The Lipkin Model
on a quantum computer

Phys. Rev. C **104,** 024305 (2021)

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Calvin W. Johnson, San Diego State University

"This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Award No. DE-SC0019465"
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Phase
transition

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Calvin Johnson – QPT #10 – Dubrovnik, July 13, 2022

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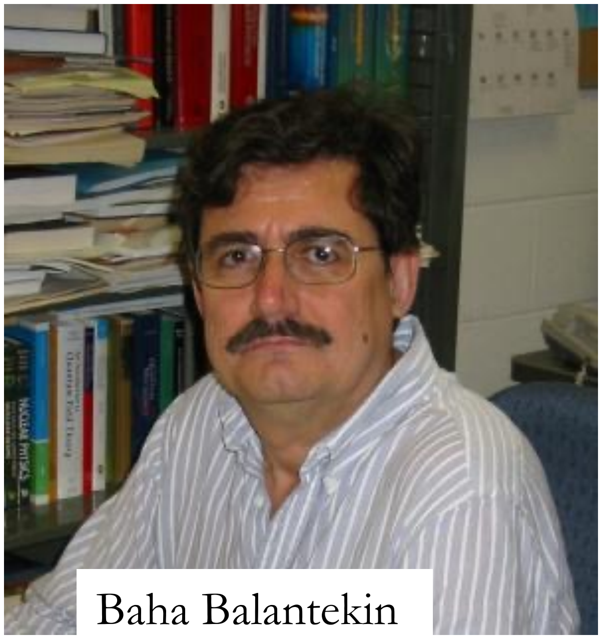

Phase transition

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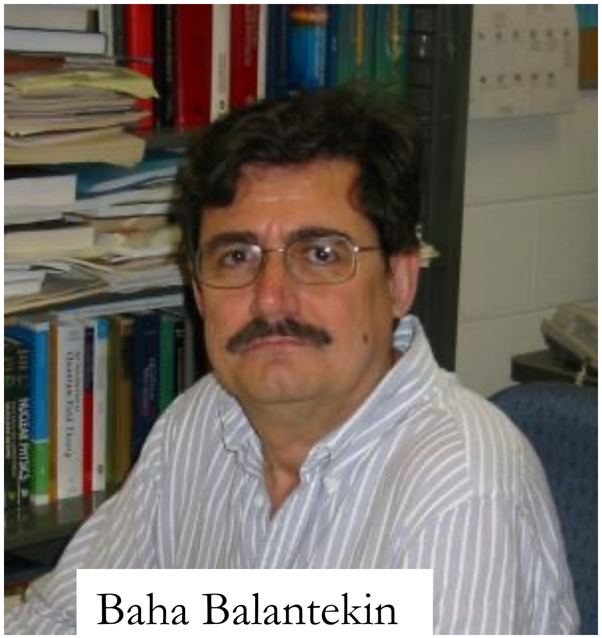
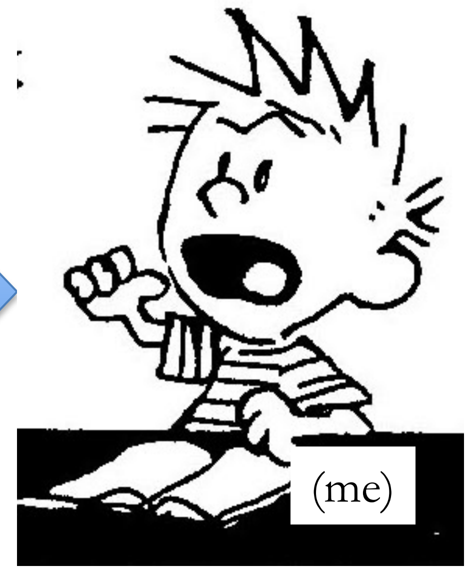


Phase transition



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See also:

Tues afternoon: Garcia-Ramos (Agassi model)
Next talk: Perez-Fernandez (Agassi model again)

Motivation

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I would like to do an *ab initio* calculation of Zr isotopes!

We can't do that on a classical computer!

But I heard *quantum computers* will solve all problems and bring paradise!

Well….

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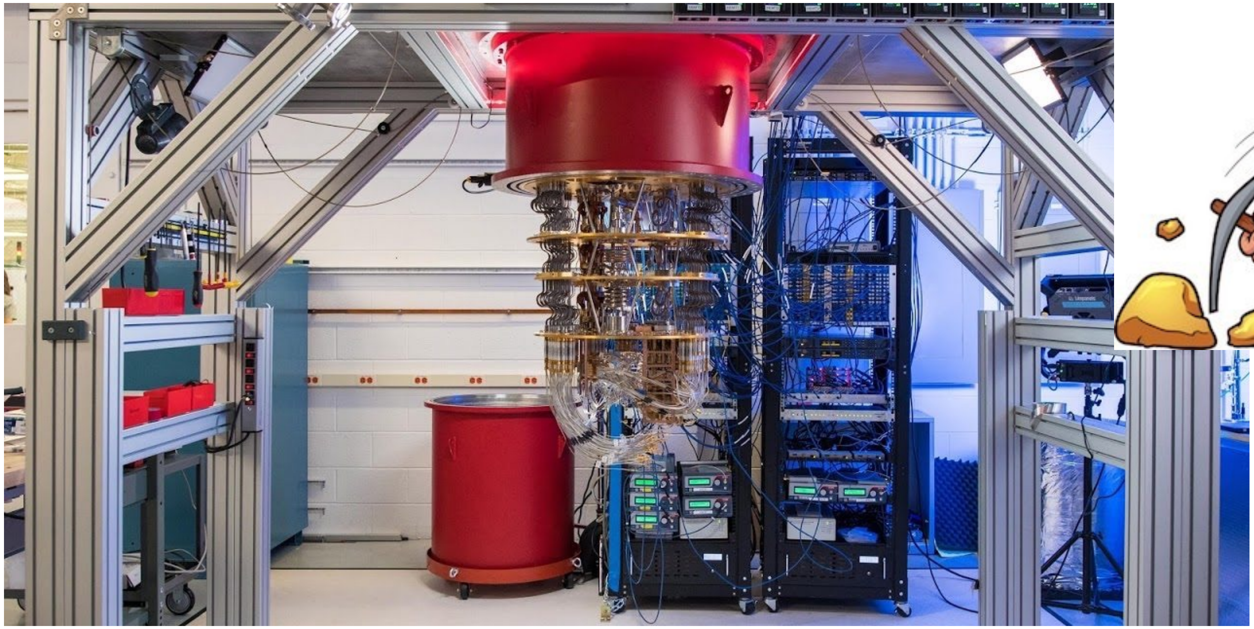
The quantum computing gold rush….



- Jan 10, 2020: Department of Energy announces $625 **million** for "Quantum Information Science Research Centers"

- Both NSF and NIST also fund quantum computing/quantum information

- The US has plans to spend $1.2B+ over the next 10 years on quantum computing and quantum information

- China (as well as India and other countries) is also putting enormous resources into development of QC/QIS (quantum computing/ quantum information science)

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What quantum computing looks like

To 'program' a quantum computer, one must learn to think in a new way:

One must be able to arrive at the desired solution through a *unitary transformation*
or product of unitary transformations…

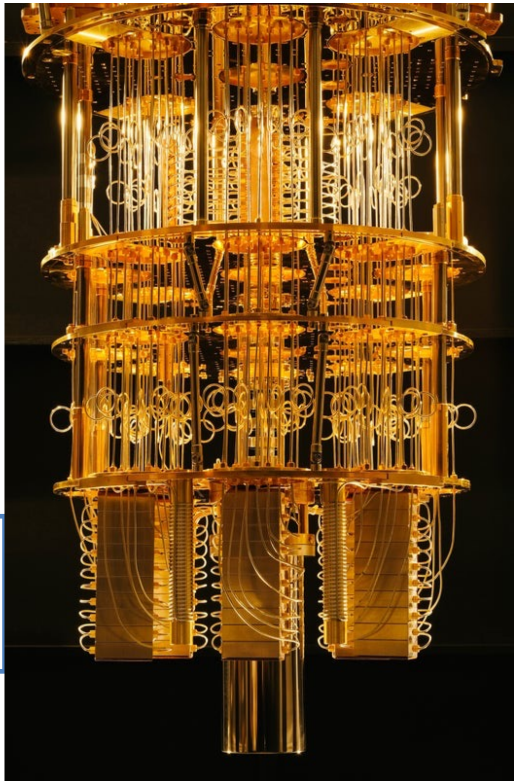
What quantum computing looks like

3 parts of a quantum computation:

Preparation of initial state (input)

"Computation" (unitary evolution)

Measurement (output)



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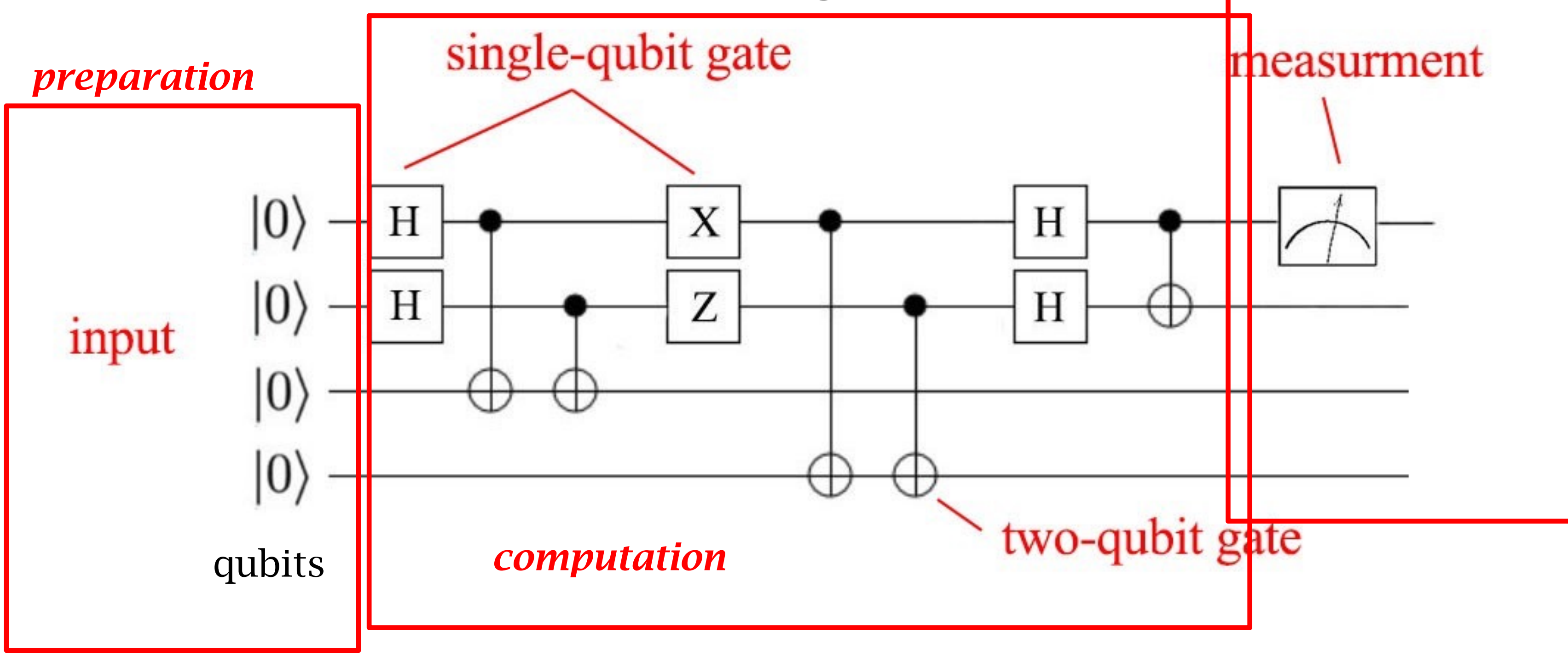
What quantum computing looks like

Some technical details

A sample quantum ‘circuit’ or algorithm



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What quantum computing looks like

3

Preparati
of initial
state
(input)

“Computation”

Quantum mechanics is *probabilistic.* But in any given run of a quantum computer, you get either 0 or 1 as an answer

This means to get out the actual answer (as a probability) you have to run the full circuit/ algorithm *many times*

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What quantum computing looks like

Example: Dumitrescu *et al*, Phys Rev Lett **120**, 210501 (2018), "Cloud quantum computing of an atomic nucleus,"

computed the binding energy of a deuteron (deuterium nucleus)
which here = lowest eigenvalue of a 2 x 2 or 3 x 3 matrix

To carry this calculation, they performed **8192 runs** (measurements)
on IBM QX5 (17 qb)
and **10,000 runs** on Rigetti 19Q (19 qb)

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The IBM group estimates to get chemical accuracy for the binding energy of BeH_2 would require > *one million measurements*

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What quantum computing looks like

How they did it: *Variational Quantum Eigensolver* (VQE)

repeat with different parameters

Vary parameters of vector by rotations

Take "expectation value" (average) of terms in Hamiltonian (energy operator)

Each average requires many measurements

What quantum computing looks like

Example: Dumitrescu *et al*, Phys Rev Lett **120**, 210501 (2018), "Cloud quantum computing of an atomic nucleus,"

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on IBM QX5 (17 qb)
and 10,000 runs on Rigetti 19Q (19 qb)

This was celebrated as a great triumph!

What quantum computing looks like

There's *gold*
(or at least highly cited
papers) in those calculations!

3), "Cloud quantum

leus)

To carry this calculation, they perfoı rem
on IBM QX5 (17 qb)
and 10,000 runs on Rigetti 19Q (19

289 citations since 2018!

What quantum computing looks like

Some technical details

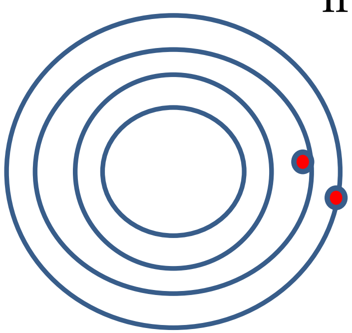
Sample application: occupation-representation of atoms and nuclei

In 'configuration-interaction' the wave function is a superposition of configurations (here, binary words)

$| \psi > = c_1 \; |1100> \; + c_2 \; |1010> + c_3 \; |1001> + \ldots.$

The c_i are called the *amplitudes* and form coefficients of a vector

If you have *M* particles in *N* orbitals, there are *N* choose *M* amplitudes … this grows exponentially!



(My own configuration interaction code can handle up to about 20 billion amplitudes on a supercomputer… but it is easy to find cases that demand more! **This requires storing 20 billion real numbers**…)

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What quantum computing looks like

Some technical details

Sample application: occupation-representation of atoms and nuclei

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$| \psi > =$ […]

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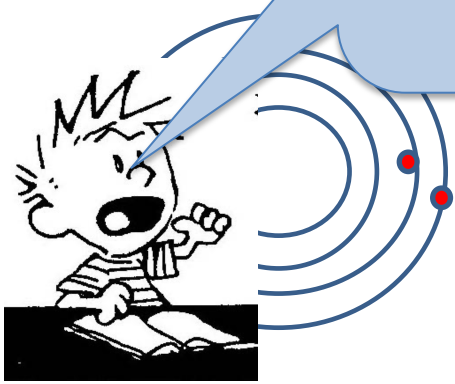
[…]itals, there are N choose M amplitudes […]ially!

How can quantum computers help with this problem?



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Sample application: occupation-representatio i

In 'con c
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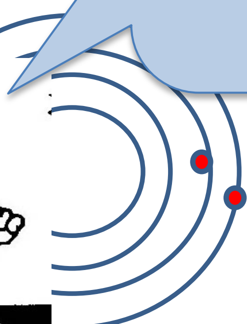
How can quantum computers help with this problem?

Let's talk about *qubits*



(My own configuration interaction code ca
about 20 billion amplitudes on a superco
easy to find cases that demand more! **Th**
storing 20 billion real numbers...)

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What quantum computing looks like

Some technical details

A qubit is a linear *superposition* of a 0 and 1:

$| \chi > = a | 0 > + b | 1 >$, where a and b are complex and

$|a|^2 + |b|^2 = 1$

We can represent this as a two-dimensional vector: $\binom{a}{b}$

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What quantum computing looks like

Some technical details

We can have multi-qubit words $|\chi_1 \chi_2 \chi_3 \chi_4 \ldots>$

n qubits represent 2^n –dimensional vector
(e.g. 35 qubits -> vector of dimension 34.7 billion)

that is, a *single* multi-qubit word can represent
a large classical vector:

$$|\chi_1 \chi_2 \chi_3 \chi_4 \ldots> \; = c_1 | 0000.. > + \; c_2 | 1000.. > + c_3 | 1100.. > + \ldots$$

1 35 qb 'word' = 34.7 *billion* elements in a vector

(There are quantum computers with 130 qb or more…)

What quantum computing looks like

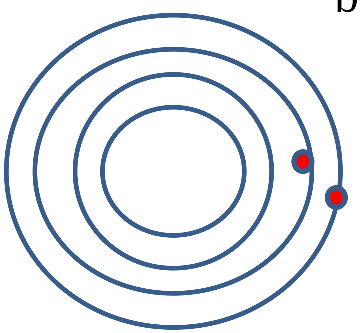
Some technical details

Sample application: occupation-representation of atoms and nuclei

Therefore in principle we can easily represent a configuration-interaction wave function

$$| \psi > = c_1 \ |1100> + c_2 \ |1010> + c_3 \ |1001> + \ldots$$

by a single word of a few qubits!



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What quantum computing looks like

Some technical details

Sample application: occupation-representation of atoms and nuclei

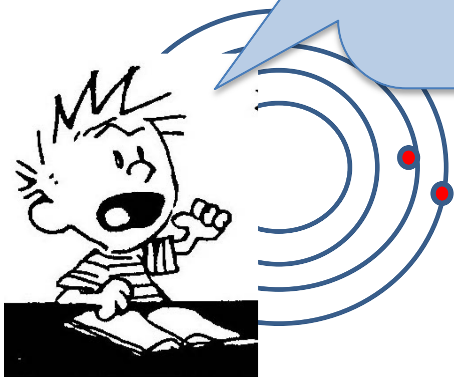
Theref sent a configuration-interaction
wave f

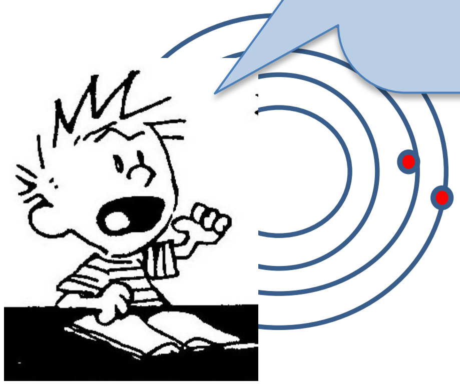
| ψ > =

s!

Can we apply this to nuclear structure?

There have been some preliminary attempts..




Should we try something simple to warm up with?


Of course, there's a classic toy model..

The LIPKIN-Meshkov-Glick MODEL

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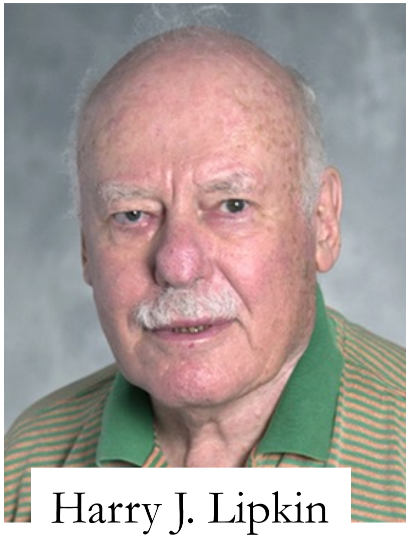
Lipkin, Meshkov, and Glick, *Nucl. Phys.* **62**, 188 (1965)



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The LIPKIN-Meshkov-Glick MODEL

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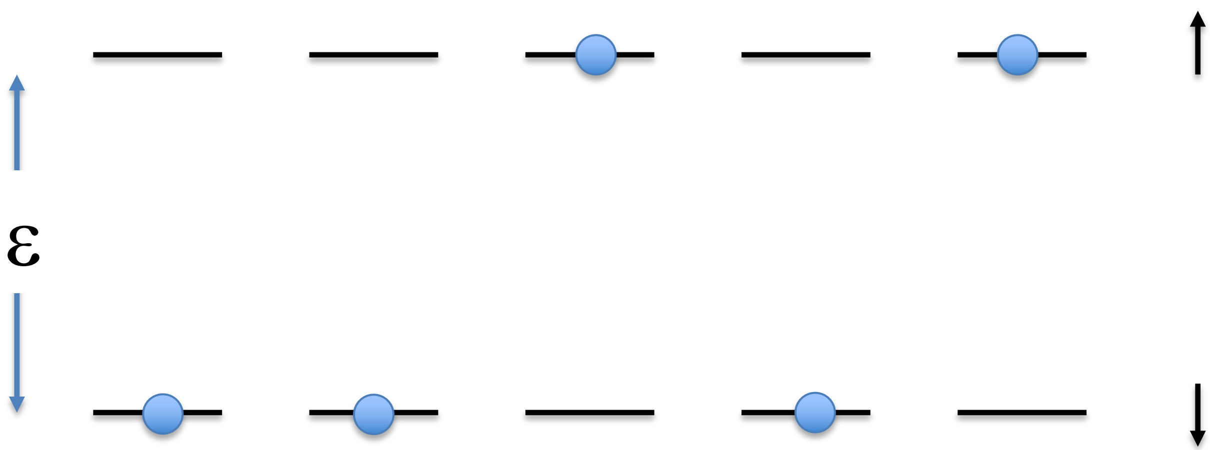

N particles, N sites, each particle either 'up' or 'down'

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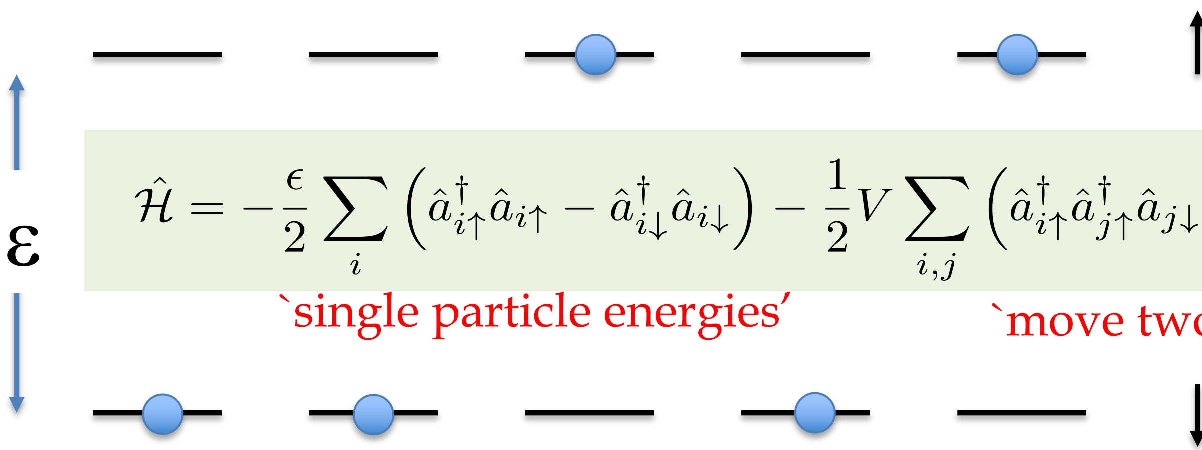

$$\hat{\mathcal{H}} = -\frac{\epsilon}{2}\sum_i \left(\hat{a}^\dagger_{i\uparrow}\hat{a}_{i\uparrow} - \hat{a}^\dagger_{i\downarrow}\hat{a}_{i\downarrow}\right) - \frac{1}{2}V\sum_{i,j}\left(\hat{a}^\dagger_{i\uparrow}\hat{a}^\dagger_{j\uparrow}\hat{a}_{j\downarrow}\hat{a}_{i\downarrow} + \hat{a}^\dagger_{i\downarrow}\hat{a}^\dagger_{j\downarrow}\hat{a}_{j\uparrow}\hat{a}_{i\uparrow}\right).$$

\`single particle energies' \`move two particles up/down'

N particles, N sites, each particle either 'up' or 'down'

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\`single particle energies'

\`move two particles up/down'

Introduce
quasispin operators…

$$\hat{J}_z = \frac{1}{2}\sum_{i=1}^{N} \hat{a}^\dagger_{i,\uparrow}\hat{a}_{i,\uparrow} - \hat{a}^\dagger_{i,\downarrow}\hat{a}_{i,\downarrow},$$

$$\hat{J}_+ = \sum_i \hat{a}^\dagger_{i,\uparrow}\hat{a}_{i,\downarrow},$$

$$\hat{J}_- = \left(\hat{J}_+\right)^\dagger = \sum_i \hat{a}^\dagger_{i,\downarrow}\hat{a}_{i,\uparrow},$$

The LIPKIN-Meshkov-Glick MODEL

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\`single particle energies' \`move two particles up/down'

Introduce
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$$\hat{J}_z = \frac{1}{2}\sum_{i=1}^{N}\hat{a}^\dagger_{i,\uparrow}\hat{a}_{i,\uparrow} - \hat{a}^\dagger_{i,\downarrow}\hat{a}_{i,\downarrow},$$

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$$\hat{J}_- = \left(\hat{J}_+\right)^\dagger = \sum_i \hat{a}^\dagger_{i,\downarrow}\hat{a}_{i,\uparrow},$$

$$\hat{\mathcal{H}} = -\epsilon\hat{J}_z - \frac{1}{2}V\left(\hat{J}_+^2 + \hat{J}_-^2\right).$$

….to get simple form

The LIPKIN-Meshkov- MODEL

Why are people so fond of the Lipkin model?

Because you can solve a 2^N dimension problem in N+1 dimension

particle energies'

`move two particles u

$$\hat{J}_z = \frac{1}{2}\sum_{i=1}^{N} \hat{a}^\dagger_{i,\uparrow}\hat{a}_{i,\uparrow} - \hat{a}^\dagger_{i,\downarrow}$$

$$\hat{J}_+ = \sum_i \hat{a}^\dagger_{i,}$$

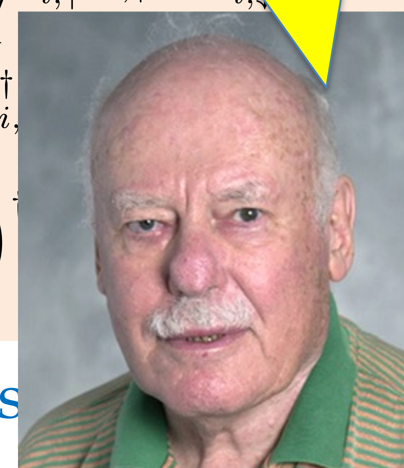
$$\hat{J}_- = \left(\hat{J}_+\right)$$

Introduce

uasispin operators…

$$-\epsilon \hat{J}_z - \frac{1}{2}V\left(\hat{J}_+^2 + \hat{J}_-^2\right).$$

….to get s



Harry J. Lipkin

The LIPKIN-Meshkov- … MODEL

Why are people so fond of the Lipkin model?

Because you can solve a 2^N dimension problem in N+1 dimension

(Also, everything *works* for the Lipkin model!)

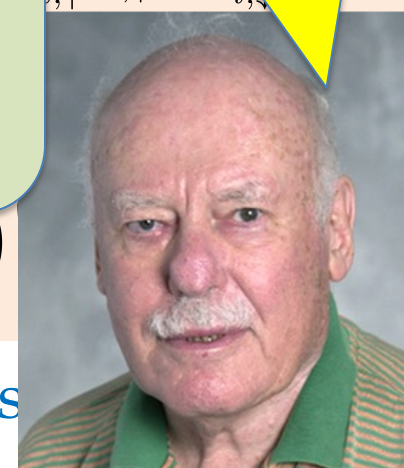
… particle e… …icles u…

$$\hat{J}_- = \left(\hat{J}_+\right)$$

$$\frac{}{2}\left(\hat{J}_+^2 + \hat{J}_-^2\right).$$

….to get s…

Igal Talmi



Harry J. Lipkin

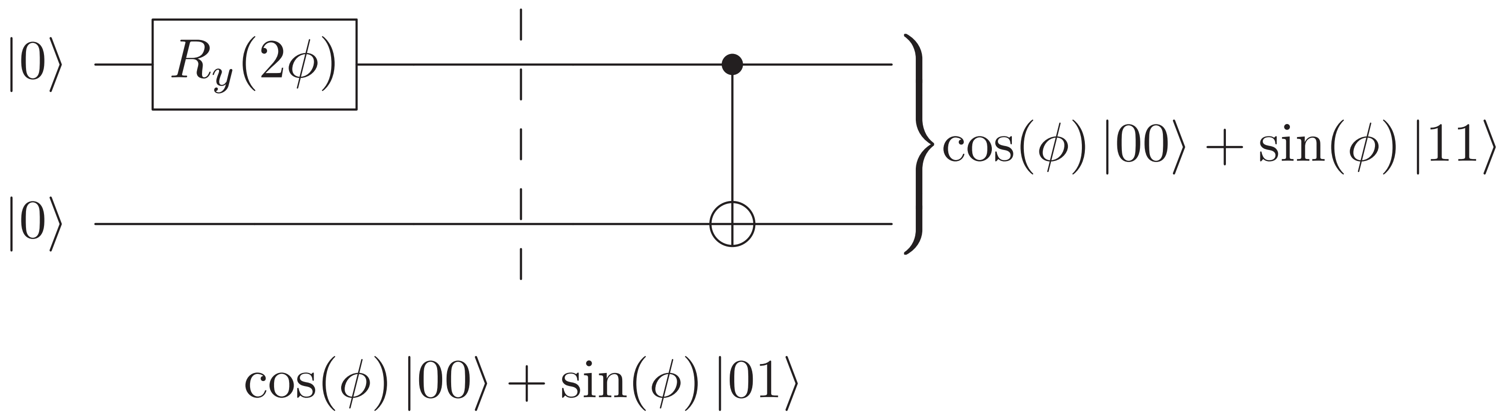


FIG. 1. A quantum circuit to prepare the two-qubit VQE trial state $|\psi(\theta)\rangle$ given by Eq. (9) with $\phi = \theta - \pi/2$ on a noiseless quantum device. At the dashed line, the intermediate state is $\cos(\phi)\,|00\rangle + \sin(\phi)\,|01\rangle$.

This circuit 'prepares' the state. Not show: evaluating the Hamiltonian

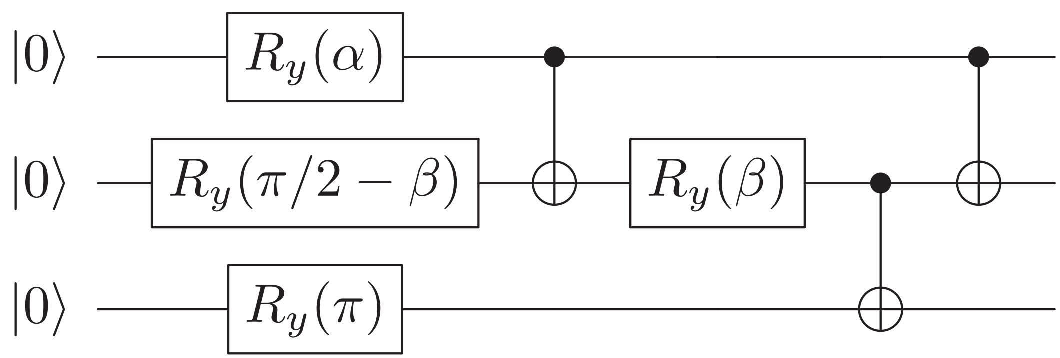
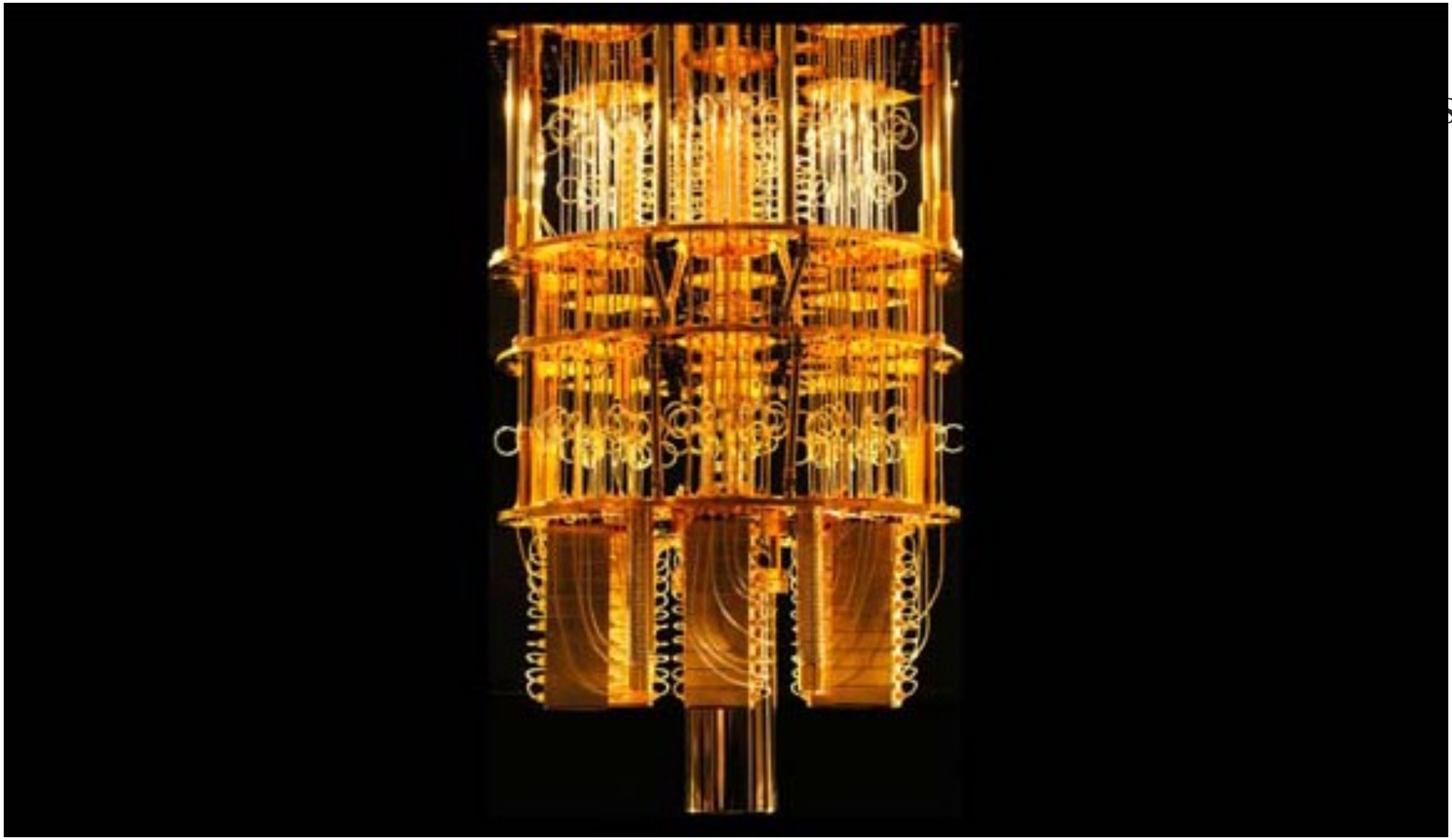
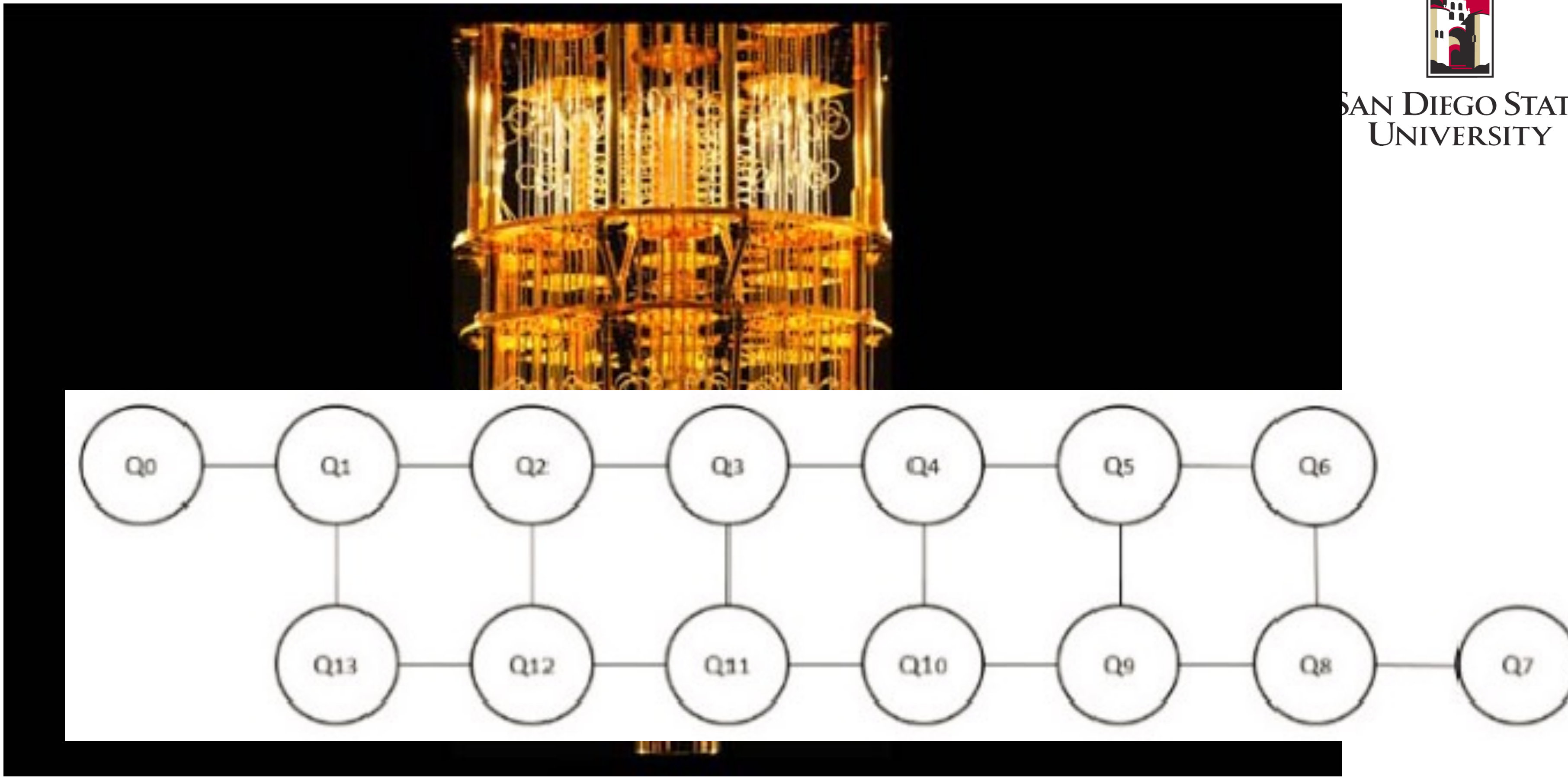


FIG. 2. A quantum circuit to prepare the three-qubit VQE trial state $|\psi\rangle$ given by Eq. (13), using variables defined in Eqs. (14)–(15).

This circuit 'prepares' the state. Not show: evaluating the Hamiltonian



IBM 'Melbourne' processor



IBM 'Melbourne' processor

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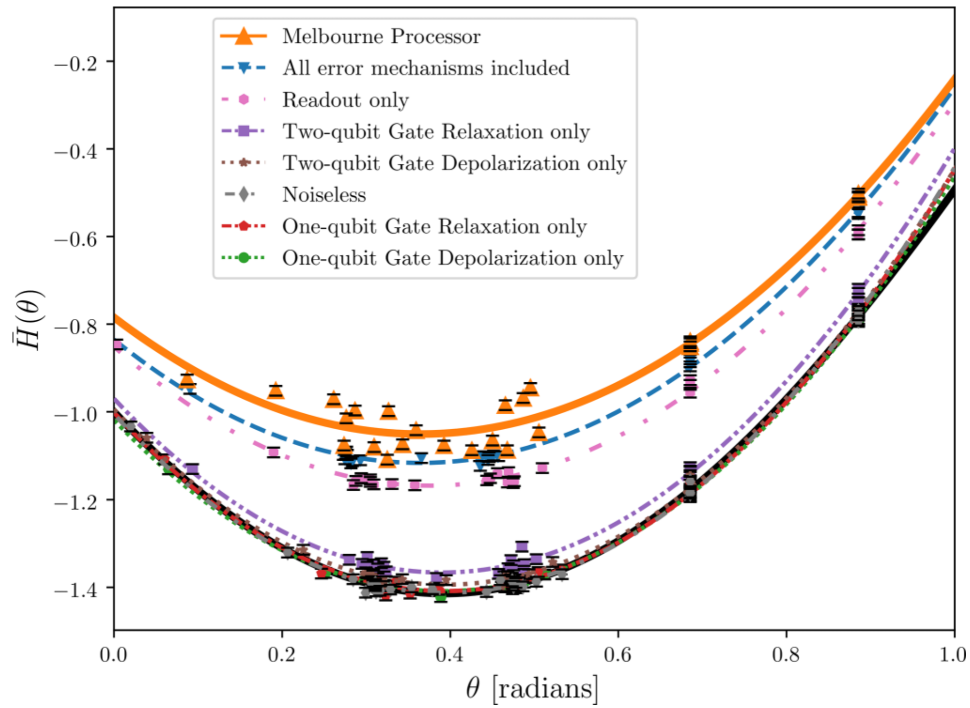

FIG. 3. Energy of variational state as a function of the VQE trial parameter θ. The results obtained using the Melbourne processor are compared to the exact result as well as to the results of classical simulations of the quantum processor that incorporate one of the five error mechanisms listed in Table I. The lines in the figure are parabolic fits for the Melbourne and simulation results, while the solid black line shows the exact value of $\bar{H}$ obtained analytically using Eq. (8). Error bars on each data point show the statistical errors $1/\sqrt{n}$, where $n = 8192$ is the number of runs over which the result for each model is averaged.

A big challenge is noise:

The main sources of noise are
(a) 2-qb gates (CNOT)
(b) Readout (measure)

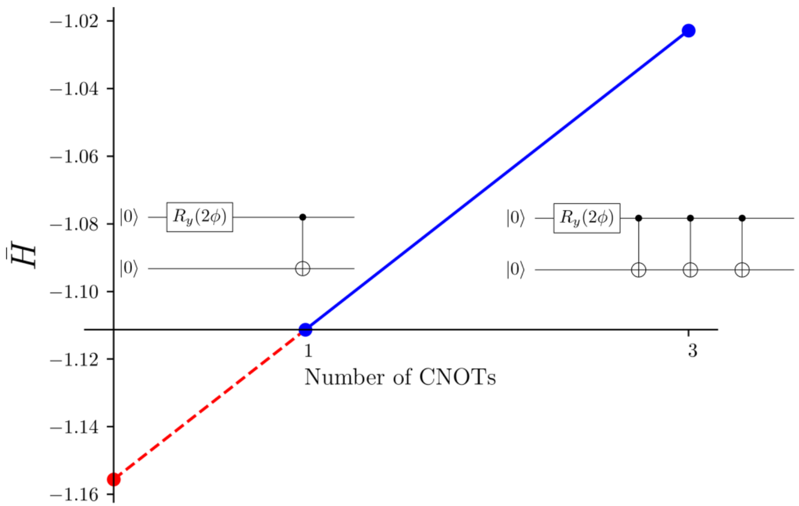

FIG. 5. Illustration of noise extrapolation method used to mitigate two-qubit errors. Linear extrapolation to zero error from two-qubit gate depolarization for the measured ground state expectation value of the Hamiltonian H with $N = 2$, as given in Eq. (7), using measured data when one or three identical CNOT gates are used to prepare the variational state in Eq. (9), using the optimum value of the variational parameter $\theta = \pi/8$. In the quantum circuit on the right, each CNOT in the quantum circuit on the left is replaced by three successive CNOTs. Because $\text{CNOT}^2 = 1$, the functionality of the two circuits in the absence of noise is the same, but in the presence of noise the circuit with the additional CNOTs will have larger error. The error-mitigated estimate for the value of the relevant observable H is obtained by extrapolating the result linearly to zero as a function of the number of CNOTs.

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Mitigation of noise in CNOT 2-qb gate:

Since $\text{CNOT}^2 = 1$, use 1, 3 CNOTs and extrapolate to `zero'

We need more than energies:
We need observables too!

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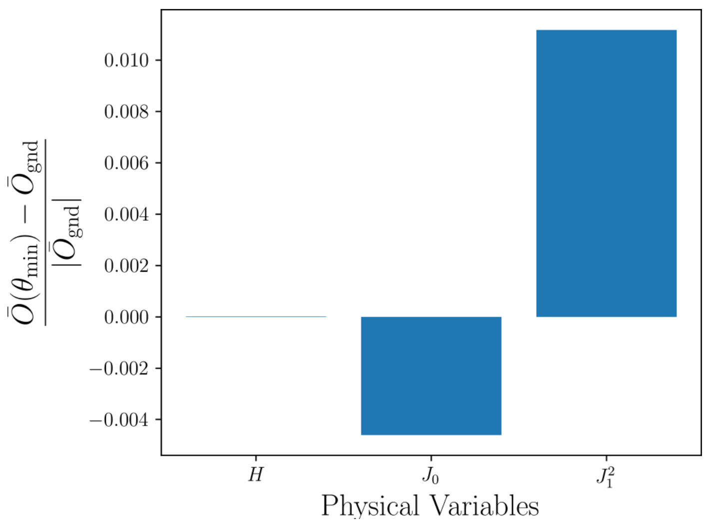

FIG. 7. Moments of physical quantities used in dark matter detection calculations are calculated using a noise model simulation of the Melbourne processor with no readout error to obtain θ_{min} and subsequently using Eq. (25), which are compared to exact values obtained analytically. Exact values for these averaged quantities are $\bar{H}_{\text{gnd}} = -\sqrt{2}$, $(\bar{J}_0)_{\text{gnd}} = -1/\sqrt{2}$, and $(\overline{J_1^2})_{\text{gnd}} = (2-\sqrt{2})/4$.

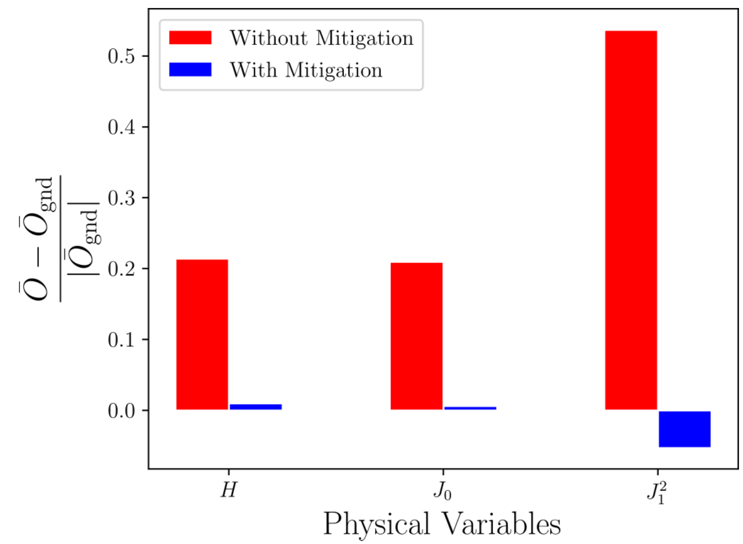

FIG. 8. Performance of error mitigation techniques for estimation of observables for the $N = 2$ Lipkin model ground state in Eq. (9) with fixed coupling $V = 1$ and the exact optimum value of the variational parameter, $\theta = \pi/8$. All data were calculated using the IBM Q simulator with all errors listed in Sec. V A. Moments of physical quantities used in dark matter detection calculations are calculated with and without using mitigation techniques for both two-qubit gate depolarization and readout errors. Exact values for these averaged quantities are $\bar{H}_{\text{gnd}} = E_{\text{gnd}}$, $(\bar{J}_0)_{\text{gnd}} = -1/\sqrt{2}$, and $(\overline{J_1^2})_{\text{gnd}} = (2-\sqrt{2})/4$. The error mitigation procedure yields improvement to the results for the quantities J_0 and J_1^2 that is similar to that obtained for the energy H.

The LIPKIN-Meshkov-Glick MODEL

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Some other quantum computing papers on the Lipkin model:

Hobday, Stevenson, Benstead, arXiv:2205.05576. VQE for Lipkin as prototype for shell model calculations

Romero *et al*: arXiv:2203:01619: Lipkin model to examine performance of VQE

Hlatshwayo *et al*. arXiv: 2203.01478: Excited states using quantum equation-of-motion

Guerro *et al* arXiv:2111.14455: Lipkin model on qudits

Robbins and Love: PRA **104**, 022412 (2021): Lipkin model on physical quantum machine

Nuclear shell model on a quantum computer

Lv, Wei, Xie, Long, arXiv:2205.12087 ‘Package’ for computing shell model (not public)

Romero, Engel, Tang, Economou, PRC **105**, 064317 (2022). Advanced VQE for shell mode.

Stetcu, Baroni, Carlson, arXiv: 2110.06098. Uses unitary coupled cluster for p-shell

Siwach, Arumugam, PRC **105**, 064318 (2022) Computing quadrupole moment of deuteron

Kiss, Grossi, et al, arXiv:2205.0864. Unitary coupled cluster for ^{6}Li (really: frozen α + deuteron all over again)

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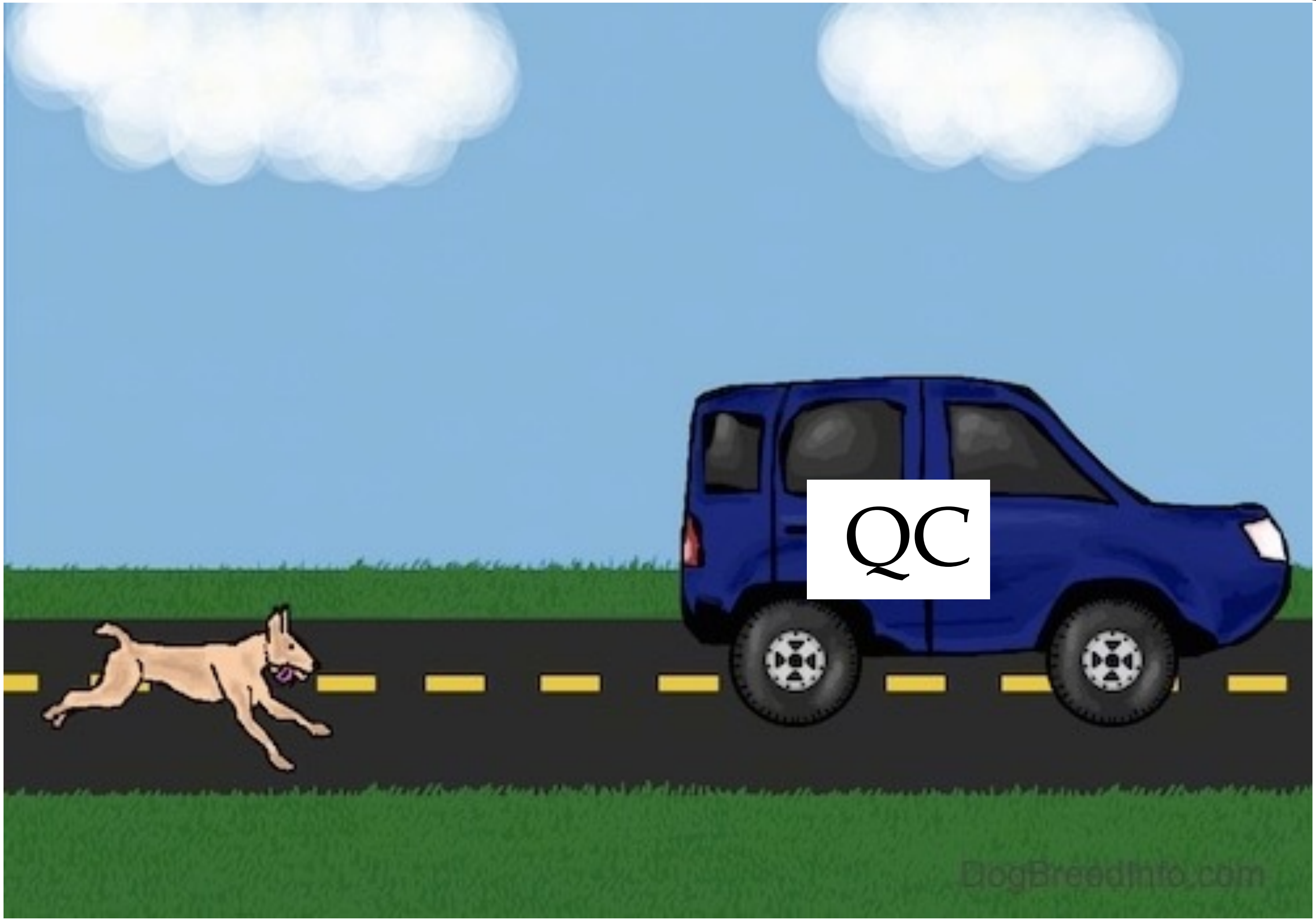

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Let’s look at the data requirements in more detail

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Consider ^{12}C, N_{max}=8

M-scheme dimension 0.6 billion

55 single-particle orbits (n l j)
440 single particle states (n l j m) | 0 1 1 0 0 1 … >

Let's look at the data requirements in more detail

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Consider ^{12}C, $N_{max}=8$

M-scheme dimension 0.6 billion

55 single-particle orbits (n l j)
440 single particle states (n l j m) | 0 1 1 0 0 1 … >

= minimum # of qubits needed (probably more)

Let's look at the data requirements in more detail

SAN DIEGO STATE UNIVERSITY

Consider ^{12}C, N_{max}=8

M-scheme dimension 0.6 billion

J-coupled 2-body matrix elements: ~ 1.5 million

$< a\ b\ J\ |\ H\ |\ c\ d\ J >$

uncoupled 2-body matrix elements ~ 10 million

$V_{ijkl}\, a^+_i\, a^+_j\, a_l\, a_k$

many-body matrix elements: ~ 1.2 trillion
(or 5 Tb storage)

Let's look at the data requirements in more detail

SAN DIEGO STATE UNIVERSITY

Consider ^{12}C, N_{max}=8

M-scheme dimension 0.6 billion *by superposition*

~~# *J-coupled 2-body matrix elements*: ~ 1.5 million~~
~~< a b J | H | c d J >~~ *input*

 # uncoupled 2-body matrix elements ~ 10 million! $\mathbf{V_{ijkl}\; a^{+}_{i}\; a^{+}_{j}\; a_{l}\; a_{k}}$ = # 'Pauli strings'

~~# *many-body matrix elements:* ~ 1.2 trillion~~
~~(or 5 Tb storage)~~ *not relevant?*

Let's look at the data requirements in more detail

Consider ^{12}C, $N_{max}=8$

M-scheme dimension 0.6 billion *by superposition*

***# uncoupled 2-body matrix elements* ~ 10 million!** $\mathbf{V_{ijkl}\ a^{+}_{i}\ a^{+}_{j}\ a_{l}\ a_{k}}$ = # 'Pauli strings'
= # of terms to be evaluated in a quantum circuit
(or, # of separate quantum circuits to be evaluated!)

A 'Pauli string' is a set of operations (σ_x, σ_y, σ_z, I) applied to each qubit. In quantum computing one uses the notation (X, Y, Z, I)

So a Pauli string is something like

$I_1 \, I_2 \, I_3 \, X_4 \, X_5 \, I_6 \, Z_7 \, X_8 \, \ldots$

which encodes a string of operations on each qubit; or, a string of operations to be measured (i.e. for a Hamiltonian).

This is related to Jordan-Wigner and other mappings

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We're still a long ways from catching the car we want!

Lessons learned

San Diego State University

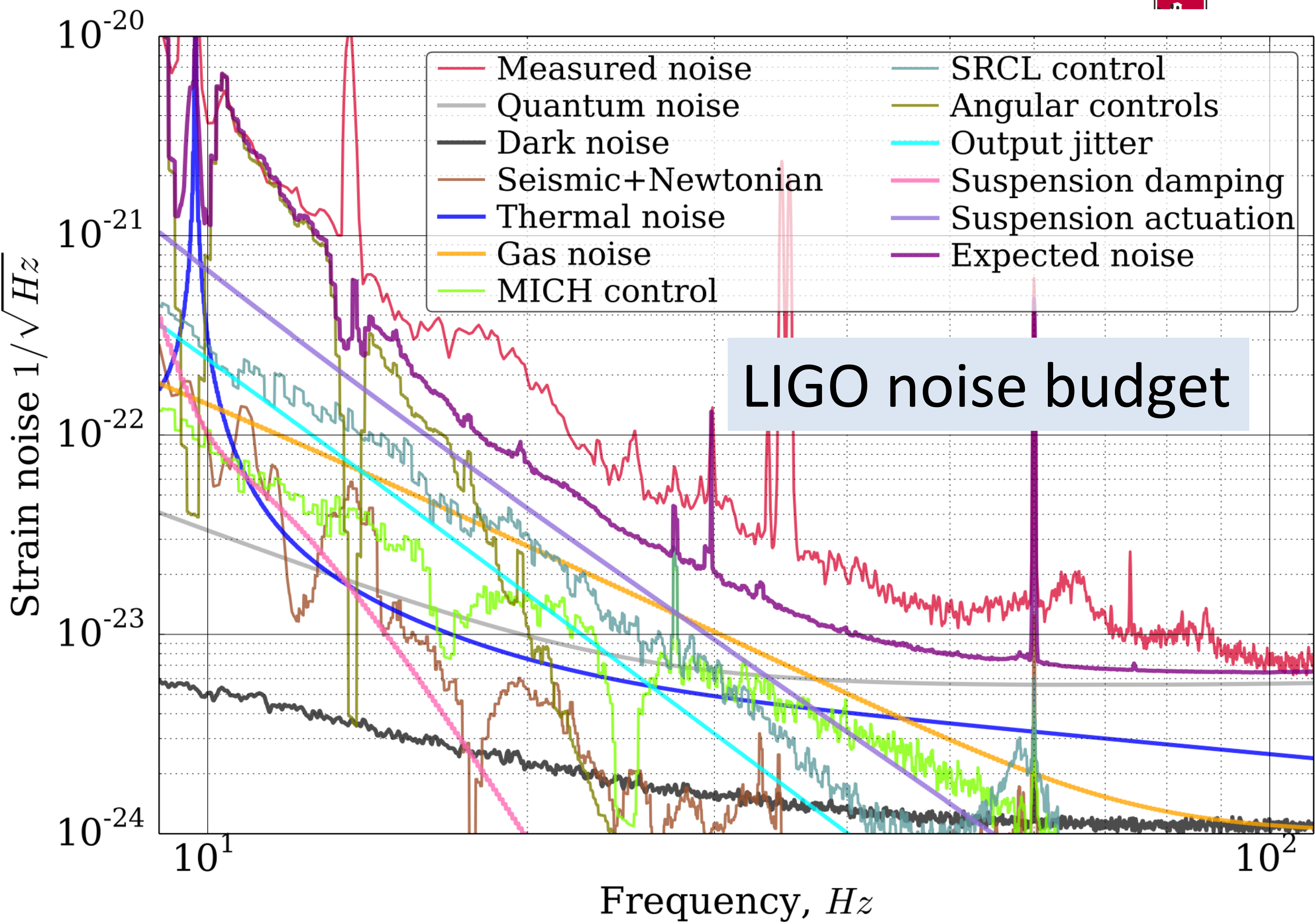
Quantum computing requires a new way of thinking—how to use unitary transformation as the basis for *processing*

Not only that, but to get an answer, one needs to run a quantum circuit a large number of times to measure the probabilities.

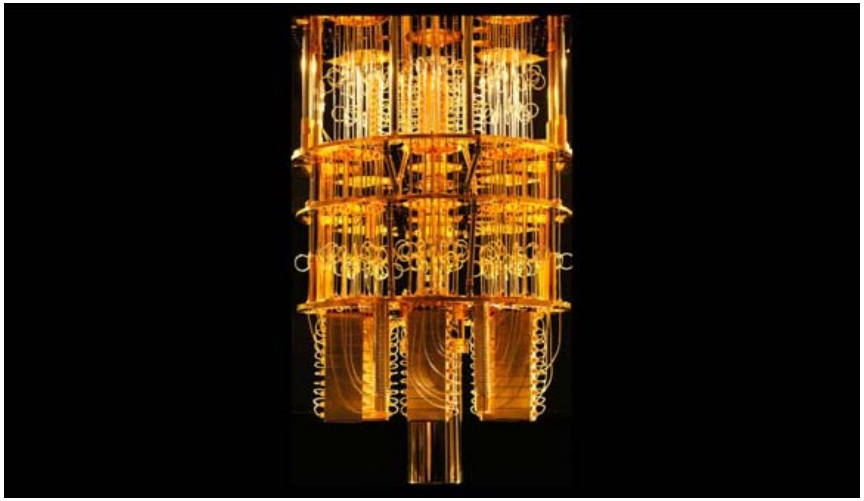
Noise and noise mitigation remains a huge issue, even in small cases

To tackle problems our community cares about, we will need on the order of > $10^{5\text{-}7}$ logical qubits (with error correction, $10^{6\text{-}9}$ physics qubits)

Nonetheless, science has stared down seemingly insurmountable challenges before



LIGO noise budget
Measured noise
Quantum noise
Dark noise
Seismic+Newtonian
Thermal noise
Gas noise
MICH control
SRCL control
Angular controls
Output jitter
Suspension damping
Suspension actuation
Expected noise
Strain noise $1/\sqrt{Hz}$
Frequency, Hz
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}



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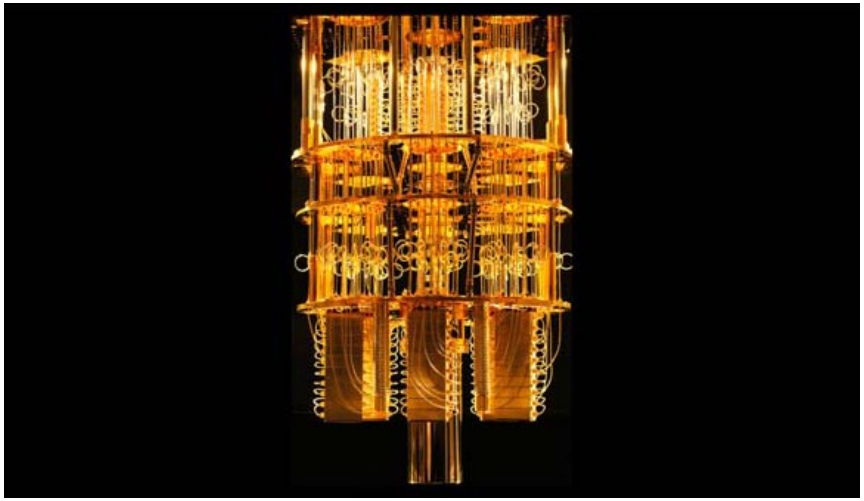

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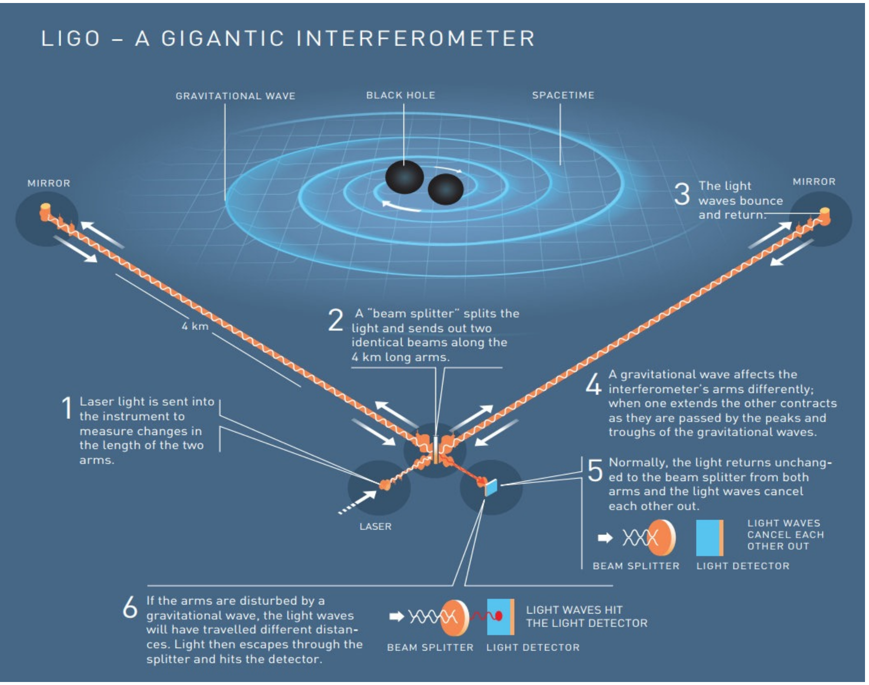
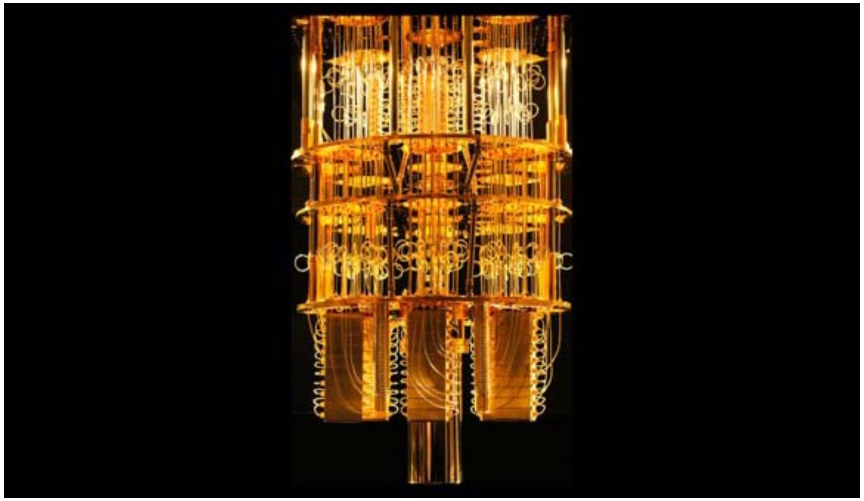


LIGO – A GIGANTIC INTERFEROMETER
GRAVITATIONAL WAVE
BLACK HOLE
SPACETIME
MIRROR
MIRROR
3 The light waves bounce and return.
4 km
2 A "beam splitter" splits the light and sends out two identical beams along the 4 km long arms.
1 Laser light is sent into the instrument to measure changes in the length of the two arms.
4 A gravitational wave affects the interferometer's arms differently; when one extends the other contracts as they are passed by the peaks and troughs of the gravitational waves.
5 Normally, the light returns unchanged to the beam splitter from both arms and the light waves cancel each other out.
LASER
LIGHT WAVES CANCEL EACH OTHER OUT
BEAM SPLITTER
LIGHT DETECTOR
6 If the arms are disturbed by a gravitational wave, the light waves will have travelled different distances. Light then escapes through the splitter and hits the detector.
LIGHT WAVES HIT THE LIGHT DETECTOR
BEAM SPLITTER
LIGHT DETECTOR



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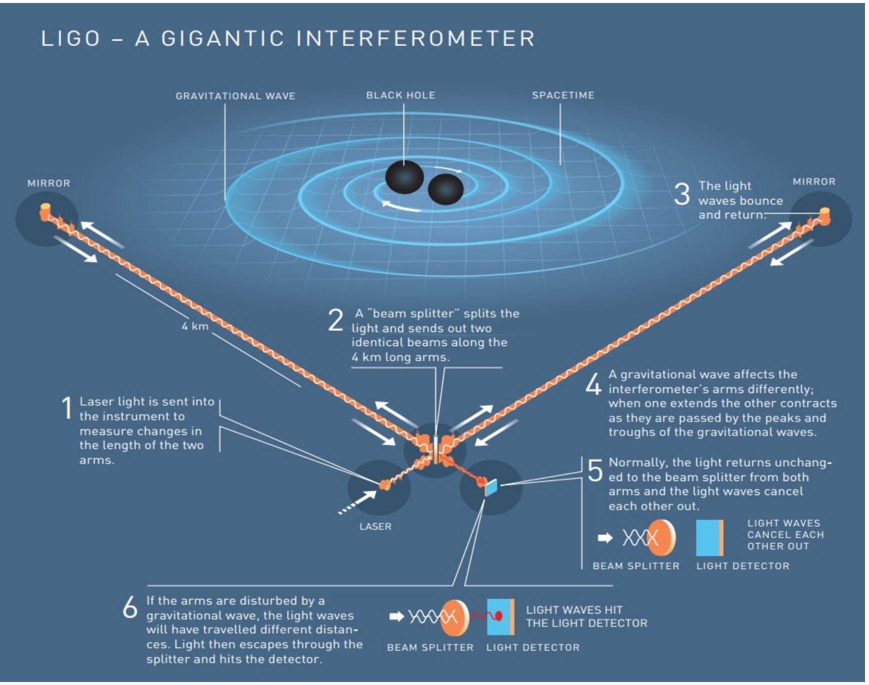
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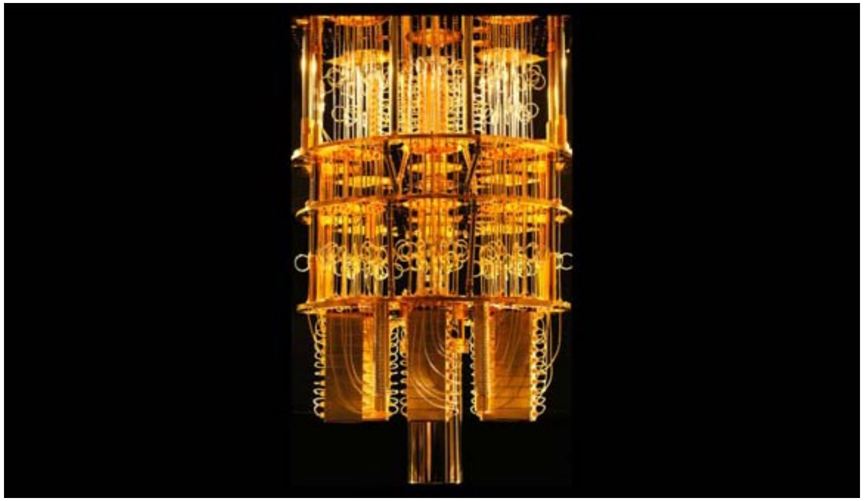

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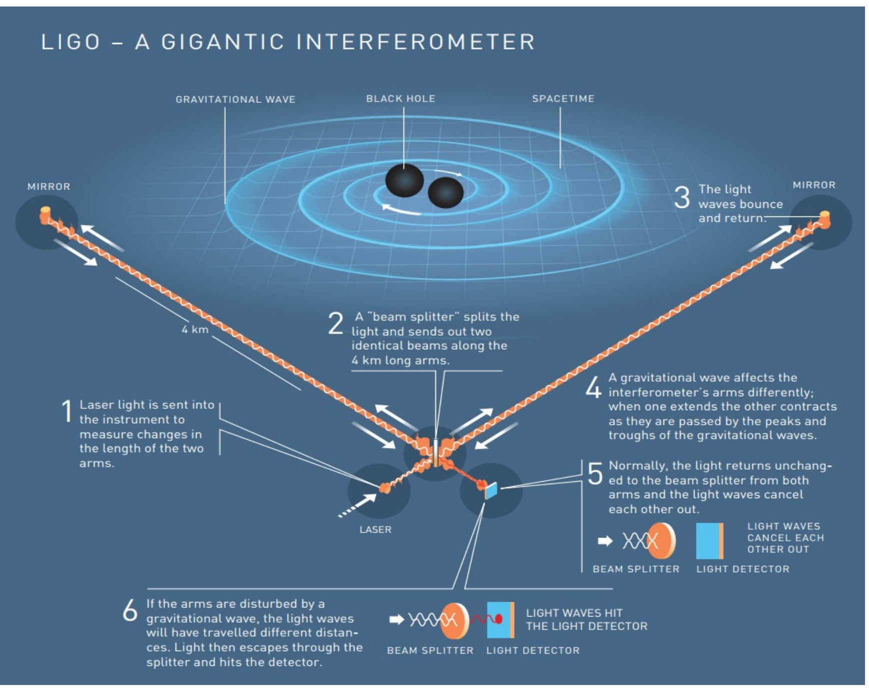

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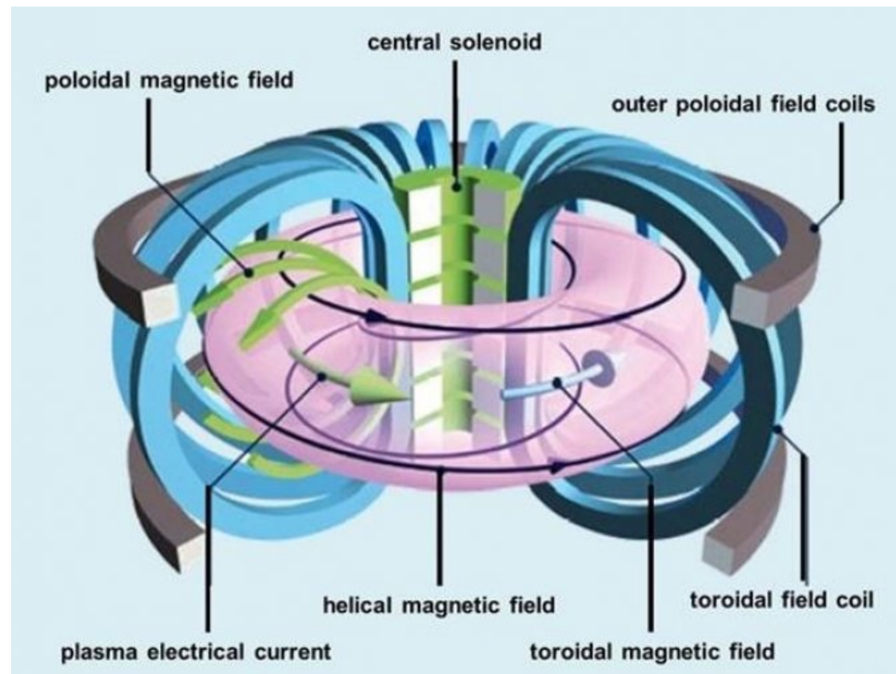

central solenoid
poloidal magnetic field
outer poloidal field coils
helical magnetic field
toroidal field coil
plasma electrical current
toroidal magnetic field

Next steps

VQE becomes more challenging as the # of qb increase.

Hence we are trying the following:

* ‘Generator coordinate’ for Lipkin (MS thesis of Kris McBrian, being written up now)

- proton—neutron Lipkin model (project of Ph.D student Antonio Cobarrubia)-– requires projection of good particle number, toy model for β, ββ decay.

* Looking at `real-time quantum Lanczos’ (MS thesis of Amanda Bowman in collaboration with Ionel Stetcu of LANL) applied to p-shell nuclides

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Hvala vam!