Quantum computing and simulation

International Conference on Quantum Technologies for HEP

CERN, Nov 2 2022

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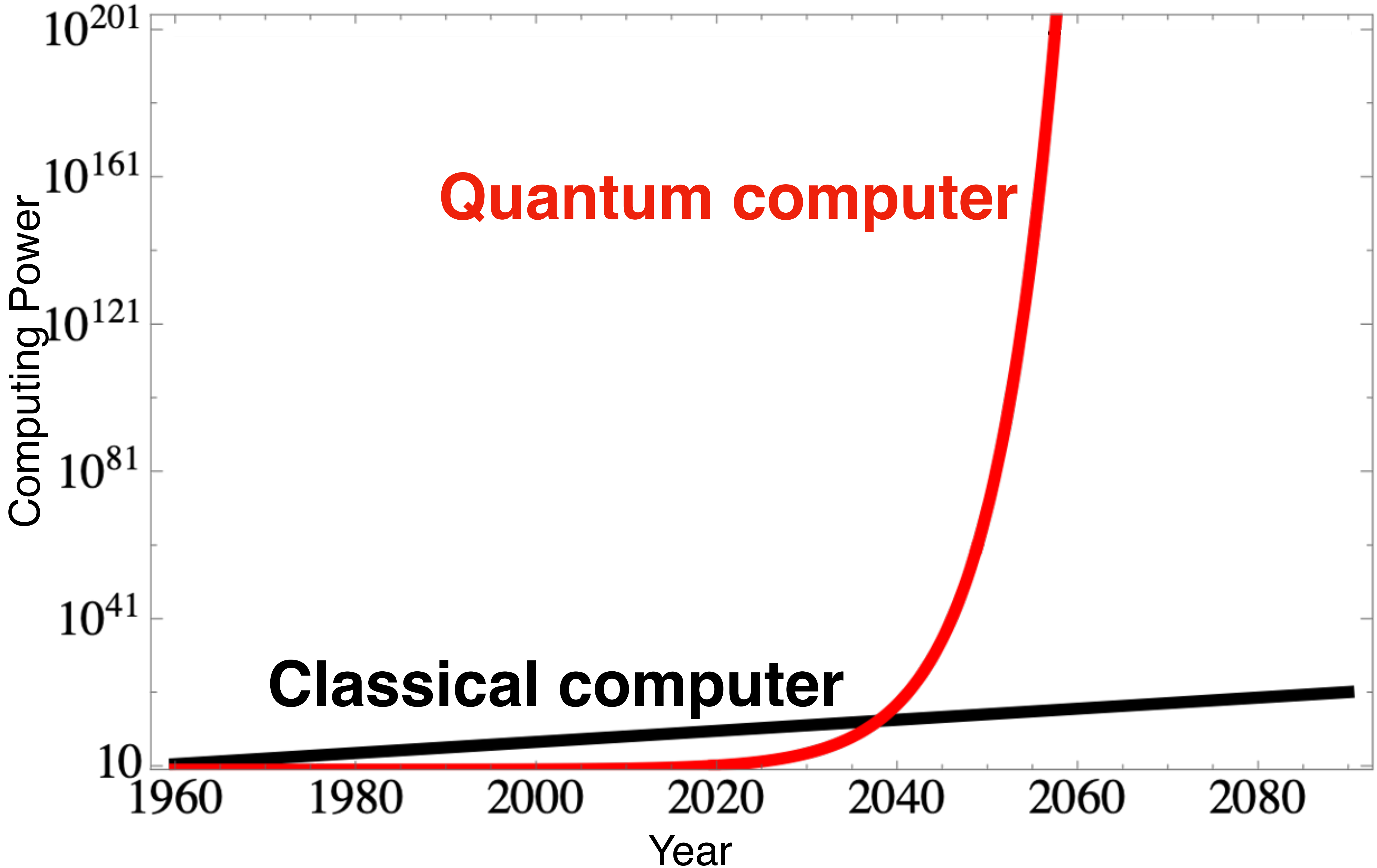
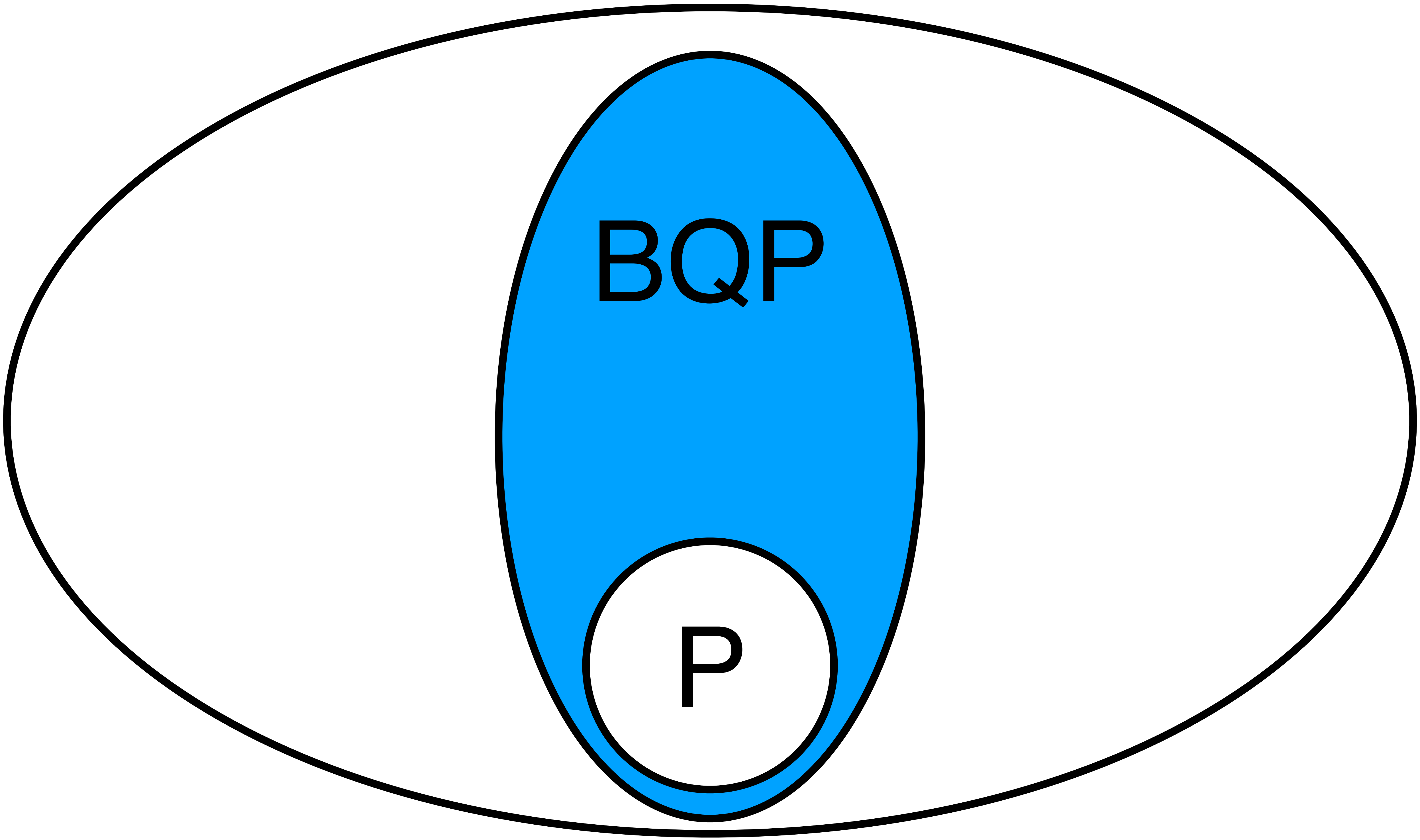
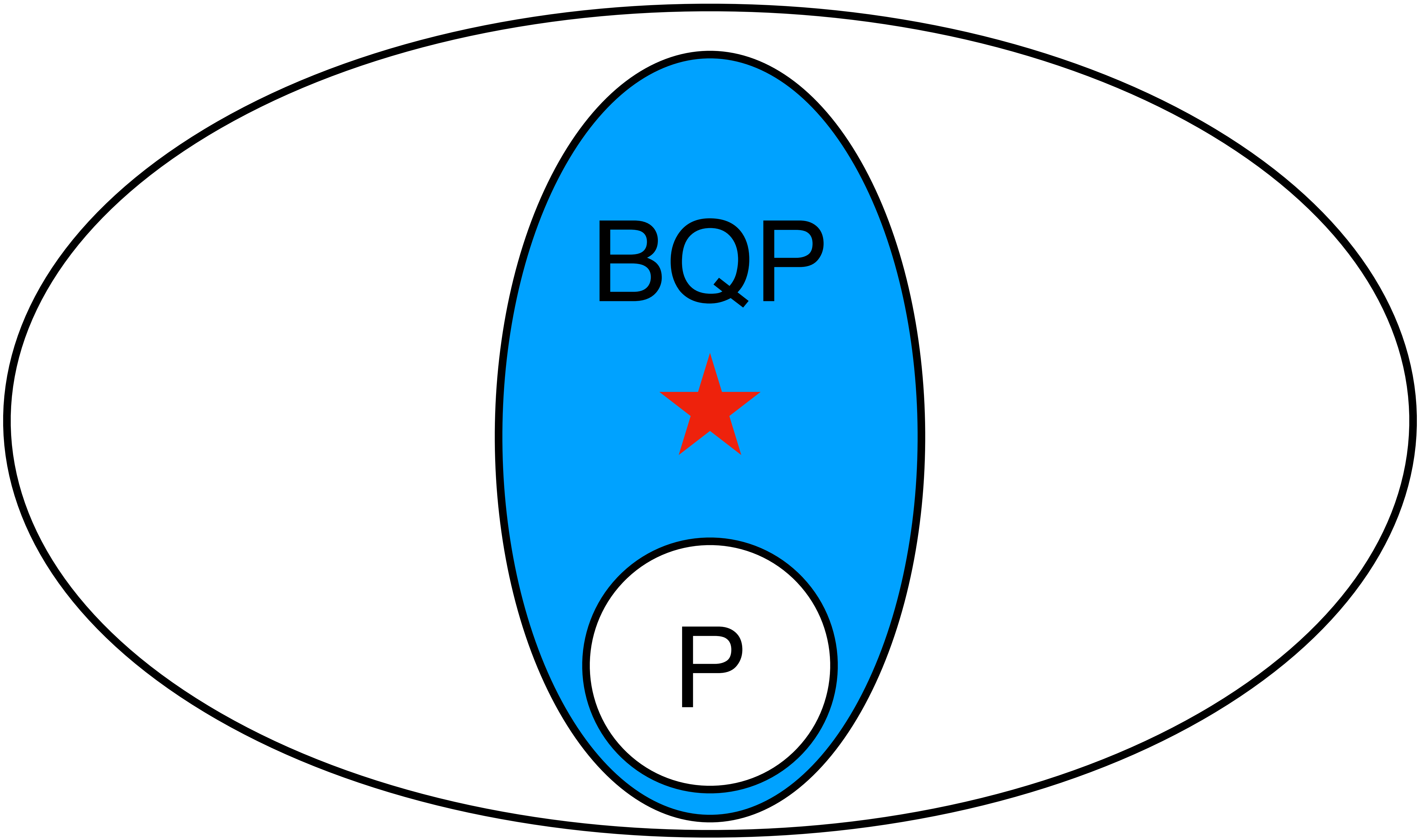
The standard argument for quantum computing is that it outperforms a classical computer exponentially



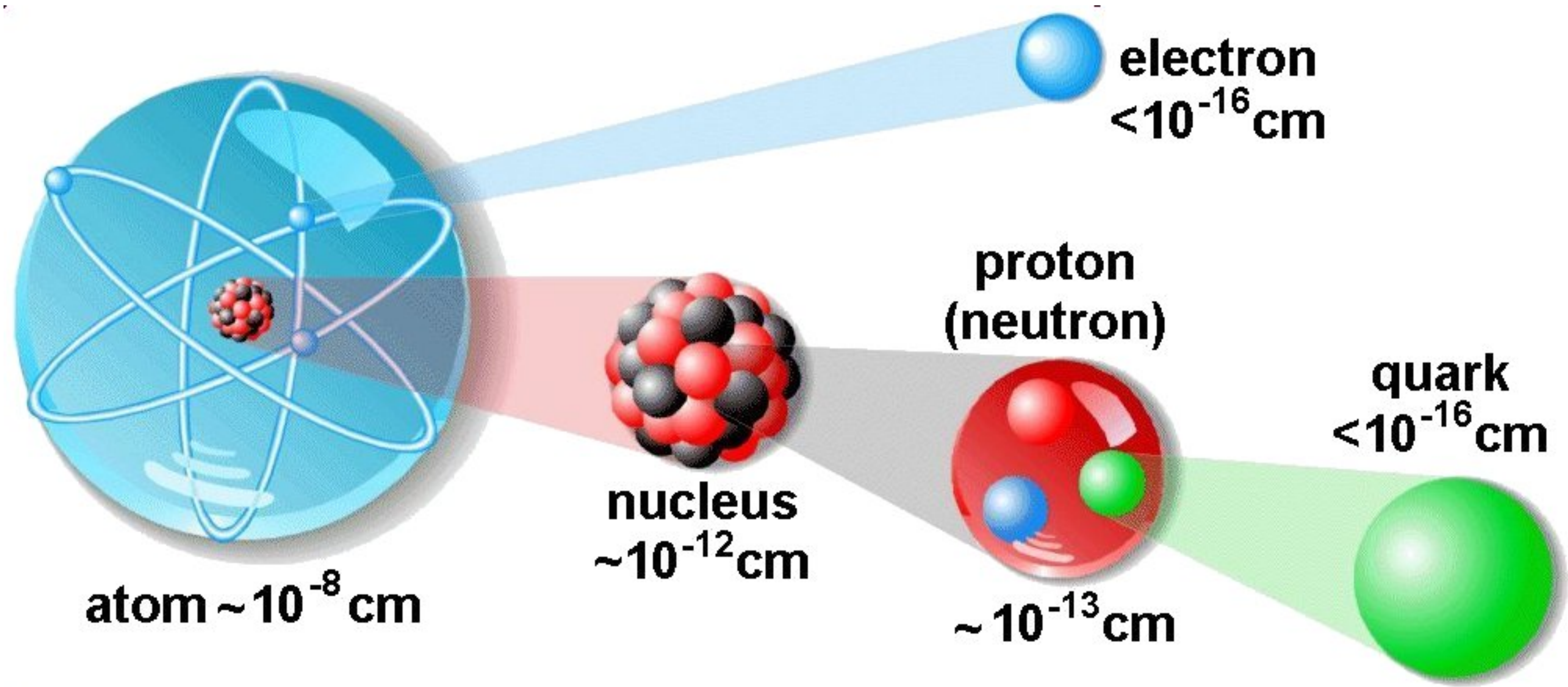
But quantum computers can not solve any problem exponentially faster than a classical computer



Need HEP problems for which a quantum computer outperforms a classical computer

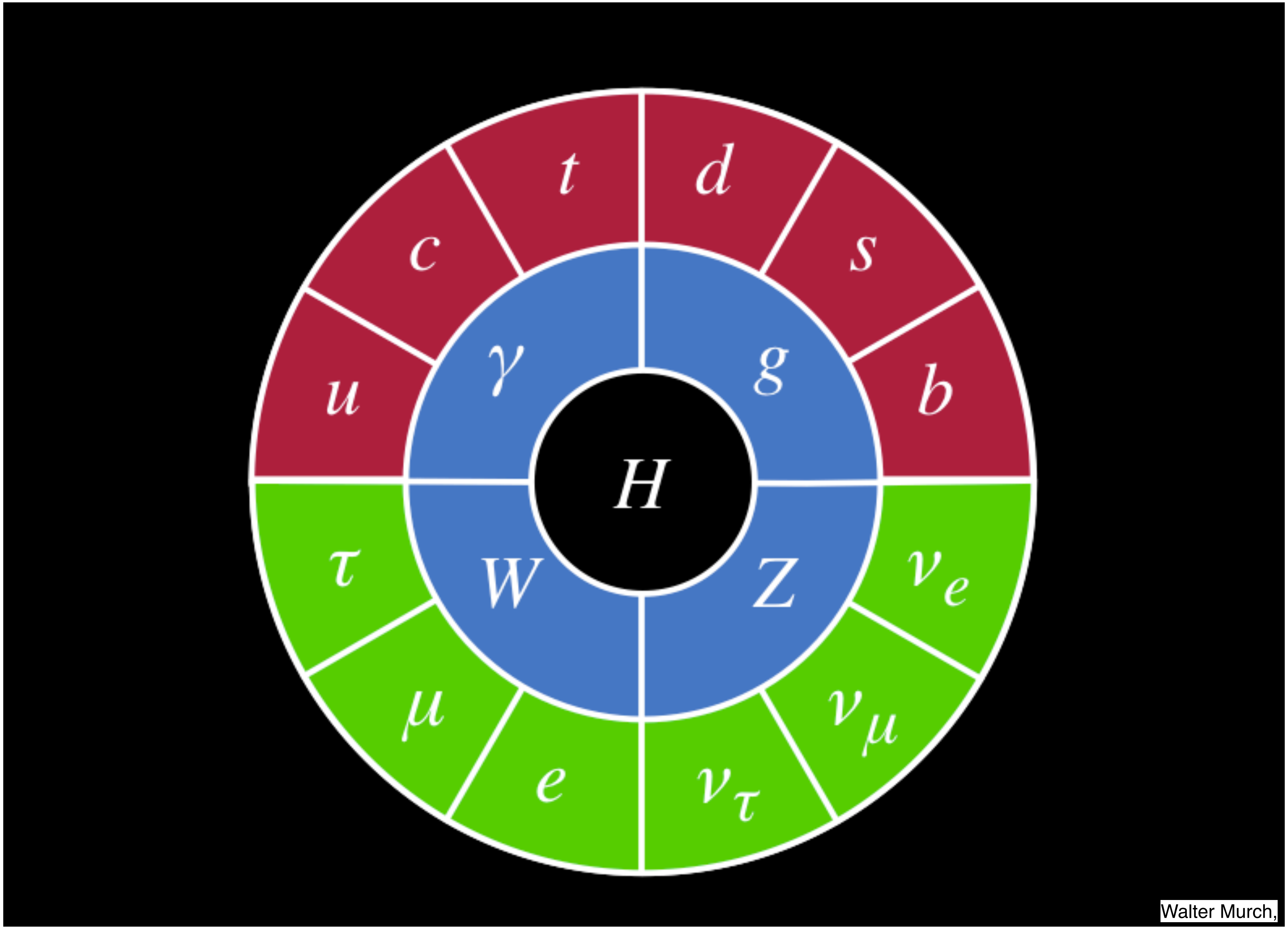


High Energy Physics aims to unravel the secrets of the most fundamental interactions

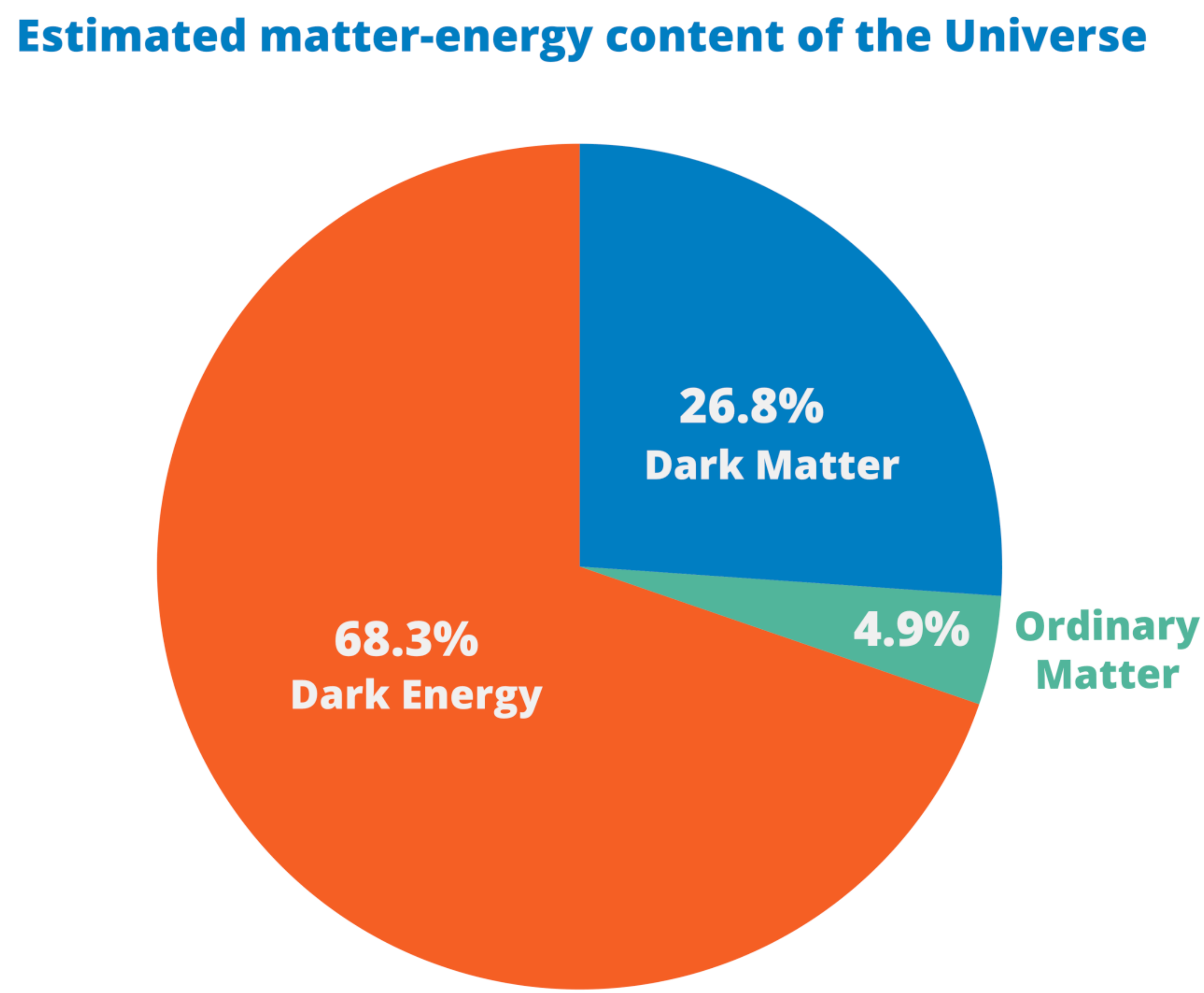


From Quora post

All known interactions of fundamental particles are described by the Standard Model of Particle Physics



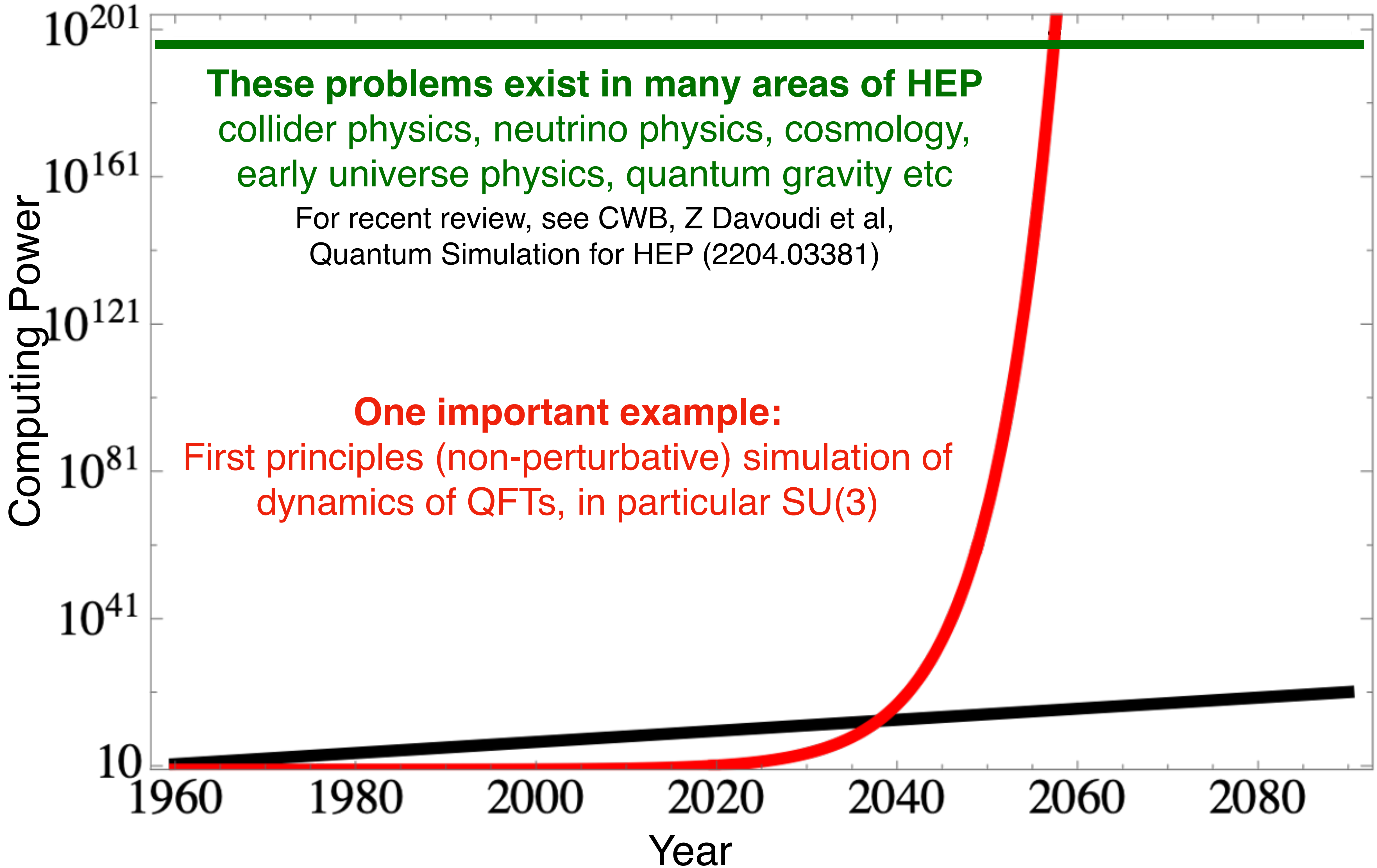
We know that our current theory of nature is incomplete, since it doesn't describe observed effects



ATLAS EXPERIMENT

BERKELEY LAB

The important message is that there are transformational problems in HEP for which QC outperforms CC



Identify the right questions to address

Find appropriate Theory Formulation

Quantum Simulations Research

Find efficient Quantum algorithms

Obtain results on realistic machines (with noise)

Identify the right questions to address

Quantum Simulations Research

Since quantum computers are typically behind classical computers in size, should find optimal problems

Energy rage that can be described by lattice is given by $\frac{1}{Nl} \lesssim E \lesssim \frac{1}{l}$

Size of system scales as $\sim \left(E_{\text{low}}/E_{\text{high}}\right)^3$

Should attempt to use Quantum computer to only address those questions that are impossible using classical computers (non-perturbative)

Effective Theories are the proven tool to isolate certain energy ranges of a problem

Effective theories allow to separate short and long distance physics from one another

One of the holy grails is to determine dynamical properties in scattering processes

Relevant Effective Theory is Soft-Collinear EFT (SCET)

$$\mathrm{d}\sigma = H \otimes J_1 \otimes \ldots \otimes J_n \otimes S$$

Most interesting object in above equation is the soft function S, which lives at the lowest energies

Soft function "knows" about energetic particles only through the directions they travel in (with essentially the speed of light)

In field theory, this is described by Wilson lines along light-like paths

Big problem for making predictions: Soft function is non-perturbative object, no known way to compute it

Effective theories allow to separate short and long distance physics from one another

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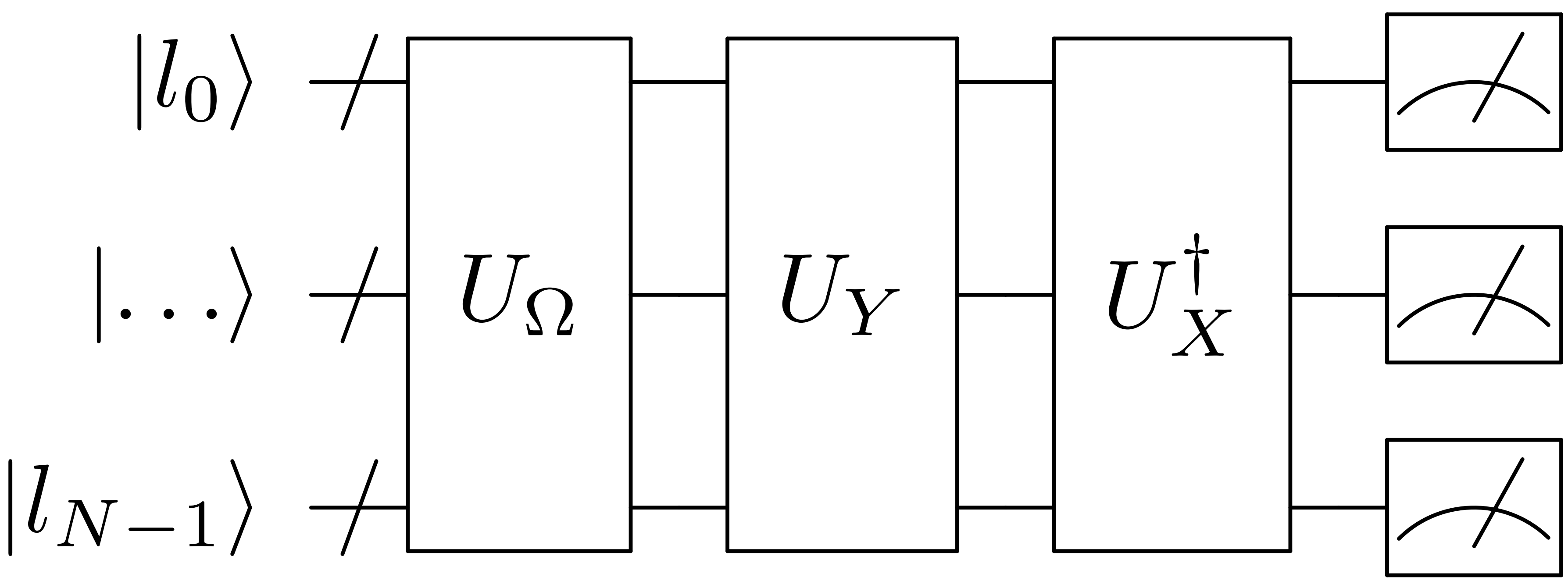
Can Quantum Computers perform first principles calculation of soft function?



CWB, Freytsis, Nachman, PRL 127 (2021), 212001

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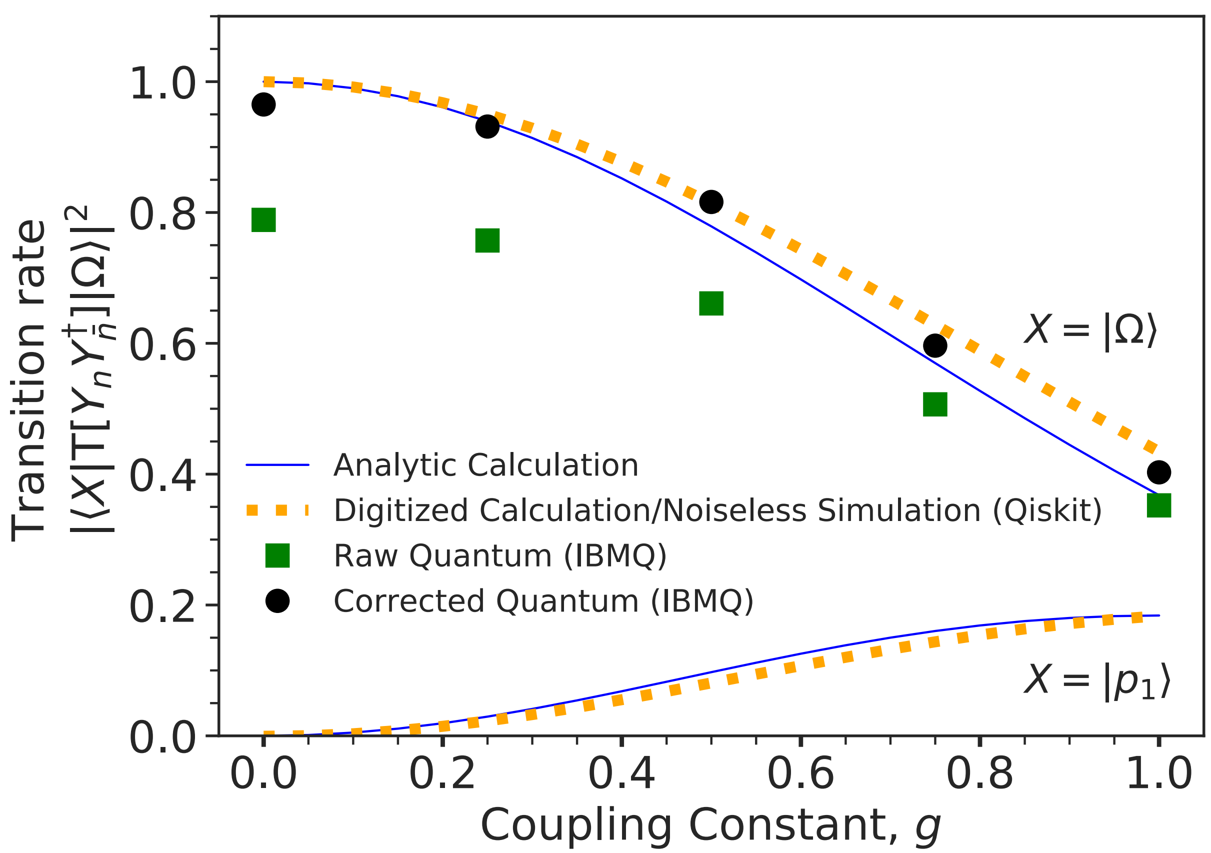

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Find appropriate Theory Formulation

Quantum Simulations Research

There are many theoretical issues one needs to deal with when implementing field theories

- Turn infinite dimensional Hilbert space into finite dimensional
- Find optimal ways to protect or utilize underlying symmetries
- Understand systematic uncertainties given truncations used

Give one example using U(1) gauge theory

$$H = \int \mathrm{d}^d x \left[E^2(x) + B^2(x) \right]$$

E and B have simple relations to the gauge field (working in $A_0 = 0$ gauge)

$$\overrightarrow{B}(x) = \overrightarrow{\nabla} \times \overrightarrow{A}(x) \qquad \overrightarrow{E}(x) = -\partial \overrightarrow{A}(x)/\partial t$$

One can write Lattice version of Hamiltonian entirely in terms of rotors and magnetic fields

$$H = \sum_{p \in \text{plaq}} \left[g^2 H_E[R_i] + \frac{1}{g^2} H_M[B_i] \right]$$

Considerable interest in "compact" U(1) gauge theory, where $-\pi < B_i < \pi$

Since $[H_E, H_M] \neq 0$, H_E and H_B can not be diagonalized simultaneously

In limit $g \to \infty$ useful to work in electric basis, where H_E is diagonal

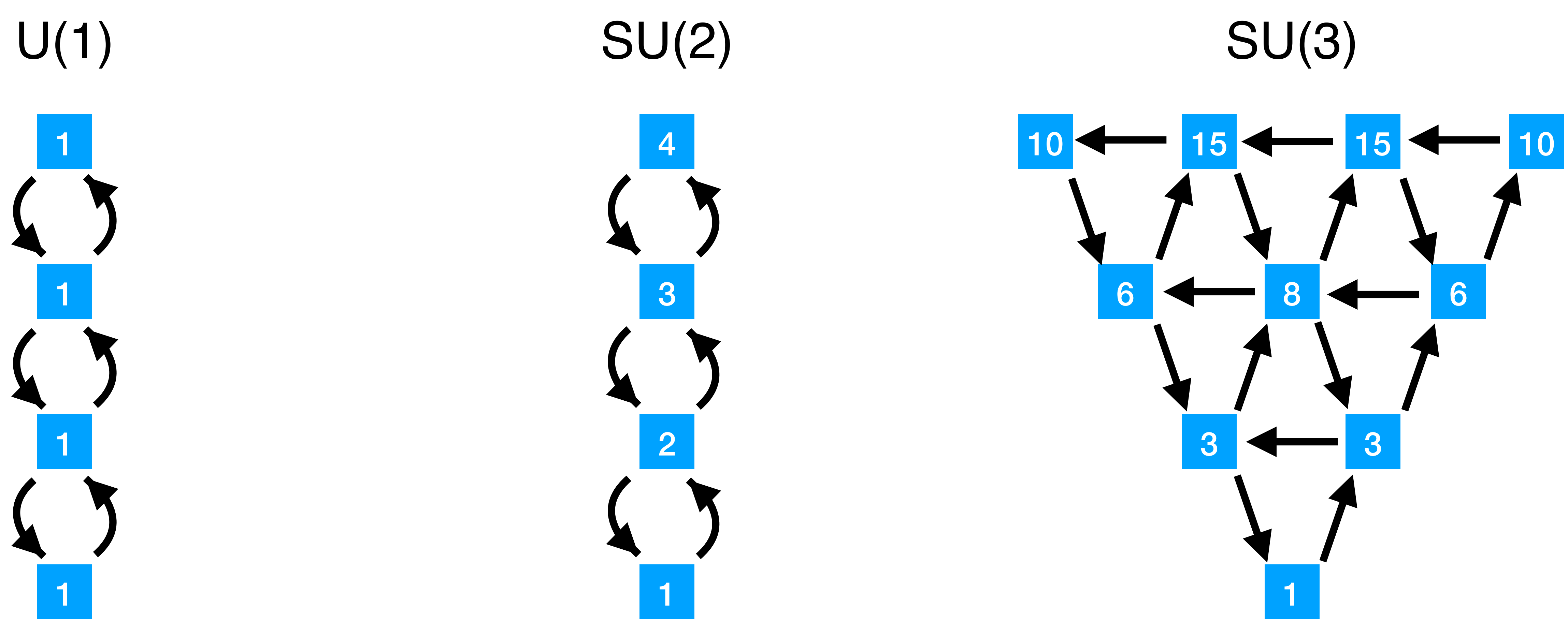
In limit $g \to 0$ useful to work in magnetic basis, where H_B is diagonal

Electric basis is easy to work with, and was basis in original work by Kogut and Susskind

Electric Hamiltonian = kinetic energy in system with symmetry of gauge group

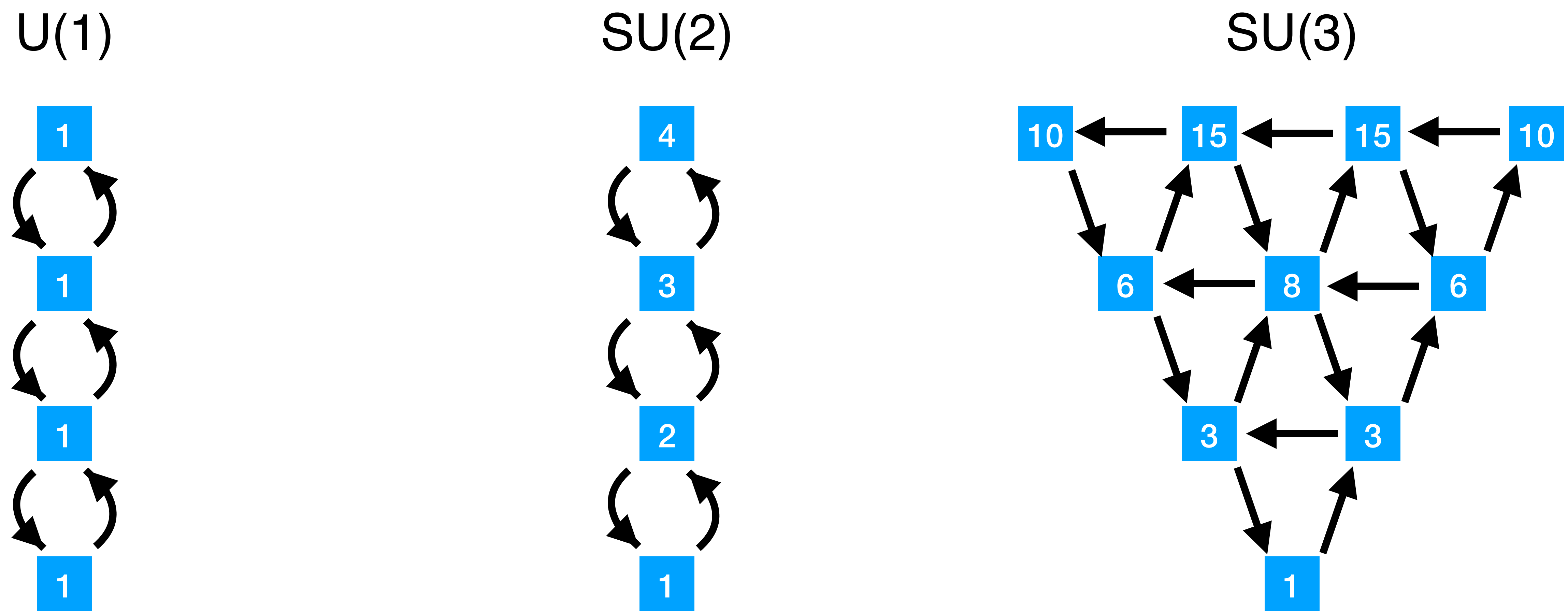
Eigenvalues/functions indexed by irreducible representations of gauge group

Magnetic Hamiltonian gives transitions between representations



Infinite number of representations (continuous gauge field), need to truncate

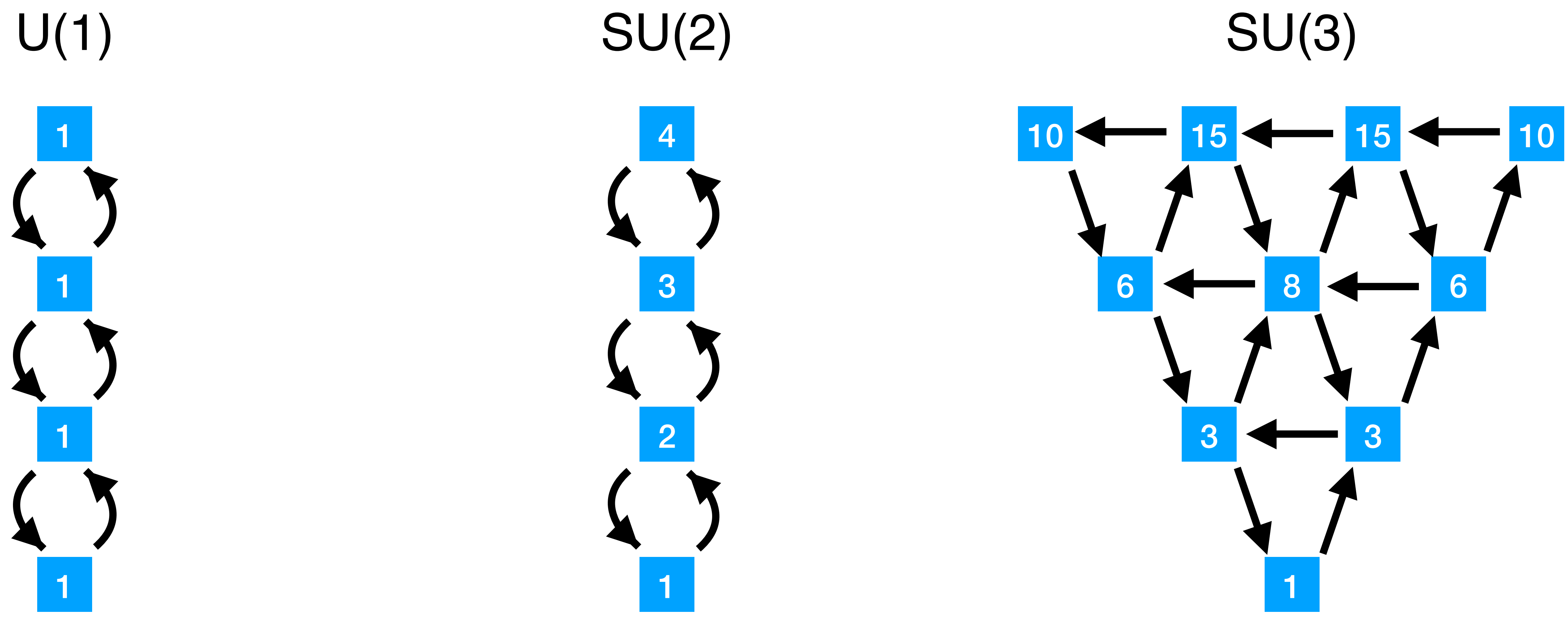
Electric basis is easy to work with, and was basis in original work by Kogut and Susskind



At large coupling, electric Hamiltonian dominates, states in lowest lying representations

Can just keep the lowest few representations (giving rise to Kogut-Susskind basis)

Electric basis is easy to work with, and was basis in original work by Kogut and Susskind



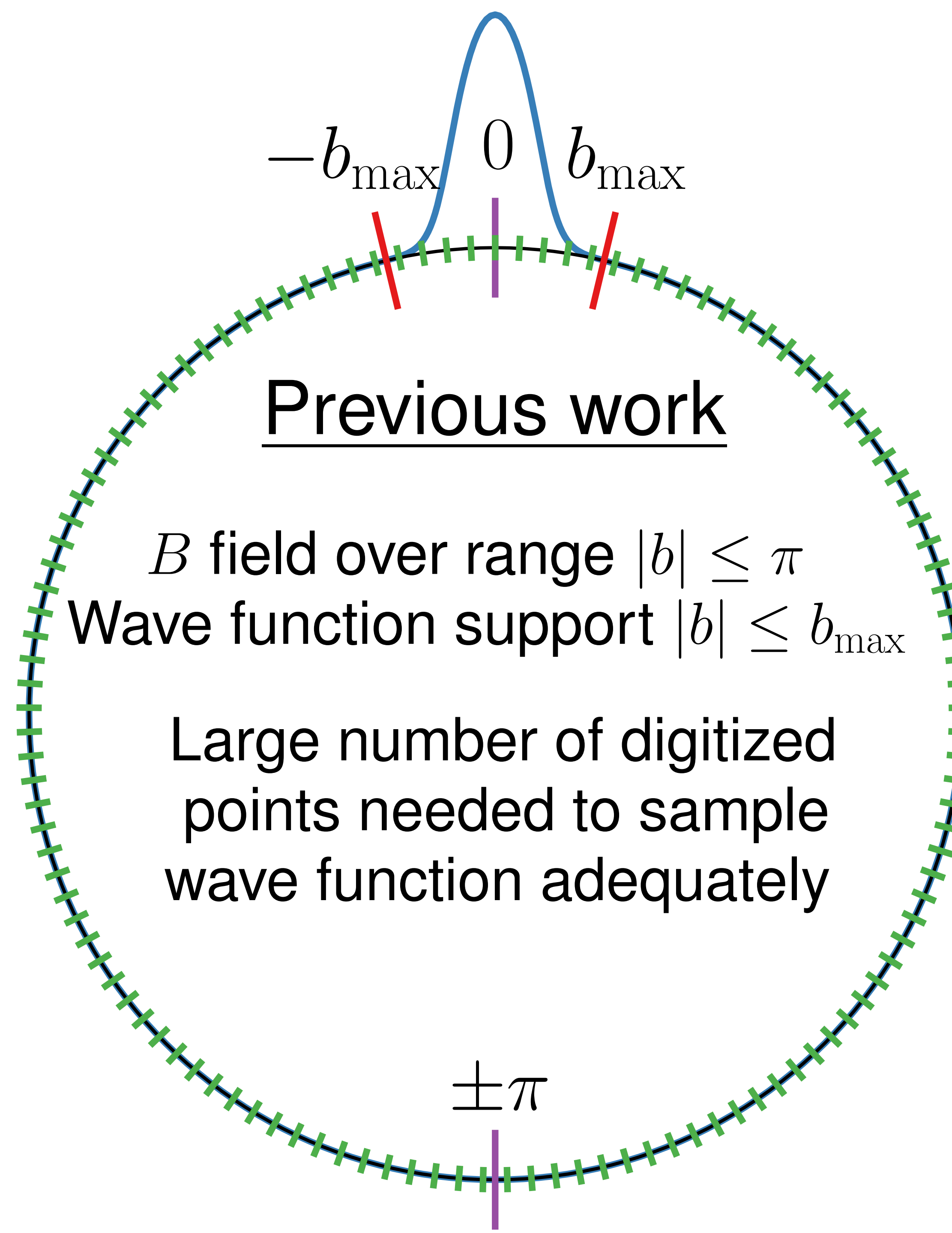
At small coupling, magnetic Hamiltonian dominates, lowest lying states require many representations

Kogut Susskind basis extremely inefficient

At small coupling, better to work directly in magnetic basis

CWB, Grabowska, 2111.08015

- In U(1) theory, representations are 1-dimensional, labeled by index k
- Correspond to the modes of a periodic field
- Keeping only representations up to maximum k amounts turns continuous U(1) group in to discrete $Z_{k_{\max}}$ group
- Amounts to discrete sampling of gauge potential



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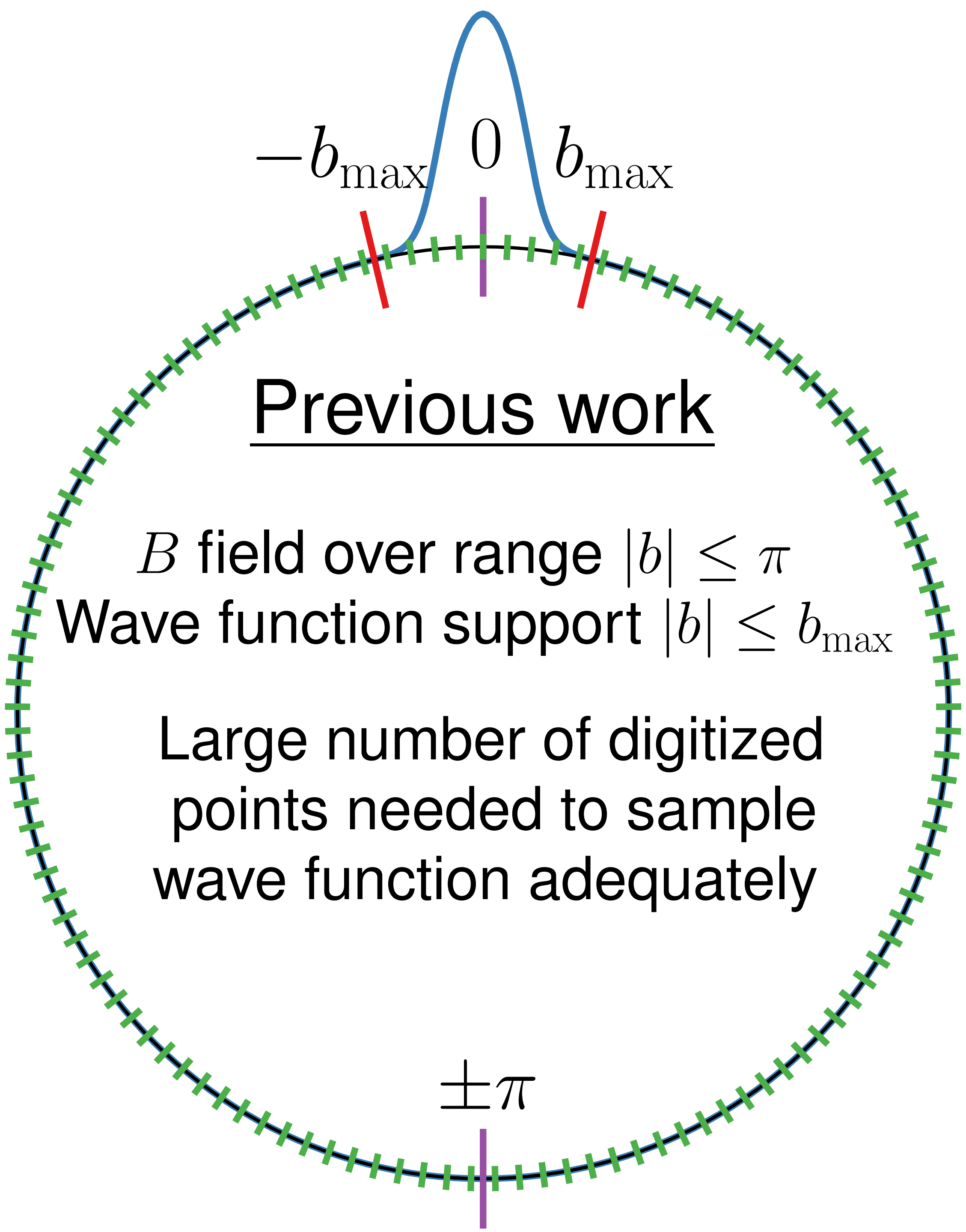
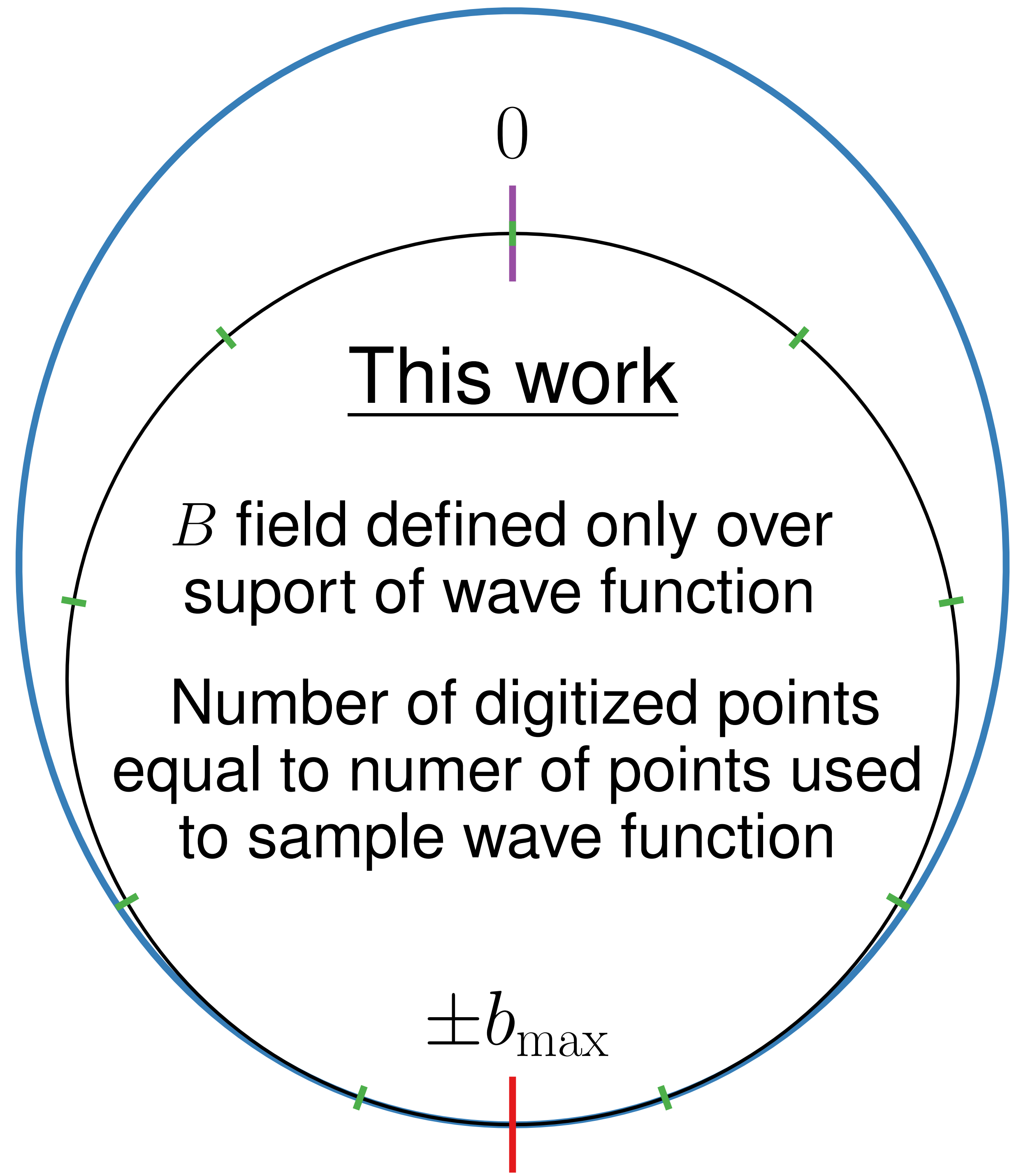
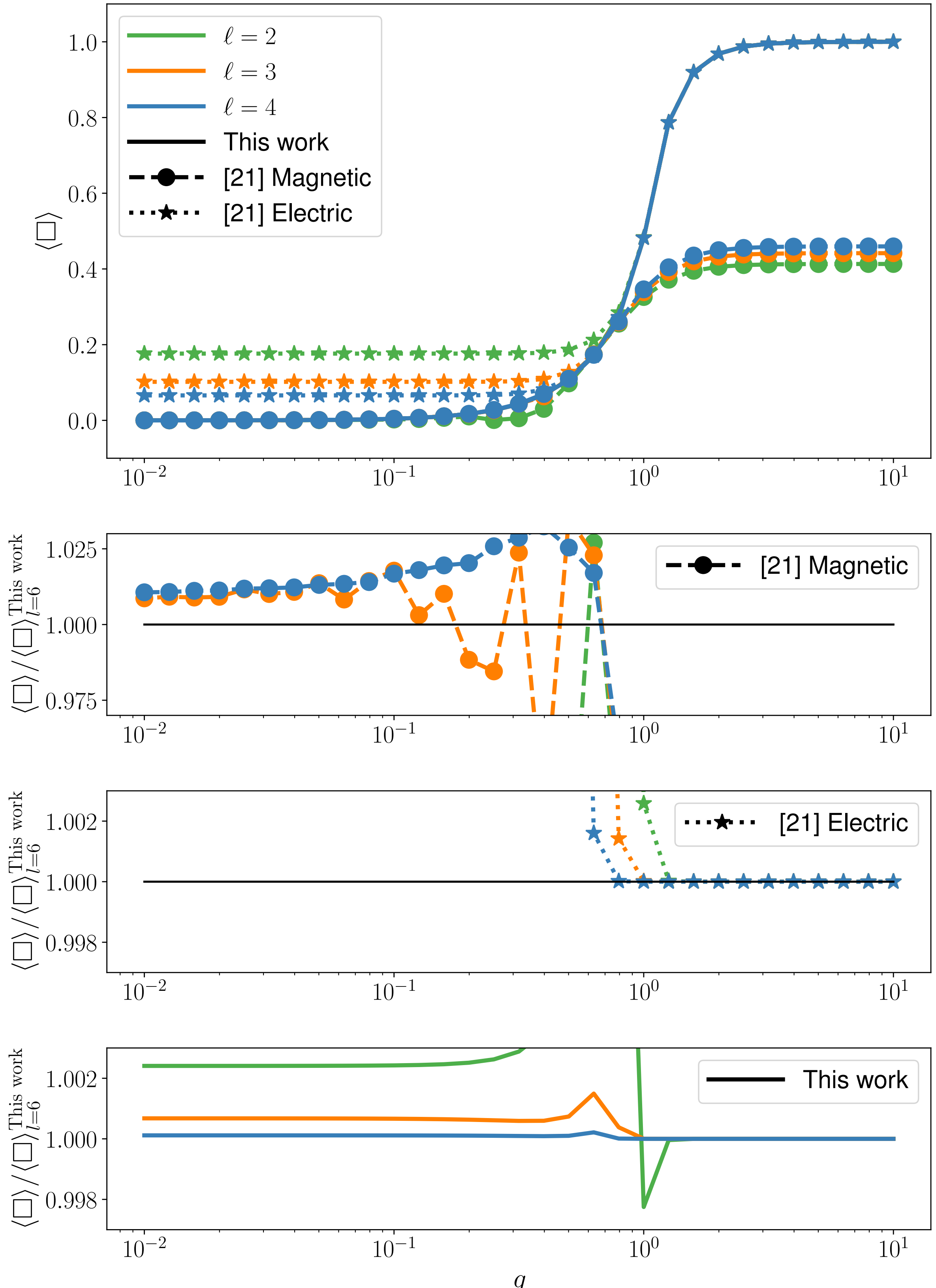
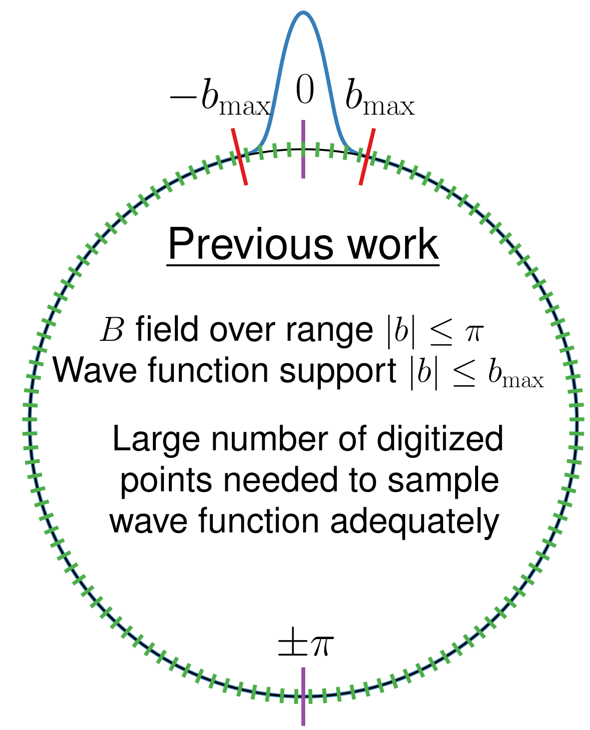


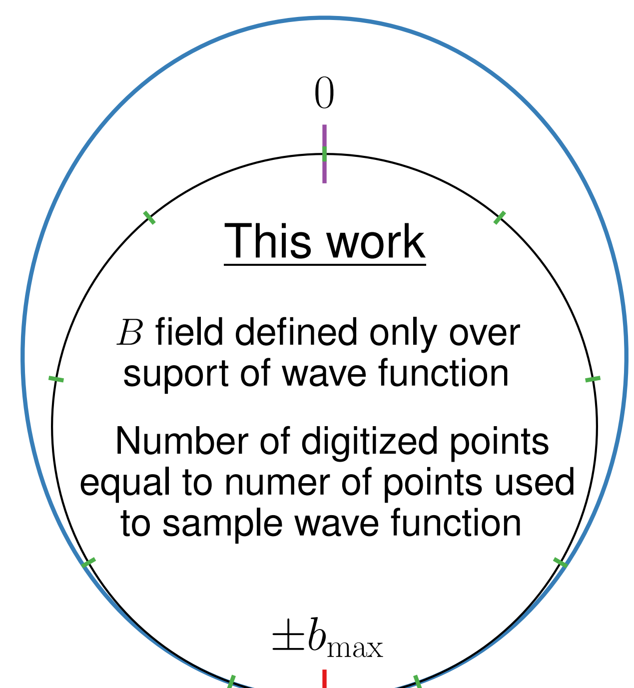


We developed a new representation of Hilbert space, that works in both limits of the coupling

CWB, Grabowska, 2111.08015



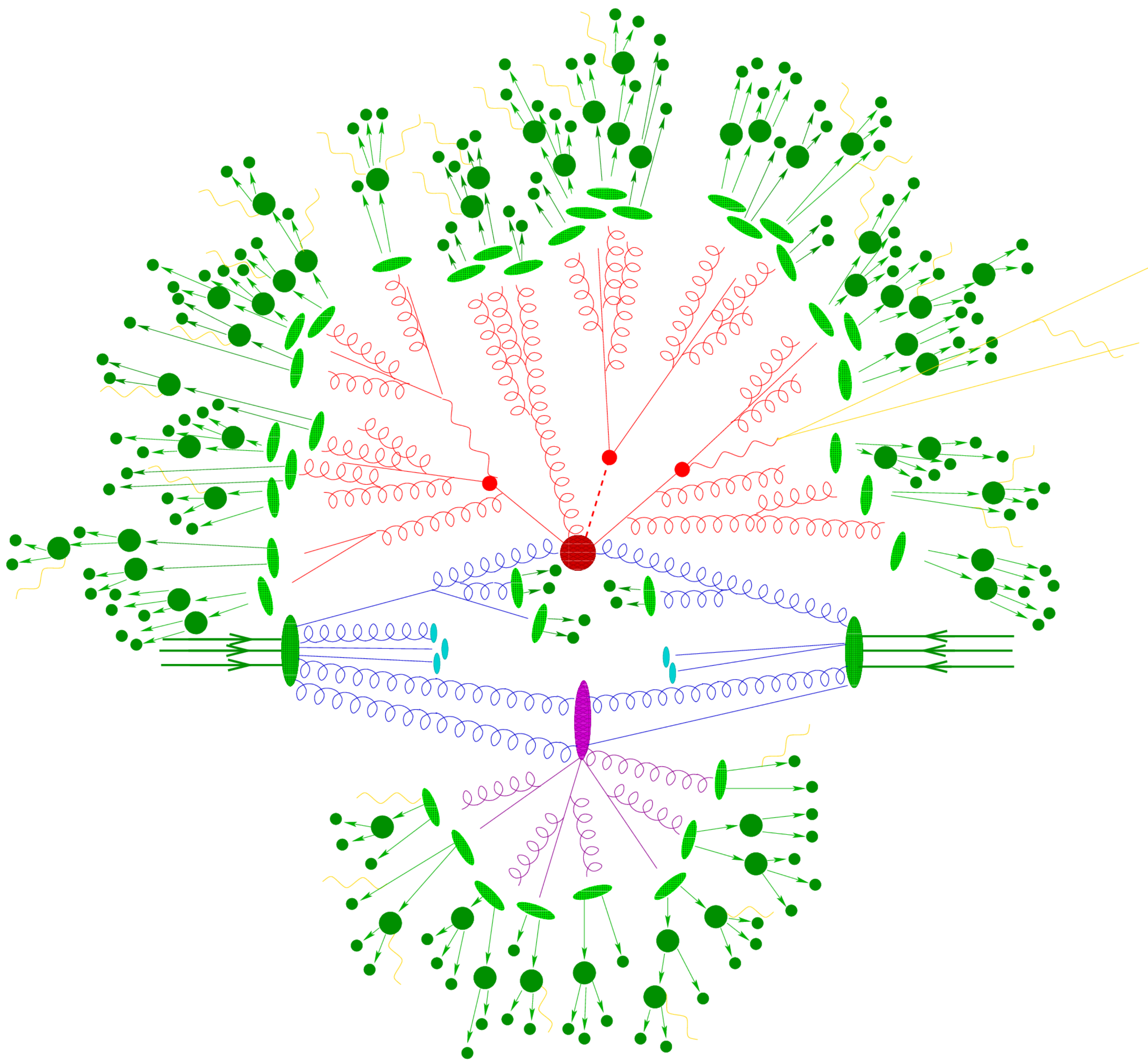




Quantum Simulations Research

Find efficient Quantum algorithms

Parton shower algorithms are ubiquitous in HEP, but most interference effects can not be treated classically



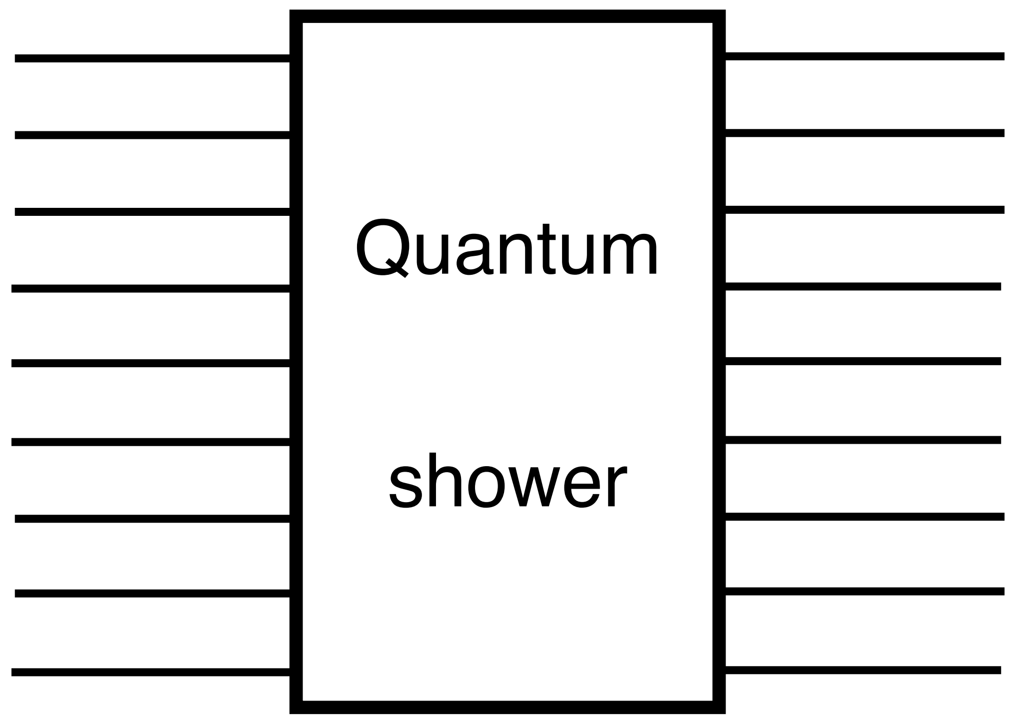
$1/N_C$ effects in dipole showers

γ/Z interference in EW showers

CKM interference in EW showers

Constructed a Quantum Shower that can compute certain interference effects with polynomial resources

CWB, Freytsis, Nachmann, PRL 127, 212001



Operation	Scaling
count particles U_{count}	N lnN
decide emission U_e	N^4 lnN
create history U_h	N^5 lnN
adjust particles U_p	N^2 lnN

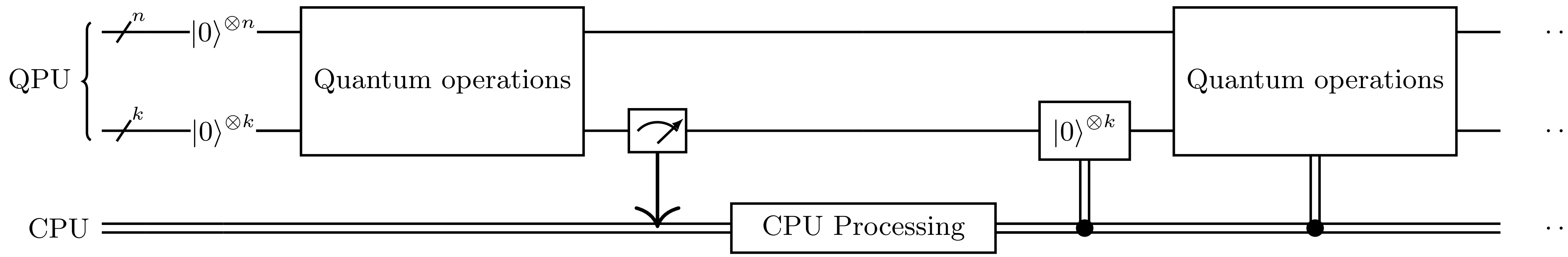
$$|000\ldots0\rangle \rightarrow A_1\,|\Psi_1\rangle + \ldots A_n\,|\Psi_n\rangle$$

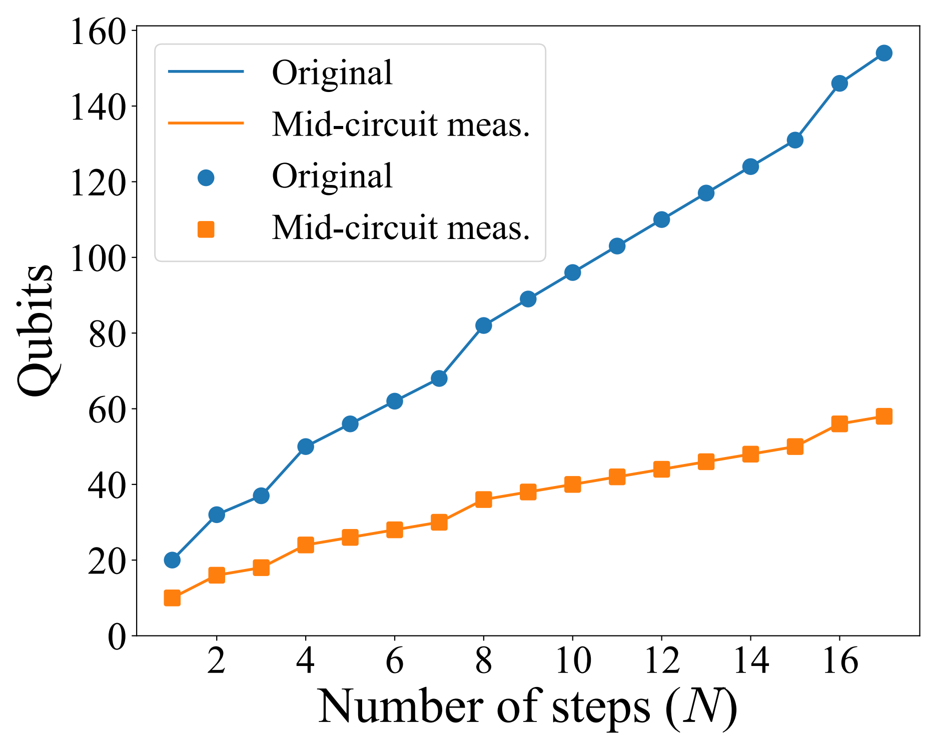
Repeated measurements of the final state selects states with probability $|A_i|^2$ ⇒ can be used as true event generator

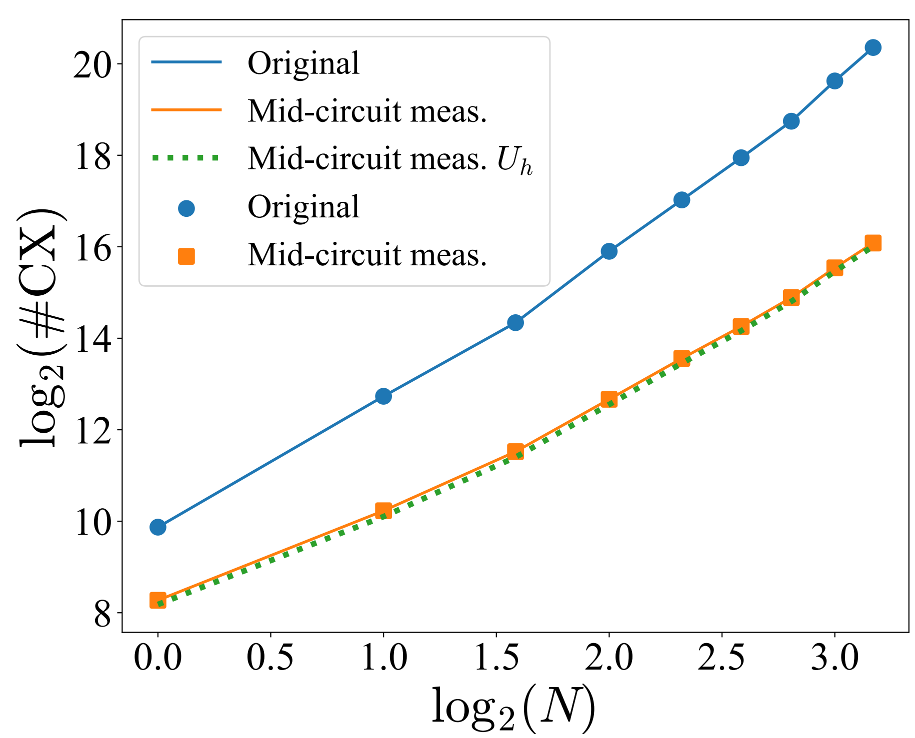
New hardware capability coming is mid-circuit measurement of select qubits

Important to develop algorithms that take this new capability into account and see how it improves algorithms

Delyiannis, Sud, Chamaki, Webb-Mac, CWB, Nachman







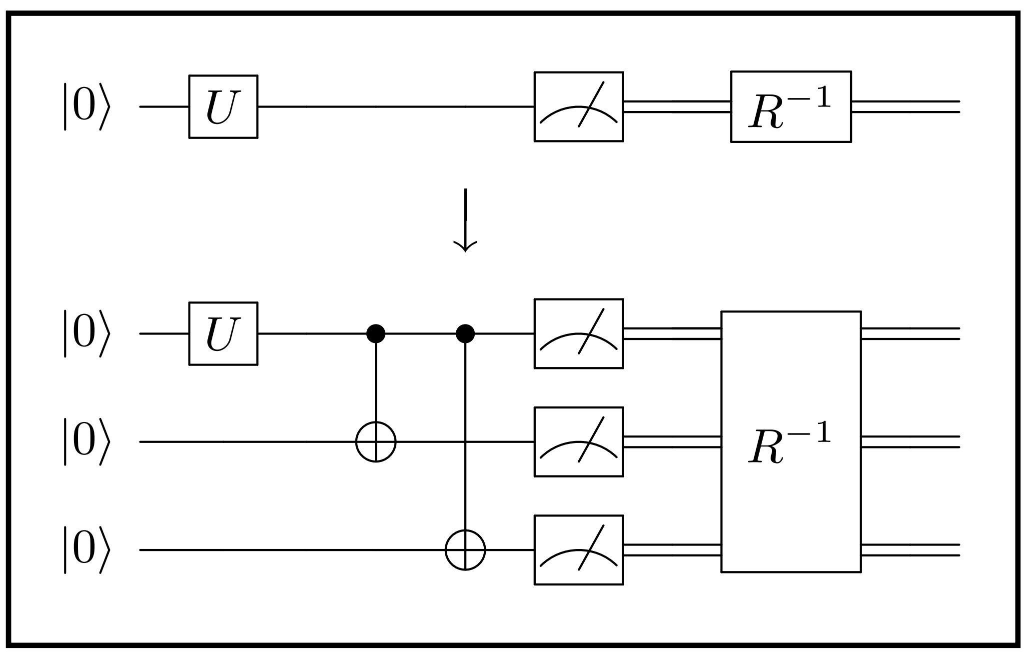
Quantum Simulations Research

Obtain results on realistic machines (with noise)

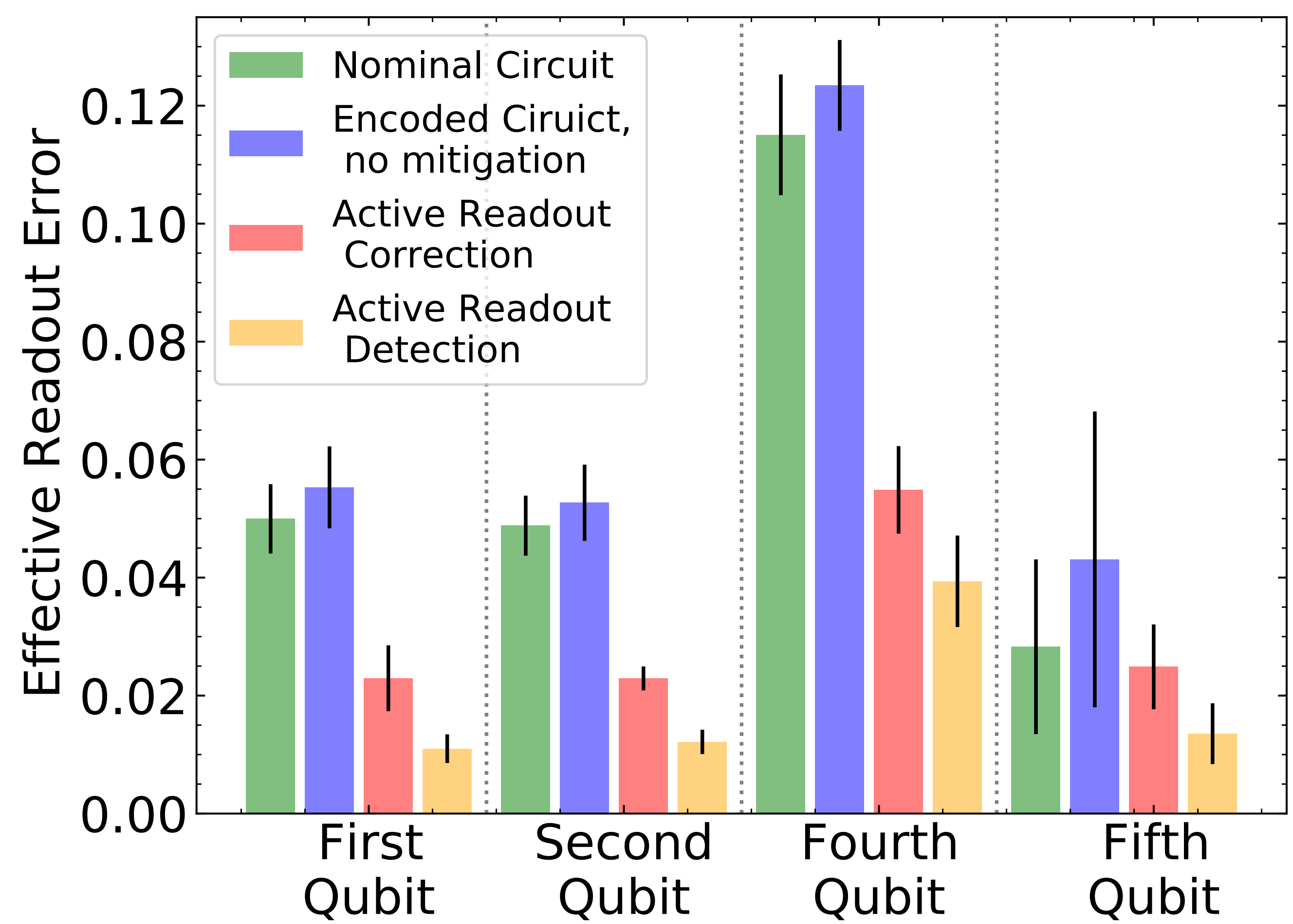
Dealing with noise in current NISQ devices is crucial to get reliable results in the near-term

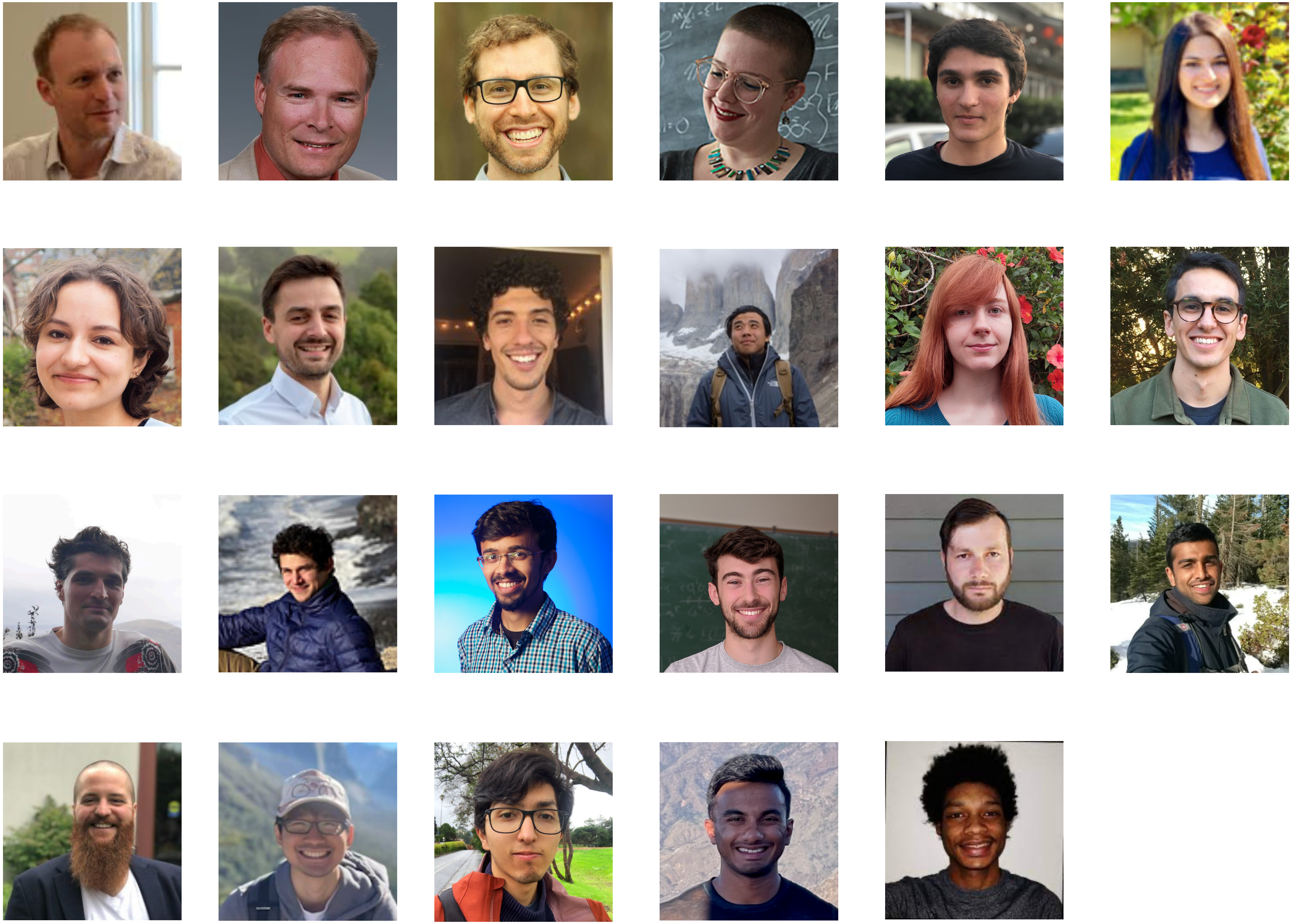
Have done work on mitigating both gate noise as well as readout errors

One example was to develop a method to actively detect / correct readout errors



Hicks, Kobrin, CWB, Nachman (2108.12432)






QUESTIONS?