HADNUCMAT @ University of Barcelona
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# Toward quantum simulation of scattering in gauge theories and other strongly correlated systems

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PART 0:
MOTIVATION: FIRST-PRINCIPLES SIMULATIONS OF SCATTERING

PART I:
BASIC ELEMENTS OF QUANTUM SIMULATION OF SCATTERING

PART II:
TOWARD DIGITAL QUANTUM SIMULATIONS OF SCATTERING

PART III:
TOWARD ANALOG QUANTUM SIMULATIONS OF SCATTERING

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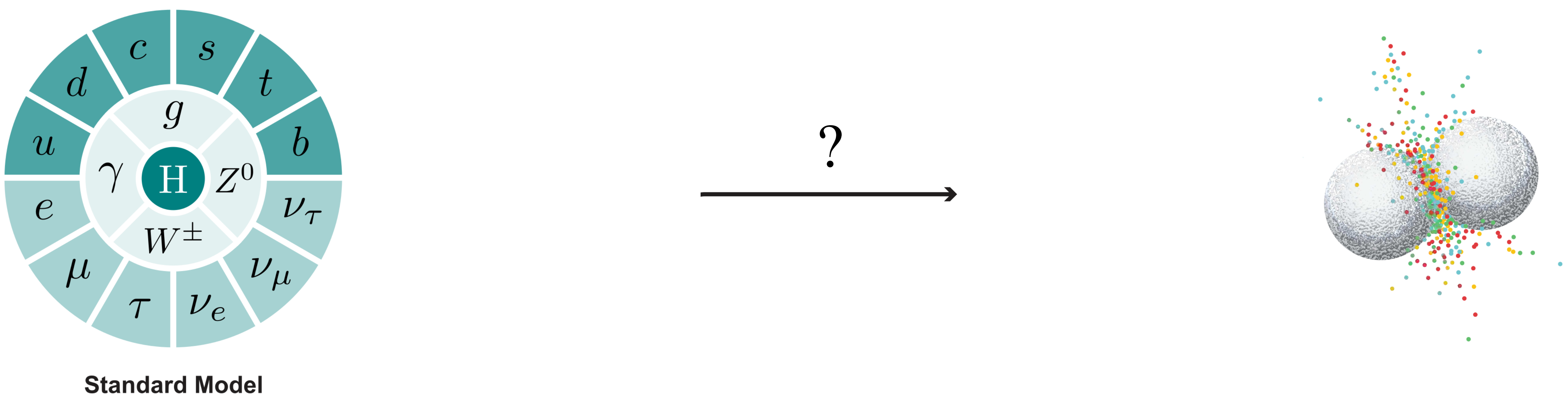
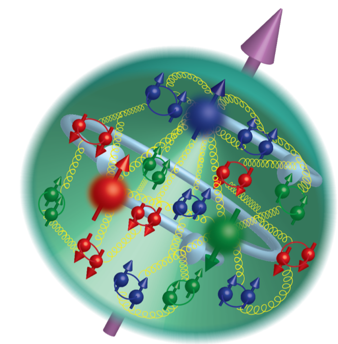
# AN OVERARCHING GOAL OF NUCLEAR AND HIGH-ENERGY PHYSICS: FIRST-PRINCIPLES PREDICTIONS FOR SCATTERING PROCESSES



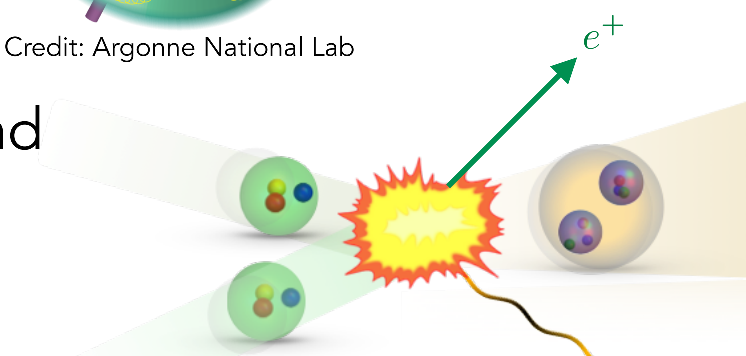
We care about scattering and reaction processes since they can:

i) teach us about the **internal structure of matter**,



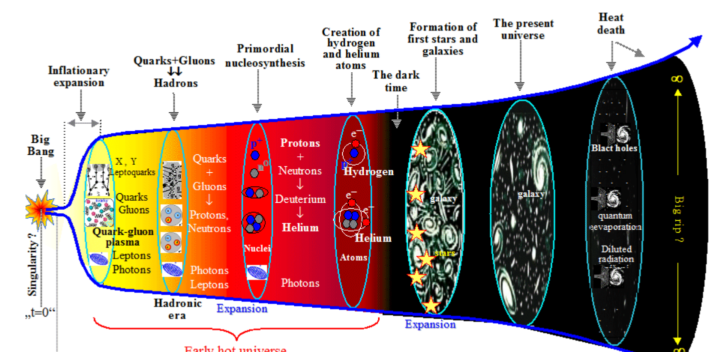
Credit: Argonne National Lab

ii) constrain astrophysical models of **stellar evolution** and of **terrestrial energy-production** mechanisms,



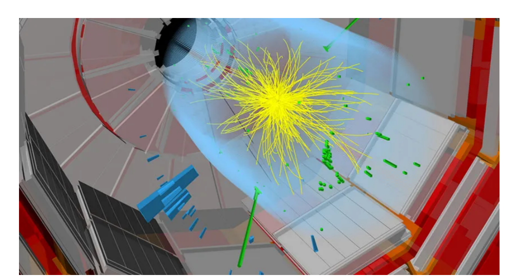

Credit: W. Detmold (MIT)

iii) illuminate **phases of matter** and reveal how **matter evolves under extreme conditions** such as post Big Bang,



Credit: https://astronuclphysics.info

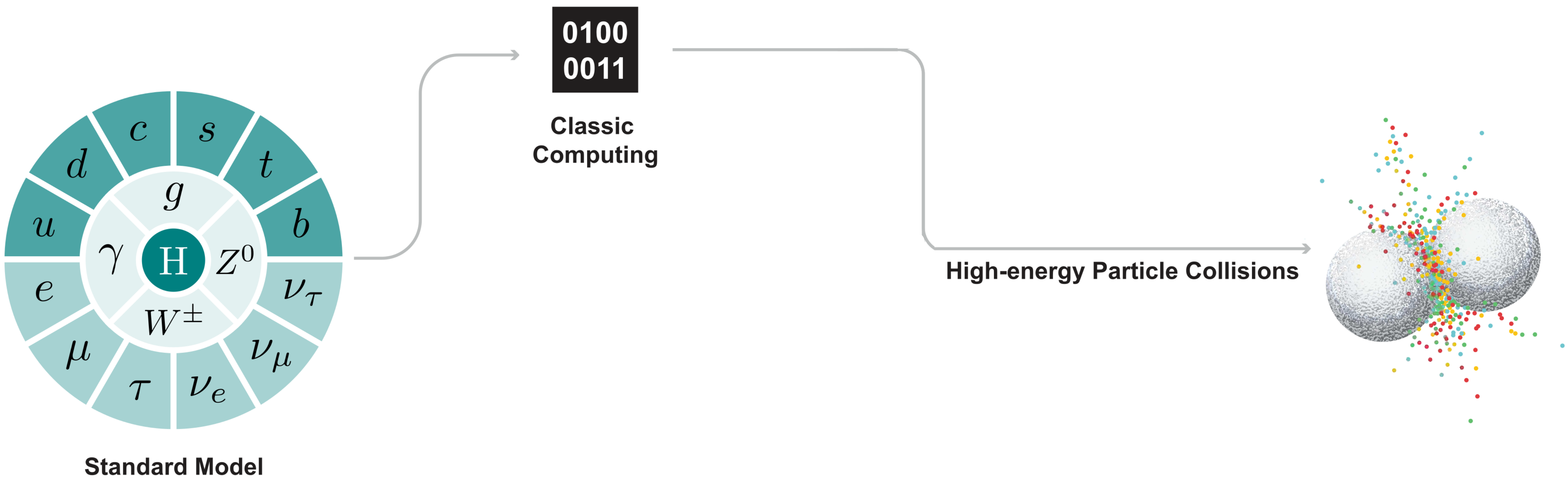
iv) lead to discovery of **new symmetries, particles, and interactions** in nature.



Credit: CMS, CERN

A barrier to making first-principles predictions is the quantum, relativistic, and nonperturbative nature of **quantum chromodynamics**, the quantum field theory of quarks and gluons!

# FIRST-PRINCIPLES PREDICTIONS FOR SCATTERING PROCESSES: CLASSICAL SIMULATIONS?



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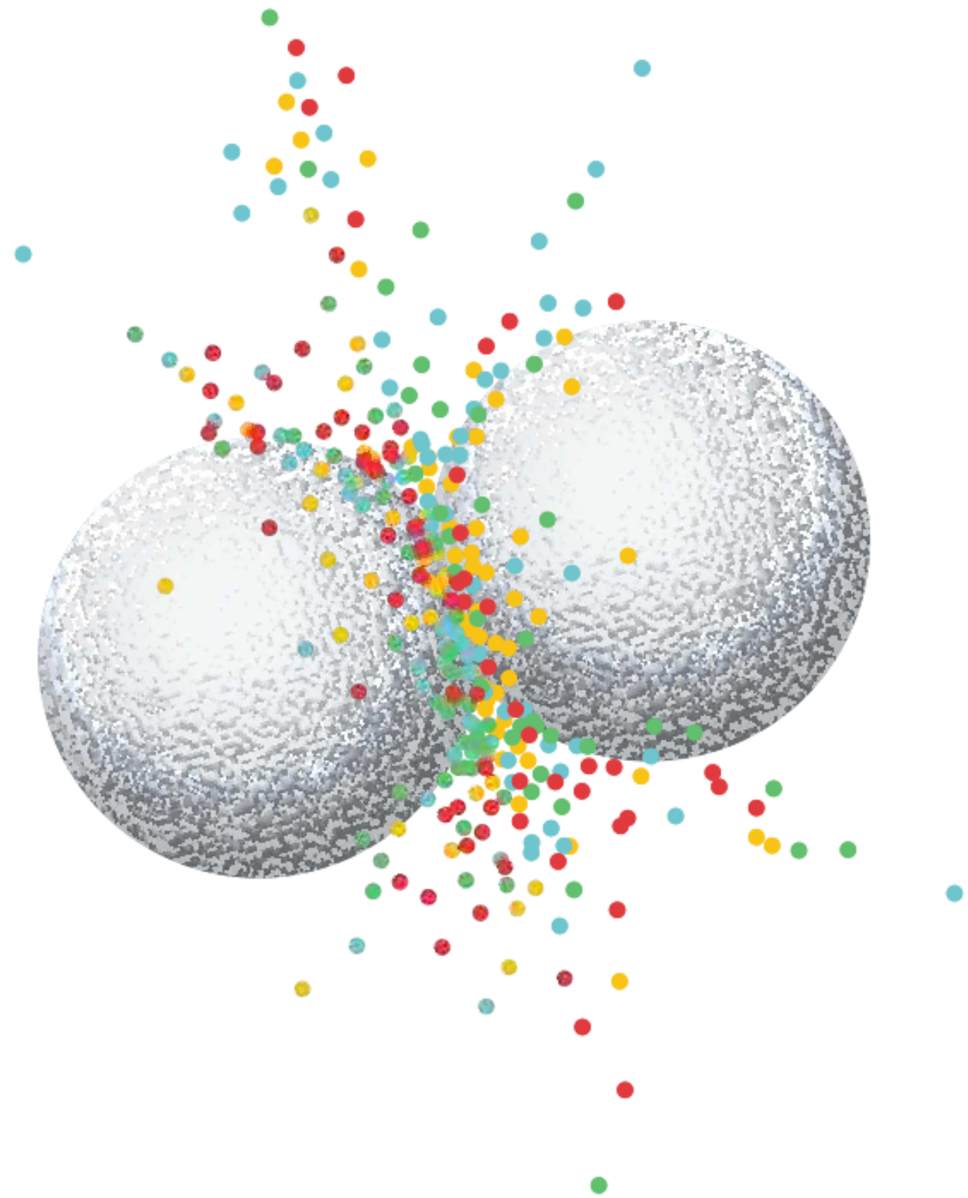
Classic Computing

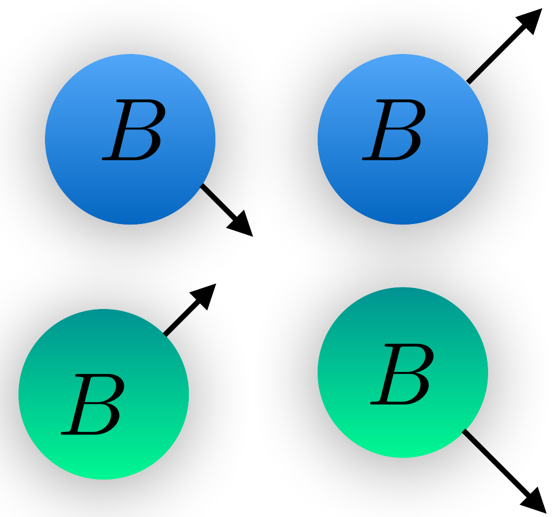
Can we classically simulate scattering of composite particles from the Standard Model?



Lattice gauge theory methods based on Monte-Carlo sampling in Euclidean (imaginary) time have enabled this…but only at low energies so far…

# SOME EXAMPLES FROM MY PAST AND CURRENT WORK WITHIN NPLQCD

Wagman, ZD et al (NPLQCD), Phys.Rev.D96,114510 (2017). Illa, ZD et al (NPLQCD), *Phys. Rev. D*103, 5, 054508 (2021). Amarasinghe, ZD et al (NPLQCD), Phys. Rev. D 107, 094508 (2023).

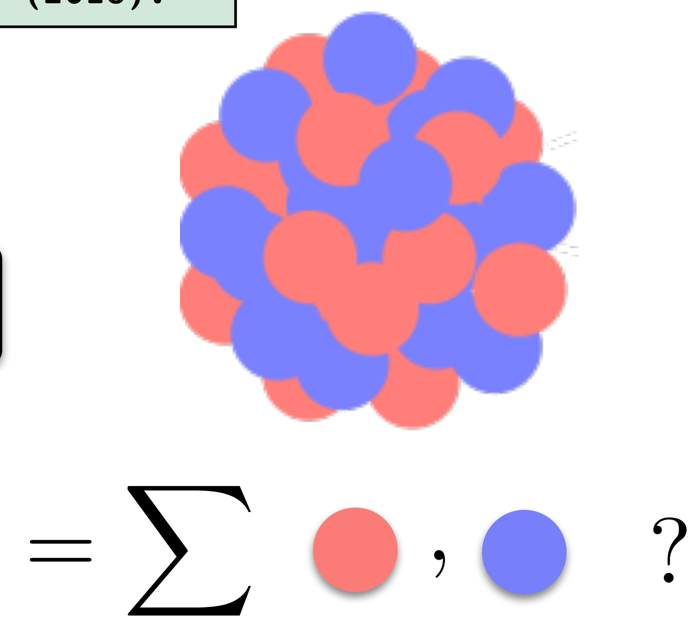



$c_1, \ldots, c_6 \rightarrow a, b \rightarrow a$

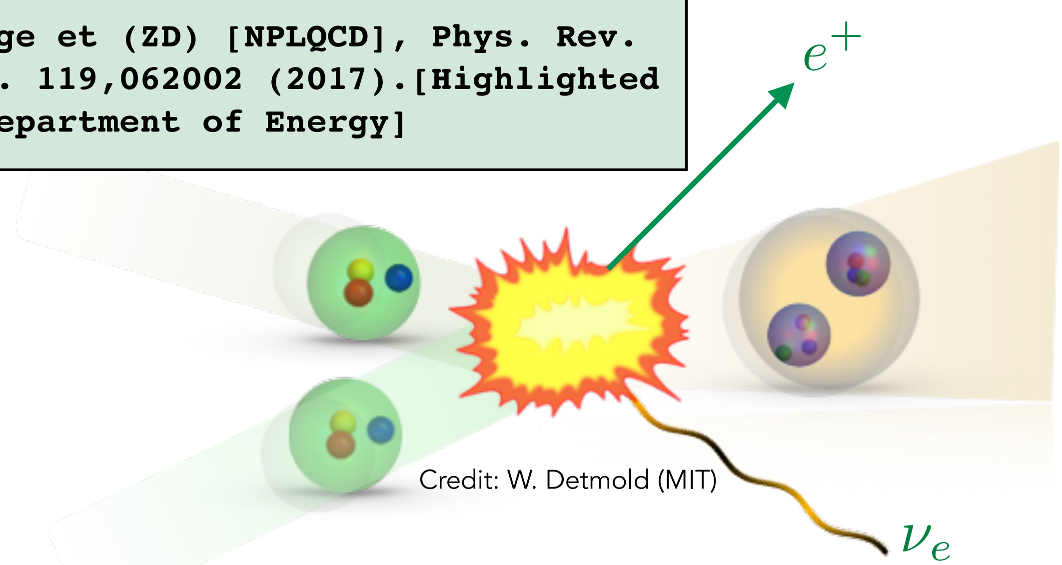
$SU(N_f = 3) \rightarrow SU(2N_f = 6) \rightarrow SU(16)$

Chang, ZD et al (NPLQCD), Phys. Rev. Lett. 120, 5, 152002 (2018).

$$g_X^{(f)}(A) = \langle A | \bar{q}_f \Gamma_X q_f | A \rangle$$

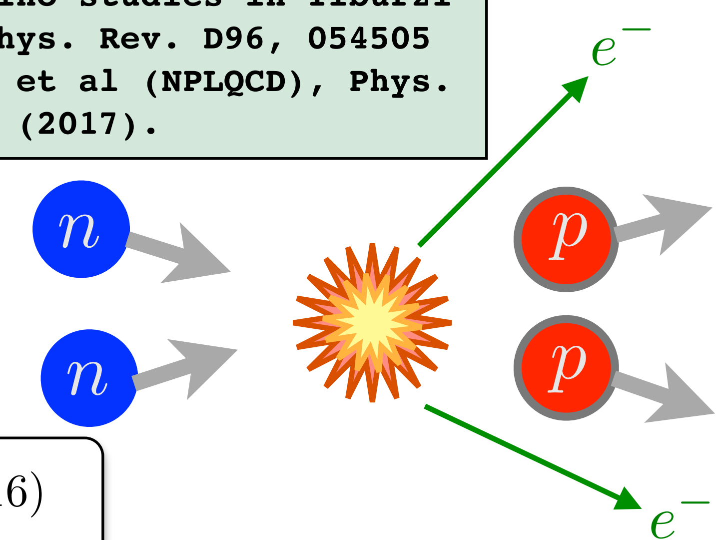



Savage et (ZD) [NPLQCD], Phys. Rev. Lett. 119,062002 (2017).[Highlighted by Department of Energy]




$$L_{1,A} = 3.9(0.1)(1.0)(0.3)(0.9)\ \mathrm{fm}^3 \ \ @\ \mu = m_\pi^{\mathrm{phys.}} = 140\ \mathrm{MeV}$$

ZD, Detmold, Fu, Grebe, Jay, Murphy, Oare, Shanahan, Wagman, arXiv:2402.09362 [hep-lat]. See also our two-neutrino studies in Tiburzi et al (ZD) (NPLQCD), Phys. Rev. D96, 054505 (2017)and Shanahan, ZD et al (NPLQCD), Phys. Rev. Lett. 119, 062003 (2017).




$$a^2 \mathcal{A}^{nn \rightarrow pp} = 0.078(16)$$
$$@\ m_\pi = 806\ \mathrm{MeV}$$

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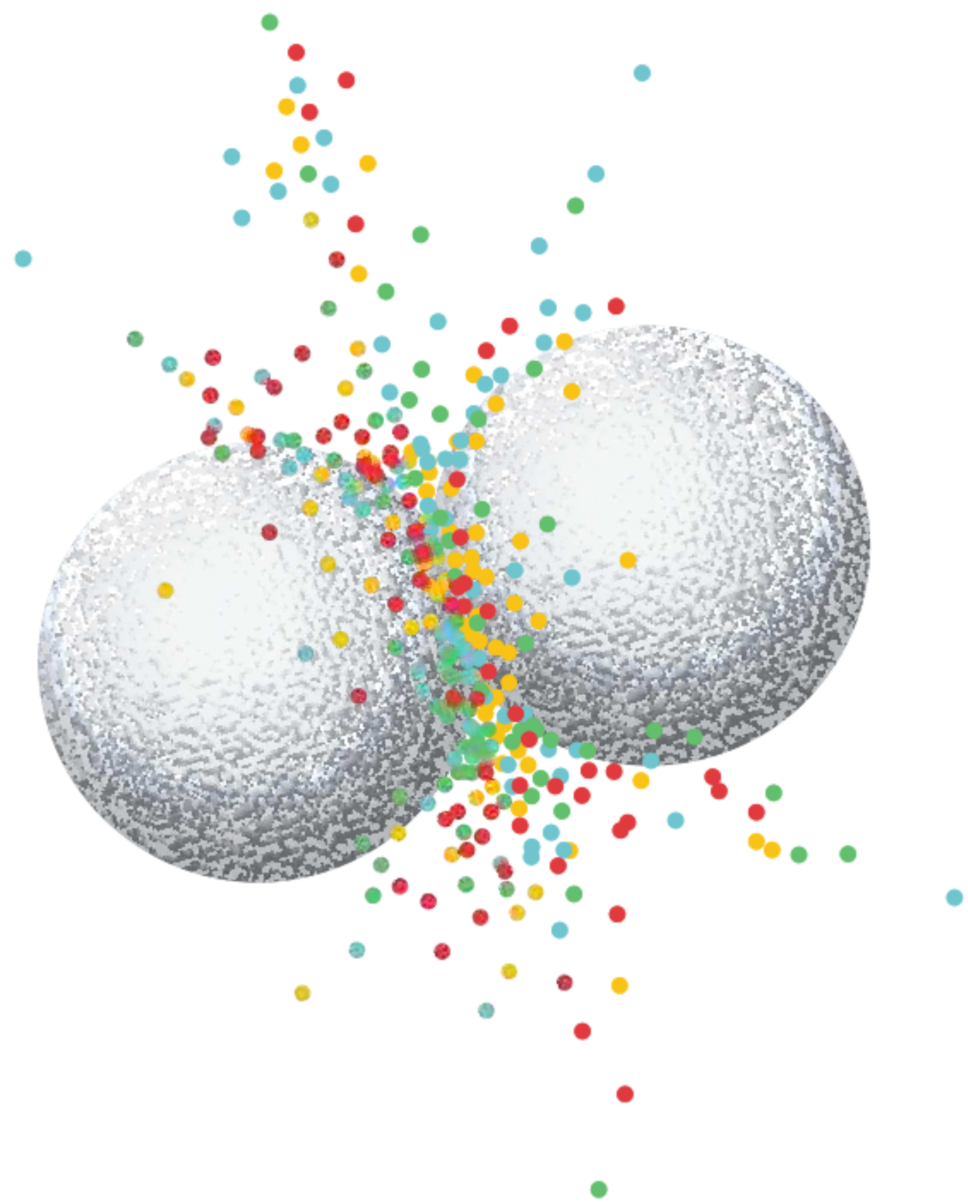
**Classic Computing**

What about high energies, like events at the Large Hadron Collider or the Relativistic Heavy-Ion Collider?



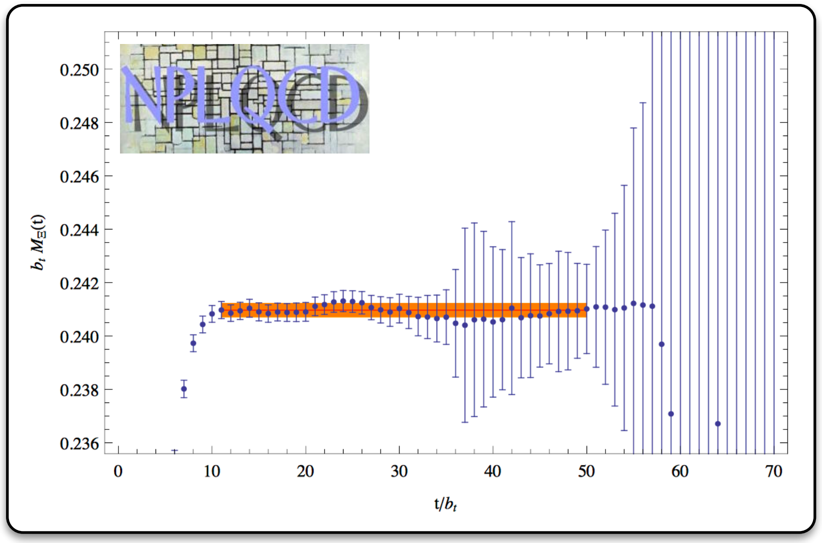
There are mainly two issues…

i) making complicated states, i.e., high-energy protons, or heavy ions, etc.,
ii) imaginary time nature of the classical Monte-Carlo calculations…no access to states as a function of Minkowski time elapsed after the collision!

# THREE FEATURES MAKE LATTICE-QCD CALCULATIONS OF NUCLEI HARD:

i) The complexity of systems grows factorially with the number of quarks.

```
Detmold and Orginos (2013)
Detmold and Savage (2010)
Doi and Endres (2013)
```

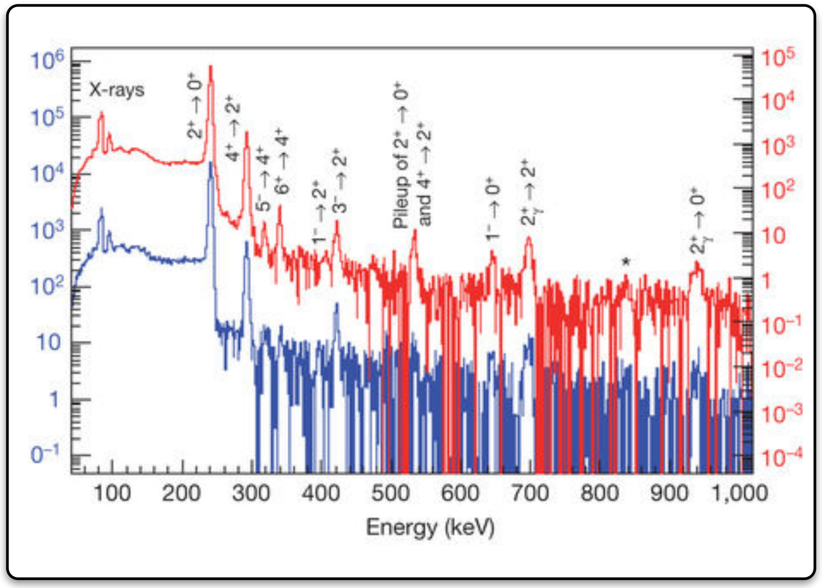



ii) There is a severe signal-to-noise degradation.

```
Paris (1984) and Lepage (1989)
Wagman and Savage (2017, 2018)
```

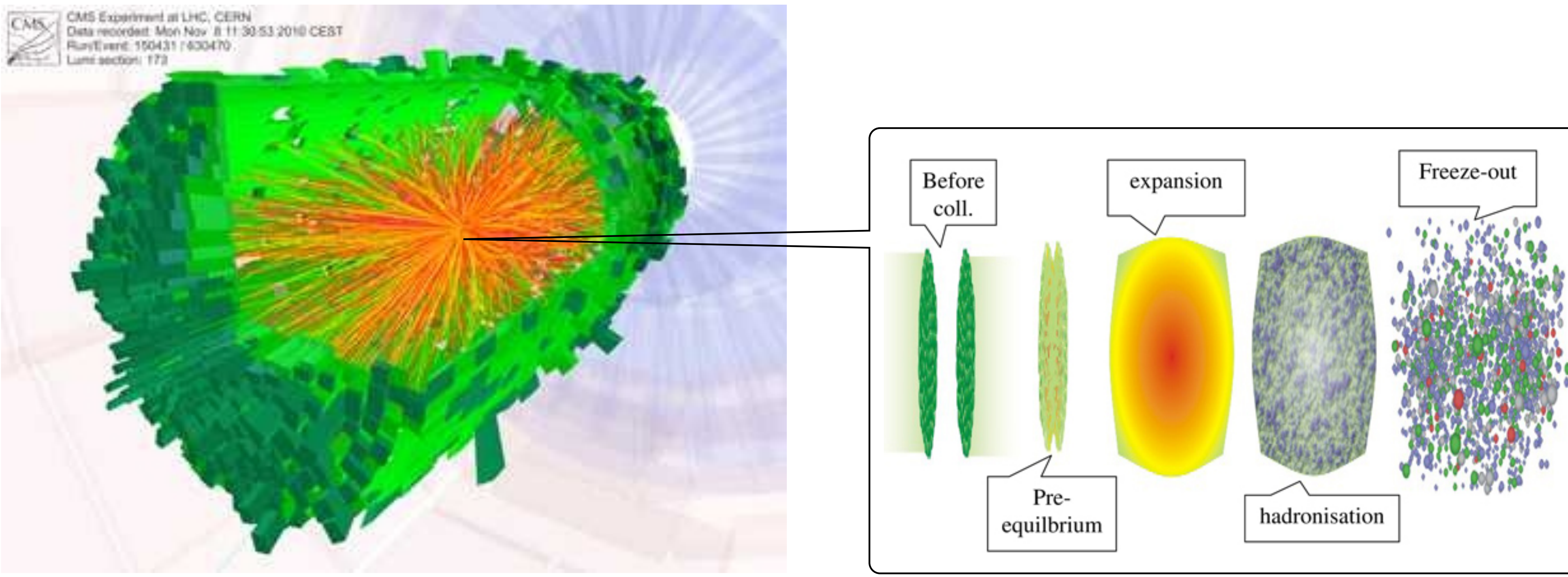
iii) Excitation gaps of nuclei are much smaller than the QCD scale.

```
Beane at al (NPLQCD) (2009)
Beane, Detmold, Orginos, Savage (2011)
ZD (2018)
Briceno, Dudek and Young (2018)
```



# SIGN PROBLEM MAKES CONVENTIONAL LATTICE-GAUGE-THEORY METHODS INTRACTABLE.

No access to real-time nonequilibrium dynamics of matter in heavy-ion collisions or after the Big Bang…




…and to a wealth of dynamical response functions, transport properties, parton distribution functions, etc.

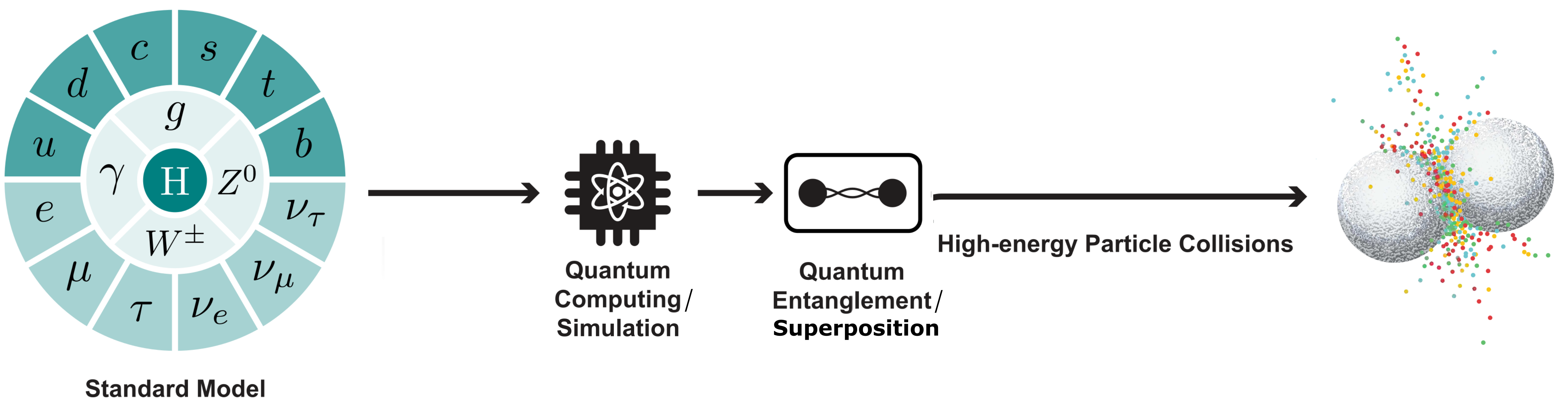
Path integral formulation:

$$e^{iS[U,q\bar{q}]}$$

Hamiltonian evolution:

$$U(t) = e^{-iHt}$$

# FIRST-PRINCIPLES PREDICTIONS FOR SCATTERING PROCESSES: QUANTUM SIMULATIONS?




Bauer, ZD, Klco, and Savage, *Nature Rev. Phys.* 5 (2023) 7, 420-432.

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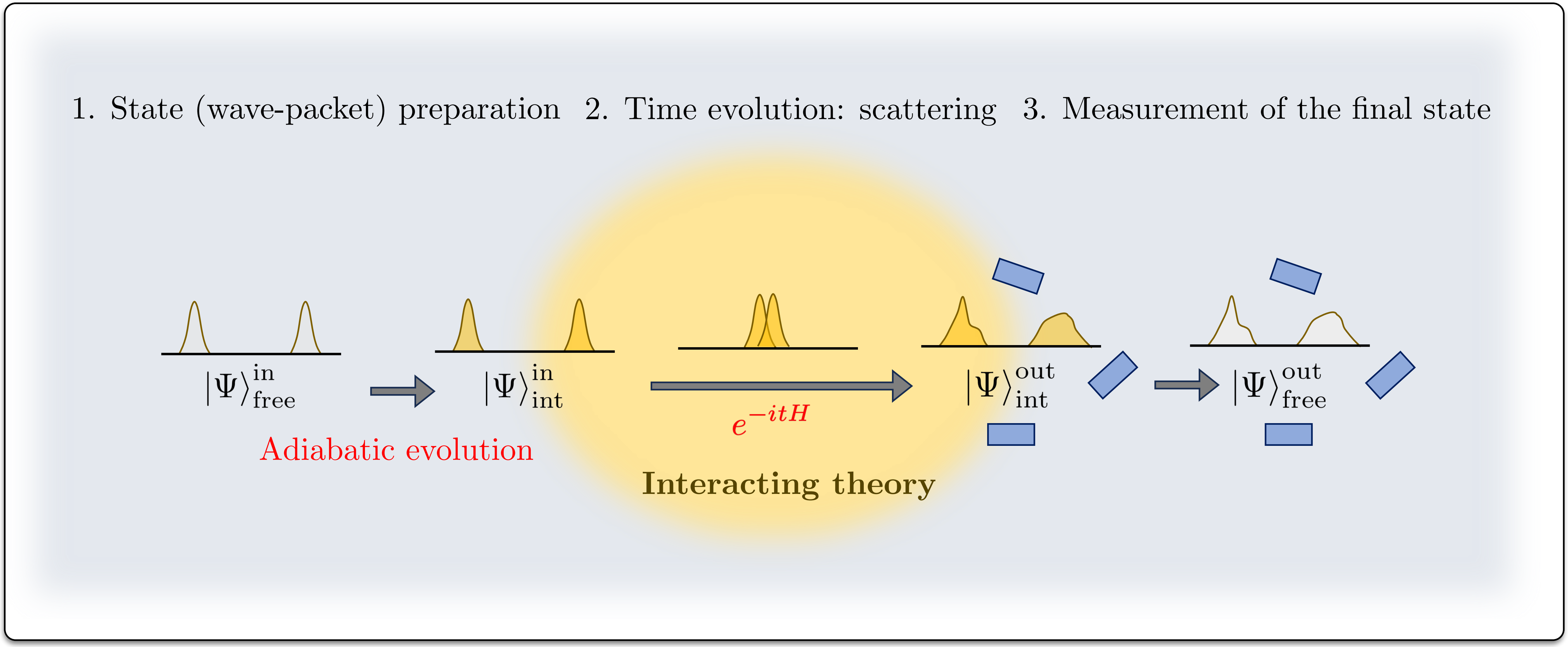
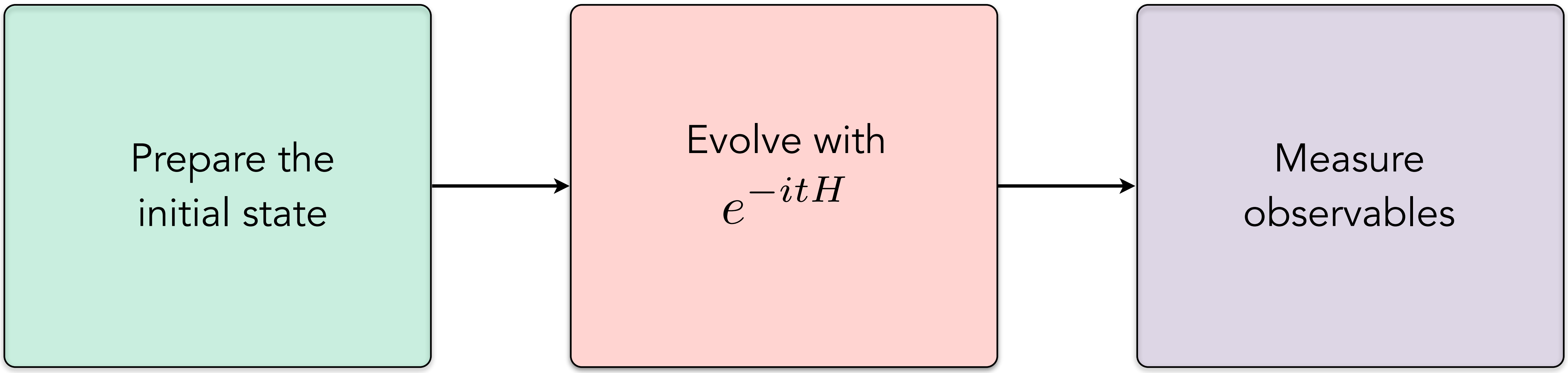
# STUDY HIGH-ENERGY SCATTERING VIA QUANTUM SIMULATION?
# THE JORDAN-LEE-PRESKILL STRATEGY




Jordan, Lee, Preskill, Science 336, 1130-1133 (2012).

Figure from: ZD, Hseih, and Kadam, arXiv:2402.00840 [quant-ph].

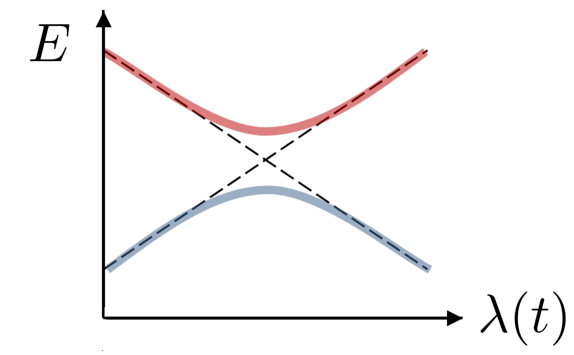
# OR MORE GENERALLY…



Prepare the initial state

# EXAMPLES OF (GROUND-)STATE PREPARATION METHODS

- **Adiabatic state preparation:** Prepare the ground state of a simple Hamiltonian, then adiabatically turn the Hamiltonian to that of the target Hamiltonian. Requires a non-closing energy gap.



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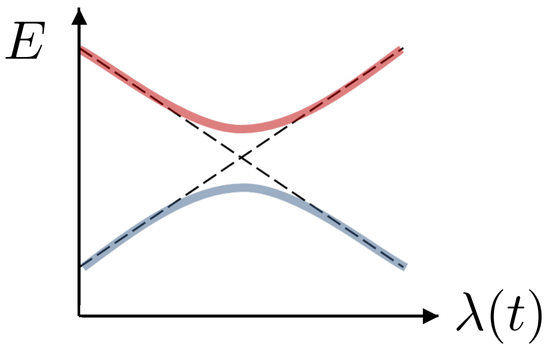


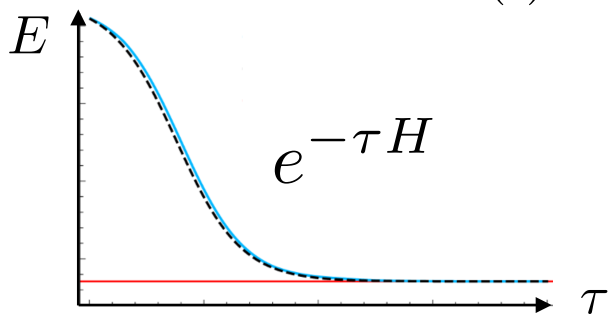

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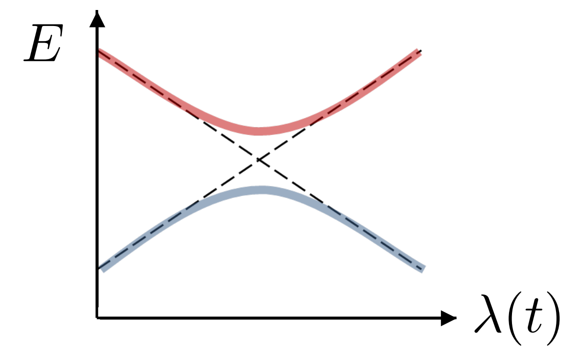


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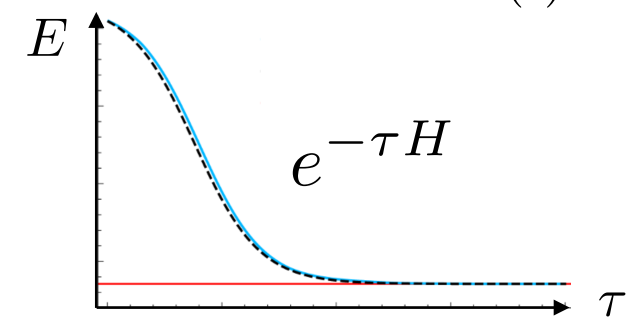
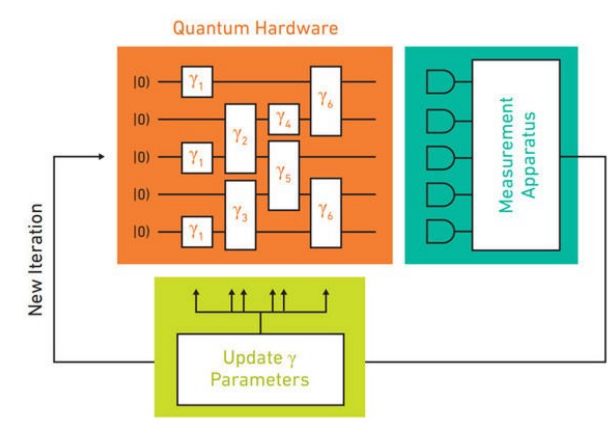



- **Variational quantum eigensolver (VQE):** Use the variational principle of quantum mechanics and classical processing to minimize the energy of a non-trivial ansatz wavefunction generated by a quantum circuit. The optimized circuit corresponding to the minimum energy generates an approximation to ground-state wavefunction. Can fail if stuck in local minima manifolds or manifolds with exponentially small gradients in qubit number.



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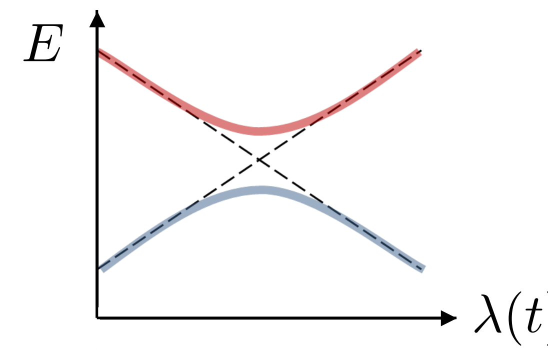


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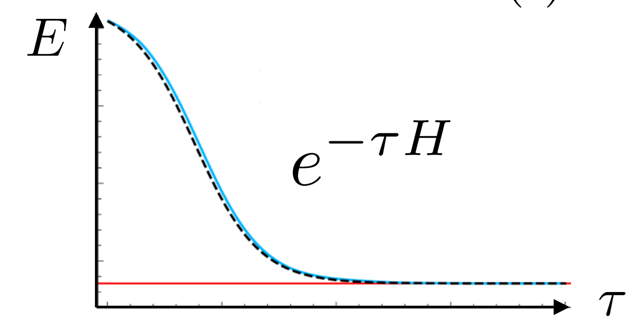


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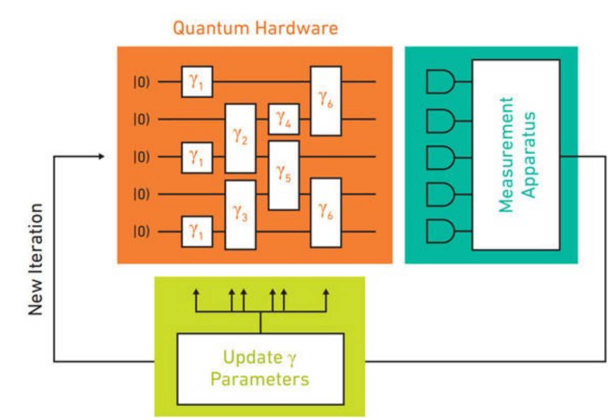



- **Classically computed states:** Use classical computing such as Monte Carlo, Tensor Networks, Neural Networks to learn the state or features of the state when possible, for a direct implementation of the state as a quantum circuit, or as close enough state to the ground state as a starting point of the above algorithms so as to achieve more efficient implementations.

`Gupta, White, ZD, arXiv:2506.02313 [quant-ph].`

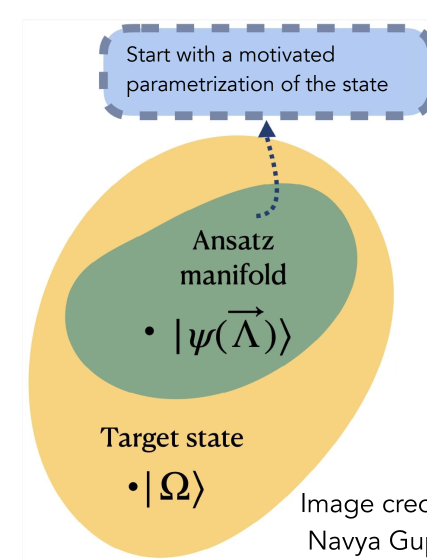


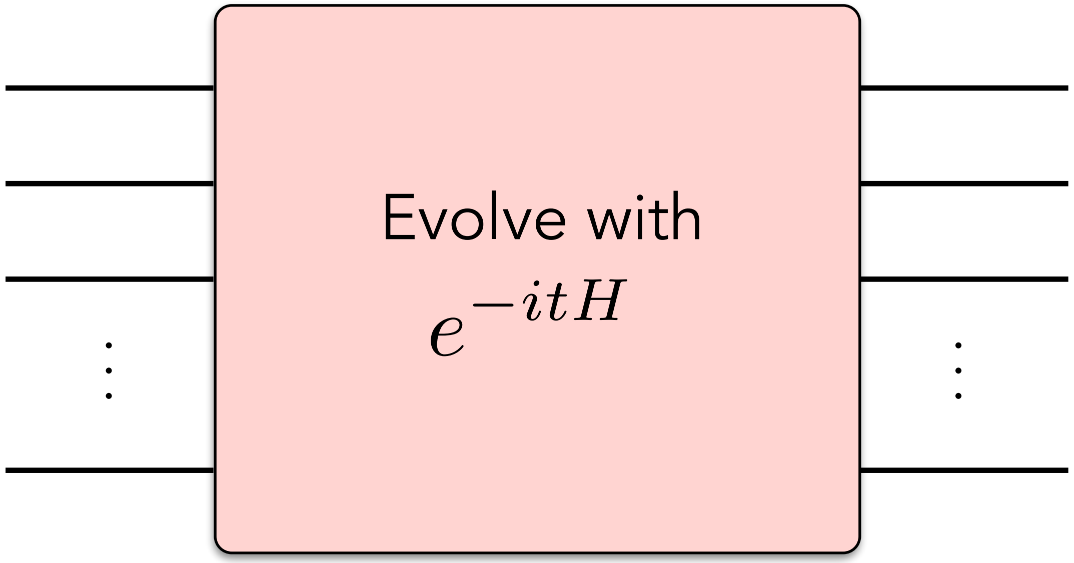

Image credit: Navya Gupta (UMD)

Evolve with

$$e^{-itH}$$

# DIFFERENT APPROACHES TO QUANTUM SIMULATION

## Analog



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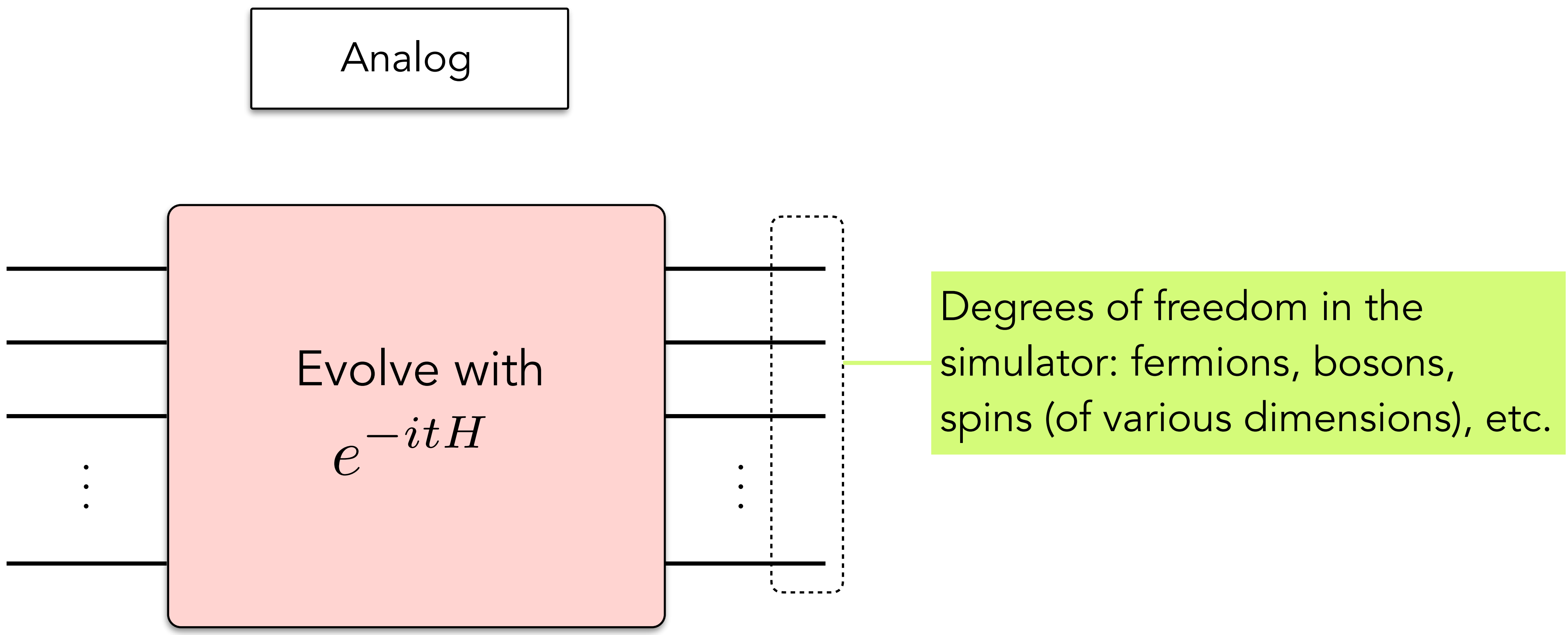

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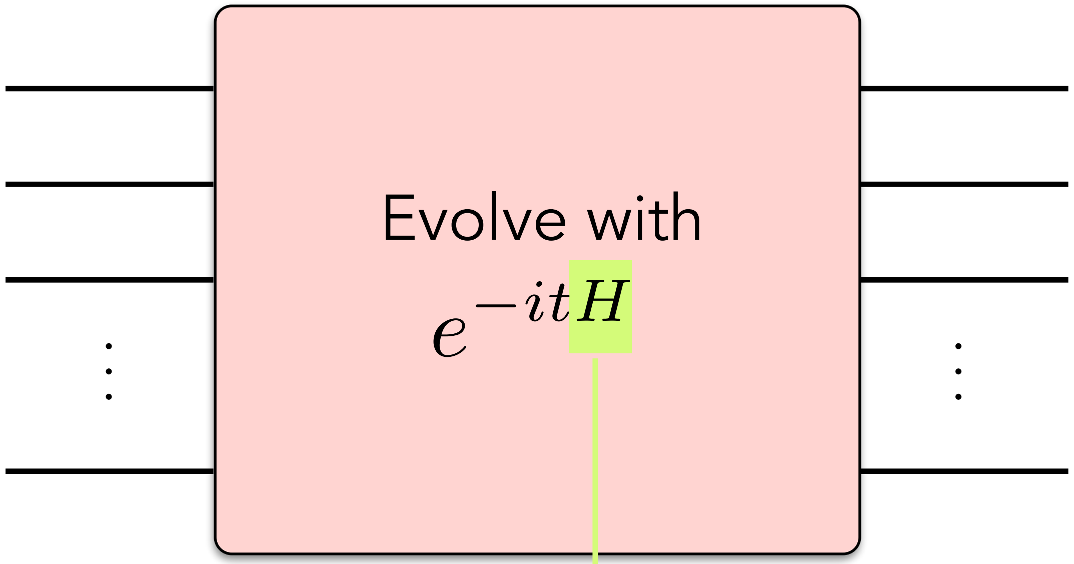
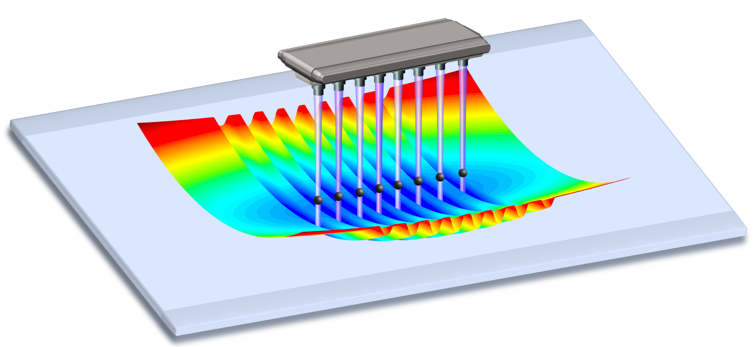
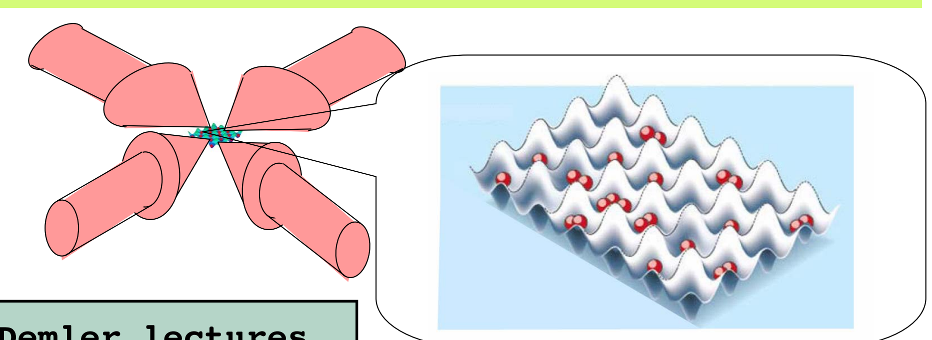



The engineered simulator Hamiltonian that mimics the Hamiltonian of target system.

Some of the leading analog simulators are: cold-atoms in optical lattices, Rydberg atoms with optical tweezers, trapped ions, superconducting circuits (including when coupled to photonics systems), etc.



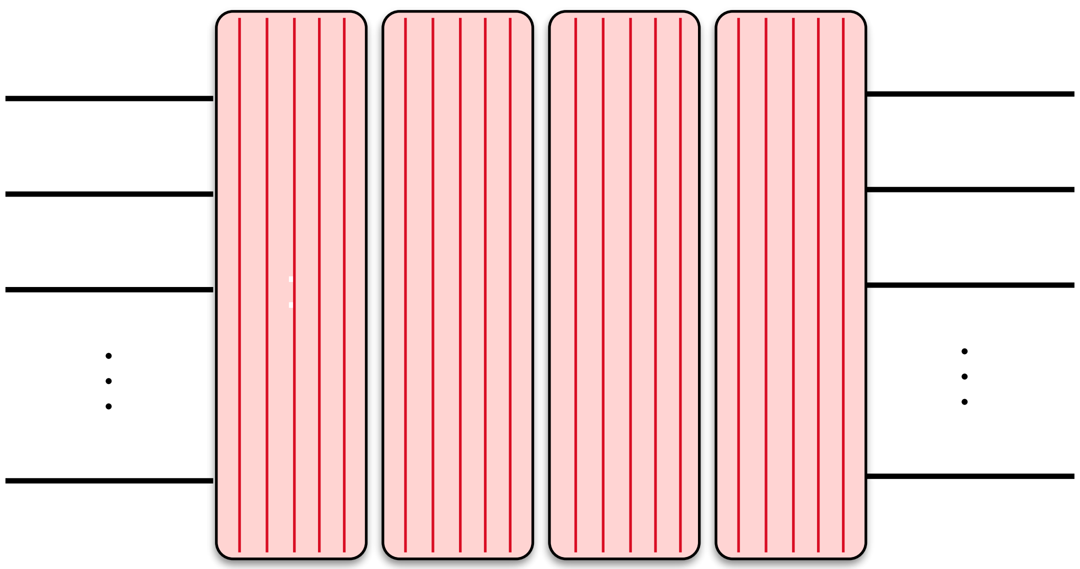
CREDIT: ANDREW SHAW, UNIVERSITY OF MARYLAND



Eugene Demler lectures, Harvard University.

# DIFFERENT APPROACHES TO QUANTUM SIMULATION

Digital



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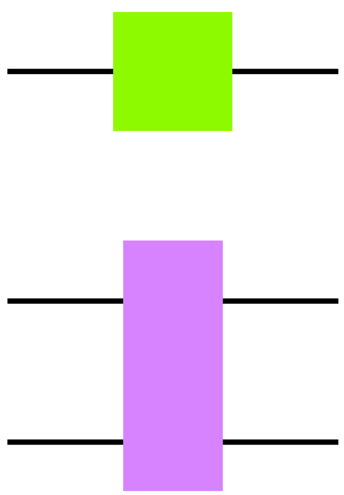
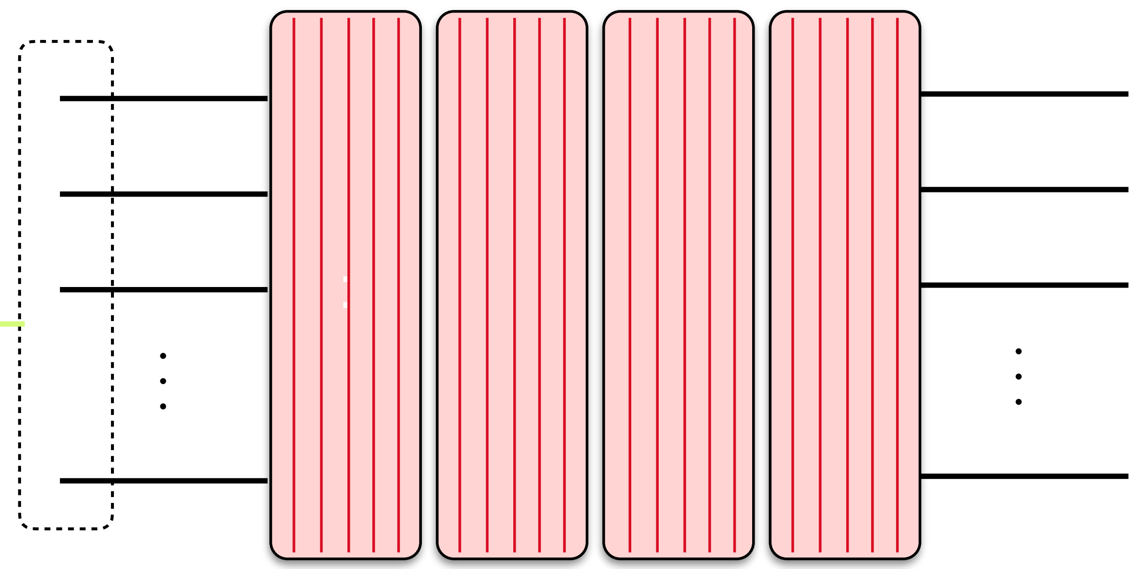


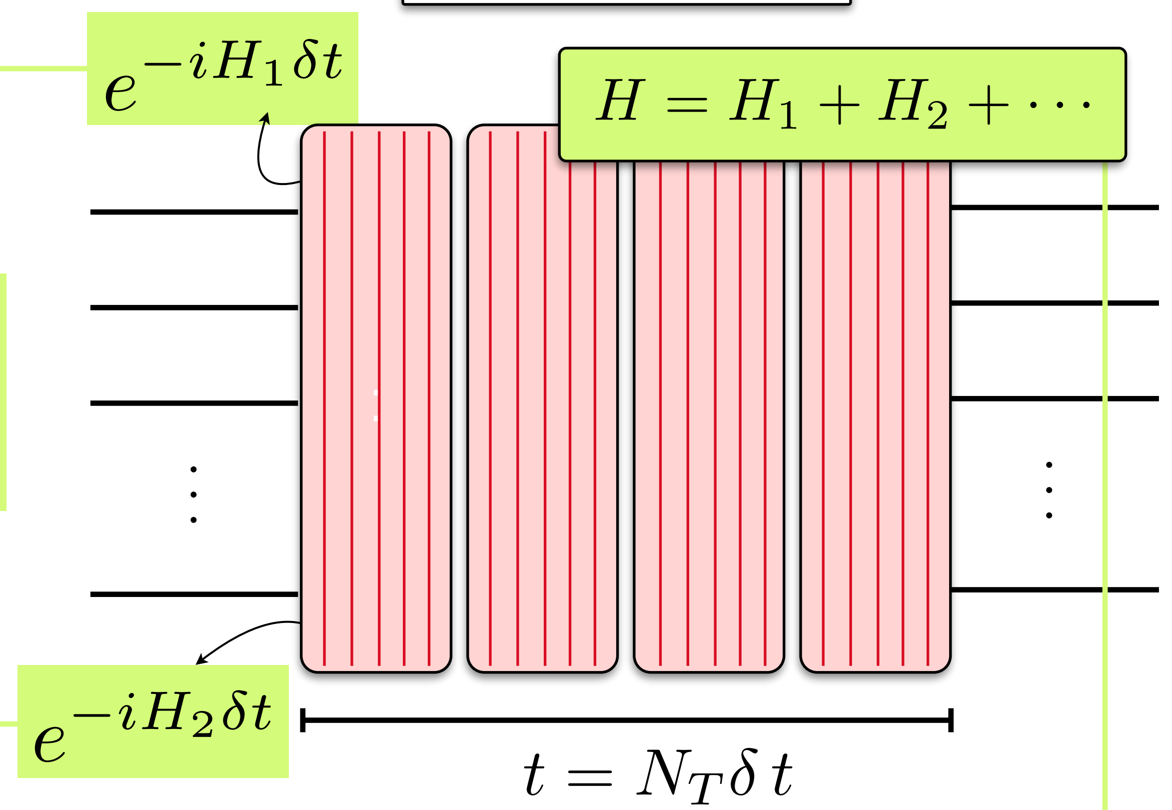
Only qubits as DOF. Only universal single- and two-qubit operations allowed.



# DIFFERENT APPROACHES TO QUANTUM SIMULATION

Example of a digital scheme:

Digital




Each of these can now potentially be decomposed to a universal set of single and two-qubit gates.

Trotter-Suzuki expansion:

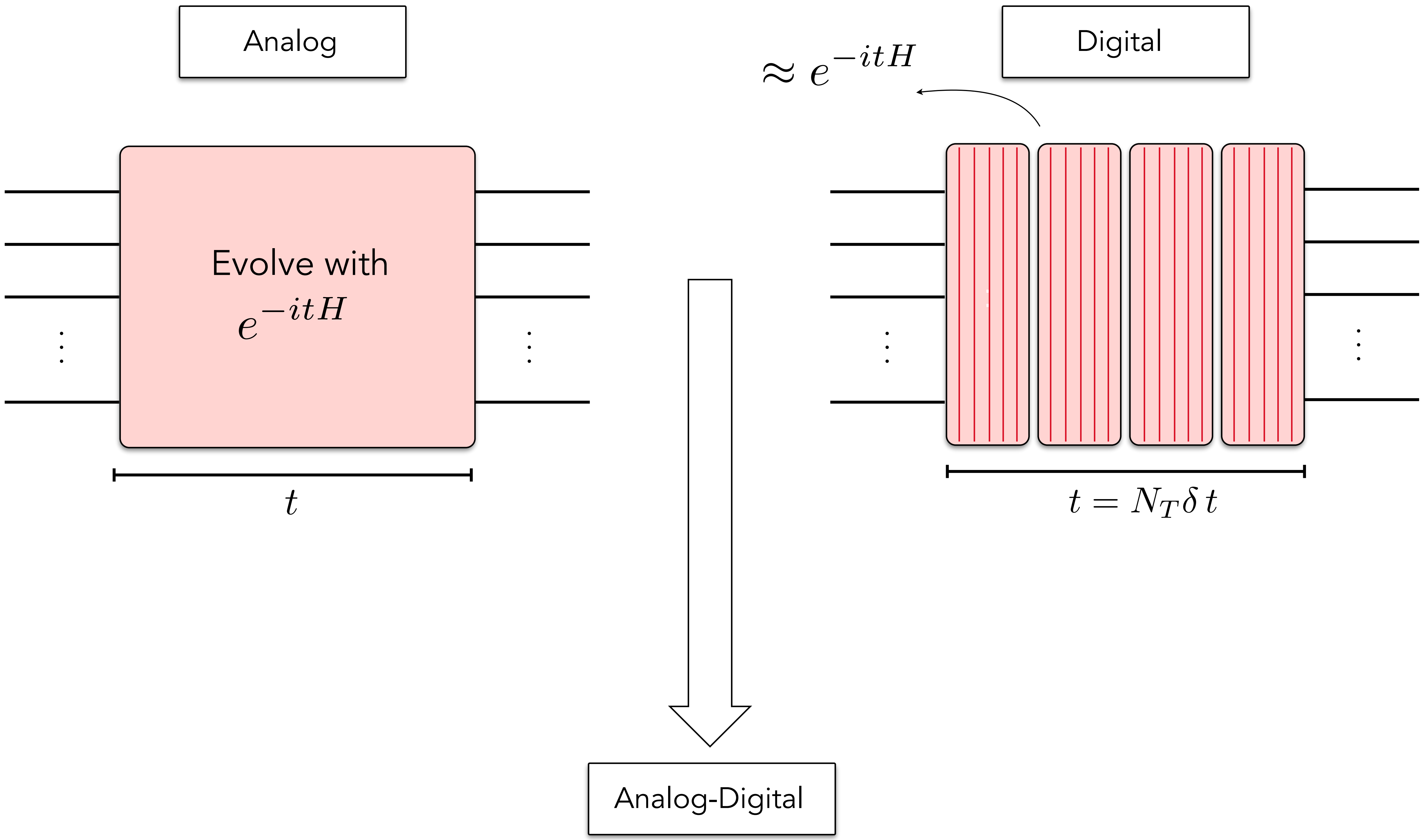
$$e^{-i(H_1+H_2+\cdots)t} = \left[e^{-iH_1\delta t}e^{-iH_2\delta t}\cdots\right]^{t/\delta t} + \mathcal{O}((\delta t)^2)$$

Other digitalization schemes also exist.

…other methods exist too.

Andrew Childs lectures on Quantum Simulation, University of Maryland.

# DIFFERENT APPROACHES TO QUANTUM SIMULATION



Measure
observables

# EXAMPLES OF ACCESSIBLE OBSERVABLES

One can measure the following quantities to learn properties of the outcome state. Some of these can be measured directly in the computational basis, but others need a change of basis or other dedicated quantum circuits to access them.

- **Energy and momentum, particle and charge** (both locally and globally)

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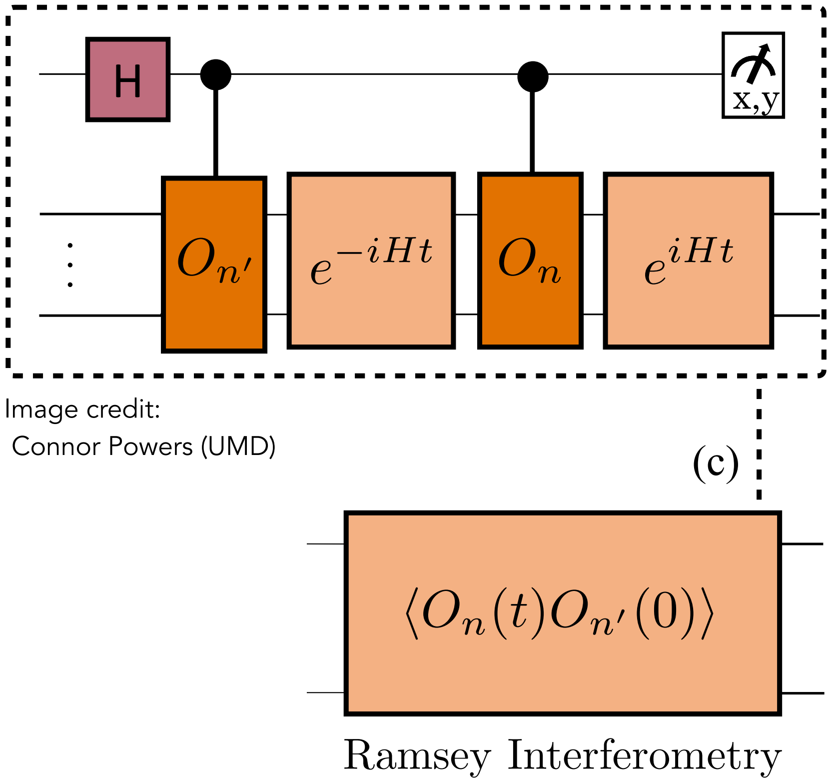


Image credit:
Connor Powers (UMD)

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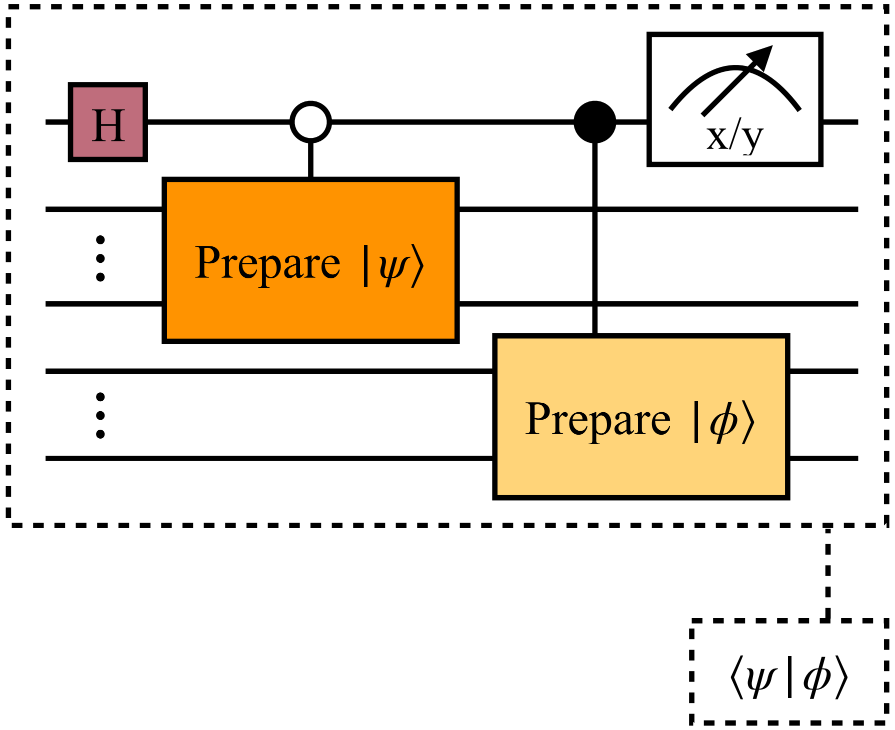
- **Asymptotic S-matrix elements** (assuming asymptotic final states are reached):
  - Exclusive processes: can be obtained from overlaps
  - Inclusive processes: can be obtained from two-current correltor via optical theorem
  - Semi-inclusive processes: can be obtained using projectors



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- **Entanglement measures** such as estimates of entanglement spectrum (which can signal thermalization or lack of).

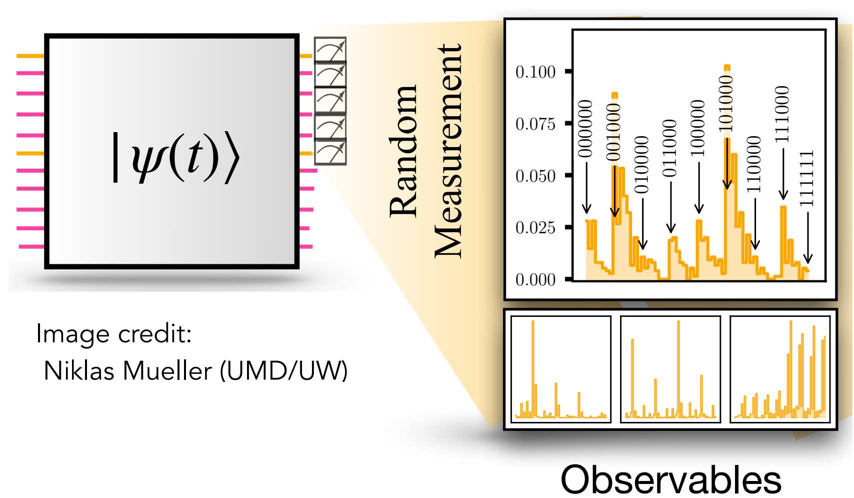


Image credit:
Niklas Mueller (UMD/UW)

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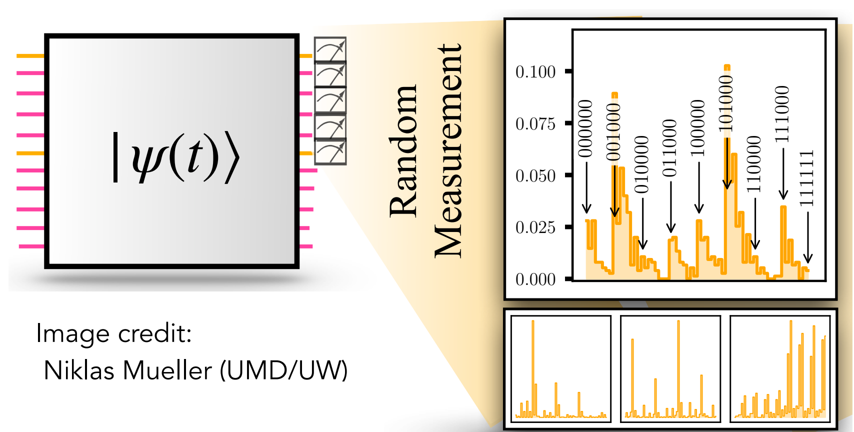


Image credit:
Niklas Mueller (UMD/UW)

Observables

Fidelities and full state tomography are hard (they demand exponentially large number of measurements).

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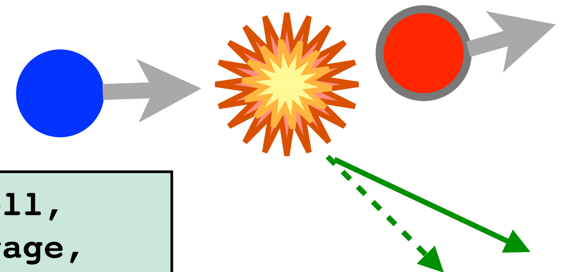
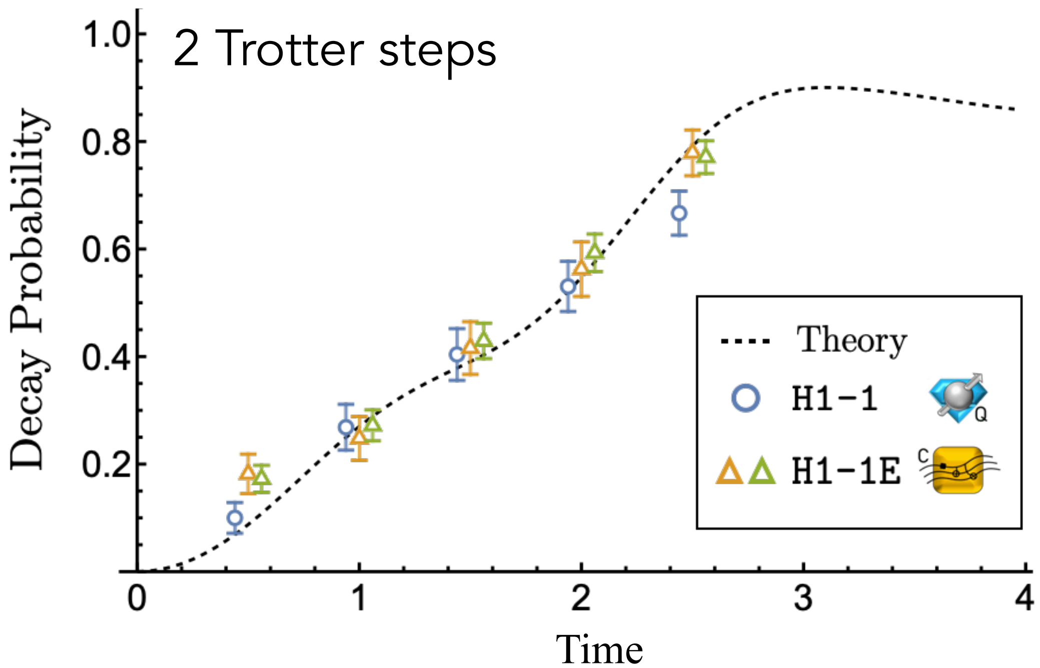
# FIRST STEPS TOWARD COLLISION/REACTION PROCESSES

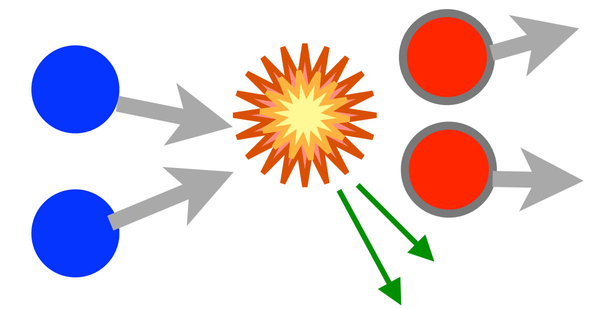
## $\beta$ decay in (1+1)D QCD (Quantinuum)



**Farrell, Chernyshev, Powell, Zemlevskiy, Illa, and Savage, Phys. Rev. D 107, 054513 (2023).**

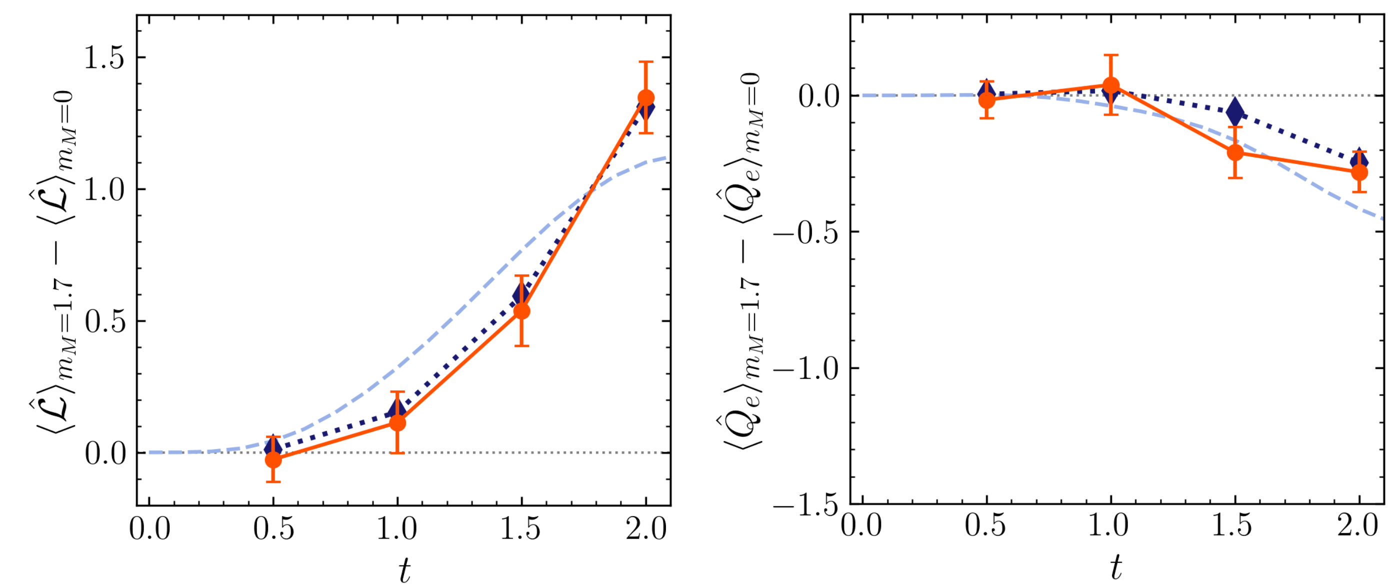



## $0\nu\beta\beta$ decay in (1+1)D QCD (IonQ)



**Chernyshev et al, arXiv:2506.05757 [quant-ph].**

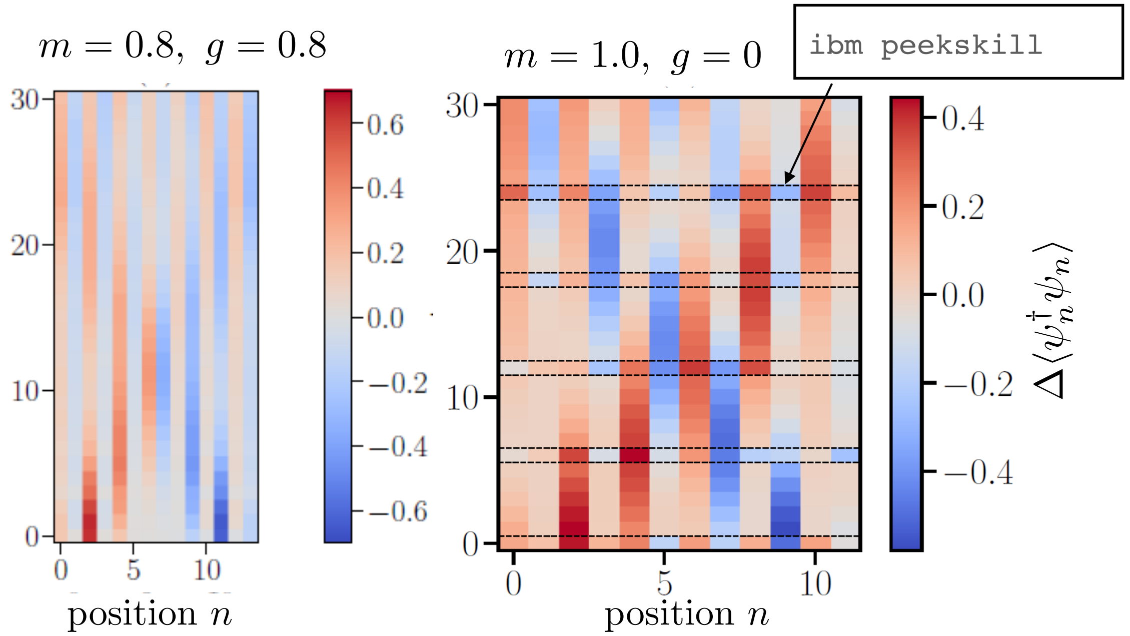
2 Trotter steps



# FIRST STEPS TOWARD NUCLEAR REACTION PROCESSES

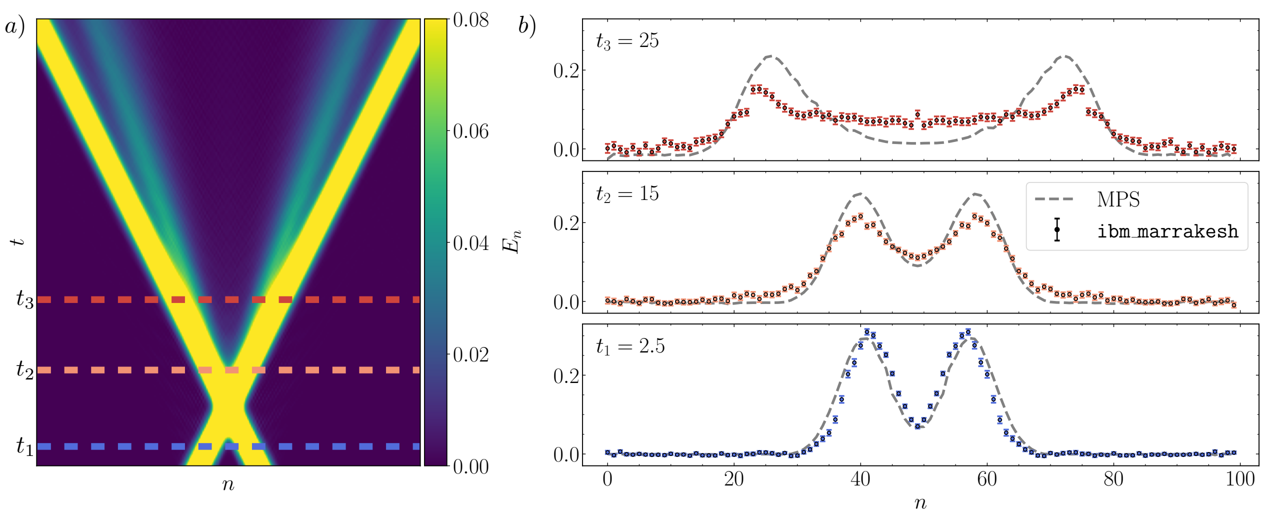
## Fermion-antifermion scattering in the (1+1)D Thirring model (IBM)

**Chai, Crippa, Jansen, Kühn, Pascuzzi, Tacchino, Tavernelli, Quantum 9, 1638 (2025).**




## Scattering in a (1+1)D Ising field theory (IBM)

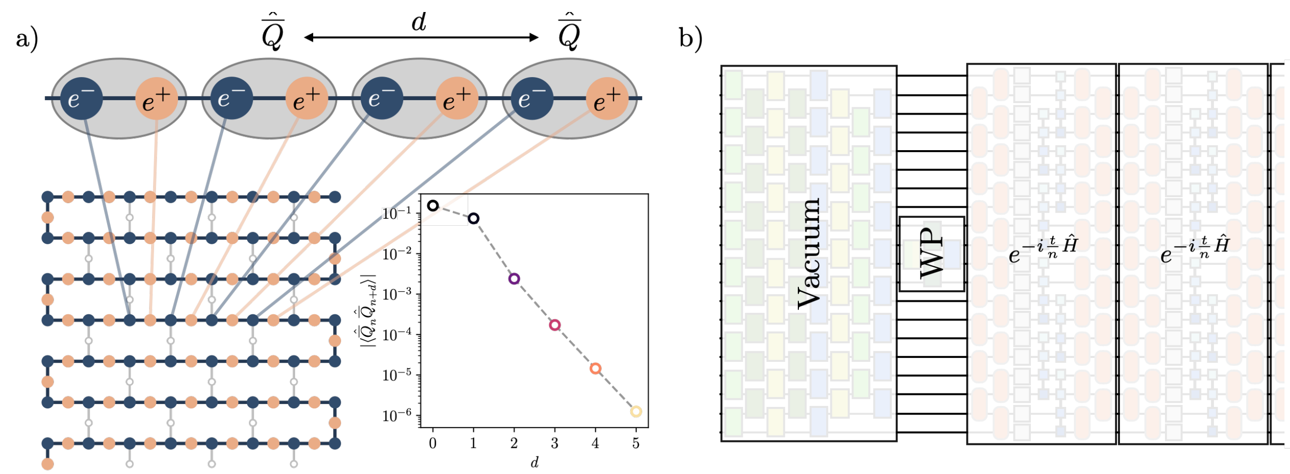
**Farrell, Zemlevskiy, Illa, Preskill, arXiv:2505.03111 [quant-ph].**



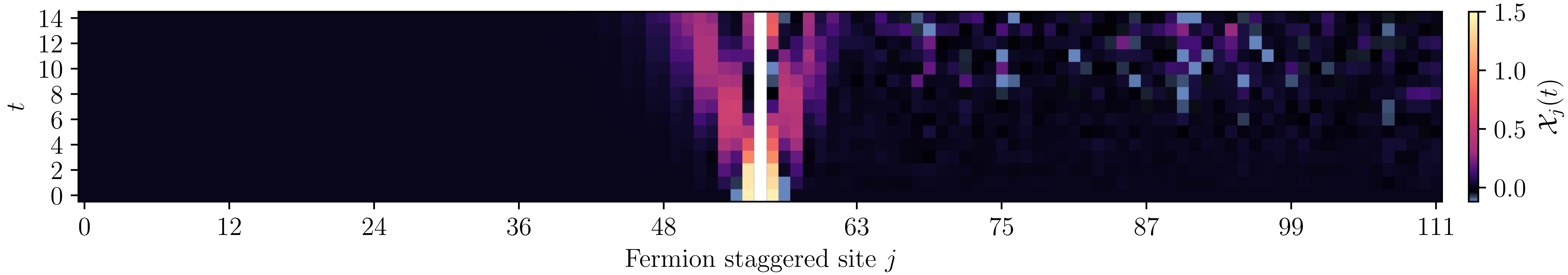

**See also Zemlevskiy, arXiv:2411.02486 [quant-ph] for a (1+1)D scalar field theory example.**

# FIRST STEPS TOWARD HADRONIC WAVE PACKETS AND THEIR COLLISIONS

Hadron wave-packet evolution in the Schwinger model (112 staggered sites with IBM with noise mitigation):




**Farrell, Illa, Ciavarella, Savage, Phys.Rev.D 109 (2024) 11, 114510.**



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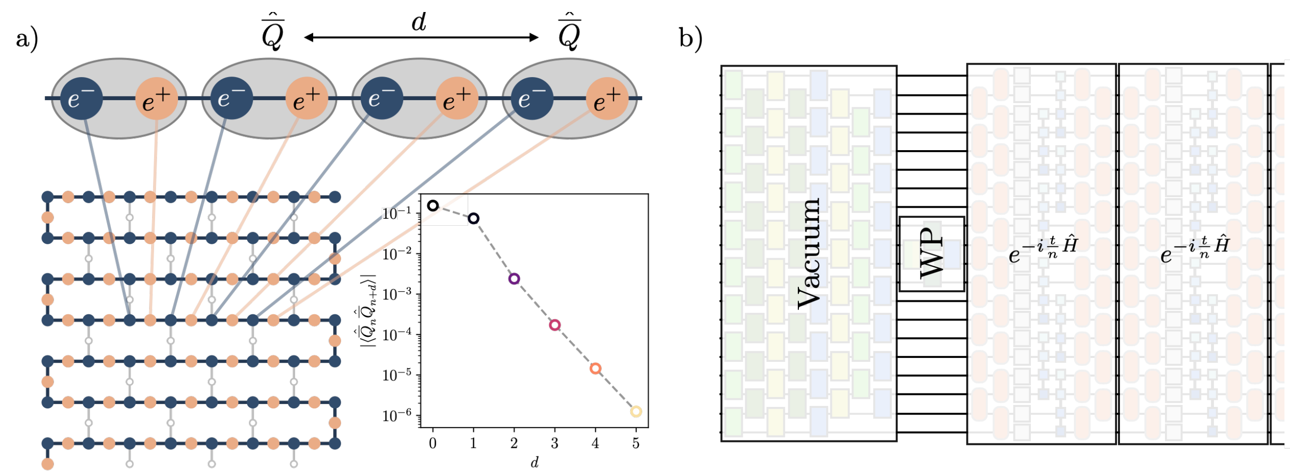
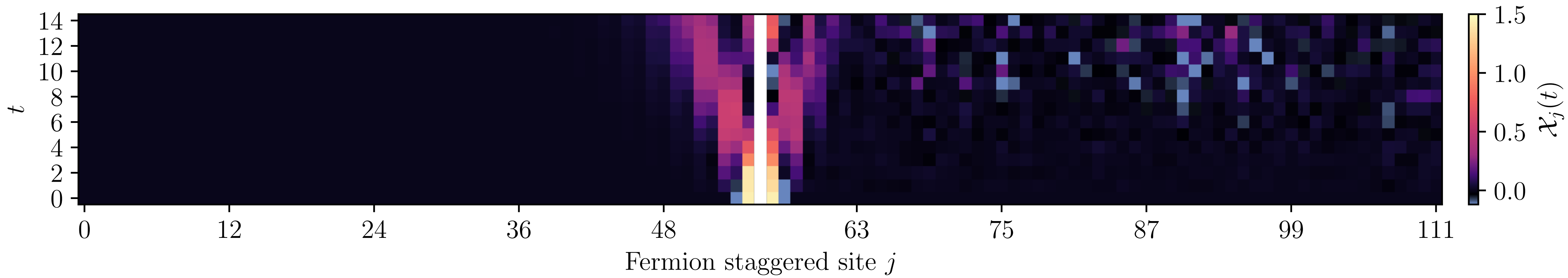
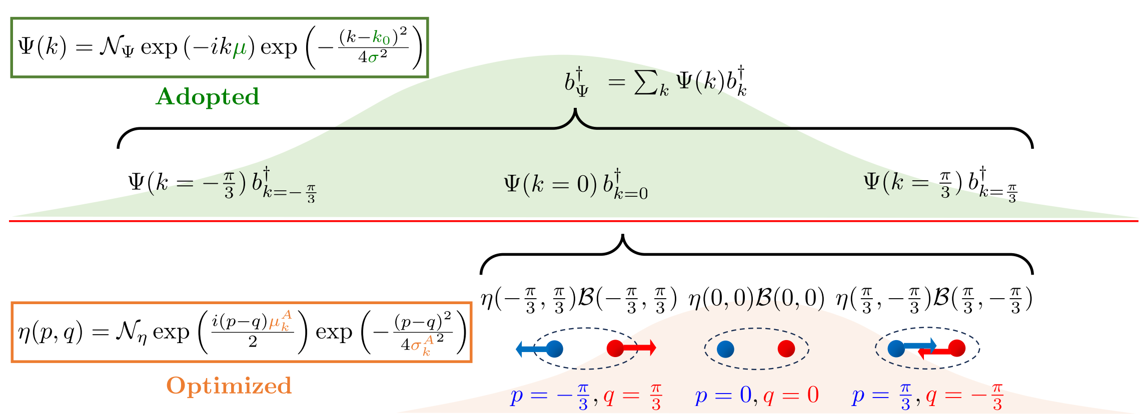
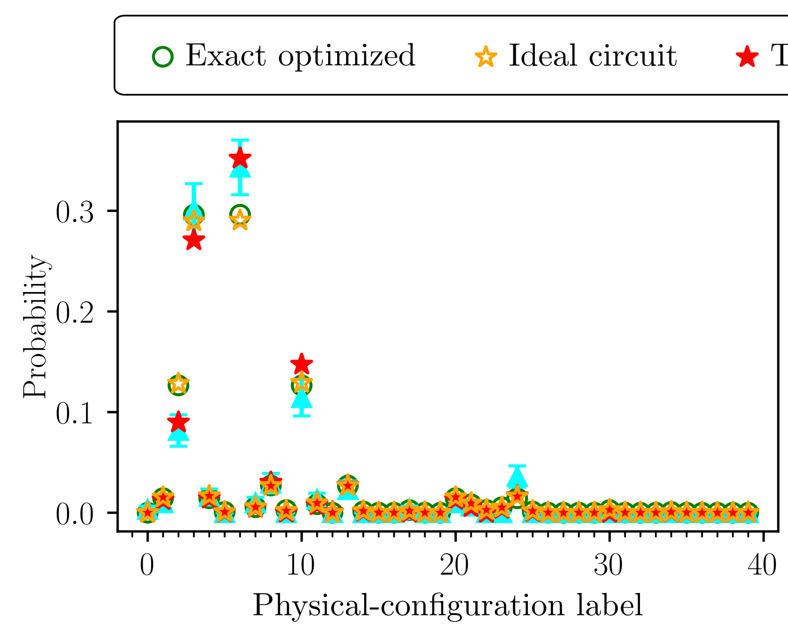


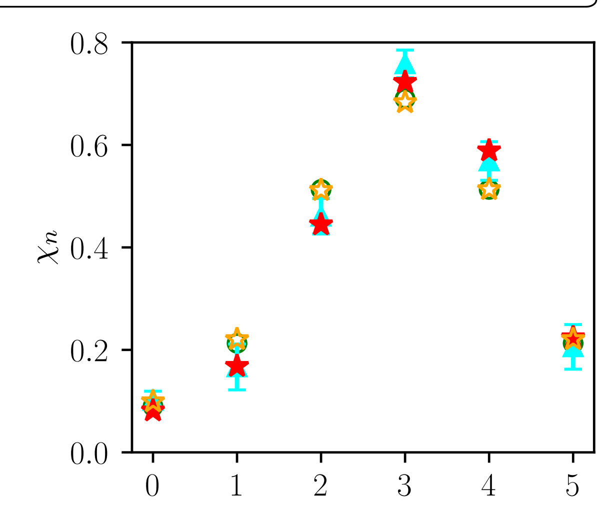

Farrell, Illa, Ciavarella, Savage, Phys.Rev.D 109 (2024) 11, 114510.



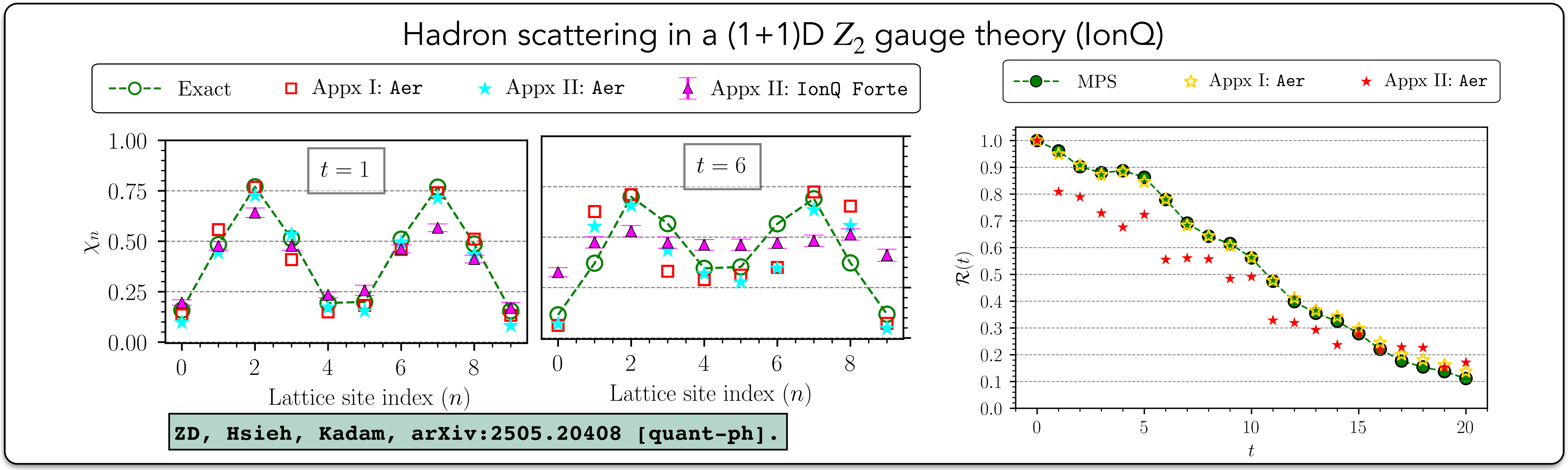

Hadron wave packet in a (1+1)D $Z_2$ gauge theory (12 staggered sites with Quantinuum, minimal noise mitigation):



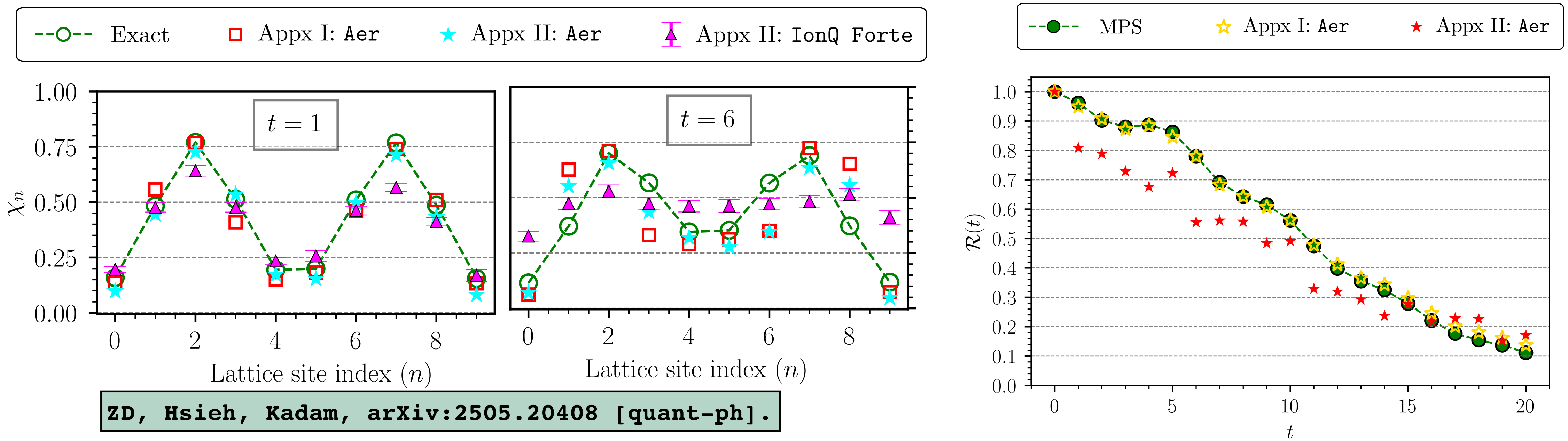




ZD, Hsieh, and Kadam, Quantum 8, 1520 (2024).

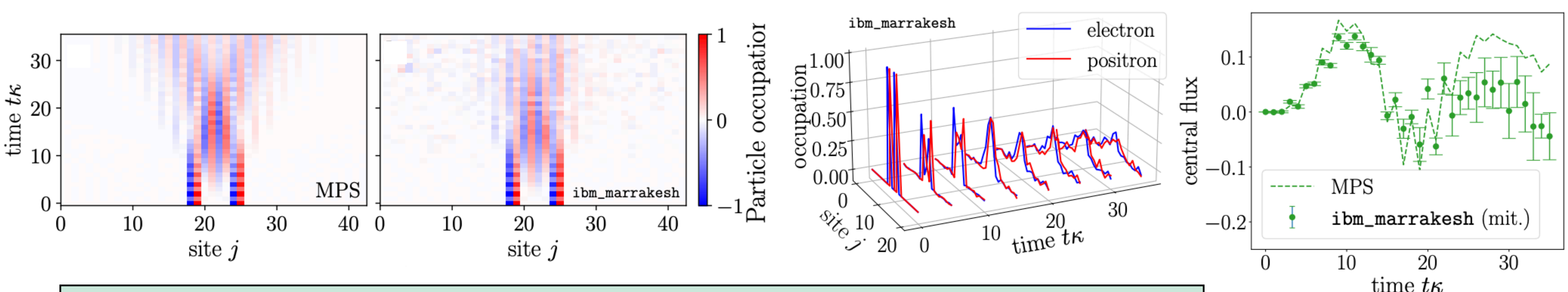

Hadron scattering in a (1+1)D $Z_2$ gauge theory (IonQ)
Exact
Appx I: Aer
Appx II: Aer
Appx II: IonQ Forte
$t = 1$
$t = 6$
$\chi_n$
Lattice site index $(n)$
ZD, Hsieh, Kadam, arXiv:2505.20408 [quant-ph].
MPS
Appx I: Aer
Appx II: Aer
$\mathcal{R}(t)$
$t$

## Hadron scattering in a (1+1)D $Z_2$ gauge theory (IonQ)



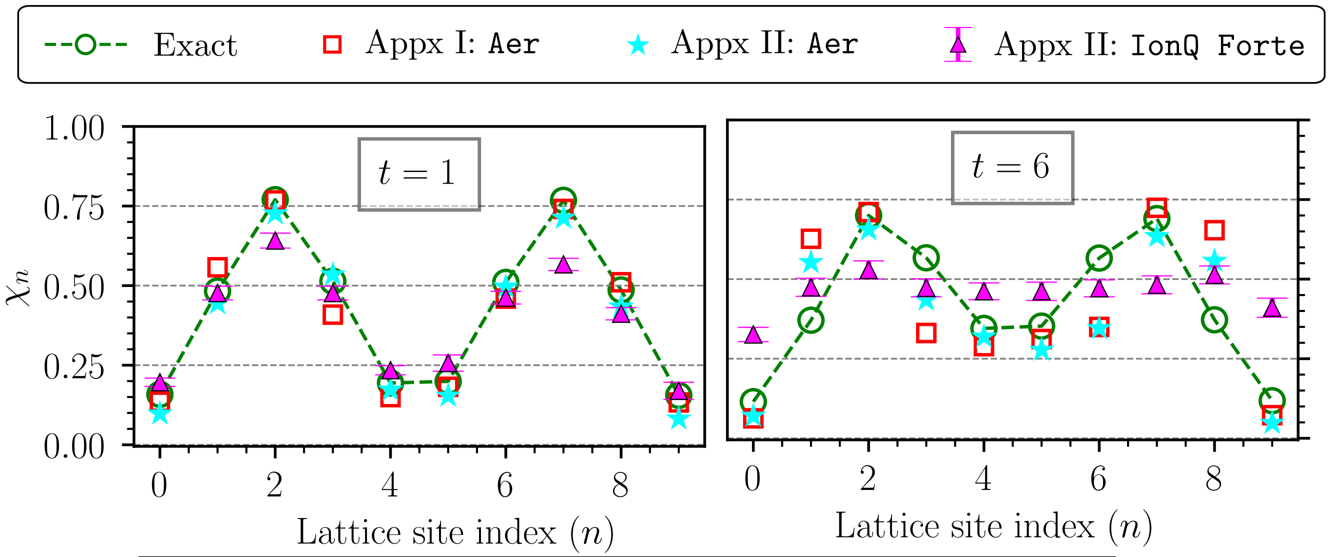

ZD, Hsieh, Kadam, arXiv:2505.20408 [quant-ph].

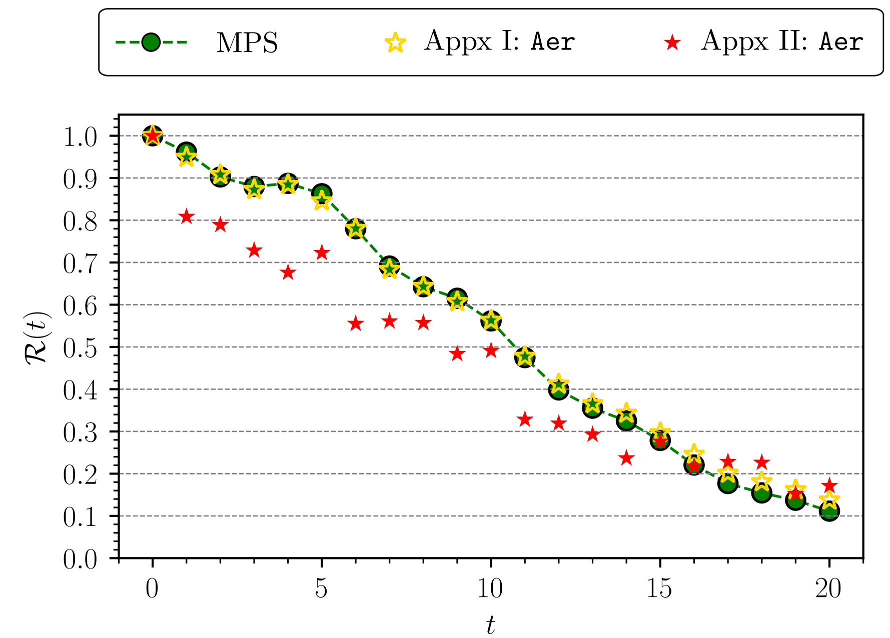
## Hadron scattering in a (1+1)D U(1) quantum link model (IBM)




Schuhmacher, Su, Osborne, Gandon, Halimeh, Tavernelli, arXiv:2505.20387 [quant-ph].

## Hadron scattering in a (1+1)D $Z_2$ gauge theory (IonQ)




ZD, Hsieh, Kadam, arXiv:2505.20408 [quant-ph].

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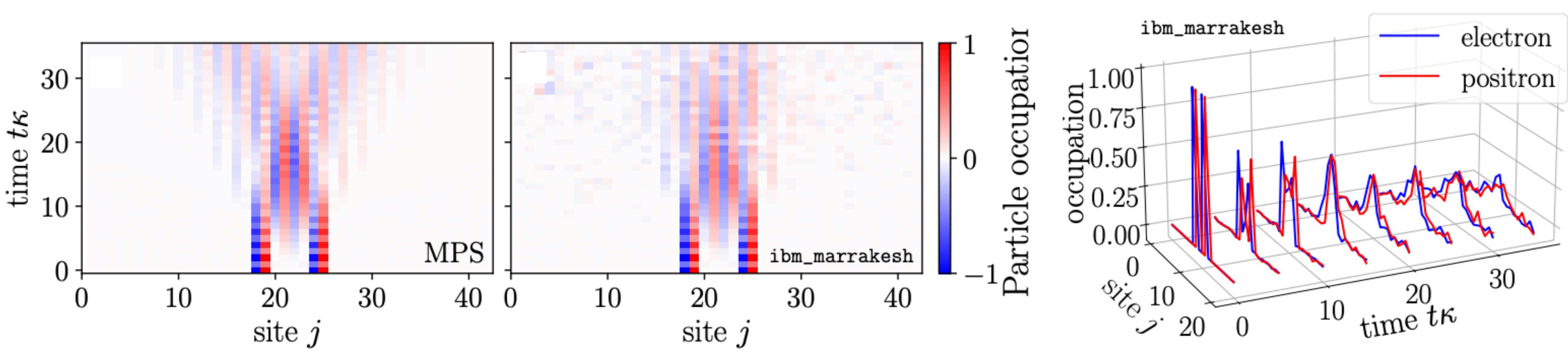
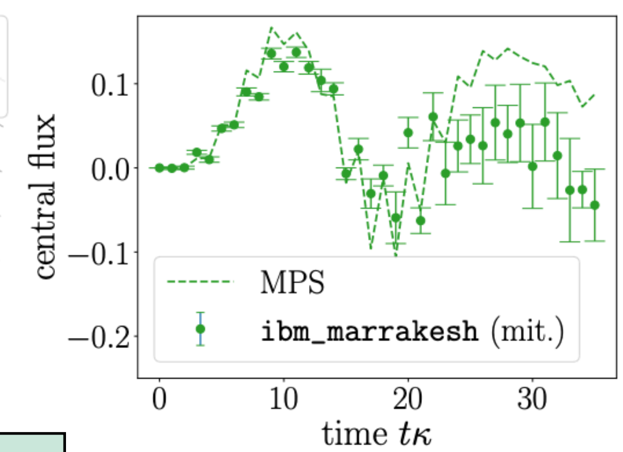
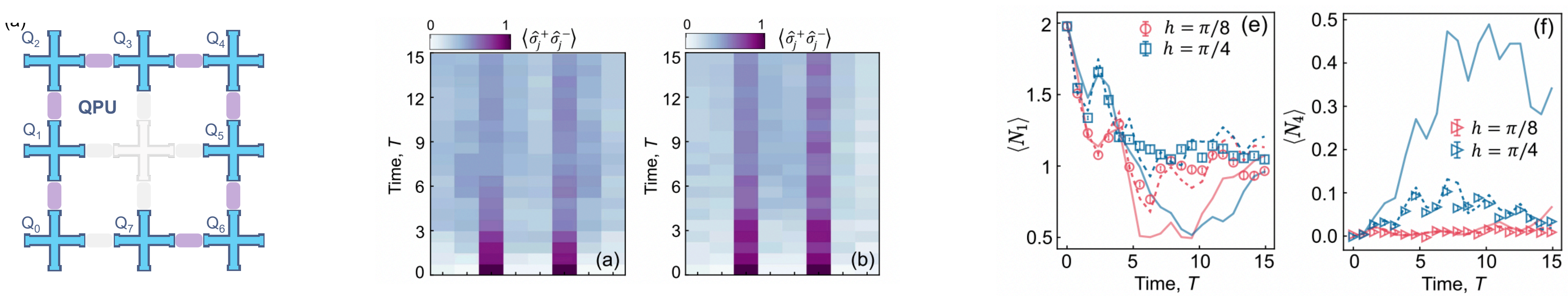


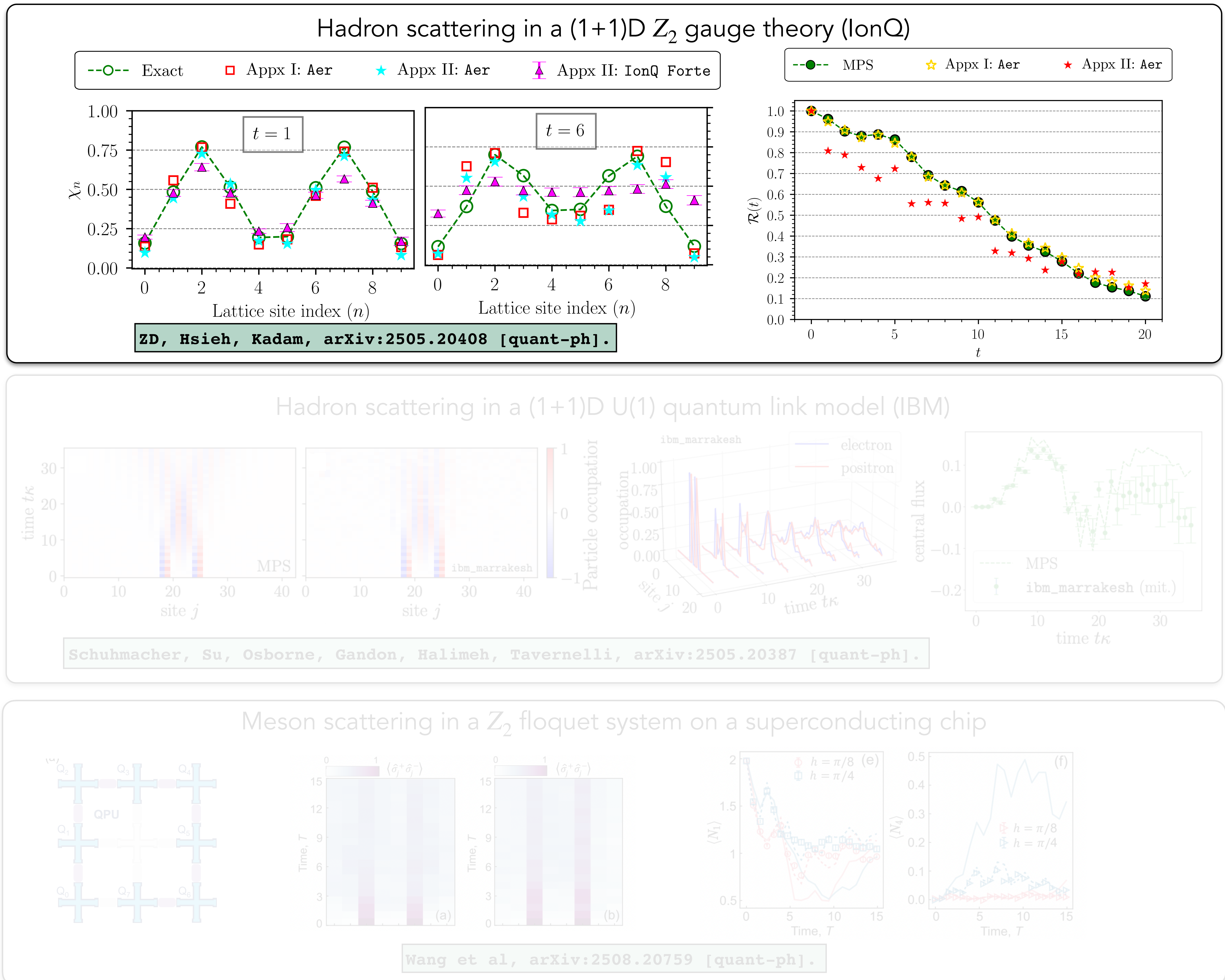




Schuhmacher, Su, Osborne, Gandon, Halimeh, Tavernelli, arXiv:2505.20387 [quant-ph].

## Meson scattering in a $Z_2$ floquet system on a superconducting chip




Wang et al, arXiv:2508.20759 [quant-ph].



Hadron scattering in a (1+1)D $Z_2$ gauge theory (IonQ)
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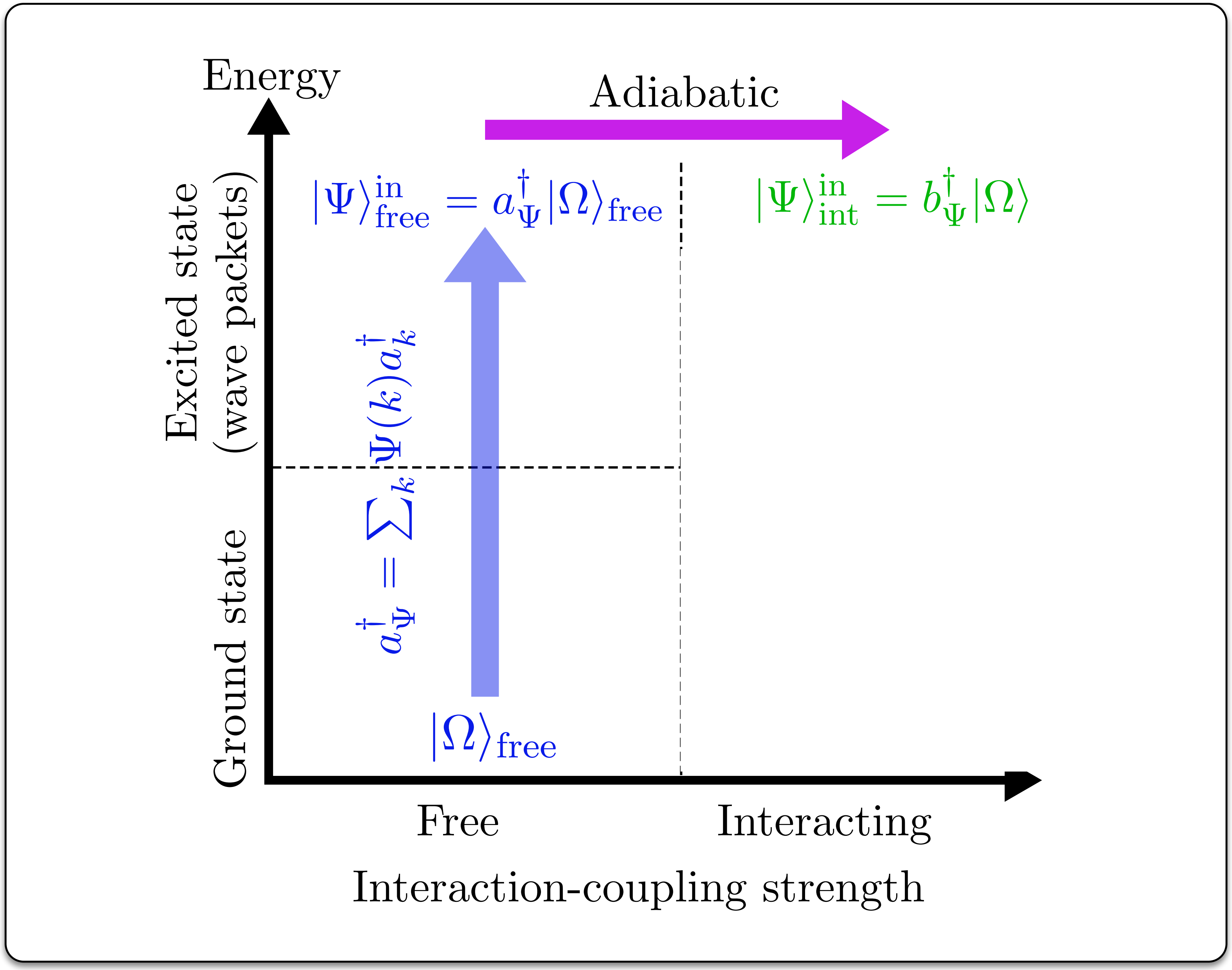
$t$
ZD, Hsieh, Kadam, arXiv:2505.20408 [quant-ph].
Hadron scattering in a (1+1)D U(1) quantum link model (IBM)
time $t\kappa$
site $j$
MPS
ibm_marrakesh
Particle occupation
electron
positron
occupation
central flux
ibm_marrakesh (mit.)
Schuhmacher, Su, Osborne, Gandon, Halimeh, Tavernelli, arXiv:2505.20387 [quant-ph].
Meson scattering in a $Z_2$ floquet system on a superconducting chip
QPU
Time, $T$
$h = \pi/8$
$h = \pi/4$
$\langle N_1 \rangle$
$\langle N_4 \rangle$
Wang et al, arXiv:2508.20759 [quant-ph].

# OUR STRATEGY COMPARED WITH JORDAN-LEE-PRESKILL



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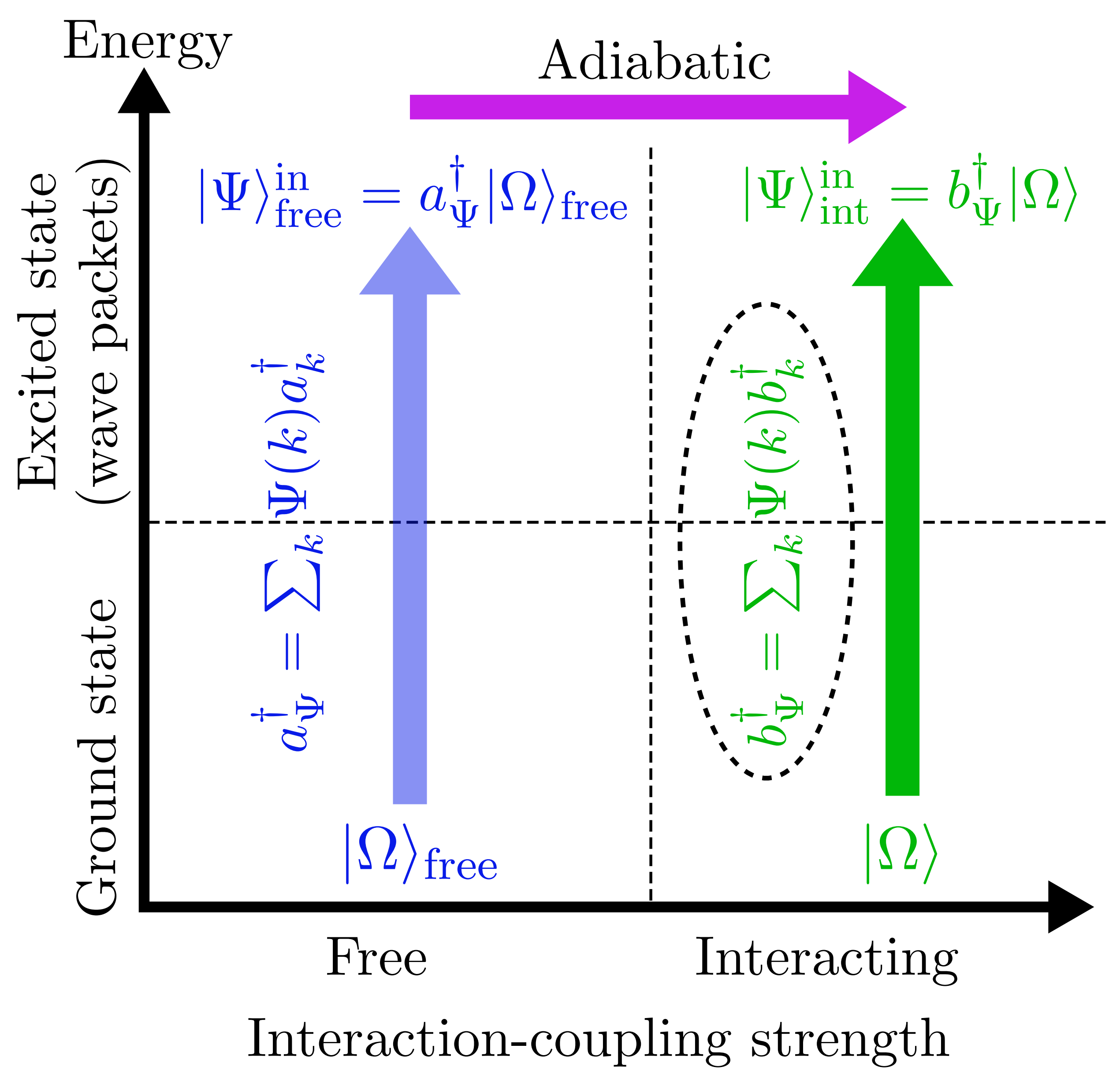



ZD, Hsieh, and Kadam, Quantum 8, 1520 (2024) and arXiv:2505.20408 [quant-ph].

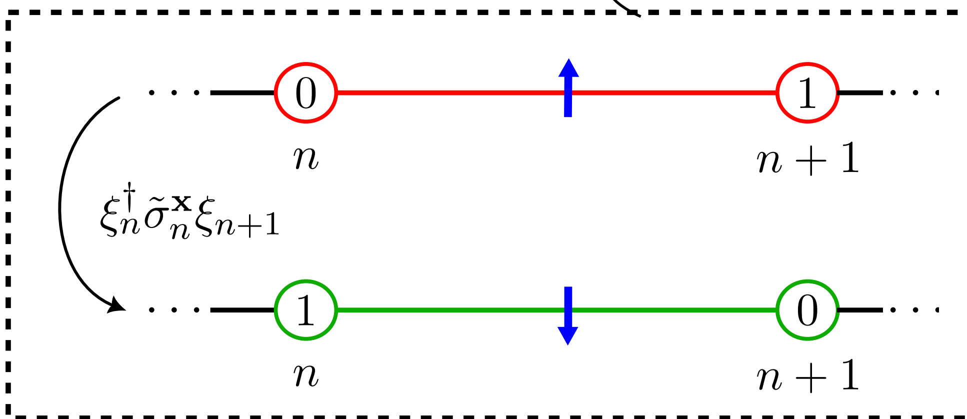
Beside Jordan, Lee, Preskill, Science 336, 1130-1133 (2012), check out other recent interesting digital algorithms for hadronic wave-packet creation in: Turco, Quinta, Seixas, and Omar, arXiv:2305.07692 [quant-ph], Kreshchuk, Vary, Love, arXiv:2310.13742 [quant-ph], Chai, Crippa, Jansen, Kühn, Pascuzzi, Tacchino, and Tavernelli, arXiv:2312.02272 [quant-ph], Farrell, Illa, Ciavarella, and Savage, arXiv:2401.08044 [quant-ph].

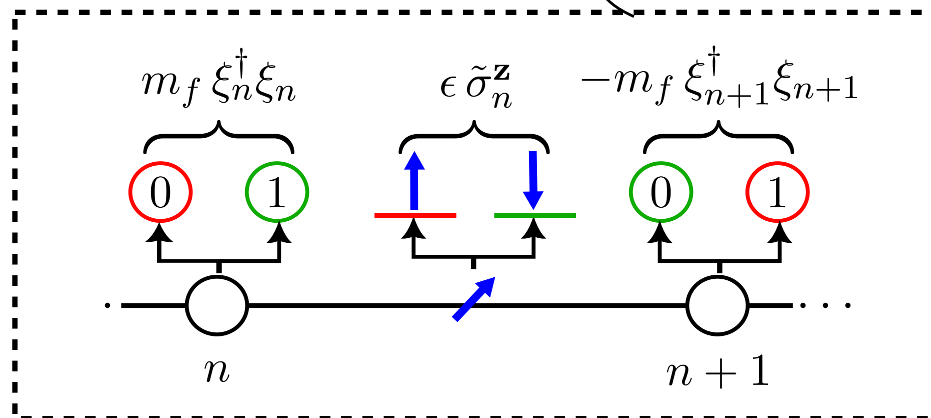
# OUR TESTING GROUND:
# $Z_2$ LATTICE GAUGE THEORY COUPLED TO FERMIONS IN 1+1 D

Hamiltonian: $$aH = \frac{1}{2}\sum_{n\in\Gamma}\left(\xi_n^\dagger \tilde{\sigma}_n^{\mathbf{x}} \xi_{n+a} + \text{H.c.}\right) + a m_f \sum_{n\in\Gamma} (-1)^{n/a} \xi_n^\dagger \xi_n + a\epsilon \sum_{n\in\Gamma} \tilde{\sigma}_n^{\mathbf{z}}$$

Fermions

Gauge bosons



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Fermions

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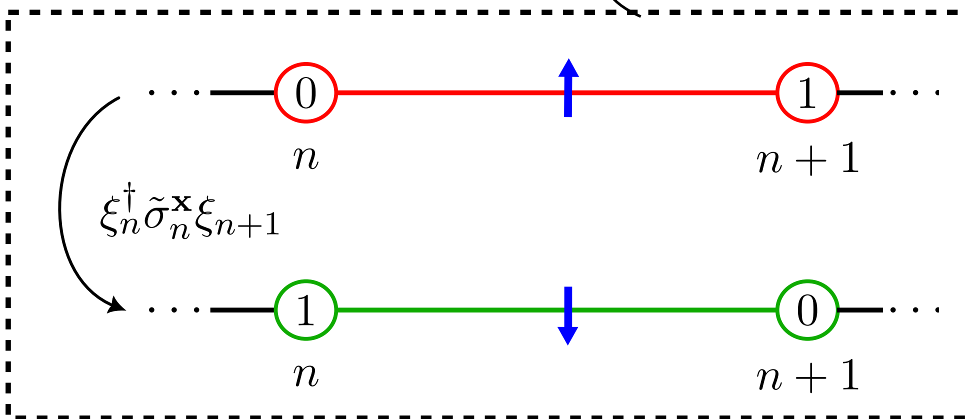
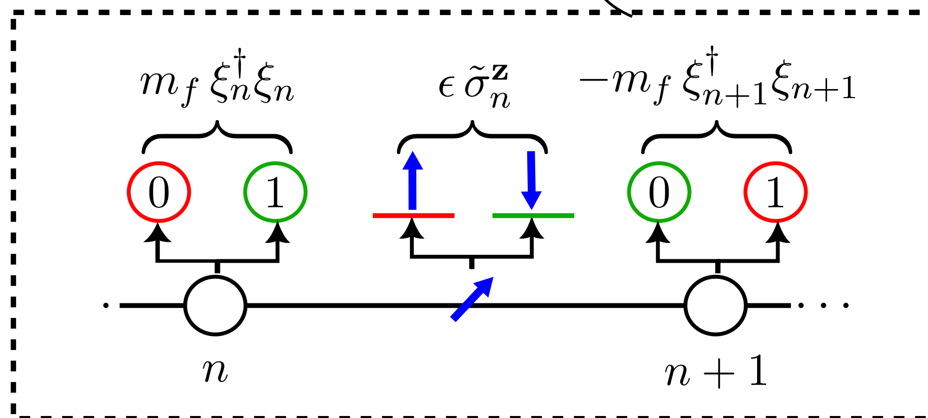
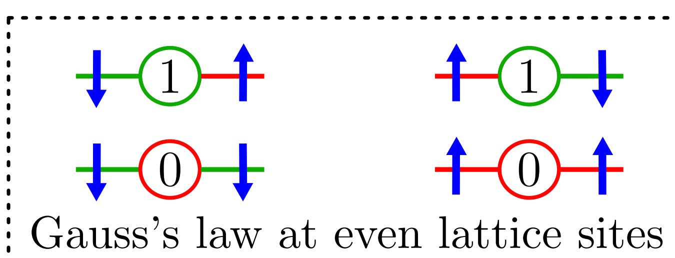
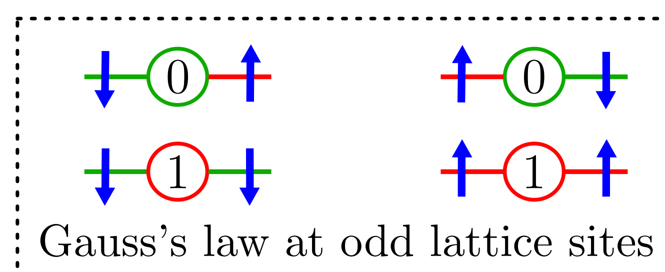


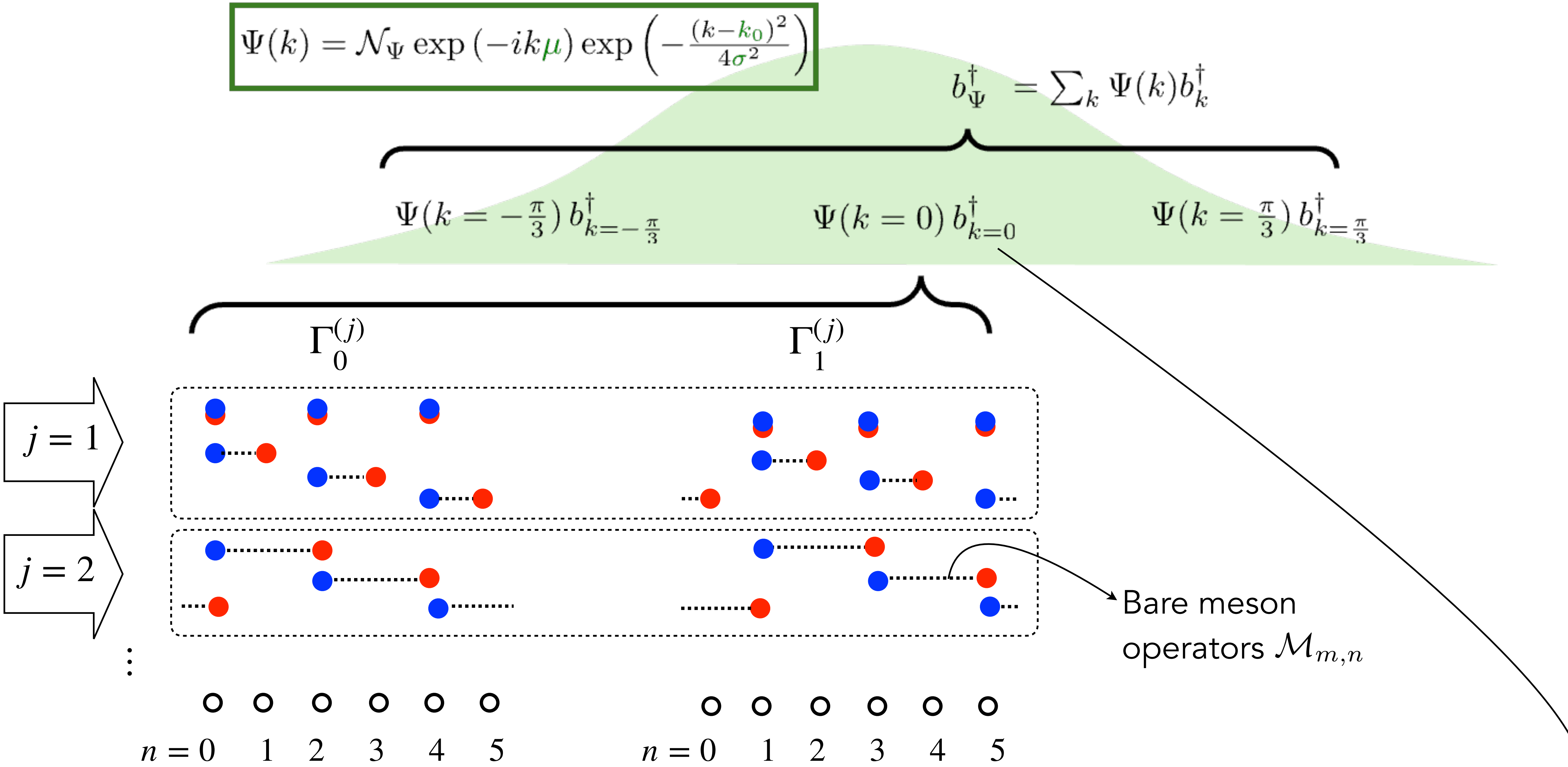




Gauss's law: $G_n \left|\psi_{\text{phys}}\right\rangle = g \left|\psi_{\text{phys}}\right\rangle \ \forall n$ with $G_n = \tilde{\sigma}^{\mathbf{z}} \tilde{\sigma}_{n-1}^{\mathbf{z}} e^{i\pi\left[\xi_n^\dagger \xi_n - \frac{1-(-1)^n}{2}\right]}$



# AN ANSATZ FOR THE MESON WAVE PACKET



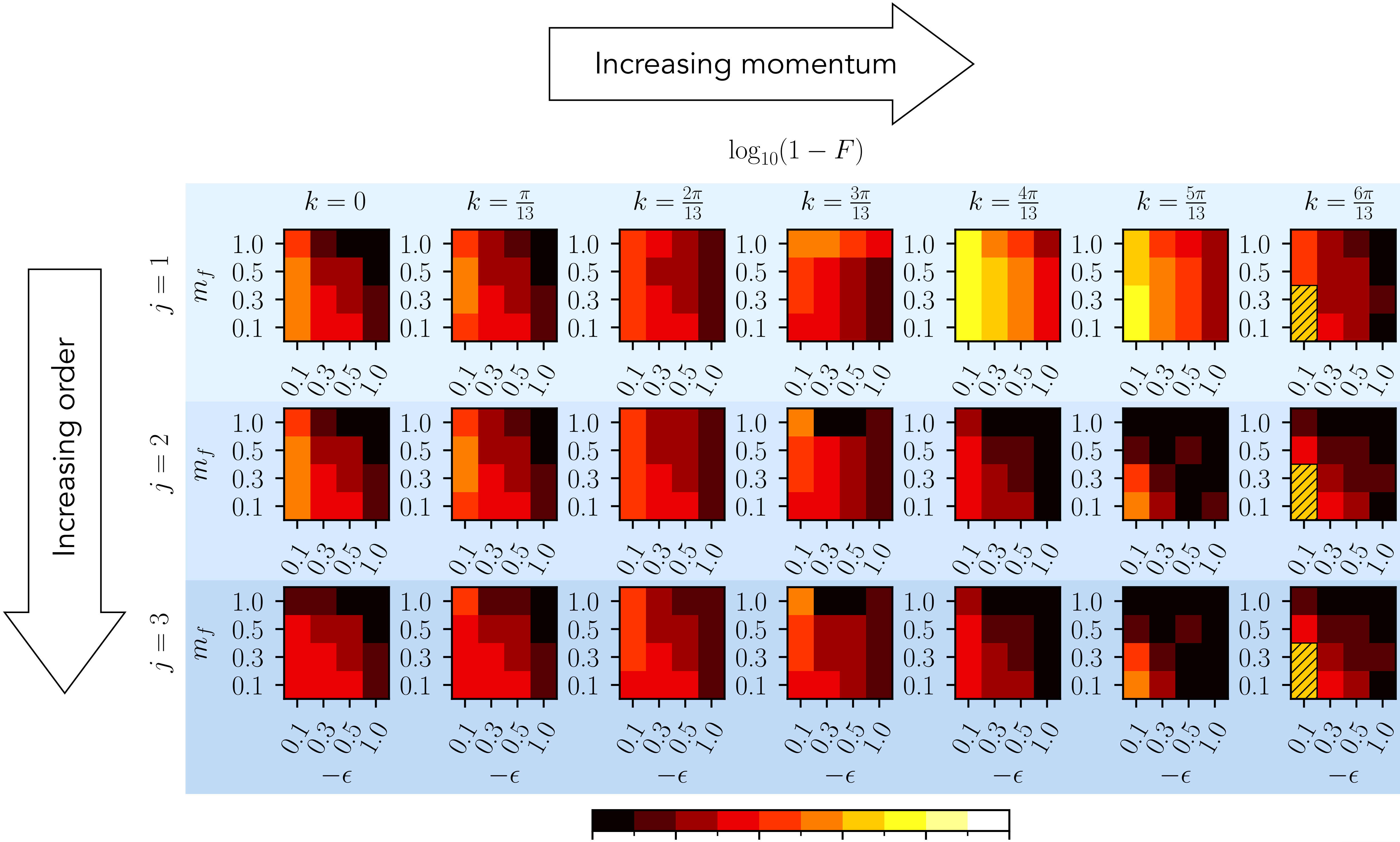

Single-particle $k$-momentum meson creation operator:

$$b_k^{(j)\dagger} = \sum_{j'=0}^{j} \sum_{m,n\in\Gamma^{(j')}} C^{(j'),k}_{m,n} \mathcal{M}_{m,n}$$

Coefficients such that short bare mesons are favored:

$$C^{(j),k}_{m,n} = \frac{1}{\mathcal{N}} e^{-\alpha_i^{(j),k}|m-n|^2} \overline{C}^k_{m,n} \quad \text{for} \quad m,n \in \Gamma_i^{(j)}$$

# HOW WELL DOES THE ANSATZ WORK?

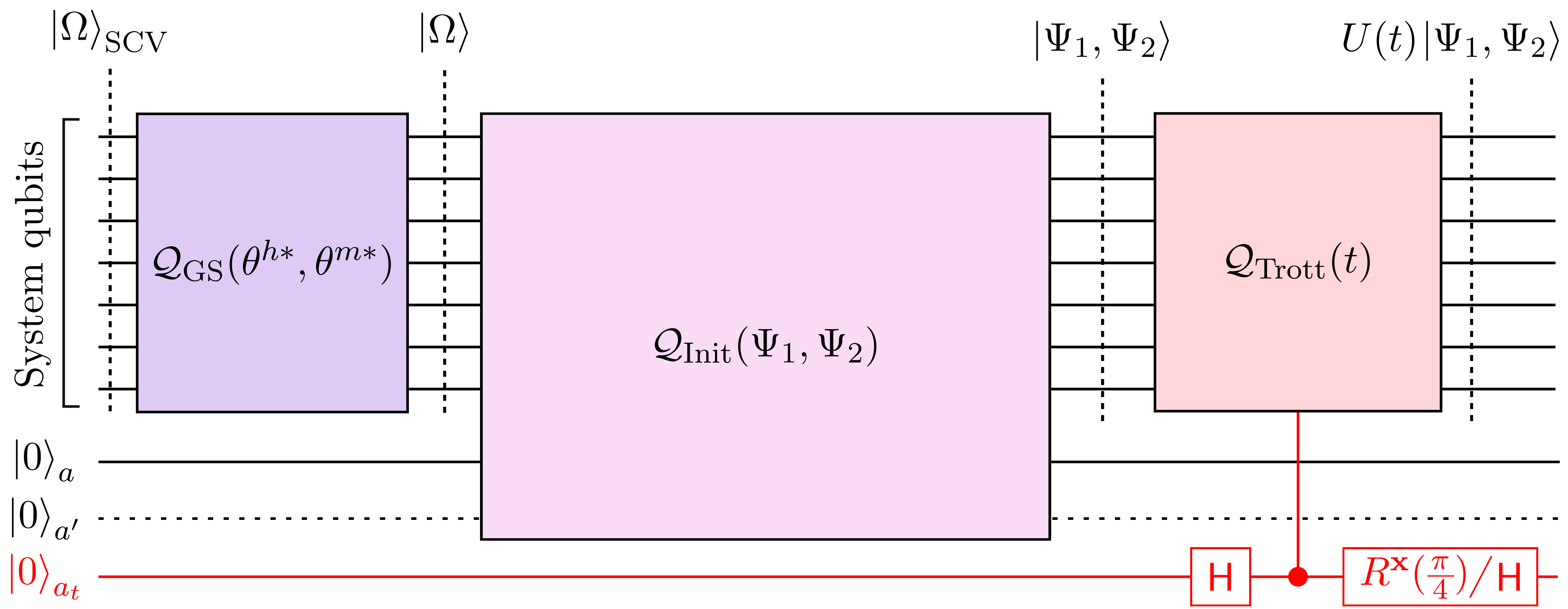



$N = 26$

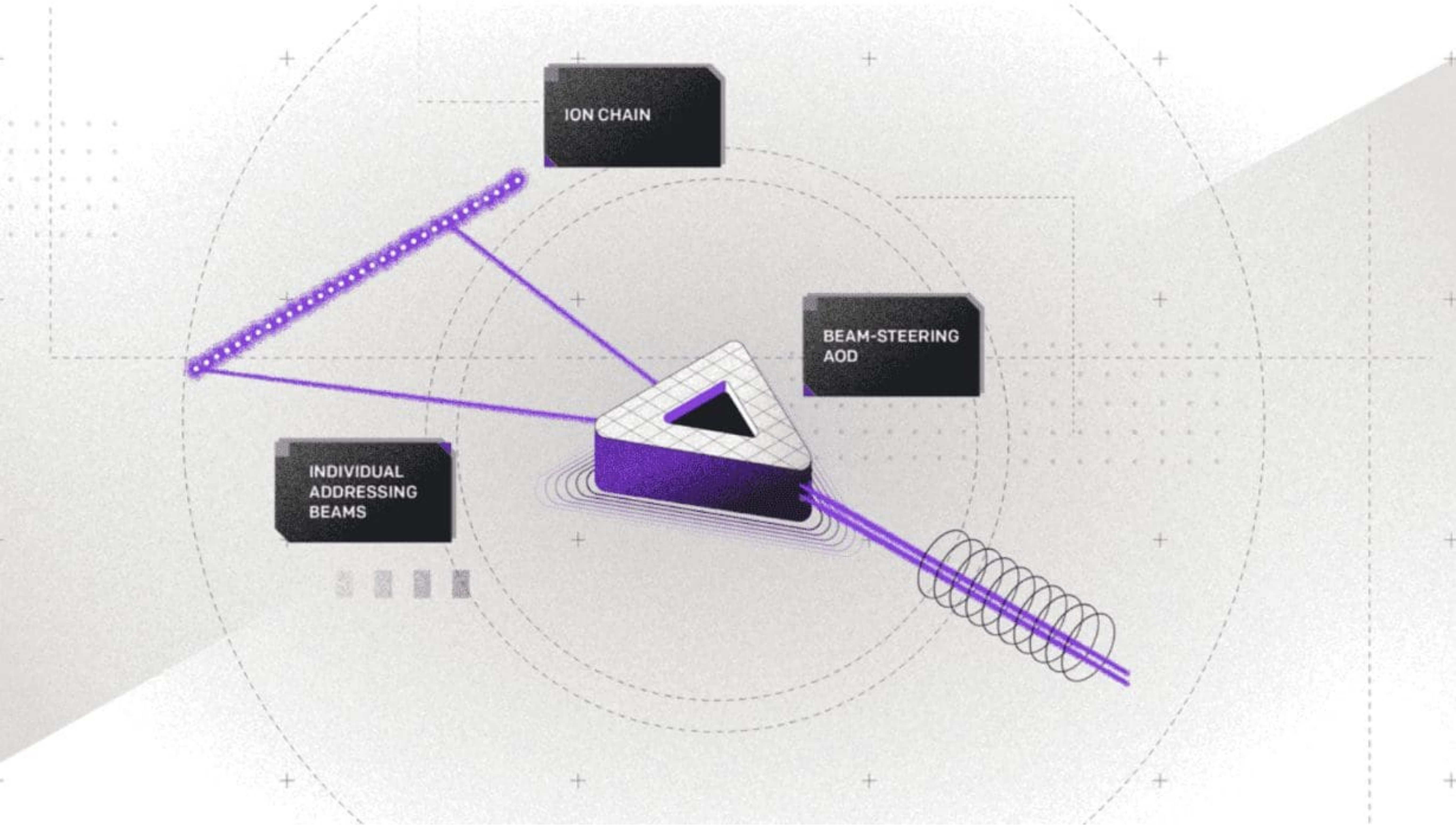
Fidelities are measured by comparing to MPS results.

ZD, Hsieh, and Kadam, arXiv:2402.00840 [quant-ph].

# OUR QUANTUM CIRCUIT FOR HADRON SCATTERING

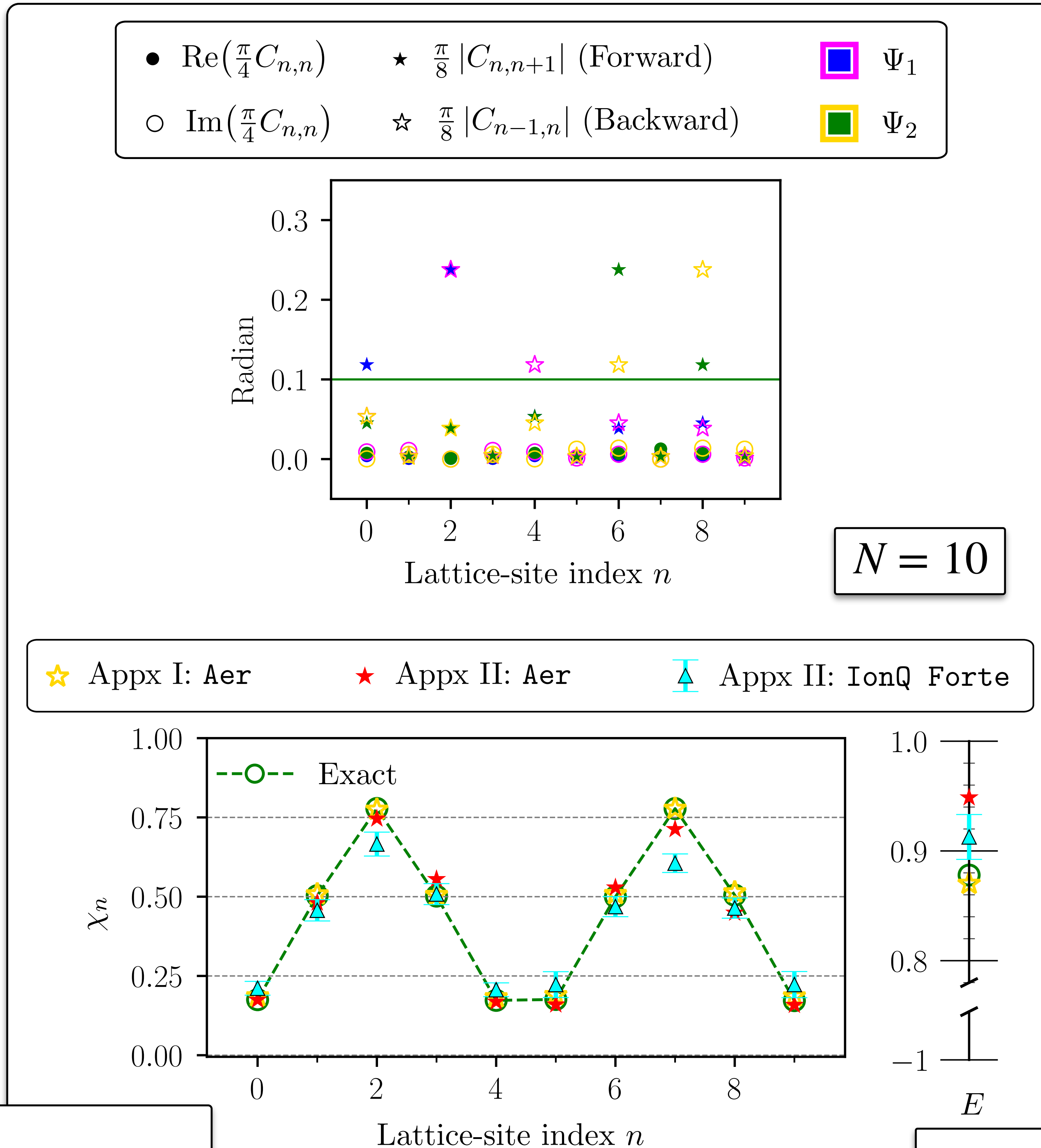


# SOME EMULATOR AND HARDWARE RESULTS




IonQ Forte quantum processor with 32 qubits

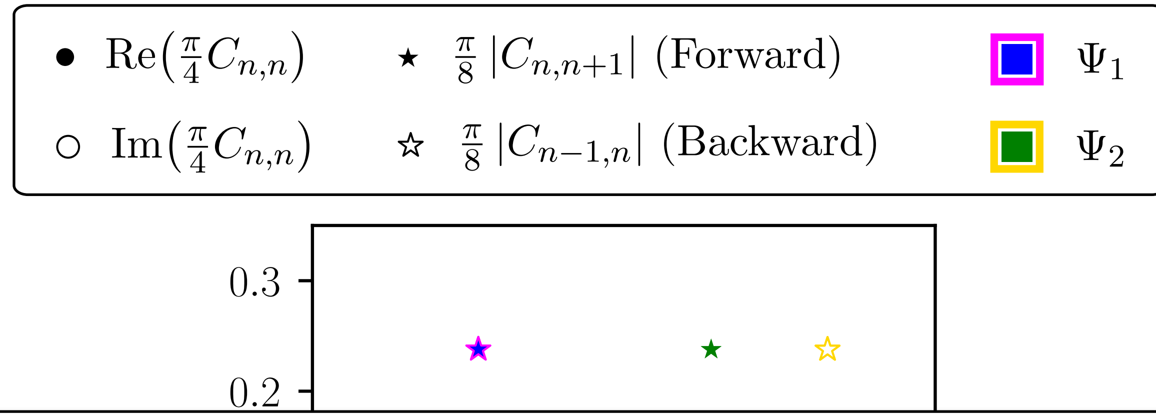
# HOW WELL CAN WE PREPARE TWO WAVE PACKETS?



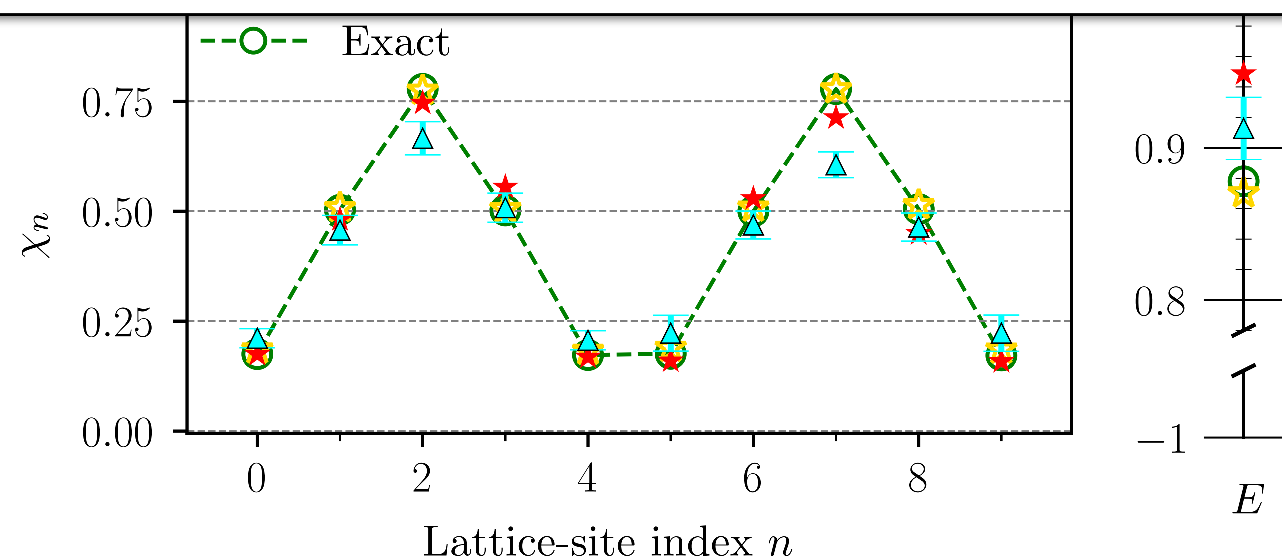

$$\chi_n = \begin{cases} \langle \psi_n^\dagger \psi_n \rangle & \text{if} \quad n \in \text{even}, \\ 1 - \langle \psi_n^\dagger \psi_n \rangle & \text{if} \quad n \in \text{odd} \end{cases}$$

$$E = \langle \tilde{\sigma}^{\mathbf{z}} \rangle$$

# HOW WELL CAN WE PREPARE TWO WAVE PACKETS?




| $N_P$ | Appx | Qubits | Single-qubit gates (raw/transpiled) | CNOT gates (raw/transpiled) |
|---|---|---|---|---|
| 5 | I | 13 | 12757/13343 | 11324/7315 |
| | II | 12 | 310/369 | 236/167 |



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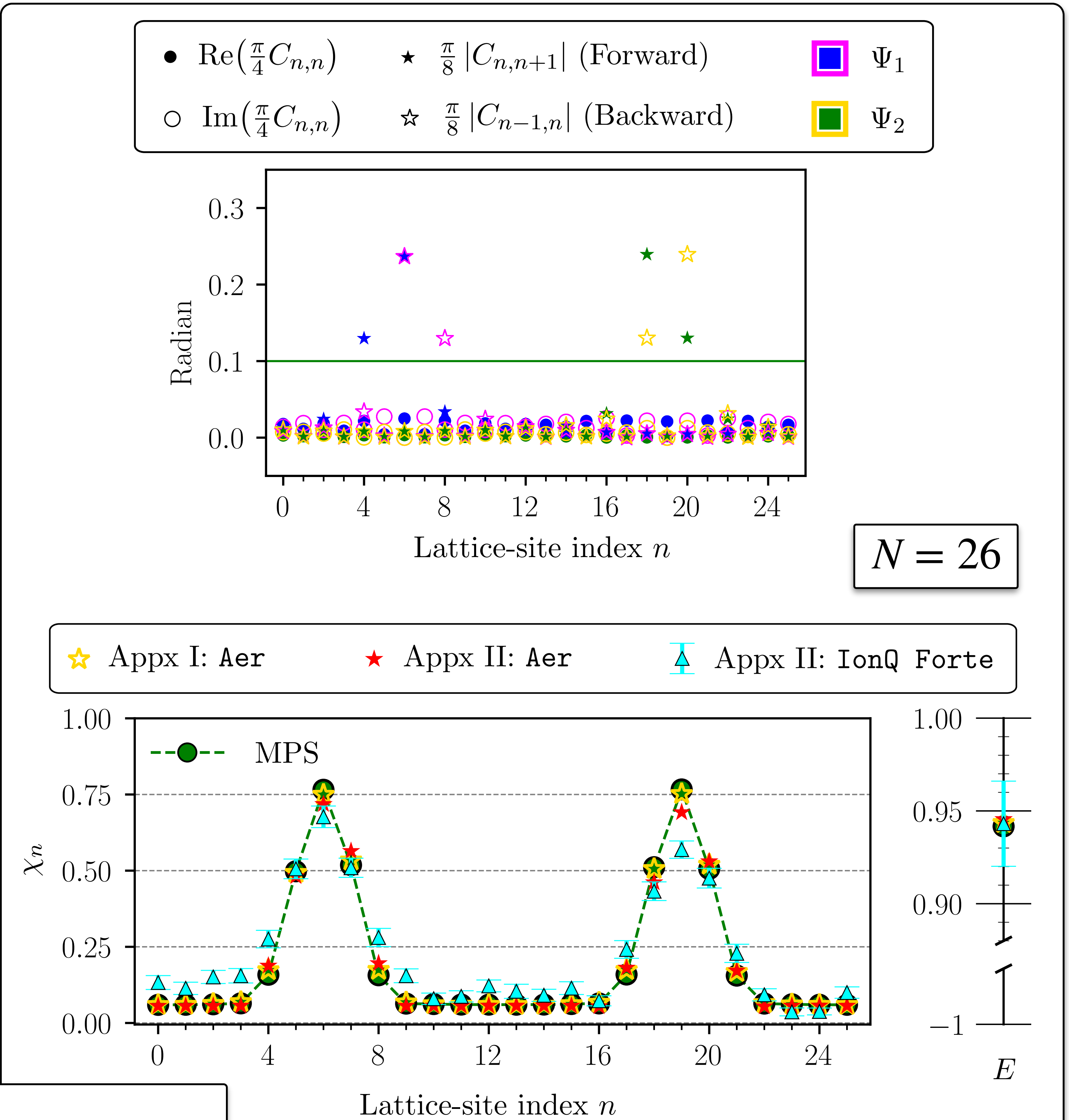
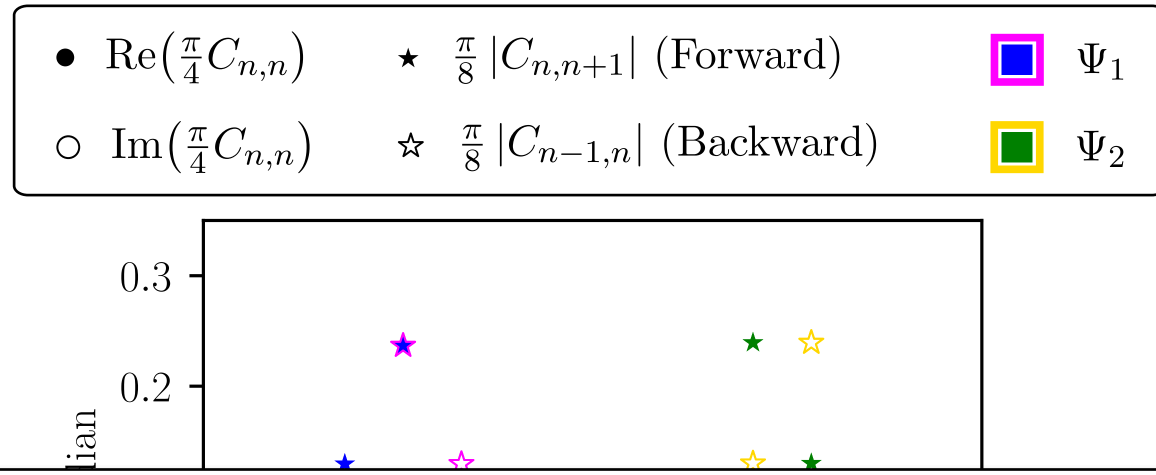


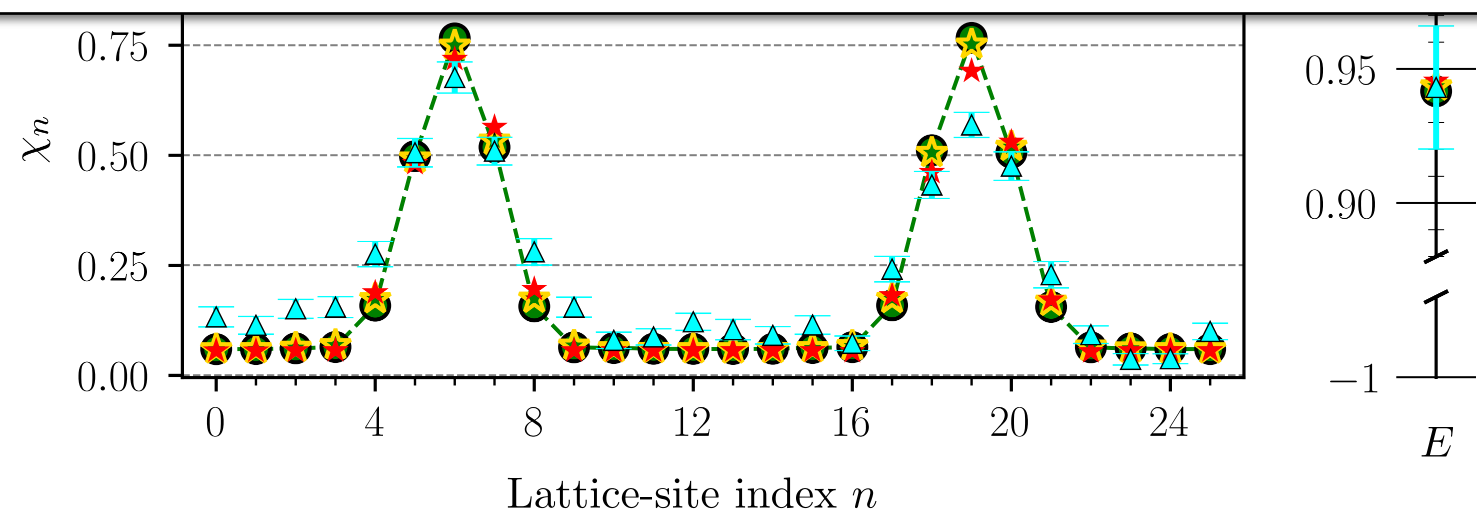

$$\chi_n = \begin{cases} \langle \psi_n^\dagger \psi_n \rangle & \text{if} \quad n \in \text{even}, \\ 1 - \langle \psi_n^\dagger \psi_n \rangle & \text{if} \quad n \in \text{odd} \end{cases}$$

$$E = \langle \tilde{\sigma}^{\mathbf{z}} \rangle$$

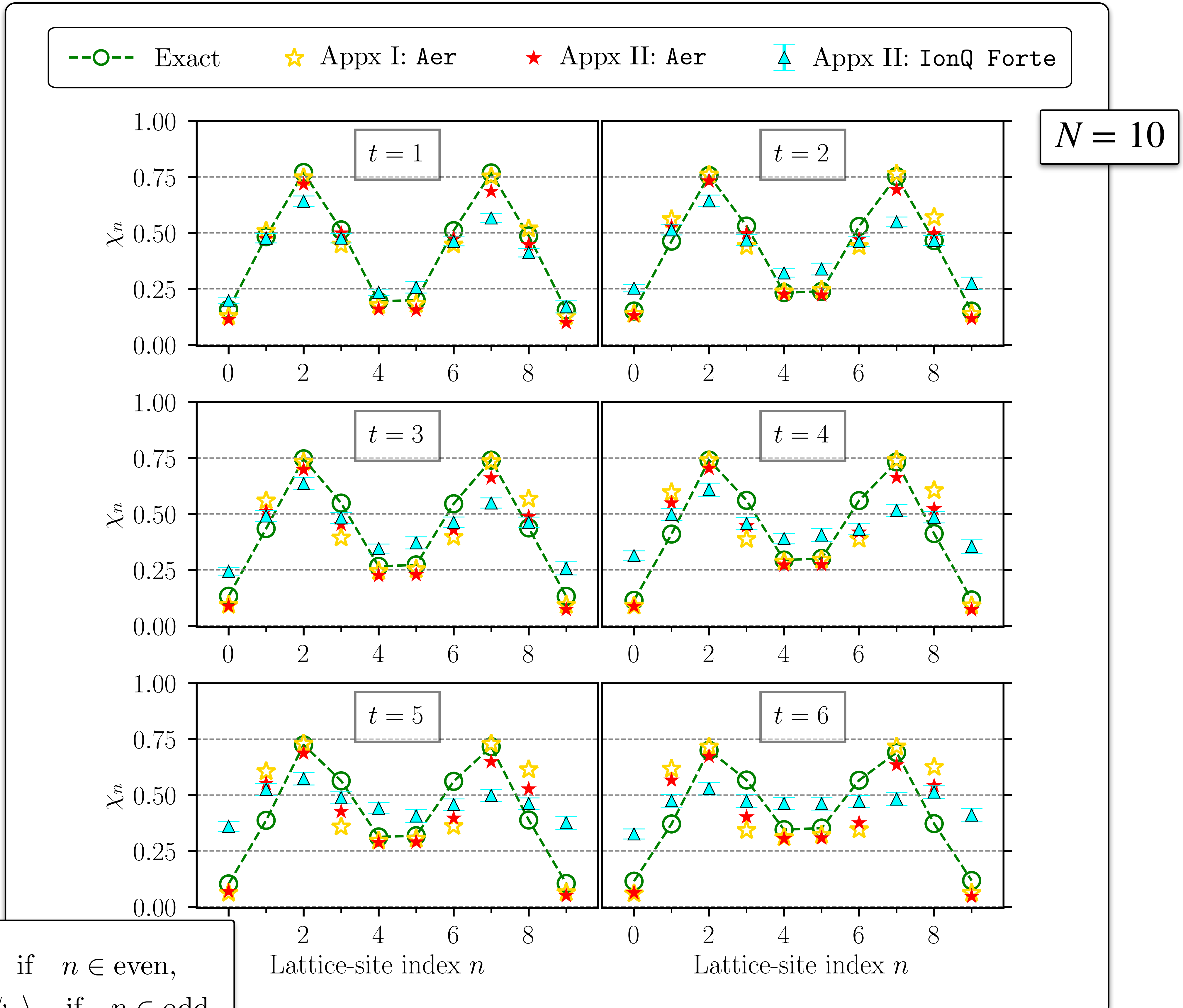
HOW WELL CAN WE PREPARE TWO WAVE PACKETS?




| $N_P$ | Appx | Qubits | Single-qubit gates (raw/transpiled) | CNOT gates (raw/transpiled) |
|---|---|---|---|---|
| 13 | I | 29 | 6925/7660 | 5948/3934 |
| | II | 28 | 494/572 | 300/197 |



# HOW FAR CAN WE EVOLVE THE TWO WAVE PACKETS?

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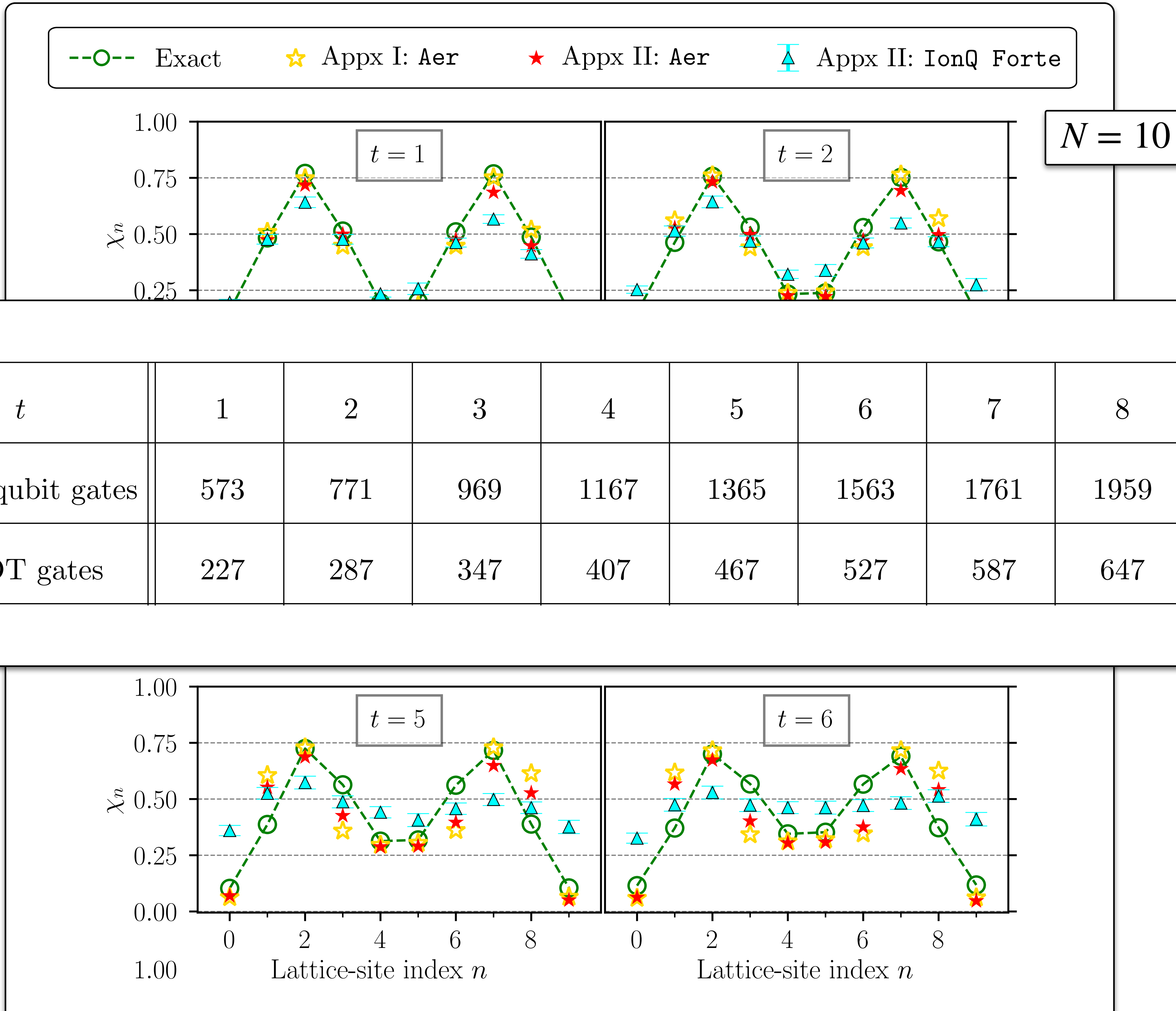
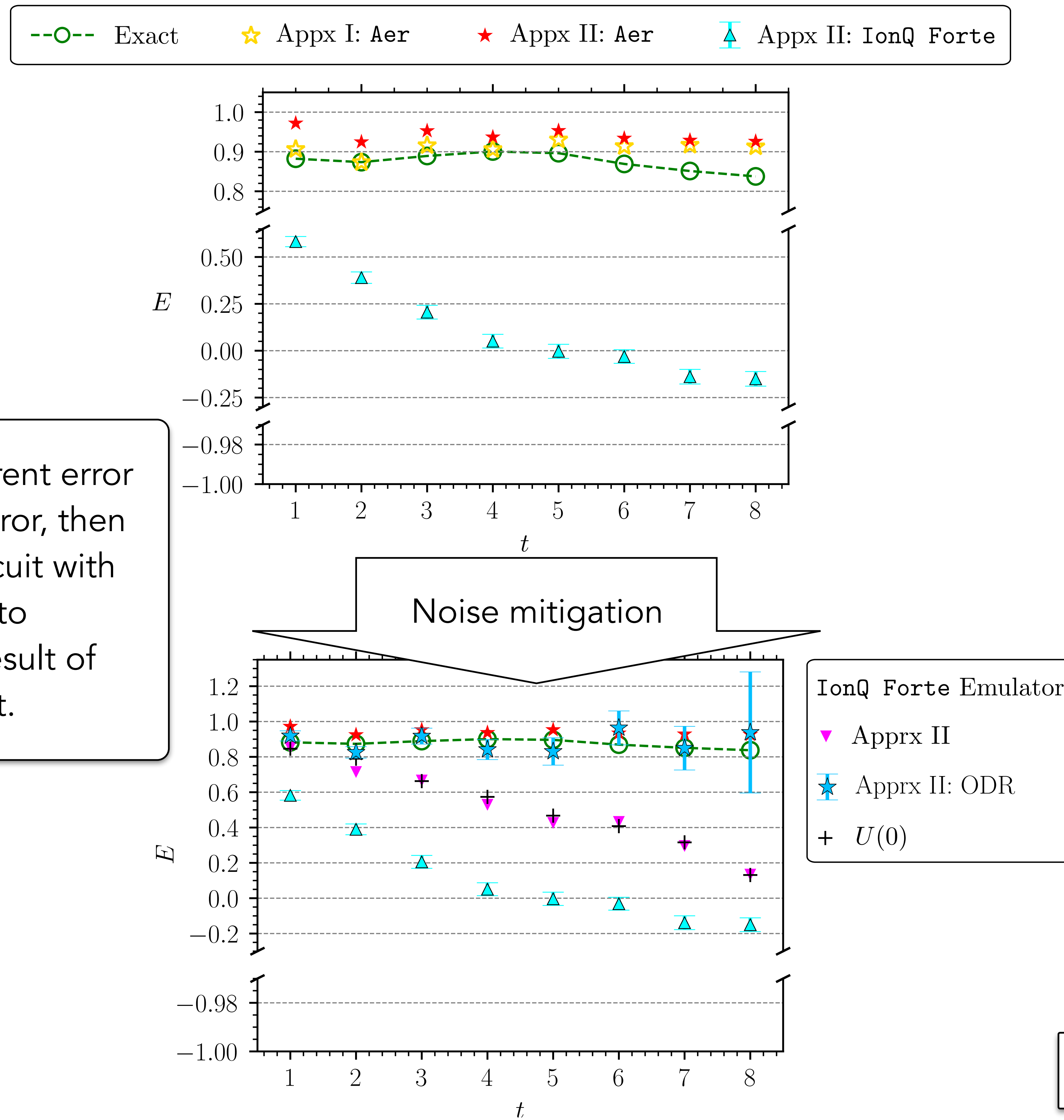



| $t$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Single-qubit gates | 573 | 771 | 969 | 1167 | 1365 | 1563 | 1761 | 1959 |
| CNOT gates | 227 | 287 | 347 | 407 | 467 | 527 | 587 | 647 |

# HOW FAR CAN WE EVOLVE THE TWO WAVE PACKETS?

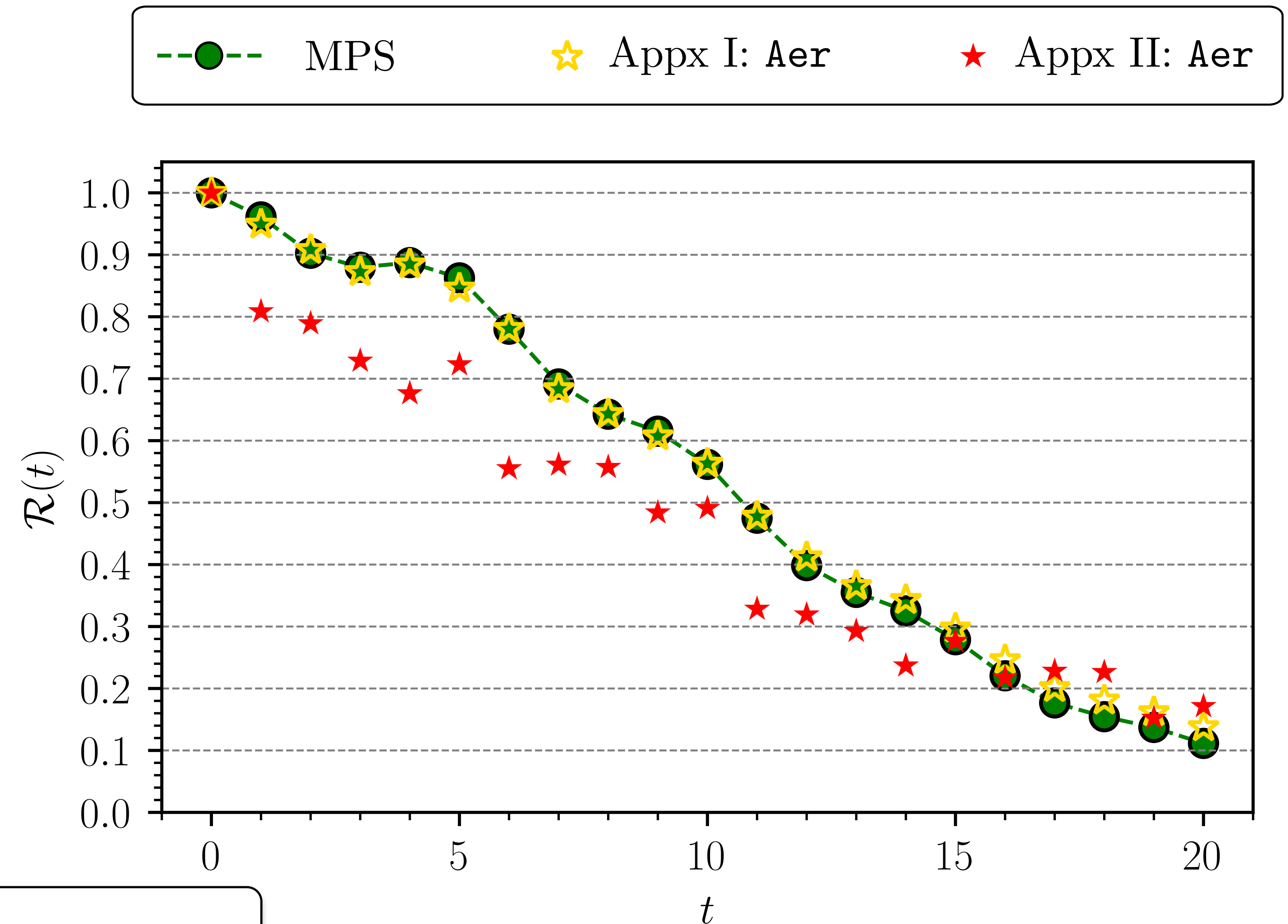



$N = 10$

* Turn the coherent error to incoherent error, then use a similar circuit with known solution to normalize the result of the target circuit.

$E = \langle \tilde{\sigma}^{\mathbf{z}} \rangle$

# WHAT ABOUT RETURN PROBABILITY (A DIAGONAL ENTRY OF S-MATRIX)?




$N = 26$

$$\mathcal{R}(t) := |\mathcal{A}(t)|^2$$

$$\mathcal{A}(t) := \langle \Psi_1, \Psi_2 | U(t) | \Psi_1, \Psi_2 \rangle$$

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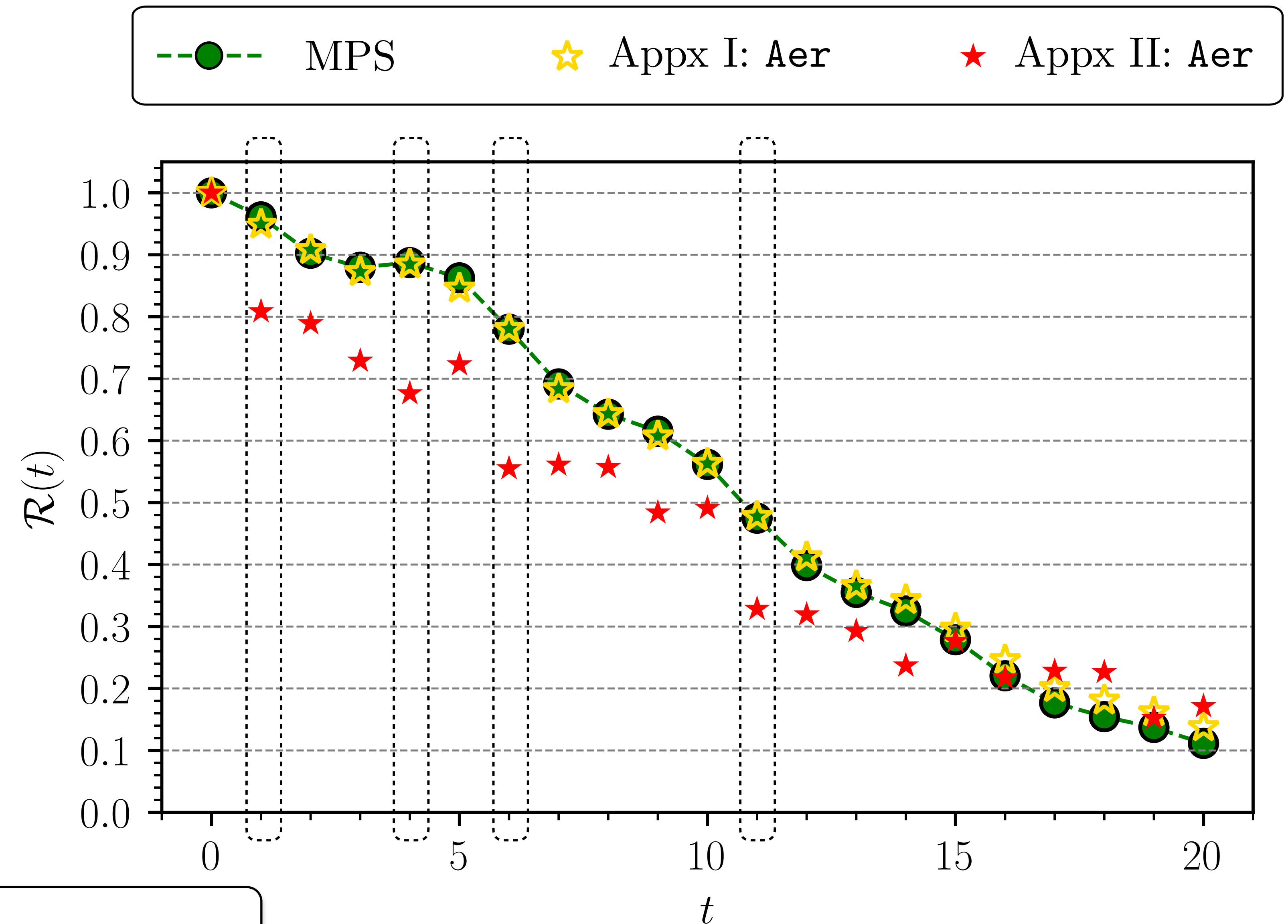


$N = 26$

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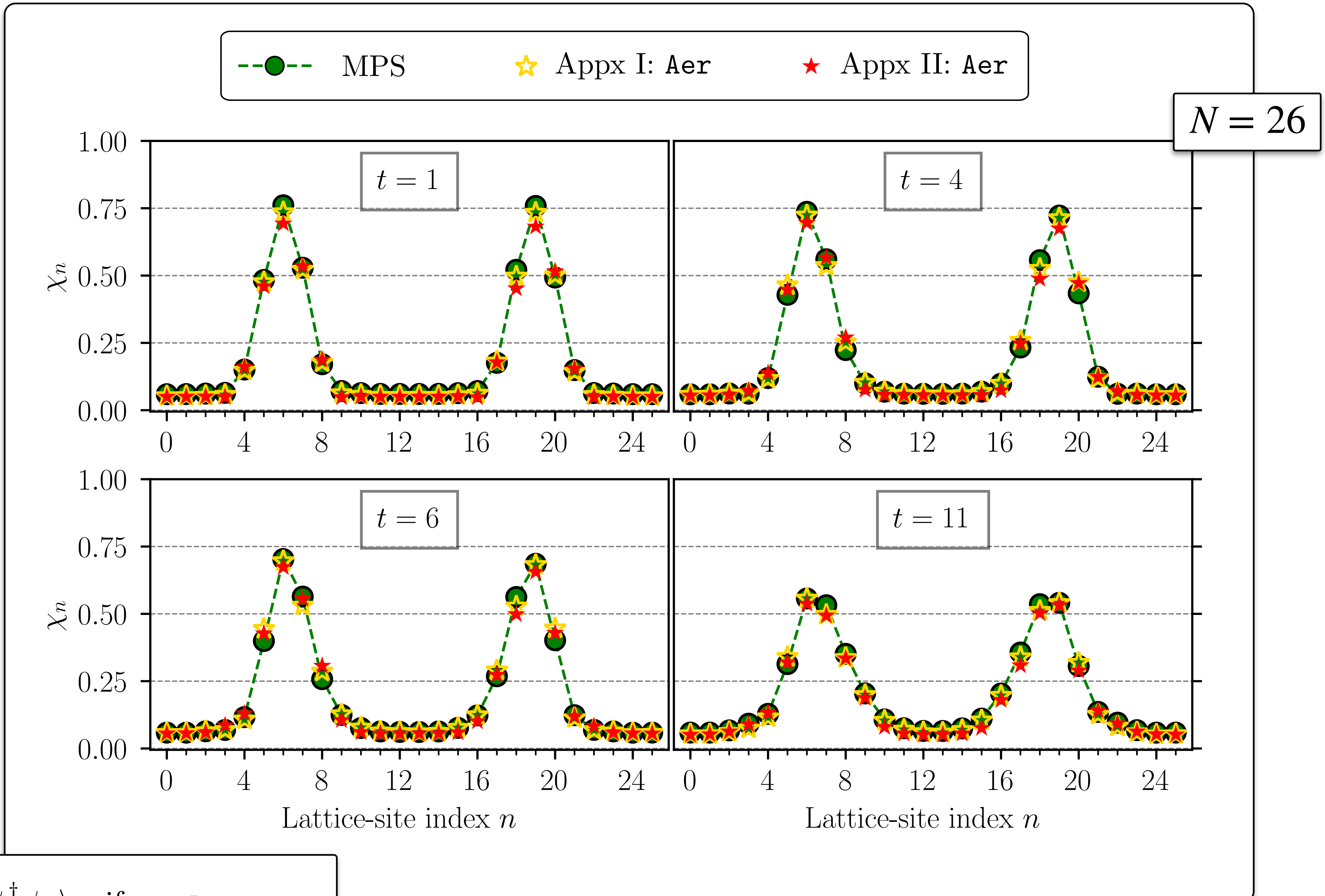
$$\mathcal{A}(t) := \langle \Psi_1, \Psi_2 | U(t) | \Psi_1, \Psi_2 \rangle$$

# WHAT ABOUT LOCAL QUANTITIES AT TIMES $\mathcal{R}(t)$ DEVIATES?




$$\chi_n = \begin{cases} \langle \psi_n^\dagger \psi_n \rangle & \text{if} \quad n \in \text{even}, \\ 1 - \langle \psi_n^\dagger \psi_n \rangle & \text{if} \quad n \in \text{odd} \end{cases}$$

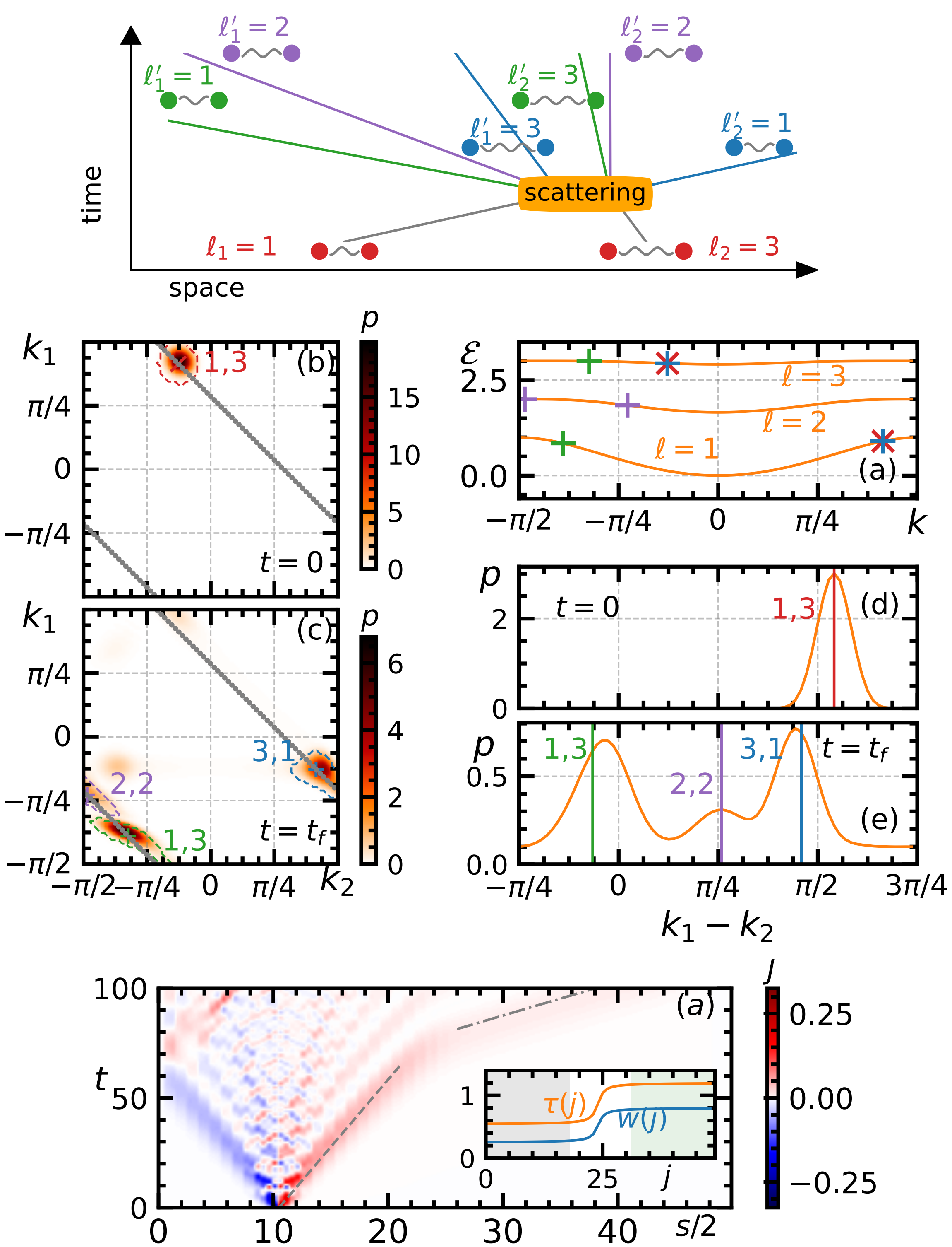
PART 0:
MOTIVATION: FIRST-PRINCIPLES SIMULATIONS OF SCATTERING

PART I:
BASIC ELEMENTS OF QUANTUM SIMULATION OF SCATTERING

PART II:
TOWARD DIGITAL QUANTUM SIMULATIONS OF SCATTERING

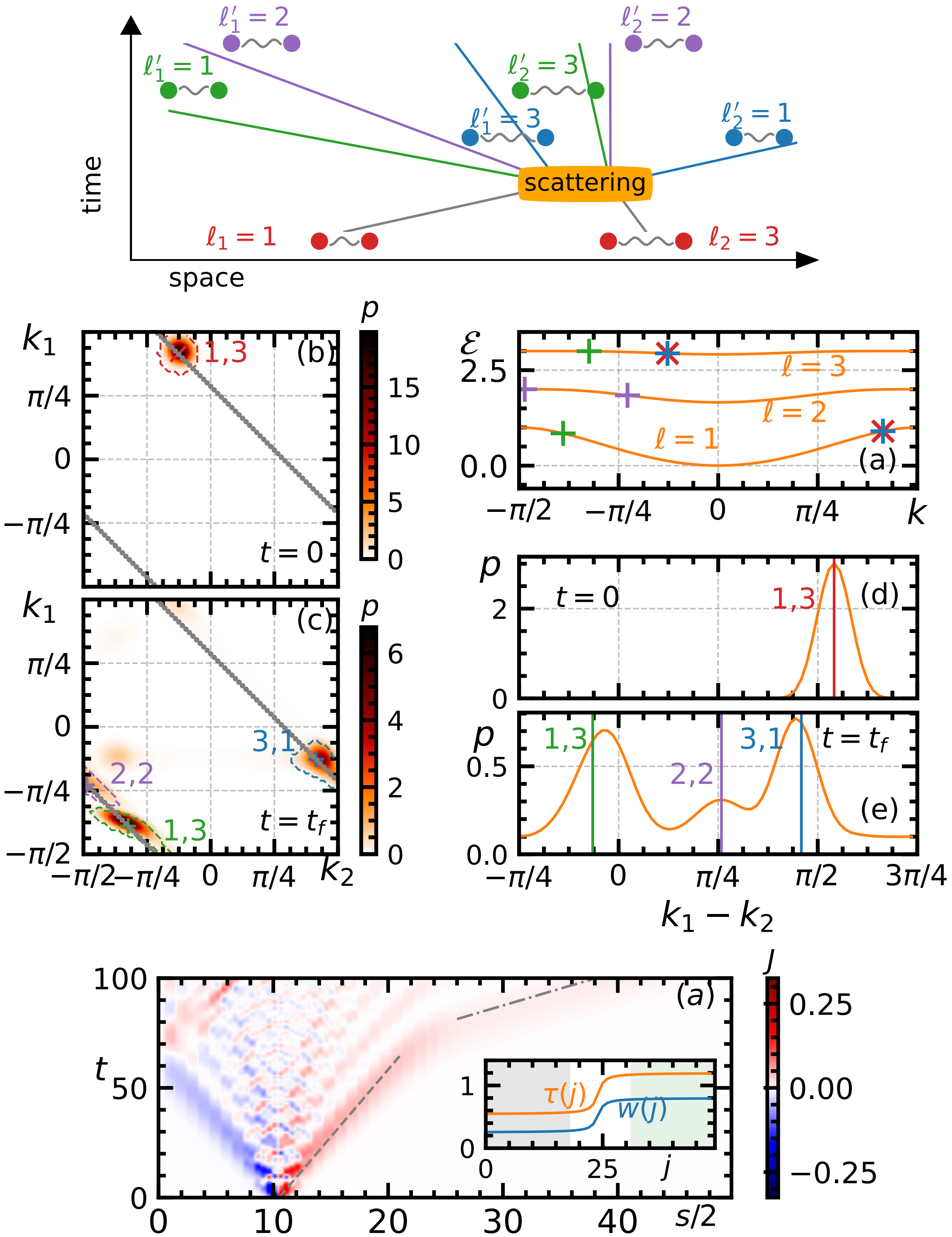
## PART III:
## TOWARD ANALOG QUANTUM SIMULATIONS OF SCATTERING

A cold-atom simulation proposal for scattering in an Ising model with a $Z_2$ LGT dual



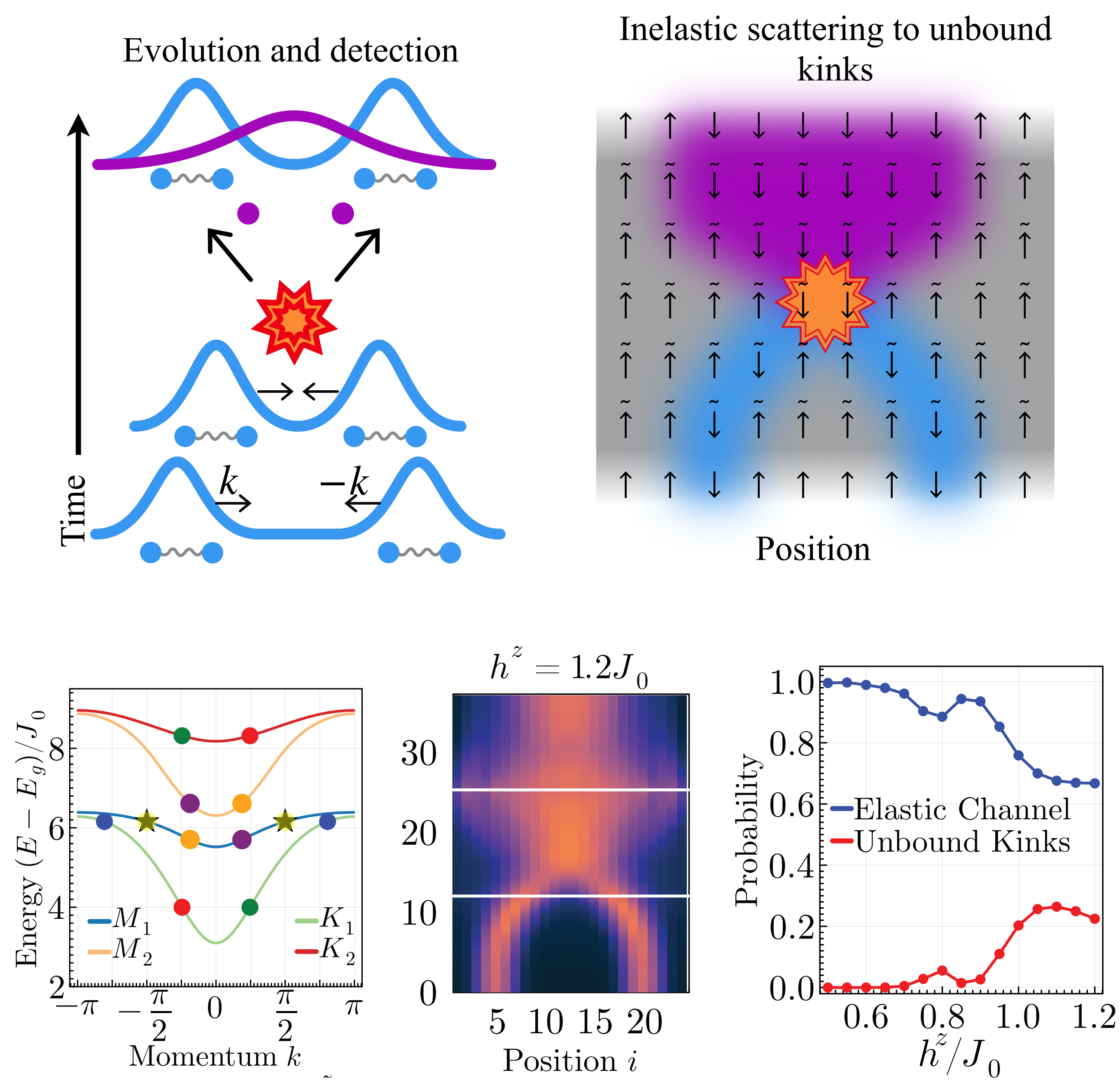

Surace and Lerose, New J. Phys. 23, 062001 (2021).

A cold-atom simulation proposal for scattering in an Ising model with a $Z_2$ LGT dual




Surace and Lerose, New J. Phys. 23, 062001 (2021).

A trapped-ion simulation proposal for scattering in an Ising model with a $Z_2$ LGT dual

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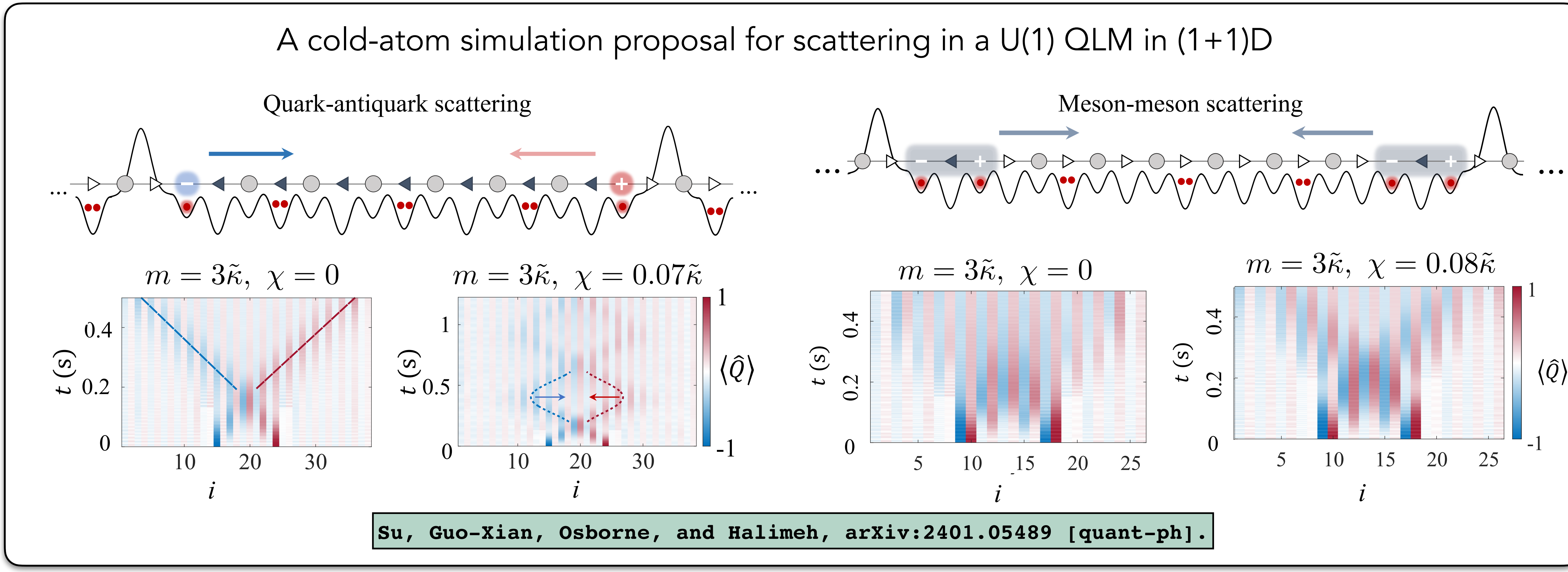
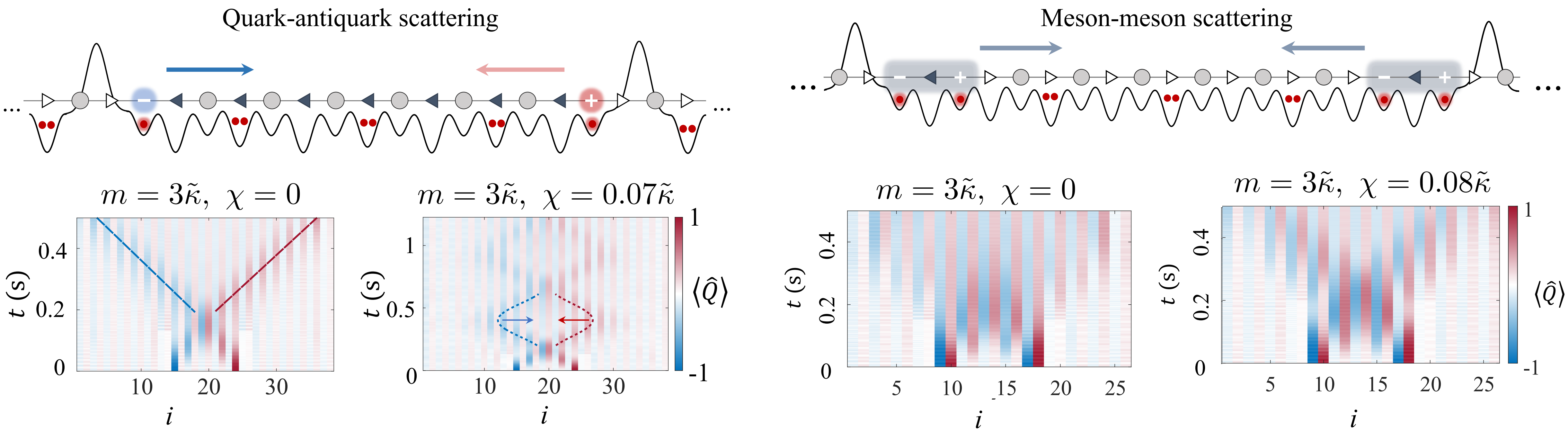
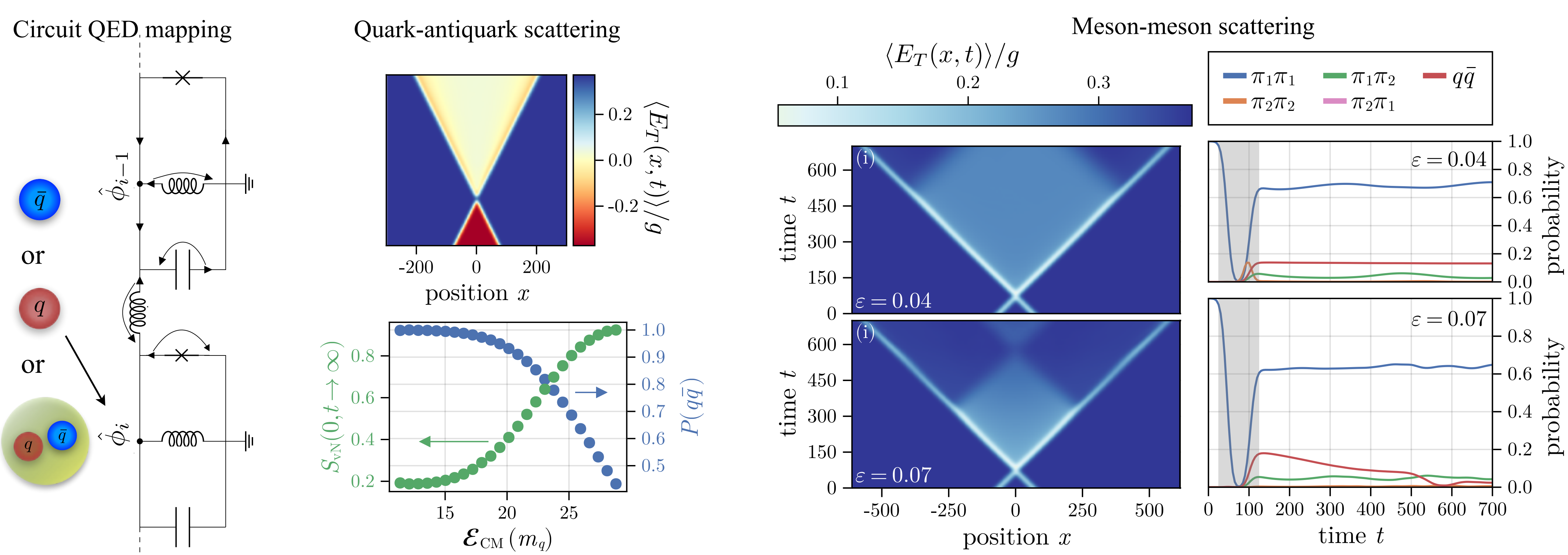

A cold-atom simulation proposal for scattering in a U(1) QLM in (1+1)D
Quark-antiquark scattering
Meson-meson scattering
m = 3κ̃, χ = 0
m = 3κ̃, χ = 0.07κ̃
m = 3κ̃, χ = 0
m = 3κ̃, χ = 0.08κ̃
t (s)
i
⟨Q̂⟩
Su, Guo-Xian, Osborne, and Halimeh, arXiv:2401.05489 [quant-ph].

## A cold-atom simulation proposal for scattering in a U(1) QLM in (1+1)D




Su, Guo-Xian, Osborne, and Halimeh, arXiv:2401.05489 [quant-ph].

## A circuit-QED simulation proposal for scattering in the Schwinger model

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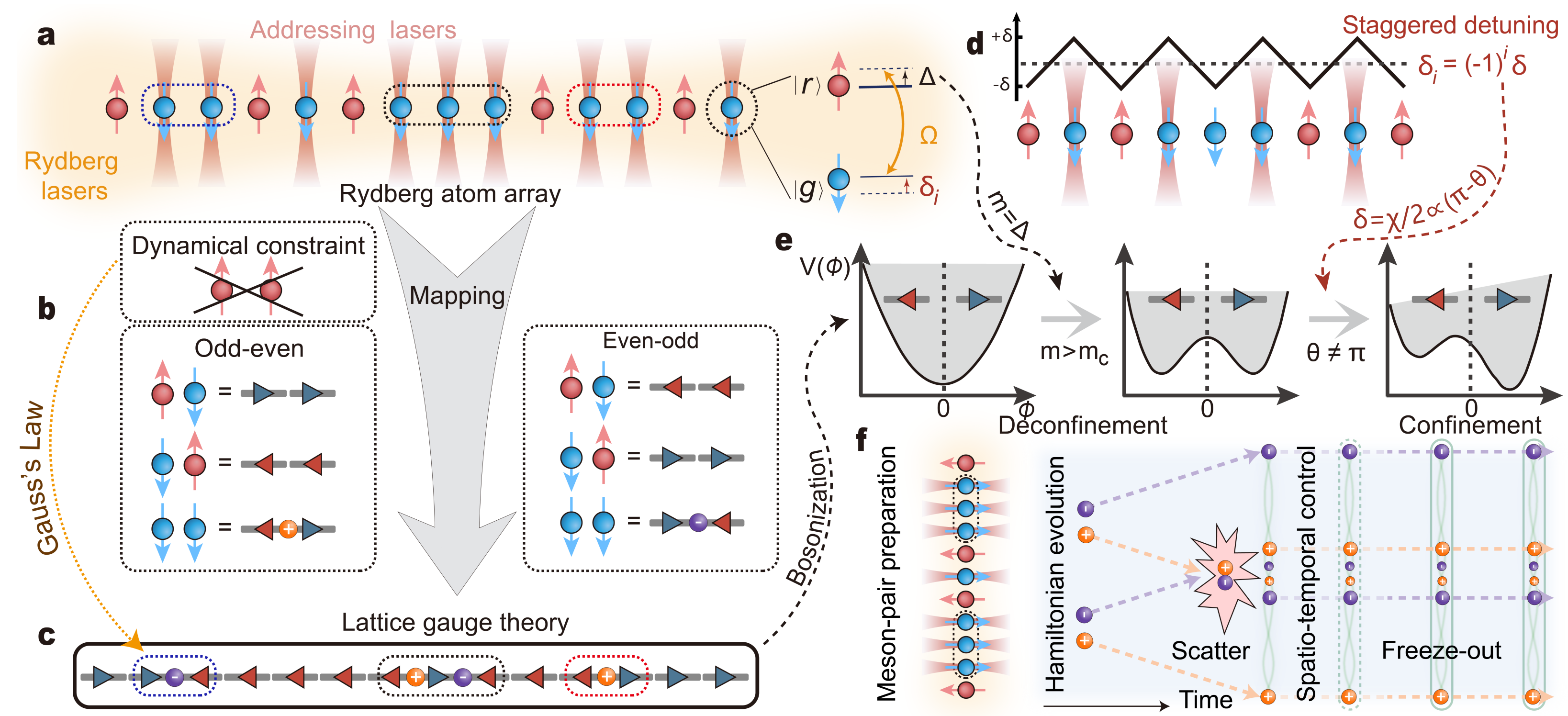
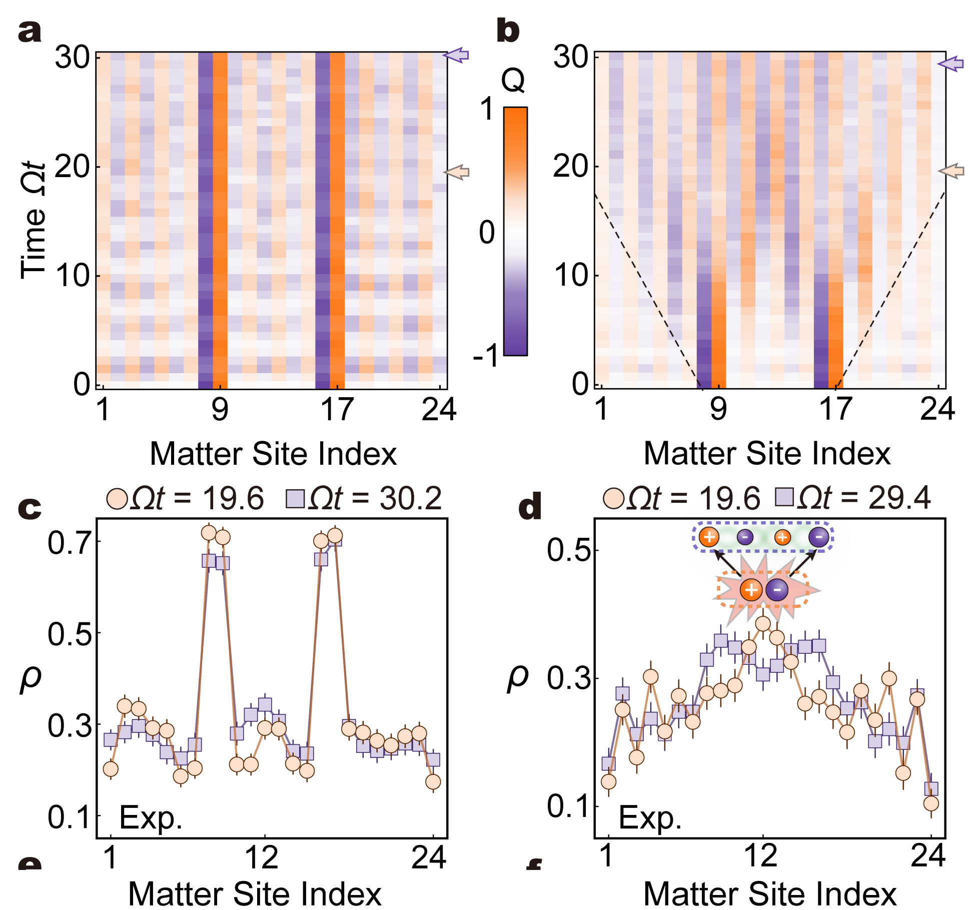
# A Rydberg-atom quantum simulation of scattering in the (1+1)D U(1) QLM

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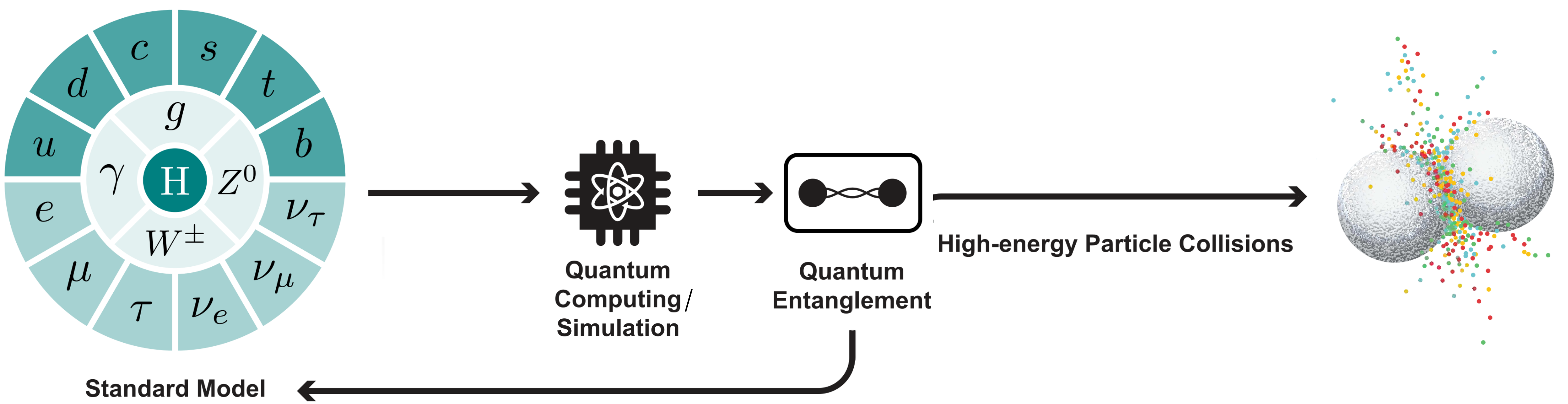
FIRST-PRINCIPLES PREDICTIONS FOR SCATTERING PROCESSES: QUANTUM SIMULATIONS? **YES! GAME IS ON BUT LONG WAY TO GO!**

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Check out our recent review:
Halimeh, Mueller, Knolle, Papić, ZD, “Quantum simulation of out-of-equilibrium dynamics in gauge theories”, arXiv:2509.03586 [quant-ph].

THANK YOU