Analog Quantum Simulation of String Breaking and Meson Scattering

Theory: Alessio Lerose, Federica Surace, Brayden Wave, Ron Belyansky, Alex Schuckert, Zohreh Davoudi, Alexey Gorshkov
Experimental: Arinjoy De, Henry Luo, Will Morong, Kate Collins, Or Katz, Chris Monroe

Observation of string-breaking dynamics in a quantum simulator. arXiv:2410.13815 (2024)
Simulating meson scattering on spin quantum simulators. arXiv:2403.07061 (2024).
String-Breaking Dynamics in Quantum Adiabatic and Diabatic Processes. arXiv:2411.10652 (2024)
Crossing the string-breaking discontinuous transition in a quantum simulator, work in progress (2025)

Elizabeth R. Bennewitz - University of Maryland, College Park
January 15, 2025

UNIVERSITY OF MARYLAND

Progress towards quantum simulation of fundamental forces

Many static and dynamical properties of matter arise from underlying fundamental quantum fields in the Standard Model that are hard to simulate classically

Near-term work (*this work):

- Given today’s (or tomorrow’s) experimental resources, what can we do?
- Use simple 1+1D spin models that share salient features with gauge theories
- Real-time dynamics, Non-equilibrium physics
- Quantum-many body physics

This work: Spin systems with confinement

Far-term work:

- Simulating gauge theories in the Standard Model or nuclear effective field theories on fault-tolerant quantum computers
- Algorithm development and resource estimation

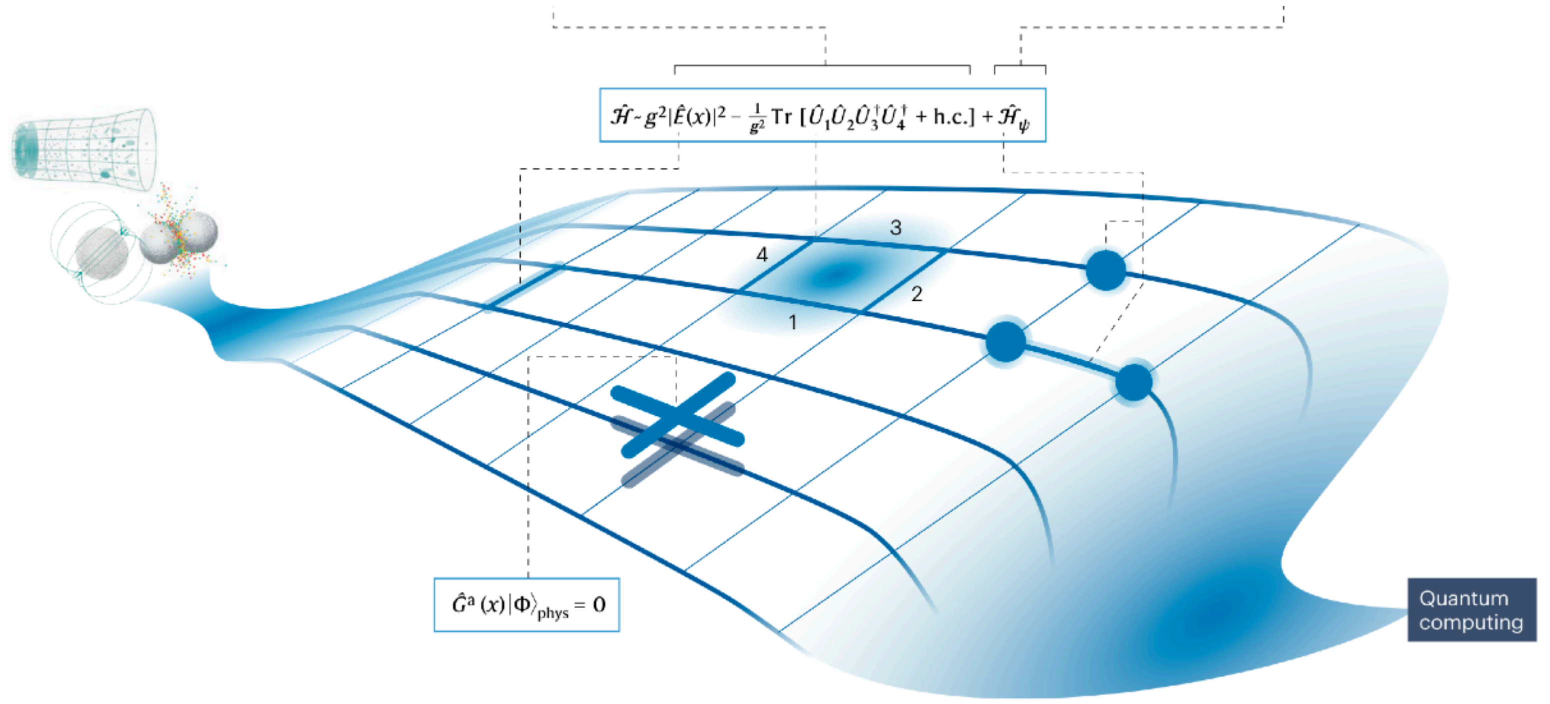
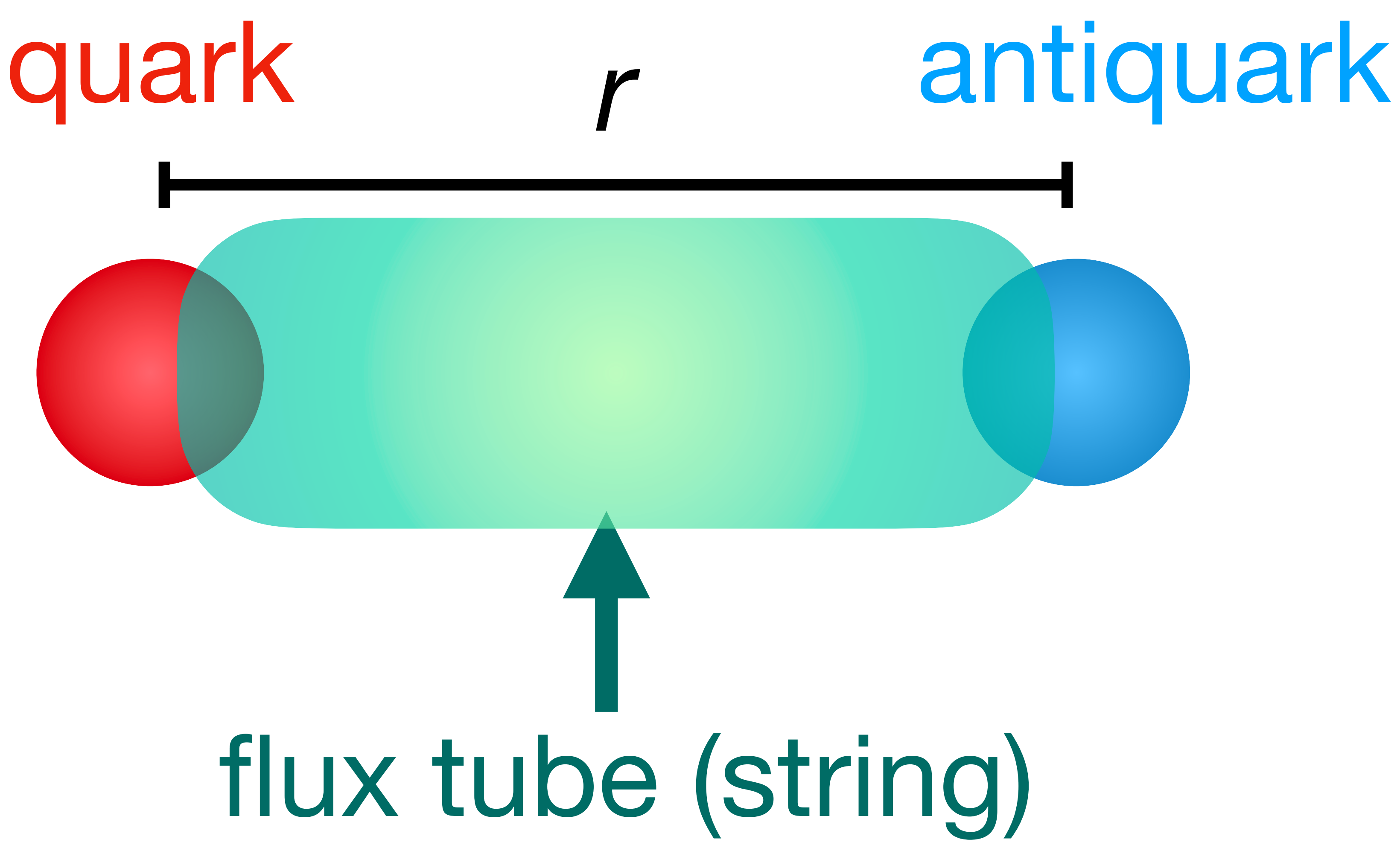


Image: C. Bauer, Z.Davoudi, N, Klco, M. J. Savage, *Nat. Revs. Phys*. 5 (2023

Quark Confinement

Strong force confines color changes, i.e. quarks and gluons, into mesons and baryons



Energy

Distance

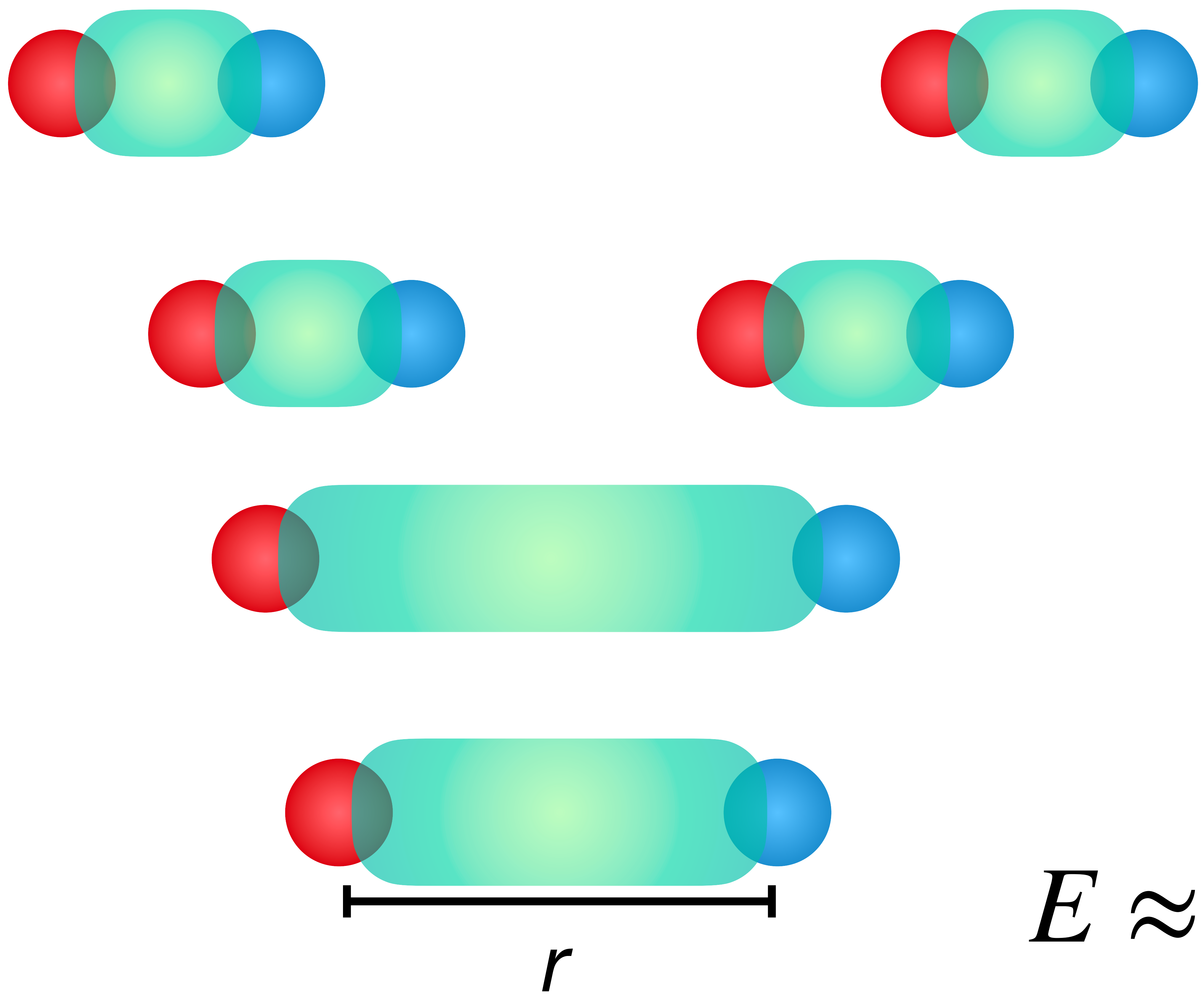
$$E \approx \sigma r$$

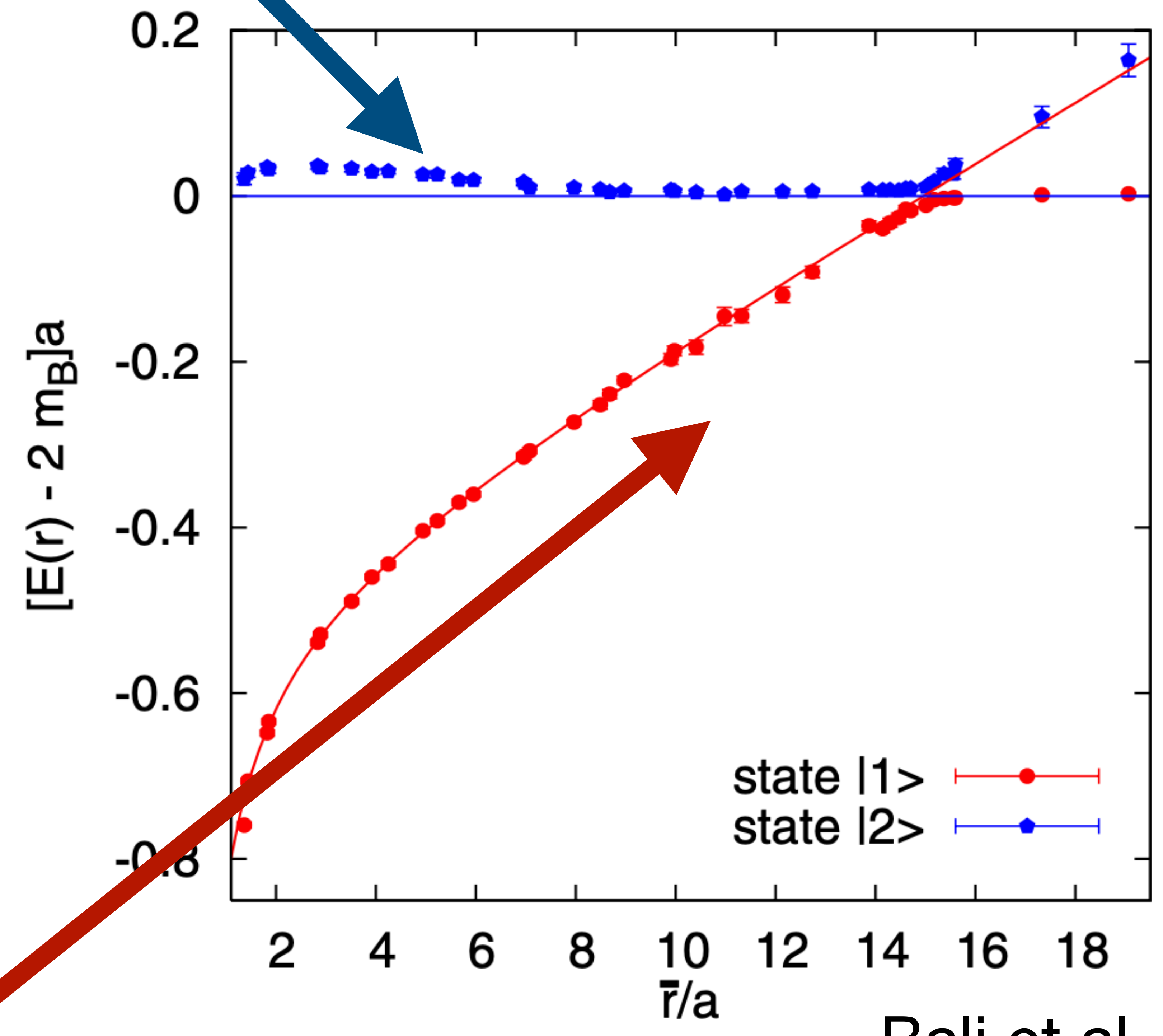
String tension

Quark Confinement

Strong force confines color changes, i.e. quarks and gluons, into mesons and baryons

$E \approx 2M$



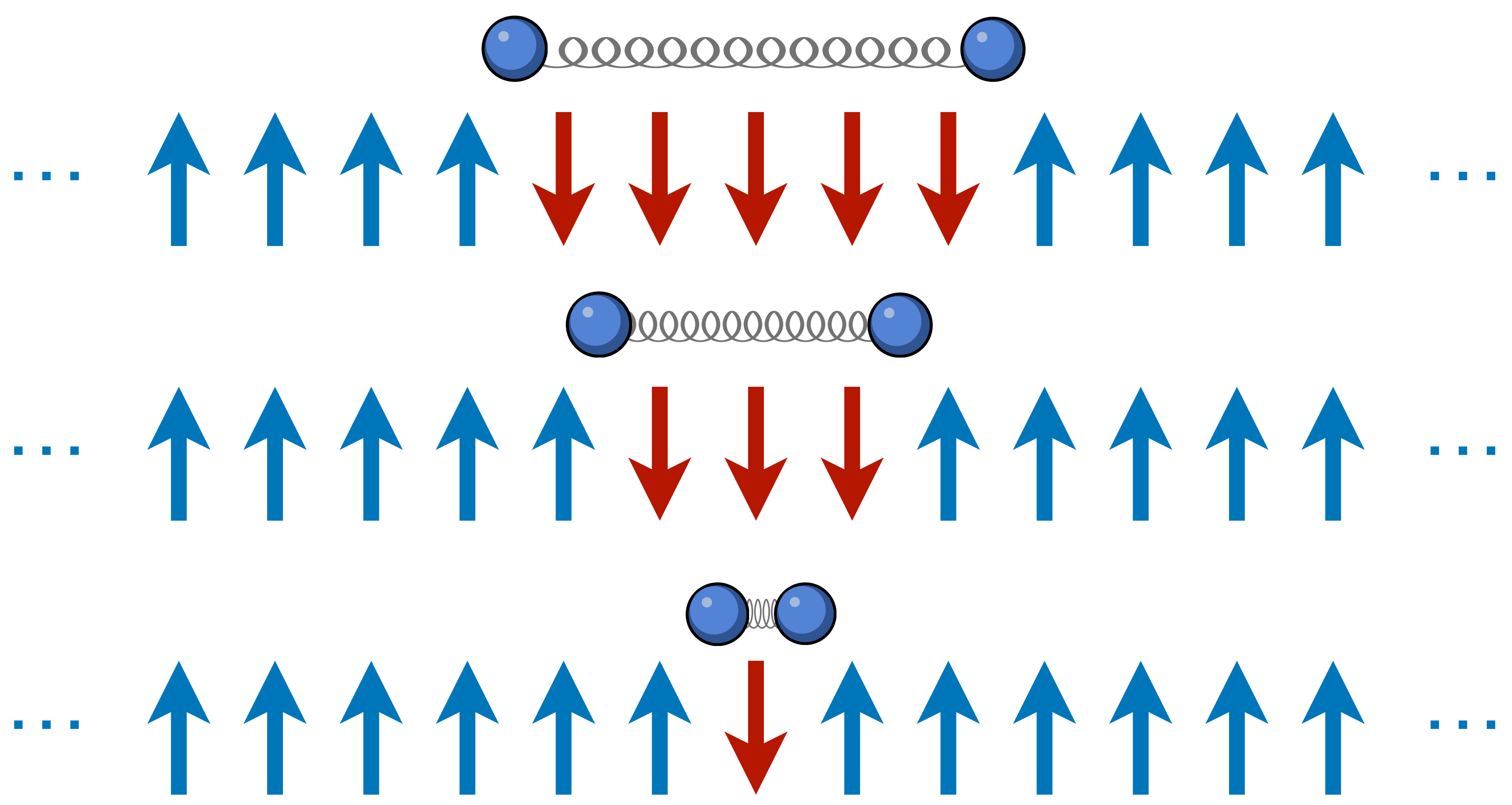


$E \approx \sigma r$

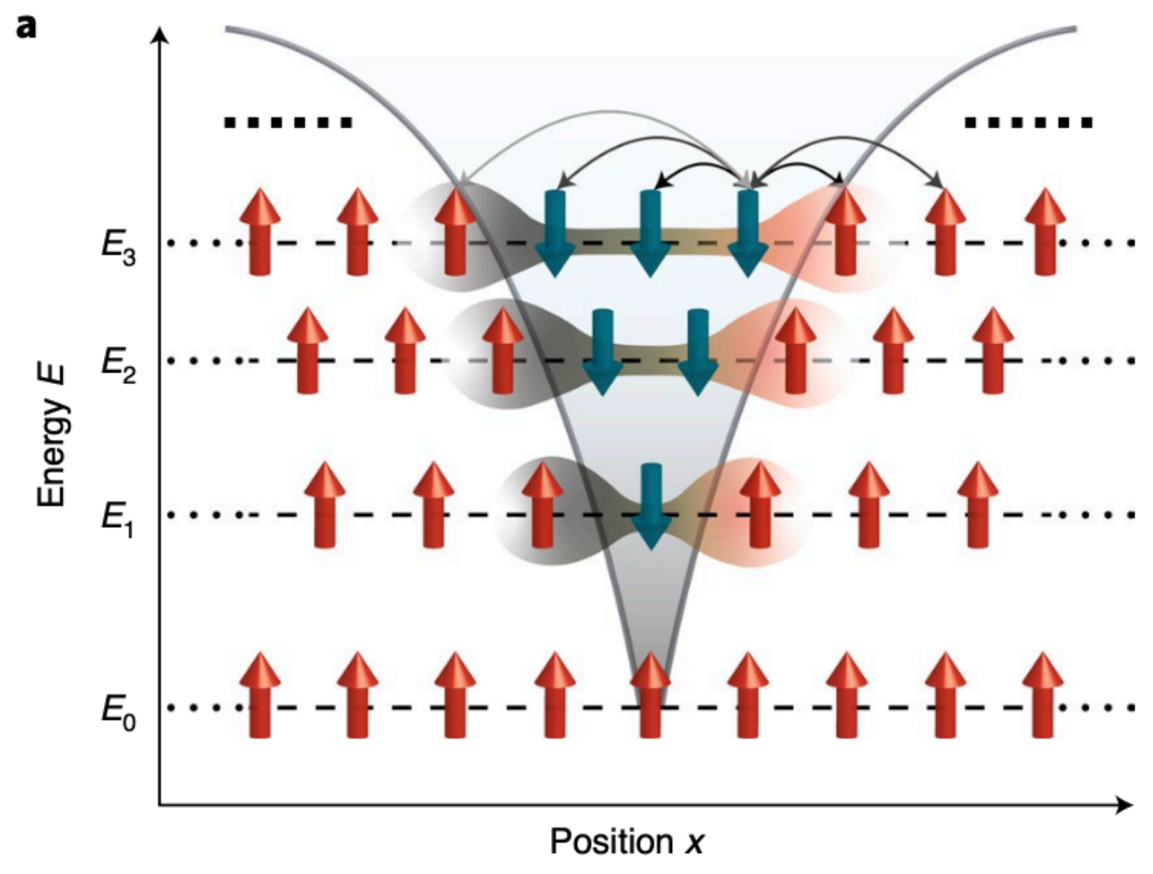
Bali et al, PRD 2005

Simulating Confinement on Quantum Simulators

An *analogous* form of confinement has been shown for spin systems where kinks are confined

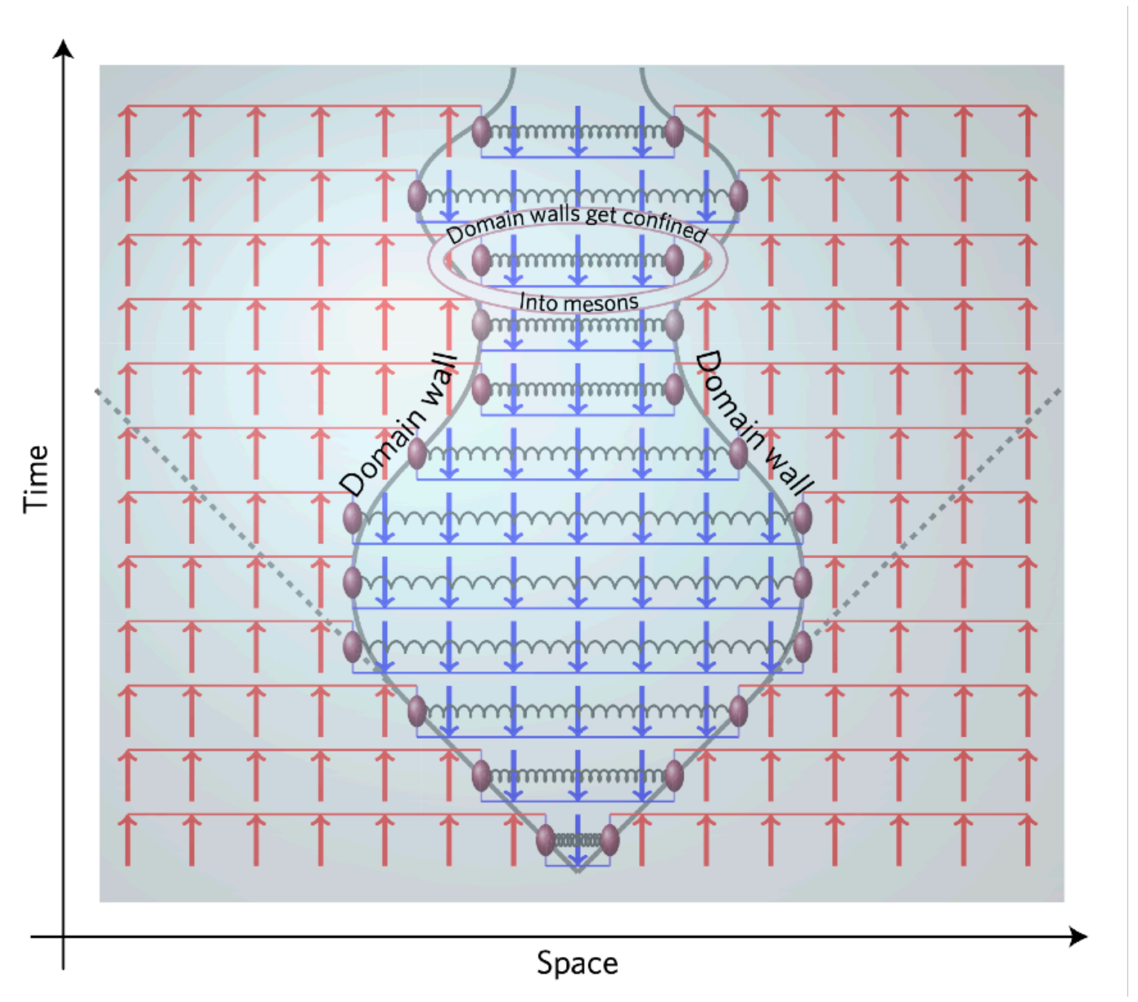


Power Law Ising Model



W. L. Tan et. al. *Nature Physics* 2021

Nearest Neighbor Ising Model



M. Kormos el. al. *Nature Physics* 2017

A. Lerose, et.al., Phys. Rev. B 102, 041118 (2020).

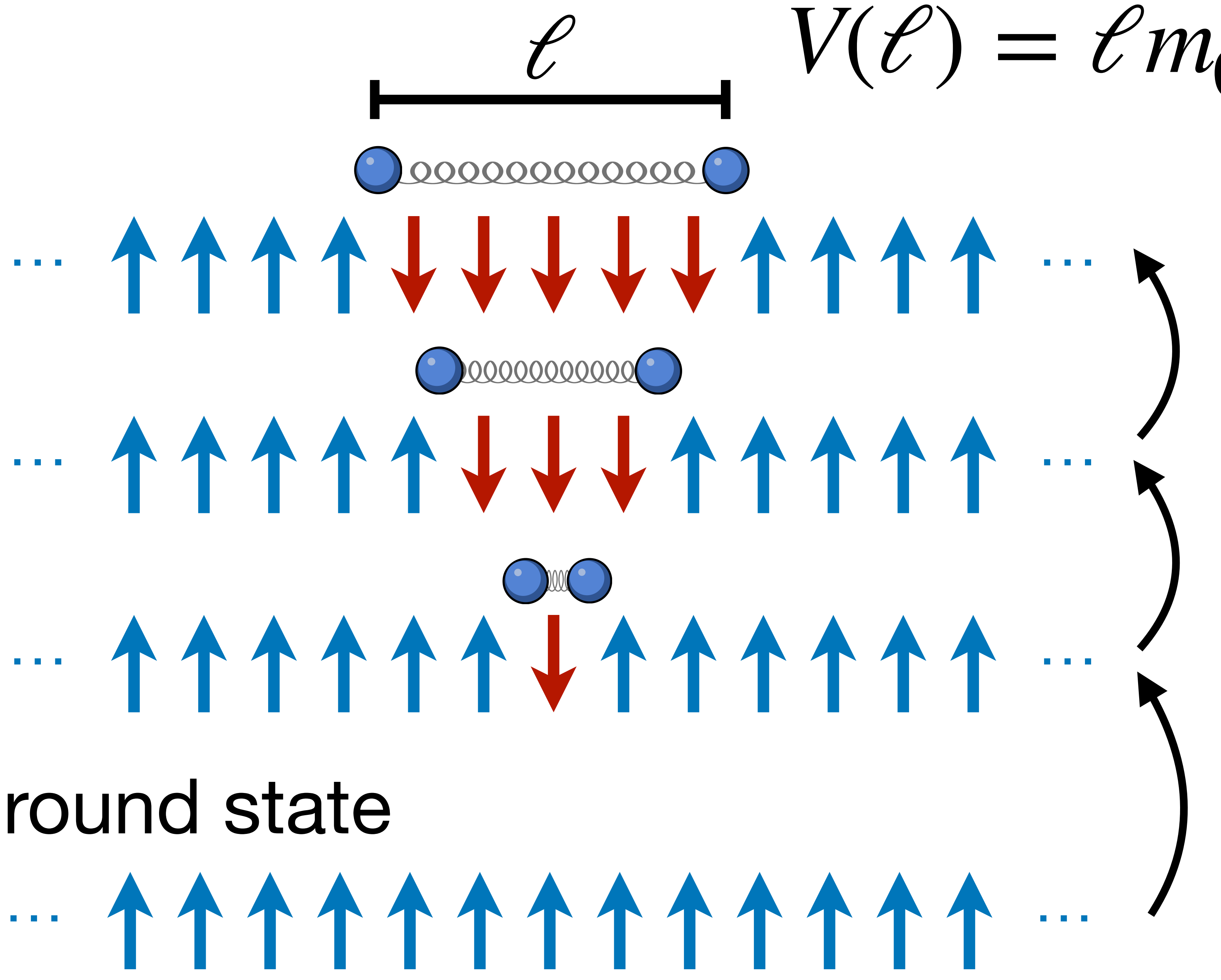
Message: Spin Hamiltonians in 1+1D exhibit confined excitations and are simpler testing grounds for quantum-simulation studies in the presence of confining forces

Confinement in the Ising Model

$$H = -\sum_{ij} J_{ij}\, \sigma_i^x \sigma_j^x - h \sum_i \sigma_i^x$$

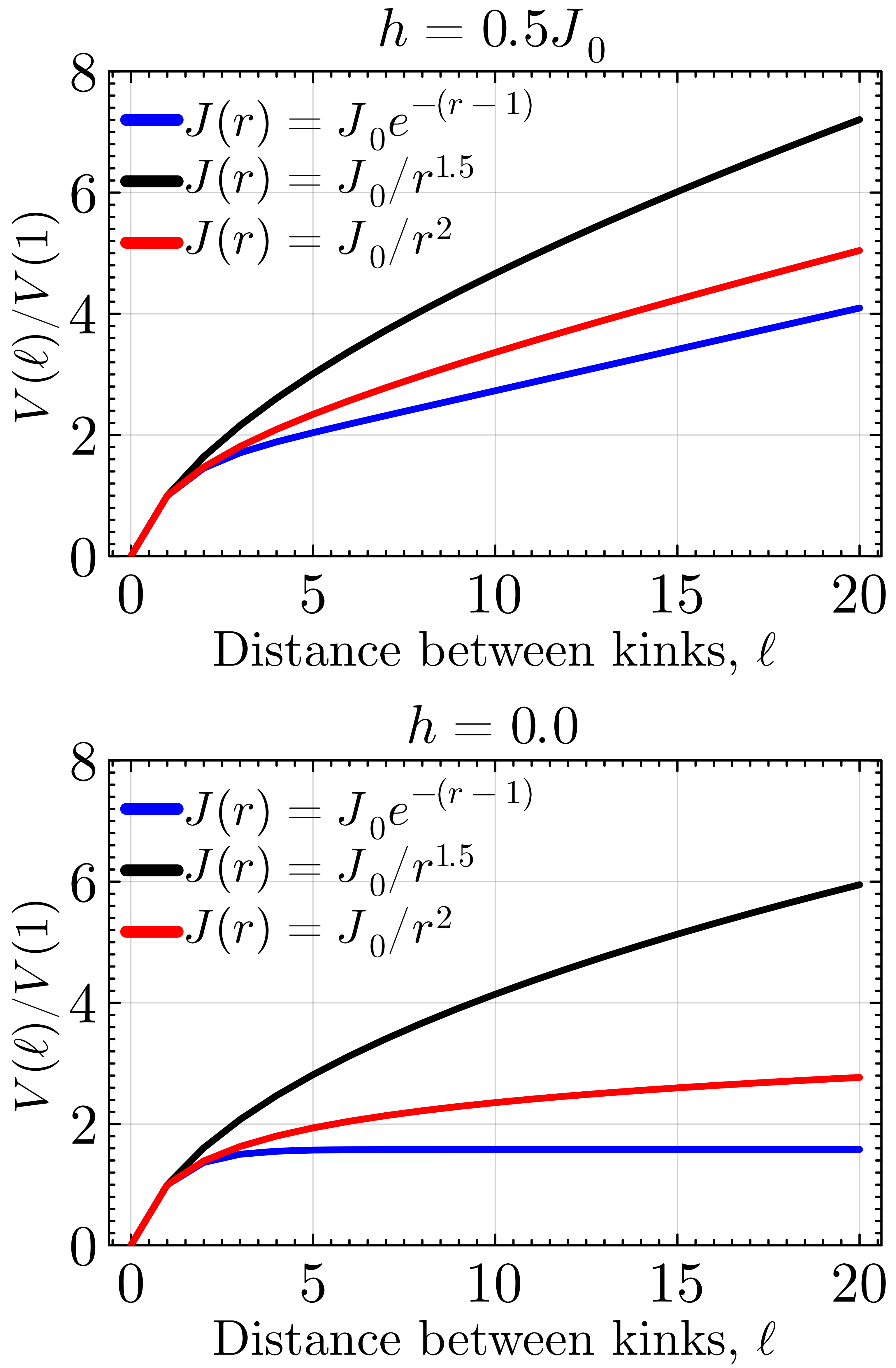
Kink-kink potential

$$V(\ell) = \ell m_0 - 4 \sum_{i=1}^{\ell-1} \sum_{r=1}^{\ell-i} J(r)$$



Ground state

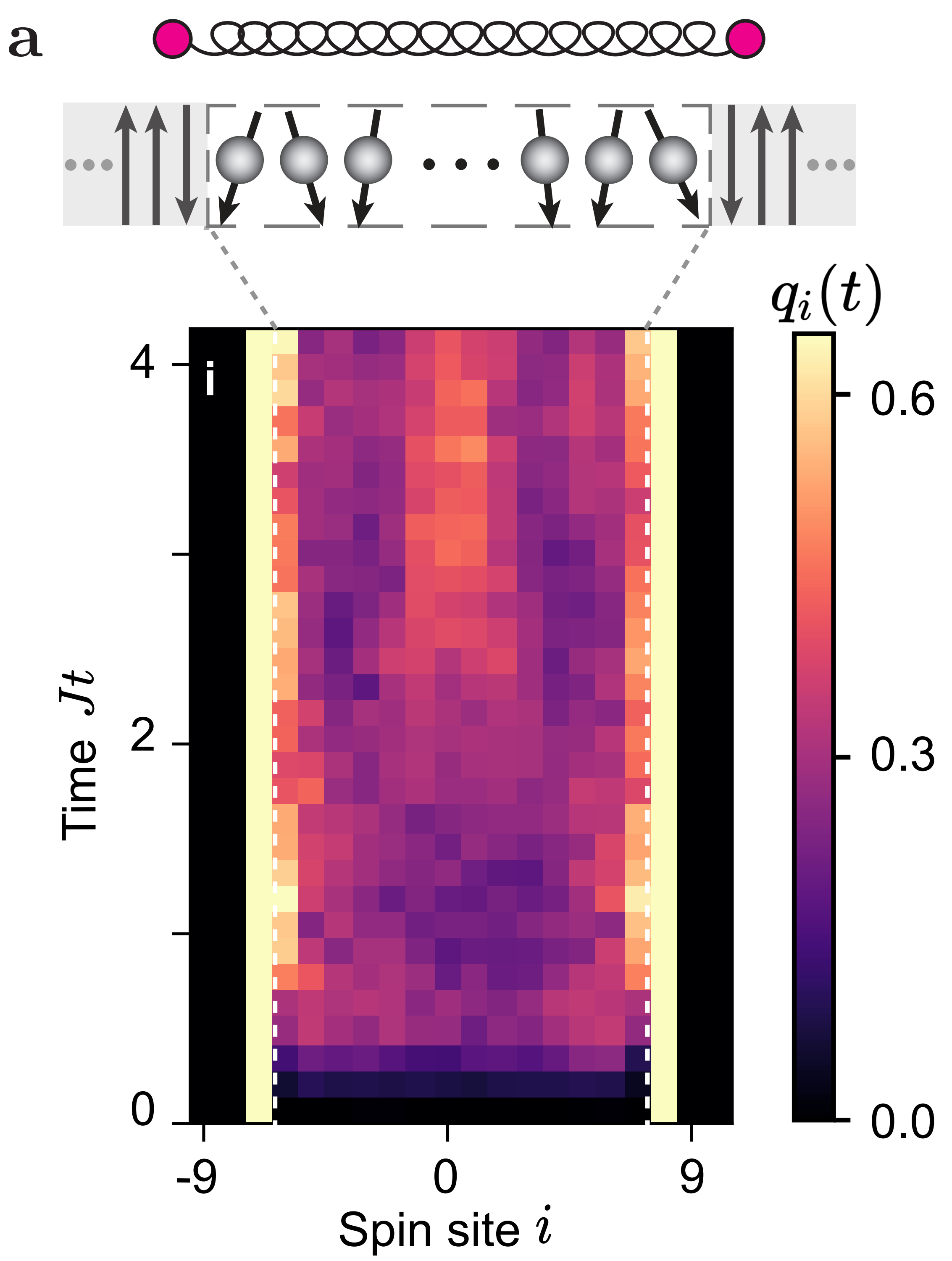
$$2h + \sum_{r=1}^{\infty} J(r) = m_0$$



Confinement in the Ising Model

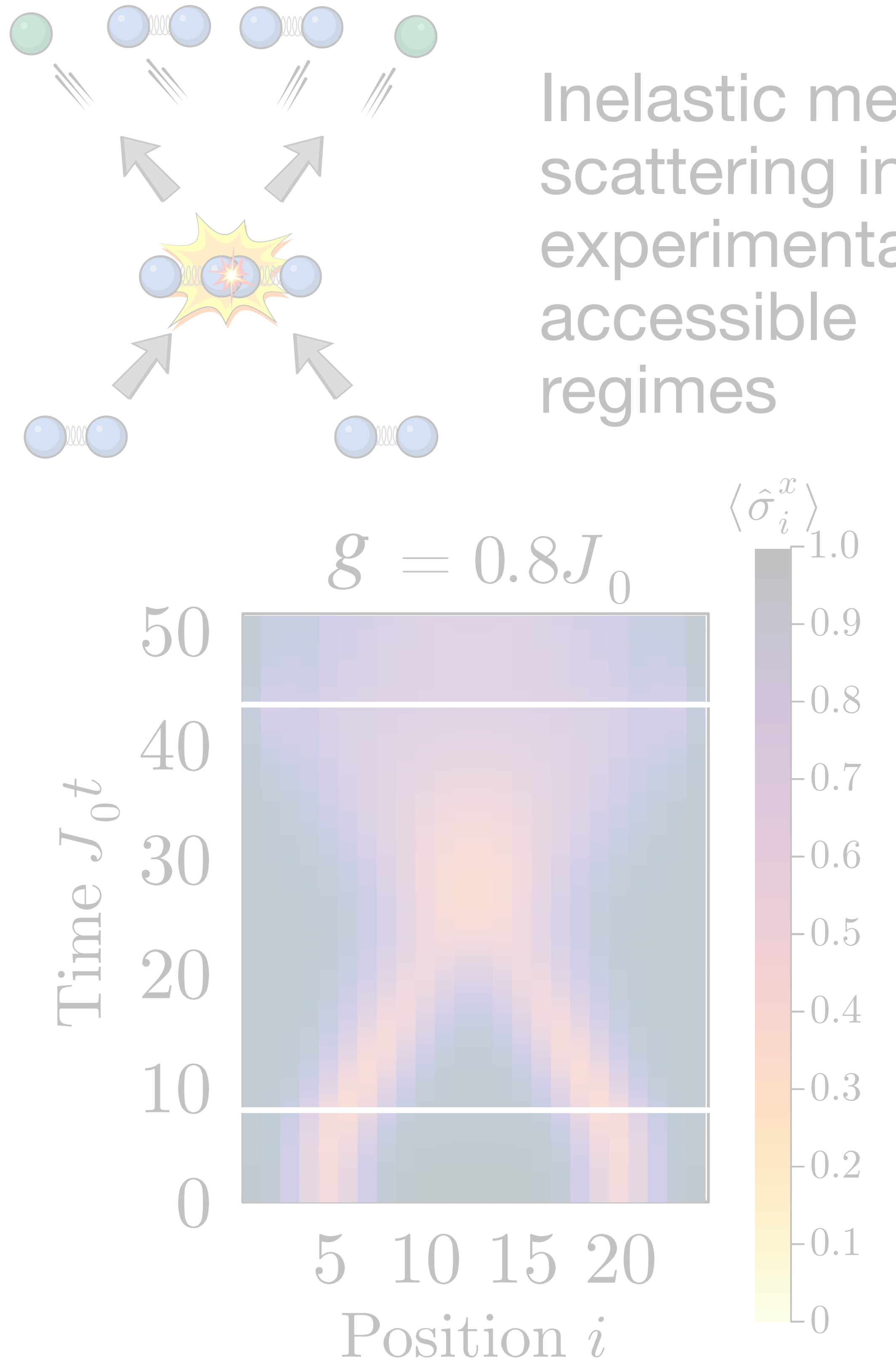
Experimental Demonstrations

Dynamical String Breaking



Experimental Proposal

Meson Scattering



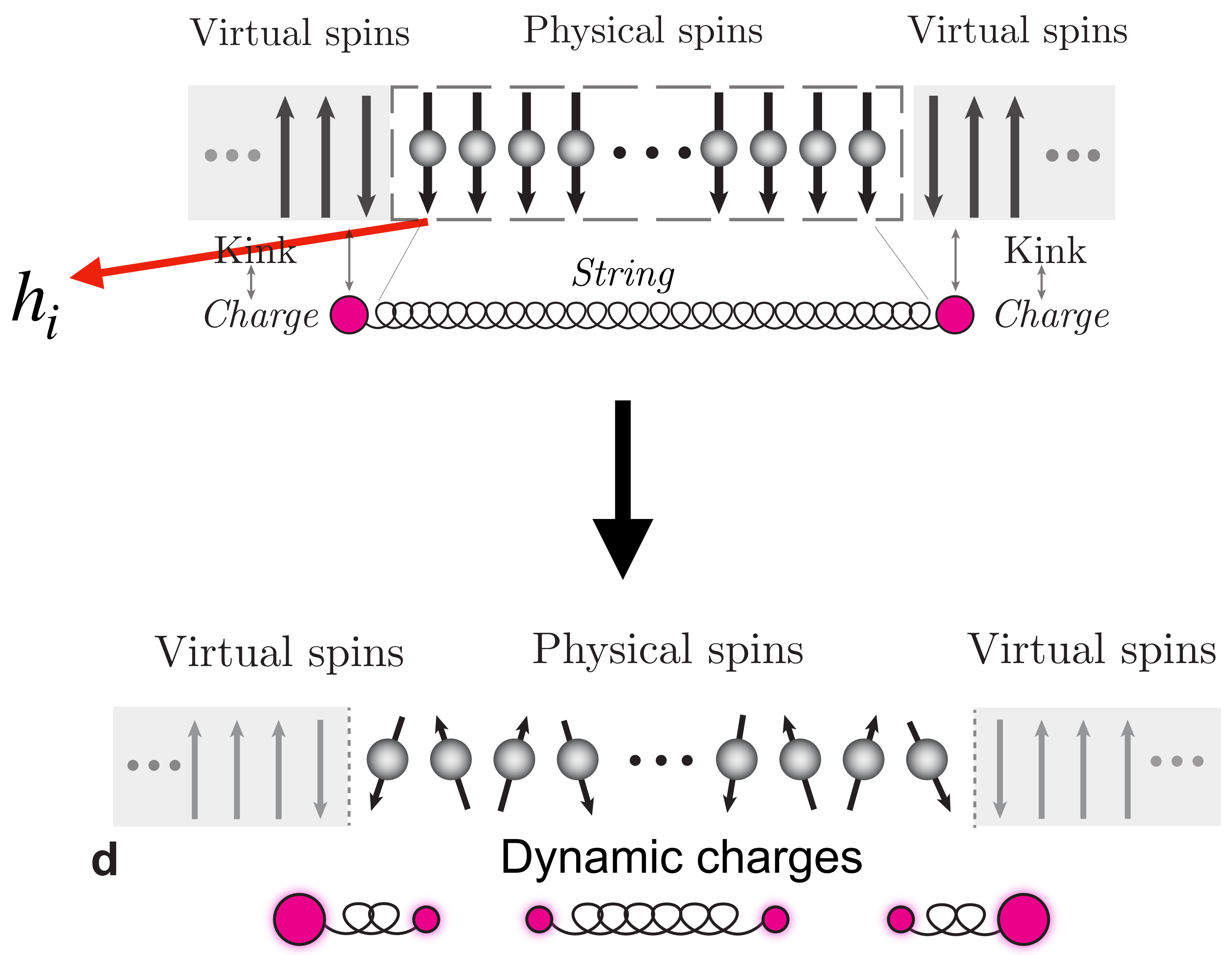
Inelastic meson scattering in experimentally accessible regimes

De, A., Lerose, A., Luo, D., Surace, F.M., Schuckert, A., **Bennewitz, E.R.**, Ware, B., Morong, W., Collins, K.S., Davoudi, Z. and Gorshkov, A.V., 2024. Observation of string-breaking dynamics in a quantum simulator. *arXiv:2410.13815*.

Bennewitz, Elizabeth R., et al. "Simulating meson scattering on spin quantum simulators." arXiv:2403.07061 (2024).

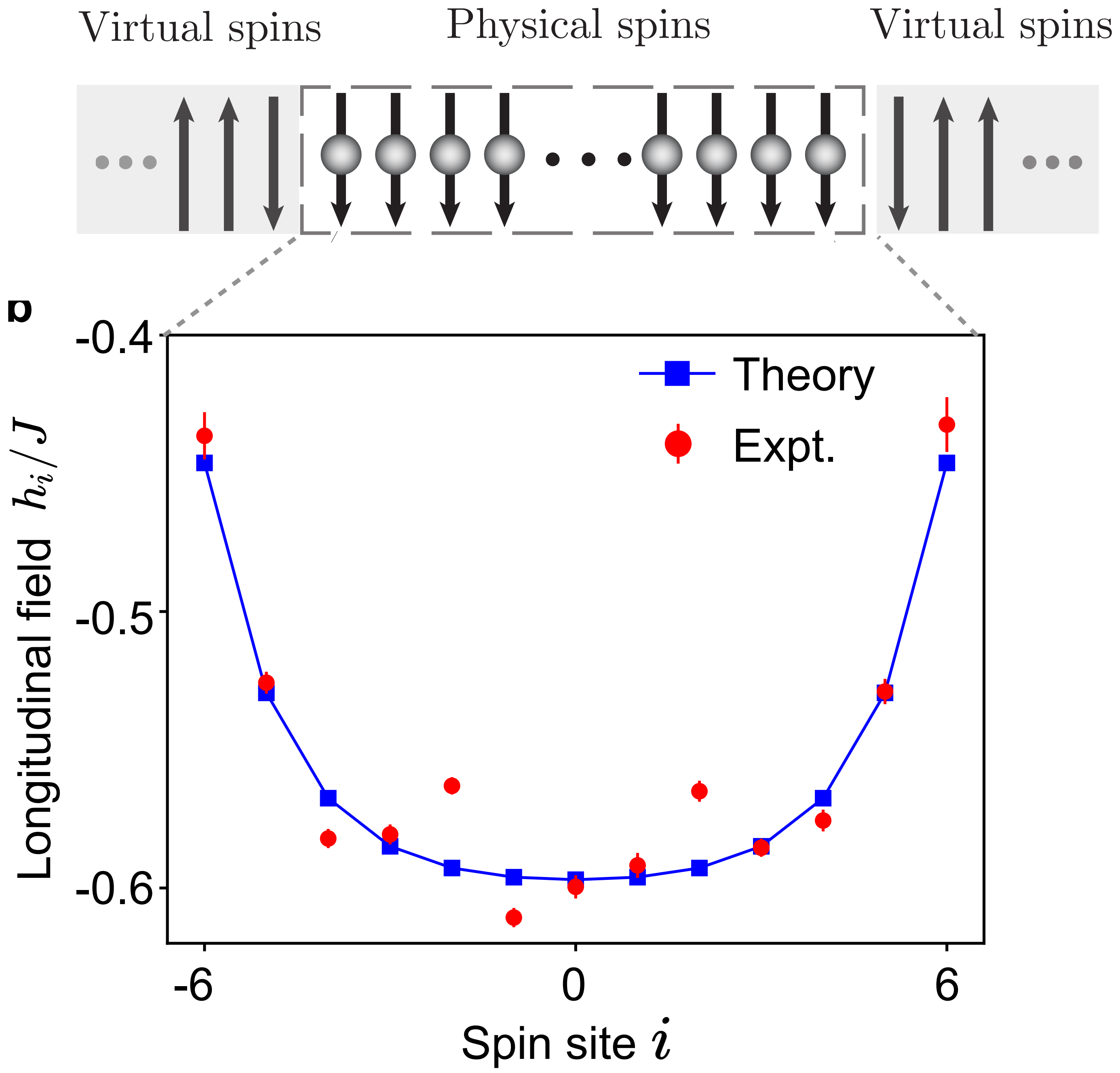
Dynamical String Breaking in the Ising Model

$$H = -\sum_{ij} J_{ij}\, \sigma_i^x \sigma_j^x - h \sum_i \sigma_i^x - g \sum_i \sigma_i^z$$



Ideally, need a semi-infinite chain to isolate the string breaking process

In practice, consider N dynamical spins and an infinite number of fictitious spins on the left and right



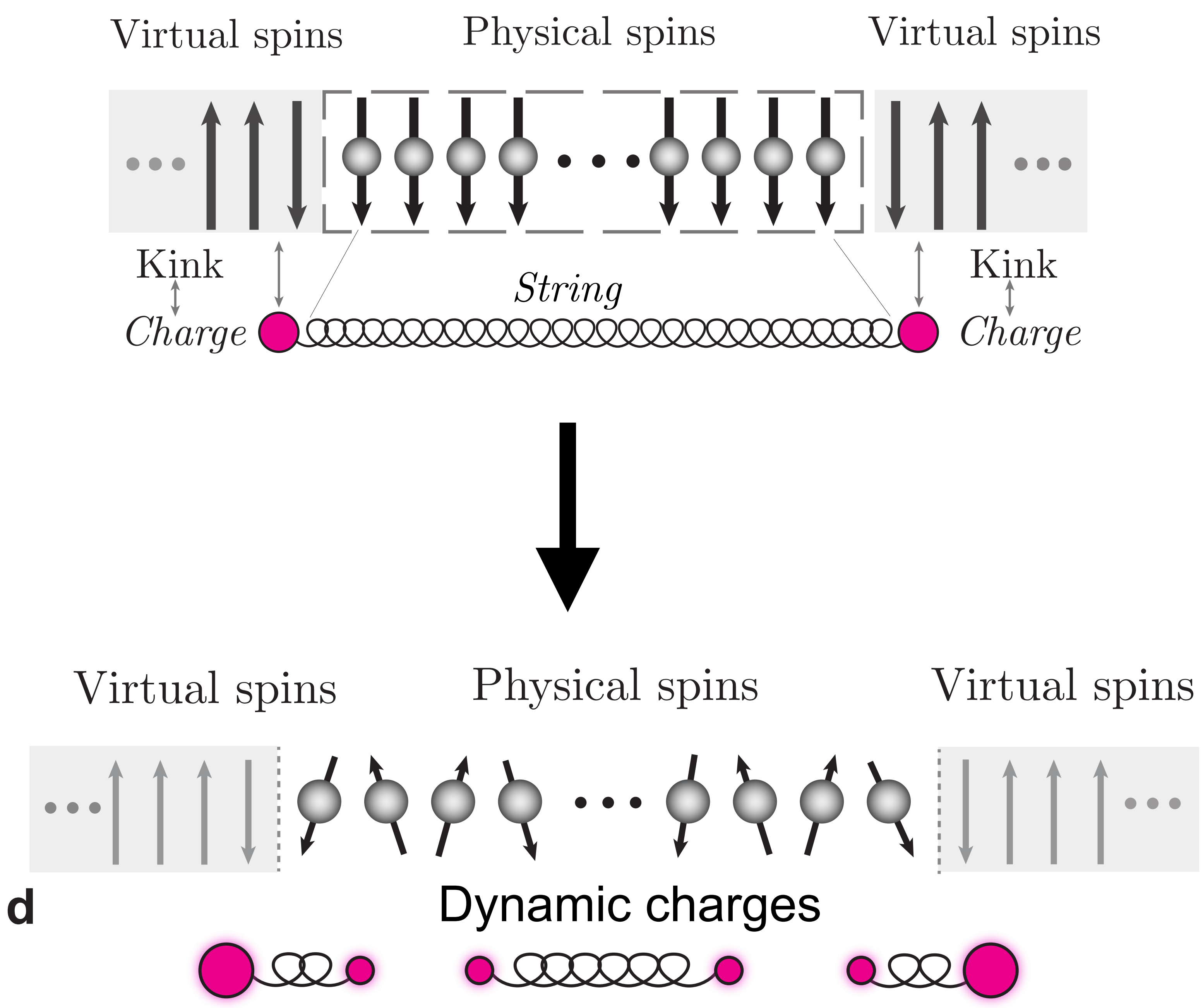
Q: For $h > 0$ and $g > 0$ when does the string break?

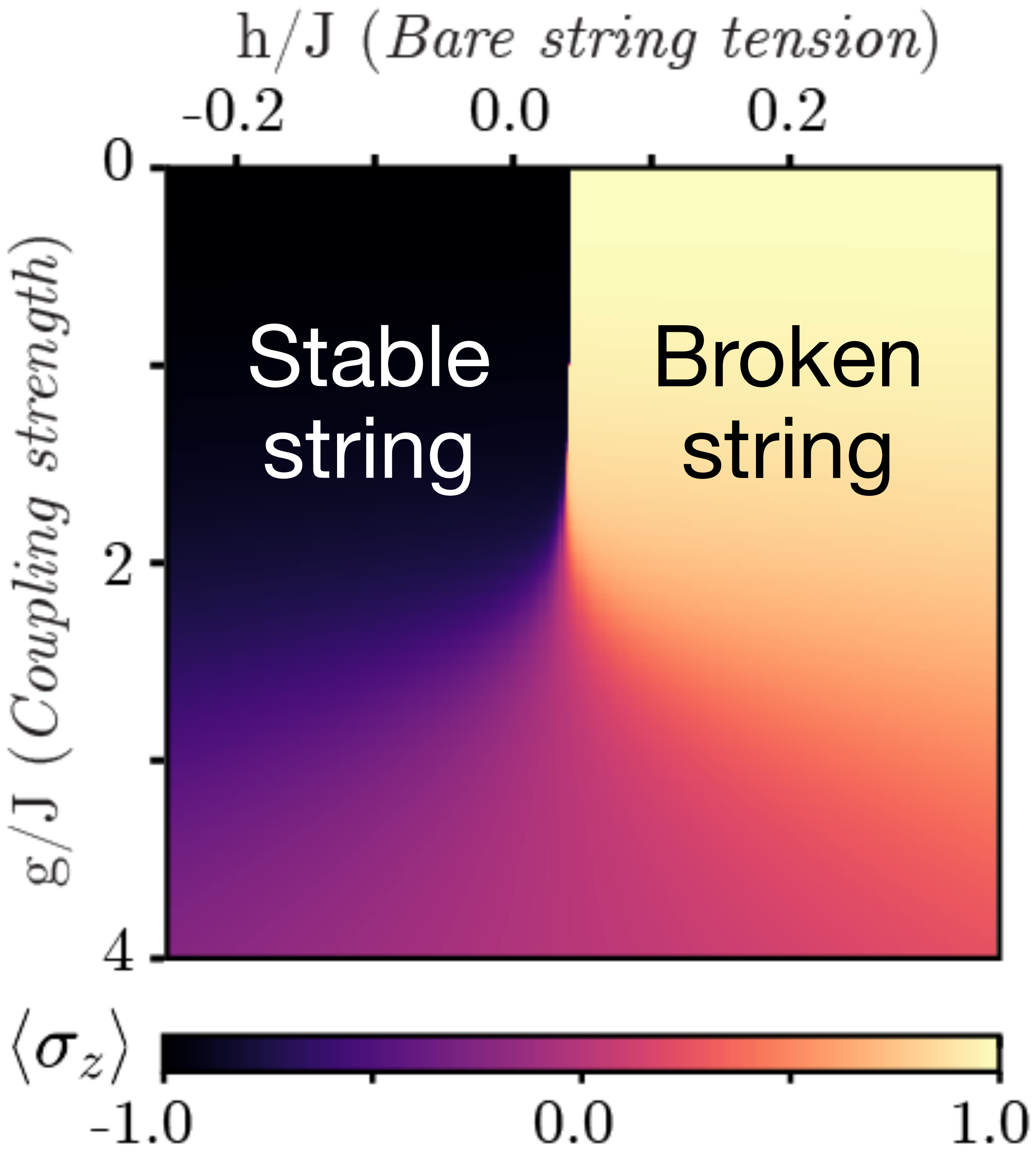
$h \equiv$ string tension

$g \equiv$ string-kink coupling and fluctuations

Dynamical String Breaking in the Ising Model

$$H = -\sum_{ij} J_{ij}\, \sigma_i^x \sigma_j^x - \sum_i (h + h_i)\, \sigma_i^x - g \sum_i \sigma_i^z \qquad J_{ij} \approx J e^{-0.78(|i-j|-1)}$$

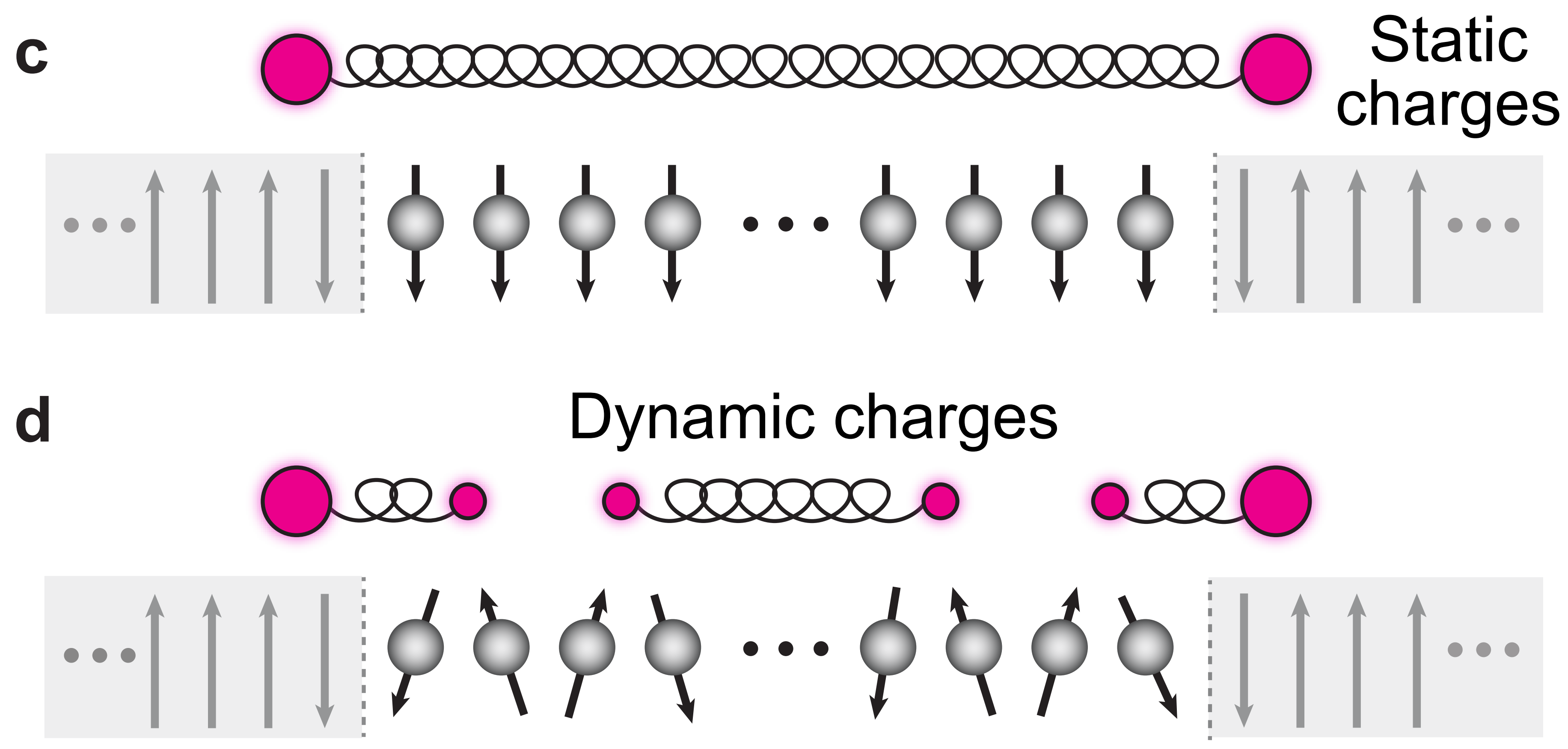


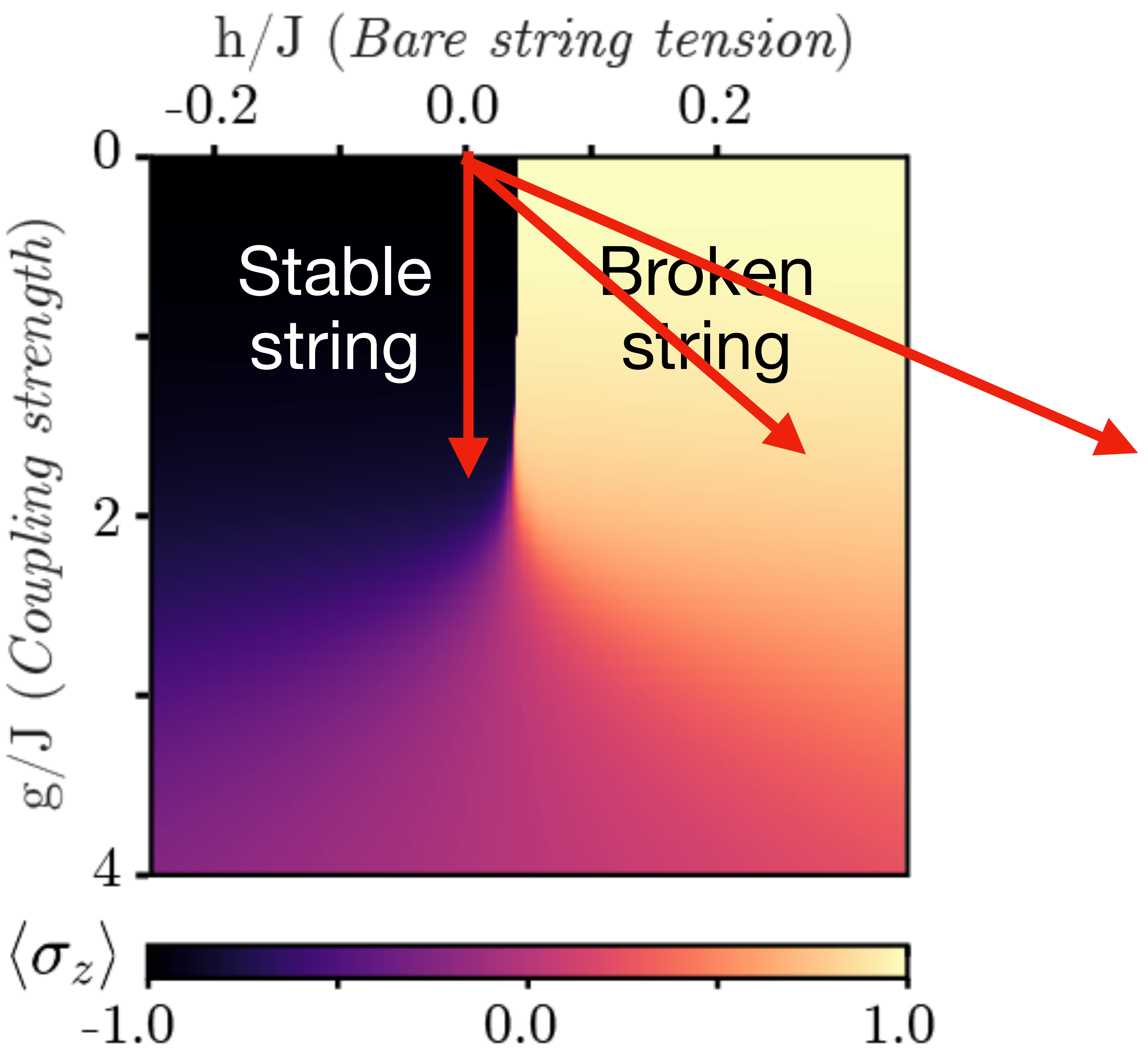


Phase Diagram:

- $N = 13$ dynamical spins
- 1st order phase transition

Dynamical String Breaking



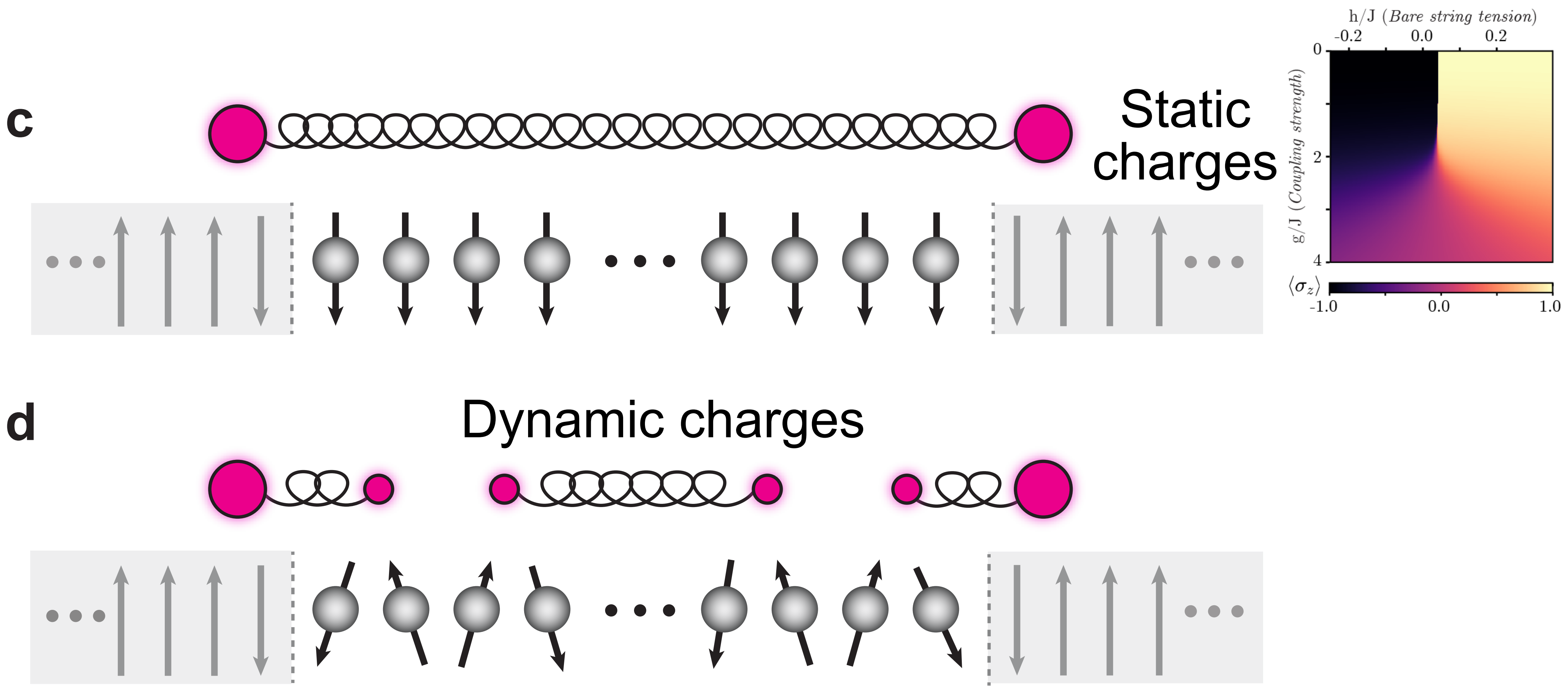


Schwinger mechanism predicts charge-pair formation initiating **in the bulk**

Our results demonstrate charge-pair formation initiating **at the edges** propagating into the bulk

For vanishing or weak string tension, charge-pairs perform coherent oscillations at the edge

Dynamical String Breaking



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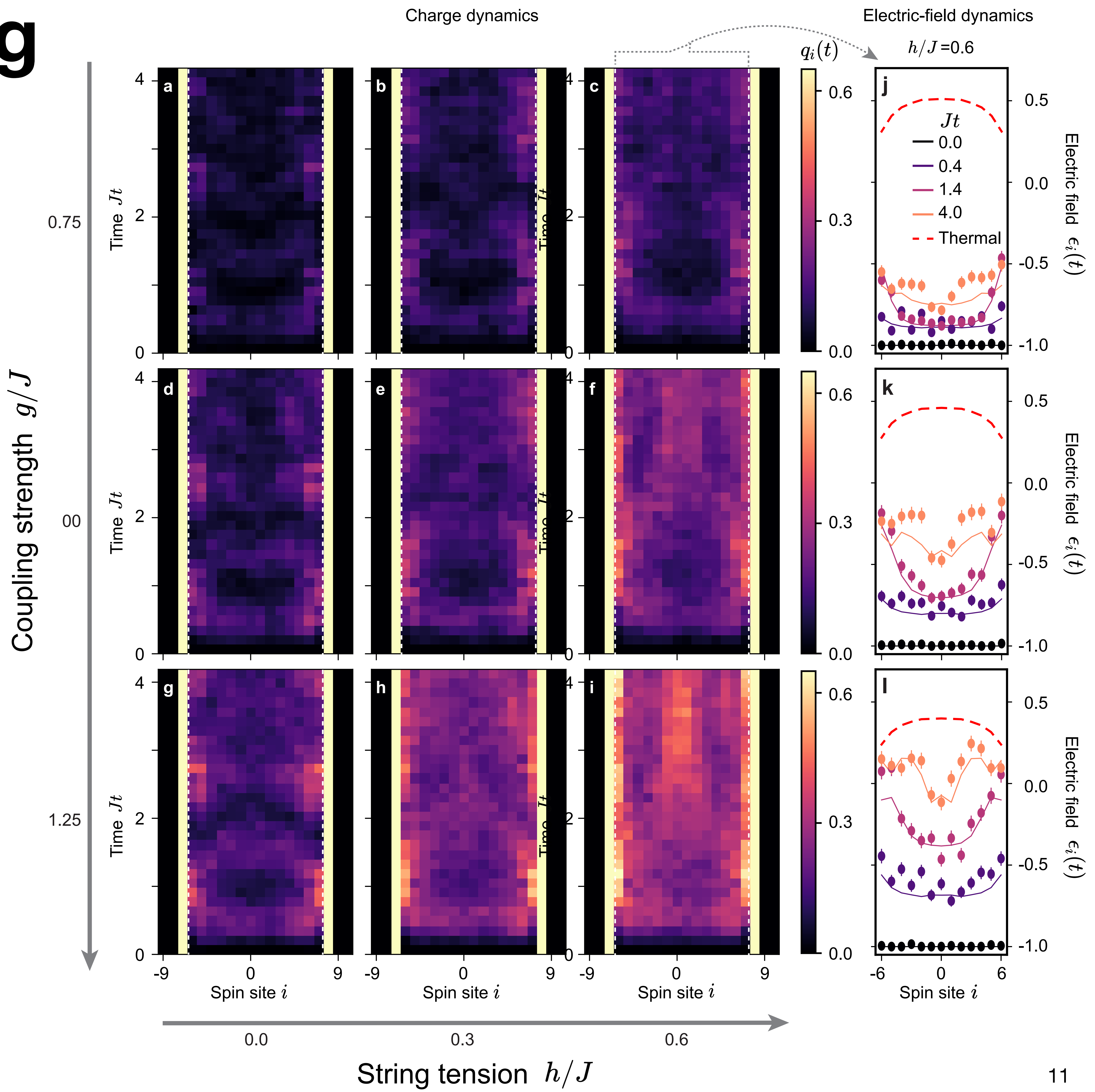
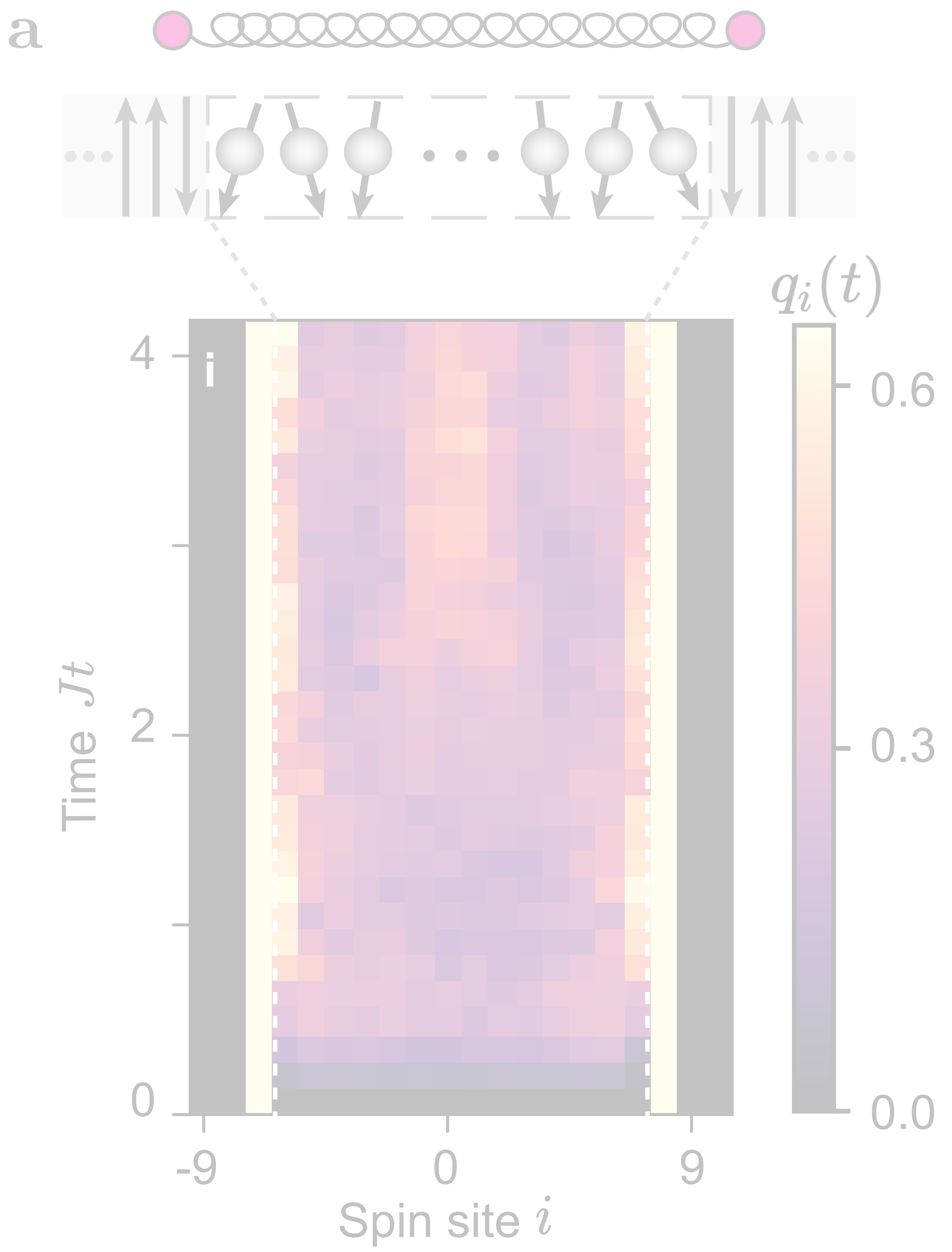


Confinement in the Ising Model

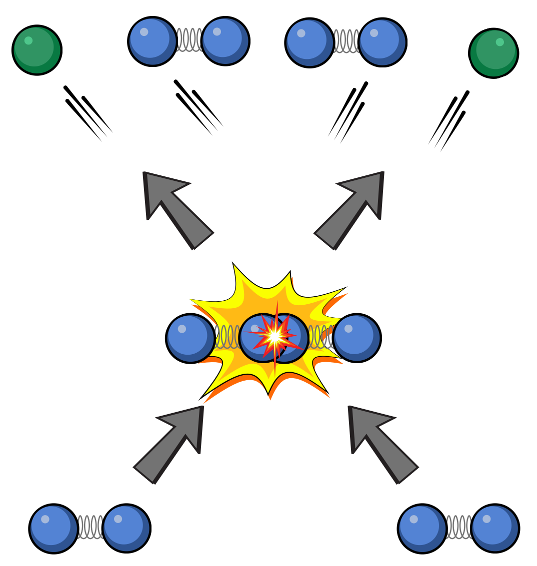
Experimental Demonstrations

Dynamical String Breaking

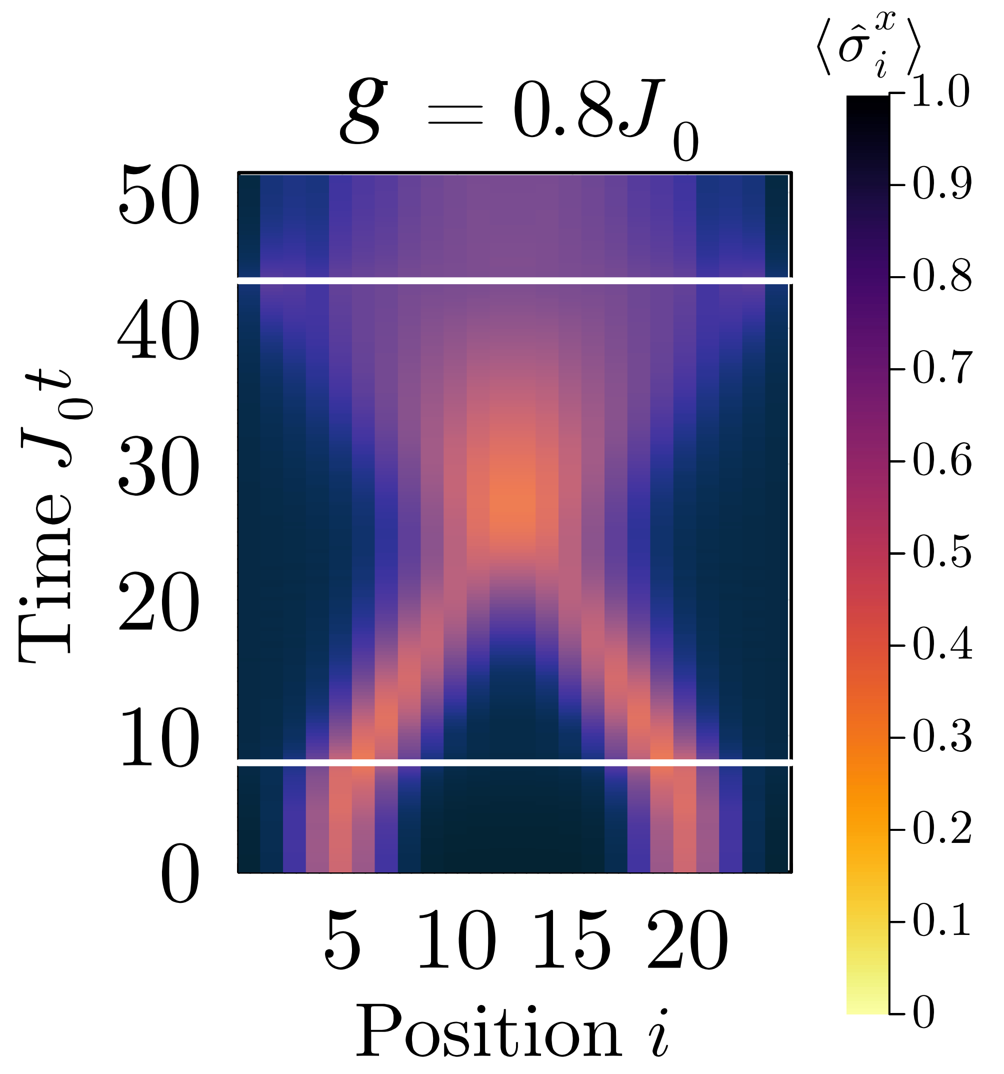


Experimental Proposal

Meson Scattering



Inelastic meson scattering in experimentally accessible regimes



De, A., Lerose, A., Luo, D., Surace, F.M., Schuckert, A., **Bennewitz, E.R.**, Ware, B., Morong, W., Collins, K.S., Davoudi, Z. and Gorshkov, A.V., 2024. Observation of string-breaking dynamics in a quantum simulator. *arXiv preprint*

Bennewitz, Elizabeth R., et al. "Simulating meson scattering on spin quantum simulators." arXiv preprint arXiv:2403.07061 (2024).

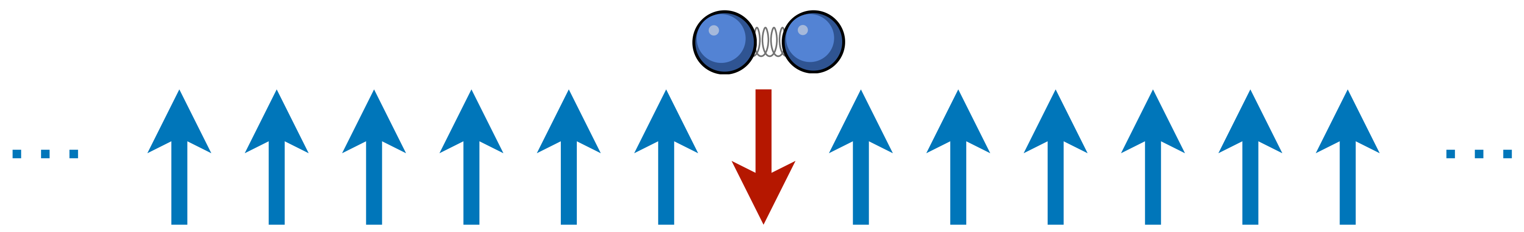
Bound excitations in the Ising Model

$$J_{ij} = J_0 e^{-\beta(r_{ij}-1)}$$

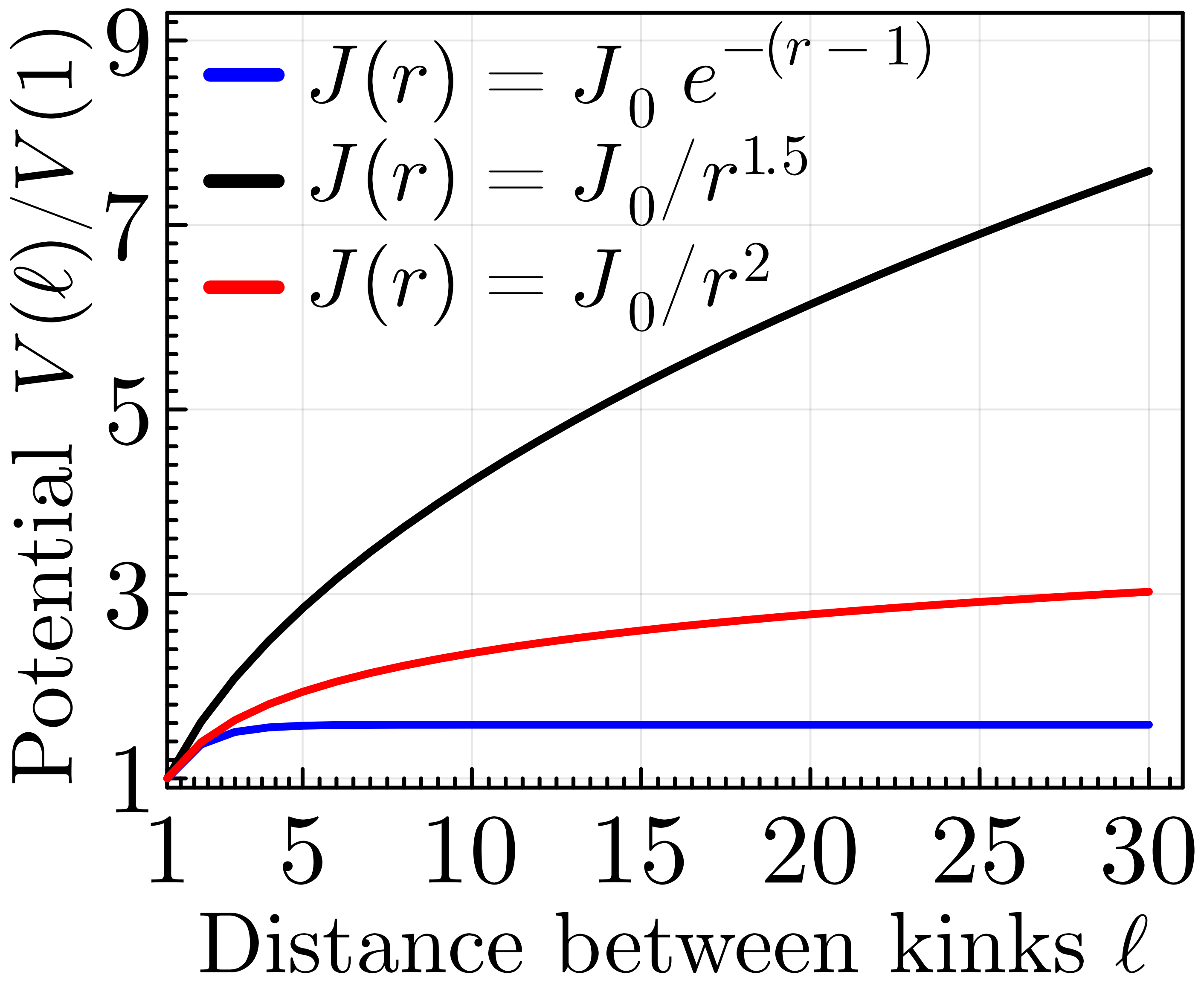
$$J_{ij} = \frac{J_0}{r_{ij}^{\alpha}}$$

$$H = -\sum_{ij} J_{ij}\, \sigma_i^x \sigma_j^x - h \sum_i \sigma_i^x - g \sum_i \sigma_i^z$$

Want to scatter mesons, *bound* two-kink states



$h = 0$



Power Law Model ($1 < \alpha < 2$):

- $V(\infty) = \infty$
- All two-kink states are bound for an infinitesimal transverse field

Exponential Decay Model:

- $V(\infty) = \text{constant}$
- Infinitesimal transverse field unbinds pairs of kinks for some ℓ_c
- Free Kinks

Bound excitations in the Ising Model

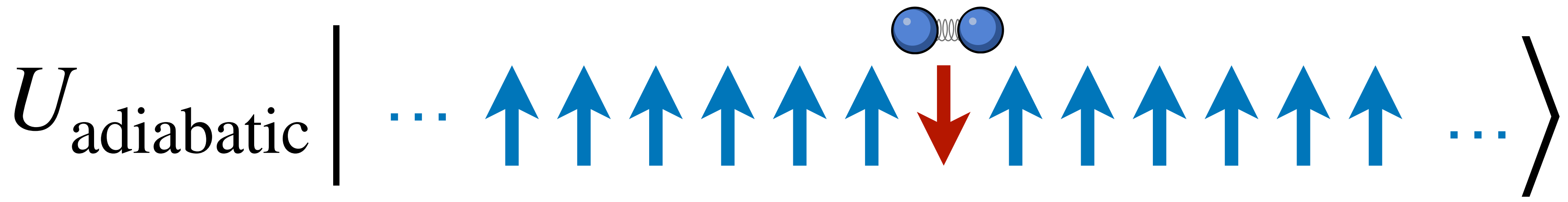
$$H = -\sum_{ij} J_{ij}\, \sigma_i^x \sigma_j^x - h \sum_i \sigma_i^x - g \sum_i \sigma_i^z$$

$$J_{ij} = J_0 e^{-\beta(r_{ij}-1)}$$

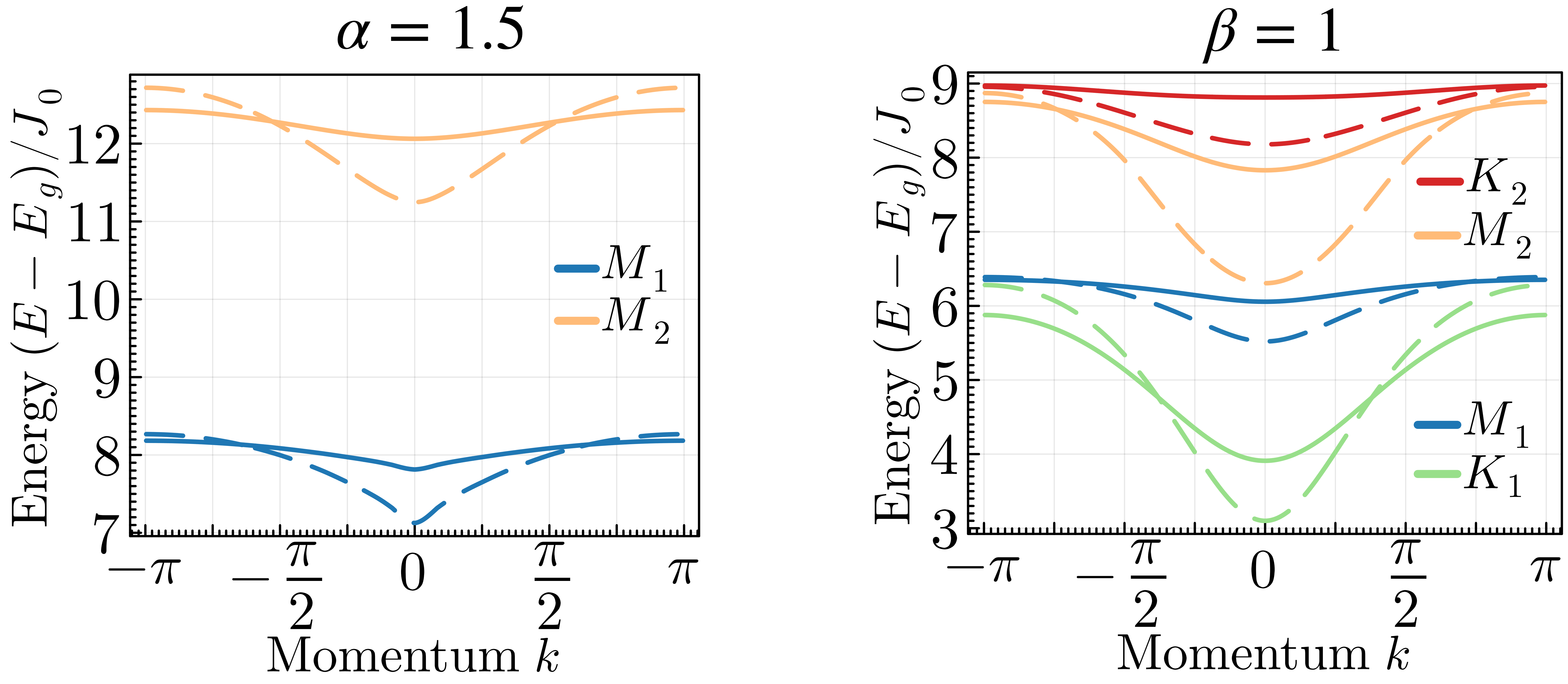
$$J_{ij} = \frac{J_0}{r_{ij}^{\alpha}}$$

Beyond infinitesimal g

- **'Dressed'** two-kink states are adiabatically connected to their **'bare'** analog, i.e.



- As g increases, kink and meson (bound two-kinks) bands evolve from initially flat to bands with dispersion



If Bloch bands remain isolated, then kink or two-kink bound (meson) states are well-defined

Meson Scattering Proposal

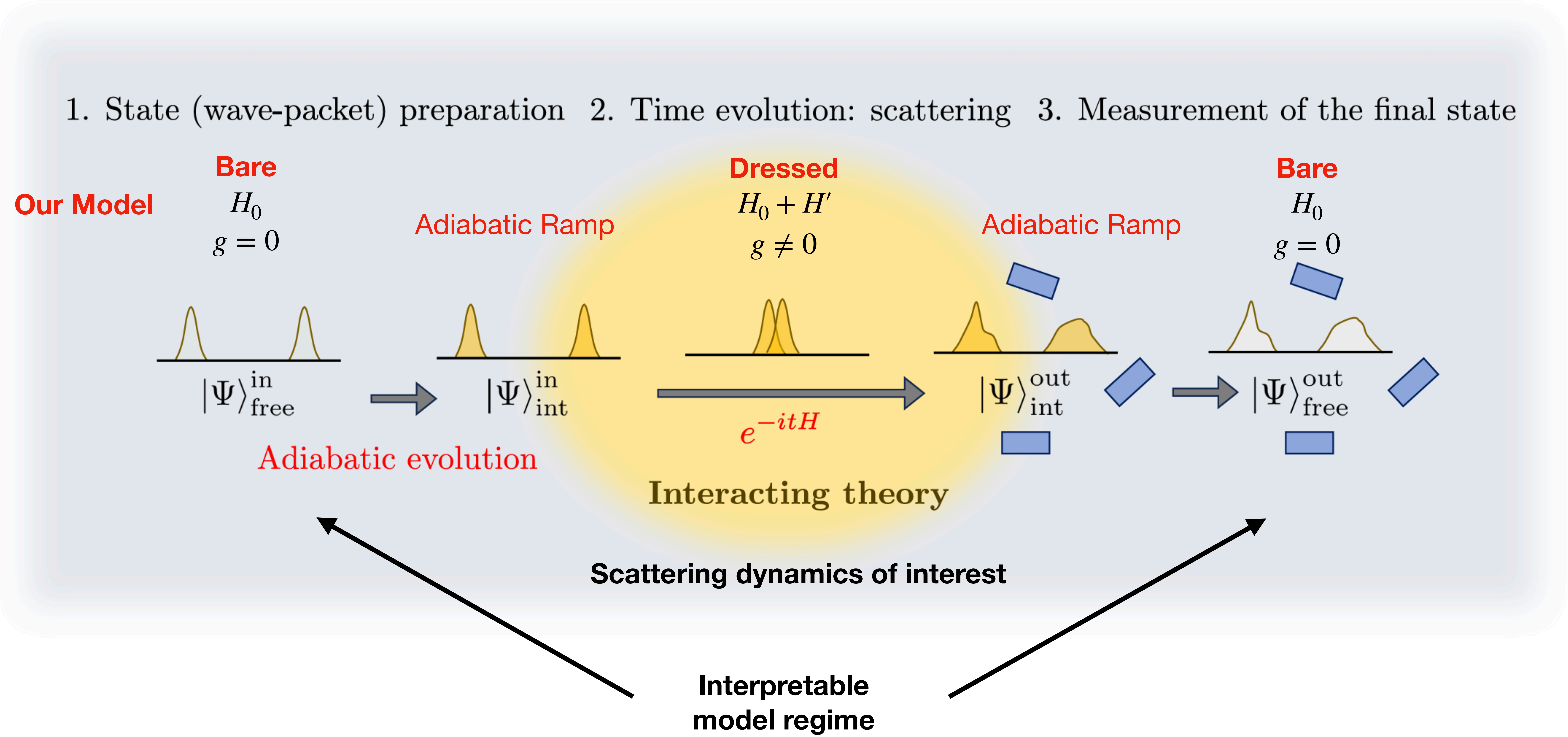
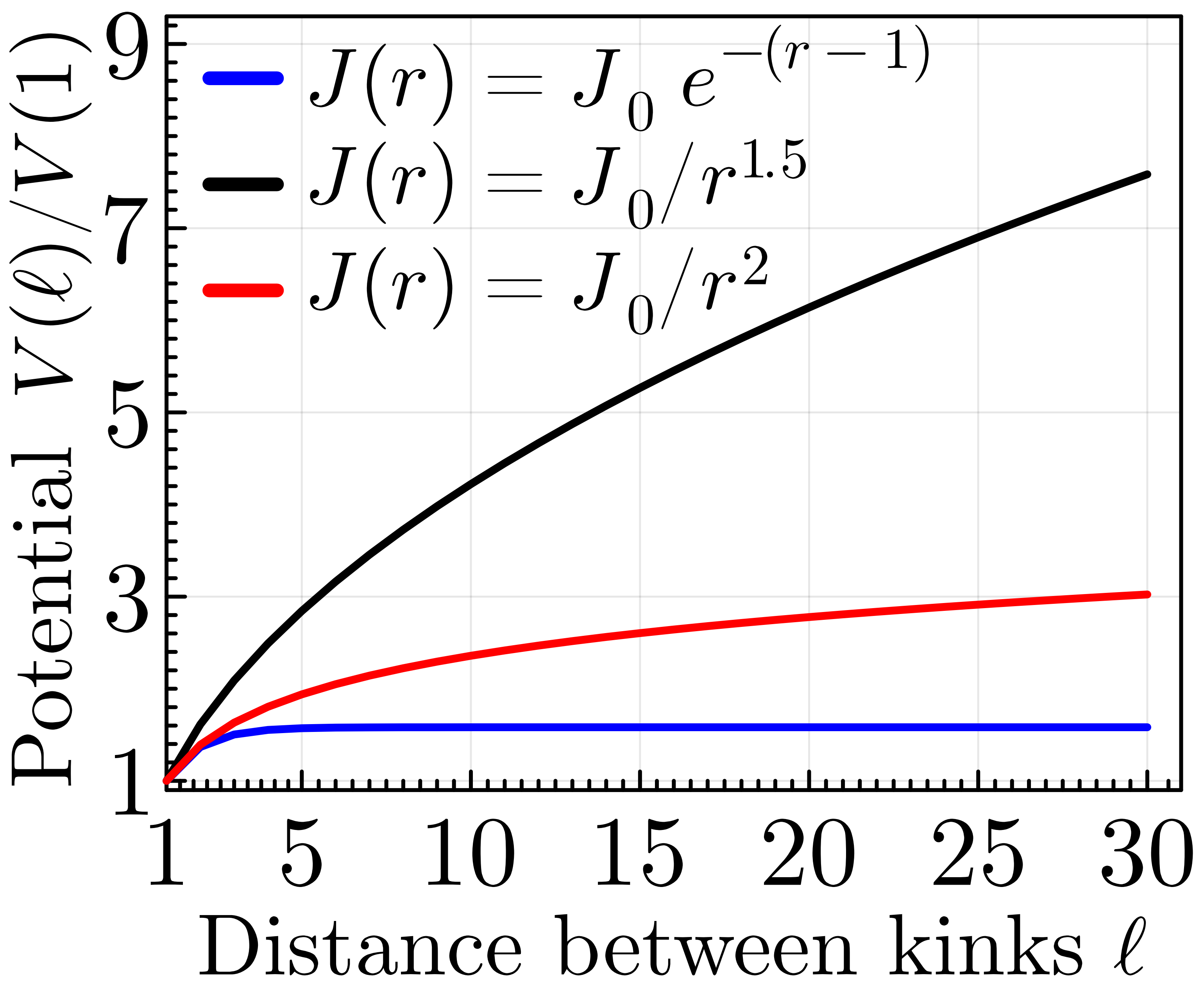


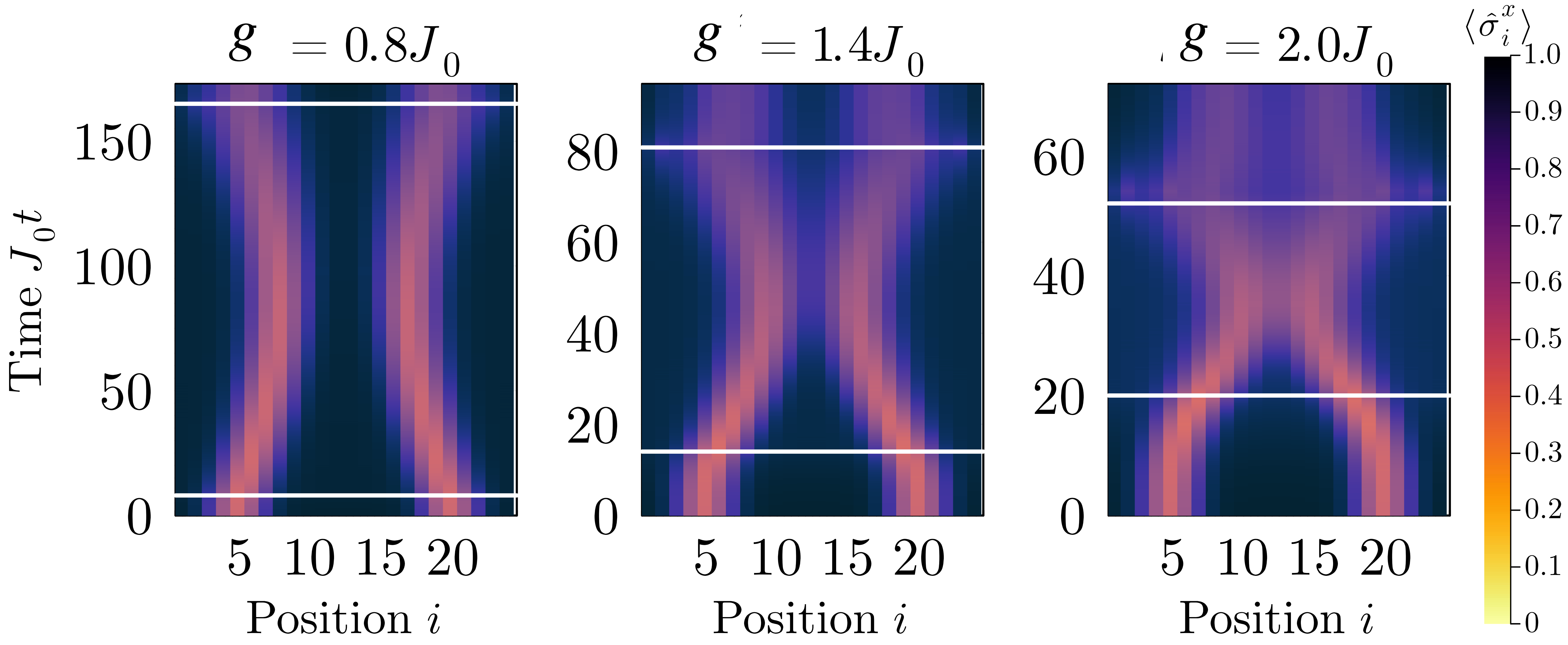
Image: Z.Davoudi, C. Hsieh, S. Kadam, arXiv: 2402.00840
S. Jordan, K. Lee, J. Preskill, Science Vol 336, Issue 6085 (201

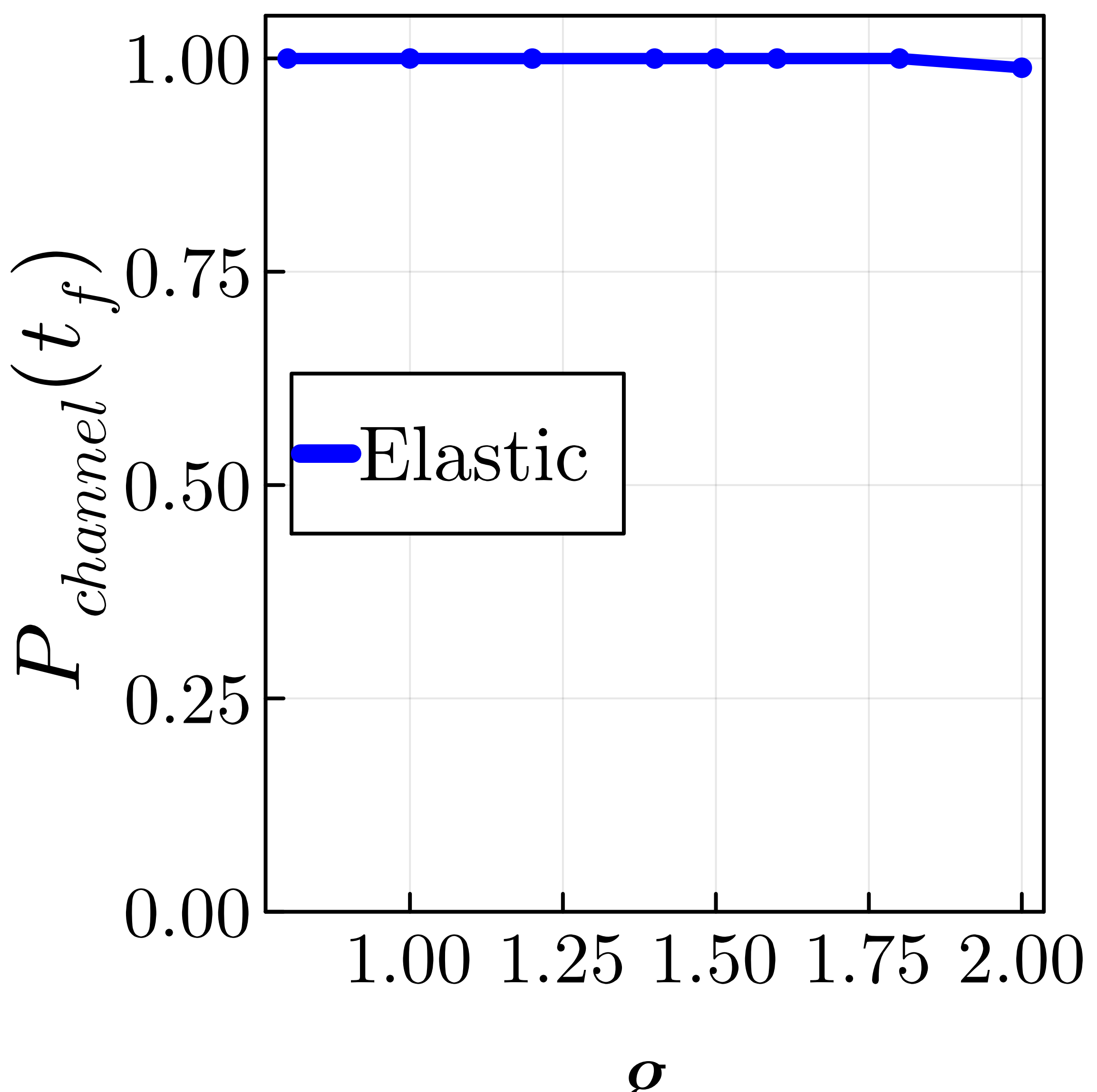
Meson Scattering for Power Law Coupling $(\alpha = 1.5)$

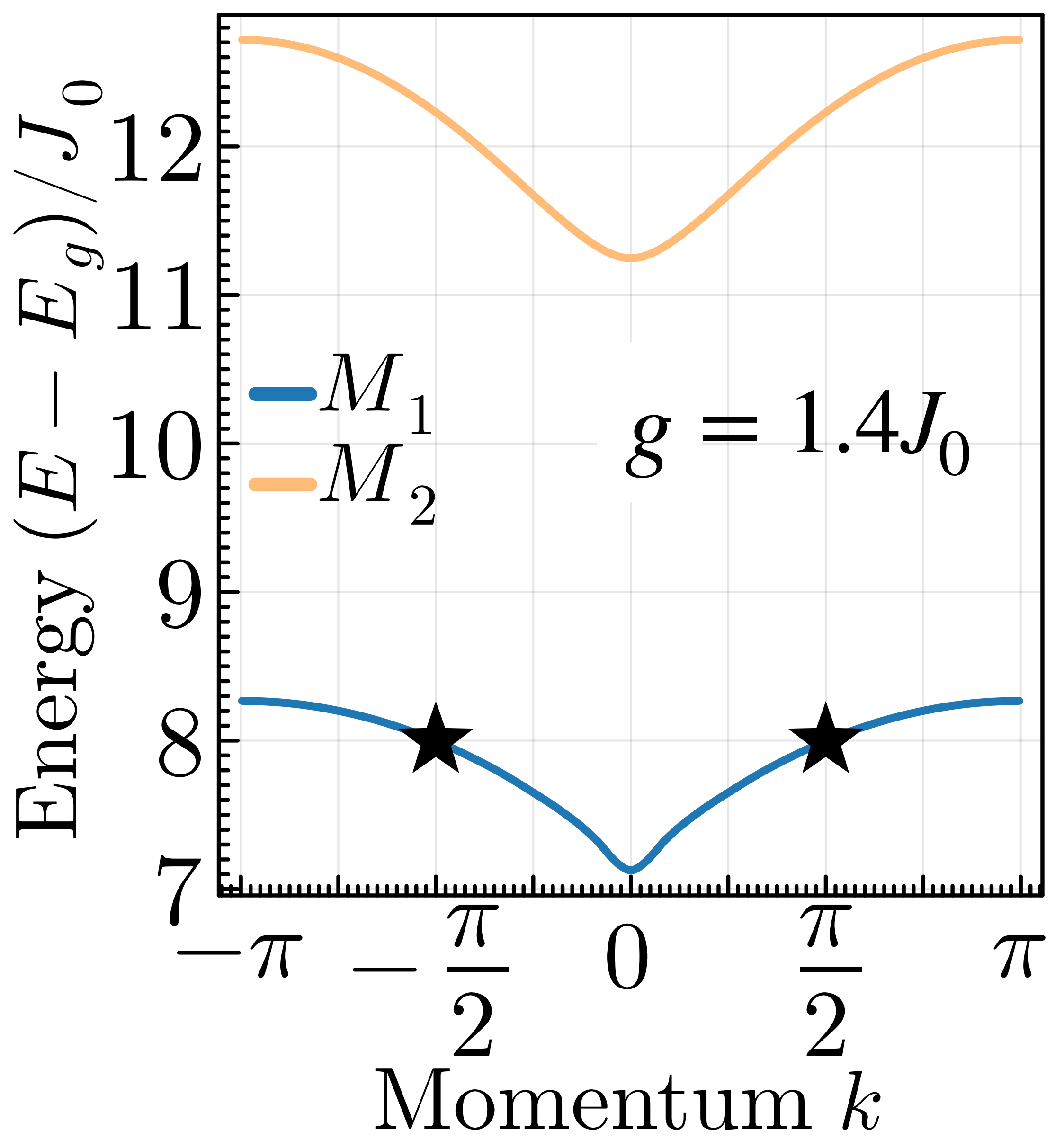
Scatter 1-mesons for $0.5 \leq h_z \leq 2$

- Only observe elastic scattering
- This model has stronger confinement









Meson Scattering with Exponential Decay ($\beta = 1$)

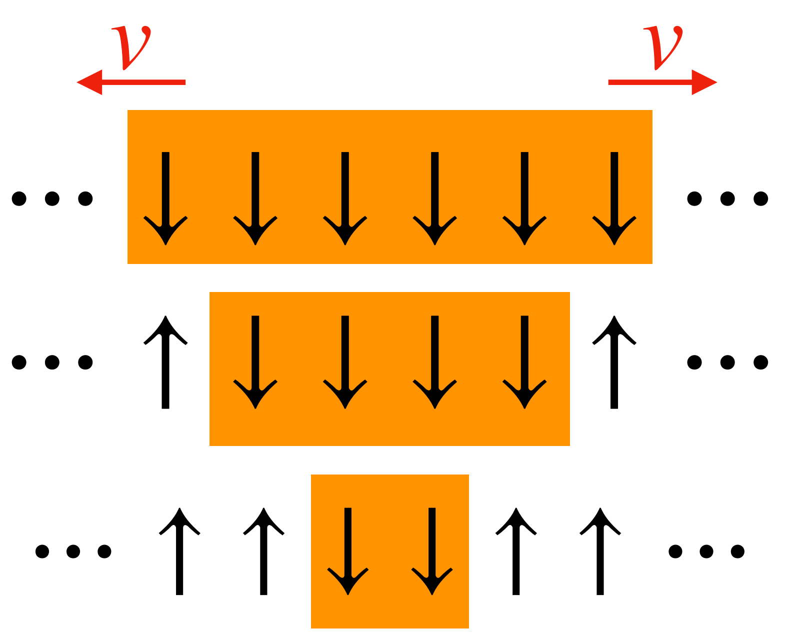
Scatter 1-meson $0.5 \leq g \leq 1.2$

For $g \lessapprox 0.7$

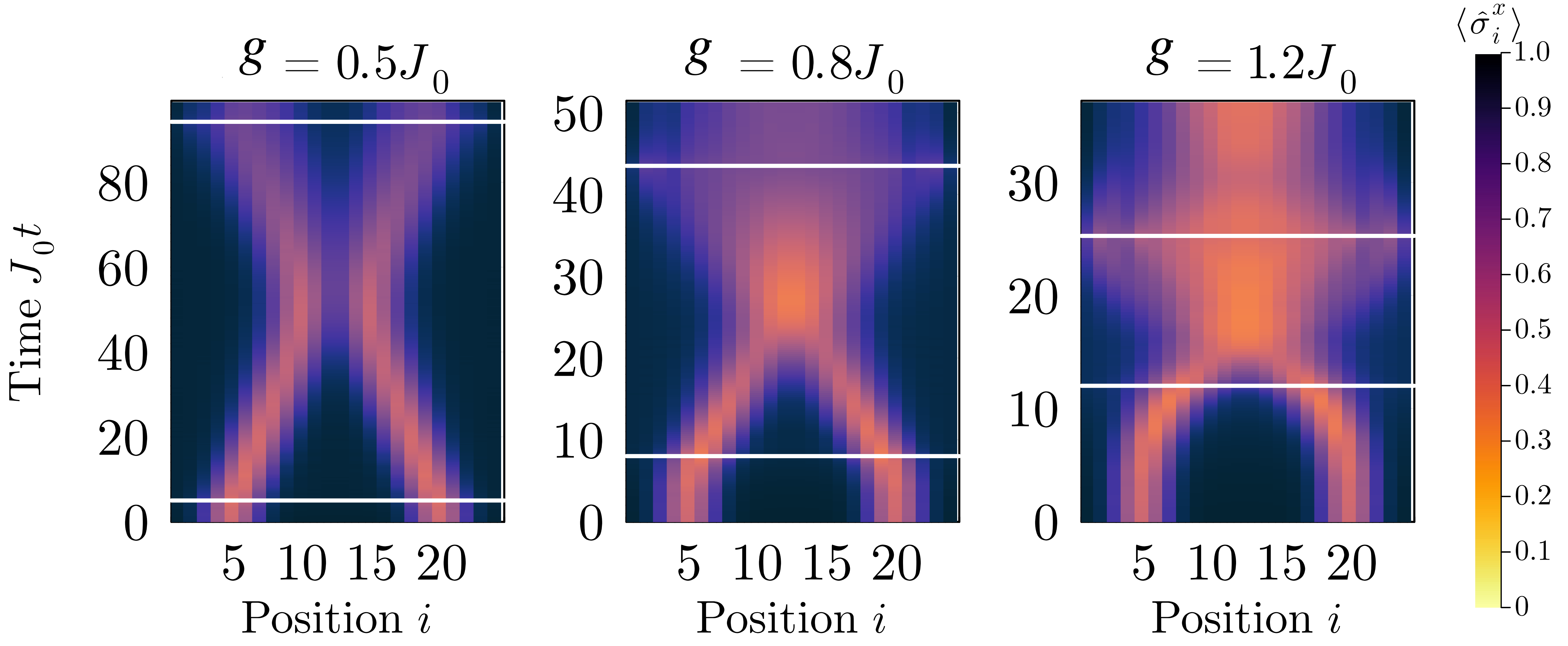
- Primarily elastic scattering

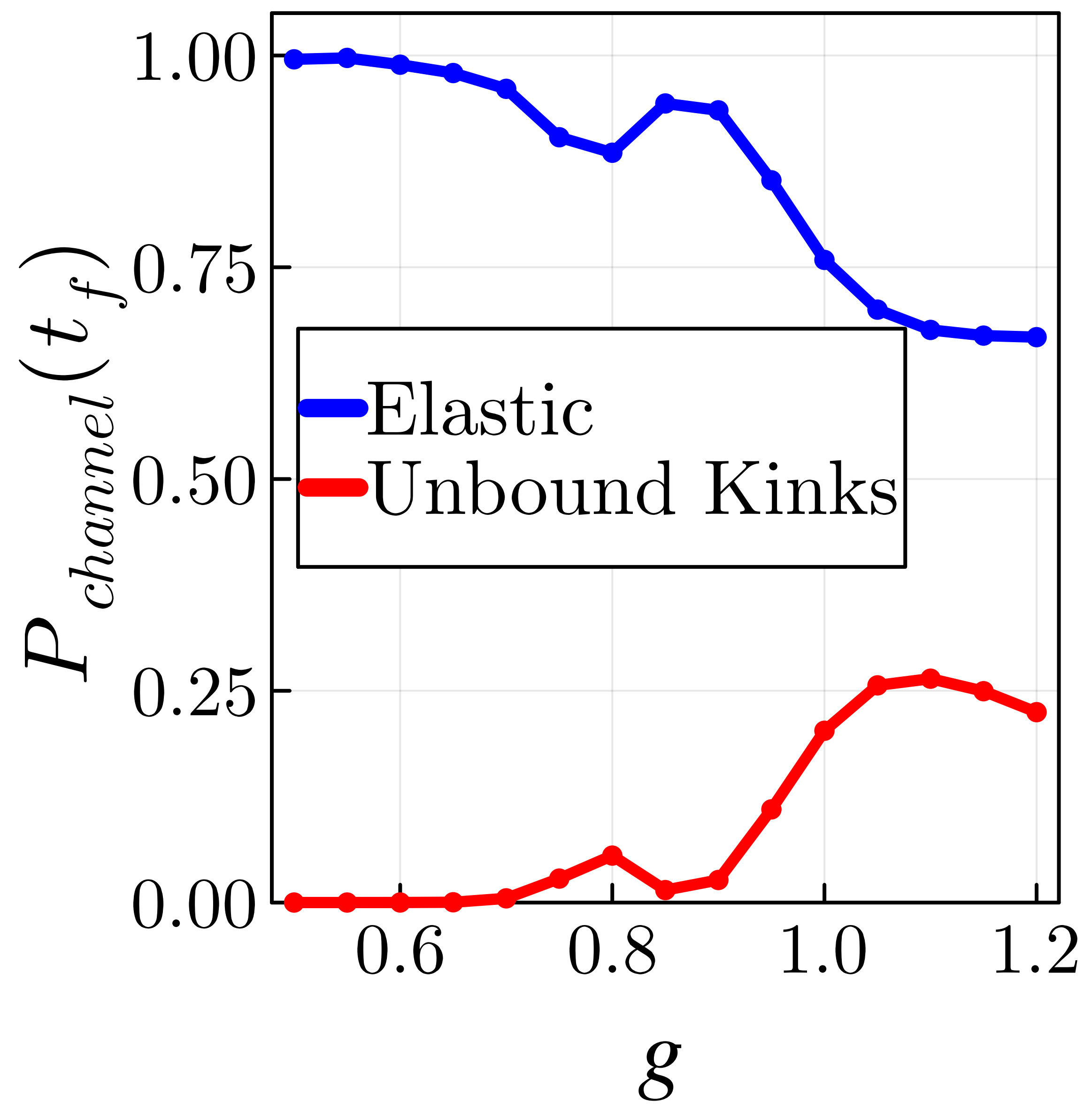
For $g > 0.75$

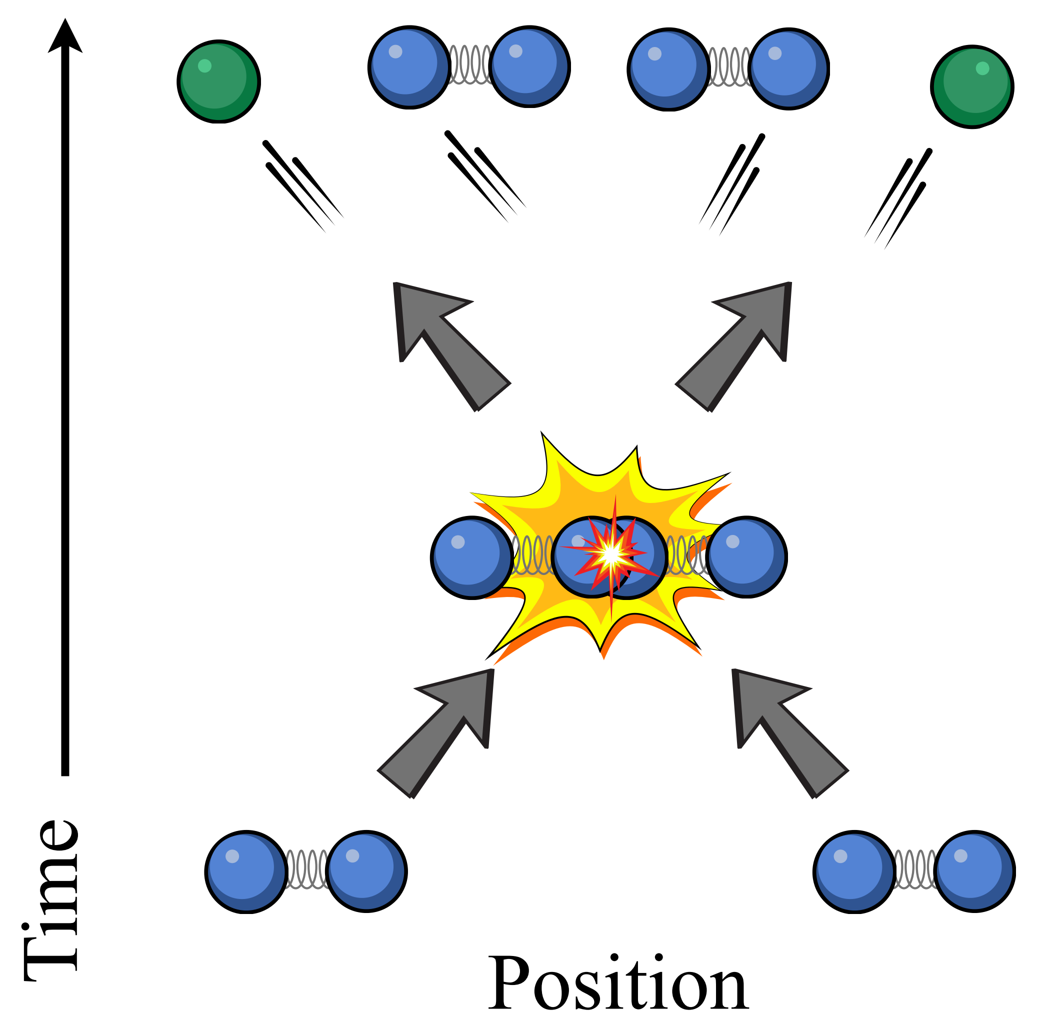
- Elastic Scattering
- Outgoing free kinks



$$\sum_{l=1}^{N/2} \mathscr{P}_{K=2} \cap \mathscr{P}_{Q=l}$$

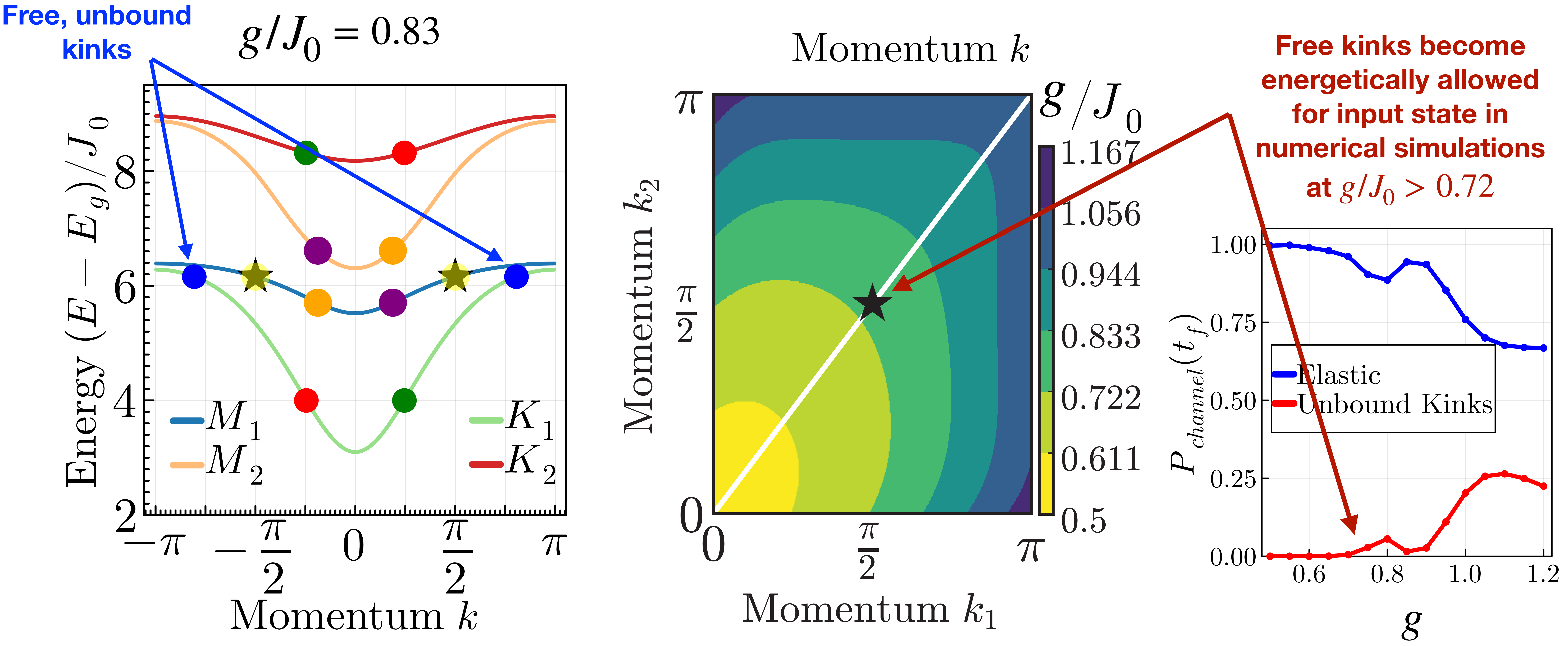






Energetic Analysis of Unbound Kink Scattering

Determine when $E_{K_1}(k_1) + E_{K_1}(k_2) = E_{M_1}\left(\frac{\pi}{2}\right) + E_{M_1}\left(-\frac{\pi}{2}\right)$ using Uniform MPS methods



Summary and Outlook

- Advancing quantum technologies offer are exciting tools to explore **real-time dynamics** and **non-equilibrium** of high energy and nuclear physics

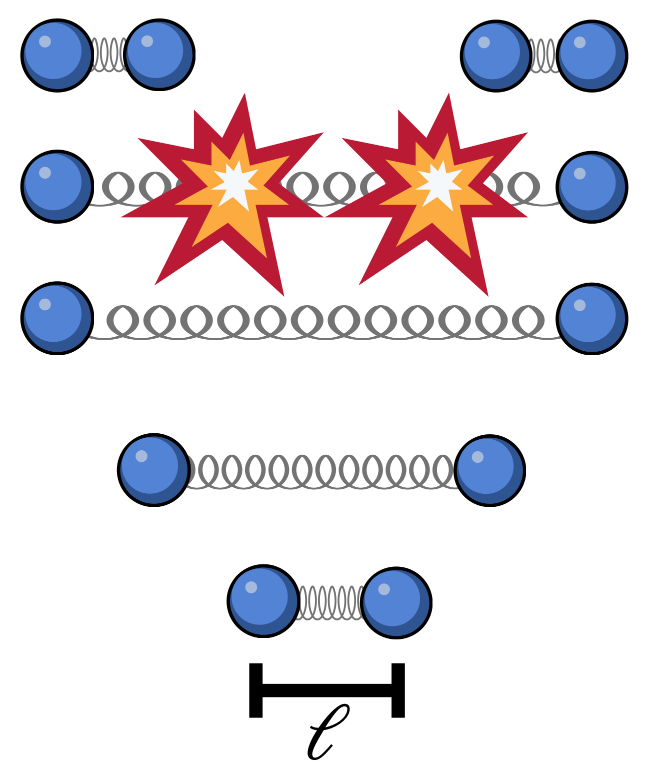
- Spin models offer **simple and experimentally realizable** toy models of bound excitations in the presence of confining forces

- Utilizing state-of-the-art control on trapped-ion simulators, we demonstrate **dynamical string breaking** unveiling a new string-breaking phenomenon

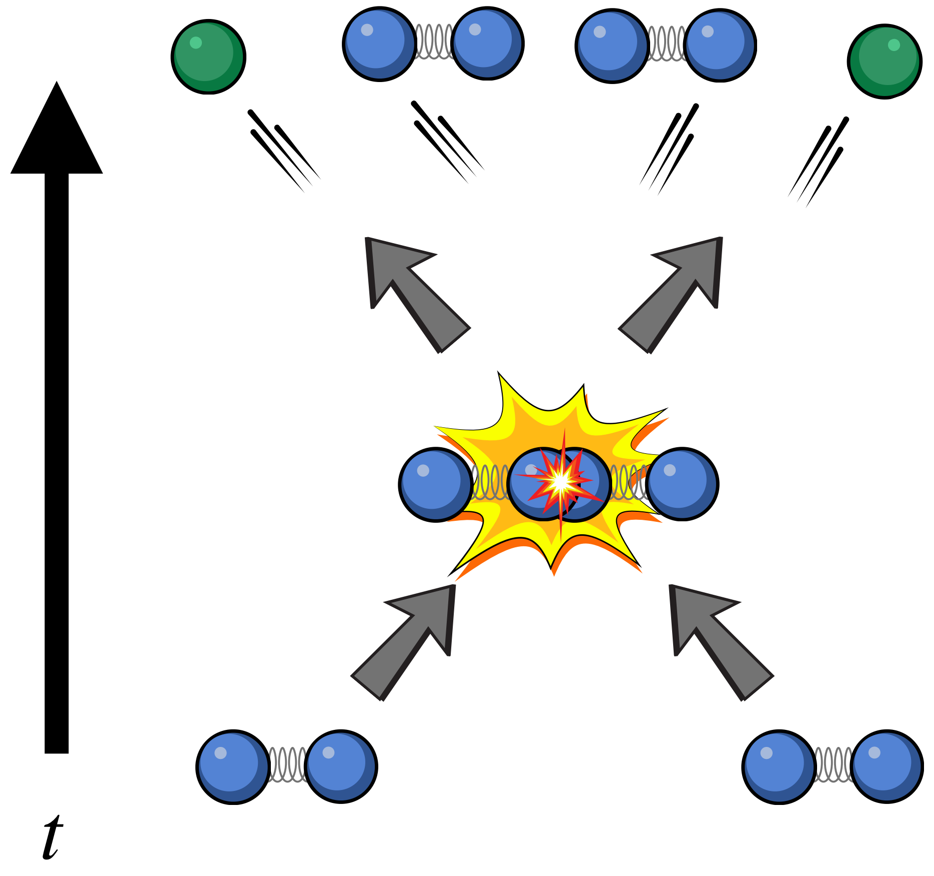
- We address the limiting experimental challenge of wave packet preparation by demonstrating two concrete protocols for meson wave packet preparations

- Demonstrate numerical evidence for prominent inelastic particle production in the form of unbound kinks with a distinct scattering signature

String Breaking



Scattering



Thank you!

Brayden Ware

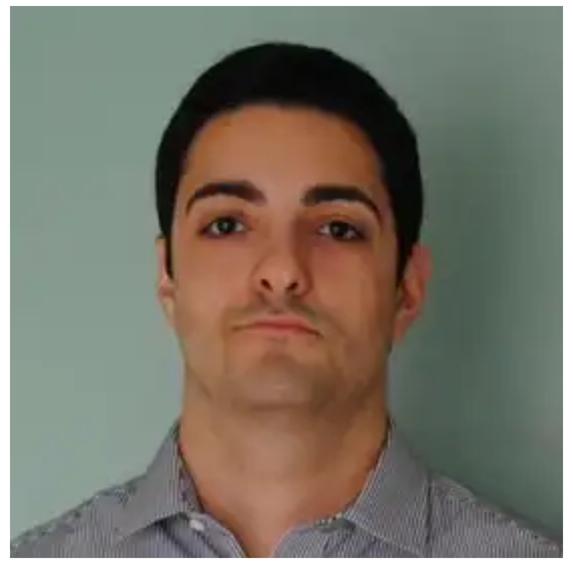
Alessio Lerose*

Arinjoy De*

Henry Luo

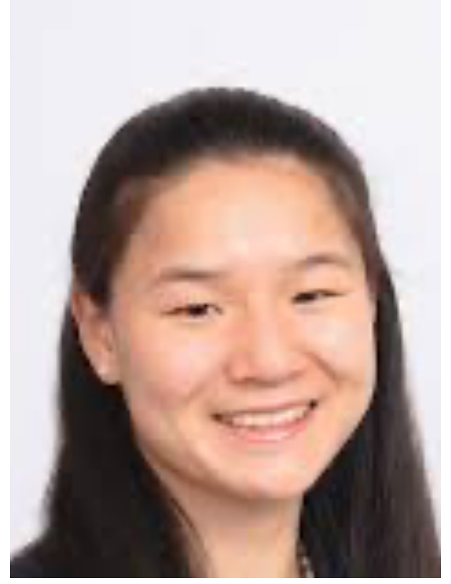
Federica Surace*

Alex Schuckert

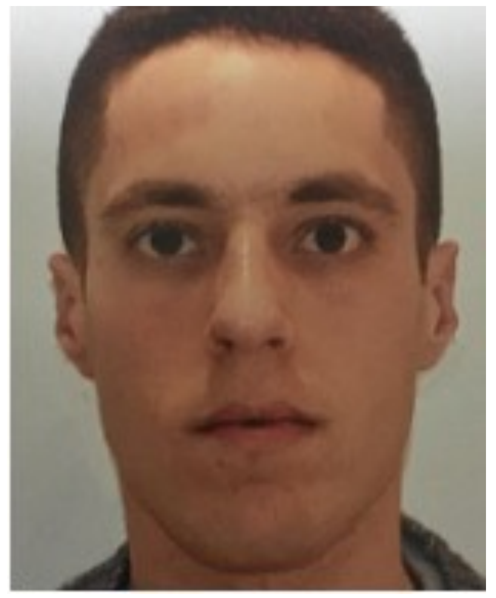


Ron Belyansky

Will Morong



Kate Collins



Or Katz

Chris Monroe

Zohreh Davoudi

Alexey V. Gorshkov

See our additional papers:

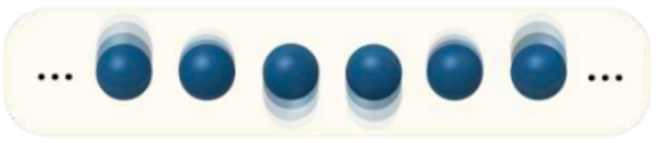
Surace, Federica Maria, et al. "String-Breaking Dynamics in Quantum Adiabatic and Diabatic Processes." *arXiv preprint arXiv:2411.10652* (2024).

Luo, D, et. al. Crossing the string-breaking discontinuous transition in a quantum simulator, work in progress (2025)

Scheme 2: Quantum Bus Mediated State Preparation

Transfer an excitation in the quantum bus register to the spin regsiter

Motional Bus Excitaiton Ω_{ik_t} **Spin Excitaiton**



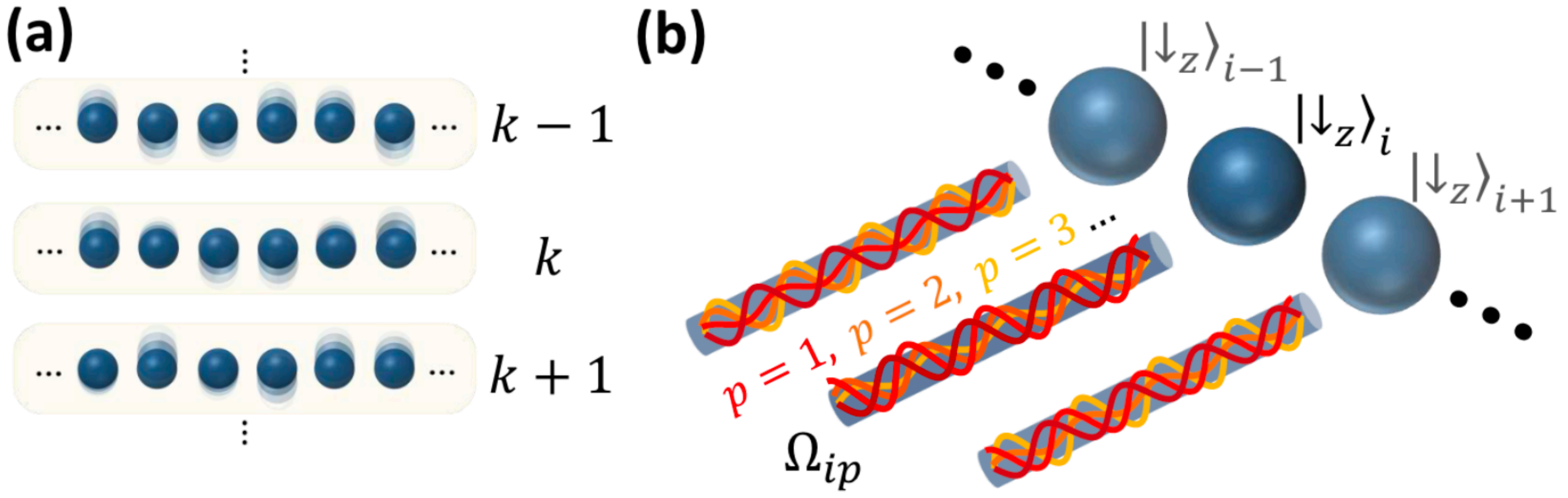
k_t $\longrightarrow$ $\cdots \uparrow \uparrow \downarrow_i \uparrow \uparrow \uparrow \cdots$

For example, the (anti-)Jaynes-Cumming Hamiltonian describes a bosonic-mode bus coupled to spins

$$\delta_{k-1} = \omega_{k-1} - \nu$$

Choose $\nu = \omega_{k_t}$ $\quad \delta_k = \omega_k - \nu$

$$\delta_{k+1} = \omega_{k+1} - \nu$$

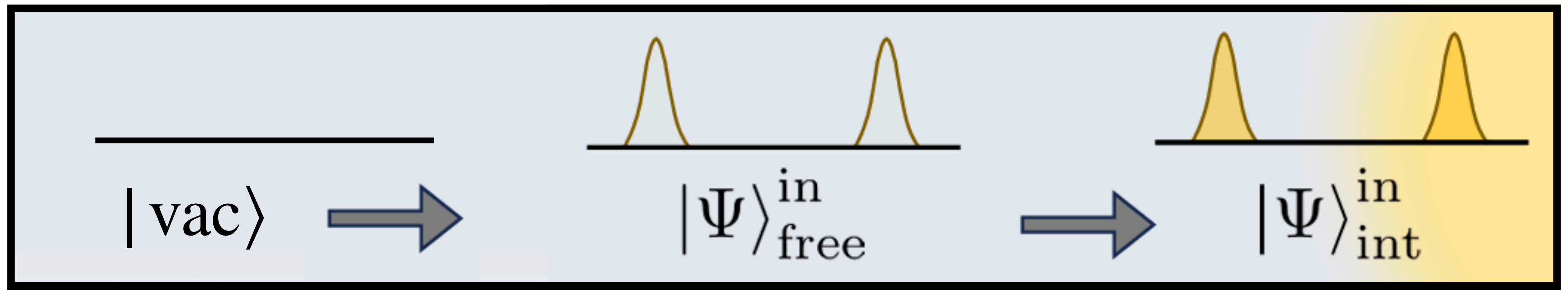


Choose $A_{ik_t} \propto \psi_i^g(x_0, k_0)$

$$H(t) = \sum_{ik} \left(A_{ik} e^{i\delta_k t} \sigma_i^- a_k + A_{ik}^* e^{-i\delta_k t} \sigma_i^+ a_k^\dagger \right) \text{ where } A_{ik} \propto \Omega_i B_{ik}$$

Image: O. Katz and C. Monroe, Phys. Rev. Lett. 131, 033604 (2023)

Gaussian wave packet state preparation



$$|\psi^{\text{in}}_{\text{free}}\rangle = \frac{1}{\mathcal{N}} \sum_{i=1}^{N} \psi^g_i(x_0, k_0)\,|\cdots \uparrow \downarrow_i \uparrow \cdots\rangle$$

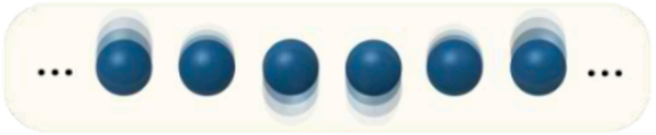
$$|\psi^{\text{in}}_{\text{int}}\rangle = U_r(t_r)\,|\psi^{\text{in}}_{\text{free}}\rangle$$

Quantum-bus-mediated state preparation

Adiabatic Ramp of the transverse field

Transfer an excitation in the quantum bus register to the spin regsiter

Motional Bus Excitation Ω_{ik_t} **Spin Excitation**



k_t → $\cdots \uparrow \uparrow \downarrow_i \uparrow \uparrow \uparrow \cdots$

$$|\psi^{\text{in}}_{\text{free}}\rangle = \frac{1}{\mathcal{N}} \sum_{i=1}^{N} \psi^g_i(x_0, k_0)\,|\cdots \uparrow \downarrow_i \uparrow \cdots\rangle$$

Drive all spins $\Omega_{ik_t} \propto \psi^i_g(x_0, k_0)$

k_t →

(b)