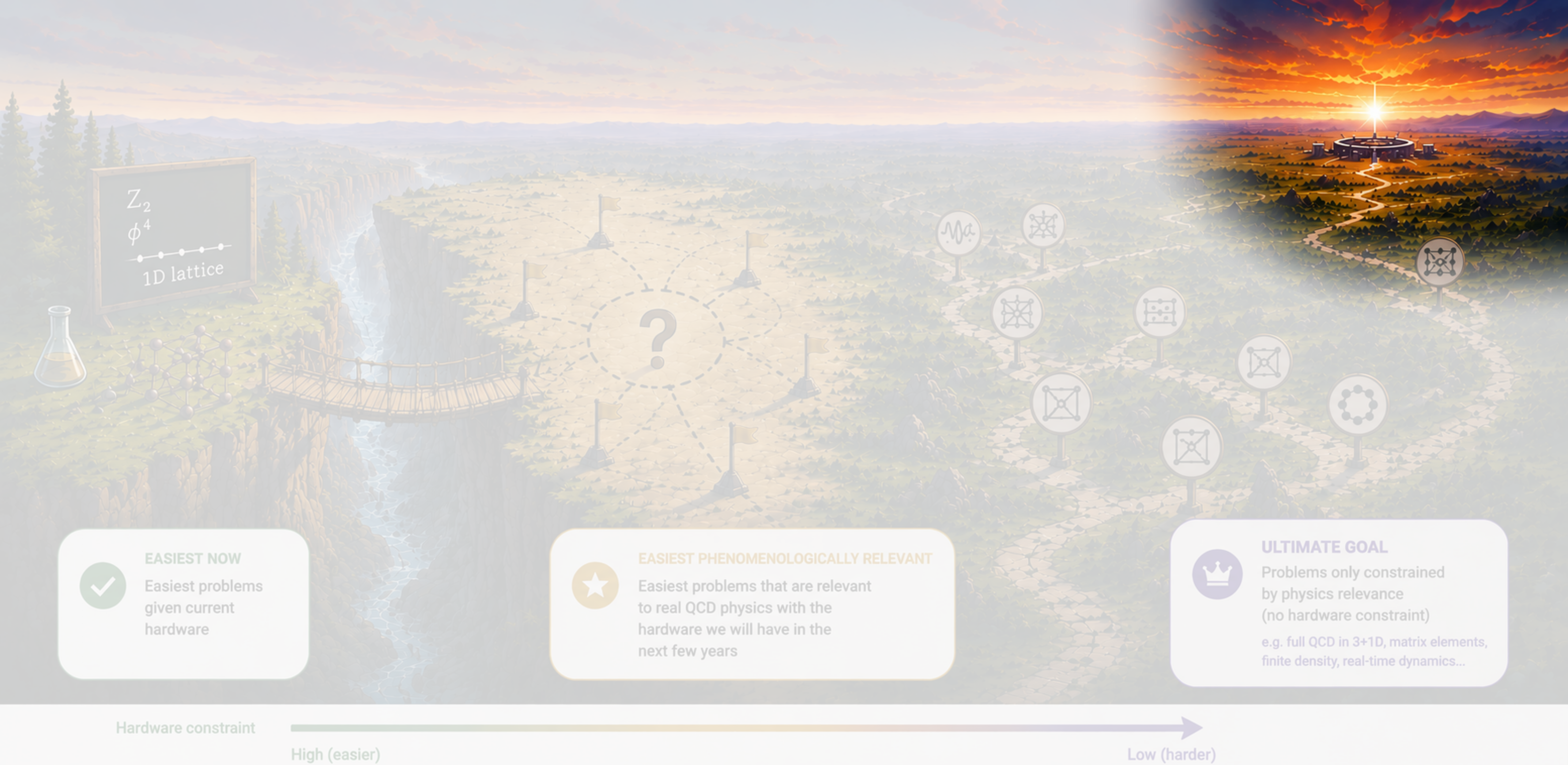
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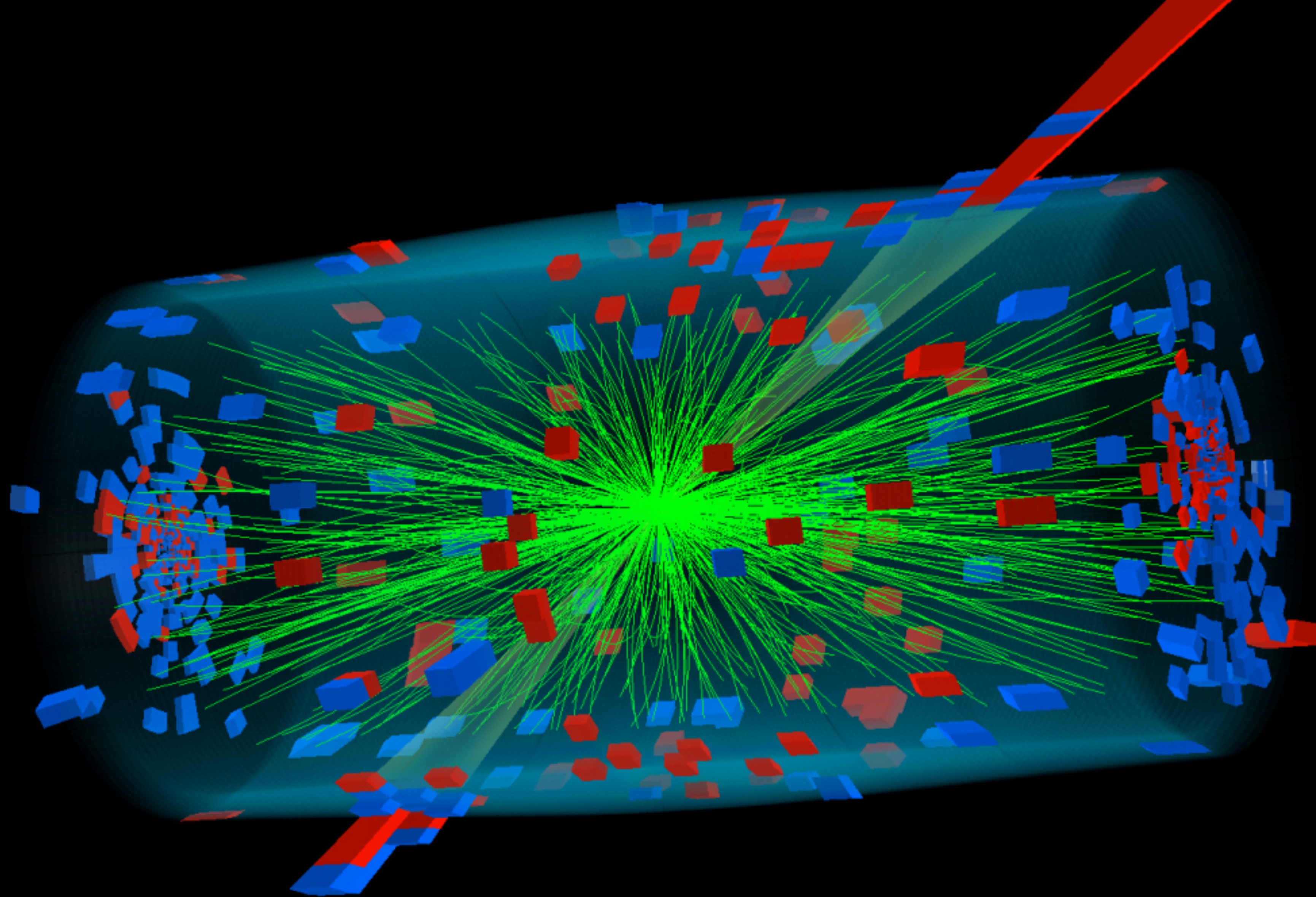
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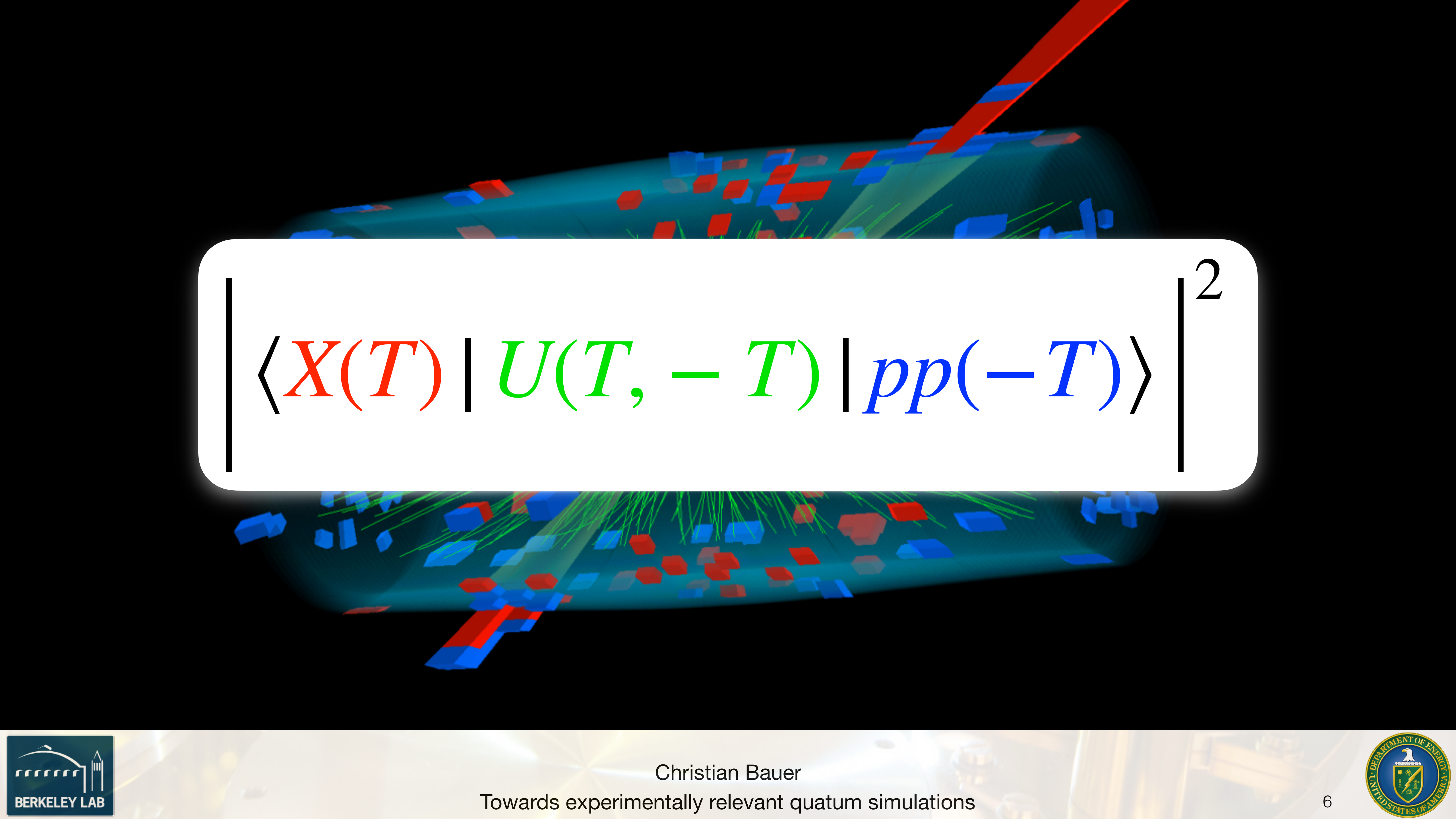
Low (harder)





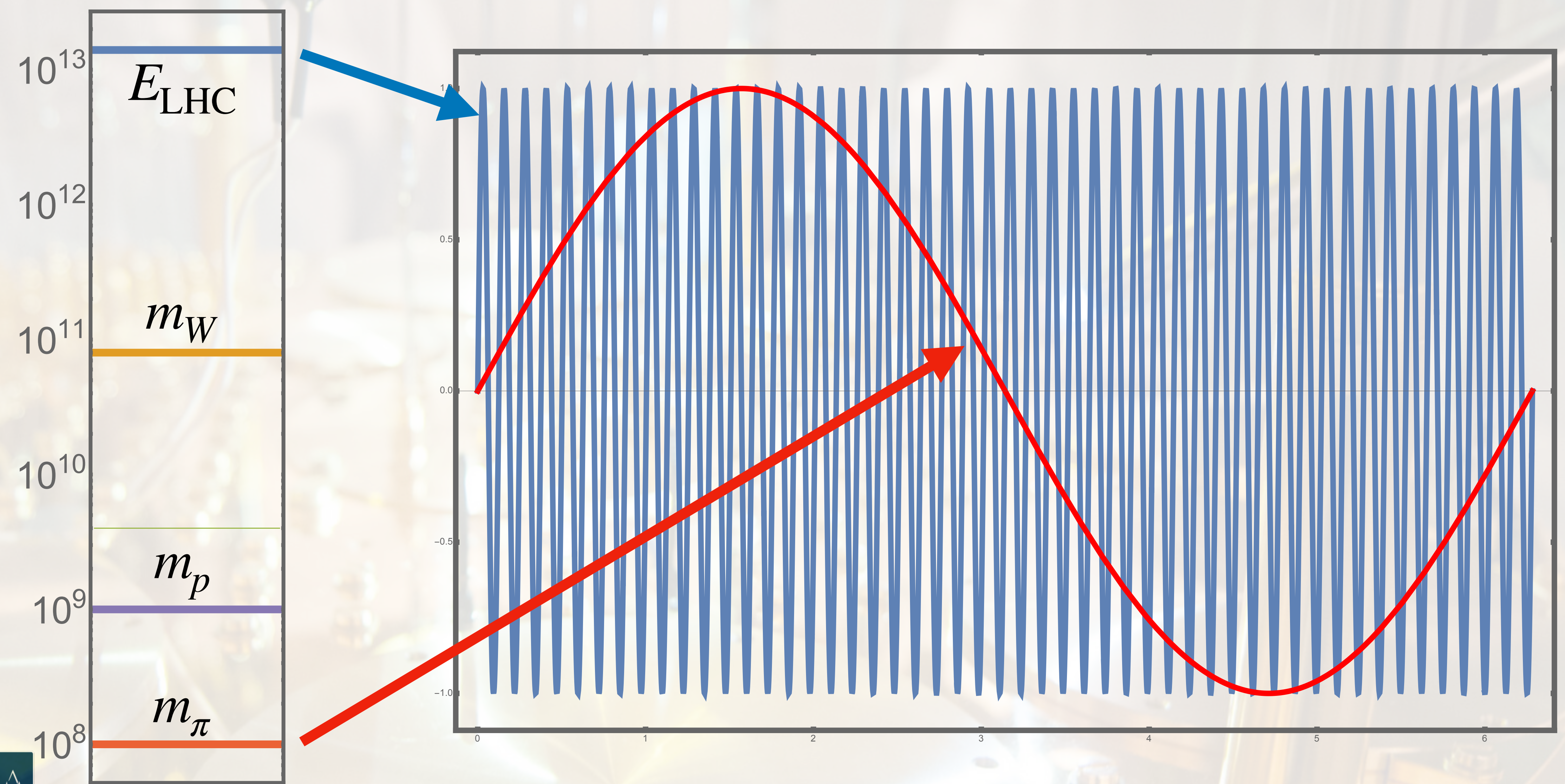
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$$\left| \langle X(T) \mid U(T, -T) \mid pp(-T) \rangle \right|^2$$

Most obvious calculation would be the scattering of LHC cross-sections. But this will not be possible within our lifetime

CWB, 2503.16602



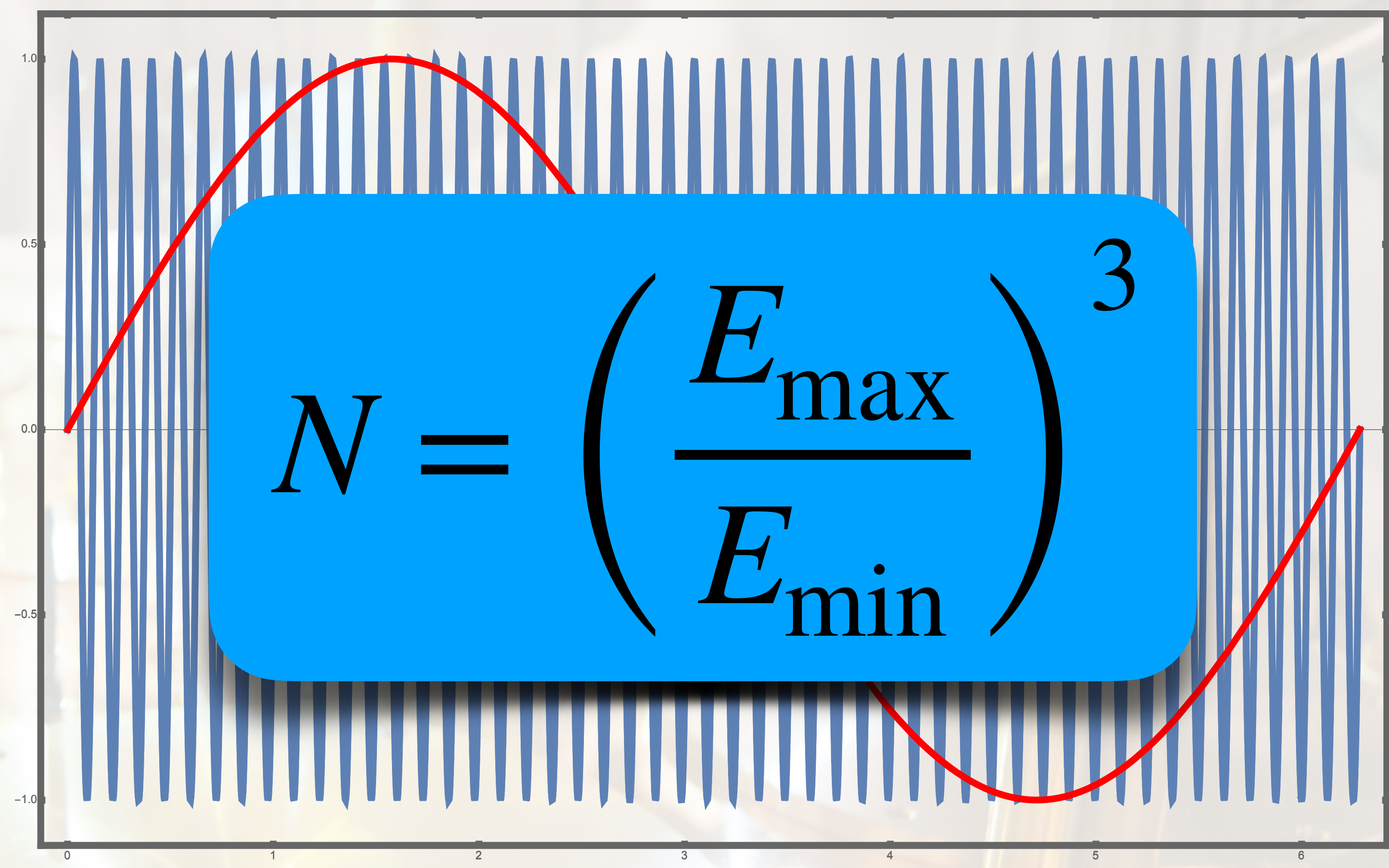
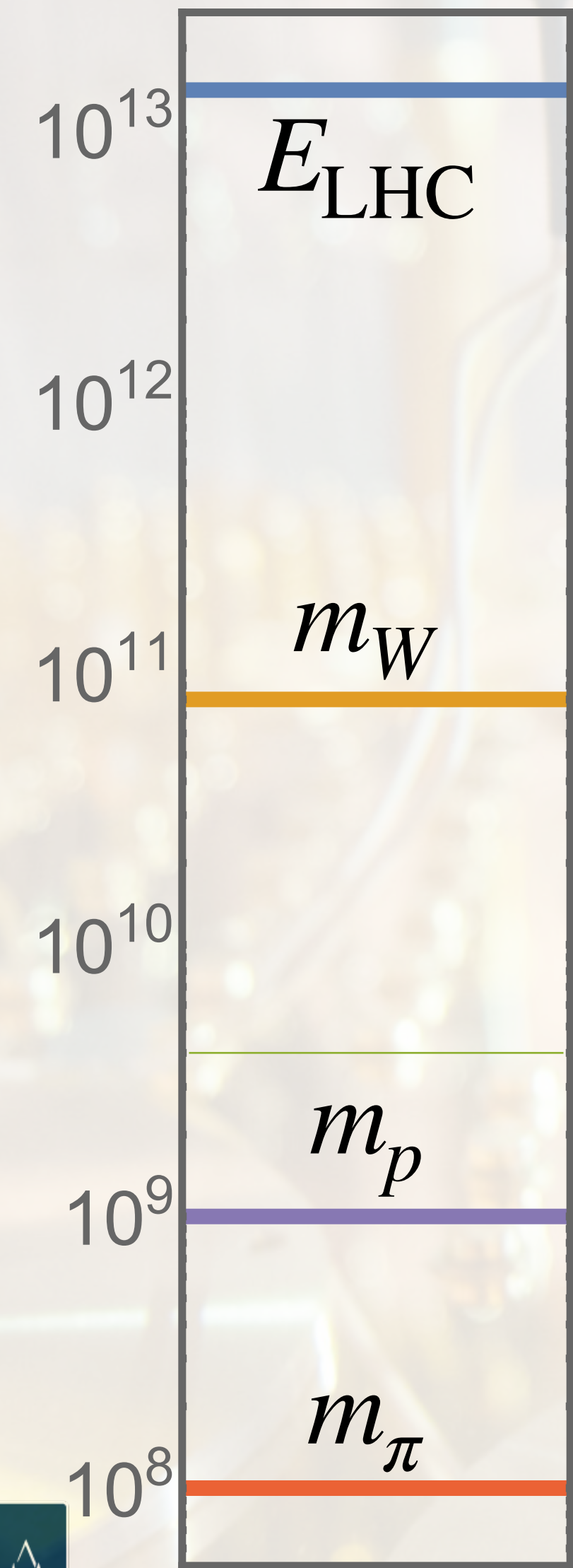
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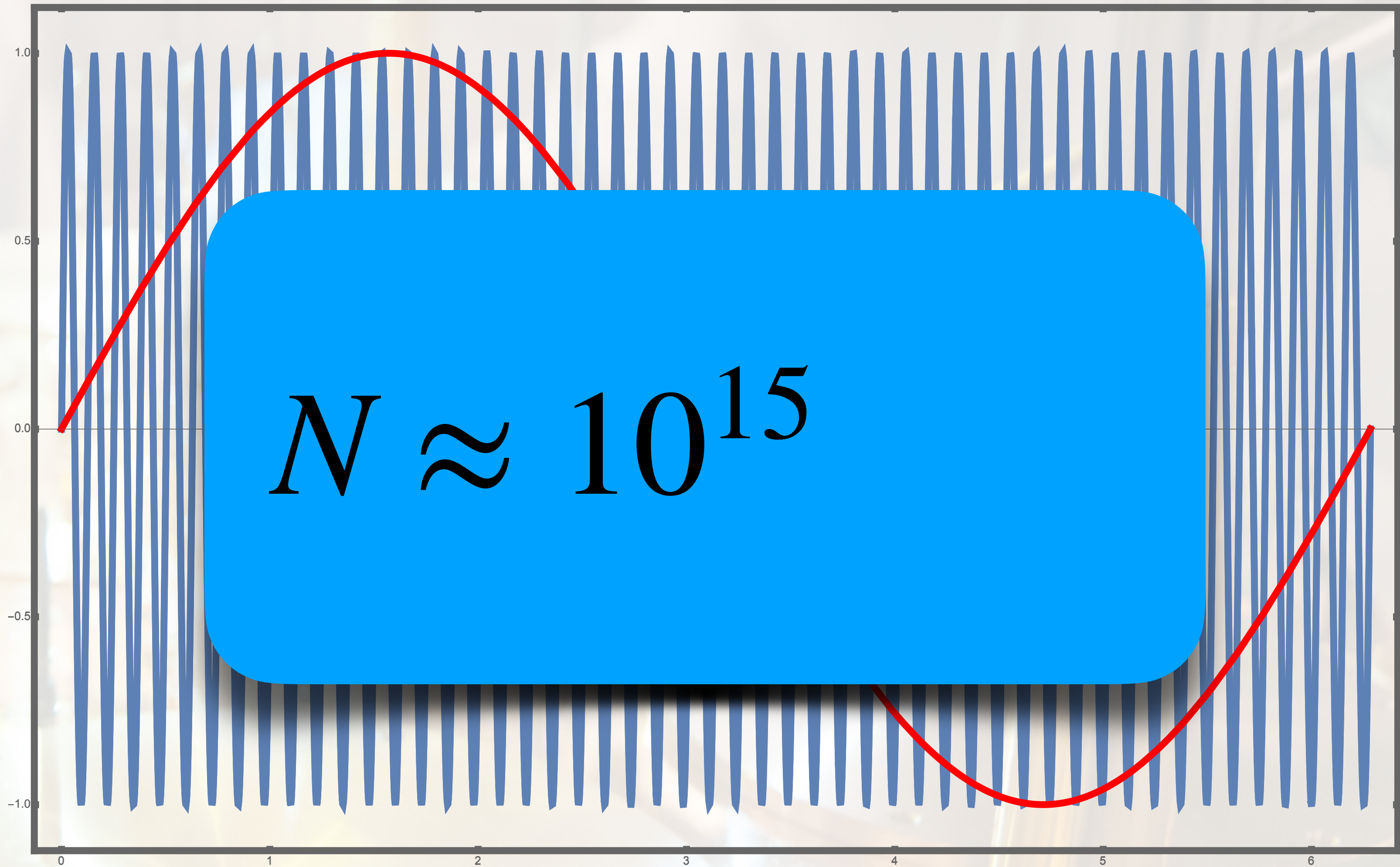
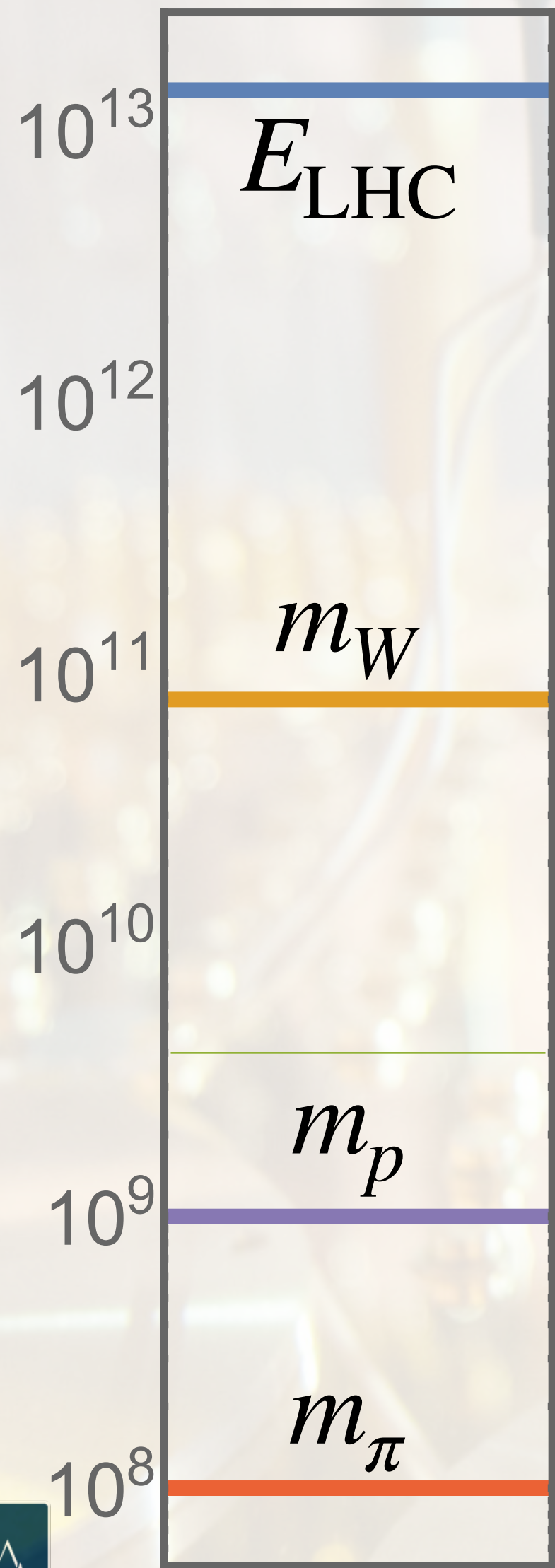
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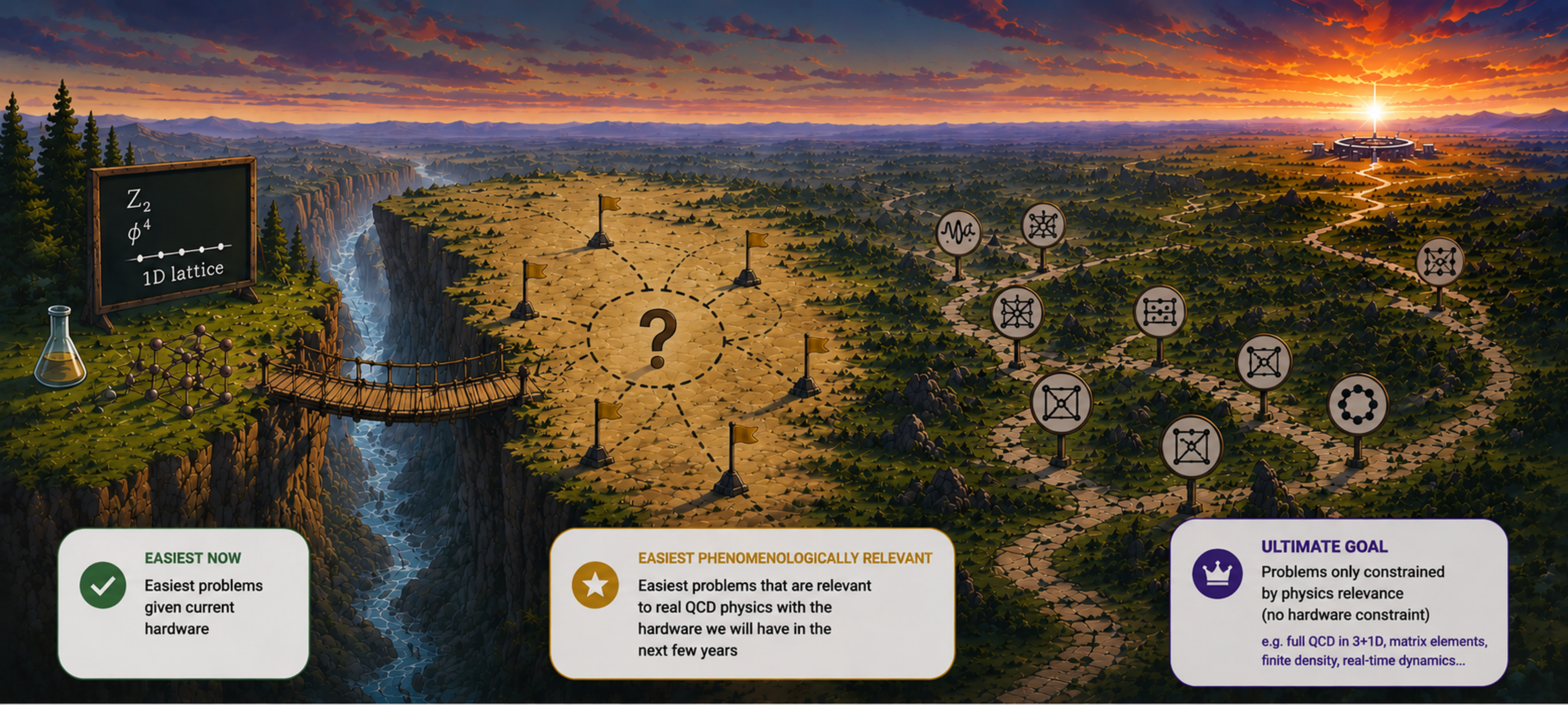
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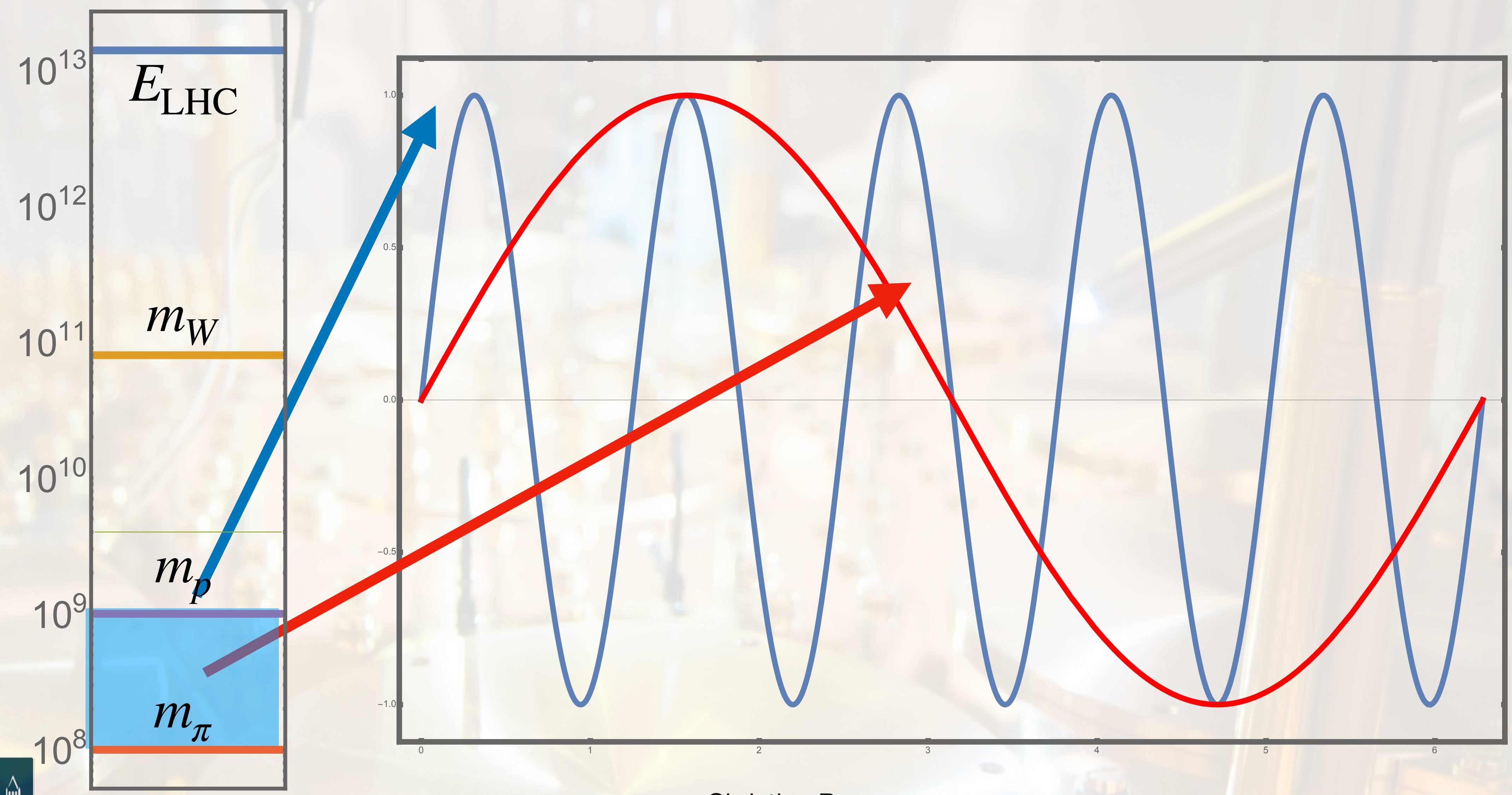
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Next best thing would be calculation of effective field theory observables. But still requires too many resources to be feasible in near term

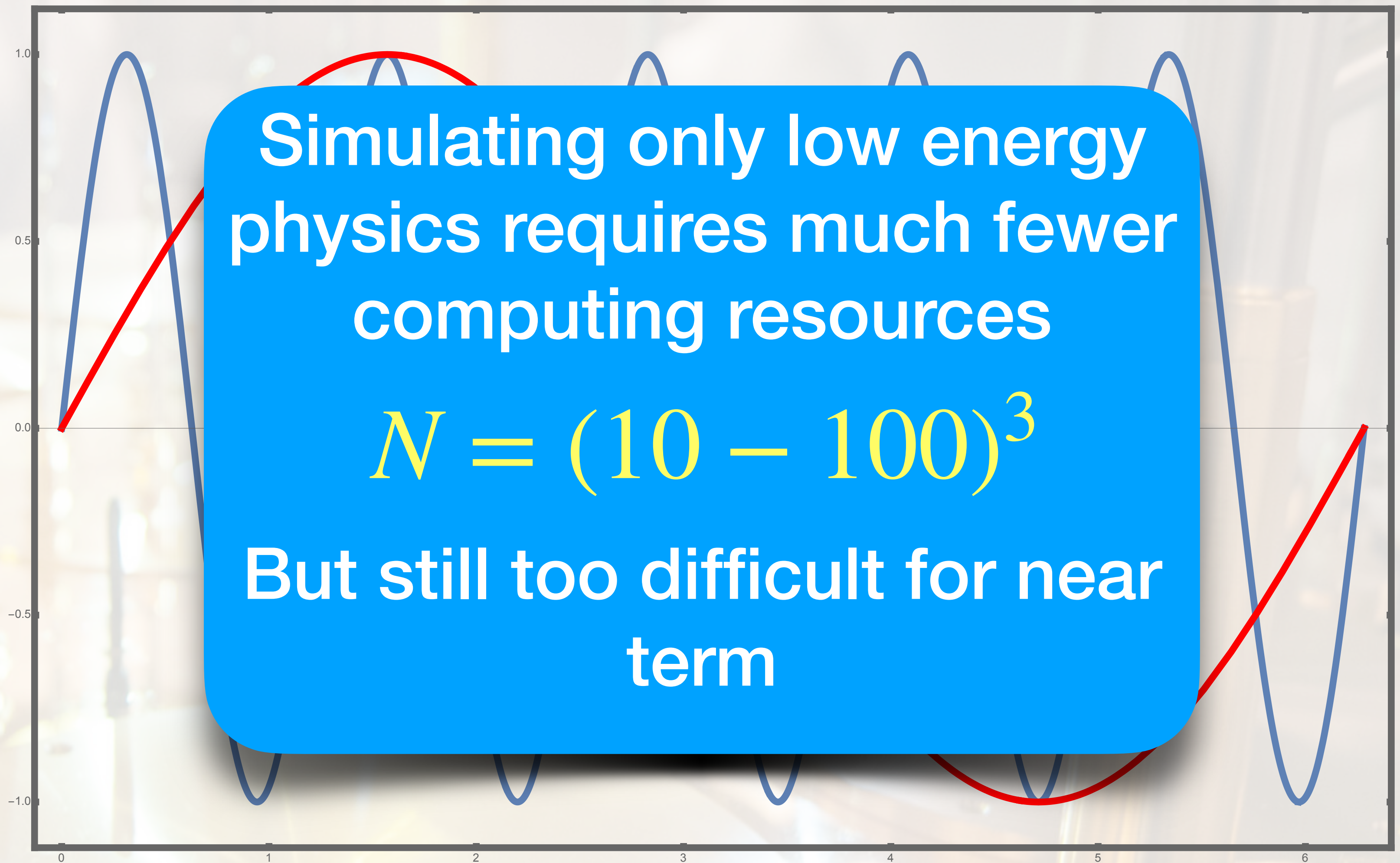
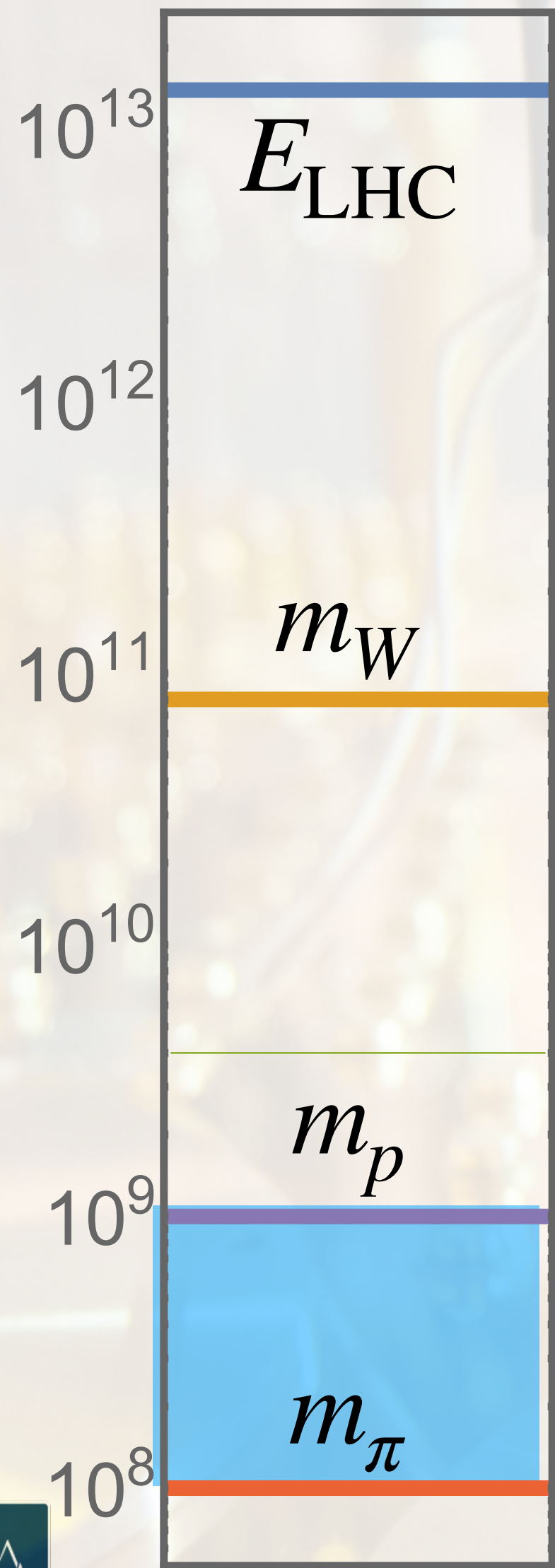


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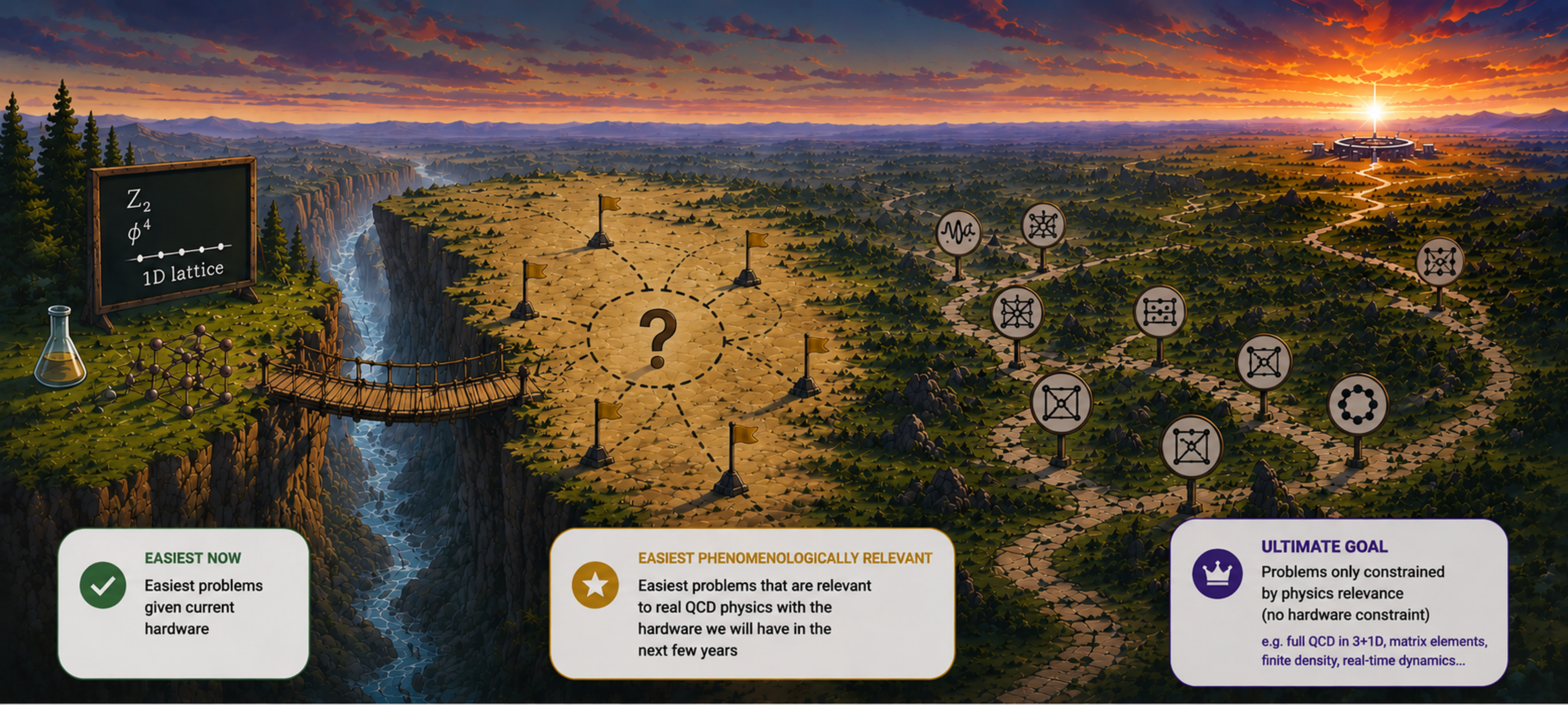
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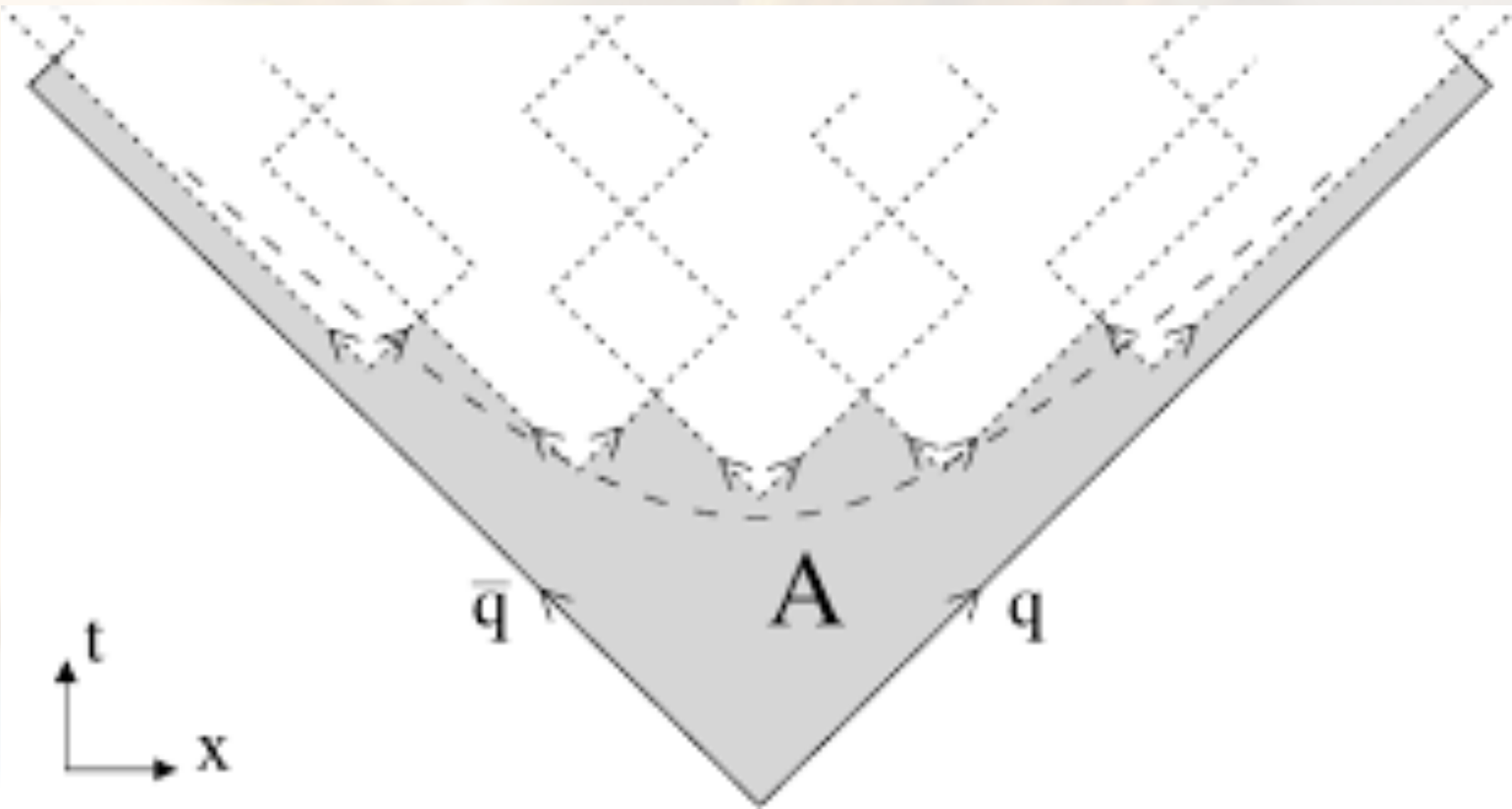
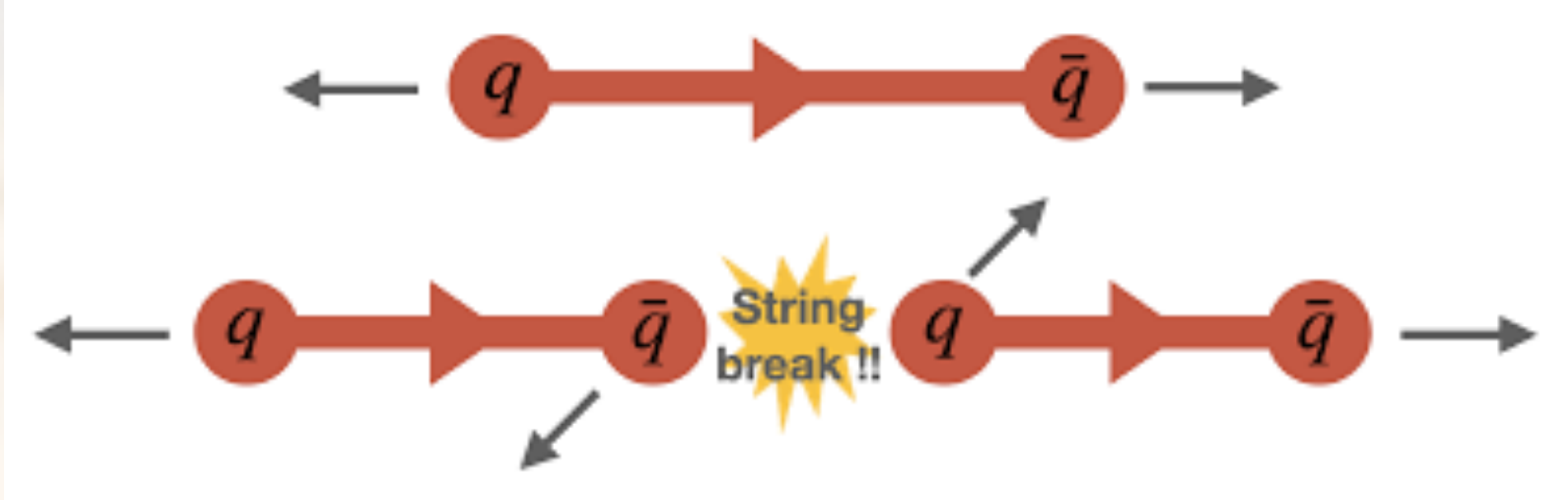
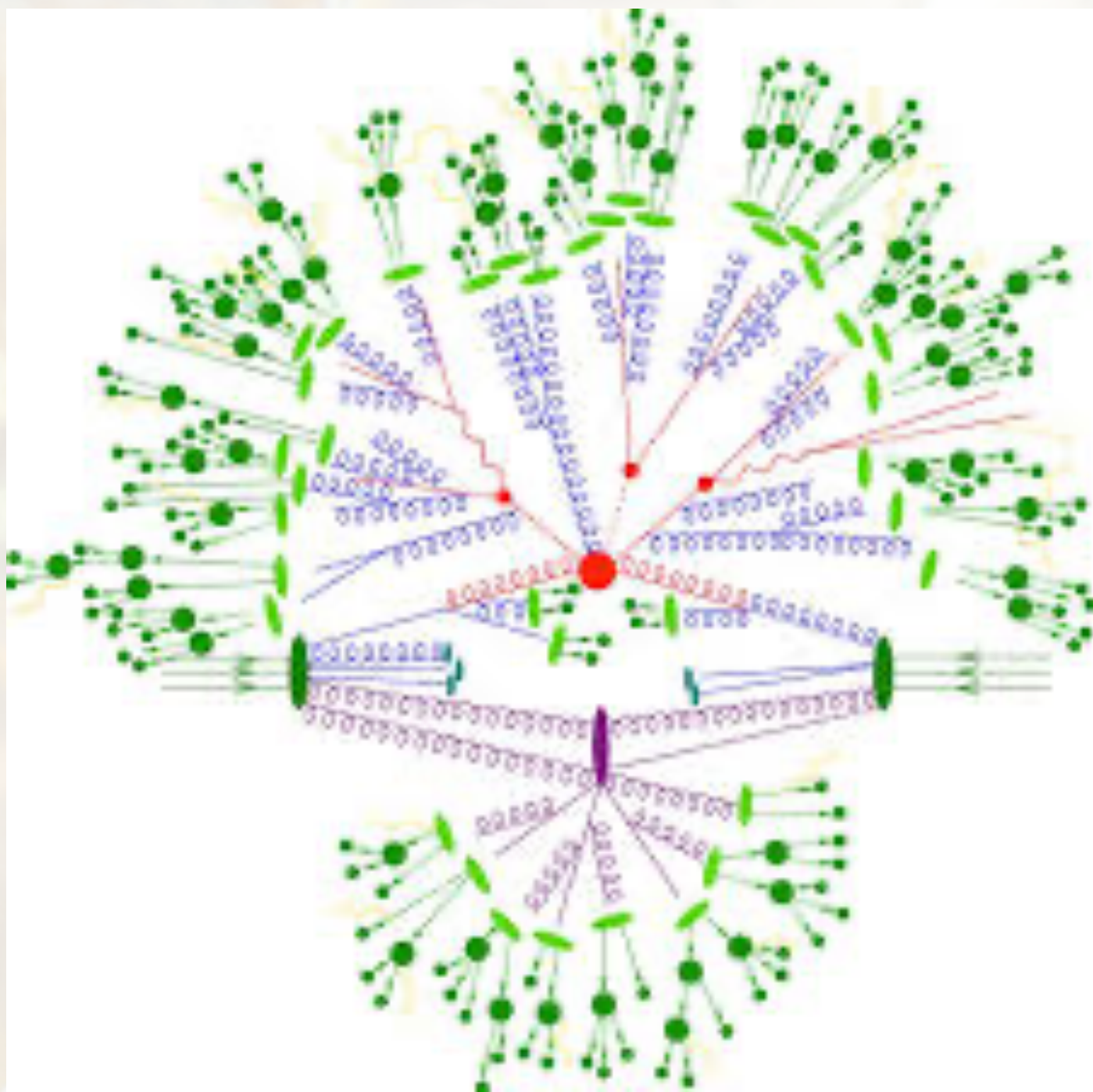
Low (harder)



The world we live in obviously exists in 3+1D, and simulations are quite expensive.
But there are many interesting simulations in lower dimensions

How partons turn into hadrons is one of the most important outstanding questions in connecting experiments to Theory

Relevant physics is simulated using very simple classical models in 1+1D or 2+1D



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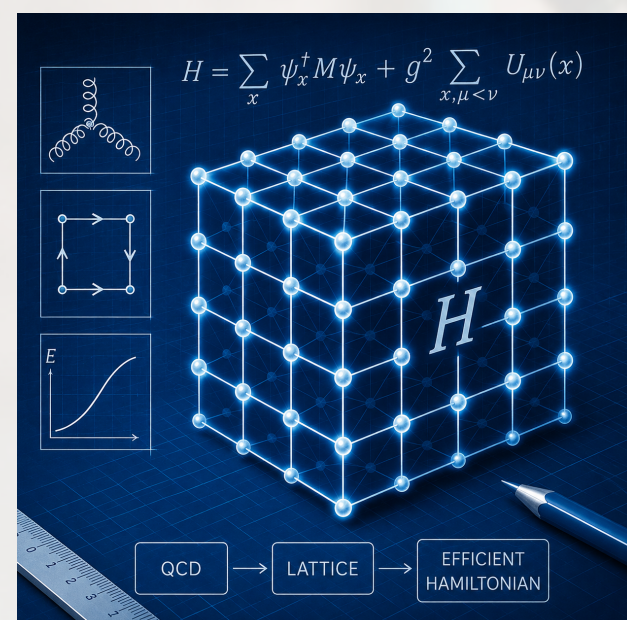
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**Can we observe effects in quantum
simulations of QCD hadronization
that are not described by the
classical models of string breaking?**

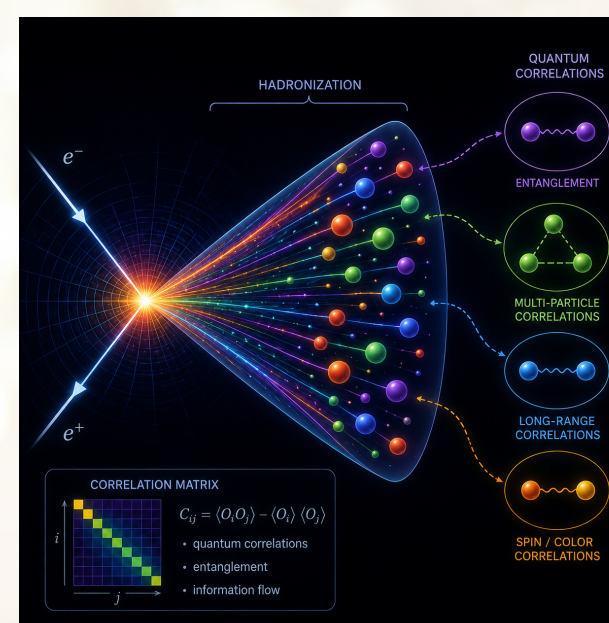
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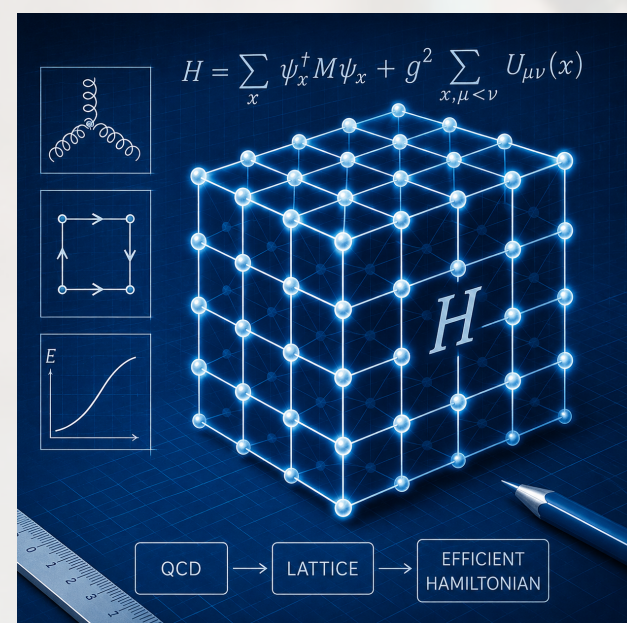
Constructing efficient Hamiltonians for QCD



Study quantum correlations in hadronization

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Constructing efficient Hamiltonians for QCD

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We very recently realized that adding an additional expansion can lead to dramatic simplifications in the lattice theory

PHYSICAL REVIEW LETTERS **133**, 111901 (2024)

arXiv: 2402.10265v4

Quantum Simulation of SU(3) Lattice Yang-Mills Theory at Leading Order in Large- N_c Expansion

Anthony N. Ciavarella^{1,*} and Christian W. Bauer^{1,2,†}

¹*Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

²*Department of Physics, University of California, Berkeley, Berkeley, California 94720, USA*

 (Received 28 February 2024; revised 26 July 2024; accepted 5 August 2024; published 9 September 2024)

Quantum simulations of the dynamics of QCD have been limited by the complexities of mapping the continuous gauge fields onto quantum computers. By parametrizing the gauge invariant Hilbert space in terms of plaquette degrees of freedom, we show how the Hilbert space and interactions can be expanded in inverse powers of N_c . At leading order in this expansion, the Hamiltonian simplifies dramatically, both in the required size of the Hilbert space as well as the type of interactions involved. Adding a truncation of the resulting Hilbert space in terms of local energy states we give explicit constructions that allow simple representations of SU(3) gauge fields on qubits and qutrits. This formulation allows a simulation of the real time dynamics of a SU(3) lattice gauge theory on a 5×5 and 8×8 lattice on `ibm_torino` with a CNOT depth of 113.

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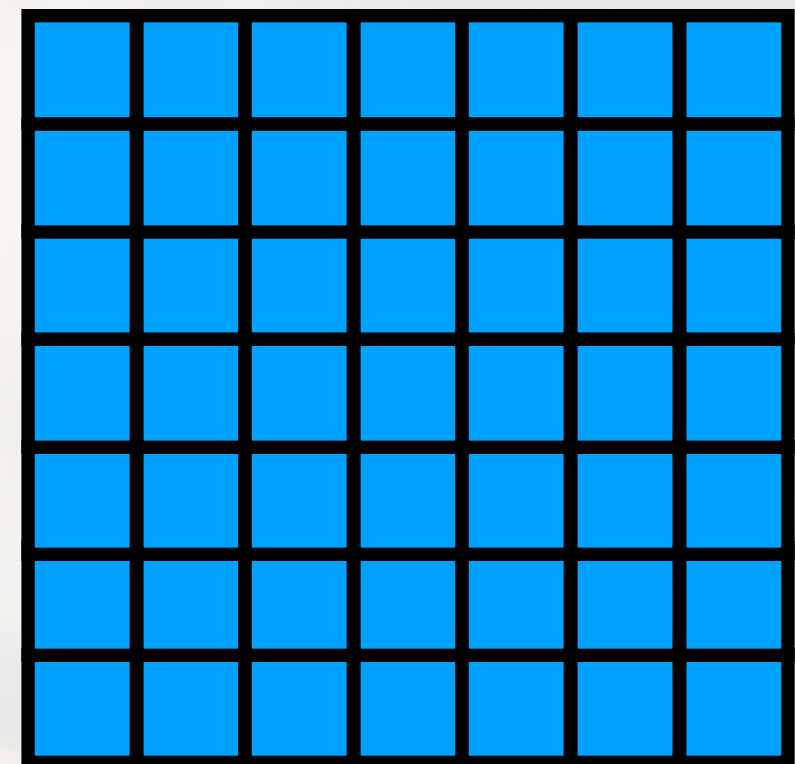
One can now work out the Hamiltonians, and obtain a relatively simple result, which can be represented by a single qubit per plaquette

$$\hat{H} = \sum_p \left(\frac{8}{3}g^2 - \frac{1}{2g^2} \right) \hat{P}_{1,p} - \frac{1}{\sqrt{2}g^2} \hat{P}_{0,p+x} \hat{P}_{0,p-x} \hat{P}_{0,p+y} \hat{P}_{0,p-y} \hat{X}_p$$

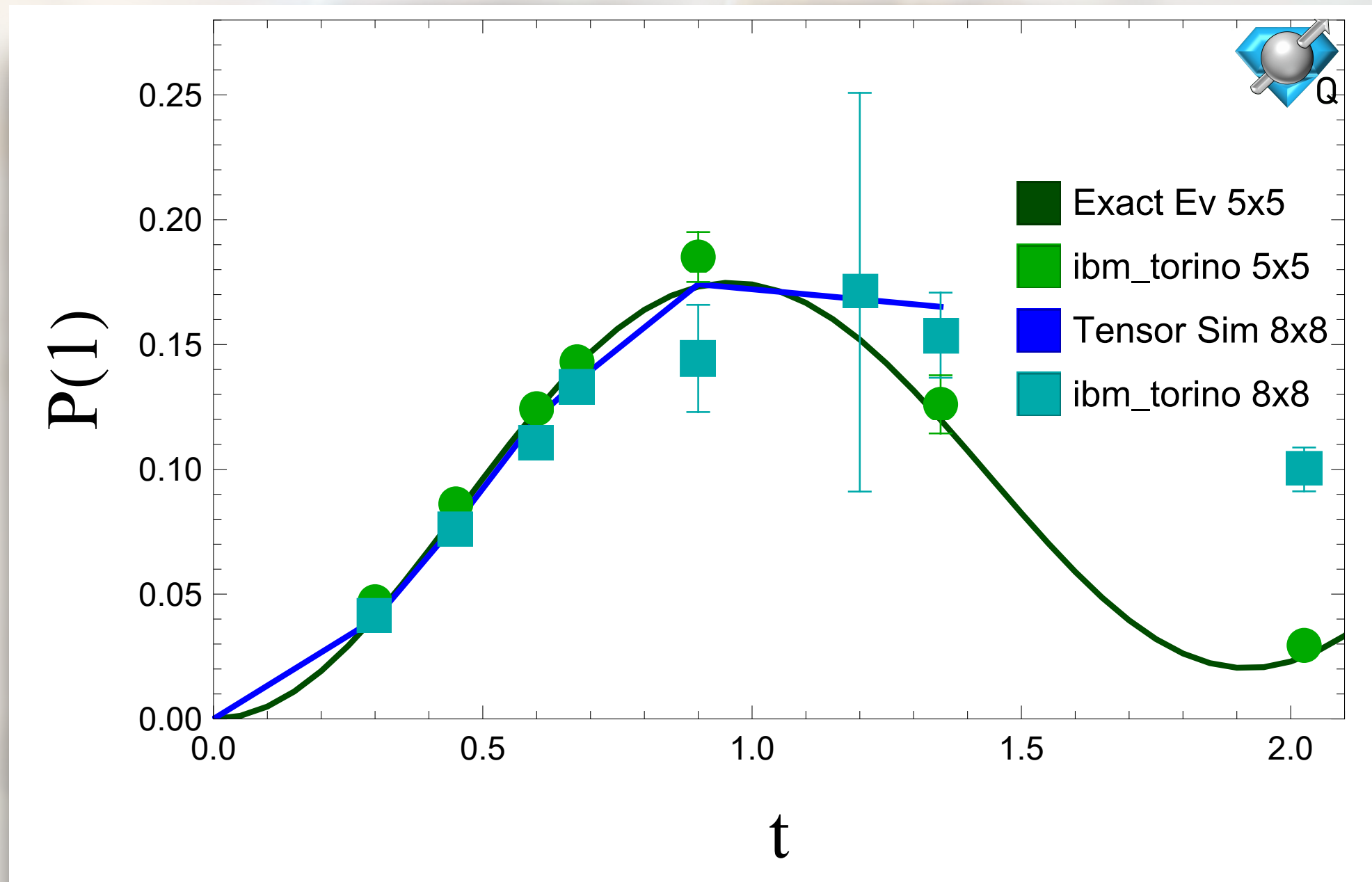
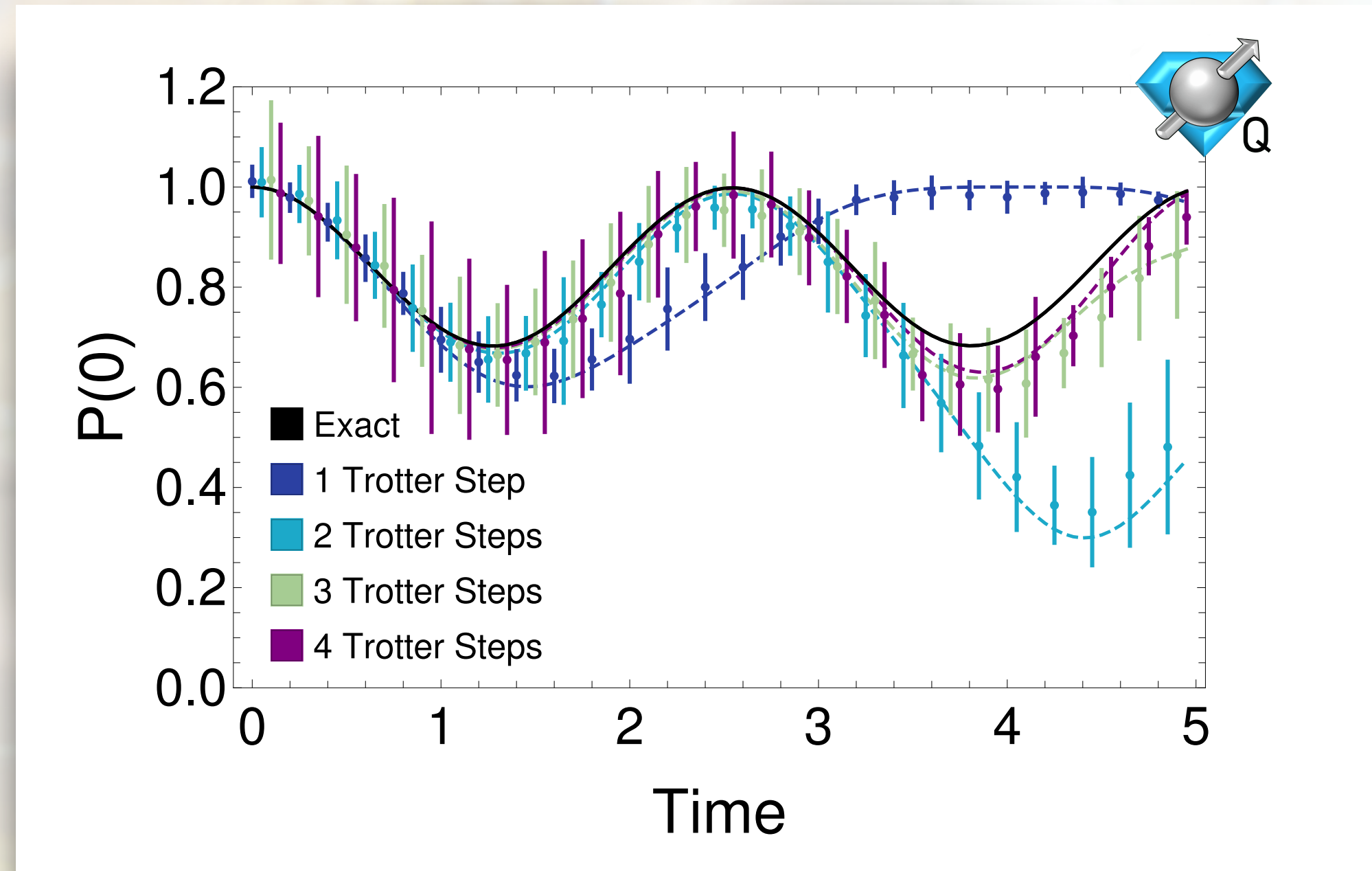
A $1/N_c$ expansion in QCD is quite standard in many classical applications. Can it help in quantum simulation?



Trailhead for quantum simulation of SU(3)
Yang-Mills lattice gauge theory in the local
multiplet basis,
2101.10227



Quantum Simulation of SU(3)
Lattice Yang Mills Theory at
Leading Order in Large N,
2402.10265



Recently extended these results to include $1/N_c$ corrections, as well as include higher truncations in the Hilbert space

Efficient Truncations of $SU(N_c)$ Lattice Gauge Theory for Quantum Simulation

Anthony N. Ciavarella ^{1,*} Ivan M. Burbano ^{1,2,3,†} and Christian W. Bauer ^{1,2,‡}

¹*Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

²*Department of Physics, University of California, Berkeley, Berkeley, CA 94720*

³*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

(Dated: March 18, 2025)

Quantum simulations of lattice gauge theories offer the potential to directly study the non-perturbative dynamics of quantum chromodynamics, but naive analyses suggest that they require large computational resources. Large N_c expansions are performed to order $1/N_c$ to simplify the Hamiltonian of pure $SU(N_c)$ lattice gauge theories. A reformulation of the electric basis is introduced with a truncation strategy based on the construction of local Krylov subspaces with plaquette operators. Numerical simulations show that these truncated Hamiltonians are consistent with traditional lattice calculations at relatively small couplings. It is shown that the computational resources required for quantum simulation of time evolution generated by these Hamiltonians is 17 – 19 orders of magnitude smaller than previous approaches.

arXiv: 2503.11888v1

The gate count is dramatically reduced when working in the $1/N_c$ expansion. For the first few truncations we find

For 2+1D with 10 lattice sites per dimension

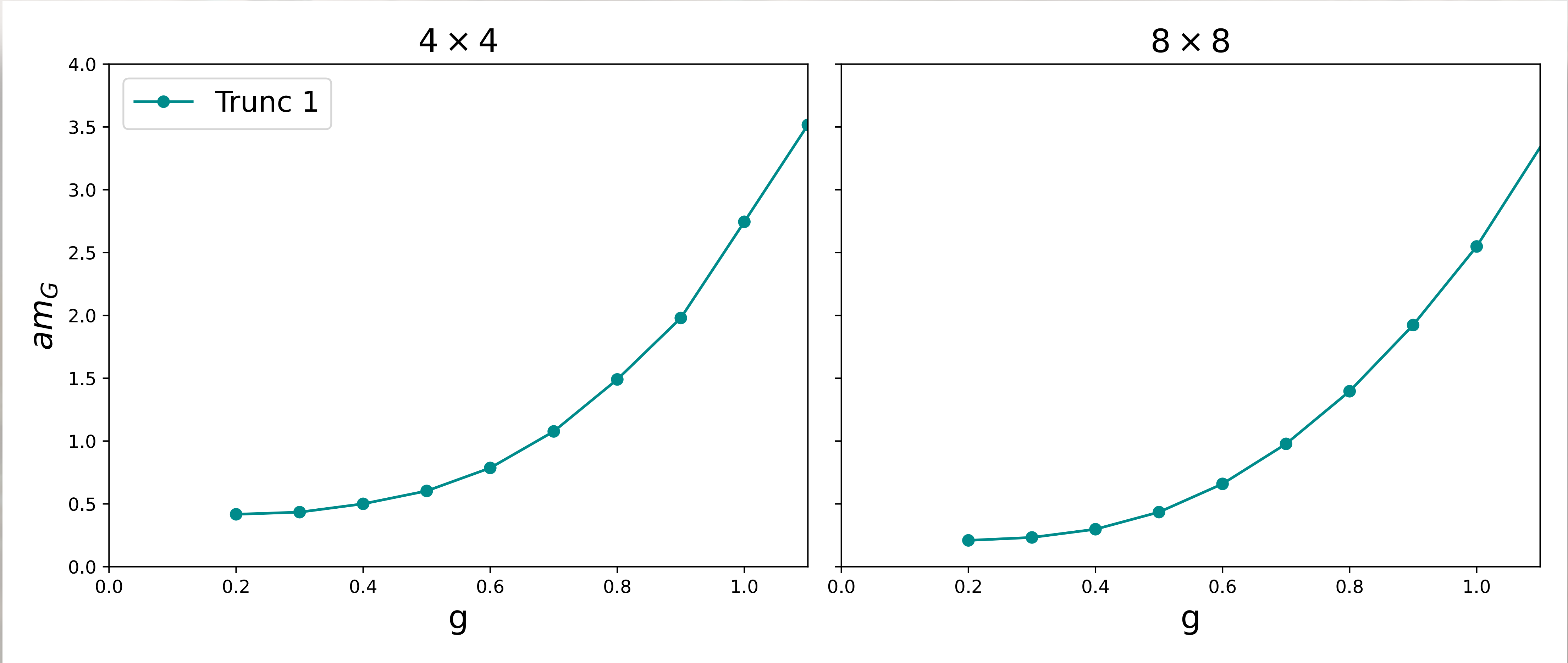
	$(1, 1, 1) \ 10 \times 10$	$(1, 2, 1) \ 10 \times 10$	$(2, 2, 2) \ 10 \times 10$ at order $1/N_c$
Qubits	100	100	500
T	64,600	72,700	9.4×10^8

For 3+1D with 10 lattice sites per dimension

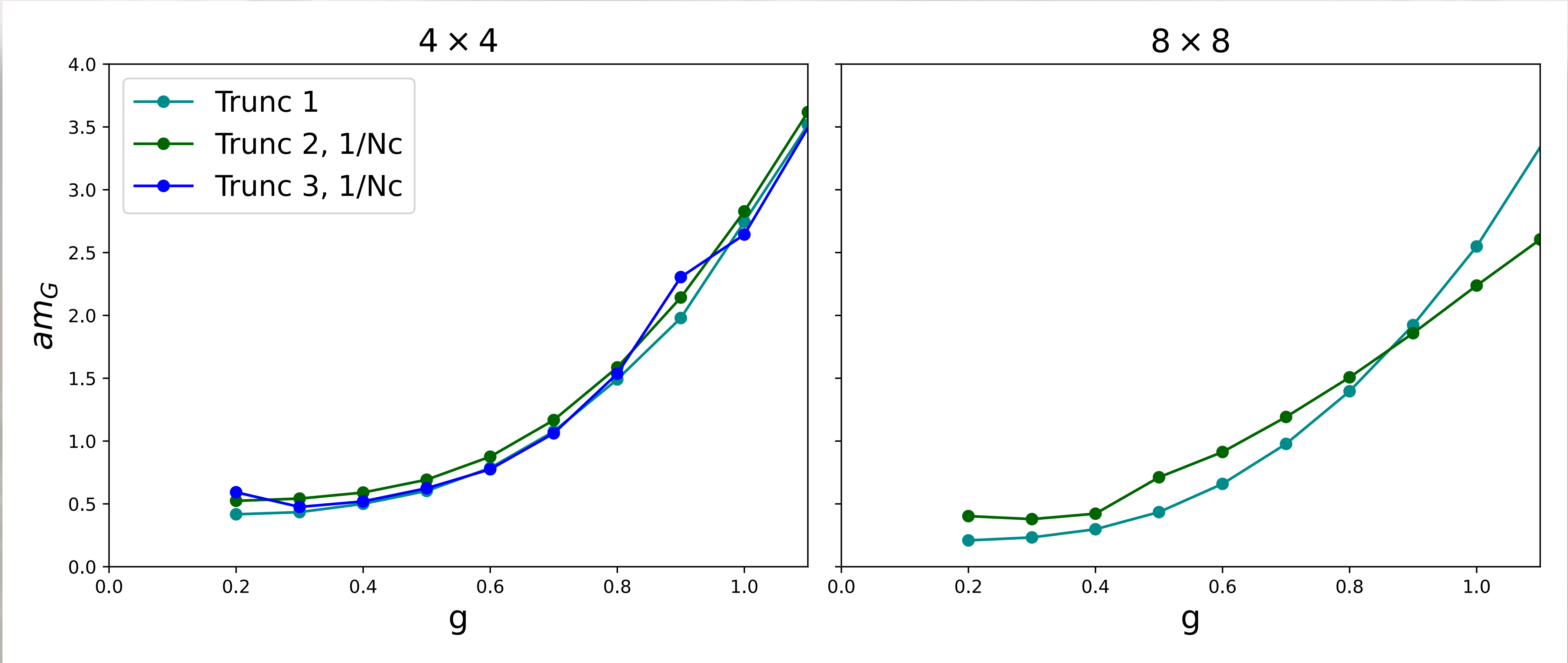
	$(1, 1, 1) \ 10 \times 10 \times 10$	$(1, 2, 1) \ 10 \times 10 \times 10$	$(2, 2, 2) \ 10 \times 10 \times 10$ at order $1/N_c$
Qubits	3,000	3,000	12,000
T	1.79×10^7	2.3×10^8	2.8×10^{10}

2+1D simulations possible with scientifically relevant quantum computers, while 3+1D requires production scale quantum computers

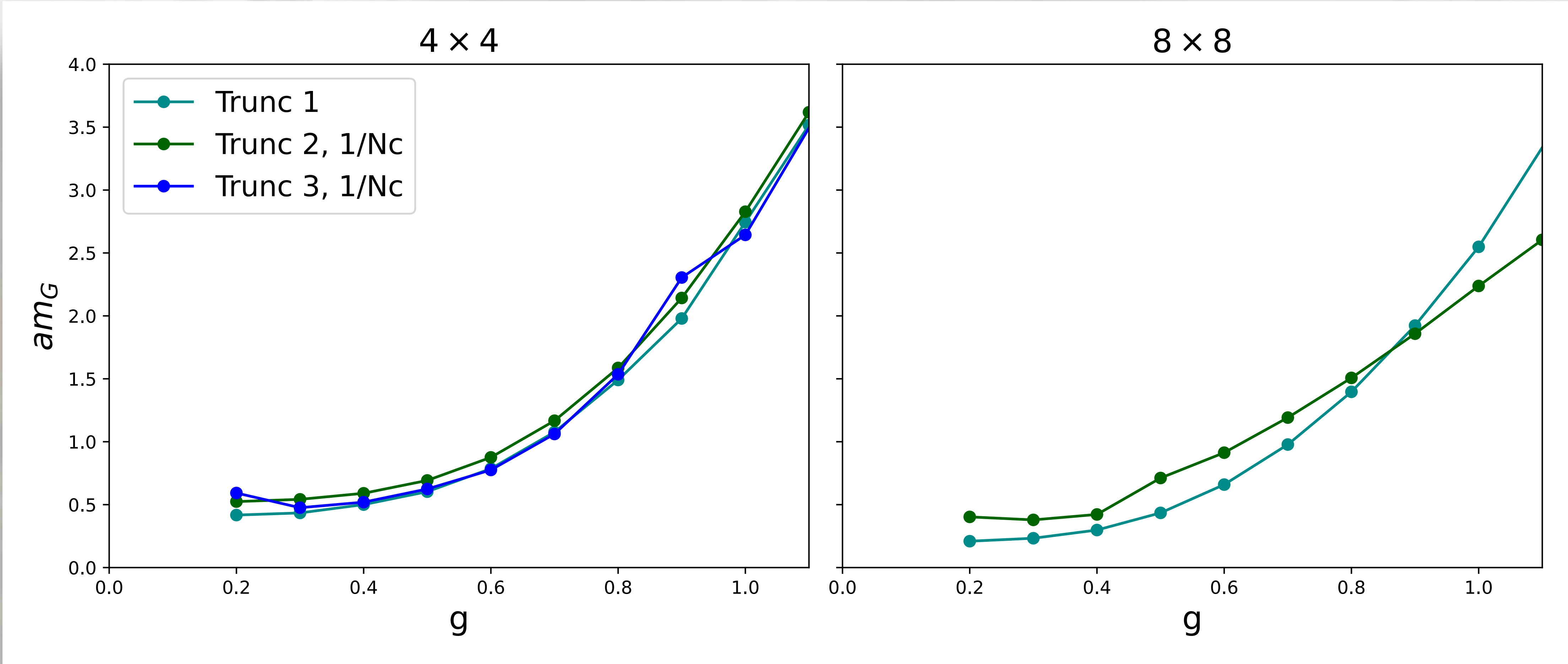
Using tensor network simulation calculated glueball mass as a function of coupling constant. Found unexpectedly good convergence down to small values of g



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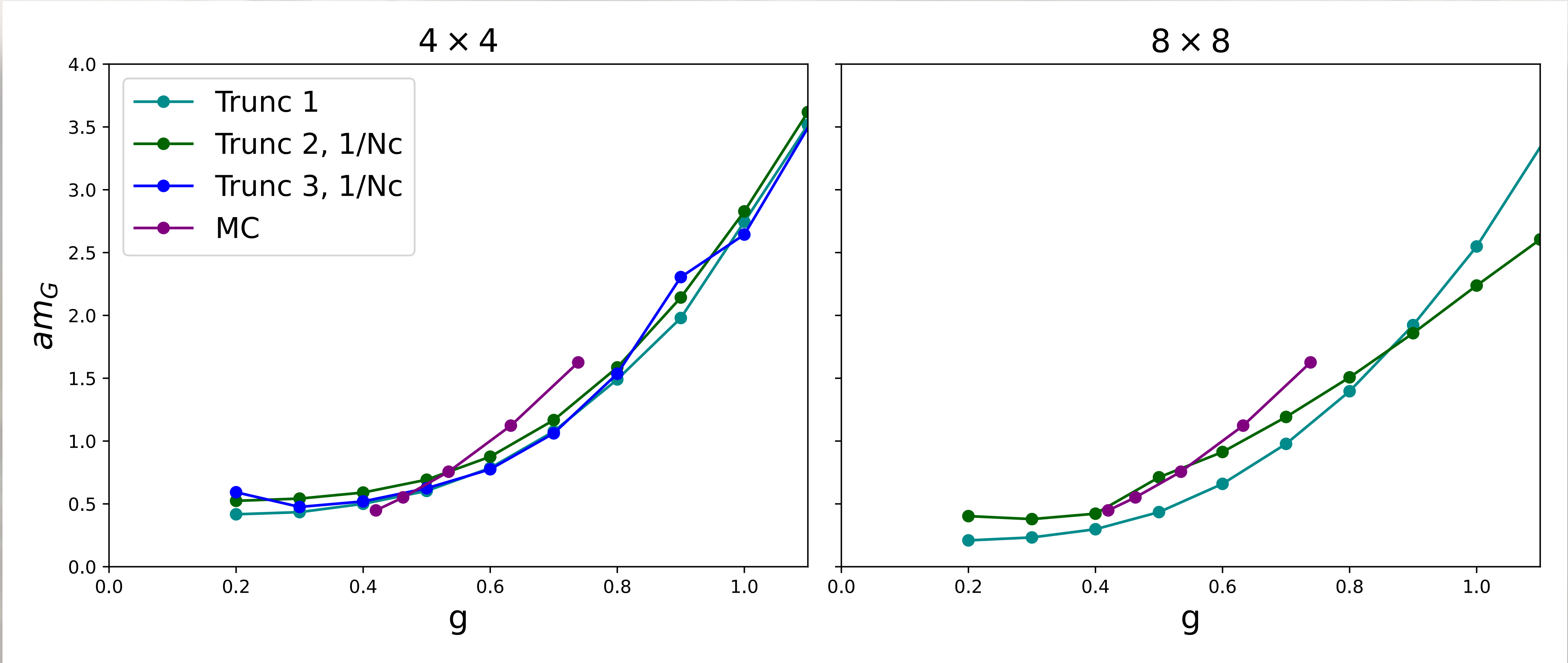


Unexpectedly good convergence and small $1/N_c$ effects.

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Using tensor network simulation calculated glueball mass as a function of coupling constant. Found unexpectedly good convergence down to small values of g

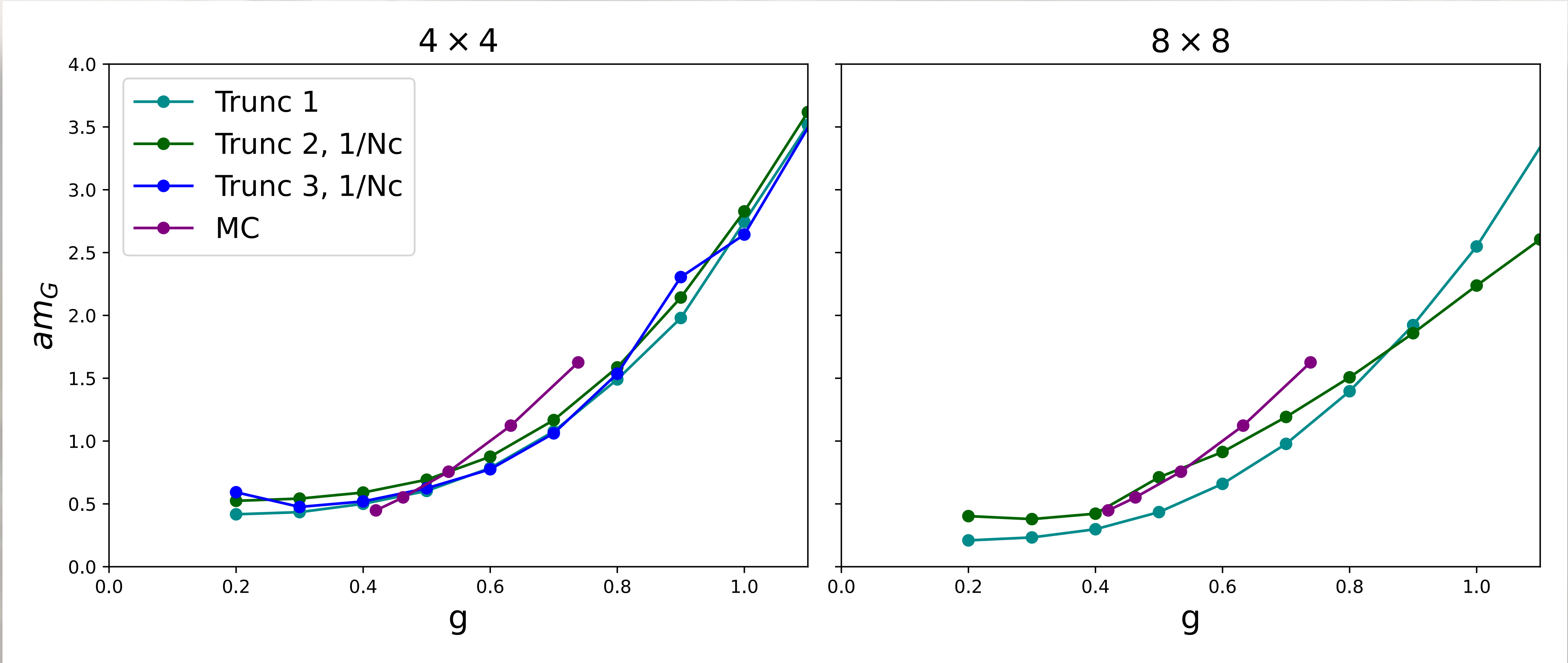


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Using tensor network simulation calculated glueball mass as a function of coupling constant. Found unexpectedly good convergence down to small values of g



Surprisingly good agreement with results from traditional MC calculation

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Have recently extended our results to include fermions. Gives more complicated Hamiltonian, but still much more tractable than full QCD

Large N_c Truncations for $SU(N_c)$ Lattice Yang-Mills Theory with Fermions

Neel S. Modi ^{1,2} Anthony N. Ciavarella ² Jad C. Halimeh ^{3,4,5,6} and Christian W. Bauer ²

¹*Leinweber Institute for Theoretical Physics and Department of Physics,
University of California, Berkeley, Berkeley, CA 94720, USA*

²*Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

³*Department of Physics and Arnold Sommerfeld Center for Theoretical Physics (ASC),
Ludwig Maximilian University of Munich, 80333 Munich, Germany*

⁴*Max Planck Institute of Quantum Optics, 85748 Garching, Germany*

⁵*Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany*

⁶*Department of Physics, College of Science, Kyung Hee University, Seoul 02447, Republic of Korea*

Quantum simulations of quantum chromodynamics (QCD) require a representation of gauge fields and fermions on the finitely many degrees of freedom available on a quantum computer. We introduce a truncation of lattice QCD coupled to staggered fermions that includes (i) a local Krylov truncation that generates allowed basis states; (ii) a maximum allowed electric energy per link; (iii) a limit on the number of fermions per site; and (iv) a truncation in the large N_c scaling of Hamiltonian matrix elements. Explicit truncated Hamiltonians for $1 + 1D$ and $2 + 1D$ lattices are given, and numerical simulations of string-breaking dynamics are performed.

arXiv:2602.02344v1

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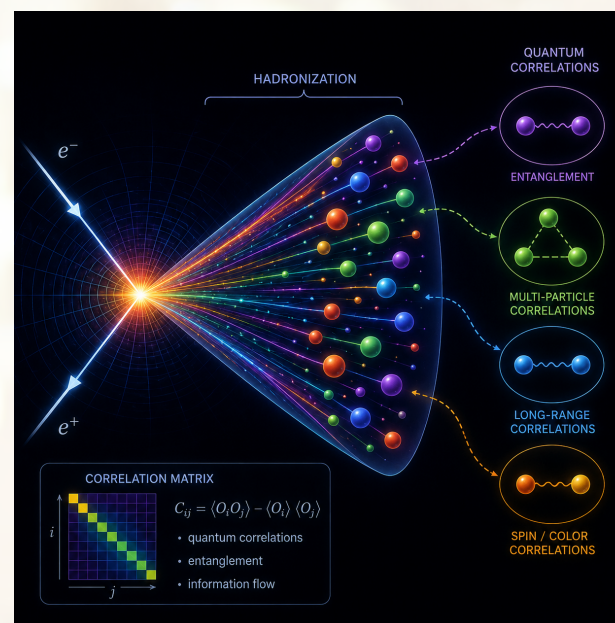
Have recently extended our results to include fermions. Gives more complicated Hamiltonian, but still much more tractable than full QCD

1. Again have several possible truncations, specified by Krylov constraints (how many times a term in the Hamiltonian is allowed to act
2. Transitions can again be different orders in 1/Nc
3. This leads to an efficient formulation of QCD that is amenable to implementation on hardware

Hopping Transition	Matrix Element	Energy (n_e, n_f)	Order in $1/N_c$
$\langle \mathbf{1}, \mathbf{N}, \mathbf{1} H_{\text{hop}}(\ell) \mathbf{1}, \mathbf{1}, \mathbf{1} \rangle$	$\sqrt{N_c}$	(1, 1)	$\mathcal{O}(1)$
$\langle \mathbf{N}, \overline{\mathbf{N}}, \mathbf{N} H_{\text{hop}}(\ell)^\dagger \mathbf{N}, \mathbf{1}, \mathbf{N} \rangle$	$\frac{1}{\sqrt{N_c}}$	(1, 1)	$\mathcal{O}(1/N_c)$
$\langle \mathbf{N}, \mathbf{N}, \mathbf{1} H_{\text{hop}}(\ell) \mathbf{N}, \mathbf{1}, \mathbf{1} \rangle$	$\sqrt{N_c - 1}$	(1, 2)	$\mathcal{O}(1)$
$\langle \mathbf{1}, \mathbf{N}, \mathbf{N} H_{\text{hop}}(\ell) \mathbf{1}, \mathbf{1}, \mathbf{N} \rangle$	$\sqrt{N_c - 1}$	(1, 2)	$\mathcal{O}(1)$
$\langle \mathbf{N}, \mathbf{N}, \mathbf{N} H_{\text{hop}}(\ell) \mathbf{N}, \mathbf{1}, \mathbf{N} \rangle$	$\frac{N_c - 1}{\sqrt{N_c}}$	(1, 2)	$\mathcal{O}(1)$
$\langle \mathbf{N}, \mathbf{Ad}, \mathbf{N} H_{\text{hop}}(\ell) \mathbf{N}, \overline{\mathbf{N}}, \mathbf{N} \rangle$	$\sqrt{\frac{N_c^2 - 1}{N_c}}$	(2, 1)	$\mathcal{O}(1)$
$\langle \mathbf{Ad}, \mathbf{Ad}, \mathbf{Ad} H_{\text{hop}}(\ell)^\dagger \mathbf{Ad}, \mathbf{N}, \mathbf{Ad} \rangle$	$\sqrt{\frac{N_c}{N_c^2 - 1}}$	(2, 1)	$\mathcal{O}(1/N_c)$
$\langle \overline{\mathbf{N}}, \mathbf{A}^2, \overline{\mathbf{N}} H_{\text{hop}}(\ell) \overline{\mathbf{N}}, \mathbf{N}, \overline{\mathbf{N}} \rangle$	$\sqrt{\frac{N_c - 1}{2}}$	(2, 1)	$\mathcal{O}(1)$
$\langle \mathbf{A}^2, \overline{\mathbf{A}^2}, \mathbf{A}^2 H_{\text{hop}}(\ell)^\dagger \mathbf{A}^2, \overline{\mathbf{N}}, \mathbf{A}^2 \rangle$	$\sqrt{\frac{2}{N_c - 1}}$	(2, 1)	$\mathcal{O}(1/N_c)$
$\langle \overline{\mathbf{N}}, \mathbf{S}^2, \overline{\mathbf{N}} H_{\text{hop}}(\ell) \overline{\mathbf{N}}, \mathbf{N}, \overline{\mathbf{N}} \rangle$	$\sqrt{\frac{N_c + 1}{2}}$	(2, 1)	$\mathcal{O}(1)$
$\langle \mathbf{S}^2, \overline{\mathbf{S}^2}, \mathbf{S}^2 H_{\text{hop}}(\ell)^\dagger \mathbf{S}^2, \overline{\mathbf{N}}, \mathbf{S}^2 \rangle$	$\sqrt{\frac{2}{N_c + 1}}$	(2, 1)	$\mathcal{O}(1/N_c)$



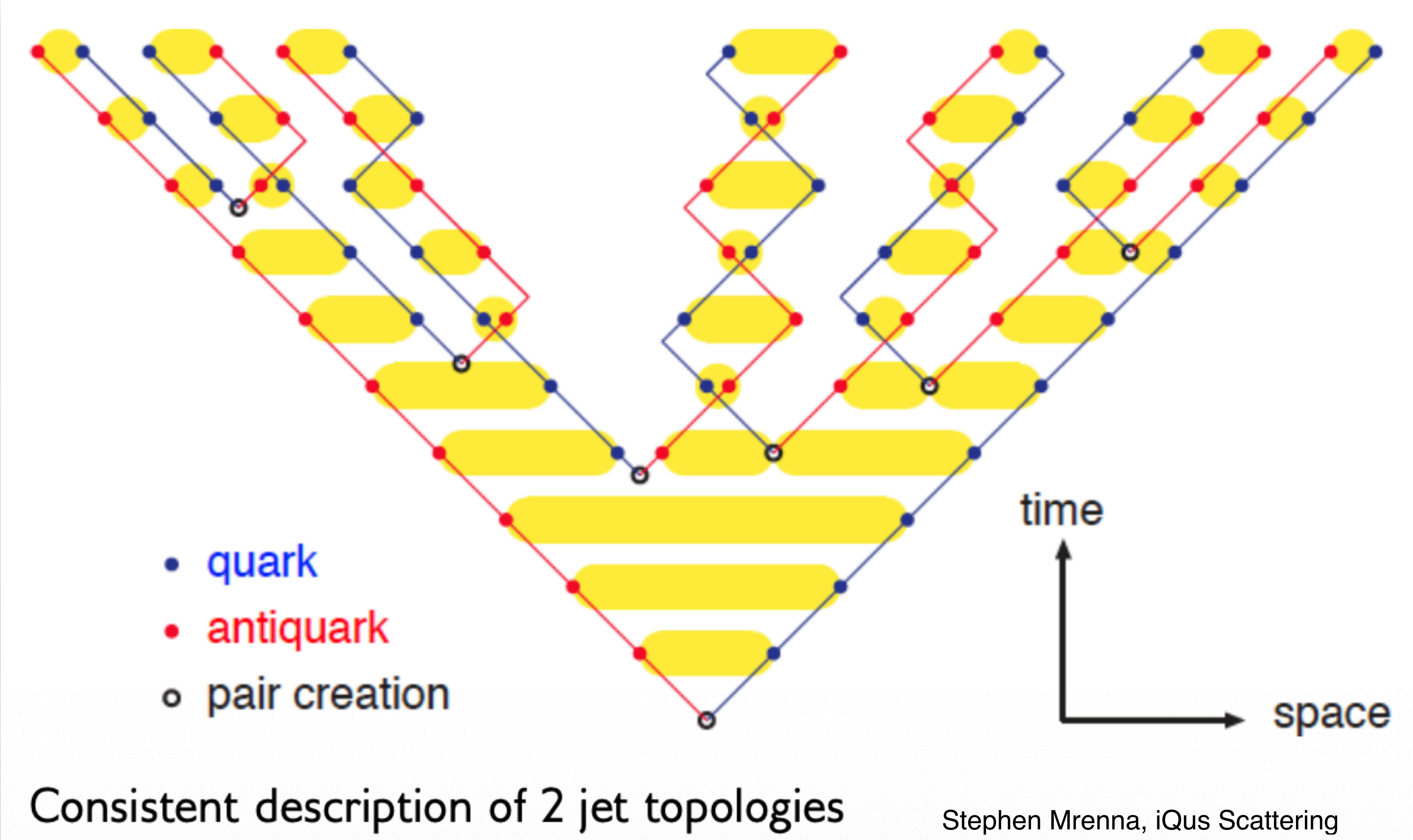
Study quantum correlations in hadronization



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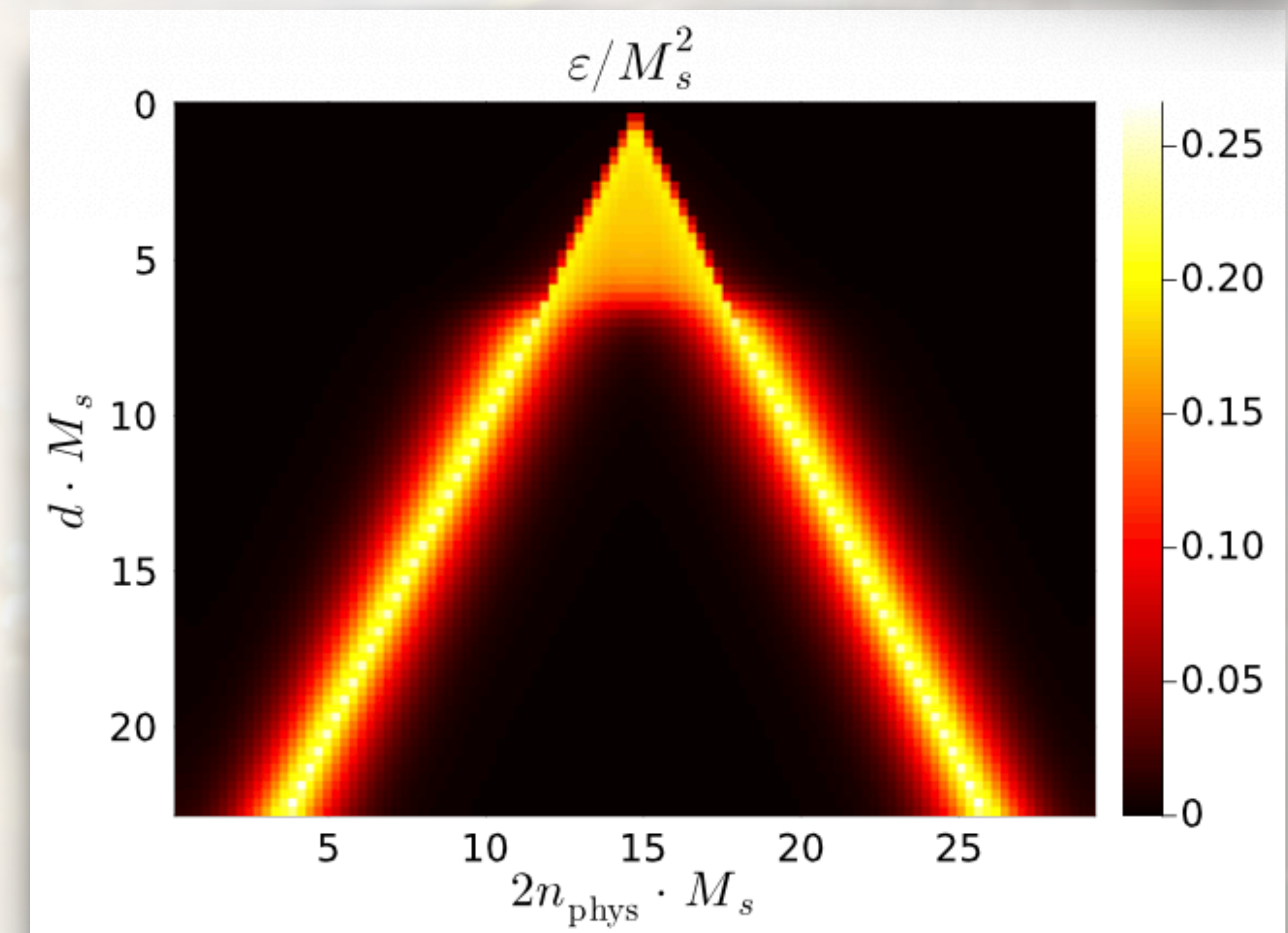
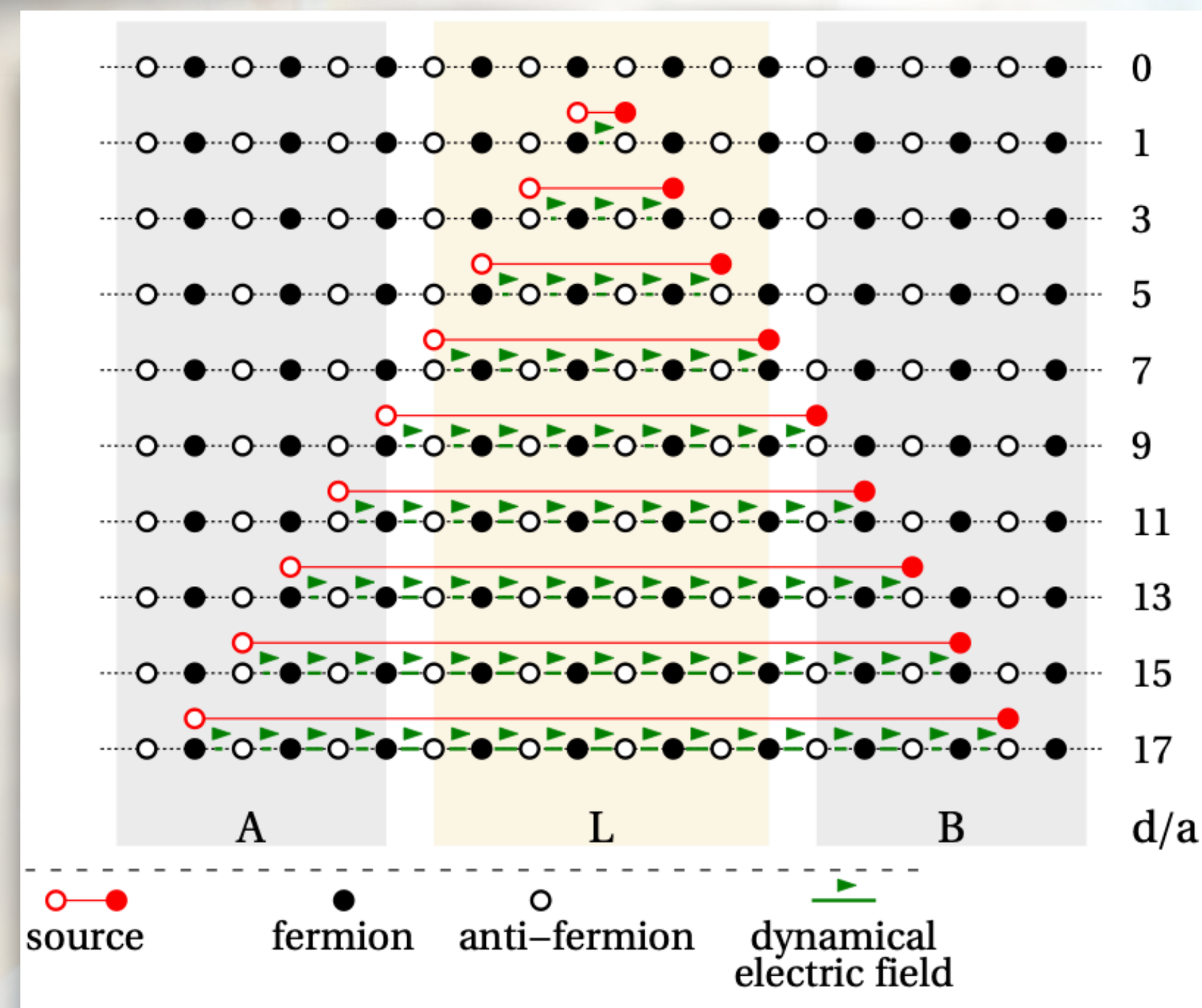
The hadronization that turns partons into hadrons can be modeled by the breaking of color strings that end on color charges (quarks)



The breaking of strings can be studied using Hamiltonian simulations, giving insight into the hadronization process for the first time

Simplest theory exhibiting strings and string breaking is so-called Schwinger Model

$$H = \frac{1}{4a} \sum_n (X_n X_{n+1} + Y_n Y_{n+1}) + \frac{m}{2} \sum_n (-1)^n (1 - Z_n) + \frac{g^2 a}{2} \sum_n \hat{L}_n^2 \quad \hat{L}_n = \sum_{k \leq n} \frac{Z_k + (-1)^k}{2}$$



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Classical models can not include intrinsically quantum correlations, which we start to see are necessary for the required physics

The Quantum Complexity of String Breaking in the Schwinger Model

Sebastian Grieninger ^{1,*} Martin J. Savage ^{1,†} and Nikita A. Zemlevskiy ^{1,‡}

¹*InQubator for Quantum Simulation (IQuS), Department of Physics,
University of Washington, Seattle, WA 98195, USA*

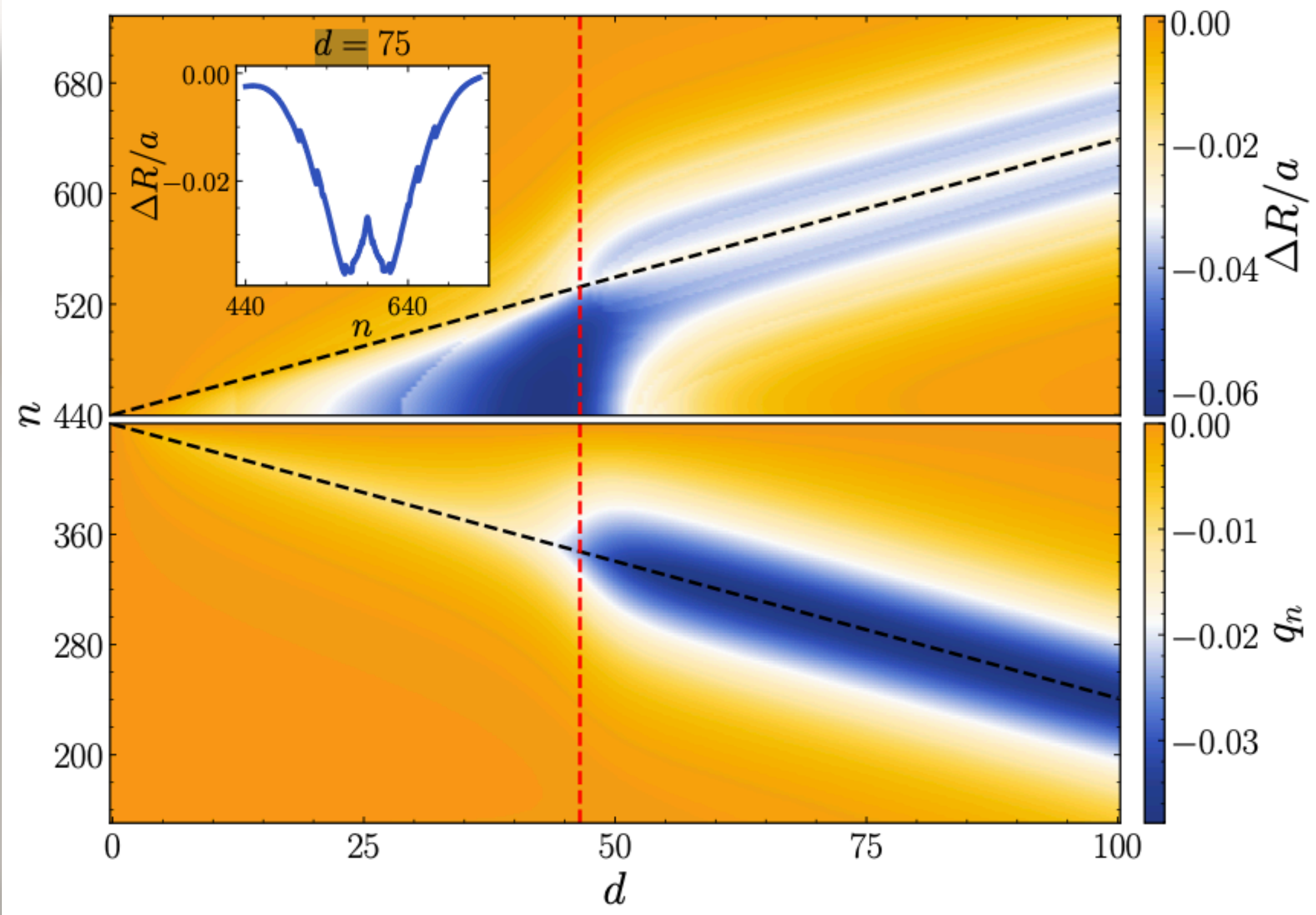
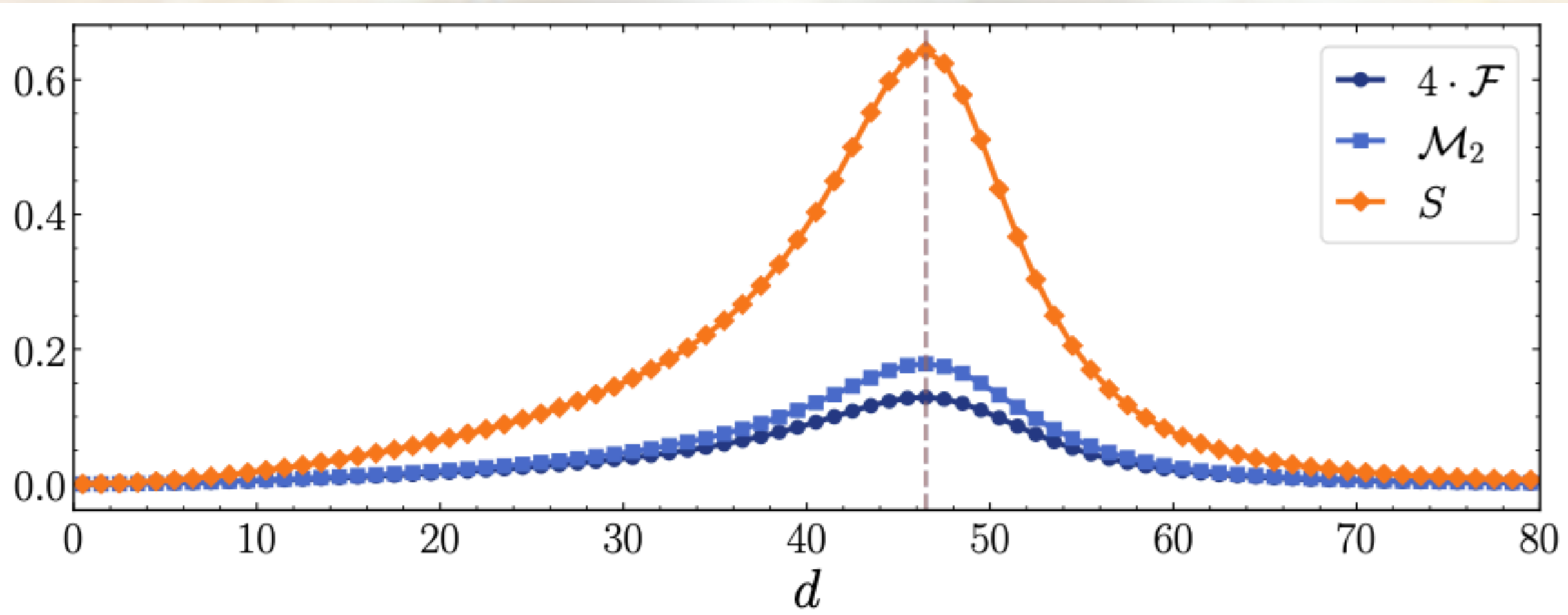
(Dated: April 15, 2026)

String breaking, the process by which flux tubes fragment into hadronic states, is a hallmark of confinement in strongly-interacting quantum field theories. A suite of quantum complexity measures is examined using Matrix Product States to characterize the string breaking process in the 1+1D Schwinger model. We demonstrate the presence of nonlocal quantum correlations along the string that may affect fragmentation dynamics, and show that entanglement and magic offer complementary perspectives on string formation and breaking beyond conventional observables.

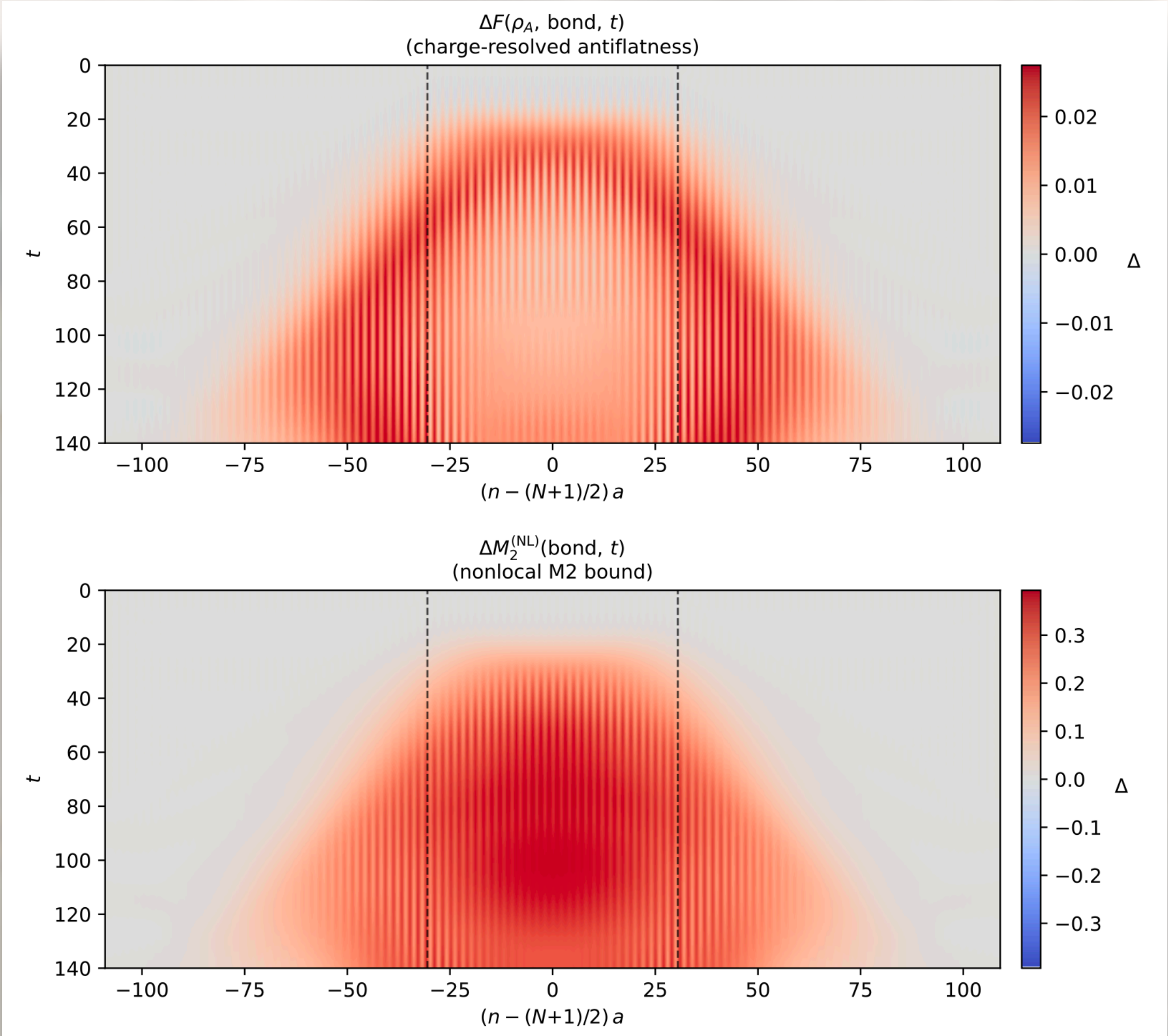
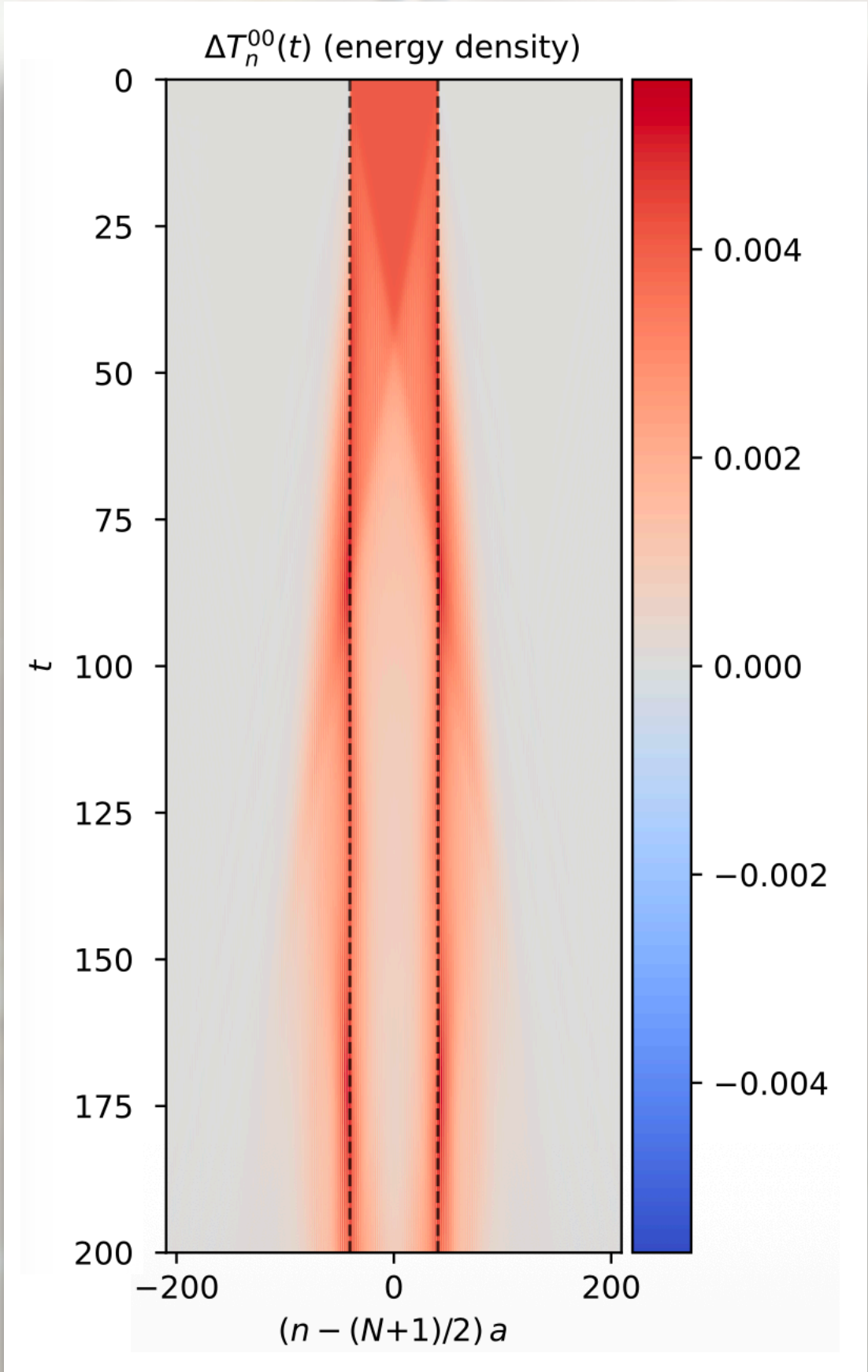
arXiv:2601.08825v2

Classical models can not include intrinsically quantum correlations, which we start to see are necessary for the required physics

Have clear evidence now that intrinsic quantum correlations exists in strings before they break, which shows that quantum computers are necessary for their studies



Have now started a program to study the dynamics of string breaking, and development of intrinsic quantum correlations

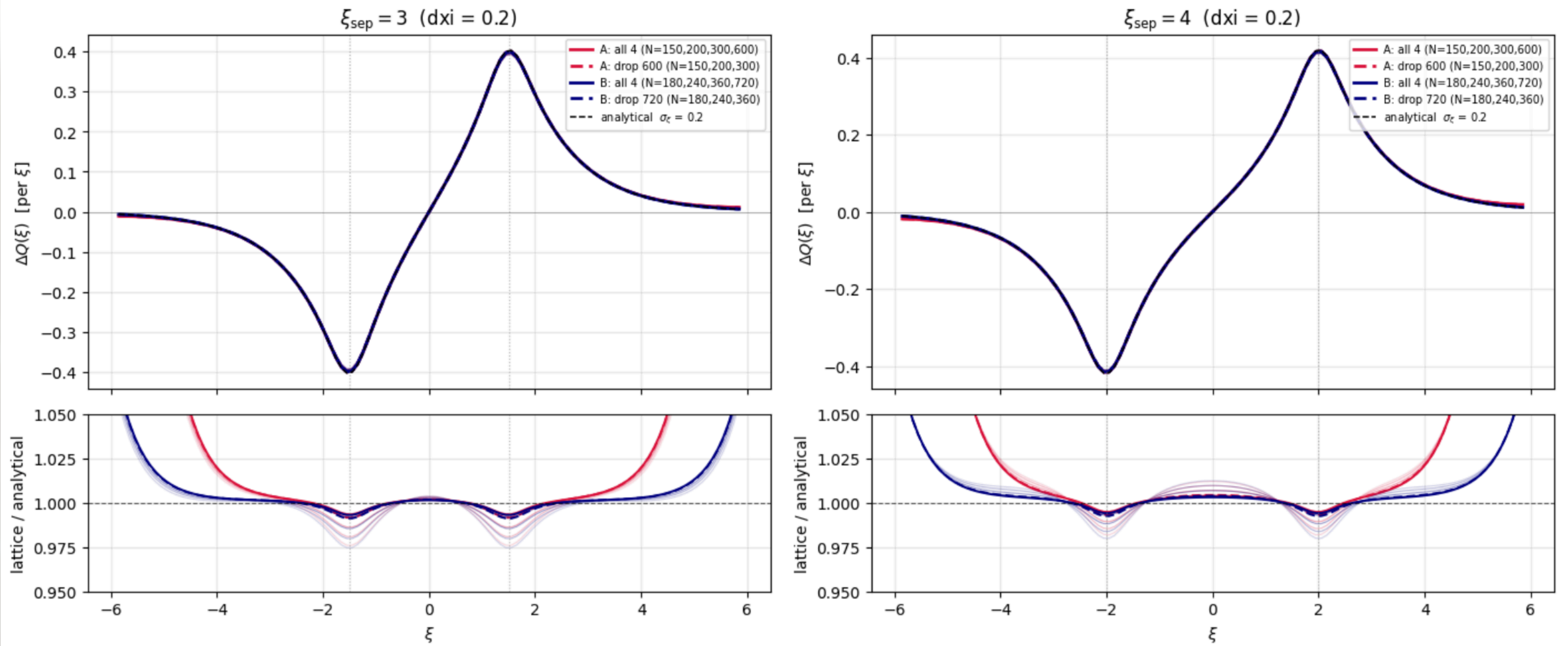


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When making connections with continuum physics, need to go beyond just quoting results for a given lattice calculation by provide systematic uncertainties

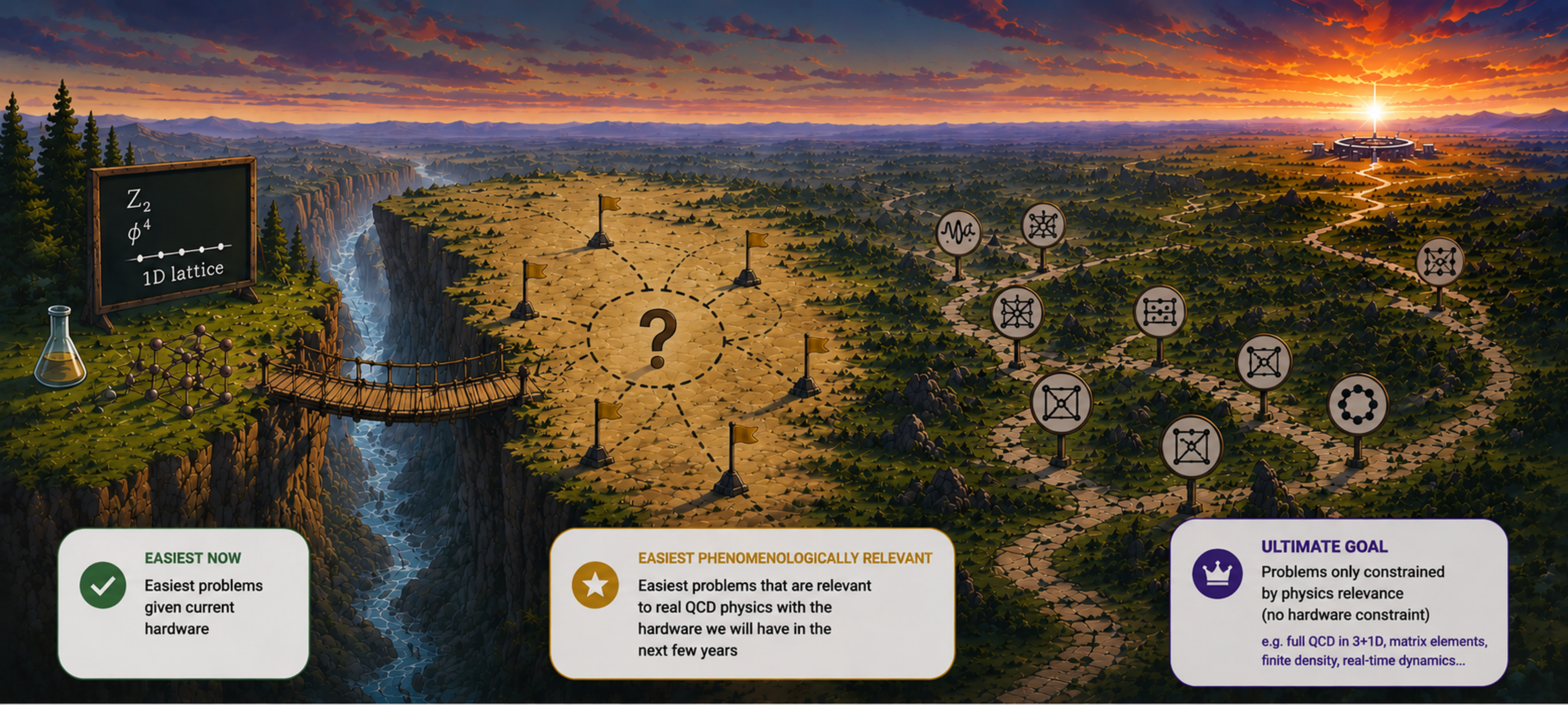
central	statistics	lattice spacing	lattice volume	truncation	Suzuki-Trotter	???
y	Δy_s	Δy_a	Δy_v	Δy_t	Δy_{st}	



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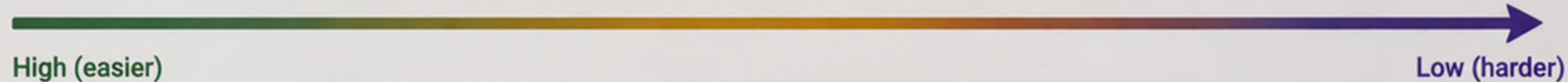


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e.g. full QCD in 3+1D, matrix elements, finite density, real-time dynamics...

Hardware constraint



High (easier)

Low (harder)

HEP has the potential to be one of the most important science cases for quantum simulation

I believe it is important for this community to transition to obtain results that provide real insight into long standing physics questions of HEP



EASIEST NOW

Easiest problems given current hardware



EASIEST PHENOMENOLOGICALLY RELEVANT

Easiest problems that are relevant to real QCD physics with the hardware we will have in the next few years



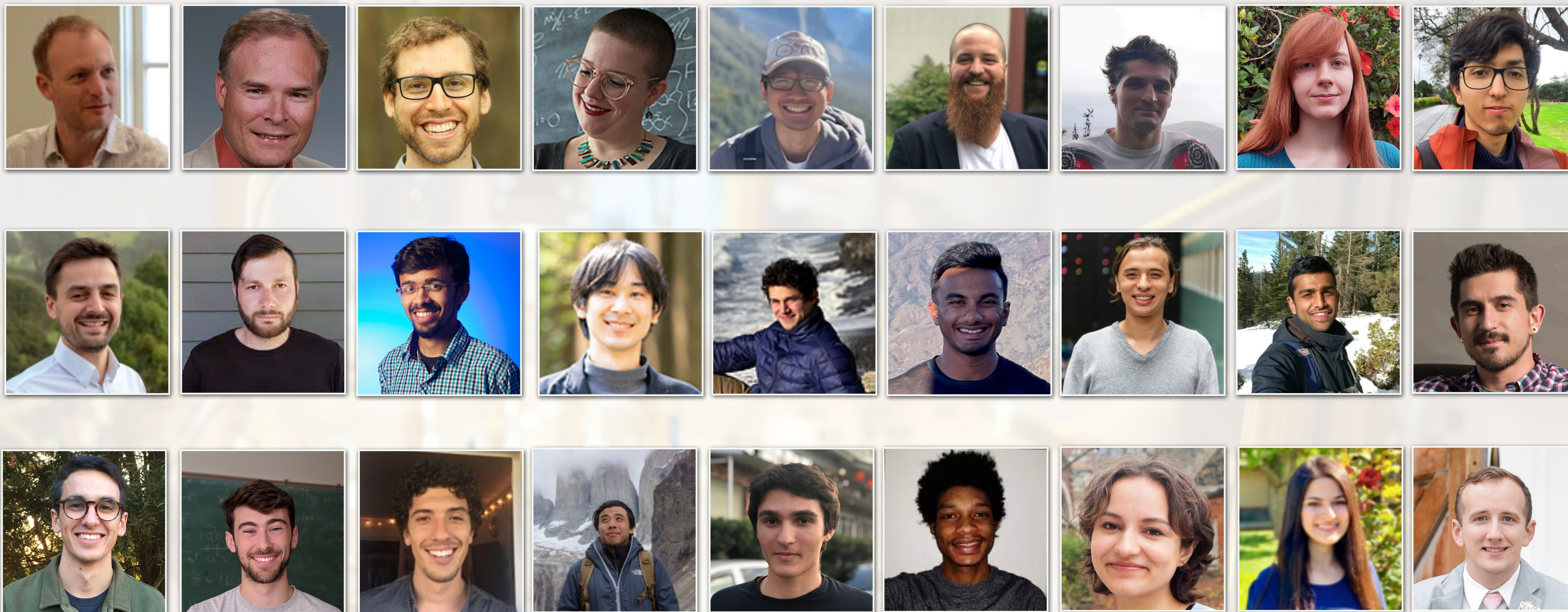
ULTIMATE GOAL

Problems only constrained by physics relevance (no hardware constraint)
e.g. full QCD in 3+1D, matrix elements, finite density, real-time dynamics...

Hardware constraint

High (easier)

Low (harder)



Christian Bauer

Towards experimentally relevant quantum simulations

