Quantum computing for nuclear theory at Jefferson Lab

Felix Ringer

Old Dominion University
Jefferson Lab

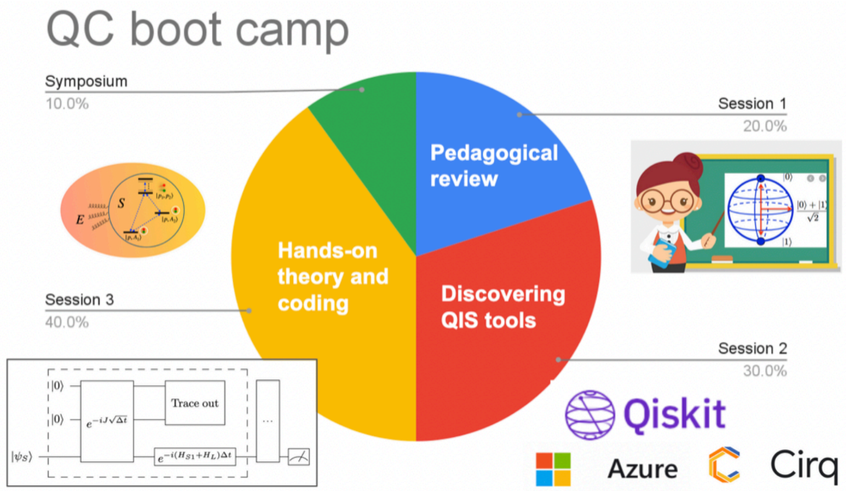
JLUO Annual Meeting, 06/28/23

OLD DOMINION UNIVERSITY

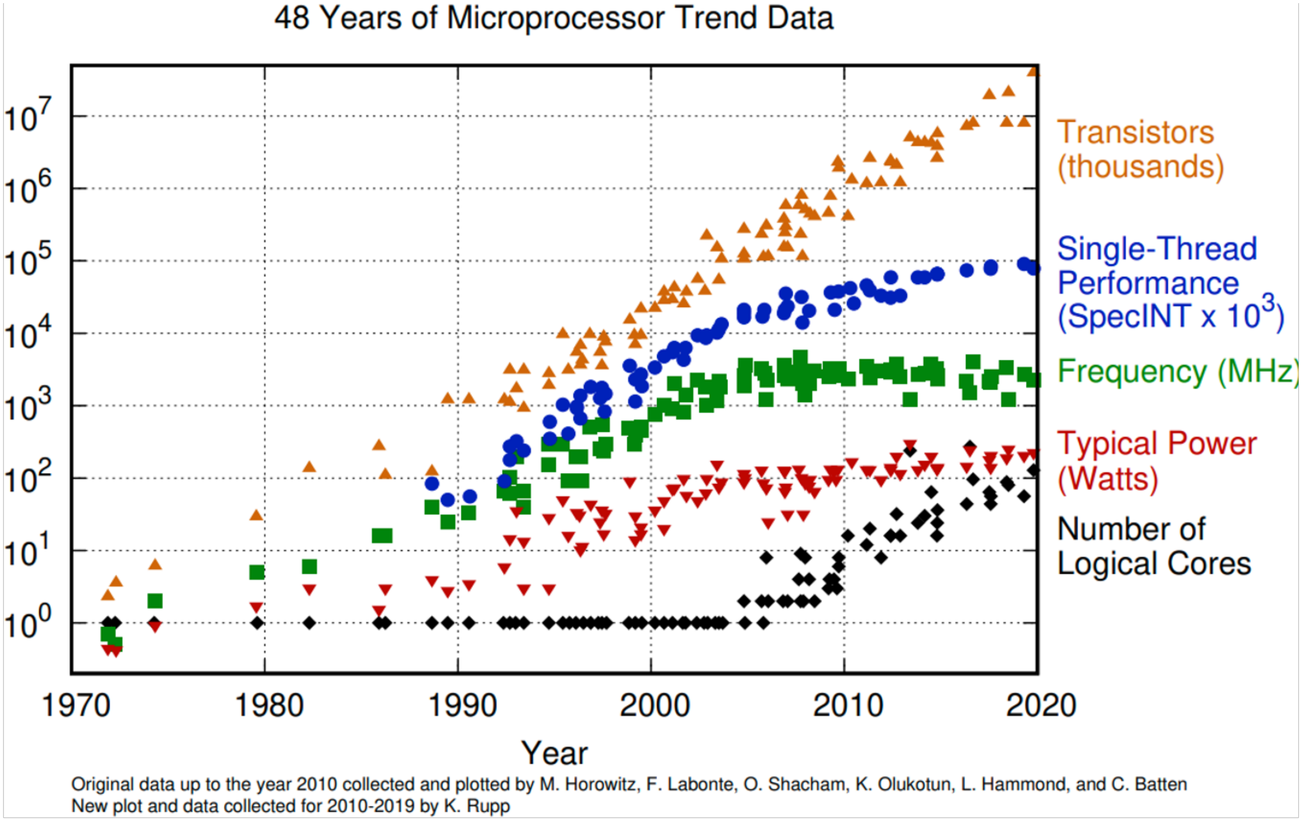
Jefferson Lab

Quantum computing Bootcamp at JLab

- June 20-30
- Funding from DOE Quantum Horizons
- Quantum computing for nuclear theory
- Lectures + symposium day on June 30th

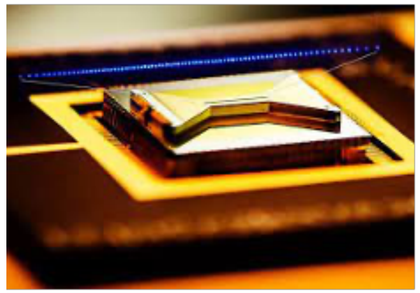


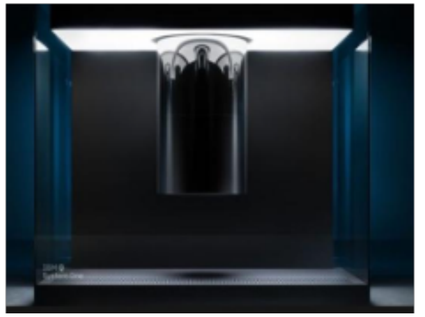
Classical & quantum computing



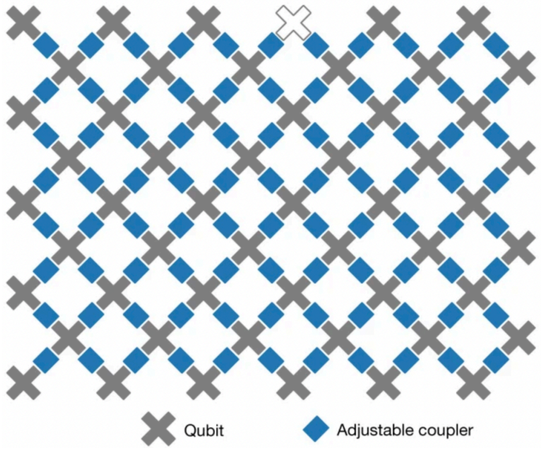
- Classical

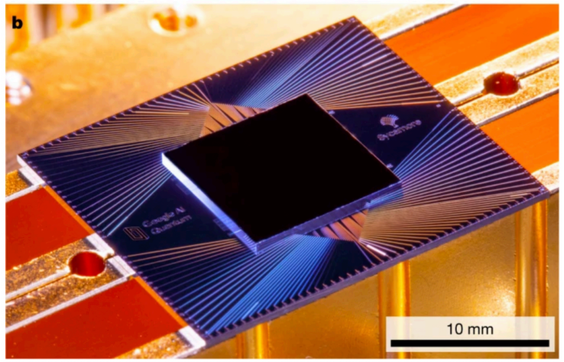
- Quantum

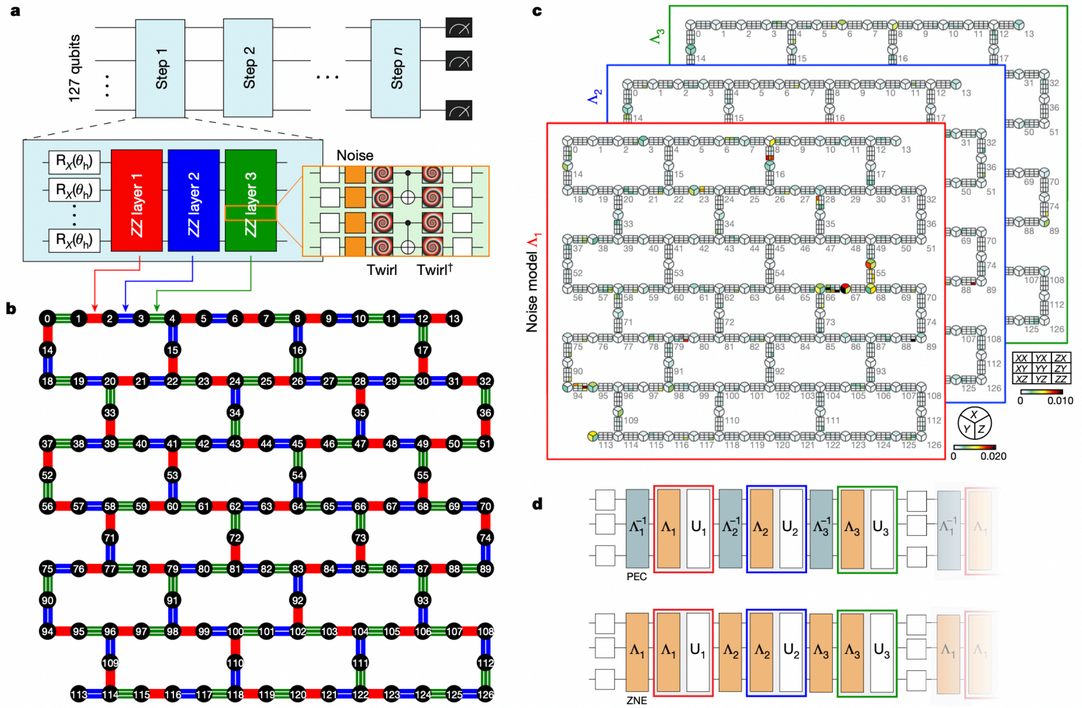




Recent progress in quantum hardware



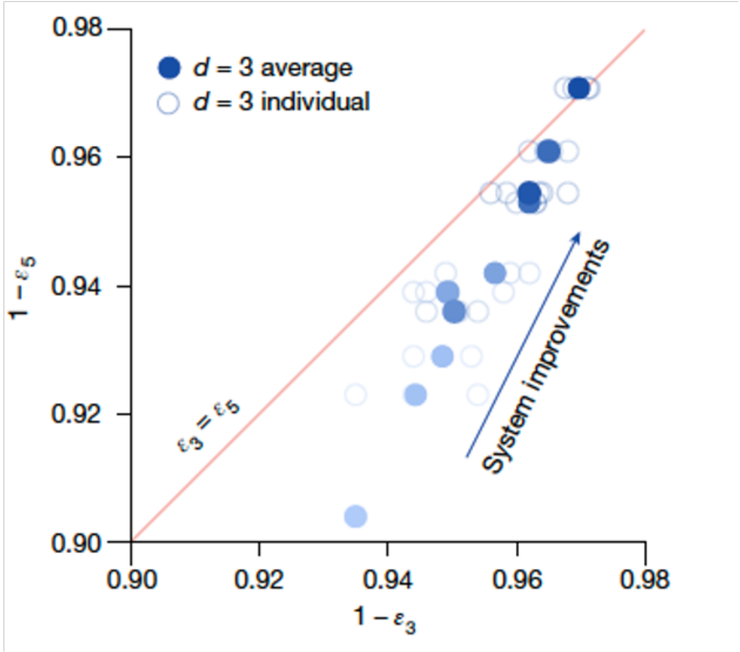




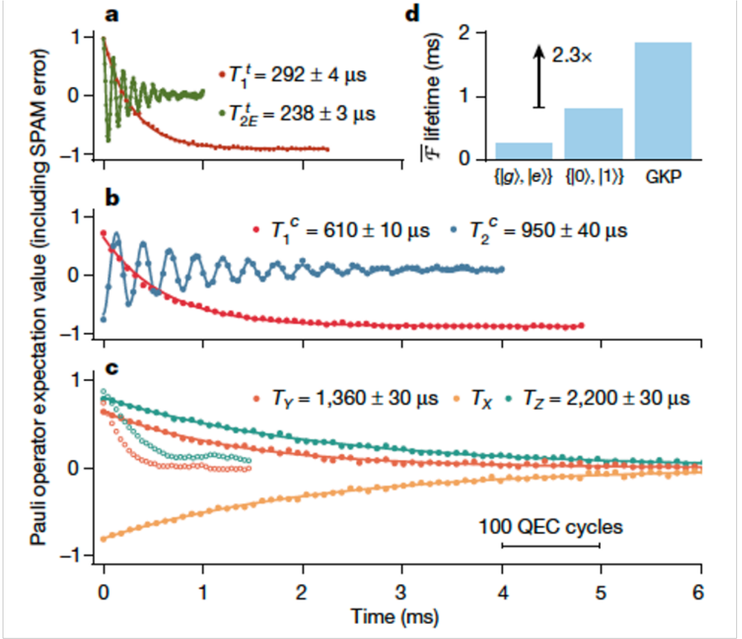
- Quantum supremacy for random circuit sampling, Nature 574 (2019), Google
- Evidence for the utility of quantum computing before fault tolerance, Nature 618 (2023), IBMQ

Recent progress in quantum hardware

- Suppressing quantum errors by scaling a surface code logical qubit, Nature 614 (2023), Google

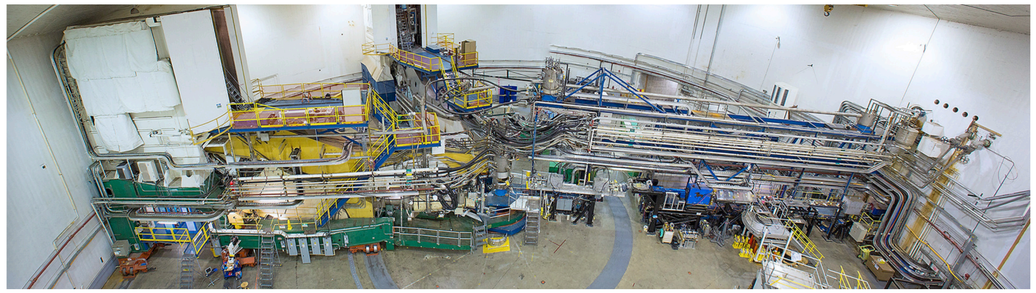


- Real-time quantum error correction beyond break even, Nature 616 (2023), Sivak et al.

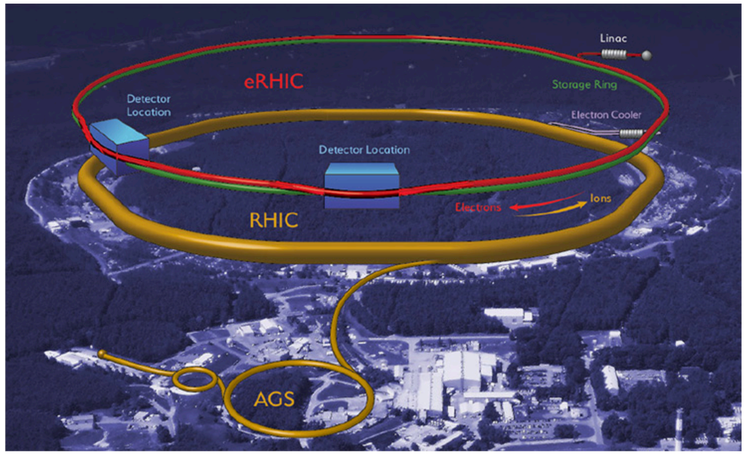


- Quantum error correction is beginning to improve performance with increasing qubit number

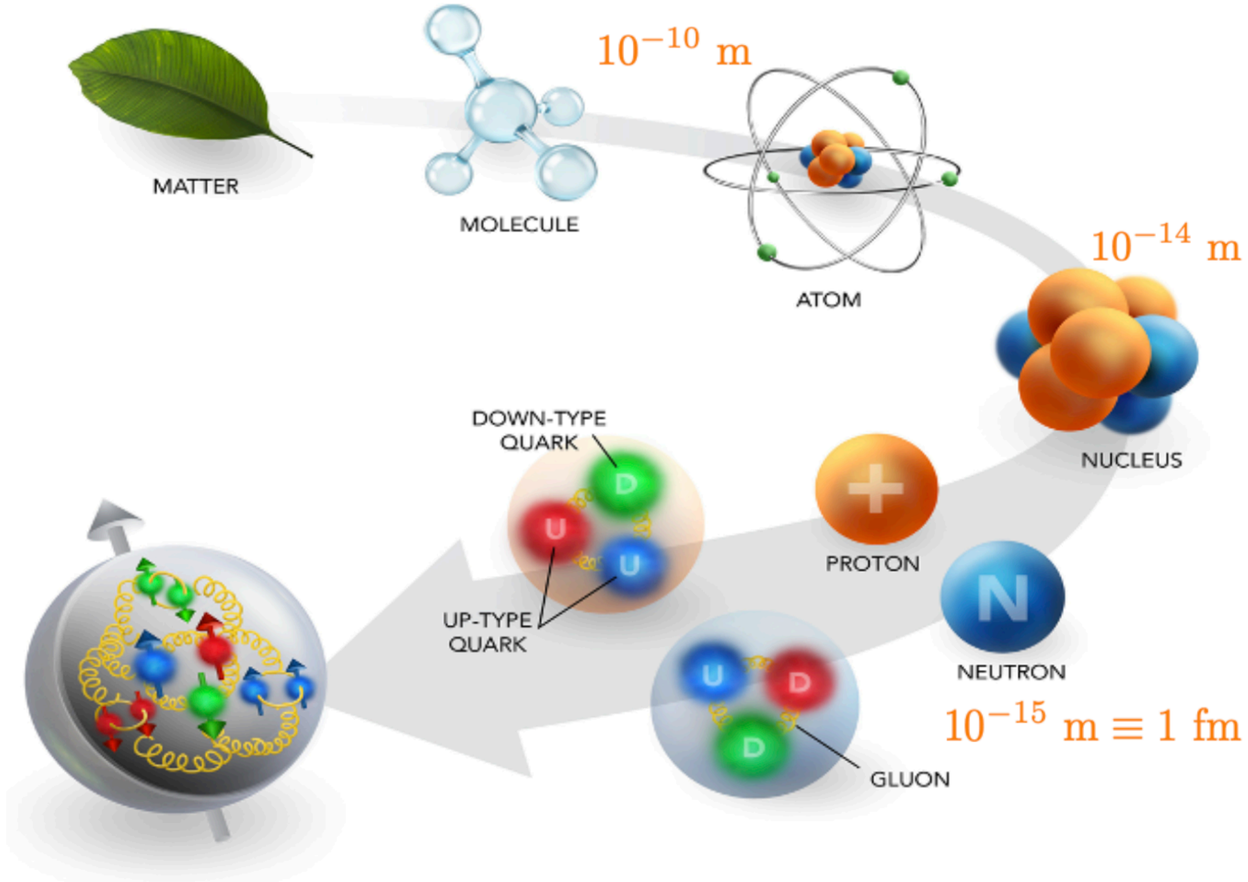
Understanding the fundamental structure of matter



CEBAF, JLab



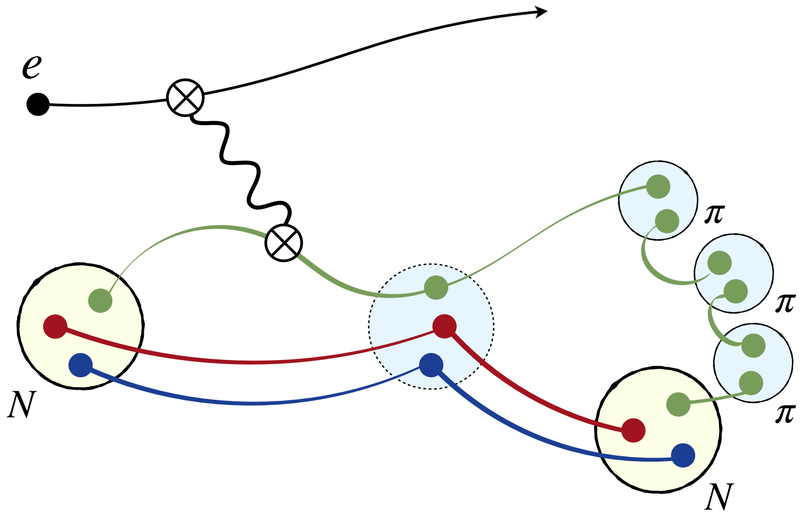
Electron Ion Collider BNL



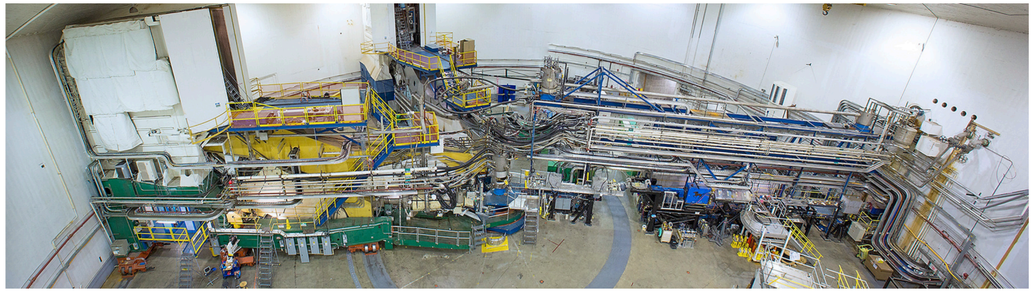
Quarks & Gluons

Quantum computing for nuclear theory

- Real-time scattering processes
  - Currently perturbative regime & Euclidean-time lattice QCD
  - Use Hamiltonian formulation of lattice field theory *Kogut, Susskind `70s*
- Finite chemical potential
- Nuclear structure calculations



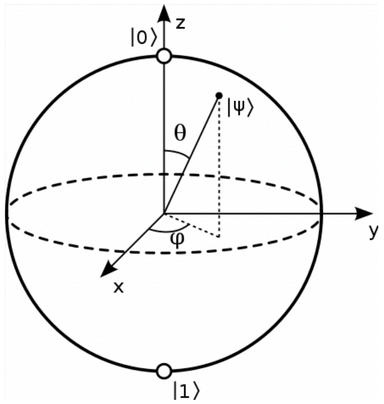
Briceno

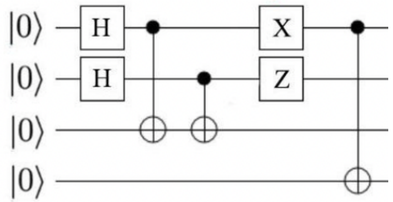


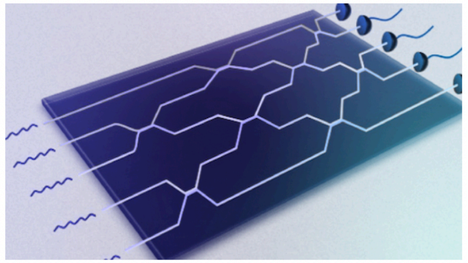
Qubit and qumode platforms

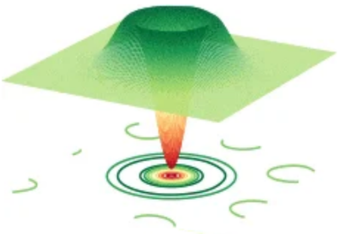
Elementary units for computing

- **Qubits**
  - Superconducting transmons, trapped ions…
  - Digital gate-based computing
- **Qumodes**
  - Photonic platforms
  - Infinite-dimensional Hilbert space
  - Continuous-variables





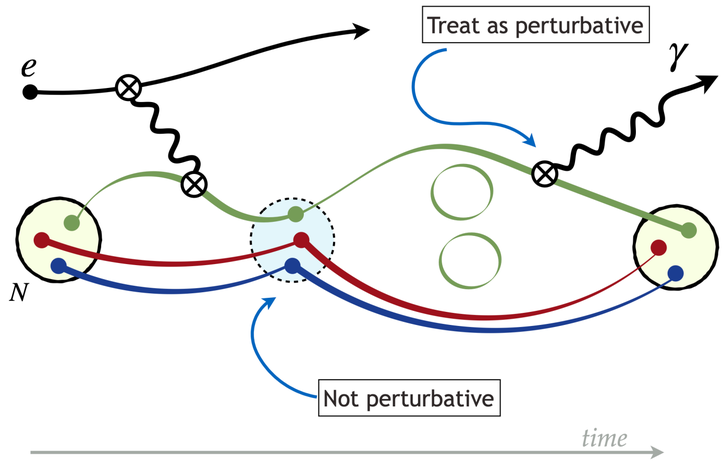


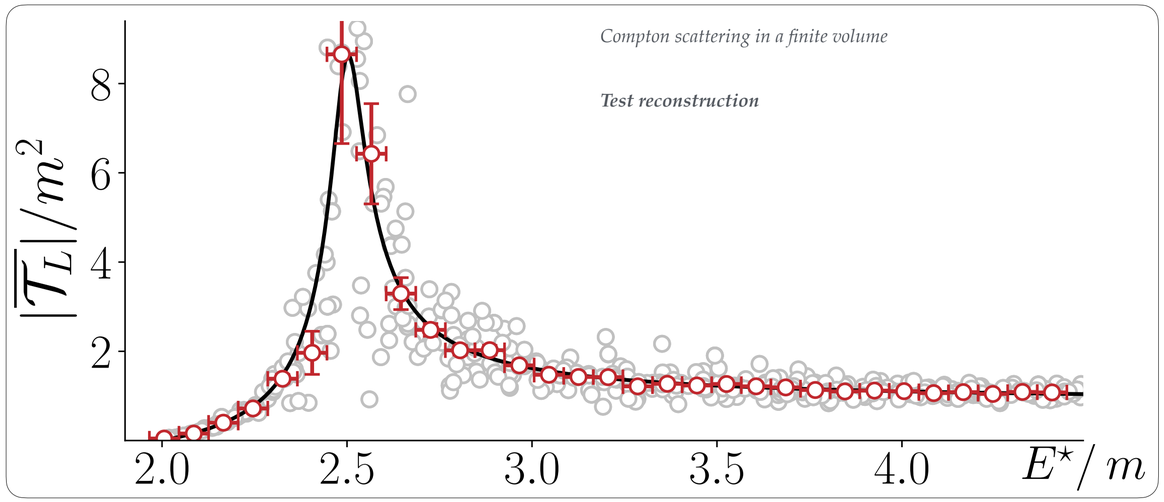


Inclusive scattering

- E.g. Compton form factors
- Two-current matrix elements
- Directly evaluate in Minkowski finite volume

$$\mathcal{T} \sim \int d^4x\, e^{ix\cdot q} \left\langle n_f \left| T\left[\mathcal{J}_{2,M}(t)\mathcal{J}_1(0)\right] \right| n_i \right\rangle_\infty$$



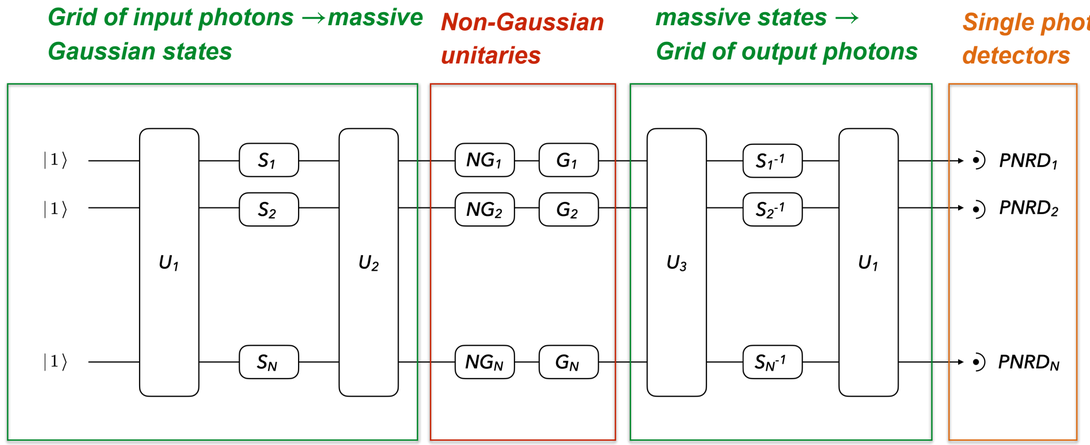


Briceno, Guerrero, Hansen, Sturzu `20

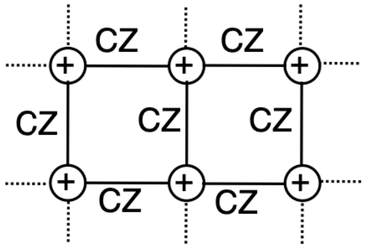
Inclusive scattering

- Simulate real-time dependent correlation functions
- Use optical squeezing to generate effective mass
- Prepare free-field eigenmodes
- Non-Gaussian gates to simulate scalar ϕ^4 theory

Briceno, Eaton, Edwards, Gonzalez, Orginos, Pfister, Siopsis - in preparation



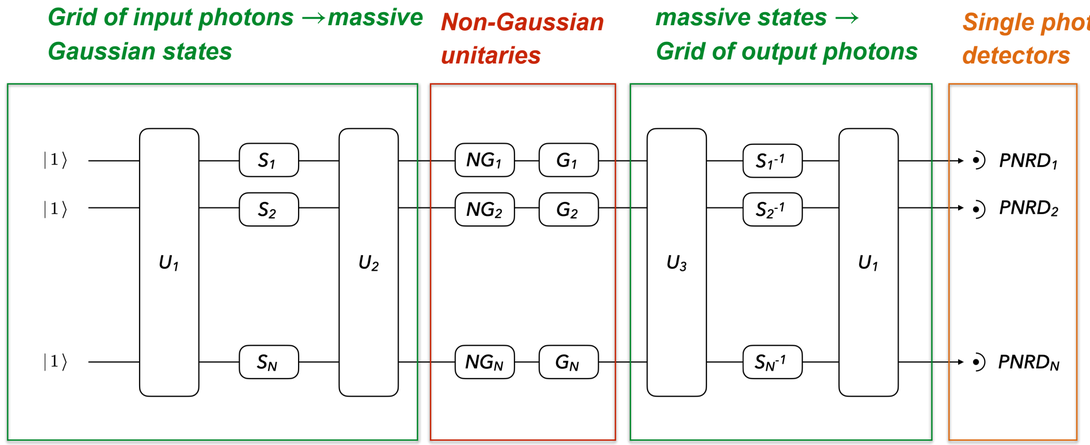
- Measurement based quantum computing with cluster states *Raussendorf, Briegel `06*



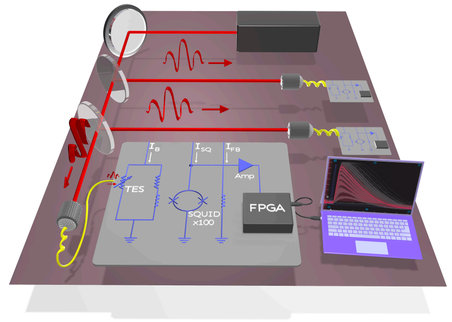
Inclusive scattering

- Simulate real-time dependent correlation functions
- Use optical squeezing to generate effective mass
- Prepare free-field eigenmodes
- Non-Gaussian gates to simulate scalar ϕ^4 theory

Briceno, Eaton, Edwards, Gonzalez, Orginos, Pfister, Siopsis - in preparation



- Close collaboration with the experimental group from Olivier Pfister at UVA
- Extension to non-Abelian field theories *Jha, Orginos, Ringer, Siopsis, Thompson - in preparation*
- PNR measurements of up to 100 photons *Eaton et al., Nature Photonics 17 (2022)*

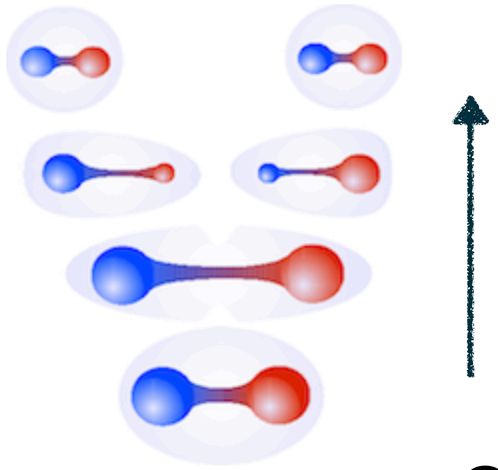


Schwinger model & Hadronization

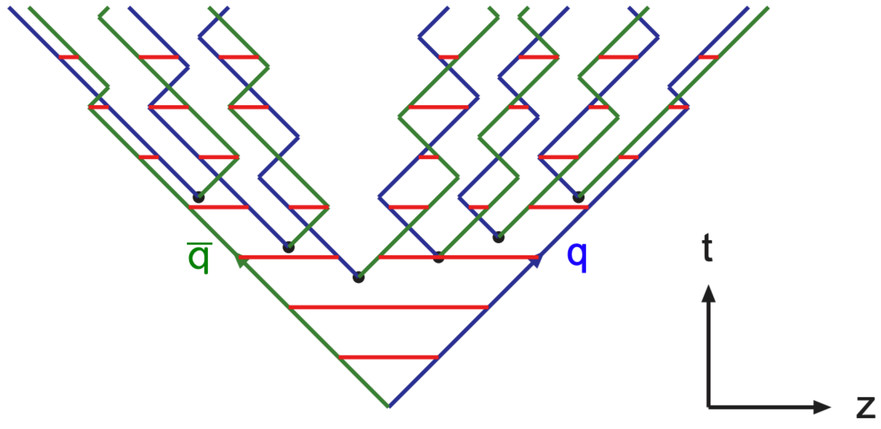
- QED in 1+1 dimensions *Schwinger `62*
- Model of hadronization
- Confining potential $V \sim r$
- Phenomenological applications

  see e.g. Kharzeev et al. `13, Schenke et al. `22

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



QCD string breaking



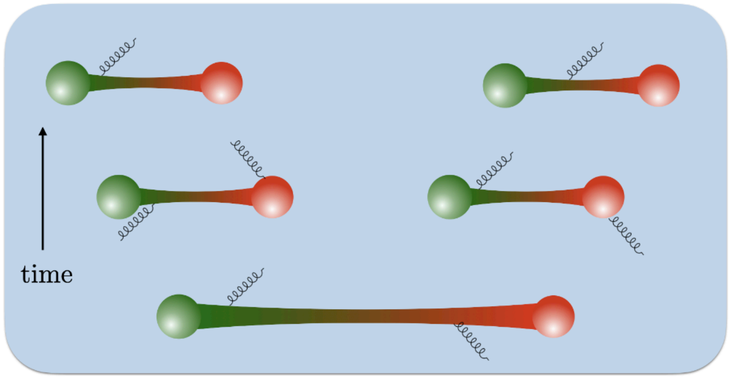
Pythia Lund string hadronization

Schwinger model & Hadronization

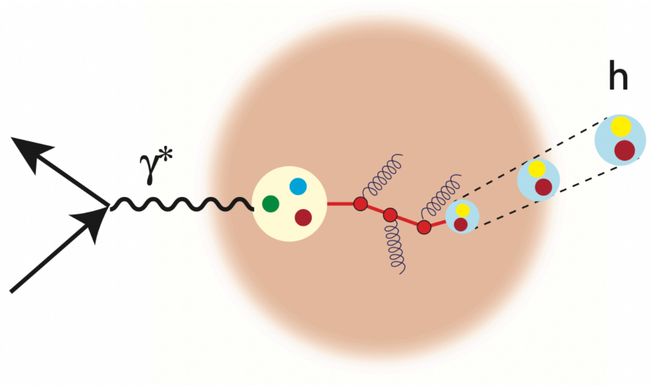
- QED in 1+1 dimensions *Schwinger `62*
- Model of hadronization
- Confining potential $V \sim r$
- Phenomenological applications

  see e.g. Kharzeev et al. `13, Schenke et al. `22

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

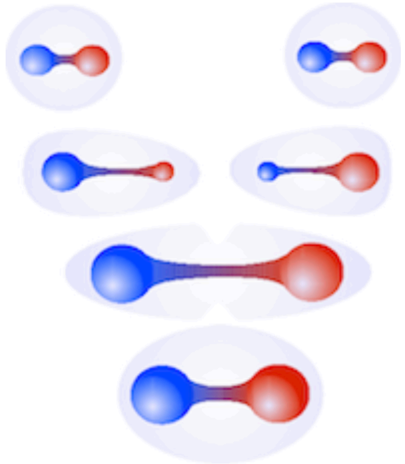


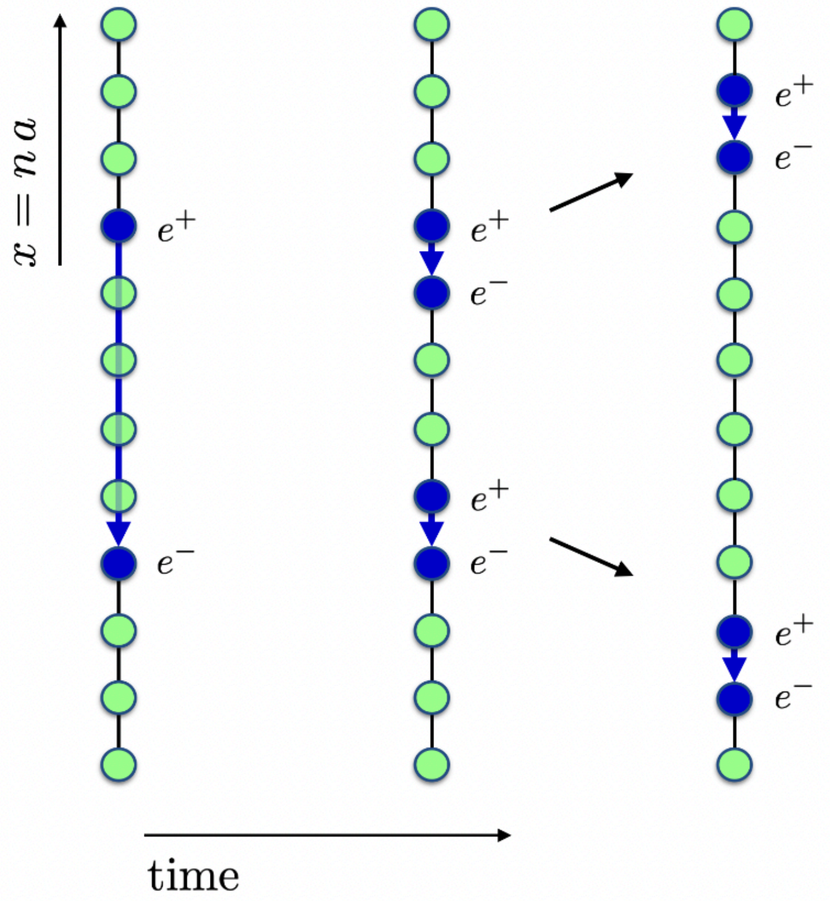
Medium modification



The string-breaking mechanism

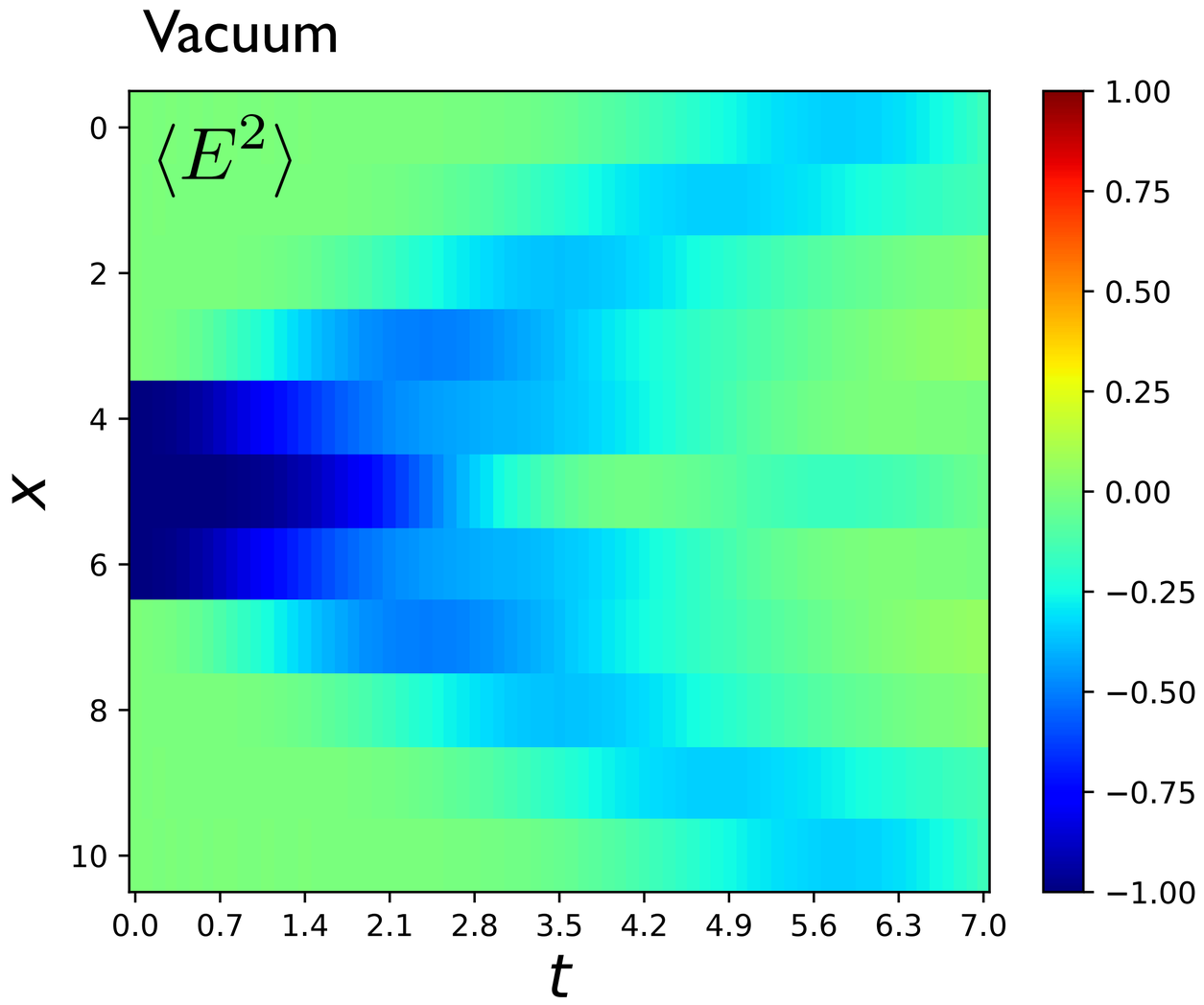
- Study real-time dynamics of hadronization
- Microscopic picture of hadronization

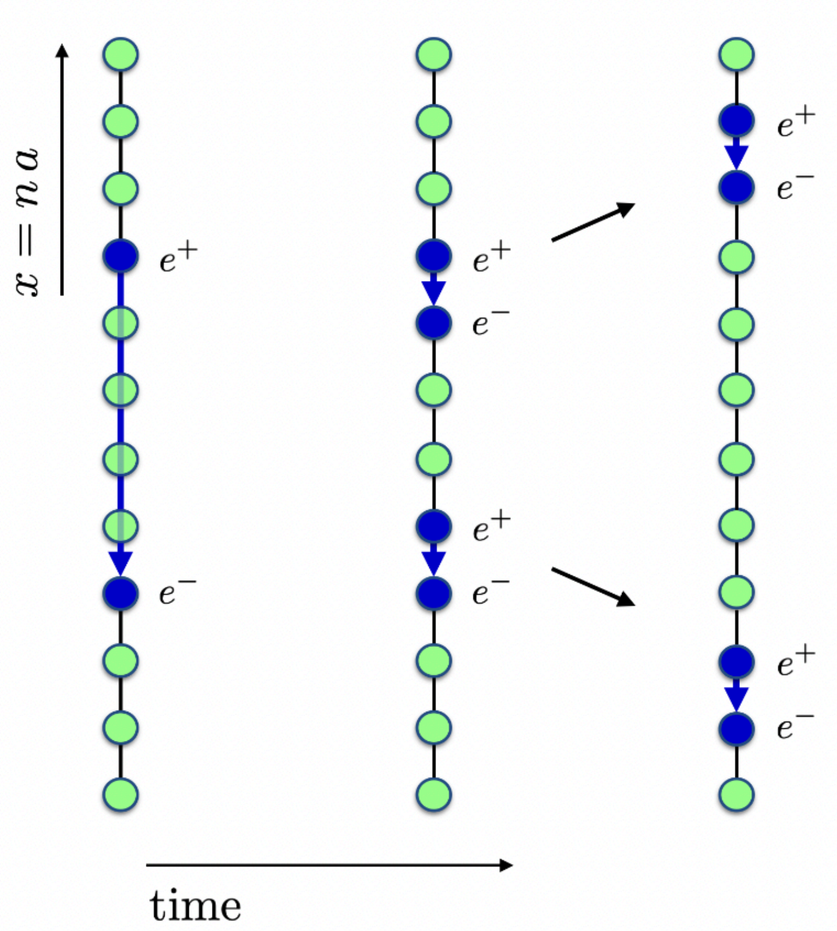




- Whether the string breaks or not depends on the fermion mass & charge (m, e)

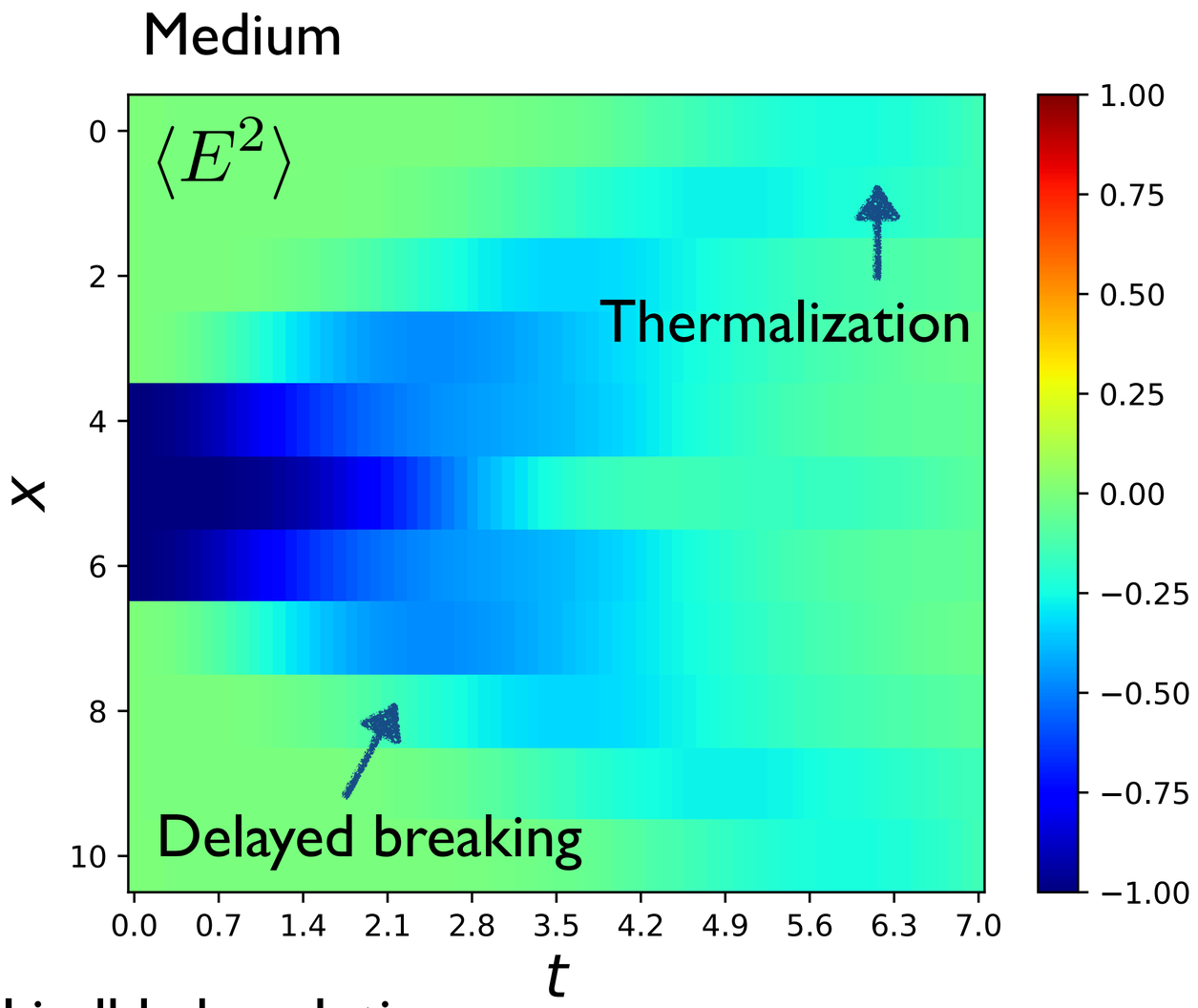
The string-breaking mechanism



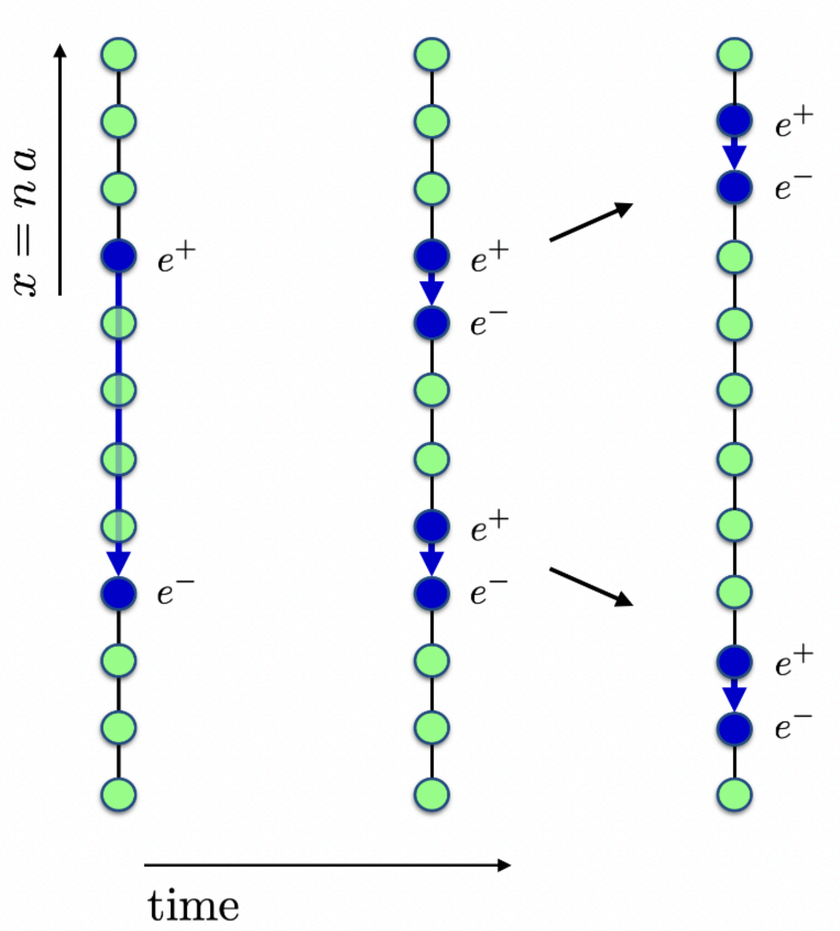


see also Kogut, Susskind; Zoller et al; Magnifico et al

The string-breaking mechanism



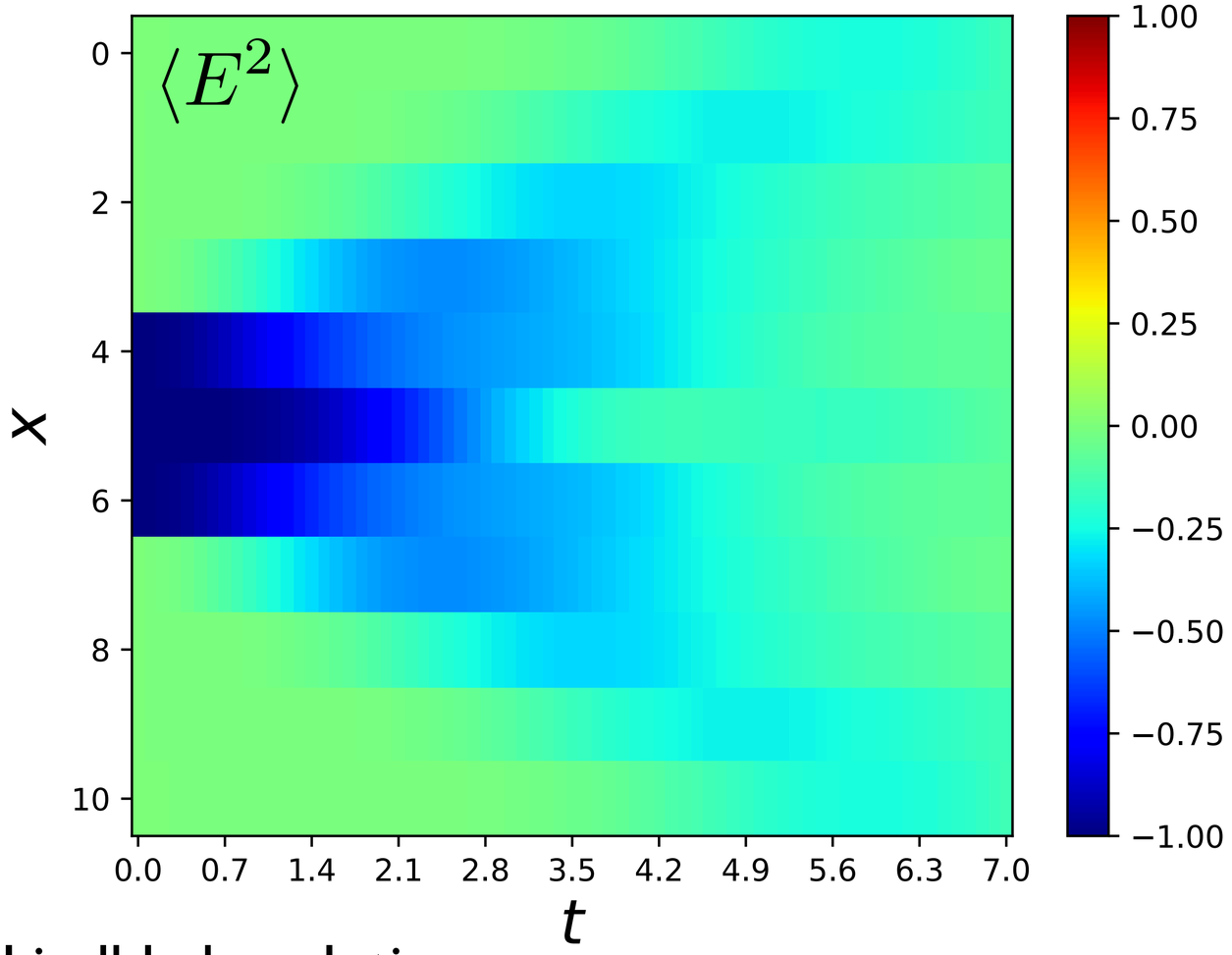
Lindblad evolution



de Jong, Lee, Mulligan, Ploskon, Ringer, Yao `21 and in preparation

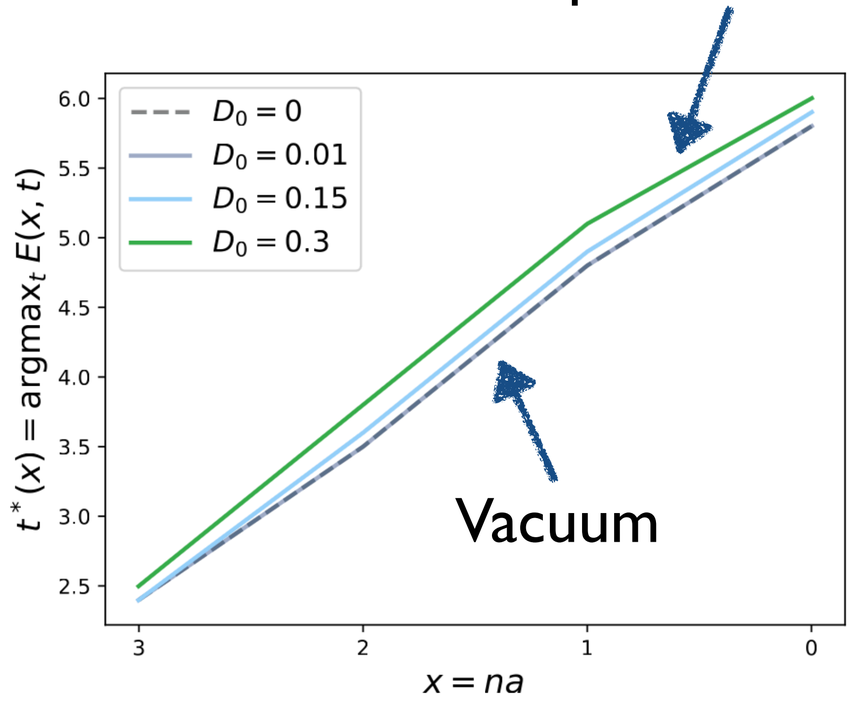
The string-breaking mechanism

Medium



Lindblad evolution

Increasingly strongly coupled to medium



Delay due to quantum-level "drag force" of the medium

Conclusions

- Progress in quantum hardware with reduced errors
- Parallel theory developments necessary (qubits & qumodes)
- Target some of the most challenging problems in NP
- Real-time dynamics of inclusive scattering, hadronization etc.