From long-range entanglement to particle collisions



Farrell, Zemlevskiy, Illa and Preskill Nat. Phys 2026

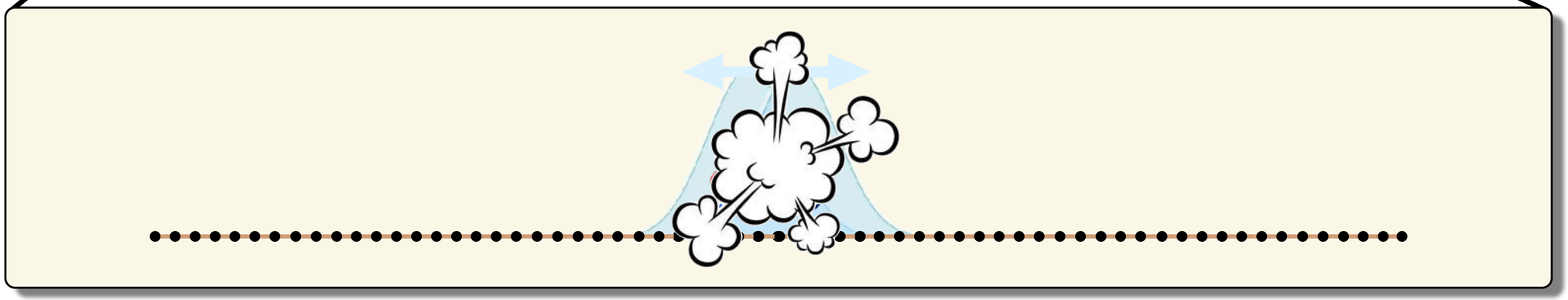
Roland Farrell

10/27/26

Quantum Talents Symposium, Munich

Scattering

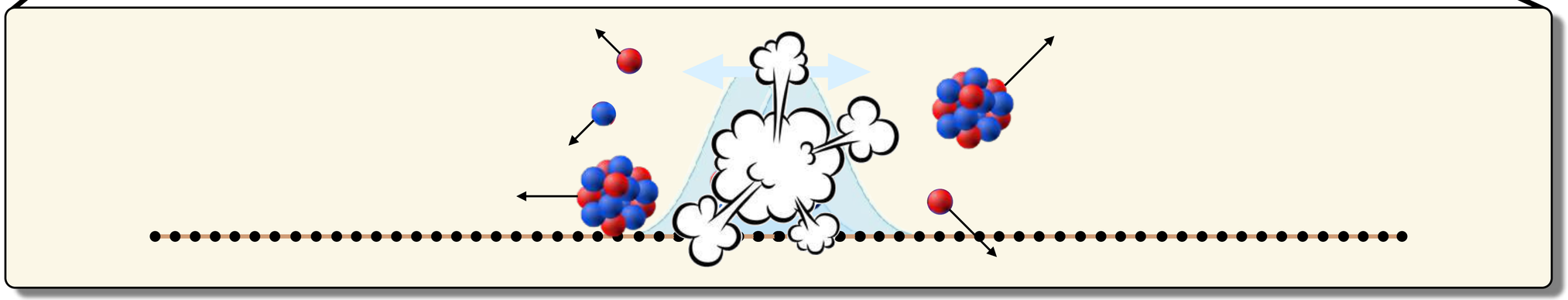




Dynamical simulations of high-energy collisions are beyond classical computing

Scattering

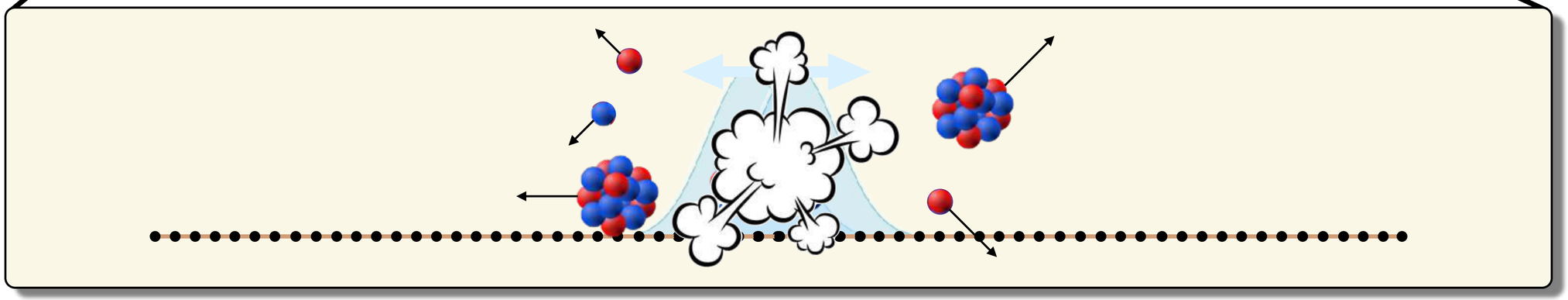




How does energy turn into new particles in real time?

Scattering

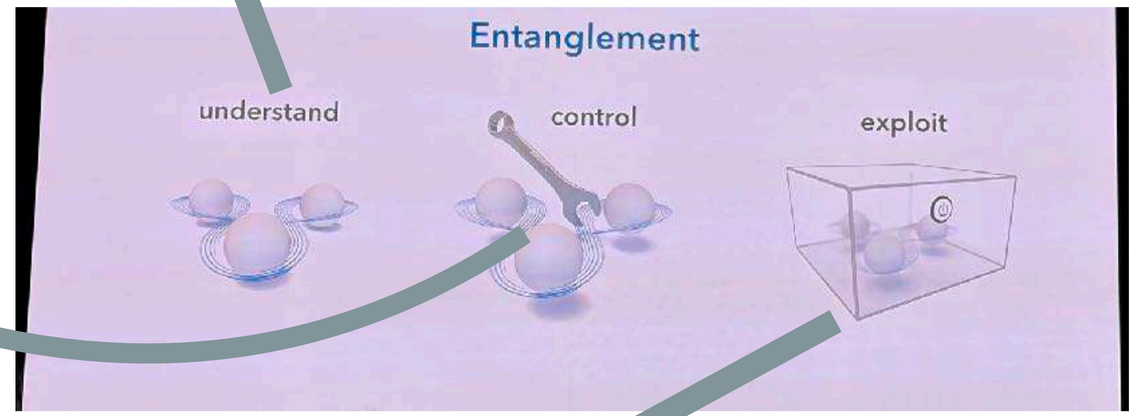




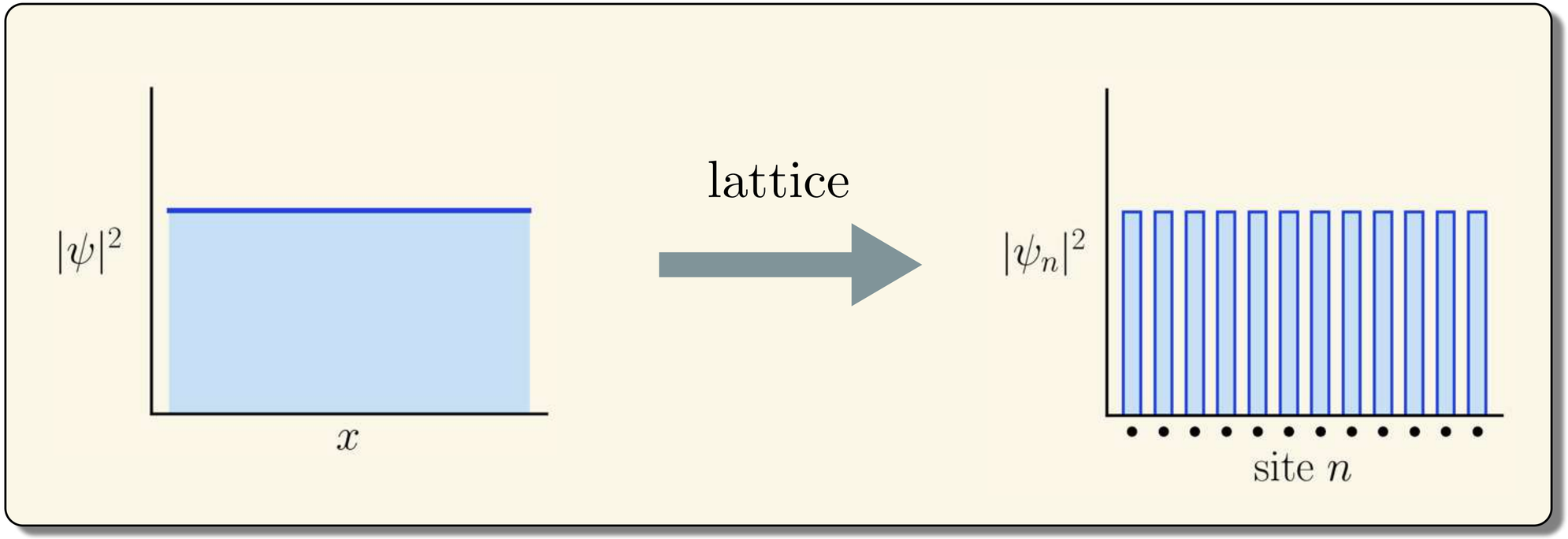
Quantum computers can simulate this. First step: prepare the particles

Outline

- Long and short-range entanglement in single-particle states
- Preparing wavepackets in Ising field theory
- Simulating particle production using `ibm_marrakesh`



A single particle $|\psi\rangle = e^{ikx}$



Momentum k plane wave: equal probability to be found everywhere

A single particle $|0\rangle$: no particle $|1\rangle$: particle

$$|W(k)\rangle = |10000\ldots\rangle + e^{ik}|01000\ldots\rangle + e^{2ik}|00100\ldots\rangle + \ldots$$

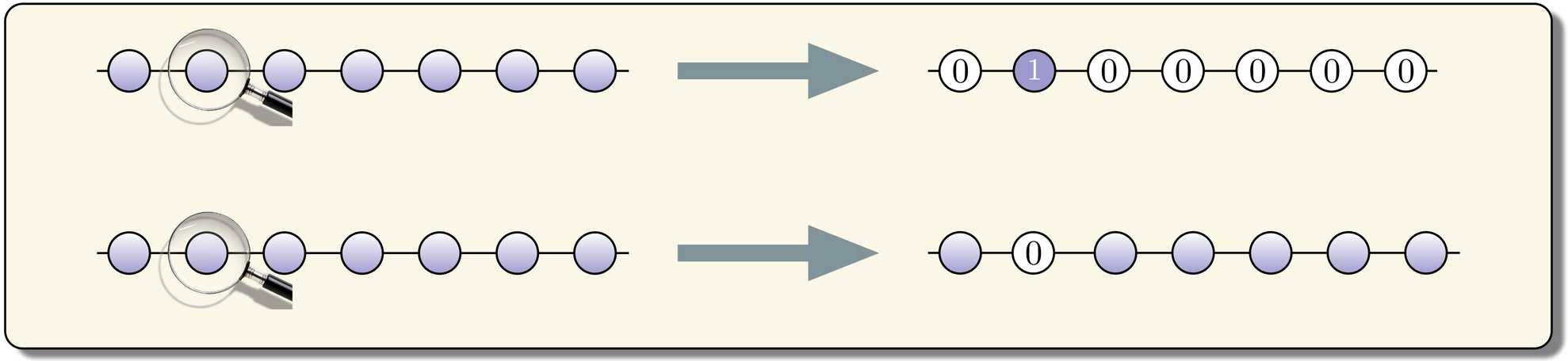
$$= \frac{1}{\sqrt{N}}\left(|10000\ldots\rangle + e^{ik}|01000\ldots\rangle + e^{2ik}|00100\ldots\rangle + \ldots\right)$$

$$\hat{T}|W(k)\rangle = e^{ik}|W(k)\rangle$$

Related to the widely studied W state* in QIS

*Dur et. al PRA 62 (2000)

$|W(k)\rangle$ has long-range entanglement

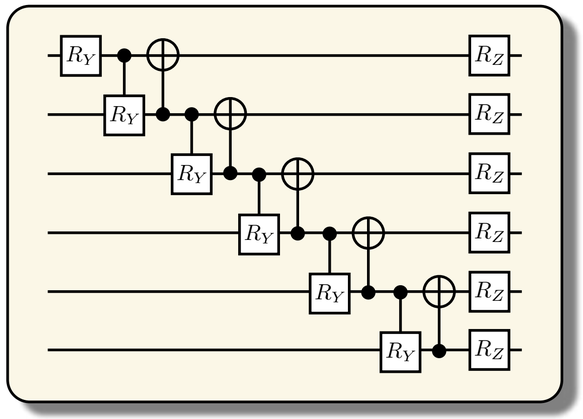


Information about site i changes state on site j

Single particle preparation circuits

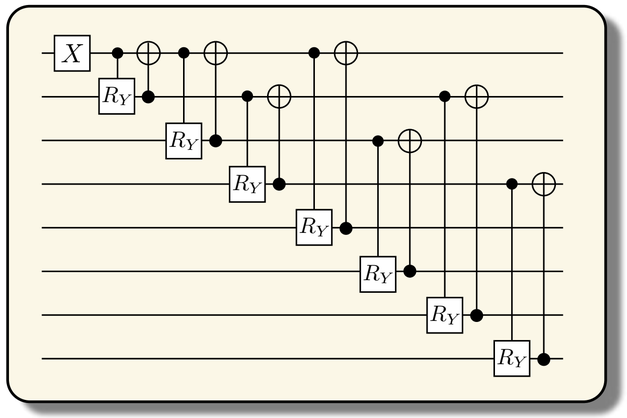
Prepare $|W(k)\rangle$

1D connectivity*



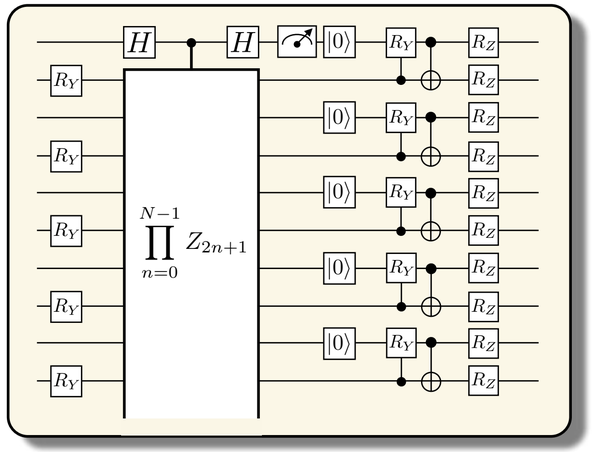
$O(N)$ depth

All-to-all connectivity*



$O(\log N)$ depth

1D connectivity +
mid-circuit measurement
& feedforward (MCM-FF)**



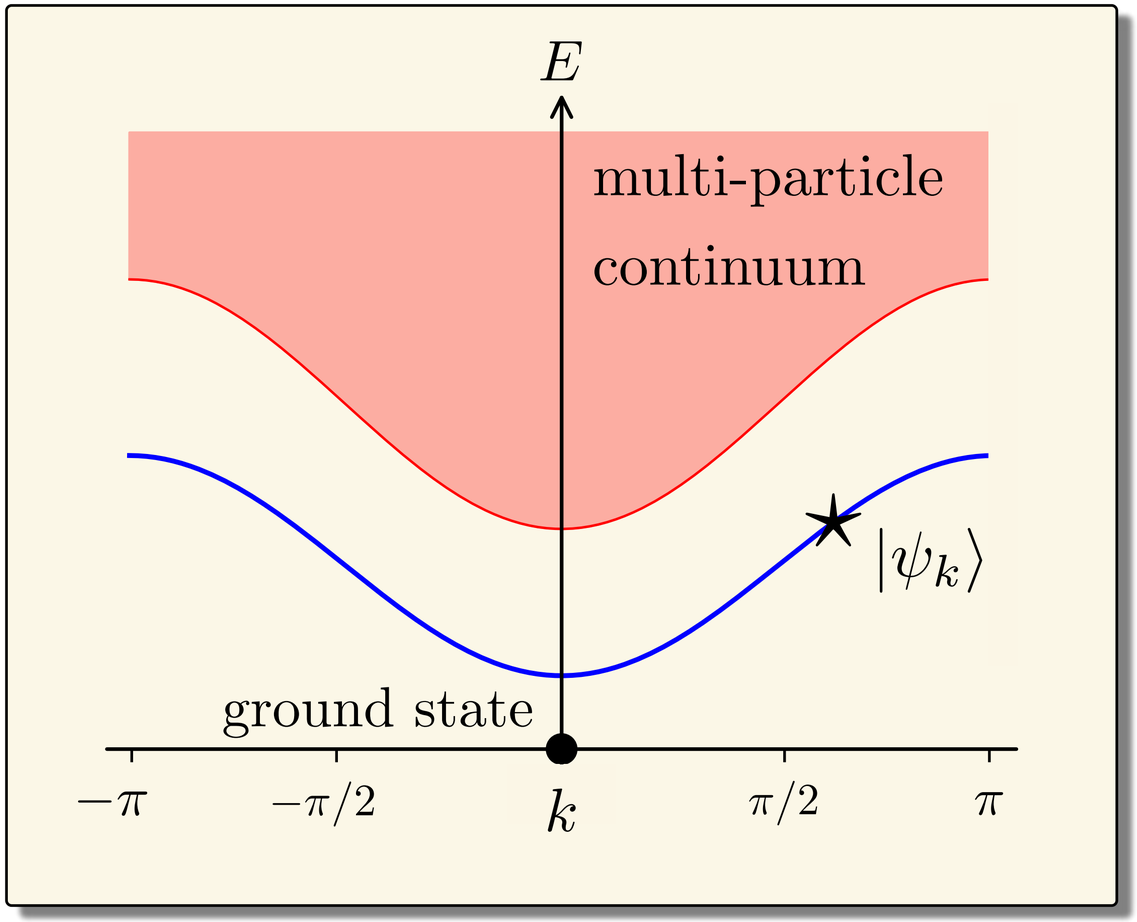
$O(1)$ depth

Shorter circuits → faster and less noisy on a quantum computer

*Cruz et. al Adv.Quantum Technol. 2019

**Piroli et al. PRL 133 (2024), Farrell et al. Nat. Phys (2026)

Particles in many-body systems



Exponentially good approximation*:

$$|\psi_k\rangle = \sum_n e^{ikn} \hat{O}_n |\text{g.s.}\rangle$$

Local operator

$$|\psi_k\rangle = \quad + e^{ik} \quad + e^{2ik} \quad + \cdots$$

Particles are excitations on top of $|\text{g.s.}\rangle$

*Haegeman et. al PRL 111 (2013)

Particles in many-body systems

$$|\psi_k\rangle = \sum_n e^{ikn} \hat{O}_n |\text{g.s.}\rangle$$

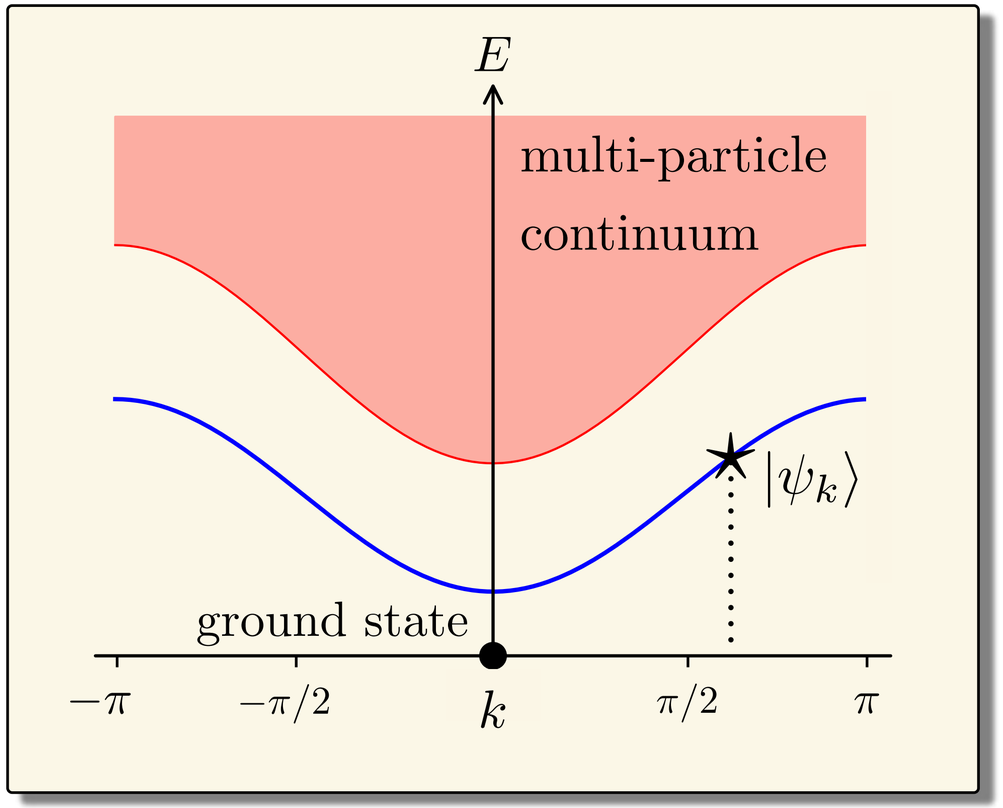
Long-range entanglement that is present in all momentum eigenstates*. W-state entanglement is universal**

Local perturbation of the ground state. Short-range entanglement

Use this structure to design an efficient state preparation algorithm

*Gioia and Wang PRX 12 (2022)
**Farrell, in preparation

State preparation via energy minimization



$|\psi_k\rangle$ is the lowest energy state with momentum k

Quantum algorithm

1. Initialize a state $|W(k)\rangle$ with momentum k
2. Apply a parameterized circuit $U(\vec{\theta})$ that preserves momentum
3. Find the optimized $\vec{\theta}^{\star}$ that minimizes the energy

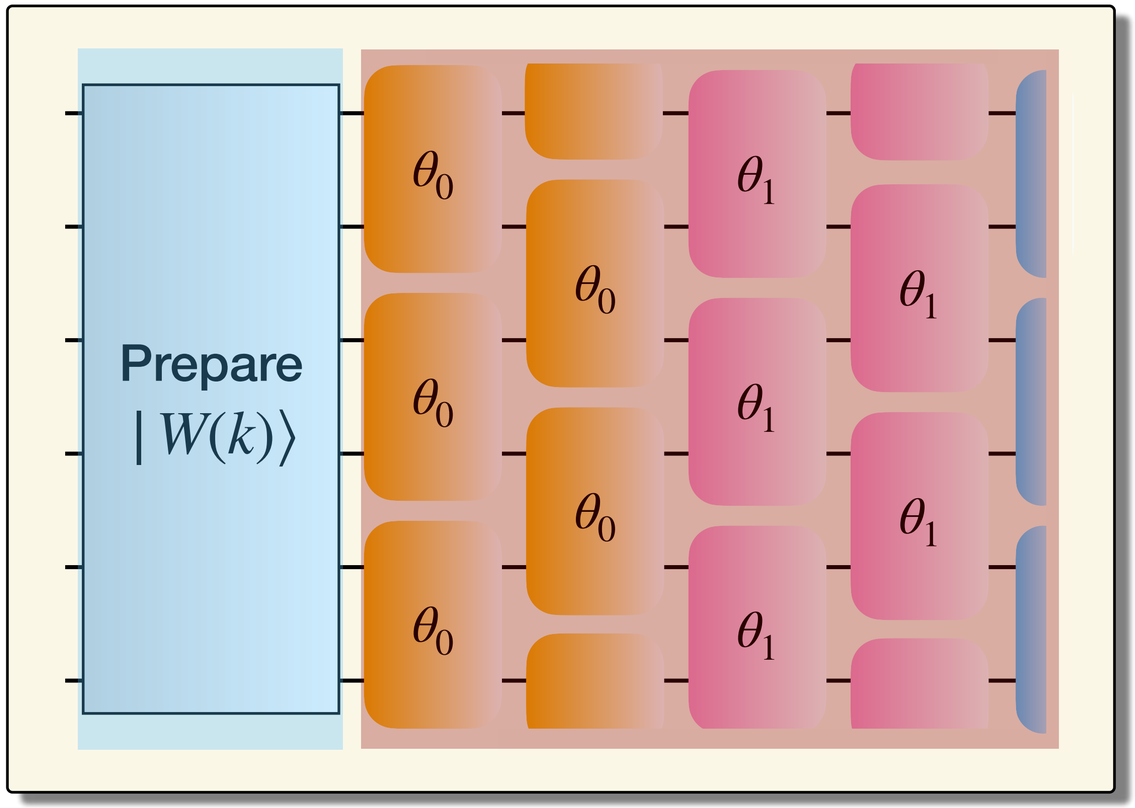
$$\longrightarrow \quad |\psi_k\rangle \approx U(\vec{\theta}^{\star})|W(k)\rangle$$

State preparation via energy minimization

Quantum algorithm

1. Initialize $|W(k)\rangle$ with momentum k
2. Apply a circuit layer $e^{i\theta \sum_n \tilde{O}_n}$ and optimize $\vec{\theta}$ to minimize the energy
3. Repeat step 2 until converged*

$$|\psi_k\rangle = \sum_n e^{ikn} \hat{O}_n |\text{g.s.}\rangle$$



*ADAPT-VQE: Grimsely et. al Nat. Commun. (2019)

State preparation via energy minimization

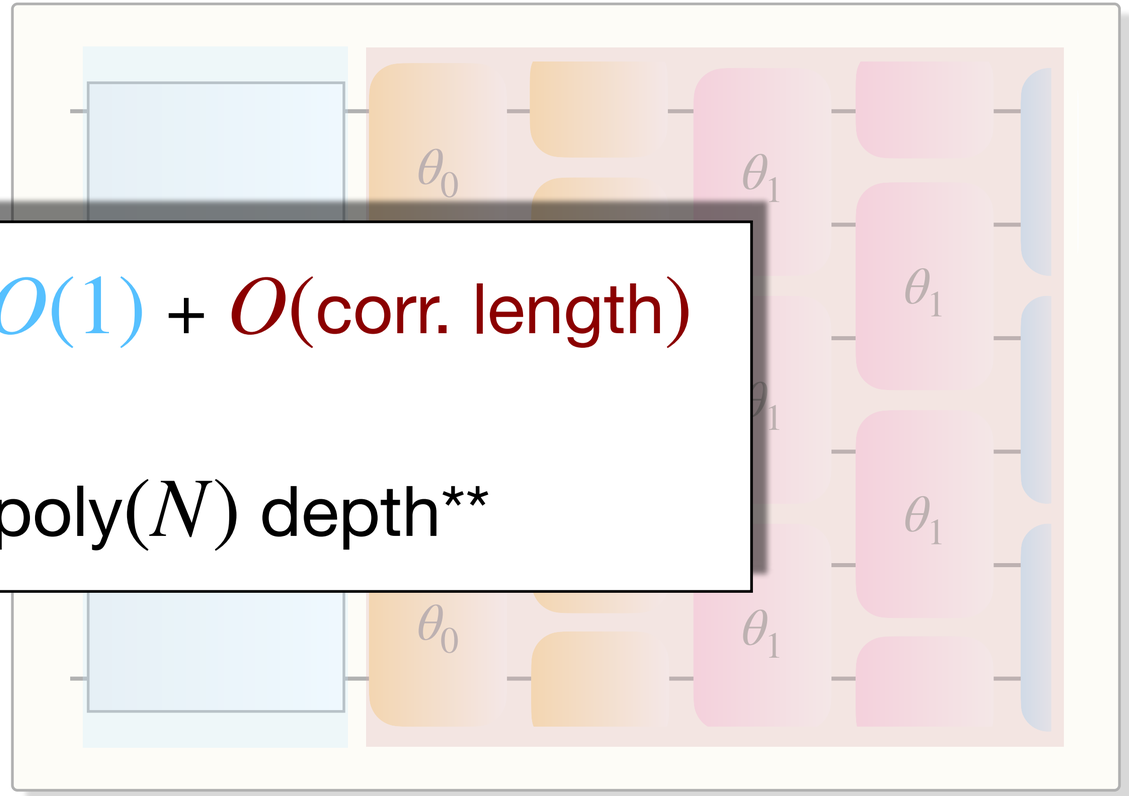
Quantum algorithm

1. Initialize $|W(k)\rangle$ with momentum k
2. Apply a
   optimize
3. Repeat

$$|\psi_k\rangle = \sum_n e^{ikn} \hat{O}_n |\text{g.s.}\rangle$$

With MCM-FF, circuit depth is $O(1)$ + O(corr. length)

- Previous methods require poly(N) depth**



*ADAPT-VQE: Grimsely et. al Nat. Commun. (2019)
**Chen et. Al PRL 2026, Chai et al. *Quantum* 2025, Davoudi et al. *Quantum* 2024, Jordan et al. *Science* 2012

Outline

- ~~Long and short-range entanglement in single-particle states~~ ✓

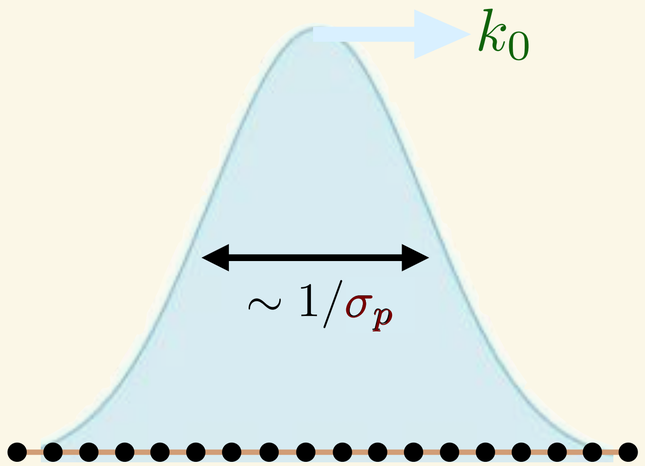
- Preparing wavepackets in Ising field theory

- Simulating particle production using `ibm_marrakesh`

Initial state in scattering is a wavepacket

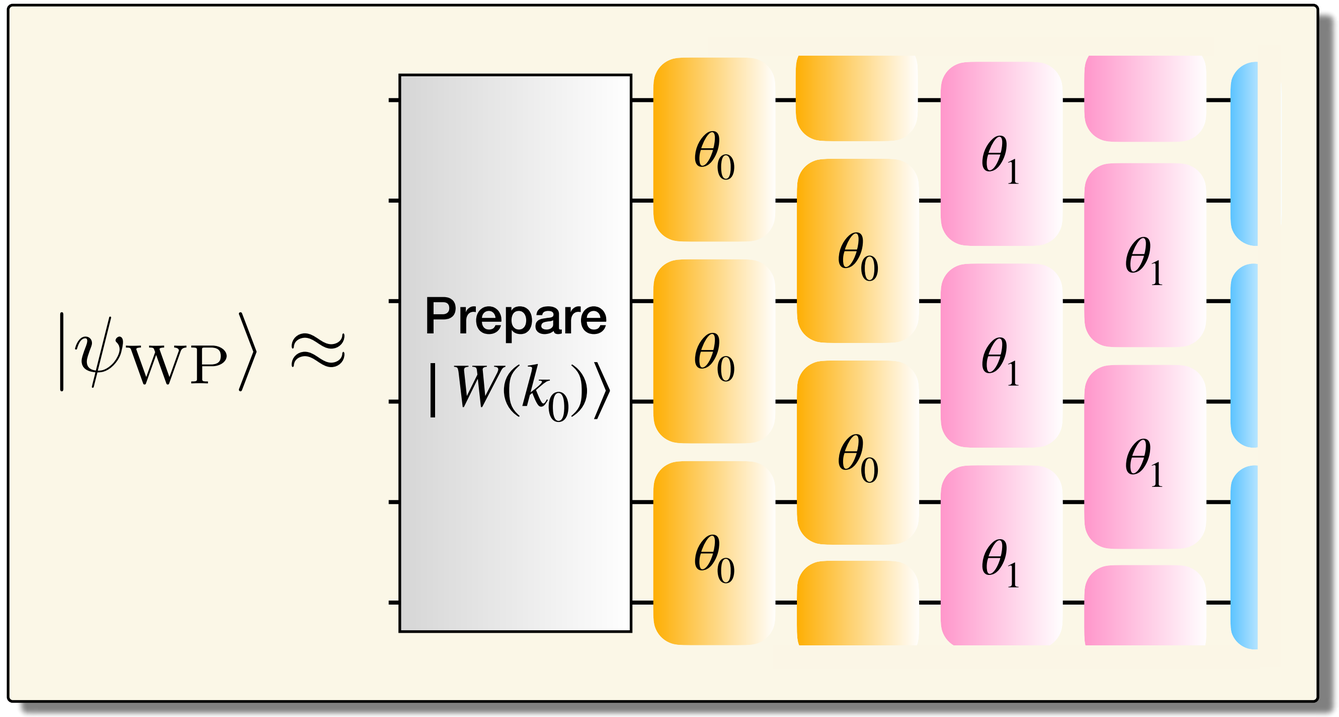
Saturates $\Delta x \Delta p \geq \hbar/2$

$$|\psi_{\mathrm{WP}}\rangle = \sum_k e^{-(k-k_0)^2/\sigma_p^2} |\psi_k\rangle$$



Need to prepare a superposition of $|\psi_k\rangle$

From single-particle states to wavepackets

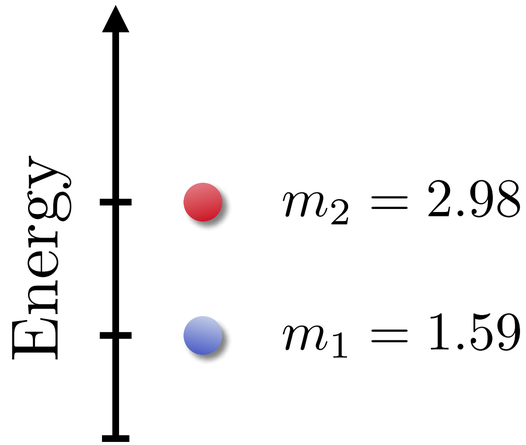


Only one change: $|W(k)\rangle \rightarrow |W(k_0)\rangle$

$$|W(k_0)\rangle = c_0|100\ldots\rangle + c_1|010\ldots\rangle + c_2|001\ldots\rangle + \ldots$$

Light and heavy particles in Ising field theory

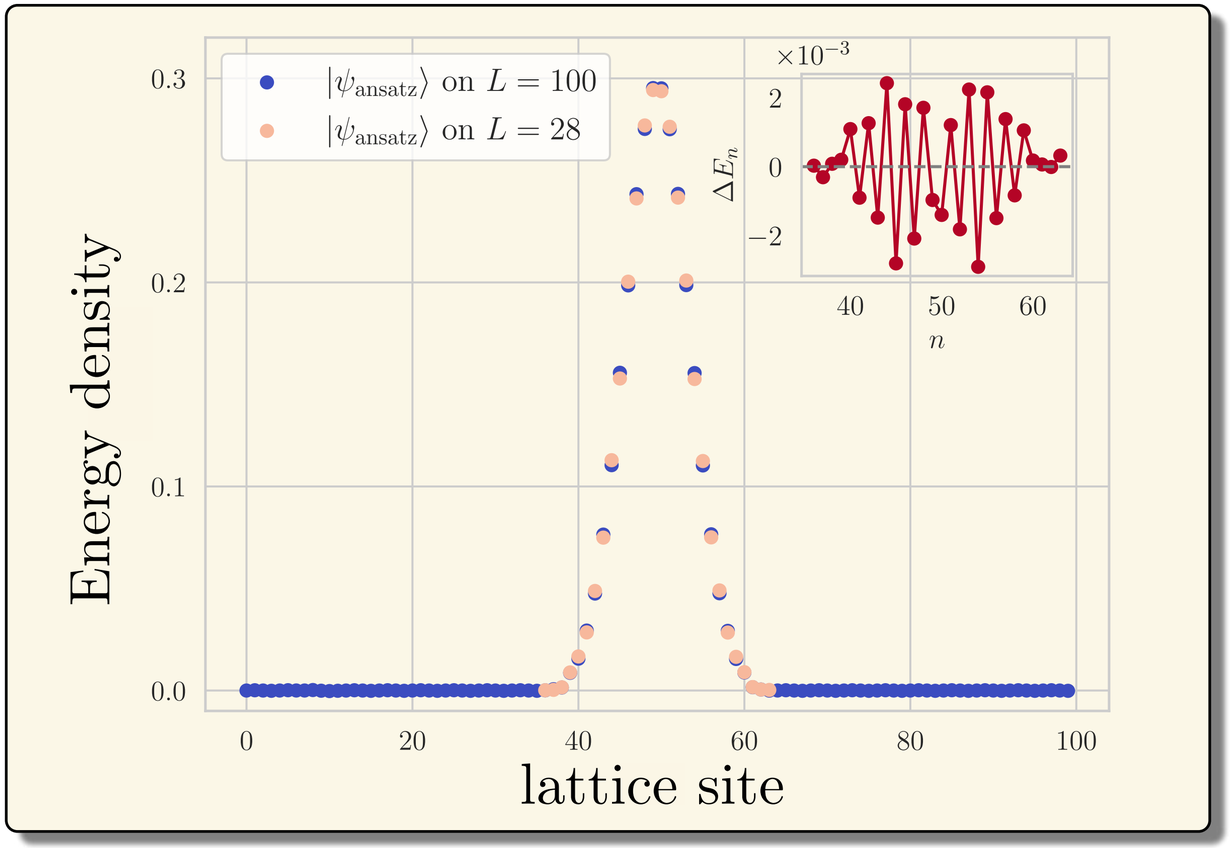
$$\hat{H} = -\sum_n \left(\hat{Z}_n \hat{Z}_{n+1} + g_x \hat{X}_n + g_z \hat{Z}_n \right)$$



Study collisions that take
light + light → light + heavy

Work with $g_x = 1.25,\ g_z = 0.15$ where there are two stable particles

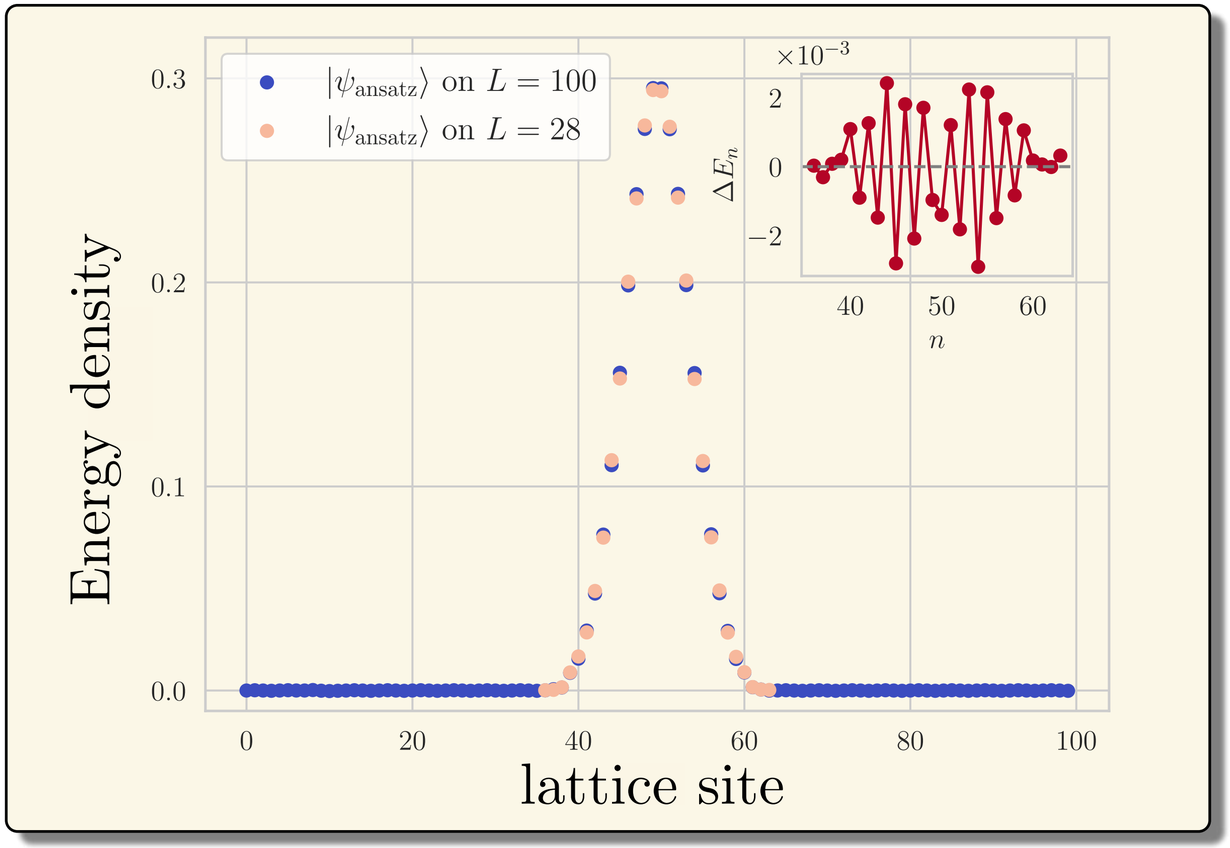
Wavepacket preparation on 100+ qubits



Circuits that minimize the energy and prepare wavepackets are determined on large lattices using a MPS circuit simulator

QUIMB

Wavepacket preparation on 100+ qubits



Circuits that minimize the energy and prepare wavepackets

are determined using MPS and deployed on a quantum computer

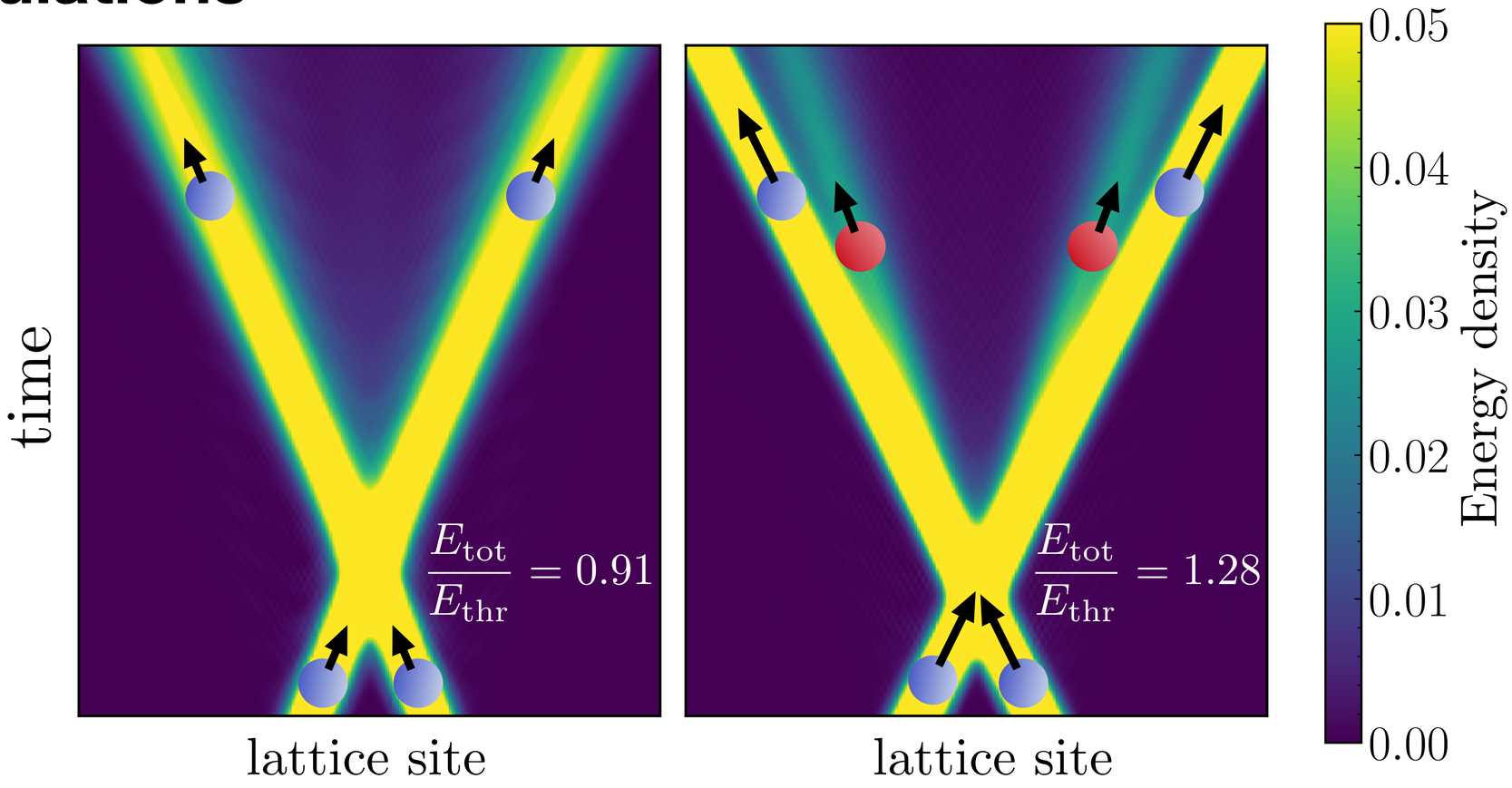
QUIMB

Outline

- ~~Long and short-range entanglement in single-particle states~~ ✓
- ~~Preparing wavepackets in Ising field theory~~ ✓
- Simulating particle production using `ibm_marrakesh`

Inelastic scattering

MPS simulations

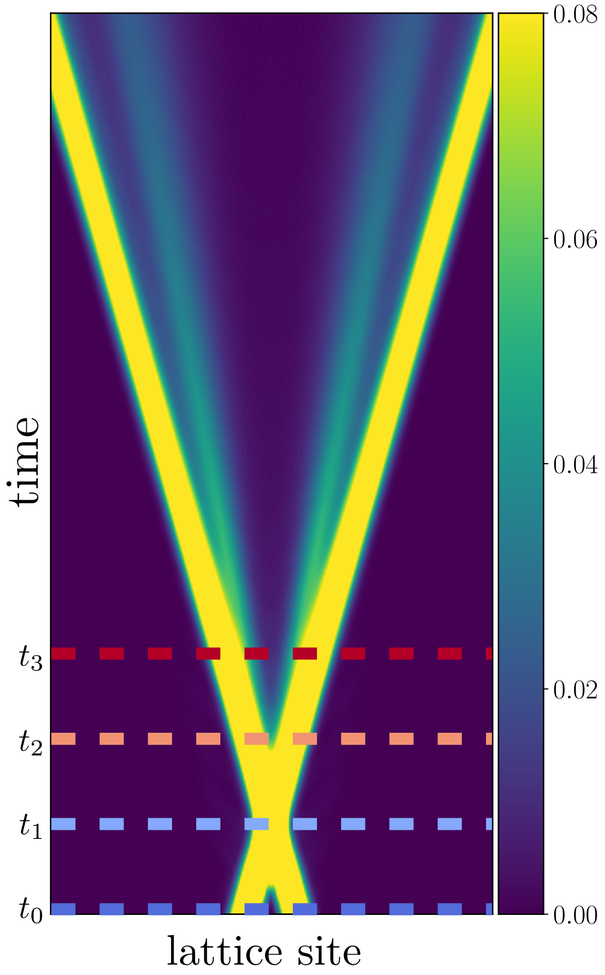


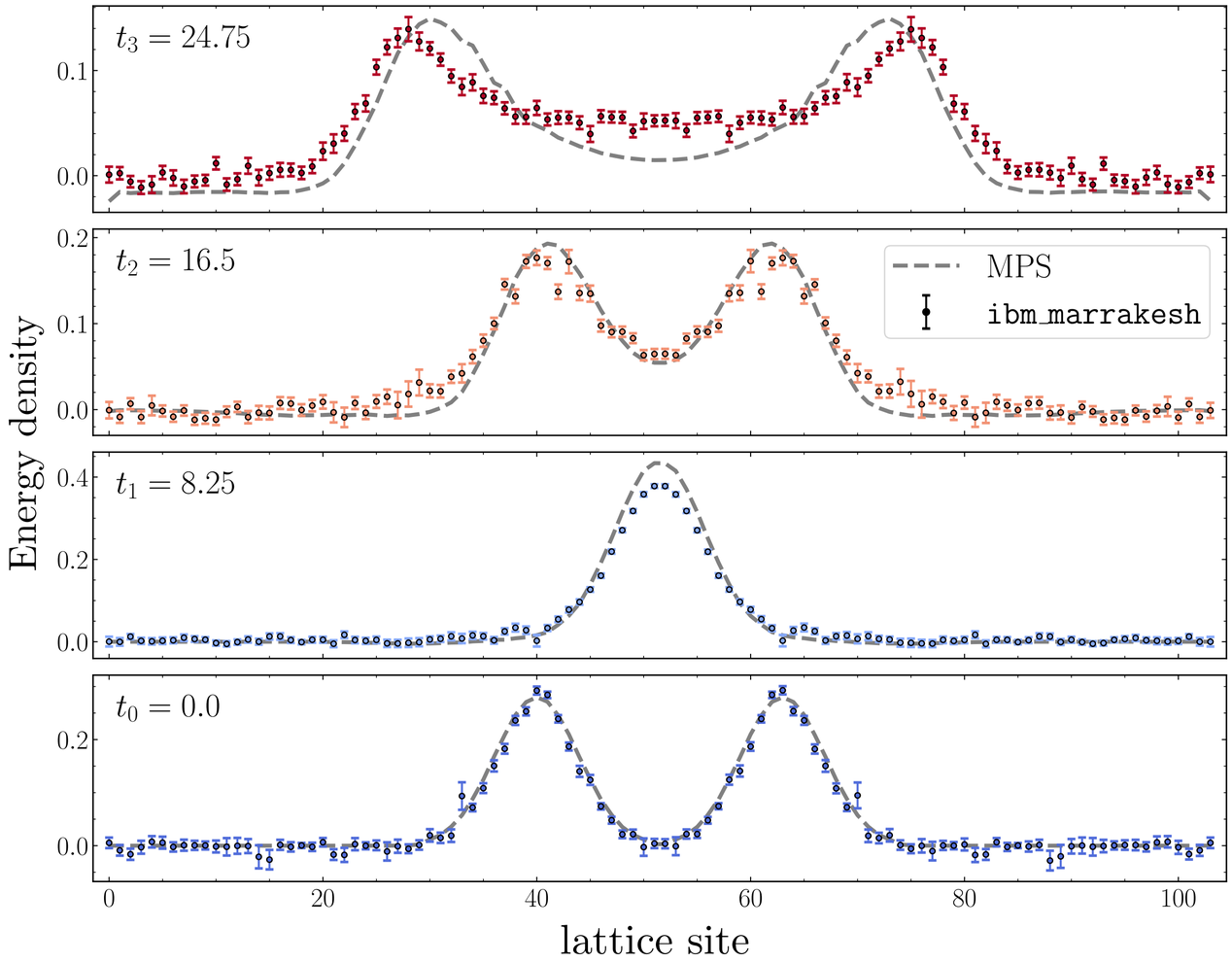
Wavepackets are prepared and evolved with Trotterized time evolution

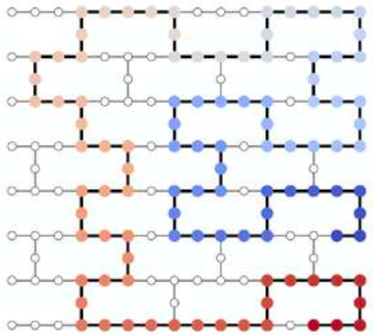
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Results from ibm_marrakesh

Used unitary $|W(k_0)\rangle$ preparation
(MCM-FF was noisier)

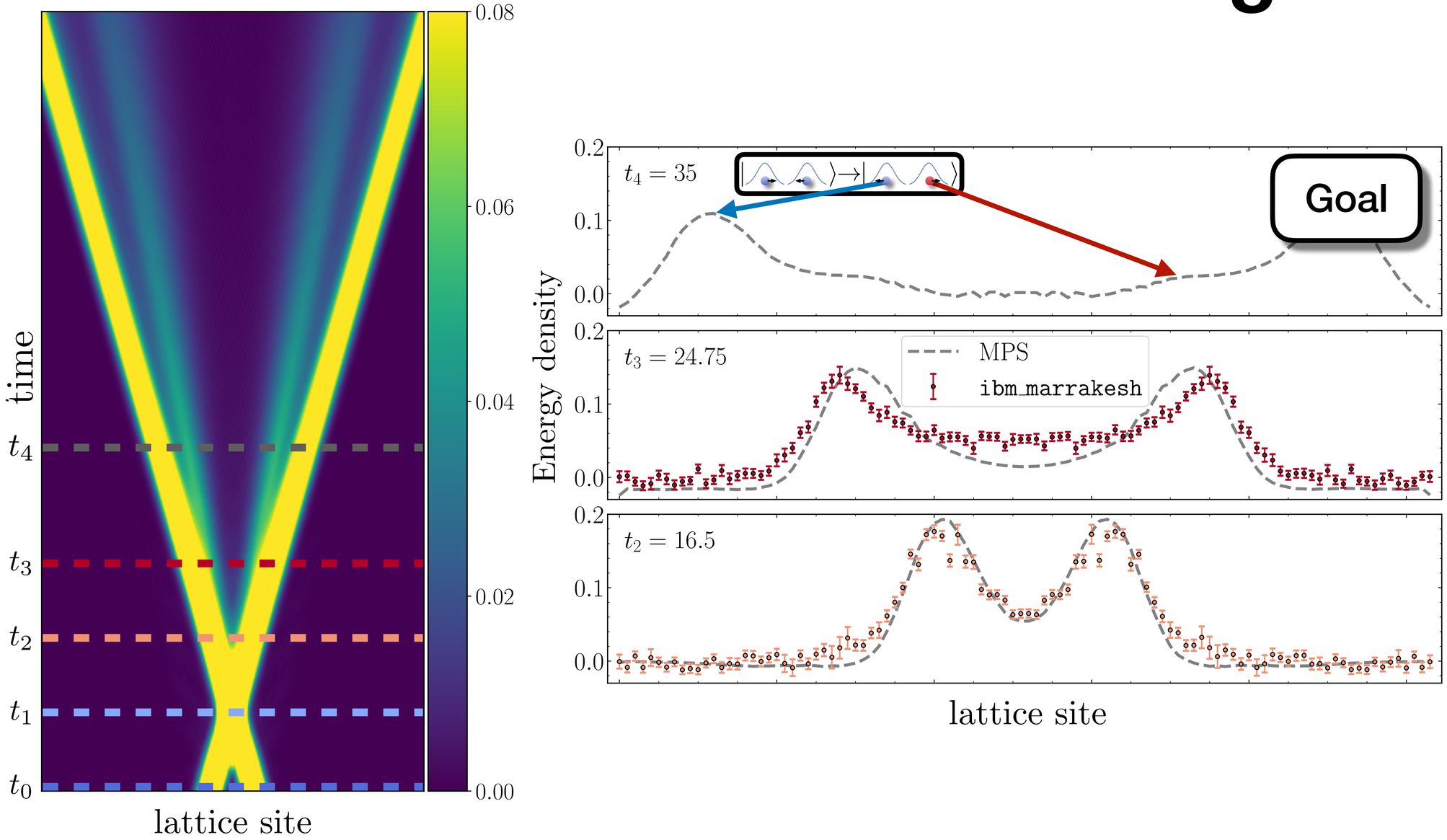




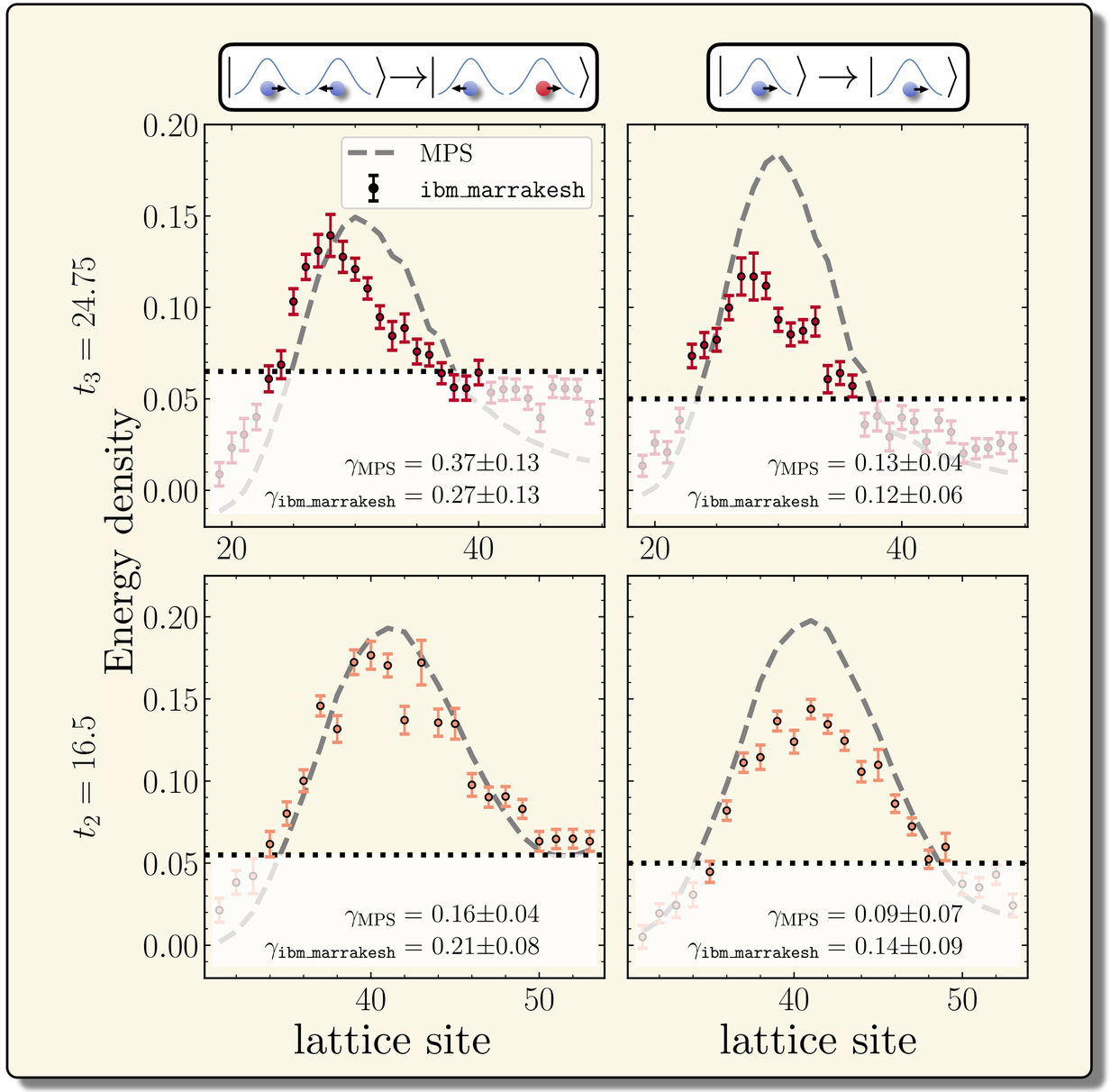


Hardware tracks MPS through the collision point in circuits with up to 5,589 2q gates on 104 qubits

Have we seen inelastic scattering?



Results: skewness γ



Particle productions detected by the skewness γ of the outgoing energy density!

Summary

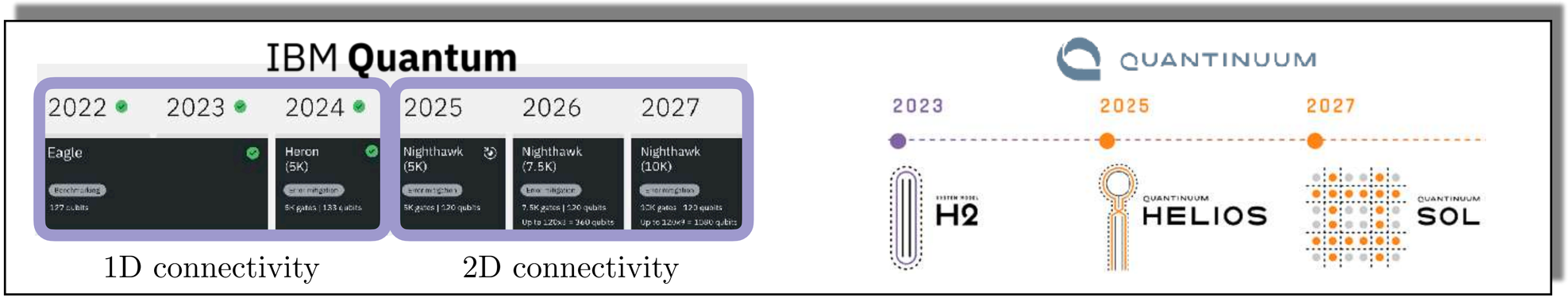
1. Particle excitations in many-body systems have the long-range entanglement of a W state

2. This structure motivated a constant circuit depth preparation protocol using MCM-FF

3. Efficient state preparation enabled inelastic particle production to be simulated for the first time on a quantum computer

Outlook

- Next, 2D: particles with spin, angular momentum, phase transitions. Much harder for classical computing



For TN simulations of 2D scattering see Pavesic et. al Nat. Comm. (2026)

Thank you for listening!

Paper link



Nikita Zemlevskiy



Marc Illa



John Preskill

