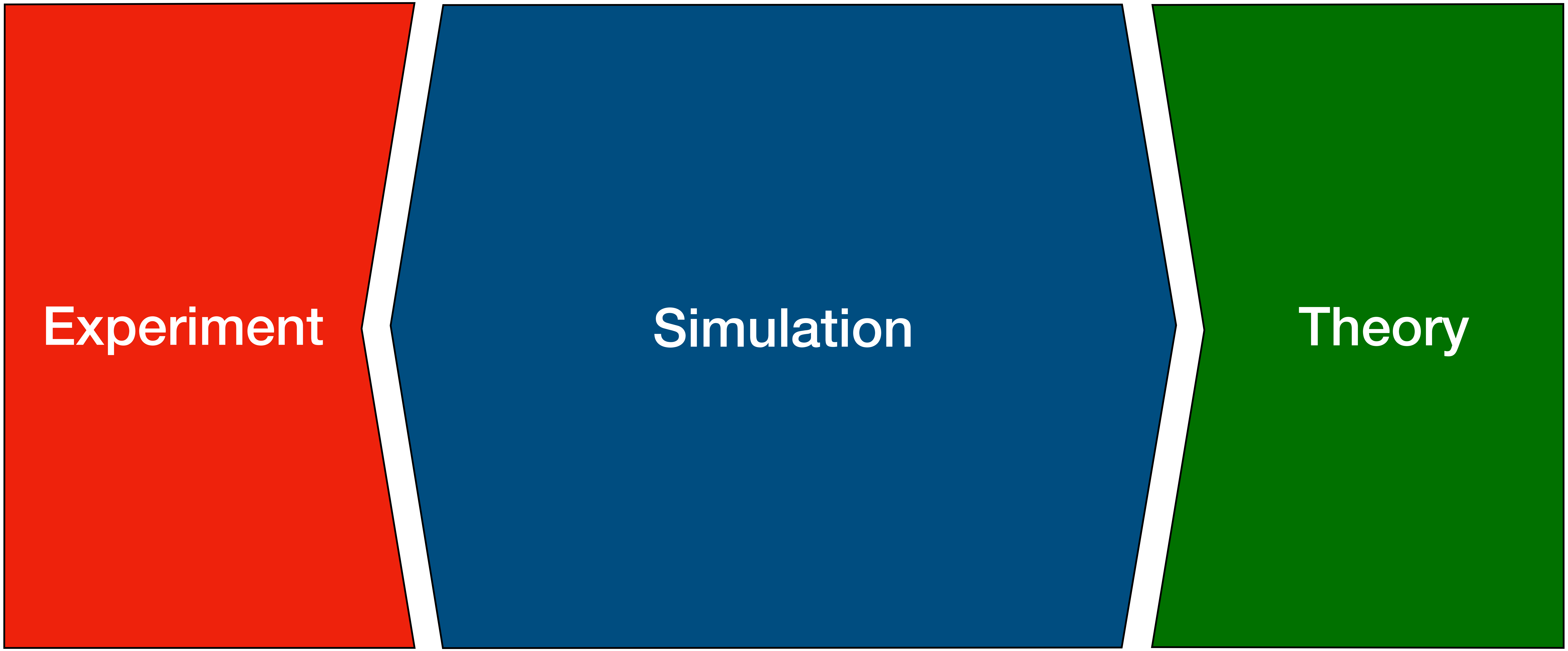
QCD and Quantum Computing

First-principles simulation of non-perturbative physics

Christian Bauer
Theory Group Leader
PI Quantum Computing
Physics Division LBNL


Experiment
Theory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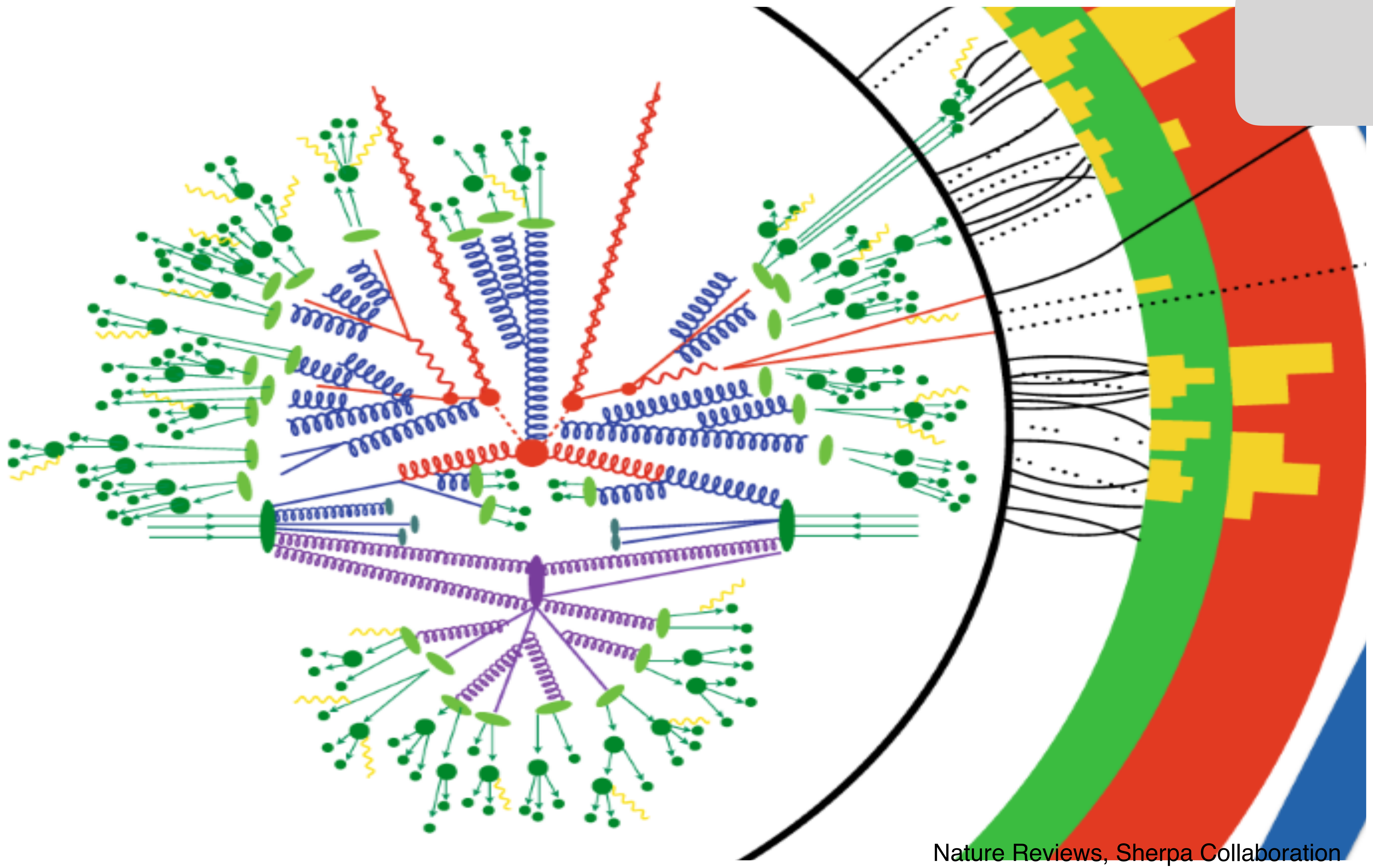
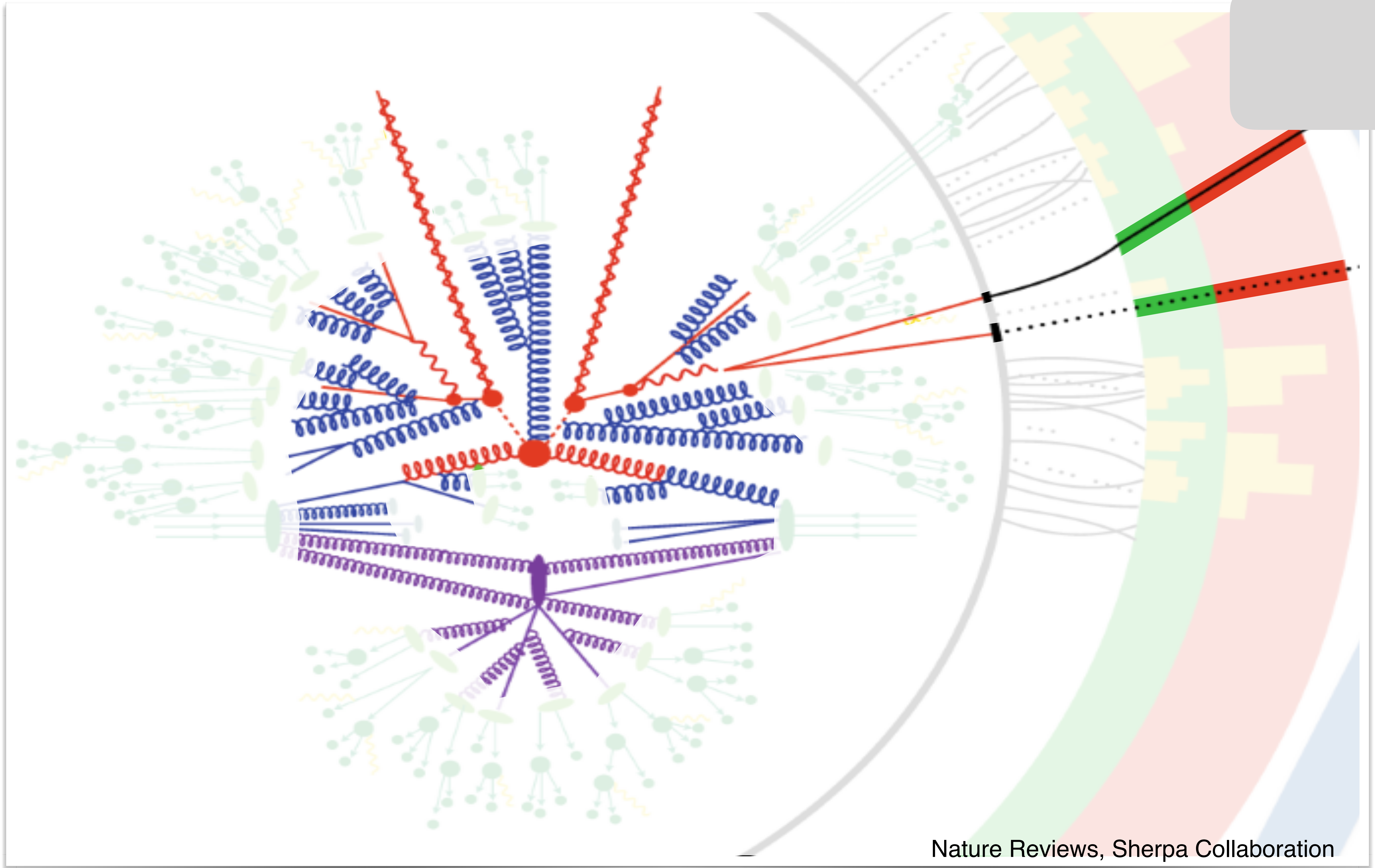


Nature Reviews, Sherpa Collaboration



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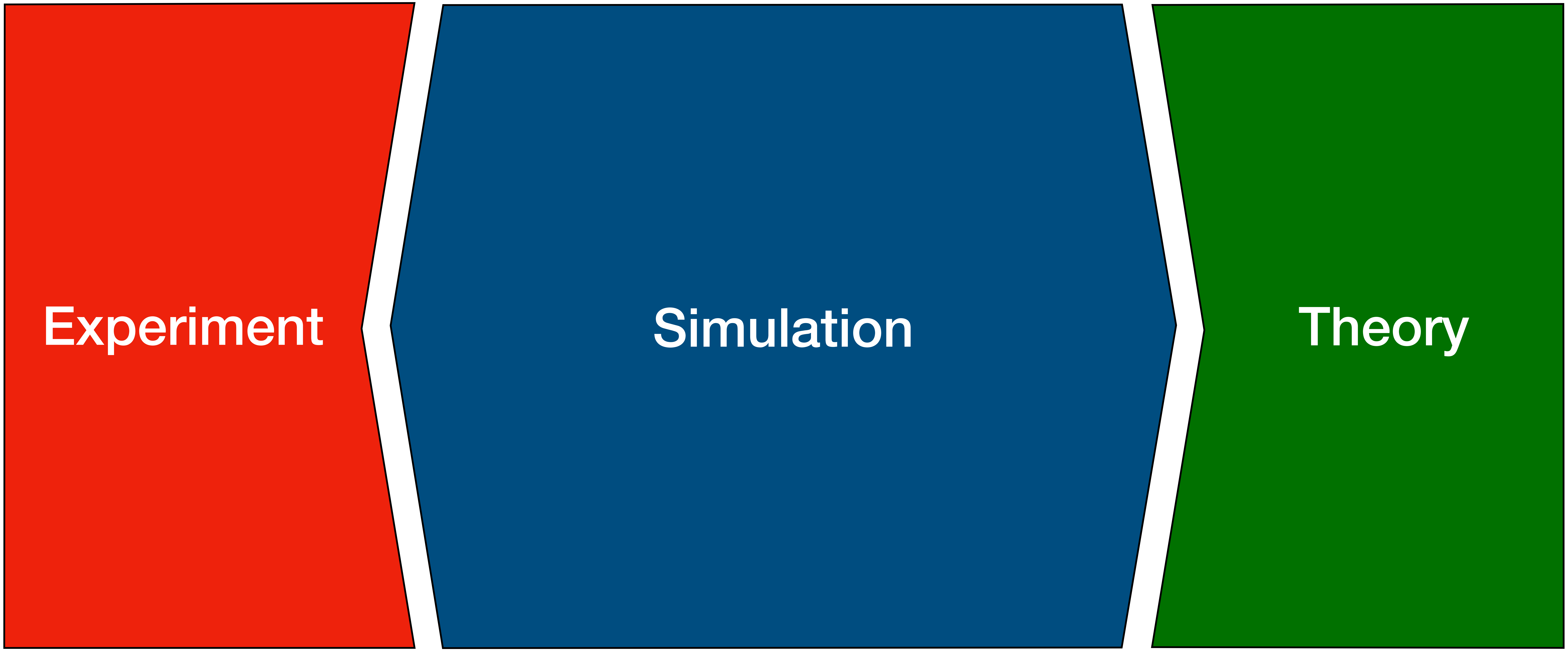
Experiment
Simulation
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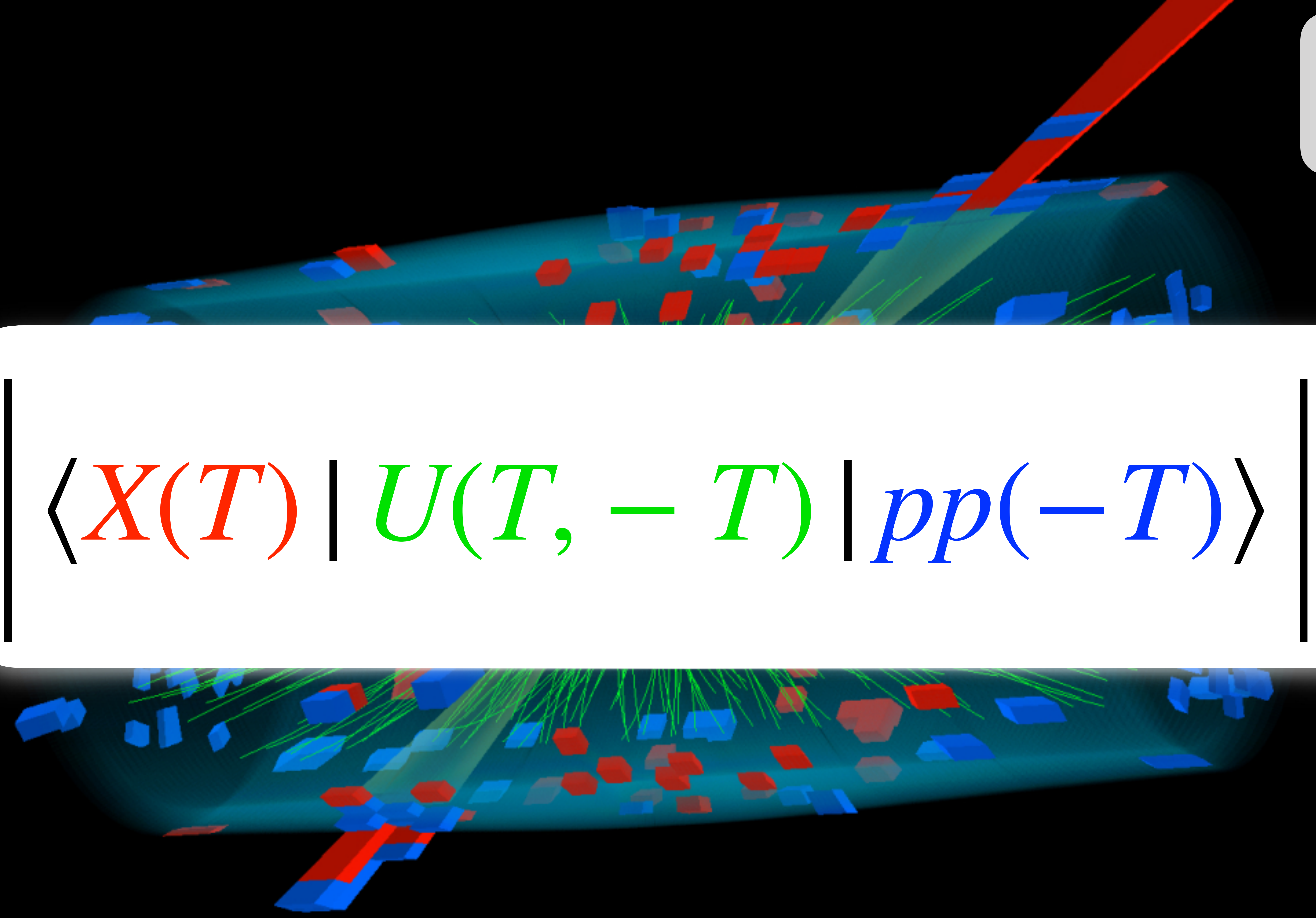
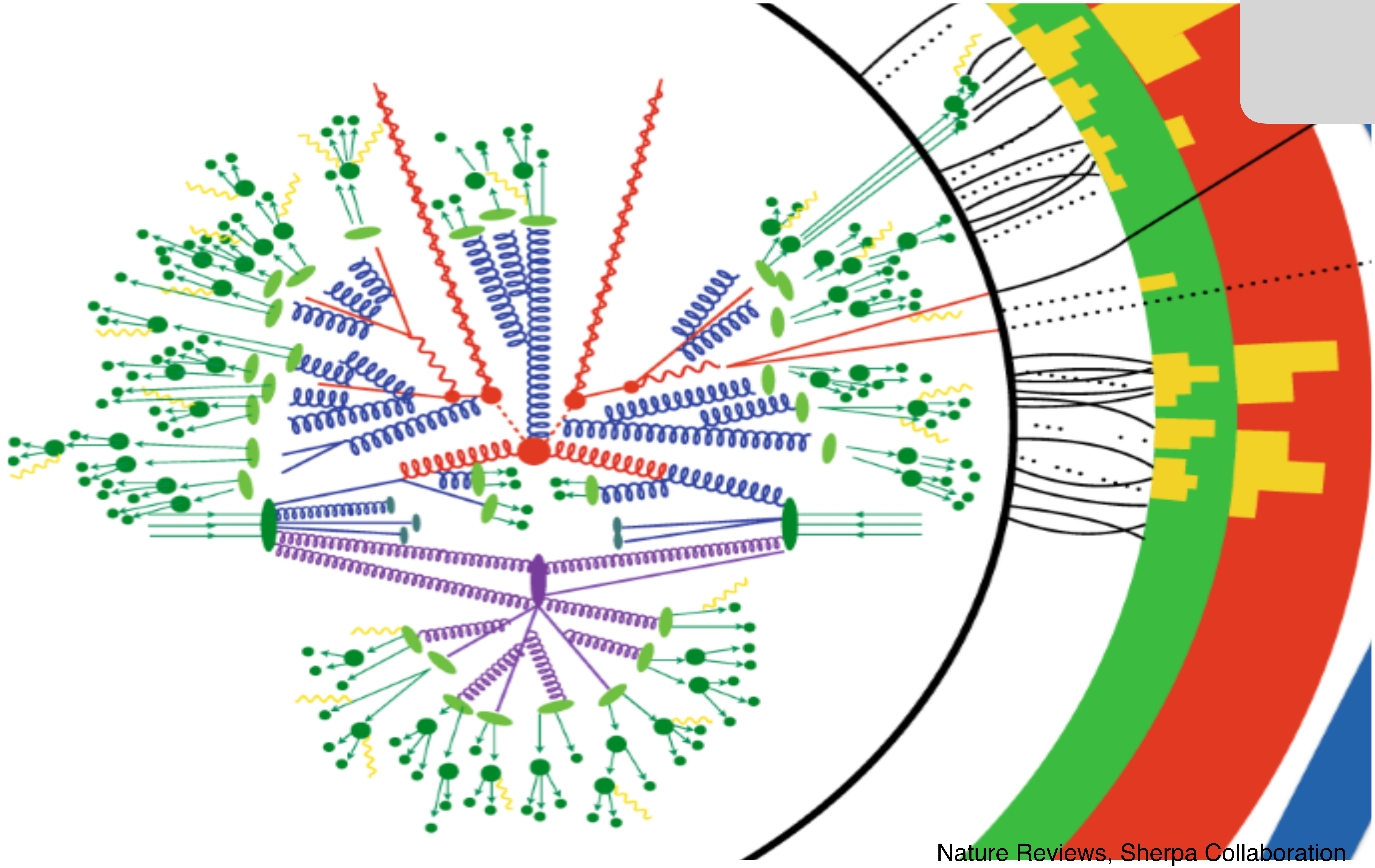
CMS Run/Event 262548/458269



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

CMS Run/Event 262548/458269



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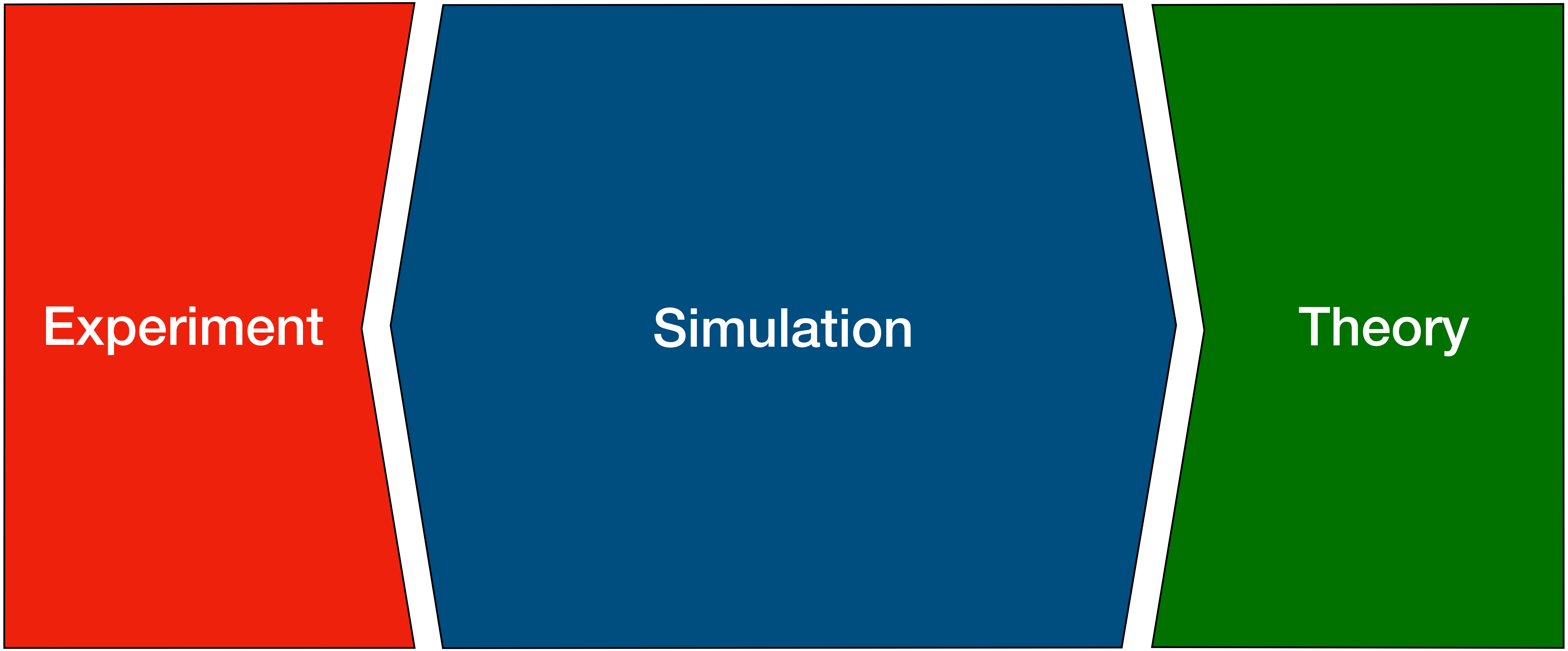
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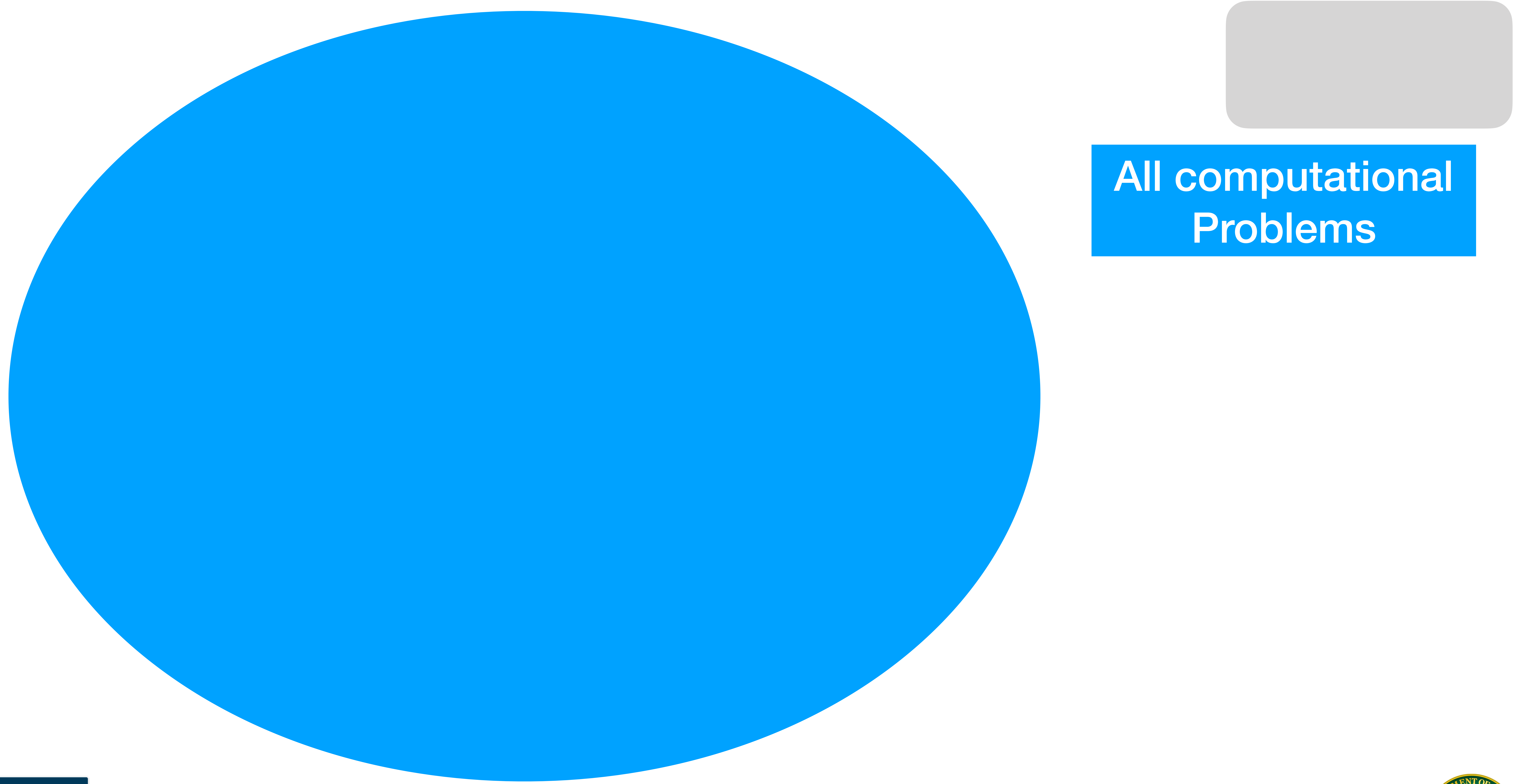
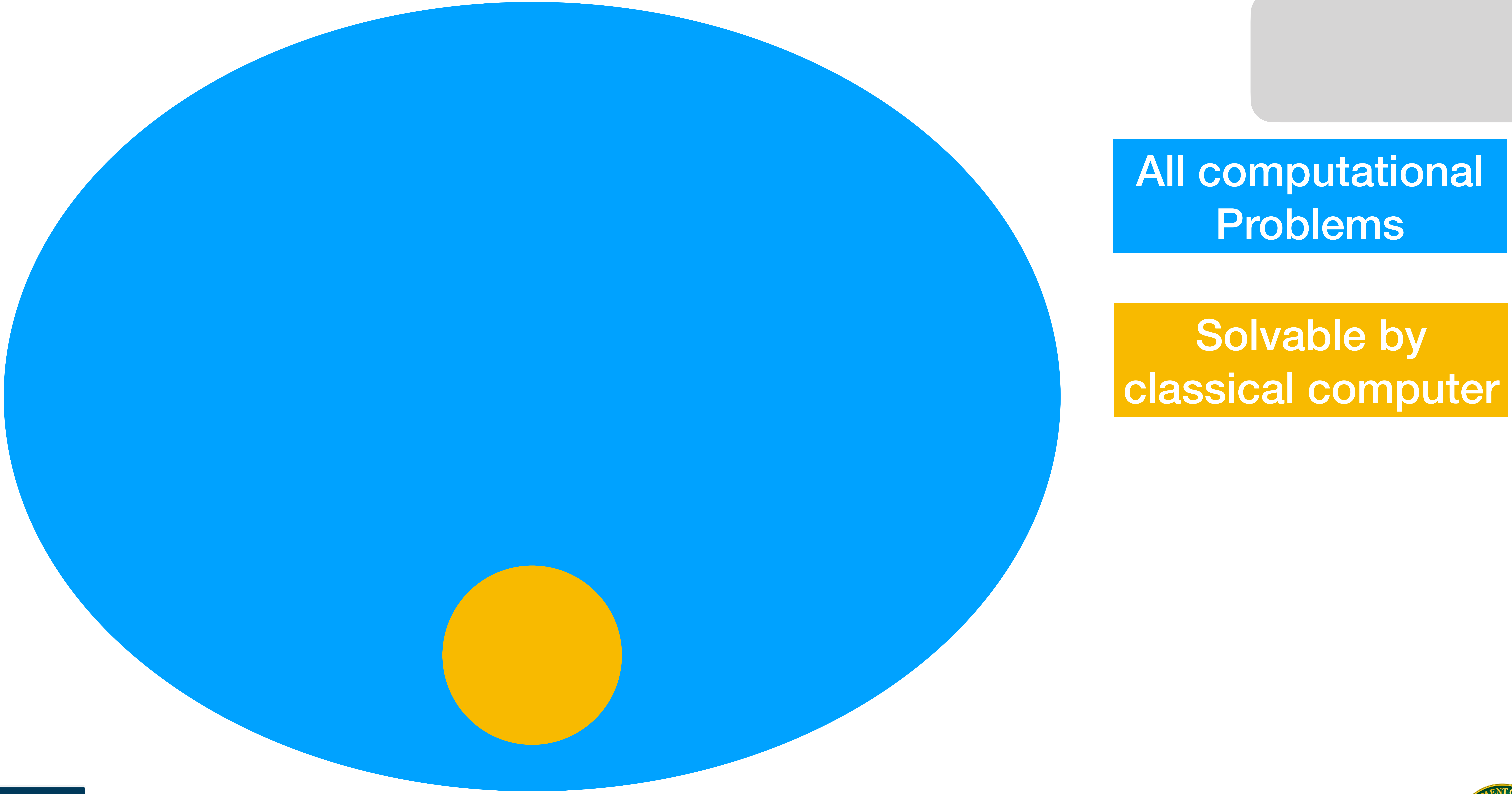
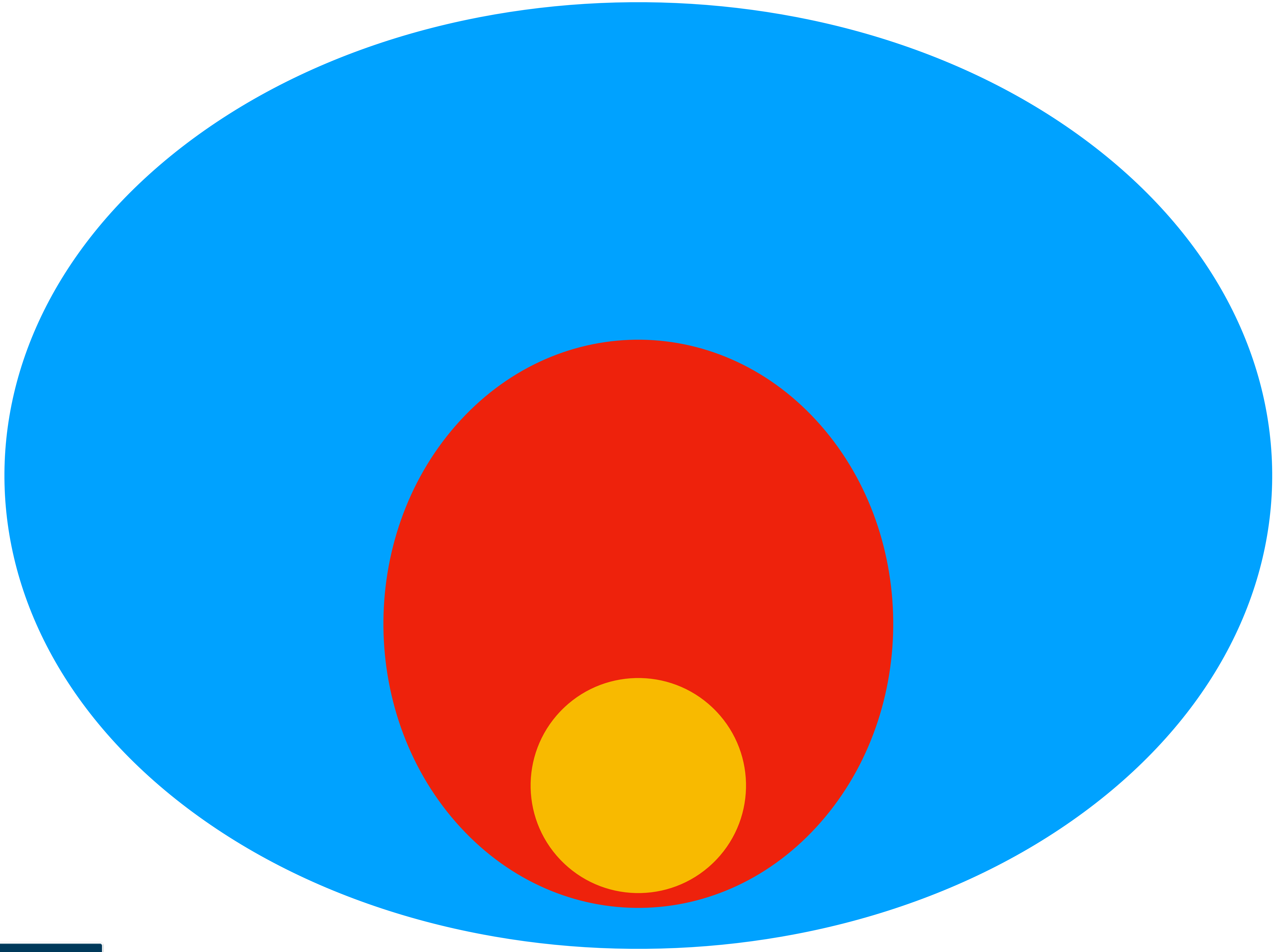

All computational
Problems

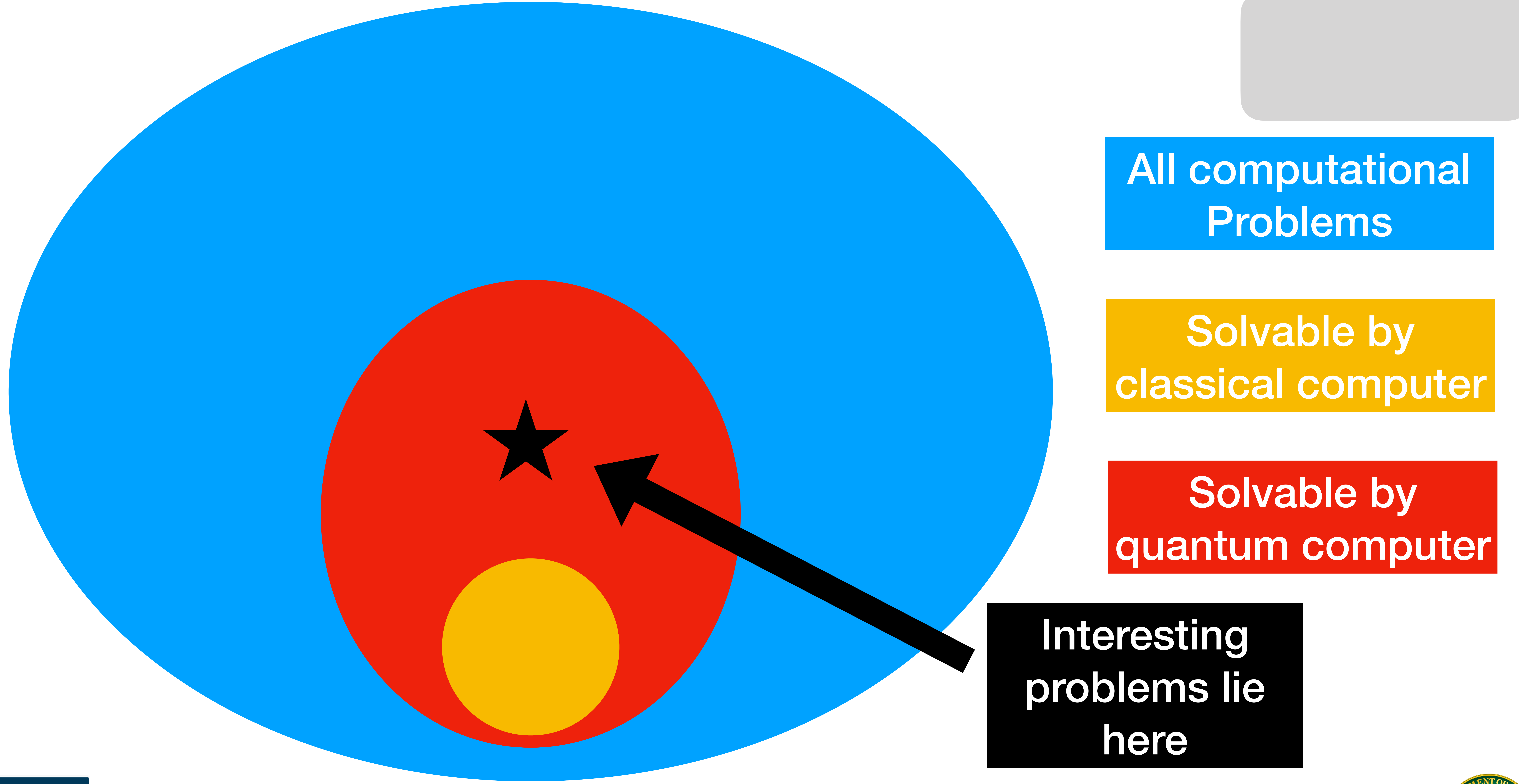

All computational Problems
Solvable by classical computer



All computational Problems

Solvable by classical computer

Solvable by quantum computer


All computational Problems
Solvable by classical computer
Solvable by quantum computer
Interesting problems lie here

All computational Problems

Solvable by classical computer

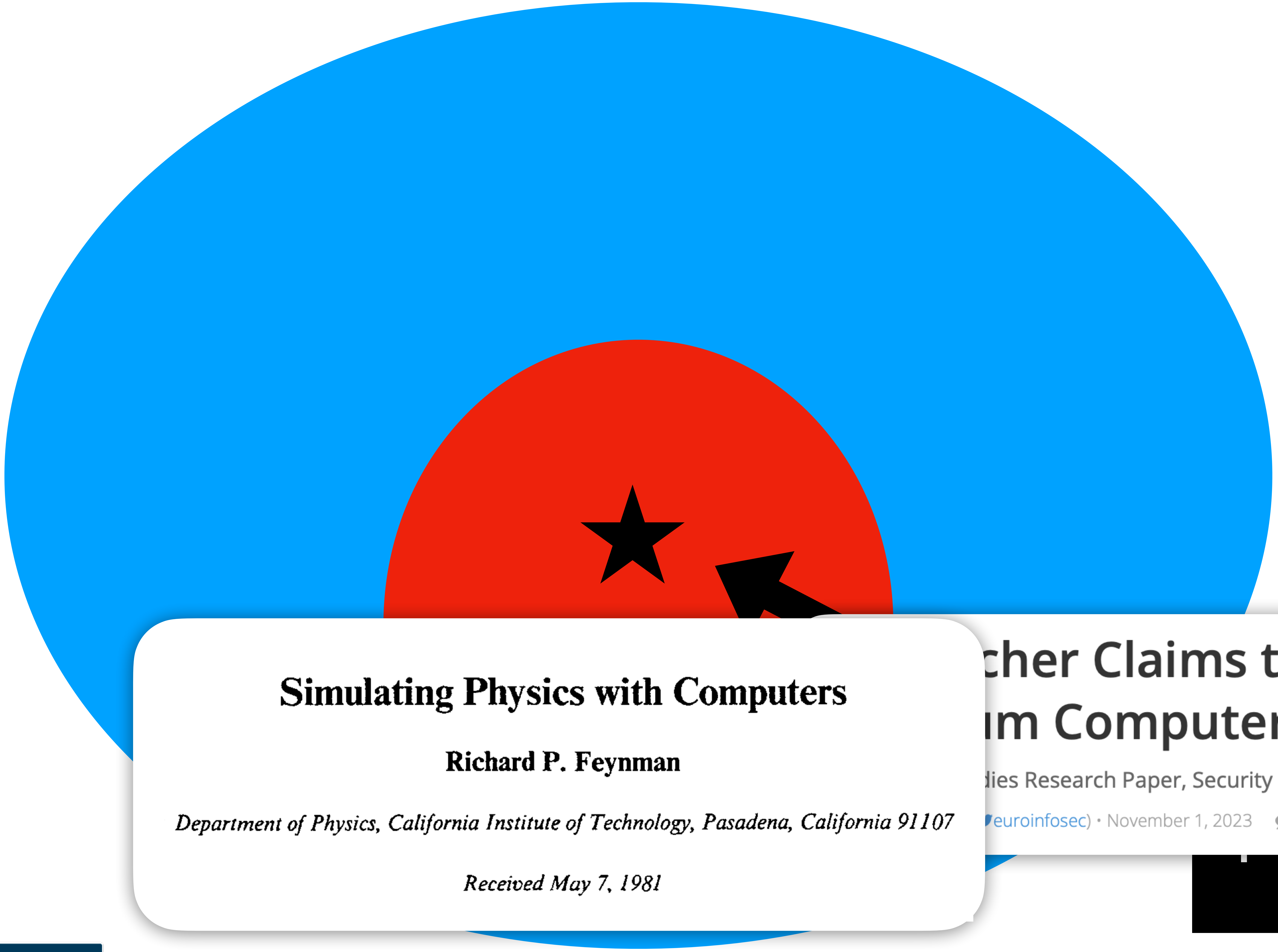
Solvable by

Researcher Claims to Crack RSA-2048 With Quantum Computer

As Ed Gerck Readies Research Paper, Security Experts Say They Want to See Proof

Mathew J. Schwartz (euroinfosec) • November 1, 2023

here



All computational Problems

Solvable by classical computer

Solvable by

Simulating Physics with Computers

Richard P. Feynman

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

Received May 7, 1981

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All computational Problems

Solvable by assical computer

Solvable by

here

There are many HEP problems of this kind
collider physics, neutrino physics, cosmology, early universe physics, quantum gravity etc

Recent review: CWB, Z Davoudi et al, Quantum Simulation for HEP (2204.03381)

Simulating Physics with Computers

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Standard approach to nonperturbative simulations: Lattice Gauge Theory, which performs path integral using Monte-Carlo integration

Requires positive definite integrand, imaginary time

$$e^{iS[\phi_j(x_i))]} \to e^{-S[\phi_j(x_i))]}$$

Can answer many static questions, but calculating dynamics requires real time, not imaginary time

Instead of doing Monte-Carlo simulation of path integral, can try to do time evolution using Schrödinger equation

Go back to the S matrix elements mentioned before

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

All elements in this expression in terms of fields $\phi(x)$

Both position x and field $\phi(x)$ are continuous

Discretizing position x and digitizing field value $\phi(x)$ turn continuous (QFT) problem into discrete (QM) problem

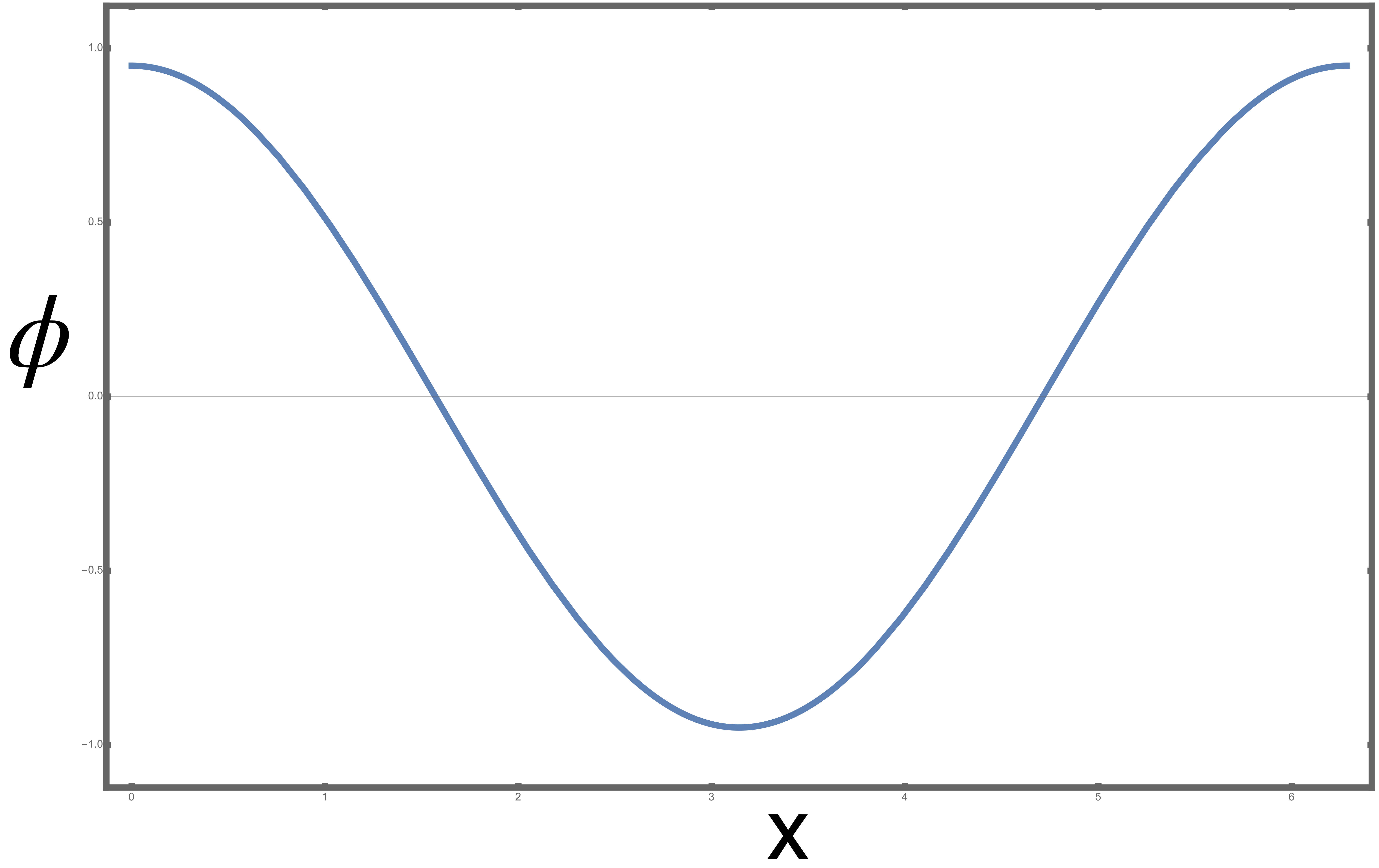
Basic idea is to map the infinite Hilbert space of QFT on a finite dimensional HS making this a QM problem

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

3 basic steps:

1. Create an initial state vector at time (-T) of two proton wave packets
2. Evolve this state forward in time from to time T using the Hamiltonian of the full interacting field theory
3. Perform a measurement of the state

To yield finite-dimensional Hilbert space, have field configurations sample position and field values at discrete points



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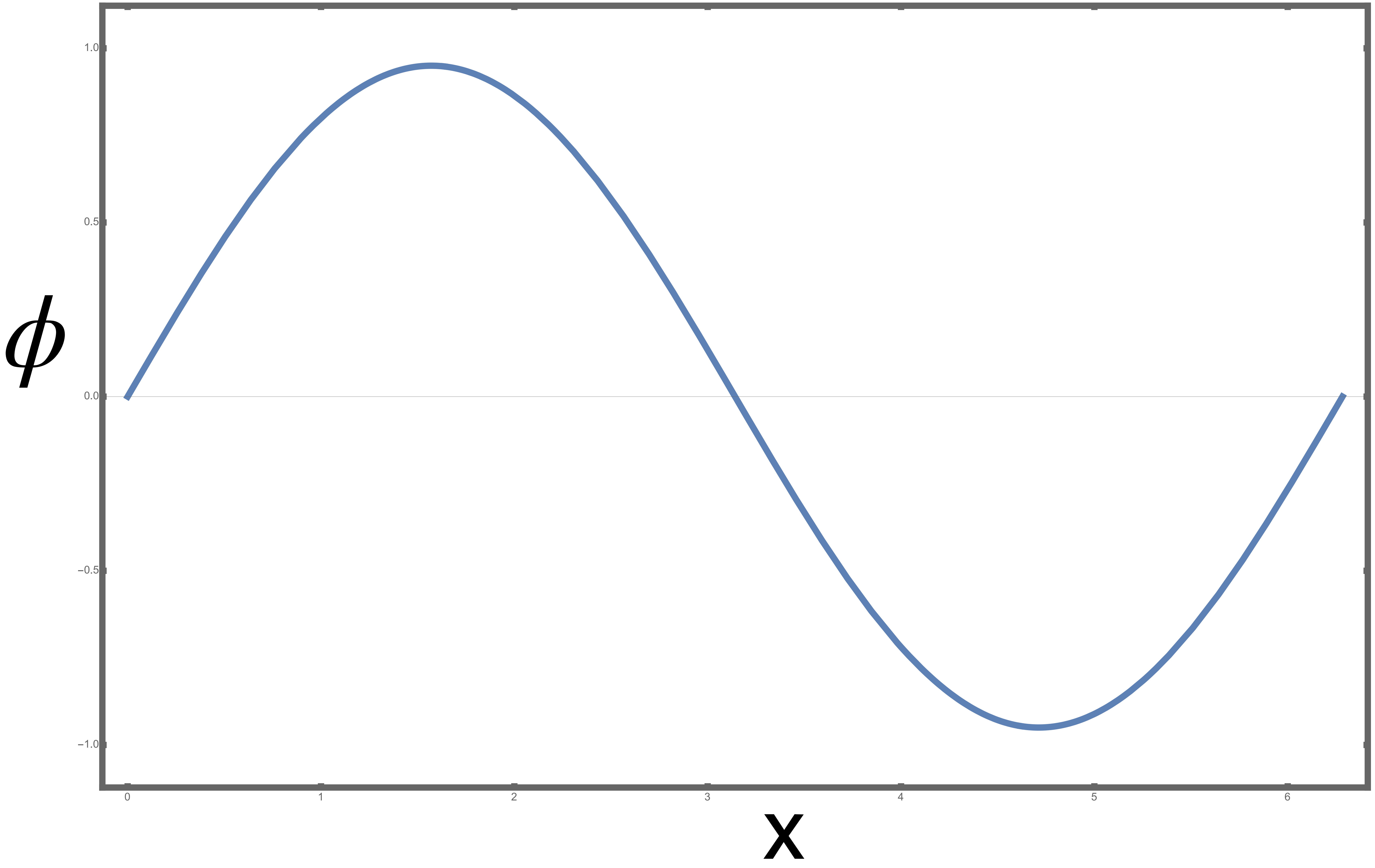

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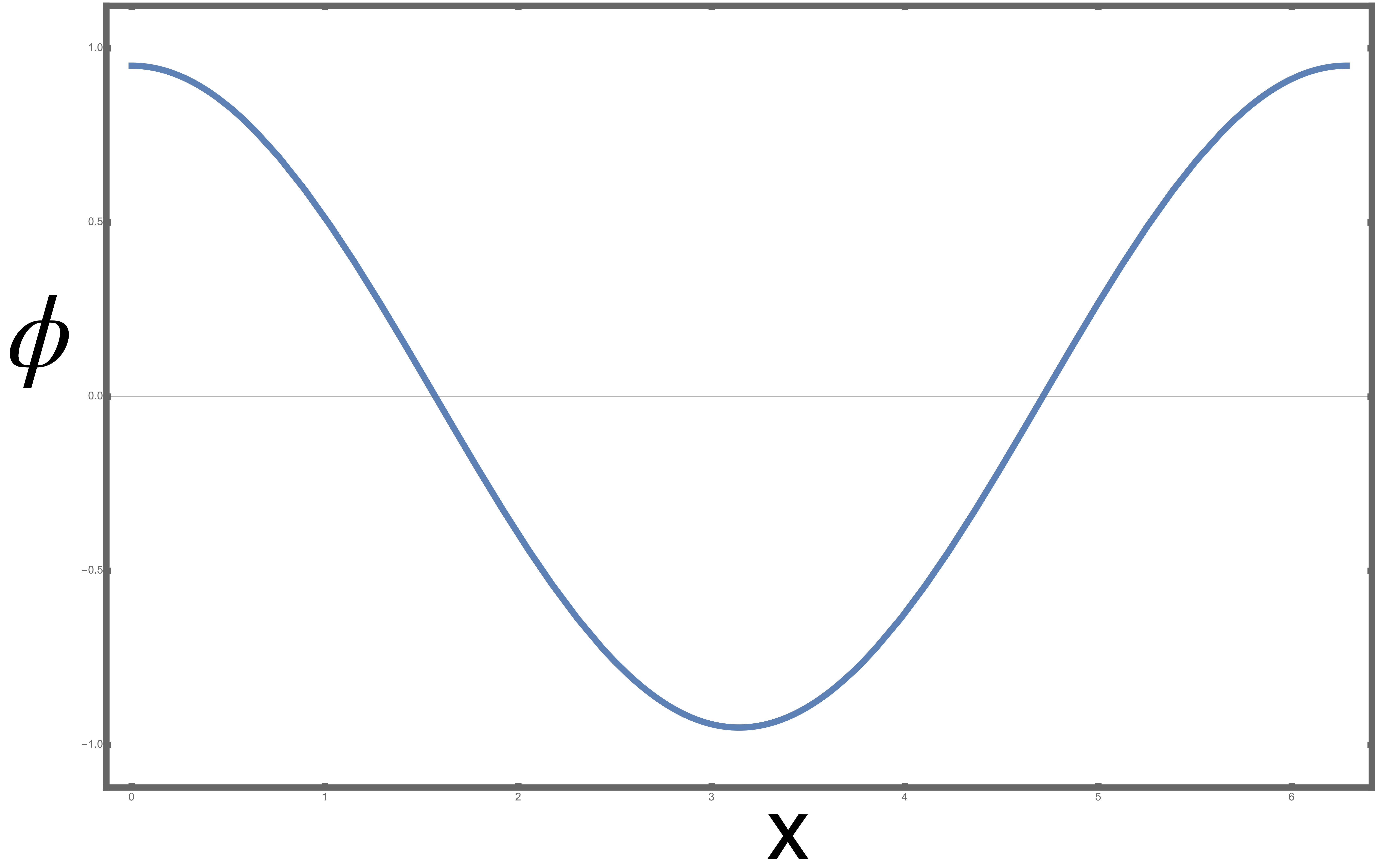

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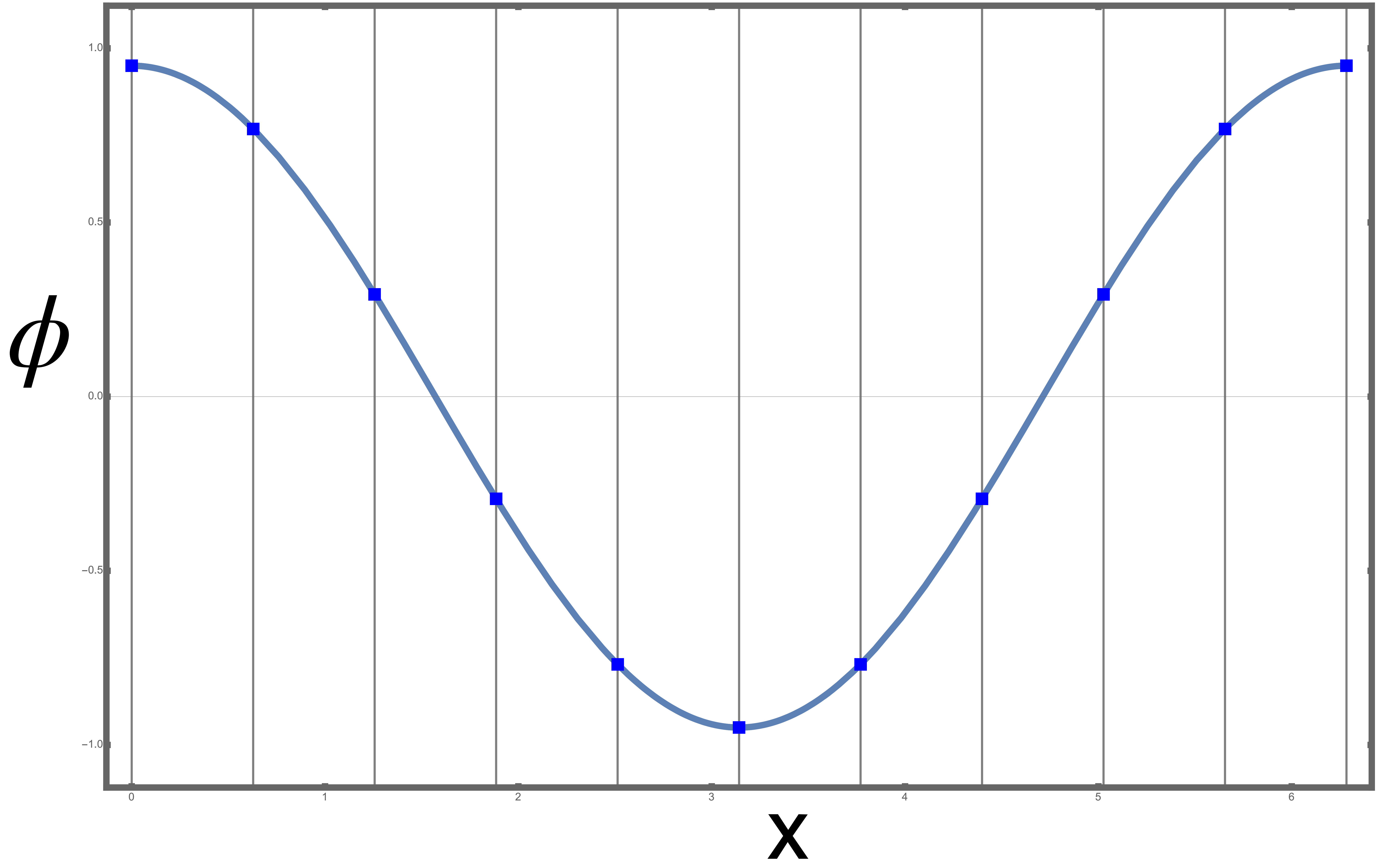

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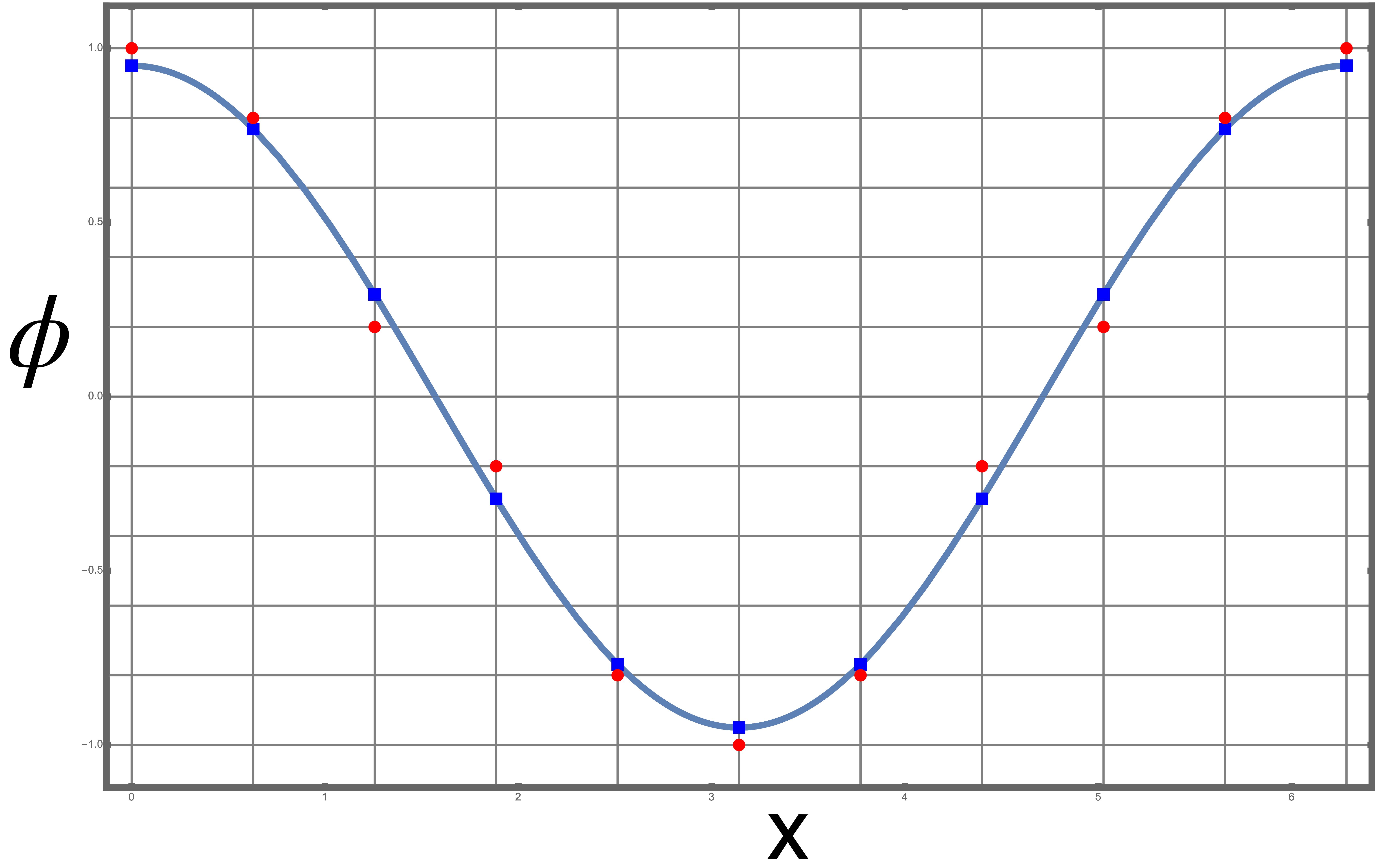

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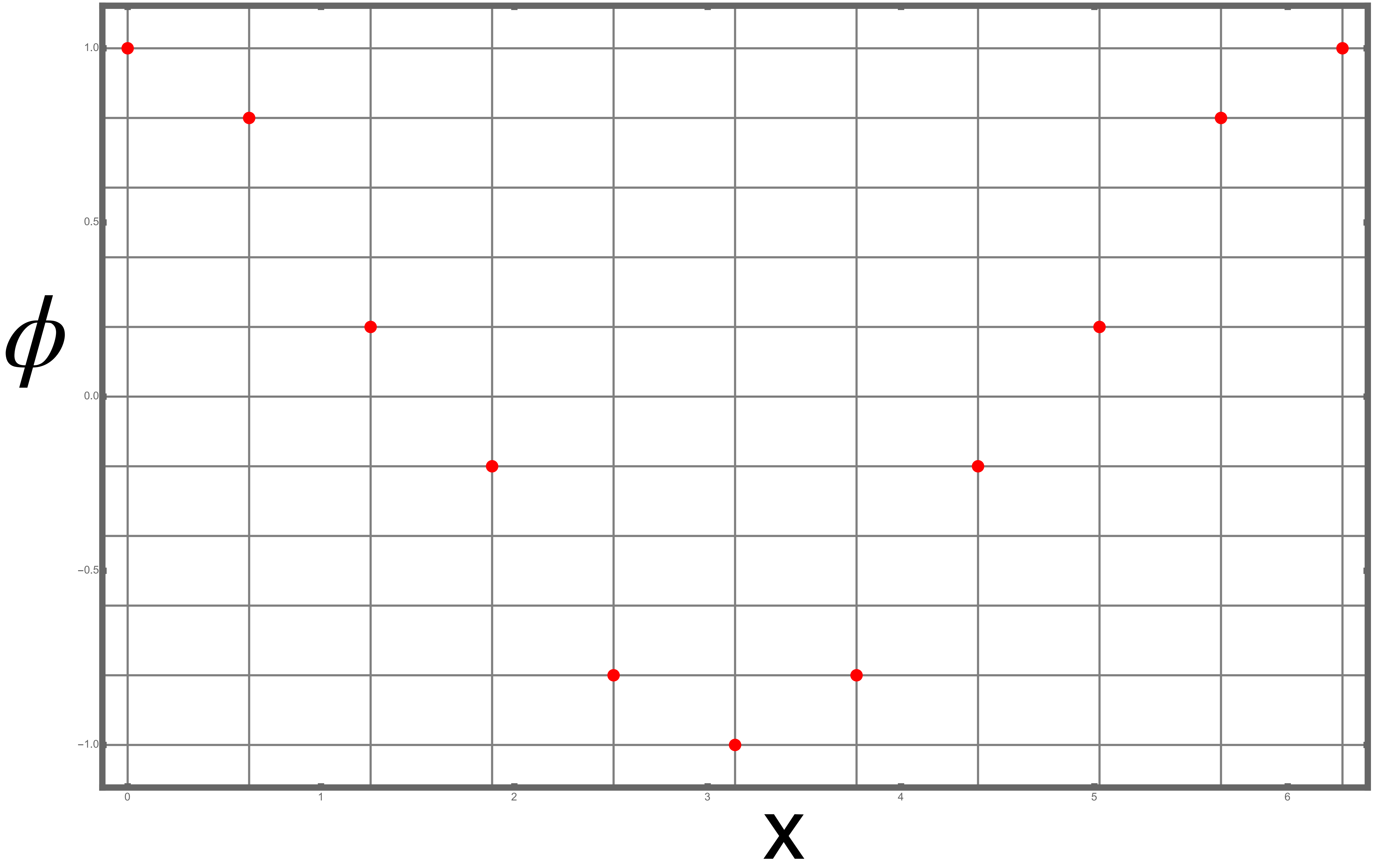

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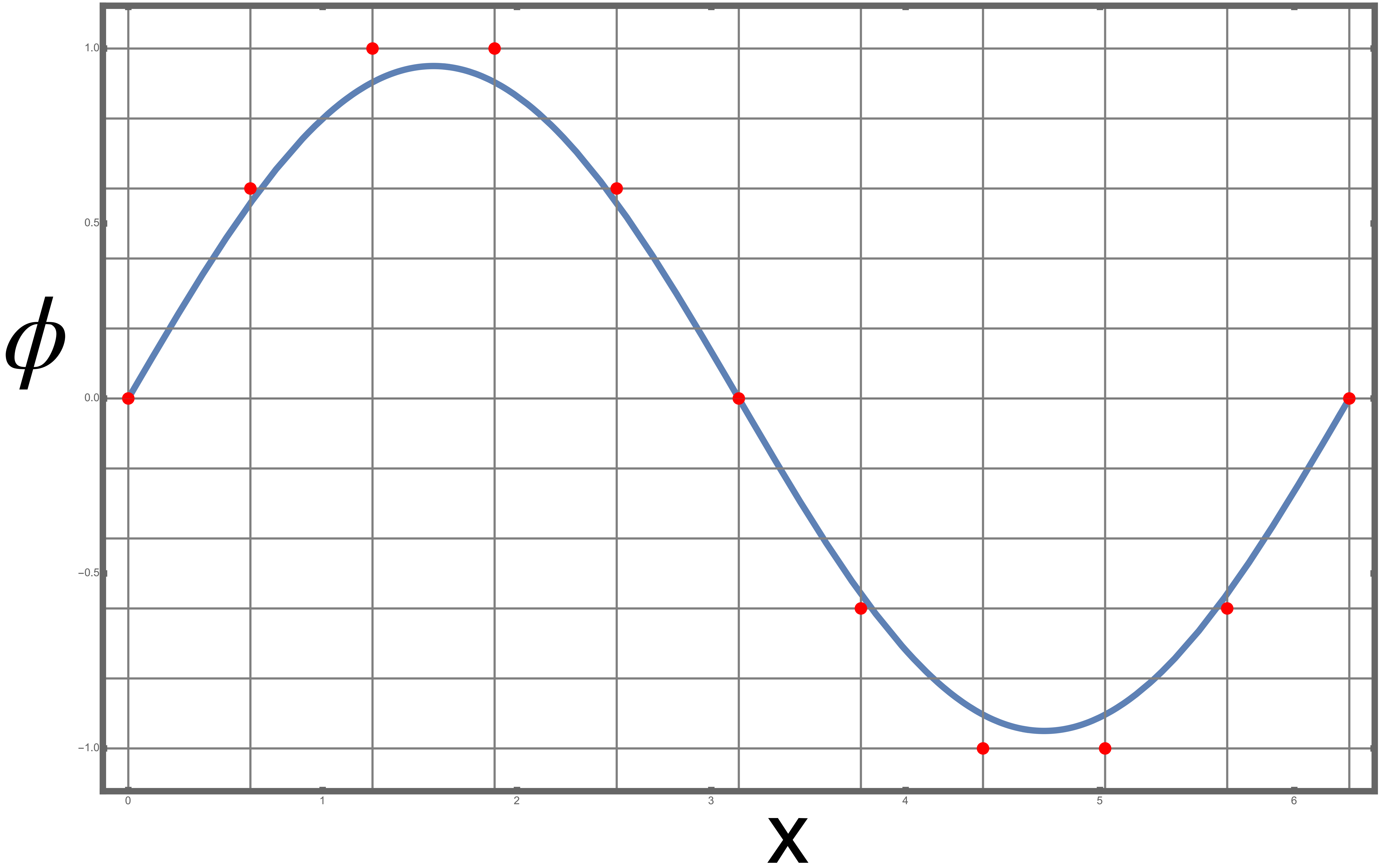

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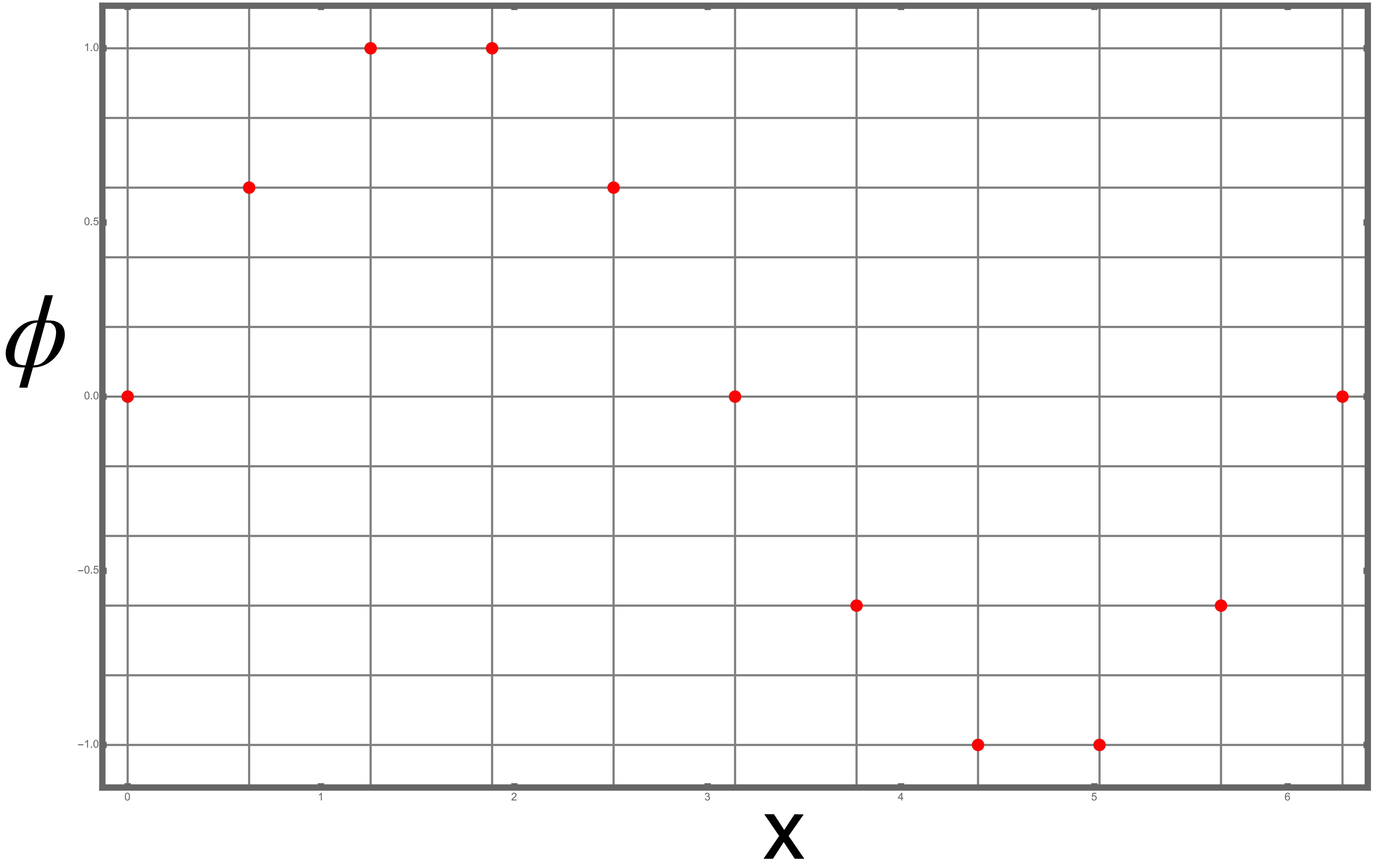

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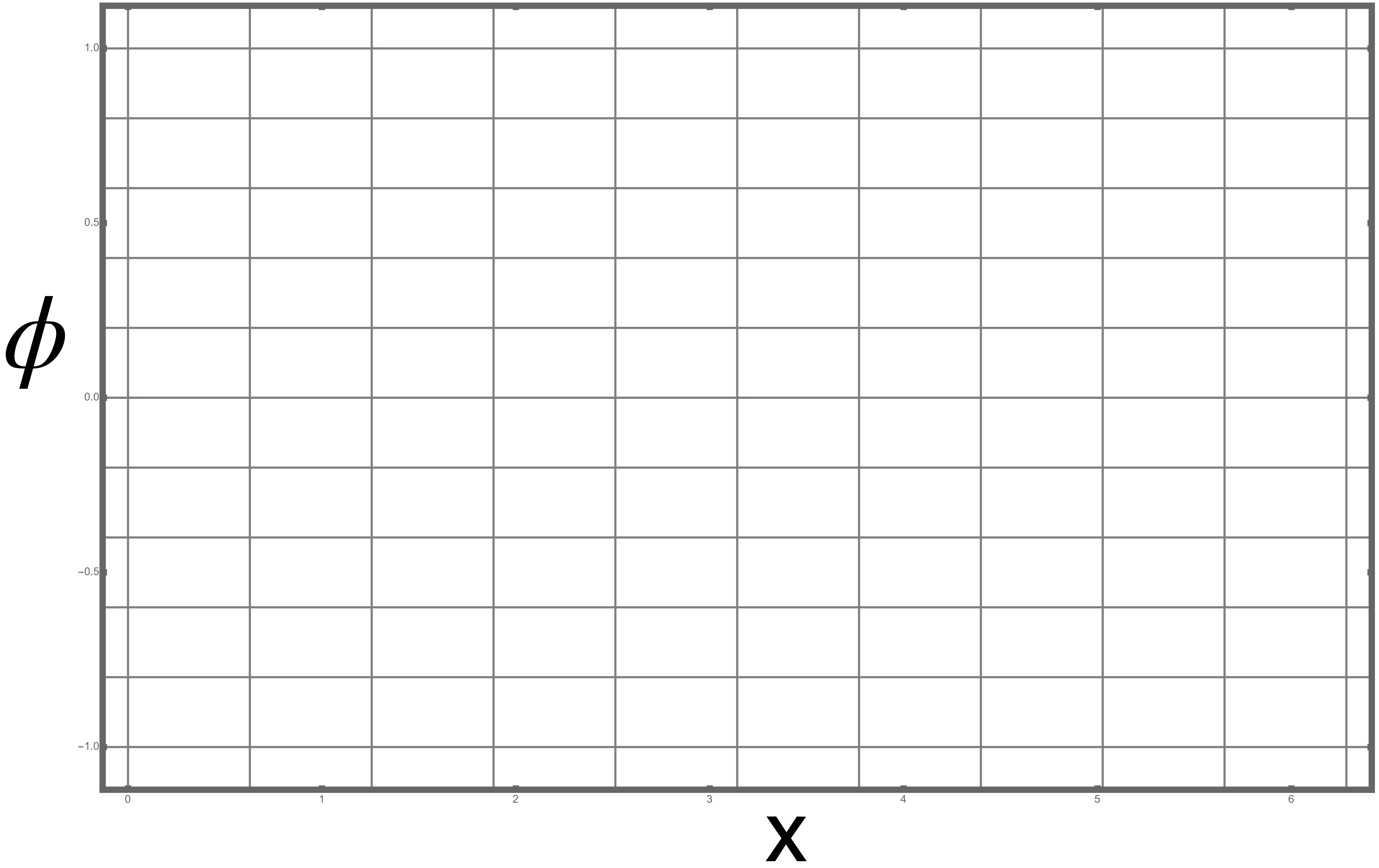

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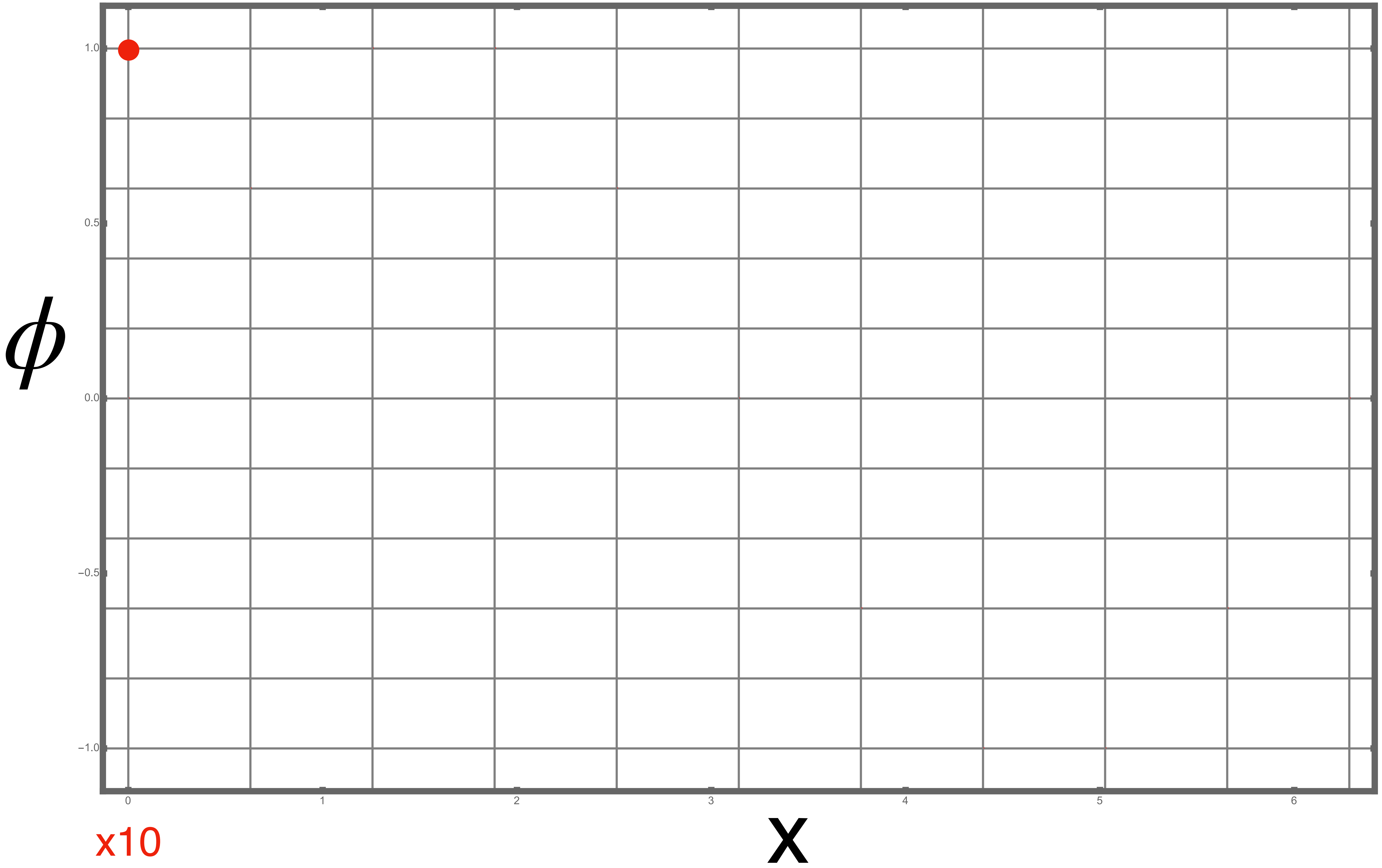

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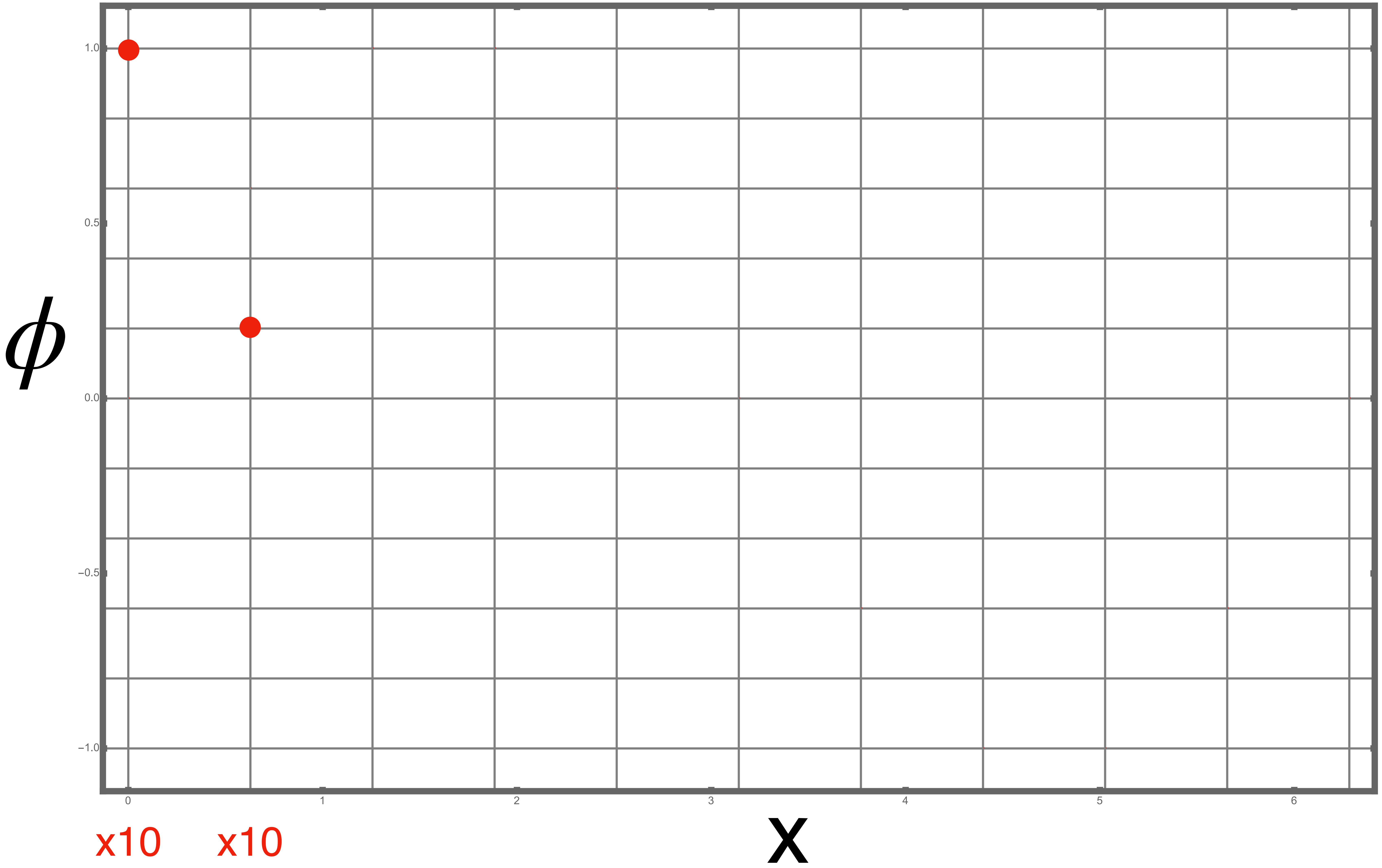

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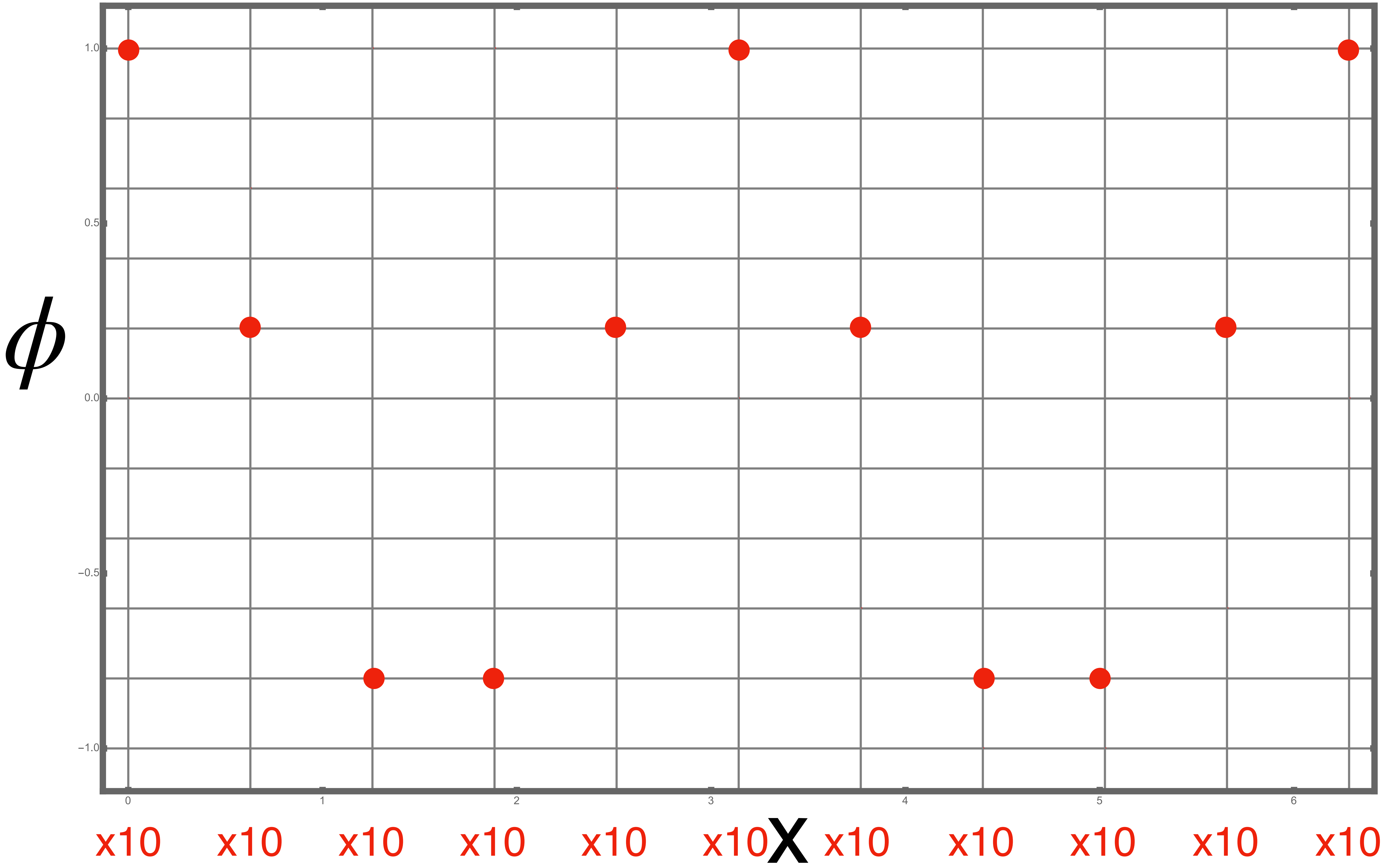

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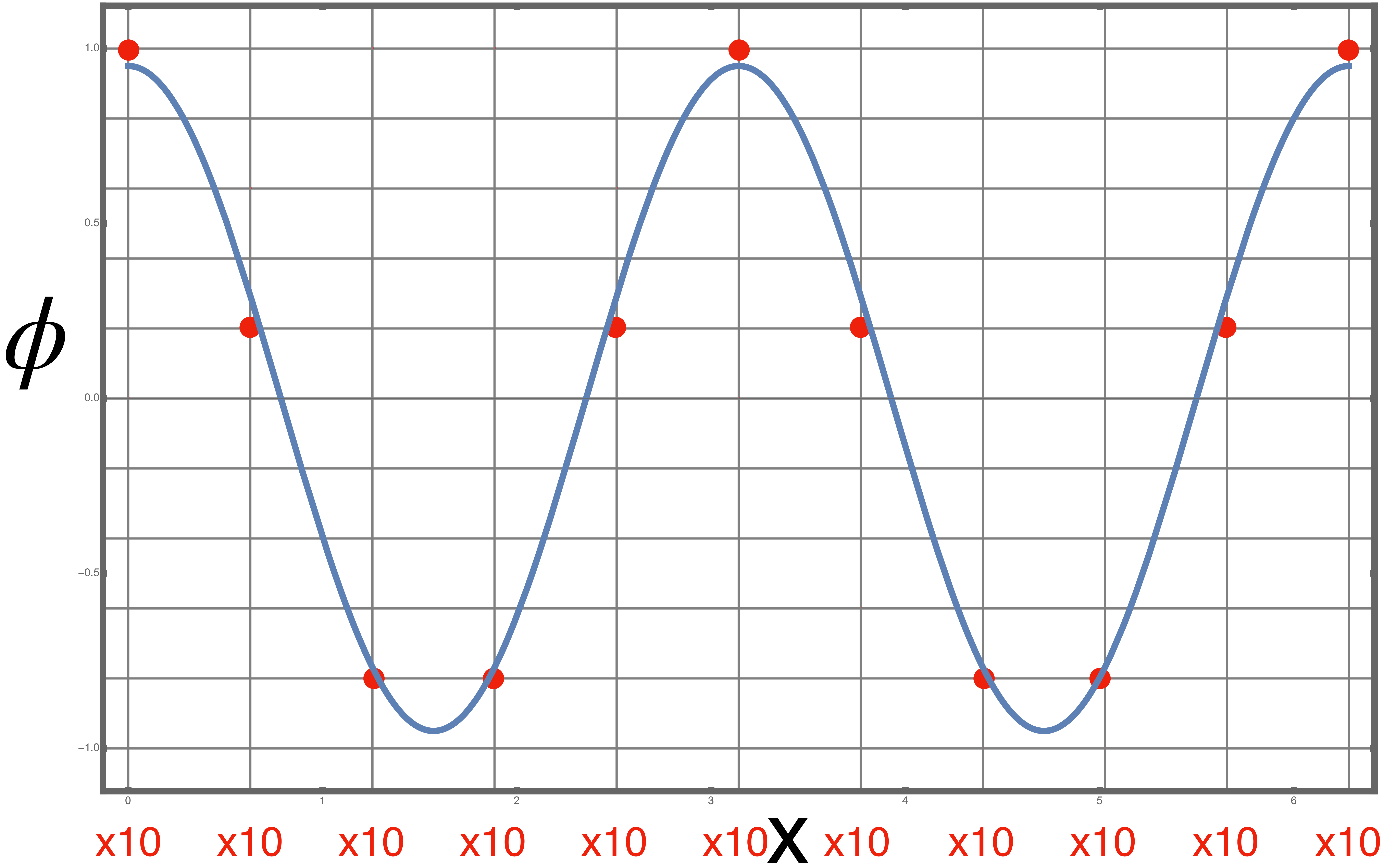

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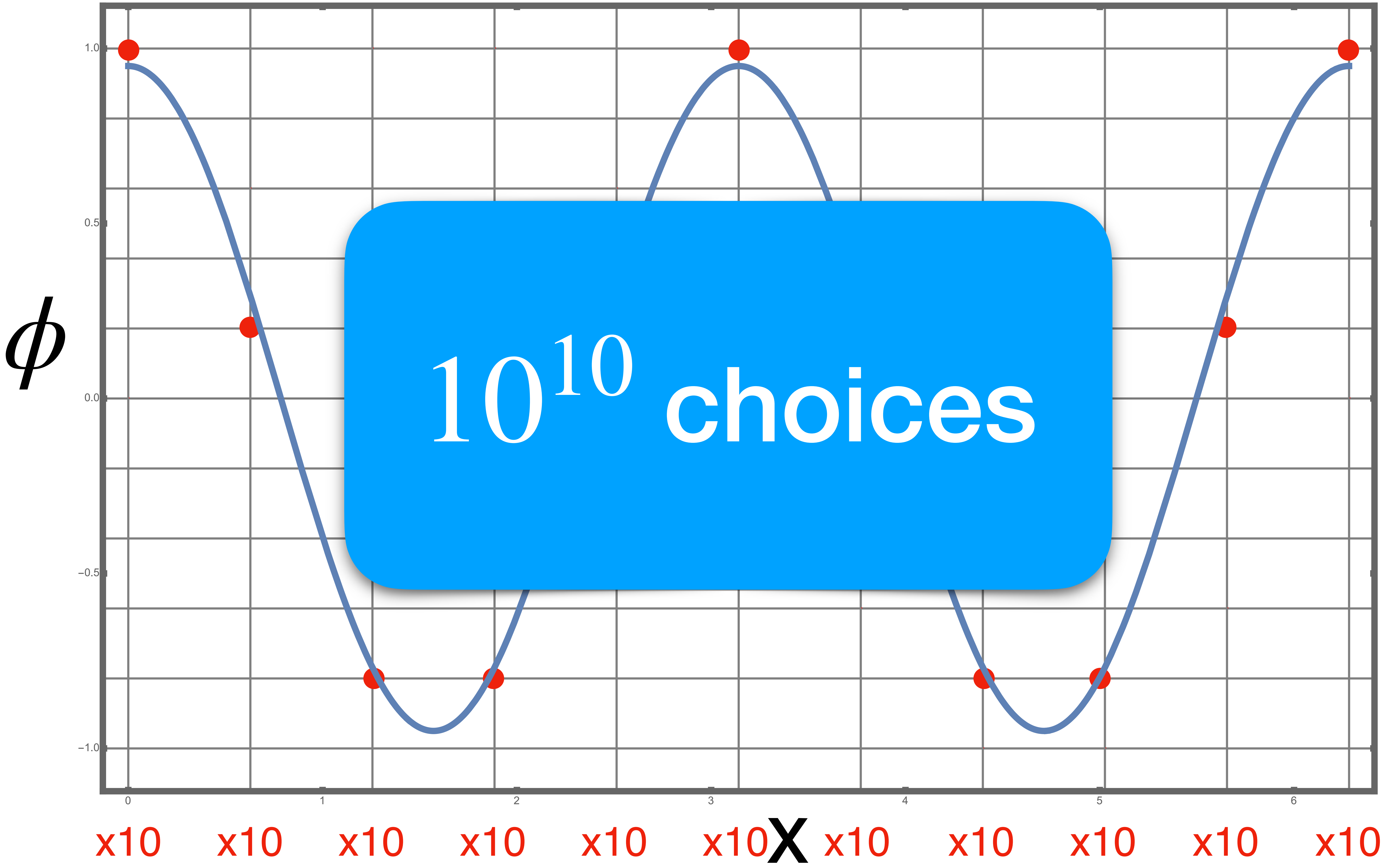


To yield finite-dimensional Hilbert space, have field configurations sample position and field values at discrete points

Size of Hilbert space:

$$n = n_j^V$$

This complexity is completely unmanageable for classical computers, which explains why this has not been pursued

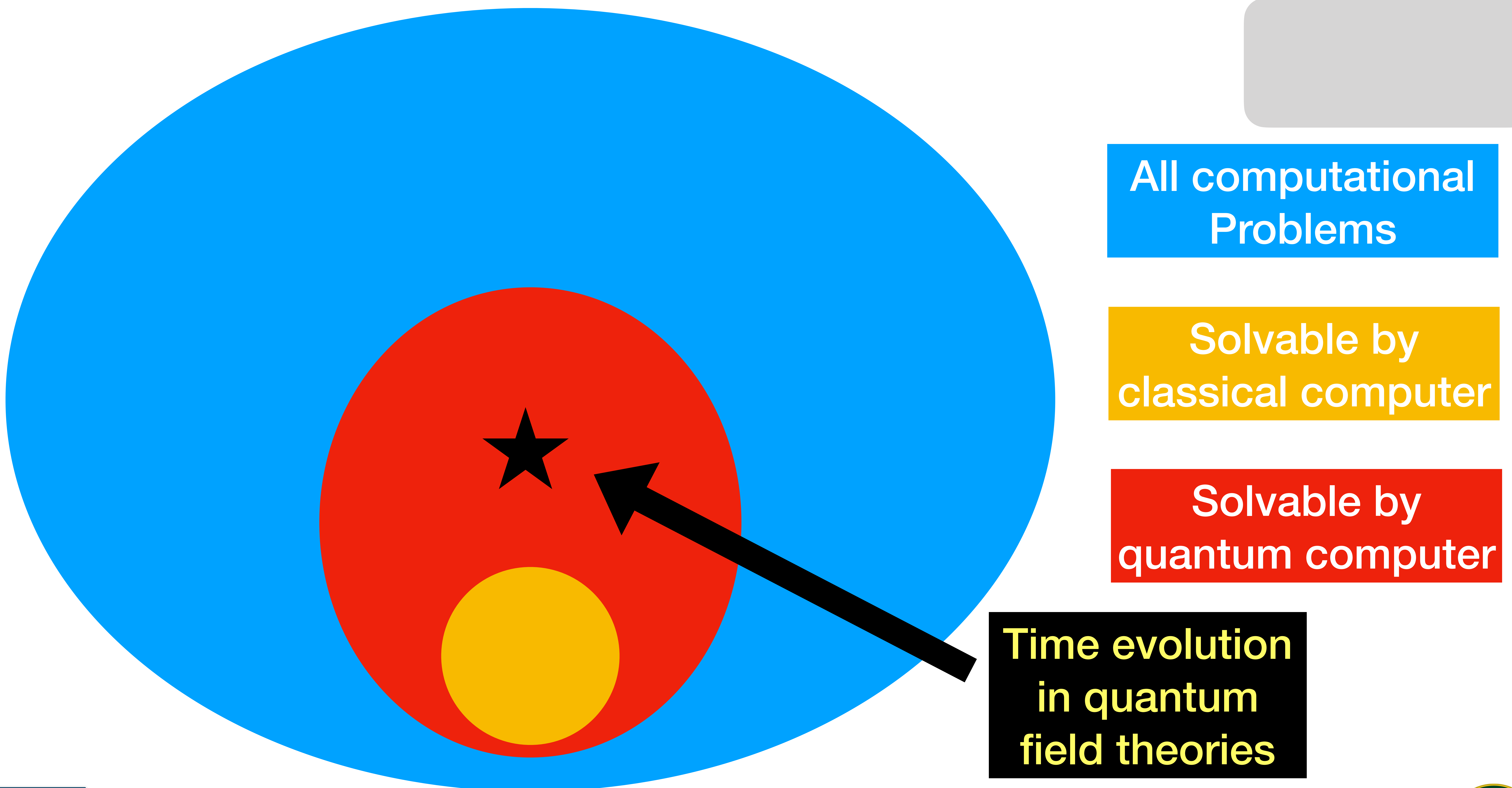
	Classical computer
nL=2	10^5
nL=3	10^18
nL=4	10^43
nL=5	10^83
nL=6	10^150

Quantum Algorithms for Quantum Field Theories

Stephen P. Jordan,[1*] Keith S. M. Lee,[2] John Preskill[3]

Quantum field theory reconciles quantum mechanics and special relativity, and plays a central role in many areas of physics. We developed a quantum algorithm to compute relativistic scattering probabilities in a massive quantum field theory with quartic self-interactions (ϕ^4 theory) in spacetime of four and fewer dimensions. Its run time is polynomial in the number of particles, their energy, and the desired precision, and applies at both weak and strong coupling. In the strong-coupling and high-precision regimes, our quantum algorithm achieves exponential speedup over the fastest known classical algorithm.

Science 336 (2012) 1130



All computational Problems
Solvable by classical computer
Solvable by quantum computer
Time evolution in quantum field theories

Quantum computers put first principles calculations of scattering cross sections (and other observables) in realm of possibility

	Classical computer	Quantum Computer
nL=2	10^5	10^1
nL=3	10^18	10^1
nL=4	10^43	10^2
nL=5	10^83	10^2
nL=6	10^150	10^2

Identify the right questions to address

Find Theory Formulation for SU(3)

Quantum Simulations Research

Find efficient Quantum algorithms

Obtain results on realistic machines (with noise)

Identify the right questions to address

Find Theory Formulation for SU(3)

Quantum Simulations Research

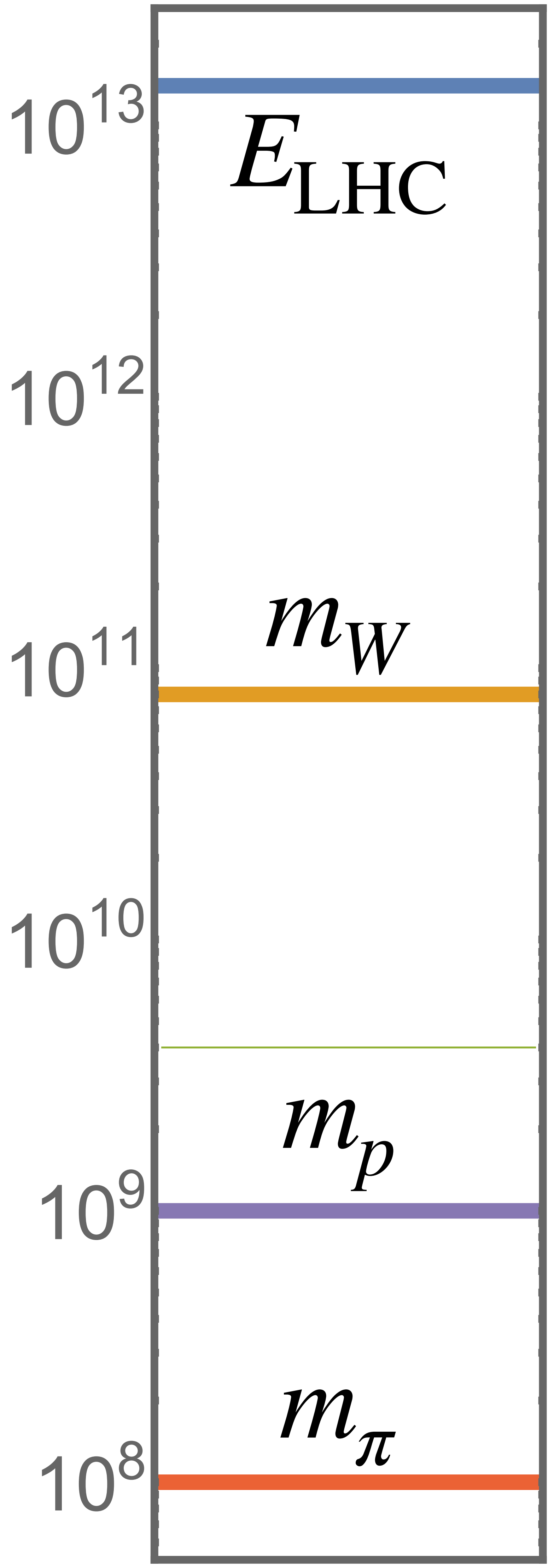
Find efficient Quantum algorithms

Obtain results on realistic machines (with noise)

Identify the right questions to address

Quantum Simulations Research

There are many energy scales that are present in LHC events, and all need to be accounted for in an adequate description



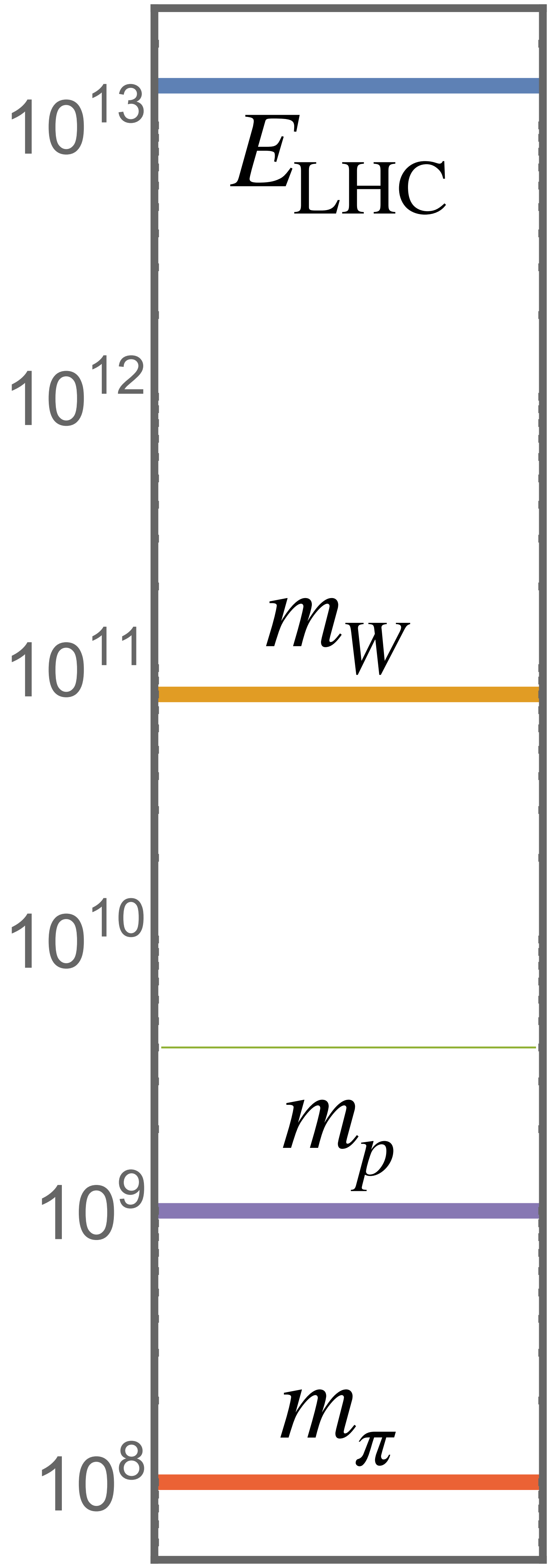
Energy of colliding protons

Scale of electroweak gauge bosons

Mass of the proton

Mass of the pion, the lightest hadron

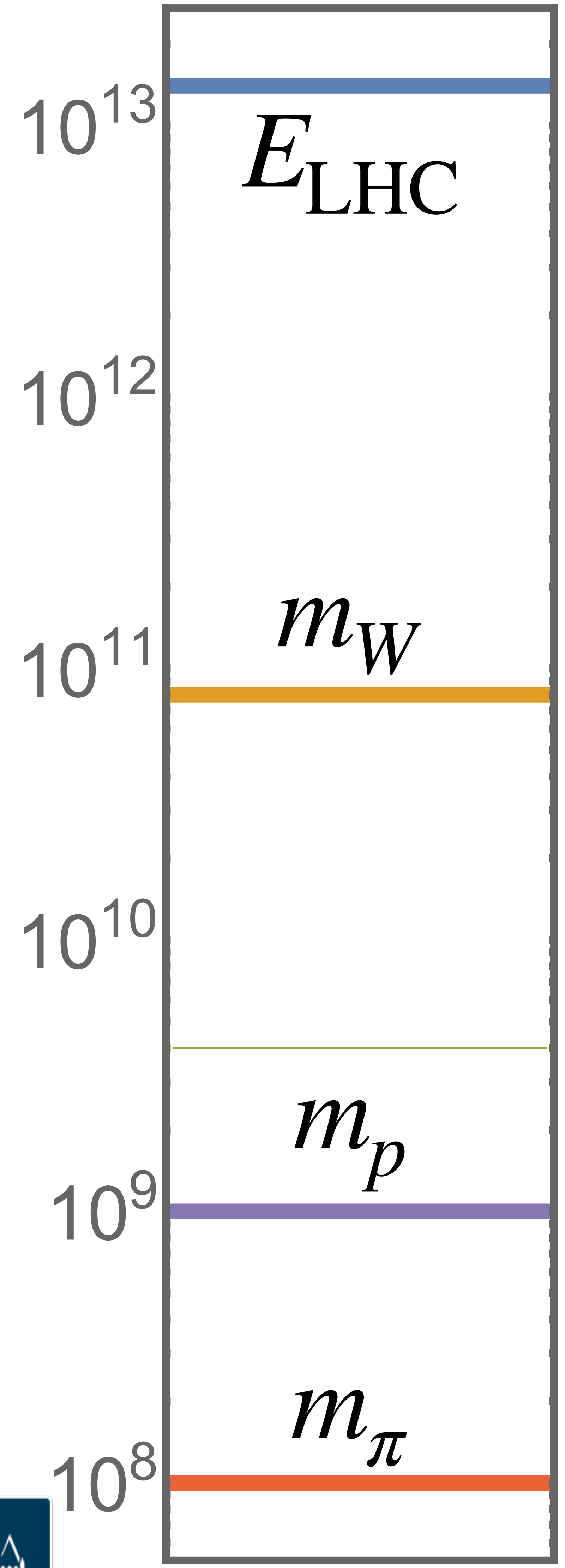
There are many energy scales that are present in LHC events, and all need to be accounted for in an adequate description

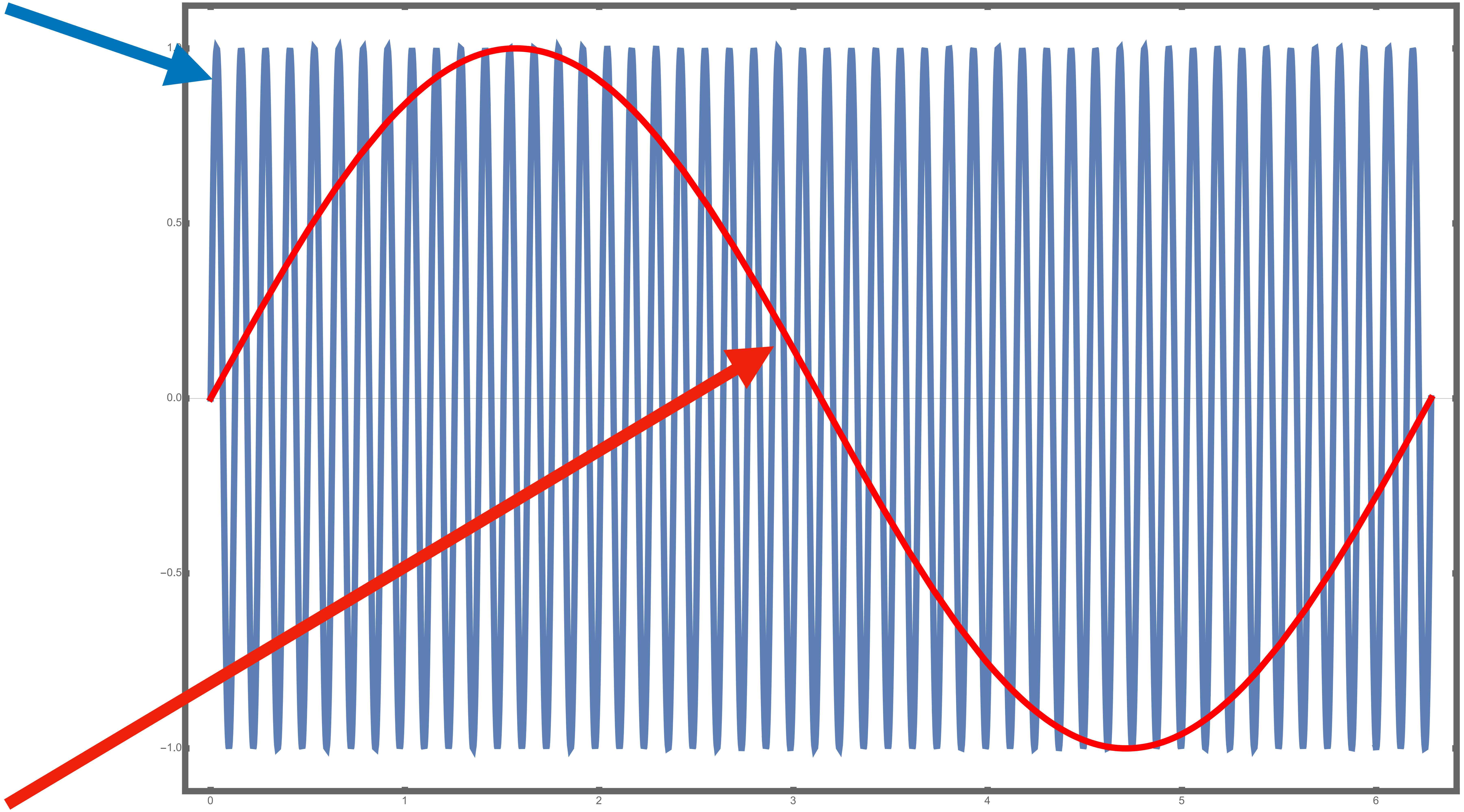


Field configurations corresonding to given energy have wavelength

$$l \sim 1/E$$

The largest and smallest energy scales set maximum and minimum wavelength of field configurations that need to be considered





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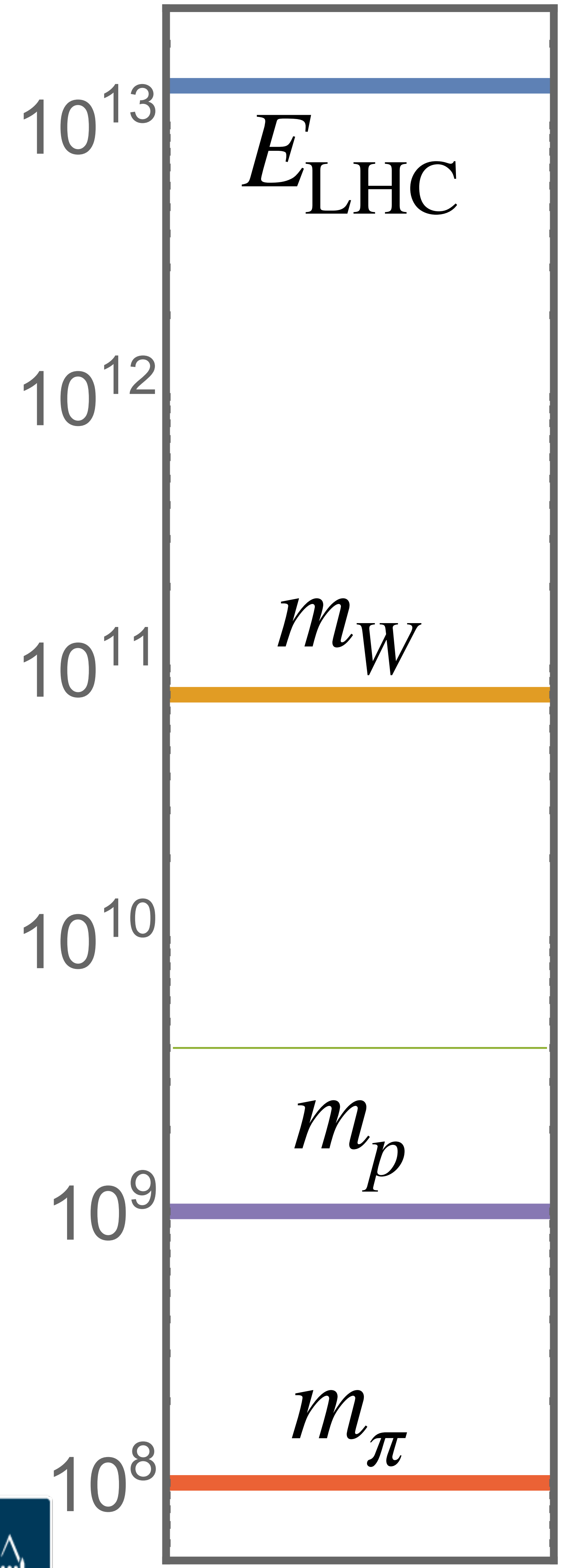

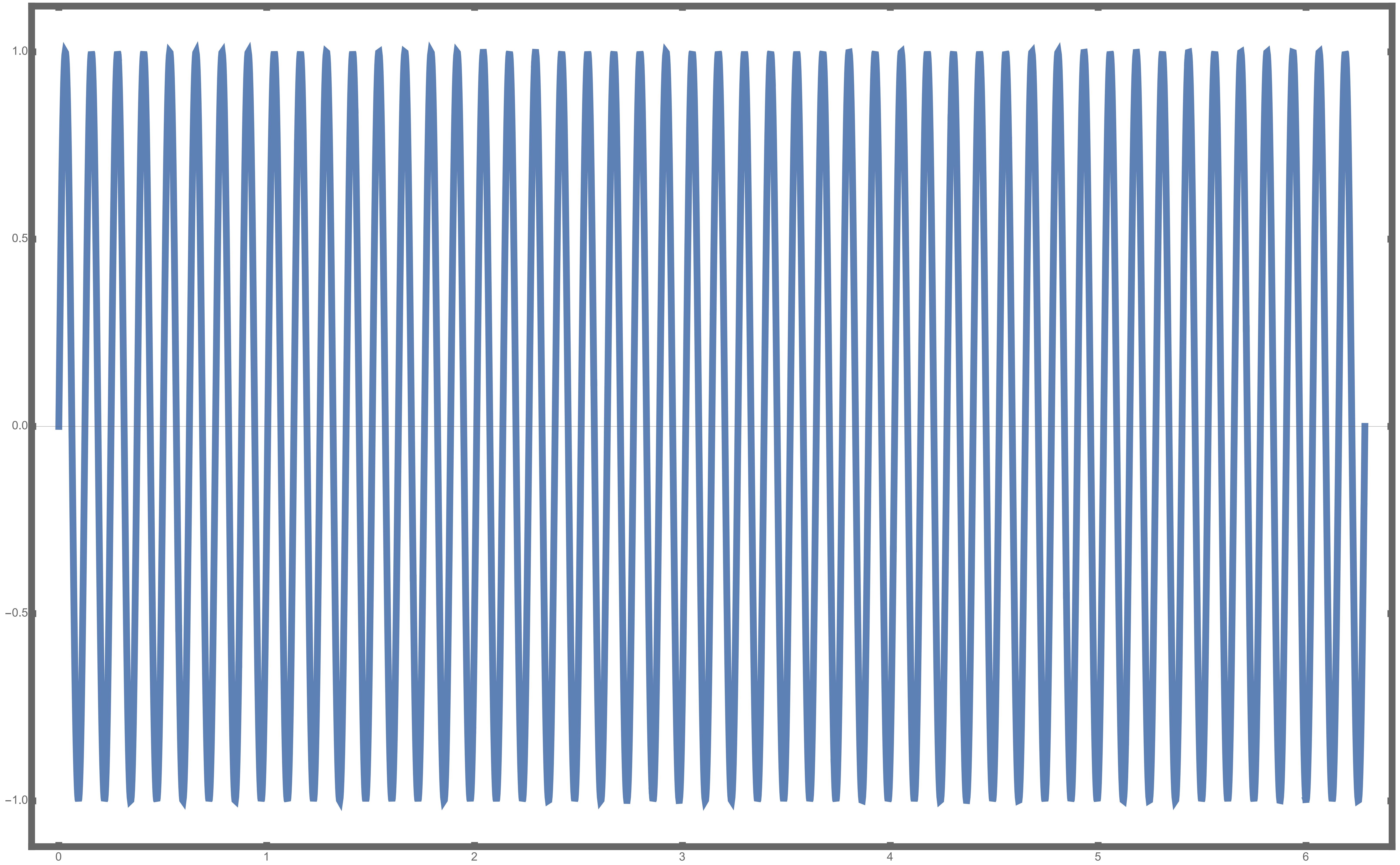

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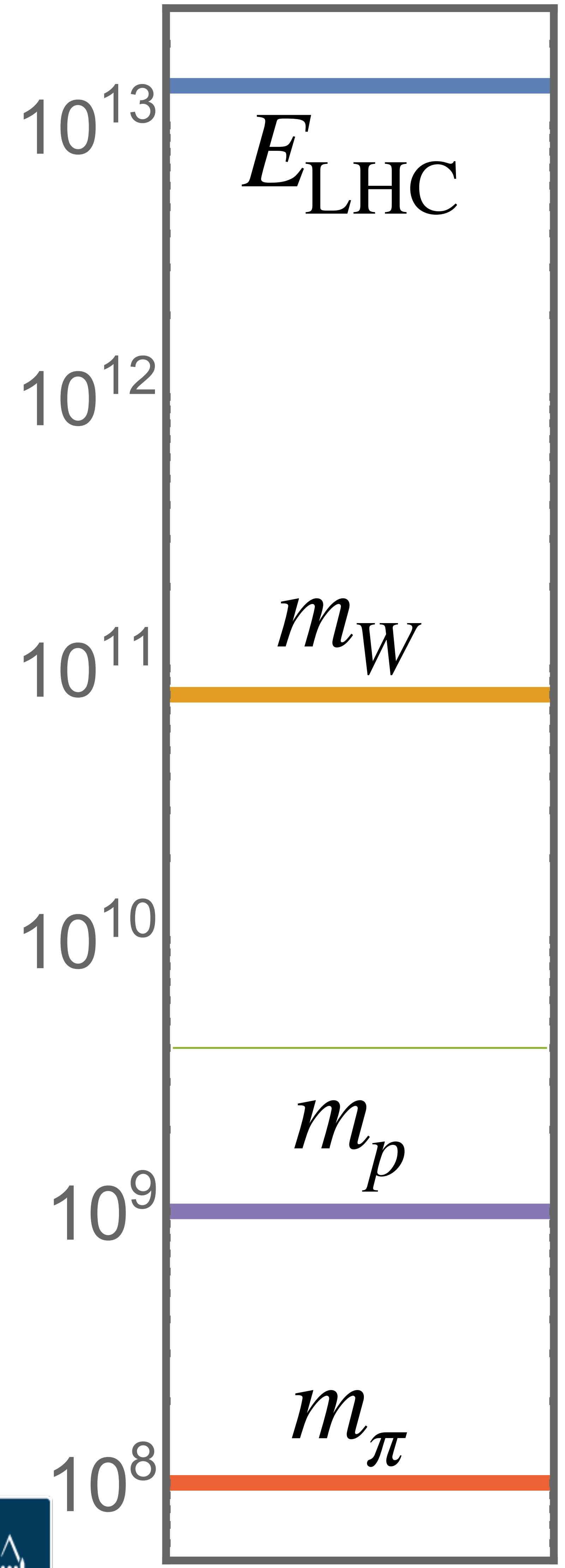

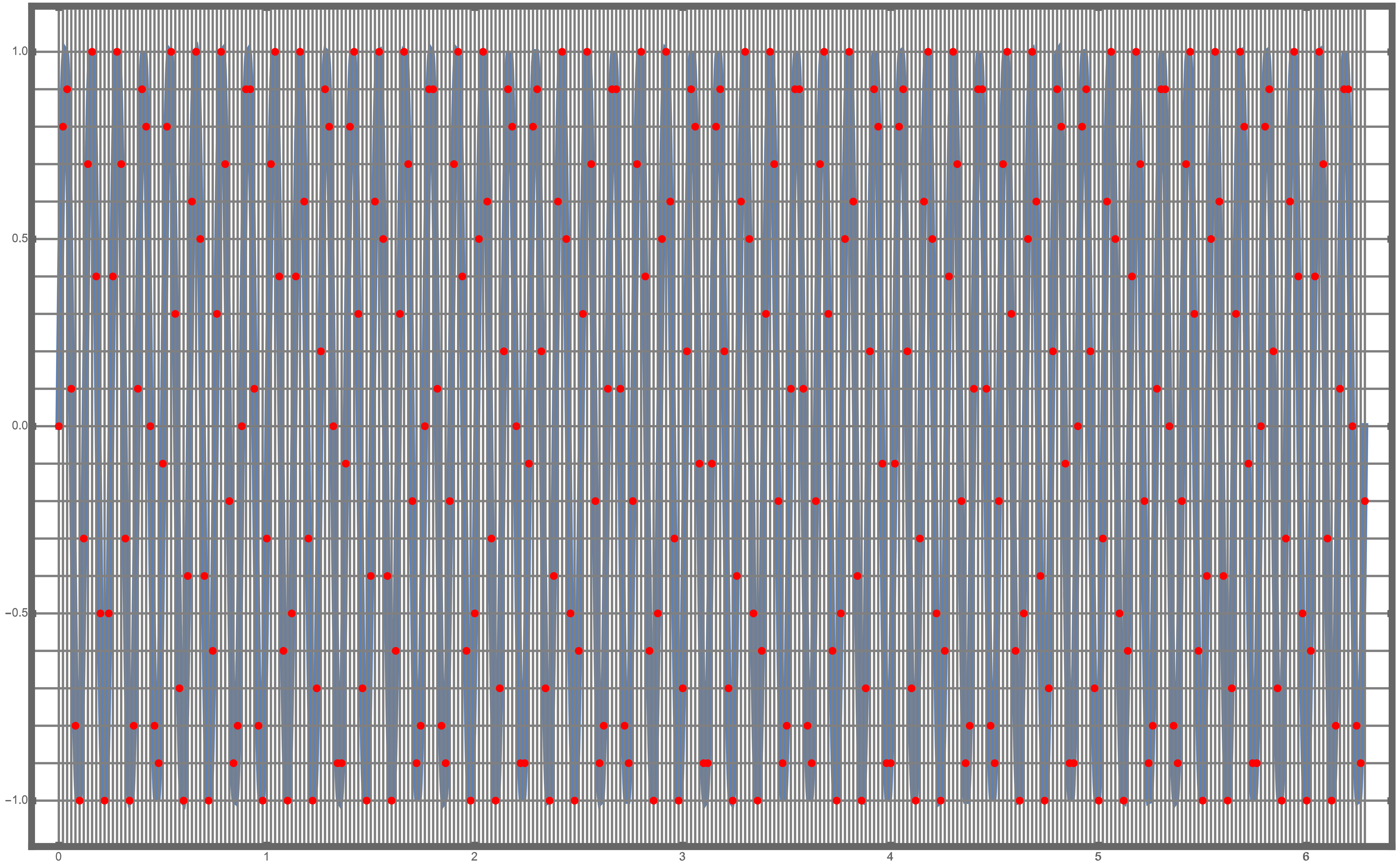

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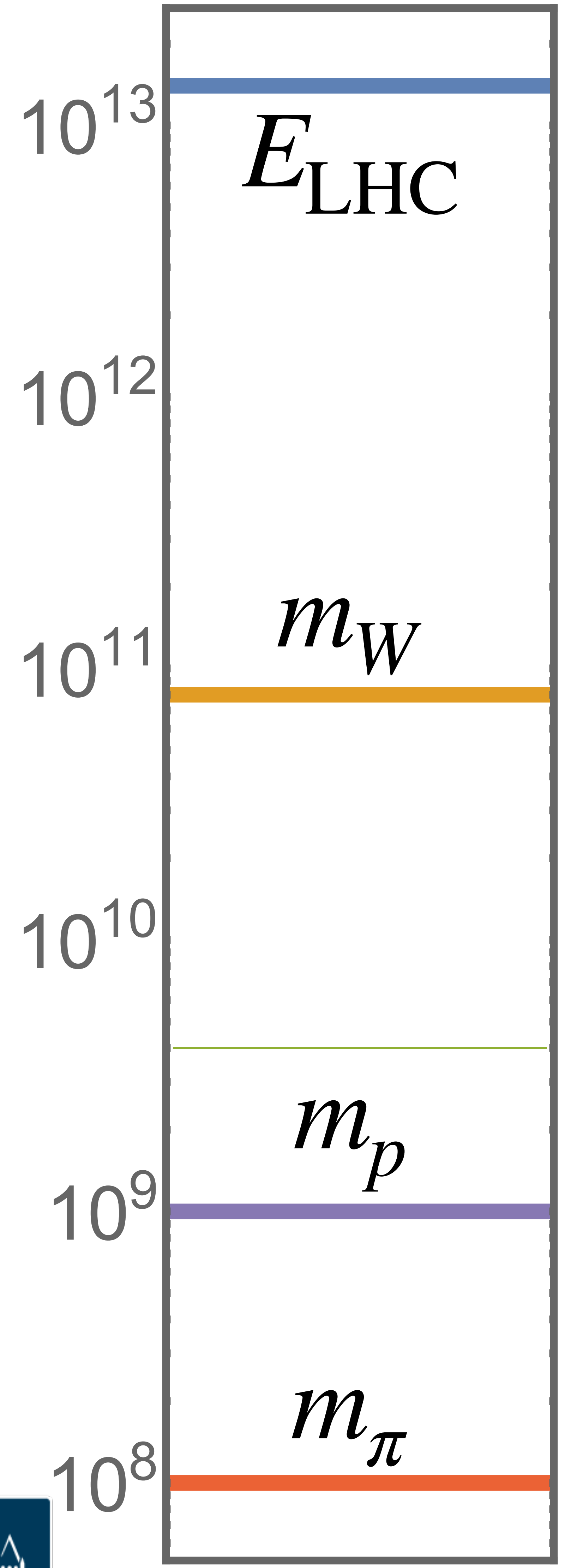
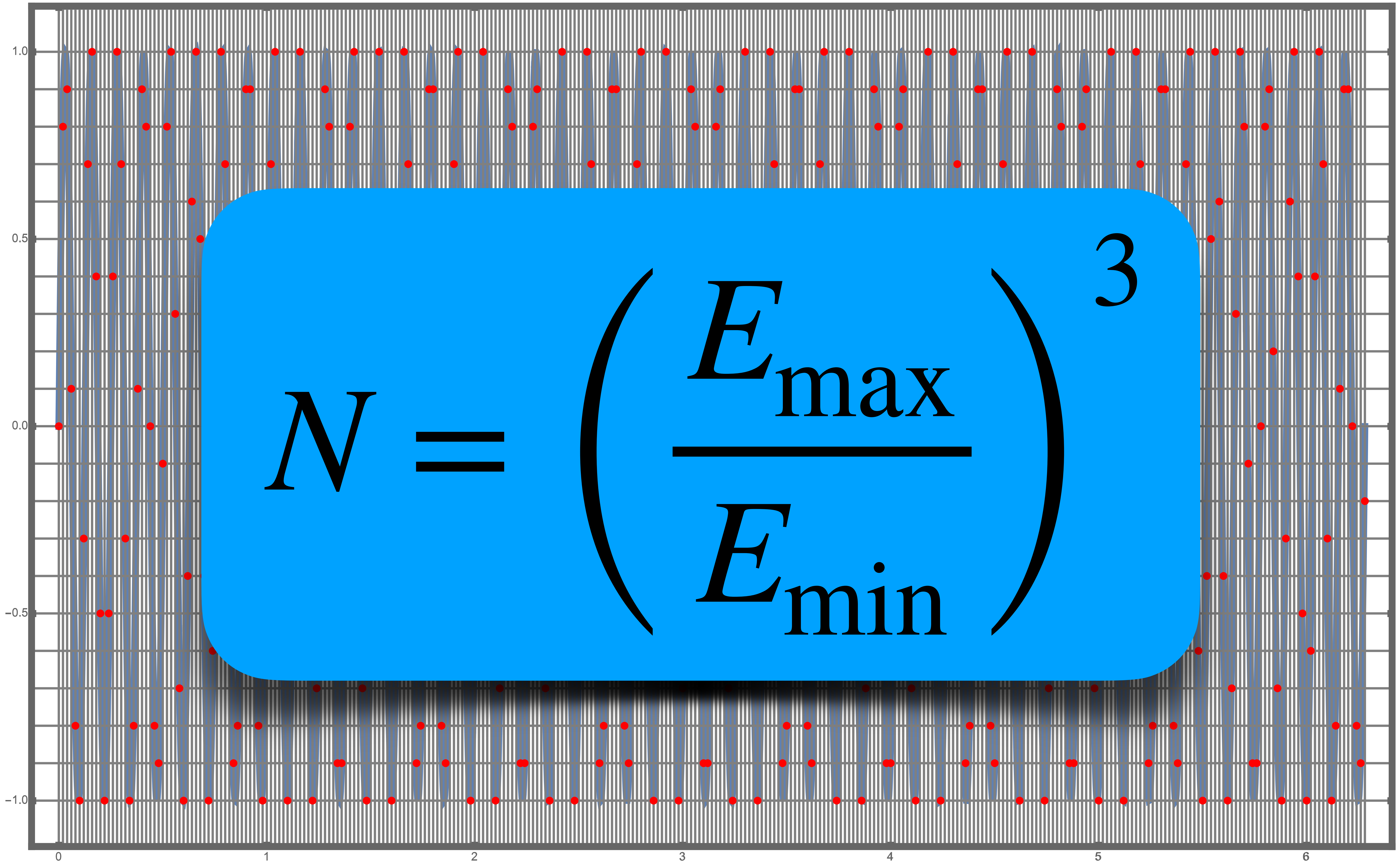
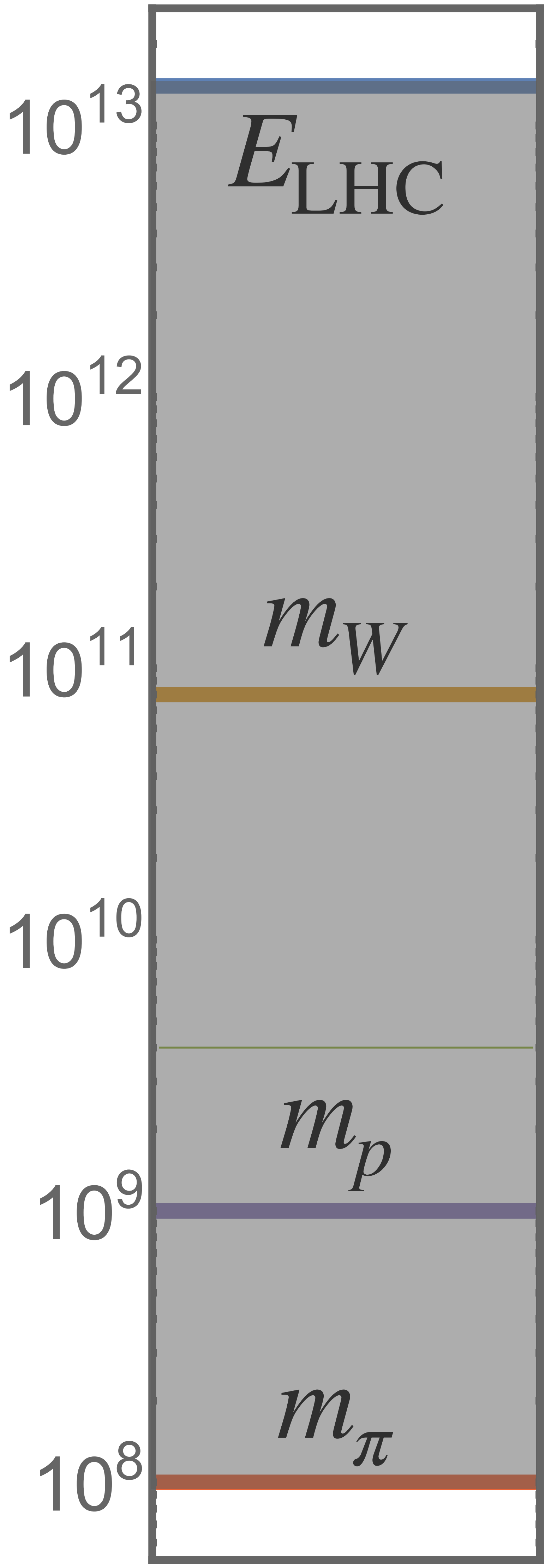
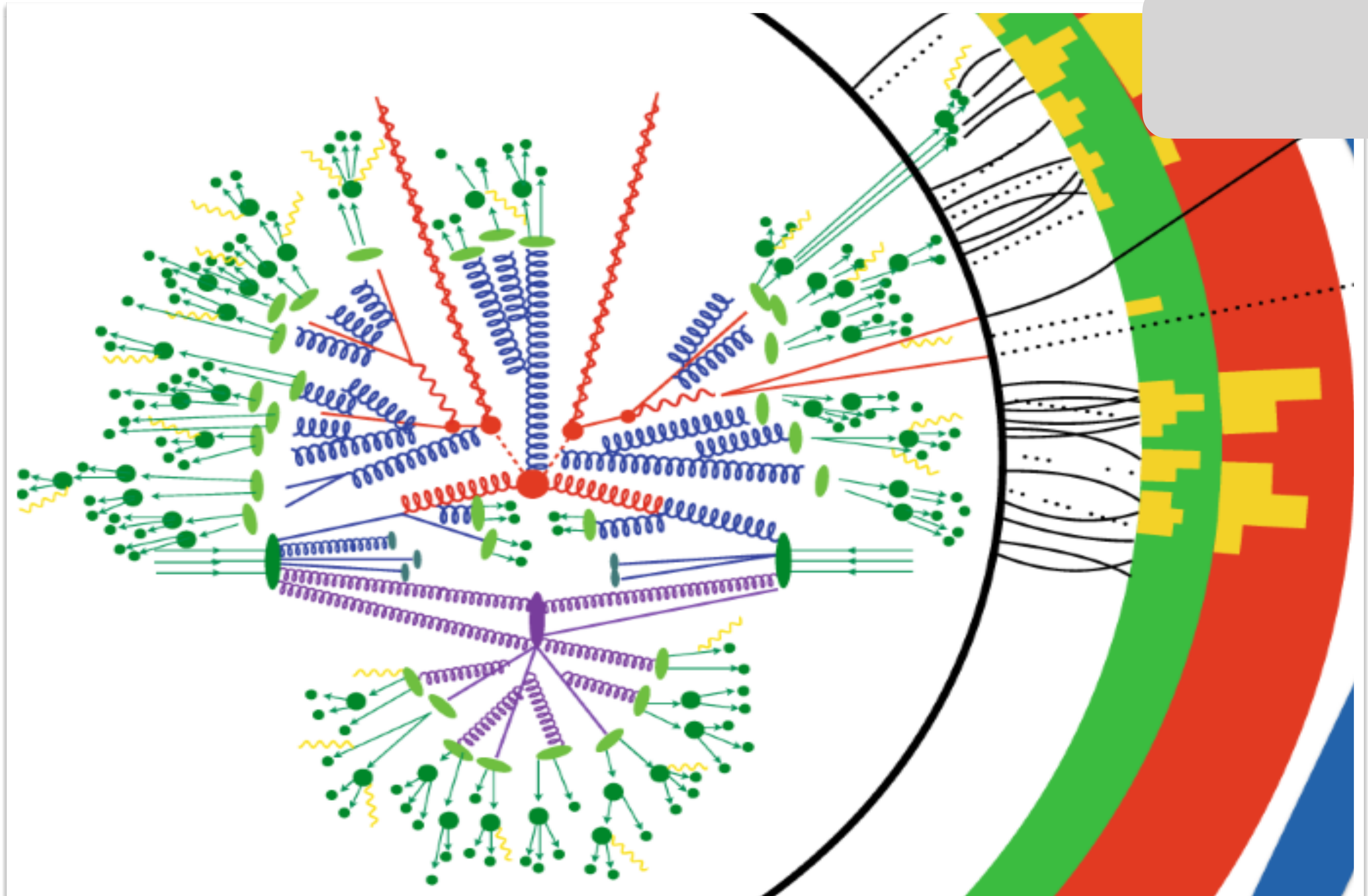


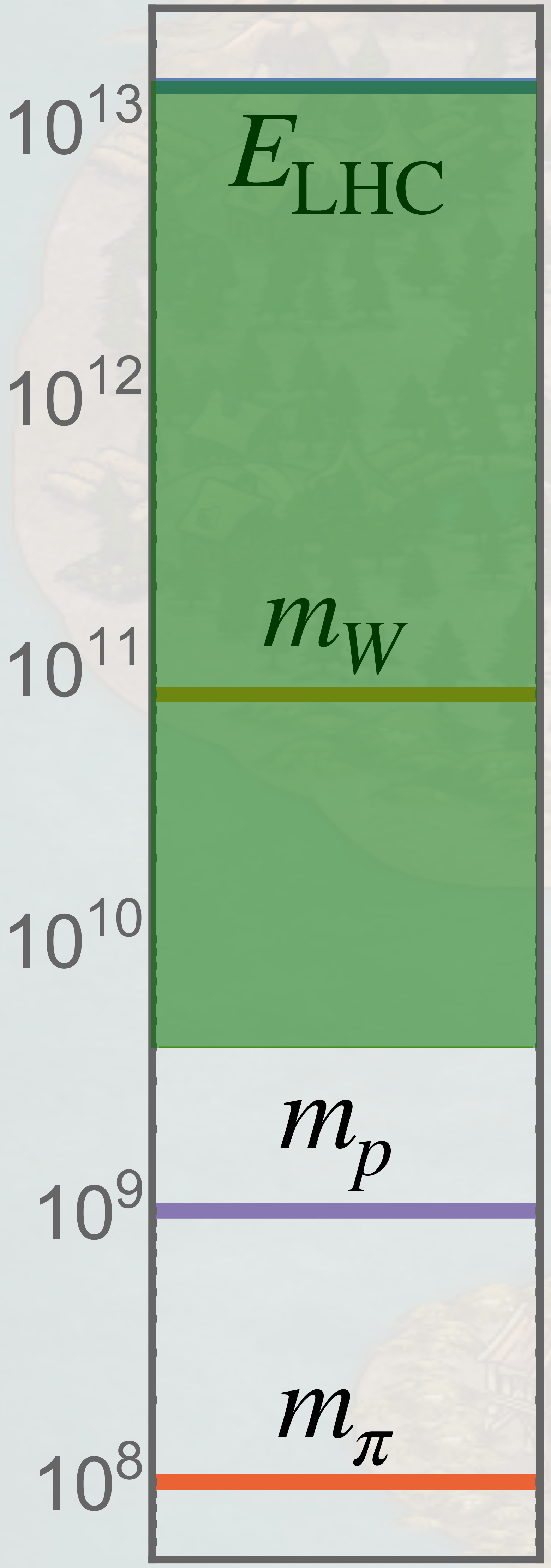


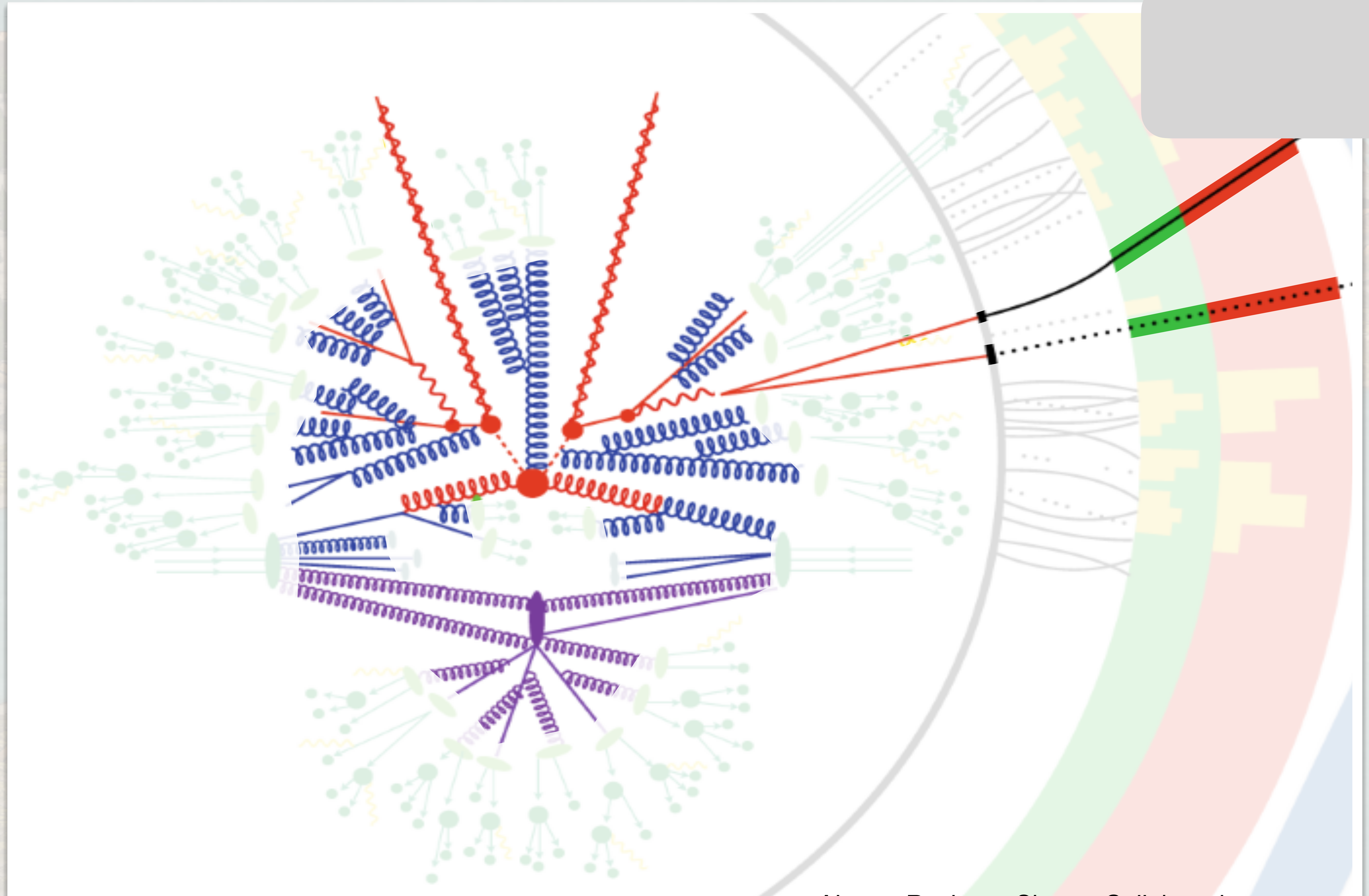
$$N = \left(\frac{E_{\max}}{E_{\min}}\right)^3$$





Nature Reviews, Sherpa Collaboration





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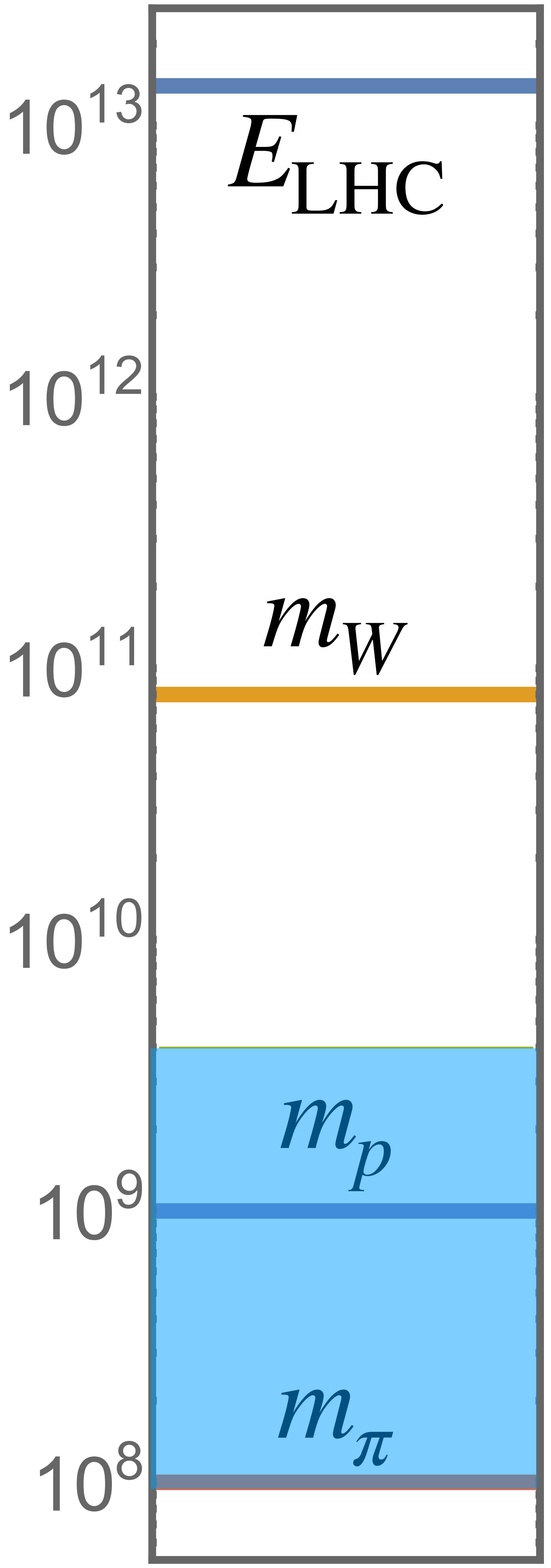

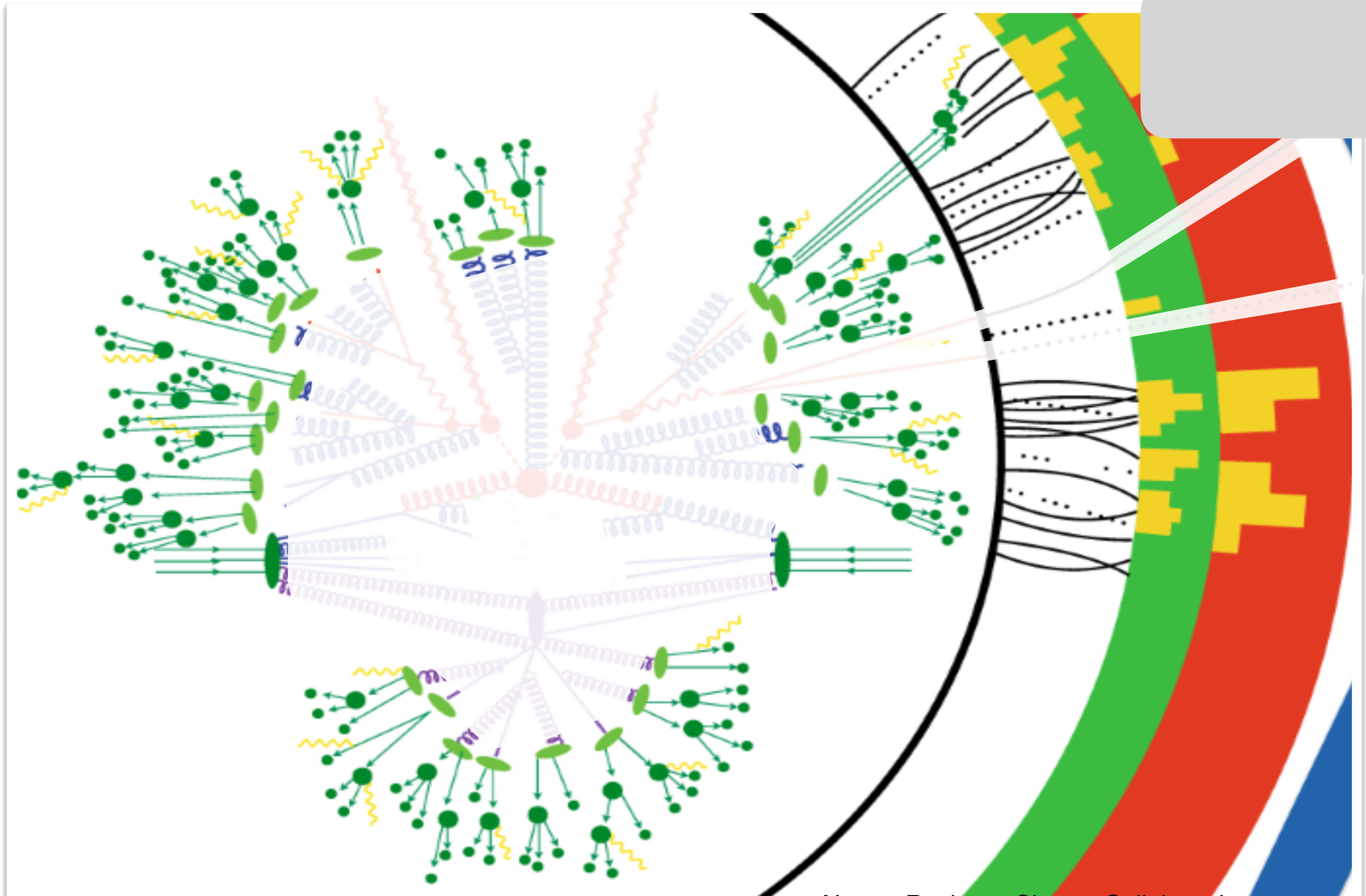

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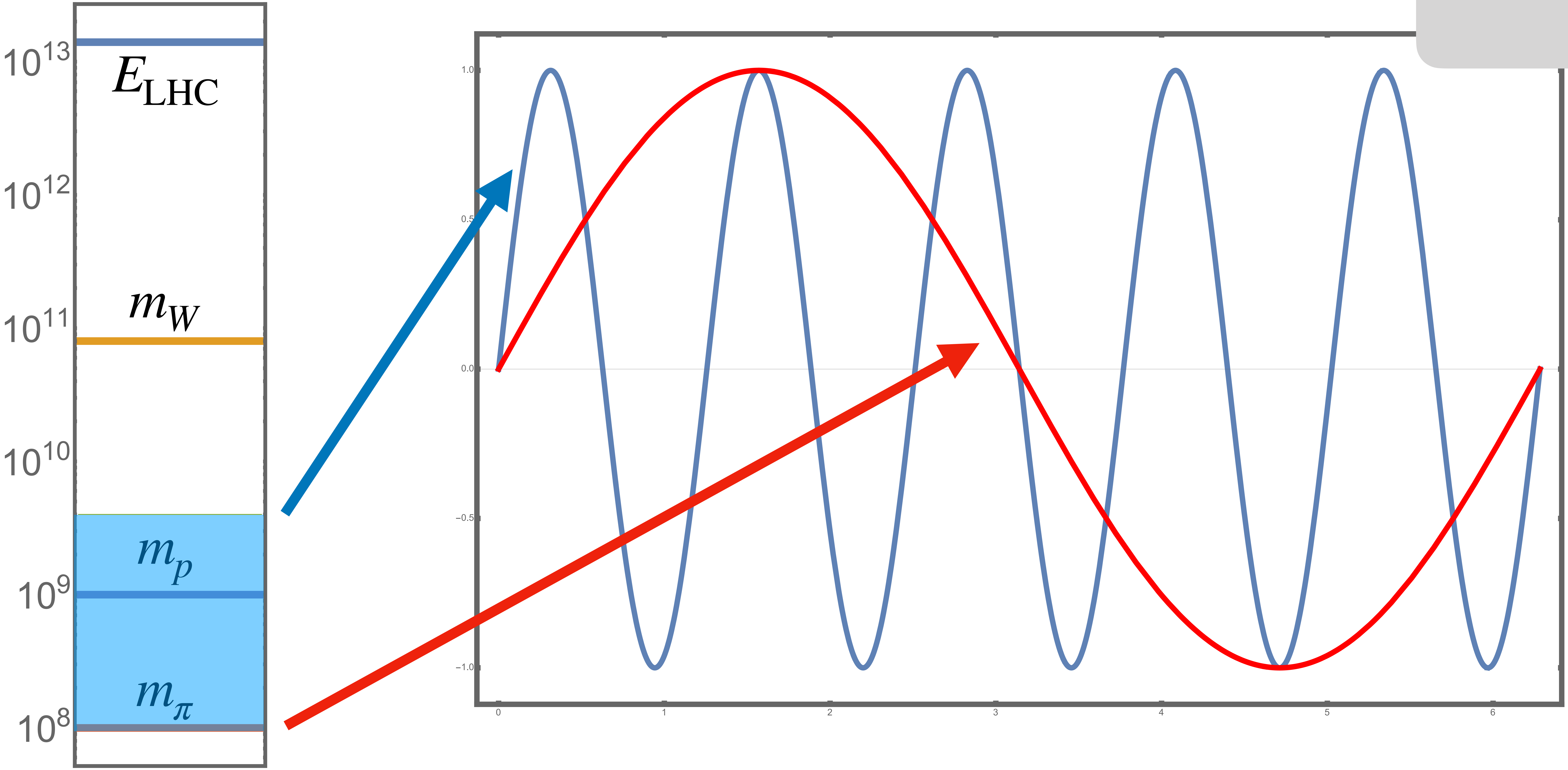
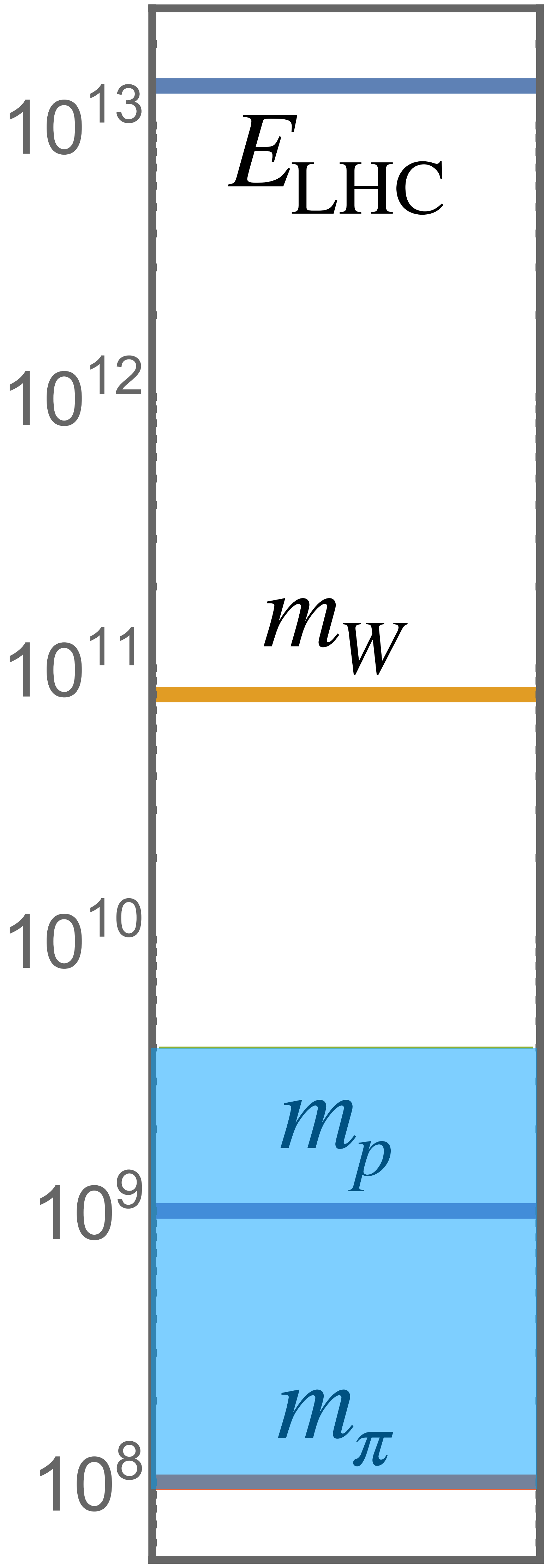


10^{13}
E_{LHC}
10^{12}
m_W
10^{11}
10^{10}
m_p
10^9
m_π
10^8



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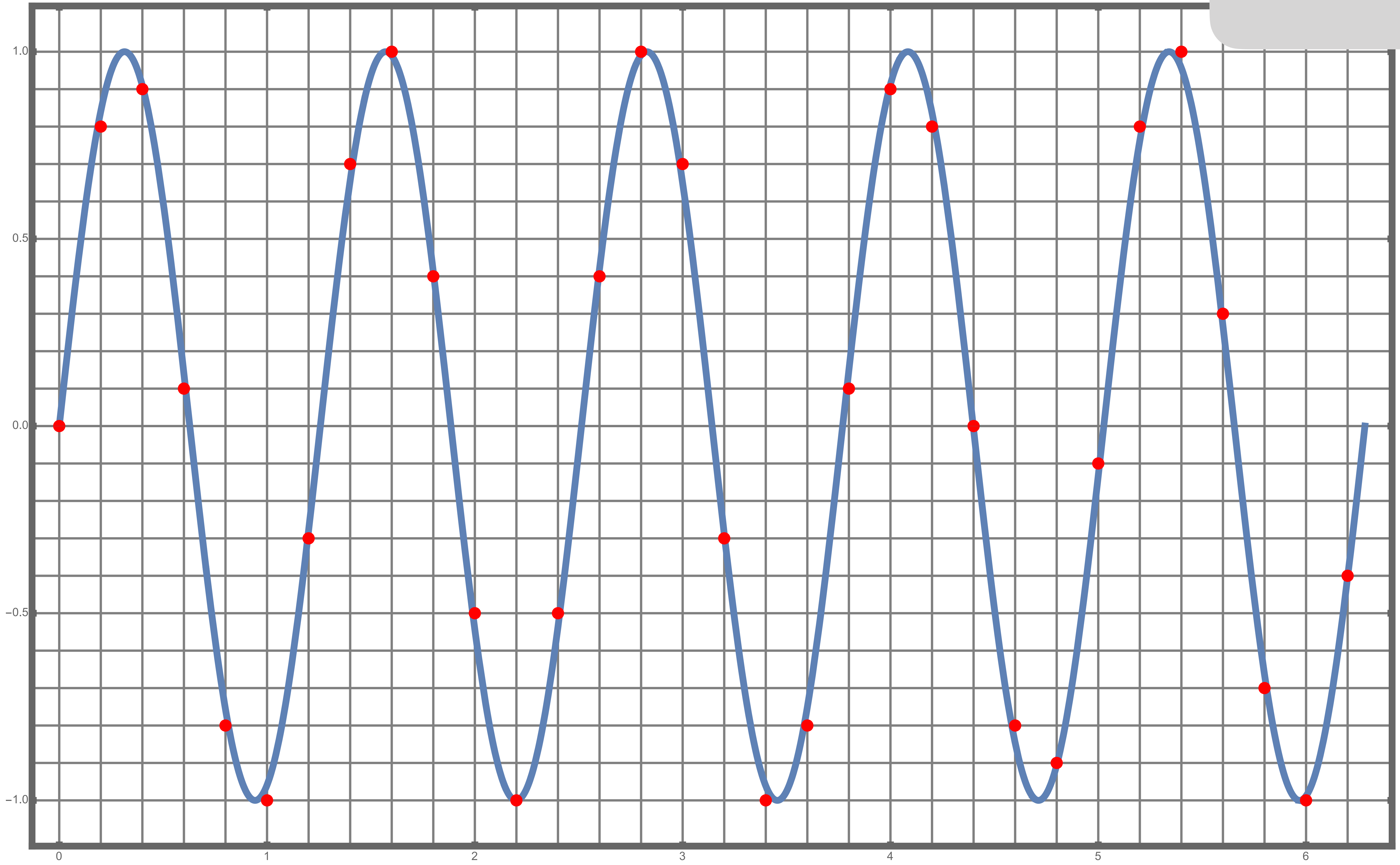

1.0
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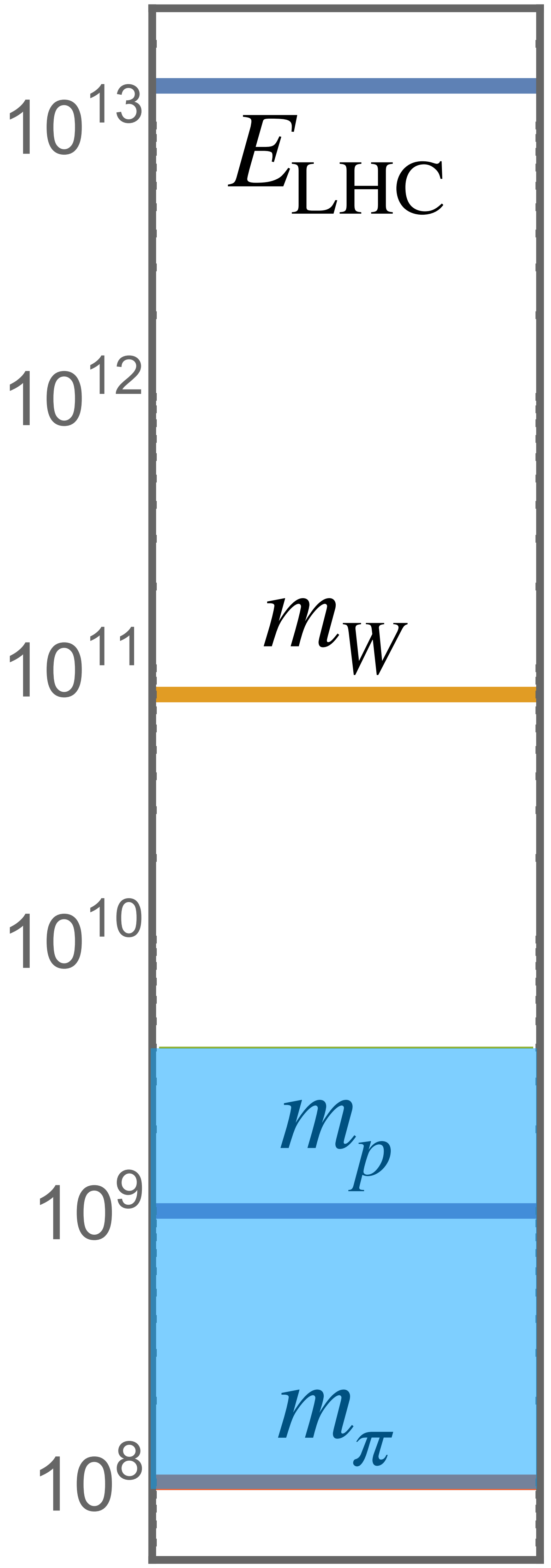
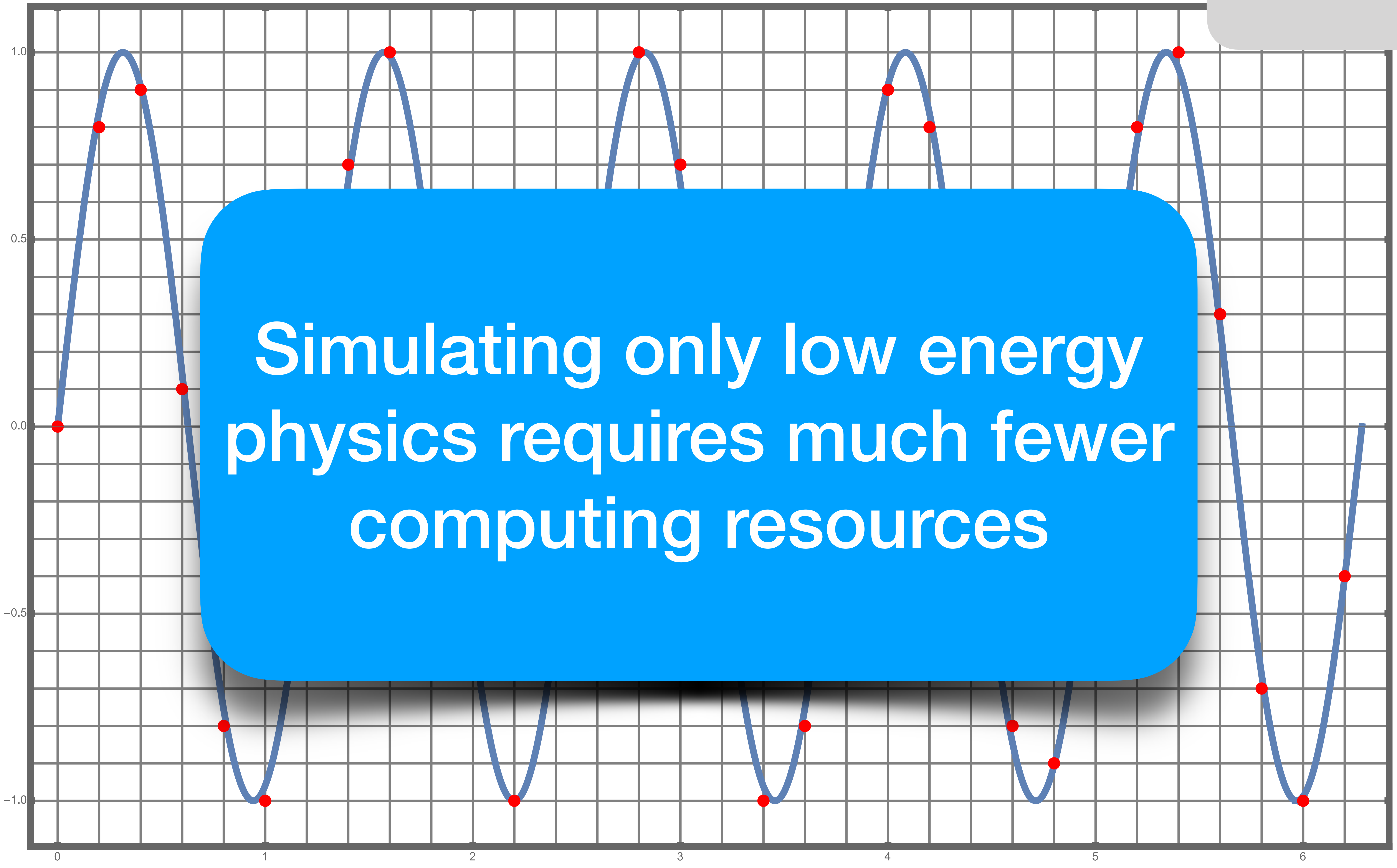
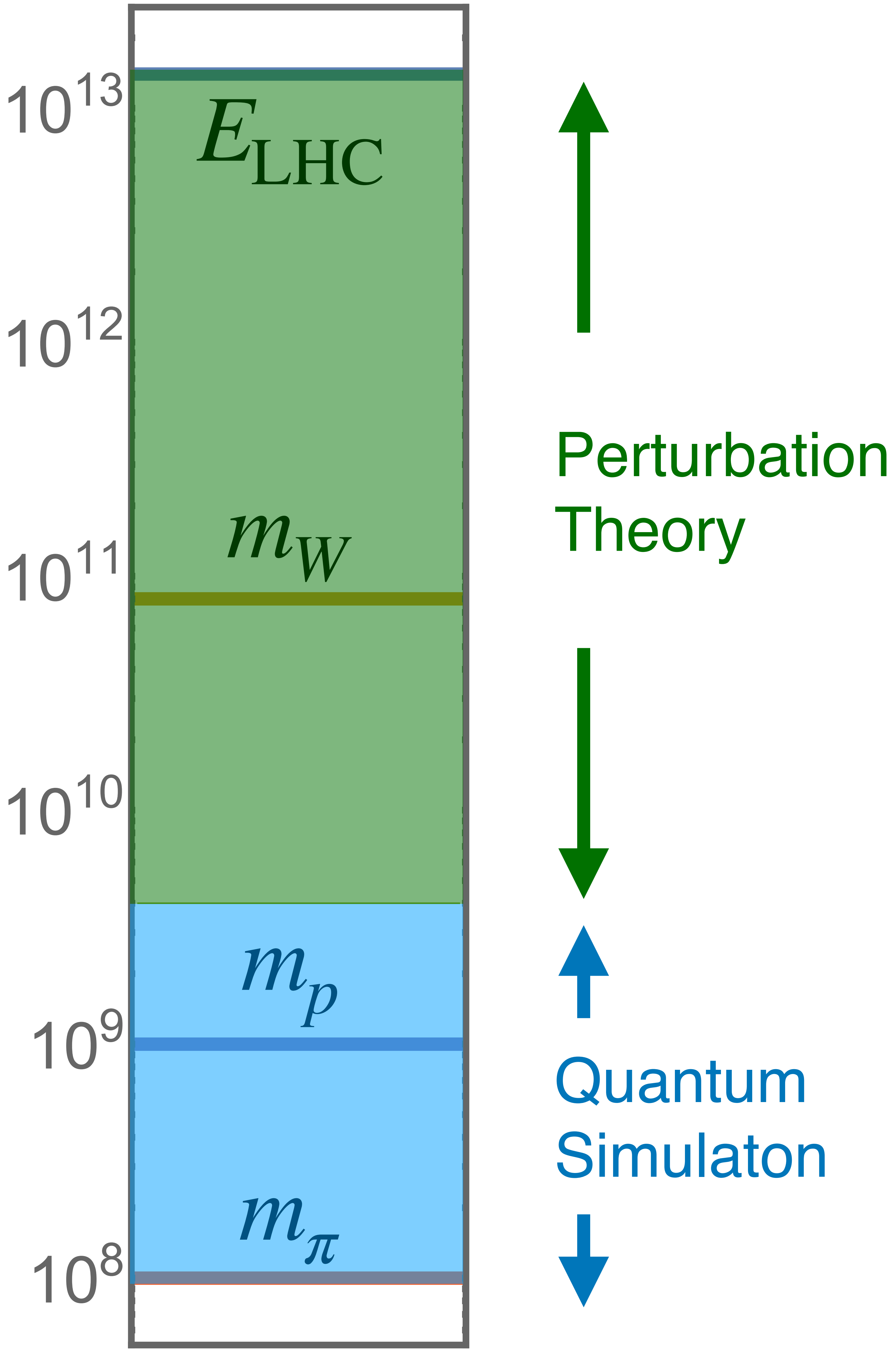




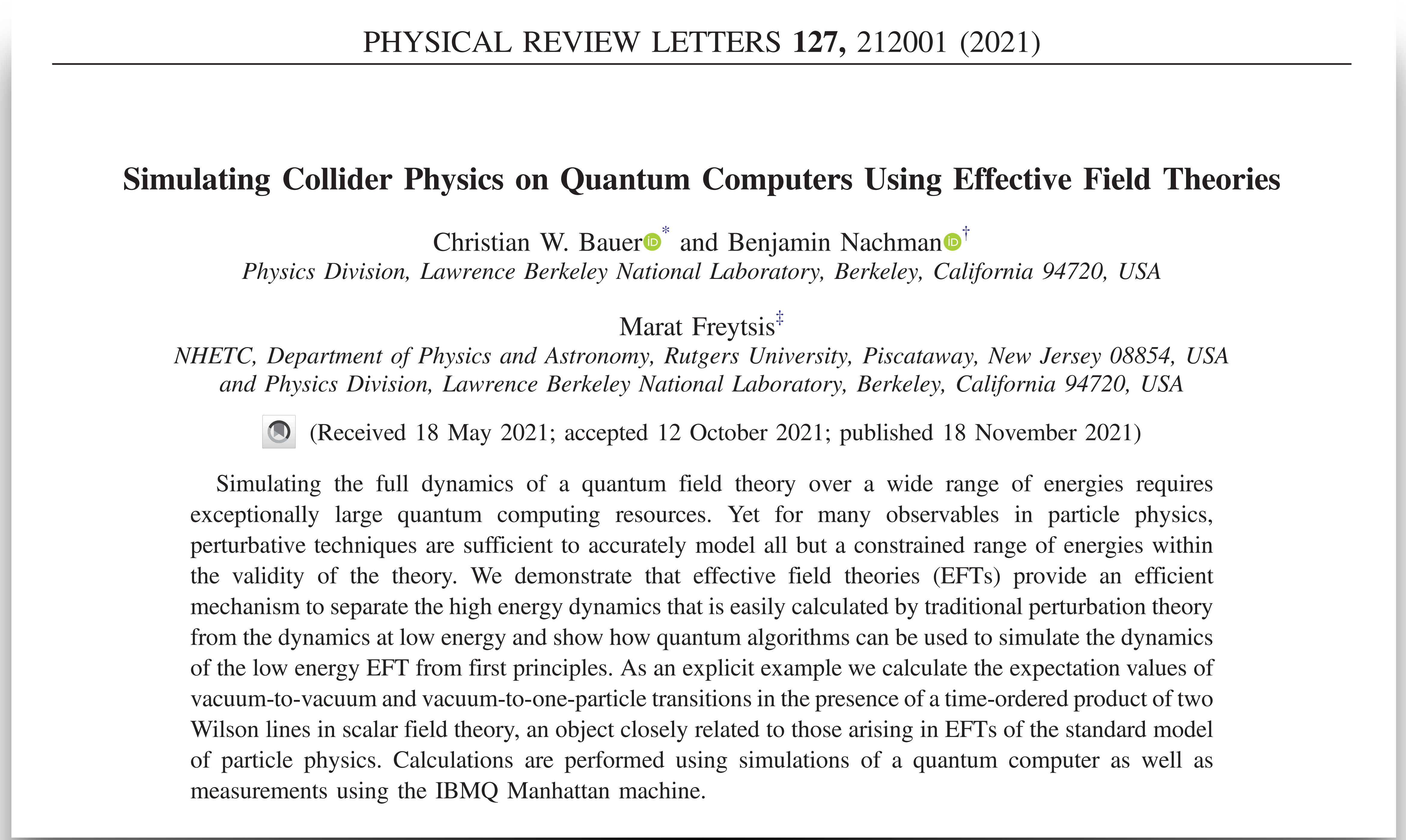
Simulating only low energy physics requires much fewer computing resources



Remaining question: What exactly do we compute in perturbation theory and using quantum computing?

Answer requires effective field theory (SCET for collider physics)

1. Use SCET to write observable in terms of matrix elements of long distance operators and matching coefficients
2. Use perturbation theory to compute matching coefficients
3. Use quantum computer to compute long distance matrix elements


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

Simulating Collider Physics on Quantum Computers Using Effective Field Theories

Christian W. Bauer* and Benjamin Nachman†
Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

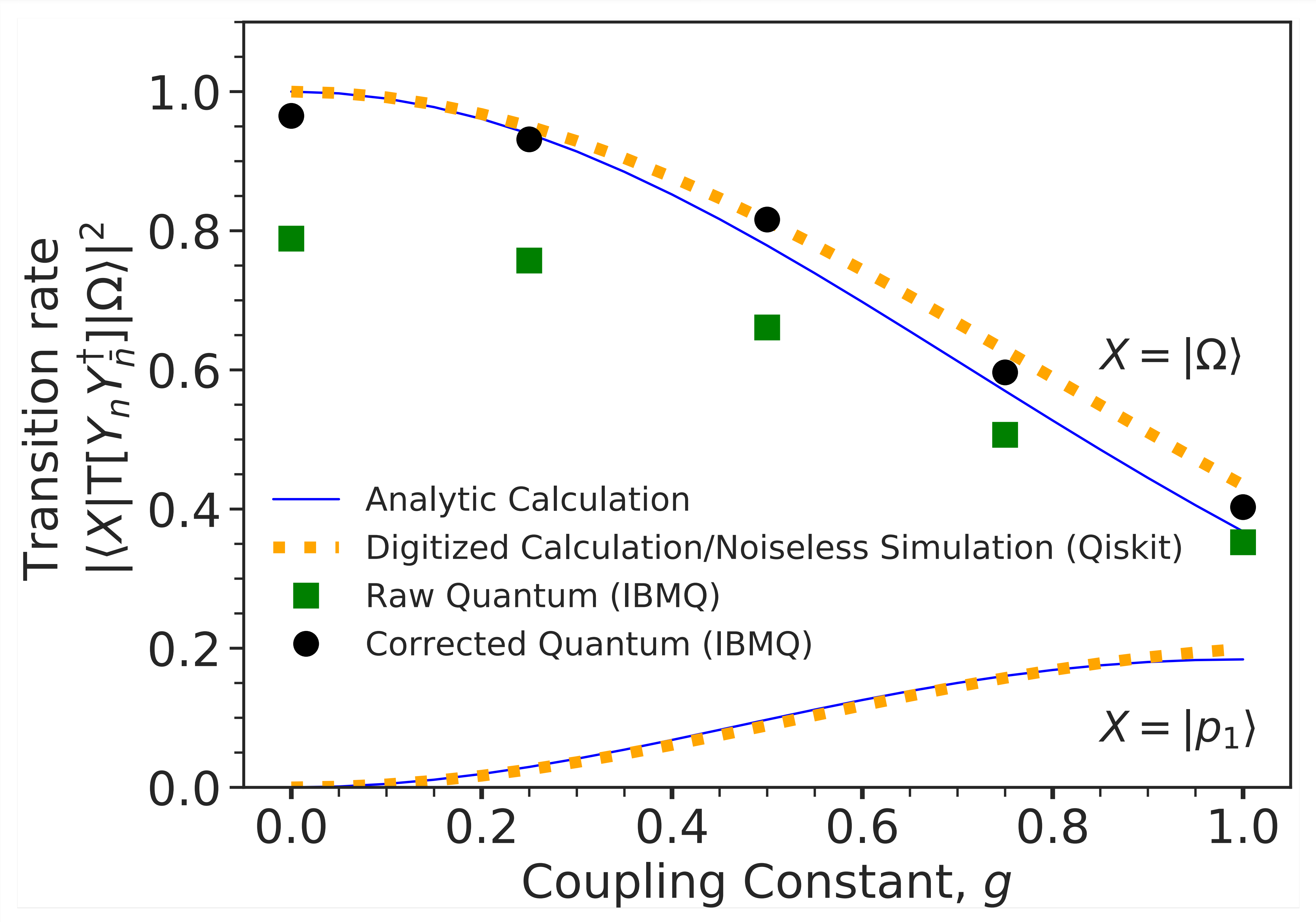
Marat Freytsis‡
NHETC, Department of Physics and Astronomy, Rutgers University, Piscataway, New Jersey 08854, USA and Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

(Received 18 May 2021; accepted 12 October 2021; published 18 November 2021)

Simulating the full dynamics of a quantum field theory over a wide range of energies requires exceptionally large quantum computing resources. Yet for many observables in particle physics, perturbative techniques are sufficient to accurately model all but a constrained range of energies within the validity of the theory. We demonstrate that effective field theories (EFTs) provide an efficient mechanism to separate the high energy dynamics that is easily calculated by traditional perturbation theory from the dynamics at low energy and show how quantum algorithms can be used to simulate the dynamics of the low energy EFT from first principles. As an explicit example we calculate the expectation values of vacuum-to-vacuum and vacuum-to-one-particle transitions in the presence of a time-ordered product of two Wilson lines in scalar field theory, an object closely related to those arising in EFTs of the standard model of particle physics. Calculations are performed using simulations of a quantum computer as well as measurements using the IBMQ Manhattan machine.

Can ontain results that agree with theory expectations from quantum hardware

Soft matrix elements (expectation values of Wilson lines) can be computed efficiently on quantum computers



Find Theory Formulation for SU(3)

Quantum Simulations Research

There are many different parts of the theory that need to be worked out when formulating a Hamiltonian lattice gauge theory

1. How to formulate a lattice theory that reproduces SU(3) in the limit of vanishing lattice spacing
   - Whether to add any additional expansions in the theory
2. What basis to choose for the Hilbert space
3. How to implement gauge invariance
4. How to truncate the theory (how to choose a discrete set of field values)

Goal is a Hamiltonian Lattice theory that reproduces QCD in continuum limit

A Trailhead for Quantum Simulation of SU(3) Yang-Mills Lattice Gauge Theory in the Local Multiplet Basis

Anthony Ciavarella,[1,*] Natalie Klco,[2,†] and Martin J. Savage[1,‡]

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[2] *Institute for Quantum Information and Matter (IQIM) and Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena CA 91125, USA*

(Dated: February 23, 2021 - 1:41)

arXiv:2101.10227v2

Phys.Rev.D 103 (2021) 9

Part 1: What lattice Hamiltonian to use in the without truncation.

In this case the Kogut-Susskind Hamiltonian is used

$$\hat{H} = \frac{g^2}{2a^{d-2}} \sum_{b,\text{links}} |\hat{\mathbf{E}}^{(b)}|^2 + \frac{1}{2a^{4-d}g^2} \sum_{\text{plaquettes}} \left[6 - \hat{\square}(\mathbf{x}) - \hat{\square}^\dagger(\mathbf{x}) \right]$$

Part 2: How to represent basis to choose for Hilbert space

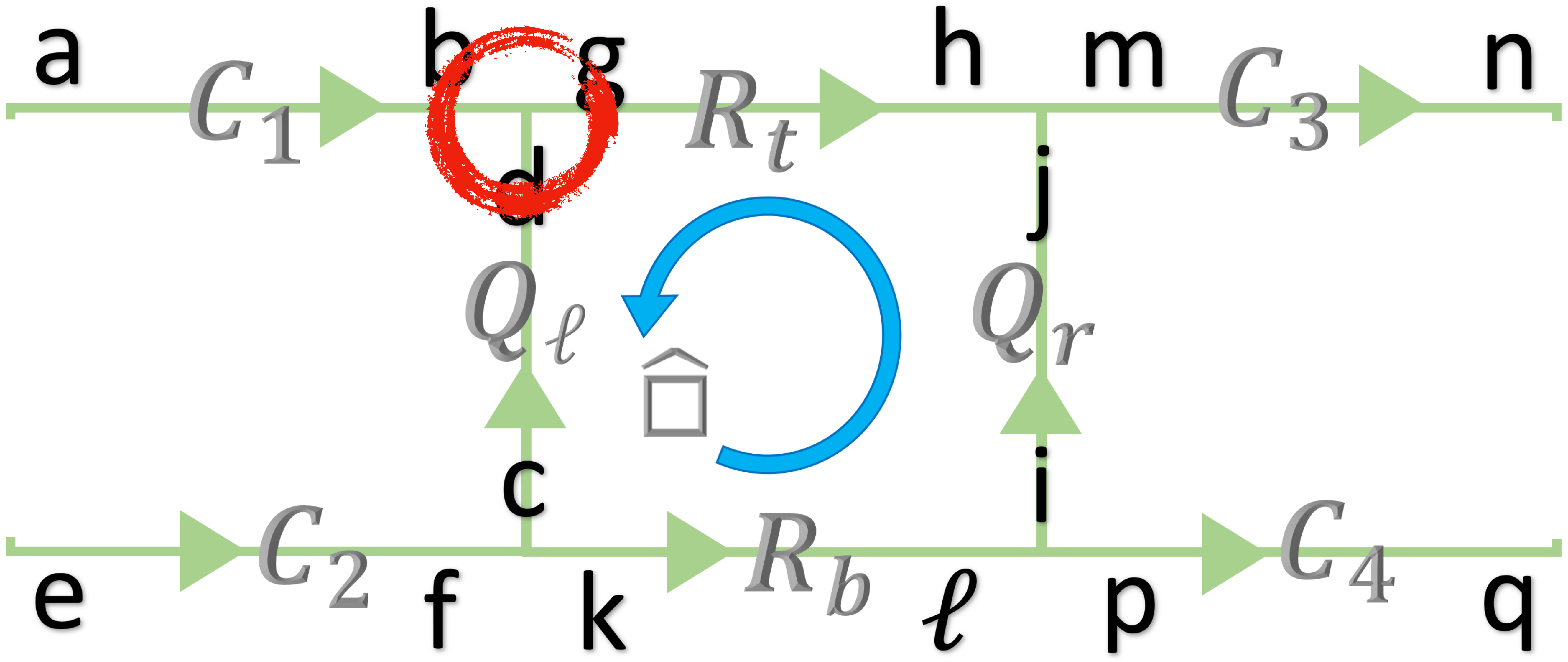
In this case a basis in representation of SU(3) was chosen in which electric Hamiltonian is diagonal

$$\sum_b |\hat{\mathbf{E}}^{(b)}|^2 \, |p,q\rangle = \frac{p^2+q^2+pq+3p+3q}{3} \, |p,q\rangle$$

$$\dim(p,q) = \frac{(p+1)(q+1)(p+q+2)}{2}$$

Part 3: How to implement gauge invariance

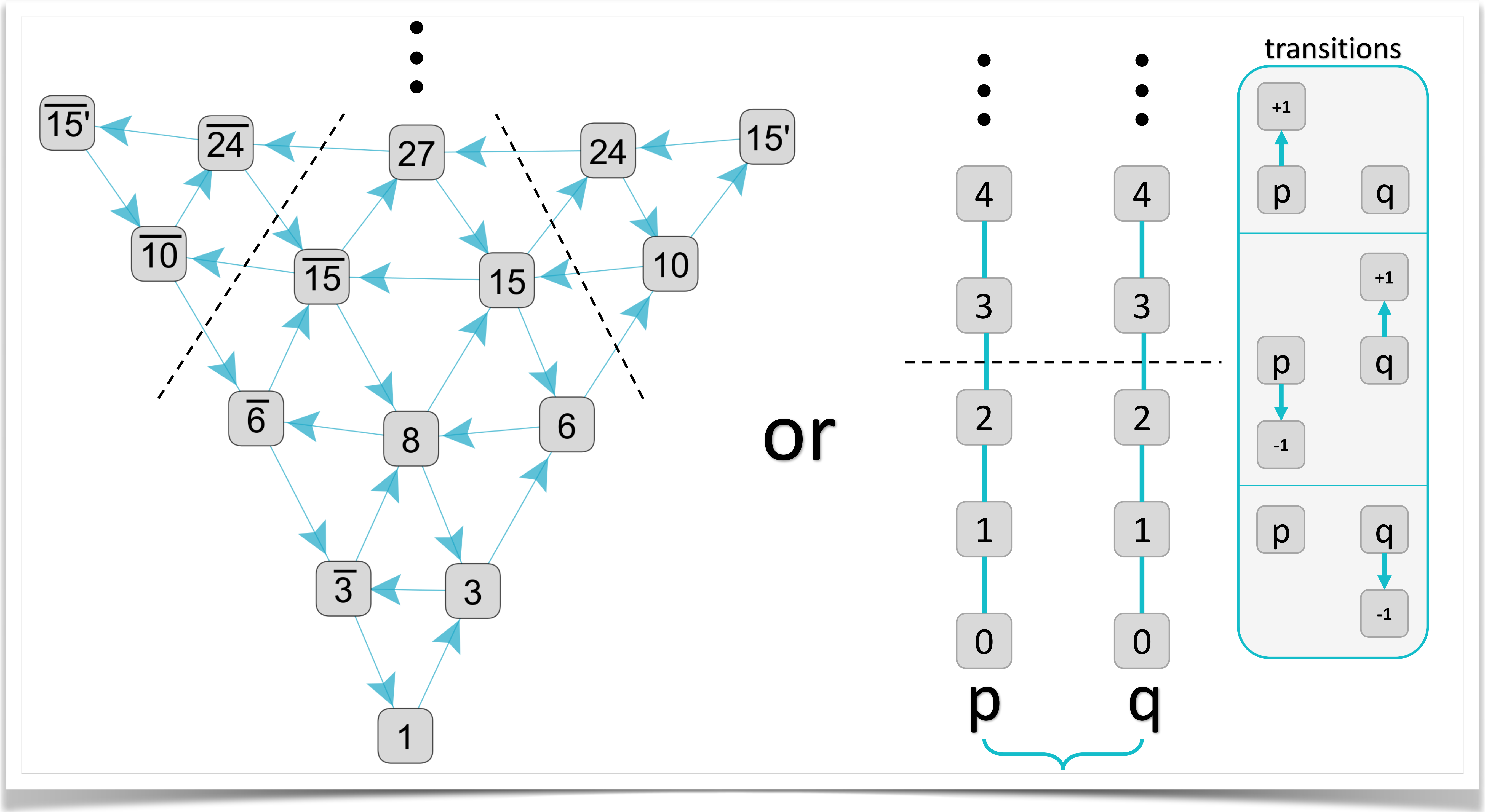
In this case gauge invariance is implemented by requiring that representations satisfy Gauss' law, therefore putting restrictions on each plaquette



$$|\psi_{3pt}\rangle \sim \sum_{b,g,d,\Gamma} \langle \mathbf{C}_1, b, \overline{\mathbf{R}}_t, g | \overline{\mathbf{Q}}_\ell, d\rangle_\Gamma \; |\mathbf{C}_1, a, b\rangle |\mathbf{Q}_\ell, c, d\rangle |\mathbf{R}_t, g, h\rangle$$

Part 4: How to truncate the theory

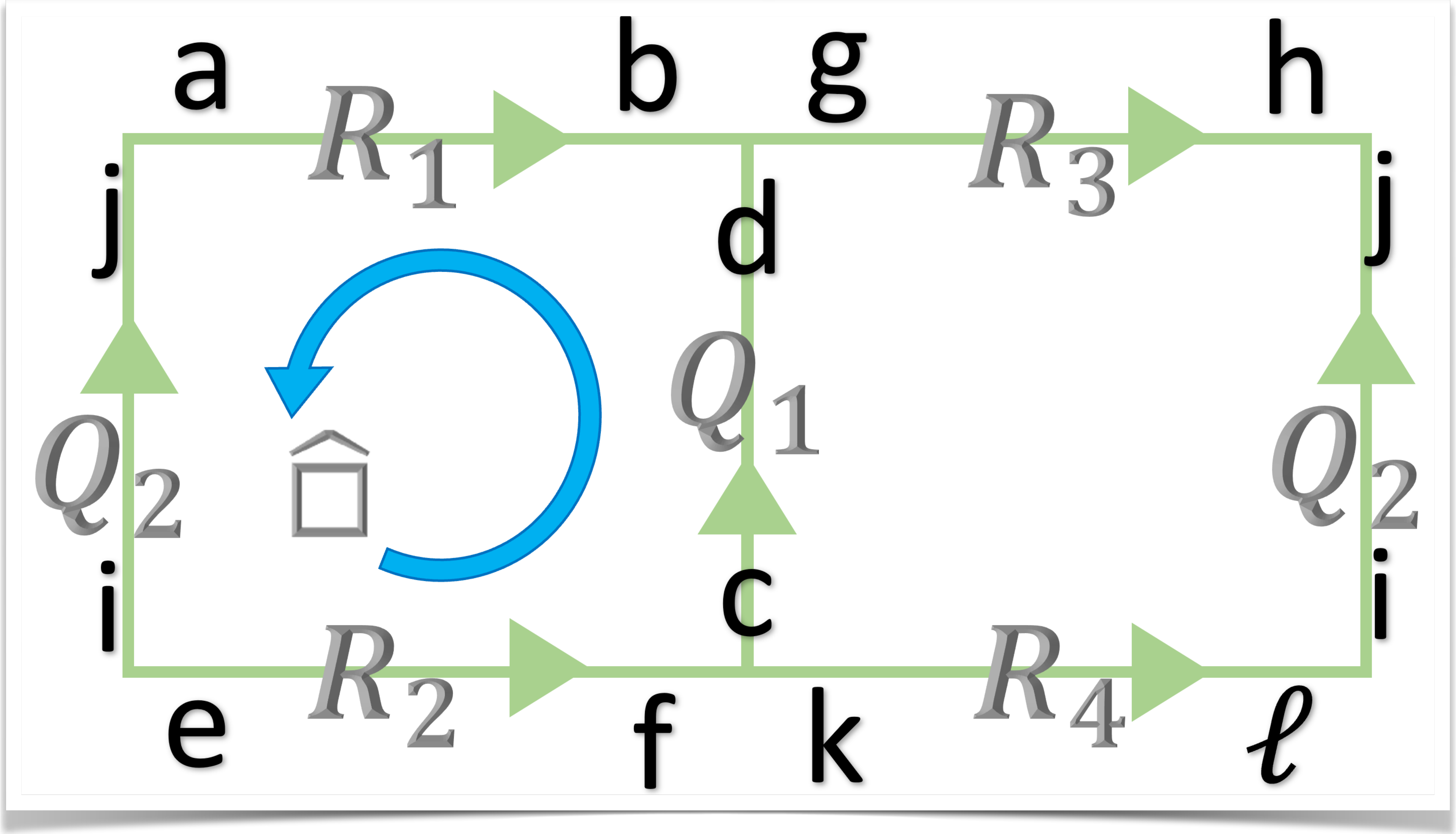
In this case theory is truncated by the maximum allowed p and q values of the representation at each link



All details in place ⇒ theoretical framework. Now needs to work out efficient quantum algorithms and get results from hardware

Paper presented above was first (and essentially still only one) that could do real SU(3) calculations on quantum hardware

Results could be obtained on a 3x2 lattice



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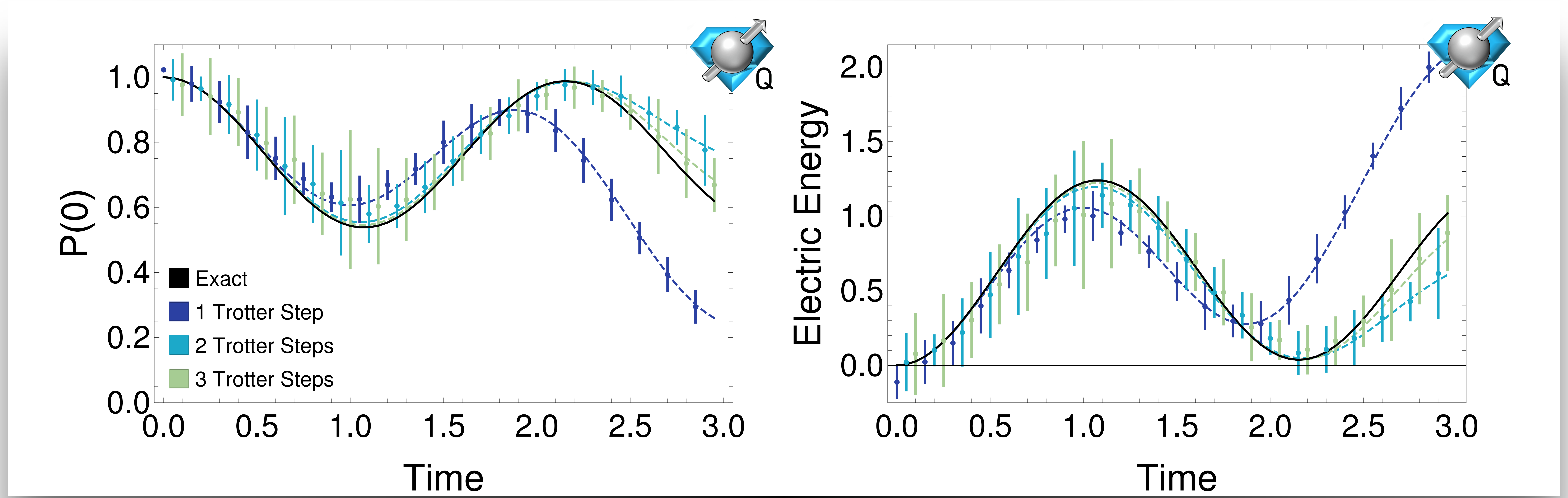


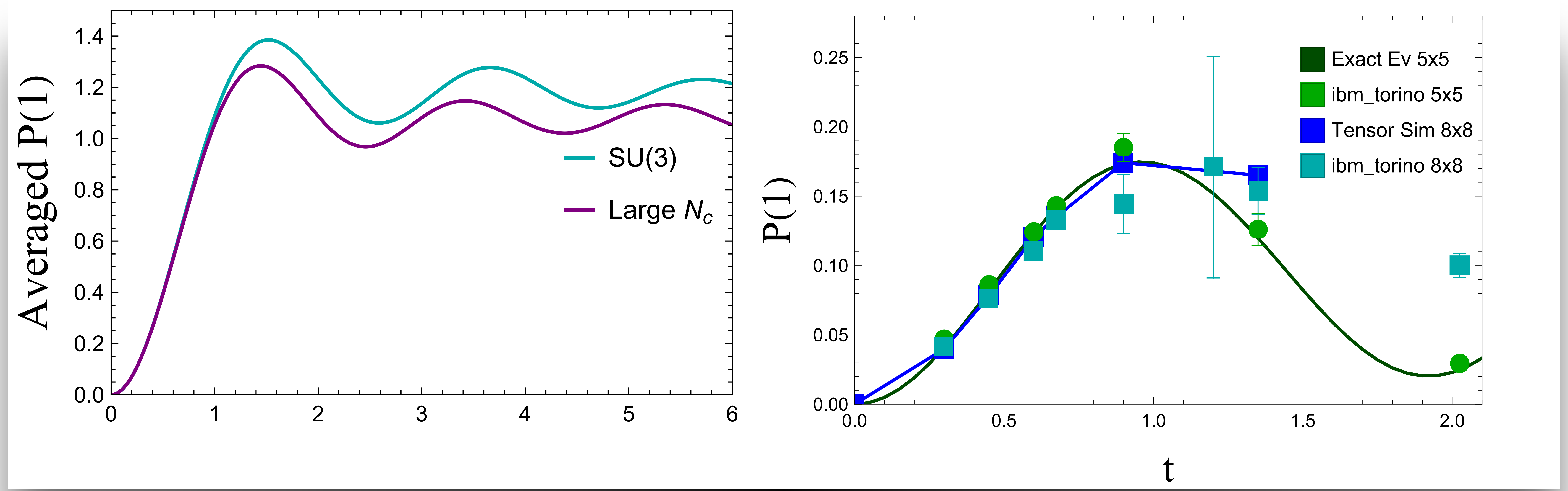
We very recently realized that adding an additional expansion can lead to dramatic simplifications in the lattice theory

1. How to formulate a lattice theory that reproduces SU(3) in the limit of vanishing lattice spacing
   - Whether to add any additional expansions in the theory
2. What basis to choose for the Hilbert space
3. How to implement gauge invariance
4. How to truncate the theory (how to choose a discrete set of field values)
5. …

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

Gives dramatic simplifications on the size of the allowed Hilbert space and dramatically simplifies interactions

Results obtained on 8x8 lattice (25 times more plaquettes than previous best)



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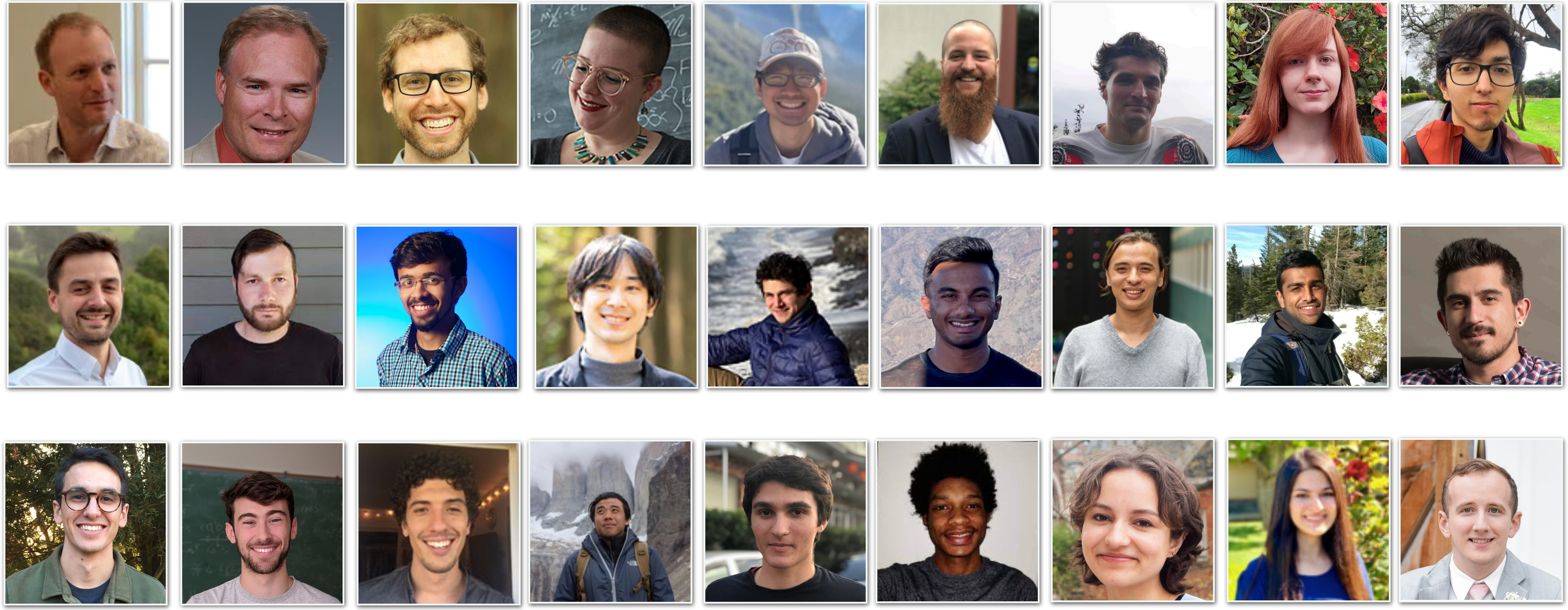
I believe that this opens the door for quantum simulation of QCD through a systematic expansion, where higher order effects can be included as computing hardware improves

Quantum computers open the door to perform currenty unattainable simulations

Using Effective Field Theories takes best advantage of quantum hardware

This will open door for exploring the most fundamental forces of the universe




QUESTIONS?