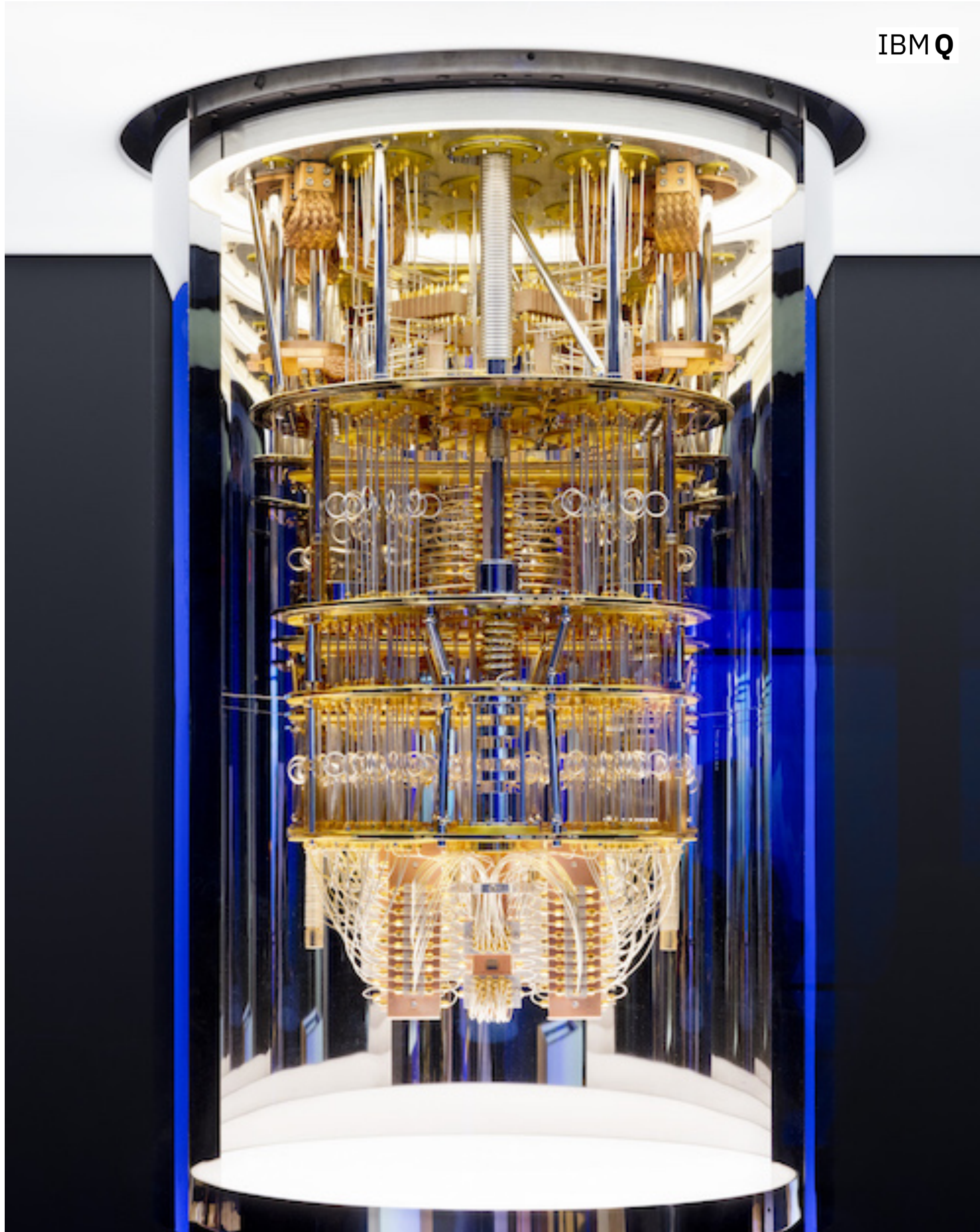
Simulating real-time dynamics of hard probes in nuclear matter on a quantum computer

James Mulligan

Lawrence Berkeley National Laboratory



arXiv: 2010.03571

Wibe de Jong
Mekena Metcalf — *LBNL (Quantum Information)*

James Mulligan
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Felix Ringer — *LBNL (Nuclear Science)*

Xiaojun Yao — *MIT (Nuclear Theory)*

BERKELEY LAB

Particle-Astro-Nuclear Seminar
Wayne State University
Nov 6 2020

Outline

Hard probes in the quark-gluon plasma

Open quantum systems in heavy-ion collisions

Quantum simulation with IBM Q

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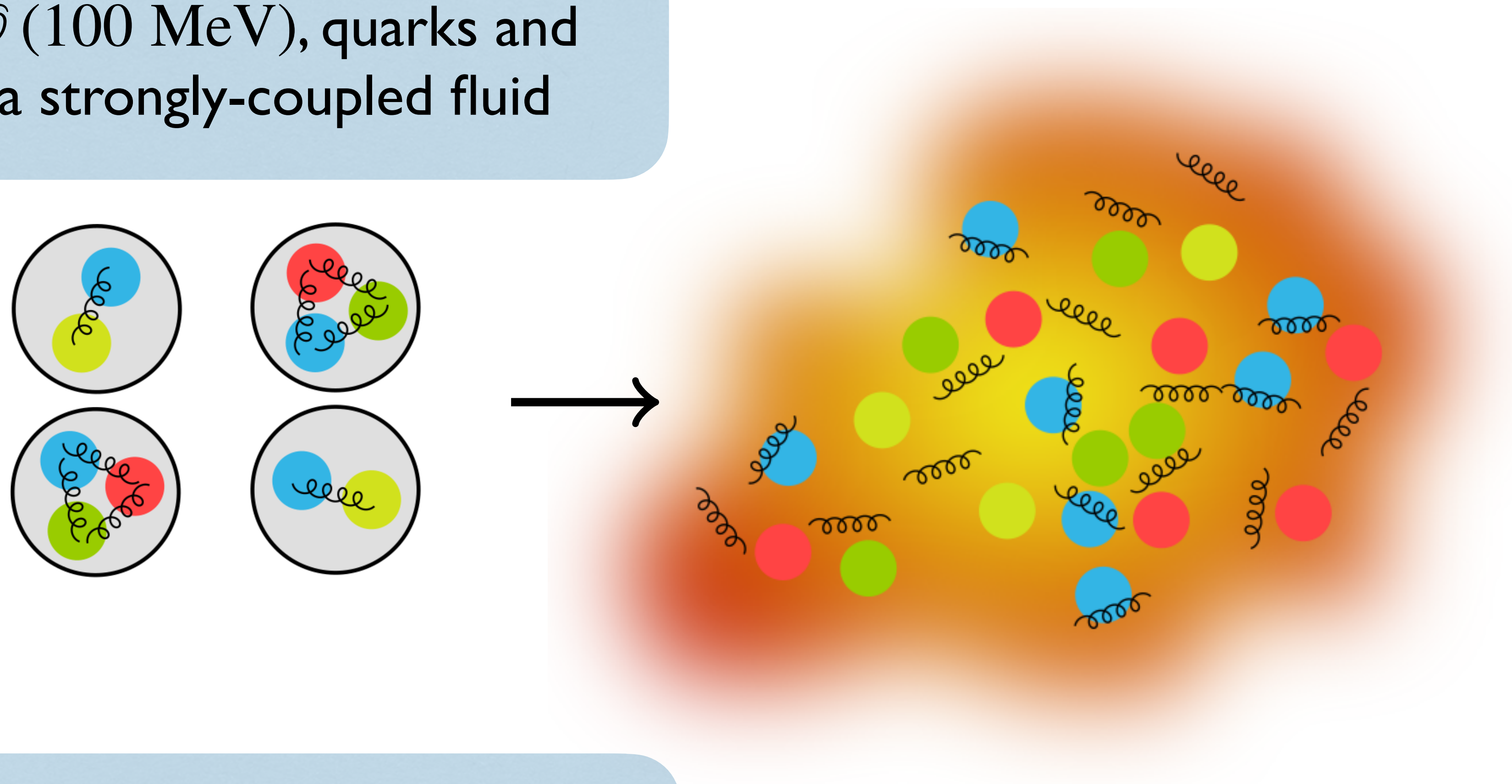
The quark-gluon plasma

If we heat nuclear matter to $T = \mathcal{O}(100\ \mathrm{MeV})$, quarks and gluons become **deconfined** into a strongly-coupled fluid



The quark-gluon plasma is a laboratory to understand how complex properties arise from Quantum Chromodynamics

How does this strongly-coupled fluid emerge from the Lagrangian?

Does deconfined QCD have quasi-particle structure?

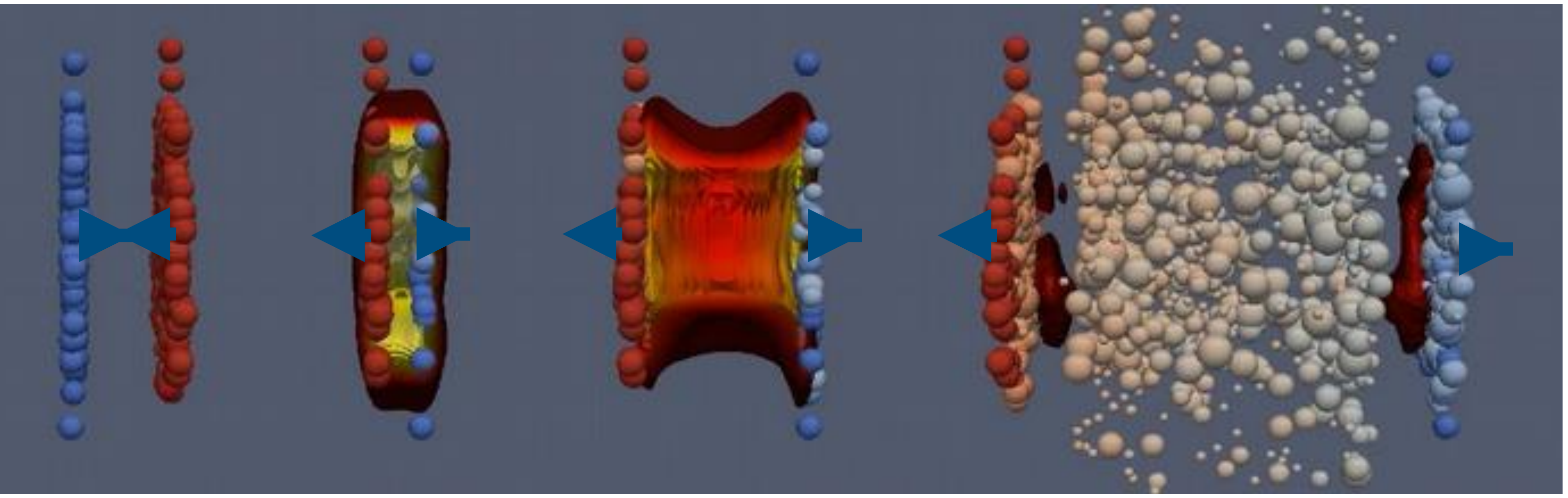
How does color confinement emerge?

Heavy-ion collisions

We collide nuclei at

Large Hadron Collider (LHC)
Relativistic Heavy Ion Collider (RHIC)

to produce a hot, dense state of matter known as the quark-gluon plasma

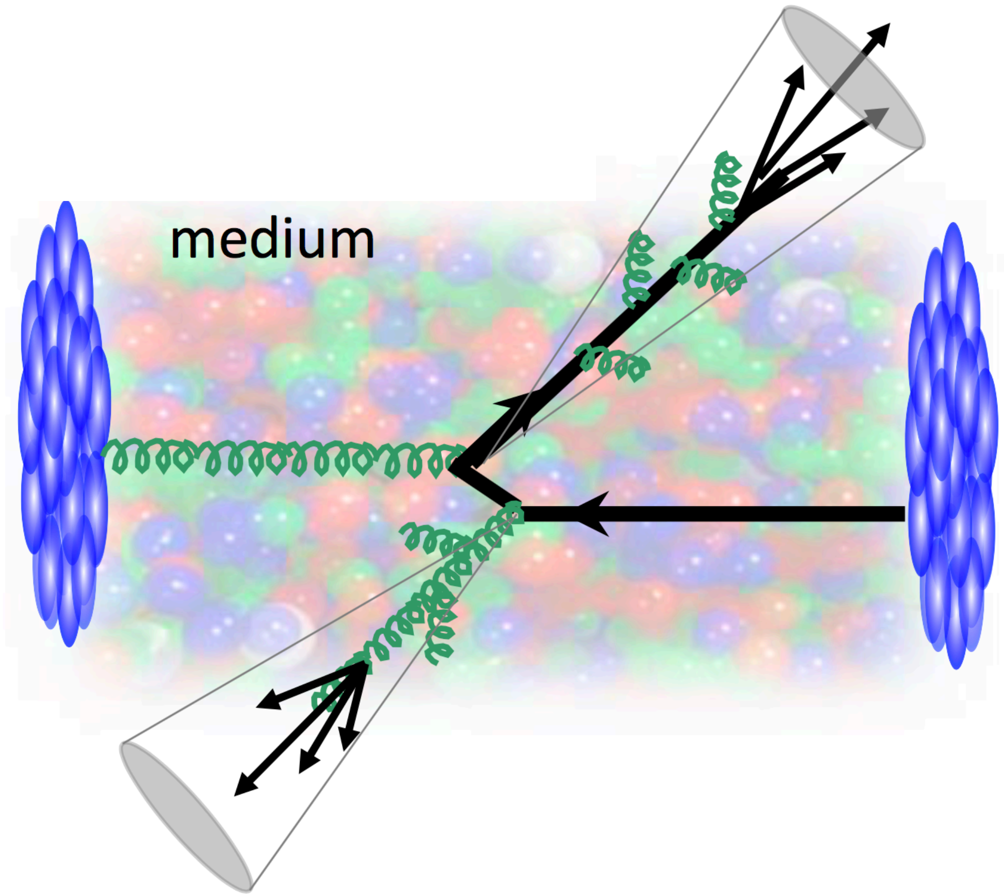


Soft collisions transform kinetic energy of nuclei into region of **large energy density** for $t \sim \mathcal{O}\left(10 \text{ fm}/c\right)$

Hard probes of the quark gluon plasma

In addition to soft scatterings, there are occasional **hard scatterings (large-Q^2)** in the collisions

- Highly energetic particles: **jets**
- Large mass particles: **heavy quarks**



These "hard probes" interact with the quark-gluon plasma as they traverse it

- By modeling these interactions, we hope to determine the structure of the QGP

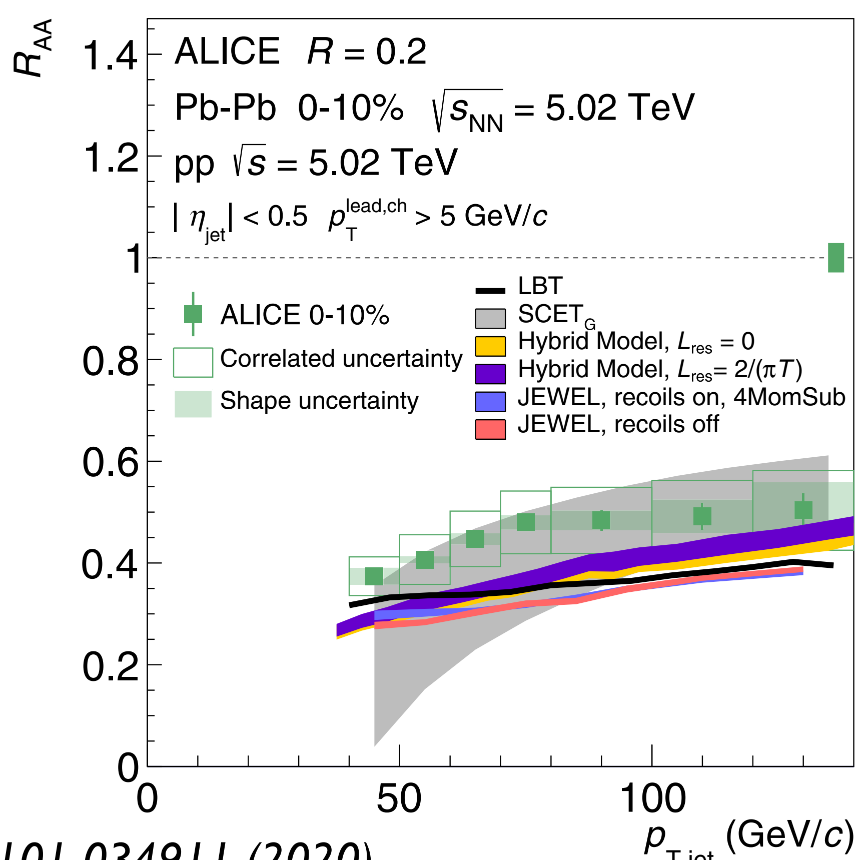
Hard probes — experiment

Experiments measure how cross-sections of hard probes are modified in heavy-ion collisions compared to proton-proton collisions

$$R_{\mathrm{AA}} = \frac{\mathrm{d}\sigma^{\mathrm{PbPb}}}{\langle T_{\mathrm{AA}} \rangle \, \mathrm{d}\sigma^{pp}}$$

Jets

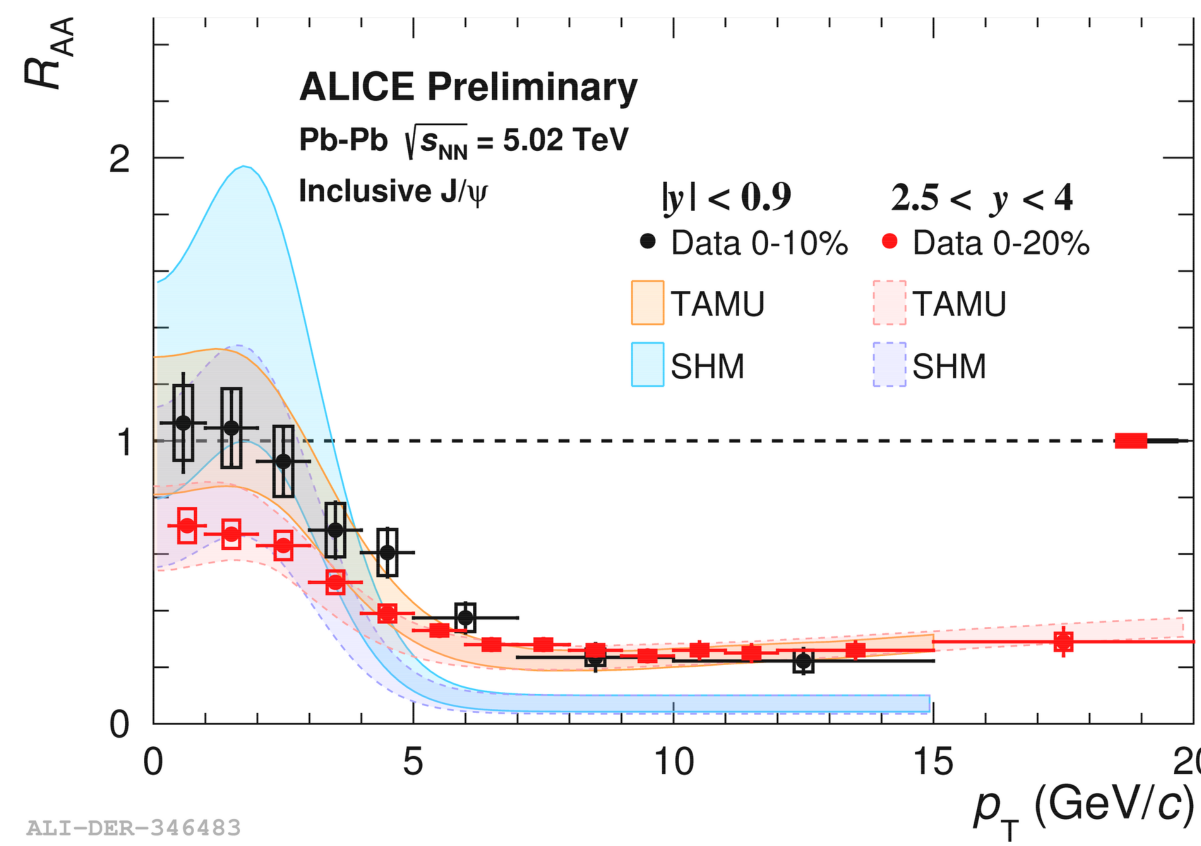
Jet yields are suppressed due to "energy loss" to the dense medium



PRC 101 034911 (2020)

Heavy quarks

Heavy quark bound pairs (quarkonium) are "melted" by the hot medium

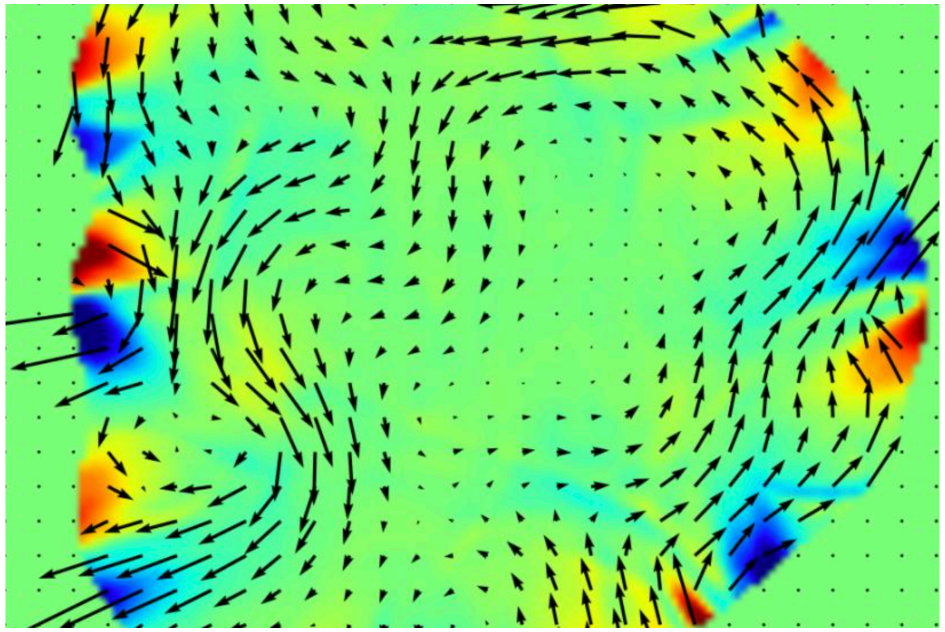


Hard probes — theory

In vacuum: calculate scattering of asymptotic states using perturbative QCD

Note that there is no sense of "time evolution"

In medium: must combine probe evolution with hydrodynamic evolution of the QGP



X.N. Wang

In heavy-ion collisions, the modifications of the probe due to its evolution through the QGP are typically put in "by hand", rather than a true real-time evolution

Medium-modified parton shower

see e.g. Majumder PRC 88 (2013)

Real-time evolution

Is there a way we can compute real-time evolution in QCD?

One could think to use **lattice QCD** to numerically solve for the modification of the probe

see e.g. Kumar, Majumder, Weber 2010.14463 (2020)

However, lattice QCD encounters a **sign problem** $\int e^{i\mathscr{L}t}$

which is typically alleviated by solving in Euclidean time $t \to it$

(i.e. not real-time evolution)

But **quantum computing** offers a way to do real-time evolution!

→ Hamiltonian formulation of QCD

see e.g. Preskill `18

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Hard probes in the quark-gluon plasma

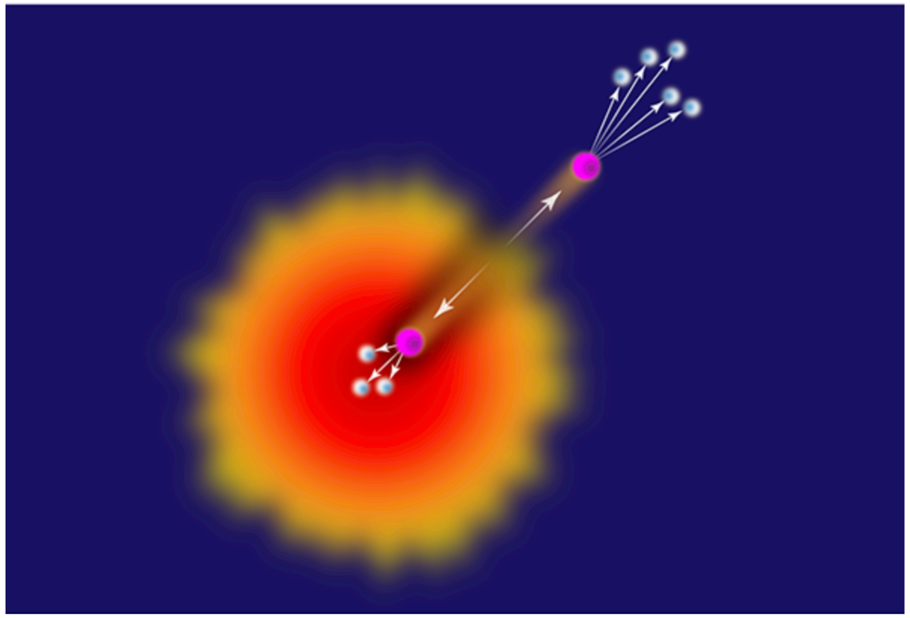
Open quantum systems in heavy-ion collisions

Quantum simulation with IBM Q

Open quantum systems and the nuclear medium

Study the real time dynamics of the quantum evolution of probes in the nuclear medium (LHC/RHIC/EIC)

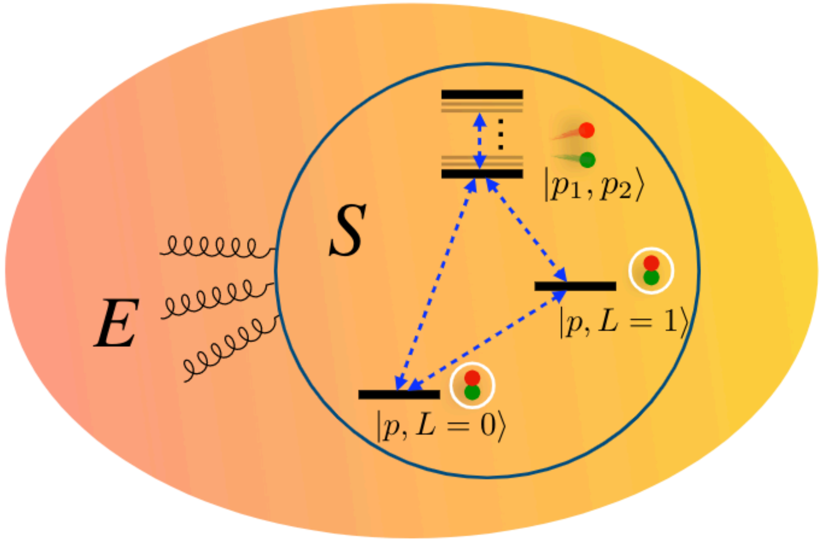
In principle one could solve for the entire QGP evolution
But here we focus on simulating the probe



System - Jet/heavy-flavor

Environment - Nuclear matter

$$H(t) = H_S(t) + H_E(t) + H_I(t)$$



Akamatsu, Rothkopf `12-`20, Müller et al `18, Mehen, Yao `18, Qiu, Ringer, Sato, Zurita `19, Vaidya, Yao `20

Open quantum systems and the nuclear medium

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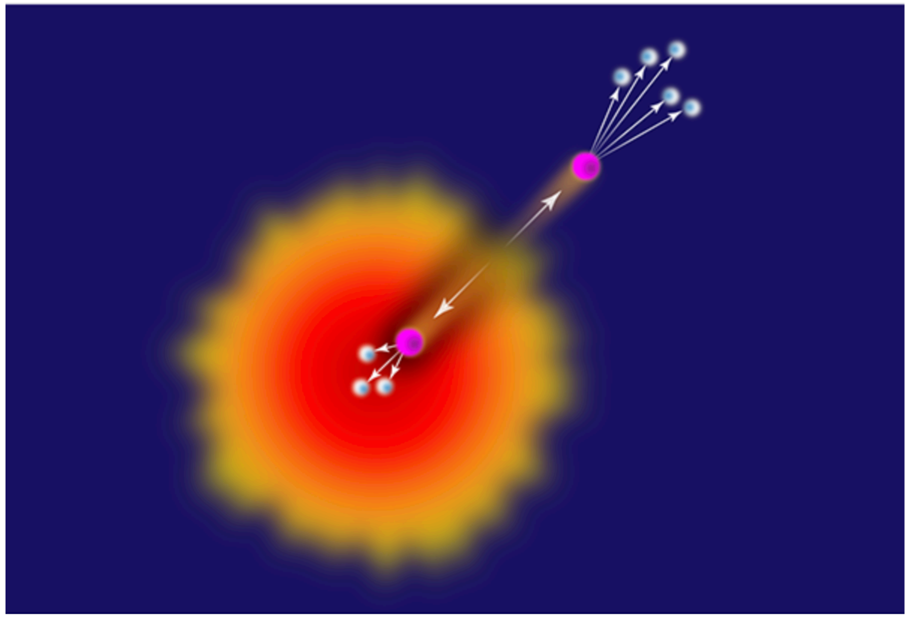

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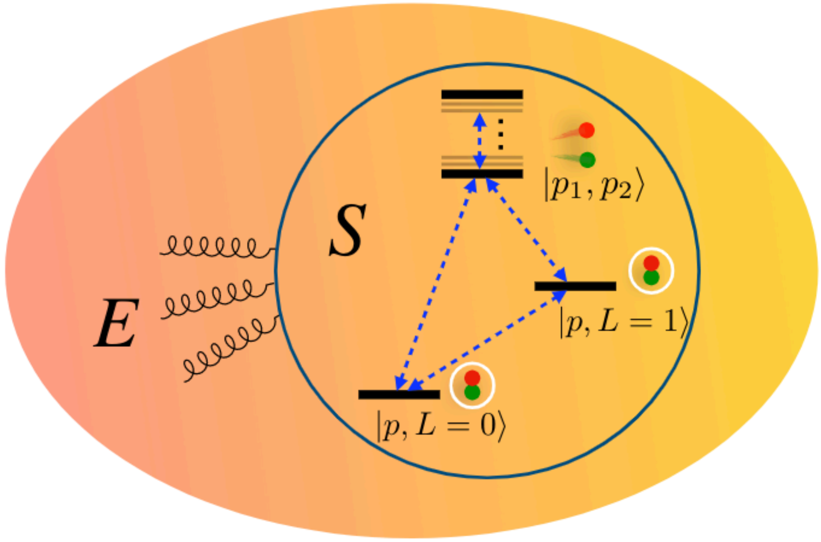

The time evolution is governed by the von Neumann equation:

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho^{(\mathrm{int})}(t) = -i\left[H_I^{(\mathrm{int})}(t), \rho^{(\mathrm{int})}(t)\right]$$

Akamatsu, Rothkopf `12-`20, Müller et al `18, Mehen, Yao `18, Qiu, Ringer, Sato, Zurita `19, Vaidya, Yao `20

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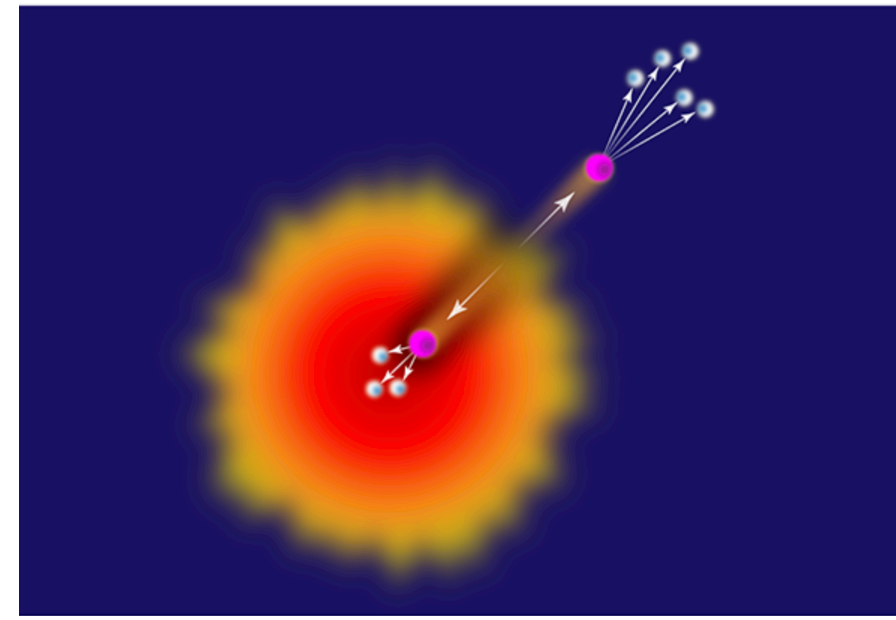

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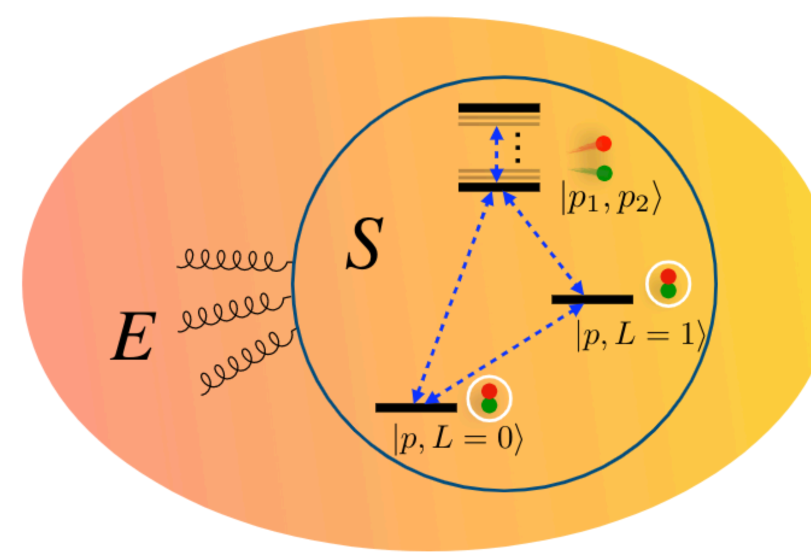


In the Markovian limit, the subsystem is described by a **Lindblad equation**

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_S = -i\,[H_S, \rho_S] + \sum_{j=1}^{m}\left(L_j\rho_S L_j^\dagger - \frac{1}{2}L_j^\dagger L_j\rho_S - \frac{1}{2}\rho_S L_j^\dagger L_j\right)$$

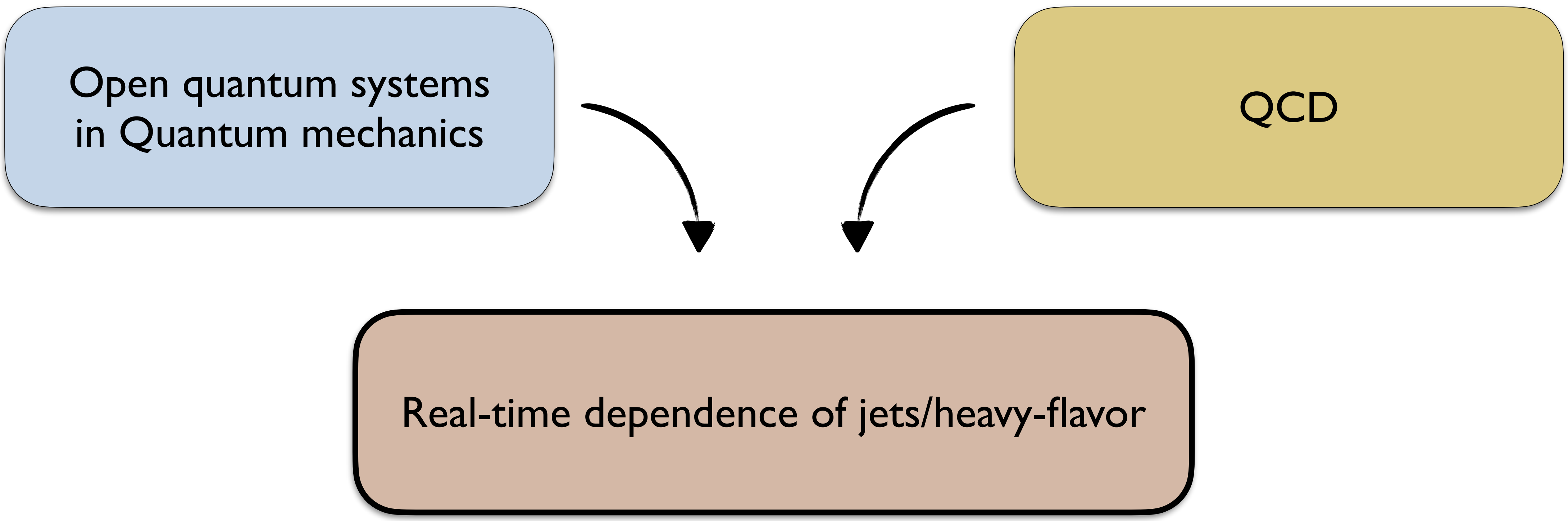
$$\rho_S = \mathrm{tr}_E[\rho]$$

See also e.g. non-global logs and CGC

Neill `15, Armesto et al. `19, Li, Kovner `20

Akamatsu, Rothkopf `12-`20, Müller et al `18, Mehen, Yao `18, Qiu, Ringer, Sato, Zurita `19, Vaidya, Yao `20

Open quantum systems and the nuclear medium



- Currently various approximations are considered *Blaizot, Escobedo `18, Yao, Mehen `18, `20*
  - Markovian limit
  - Small coupling of system and environment
  - Semi-classical transport

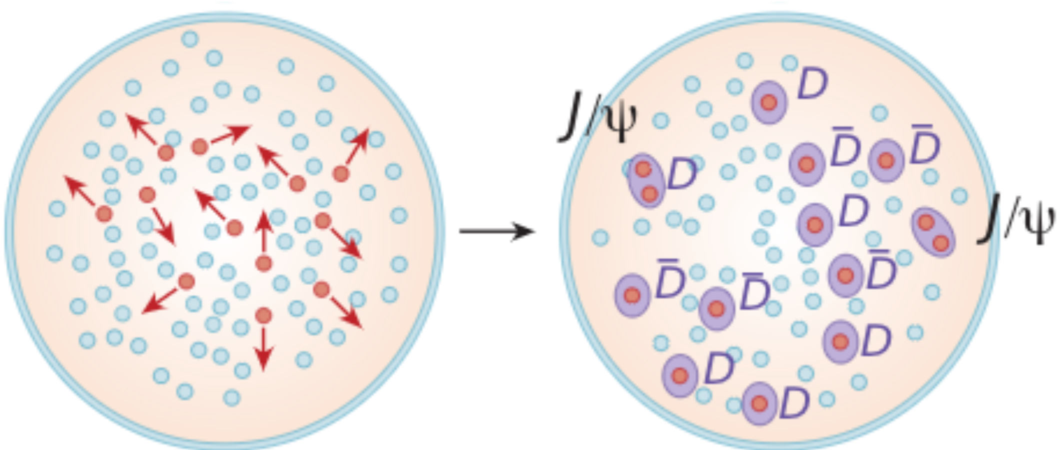
Akamatsu, Rothkopf et al. `12-`20, Brambilla et al. `17-`20
Yao, Mueller, Mehen `18-`20, Sharma, Tiwari `20
Yao, Vaidya `19, Vaidya `20

Quarkonium suppression

Open quantum system formalism for quarkonia

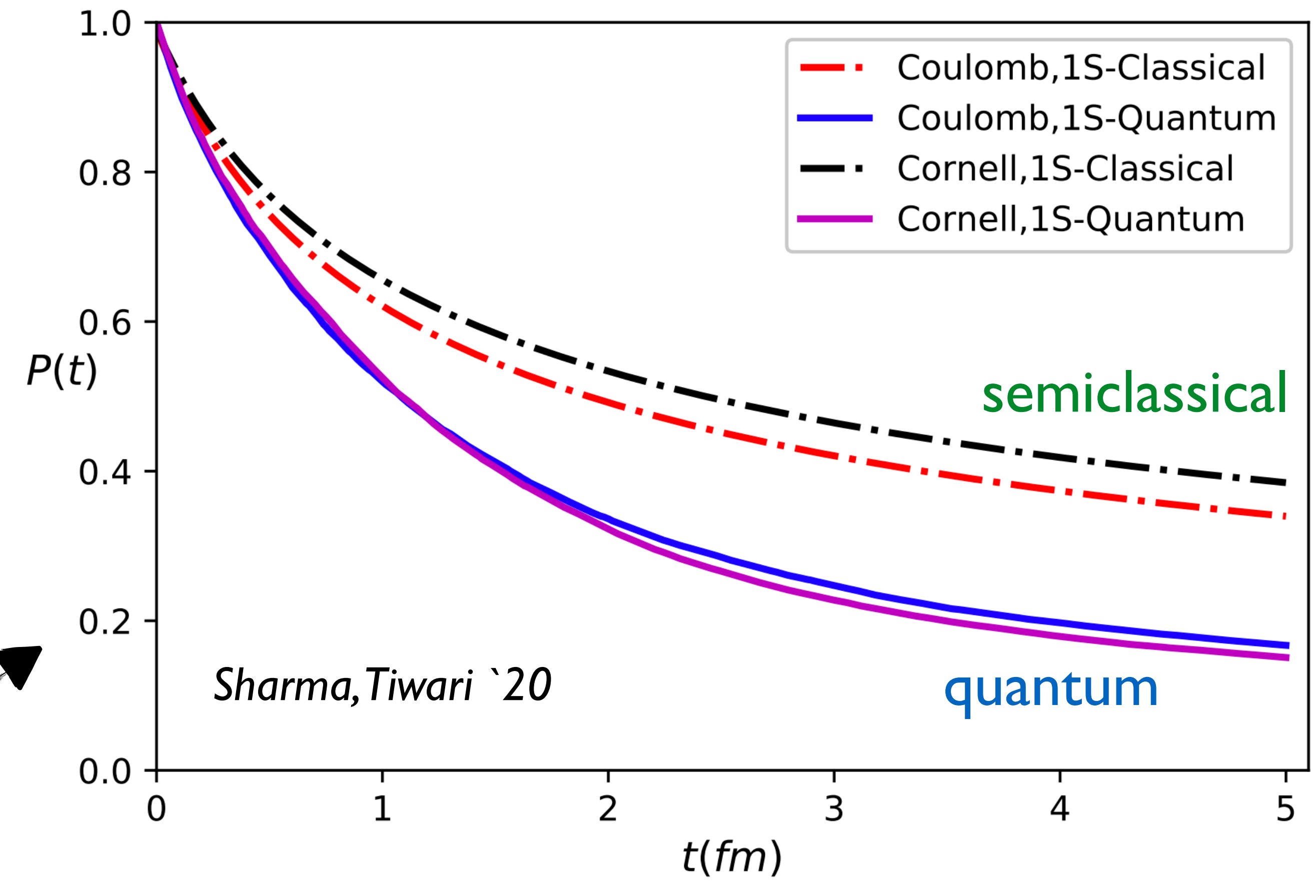
Akamatsu, Rothkopf et al. `12-`20, Brambilla et al. `17-`20
Yao, Mueller, Mehen `18-`20, Sharma, Tiwari `20

Quarkonium production in heavy-ion collisions



NRQCD + semiclassical approach compared to full quantum evolution

Survival probability of the vacuum state



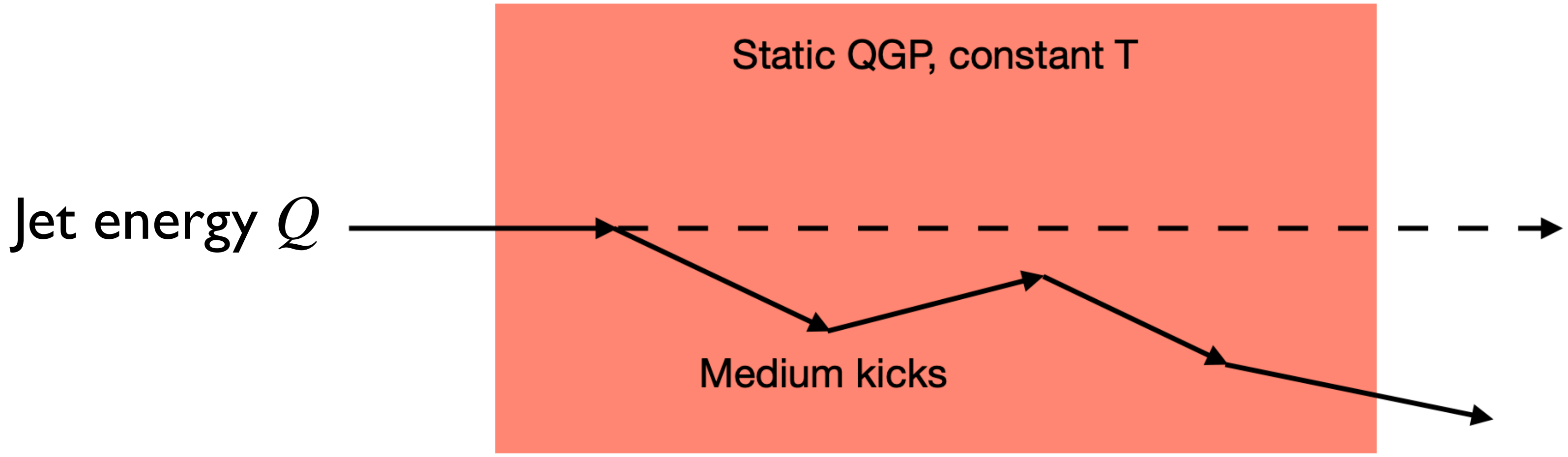
Bjorken expanding QGP $T_0 = 475\ \mathrm{MeV}$

Jet broadening

Open quantum system formalism for jets

Yao, Vaidya JHEP 10 (2020)

First steps in the direction of jet physics



Soft Collinear Effective Theory

- Forward scattering, Glauber gluon exchange

Markovian master equation describes evolution of jet density matrix:

$$\partial_t P(Q,t) = -R(Q)P(Q,t) + \int \widetilde{\mathrm{d}q} K(Q,q)P(q,t)$$

where the probability to be in a given momentum state is:

$$P(Q,t) = \langle Q|\rho_S(t)|Q\rangle$$

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Quantum computing

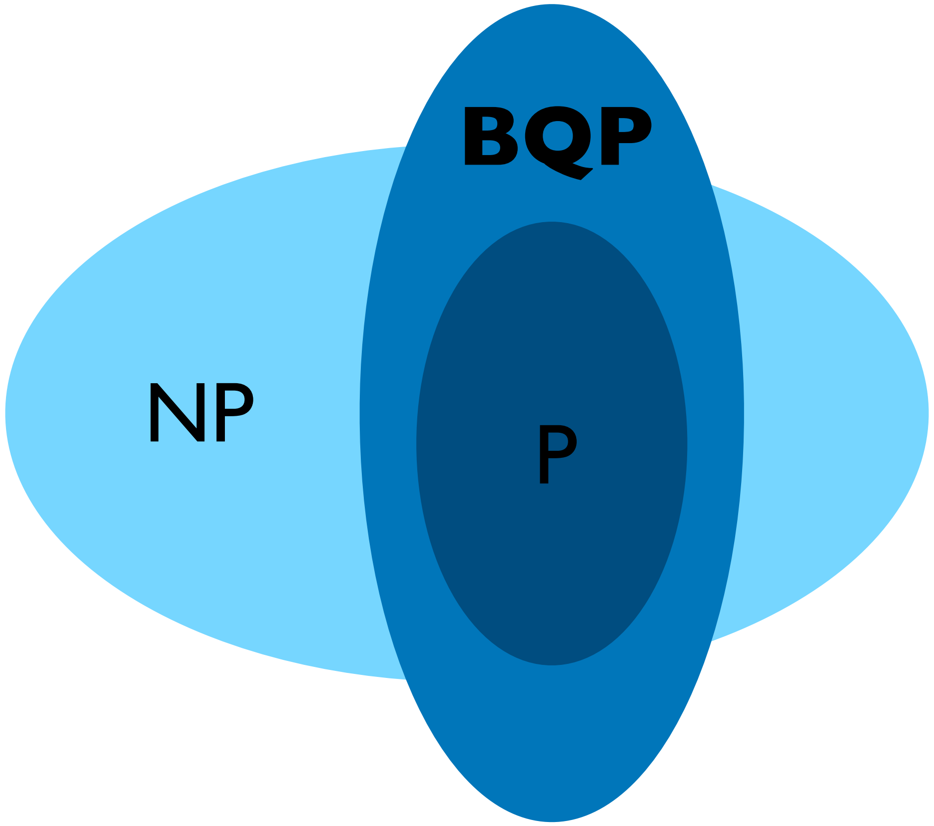
Superposition and entanglement

$$|\psi\rangle = \sum_{i=1}^{2^N} a_i \, |\psi_i\rangle$$

For N qubits, there are 2^N amplitudes

e.g. $|\psi\rangle = a_1|000\rangle + a_2|001\rangle + a_3|010\rangle + a_4|011\rangle + a_5|100\rangle + a_6|101\rangle + a_7|110\rangle + a_8|111\rangle$

If one can control this high-dimensional space, e.g. with appropriate interference of amplitudes, then one can potentially achieve **exponential speedup** of certain computations



It is expected that quantum computers can solve *some* classically hard problems with exponential speedup

These include a number of highly impactful problems such as quantum simulation

Quantum devices

Superconducting circuits

IBM Q

Google rigetti

…

And a variety of others…

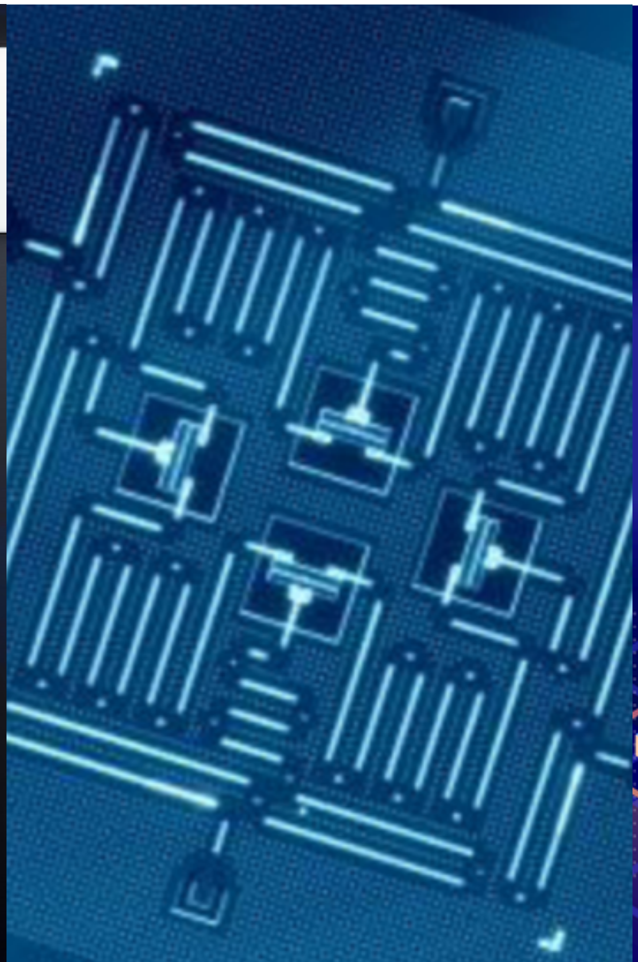
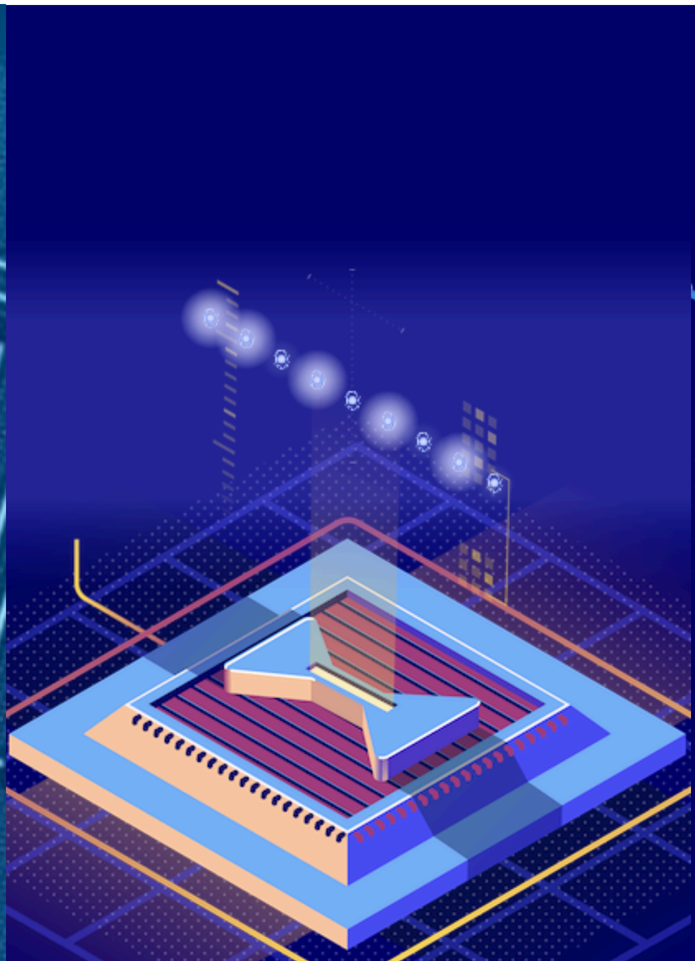
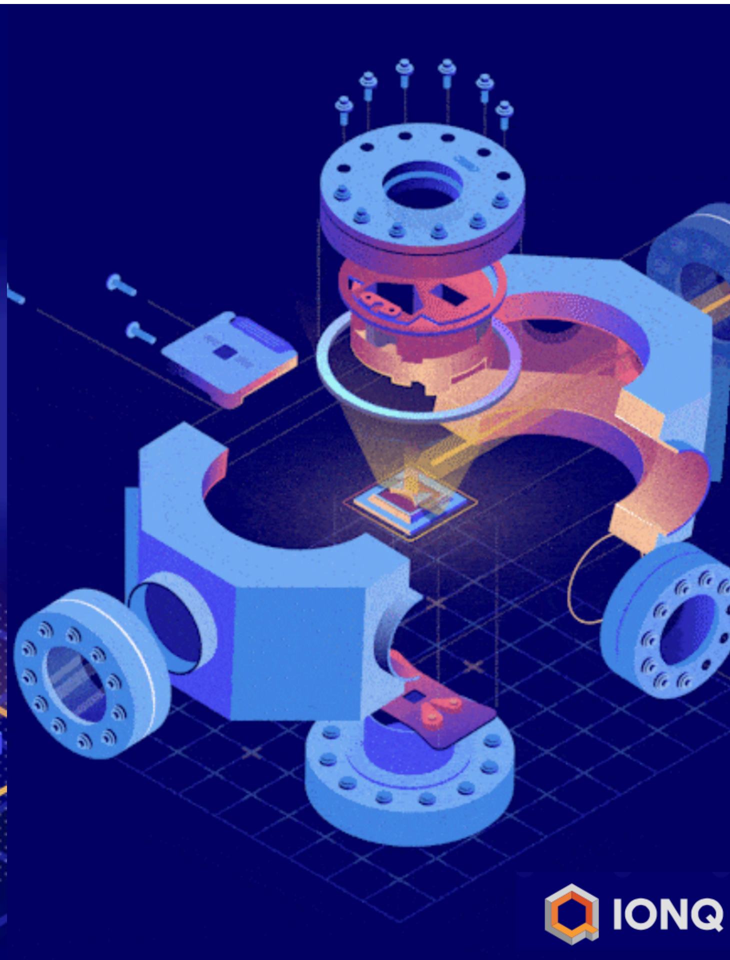
Trapped ions
Optical lattice
Photonics
Topological
…

IONQ

Honeywell

Ψ PsiQuantum

…

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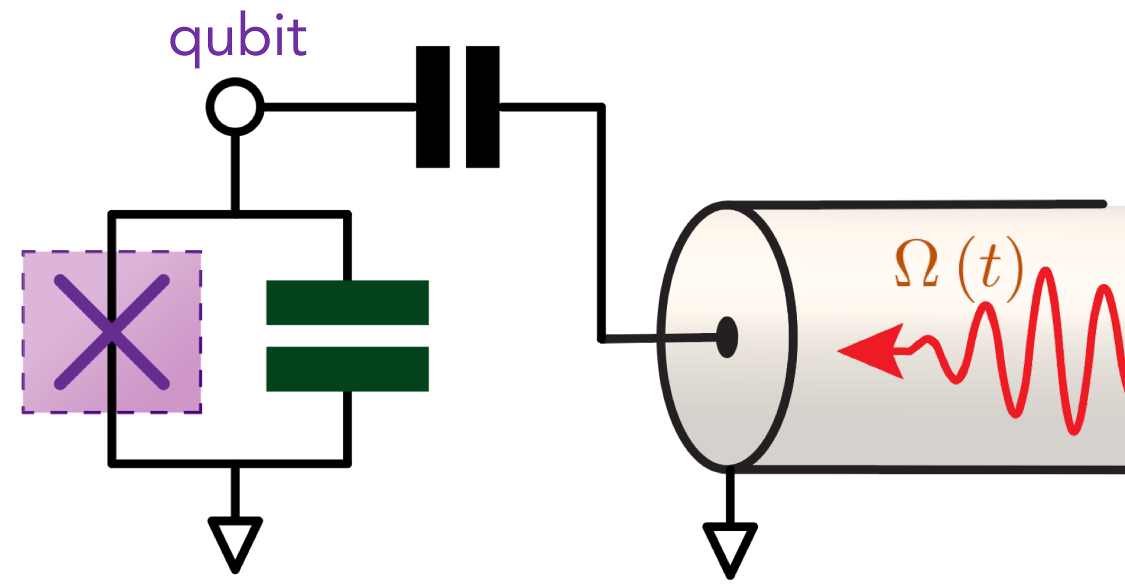
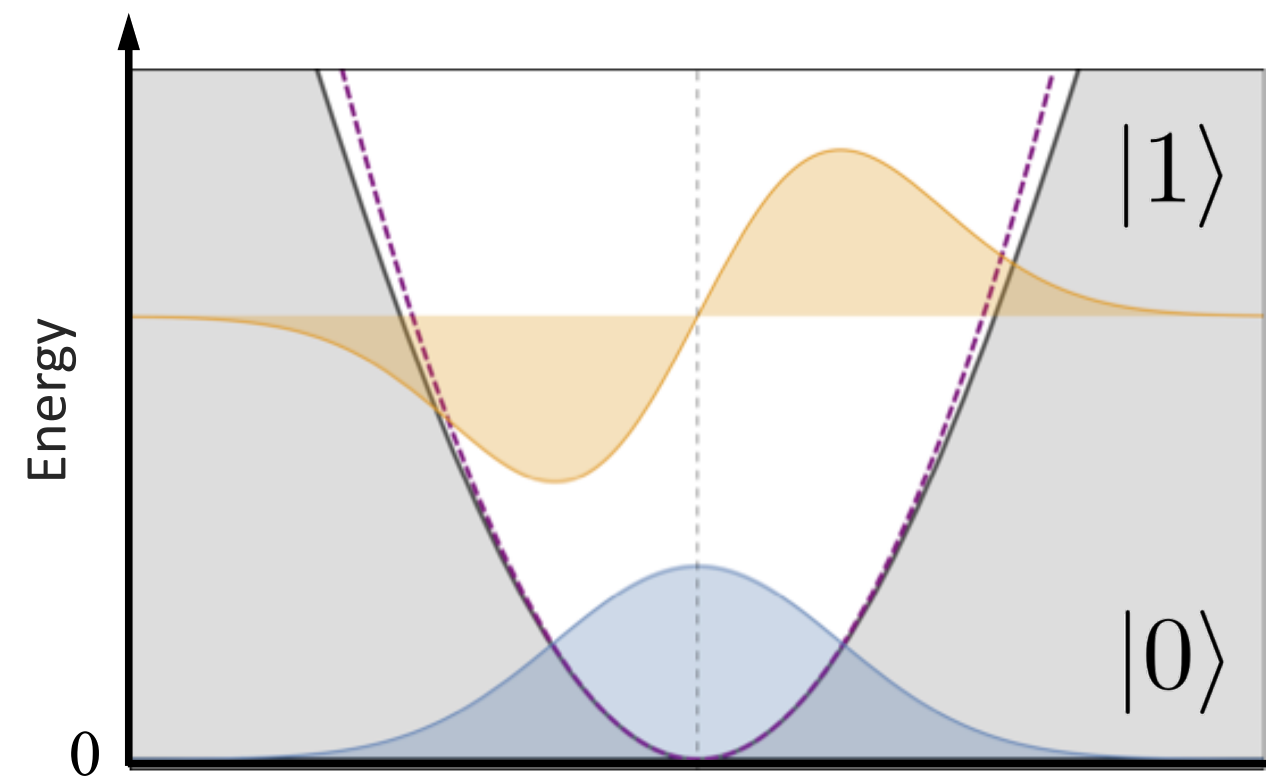


Qubits: Nonlinear quantum oscillator
Gates: coupled microwave pulses



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Quantum devices

Superconducting circuits

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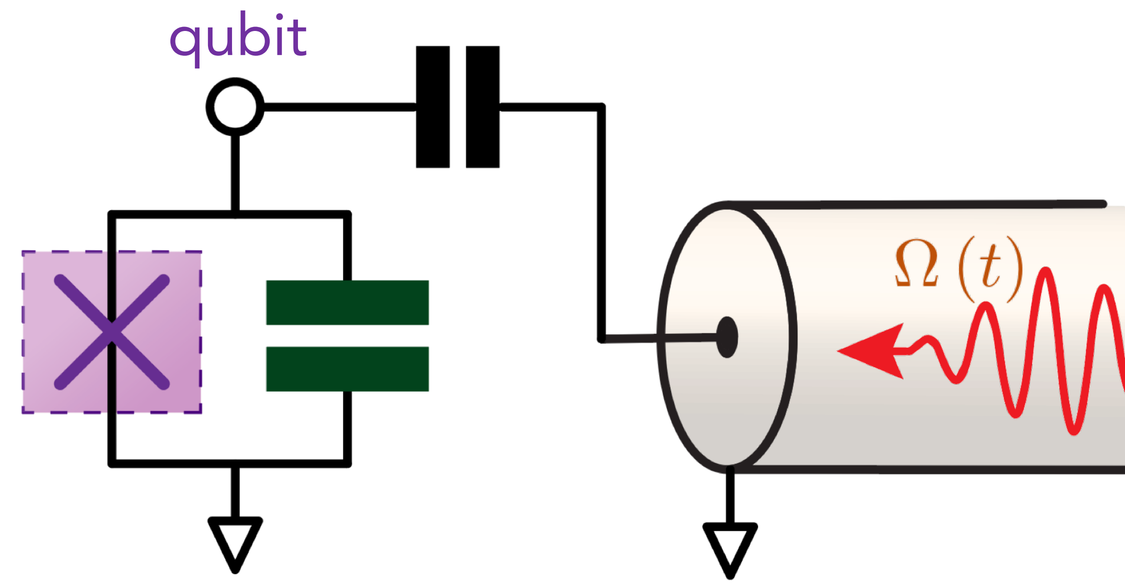
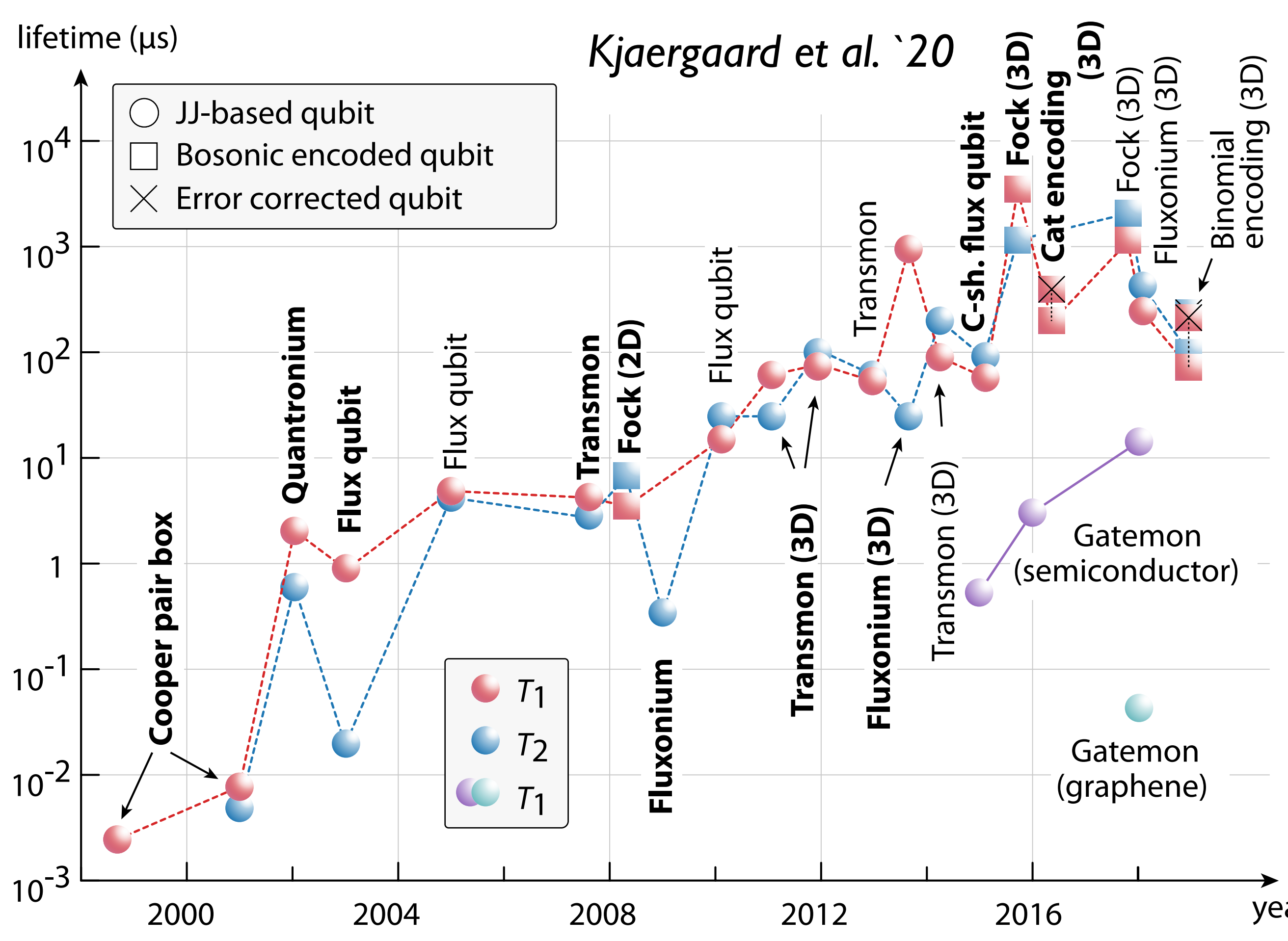


Qubit coherence times have become $\mathcal{O}\left(100\ \mu s\right)$, long enough to perform $\mathcal{O}\left(10-100\right)$ two-qubit operations



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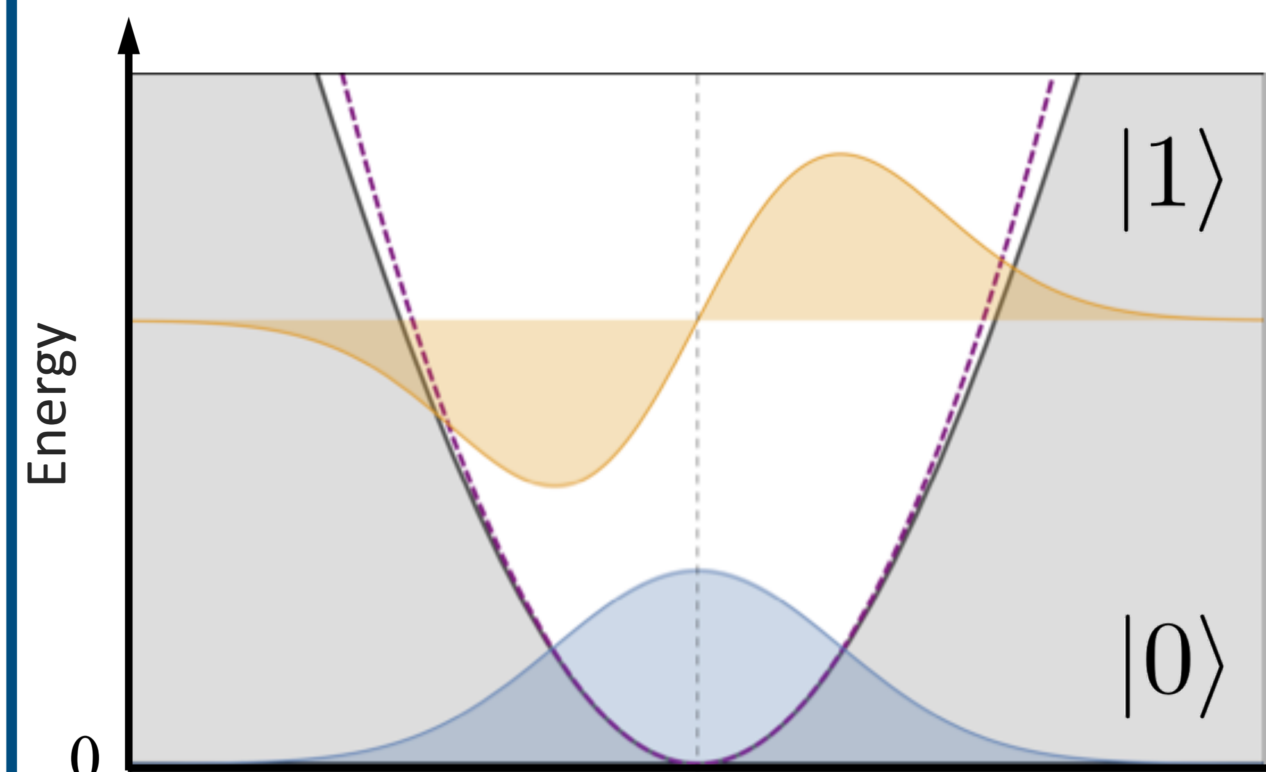

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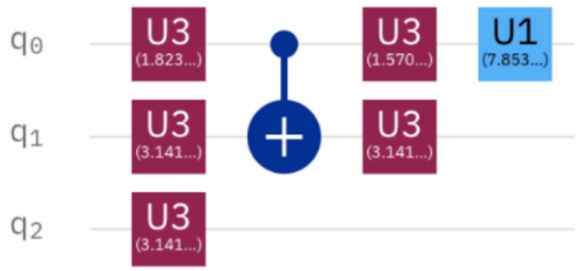
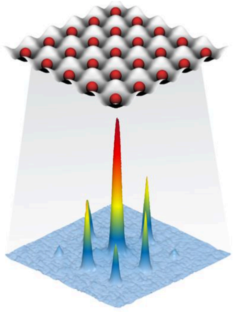
Quantum computing

Digital quantum computers Universal	**Analog quantum computers** Application-specific





Both will likely be useful in the "near"-term

The dream: universal, fault-tolerant digital quantum computer

Shor, Preskill, Kitaev, Zoller …

Noisy Intermediate Scale Quantum (NISQ) era

Decoherence, limited number of qubits, imperfect gates

Aim: achieve quantum advantage without full quantum error correction

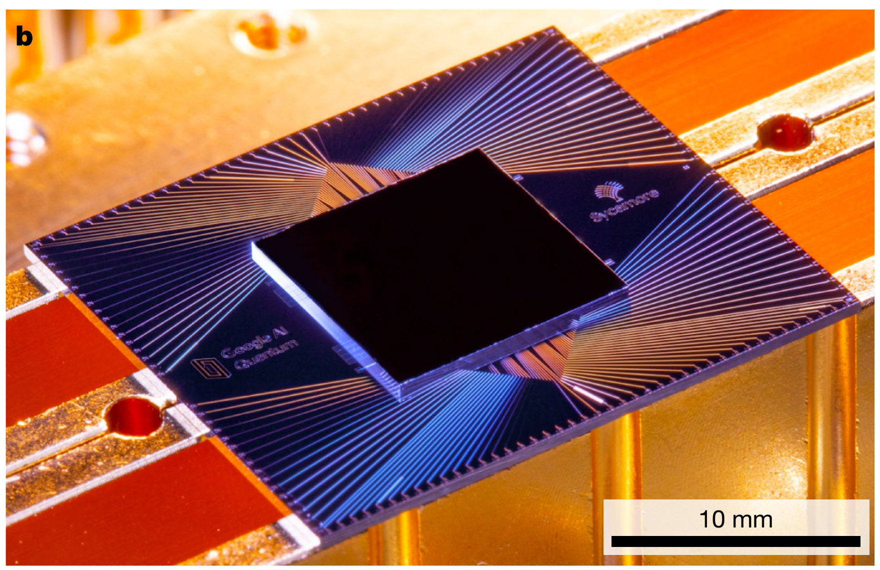
Experimentation and data analysis

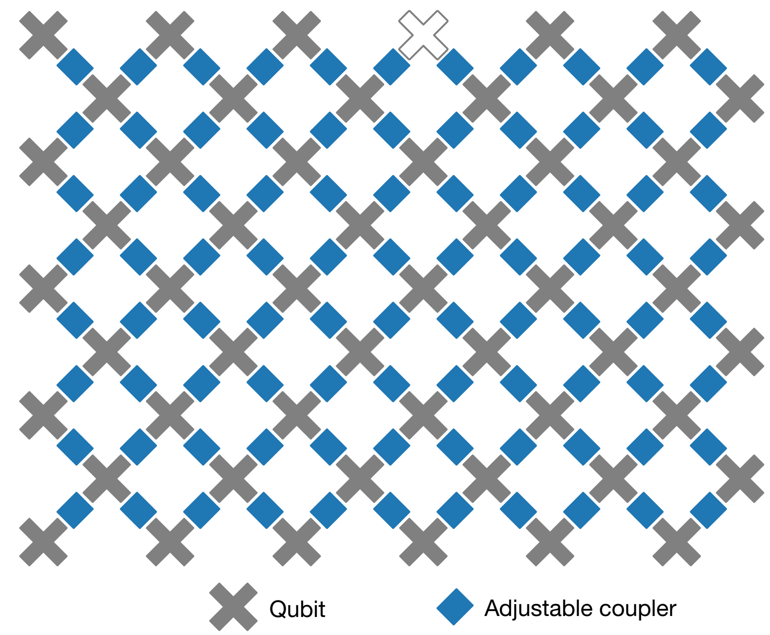
Quantum supremacy

Google
Martinis et al. `19

Article

Quantum supremacy using a programmable superconducting processor





53-qubit sycamore device
99%+ gate fidelities

Algorithm: sampling of random circuits

$\mathcal{O}\left(10^3\right)$ **times faster than best classical supercomputers**

Quantum simulation

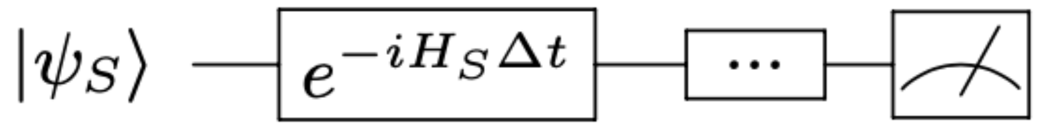
Feynman `81
Lloyd `96

It is exponentially expensive to simulate an N-body quantum system on a classical computer

2^N amplitudes!

But a quantum computer can naturally simulate a quantum system

State preparation
Time evolution
Measurement



Holds great promise for particle physics

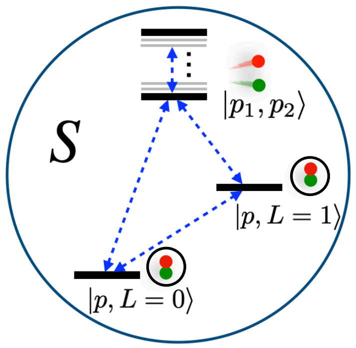
- Solve the **real-time dynamics** of QCD

  Go beyond lattice QCD limitations (static quantities — sign problem)

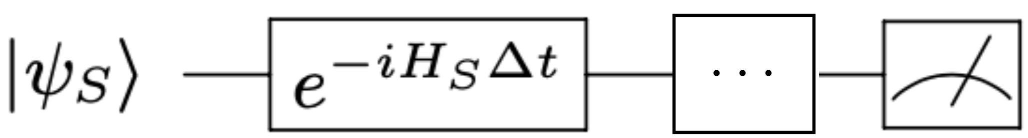
see e.g. *Jordan, Lee, Preskill `11, Preskill `18,*
Klco, Savage et al.`18-`20, Cloet, Dietrich et al. `19

Closed quantum systems

Time evolution of closed systems



- Quantum simulation of the Schrödinger equation



Evolution in time steps $\Delta t = t/N_{\text{cycle}}$

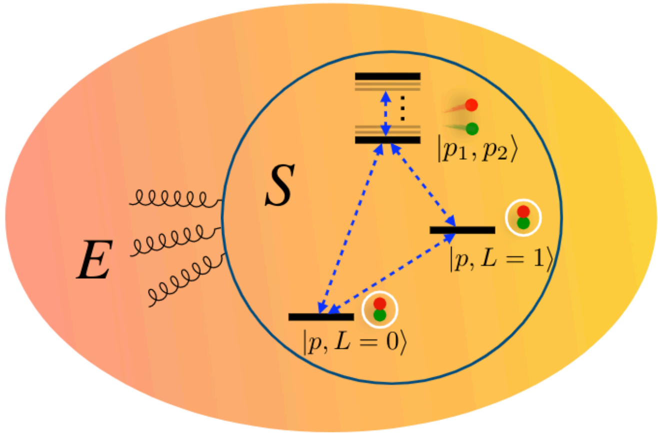
- The evolution is unitary and time reversible

→ For open quantum systems we need to introduce a non-unitarity part

Non-unitarity and time irreversible evolution

In open quantum systems, the subsystem evolution is non-unitary

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_S = -i\left[H_S, \rho_S\right] + \sum_{j=1}^{m}\left(L_j \rho_S L_j^\dagger - \frac{1}{2}L_j^\dagger L_j \rho_S - \frac{1}{2}\rho_S L_j^\dagger L_j\right)$$



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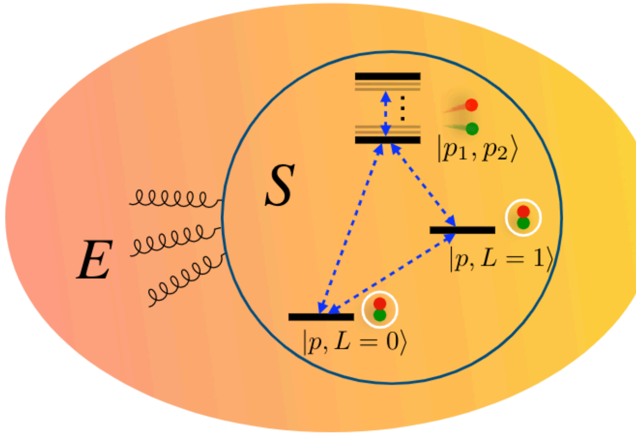
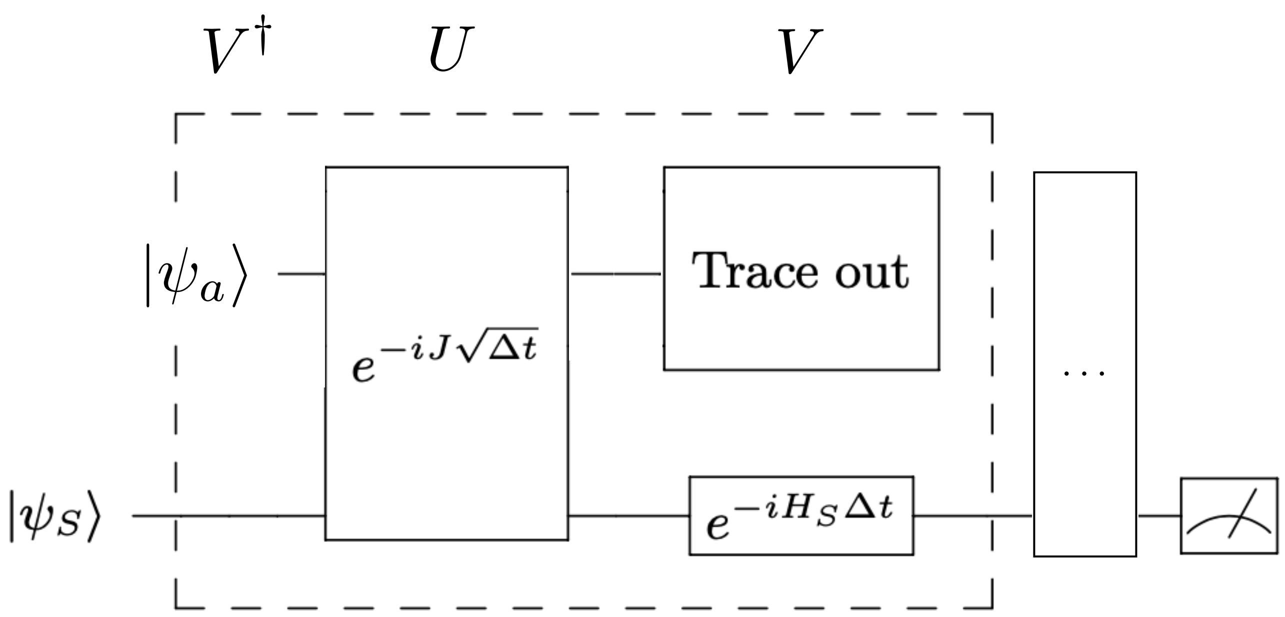


The Stinespring dilation theorem

Any allowed quantum operation can be written as a unitary evolution acting on a larger space (after coupling to appropriate ancilla), and reducing back to the subsystem



$$V^\dagger V = 1 \qquad VV^\dagger \neq 1$$

$$J = \begin{pmatrix} 0 & L_1^\dagger & \dots & L_m^\dagger \\ L_1 & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & 0 \\ L_m & 0 & \dots & 0 \end{pmatrix}$$

- Evolve in time steps $\Delta t = t/N_{\text{cycle}}$

Quantum simulation of open quantum systems

Toy model setup

Two-level system in a thermal environment

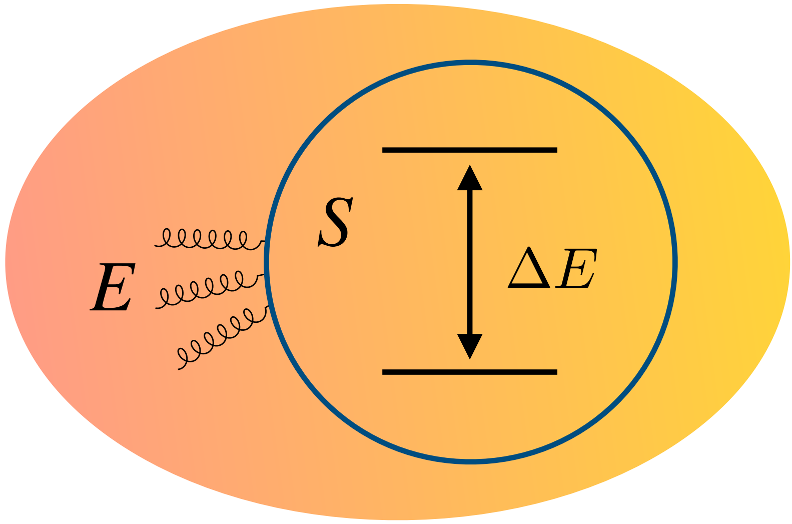
e.g. bound/unbound $J/\psi,\ c\bar{c}$

$$H_S = -\frac{\Delta E}{2} Z$$

$$H_E = \int \mathrm{d}^3x \left[\frac{1}{2}\Pi^2 + \frac{1}{2}(\nabla\phi)^2 + \frac{1}{2}m^2\phi^2 + \frac{1}{4!}\lambda\phi^4\right]$$

$$H_I = gX \otimes \phi(x=0)$$

Pauli matrices X, Y, Z, interaction strength g



$$\rho_E = \frac{e^{-\beta H_E}}{\mathrm{Tr}_E\, e^{-\beta H_E}}$$

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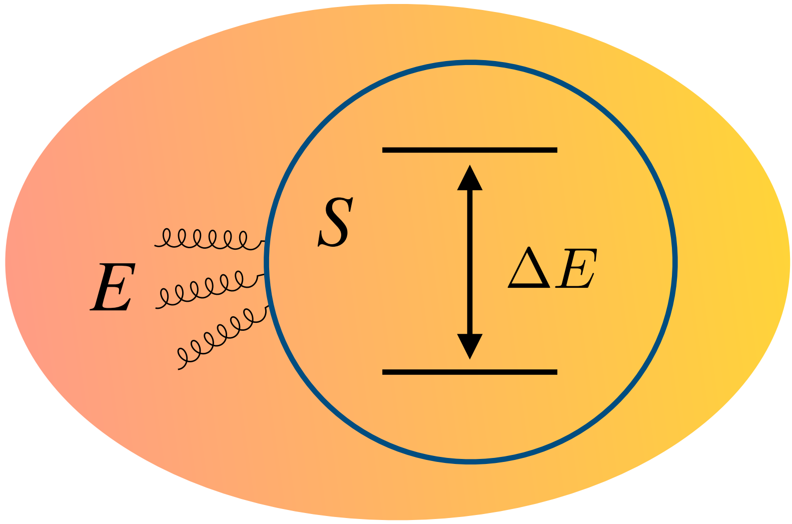

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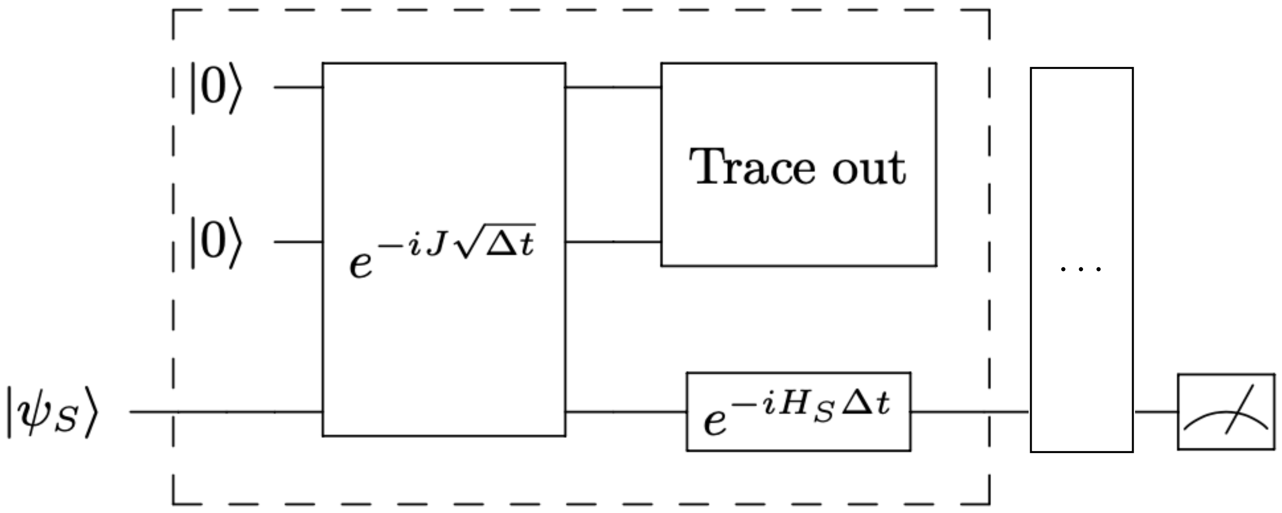
Pauli matrices $X, Y, Z,$ interaction strength g

Lindblad operators

$$L_j \sim g(X \mp iY) \qquad j = 0, 1$$

$$J = \begin{pmatrix} 0 & L_0^\dagger & L_1^\dagger & 0 \\ L_0 & 0 & 0 & 0 \\ L_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

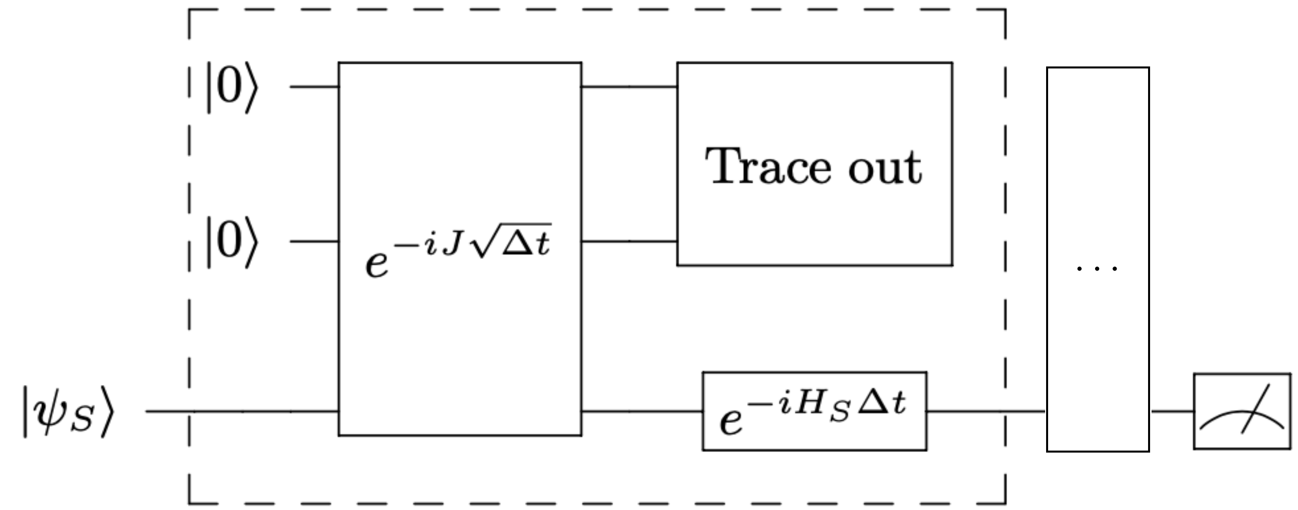


Quantum circuit synthesis

Approximate unitary operations with a compiled circuit of one- and two-qubit gates

Optimization problem w/unitary loss function

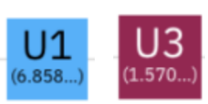
`qsearch` *Siddiqi et al. `20*



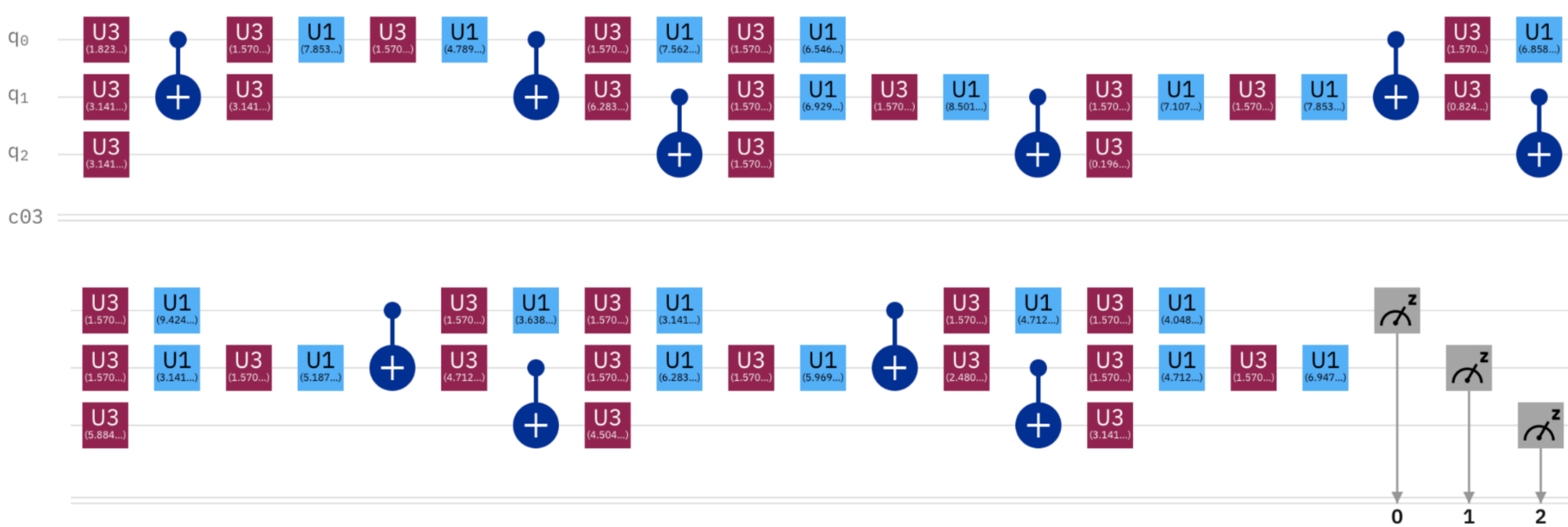
10 CNOT gates/cycle

IBM **Q**

Single qubit



CNOT



Error mitigation

Readout error

Constrained matrix inversion

IBM Q qiskit-ignis

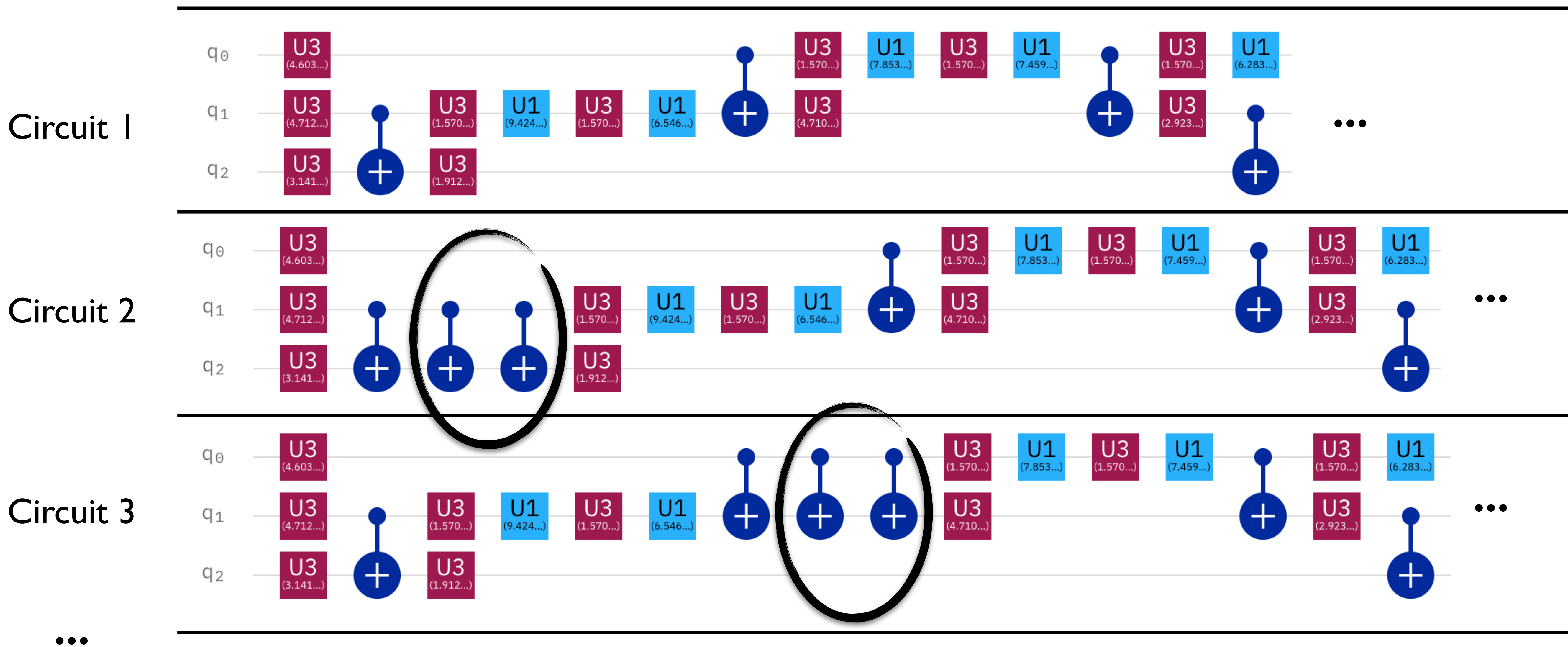
Unfolding

Nachman, Urbanek, de Jong, Bauer `19

Gate error

Zero-noise extrapolation of CNOT noise using Random Identity Insertions

He, Nachman, de Jong, Bauer `20



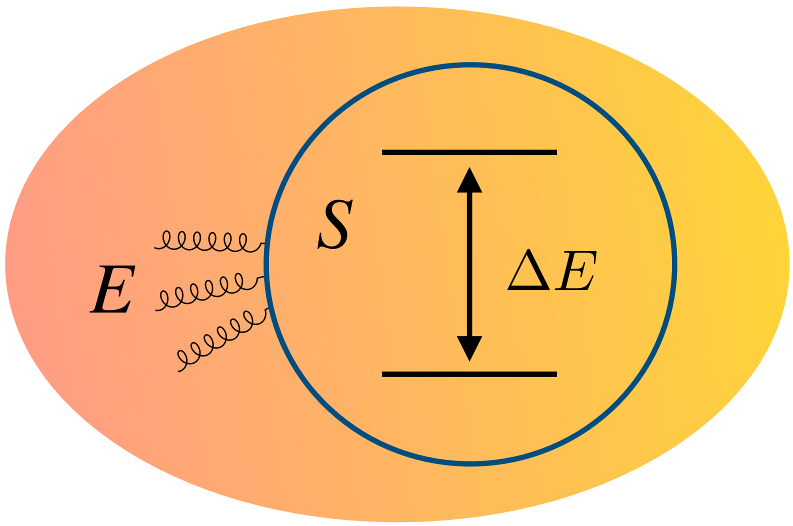
Quantum simulation of open quantum systems

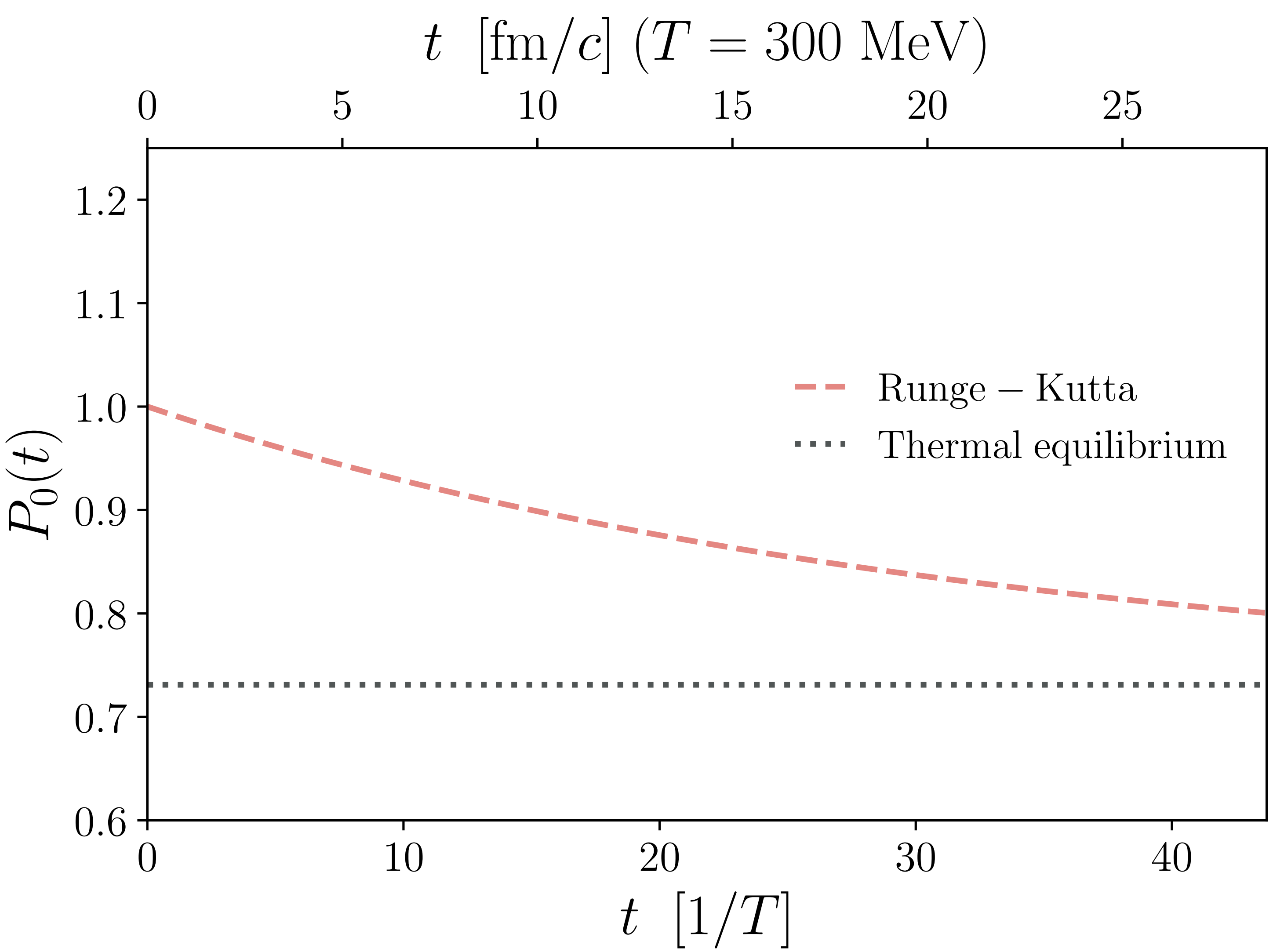
arXiv: 2010.03571

Real-time evolution

$P_0(t)$ describes fraction that remains in "bound state"

Similar to t-dependent $R_{AA} = \dfrac{\mathrm{d}\sigma_{AA}}{\langle N_{\mathrm{coll}}\rangle\, \mathrm{d}\sigma_{pp}}$





Quantum simulation of open quantum systems

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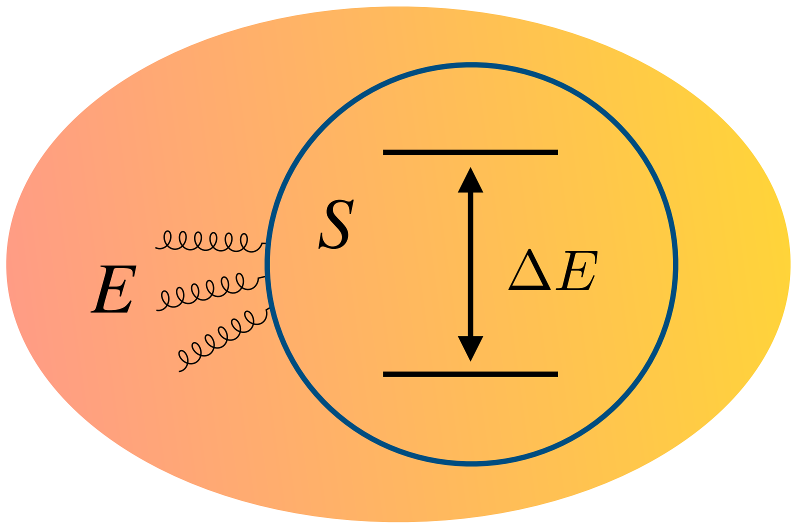

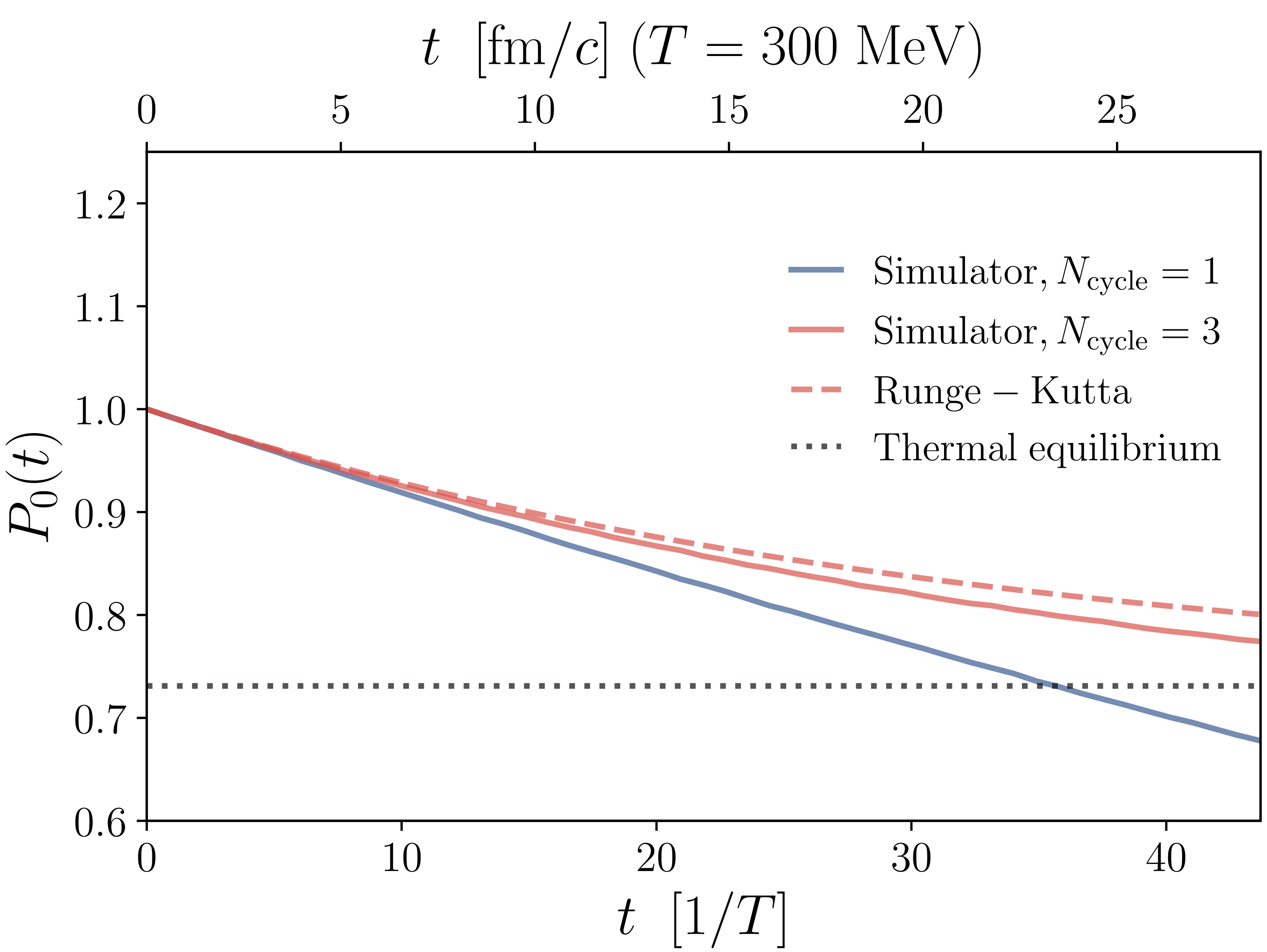

The algorithm converges to Lindblad evolution with a small number of cycles

Quantum simulation of open quantum systems

arXiv: 2010.03571

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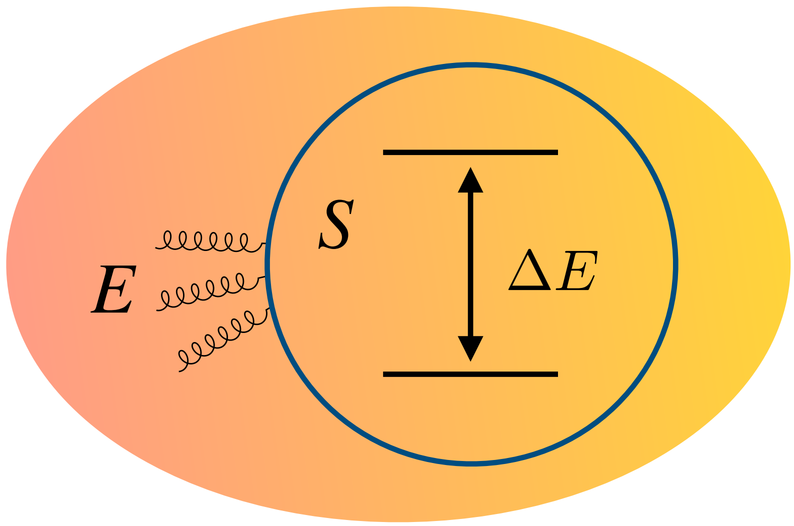

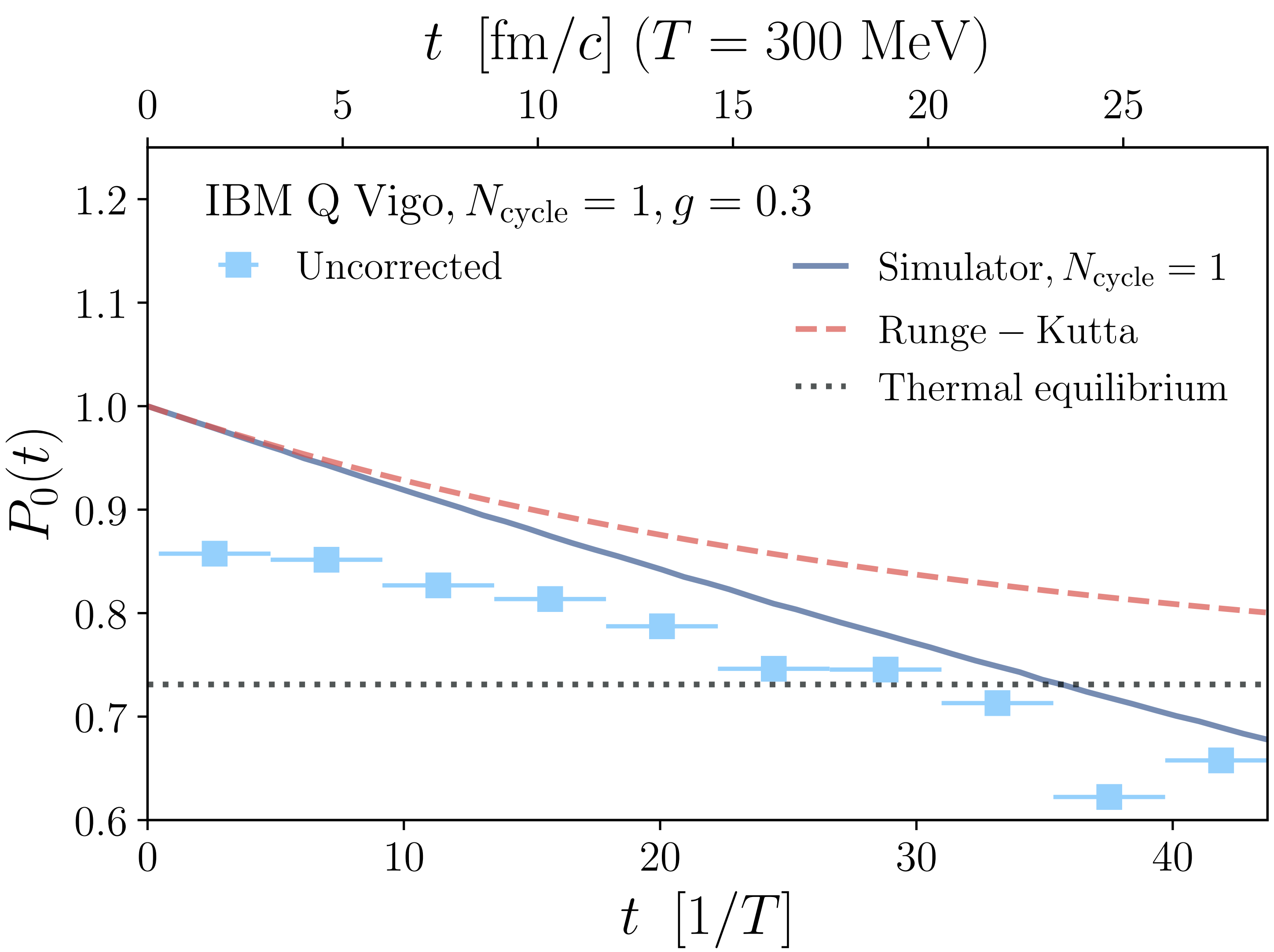

IBM Q Vigo device

Quantum simulation of open quantum systems

arXiv: 2010.03571

Real-time evolution

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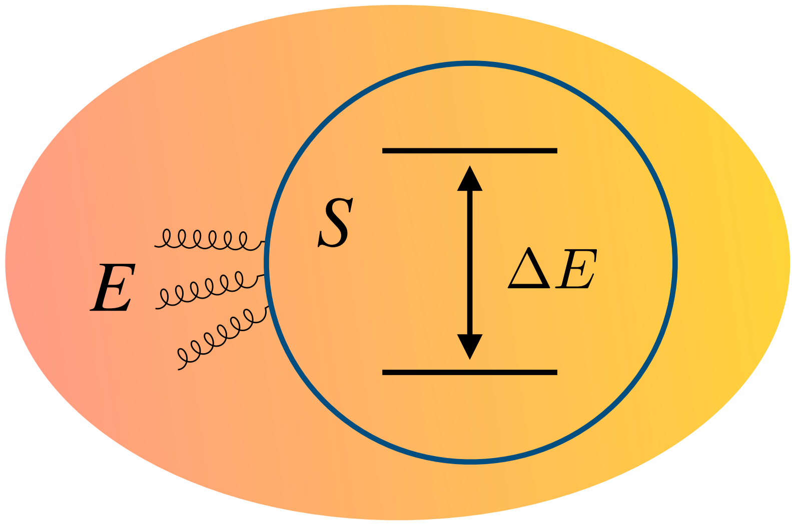
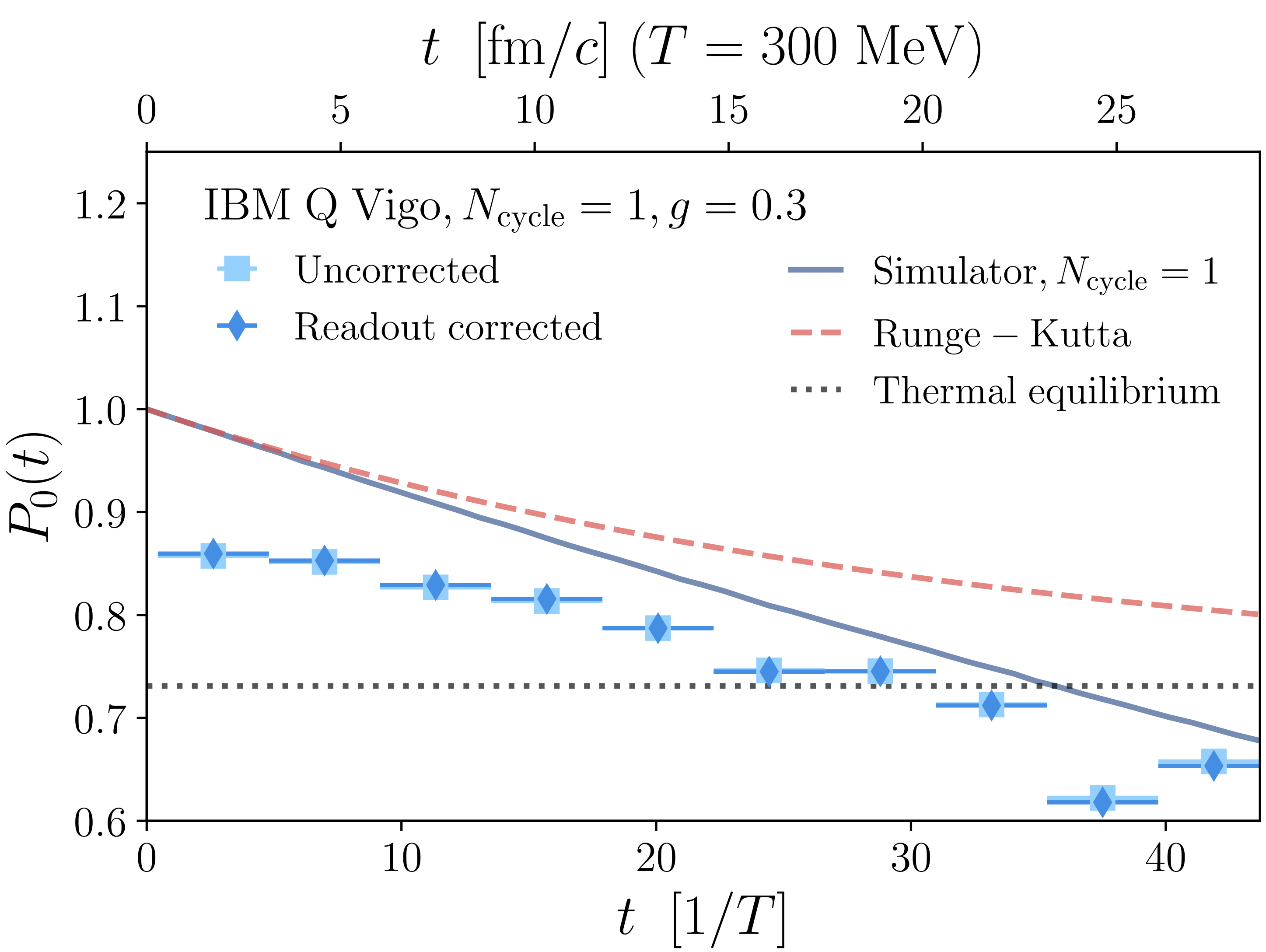




IBM Q Vigo device

Readout correction small

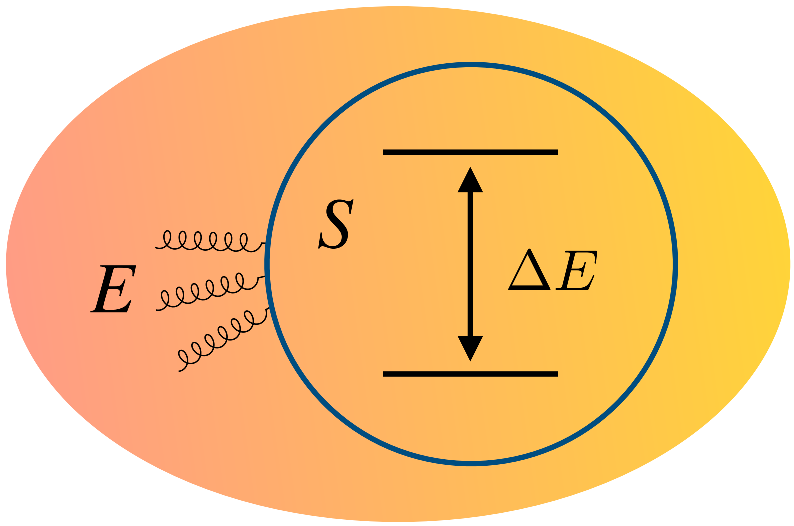
Quantum simulation of open quantum systems

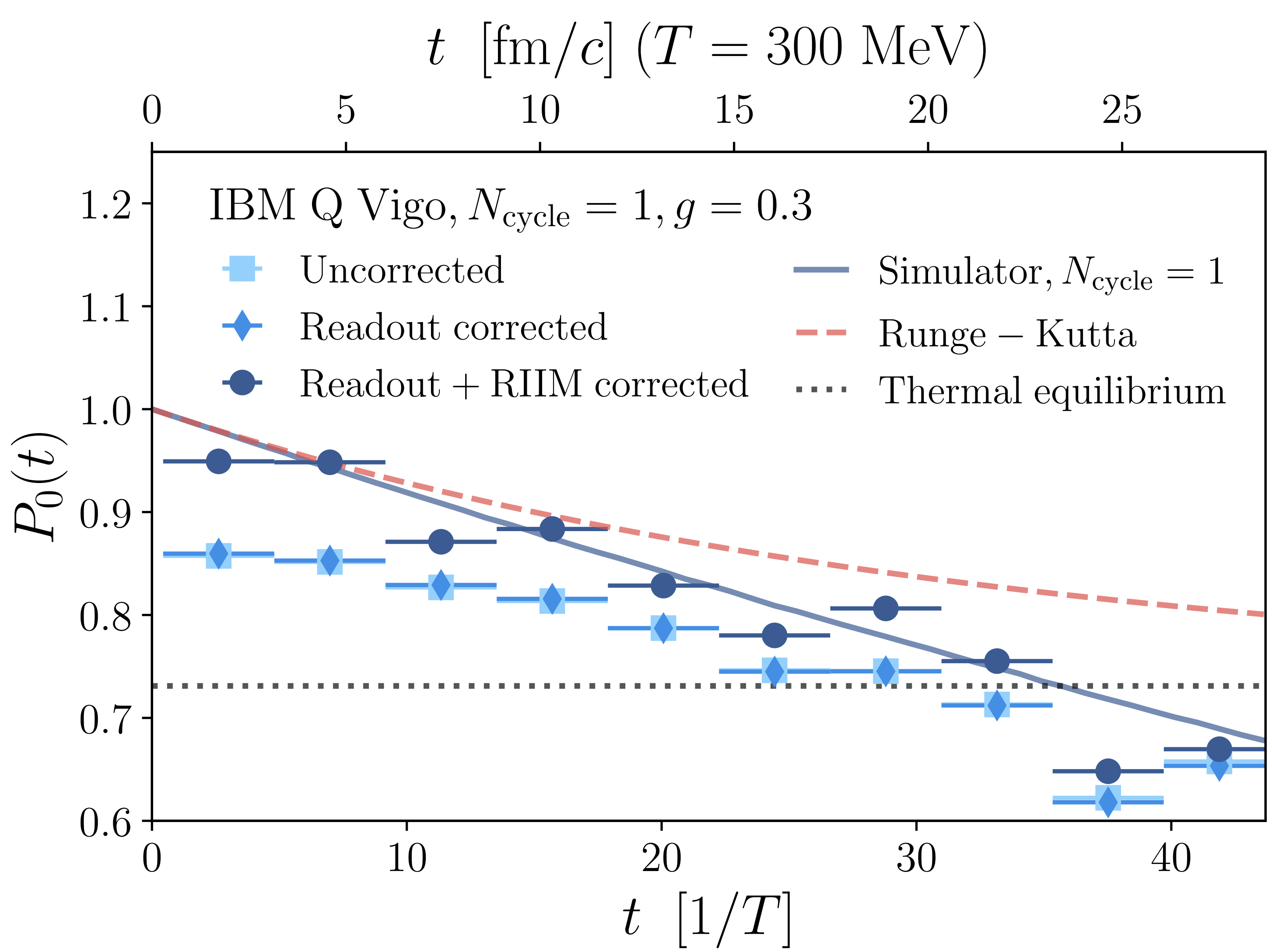
arXiv: 2010.03571

Real-time evolution

$P_0(t)$ describes fraction that remains in "bound state"

Similar to *t*-dependent $R_{AA} = \frac{\mathrm{d}\sigma_{AA}}{\langle N_{\mathrm{coll}}\rangle \, \mathrm{d}\sigma_{pp}}$





IBM Q Vigo device

Readout correction small

CNOT gate error correction gives good agreement

Random Identity Insertion Method (RIIM)

Bauer, He, de Jong, Nachman `20

Proof of concept

Conclusions and outlook

- **Open quantum system formalism describes the real-time evolution of hard probes in heavy-ion collisions**
  - Allows to go beyond semiclassical approximations in current models
- **Proof of concept that these systems can be simulated on current and near-term quantum computers (IBM Q)**
  - NISQ era digital quantum computing
  - Recently developed error mitigation techniques
- **Future steps**
  - Extension toward QCD (jets & heavy-flavor)
  - Explore different digital/analog devices
  - Cold nuclear matter at the EIC