Quantum simulation of open quantum systems in heavy-ion collisions

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arXiv: 2010.03571

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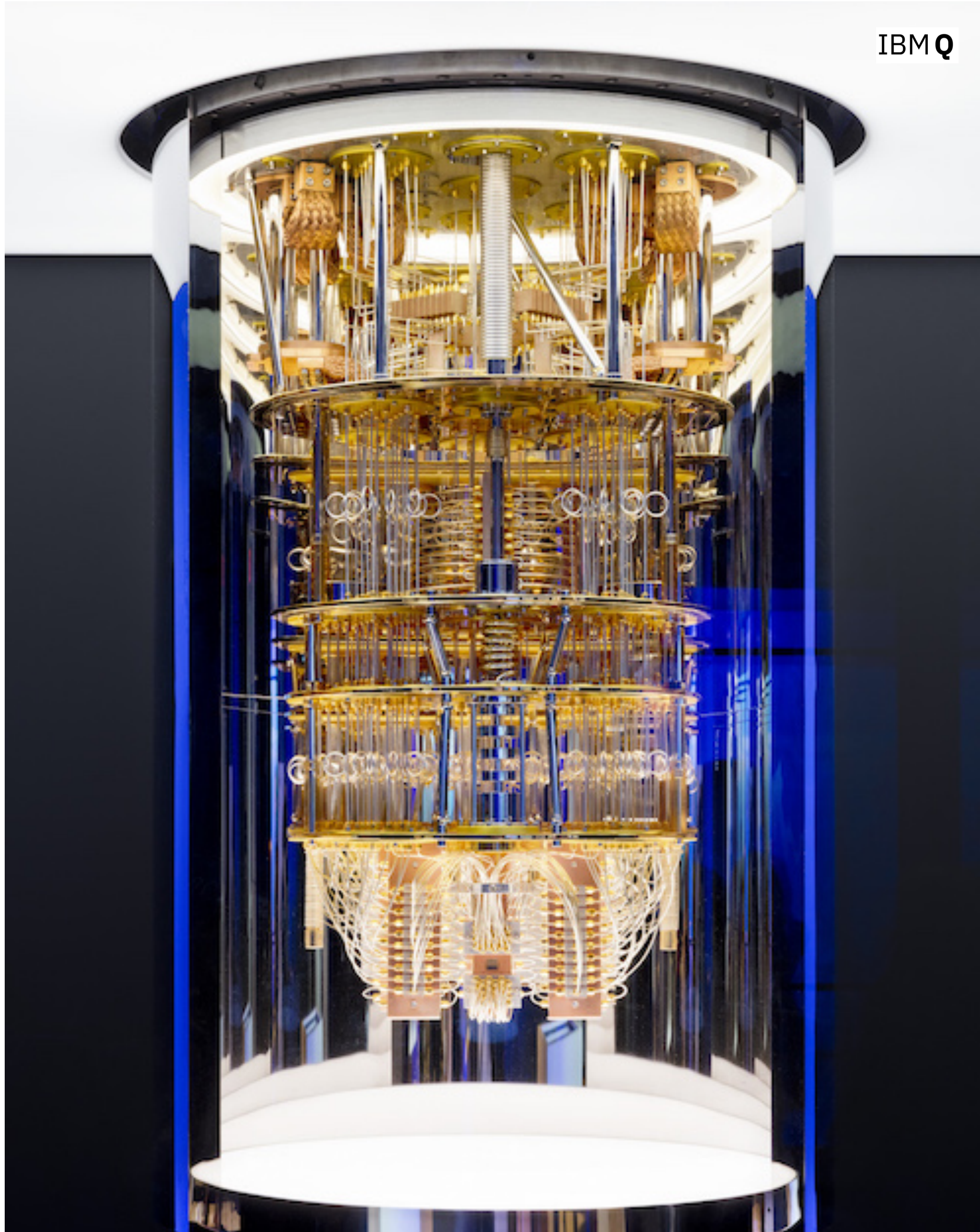
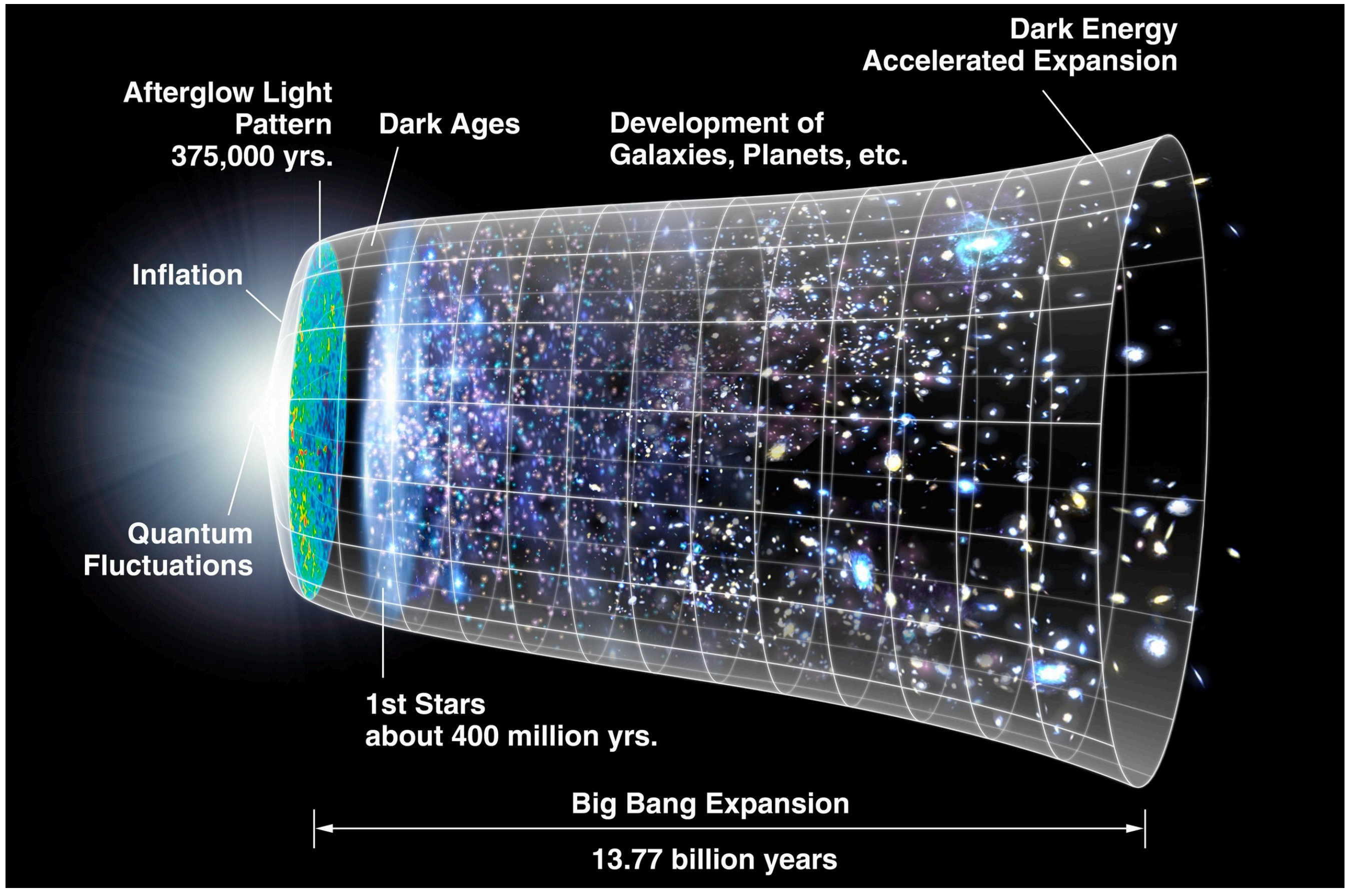
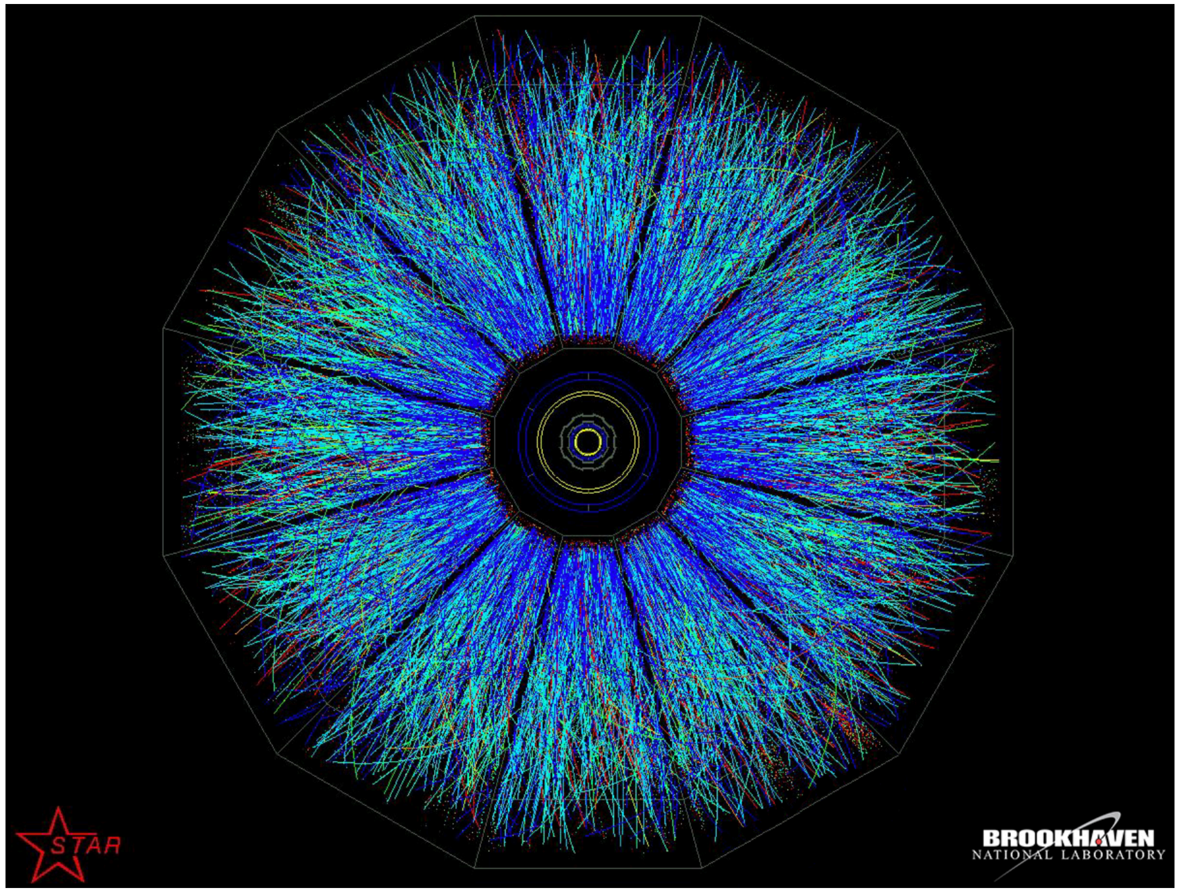
BERKELEY LAB

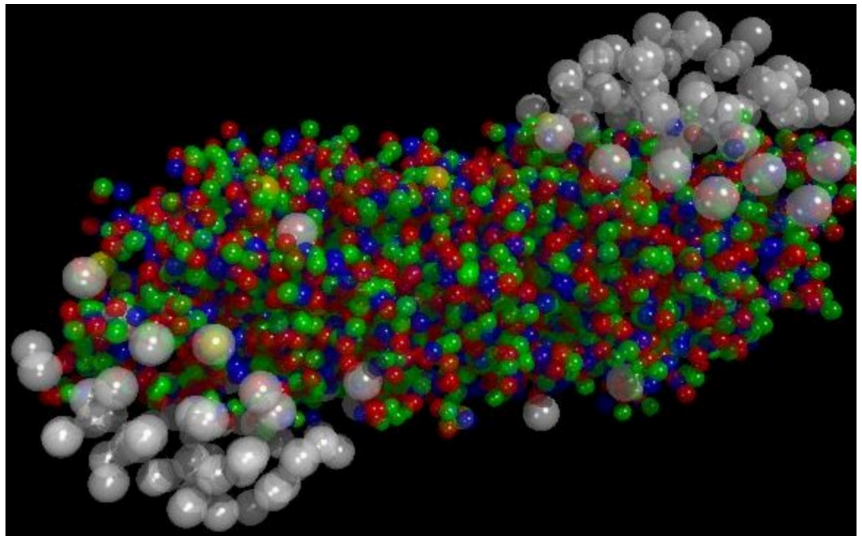
LBNL NSD staff meeting
10/20/2020



Heavy-ion collisions — the Quark Gluon Plasma



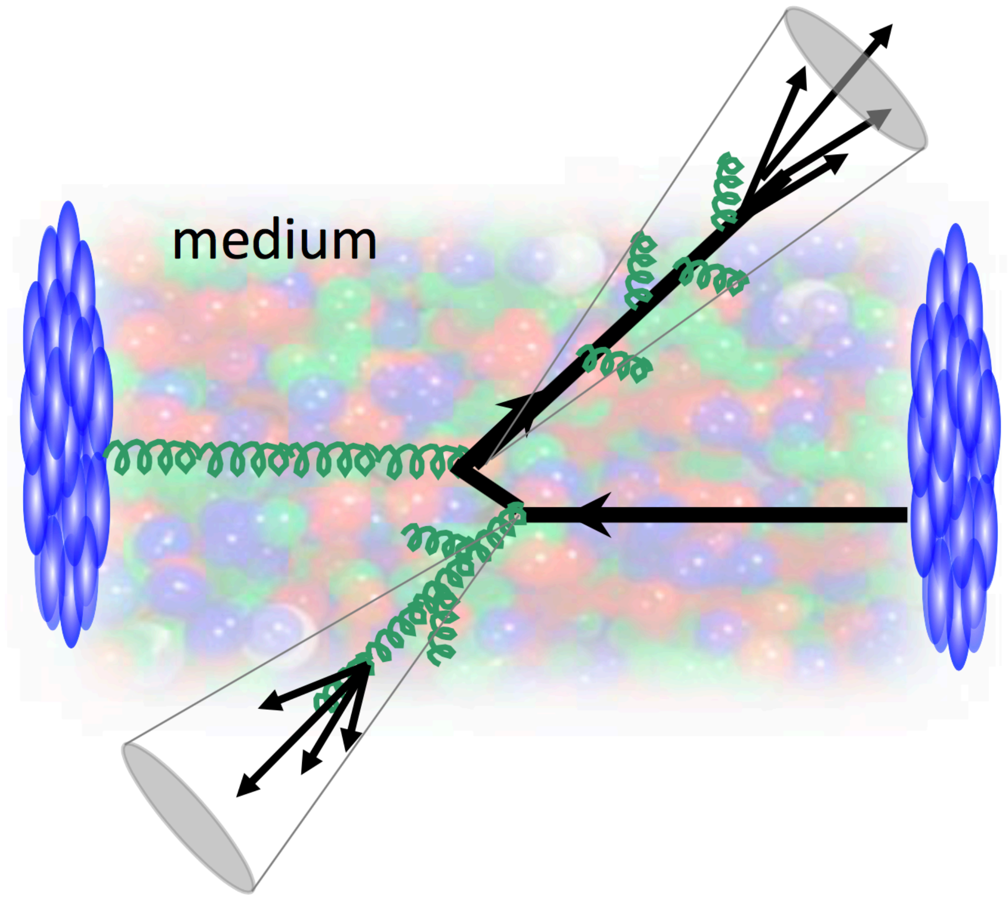




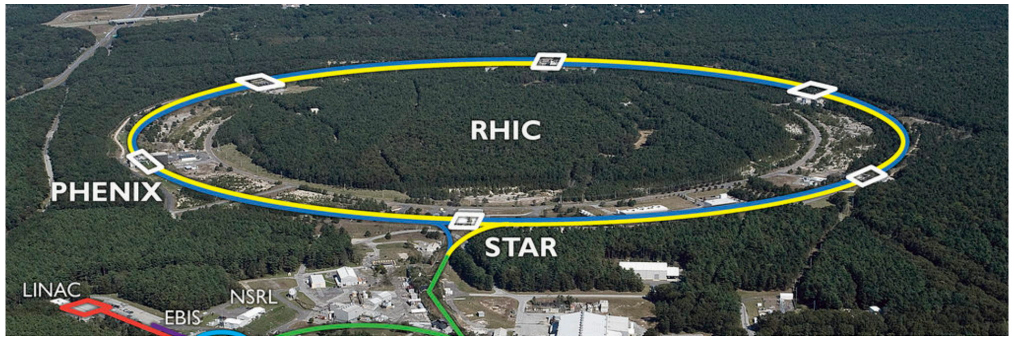
Described by Quantum chromodynamics (QCD)

Unbound quarks and gluons

Hard probes of the Quark Gluon Plasma

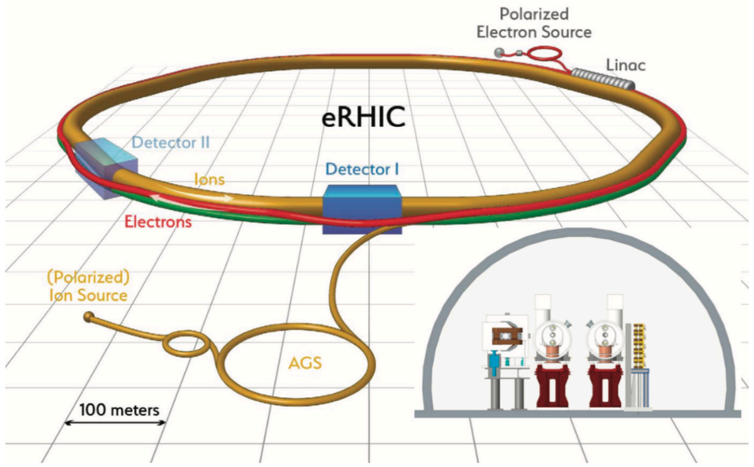


LHC, RHIC



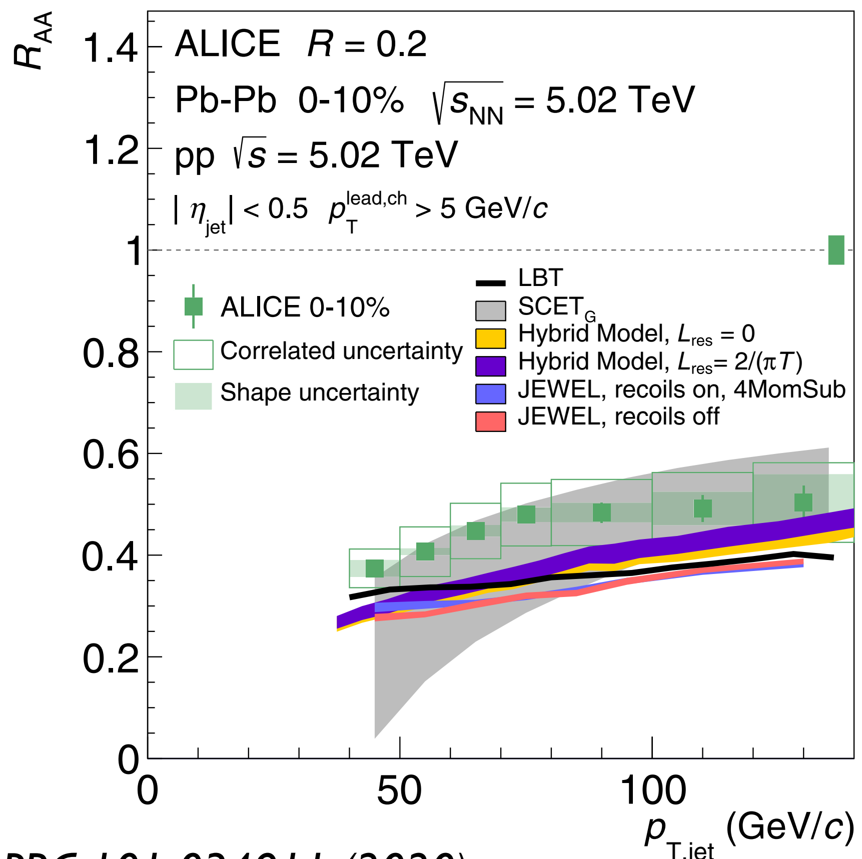
- Highly energetic particles and jets

EIC - cold nuclear matter



Hard probes of the Quark Gluon Plasma

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



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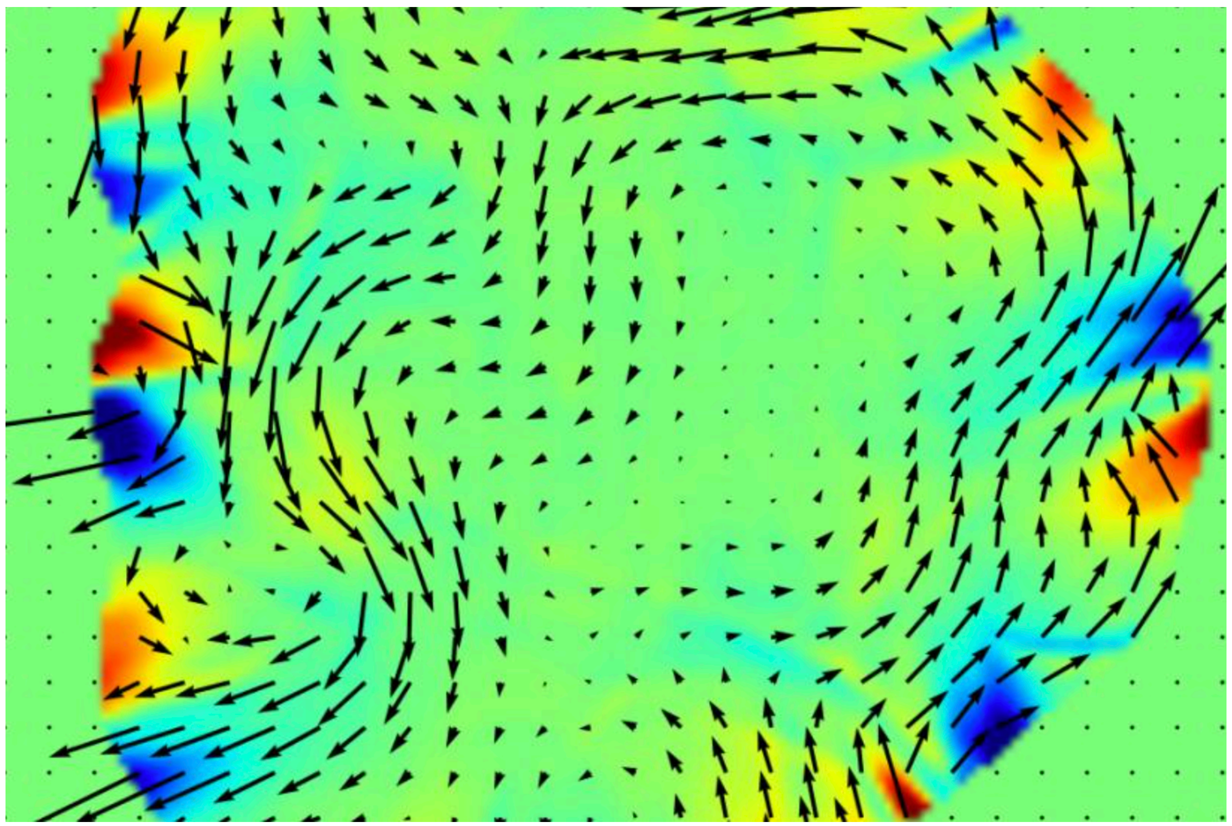


X.N.Wang et al.

- Study the **real-time** dynamics of hard probes
- Combine with hydrodynamic models of the QGP
- Study the microscopic structure of the medium

Outline

Open quantum systems in heavy-ion collisions

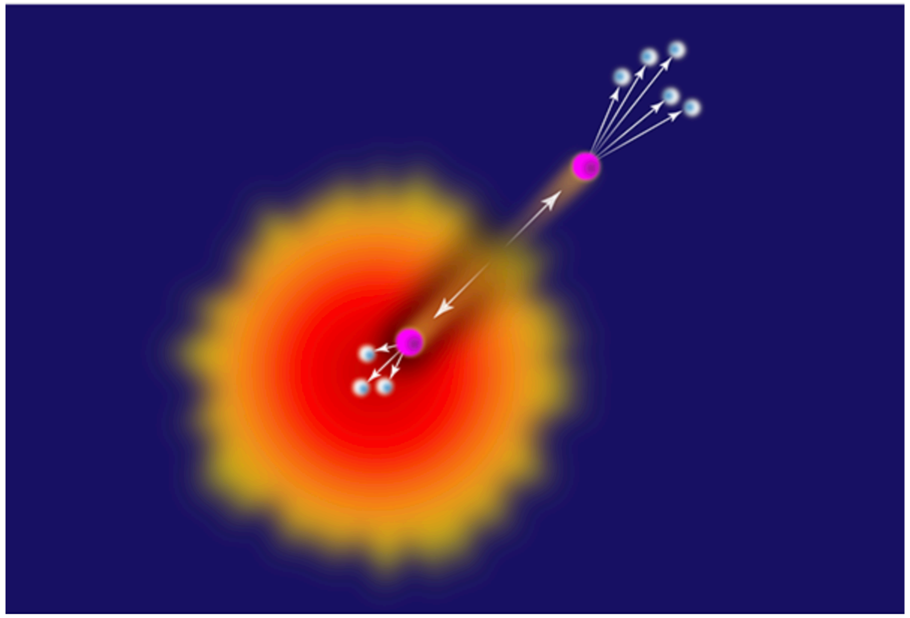
Quantum simulation with IBM Q

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)

- **System** - Jet/heavy-flavor

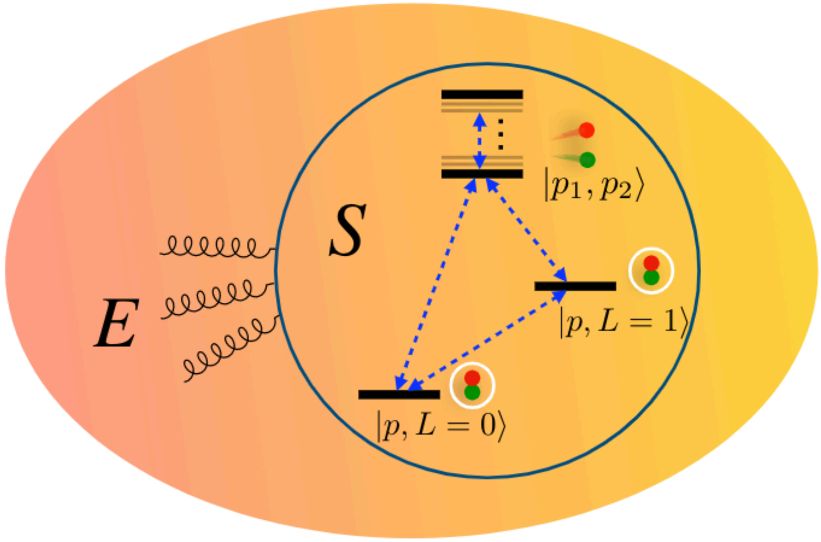
- **Environment** - Nuclear matter



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

- The time evolution is governed by the von Neumann equation

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



Hamiltonian formulation of QCD

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

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

- **System** - Jet/heavy-flavor

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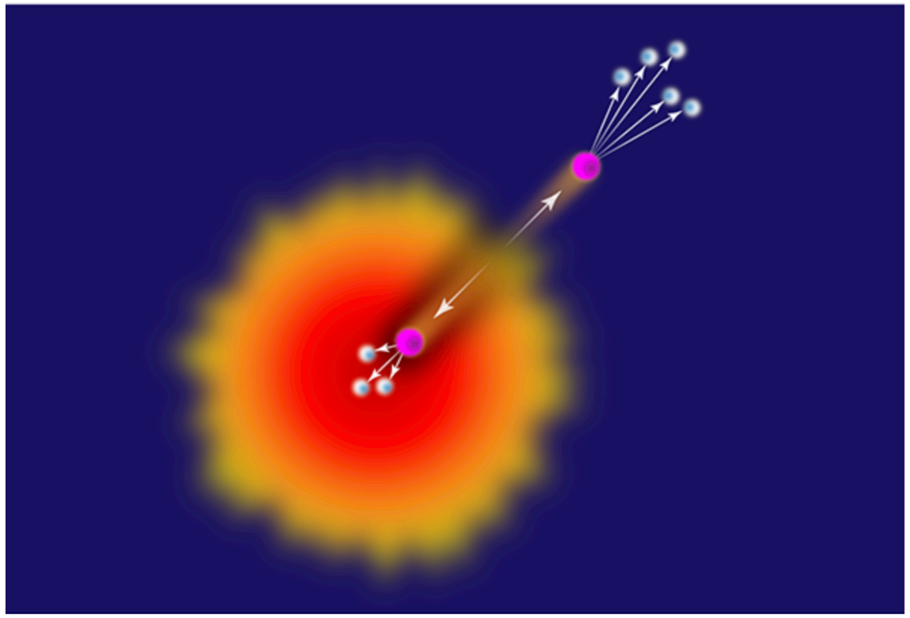
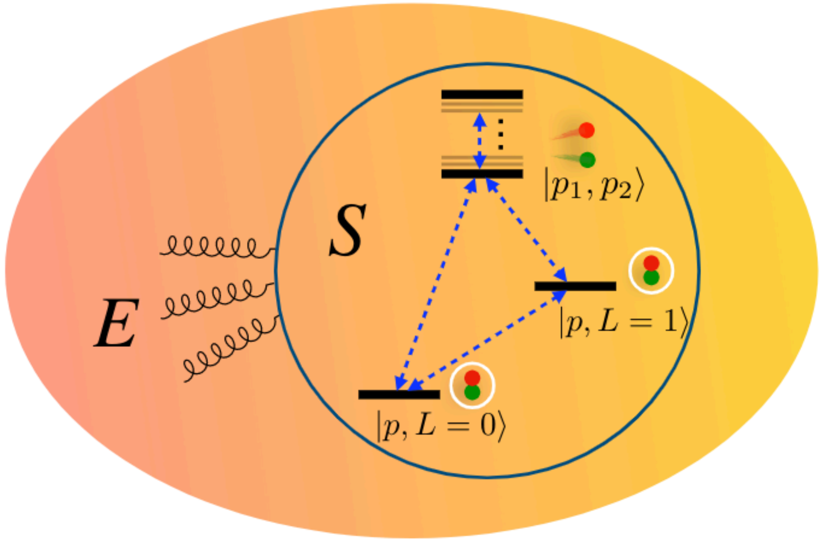


$$H(t) = H_S(t) + H_E(t) + H_I(t)$$

- Lindblad equation in the Markovian limit

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

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

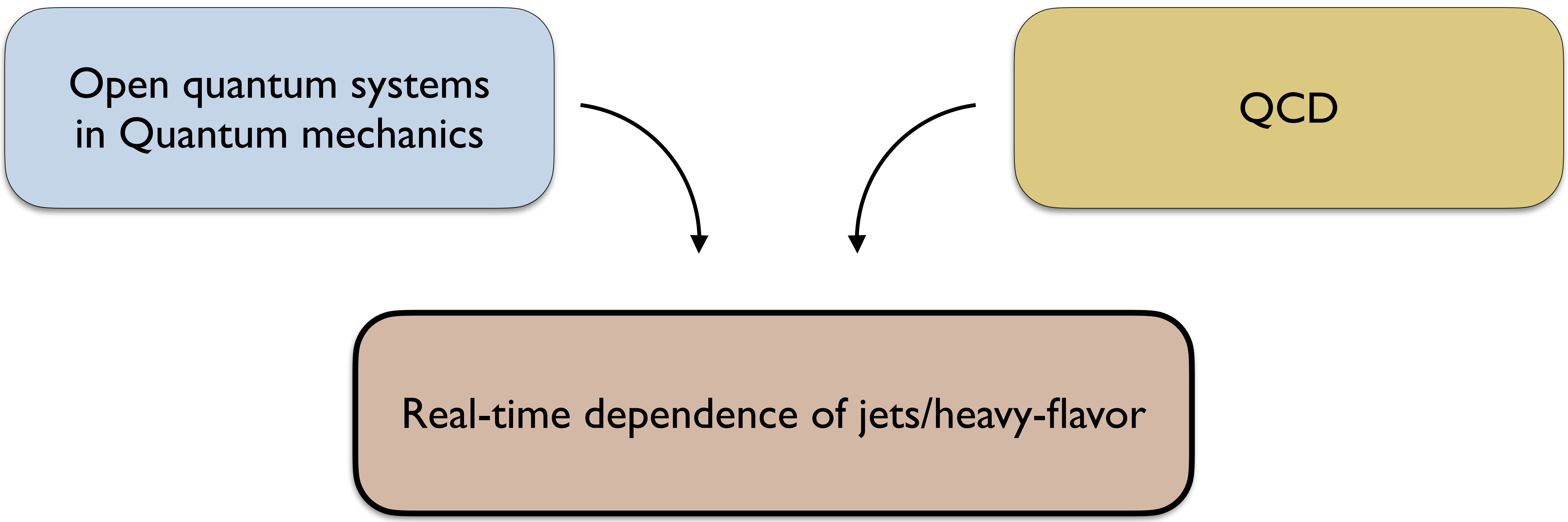


- See also e.g. non-global logs and CGC

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

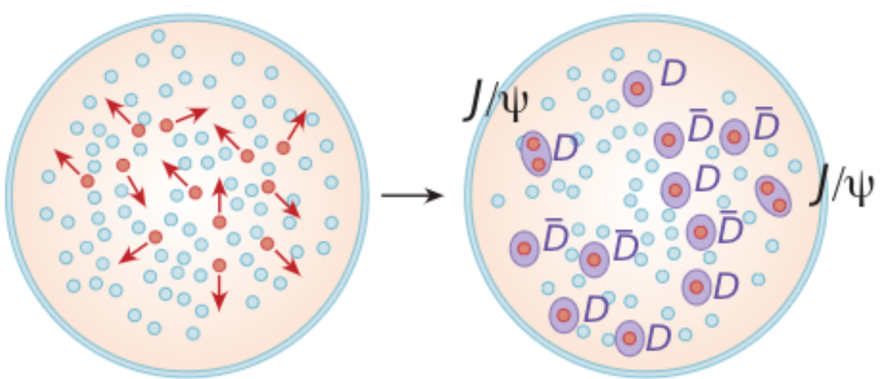
Akamatsu, Rothkopf et al. `12-`20, Brambilla et al. `17-`20
Yao, Mueller, Mehen `18-`20, Sharma, Tiwari `20

Yao, Vaidya `19, Vaidya `20

Quarkonium suppression

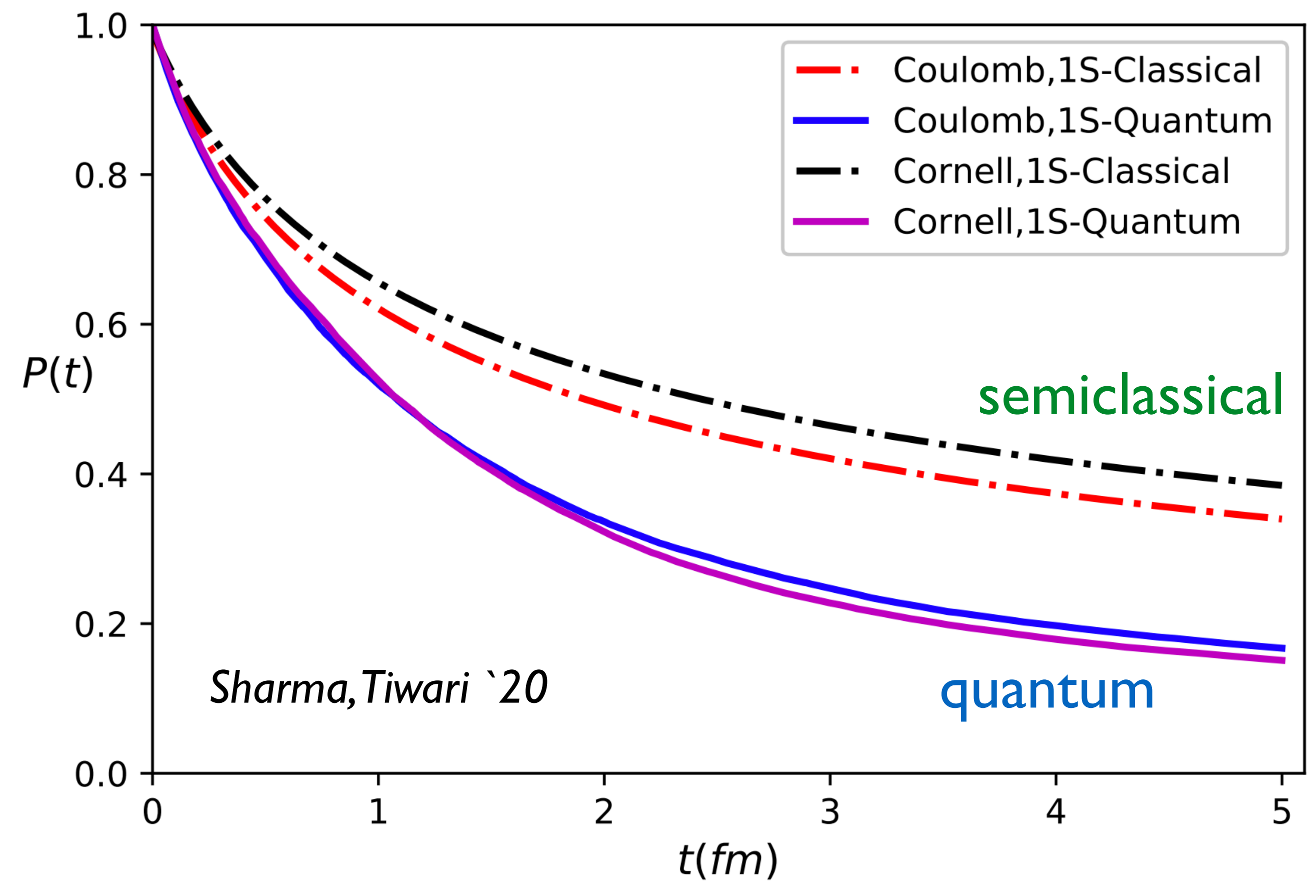
Akamatsu, Rothkopf et al. `12-`20, Brambilla et al. `17-`20
Yao, Mueller, Mehen `18-`20, Sharma, Tiwari `20

- Quarkonium production



- NRQCD + semiclassical approach compared to full quantum evolution

Survival probability of the vacuum state



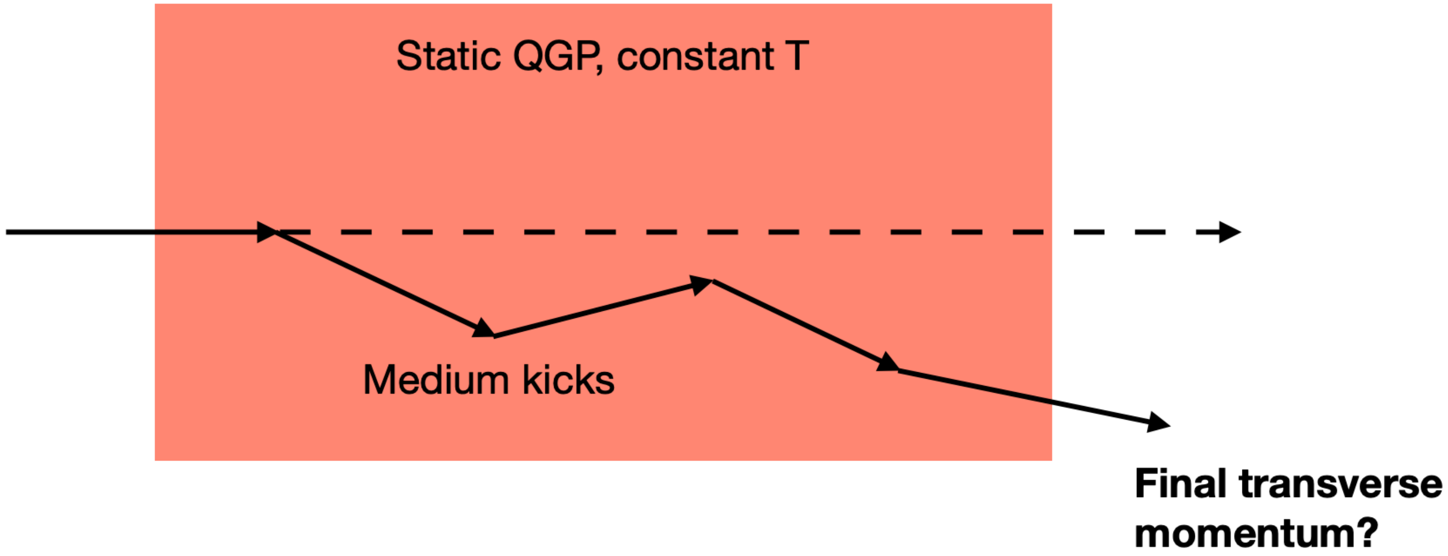
Bjorken expanding QGP $T_0 = 475\ \mathrm{MeV}$

Jet broadening

Yao, Vaidya `19

- First steps in the direction of jet physics
- Soft and collinear modes
- Forward scattering/Glauber gluons

$$H_I = \sum_\alpha O_\alpha^{(S)} \otimes O_\alpha^{(E)}$$

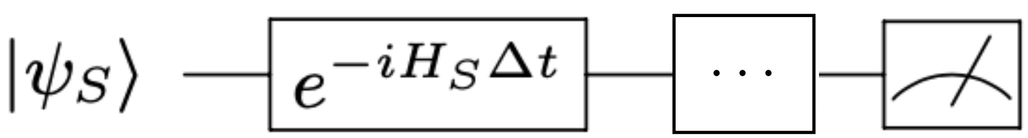


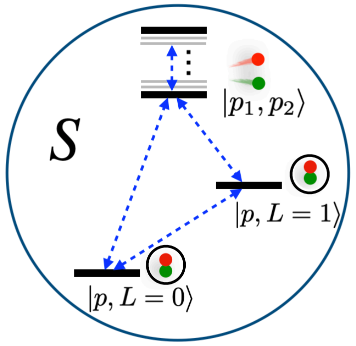
- Markovian master equation resums large logarithms $P(Q,t) = \langle Q|\rho_S(t)|Q\rangle$

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

Closed quantum systems

- **Time evolution of closed systems**
  - Quantum simulation of the Schrödinger equation





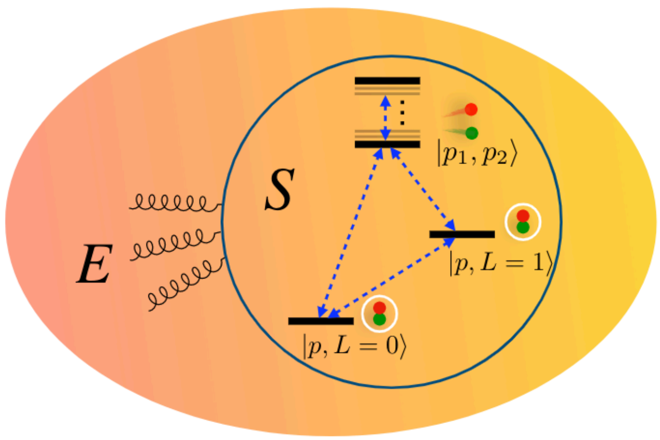
Evolution in time steps $\Delta t = t/N_{\text{cycle}}$

  - The evolution is unitary and time reversible

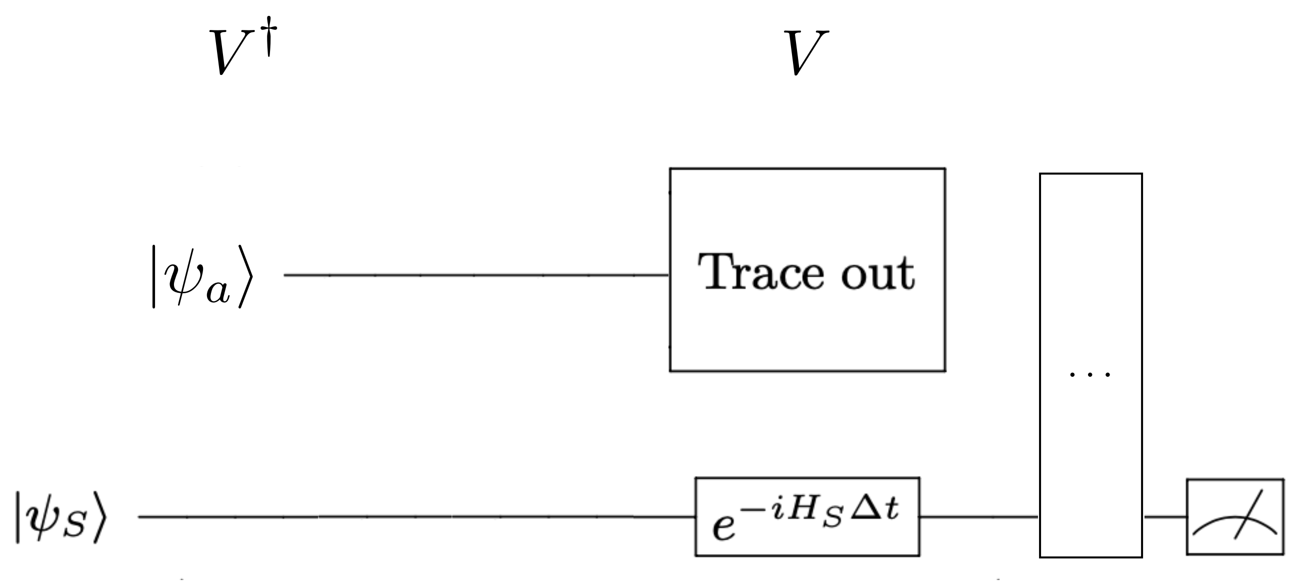
→ For open quantum systems we need to introduce a non-unitarity part

Non-unitarity and time irreversible evolution

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



- **The Stinespring dilation theorem**

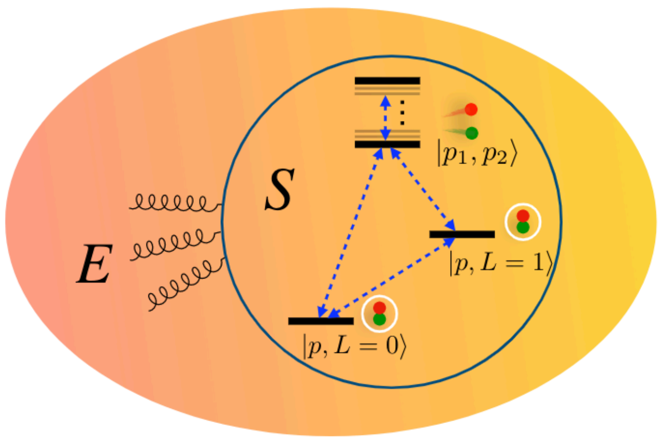


- Introducing and tracing out an ancillary system is not a unitary operation (operator theory)

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

Non-unitarity and time irreversible evolution

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



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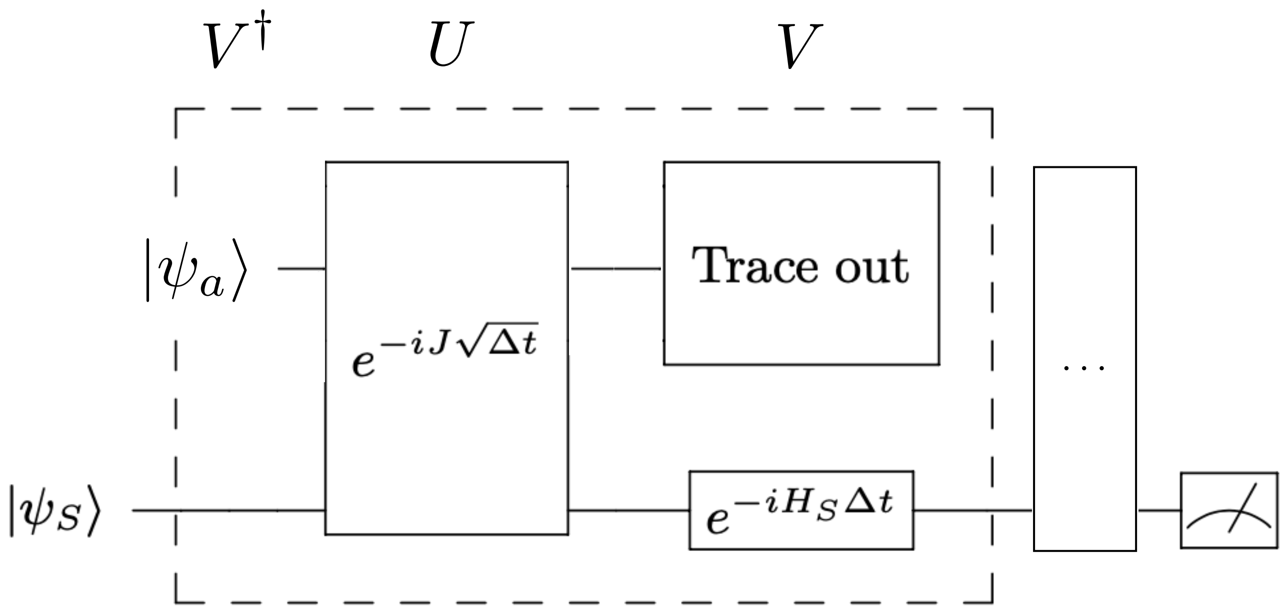

- Introducing and tracing out an ancillary system is not a unitary operation (operator theory)

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

- Sandwich in between a unitary evolution step
- Evolve in time steps $\Delta t = t/N_{\text{cycle}}$

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

Outline

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Quantum computing

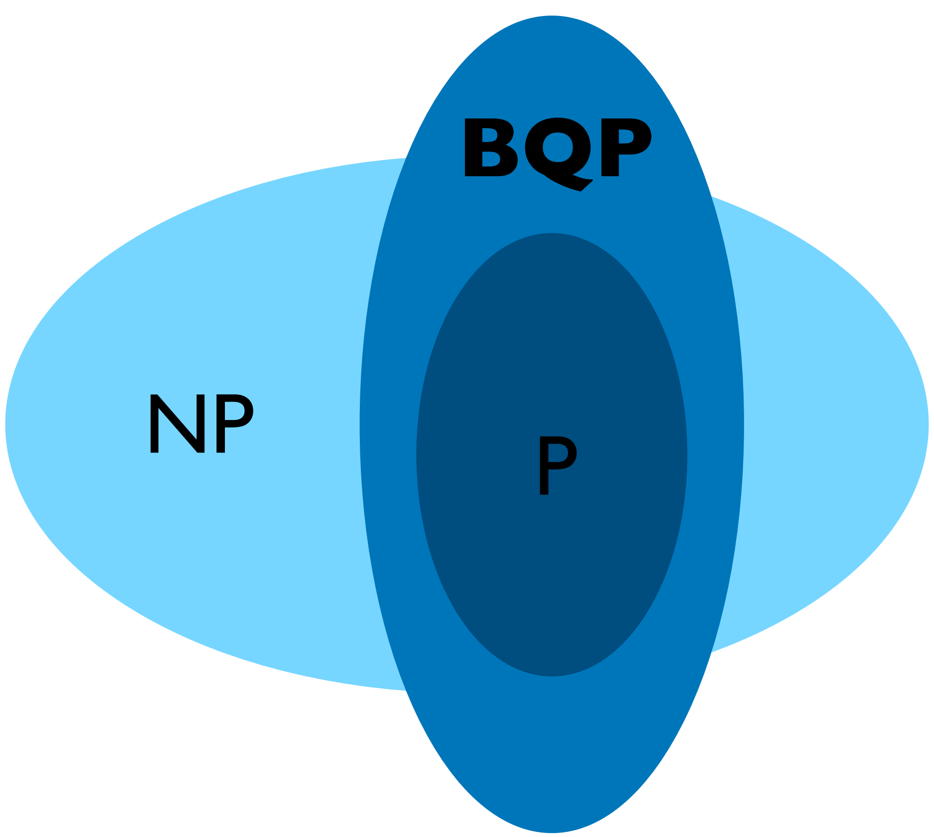
Superposition and entanglement

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

For N qubits, there are 2^N amplitudes

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

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

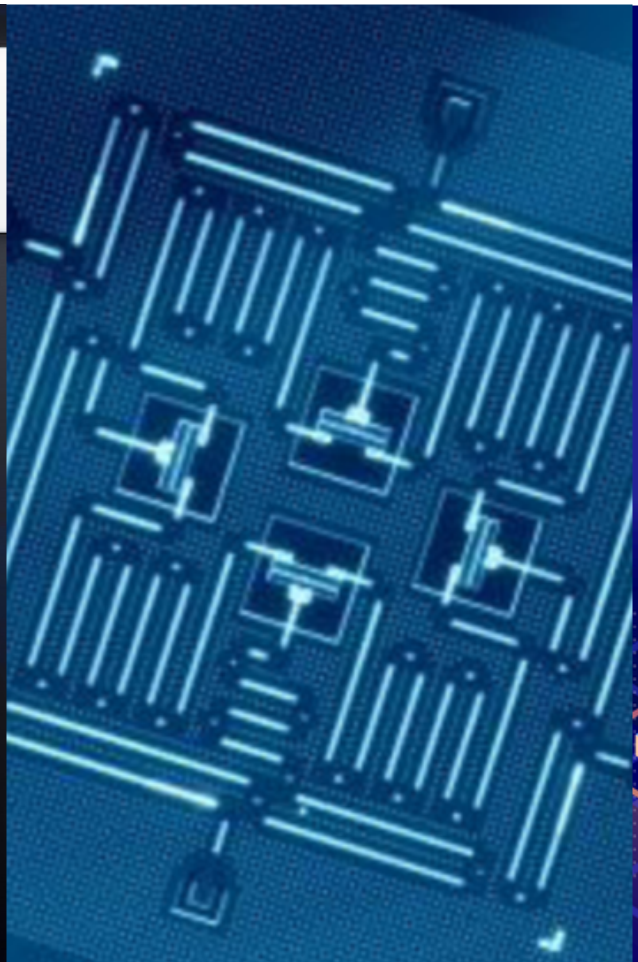
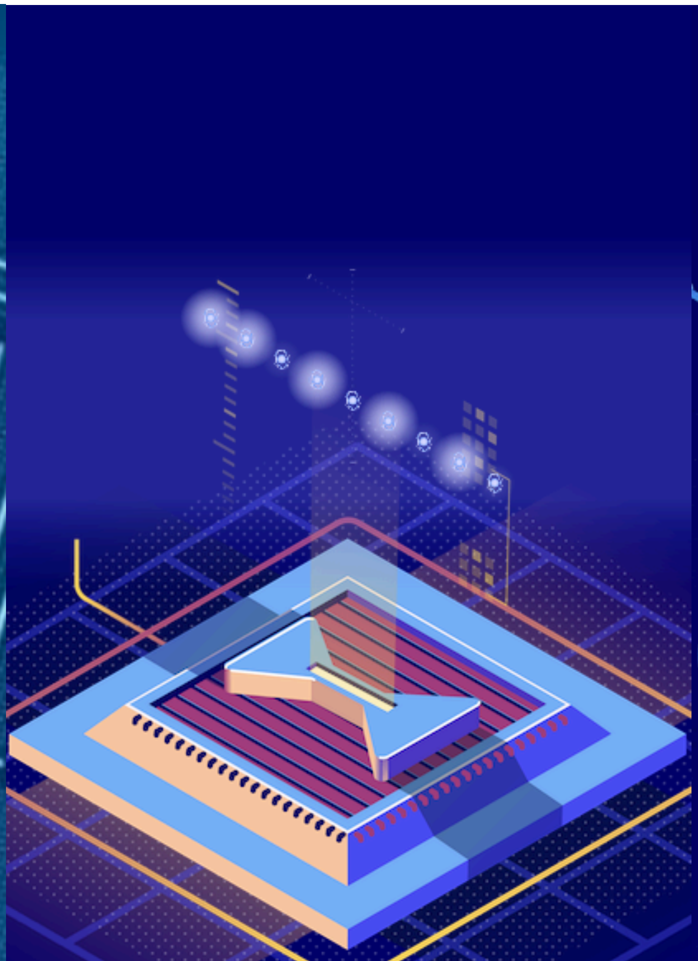
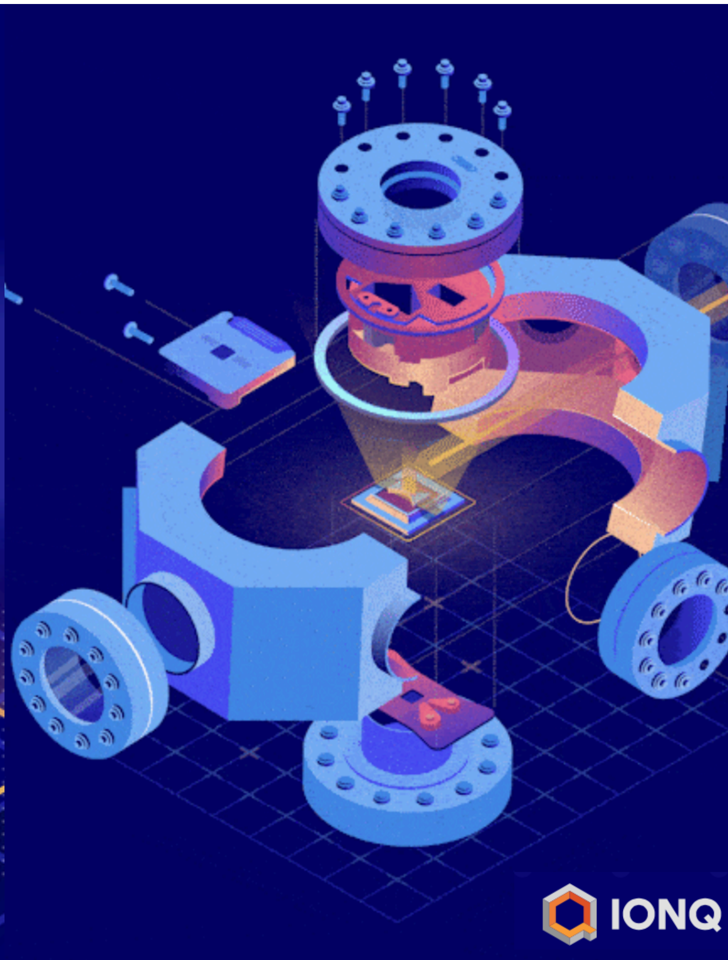
…

And a variety of others…

Trapped ions
Optical lattice
Photonics
Topological
…

IONQ
Honeywell
Ψ PsiQuantum

…

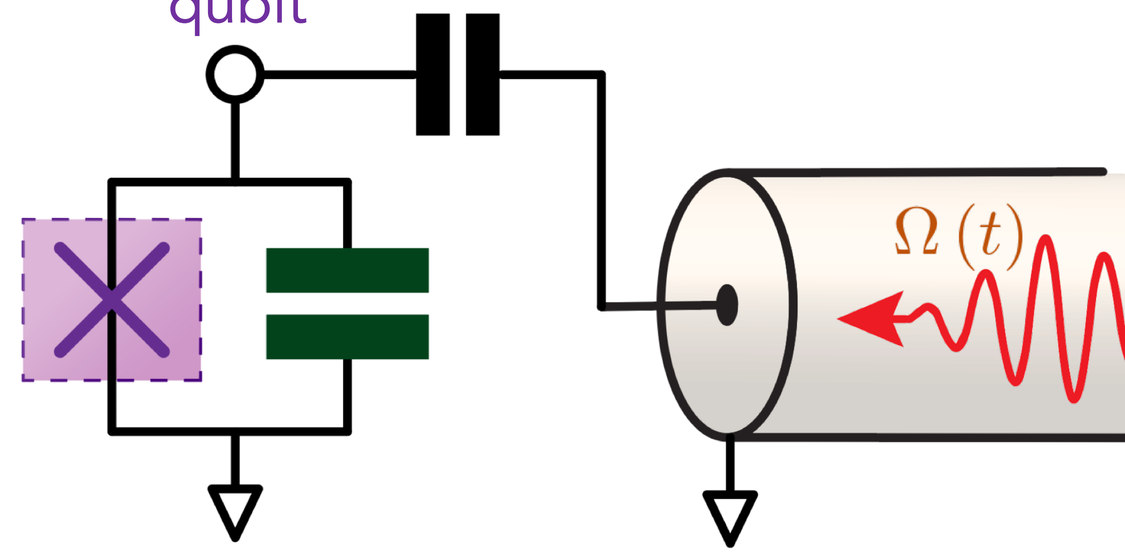




Quantum devices

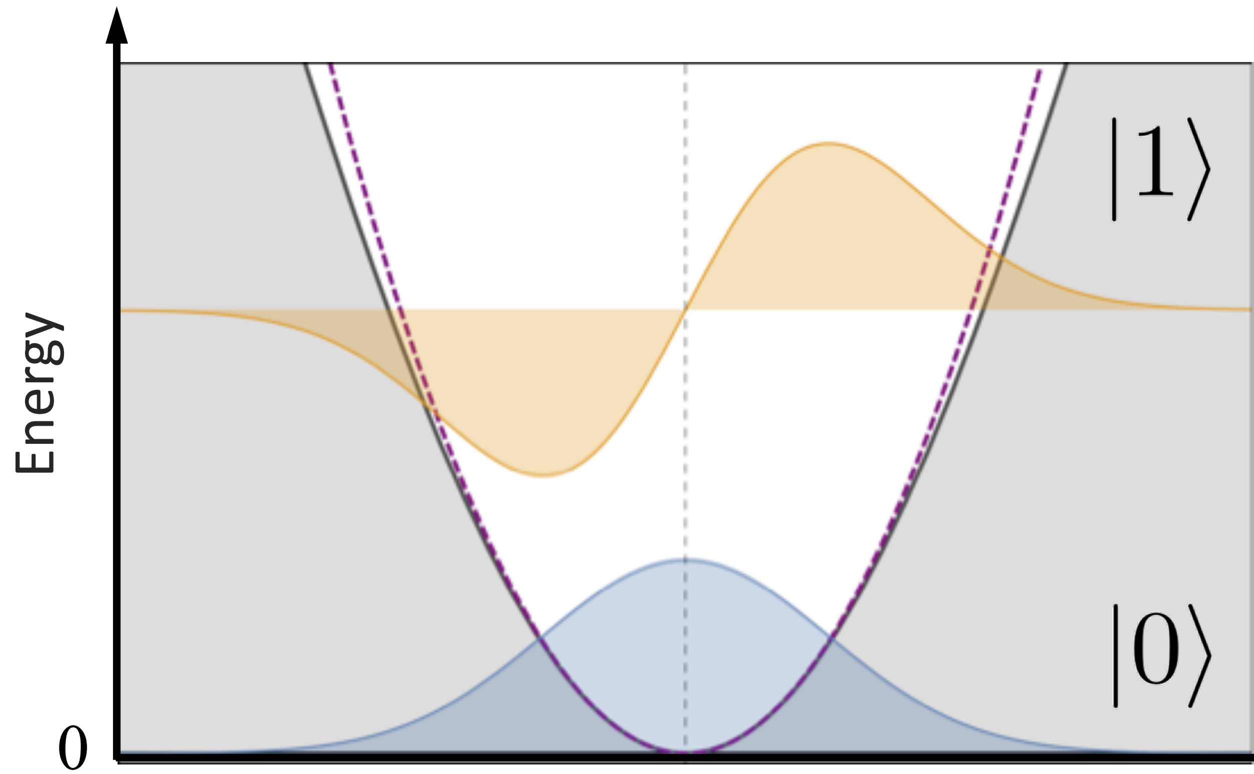
Superconducting circuits

IBM Q

Google rigetti



Qubits: Nonlinear quantum oscillator
Gates: coupled microwave pulses



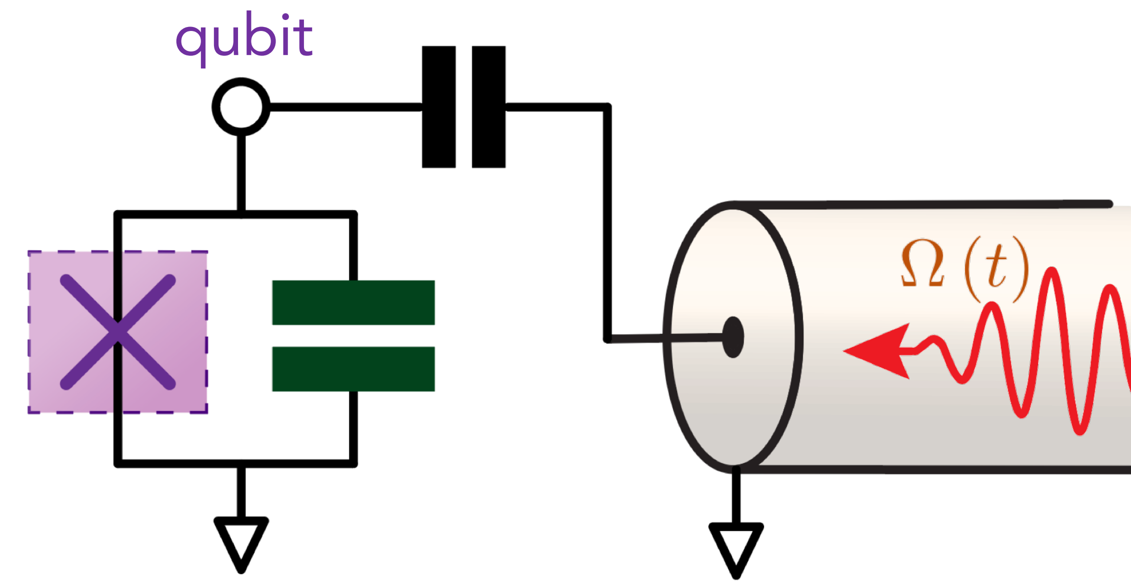
Zlatko Minev — Qiskit Global Summer School 2020

Quantum devices

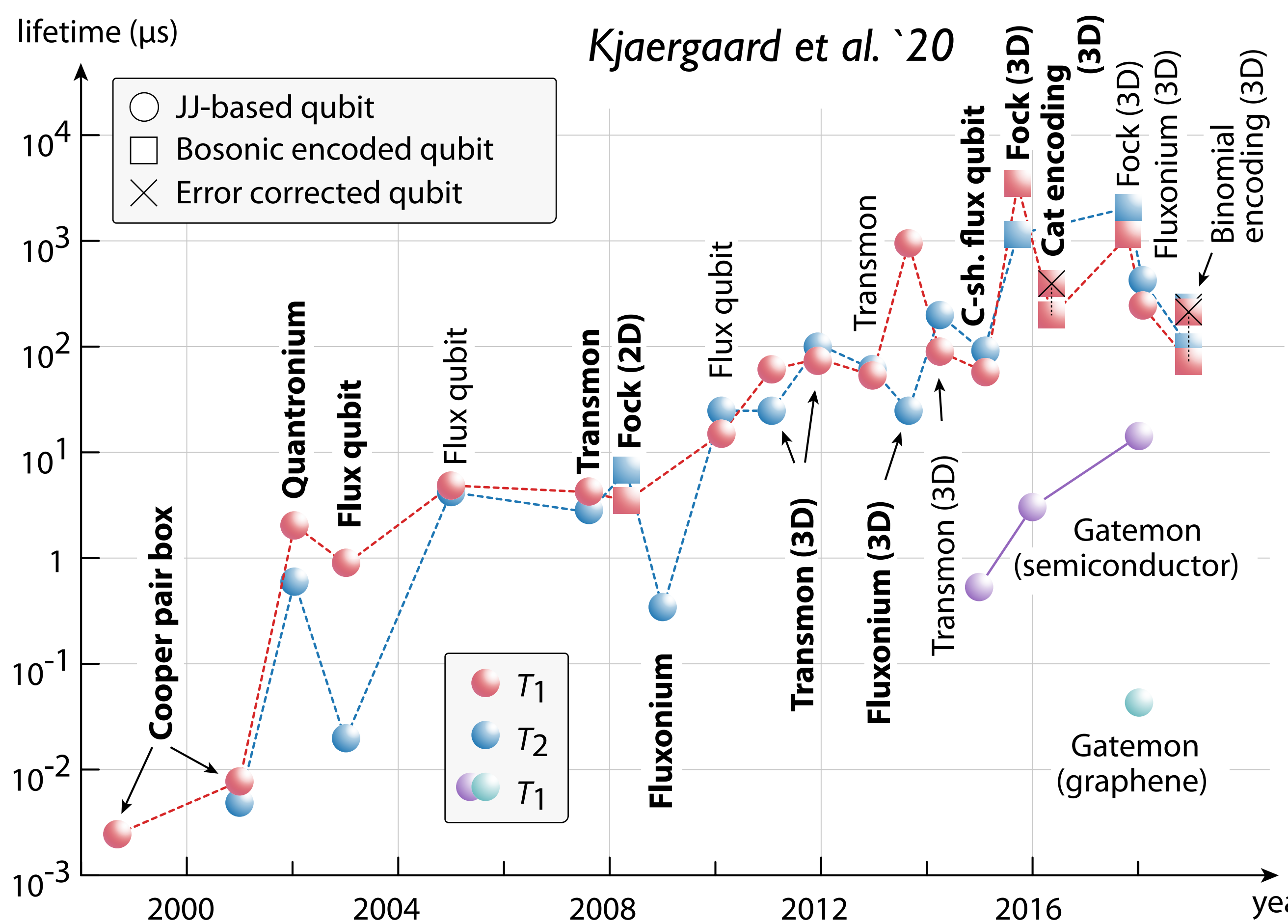
Superconducting circuits

IBM Q

Google rigetti



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



Qubits: Nonlinear quantum oscillator
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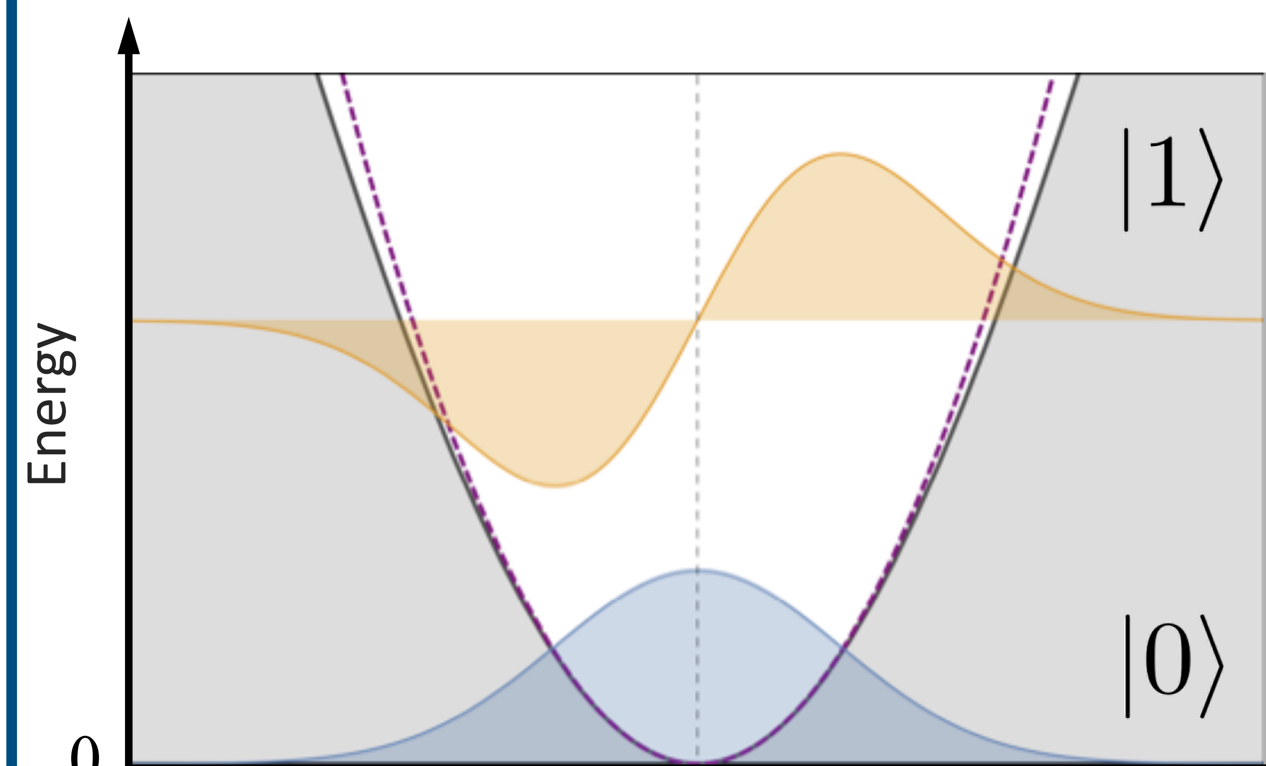

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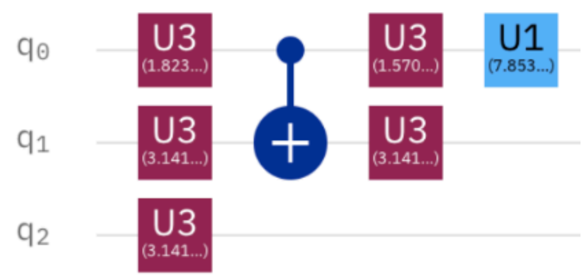
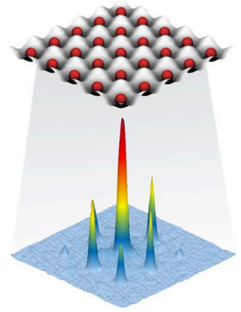
Quantum computing

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

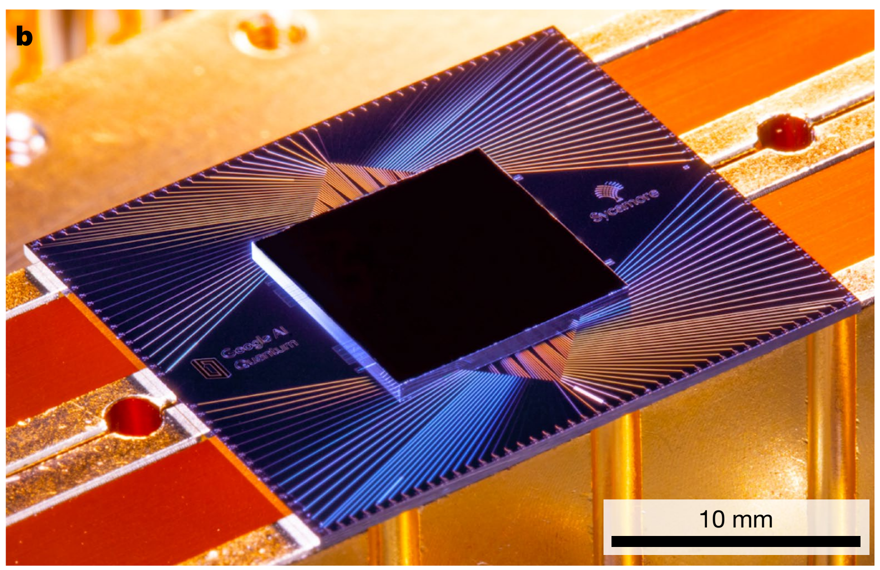
QUANTUM SYSTEMS ACCELERATOR
Catalyzing the Quantum Ecosystem
@LBNL

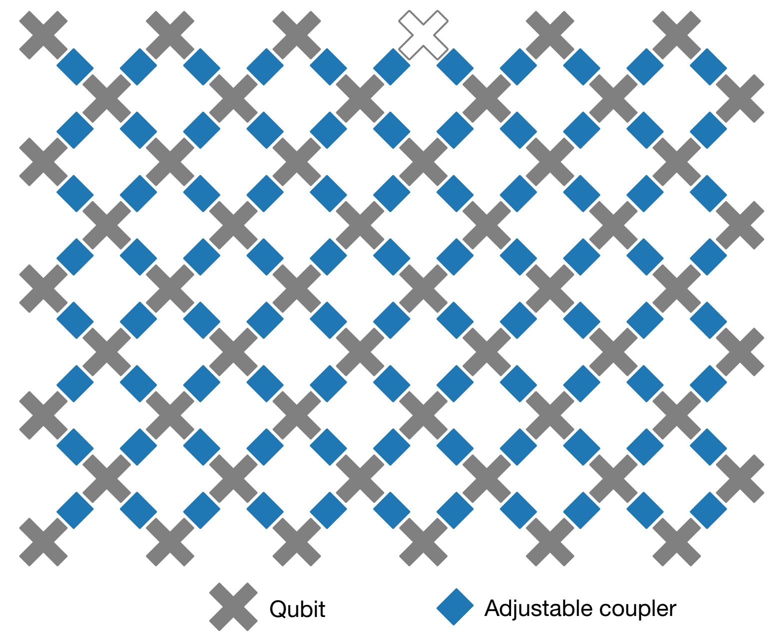
Quantum supremacy

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

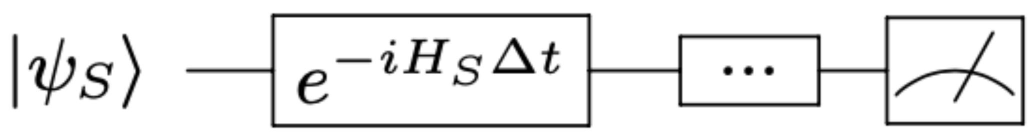
Feynman `81

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)

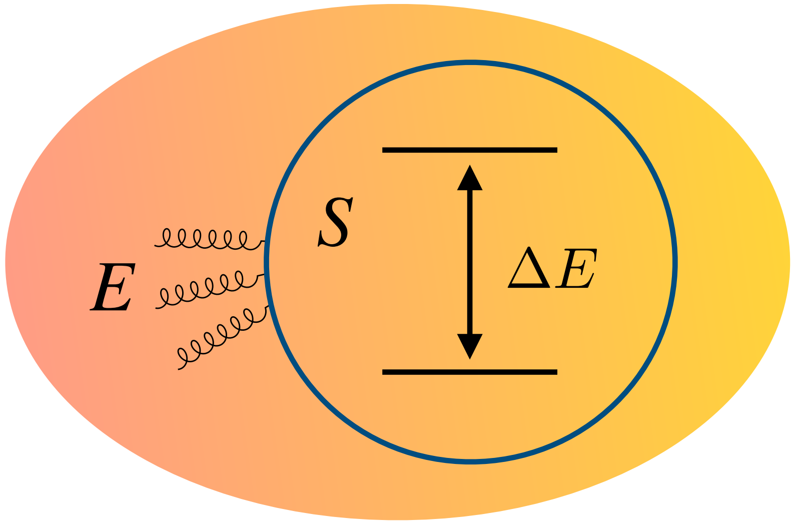
see e.g. *Jordan, Lee, Preskill `11, Preskill `18,*
Klco, Savage et al.`18-`20, Cloet, Dietrich et al. `19

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

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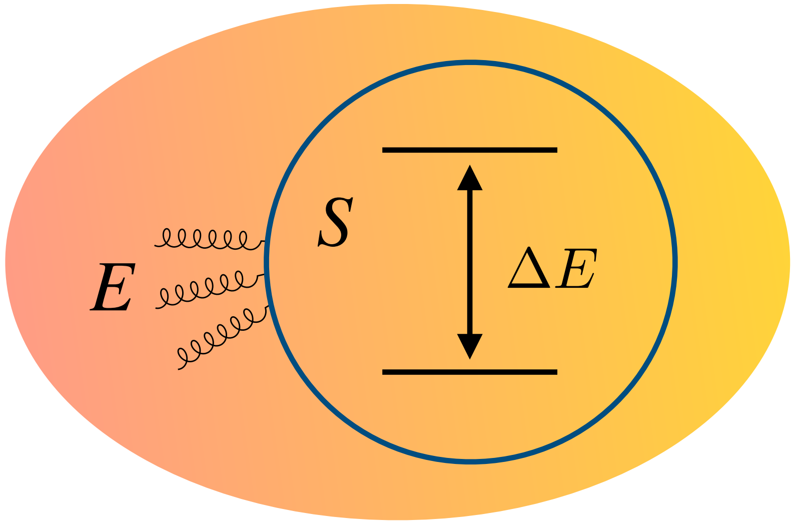

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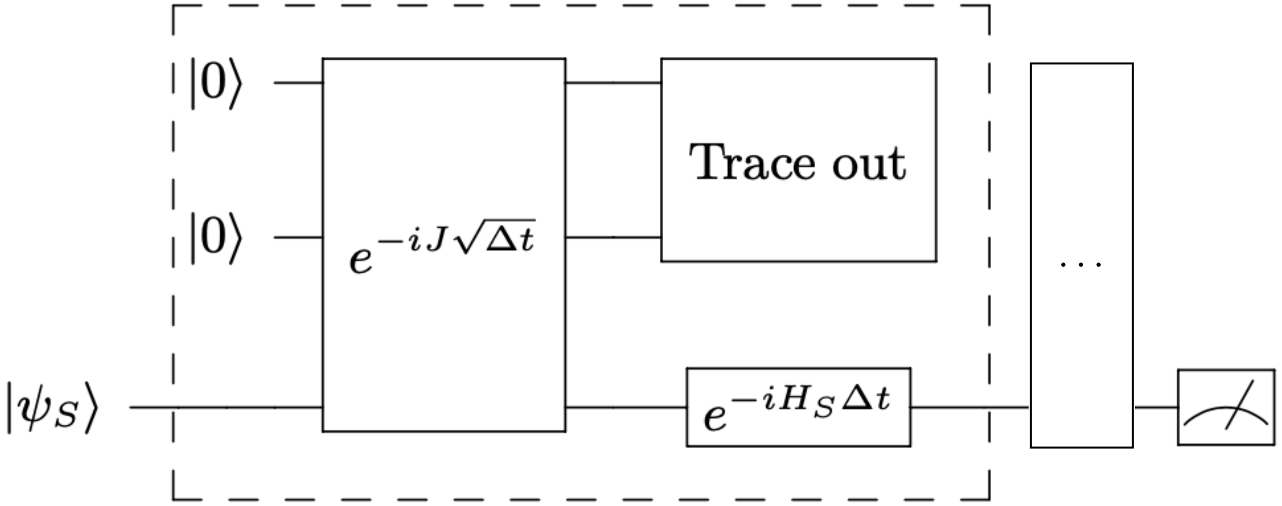
Pauli matrices $X, Y, Z,$ interaction strength g

Lindblad operators

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

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

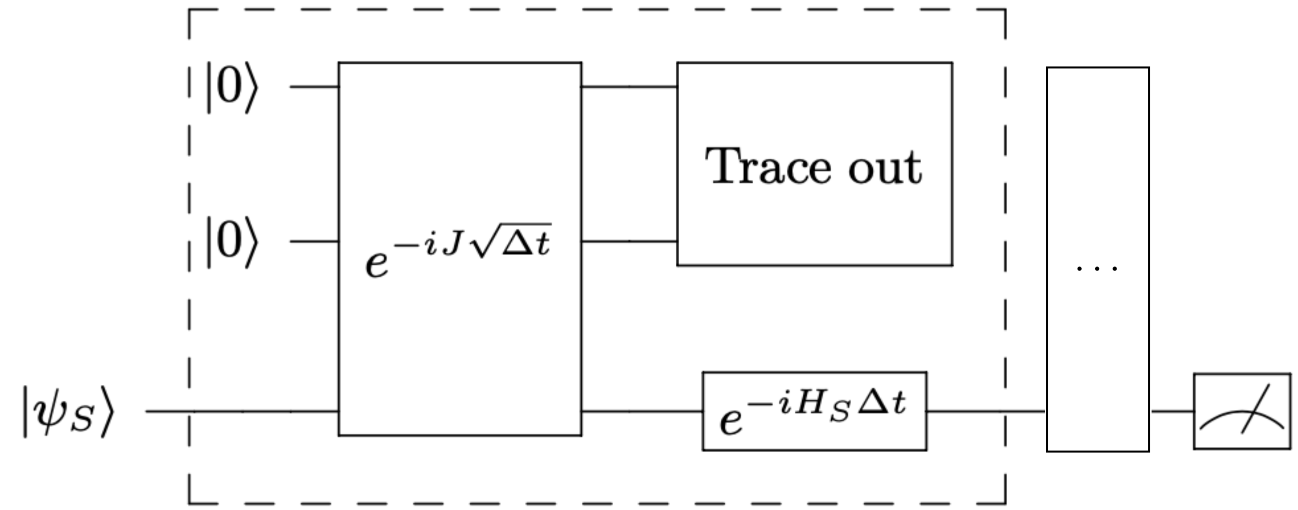


Quantum circuit synthesis

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

Optimization problem w/unitary loss function

`qsearch` *Siddiqi et al. `20* @LBNL

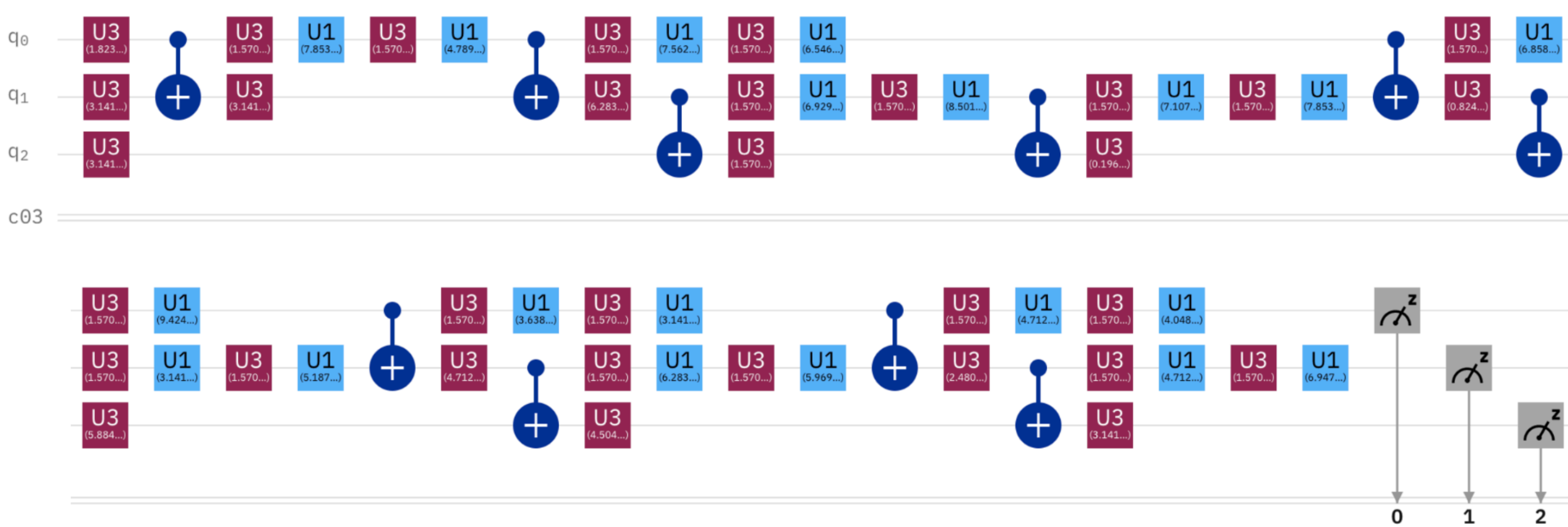


10 CNOT gates/cycle

IBM **Q**

Single qubit

CNOT



Error mitigation

Readout error

Constrained matrix inversion

IBM Q qiskit-ignis

Unfolding

Nachman, Urbanek, de Jong, Bauer `19

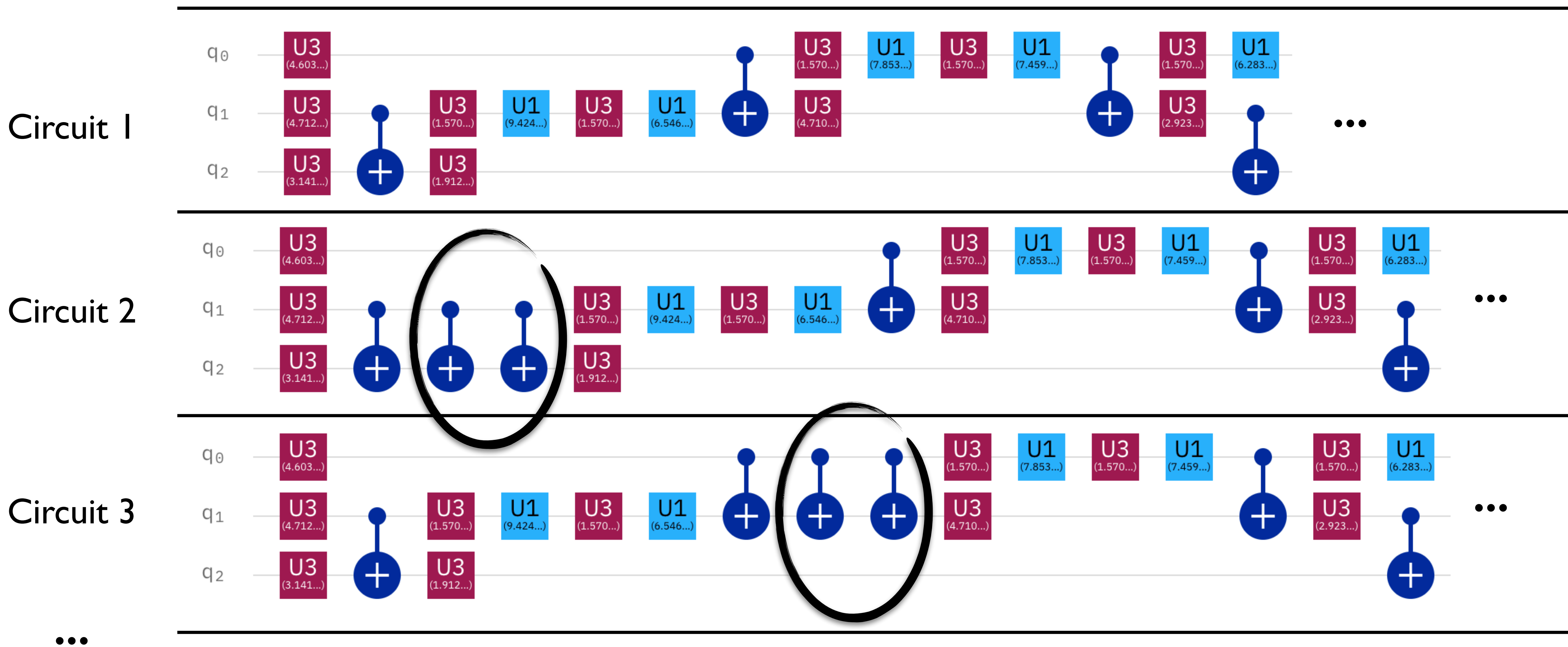
@LBNL

Gate error

Zero-noise extrapolation of CNOT noise using Random Identity Insertions

He, Nachman, de Jong, Bauer `20

@LBNL



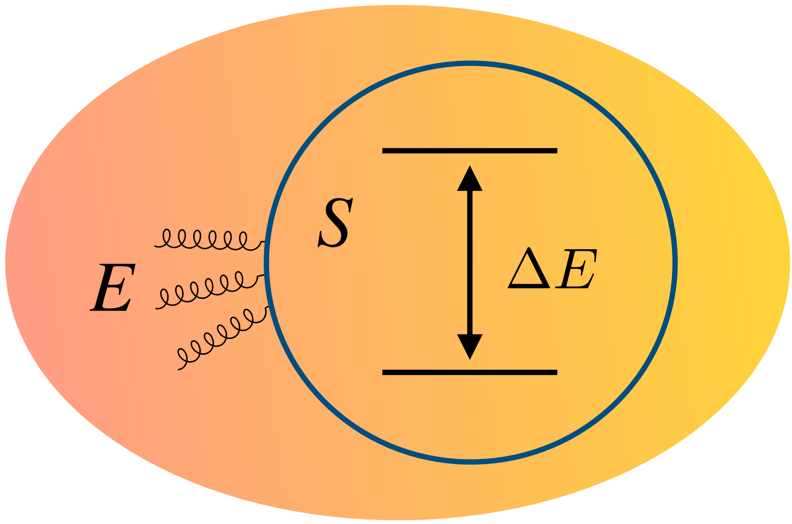
Quantum simulation of open quantum systems

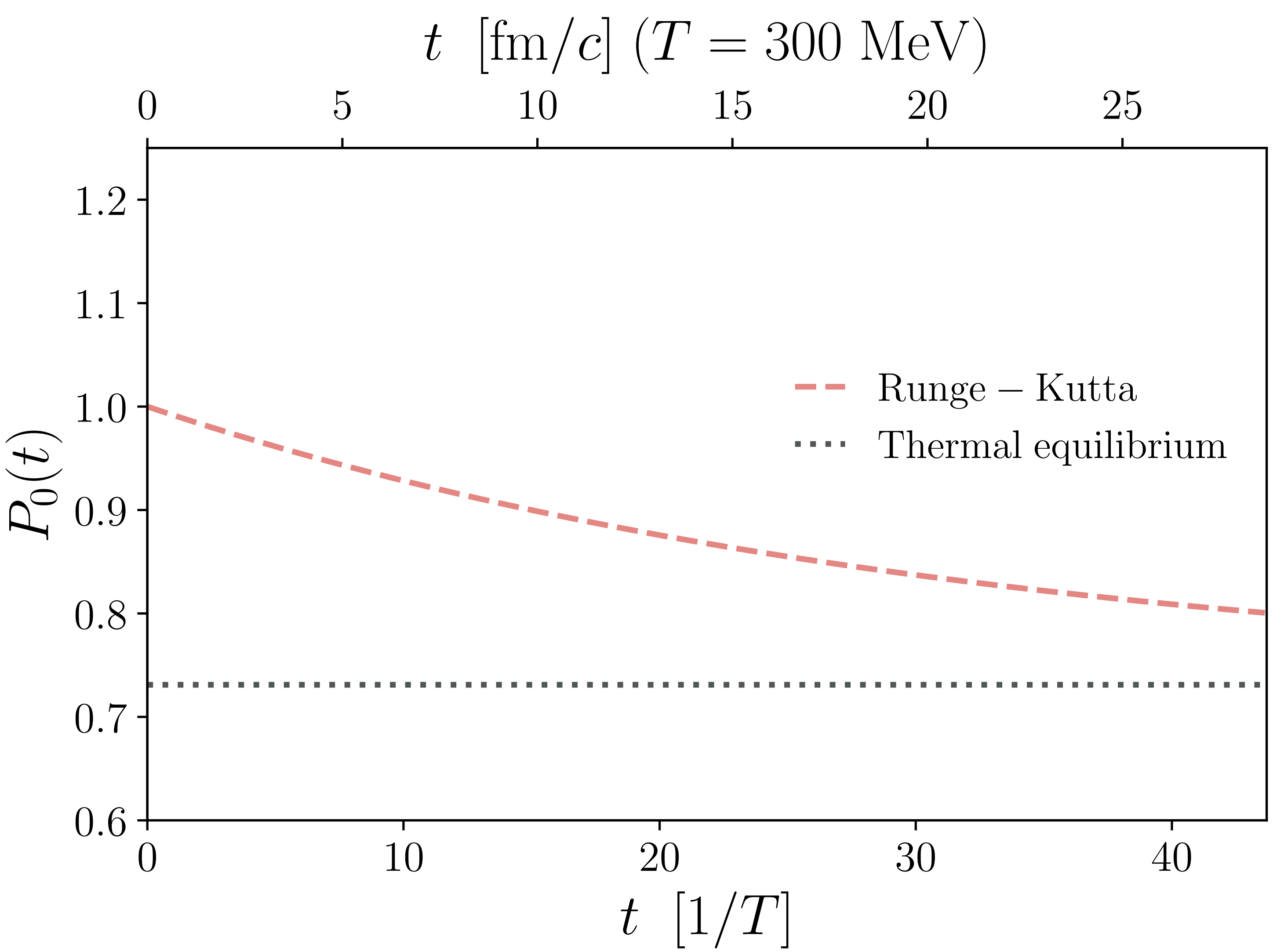
arXiv: 2010.03571

Real-time evolution

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

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





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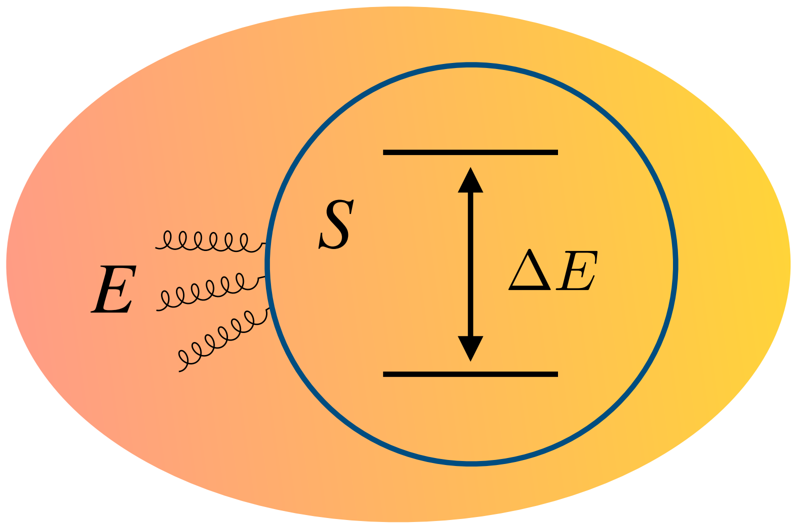
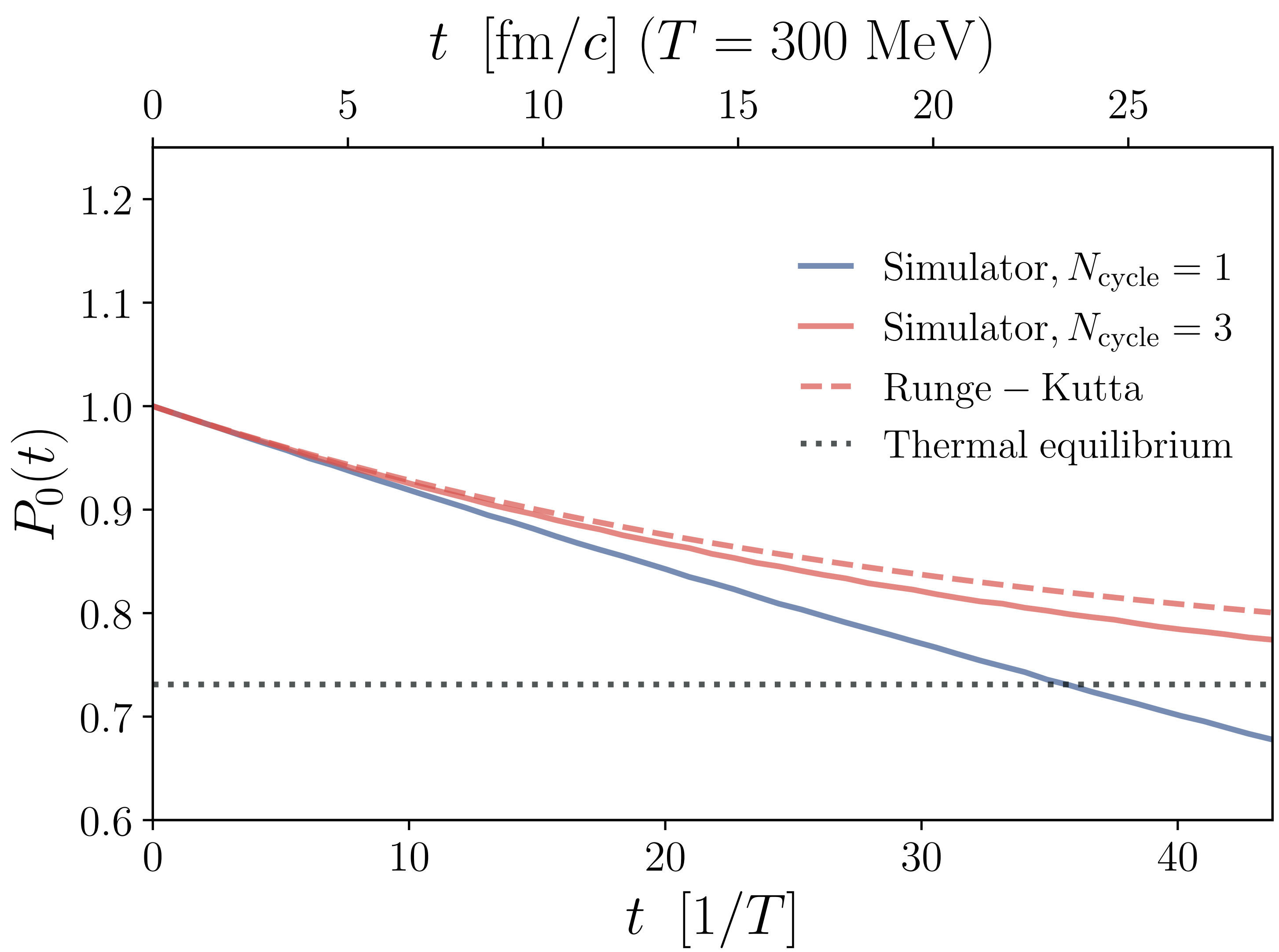




The algorithm converges to Lindblad evolution with a small number of cycles

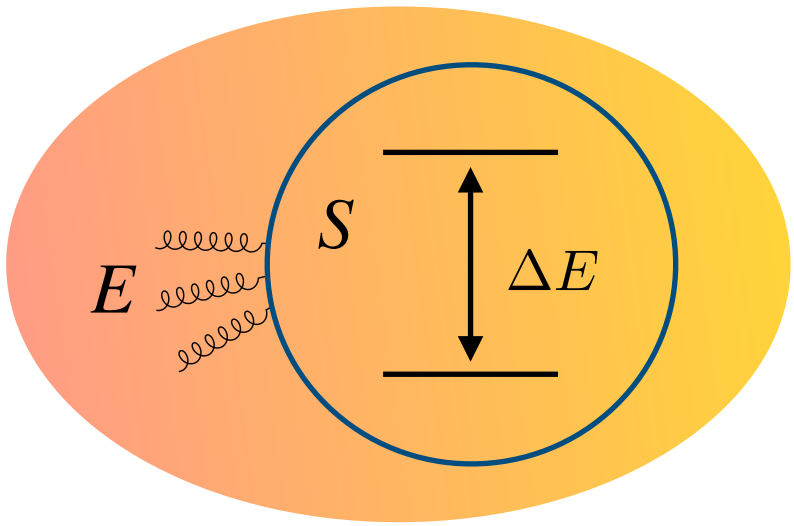
Quantum simulation of open quantum systems

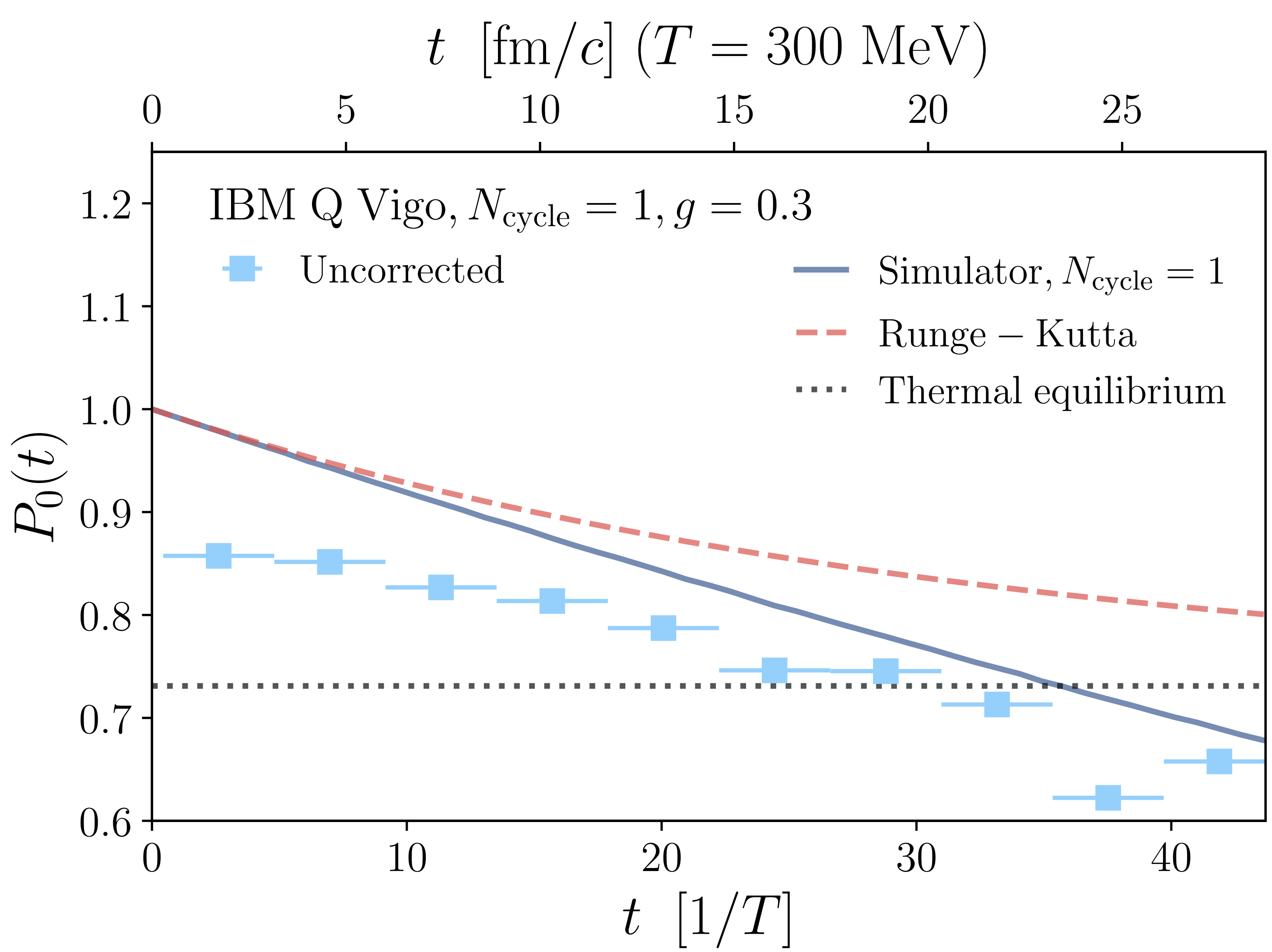
arXiv: 2010.03571

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

Quantum simulation of open quantum systems

arXiv: 2010.03571

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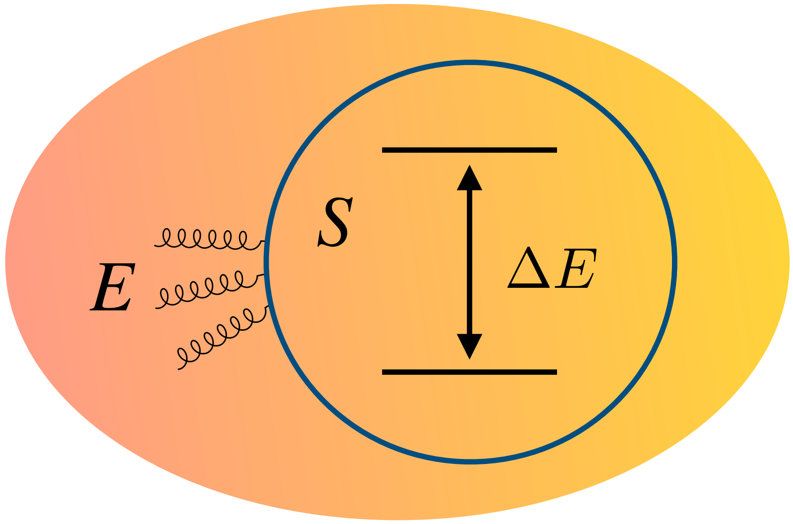

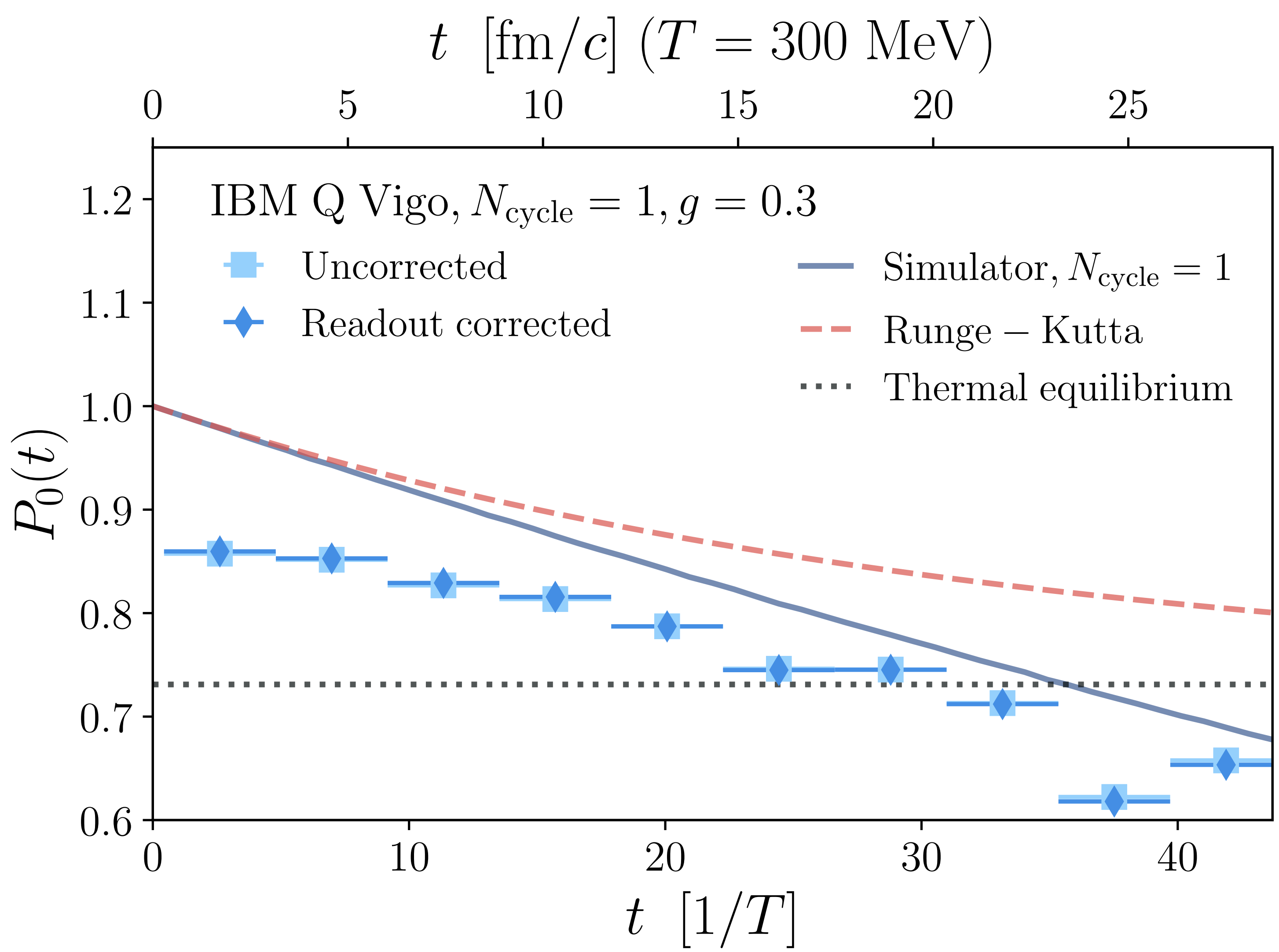

IBM Q Vigo device

Readout correction small

Quantum simulation of open quantum systems

arXiv: 2010.03571

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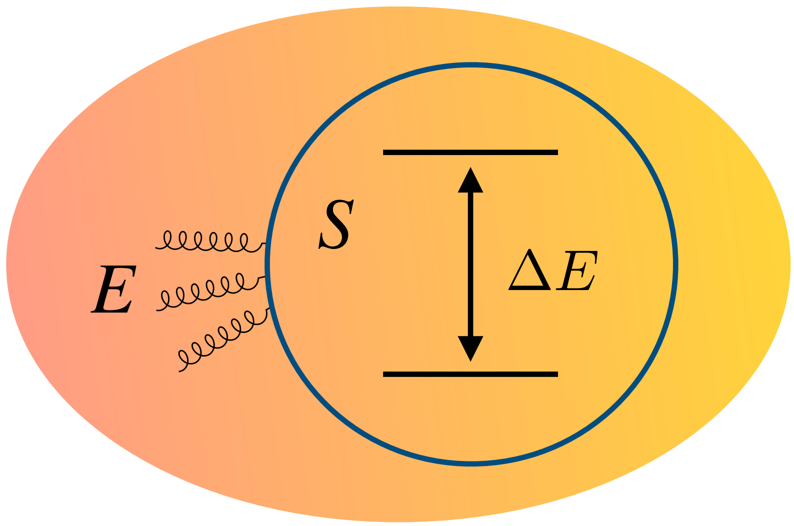

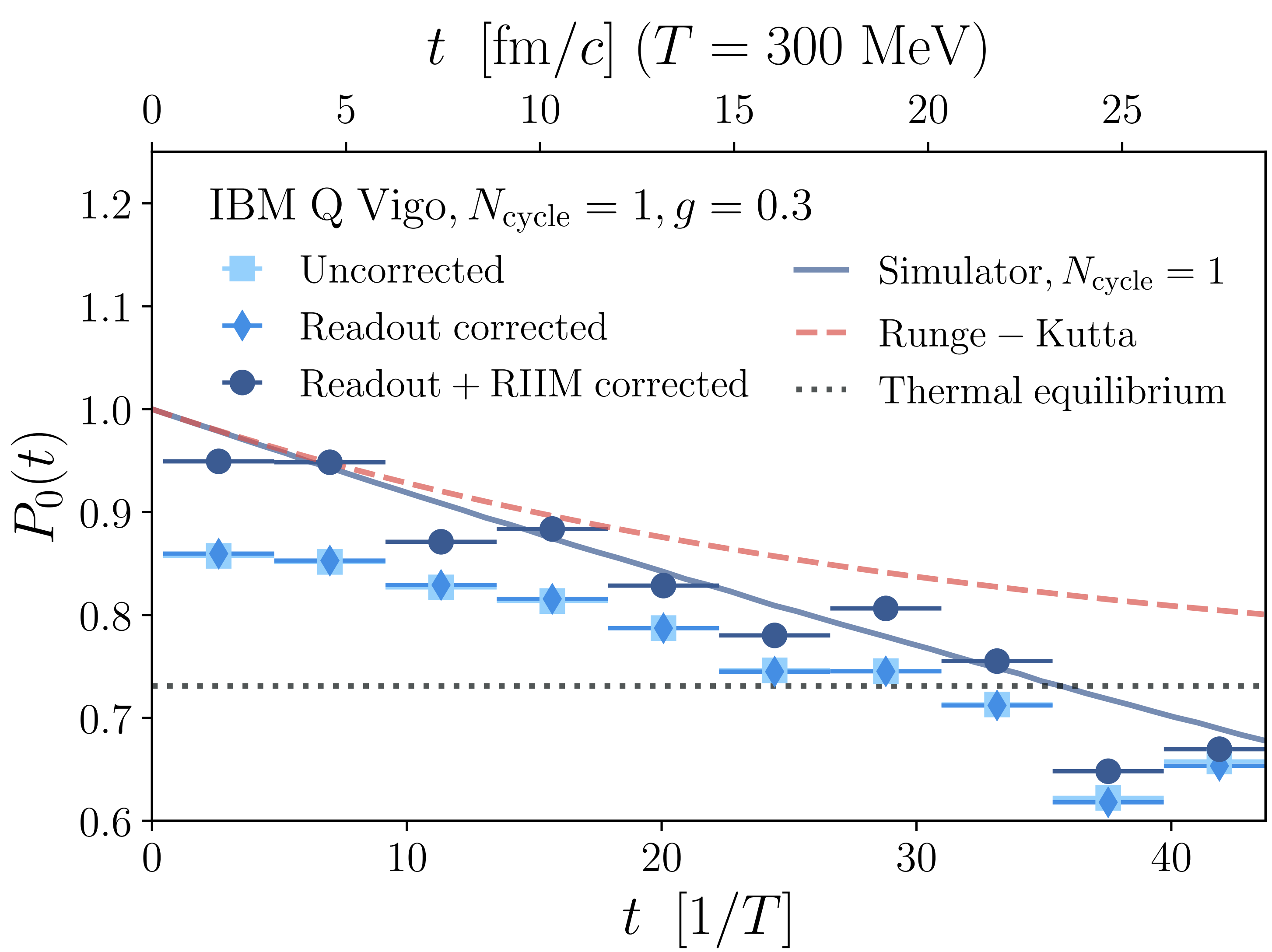

IBM Q Vigo device

Readout correction small

CNOT gate error correction gives good agreement

Random Identity Insertion Method (RIIM)

Bauer, He, de Jong, Nachman `20

Proof of concept

Outline

Open quantum systems in heavy-ion collisions

Quantum simulation with IBM Q

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