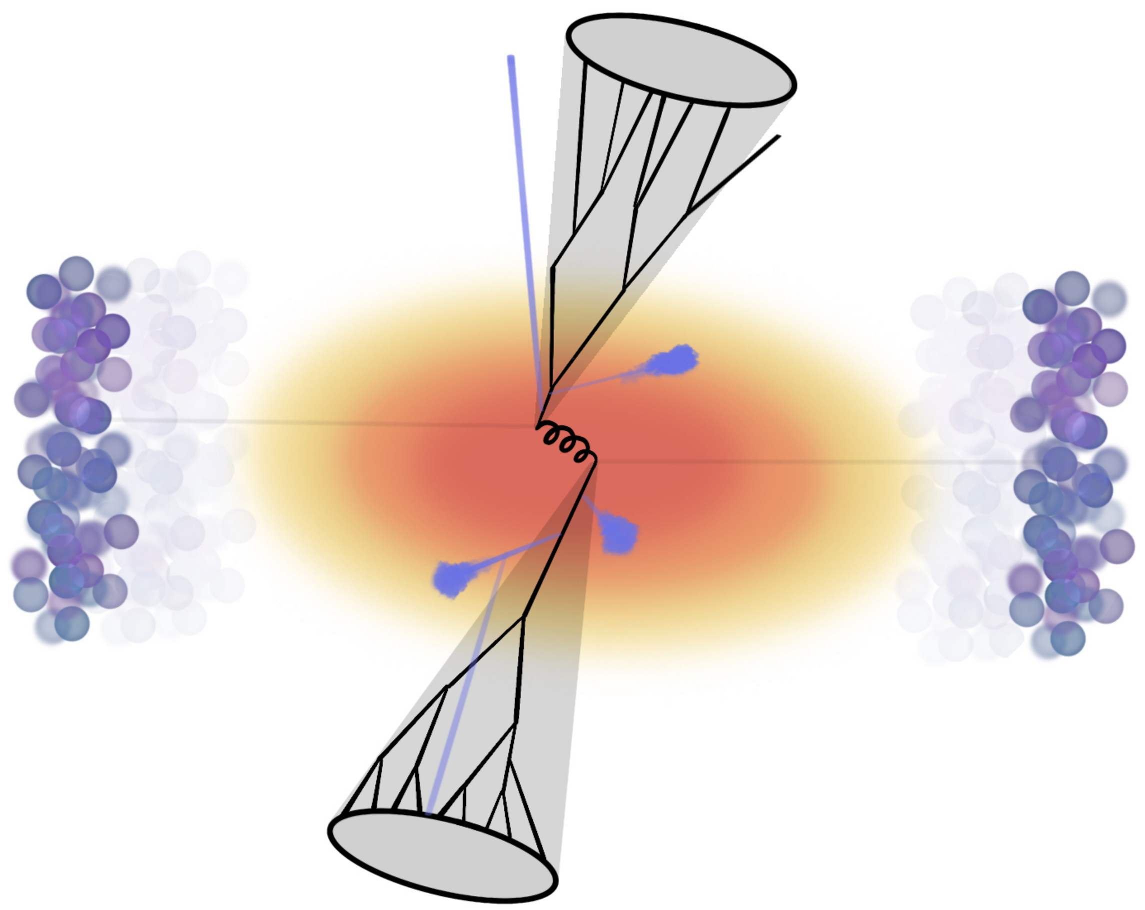
Simulating real-time dynamics of nuclear matter on quantum computers



James Mulligan
University of California, Berkeley

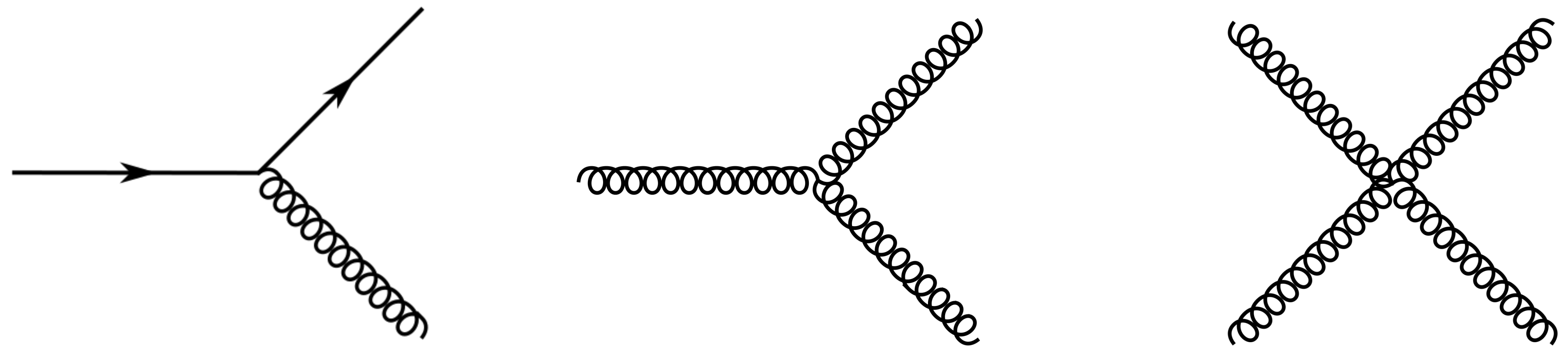
Seminar in Hadronic Physics
McGill University
Feb 21, 2022

Quantum chromodynamics

$$\mathscr{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \sum_{j=1}^{6} \bar{q}_j \left(i\gamma^\mu D_\mu - m_j \right) q_j$$

Perturbative QCD

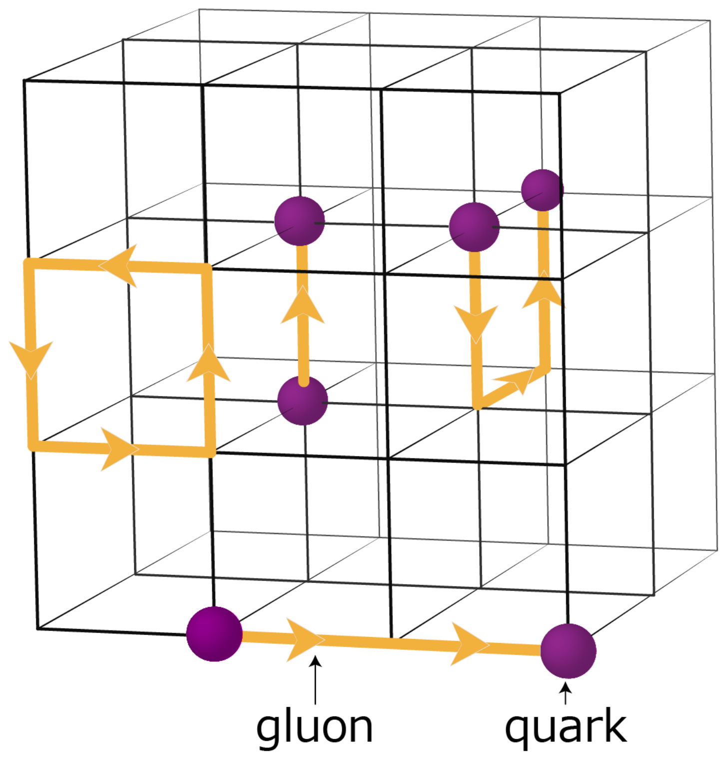
For $\alpha_s \ll 1$, compute scattering amplitudes with Feynman diagrams



$$\sigma = \sigma^{(0)} + \alpha_s \sigma^{(1)} + \alpha_s^2 \sigma^{(2)} + \ldots$$

Lattice QCD

For low-density systems, compute static quantities with lattice regularization



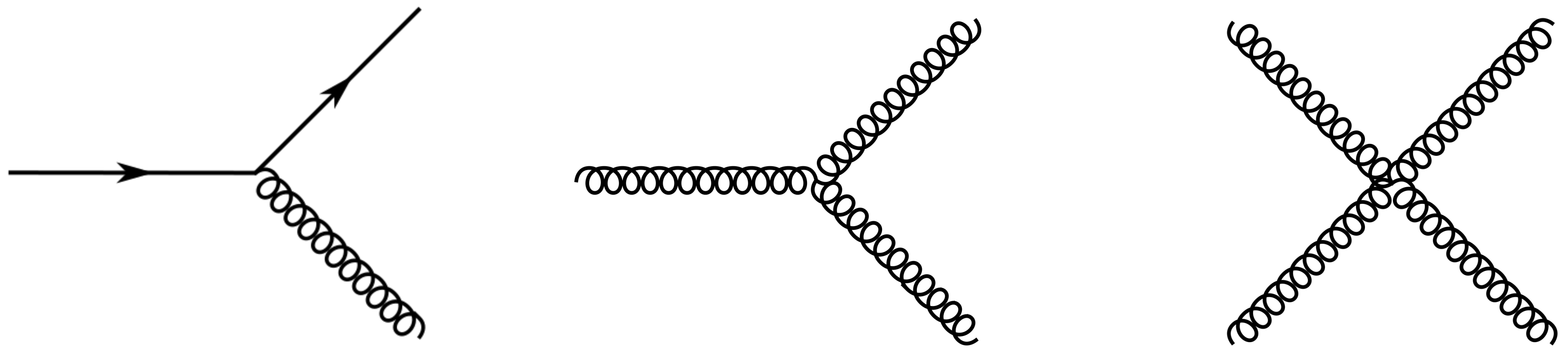
- Hadron spectra
- Deconfinement transition
- Chiral symmetry restoration

Quantum chromodynamics

$$\mathscr{L} = -\frac{1}{4}F^{a}_{\mu\nu}F^{a\mu\nu} + \sum_{j=1}^{6} \bar{q}_j\left(i\gamma^{\mu}D_{\mu} - m_j\right)q_j$$

Perturbative QCD

For $\alpha_s \ll 1$, compute scattering amplitudes with Feynman diagrams

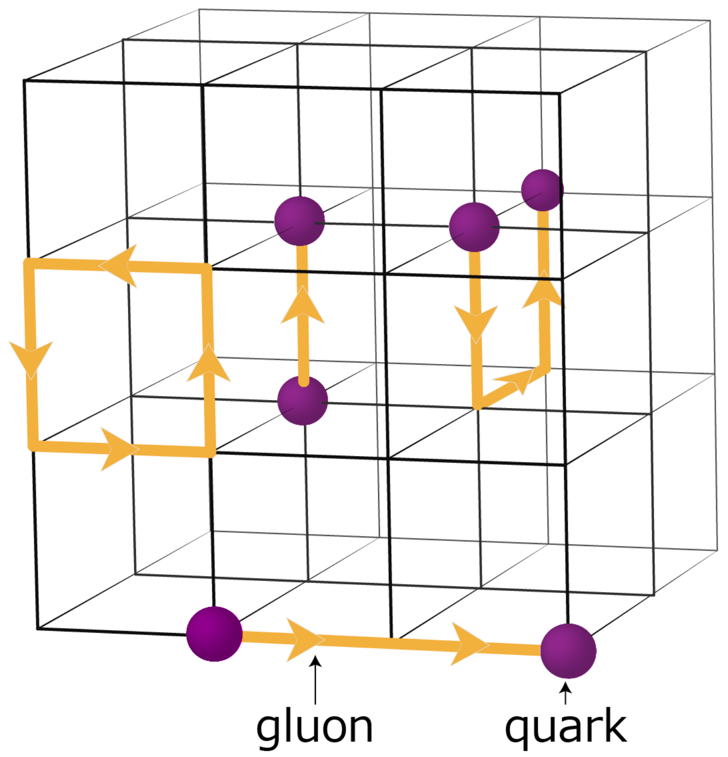


$$\sigma = \sigma^{(0)} + \alpha_s\sigma^{(1)} + \alpha_s^2\sigma^{(2)} + \ldots$$

...but no strong coupling!

Lattice QCD

For low-density systems, compute static quantities with lattice regularization



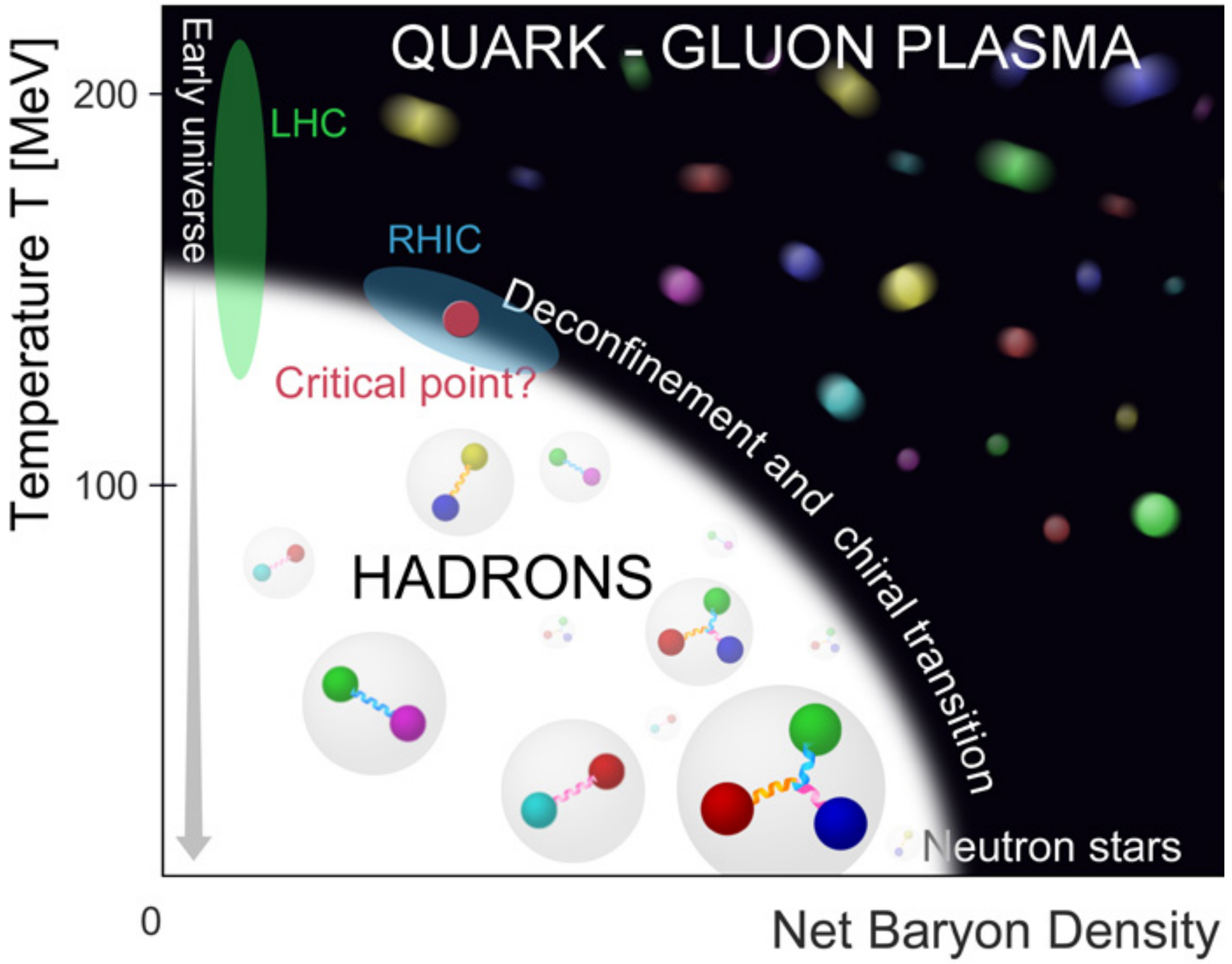
- Hadron spectra
- Deconfinement transition
- Chiral symmetry restoration

...but no dynamics!

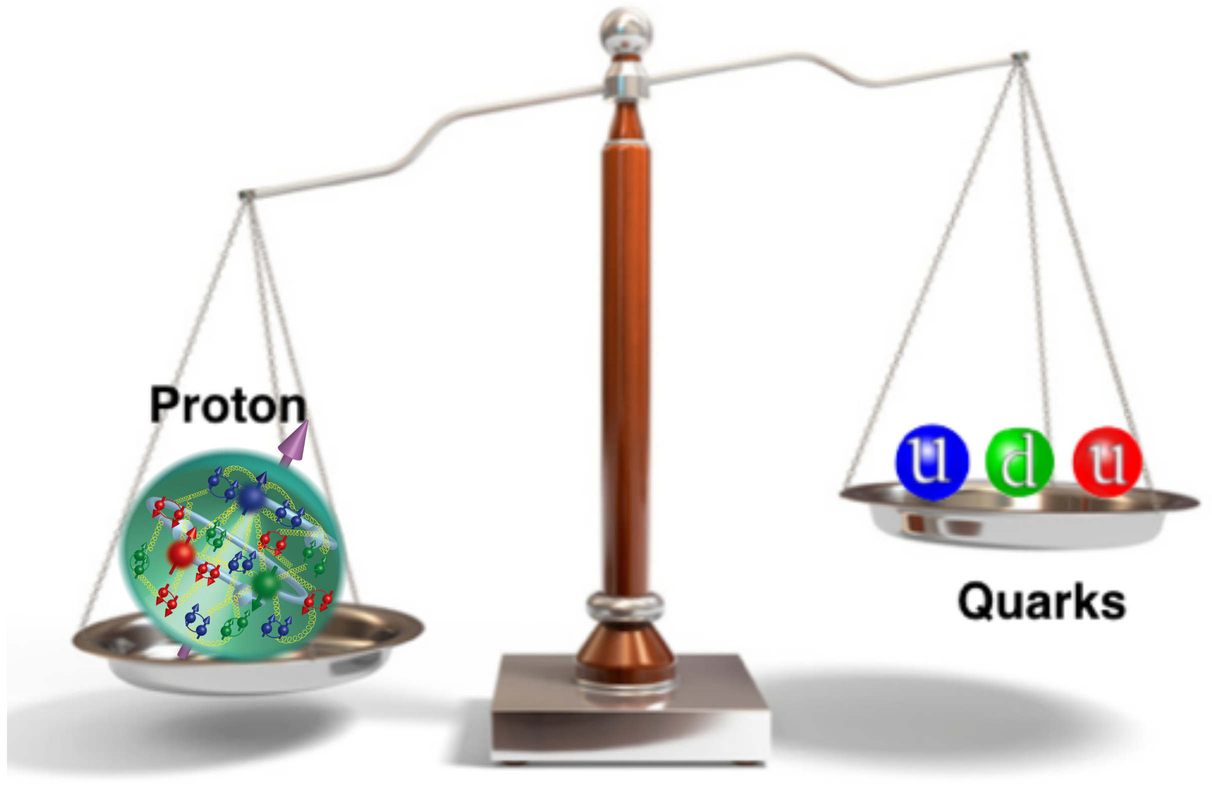
Emergence in QCD

While we know the Lagrangian…we still often don't know how to solve it

What is the landscape of QCD matter?



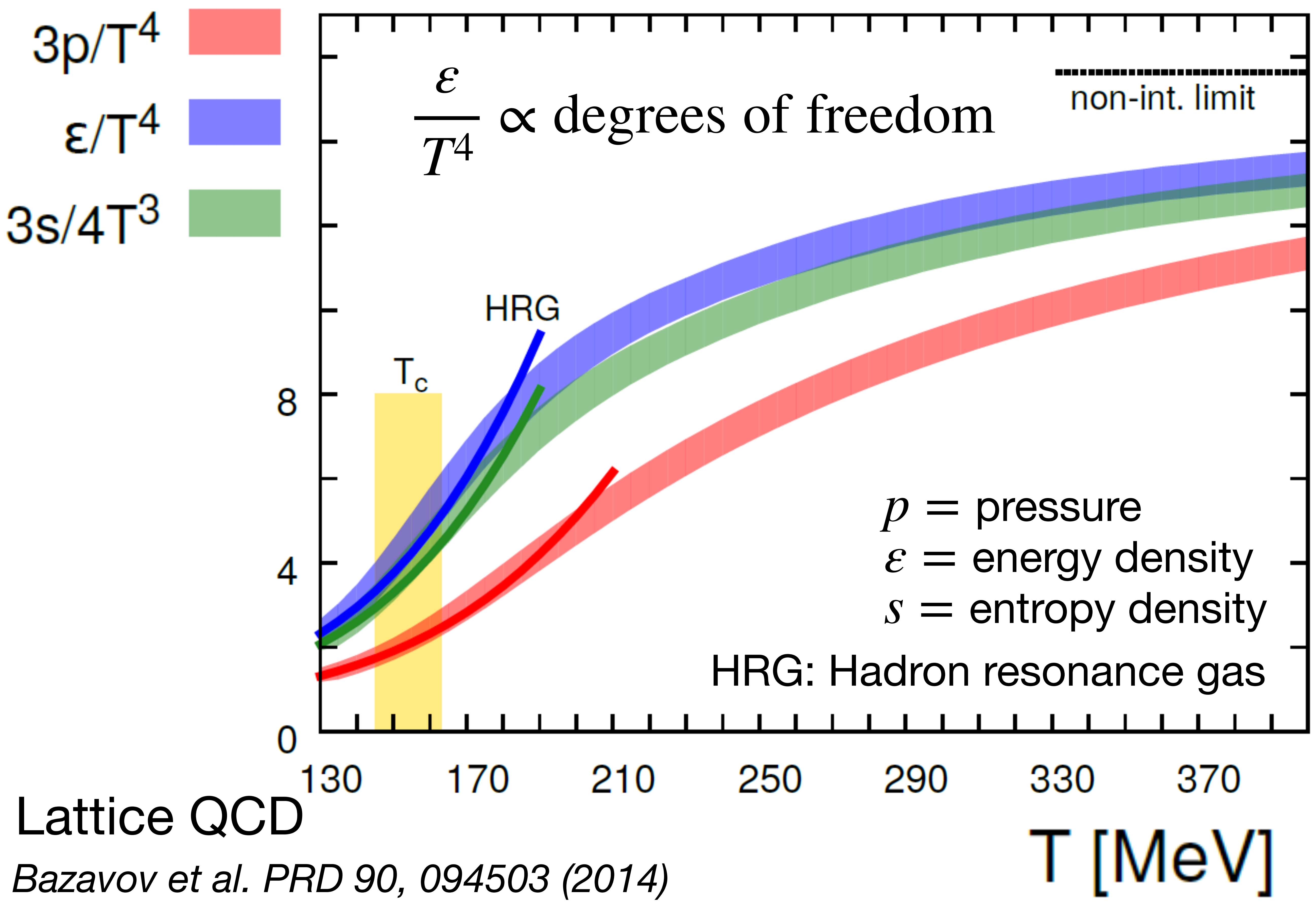
What are the *dynamics* that confine quarks and gluons into hadrons?



Opportunity to study a strongly-interacting, many-body quantum field theory

The quark-gluon plasma

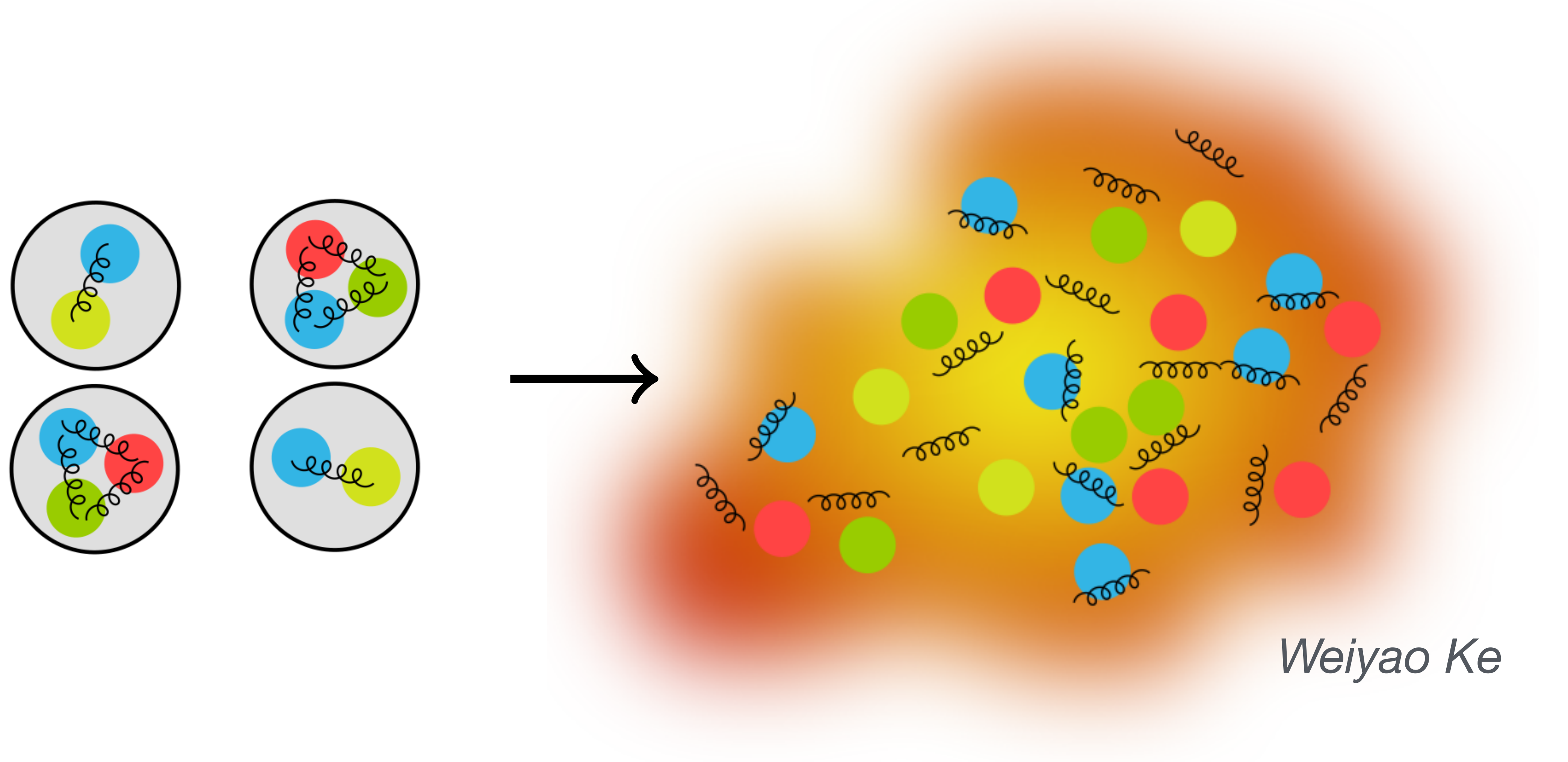
If we heat nuclear matter to $T = \mathcal{O}(100~\mathrm{MeV})$, thermodynamic quantities exhibit a rapid rise near a crossover temperature T_c



Lattice QCD

Bazavov et al. PRD 90, 094503 (2014)

Deconfinement of quarks and gluons



Weiyao Ke

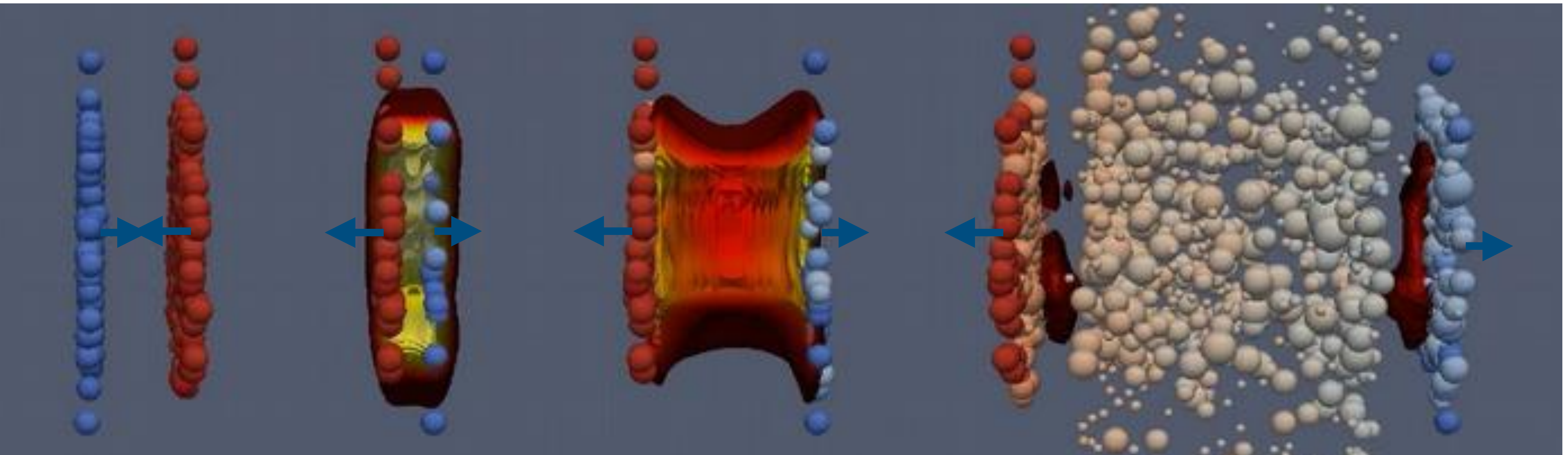
Heavy-ion collisions

We collide nuclei together at the

Large Hadron Collider (LHC)

Relativistic Heavy Ion Collider (RHIC)

to produce droplets of hot, dense quark-gluon plasma



MADAI Collaboration

Soft collisions transform kinetic energy of nuclei into region of large energy density

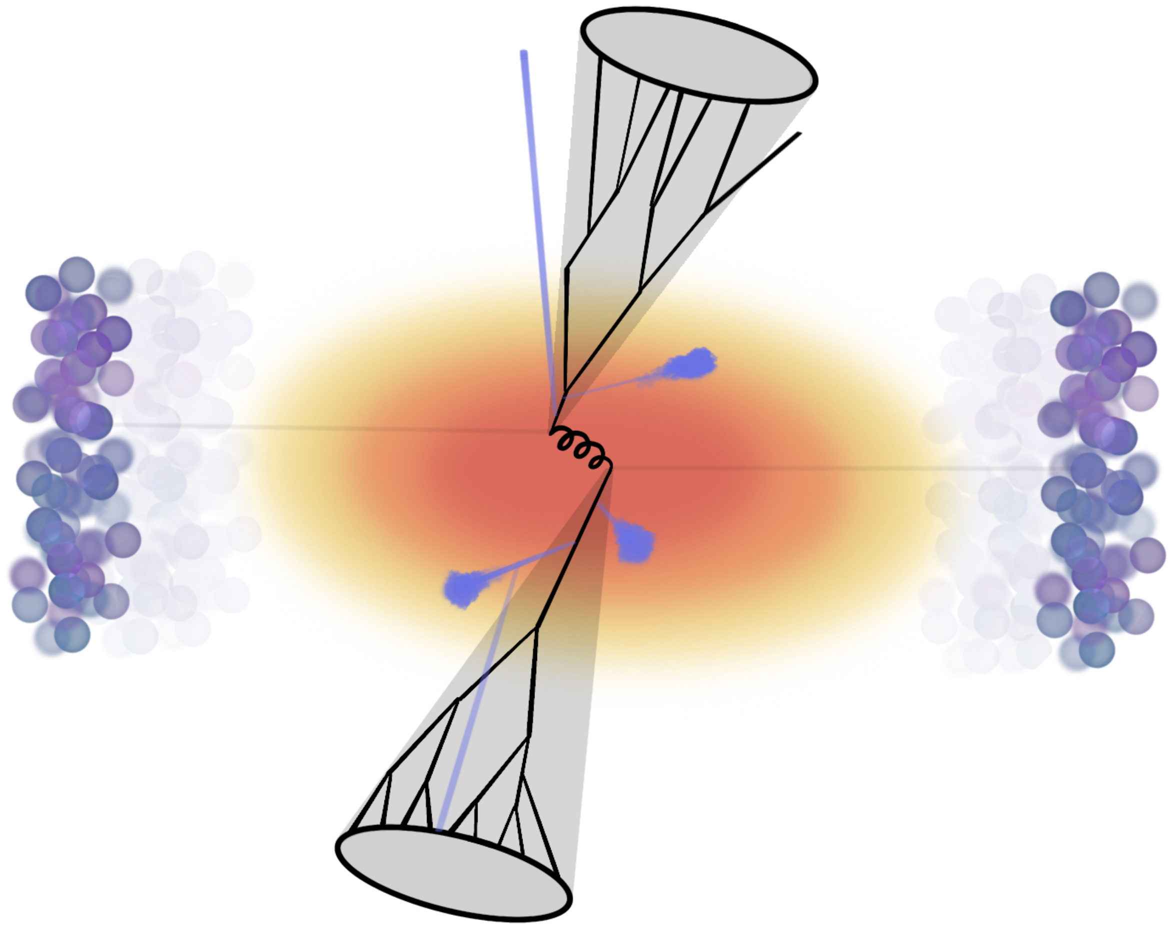
$T \approx 150\text{-}500$ MeV $\quad t \sim \mathcal{O}\left(10 \text{ fm}/c\right)$

Real-time dynamics

Non-equilibrium dynamics are key to heavy-ion collisions

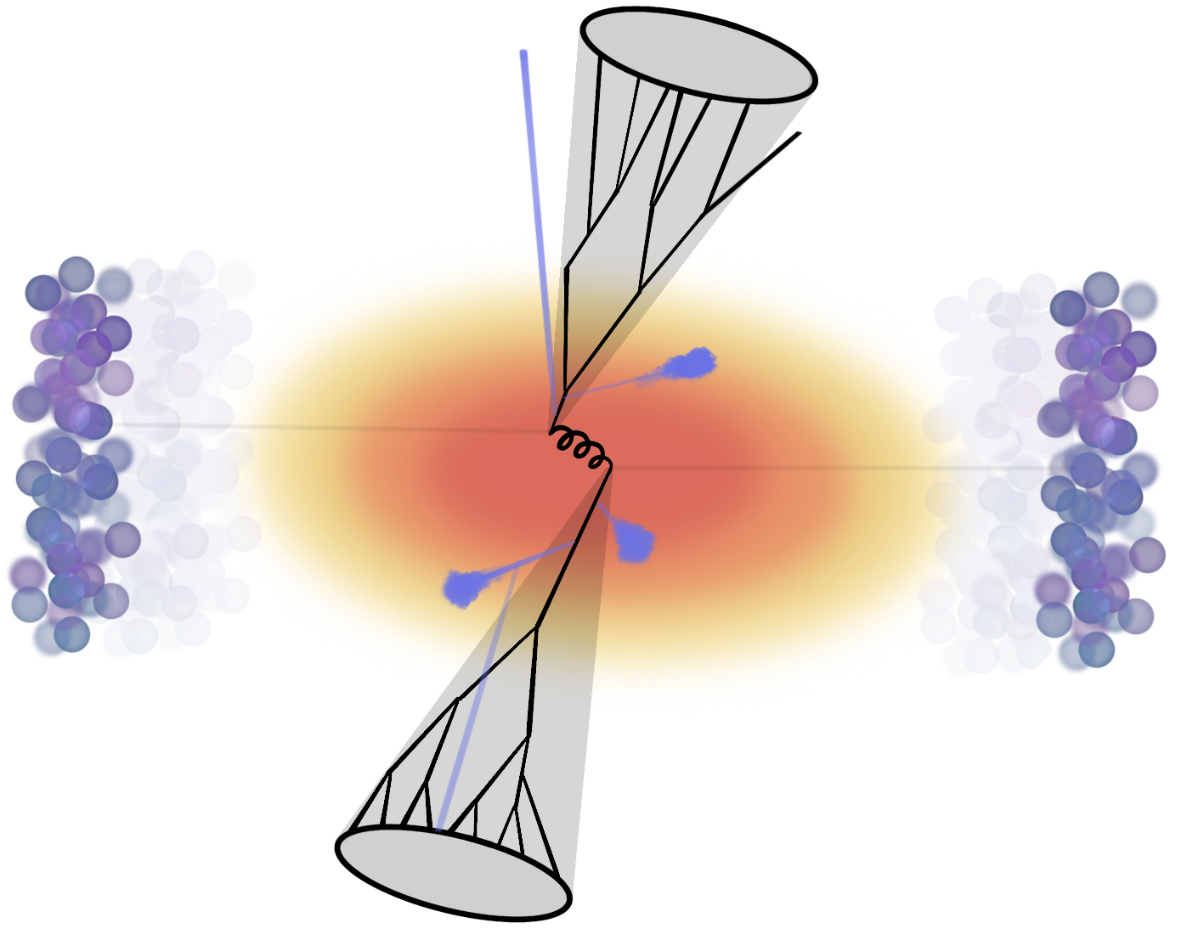
- Spacetime picture of fragmentation and hadronization
- Thermalization
- Transport coefficients

Cohen, Lamm, Lawrence, Yamauchi (2021)



Real-time dynamics

Non-equilibrium dynamics are key to heavy-ion collisions



- Spacetime picture of fragmentation and hadronization
- Thermalization
- Transport coefficients

Cohen, Lamm, Lawrence, Yamauchi (2021)

Can we simulate real-time dynamics in QCD?

Traditional Lattice QCD cannot simulate dynamics due to a sign problem

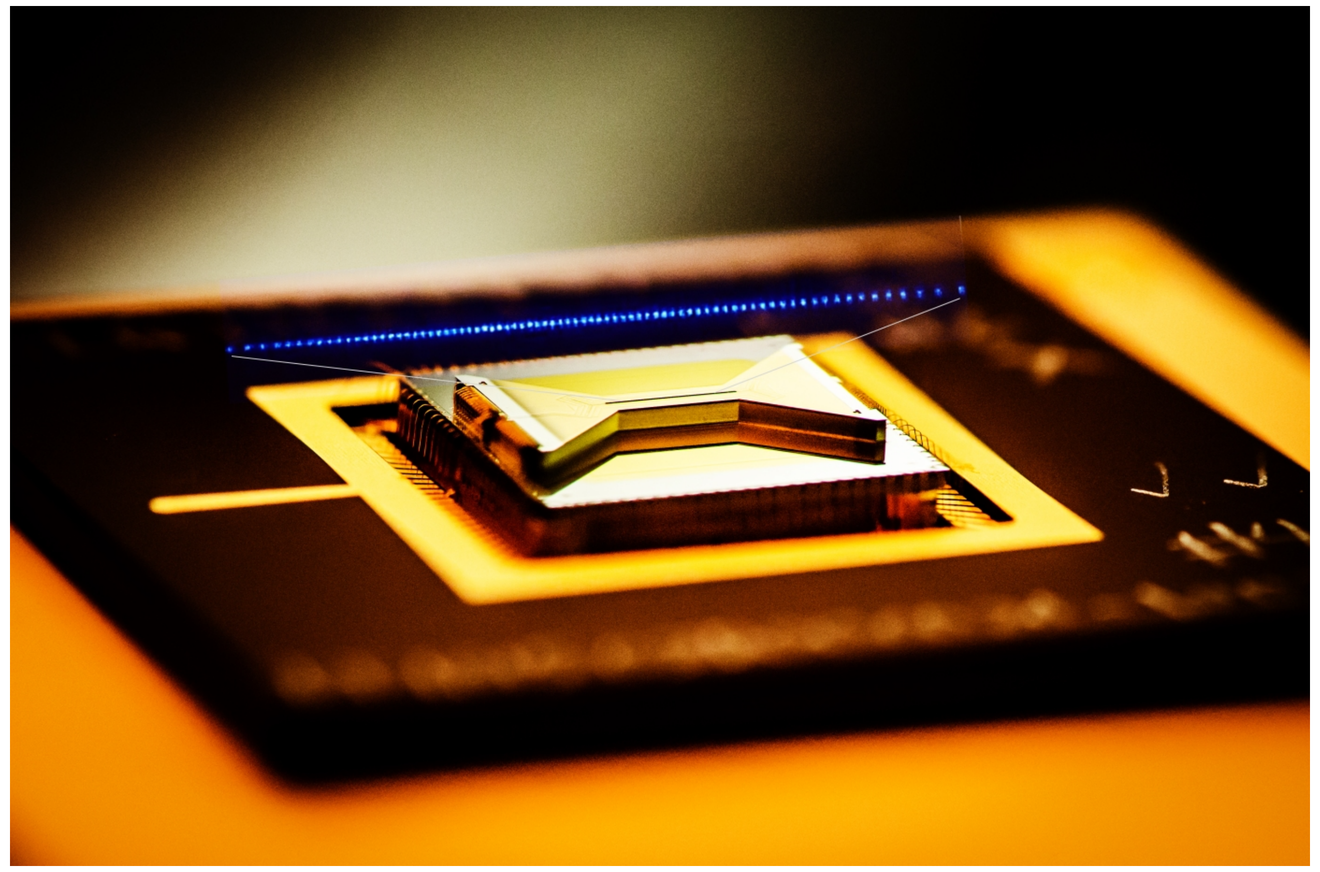
$$\int e^{i\mathscr{L}t} \qquad\qquad t \to it$$

Quantum computers may be able to directly simulate the
Hamiltonian formulation of QCD

A new type of experiment

Quantum simulation

Tunable interactions between qubits



IONQ

Rapid advances in qubit coherence times and quantum gates

Superconducting circuits

IBM **Q**

Google rigetti

Trapped ions

IONQ

Honeywell

And a variety of others:

Optical lattice
Photonics
Rydberg atoms
Topological
…

Ψ PsiQuantum

…

State-of-the-art: $\mathcal{O}(10)$ qubits, $\mathcal{O}(100)$ two-qubit operations

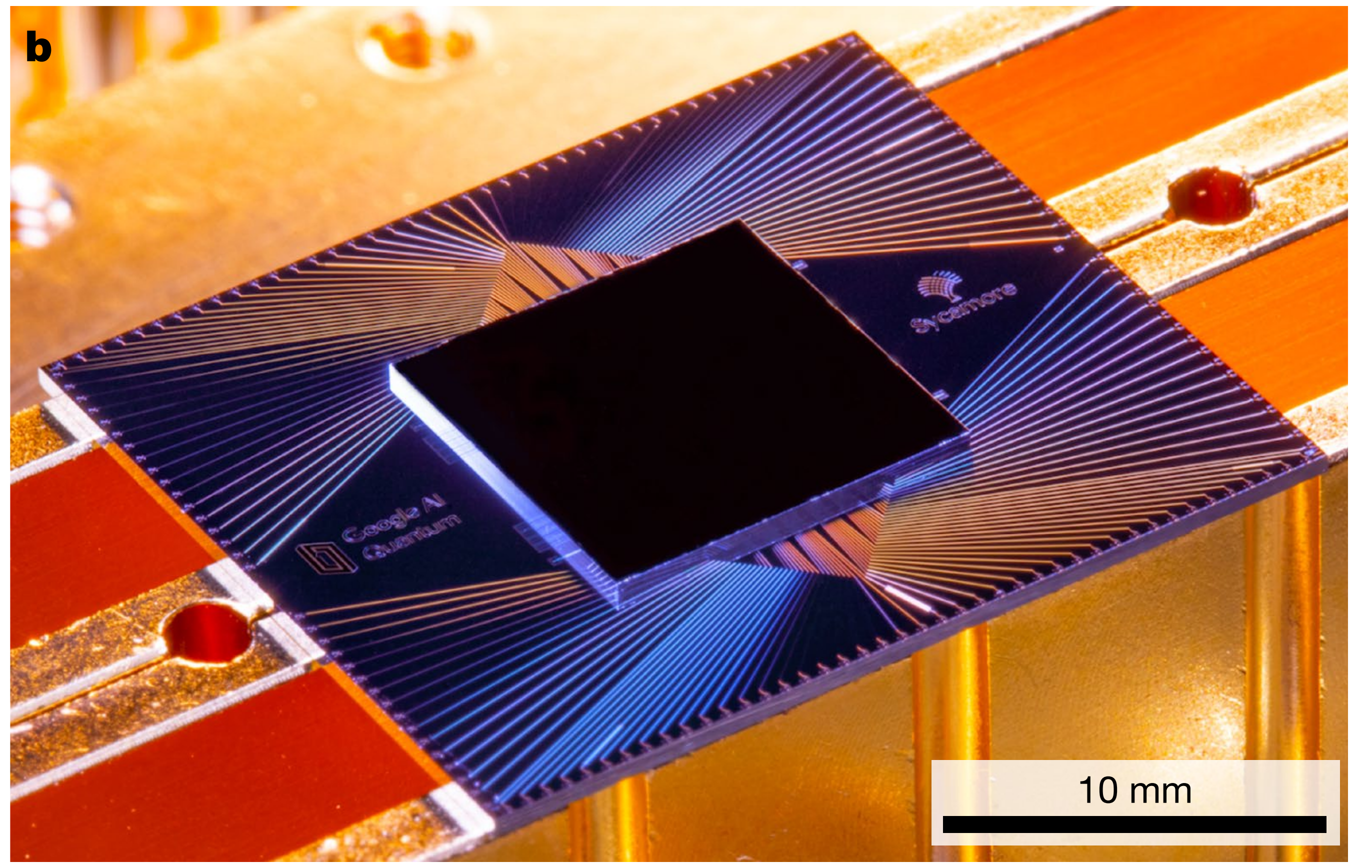
Quantum advantage

2019

Article

Quantum supremacy using a programmable superconducting processor Google

Martinis et al., Nature (2019)



53-qubit superconducting circuit device

Algorithm: sampling of random circuits

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

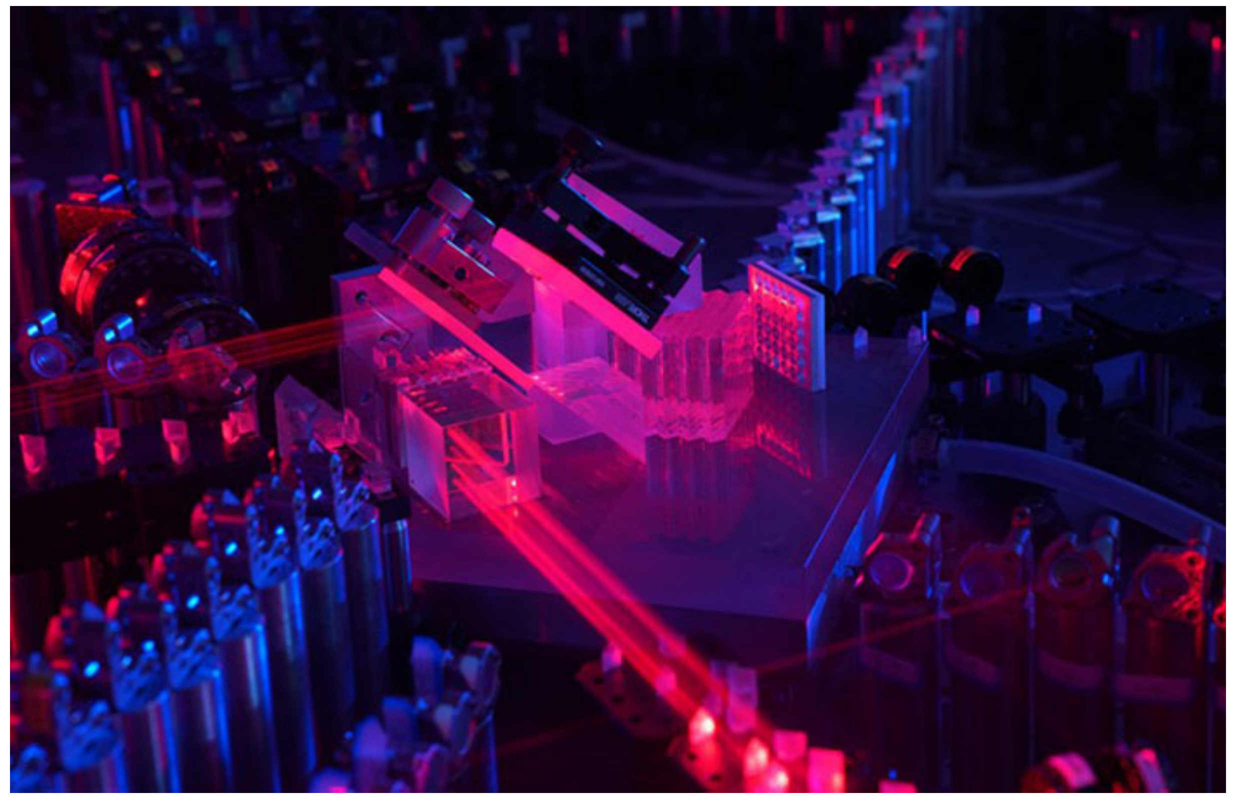
See also: Pan et al., PRL (2021)

2020-2021

Quantum computational advantage using photons

Han-Sen Zhong[1,2*], Hui Wang[1,2*], Yu-Hao Deng[1,2*], Ming-Cheng Chen[1,2*], Li-Chao Peng[1,2], Yi-Han Luo[1,2], Jian Qin[1,2], Dian Wu[1,2], Xing Ding[1,2], Yi Hu[1,2], Peng Hu[3], Xiao-Yan Yang[3], Wei-Jun Zhang[3], Hao Li[3], Yuxuan Li[4], Xiao Jiang[1,2], Lin Gan[4], Guangwen Yang[4], Lixing You[3], Zhen Wang[3], Li Li[1,2], Nai-Le Liu[1,2], Chao-Yang Lu[1,2], Jian-Wei Pan[1,2†]

Pan et al., Science (2020)



Photonic device — special-purpose

Algorithm: boson sampling

Claim: $\mathcal{O}\left(10^{14}\right)$ times faster than best classical supercomputers

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

Quantum computing

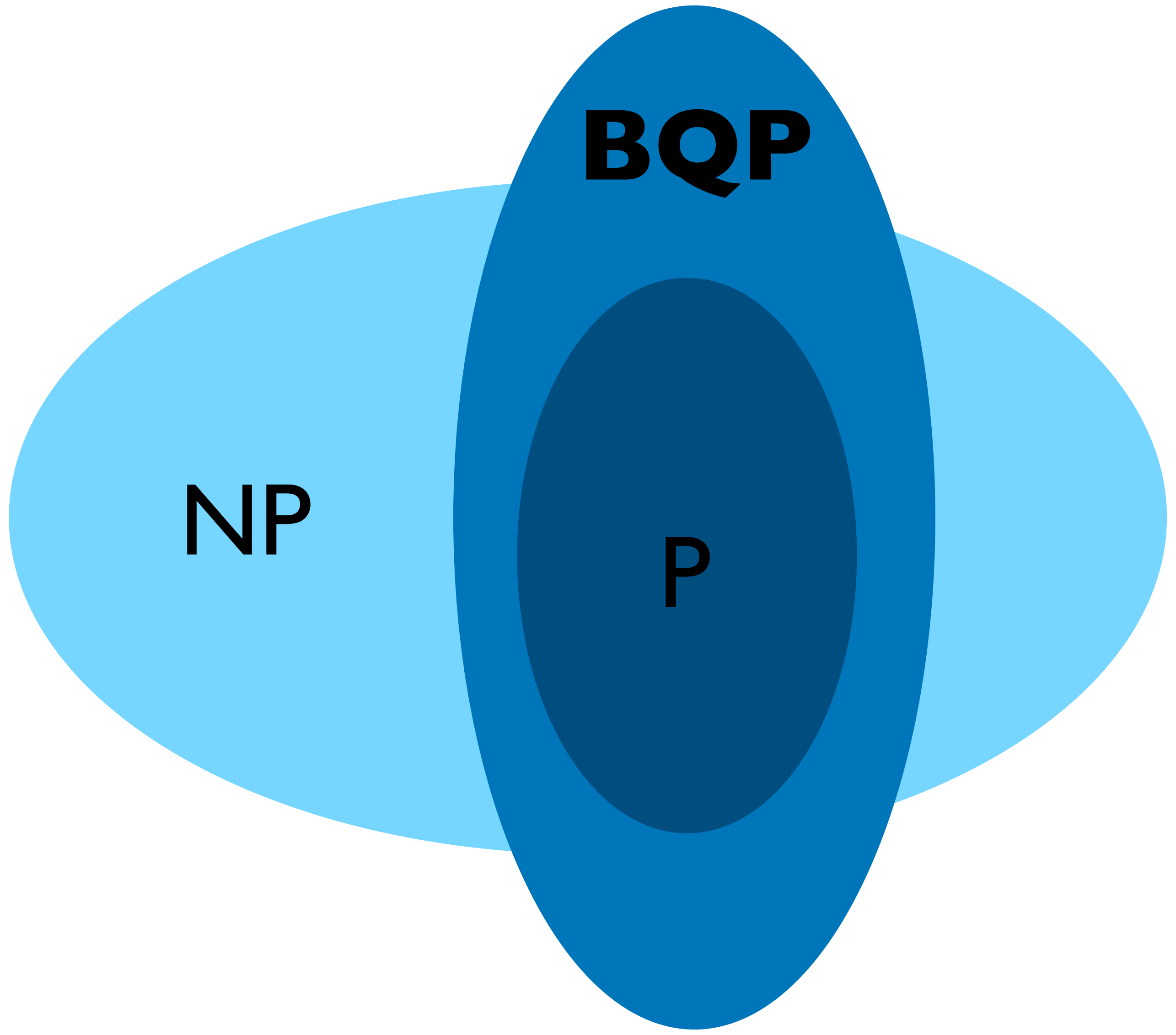
Superposition and entanglement

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

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



Computational complexity

P: Polynomial-time solution on classical computer

NP: Polynomial-time verification on classical computer

BQP: Polynomial-time solution on quantum computer

QC can solve *some* classically hard problems

Quantum computing

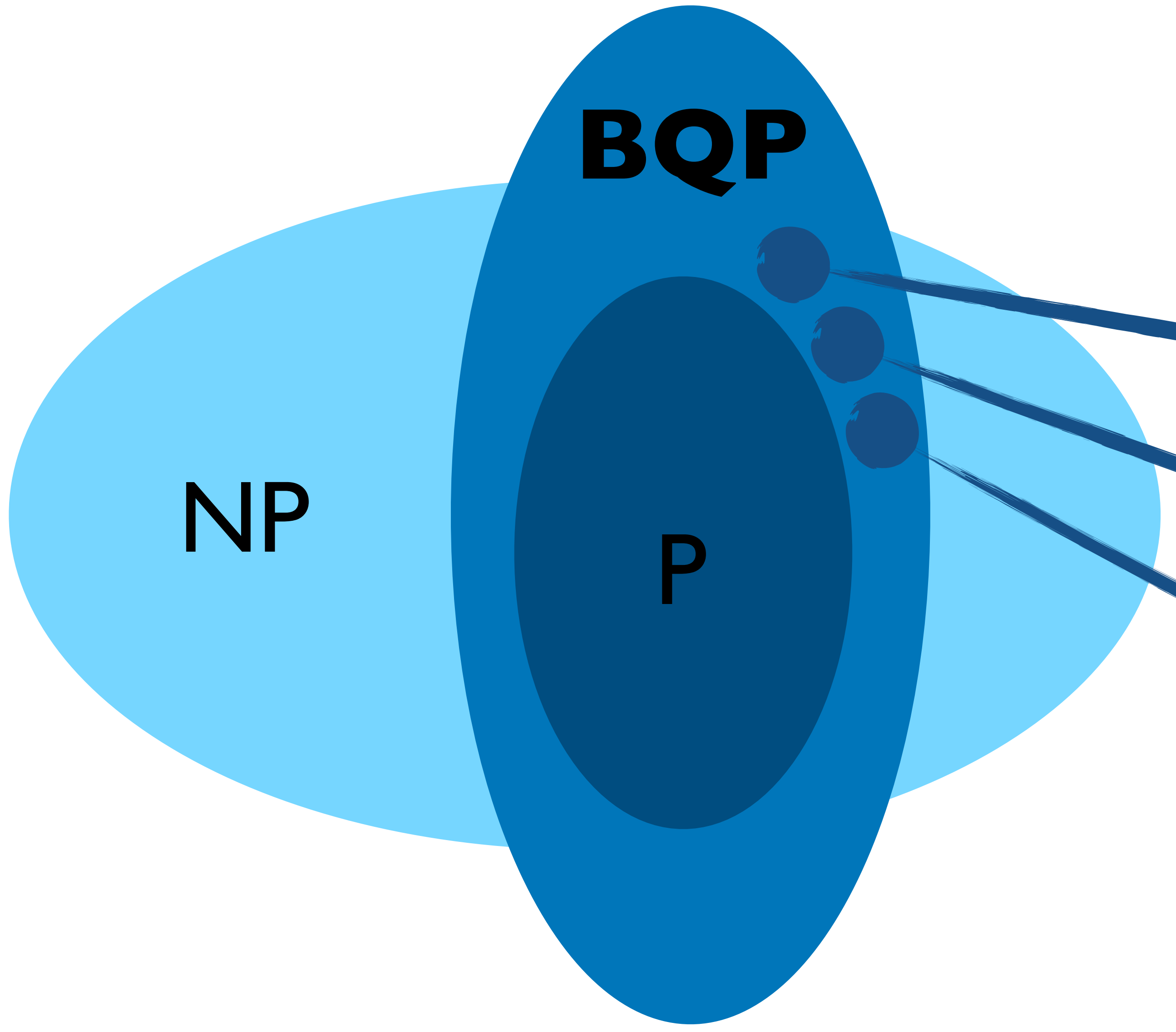
Superposition and entanglement

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

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



Dynamics of many-body non-relativistic quantum system

Feynman (1982), Lloyd (1996)

Scattering in scalar field theory

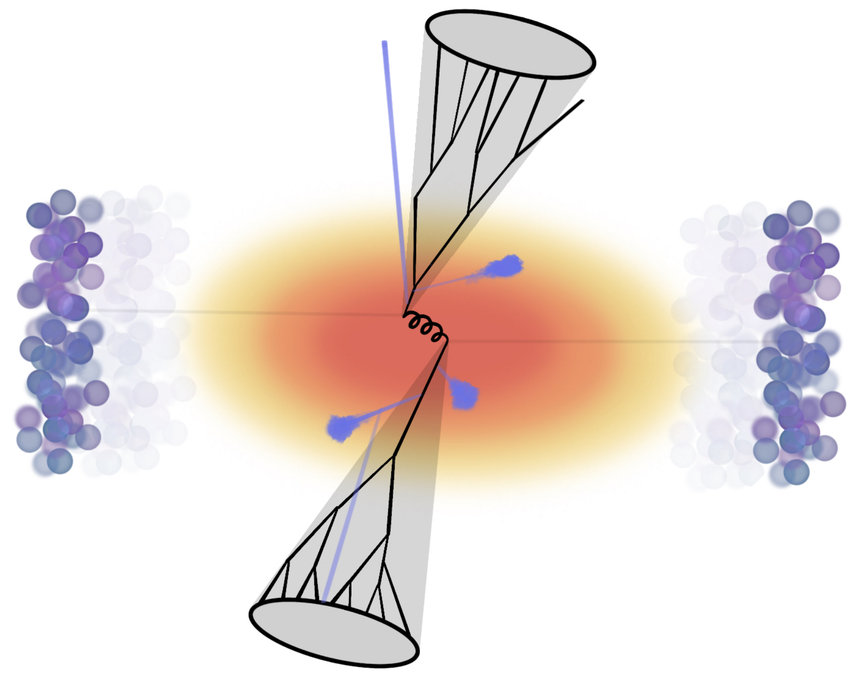
Jordan, Lee, Preskill (2012-2018)

QCD?

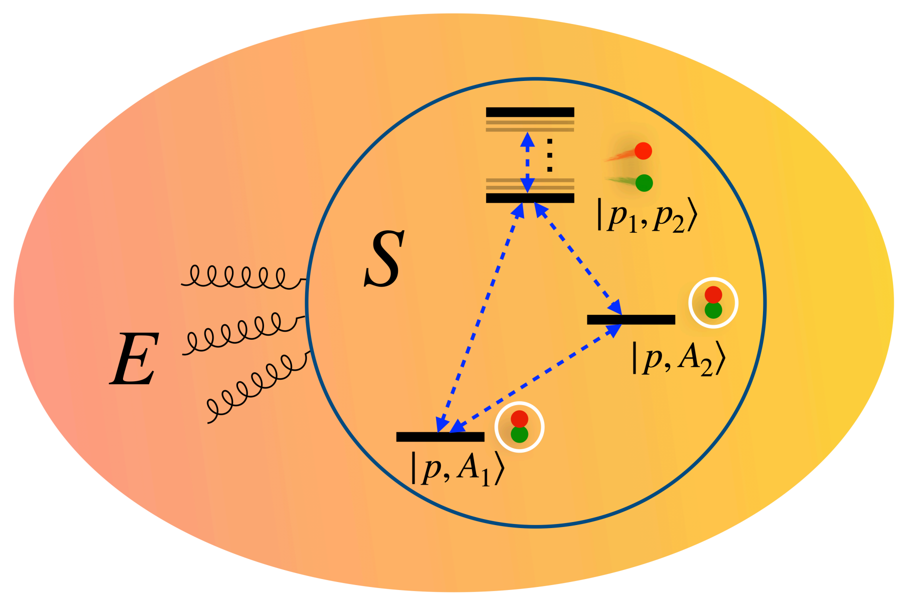
Preskill (2018), Klco, Savage (2018), Muschik et al. (2016), Davoudi et al. (2019), …

Outline

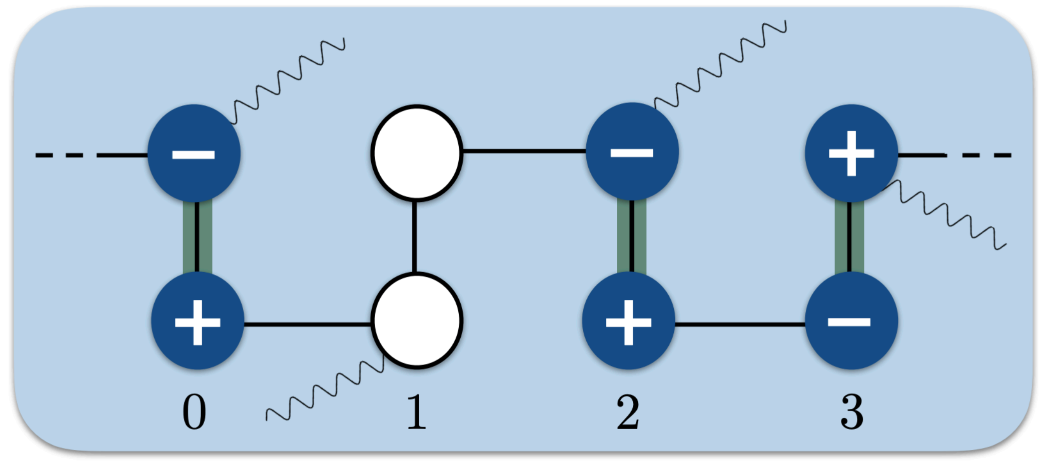
1. Formulating the problem: Open quantum systems in heavy-ion collisions



2. Simulating particle states: hard probes

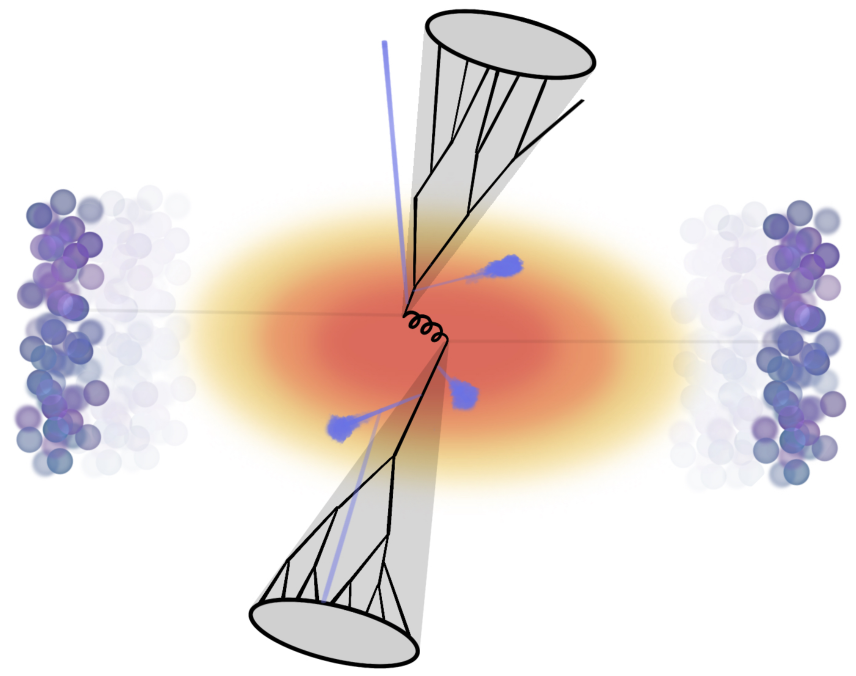


3. Simulating quantum field theories: thermalization and hadronization



Outline

1. Formulating the problem: Open quantum systems in heavy-ion collisions



2. Simulating particle states: hard probes

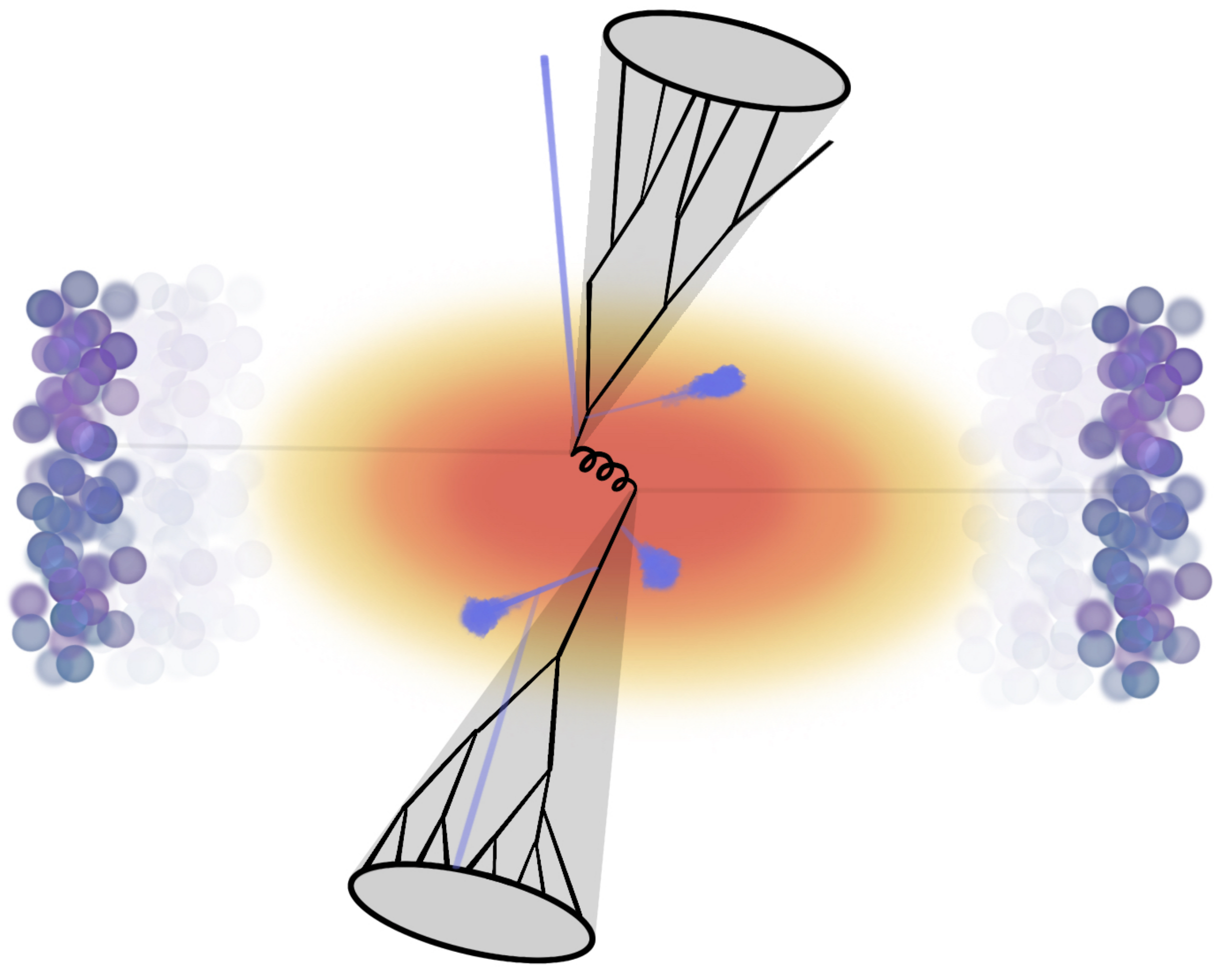
3. Simulating quantum field theories: thermalization and hadronization

Probing the quark-gluon plasma

The QGP is too small and short-lived to be probed by scattering beams
→ Use "self-produced" probes

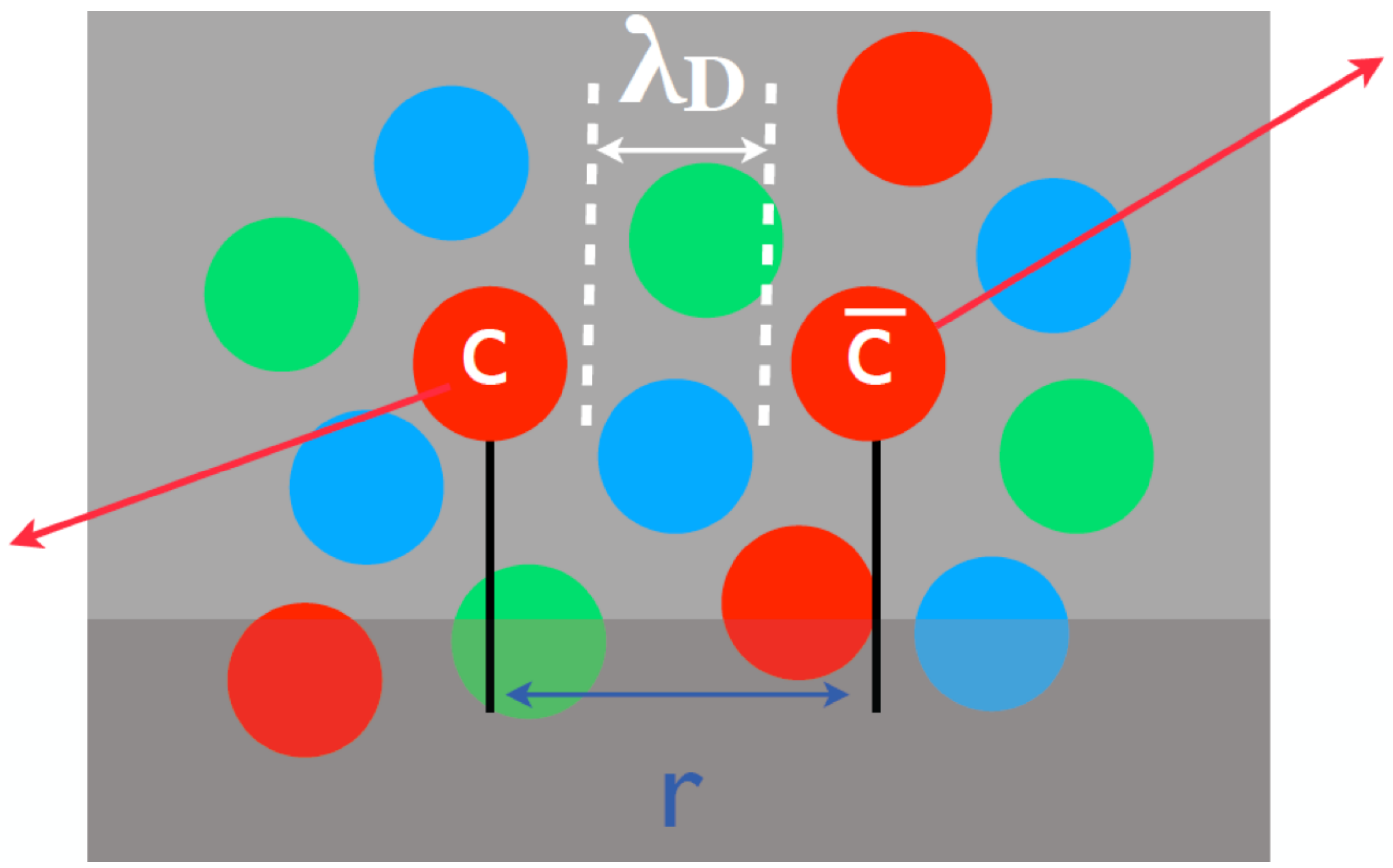
Jets

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



Heavy quarks

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

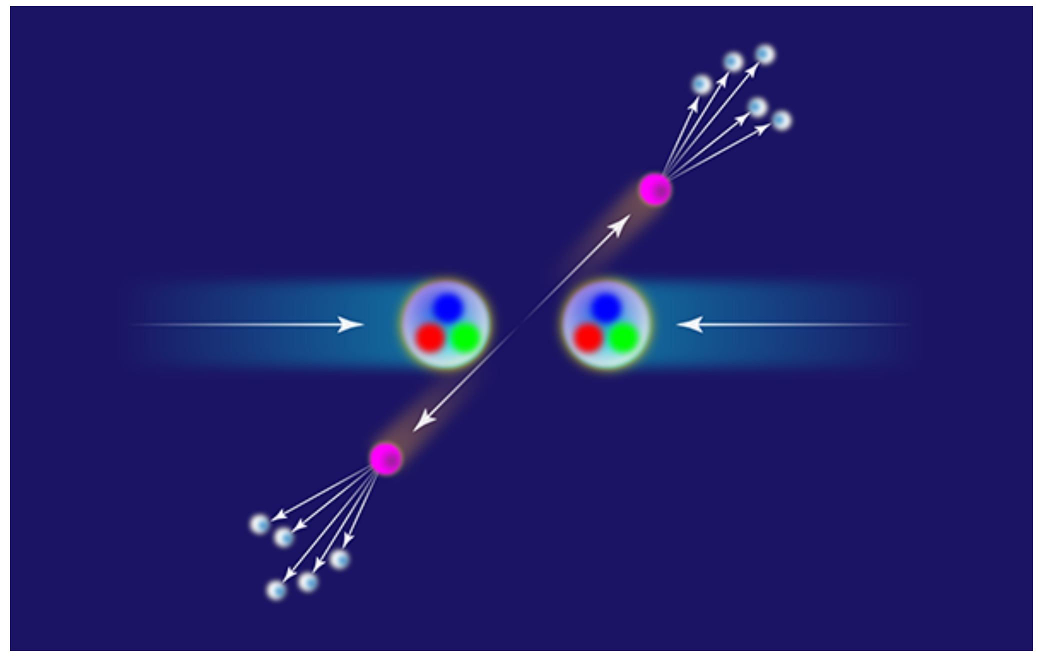


Real-time dynamics of the probe

Focus on calculating the evolution of the *probes* rather than the full quark-gluon plasma

In vacuum: calculate scattering of asymptotic states using perturbative QCD

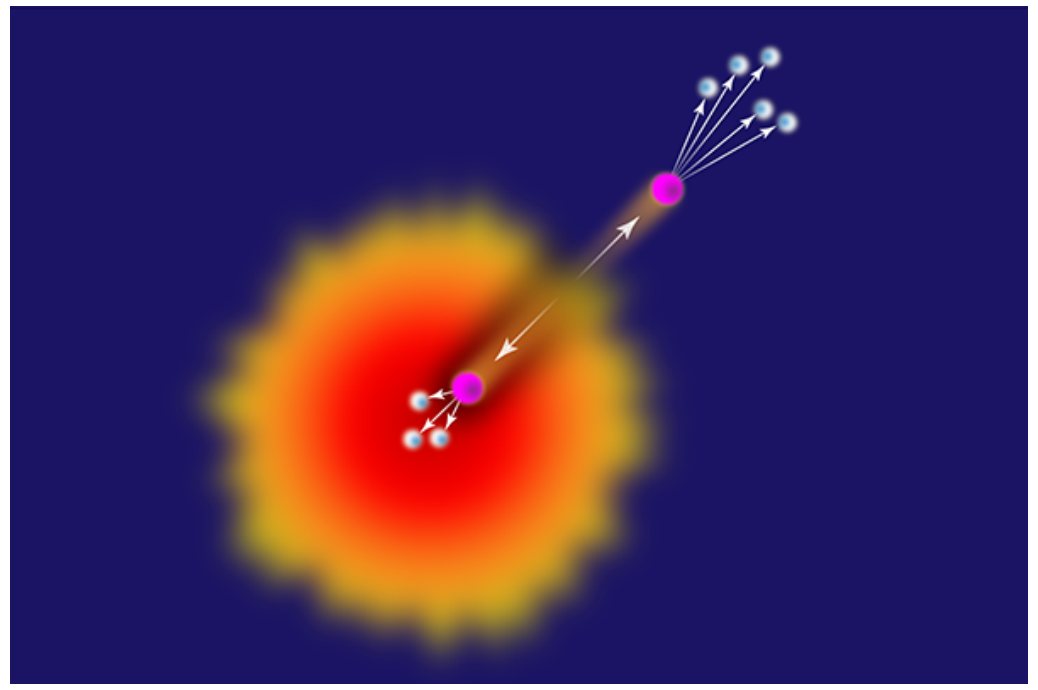
- No sense of "time evolution"



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

- Current theory approaches use modeling

Majumder PRC 88 (2013)
Caucal, Iancu, Mueller, Soyez PRL 120 (2018)
…



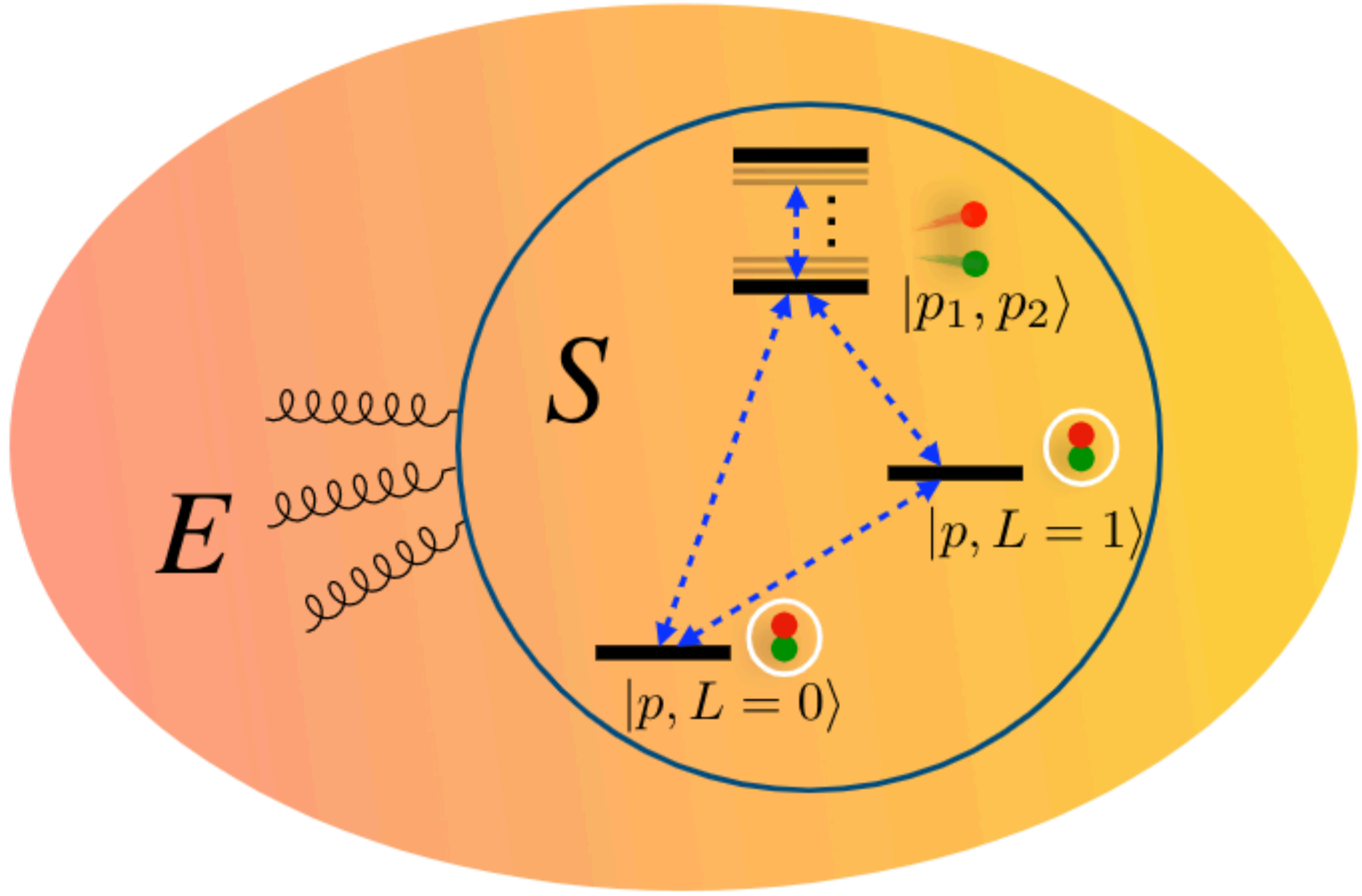
Open quantum systems

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

Subsystem - Probe — Jet, heavy quarks, …

Environment - Nuclear matter

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



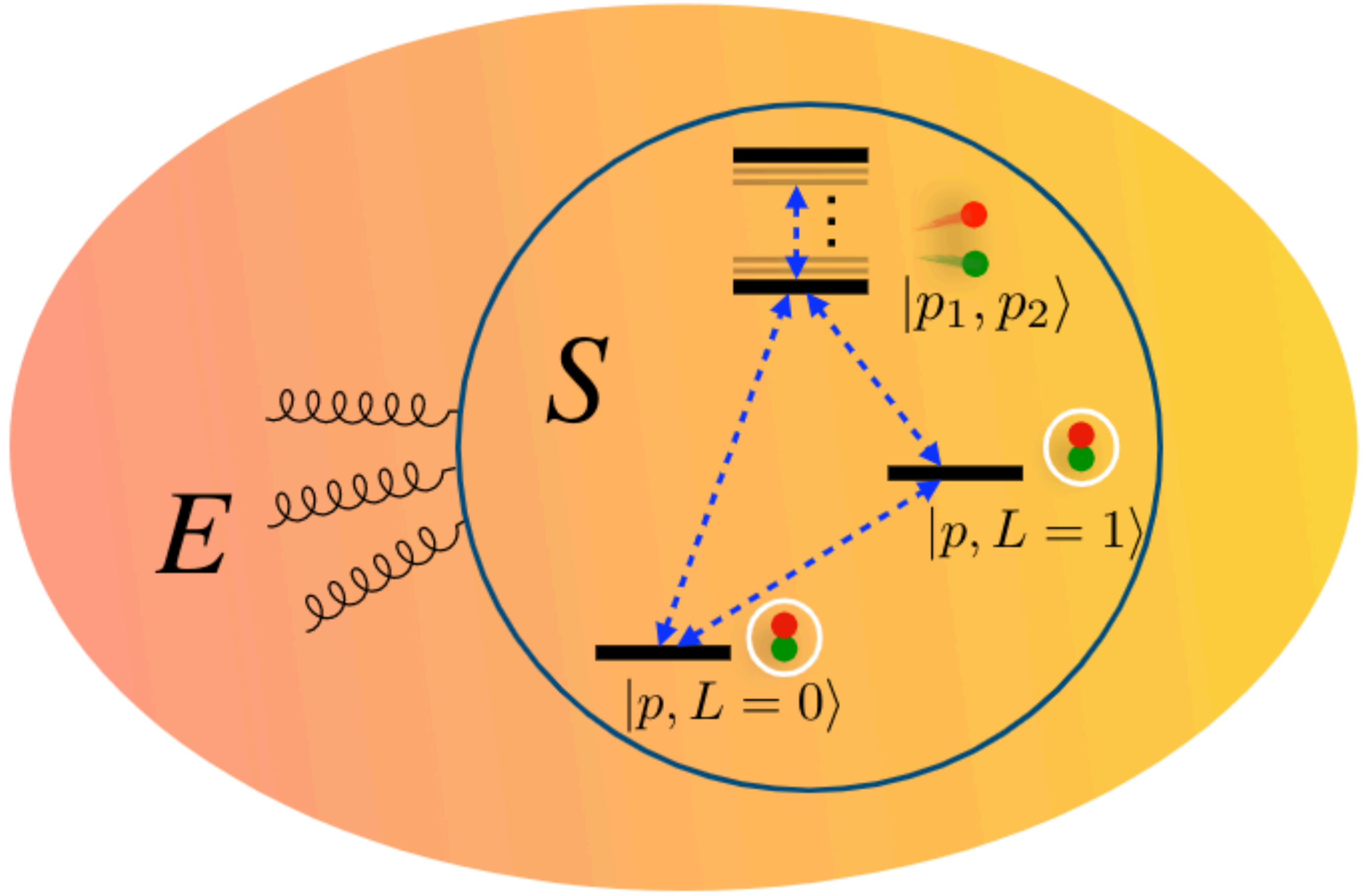
Open quantum systems

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

Subsystem - Probe — Jet, heavy quarks, …

Environment - Nuclear matter

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



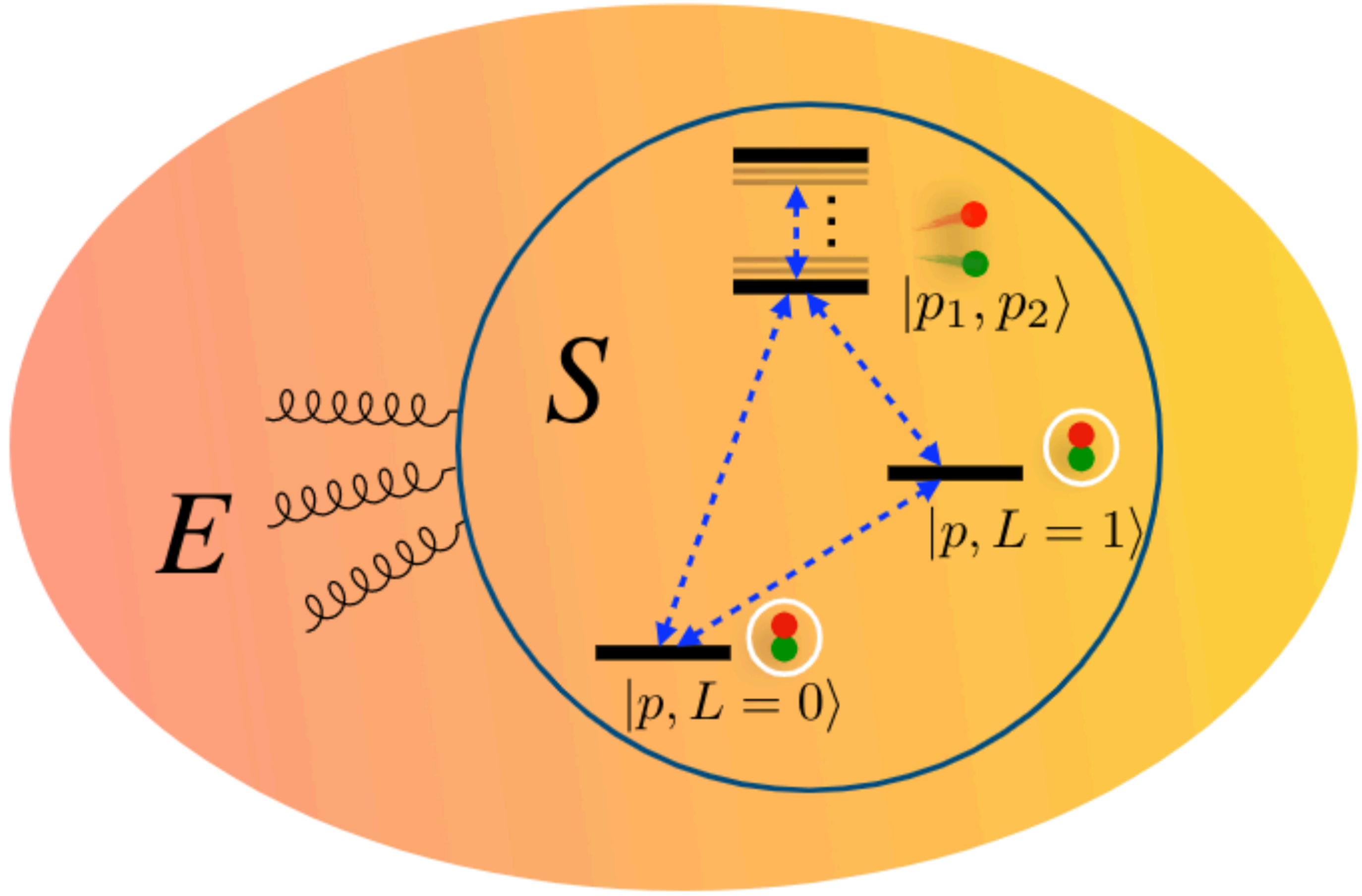
The time evolution of the full system is governed by the von Neumann equation:

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

$$\rho = \sum_n p_n |\psi_n\rangle\langle\psi_n|$$

Open quantum systems

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



Subsystem - Probe — Jet, heavy quarks, …

Environment - Nuclear matter

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

The time evolution of the full system is governed by the von Neumann equation:

$$\frac{\mathrm{d}\rho(t)}{\mathrm{d}t} = -i\big[H, \rho(t)\big]$$

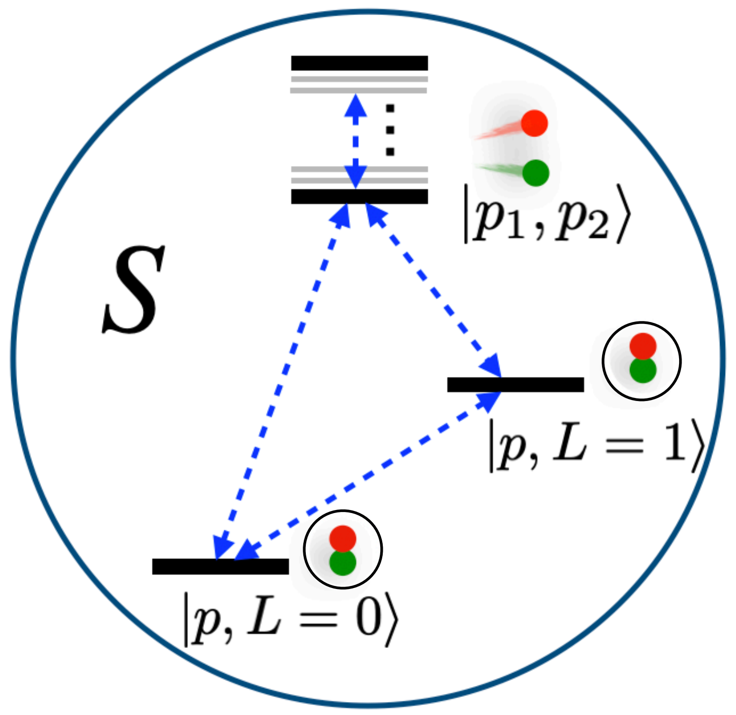
$$\rho = \sum_n p_n |\psi_n\rangle\langle\psi_n|$$

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

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

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

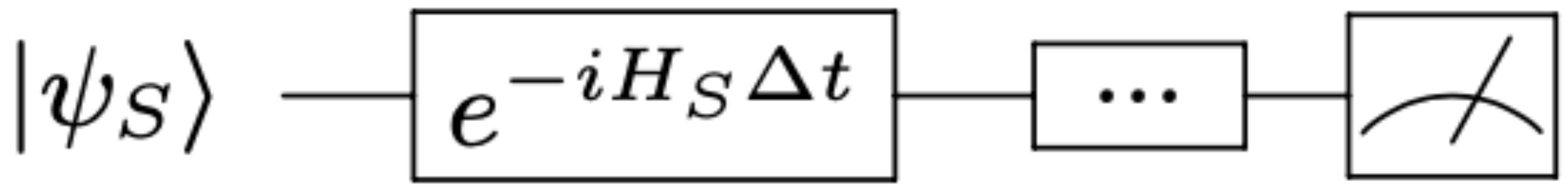
Quantum simulation



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



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

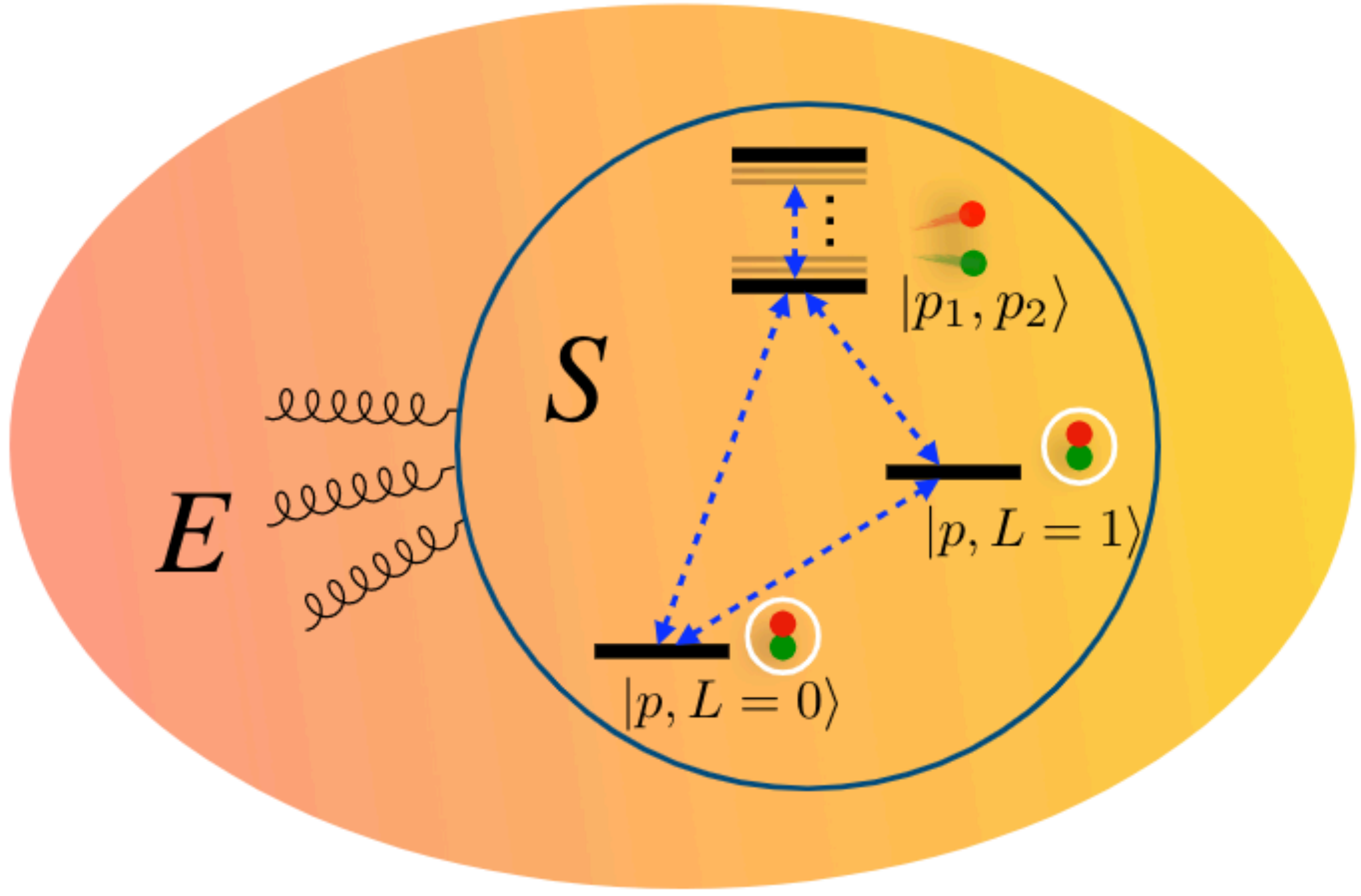
Time evolution of closed systems

- Quantum simulation of the Schrödinger equation
- The evolution is unitary and time reversible

Non-unitary evolution

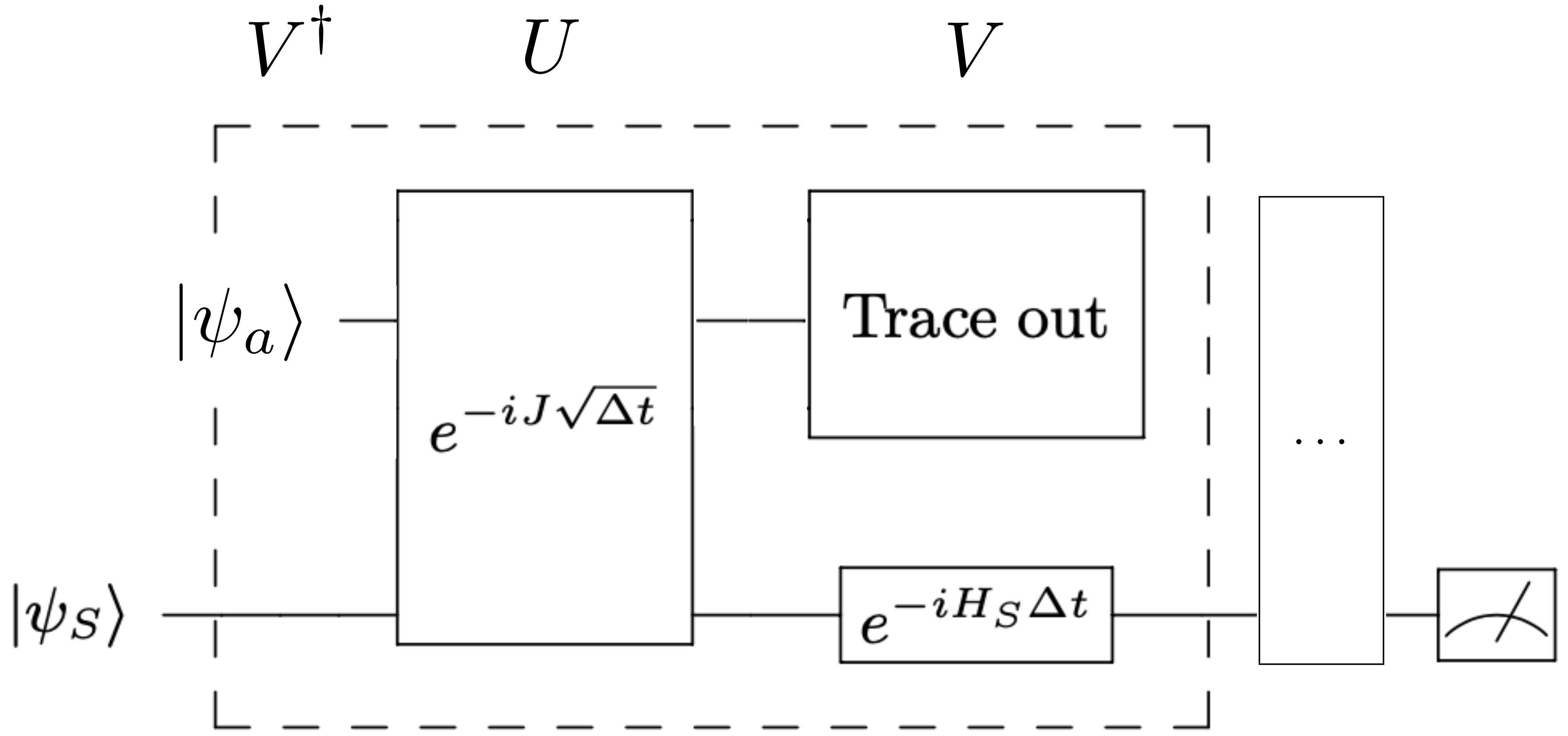
In open quantum systems, the subsystem evolution is non-unitary

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



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



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

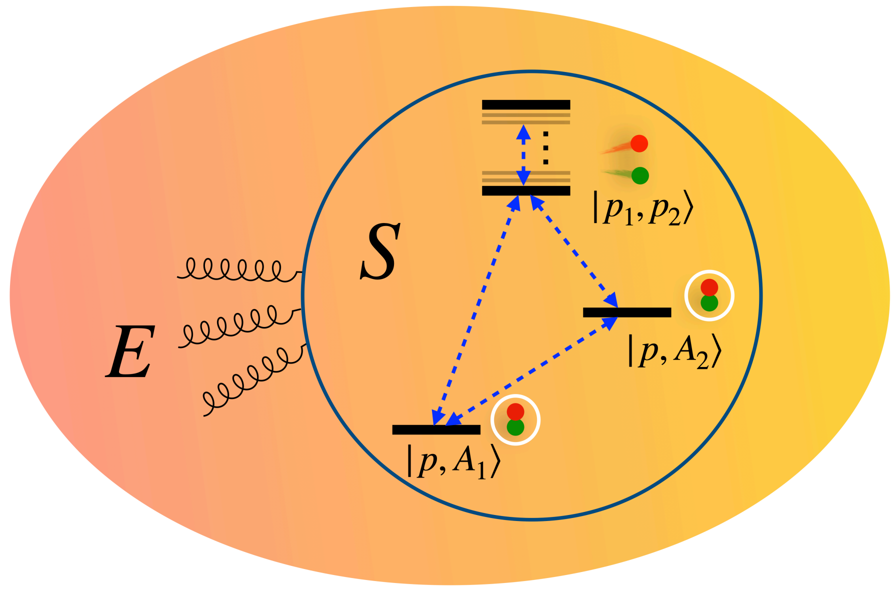
$$V^\dagger V = 1 \qquad VV^\dagger \neq 1$$

Quantum algorithm to simulate Lindblad evolution of open system

Outline

1. Formulating the problem: Open quantum systems in heavy-ion collisions

2. Simulating particle states: hard probes

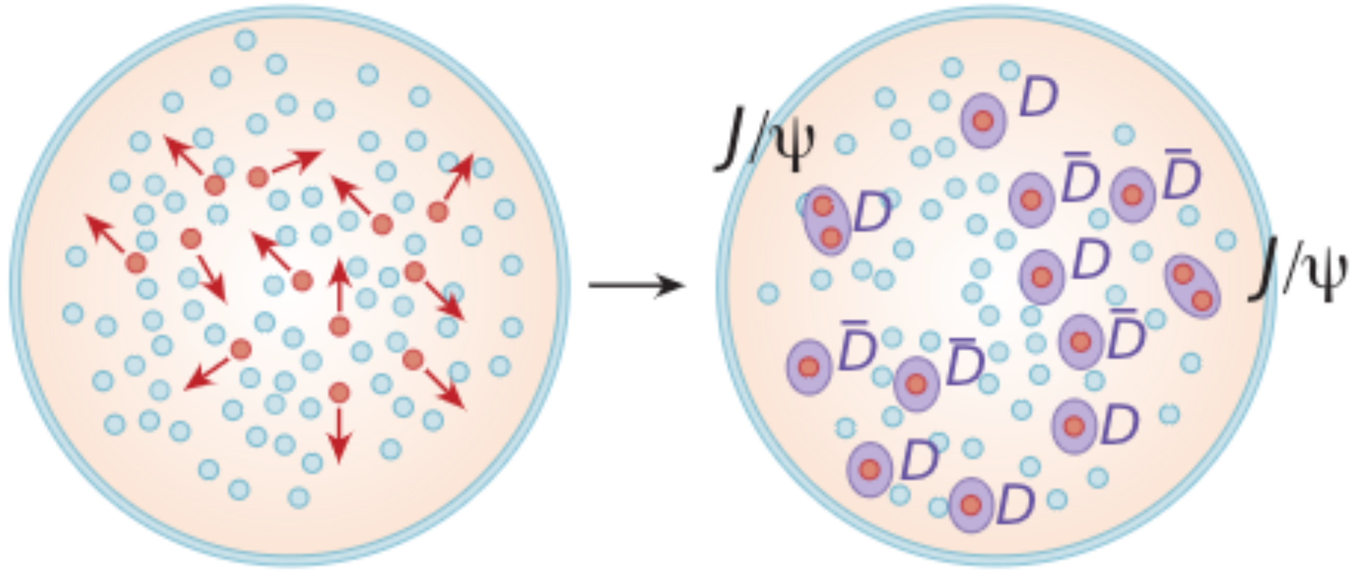


3. Simulating quantum field theories: thermalization and hadronization

Open quantum systems: Quarkonia

The evolution of quarkonia in the QGP can be described by the Lindblad equation

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



P. Braun-Munzinger and J. Stachel, Nature (2007)

"Simple" system: reduces to quantum mechanics (NRQCD)

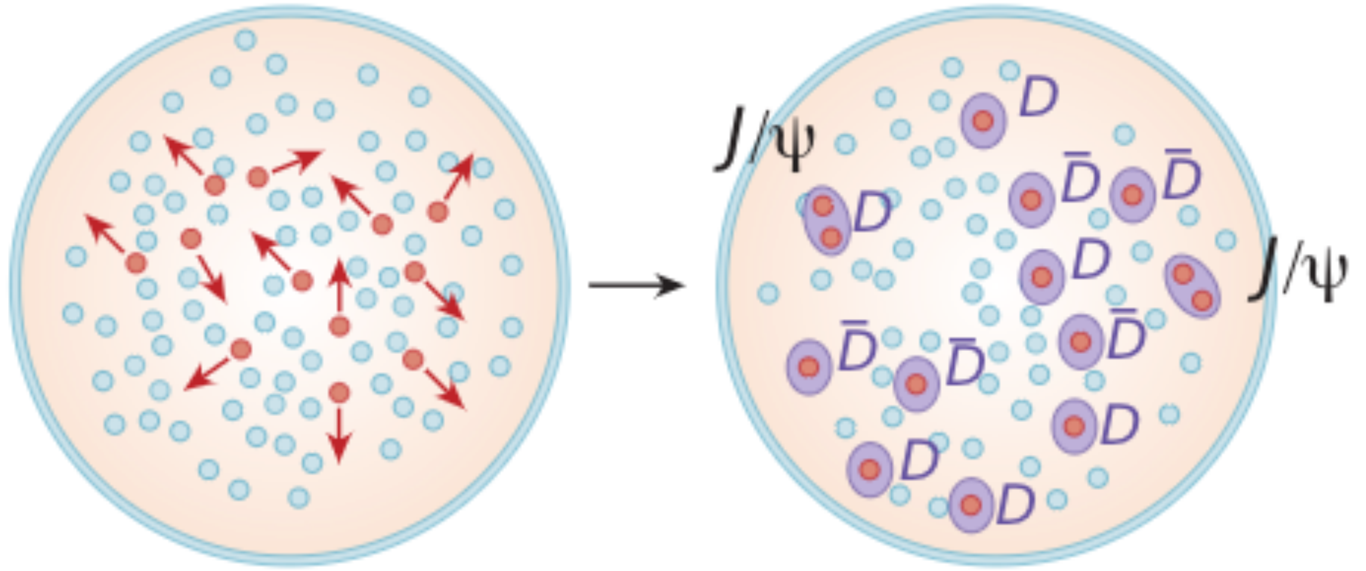
Currently various approximations are considered

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

Open quantum systems: Quarkonia

The evolution of quarkonia in the QGP can be described by the Lindblad equation

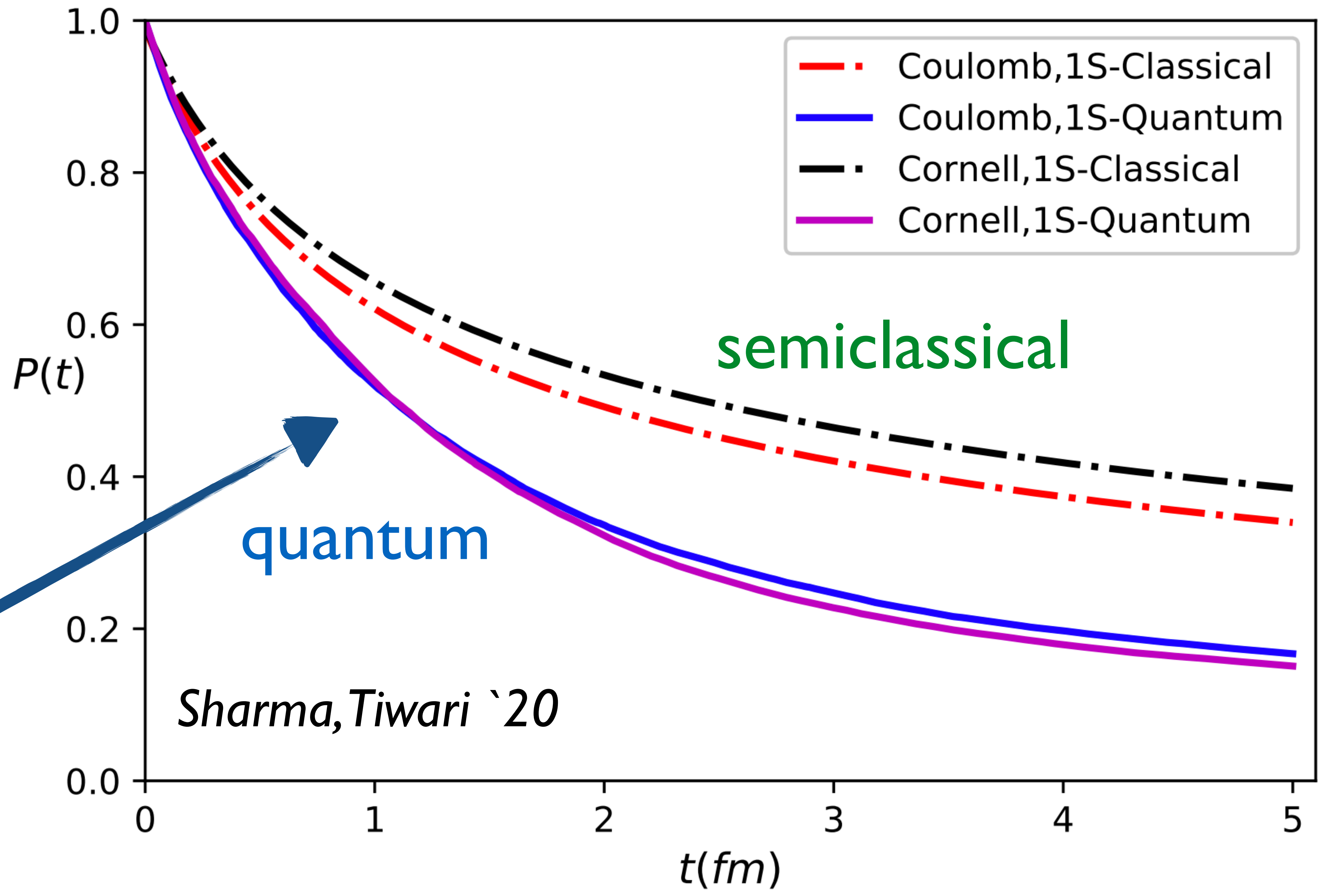
Akamatsu, Rothkopf et al. `12-`20, Brambilla et al. `17-`20
Yao, Mueller, Mehen `18-`20, Sharma, Tiwari `20



P. Braun-Munzinger and J. Stachel, Nature (2007)

"Simple" system: reduces to quantum mechanics (NRQCD)

Survival probability of the vacuum state



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

Currently various approximations are considered

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

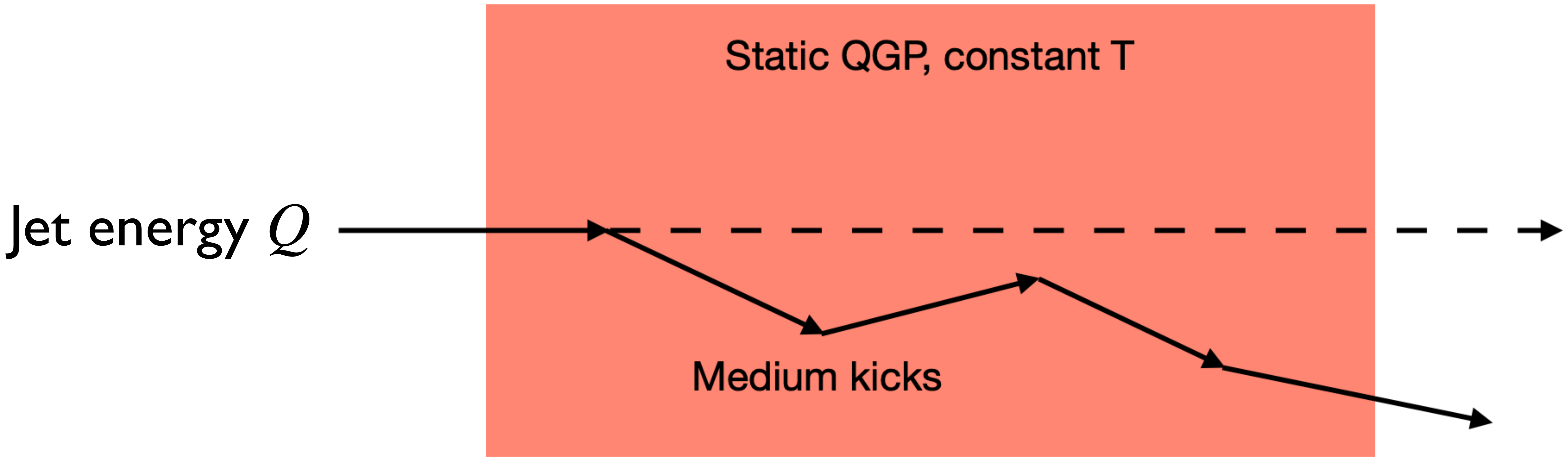
NRQCD + semiclassical approach vs. full quantum evolution

Quantum treatment has important phenomenological consequences

Open quantum systems: Jet broadening

First steps in the direction of jet physics

Yao, Vaidya JHEP 10 024 (2020)
Vaidya JHEP 11 064 (2021)
Vaidya 2101.02225
Vaidya 2107.00029
Vaidya 2109.11568



Soft Collinear Effective Theory

- Forward scattering, Glauber gluon exchange

Markovian master equation describes evolution of jet density matrix:

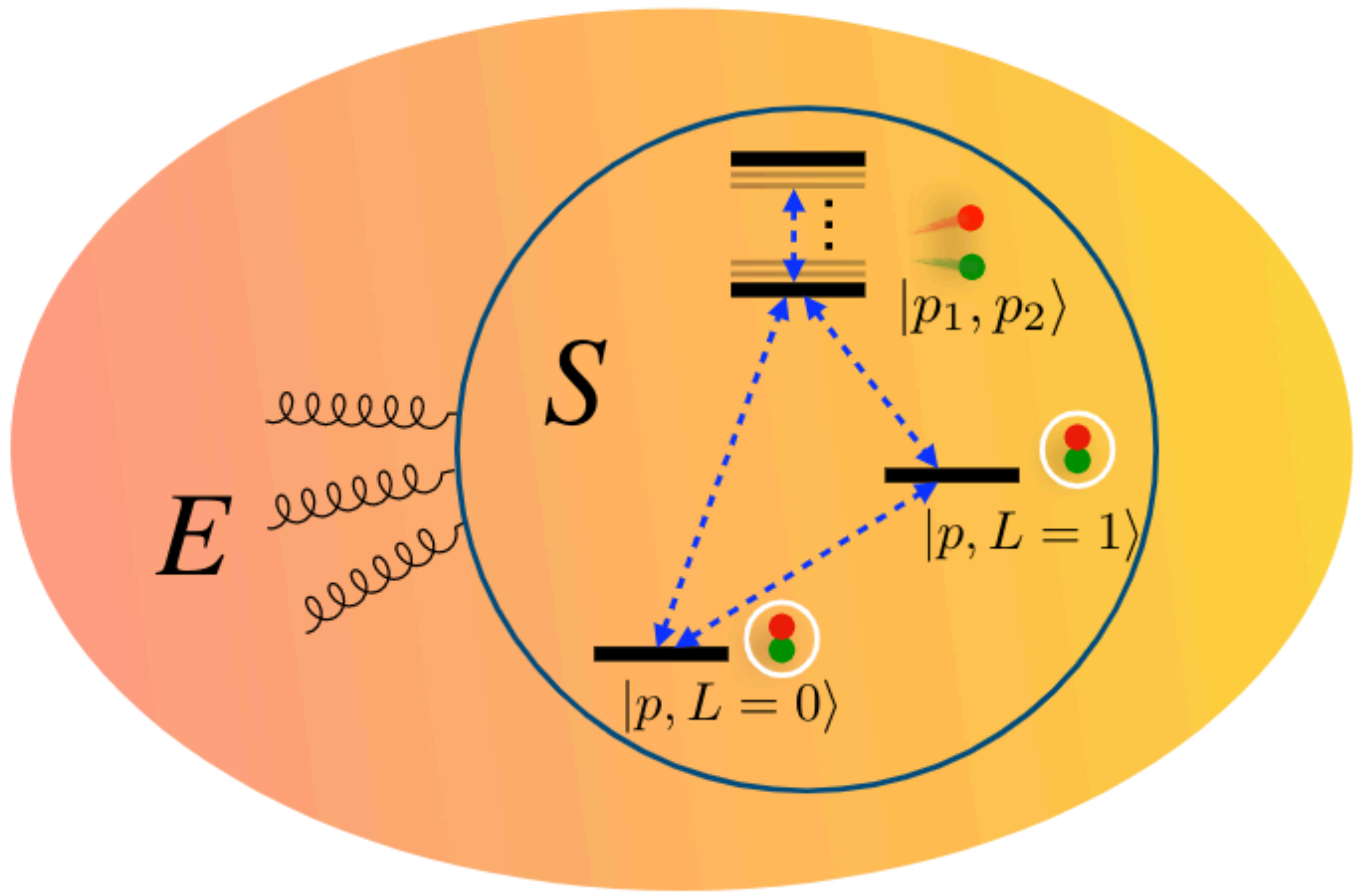
$$\partial_t P(Q,t) = -R(Q)P(Q,t) + \int \widetilde{\mathrm{d}q} K(Q,q)P(q,t)$$

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

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

Quantum simulation of open quantum systems

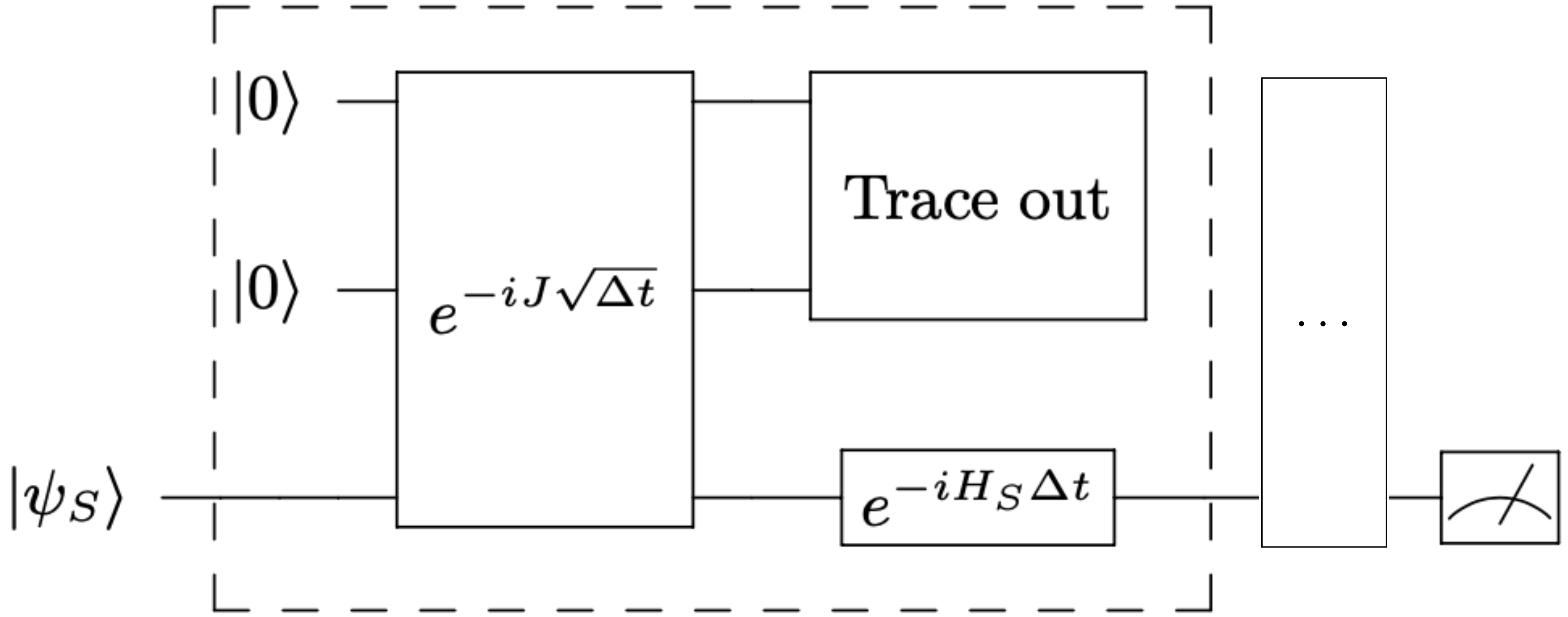
Straightforward application for subsystems that can be described by particle states



Requires:

- H_S — subsystem Hamiltonian
- $|\psi_S\rangle$ — subsystem initial state
- L_i — Lindblad operators

Quantum circuit: Lindblad evolution



Since current quantum devices are small and noisy, simplify to a toy model in order to illustrate proof-of-concept

Quantum simulation of open quantum systems

Toy model setup

Two-level system in a thermal environment

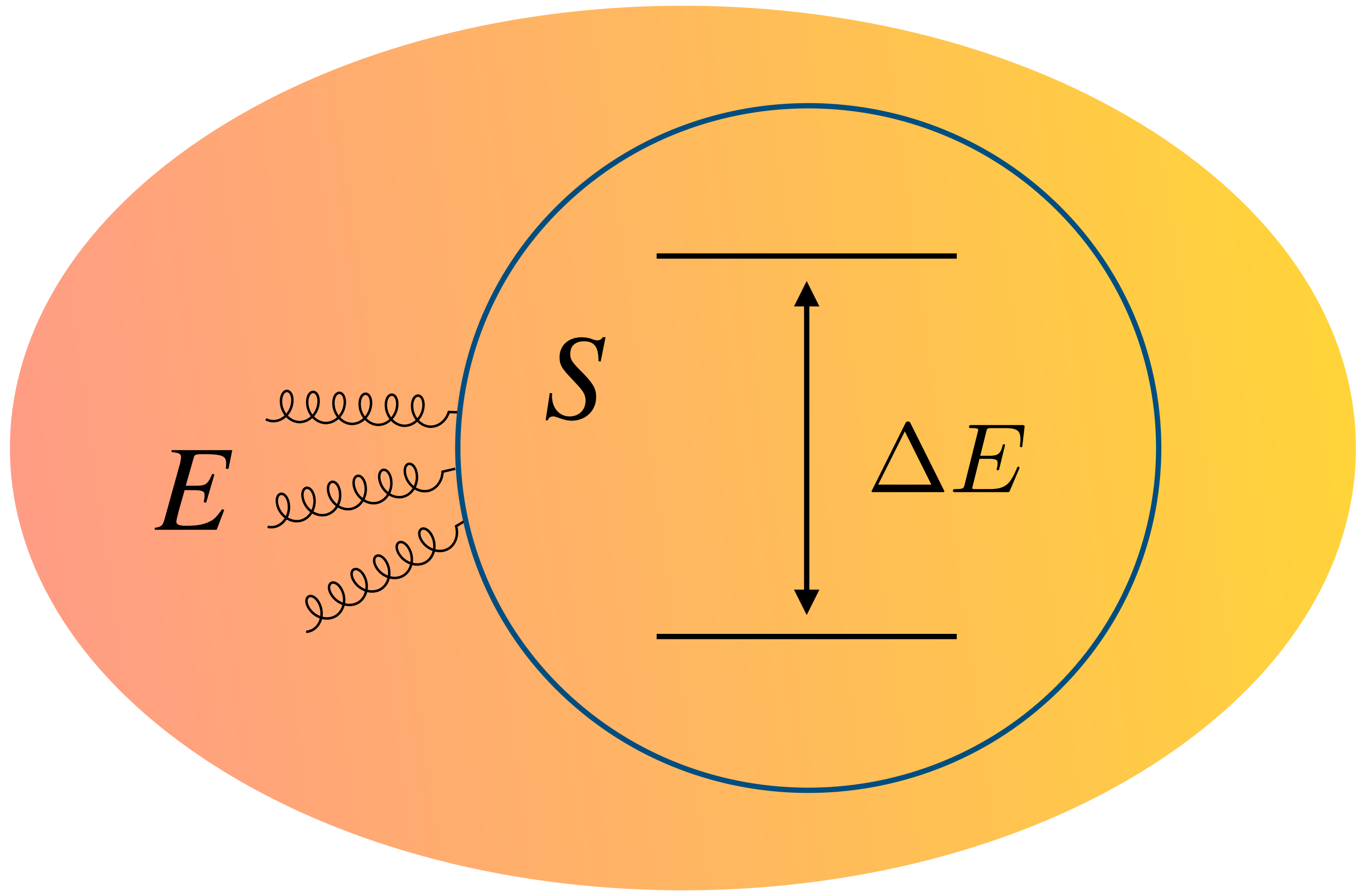
e.g. bound/unbound $J/\psi, c\bar{c}$

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

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

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

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



Pauli matrices X, Y, Z, interaction strength g

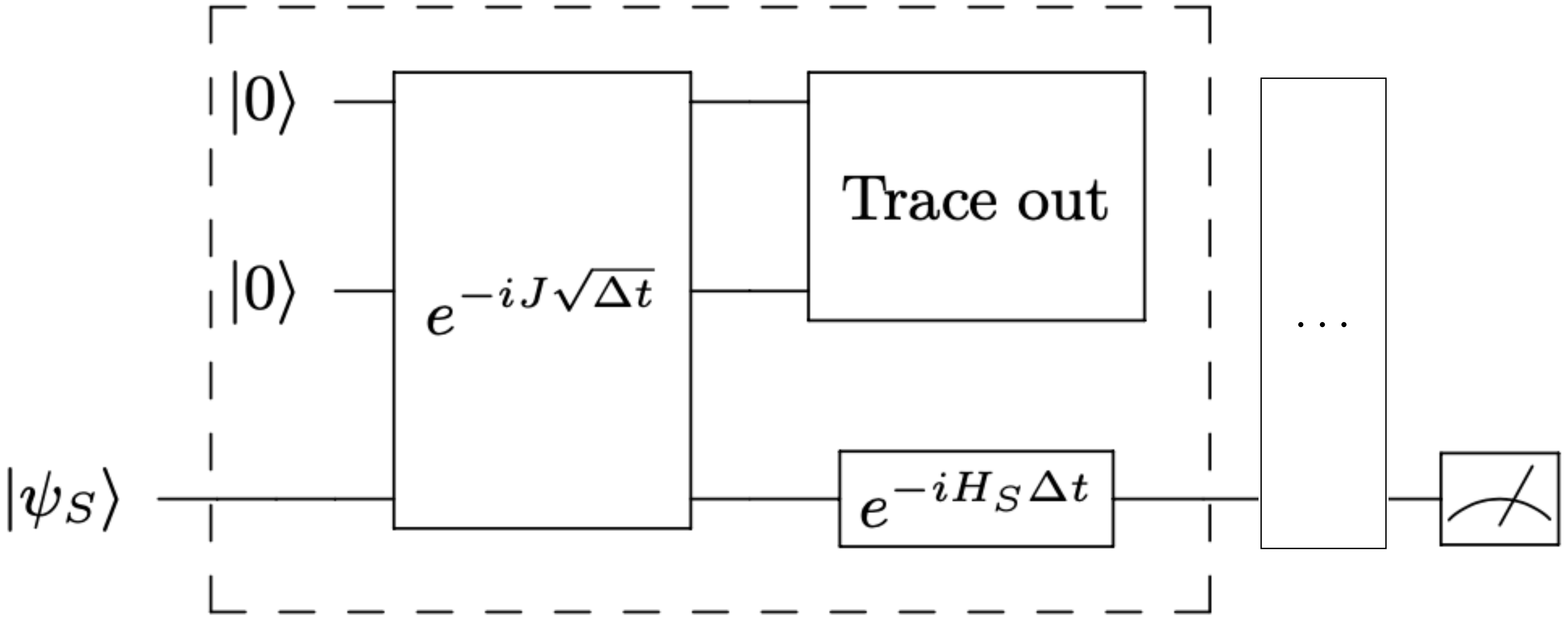
Lindblad operators

$$L_j \sim g(X \mp iY)$$

$$j = 0, 1$$

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

Quantum circuit: Lindblad evolution

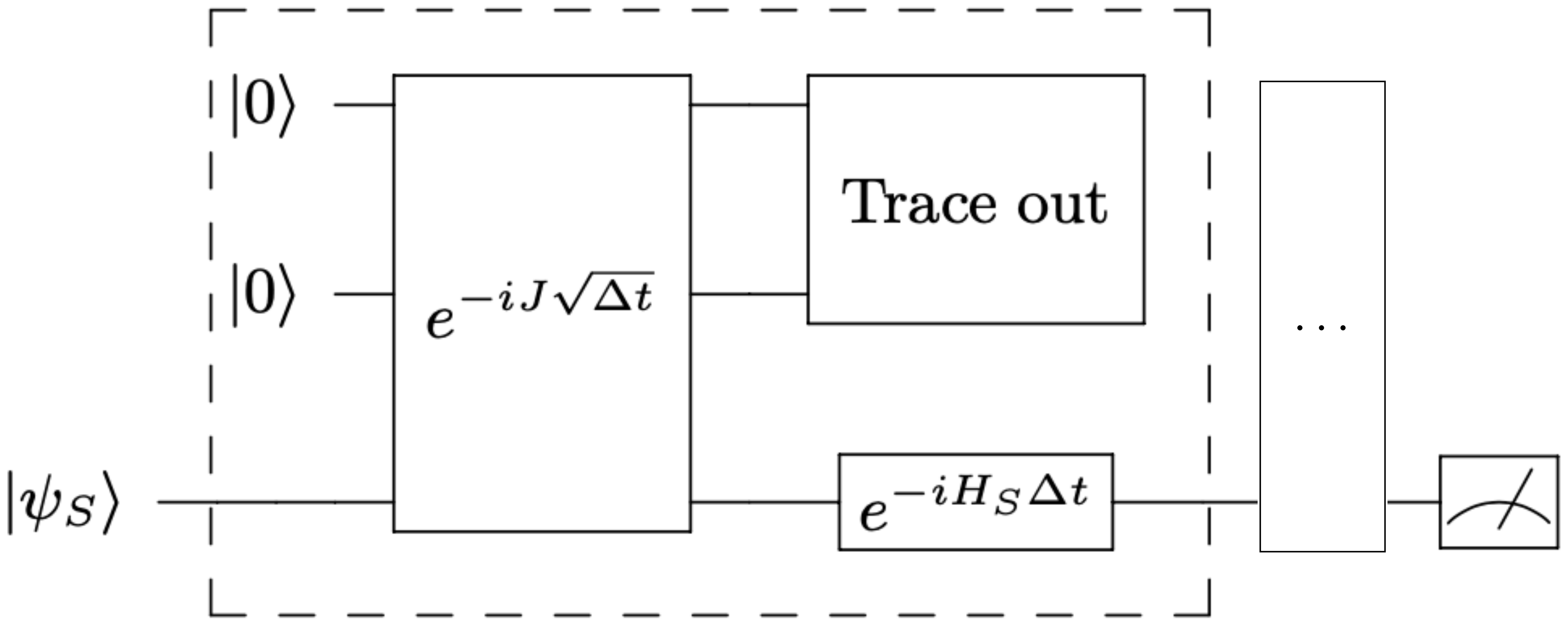


Quantum circuit synthesis

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

Optimization problem w/unitary loss function

`qsearch` *Siddiqi et al. `20*

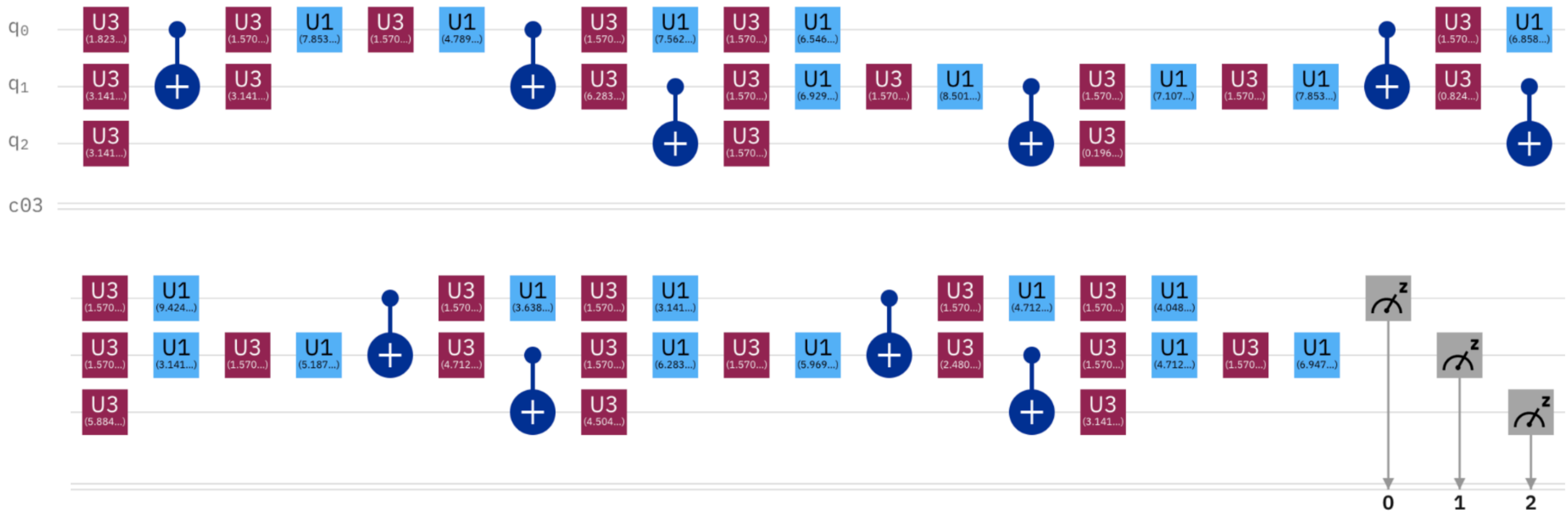


10 CNOT gates/cycle

IBM **Q**

Single qubit

CNOT

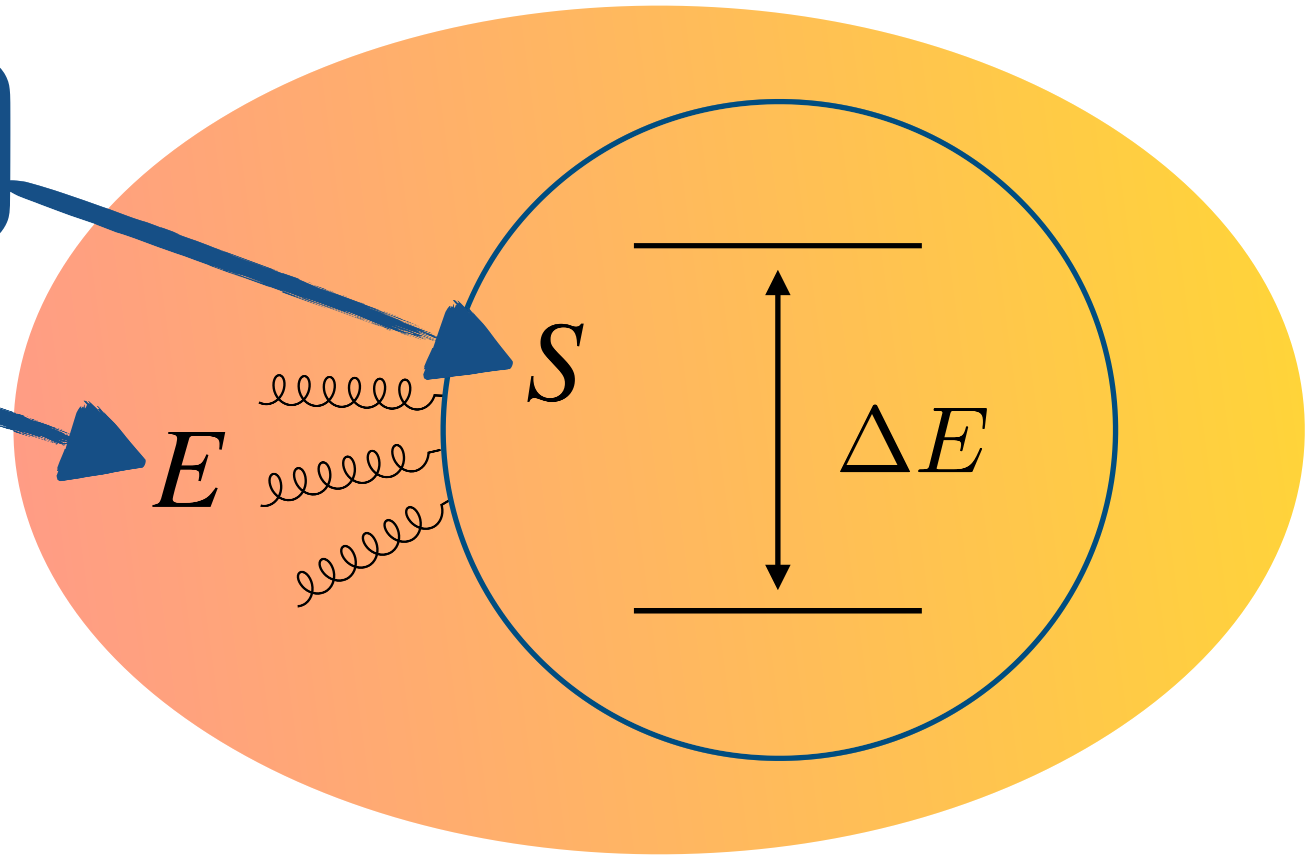


Quantum simulation of open quantum systems

Jong, Metcalf, Mulligan, Ploskon, Ringer, Yao
PRD 104 L051501 (2021)

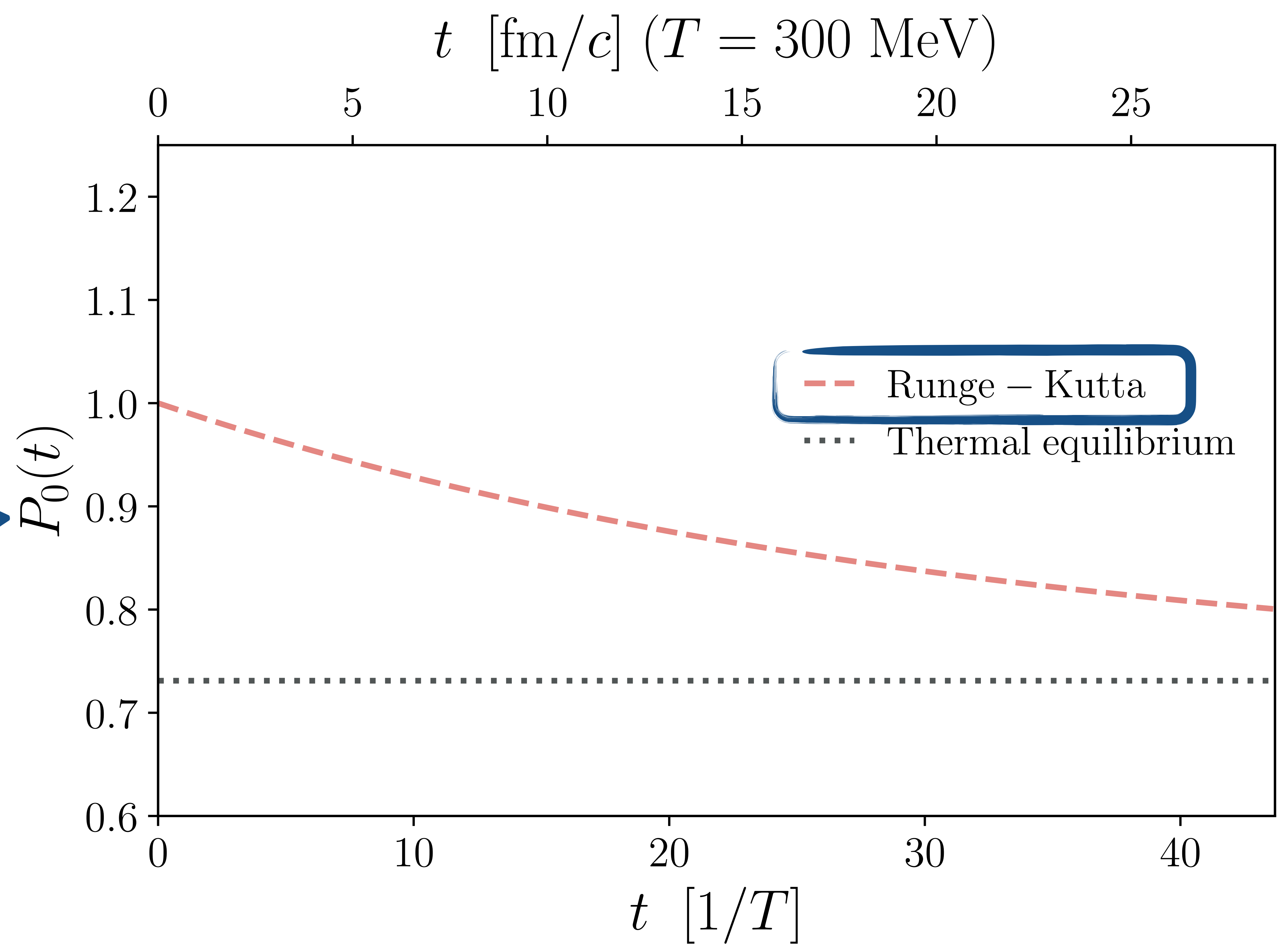
Two-level system

Thermal scalar field theory

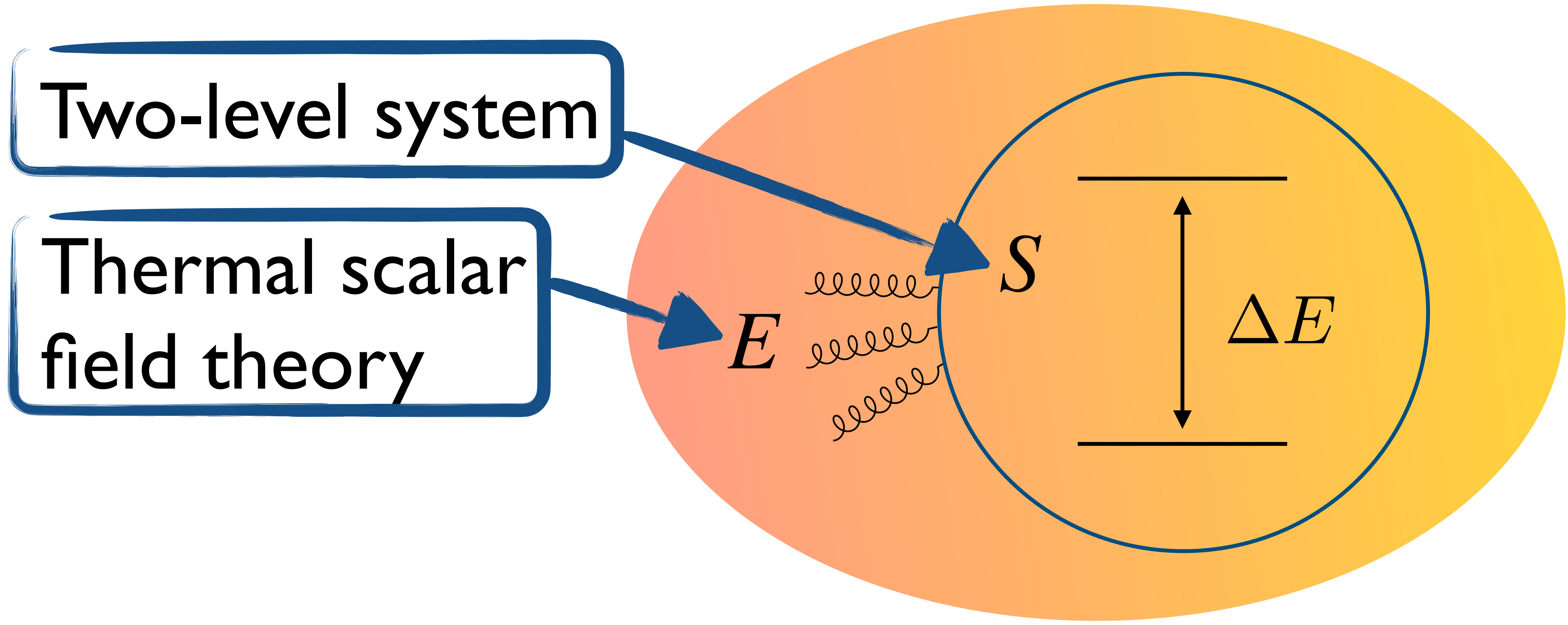


$P_0(t)$ describes fraction that remains in "bound state"

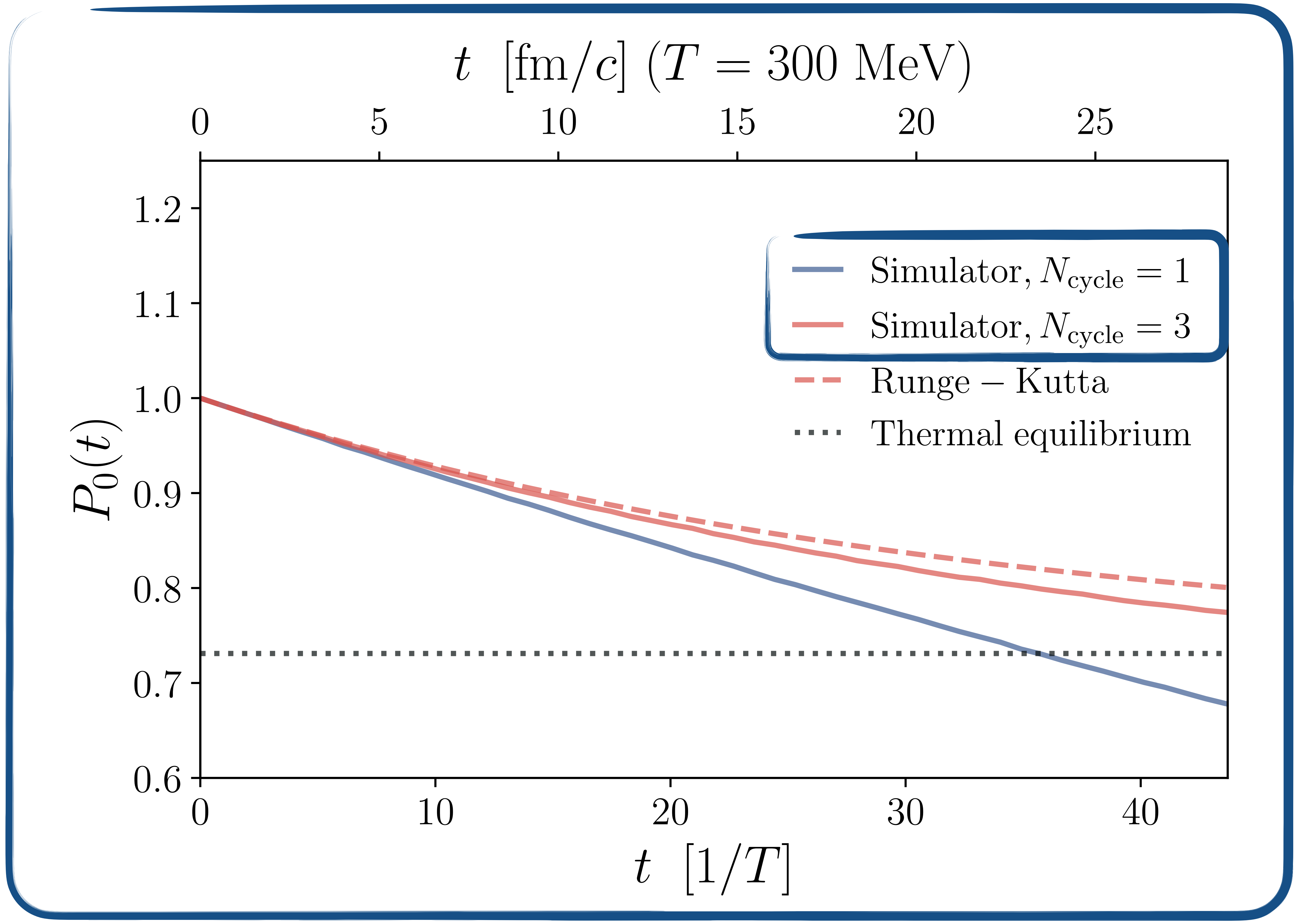
Similar to t-dependent $R_{AA} = \frac{\mathrm{d}\sigma_{AA}}{\langle N_{\text{coll}} \rangle \, \mathrm{d}\sigma_{pp}}$



Quantum simulation of open quantum systems



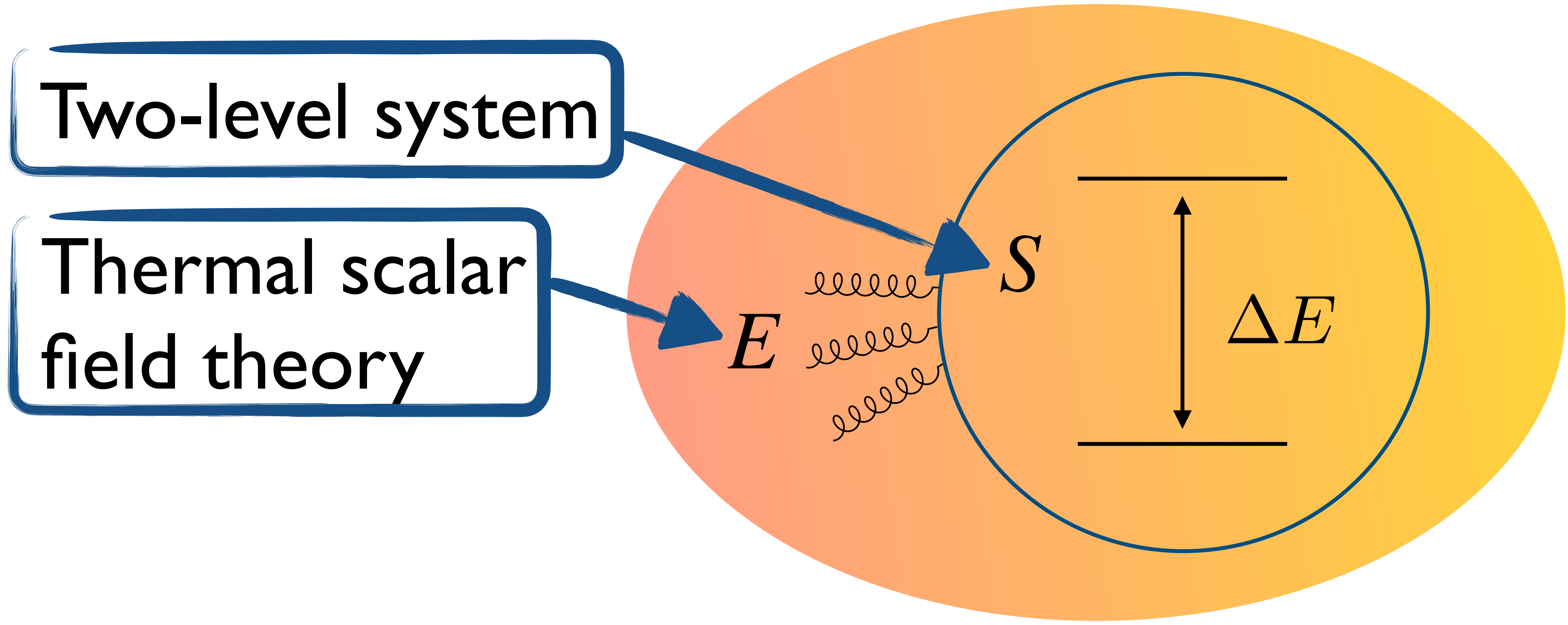
Jong, Metcalf, Mulligan, Ploskon, Ringer, Yao
PRD 104 L051501 (2021)



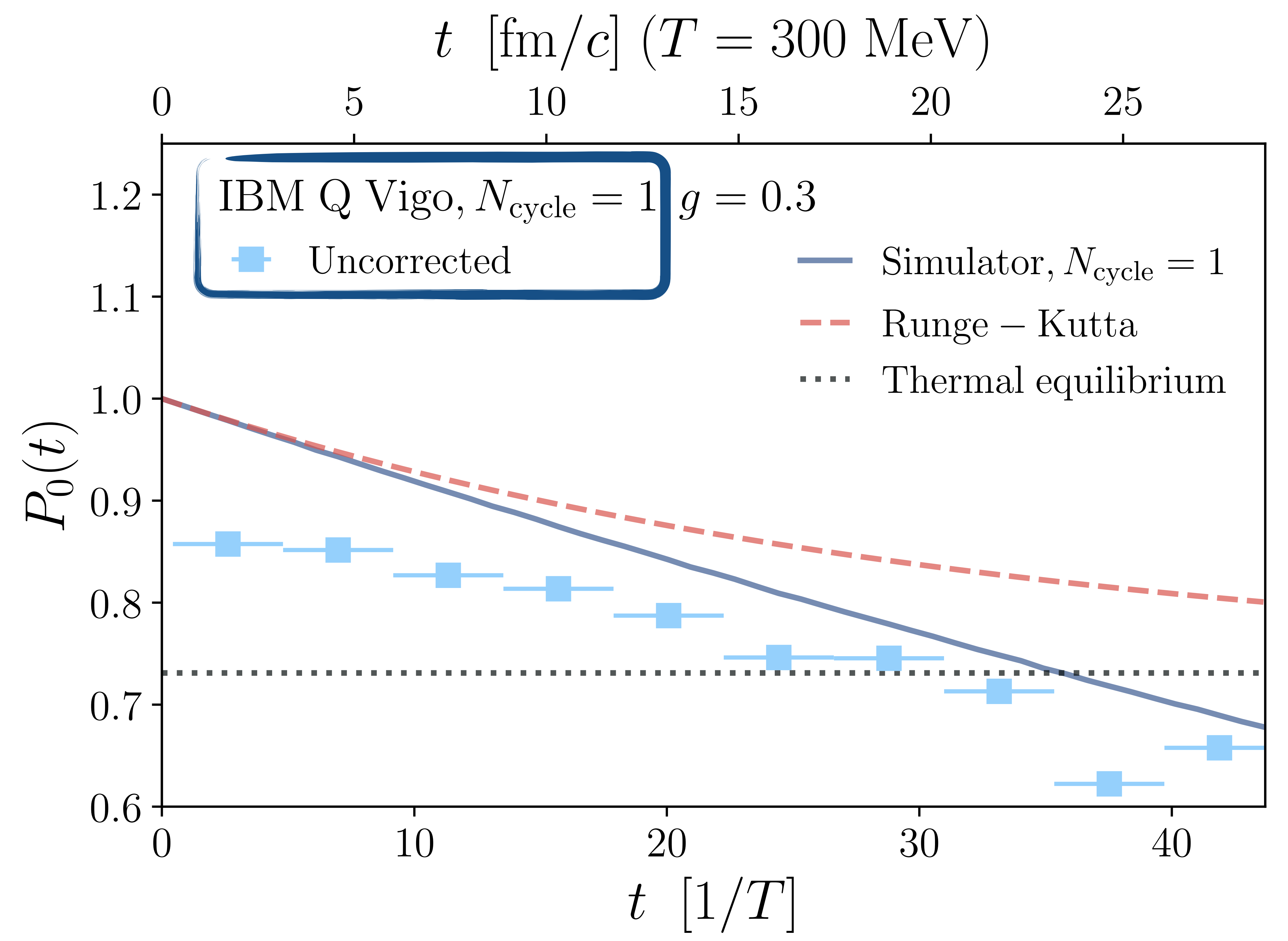
$P_0(t)$ describes fraction that remains in "bound state"

A classical simulation of the quantum circuit shows convergence to Lindblad evolution with a small number of cycles

Quantum simulation of open quantum systems



Jong, Metcalf, Mulligan, Ploskon, Ringer, Yao
PRD 104 L051501 (2021)



Quantum simulation on IBM Q Vigo device with $N_{\mathrm{cycle}} = 1$

- Without error mitigation

Noise in quantum device causes disagreement with simulated circuit

Error mitigation

Readout error

Constrained matrix inversion
IBM **Q** `qiskit-ignis`

Unfolding
Nachman, Urbanek, de Jong, Bauer (2019)

Gate error

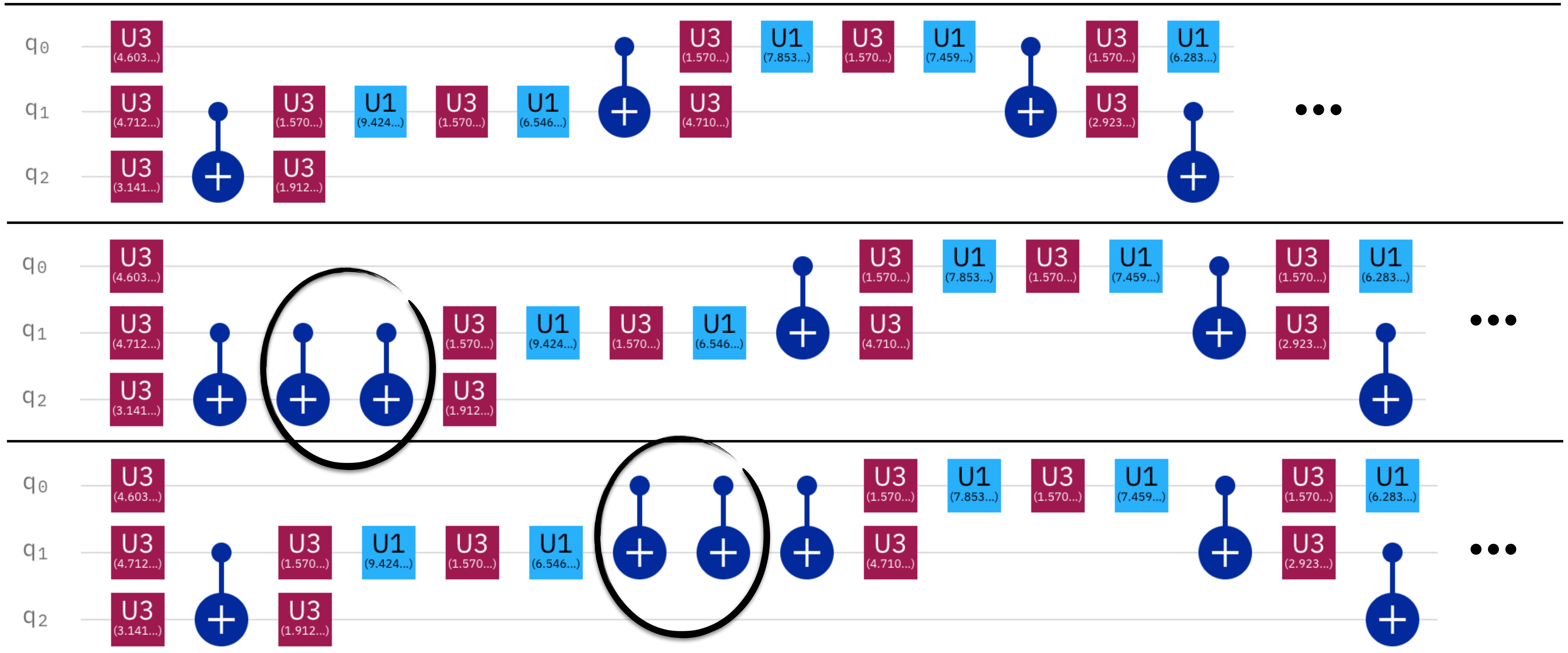
Zero-noise extrapolation of CNOT noise using Random Identity Insertions
He, Nachman, de Jong, Bauer (2020)

Circuit 1

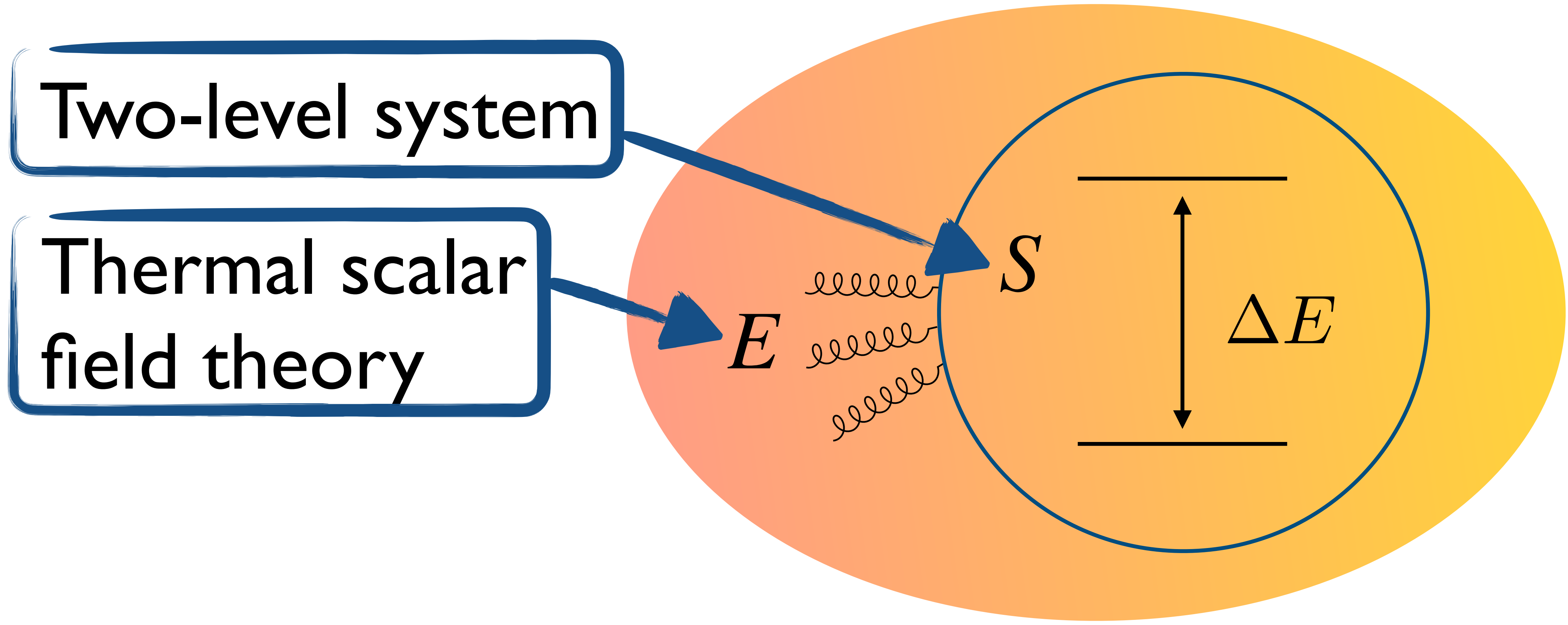
Circuit 2

Circuit 3

…



Quantum simulation of open quantum systems



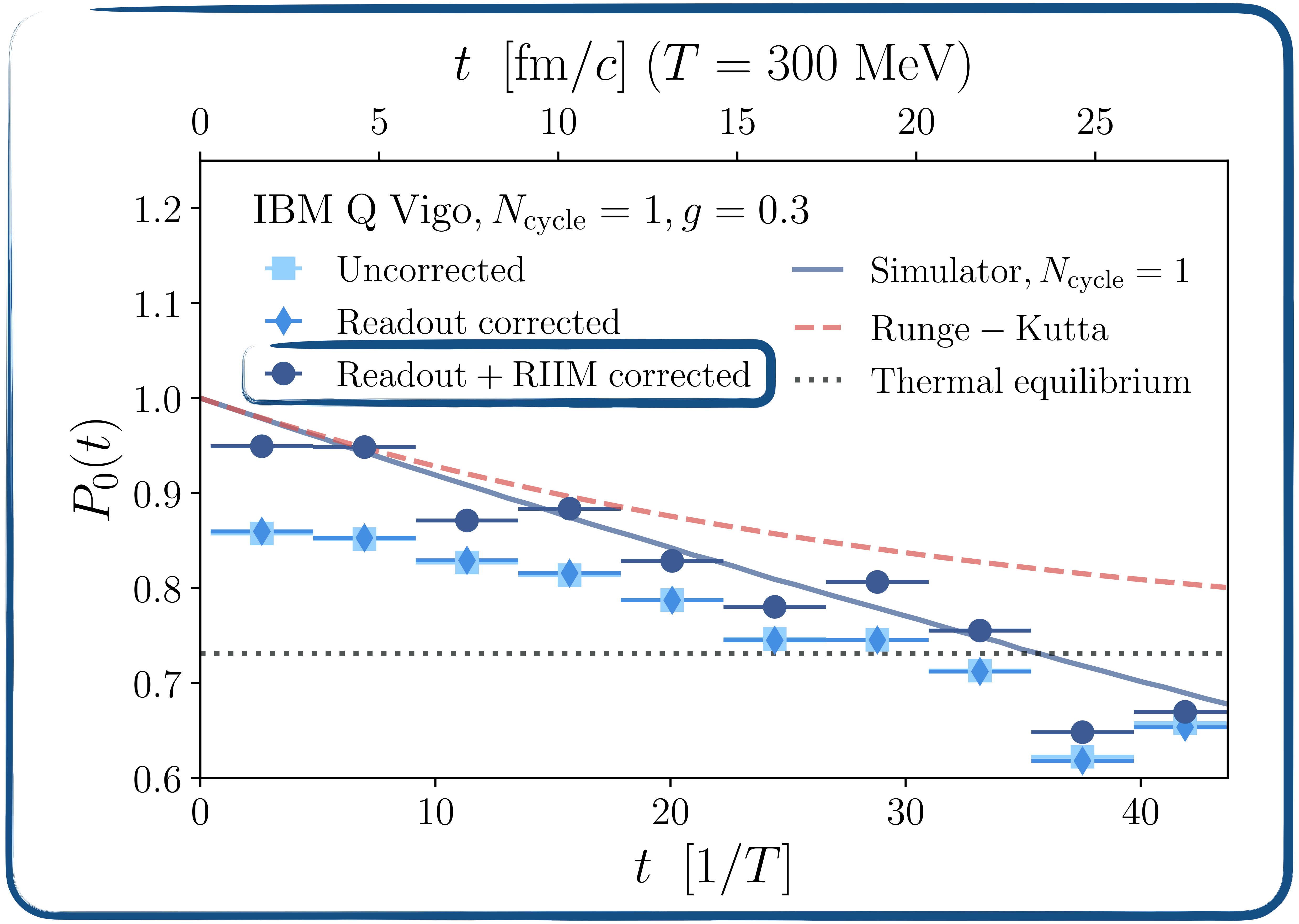
Quantum simulation on IBM Q Vigo device with $N_{\text{cycle}} = 1$

CNOT gate error correction gives good agreement

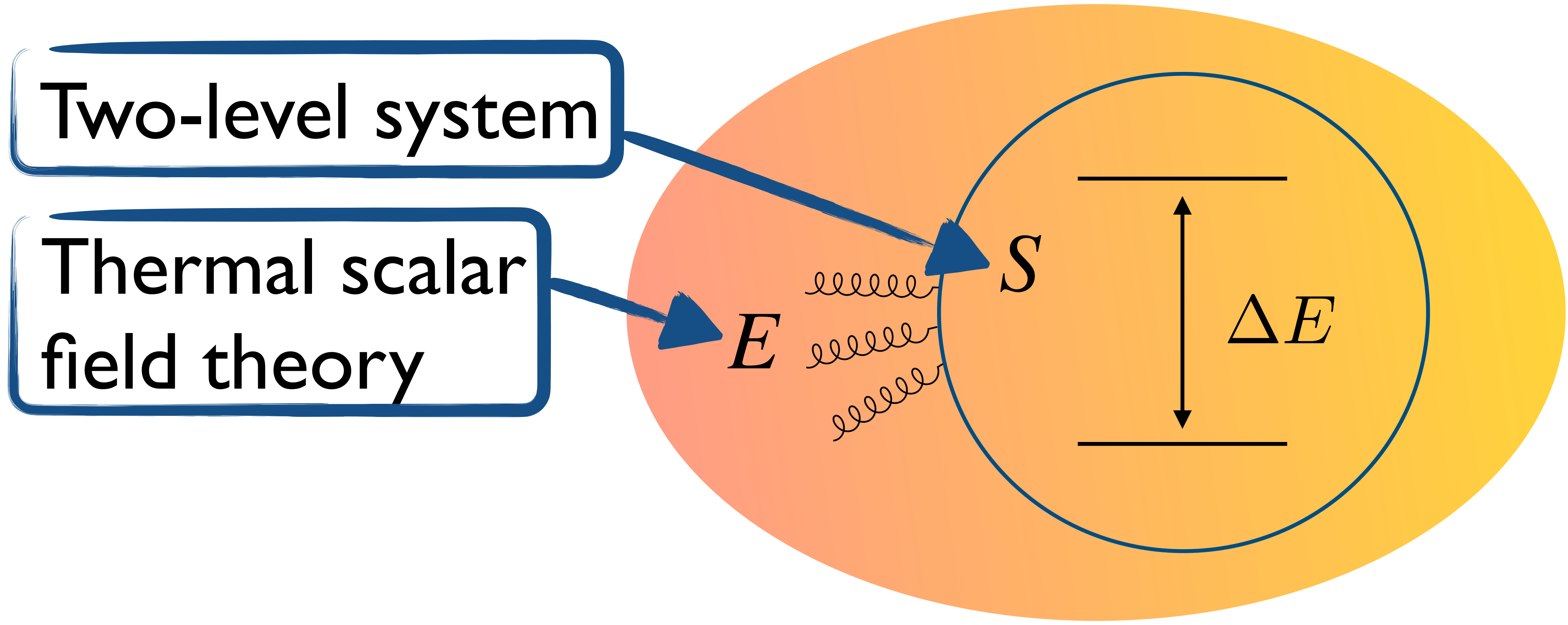
Random Identity Insertion Method (RIIM)
Bauer, He, de Jong, Nachman (2021)

Proof of concept

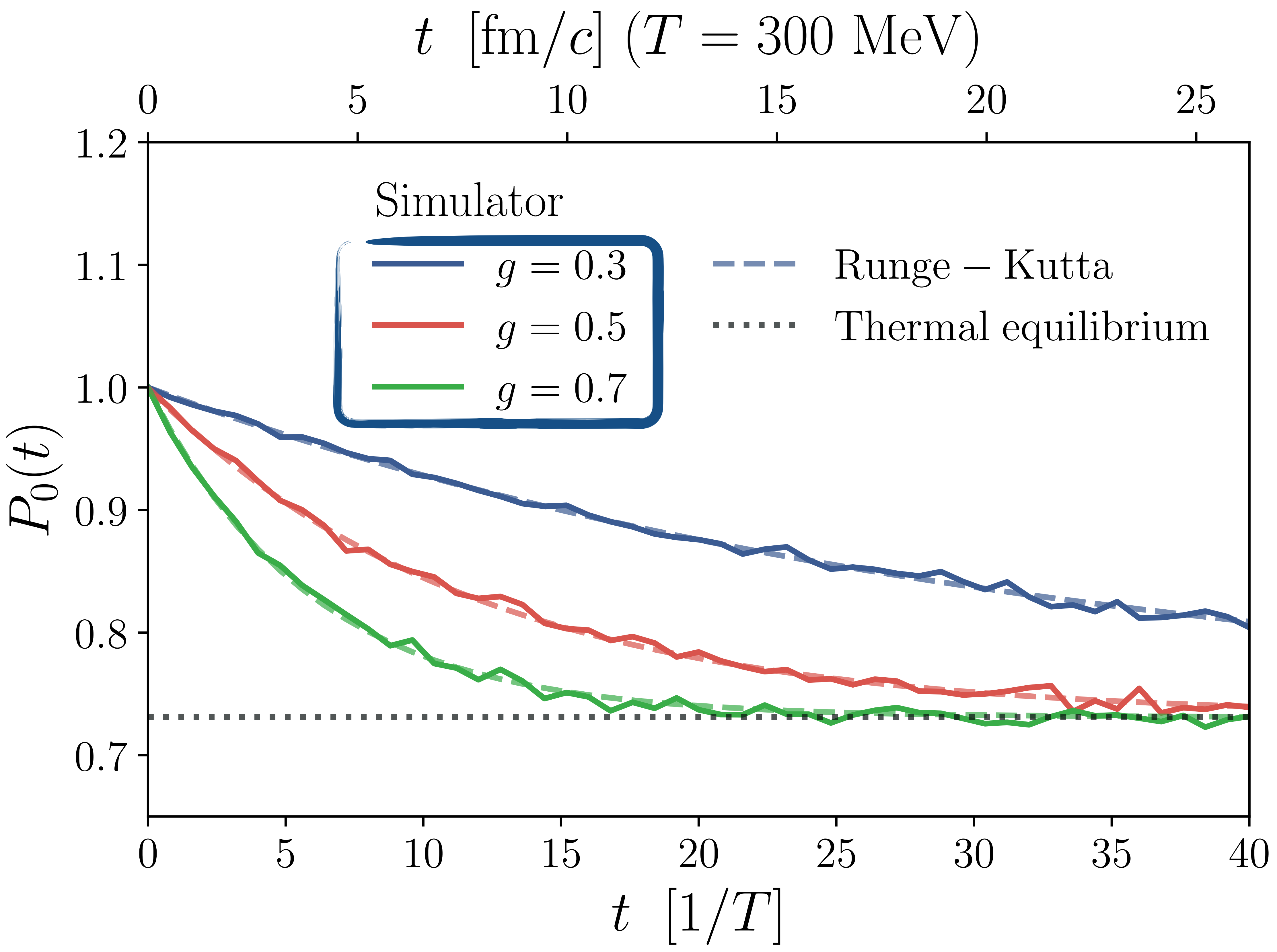
Jong, Metcalf, Mulligan, Ploskon, Ringer, Yao
PRD 104 L051501 (2021)



Quantum simulation of open quantum systems



Jong, Metcalf, Mulligan, Ploskon, Ringer, Yao
PRD 104 L051501 (2021)



Stronger coupling results in faster thermalization

By exploring different environment density matrix, can vary medium properties

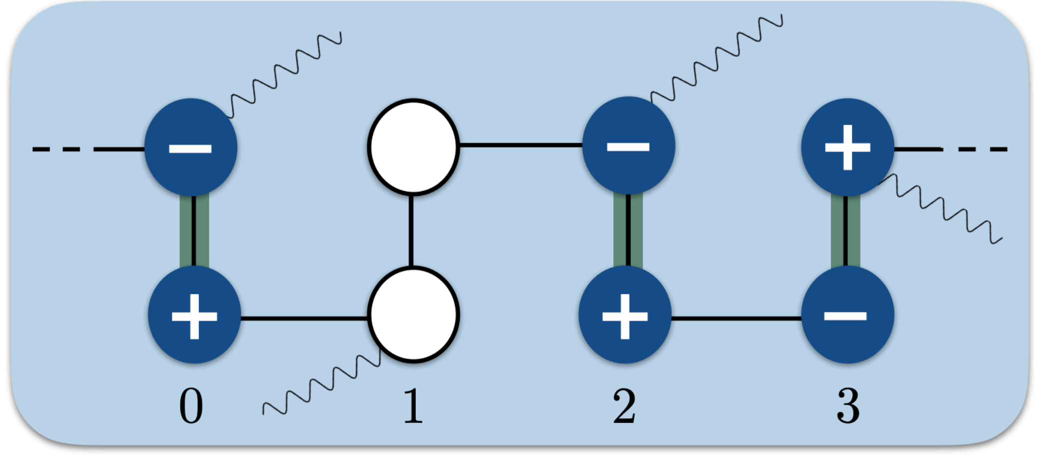
- Probe-medium coupling
- Initial temperature
- Microscopic structure

Outline

1. Formulating the problem: Open quantum systems in heavy-ion collisions

2. Simulating particle states: hard probes

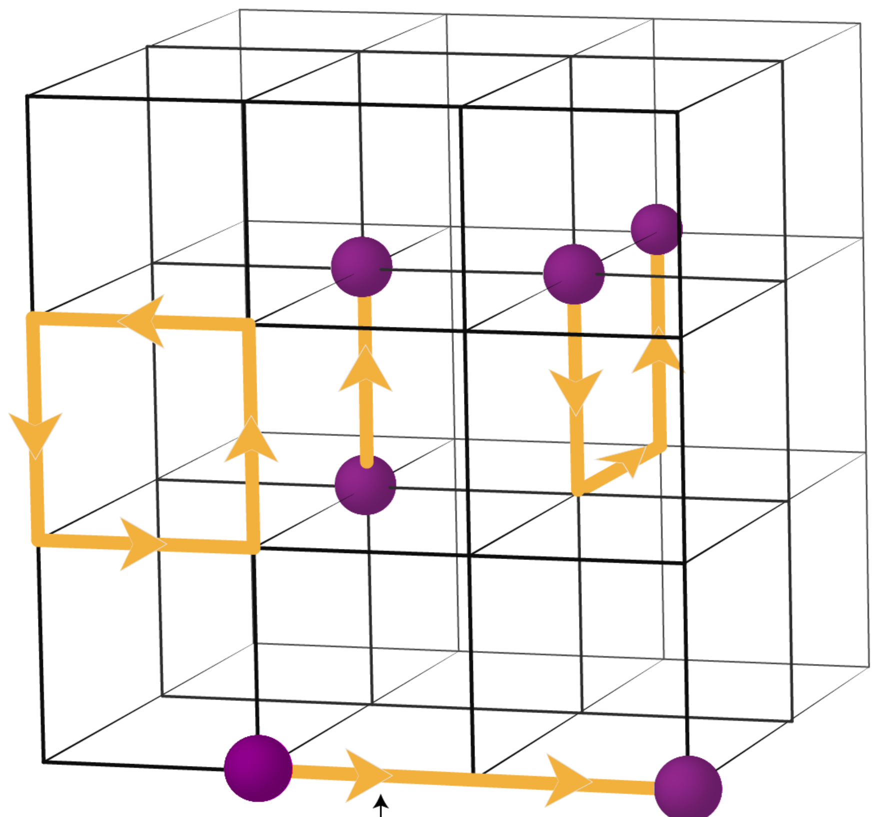
3. Simulating quantum field theories: thermalization and hadronization



Simulating QCD on quantum computers

Discretize space on a lattice, and digitize fields

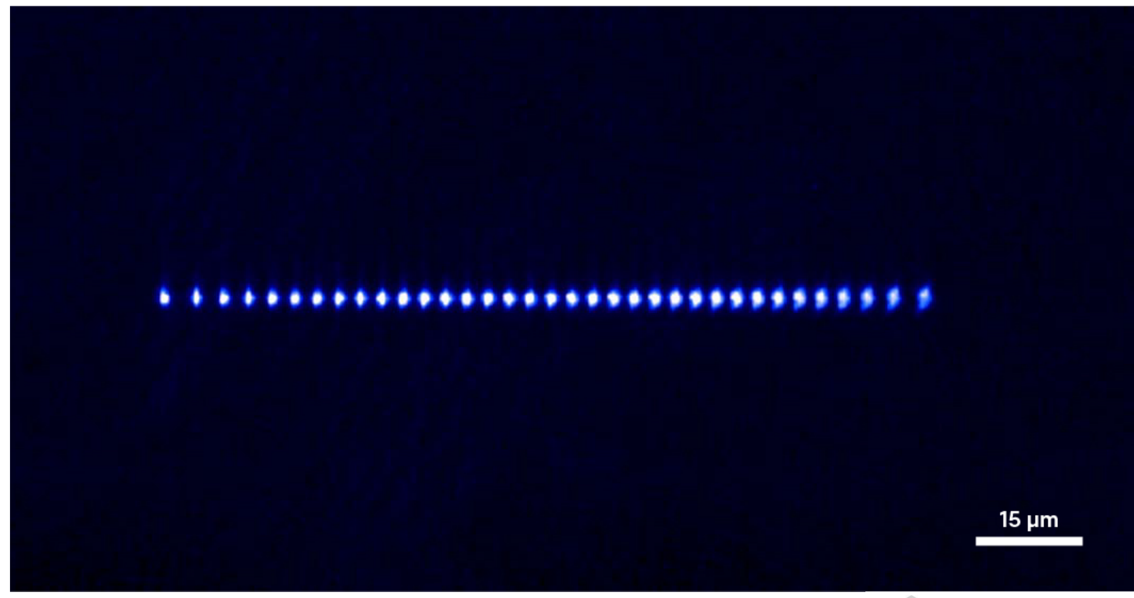
- No sign problem: real-time evolution and high density



Long-term goal: simulate limited energy range of QCD

- Good candidate: strongly-coupled regime
- Computing S-matrix at LHC not feasible: $\sim \mathcal{O}\left(10^{18}\right)$ qubits

Bauer, Nachman, Freytsis (2021)



IONQ

Near-term goals:

- Formulate how to efficiently digitize QCD
- Simulate simpler QFTs in order to gain insights about QCD

Klco et al. (2021)
Raychowdhury, Stryker (2020)
Alexandru et al. (2019)
Davoudi et al. (2019)
Muschik et al. (2016)
…

Schwinger model

Schwinger (1962)

$U(1)$ **gauge theory in 1+1D**

$$\mathcal{L} = \overline{\psi}(i\not{D} - m)\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

- Confinement
- Chiral symmetry breaking

Schwinger model

Schwinger (1962)
Kogut, Susskind (1973-1977)

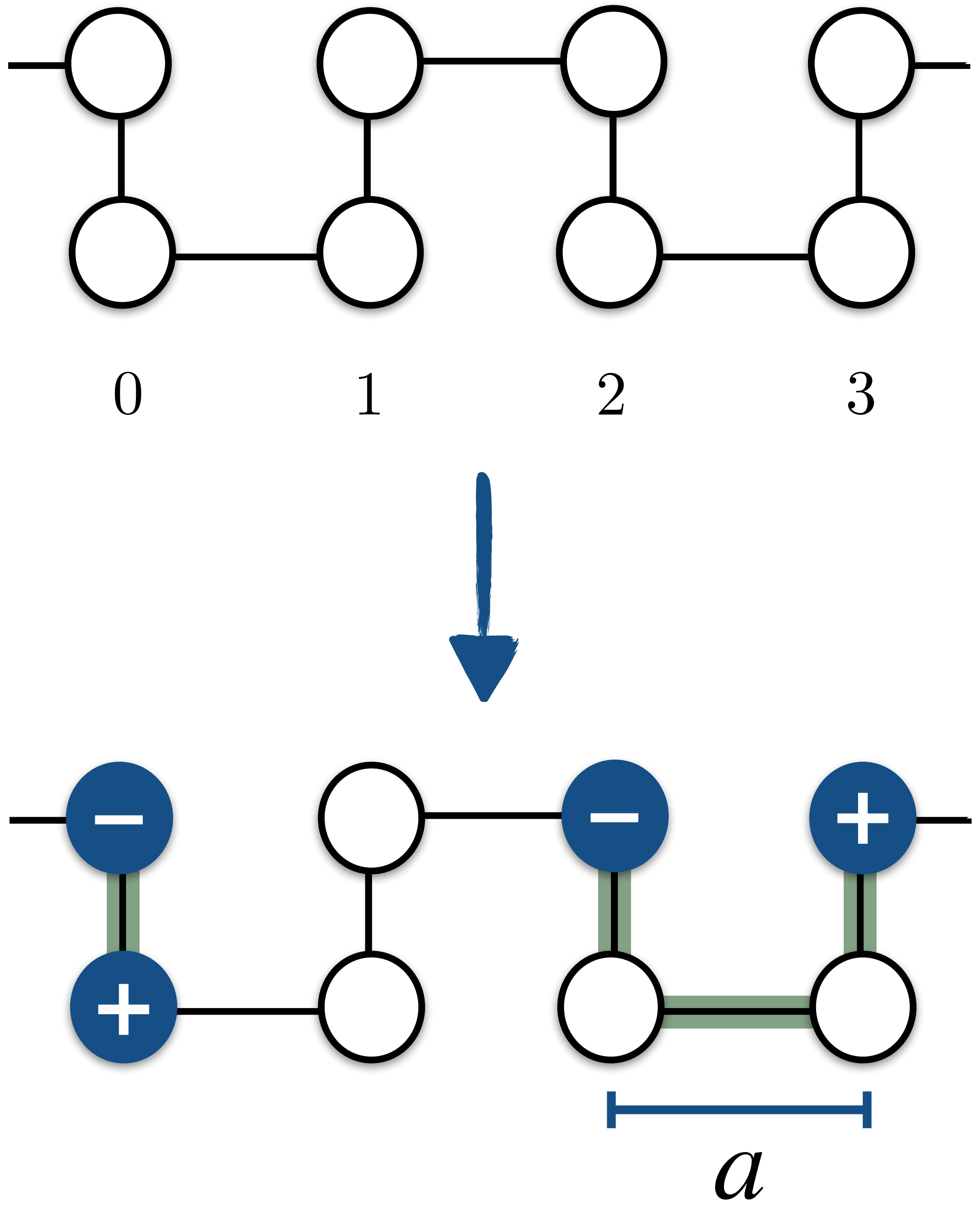
$U(1)$ gauge theory in 1+1D

$$\mathcal{L} = \overline{\psi}(i\not{D} - m)\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

- Confinement
- Chiral symmetry breaking

Discretized Hamiltonian — staggered fermions

$$H_S = \frac{1}{2a}\sum_{n=0}^{N_f-1}\left(\sigma^+(n)L_n^-\sigma^-(n+1) + \sigma^+(n+1)L_n^+\sigma^-(n)\right)$$
$$+ \sum_{n=0}^{N_f-1}\left(\frac{ae^2}{2}\ell_n^2 + m(-1)^n\frac{\sigma_z(n)+1}{2}\right)$$

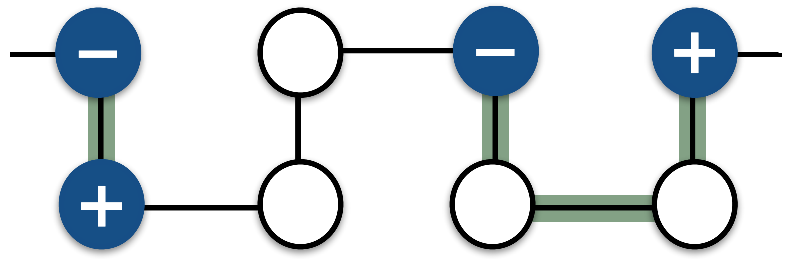


$N_f = 2N$ lattice sites
$\sigma^\pm$ create/destroy fermion
$L_n^\pm$ create/destroy gauge link

Schwinger model

Klco, Savage (2018)
Jong, Lee, Mulligan, Ploskon, Ringer, Yao 2106.08394

Number of physical states:



$$\sum_{M=1}^{N} \frac{2N}{M} \sum_{K=0}^{N-M} \binom{M-1+K}{M-1} \binom{2N-2K-M-1}{M-1} + 3$$

N	# states
2	13
4	117
6	1186
100	$\approx 1.4 \cdot 10^{51}$

Truncate the Hilbert space: subgroups of definite momentum and parity

- $\mathbf{k} = 0$, positive parity

$N = 2$

$$H_S^{\mathbf{k=0},+} = \begin{pmatrix} -2m & \frac{1}{a} & 0 & 0 & 0 \\ \frac{1}{a} & \frac{ae^2}{2} & \frac{1}{\sqrt{2}a} & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}a} & ae^2 + 2m & \frac{1}{\sqrt{2}a} & 0 \\ 0 & 0 & \frac{1}{\sqrt{2}a} & \frac{3ae^2}{2} & \frac{1}{\sqrt{2}a} \\ 0 & 0 & 0 & \frac{1}{\sqrt{2}a} & 2ae^2 - 2m \end{pmatrix}$$

$N = 4$

$$H_S^{\mathbf{k=0},+} =$$

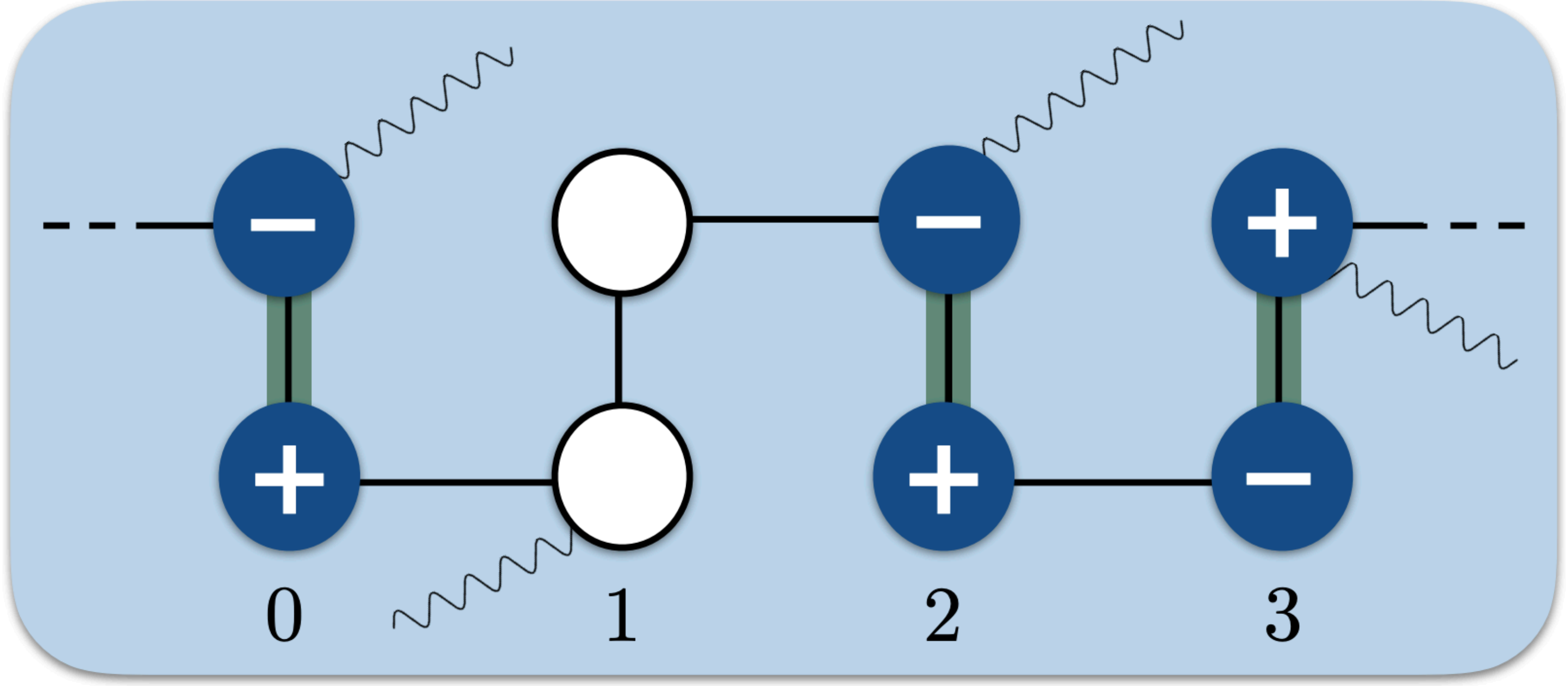
$$\begin{pmatrix}
-4m & \frac{\sqrt{2}}{a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{\sqrt{2}}{a} & \frac{ae^2}{2}-2m & \frac{1}{a} & \frac{1}{\sqrt{2}a} & \frac{1}{\sqrt{2}a} & \frac{1}{\sqrt{2}a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{a} & ae^2 & 0 & 0 & 0 & \frac{1}{2a} & \frac{1}{a} & \frac{1}{2a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{\sqrt{2}a} & 0 & ae^2 & 0 & 0 & 0 & 0 & \frac{1}{\sqrt{2}a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{\sqrt{2}a} & 0 & 0 & ae^2 & 0 & 0 & \frac{1}{\sqrt{2}a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{\sqrt{2}a} & 0 & 0 & 0 & ae^2 & 0 & 0 & \frac{1}{\sqrt{2}a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{1}{2a} & 0 & 0 & 0 & \frac{3}{2}ae^2-2m & 0 & 0 & \frac{1}{2a} & \frac{1}{2a} & \frac{1}{2a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{1}{a} & 0 & \frac{1}{\sqrt{2}a} & 0 & 0 & \frac{3}{2}ae^2+2m & 0 & \frac{1}{2a} & 0 & \frac{1}{2a} & \frac{1}{a} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{1}{2a} & \frac{1}{\sqrt{2}a} & 0 & \frac{1}{\sqrt{2}a} & 0 & 0 & \frac{3}{2}ae^2+2m & 0 & \frac{1}{2a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2a} & \frac{1}{2a} & 0 & 2ae^2 & 0 & 0 & 0 & \frac{1}{2a} & \frac{1}{2a} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2a} & 0 & \frac{1}{2a} & 0 & 2ae^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2a} & \frac{1}{2a} & 0 & 0 & 0 & 2ae^2 & 0 & \frac{1}{2a} & \frac{1}{2a} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{a} & 0 & 0 & 0 & 0 & 2ae^2+4m & 0 & \frac{1}{a} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2a} & 0 & \frac{1}{2a} & 0 & \frac{5}{2}ae^2-2m & 0 & \frac{1}{2a} & & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2a} & 0 & \frac{1}{2a} & \frac{1}{a} & 0 & \frac{5}{2}ae^2+2m & \frac{1}{a} & \frac{1}{\sqrt{2}a} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2a} & \frac{1}{a} & 3ae^2 & 0 & \frac{1}{a} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{\sqrt{2}a} & 0 & 3ae^2 & \frac{1}{\sqrt{2}a} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{a} & \frac{1}{\sqrt{2}a} & \frac{7}{2}ae^2-2m & \frac{1}{a} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{a} & 4ae^2-4m
\end{pmatrix}$$

Schwinger model — open system

Jong, Lee, Mulligan, Ploskon, Ringer, Yao 2106.08394

Couple the Schwinger model to a thermal scalar field theory $\phi(x)$

$$H_I = \lambda \int \mathrm{d}x\, \phi(x)\overline{\psi}(x)\psi(x)$$



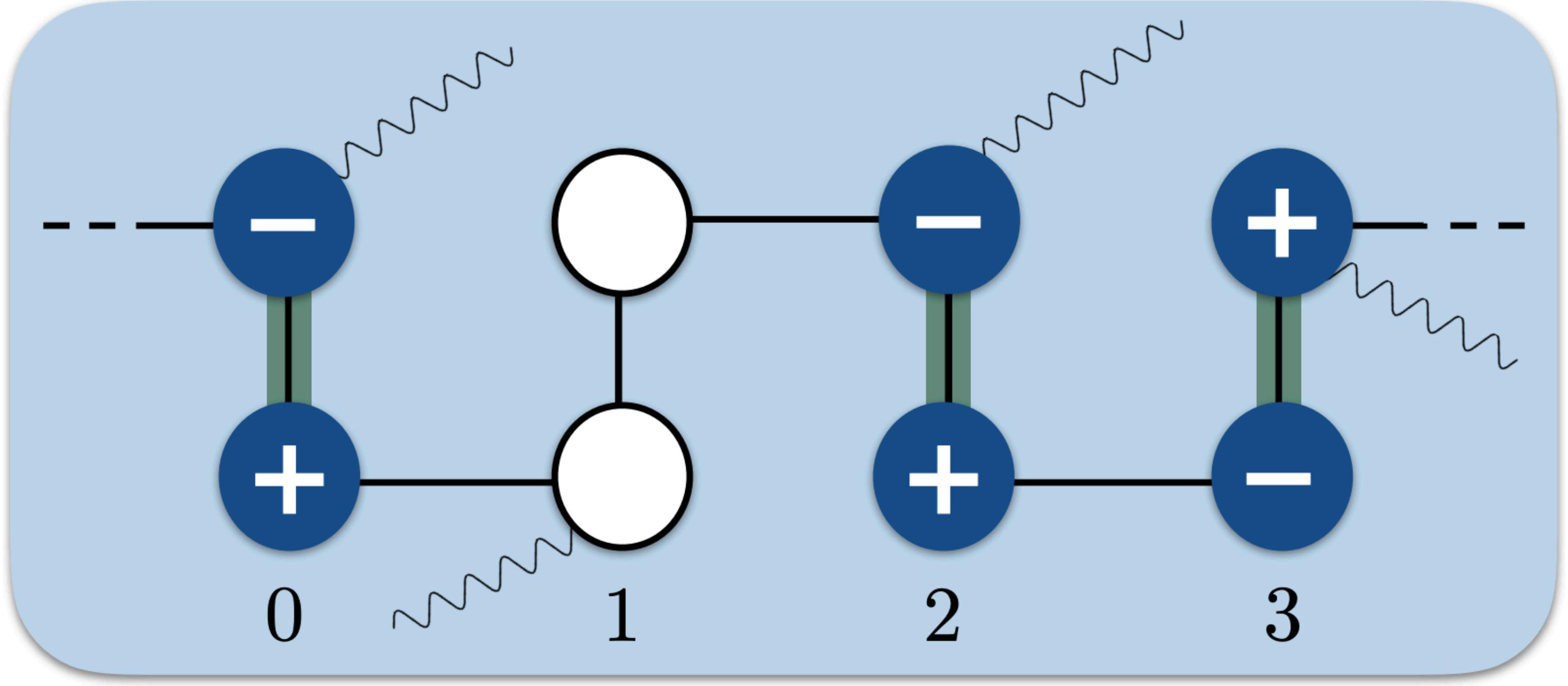
τ_S — subsystem intrinsic time scale
τ_R — subsystem relaxation time
τ_E — environment correlation time

Schwinger model — open system

Jong, Lee, Mulligan, Ploskon, Ringer, Yao 2106.08394

Couple the Schwinger model to a thermal scalar field theory $\phi(x)$

$$H_I = \lambda \int \mathrm{d}x\, \phi(x)\overline{\psi}(x)\psi(x)$$



In the Quantum Brownian Motion limit,

$\tau_R \gg \tau_E$ — Markovian approximation

$\tau_S \gg \tau_E$ — valid if $T \gg \Delta E_S$

τ_S — subsystem intrinsic time scale

τ_R — subsystem relaxation time

τ_E — environment correlation time

the subsystem is described by a Lindblad equation:

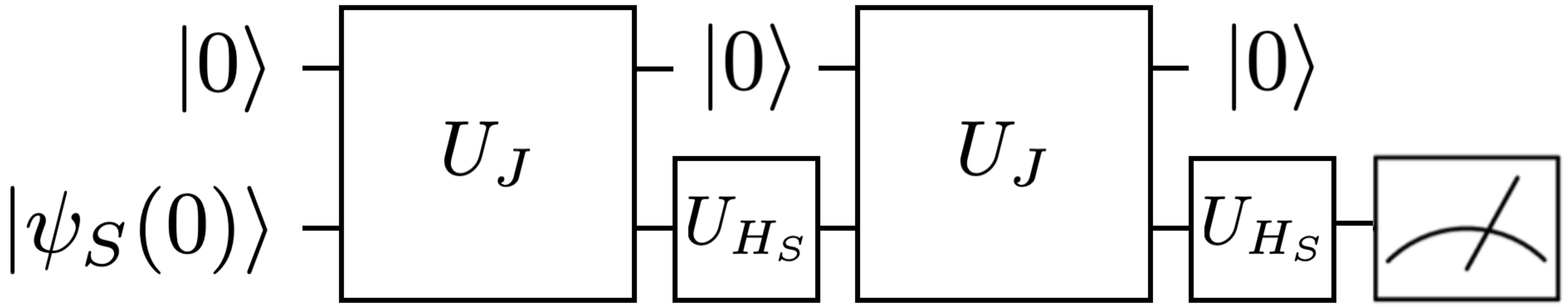
$$\boxed{\frac{\mathrm{d}\rho_S(t)}{\mathrm{d}t} = -i\big[H_S, \rho_S(t)\big] + L\rho_S(t)L^\dagger - \frac{1}{2}\{L^\dagger L, \rho_S(t)\}}$$

$$L = \sqrt{aN_f D}\Big(O_S - \frac{1}{4T}[H_S, O_S]\Big) \qquad O_S(x) = \overline{\psi}(x)\psi(x) \qquad D = \lambda^2 \int \mathrm{d}t\,\mathrm{d}x\, \mathrm{Tr}_E\big(\rho_E\, \phi(t,x)\phi(0,0)\big)$$

Non-equilibrium dynamics and thermalization

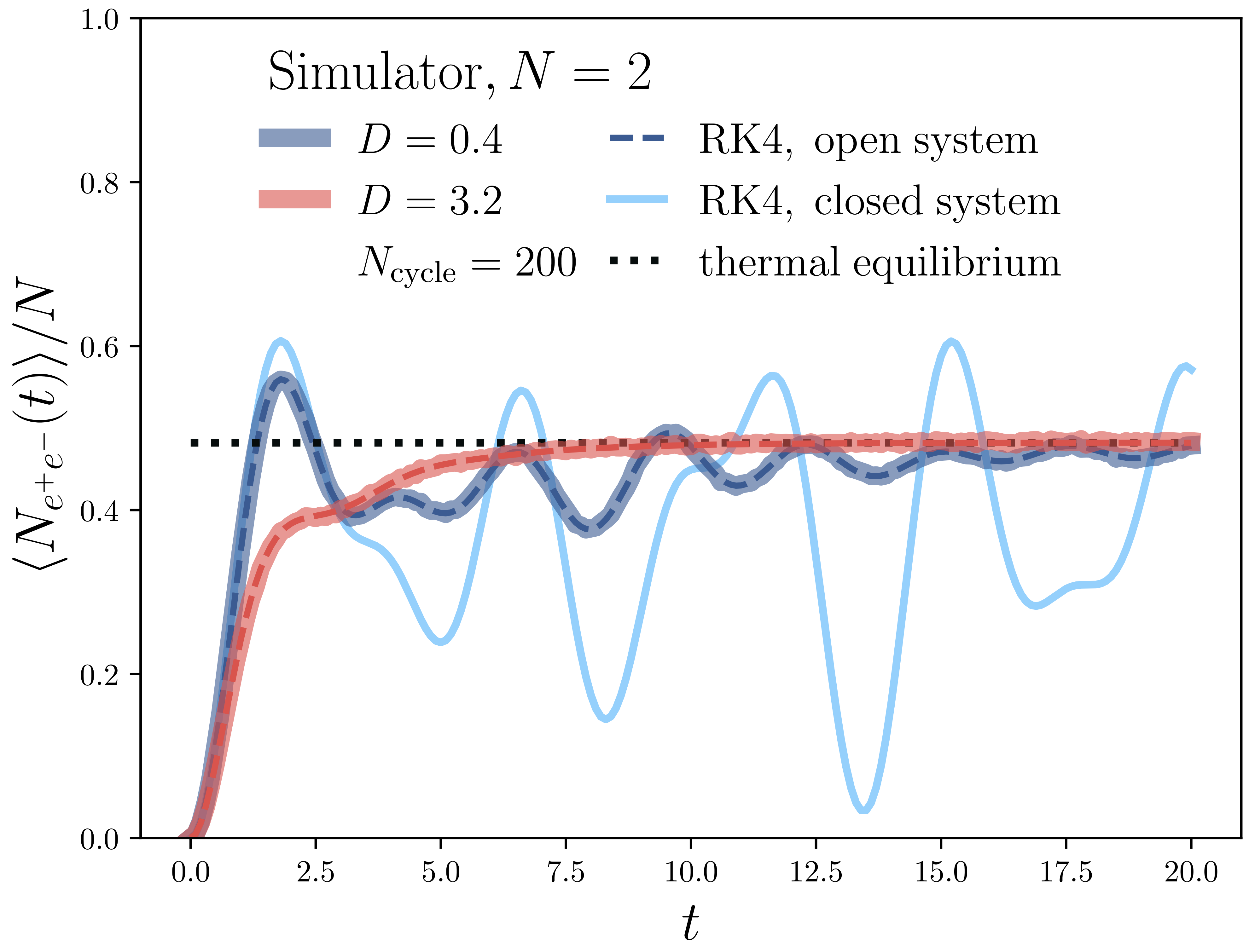
Jong, Lee, Mulligan, Ploskon, Ringer, Yao 2106.08394

We construct a quantum circuit to solve the Lindblad evolution



Classical simulation of the quantum circuit reproduces the thermalization observed in numerical solution

Number of e^+e^- pairs



Note: The environment correlator $D \sim \lambda^2$ determines how fast the system equilibrates

Non-equilibrium dynamics and thermalization

Jong, Lee, Mulligan, Ploskon, Ringer, Yao 2106.08394

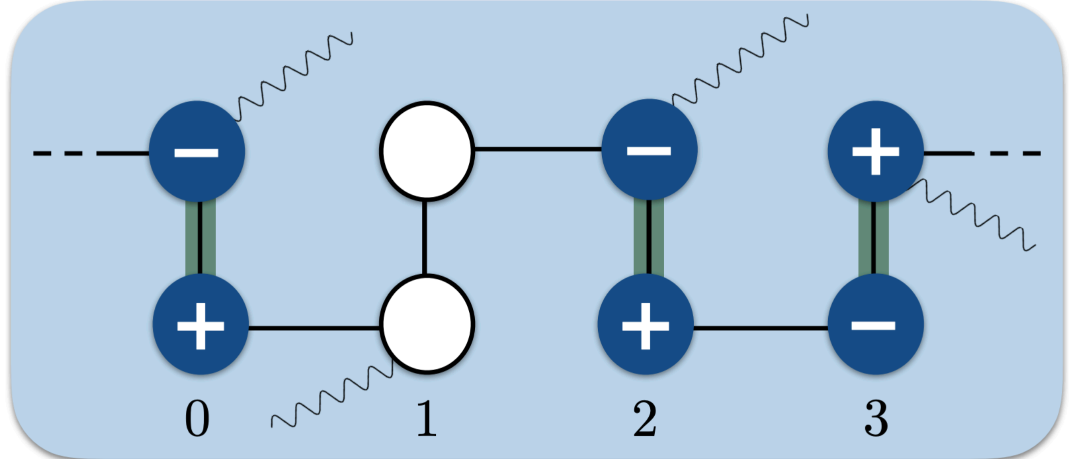
Simulation on IBM Q device

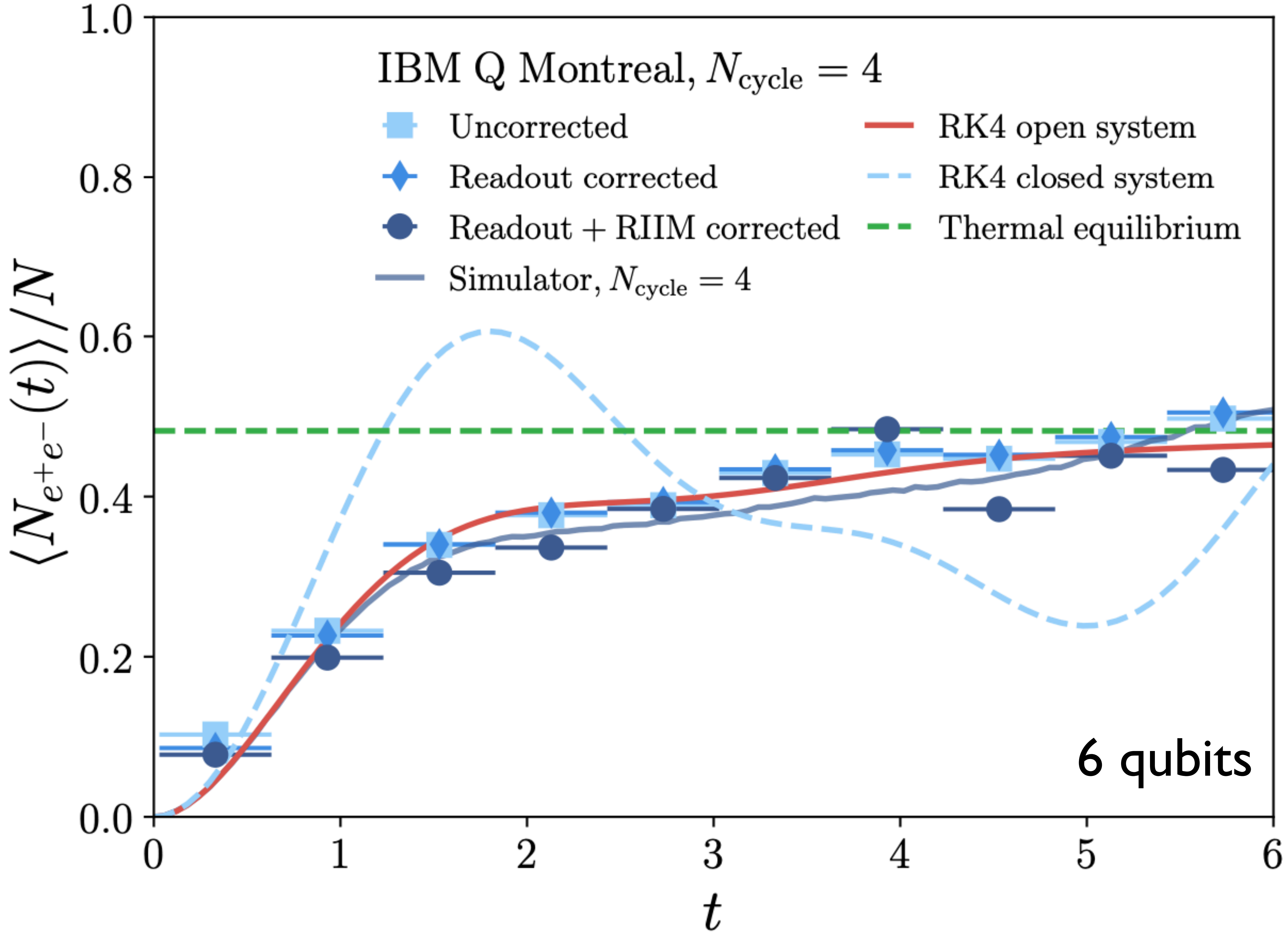
- Error mitigation applied

Number of e^+e^- pairs

First quantum simulation of open quantum systems described by quantum field theories

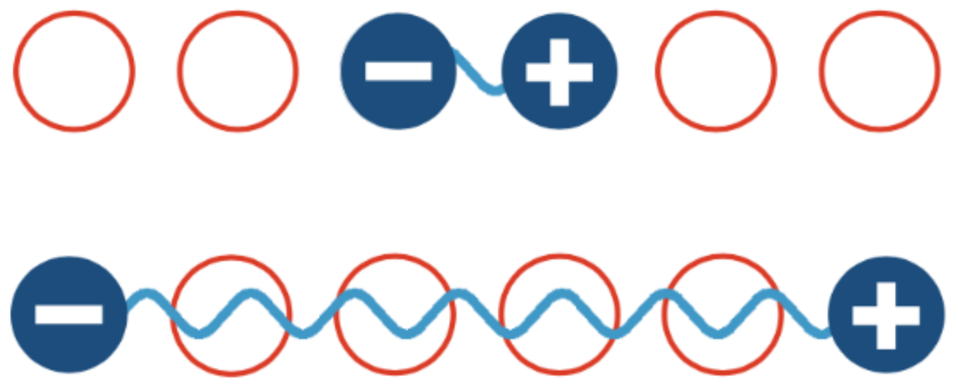
Real-time dynamics of thermalization process





Hadronization

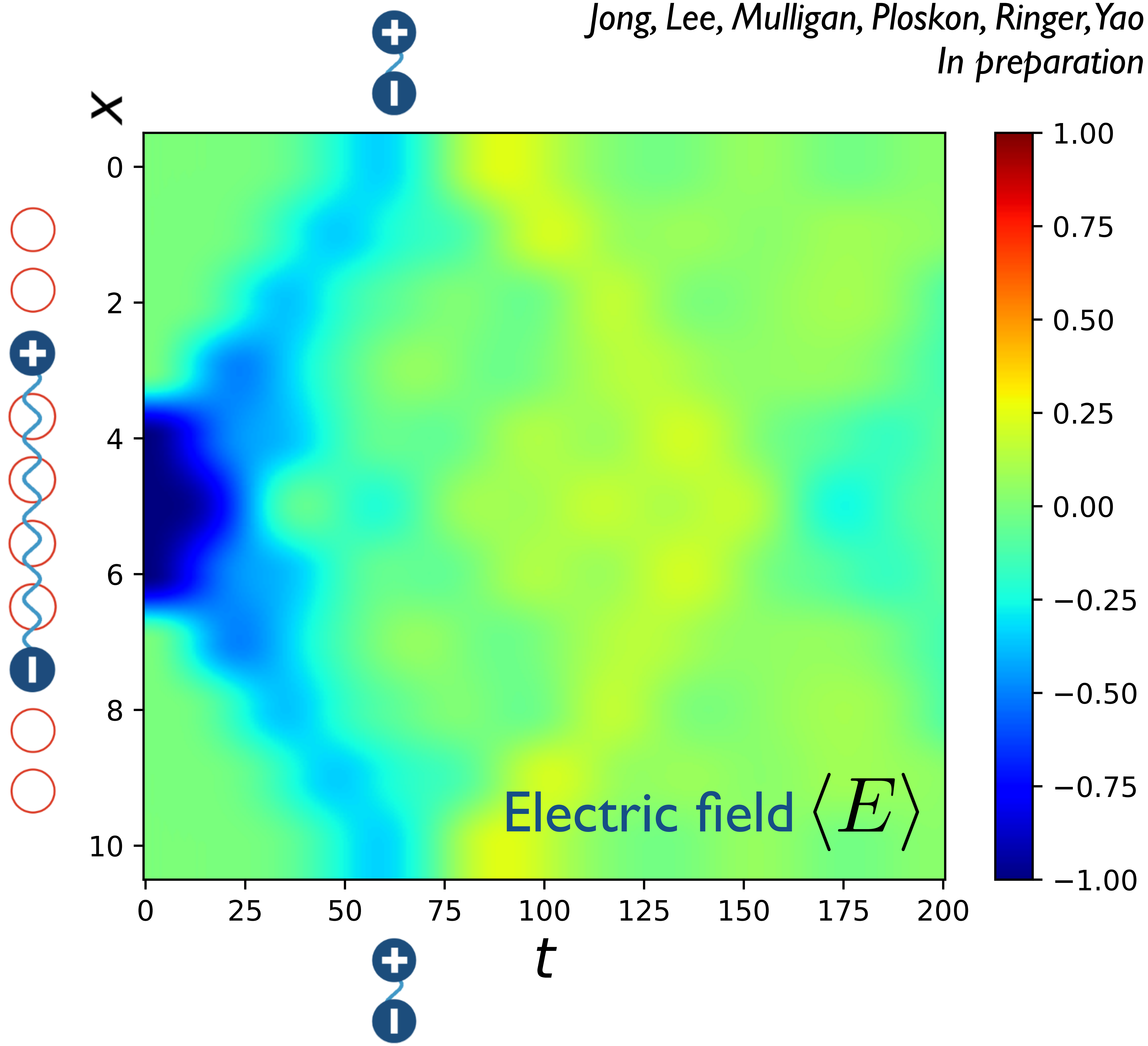
We can also study dynamics of QED strings



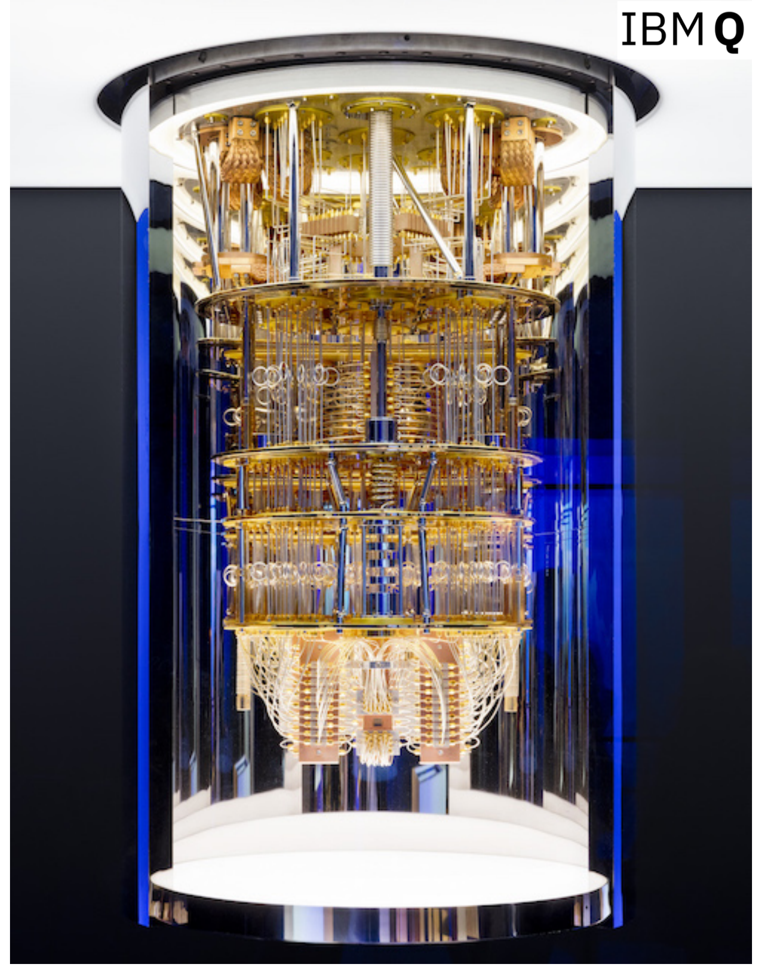
Real-time picture of string breaking mechanism

Long-term goal: "movie" of hadronization process in QCD

Jong, Lee, Mulligan, Ploskon, Ringer, Yao
In preparation



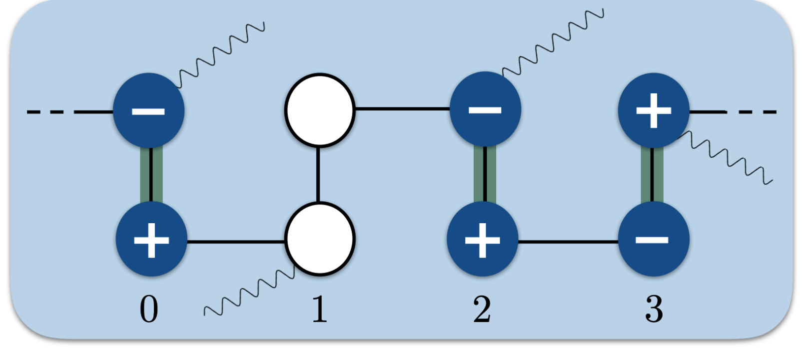
Summary



A new type of experiment is emerging: Real-time evolution of QCD dynamics in heavy-ion collisions on quantum computers

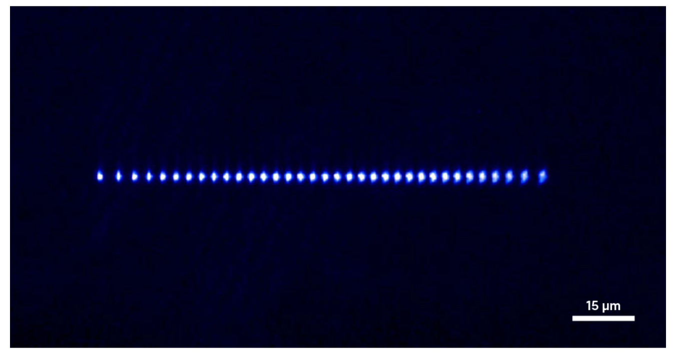
Open quantum system formalism — early work to simulate a variety of probes

- Particle states: e.g. quarkonium dissociation and recombination
- Quantum field theories: thermalization, hadronization



Many open questions — but long-term potential for a new game-changing tool in our understanding of QCD

- Scalable extension to $SU(3)$?
- Sufficient improvements to qubit quality and error correction?



IONQ