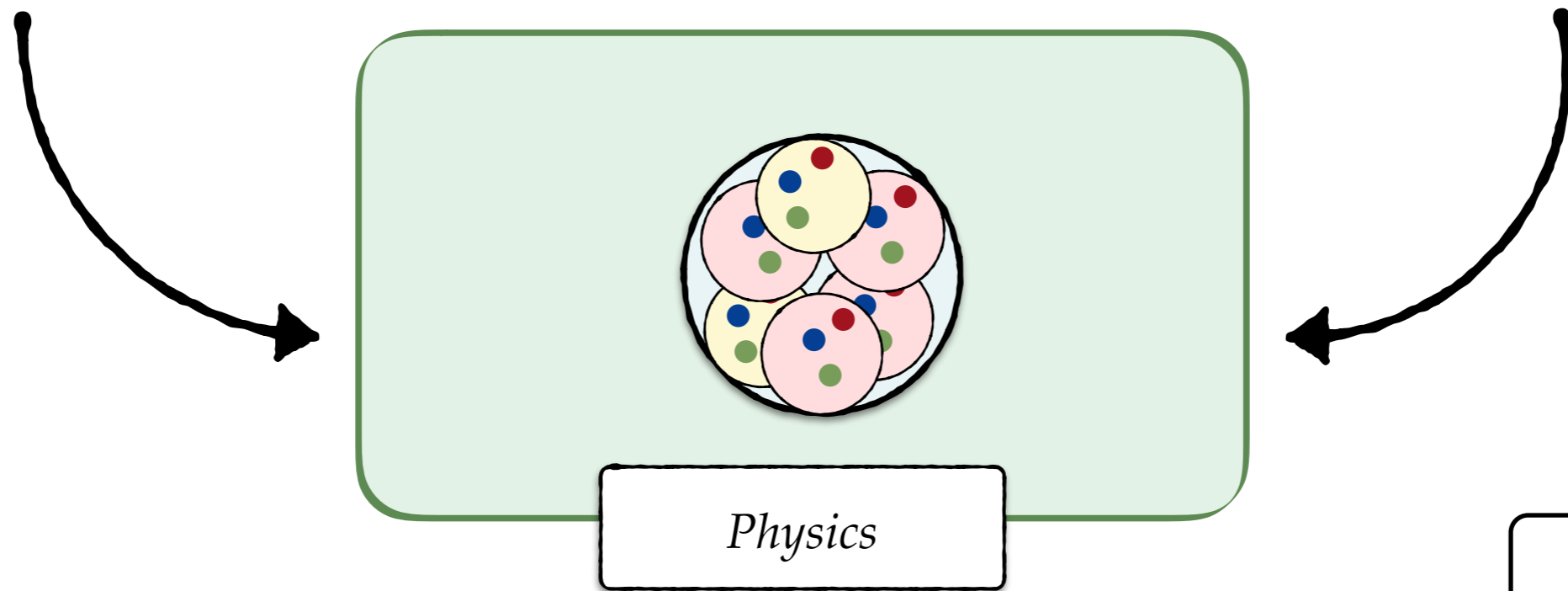
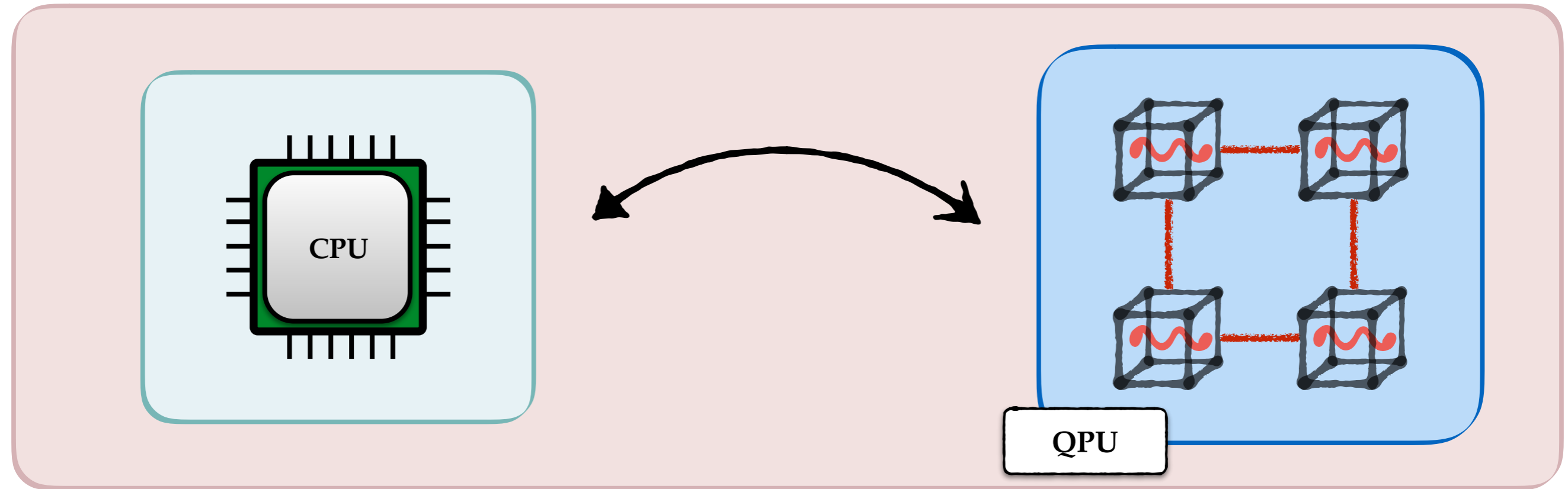
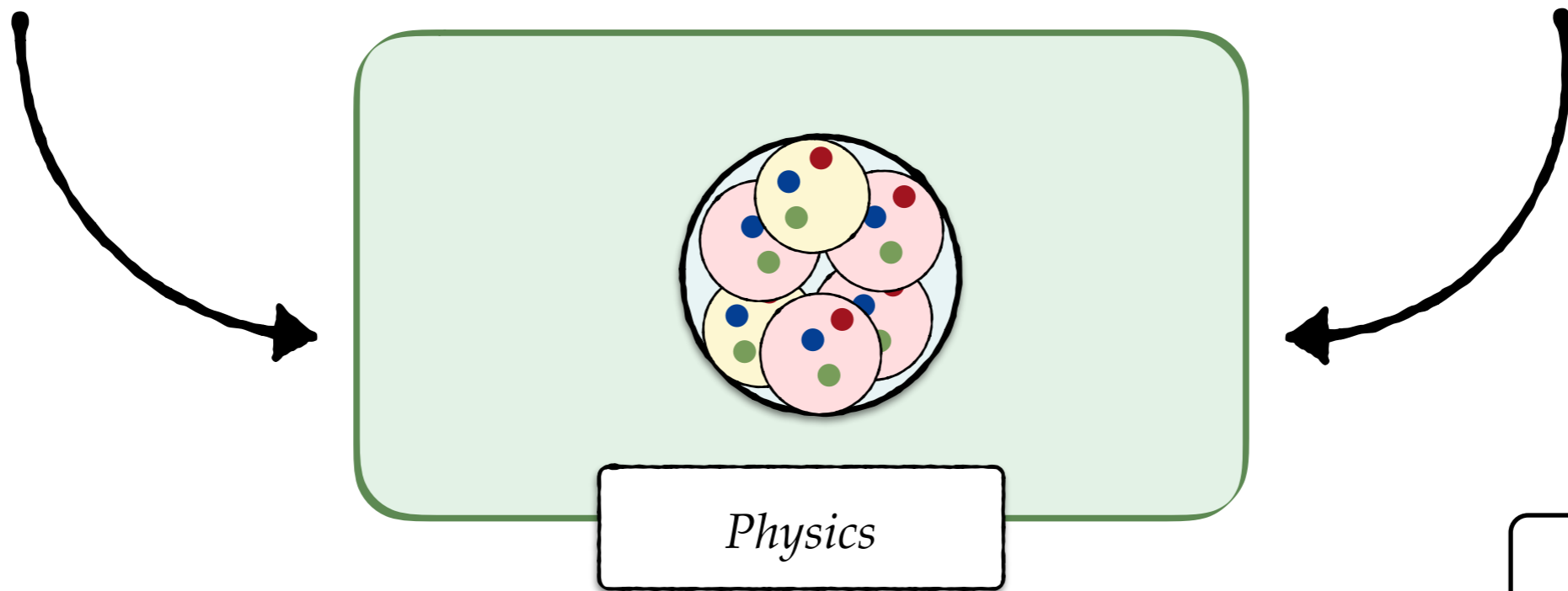
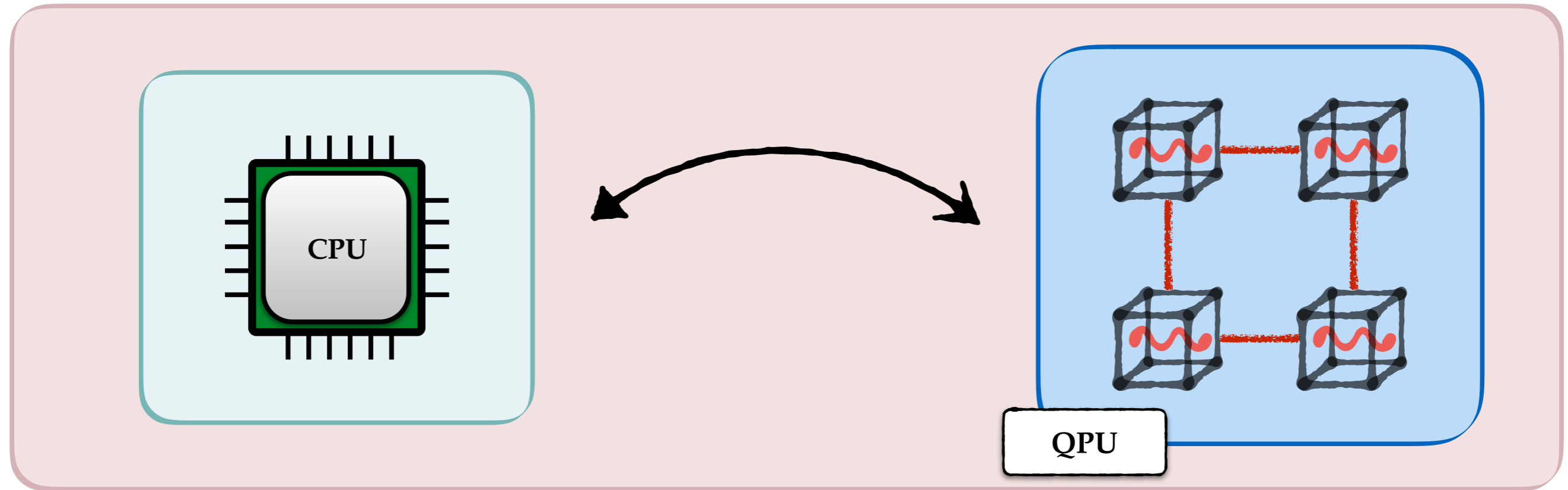


# LBBSM

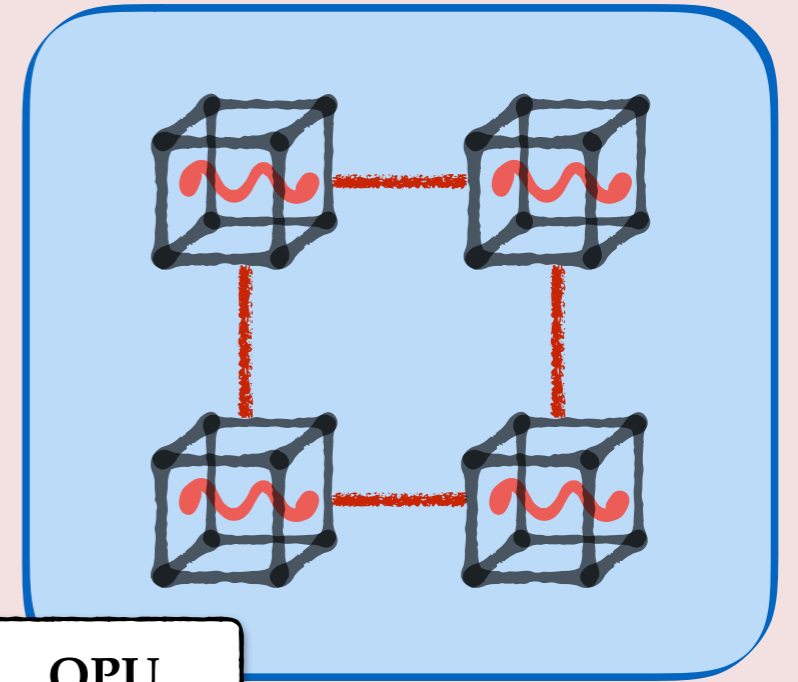
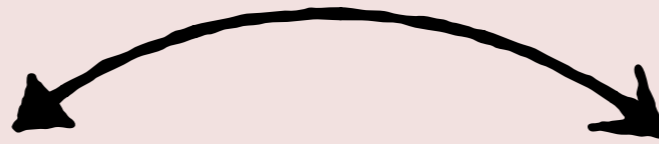
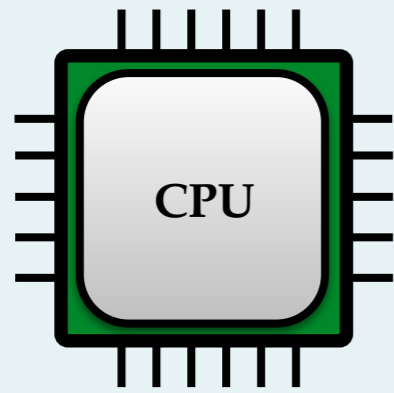
Ciaran Hughes



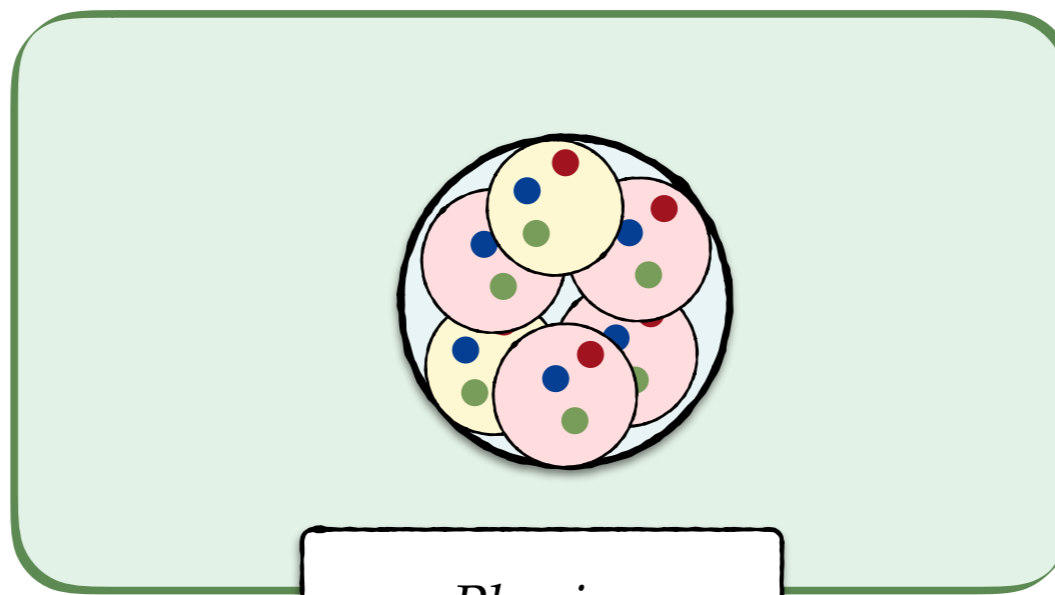
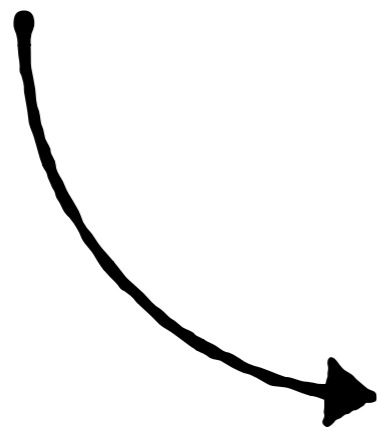


# Lattice "Beyond" BSM

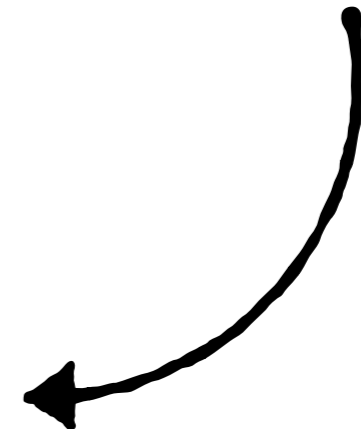
Ciaran Hughes



QPU



Physics



L4BSM, 2019

# Some Things You Just Cannot Do (Right Now)!

*“Involving a strongly interacting theory”*

---

# Some Things You Just Cannot Do (Right Now)!

*“Involving a strongly interacting theory”*

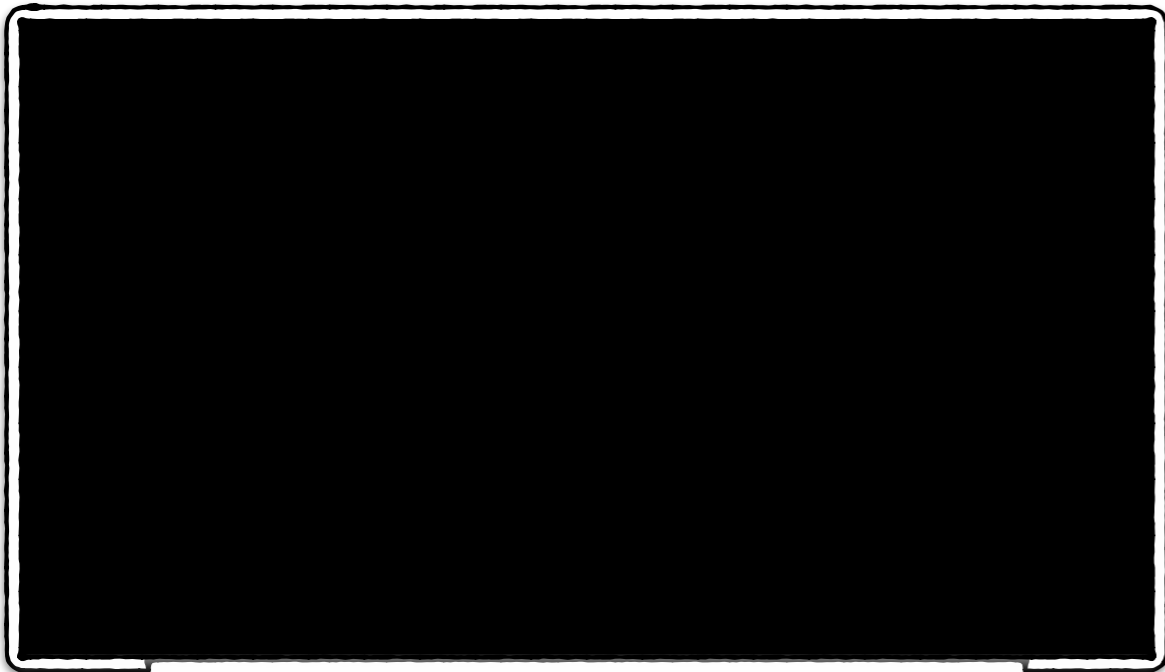
---



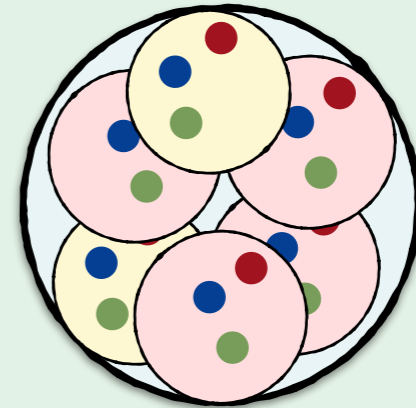
Jose Rodriguez (Skype/Microsoft)

# Some Things You Just Cannot Do (Right Now)!

*"Involving a strongly interacting theory"*



Jose Rodriguez (Skype/Microsoft)



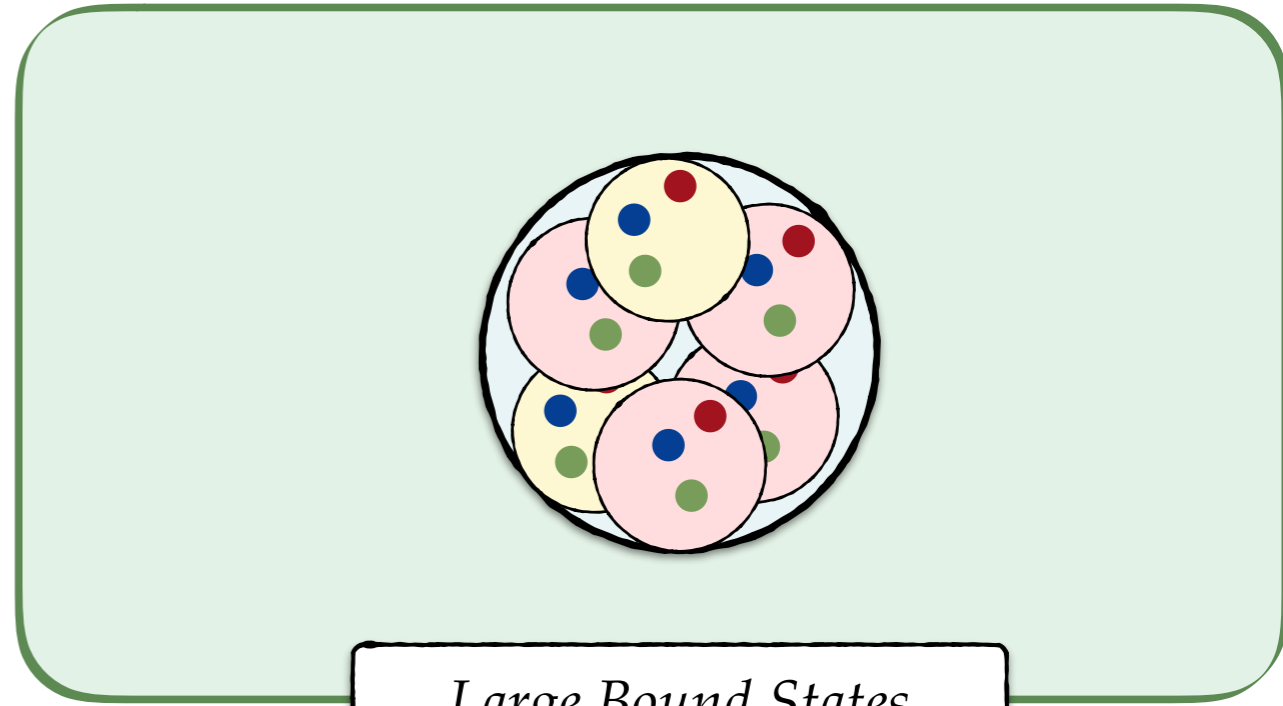
*Large Bound States*

# Some Things You Just Cannot Do (Right Now)!

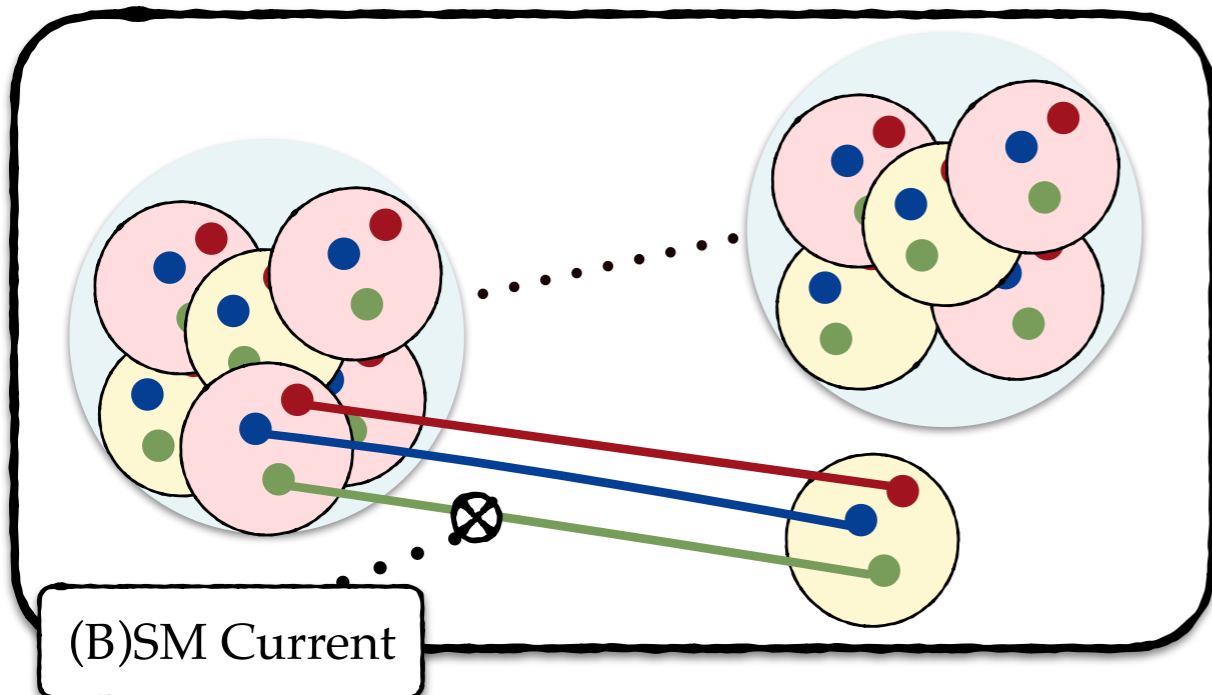
*"Involving a strongly interacting theory"*



Jose Rodriguez (Skype/Microsoft)



*Large Bound States*



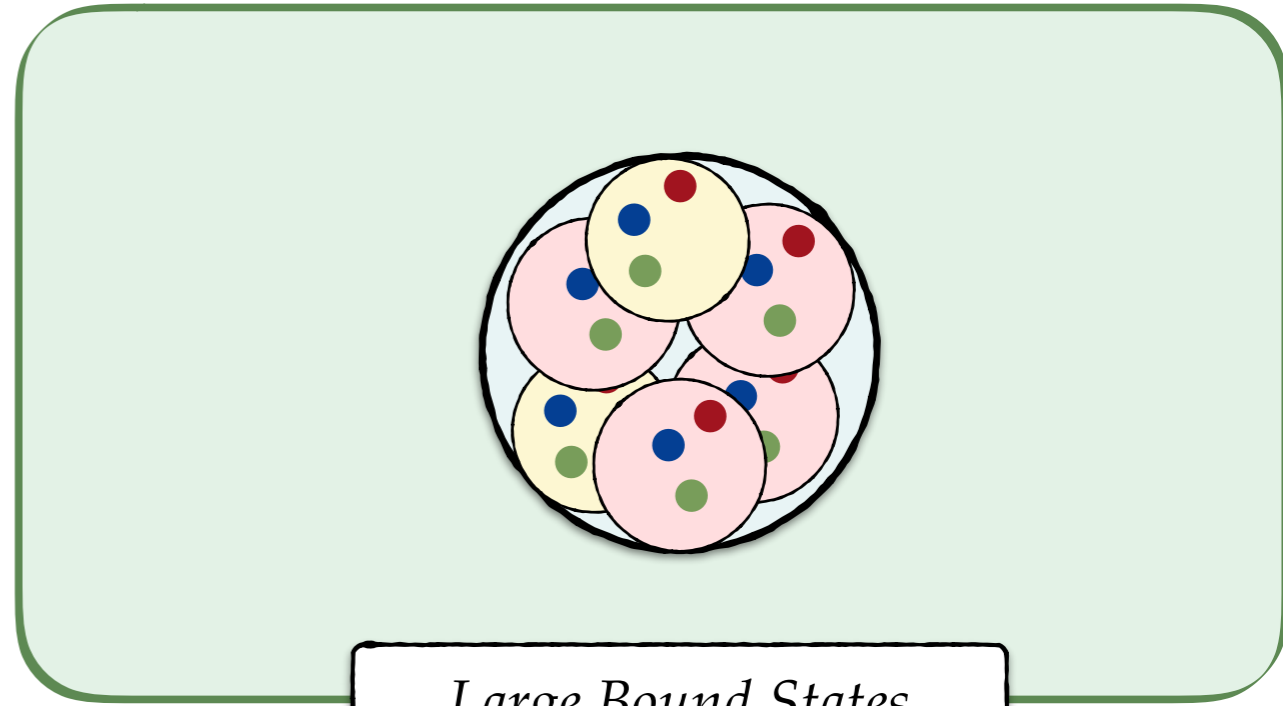
(B)SM Current

# Some Things You Just Cannot Do (Right Now)!

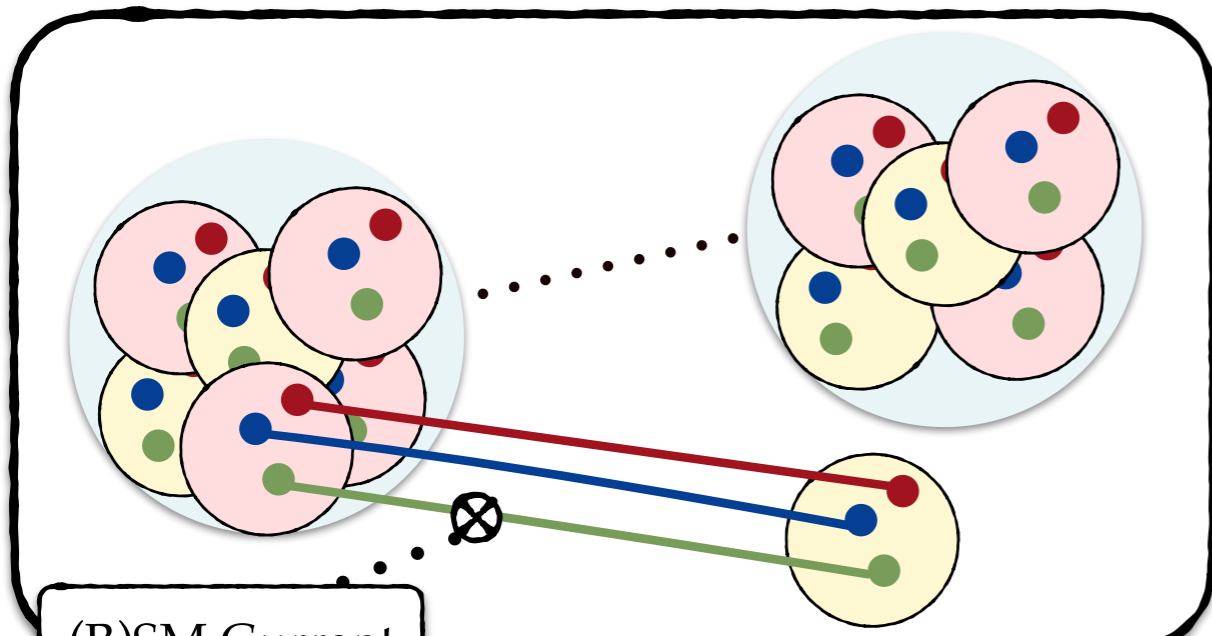
*"Involving a strongly interacting theory"*



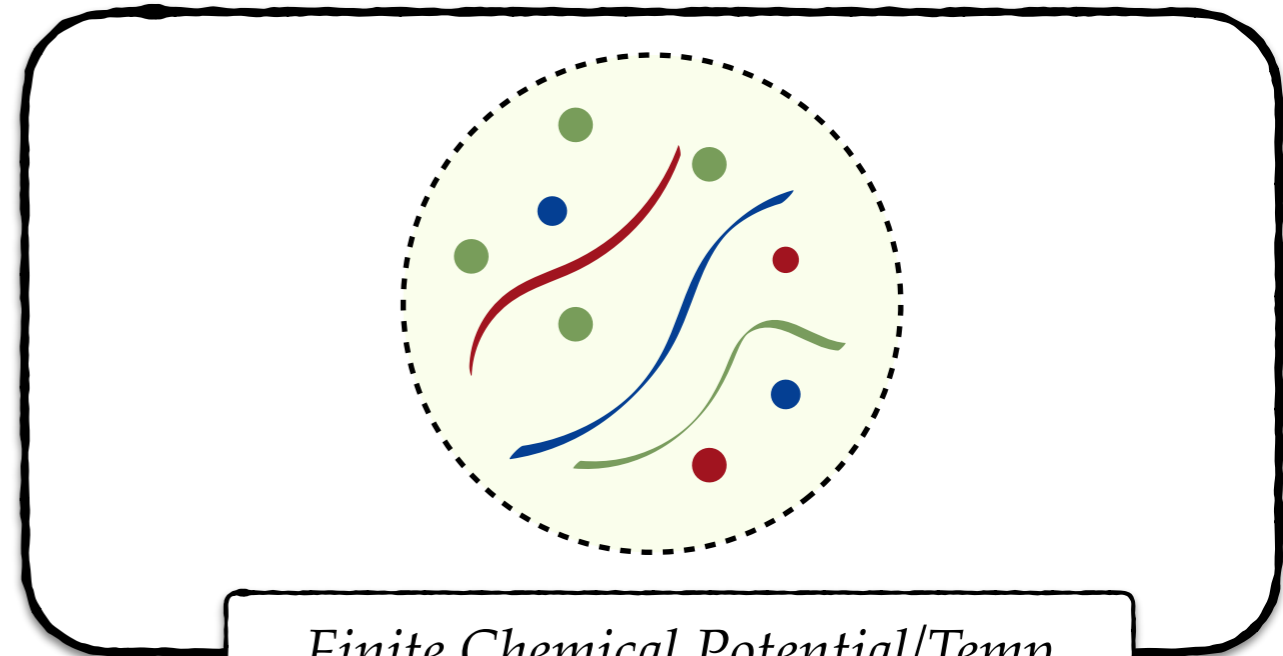
Jose Rodriguez (Skype/Microsoft)



*Large Bound States*



(B)SM Current

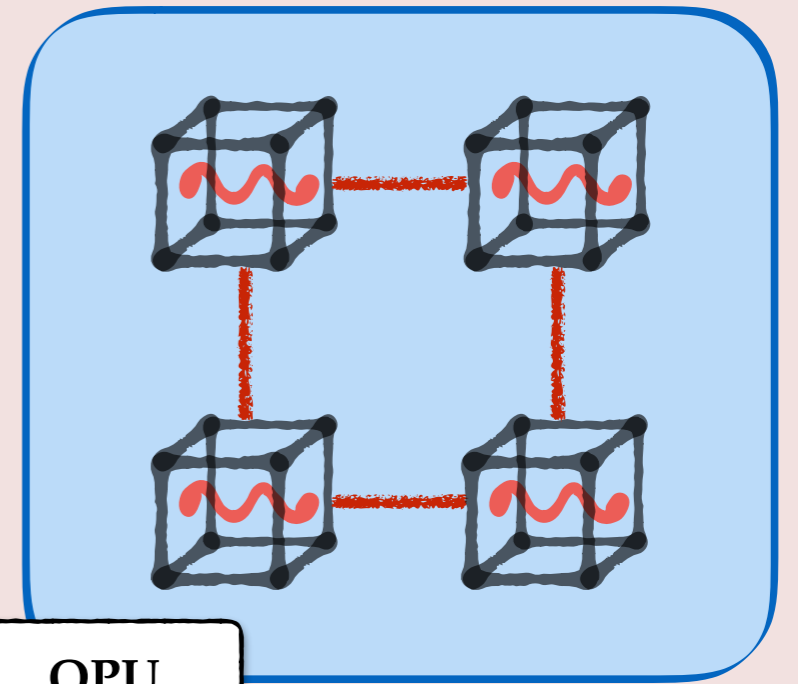


*Finite Chemical Potential/Temp*



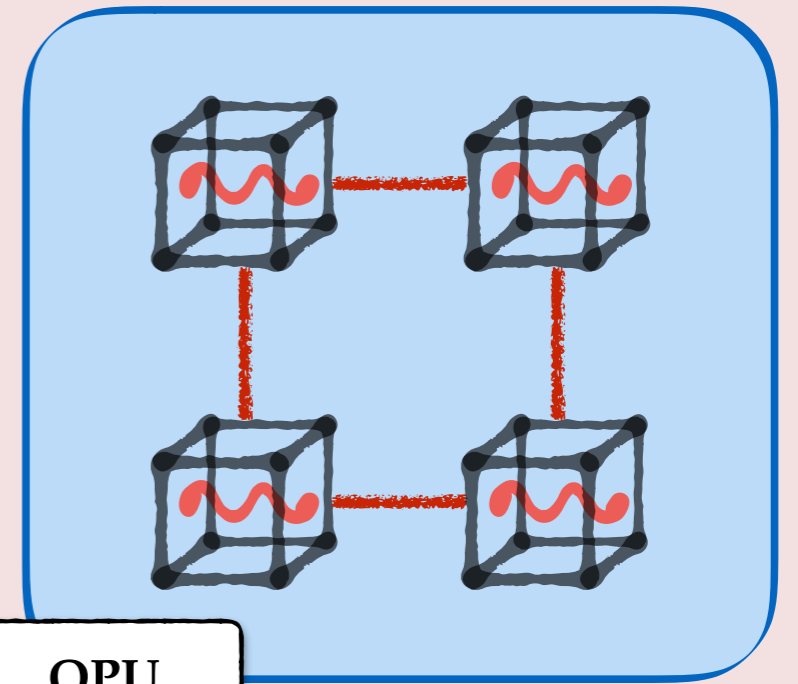
# Lattice "Beyond" BSM

Ciaran Hughes

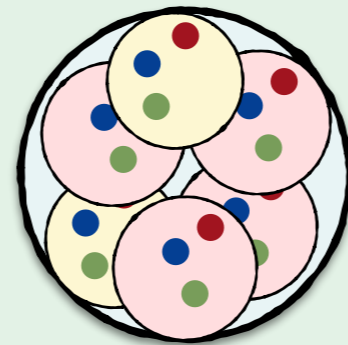


# Lattice "Beyond" BSM

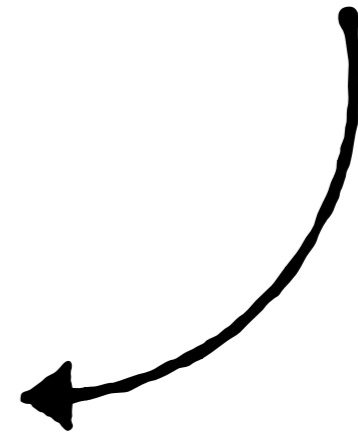
Ciaran Hughes



QPU



*Physics*



# Naive Resource Requirements for QC

---

*How many logical qubits are needed for  $SU(3)$  Hamiltonian?*

# Naive Resource Requirements for QC

---

*How many logical qubits are needed for SU(3) Hamiltonian?*

- Pick a lattice spacing and volume size:
  - $10 \times 10 \times 10 = 1000$  spatial volume dof

# Naive Resource Requirements for QC

*How many logical qubits are needed for SU(3) Hamiltonian?*

- Pick a lattice spacing and volume size:
  - $10 \times 10 \times 10 = 1000$  spatial volume dof
- 8 Continuous gluon dof need to be made finite:
  - Keep  $x$  gauge field dof

# Naive Resource Requirements for QC

*How many logical qubits are needed for SU(3) Hamiltonian?*

- 👤 Pick a lattice spacing and volume size:
  - 👤  $10 \times 10 \times 10 = 1000$  spatial volume dof
- 👤 8 Continuous gluon dof need to be made finite:
  - 👤 Keep  $x$  gauge field dof
- 👤 Need enough logical qubits to store  $x^{8000}$  dof :
  - 👤 Need  $8000 \log_2(x)$  logical qubits

# Naive Resource Requirements for QC

*How many logical qubits are needed for SU(3) Hamiltonian?*

- Pick a lattice spacing and volume size:
  - $10 \times 10 \times 10 = 1000$  spatial volume dof
- 8 Continuous gluon dof need to be made finite:
  - Keep  $x$  gauge field dof
- Need enough logical qubits to store  $x^{8000}$  dof :
  - Need  $8000 \log_2(x)$  logical qubits

This is just to write down the Hamiltonian!

# Naive Resource Requirements for QC

*How many logical qubits are needed for SU(3) Hamiltonian?*

- 👤 Pick a lattice spacing and volume size:
  - 👤  $10 \times 10 \times 10 = 1000$  spatial volume dof
- 👤 8 Continuous gluon dof need to be made finite:
  - 👤 Keep  $x$  gauge field dof
- 👤 Need enough logical qubits to store  $x^{8000}$  dof :
  - 👤 Need  $8000 \log_2(x)$  logical qubits

This is just to write down the Hamiltonian!

Also need to prepare initial state, perform time evolution, read-out, etc



# Current Resources for QC

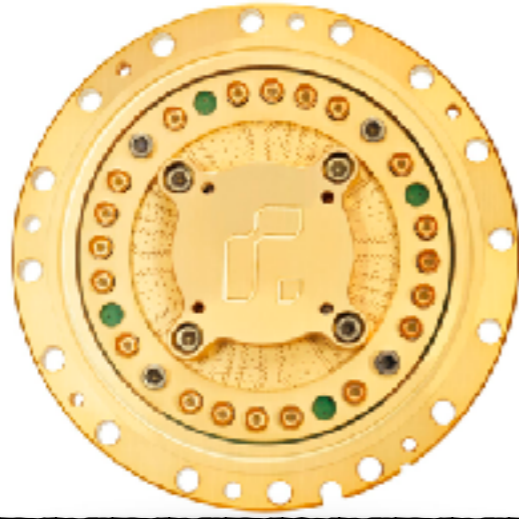
---

*How many qubits are possible?*

# Current Resources for QC

---

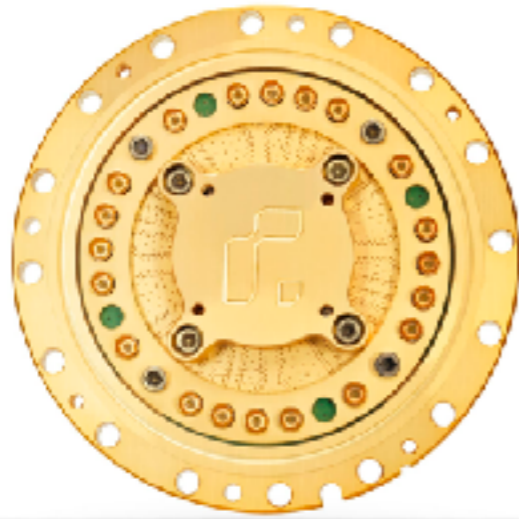
*How many qubits are possible?*



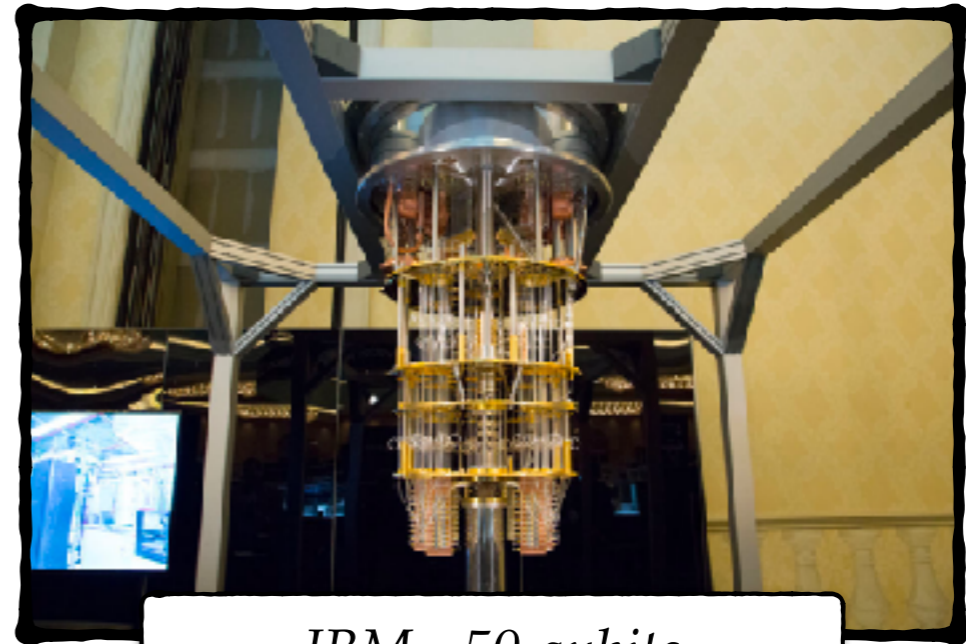
*Rigetti - 19 qubits*

# Current Resources for QC

*How many qubits are possible?*



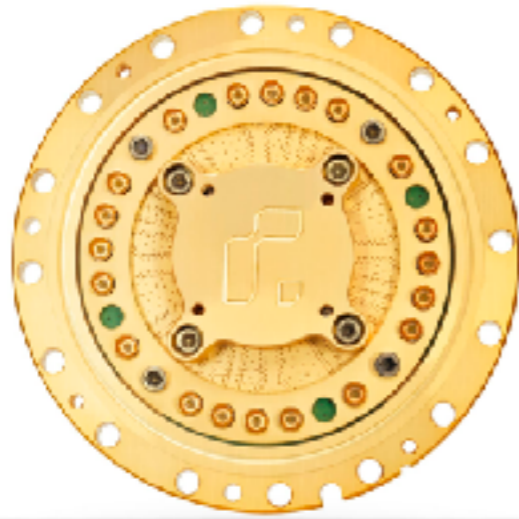
*Rigetti - 19 qubits*



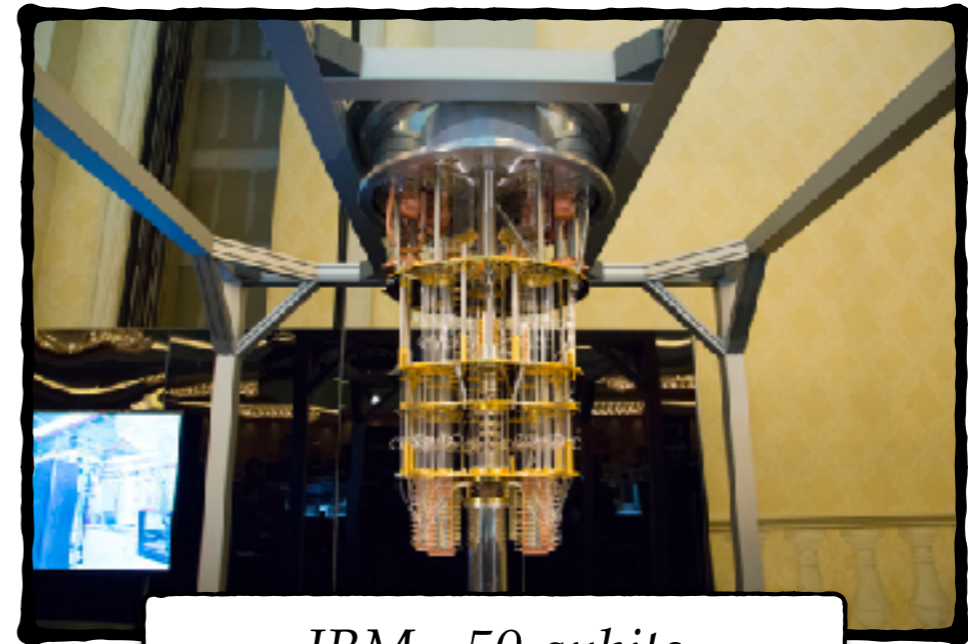
*IBM - 50 qubits*

# Current Resources for QC

*How many qubits are possible?*



*Rigetti - 19 qubits*



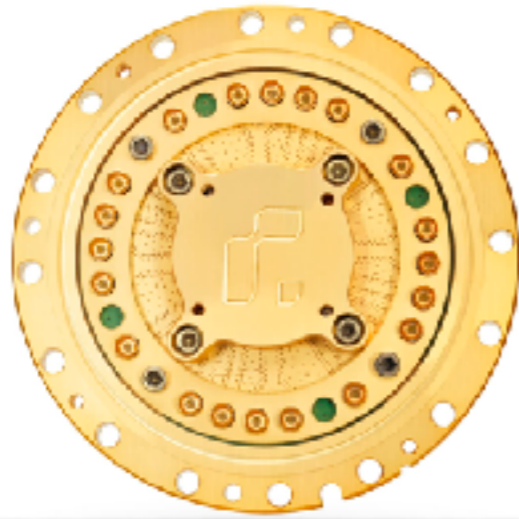
*IBM - 50 qubits*



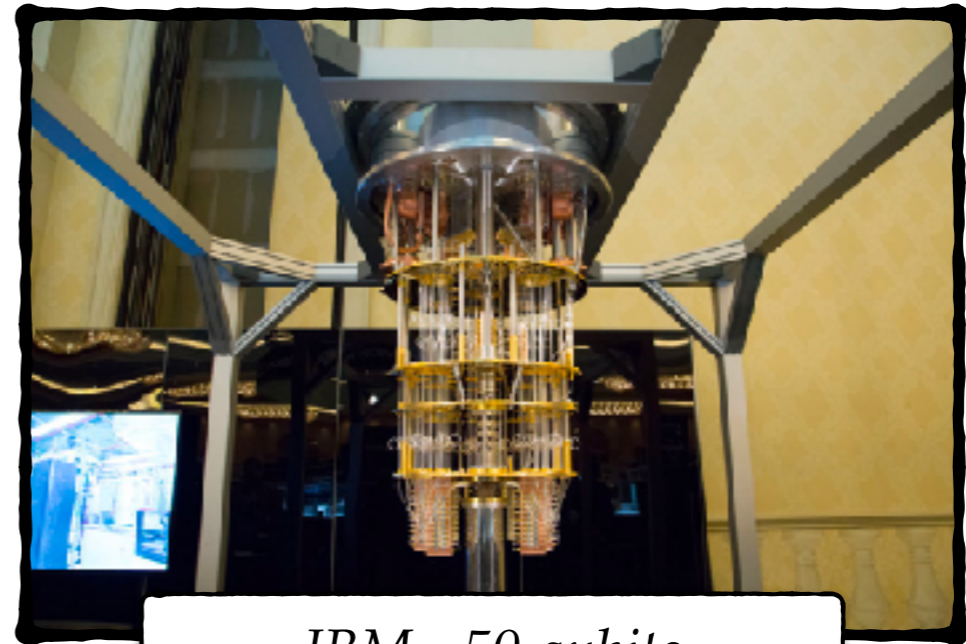
*Google - 72 qubits*

# Current Resources for QC

*How many qubits are possible?*



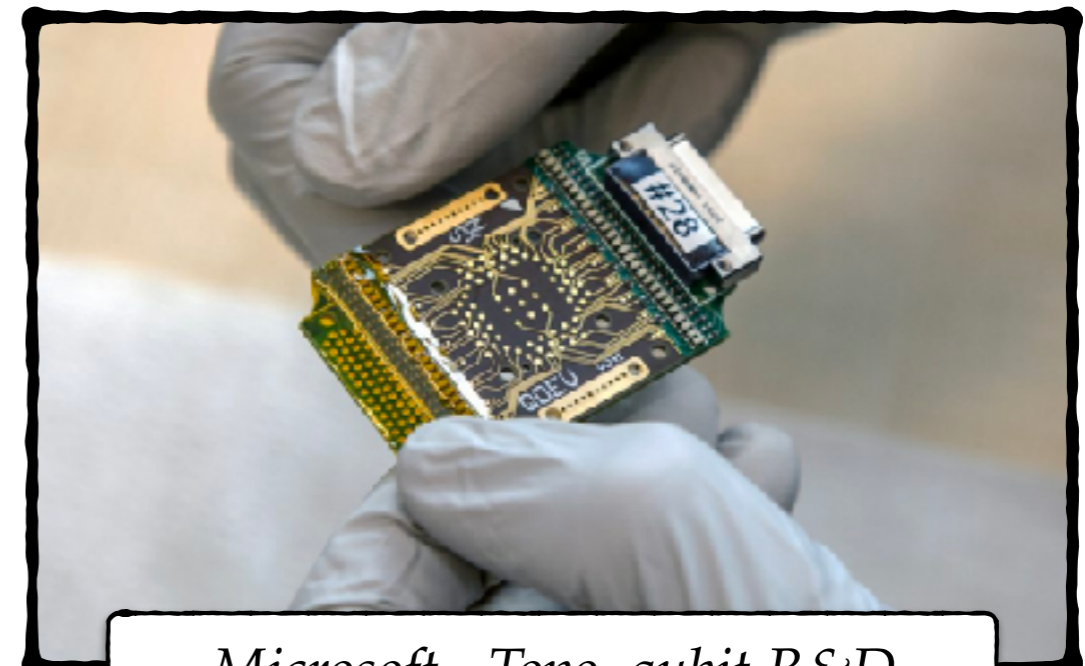
*Rigetti - 19 qubits*



*IBM - 50 qubits*




*Google - 72 qubits*




*Microsoft - Topo. qubit R&D*

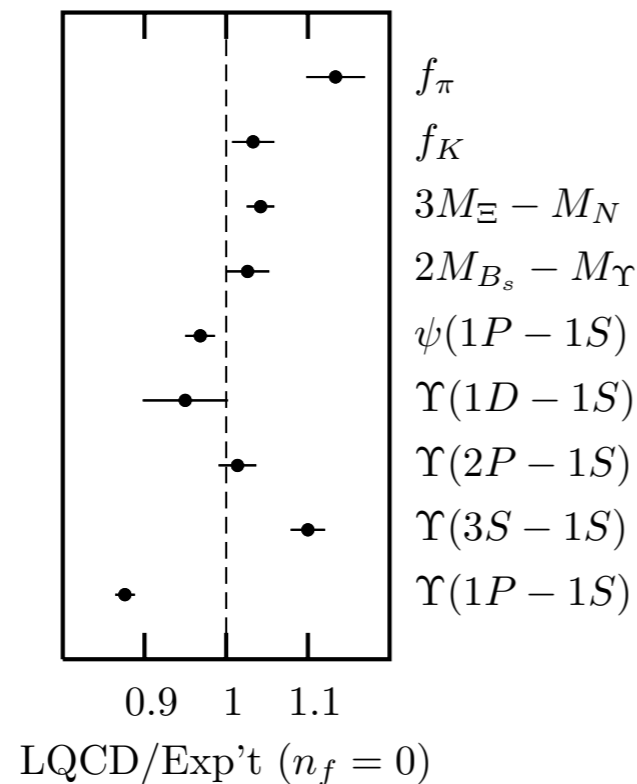
# Current Resources In the NISQ-era

---

 *Don't be so pessimistic, classical lattice gauge theory only became trusted within 20yrs through methodology research, hardware and algorithmic ingenuity and creativity, e.g., arxiv: 0304004*

# Current Resources In the NISQ-era

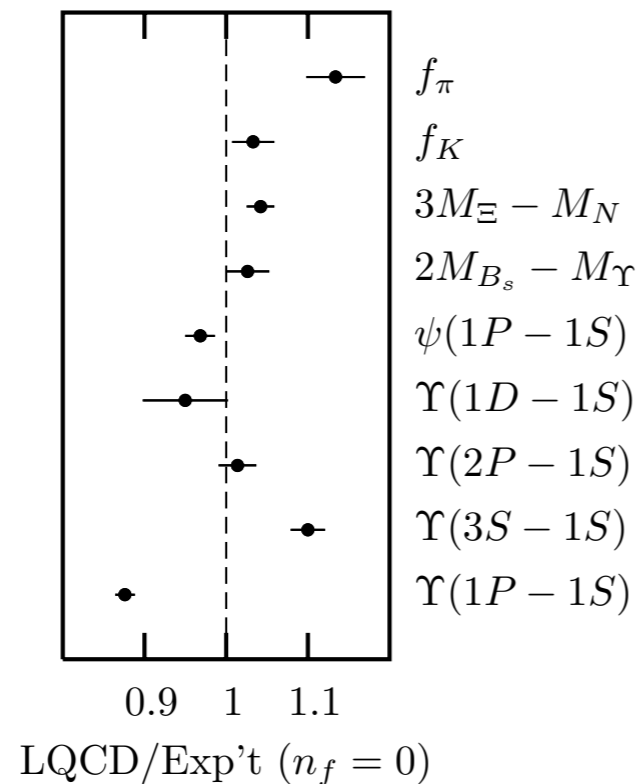
 *Don't be so pessimistic, classical lattice gauge theory only became trusted within 20yrs through methodology research, hardware and algorithmic ingenuity and creativity, e.g., arxiv: 0304004*



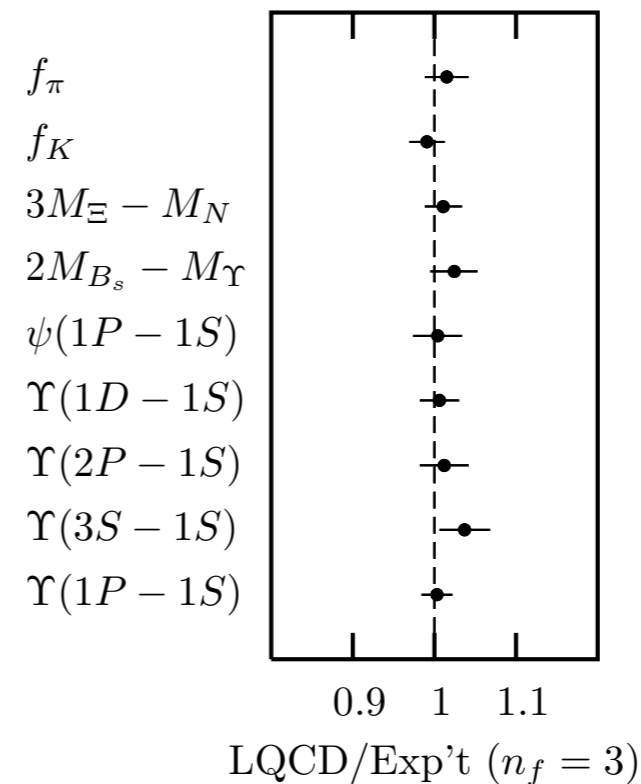
*Early 2000*

# Current Resources In the NISQ-era

👤 *Don't be so pessimistic, classical lattice gauge theory only became trusted within 20yrs through methodology research, hardware and algorithmic ingenuity and creativity, e.g., arxiv: 0304004*



*Early 2000*



*Gold-plated 2003*



# Research Objectives

---


*1) What resources are actually required during different stages of a quantum computation of a realistic theory?*

# Research Objectives

---

*1) What resources are actually required during different stages of a quantum computation of a realistic theory?*

*2) How can we pragmatically improve methodologies to significantly reduce the resources needed at each stage?*



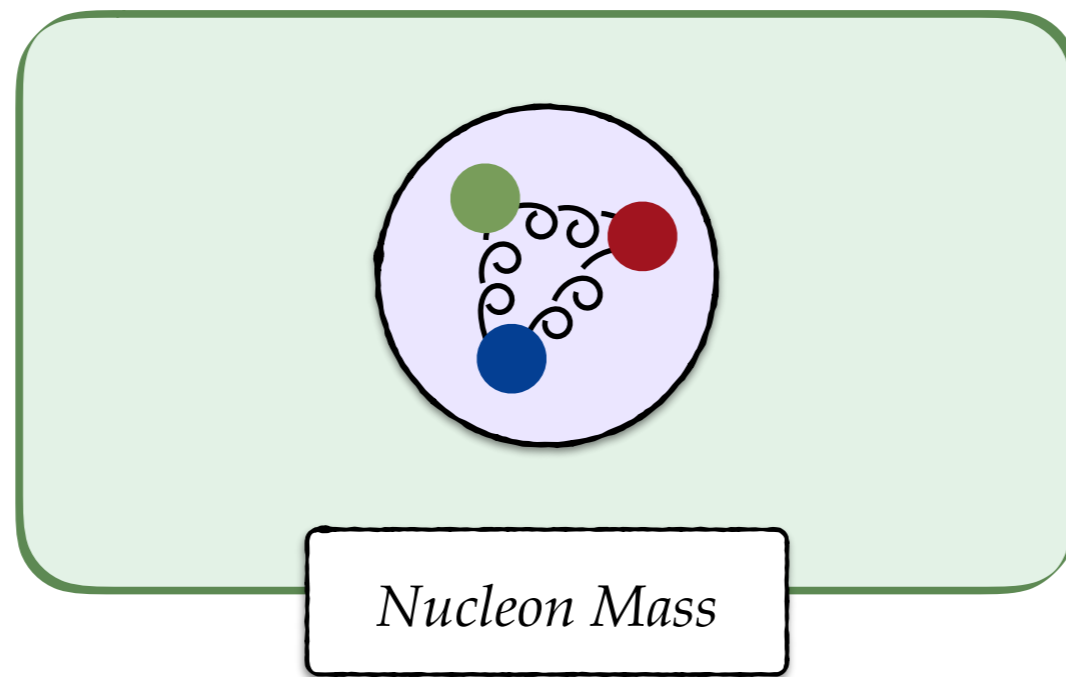
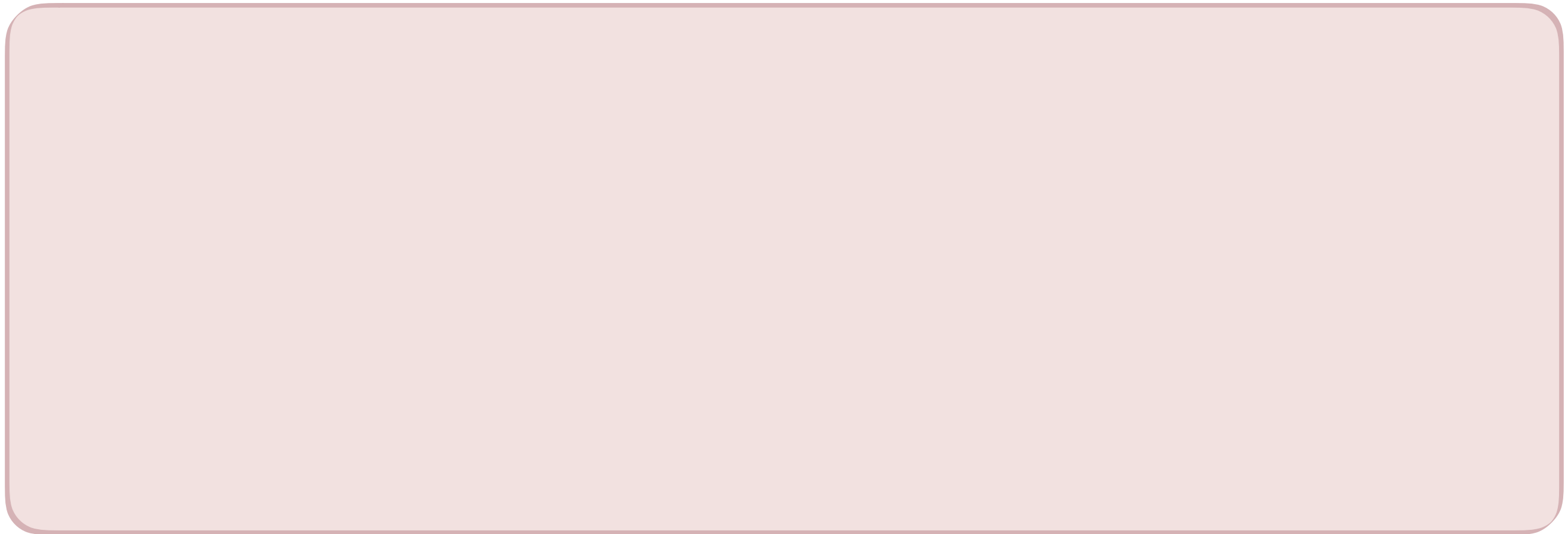
# Is it possible?

---

*Utilise our expertise in classical lattice gauge theory and employ precision, algorithm and methodology improvements to quantum lattice gauge theory!*

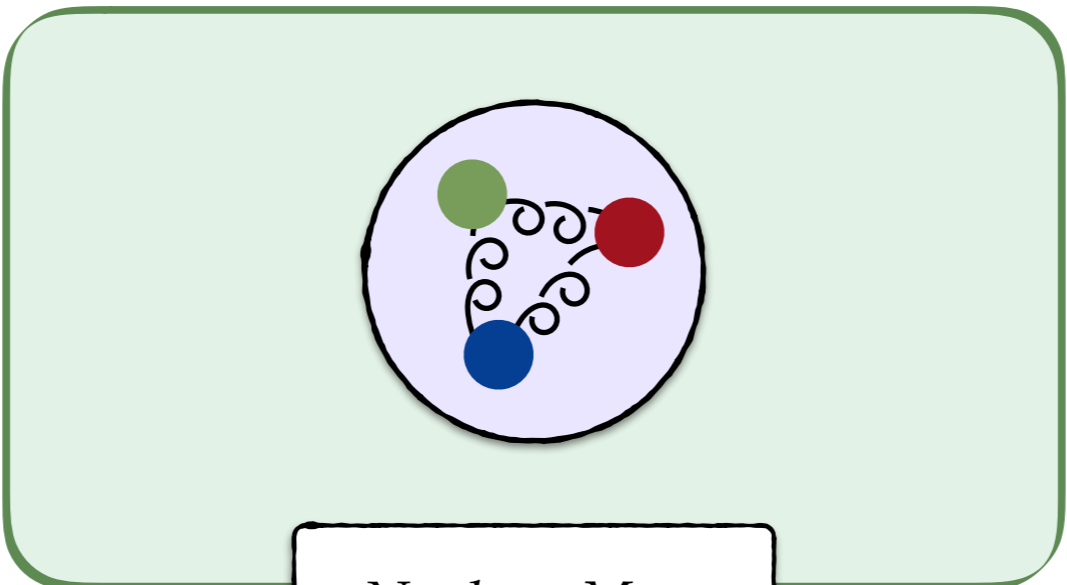
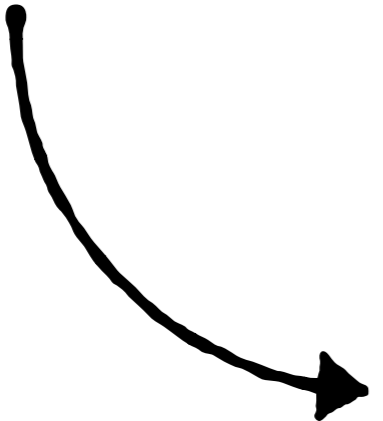
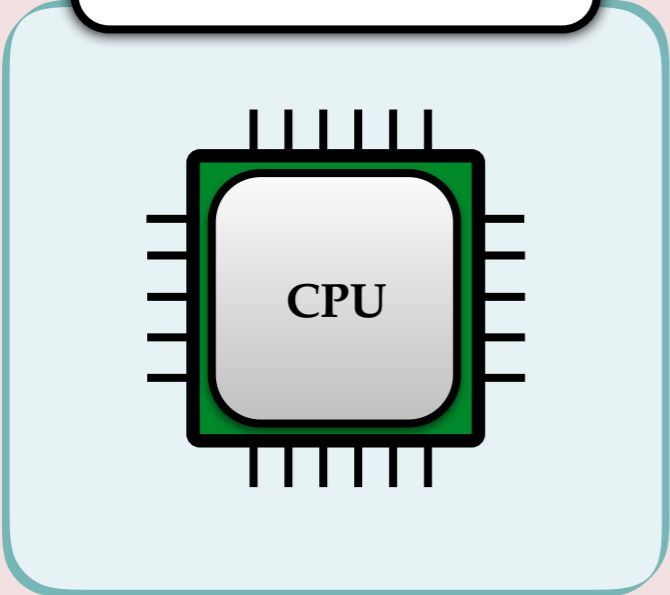
# Is it possible?

---



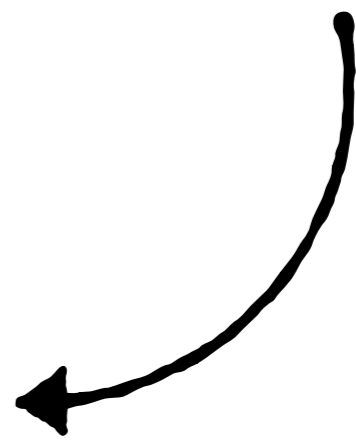
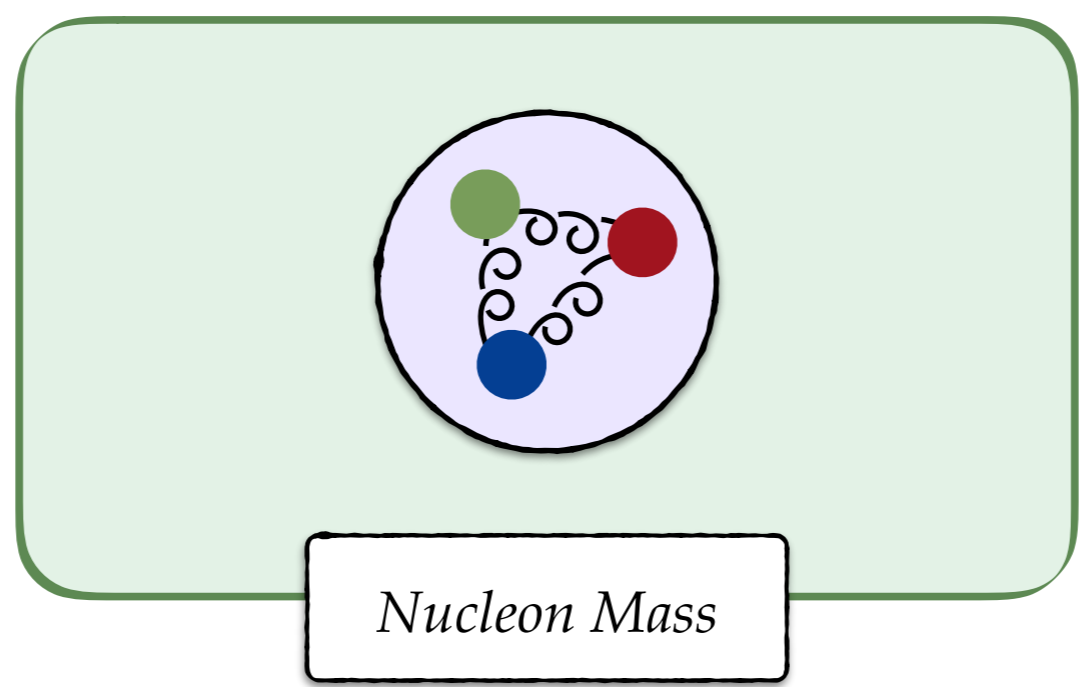
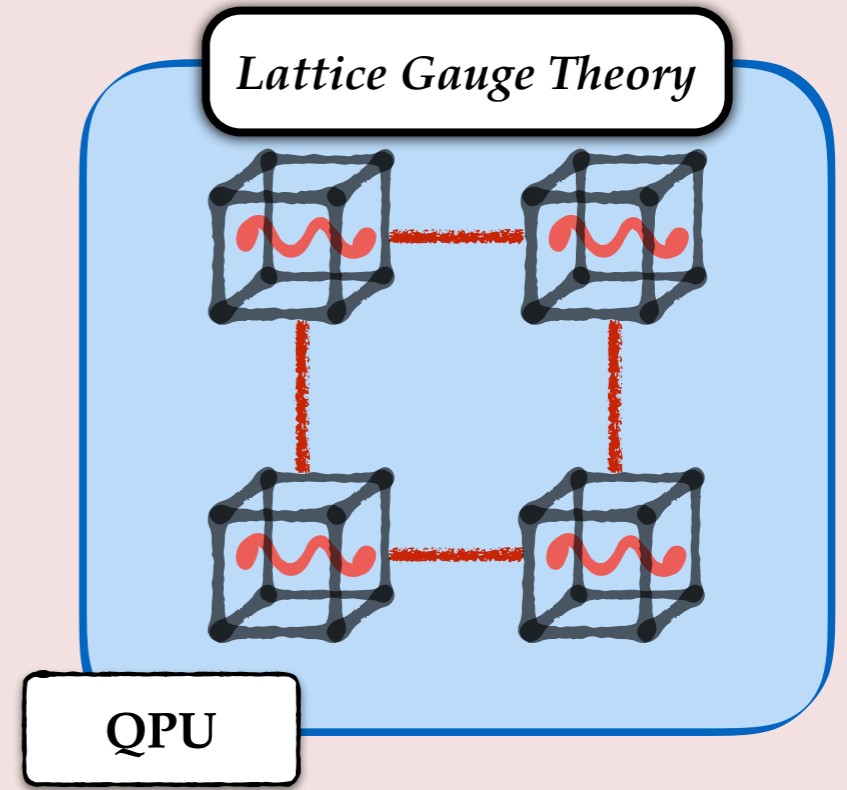
# Is it possible?

*Lattice Gauge Theory*

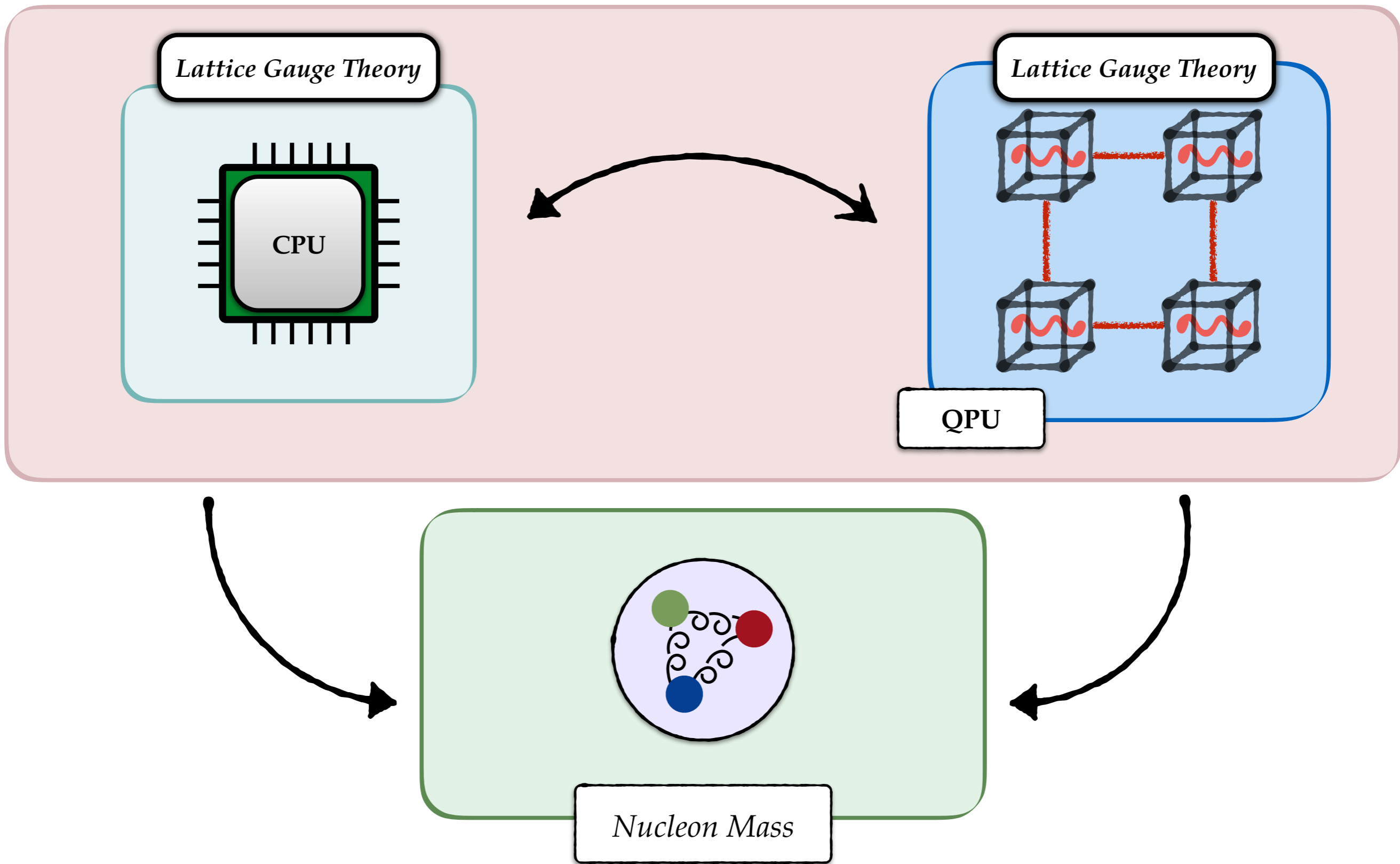


*Nucleon Mass*

# Is it possible?



# Is it possible?



# Naive Resource Requirements for QC

*How many logical qubits are needed for SU(3) Hamiltonian?*

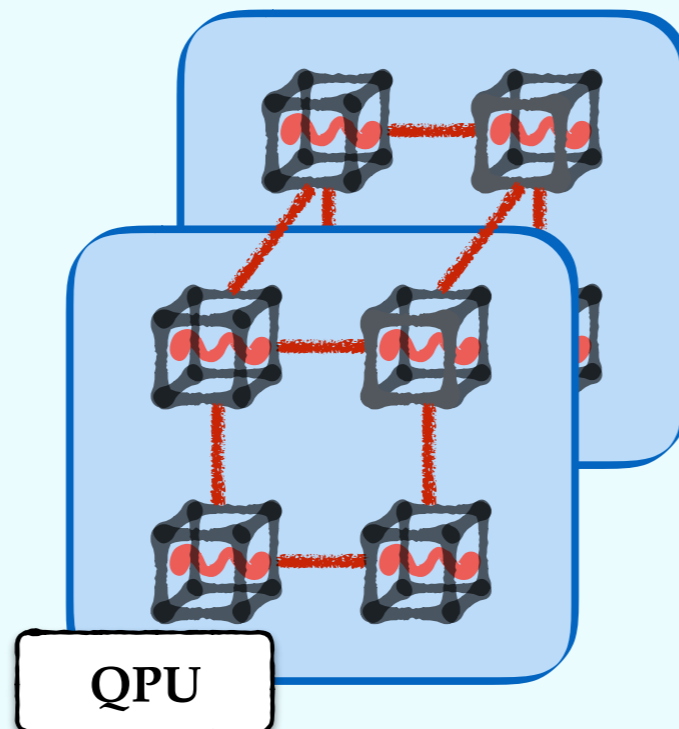
- Pick a lattice spacing and volume size:
  - $10 \times 10 \times 10 = 1000$  spatial volume dof
- 8 Continuous gluon dof need to be made finite:
  - Keep  $x$  gauge field dof
- Need enough logical qubits to store  $x^{8000}$  dof :
  - Need  $8000 \log_2(x)$  logical qubits

This is just to write down the Hamiltonian!

Also need to prepare initial state, perform time evolution, read-out, etc



- 📌 This talk will be a bigger picture sketch of results from [arxiv:1811.03629](https://arxiv.org/abs/1811.03629)
- 📌 For more details, please contact me ([chughes@fnal.gov](mailto:chughes@fnal.gov))!



# Gauge Field Digitization

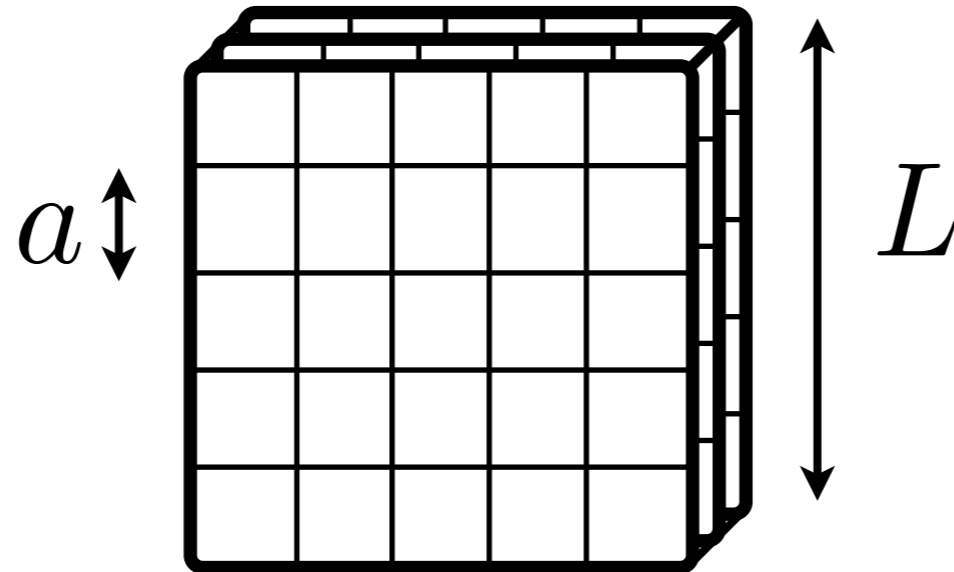
---

- All continuous quantities need to be made finite to perform computation in finite time, e.g., infinite volume continuum.

# Gauge Field Digitization

---

- All continuous quantities need to be made finite to perform computation in finite time, e.g., infinite volume continuum.



# Gauge Field Digitization

---

- Each gauge field at a specific spacetime point,  $x_\mu$ , is an element of a continuous group  $\longrightarrow$  infinite number of dof

# Gauge Field Digitization

---

• Each gauge field at a specific spacetime point,  $x_\mu$ , is an element of a continuous group  $\longrightarrow$  infinite number of dof



• Necessary to make infinite number of gauge field dof finite in order to perform any computation in finite time

# Gauge Field Digitization

---

• Each gauge field at a specific spacetime point,  $x_\mu$ , is an element of a continuous group  $\longrightarrow$  infinite number of dof



• Necessary to make infinite number of gauge field dof finite in order to perform any computation in finite time

• E.g., gauge link  $U_\mu = \mathcal{P} \exp \left( \int A_\mu dx^\mu \right)$   
to be in  $U(1)$

# Gauge Field Digitization

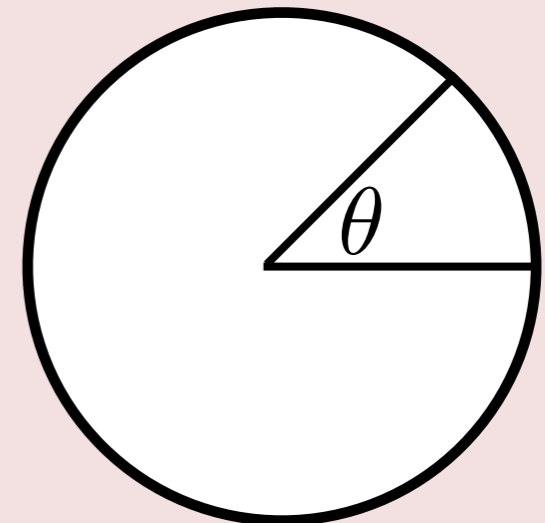
Each gauge field at a specific spacetime point,  $x_\mu$ , is an element of a continuous group  $\longrightarrow$  infinite number of dof



Necessary to make infinite number of gauge field dof finite in order to perform any computation in finite time

E.g., gauge link  $U_\mu = \mathcal{P} \exp \left( \int A_\mu dx^\mu \right)$   
to be in  $U(1)$

$U_\mu$  described by a circle



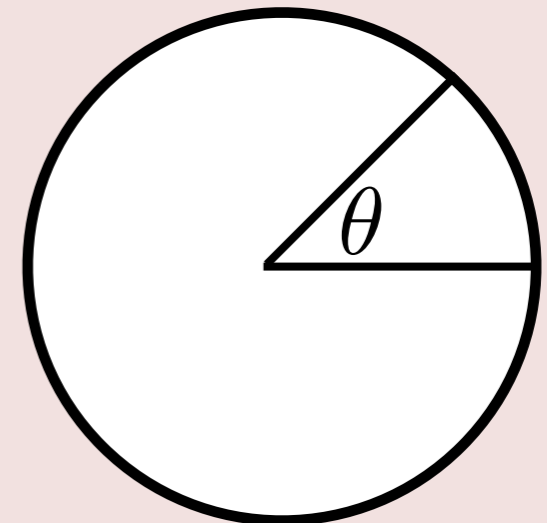
# Gauge Field Digitization

- Each gauge field at a specific spacetime point,  $x_\mu$ , is an element of a continuous group  $\longrightarrow$  infinite number of dof



- Necessary to make infinite number of gauge field dof finite in order to perform any computation in finite time

- E.g., gauge link  $U_\mu = \mathcal{P} \exp \left( \int A_\mu dx^\mu \right)$  to be in  $U(1)$
- $U_\mu$  described by a circle
- Digitize by sampling over the circle:





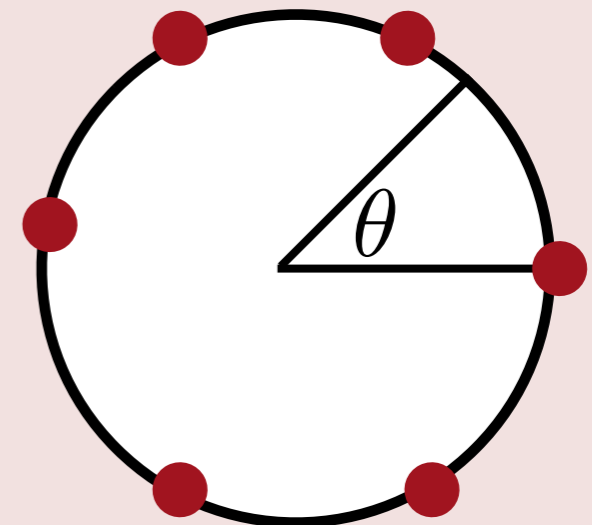
# Gauge Field Digitization

- Each gauge field at a specific spacetime point,  $x_\mu$ , is an element of a continuous group  $\longrightarrow$  infinite number of dof



- Necessary to make infinite number of gauge field dof finite in order to perform any computation in finite time

- E.g., gauge link  $U_\mu = \mathcal{P} \exp \left( \int A_\mu dx^\mu \right)$  to be in  $U(1)$
- $U_\mu$  described by a circle
- Digitize by sampling over the circle:



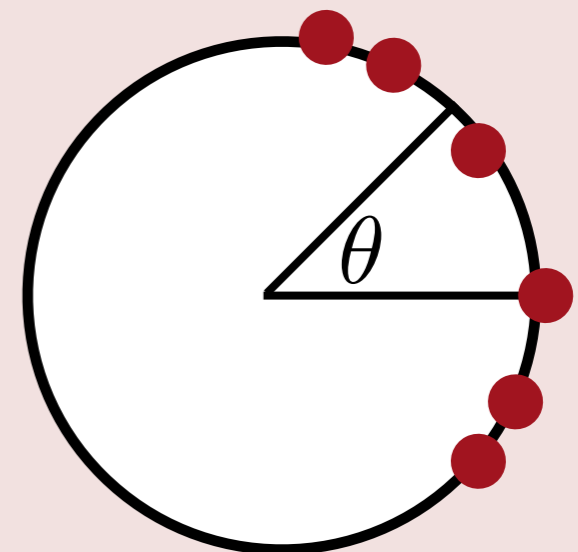
# Gauge Field Digitization

- Each gauge field at a specific spacetime point,  $x_\mu$ , is an element of a continuous group  $\longrightarrow$  infinite number of dof



- Necessary to make infinite number of gauge field dof finite in order to perform any computation in finite time

- E.g., gauge link  $U_\mu = \mathcal{P} \exp \left( \int A_\mu dx^\mu \right)$  to be in  $U(1)$
- $U_\mu$  described by a circle
- Digitize by sampling over the circle:

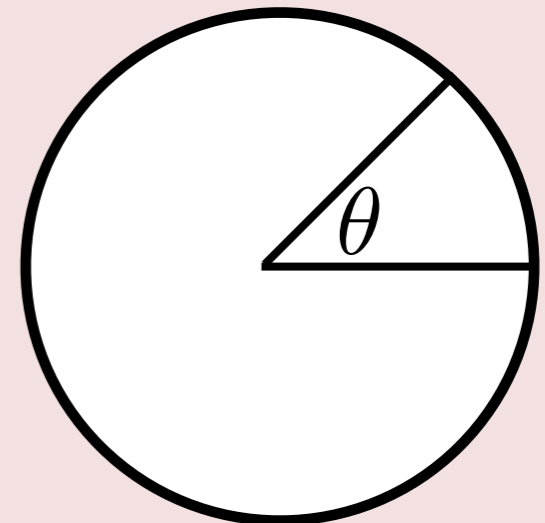


# Gauge Field Digitization: Classical LGT

Each gauge field at a specific spacetime point,  $x_\mu$ , is an element of a continuous group  $\longrightarrow$  infinite number of dof



Necessary to make infinite number of gauge field dof finite in order to perform any computation in finite time



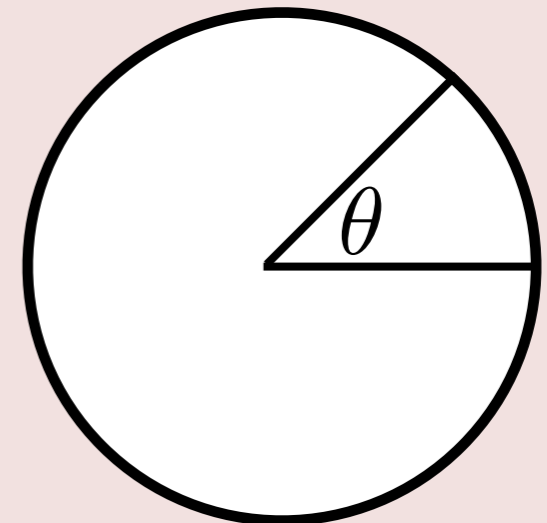
# Gauge Field Digitization: Classical LGT

Each gauge field at a specific spacetime point,  $x_\mu$ , is an element of a continuous group  $\longrightarrow$  infinite number of dof



Necessary to make infinite number of gauge field dof finite in order to perform any computation in finite time

Not usually discussed in lattice QCD, as each gauge field can have  $2^{64}$  values on a 64-bit machine



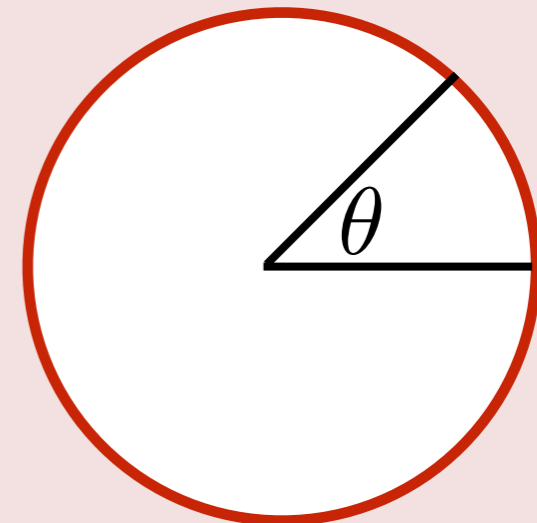
# Gauge Field Digitization: Classical LGT

Each gauge field at a specific spacetime point,  $x_\mu$ , is an element of a continuous group  $\longrightarrow$  infinite number of dof



Necessary to make infinite number of gauge field dof finite in order to perform any computation in finite time

Not usually discussed in lattice QCD, as each gauge field can have  $2^{64}$  values on a 64-bit machine



# Gauge Field Digitization: Classical LGT

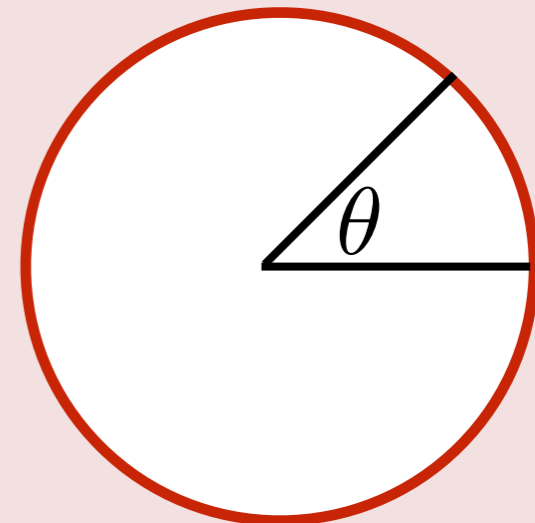
Each gauge field at a specific spacetime point,  $x_\mu$ , is an element of a continuous group  $\longrightarrow$  infinite number of dof



Necessary to make infinite number of gauge field dof finite in order to perform any computation in finite time

Not usually discussed in lattice QCD, as each gauge field can have  $2^{64}$  values on a 64-bit machine

Importance sampling means don't need to integrate over all values.



# Gauge Field Digitization: $SU(2)$

---

- 📌 Necessary to make gauge field continuous degrees of freedom finite to perform any computation in finite time

# Gauge Field Digitization: $SU(2)$

---

📌 Necessary to make gauge field continuous degrees of freedom finite to perform any computation in finite time

📌 E.g., take a gauge link  $U_\mu \in SU(2)$



# Gauge Field Digitization: $SU(2)$

---

📌 Necessary to make gauge field continuous degrees of freedom finite to perform any computation in finite time

📌 E.g., take a gauge link  $U_\mu \in SU(2)$

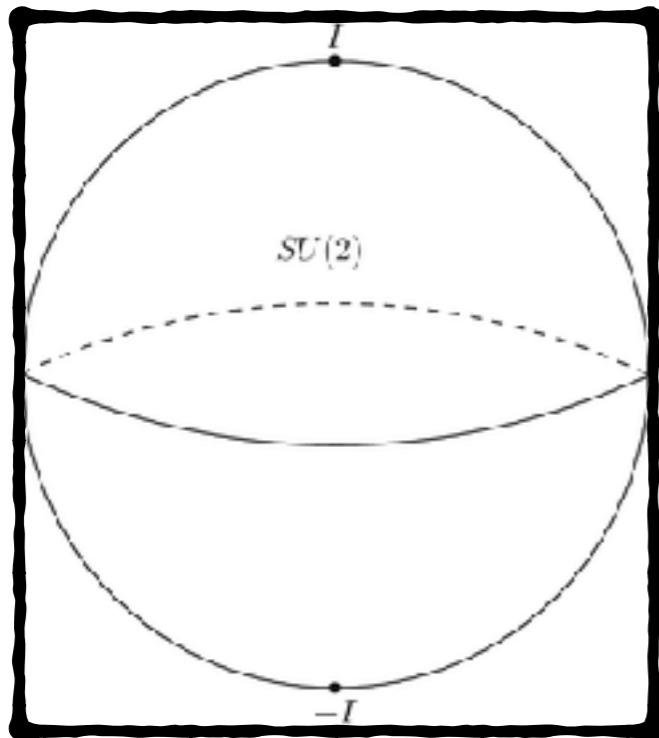
📌 Each  $U_\mu$  described by point on three-sphere:  $a^2 + b^2 + c^2 + d^2 = 1$

# Gauge Field Digitization: $SU(2)$

📍 Necessary to make gauge field continuous degrees of freedom finite to perform any computation in finite time

📍 E.g., take a gauge link  $U_\mu \in SU(2)$

📍 Each  $U_\mu$  described by point on three-sphere:  $a^2 + b^2 + c^2 + d^2 = 1$

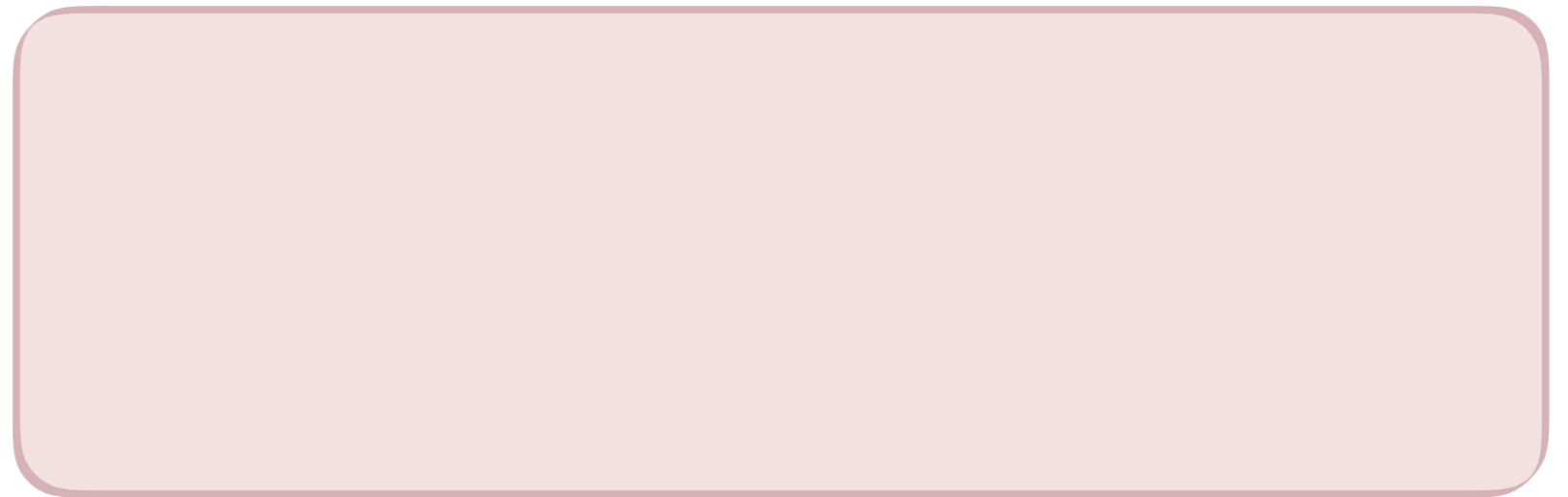
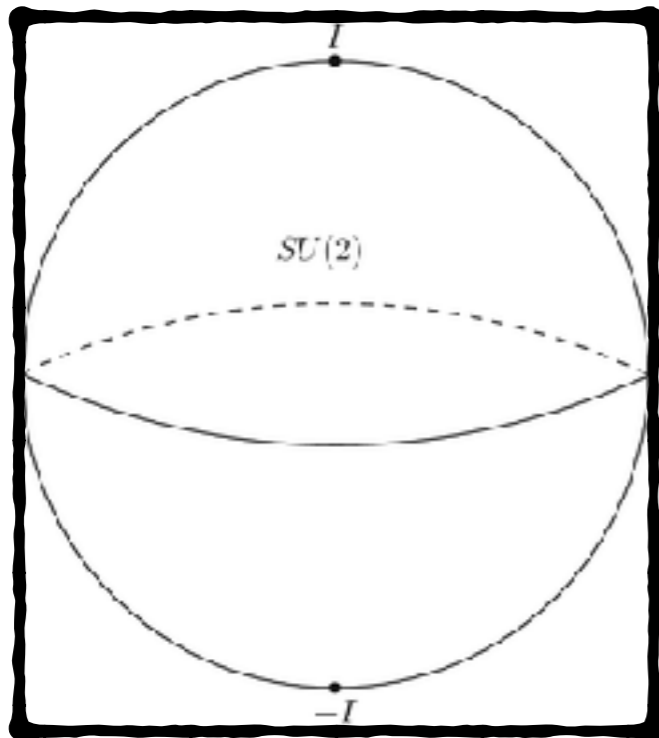


# Gauge Field Digitization: 1) Fixed-Point

📍 Necessary to make gauge field continuous degrees of freedom finite to perform any computation in finite time

📍 E.g., take a gauge link  $U_\mu \in SU(2)$

📍 Each  $U_\mu$  described by point on three-sphere:  $a^2 + b^2 + c^2 + d^2 = 1$

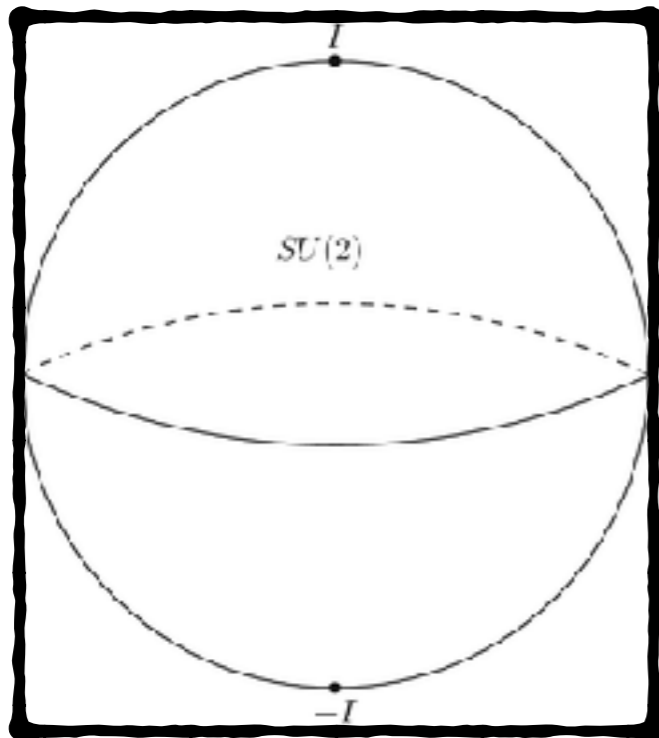


# Gauge Field Digitization: 1) Fixed-Point

📌 Necessary to make gauge field continuous degrees of freedom finite to perform any computation in finite time

📌 E.g., take a gauge link  $U_\mu \in SU(2)$

📌 Each  $U_\mu$  described by point on three-sphere:  $a^2 + b^2 + c^2 + d^2 = 1$



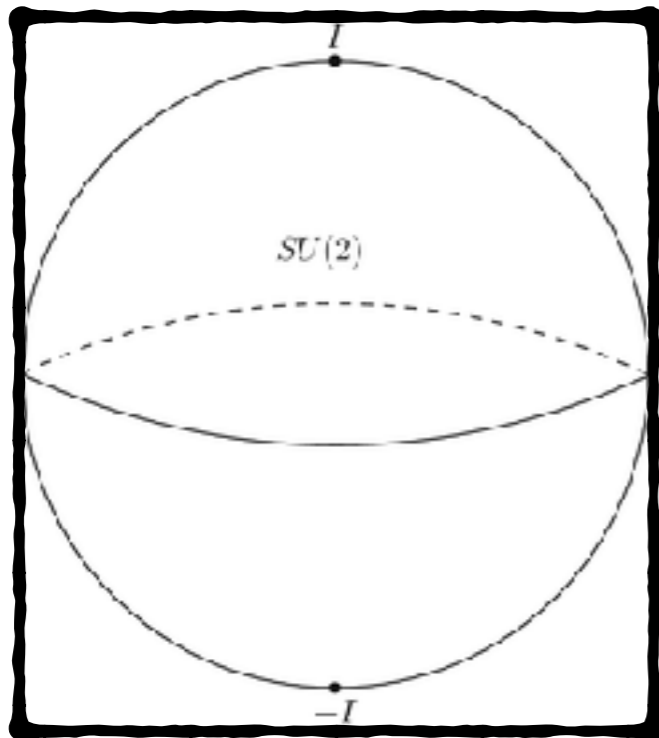
📌 Take the 64-bit values of  $a$ ,  $b$  and  $c$

# Gauge Field Digitization: 1) Fixed-Point

- Necessary to make gauge field continuous degrees of freedom finite to perform any computation in finite time

- E.g., take a gauge link  $U_\mu \in SU(2)$

- Each  $U_\mu$  described by point on three-sphere:  $a^2 + b^2 + c^2 + d^2 = 1$



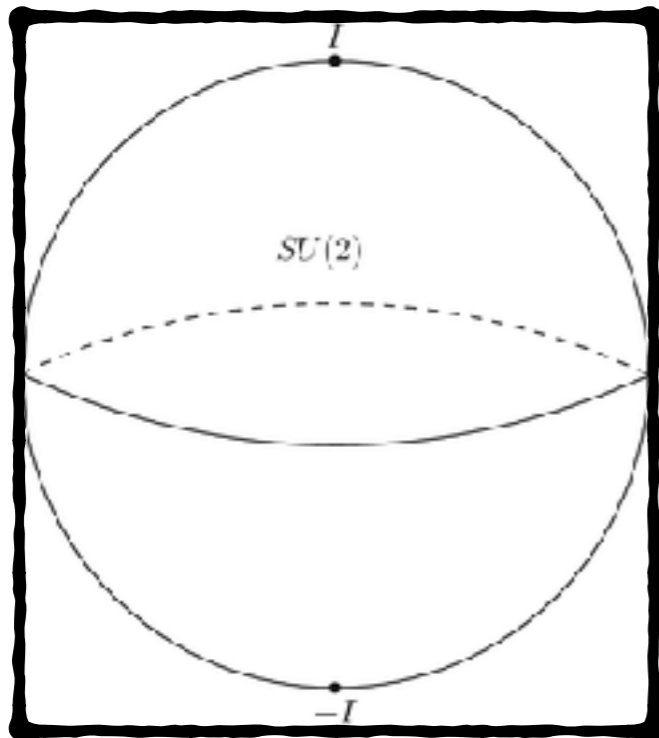
- Take the 64-bit values of  $a, b$  and  $c$
- Project these to  $n$ -bit numbers

# Gauge Field Digitization: 1) Fixed-Point

- Necessary to make gauge field continuous degrees of freedom finite to perform any computation in finite time

- E.g., take a gauge link  $U_\mu \in SU(2)$

- Each  $U_\mu$  described by point on three-sphere:  $a^2 + b^2 + c^2 + d^2 = 1$



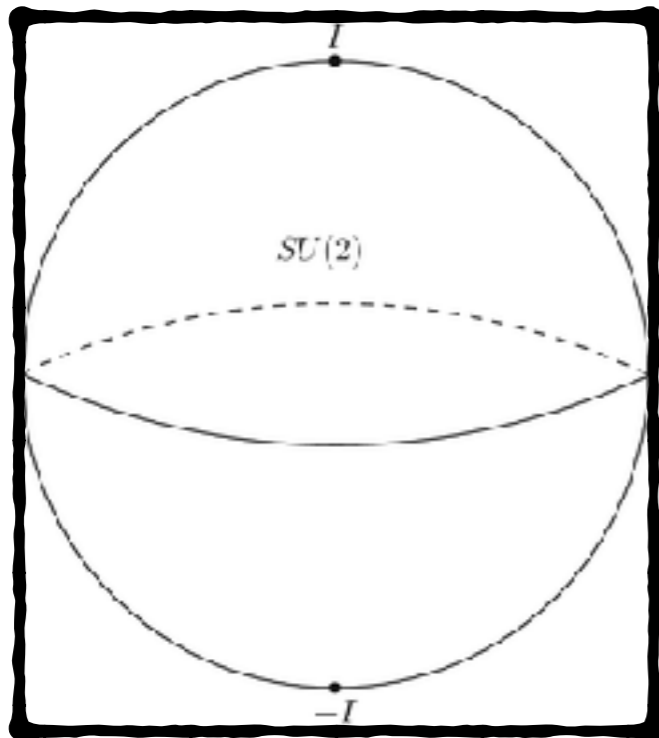
- Take the 64-bit values of  $a, b$  and  $c$
- Project these to  $n$ -bit numbers
- Compute  $n$ -bit  $d^2 = 1 - a^2 - b^2 - c^2$

# Gauge Field Digitization: 1) Fixed-Point

- Necessary to make gauge field continuous degrees of freedom finite to perform any computation in finite time

- E.g., take a gauge link  $U_\mu \in \text{SU}(2)$

- Each  $U_\mu$  described by point on three-sphere:  $a^2 + b^2 + c^2 + d^2 = 1$



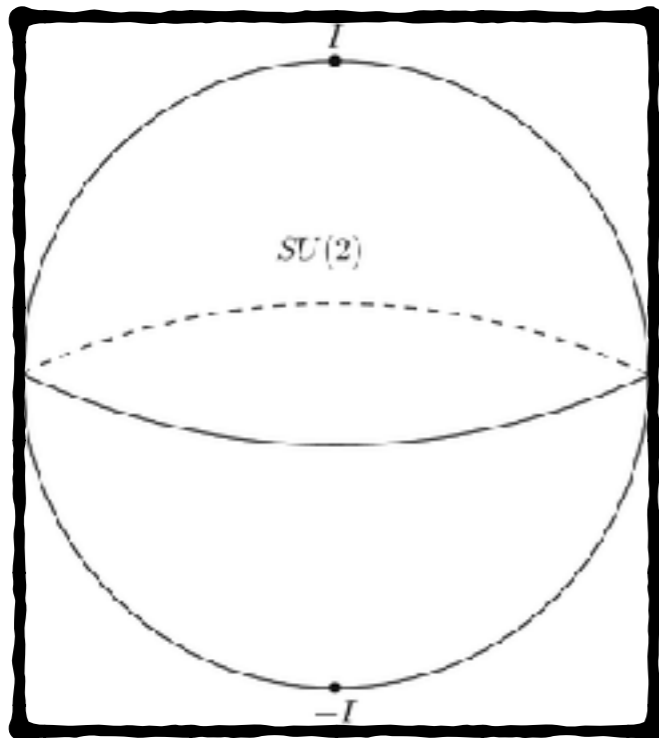
- Take the 64-bit values of  $a, b$  and  $c$
- Project these to  $n$ -bit numbers
- Compute  $n$ -bit  $d^2 = 1 - a^2 - b^2 - c^2$
- Do all calculations with  $n$ -bit precision

# Gauge Field Digitization: 2) Indexed Mesh

📍 Necessary to make gauge field continuous degrees of freedom finite to perform any computation in finite time

📍 E.g., take a gauge link  $U_\mu \in \text{SU}(2)$

📍 Each  $U_\mu$  described by point on three-sphere:  $a^2 + b^2 + c^2 + d^2 = 1$



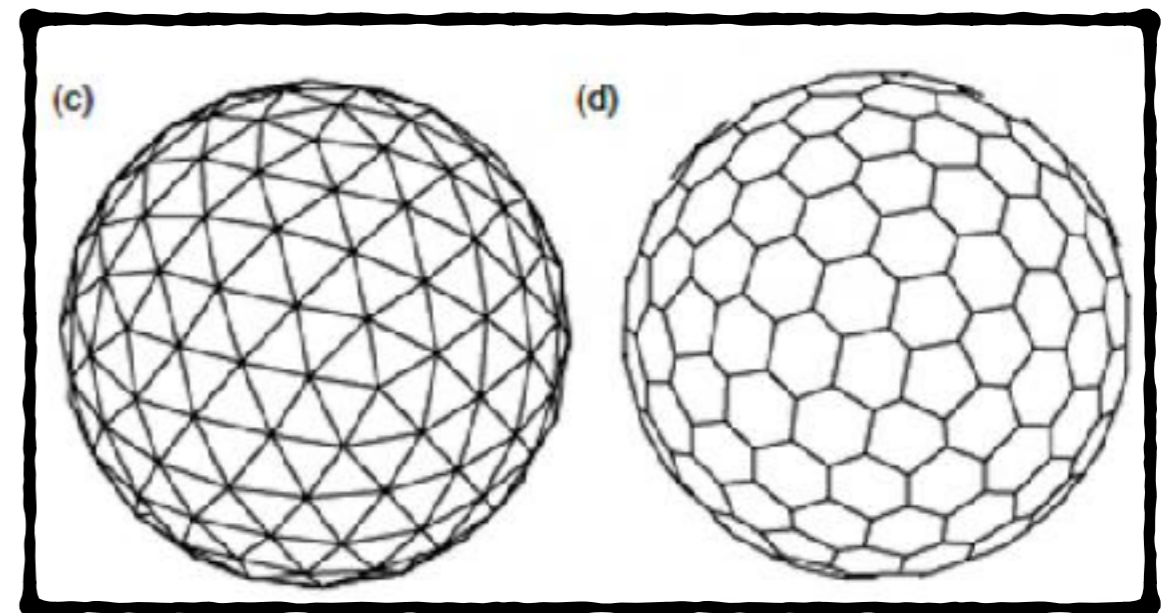
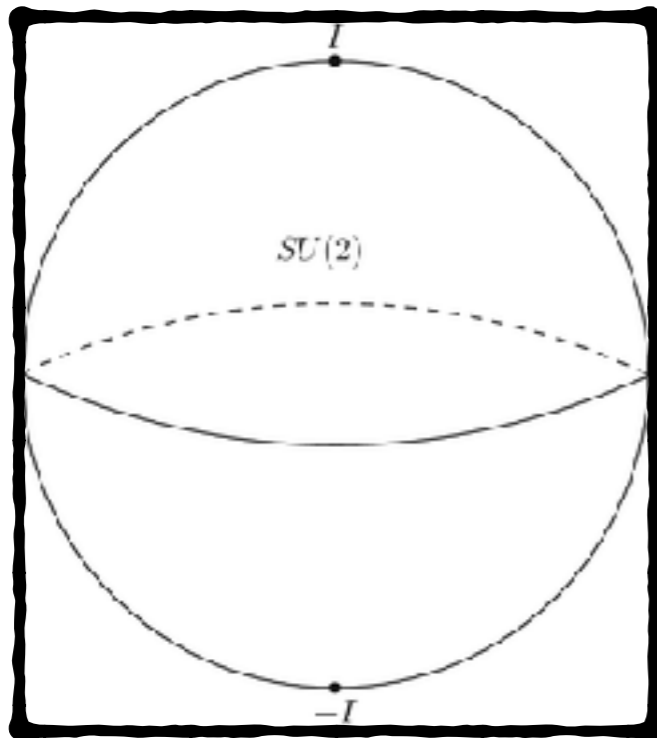


# Gauge Field Digitization: 2) Indexed Mesh

• Necessary to make gauge field continuous degrees of freedom finite to perform any computation in finite time

• E.g., take a gauge link  $U_\mu \in SU(2)$

• Each  $U_\mu$  described by point on three-sphere:  $a^2 + b^2 + c^2 + d^2 = 1$

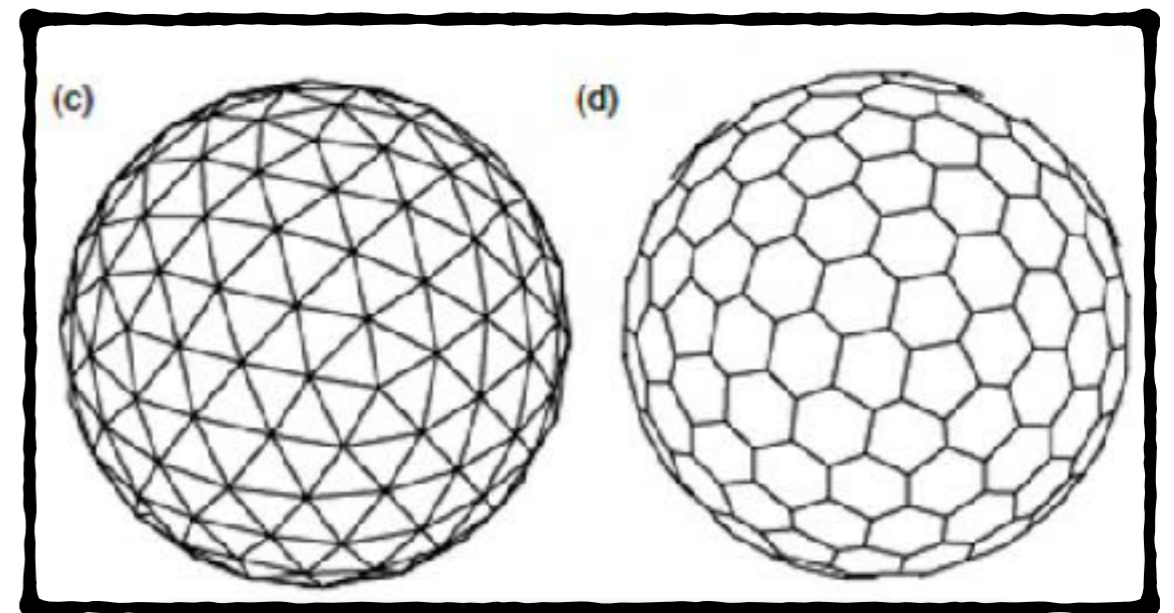
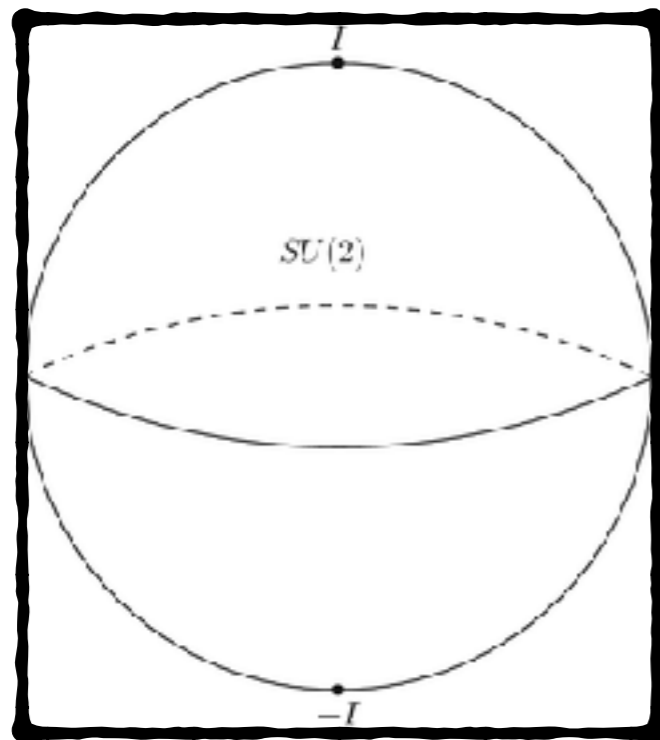


# Gauge Field Digitization: 2) Indexed Mesh

• Necessary to make gauge field continuous degrees of freedom finite to perform any computation in finite time

• E.g., take a gauge link  $U_\mu \in SU(2)$

• Each  $U_\mu$  described by point on three-sphere:  $a^2 + b^2 + c^2 + d^2 = 1$



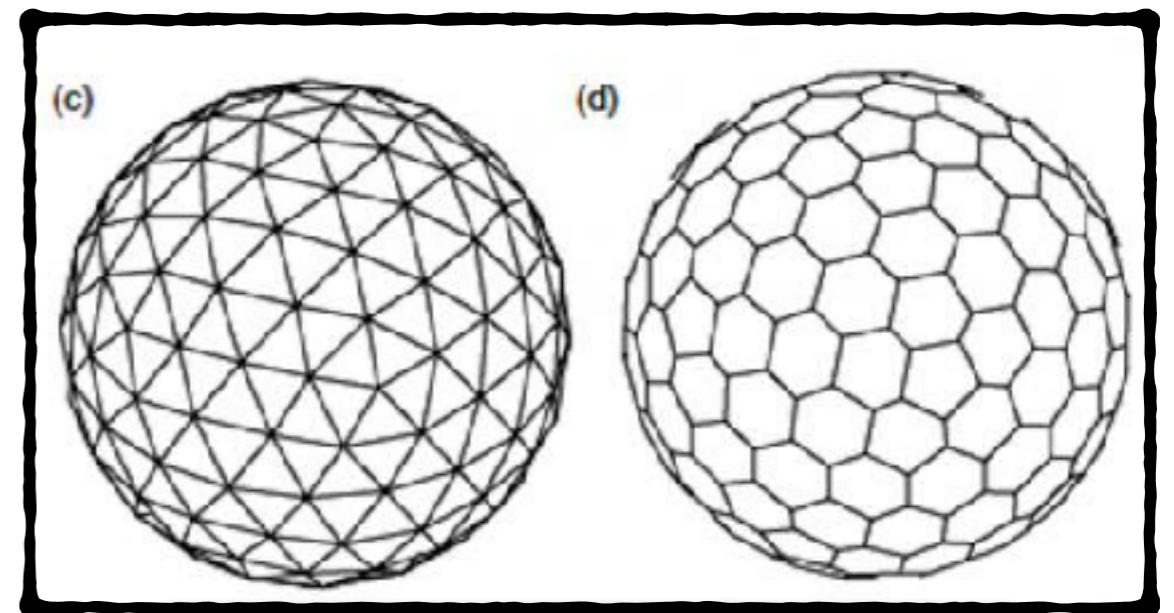
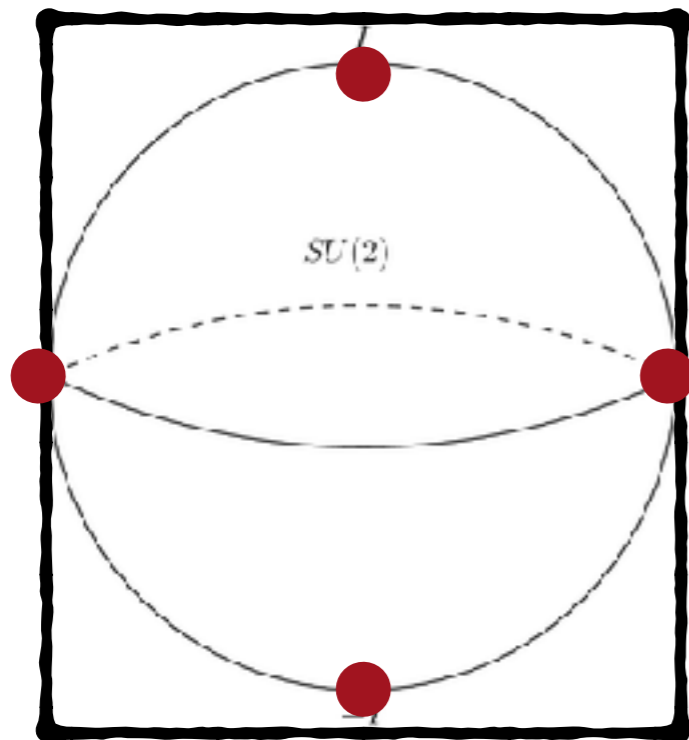
Number of qubits:  $\log_2(\text{mesh size})$

# Gauge Field Digitization: 2) Indexed Mesh

📍 Necessary to make gauge field continuous degrees of freedom finite to perform any computation in finite time

📍 E.g., take a gauge link  $U_\mu \in SU(2)$

📍 Each  $U_\mu$  described by point on three-sphere:  $a^2 + b^2 + c^2 + d^2 = 1$

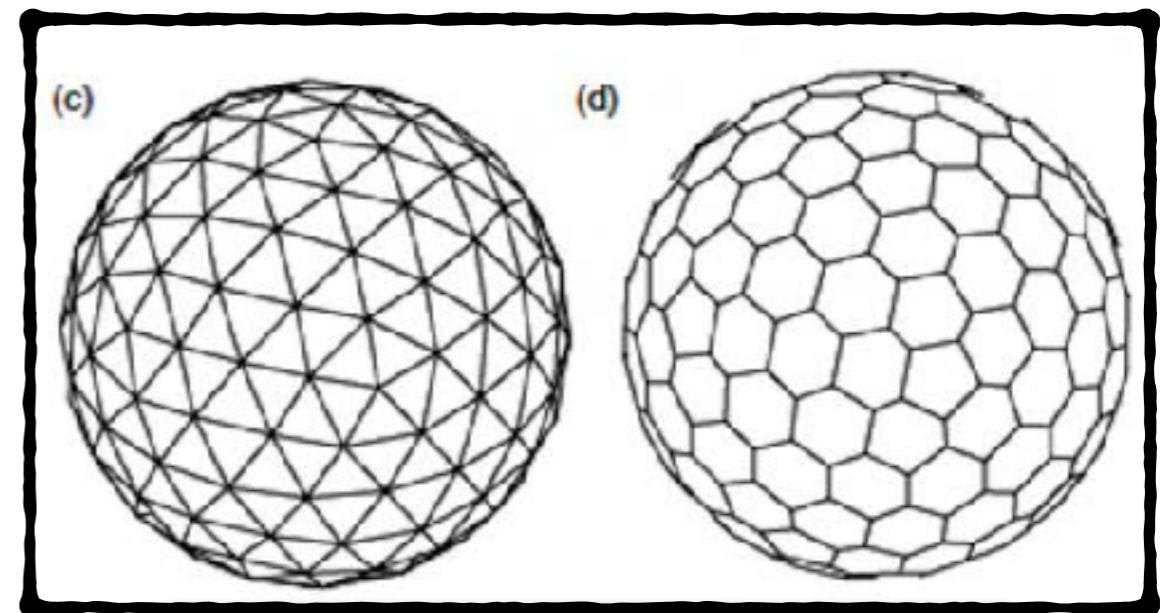
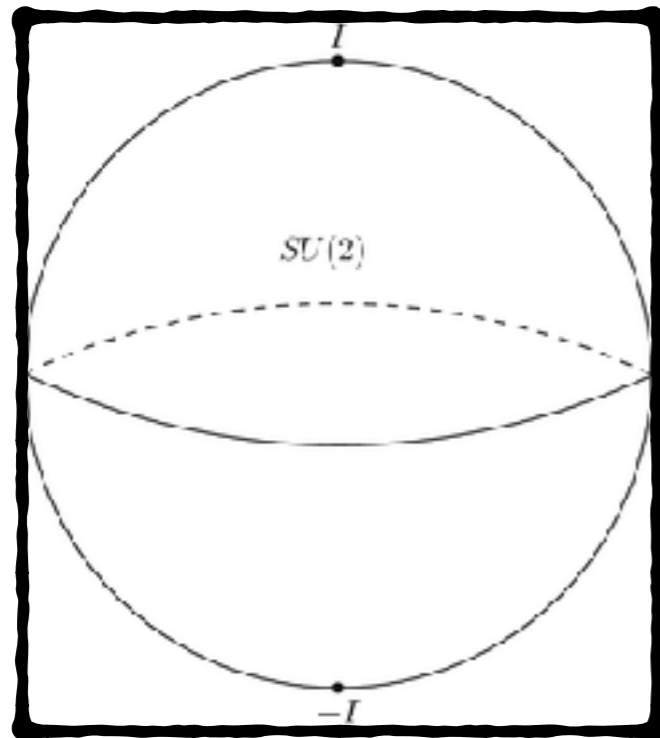


Number of qubits:  $\log_2(\text{mesh size})$

# Gauge Field Digitization: 2) Indexed Mesh

📌 Necessary to make gauge field continuous degrees of freedom finite to perform any computation in finite time

📌 Project to mesh by



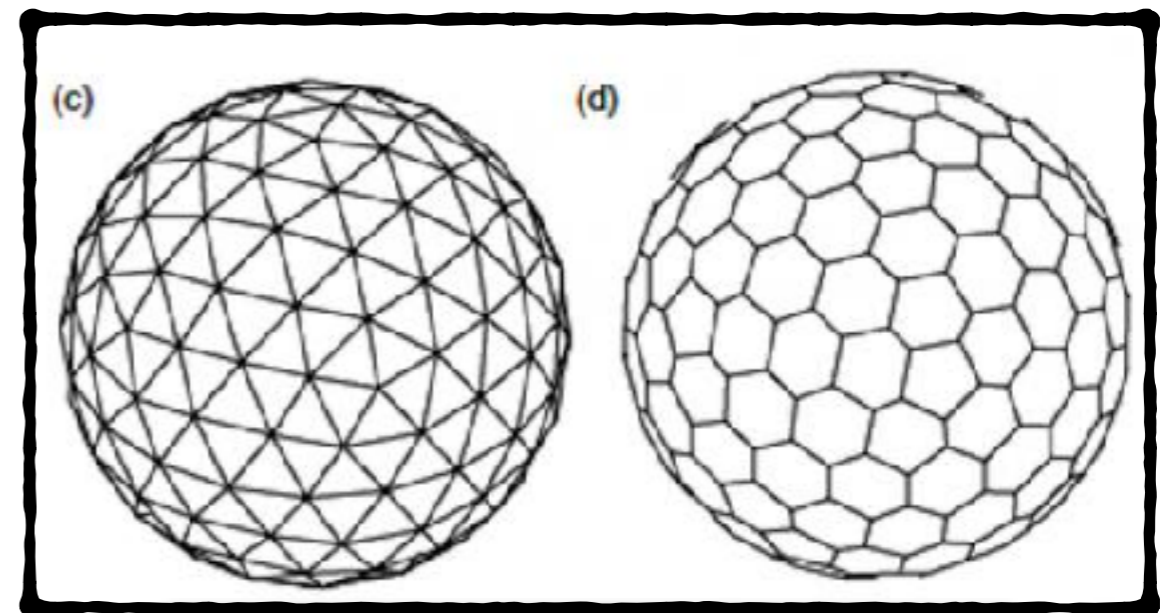
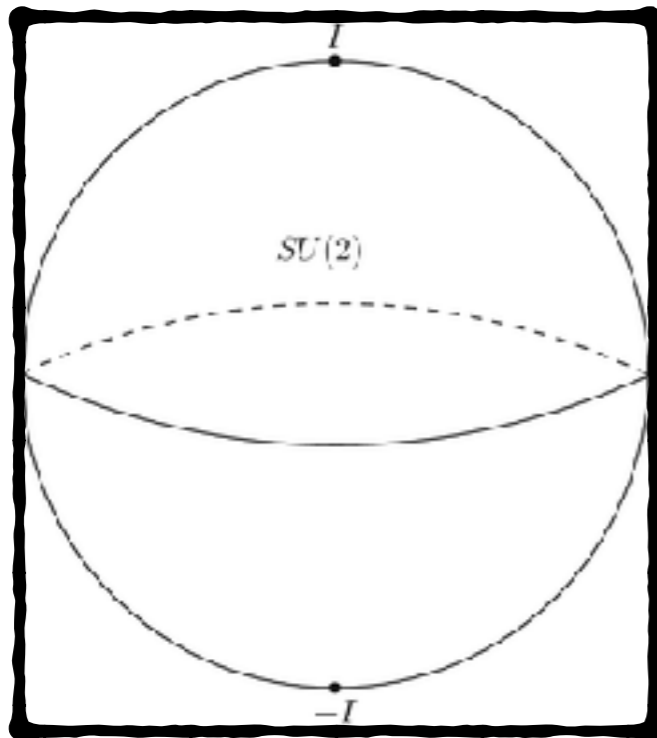
*Number of qubits:  $\log_2(\text{mesh size})$*

# Gauge Field Digitization: 2) Indexed Mesh

📌 Necessary to make gauge field continuous degrees of freedom finite to perform any computation in finite time

📌 Project to mesh by

📌 L2 norm :  $D(A, B) = \|A - B\|$ , with  $\|M\| = \text{Tr}(M^\dagger M)$   
:  $\Delta a^2 + \Delta b^2 + \Delta c^2 + \Delta d^2$



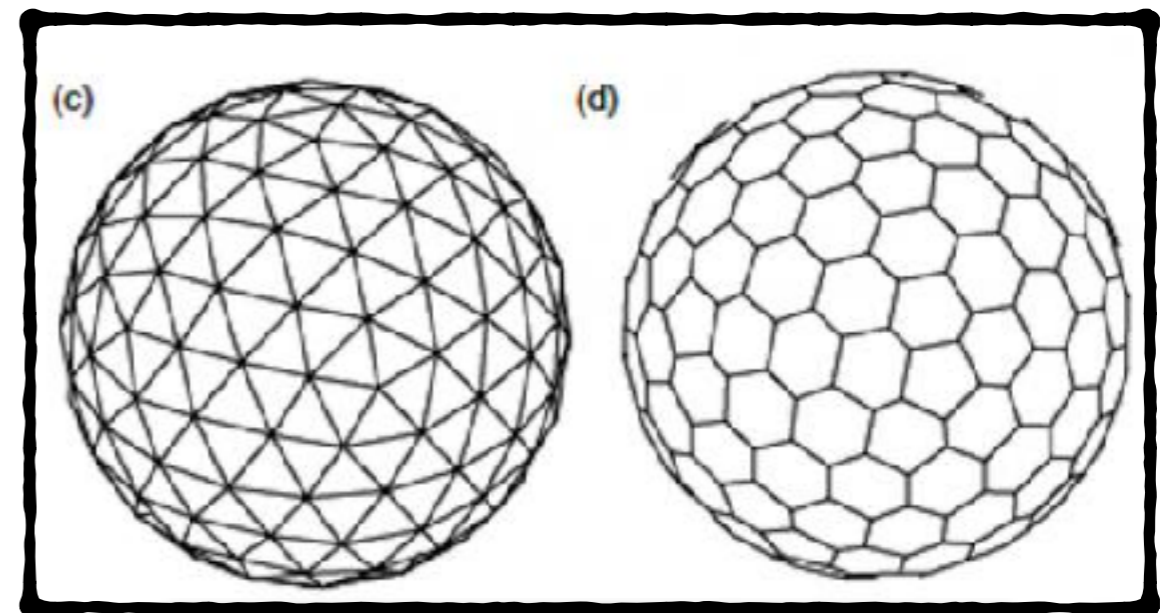
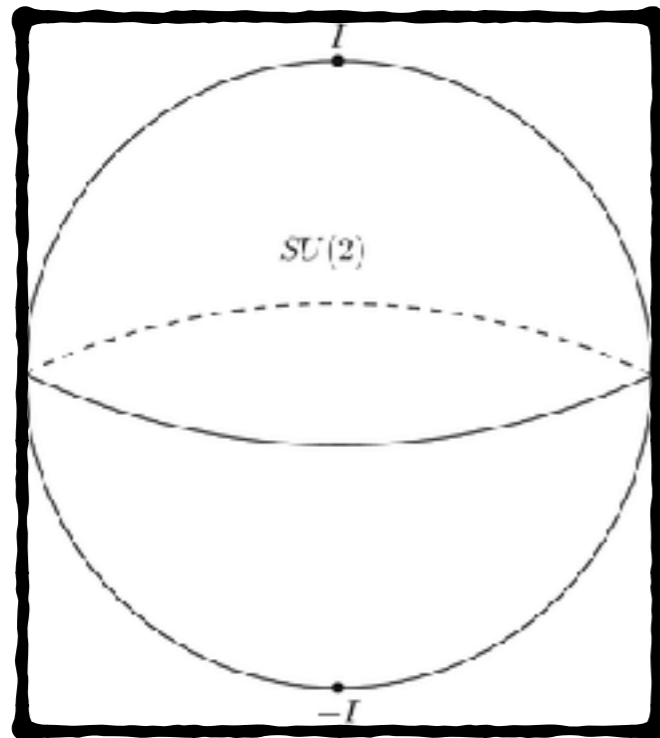
Number of qubits:  $\log_2(\text{mesh size})$

# Gauge Field Digitization: 2) Indexed Mesh

• Necessary to make gauge field continuous degrees of freedom finite to perform any computation in finite time

• Project to mesh by

• Action Preserving Method : Use mesh links that minimise changes to the action (or any observable)



*Number of qubits:  $\log_2(\text{mesh size})$*

# Gauge Field Digitization

---

*1 ) What resources are actually required during different stages of a quantum computation of a realistic theory?*

# Gauge Field Digitization

---

*1 ) What resources are actually required during different stages of a quantum computation of a realistic theory?*



*How many qubits are needed to simulate (3+1)D SU(2) Gauge theory???*



# Gauge Field Digitization

---

*1 ) What resources are actually required during different stages of a quantum computation of a realistic theory?*



*How many qubits are needed to simulate (3+1)D SU(2) Gauge theory???*



*The only tool we have to answer this is classical lattice gauge theory!!!*

# Classical Lattice Quantities

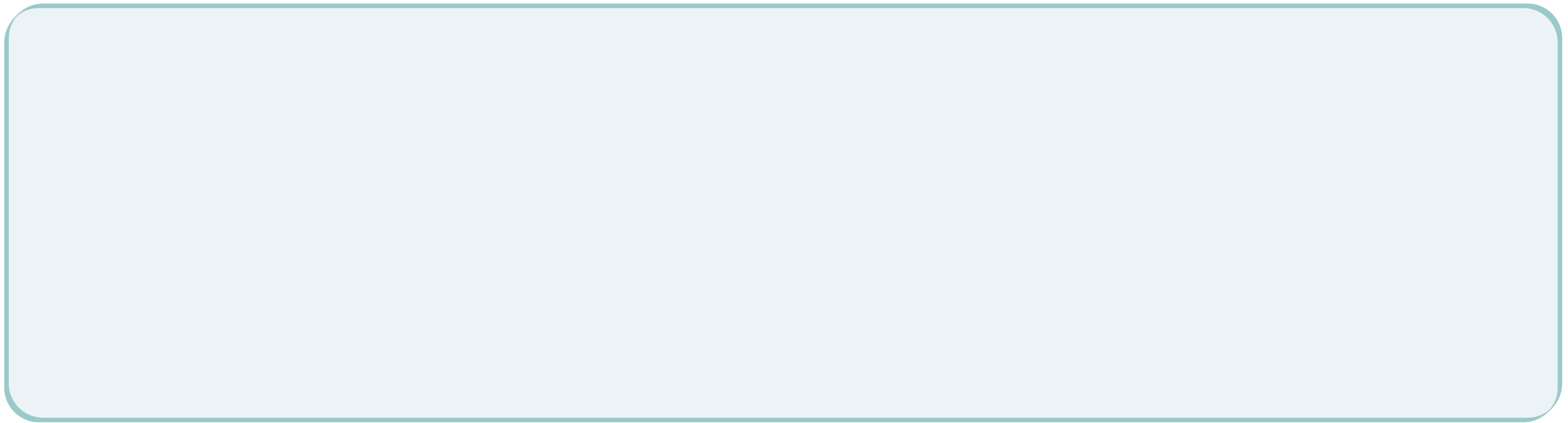
---

Down  
the  
Rabbit  
HOLE



# A (Bigger Picture) Lattice Calculation: Wilson loops

---



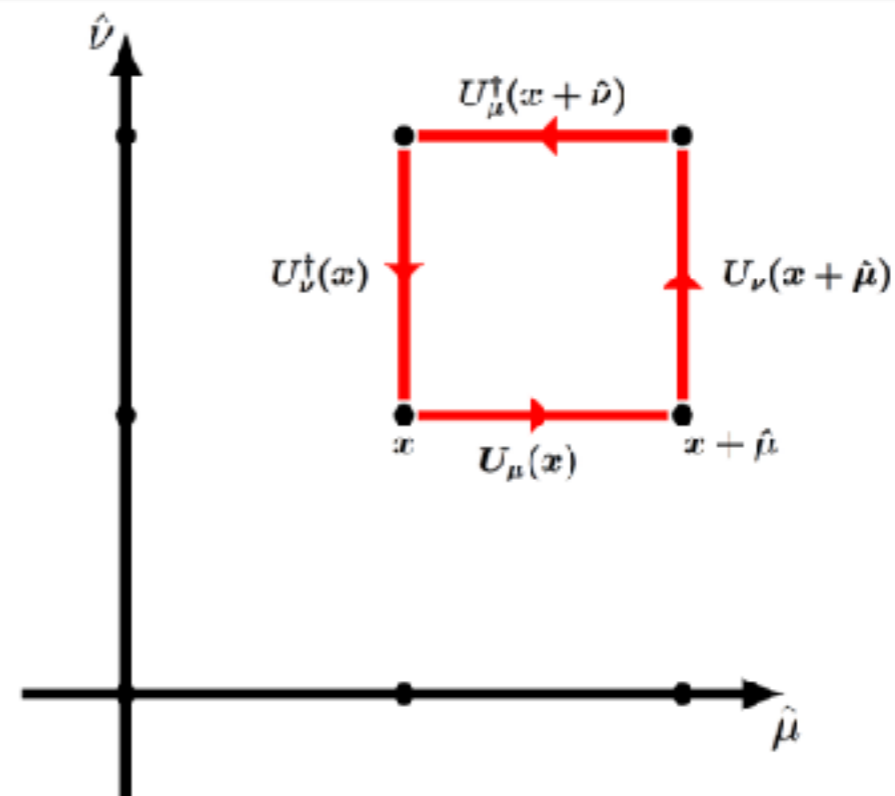
# A (Bigger Picture) Lattice Calculation: Wilson loops

---

- **Feynman Path Integral Approach to QFT:** (Numerically) Integrate over all field configurations

# A (Bigger Picture) Lattice Calculation: Wilson loops

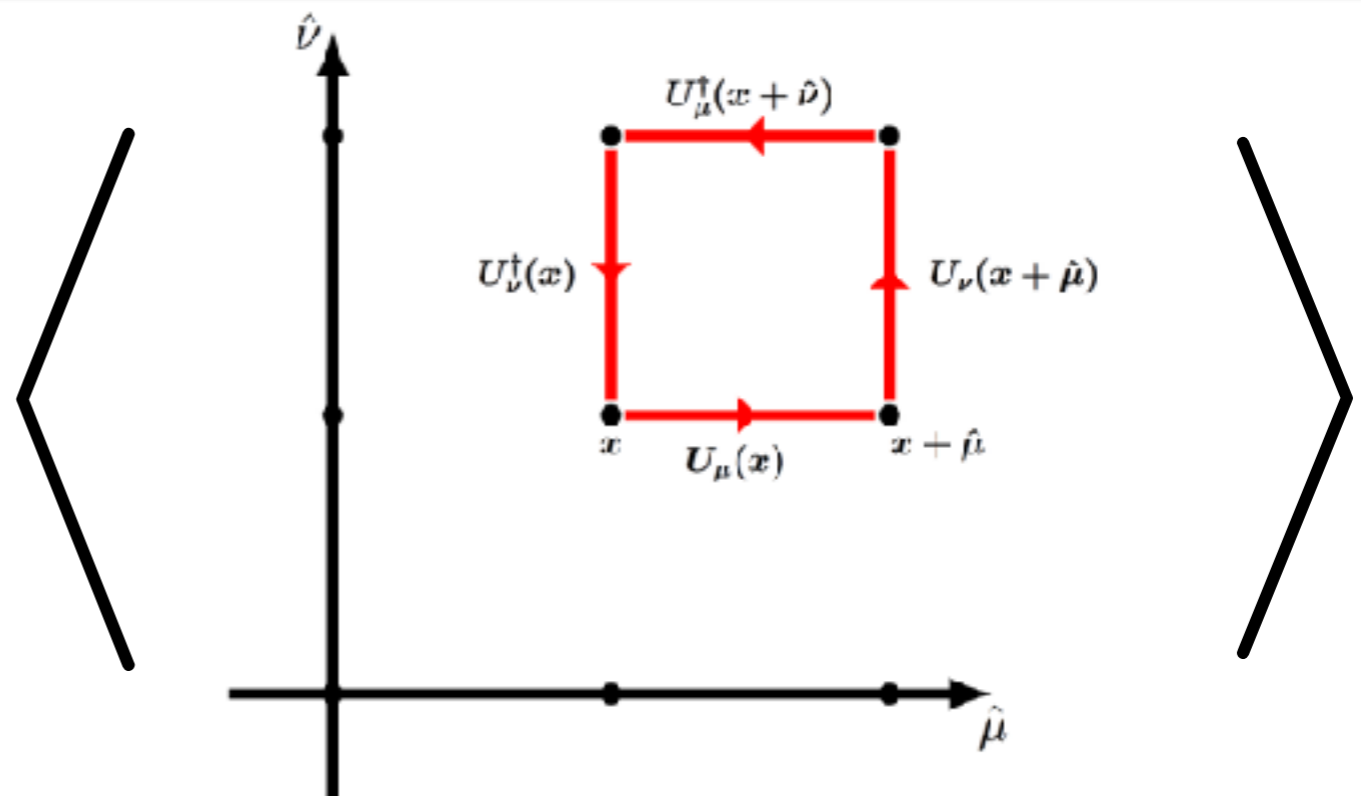
- Feynman Path Integral Approach to QFT: (Numerically) Integrate over all field configurations
  - Simplest Gauge Invariant Quantities: Wilson loops



# A (Bigger Picture) Lattice Calculation: Plaquette

- Feynman Path Integral Approach to QFT: (Numerically) Integrate over all field configurations
  - Simplest Gauge Invariant Quantities: Wilson loops
  - Building Blocks for Gauge Action

$$\square = \sum_x \sum_{\mu < \nu} \text{Re Tr}$$



# A (Bigger Picture) Lattice Calculation: P6 Wilson loops

---

- **Feynman Path Integral Approach to QFT:** (Numerically) Integrate over all field configurations
  - **Other Gauge Invariant Quantities:** Perimeter 6 Wilson loops

# A (Bigger Picture) Lattice Calculation: P6 Wilson loops

---

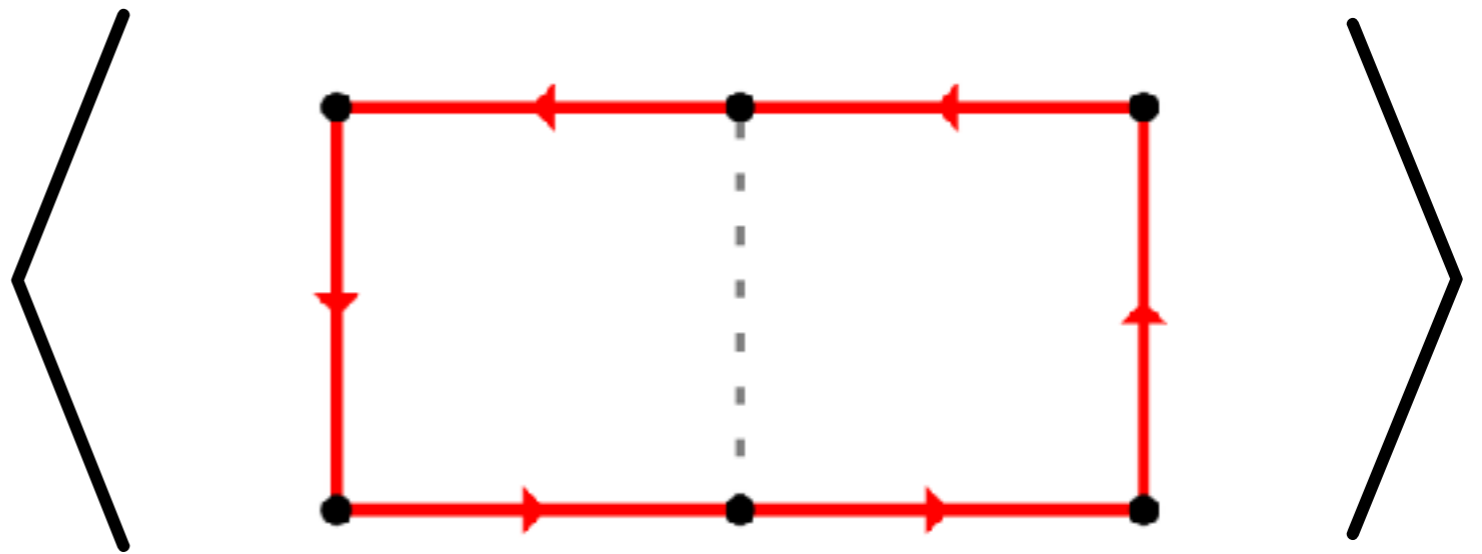
- **Feynman Path Integral Approach to QFT:** (Numerically) Integrate over all field configurations
  - Other Gauge Invariant Quantities: Perimeter 6 Wilson loops
  - Useful for action improvement



# A (Bigger Picture) Lattice Calculation: P6 Wilson loops

- **Feynman Path Integral Approach to QFT:** (Numerically) Integrate over all field configurations
  - Other Gauge Invariant Quantities: Perimeter 6 Wilson loops
  - Useful for action improvement

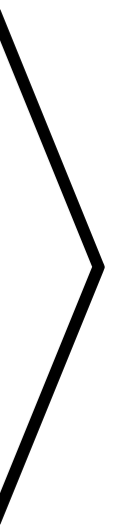
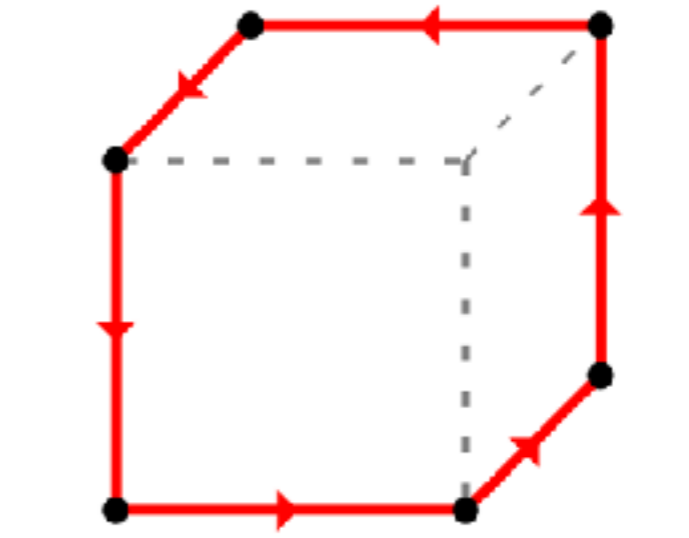
$$\mathcal{P}_1 = \sum_x \sum_{\mu < \nu} \text{Re Tr}$$



# A (Bigger Picture) Lattice Calculation: P6 Wilson loops

- **Feynman Path Integral Approach to QFT:** (Numerically) Integrate over all field configurations
  - Other Gauge Invariant Quantities: Perimeter 6 Wilson loops
  - Useful for action improvement

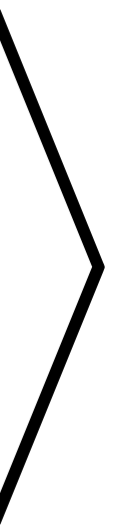
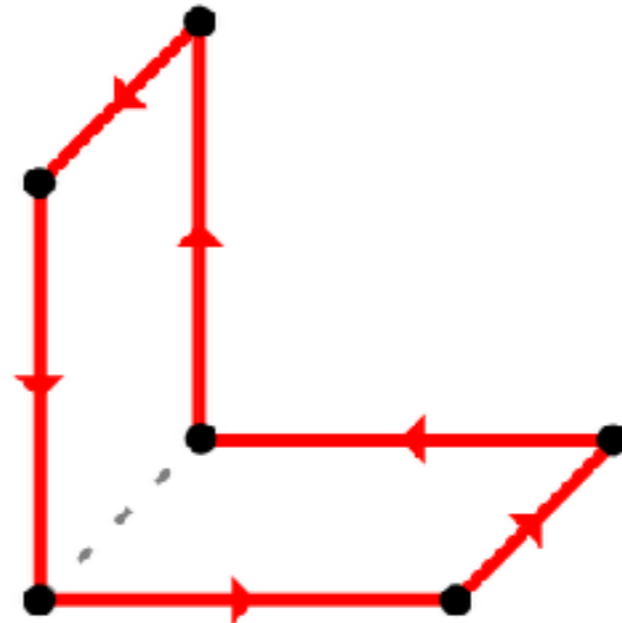
$$\mathcal{P}_2 = \sum_x \sum_{\mu < \nu} \text{Re Tr}$$



# A (Bigger Picture) Lattice Calculation: P6 Wilson loops

- Feynman Path Integral Approach to QFT: (Numerically) Integrate over all field configurations
  - Other Gauge Invariant Quantities: Perimeter 6 Wilson loops
  - Useful for action improvement

$$\mathcal{P}_3 = \sum_x \sum_{\mu < \nu} \text{Re Tr}$$



# A (Bigger Picture) Lattice Calculation: Static Potential

---

- **Feynman Path Integral Approach to QFT:** (Numerically) Integrate over all field configurations
  - Static Potential Between quarks: Wilson loop  $W(t, r)$  of spatial length  $r$  and temporal length  $t$  scales as....

# A (Bigger Picture) Lattice Calculation: Static Potential

---

- **Feynman Path Integral Approach to QFT:** (Numerically) Integrate over all field configurations
  - Static Potential Between quarks: Wilson loop  $W(t, r)$  of spatial length  $r$  and temporal length  $t$  scales as....

$$W(t, r) \sim \exp(-tV(r))$$

# A (Bigger Picture) Lattice Calculation: Polyakov loop

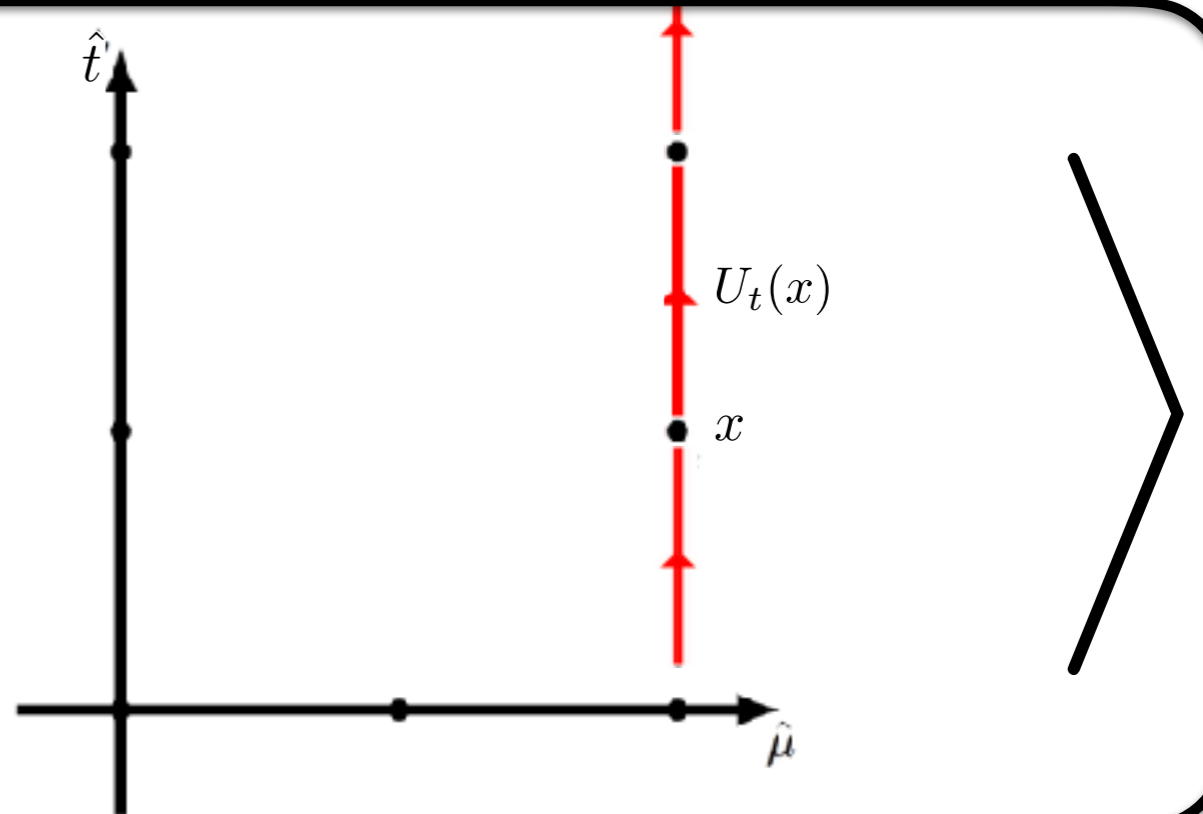
---

- **Feynman Path Integral Approach to QFT: (Numerically) Integrate over all field configurations**
  - Other Gauge Invariant Quantities: Polyakov Loop
  - Order Parameter for deconfinement transition

# A (Bigger Picture) Lattice Calculation: Polyakov loop

- Feynman Path Integral Approach to QFT: (Numerically) Integrate over all field configurations
  - Other Gauge Invariant Quantities: Polyakov Loop
  - Order Parameter for deconfinement transition

$$\Omega = \sum_x \text{Re Tr}$$





show me the data!

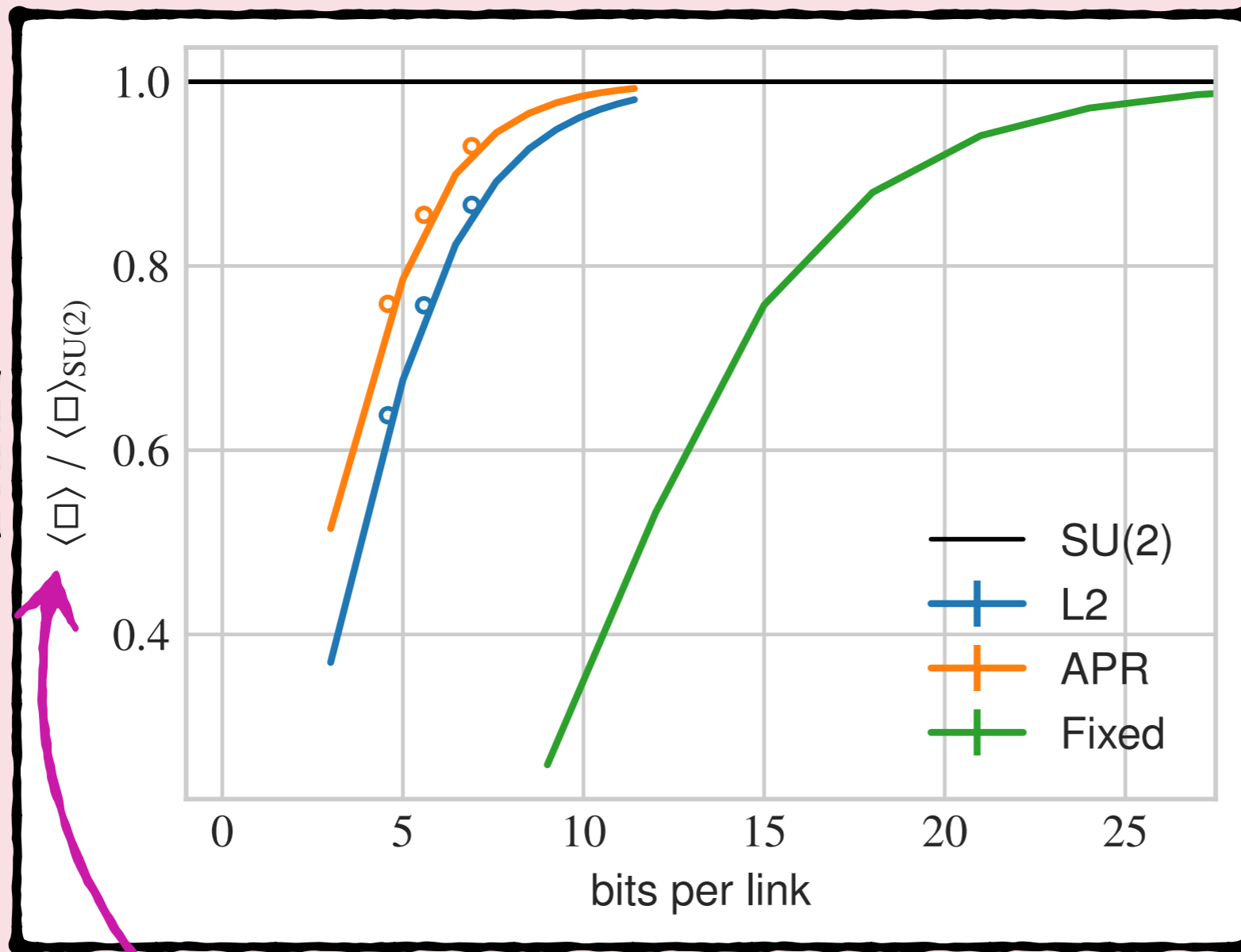
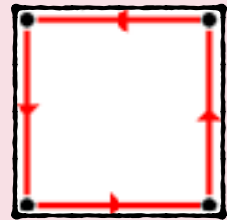
👤 Important to see the data for yourself and make own conclusions



How Many (qu)bits do you need: Plaquette?

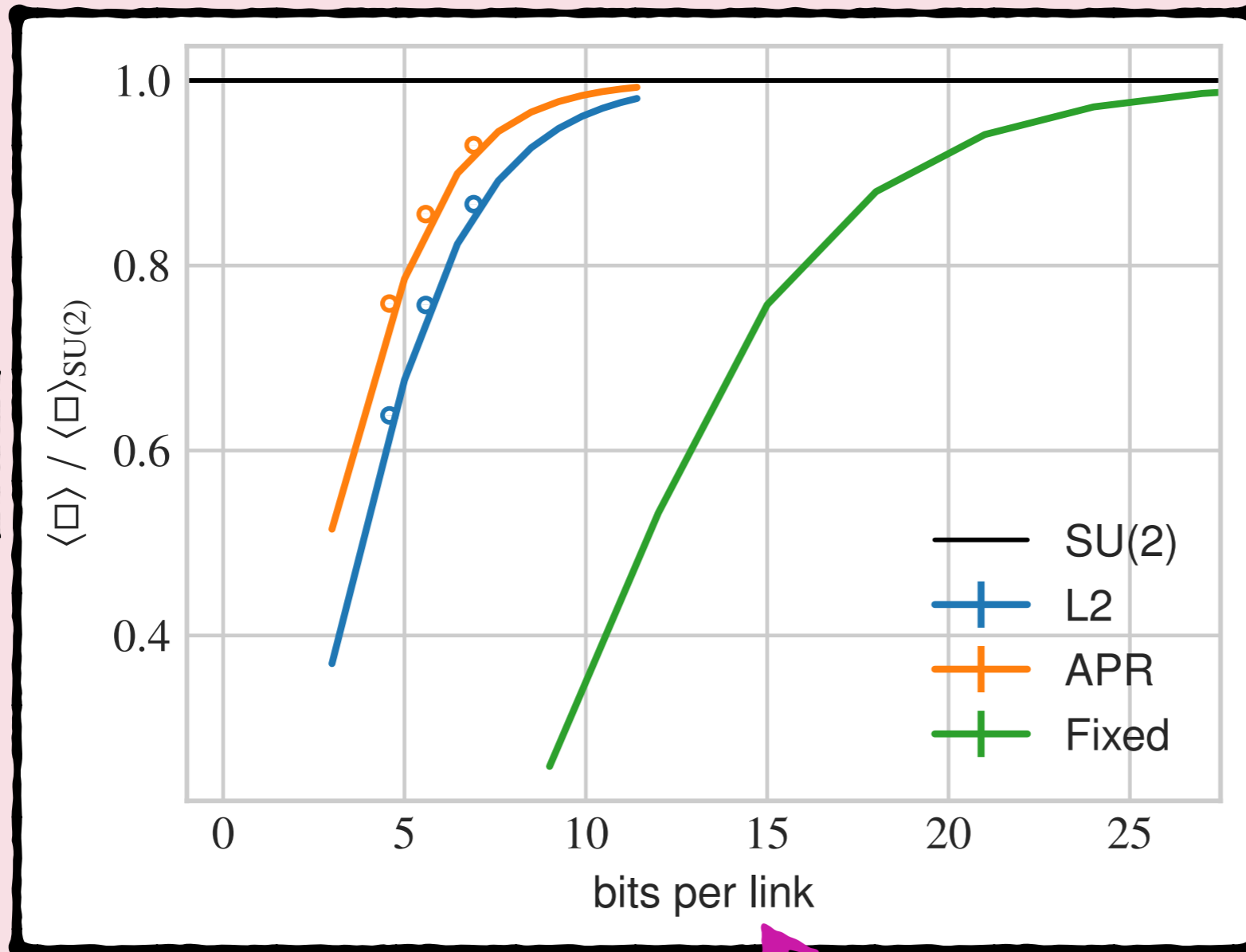
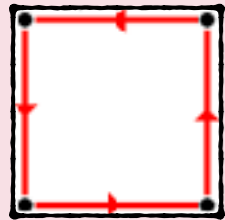
---

# How Many (qu)bits do you need: Plaquette?



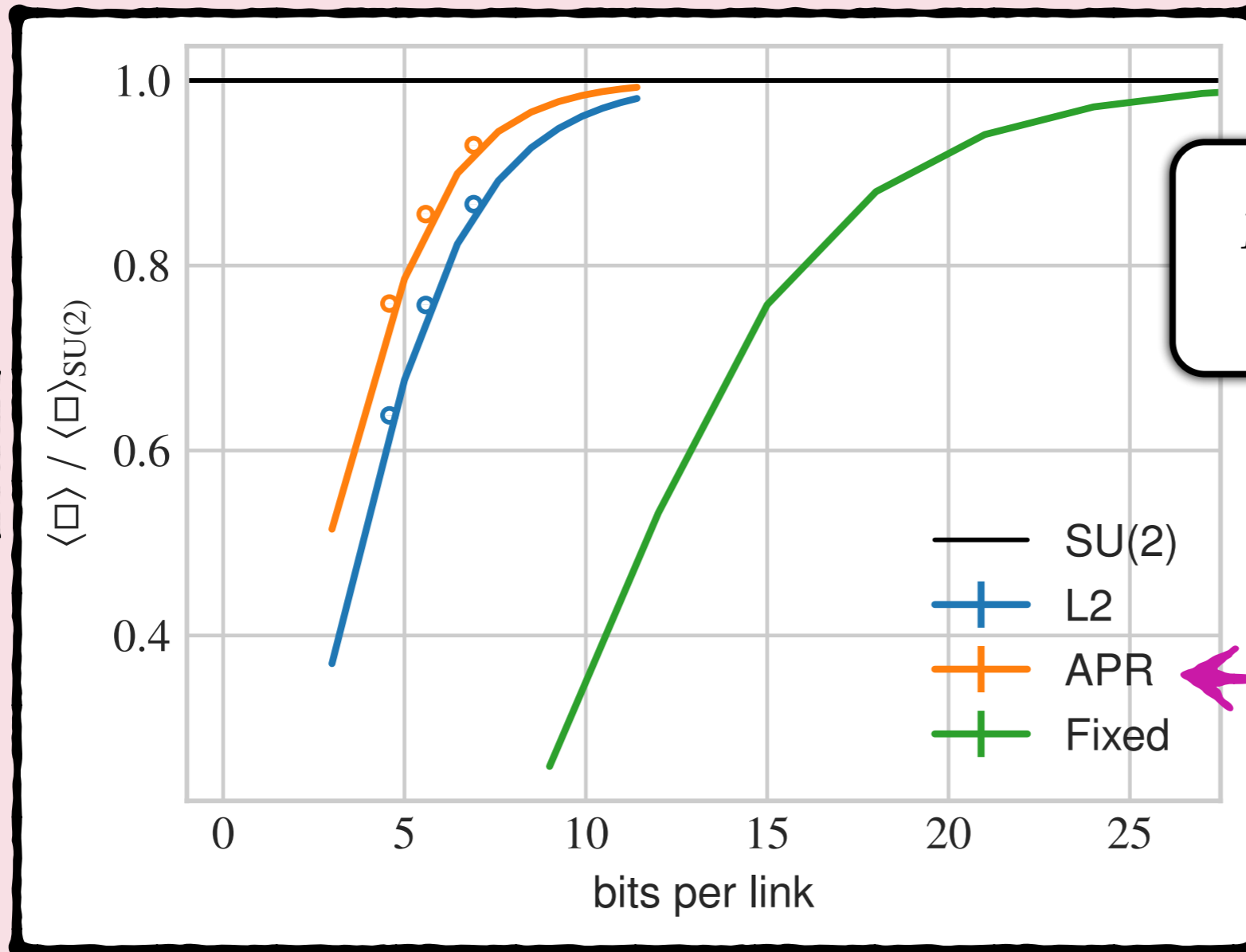
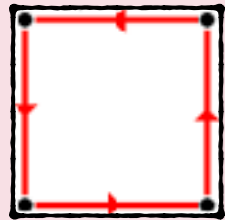
*The relative systematic error  
in an observable*

# How Many (qu)bits do you need: Plaquette?

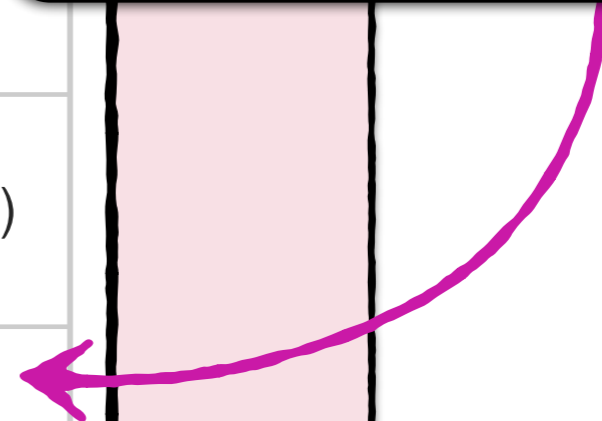


*As a function of the number of (qu)bits needed per gauge link*

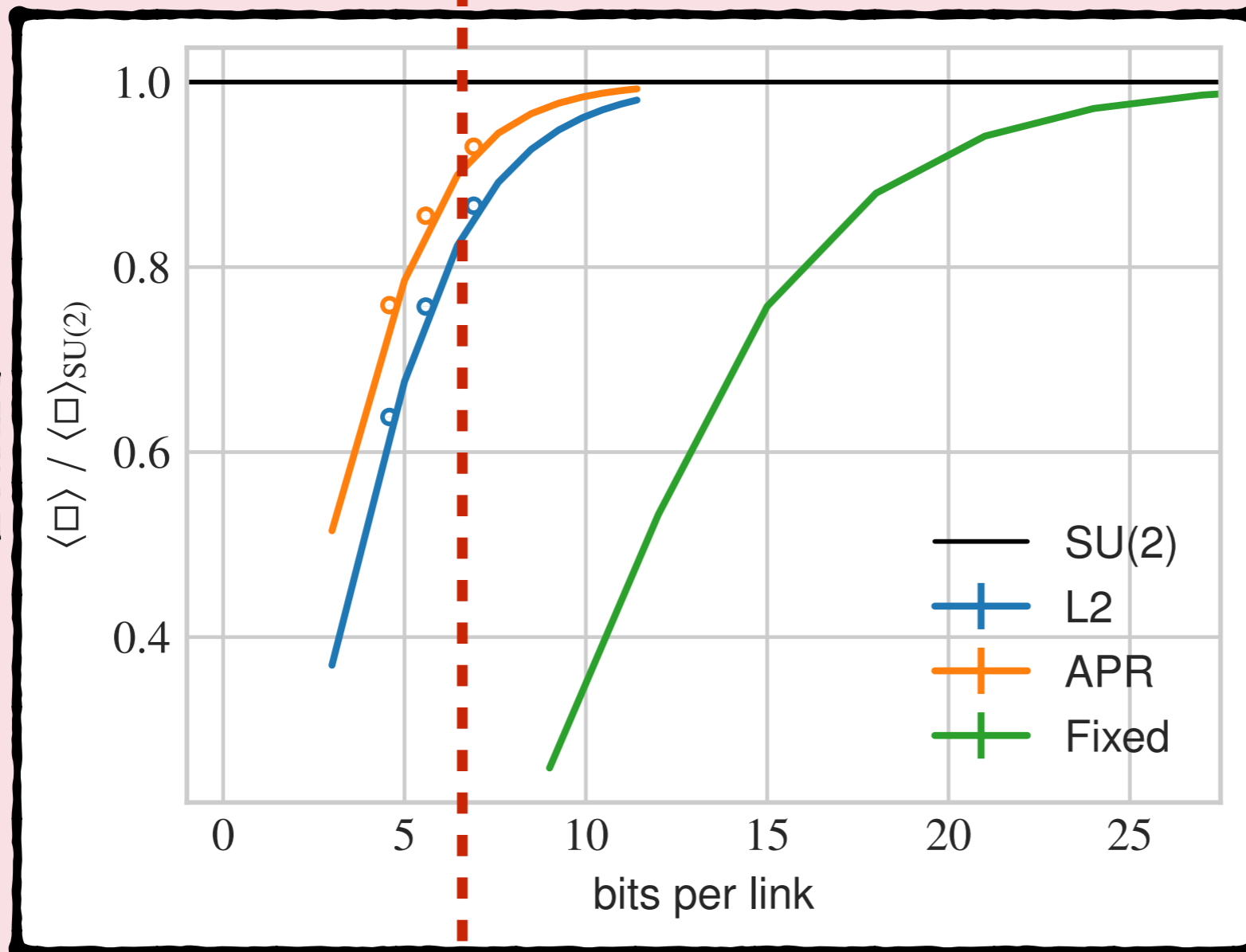
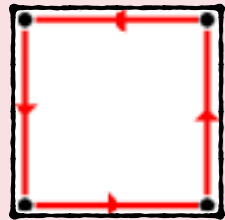
# How Many (qu)bits do you need?



*For different digitization schemes*

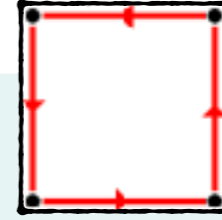
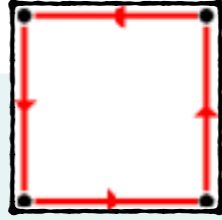


# How Many (qu)bits do you need?

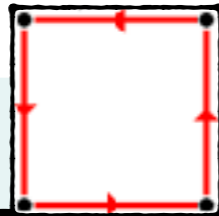


# How Many (qu)bits do you need: Volume?

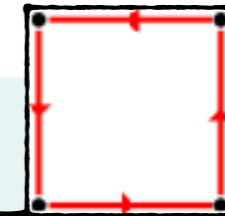
---



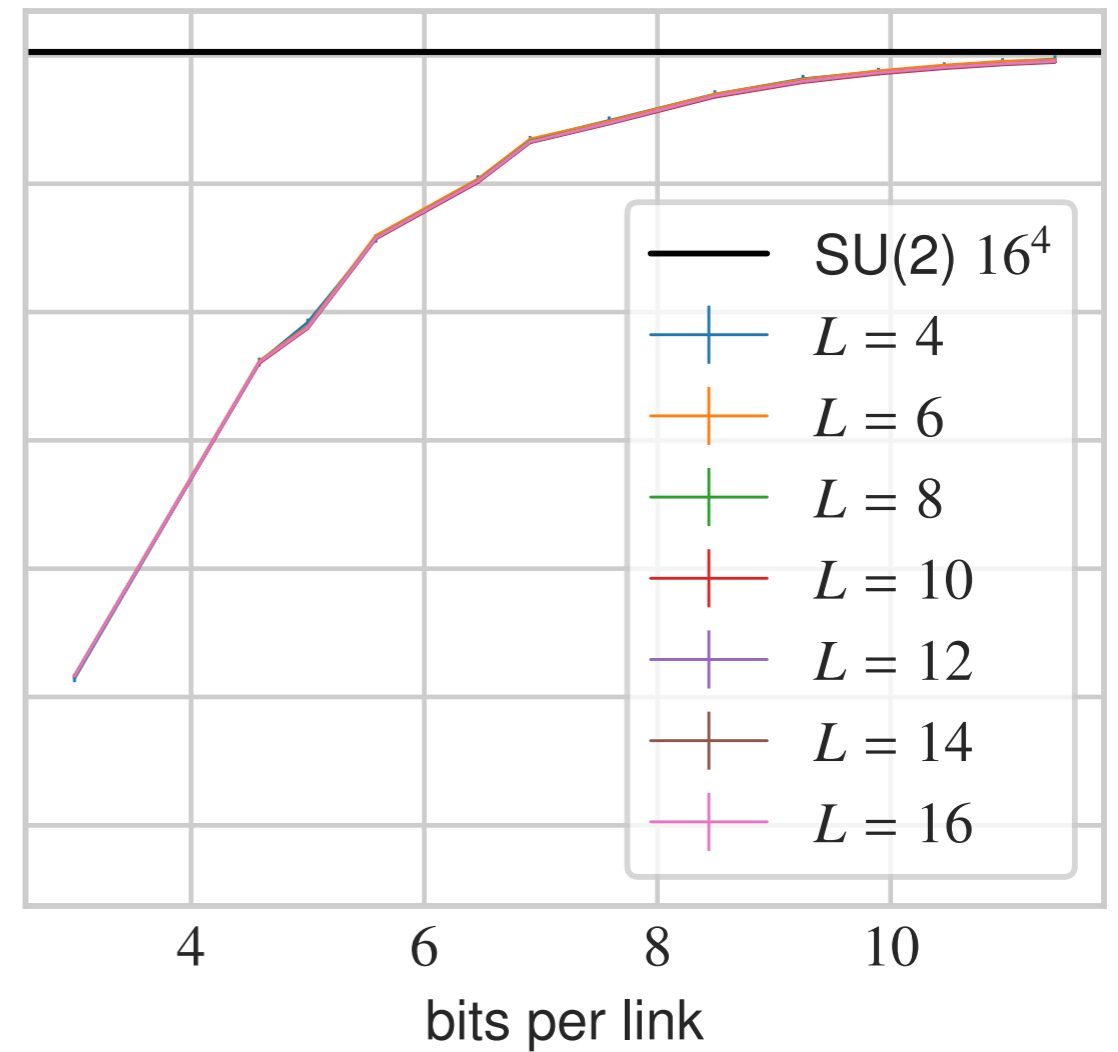
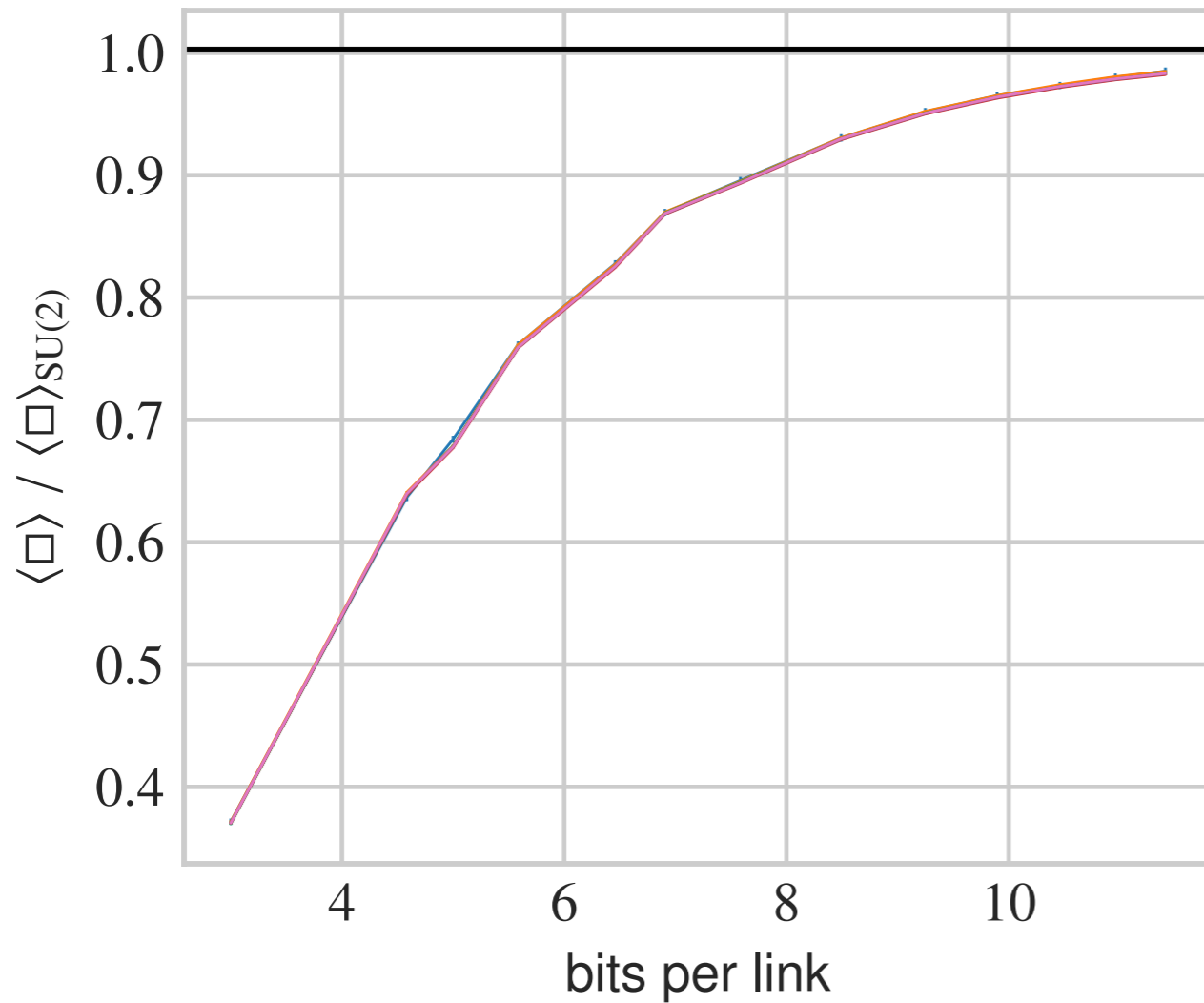
# How Many (qu)bits do you need: Volume?



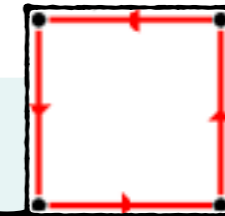
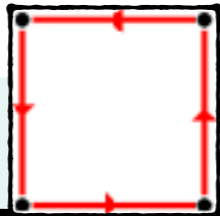
L2



APR

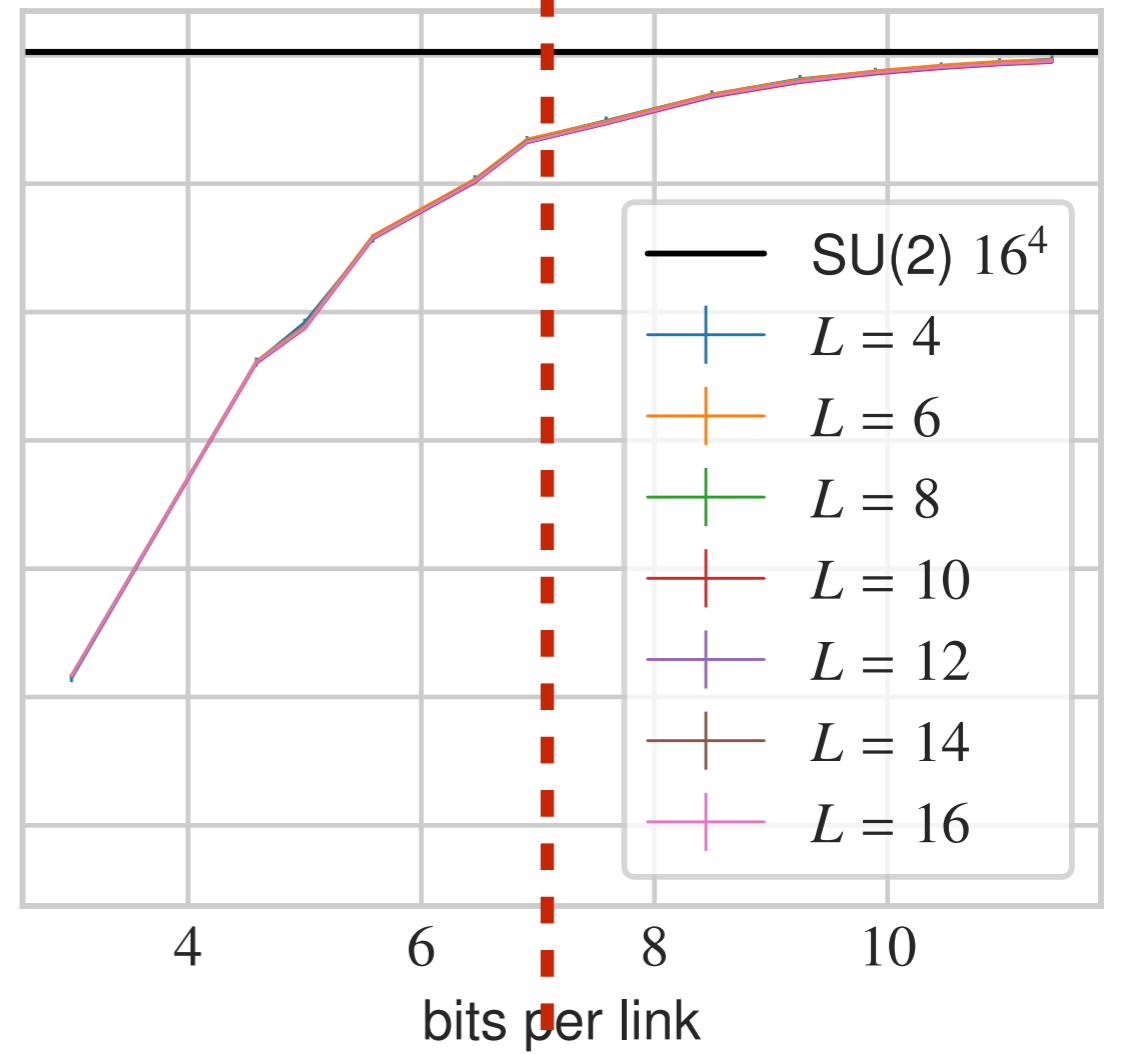
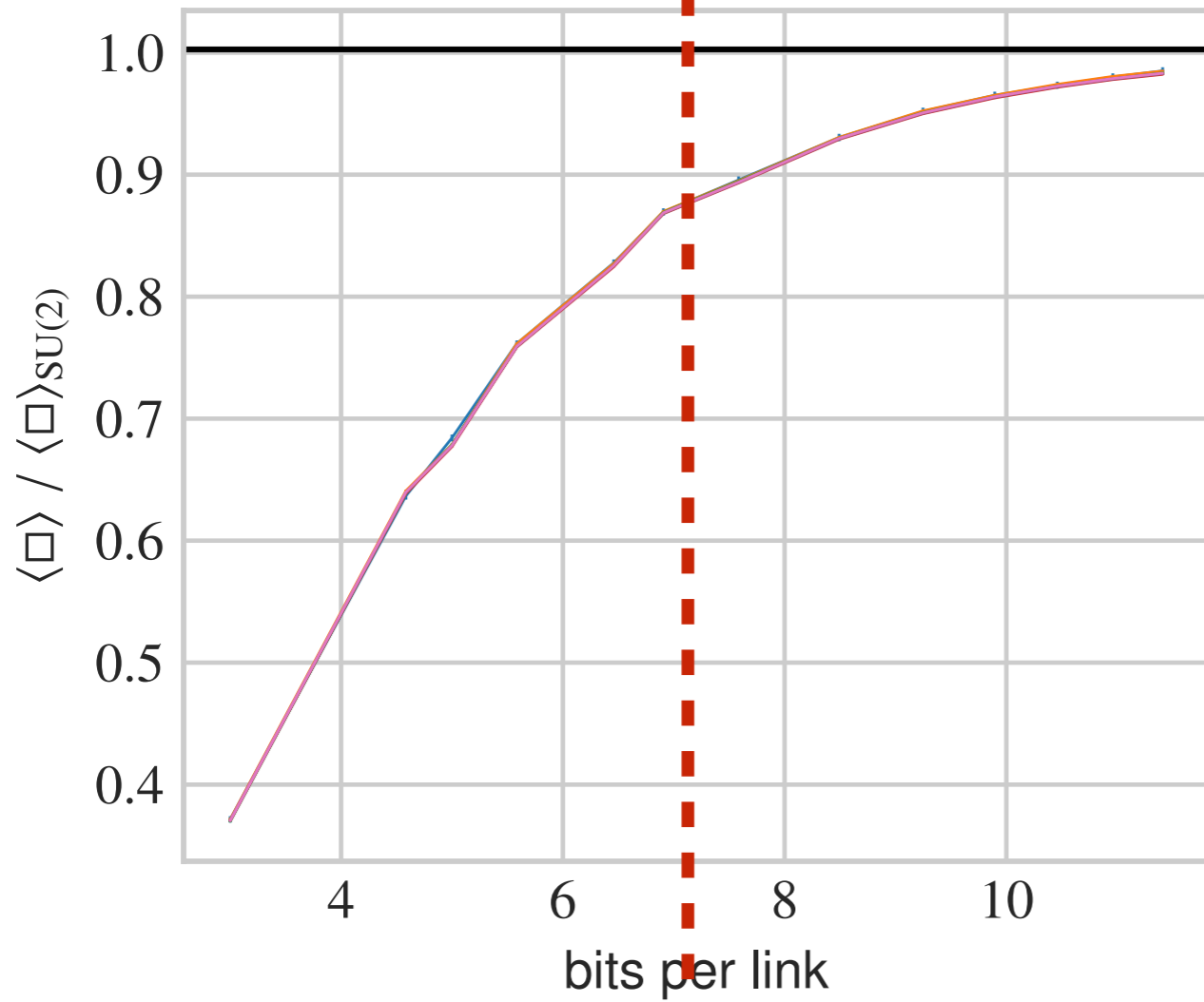


# How Many (qu)bits do you need: Volume?



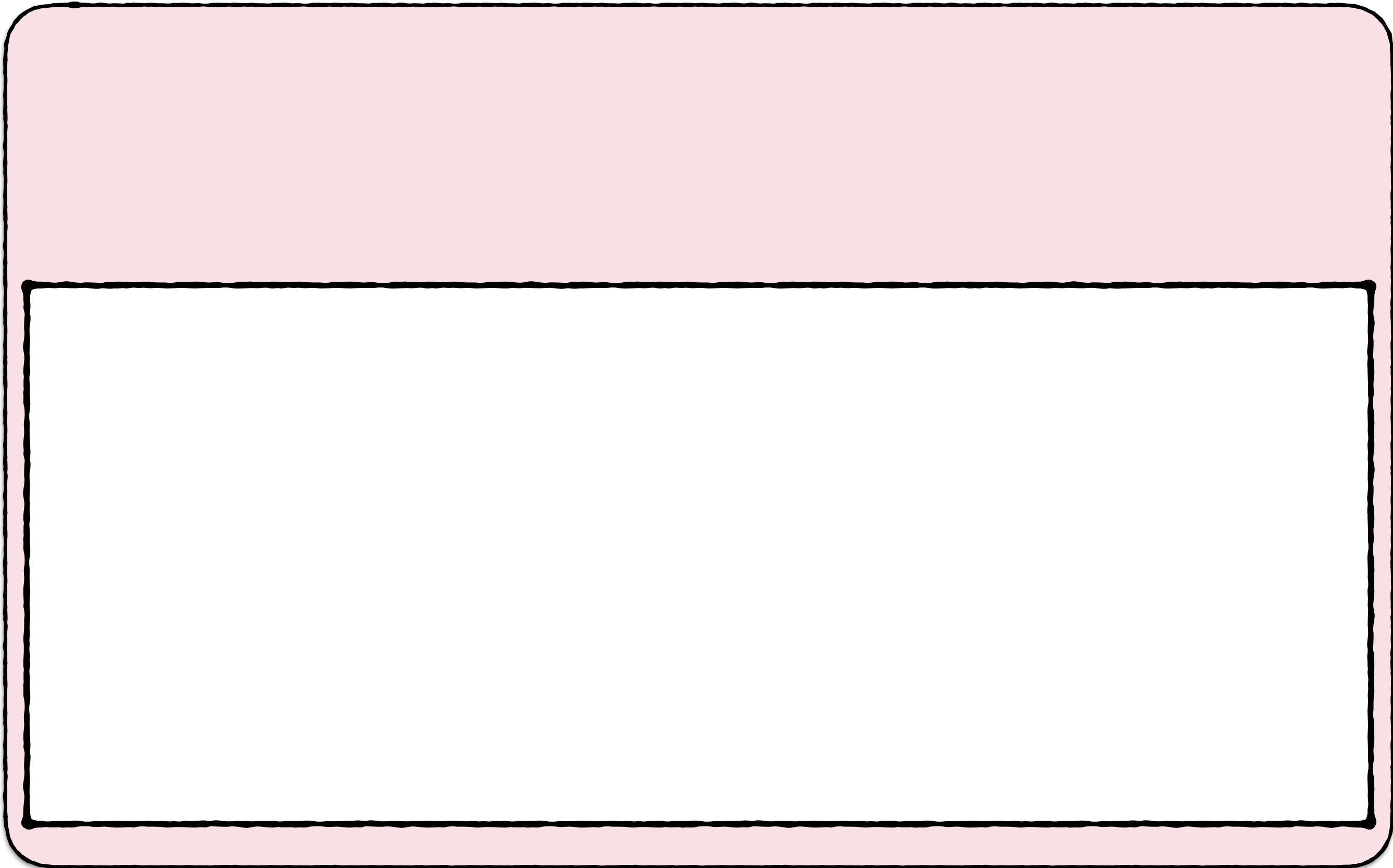
L2

APR

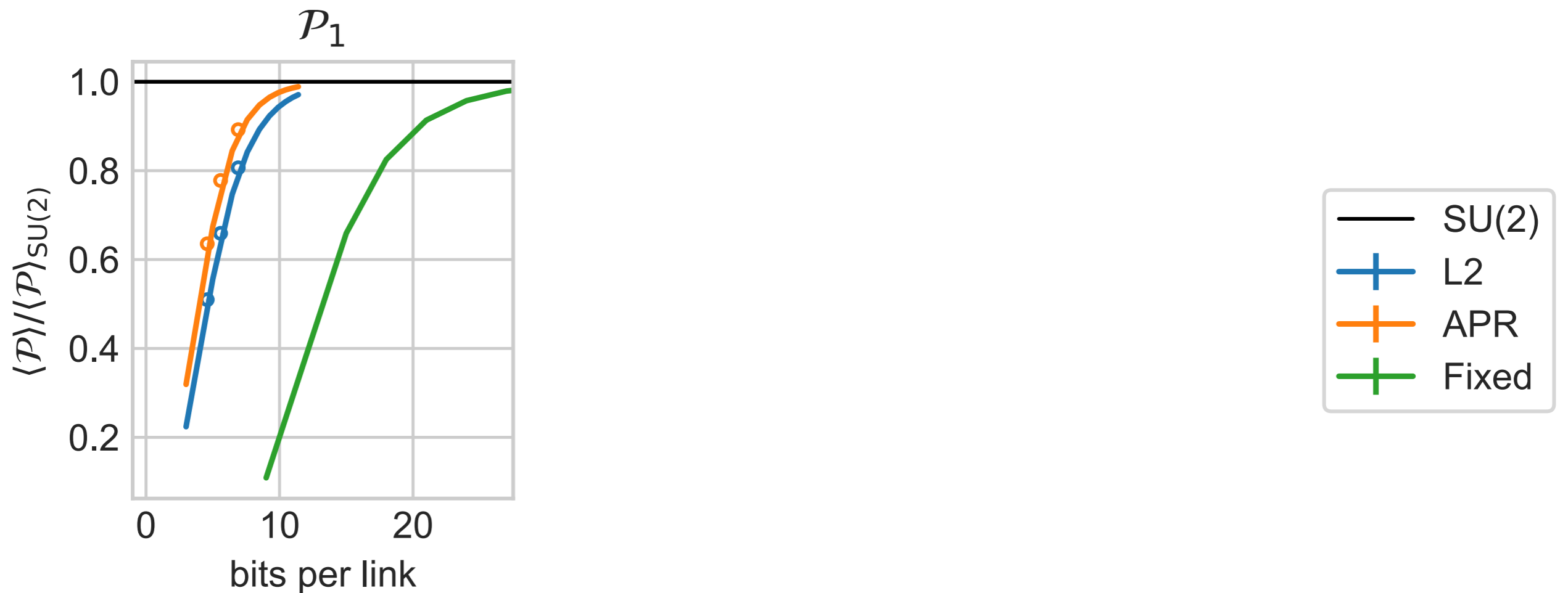
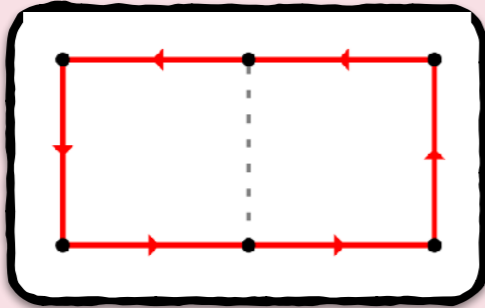




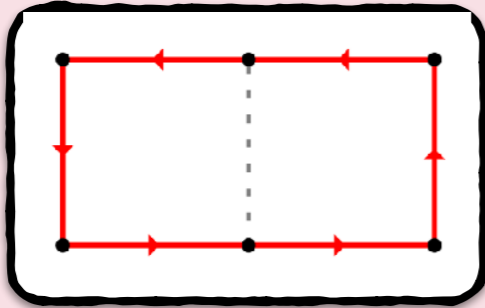
How Many (qu)bits do you need: P6 Wilson Loops?



# How Many (qu)bits do you need: P6 Wilson Loops?



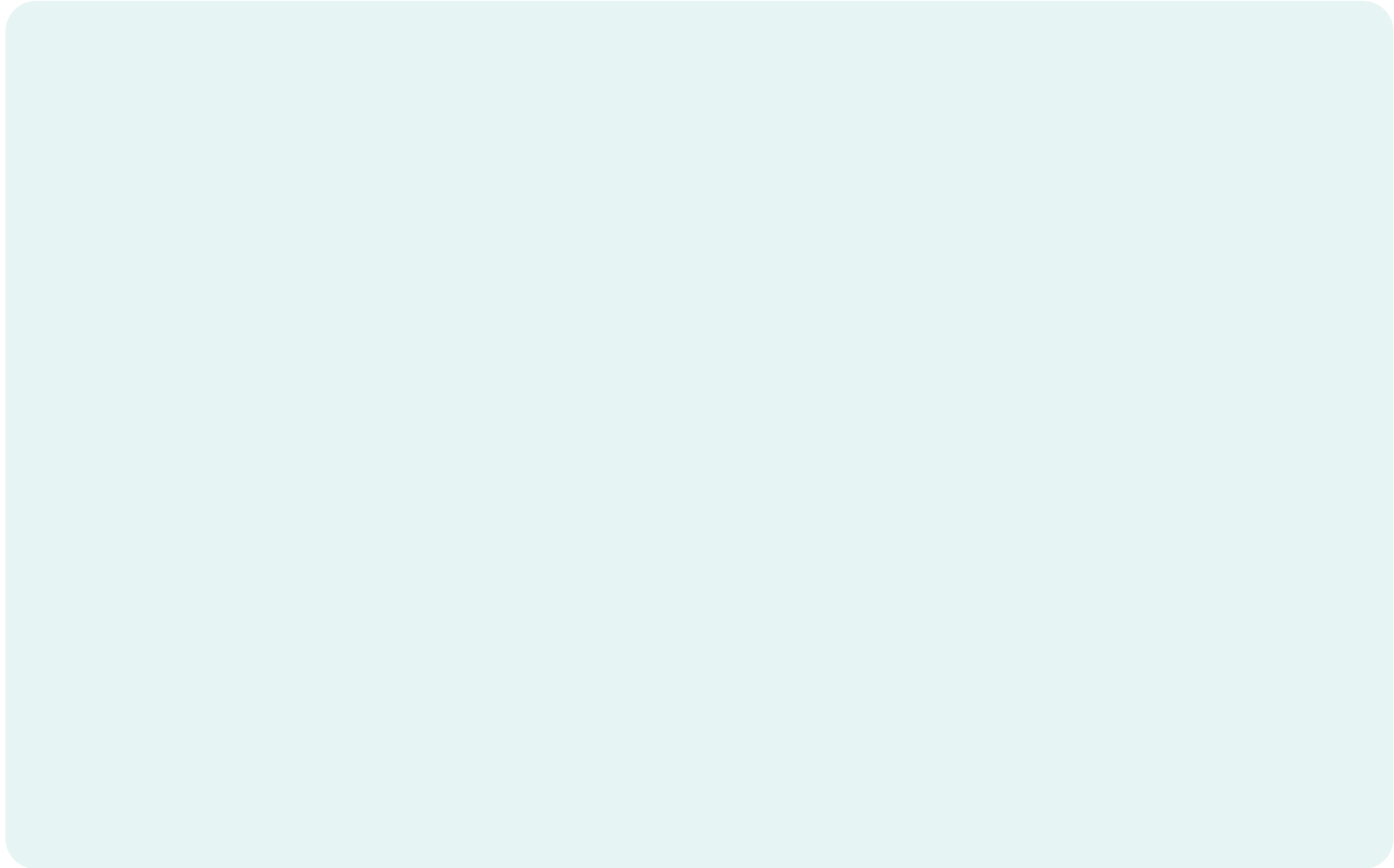
# How Many (qu)bits do you need: P6 Wilson Loops?



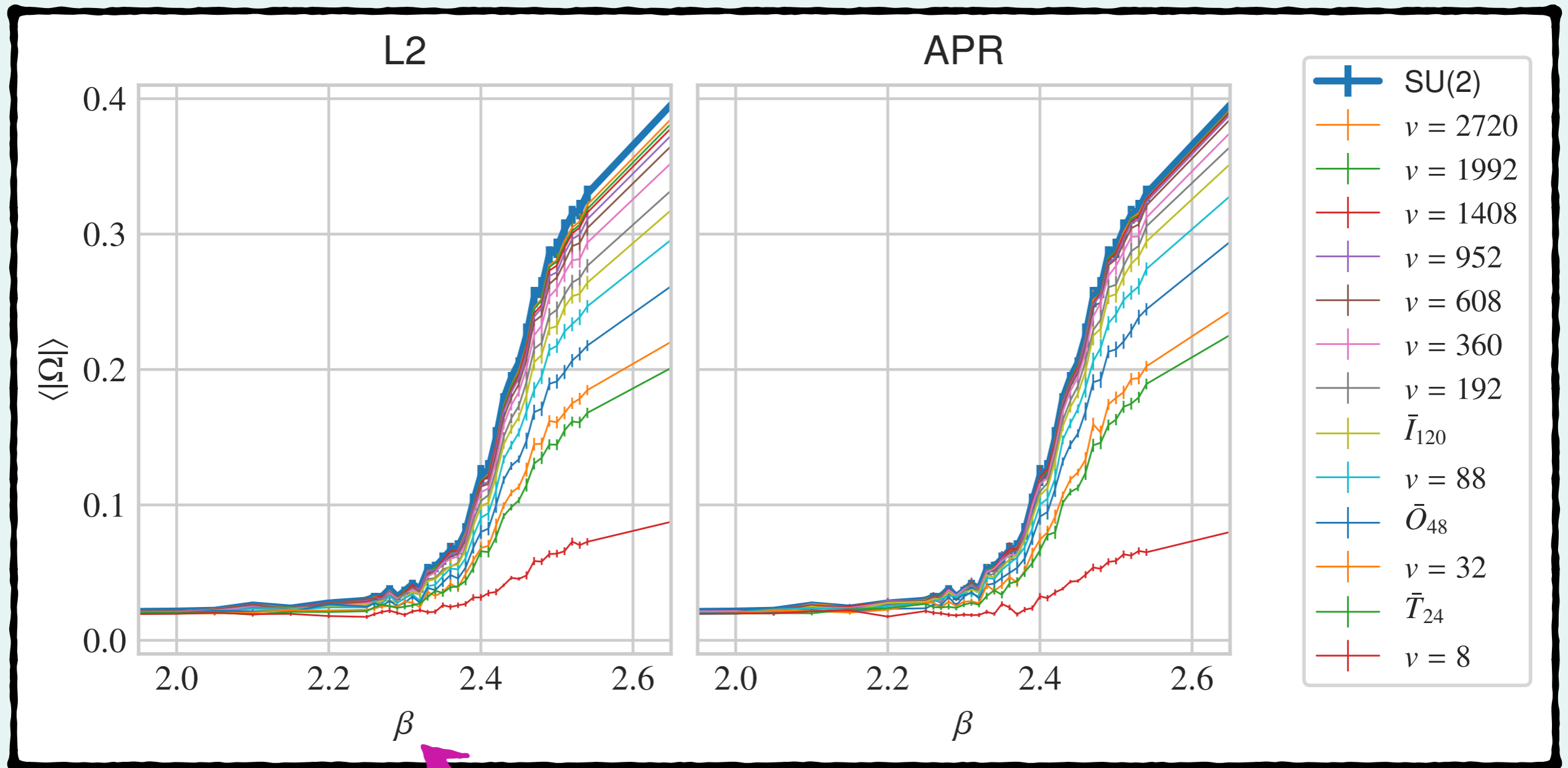




# How Many (qu)bits do you need: Polyakov Loop?

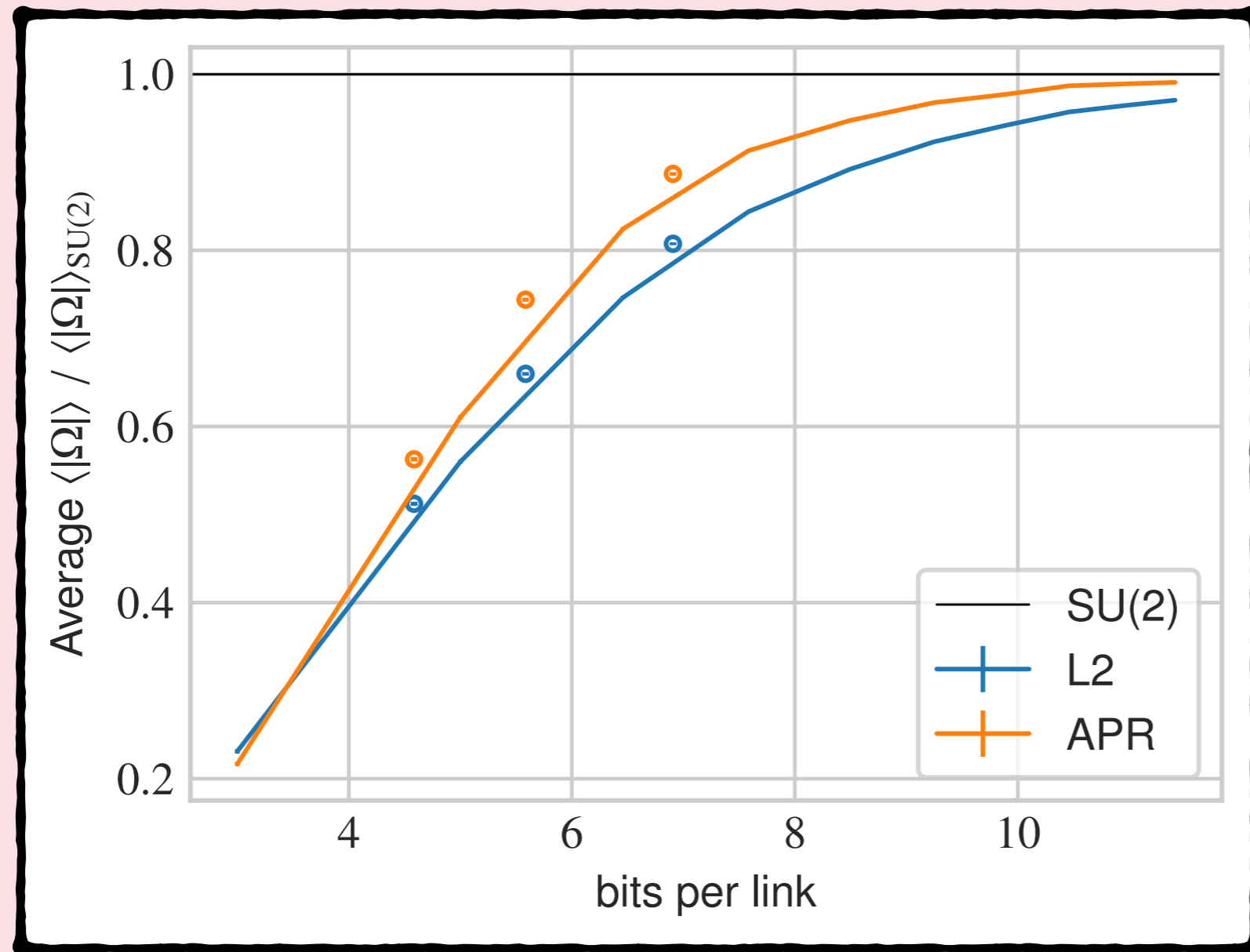


# How Many (qu)bits do you need: Polyakov Loop?



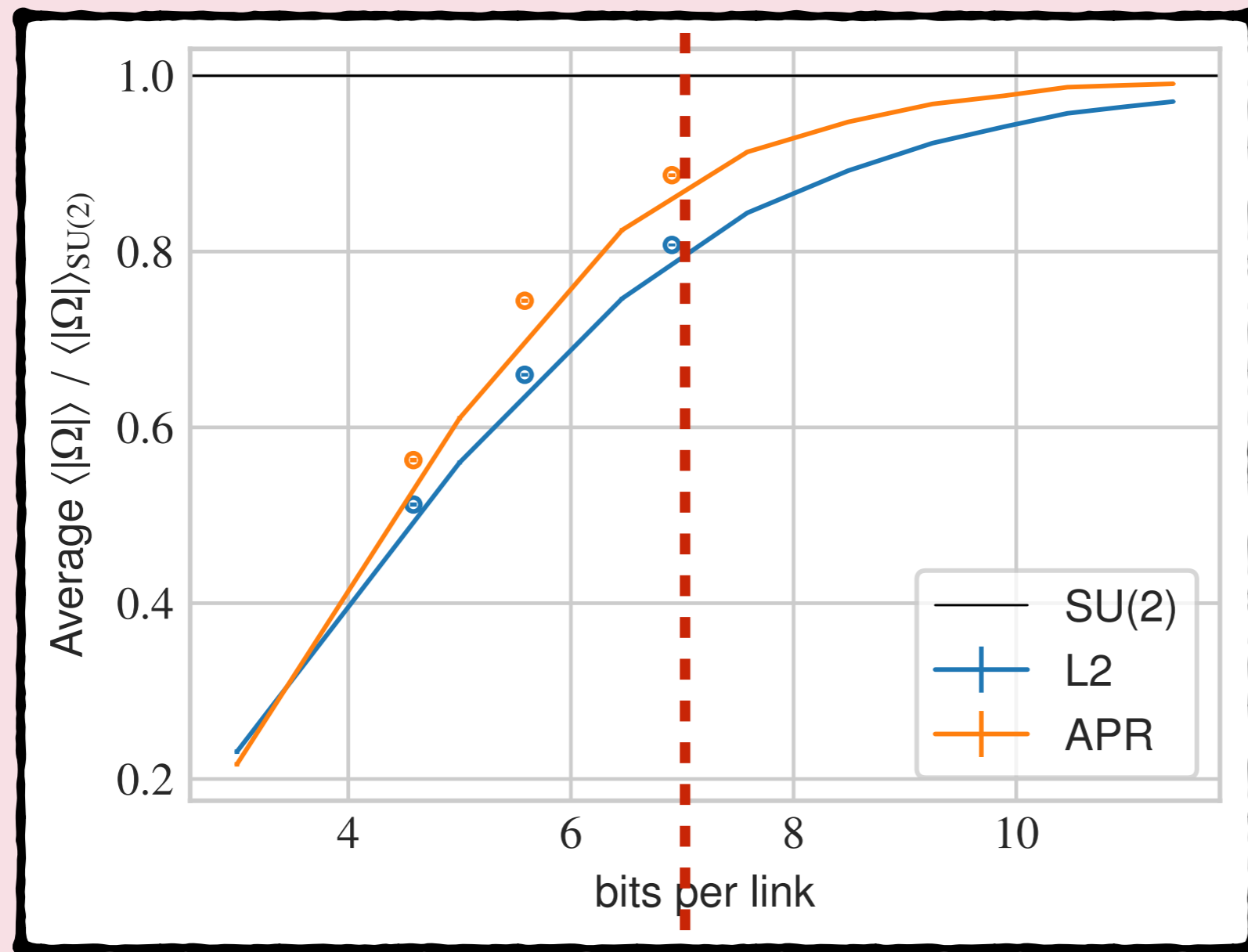
*NB: Temperature*

# How Many (qu)bits do you need: Polyakov Loop?

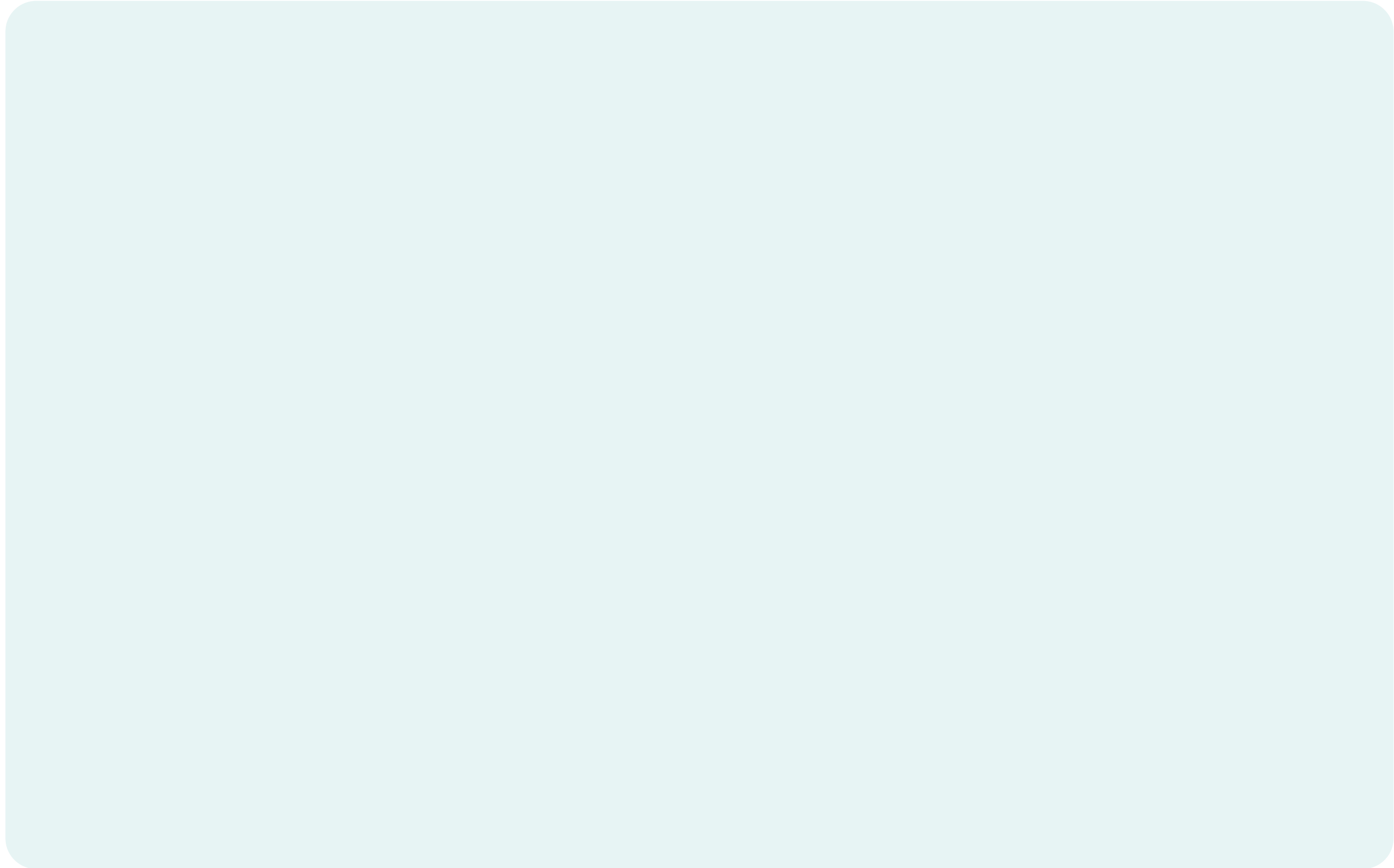




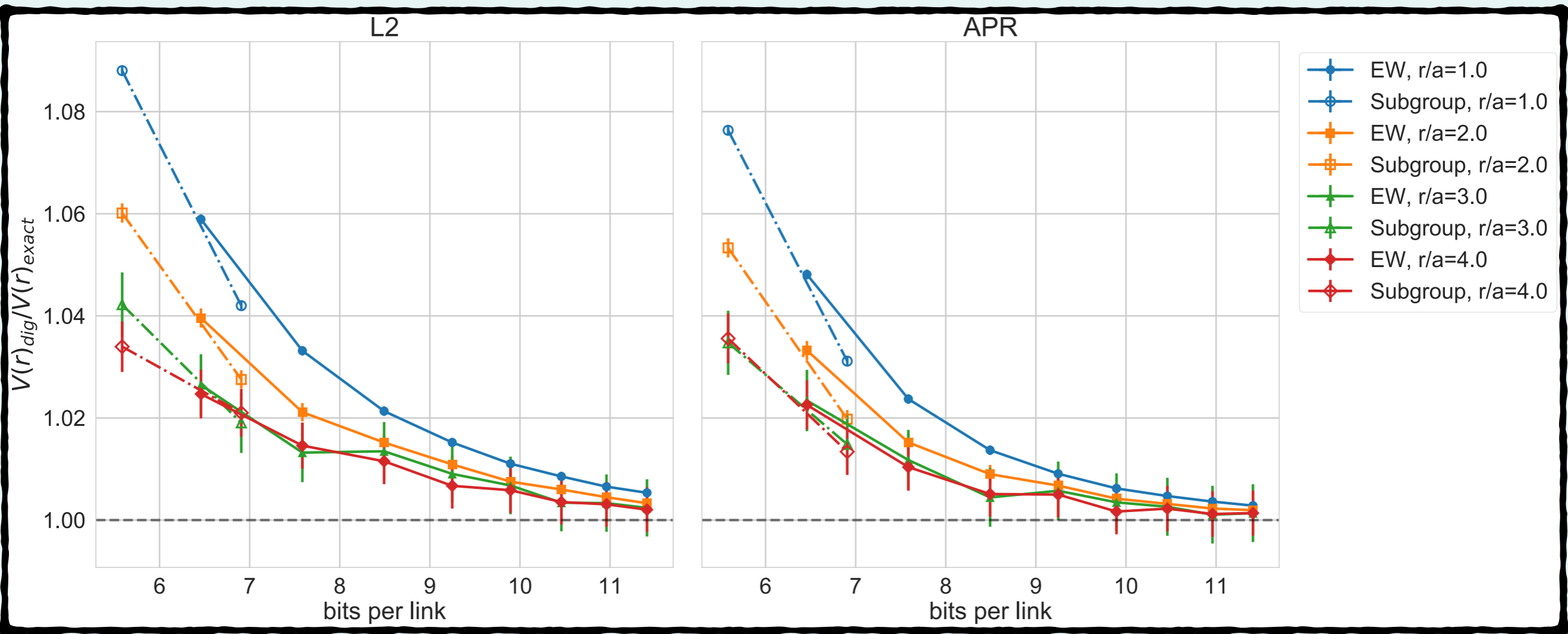
# How Many (qu)bits do you need: Polyakov Loop?



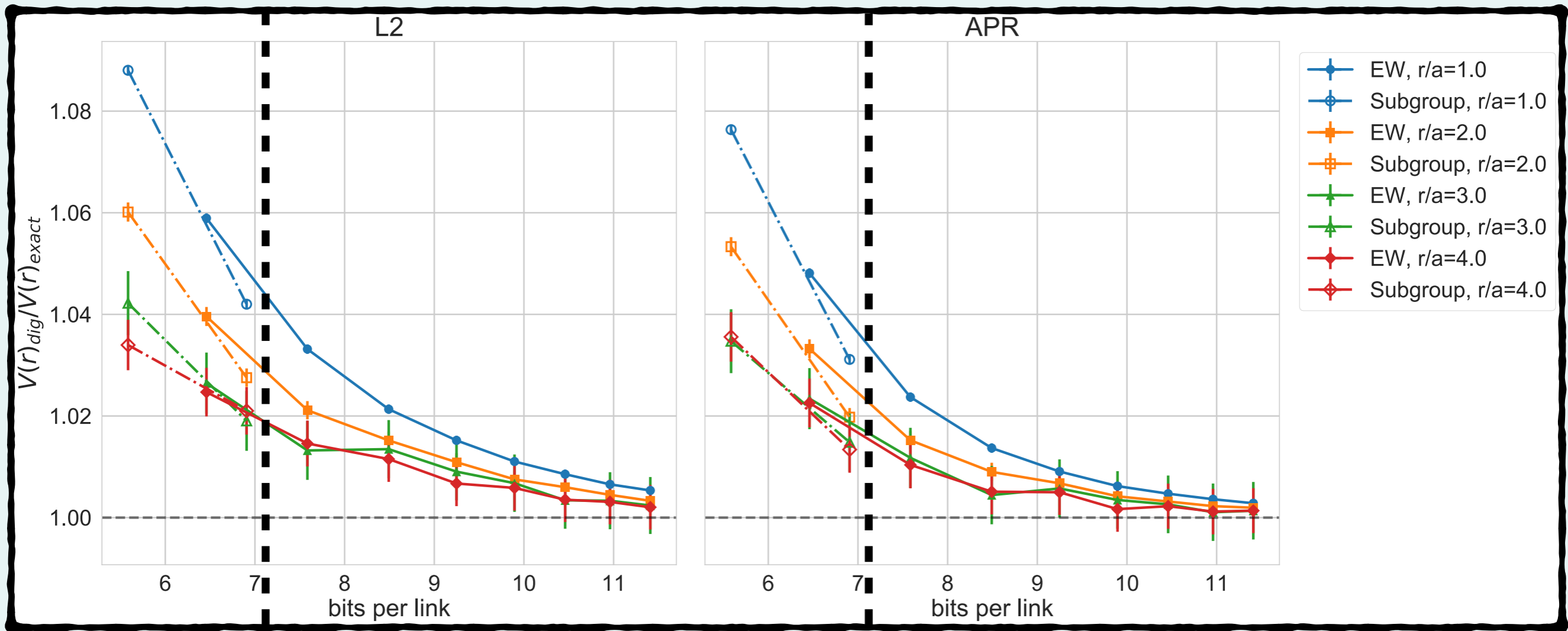
How Many (qu)bits do you need: Static potential?



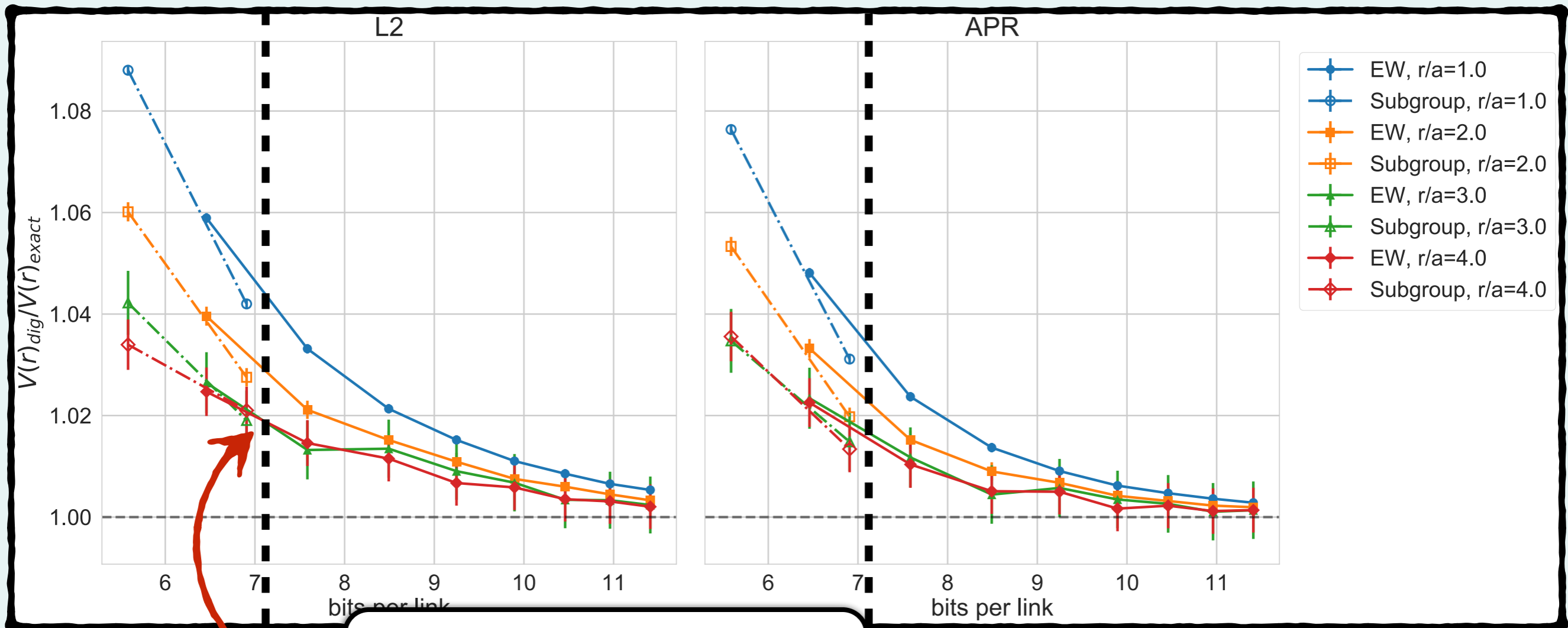
# How Many (qu)bits do you need: Static potential?



# How Many (qu)bits do you need: Static potential?

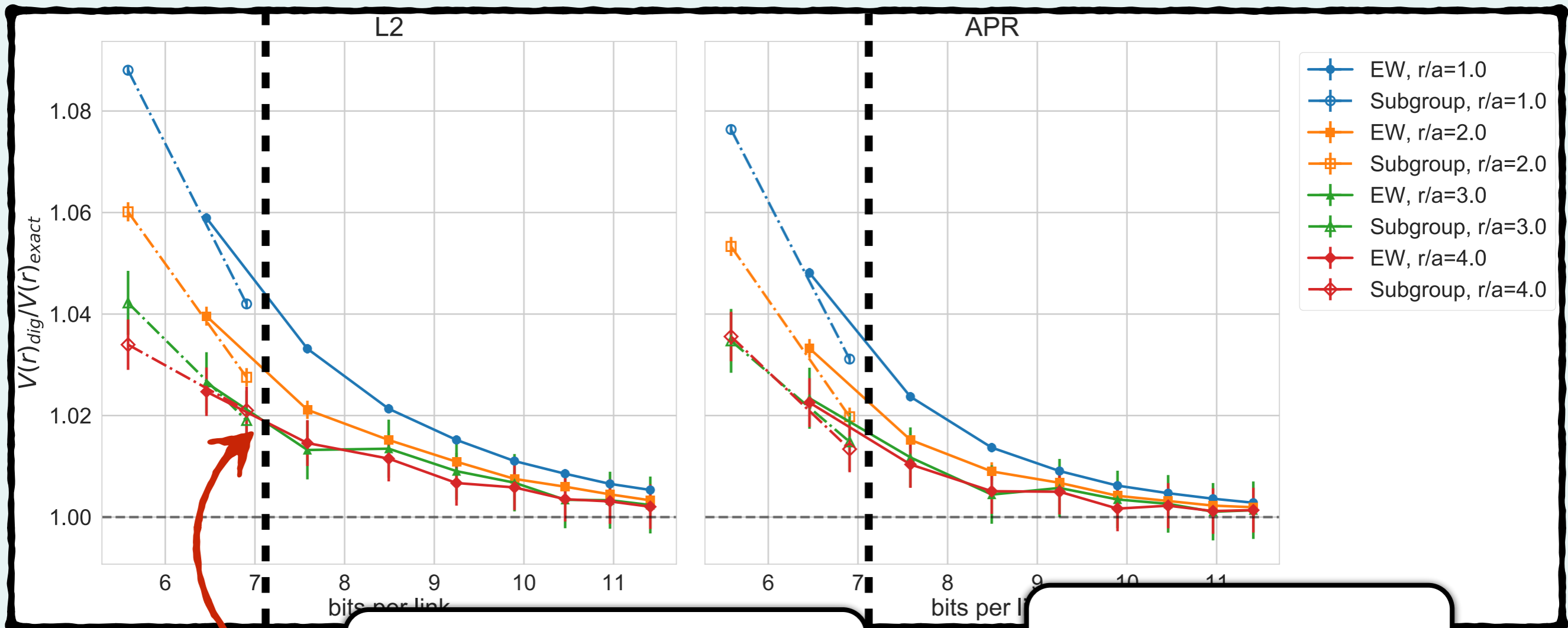


# How Many (qu)bits do you need: Static potential?



*With 7 (qu)bits per link,  
digitization error ~2%*

# How Many (qu)bits do you need: Static potential?



*With 7 (qu)bits per link,  
digitization error ~2%*

*Implications for NISQ-  
era QC!*

# Summary Of Results

---

*1 ) What resources are actually required during different stages of a quantum computation of a realistic theory*

# Summary Of Results

---

*1 ) What resources are actually required during different stages of a quantum computation of a realistic theory*

*Digitization: How many logical qubits are needed for  $SU(2)$  Hamiltonian?*





# Summary Of Results

---

*1 ) What resources are actually required during different stages of a quantum computation of a realistic theory*

*Digitization: How many logical qubits are needed for  $SU(2)$  Hamiltonian?*

*~7 qubits*



# Summary Of Results

1 ) *What resources are actually required during different stages of a quantum computation of a realistic theory*

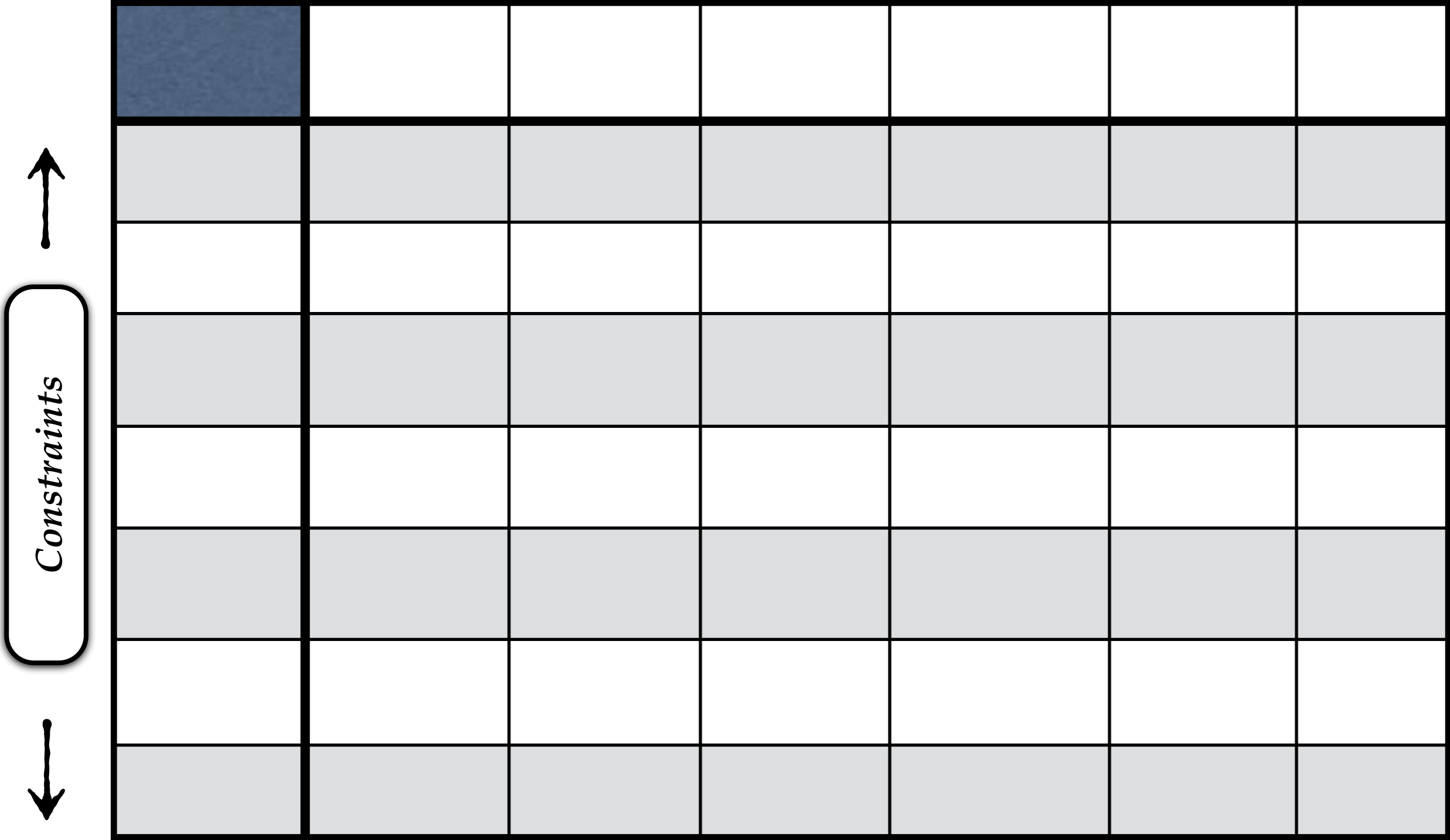
*Digitization: How many logical qubits are needed for  $SU(2)$  Hamiltonian?*

*~7 qubits*

2) *How can we pragmatically improve methodologies to significantly reduce the resources needed at each stage?*

*Active Area*

# Stages Of a Quantum Computation







# Stages Of a Quantum Computation



Number Of Qubits						
Noisy Qubits						
Connectivity of Qubits						

# Stages Of a Quantum Computation



Number Of Qubits						
Noisy Qubits						
Connectivity of Qubits						
Decoherence						

# Stages Of a Quantum Computation



Number Of Qubits						
Noisy Qubits						
Connectivity of Qubits						
Decoherence						
Gate Depth						



# Stages Of a Quantum Computation



A grid diagram representing the stages of a quantum computation. The vertical axis is labeled "Constraints" and has an upward-pointing arrow above it and a downward-pointing arrow below it. The horizontal axis is labeled "Stages" and has arrows pointing left and right. The grid consists of 7 columns and 7 rows. The first row is a solid dark blue header. The first column contains the following labels from top to bottom: "Number Of Qubits", "Noisy Qubits", "Connectivity of Qubits", "Decoherence", "Gate Depth", "Readout Error", and an empty cell. The remaining cells in the grid are empty.

Number Of Qubits						
Noisy Qubits						
Connectivity of Qubits						
Decoherence						
Gate Depth						
Readout Error						

# Stages Of a Quantum Computation



Number Of Qubits						
Noisy Qubits						
Connectivity of Qubits						
Decoherence						
Gate Depth						
Readout Error						
Error Correction						

# Stages Of a Quantum Computation



	Discretization					
Number Of Qubits						
Noisy Qubits						
Connectivity of Qubits						
Decoherence						
Gate Depth						
Readout Error						
Error Correction						

# Stages Of a Quantum Computation



	Discretization	Digitization				
Number Of Qubits						
Noisy Qubits						
Connectivity of Qubits						
Decoherence						
Gate Depth						
Readout Error						
Error Correction						

# Stages Of a Quantum Computation



	Discretization	Digitization	Circuitize			
Number Of Qubits						
Noisy Qubits						
Connectivity of Qubits						
Decoherence						
Gate Depth						
Readout Error						
Error Correction						

# Stages Of a Quantum Computation



	Discretization	Digitization	Circuitize	Initial State Preparation		
Number Of Qubits						
Noisy Qubits						
Connectivity of Qubits						
Decoherence						
Gate Depth						
Readout Error						
Error Correction						

# Stages Of a Quantum Computation



	Discretization	Digitization	Circuitize	Initial State Preparation	Time Evolution	
Number Of Qubits						
Noisy Qubits						
Connectivity of Qubits						
Decoherence						
Gate Depth						
Readout Error						
Error Correction						

# Stages Of a Quantum Computation



	Discretization	Digitization	Circuitize	Initial State Preparation	Time Evolution	Readout
Number Of Qubits						
Noisy Qubits						
Connectivity of Qubits						
Decoherence						
Gate Depth						
Readout Error						
Error Correction						



# Stages Of a Quantum Computation



	Discretization	Digitization	Circuitize	Initial State Preparation	Time Evolution	Readout
Number Of Qubits		✓				
Noisy Qubits						
Connectivity of Qubits						
Decoherence						
Gate Depth						
Readout Error						
Error Correction						

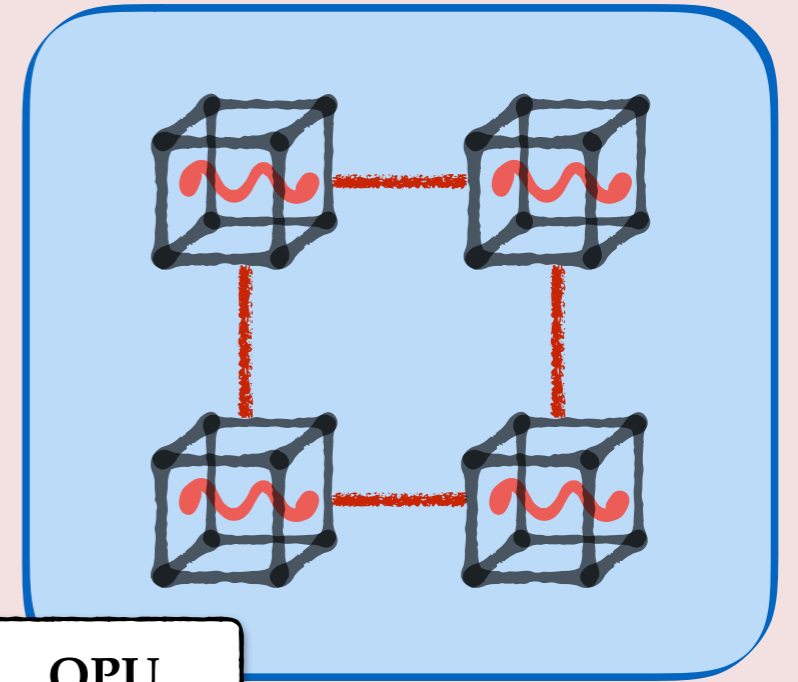
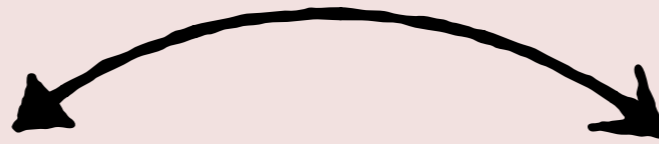
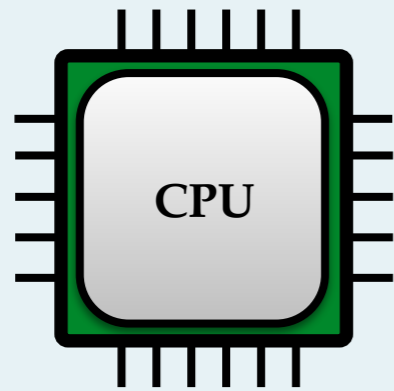
# Solutions for Future Quantum Computers from Lattice Monte Carlo and Beyond

---

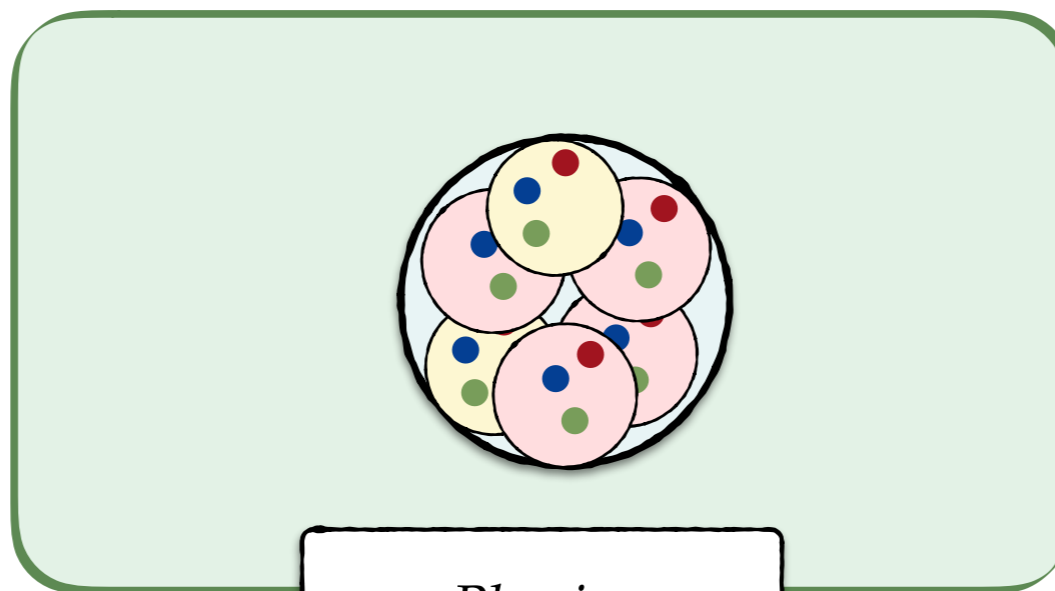
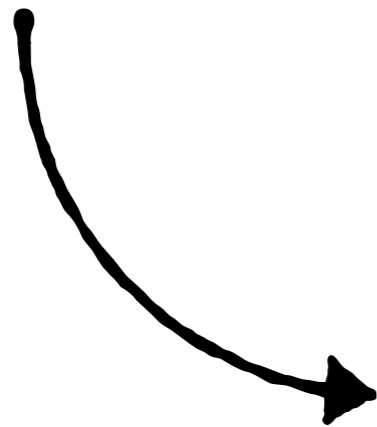
*Big improvements in digital QC are going to be made when hardware, algorithms and methodology work together.*

# Lattice "Beyond" BSM

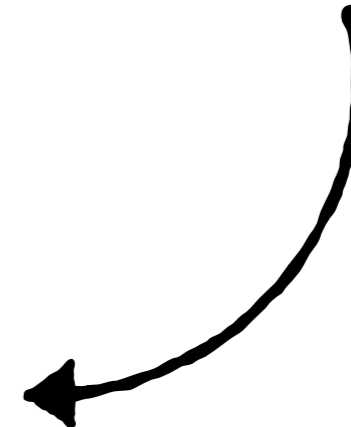
Ciaran Hughes



QPU



Physics



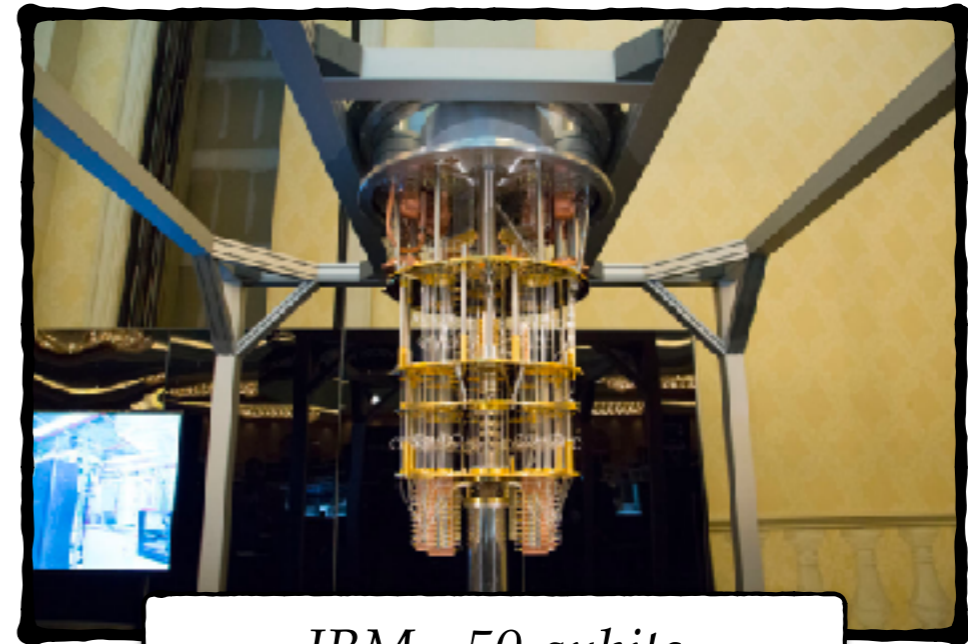
[chughes@fnal.gov](mailto:chughes@fnal.gov)

# Back-Up Slides

# Current Resources for QC

---

*How many qubits are possible?*



*IBM - 50 qubits*

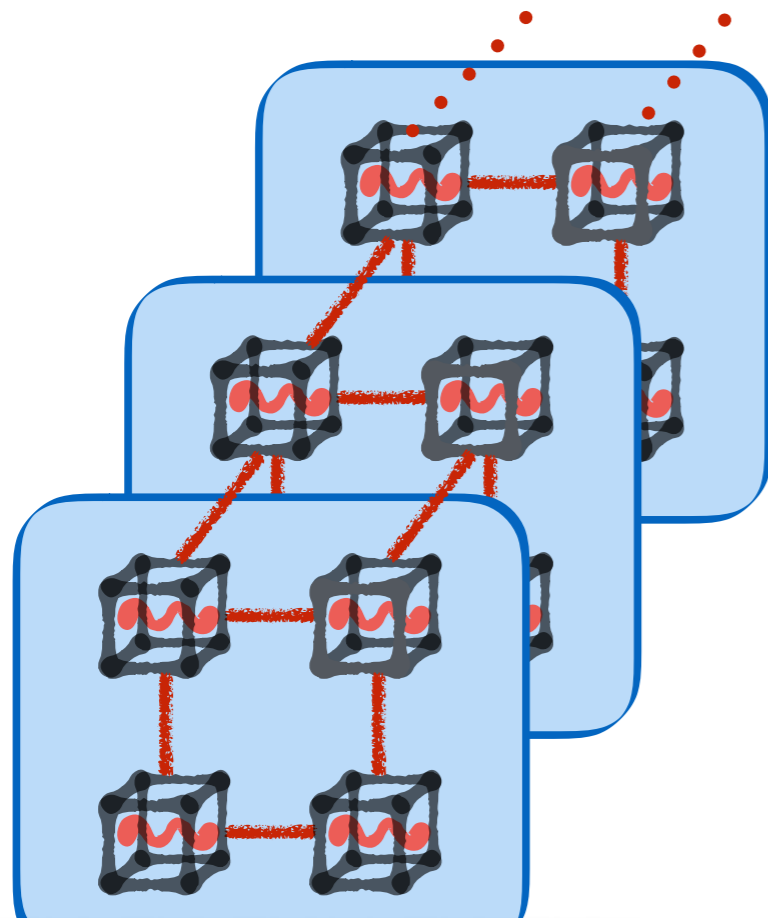
# Current Resources In the NISQ-era

---

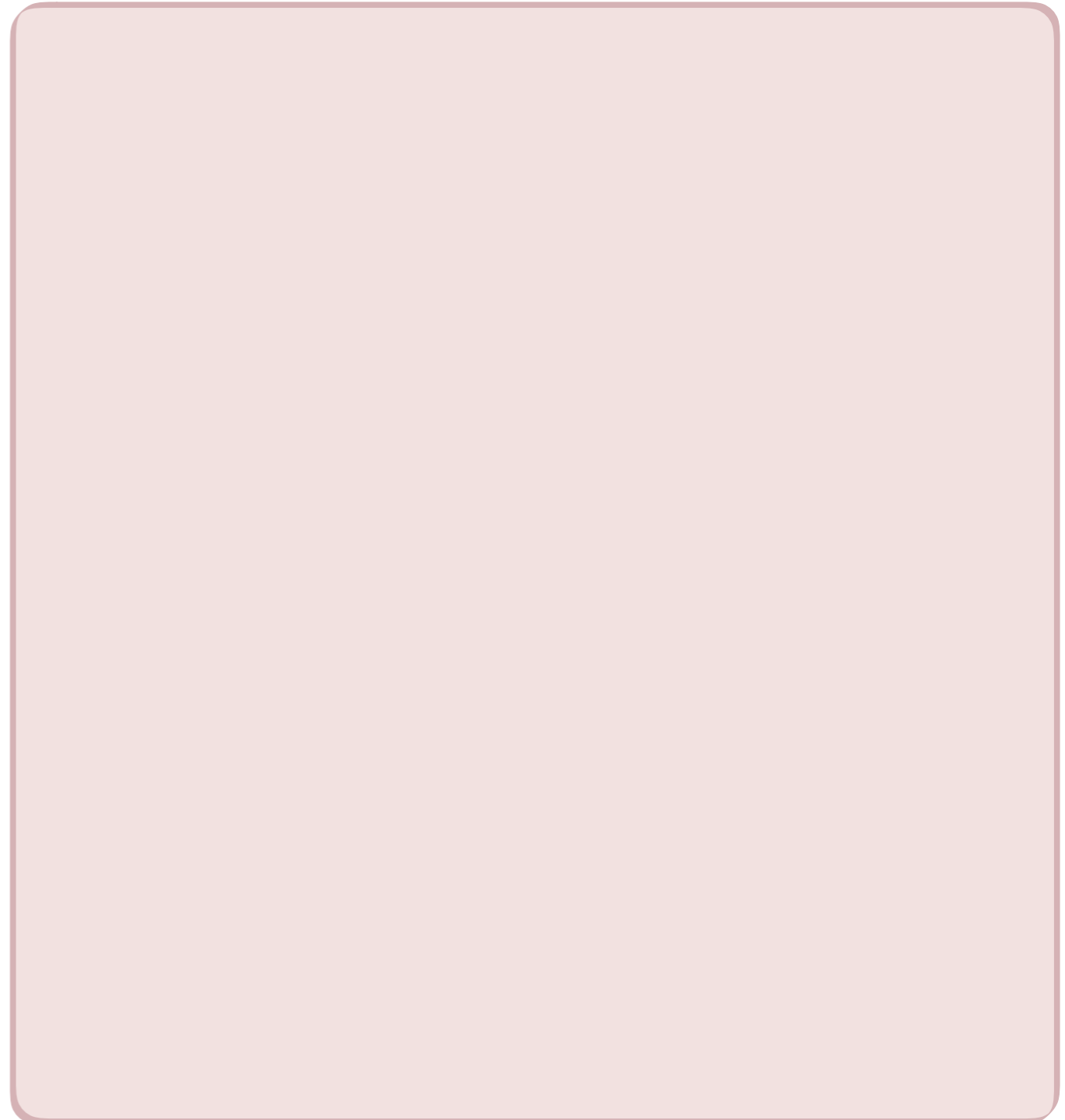
*How many qubits/gates do we actually have?*

# Current Resources In the NISQ-era

*How many qubits/gates do we actually have?*

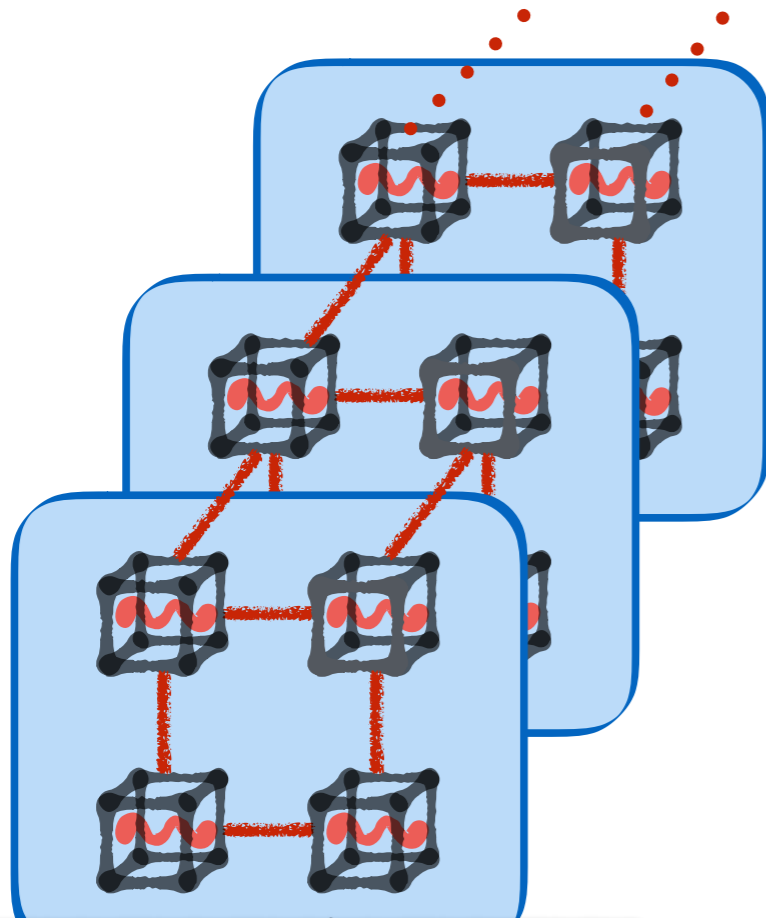


*IBM Q Tokyo - 20 qubits*



# Current Resources In the NISQ-era

*How many qubits/gates do we actually have?*



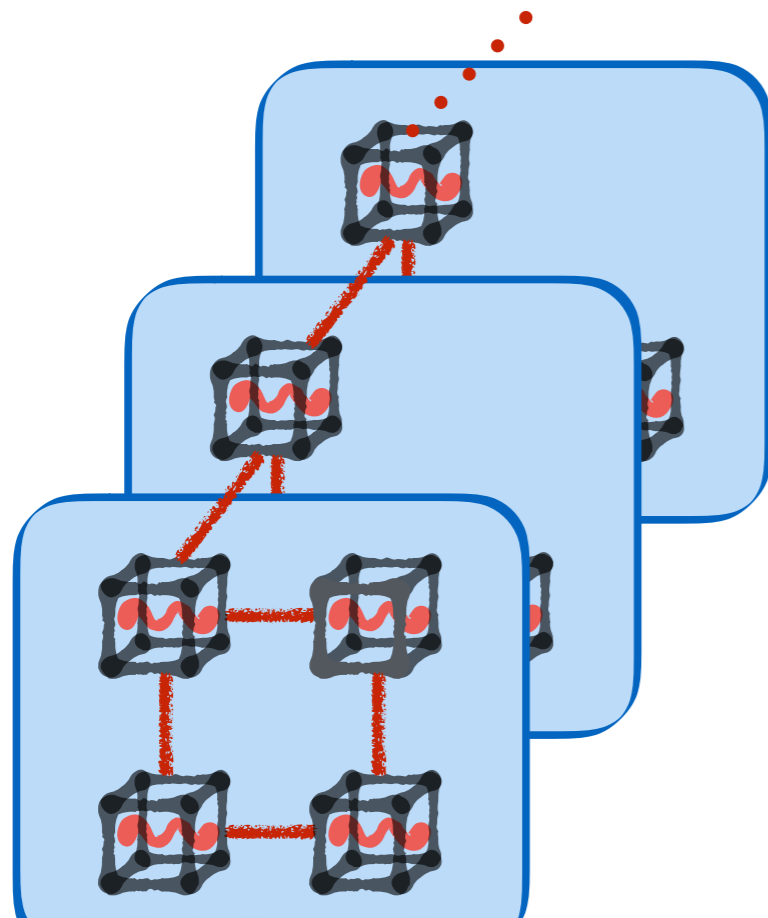
*IBM Q Tokyo - 20 qubits*

1) Number of qubits severely limited



# Current Resources In the NISQ-era

*How many qubits/gates do we actually have?*

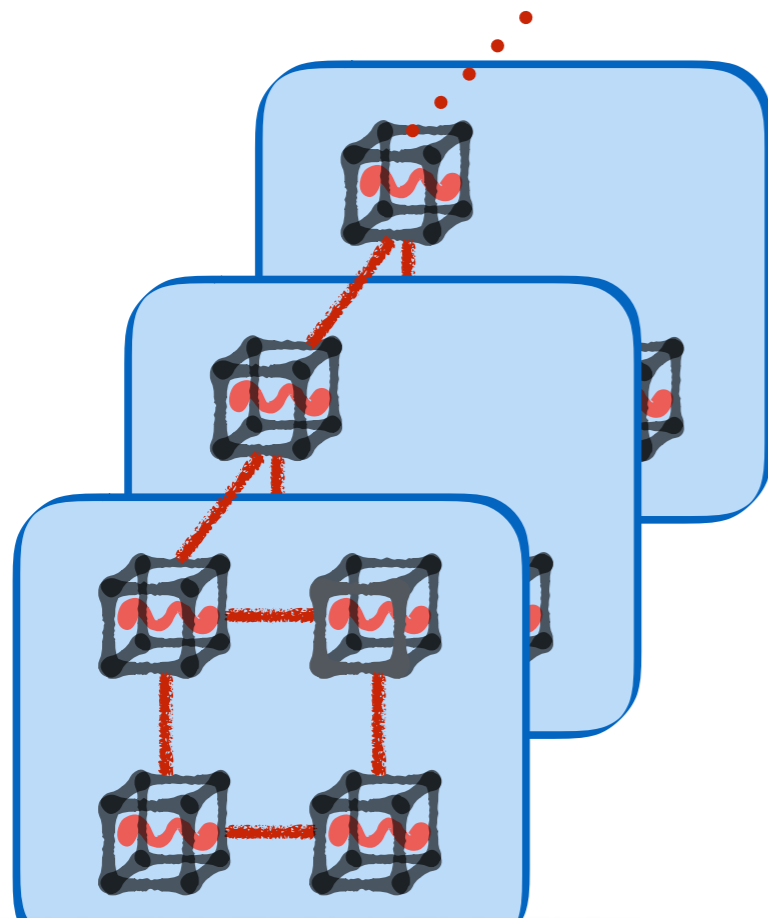


*IBM Q Tokyo - 20 qubits*

1) Number of qubits severely limited

# Current Resources In the NISQ-era

*How many qubits/gates do we actually have?*

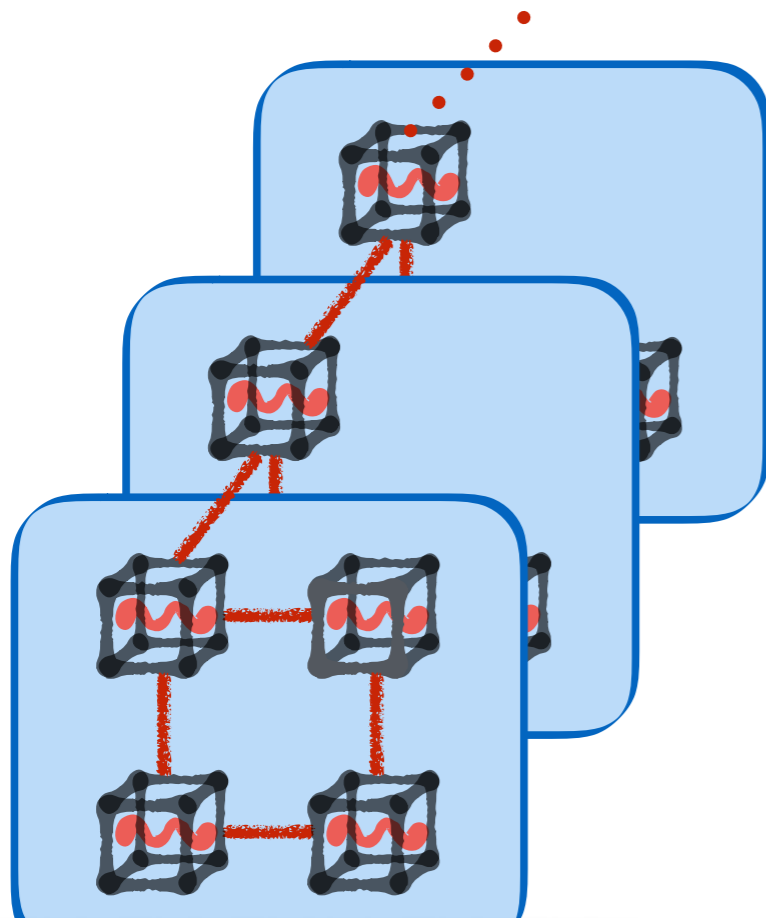


*IBM Q Tokyo - 20 qubits*

- 1) Number of qubits severely limited
- 2) Qubits noisy

# Current Resources In the NISQ-era

*How many qubits/gates do we actually have?*

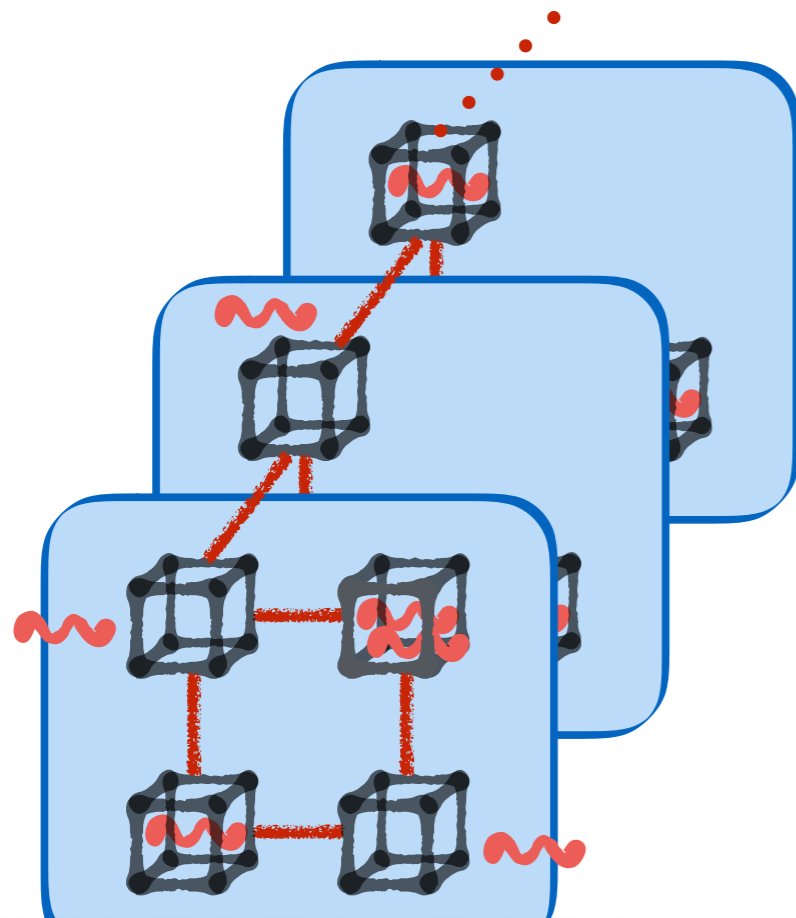


*IBM Q Tokyo - 20 qubits*

- 1) Number of qubits severely limited
- 2) Qubits noisy:  $T_1 \sim 89\mu s$

# Current Resources In the NISQ-era

*How many qubits/gates do we actually have?*

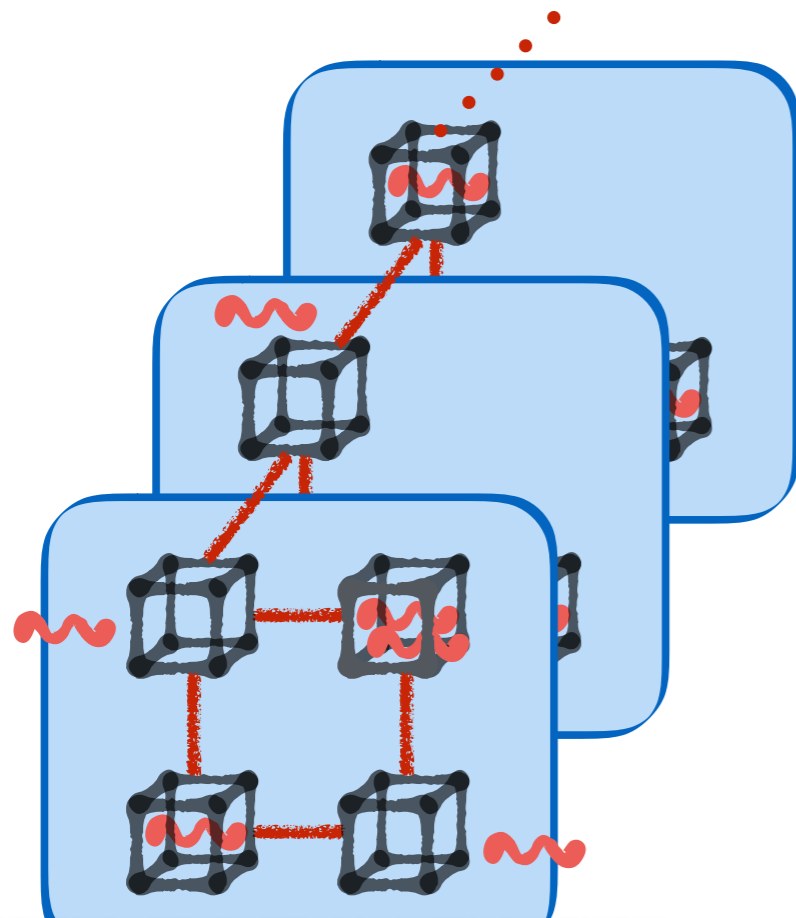


*IBM Q Tokyo - 20 qubits*

- 1) Number of qubits severely limited
- 2) Qubits noisy:  $T_1 \sim 89\mu s$

# Current Resources In the NISQ-era

*How many qubits/gates do we actually have?*

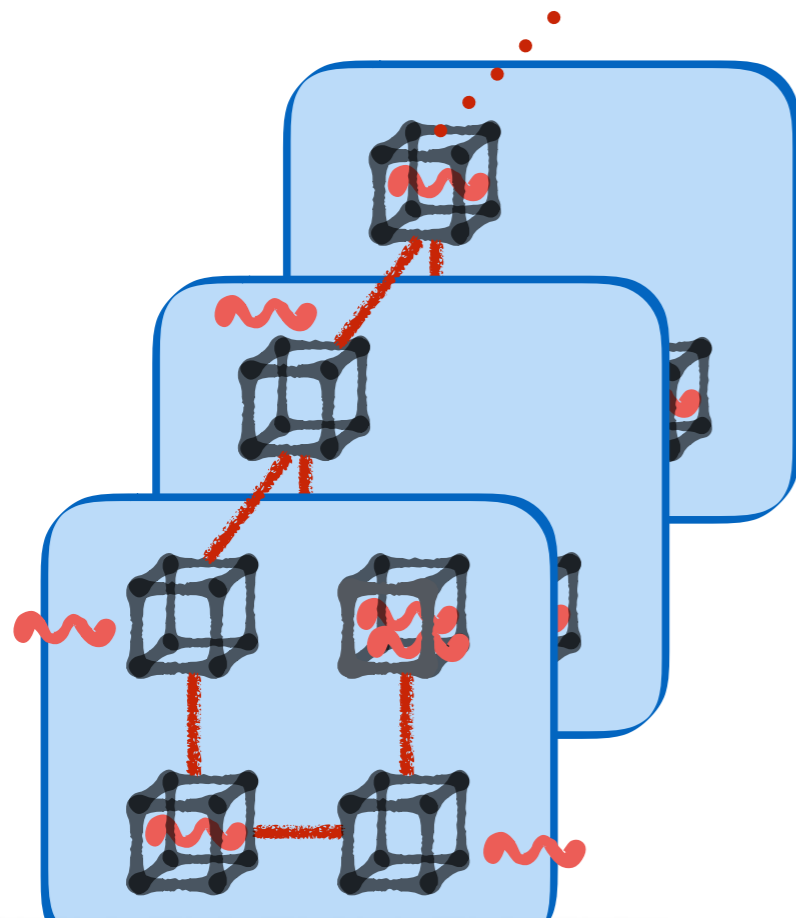


*IBM Q Tokyo - 20 qubits*

- 1) Number of qubits severely limited
- 2) Qubits noisy:  $T_1 \sim 89\mu s$
- 3) Connectivity of qubits limited!

# Current Resources In the NISQ-era

*How many qubits/gates do we actually have?*

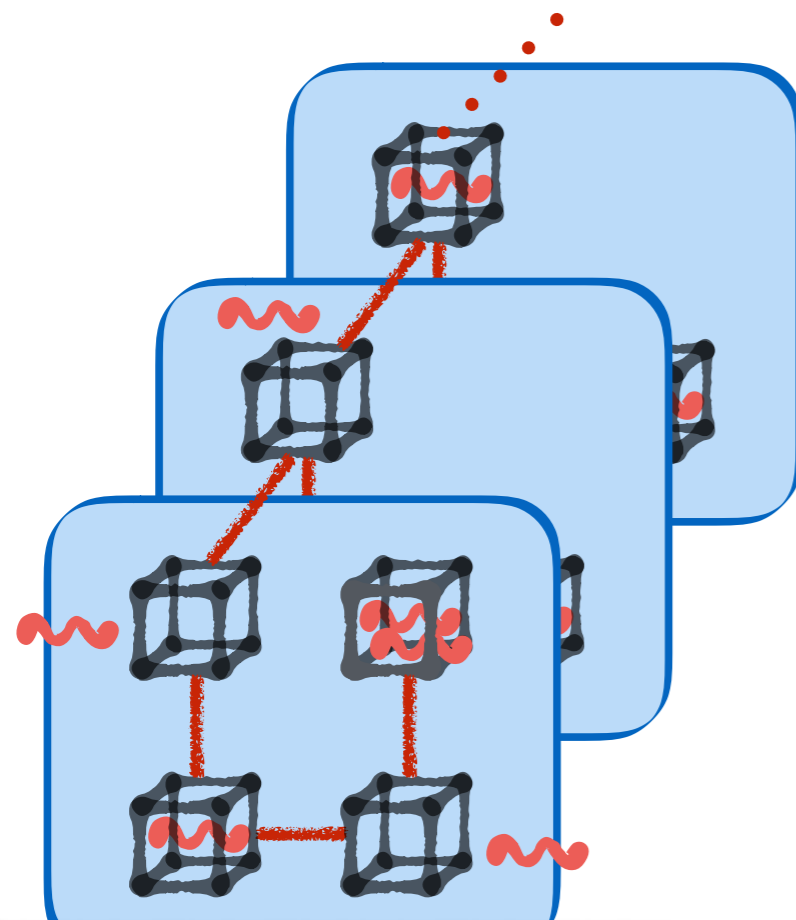


*IBM Q Tokyo - 20 qubits*

- 1) Number of qubits severely limited
- 2) Qubits noisy:  $T_1 \sim 89\mu s$
- 3) Connectivity of qubits limited!

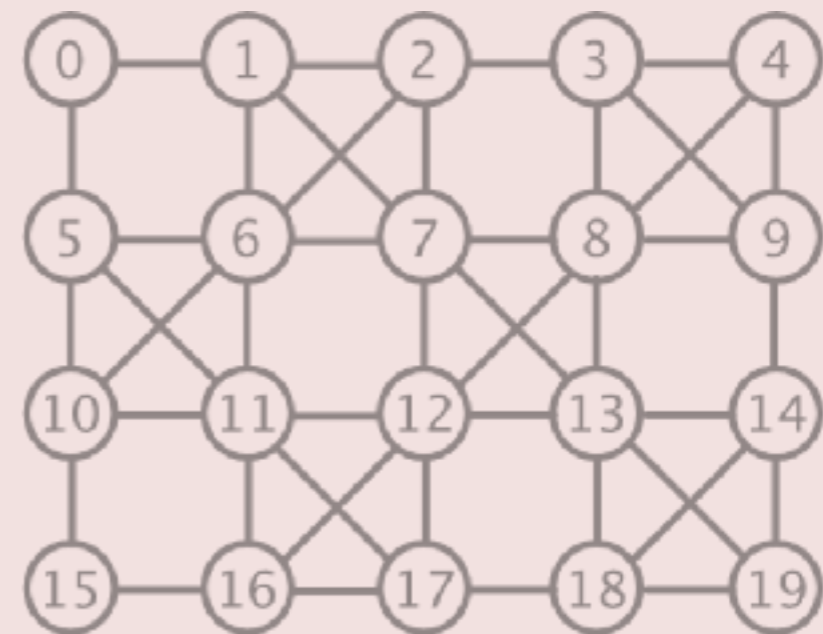
# Current Resources In the NISQ-era

*How many qubits/gates do we actually have?*



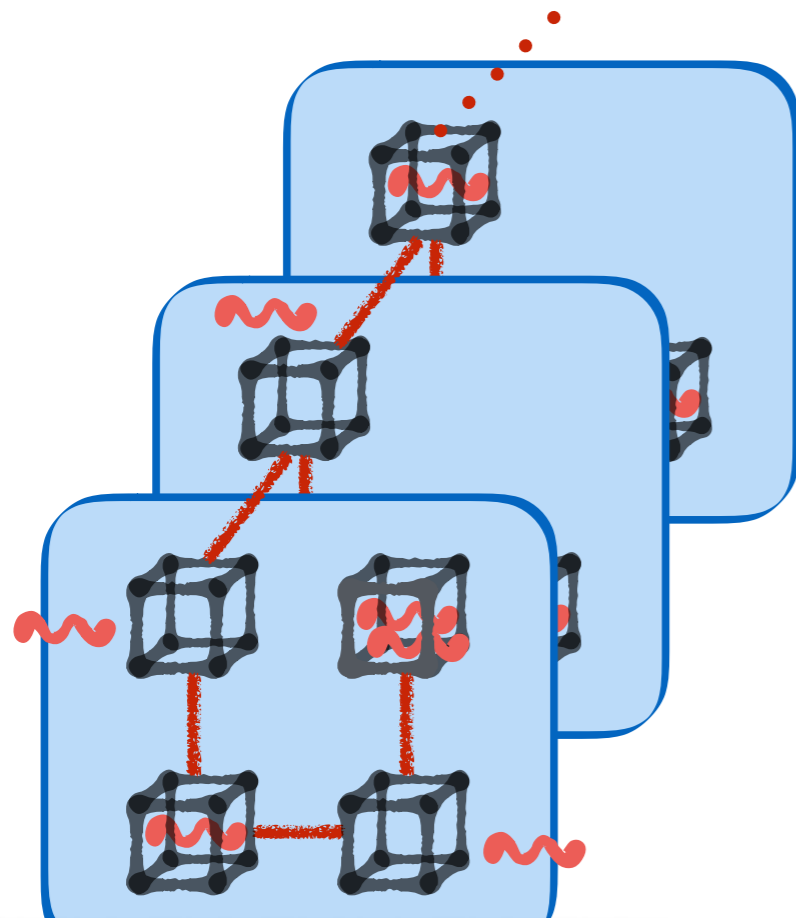
IBM Q Tokyo - 20 qubits

- 1) Number of qubits severely limited
- 2) Qubits noisy:  $T_1 \sim 89\mu s$
- 3) Connectivity of qubits limited!



# Current Resources In the NISQ-era

*How many qubits/gates do we actually have?*



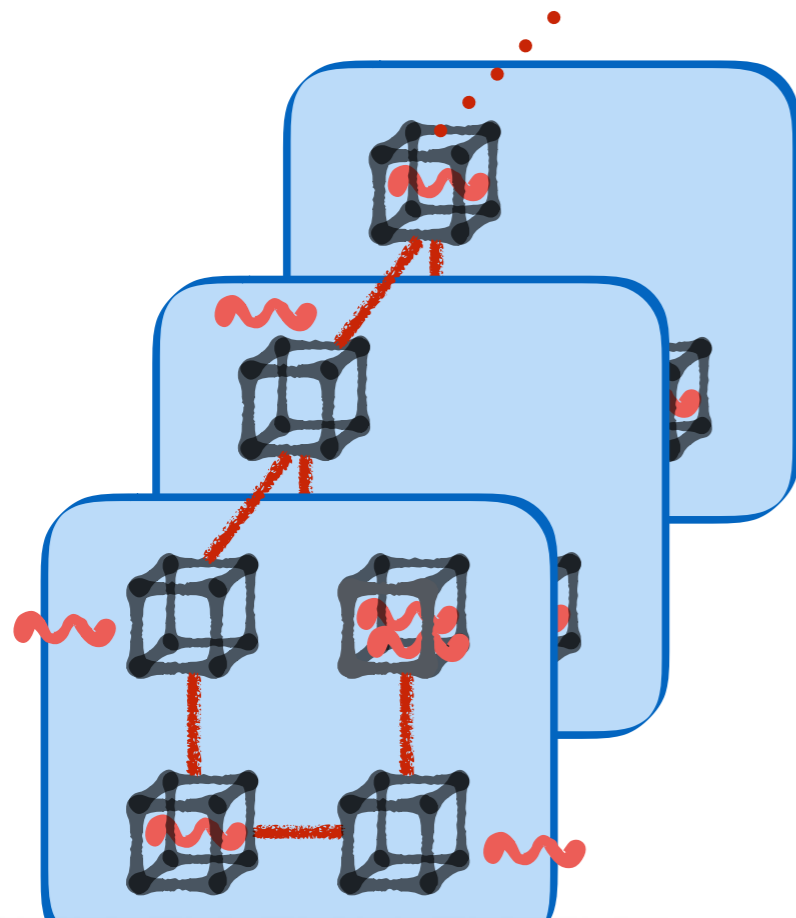
*IBM Q Tokyo - 20 qubits*

- 1) Number of qubits severely limited
- 2) Qubits noisy:  $T_1 \sim 89\mu s$
- 3) Connectivity of qubits limited!
- 4) Coherence time



# Current Resources In the NISQ-era

*How many qubits/gates do we actually have?*

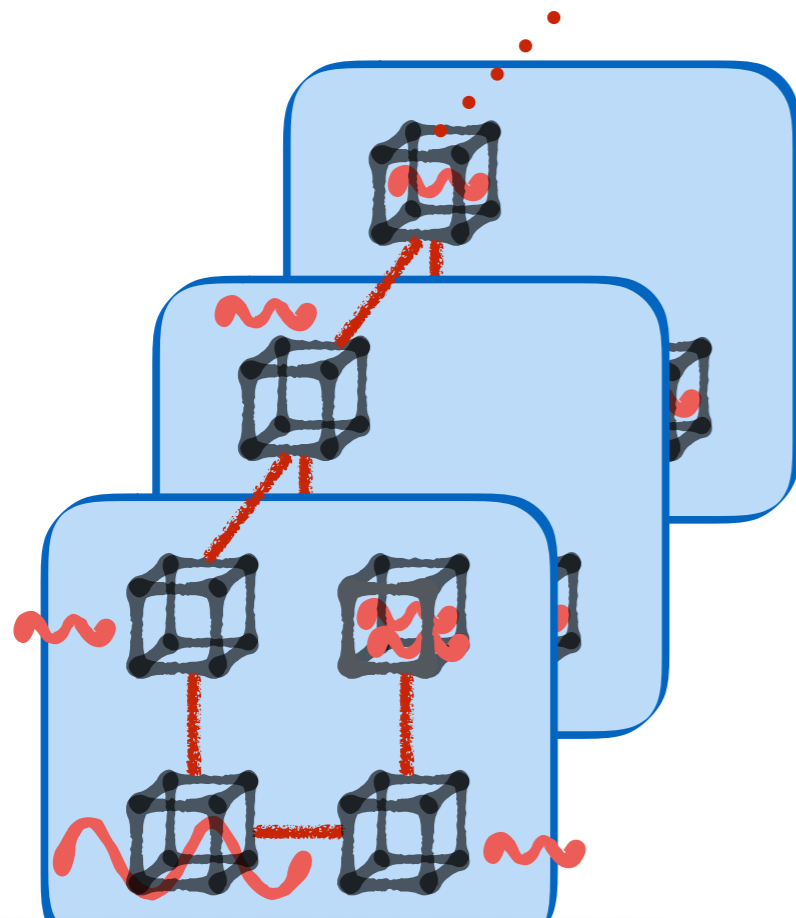


*IBM Q Tokyo - 20 qubits*

- 1) Number of qubits severely limited
- 2) Qubits noisy:  $T_1 \sim 89\mu s$
- 3) Connectivity of qubits limited!
- 4) Coherence time:  $T_2 \sim 57\mu s$

# Current Resources In the NISQ-era

*How many qubits/gates do we actually have?*

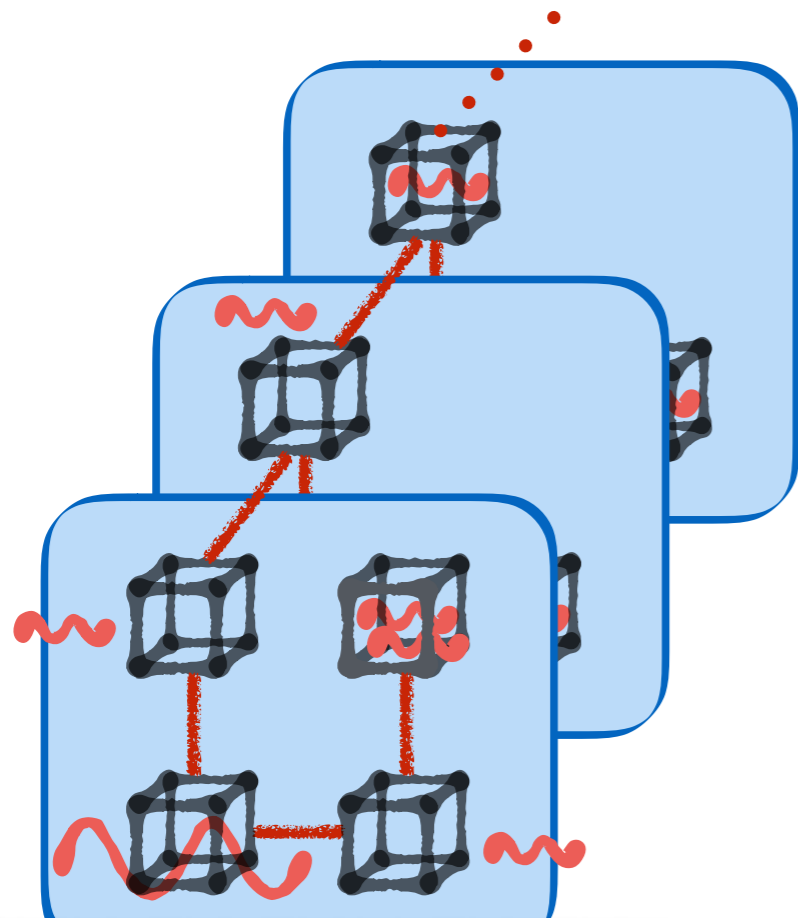


*IBM Q Tokyo - 20 qubits*

- 1) Number of qubits severely limited
- 2) Qubits noisy:  $T_1 \sim 89\mu s$
- 3) Connectivity of qubits limited!
- 4) Coherence time:  $T_2 \sim 57\mu s$

# Current Resources In the NISQ-era

*How many qubits/gates do we actually have?*

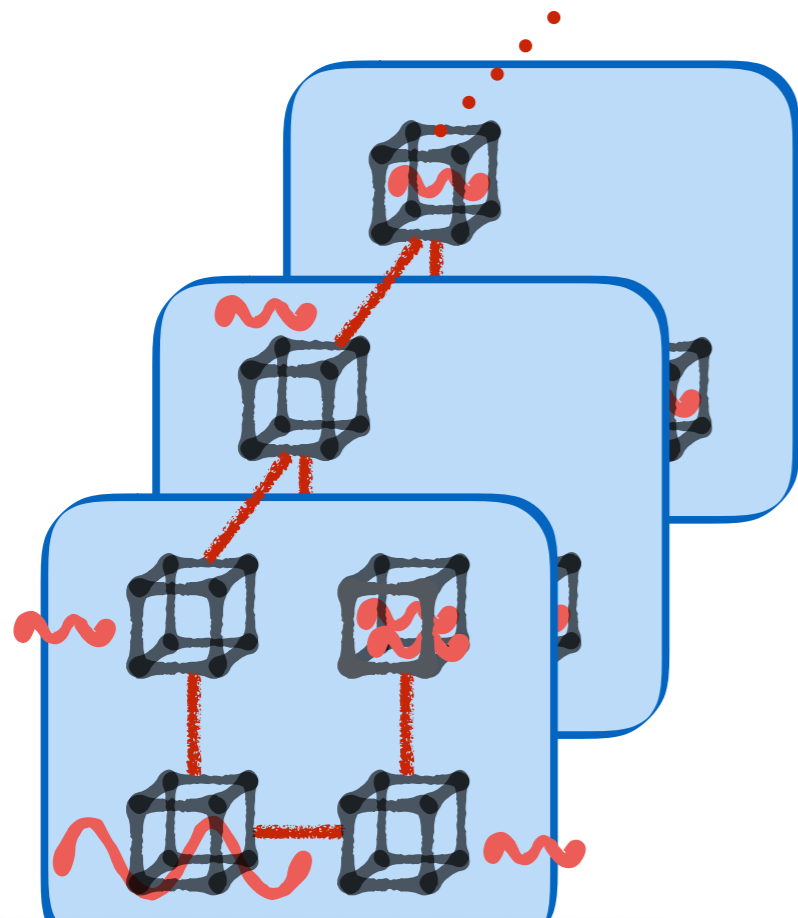


*IBM Q Tokyo - 20 qubits*

- 1) Number of qubits severely limited
- 2) Qubits noisy:  $T_1 \sim 89\mu s$
- 3) Connectivity of qubits limited!
- 4) Coherence time:  $T_2 \sim 57\mu s$
- 5) Gate Depth Small

# Current Resources In the NISQ-era

*How many qubits/gates do we actually have?*

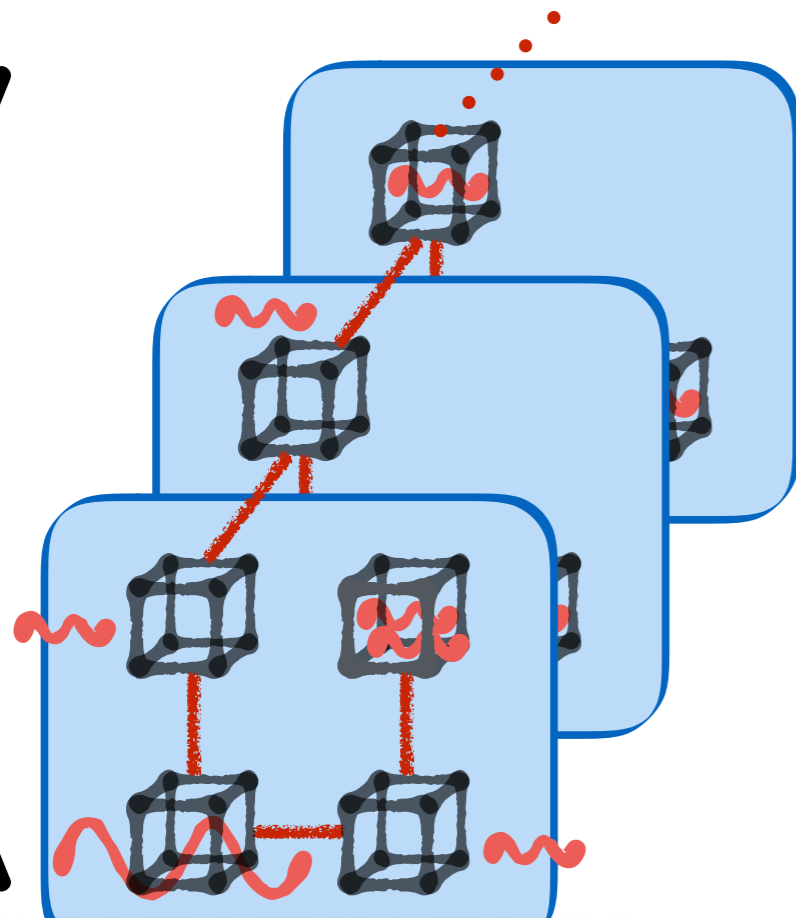


*IBM Q Tokyo - 20 qubits*

- 1) Number of qubits severely limited
- 2) Qubits noisy:  $T_1 \sim 89\mu s$
- 3) Connectivity of qubits limited!
- 4) Coherence time:  $T_2 \sim 57\mu s$
- 5) Gate Depth Small - Gate Error  $2 \times 10^{-3}$

# Current Resources In the NISQ-era

*How many qubits/gates do we actually have?*

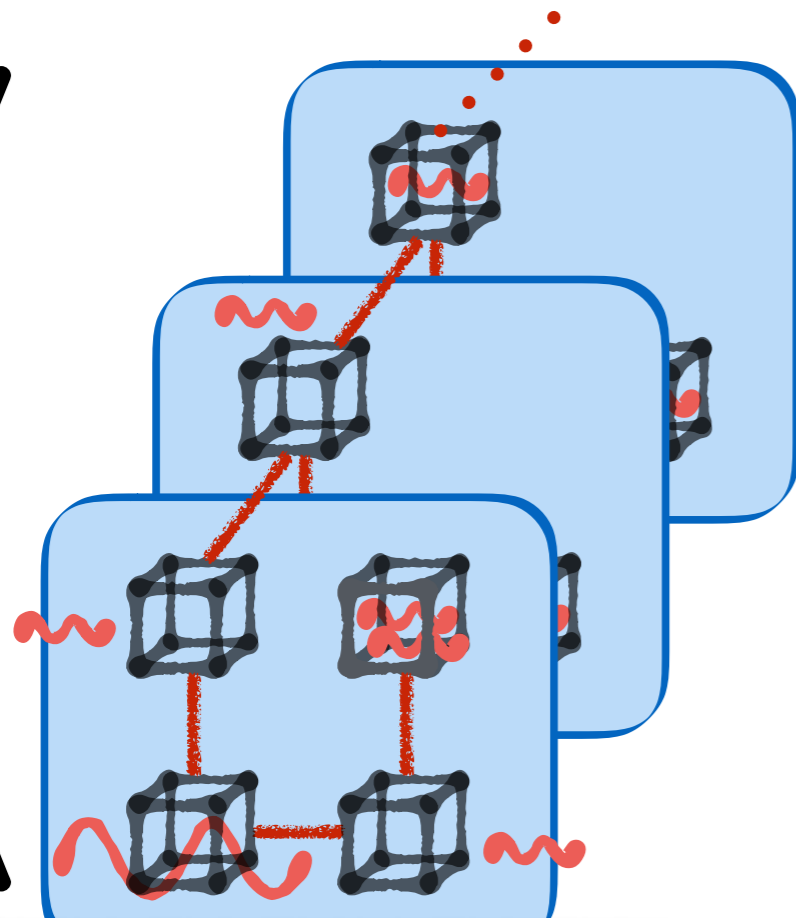


*IBM Q Tokyo - 20 qubits*

- 1) Number of qubits severely limited
- 2) Qubits noisy:  $T_1 \sim 89\mu s$
- 3) Connectivity of qubits limited!
- 4) Coherence time:  $T_2 \sim 57\mu s$
- 5) Gate Depth Small - Gate Error  $2 \times 10^{-3}$
- 6) Read-out Error large:  $6 \times 10^{-2}$

# Current Resources In the NISQ-era

*How many qubits/gates do we actually have?*



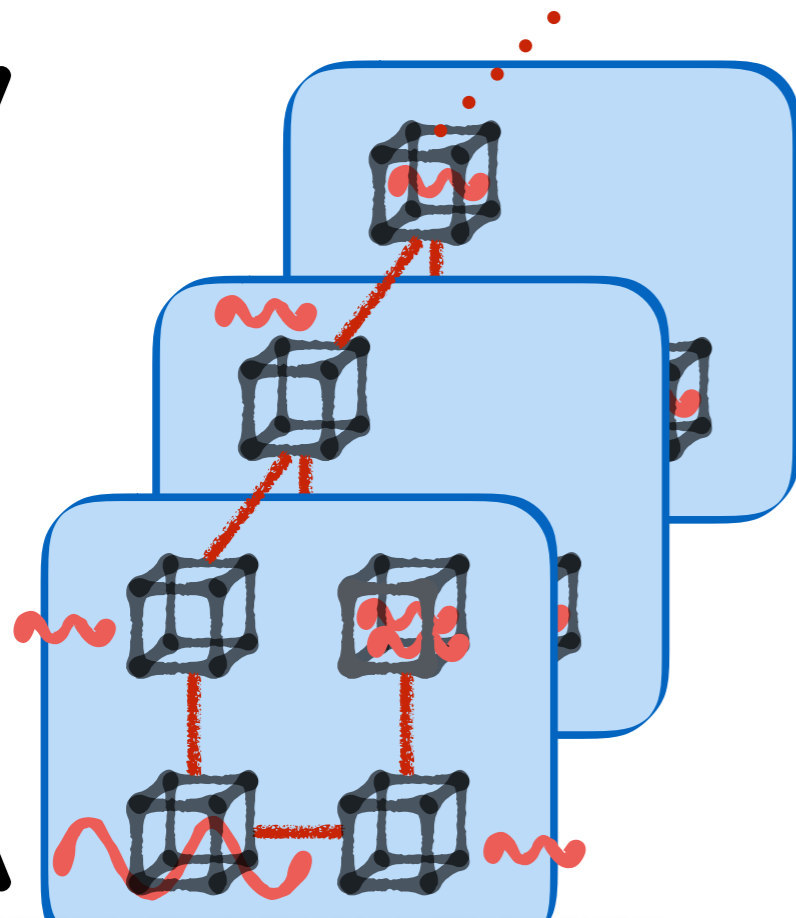
IBM Q Tokyo - 20 qubits

- 1) Number of qubits severely limited
- 2) Qubits noisy:  $T_1 \sim 89\mu s$
- 3) Connectivity of qubits limited!
- 4) Coherence time:  $T_2 \sim 57\mu s$
- 5) Gate Depth Small - Gate Error  $2 \times 10^{-3}$
- 6) Read-out Error large:  $6 \times 10^{-2}$
- 7) No quantum error correction

# Current Resources In the NISQ-era

*Arxiv:1803.03326v2*

*State of the art: (1+1)D Schwinger model on 2-spatial sites: 6 qubits reduced to 2 qubits*



*IBM Q Tokyo - 20 qubits*

- 1) Number of qubits severely limited
- 2) Qubits noisy:  $T_1 \sim 89\mu s$
- 3) Connectivity of qubits limited!
- 4) Coherence time:  $T_2 \sim 57\mu s$
- 5) Gate Depth Small - Gate Error  $2 \times 10^{-3}$
- 6) Read-out Error large:  $6 \times 10^{-2}$
- 7) No quantum error correction