A cold-atom particle collider

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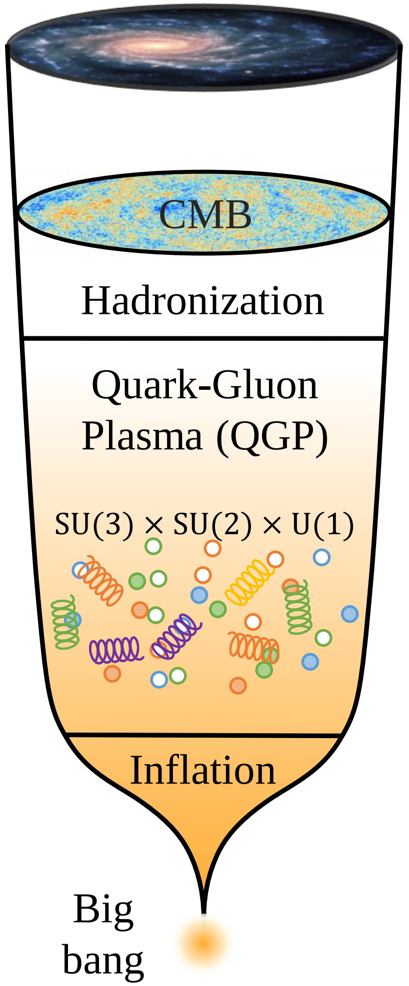
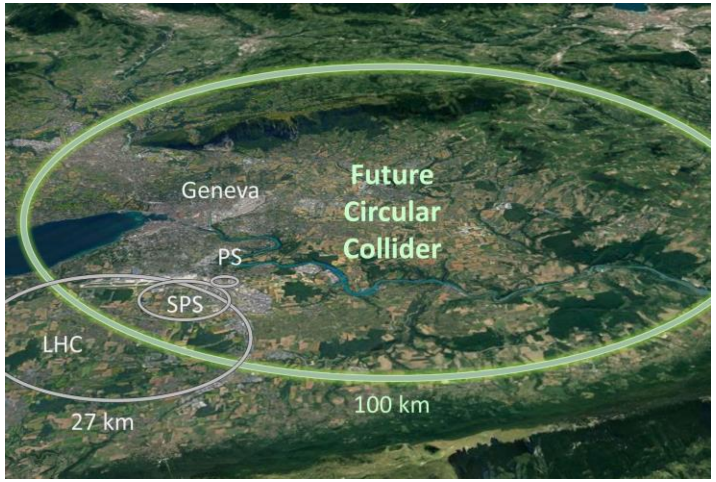
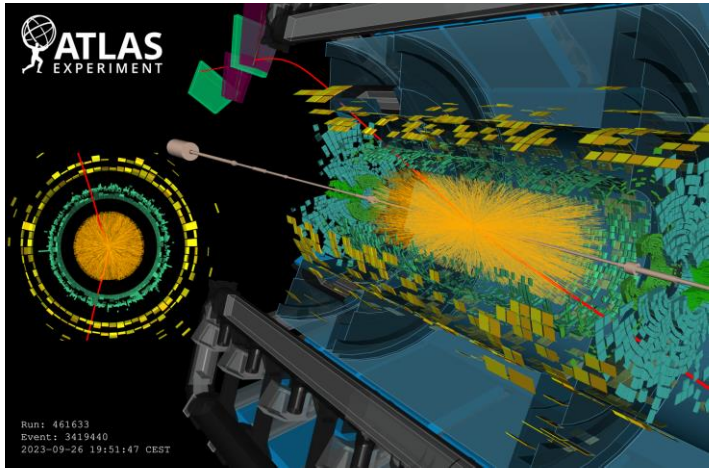
Jian-Wei Pan Lab, Uni-Heidelberg
03.09.2024

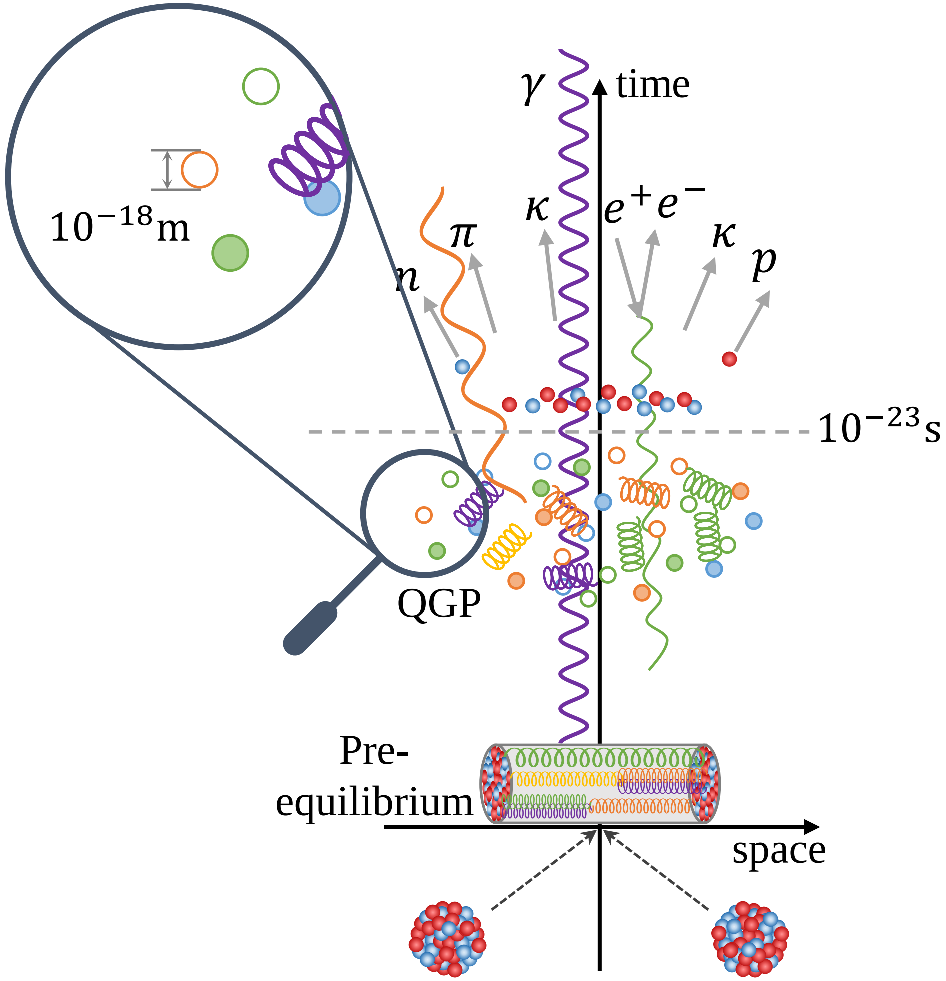
G.X. Su, Jesse Osborne, Jad C. Halimeh, arXiv:2401.05489 (Accepted in PRX Quantum)

Real-time and microscopic dynamics?

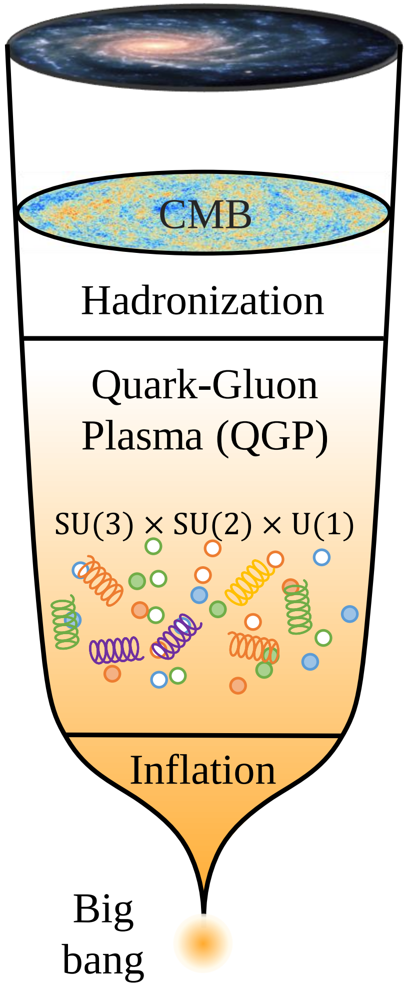






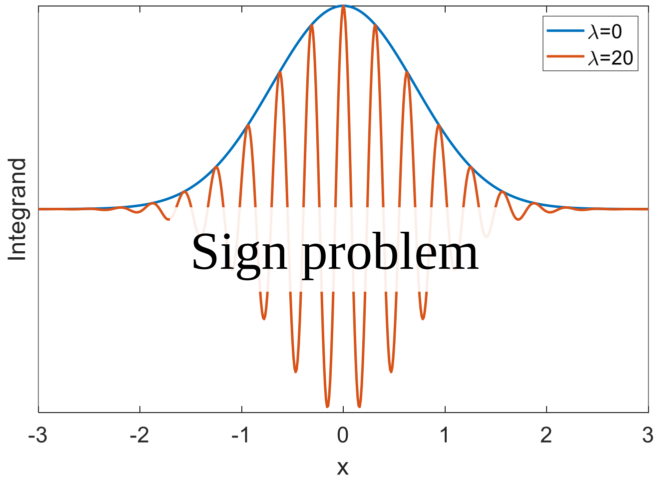


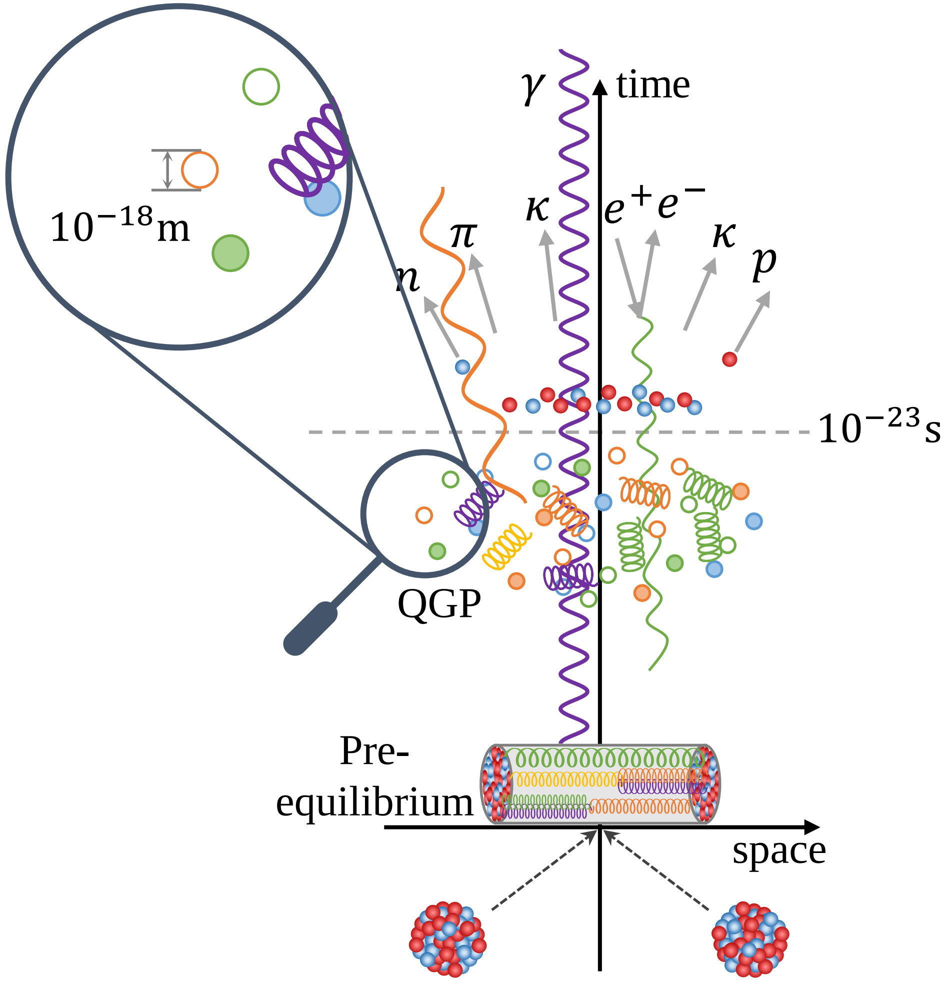
Real-time and microscopic dynamics?



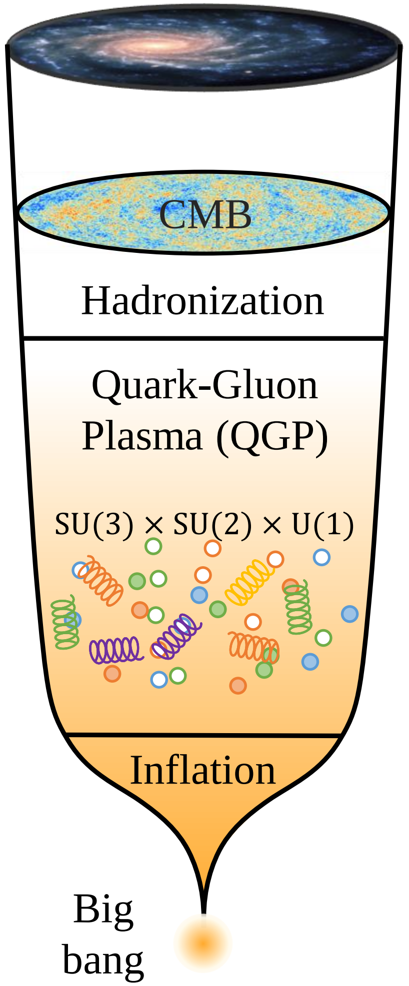
Numerical methods

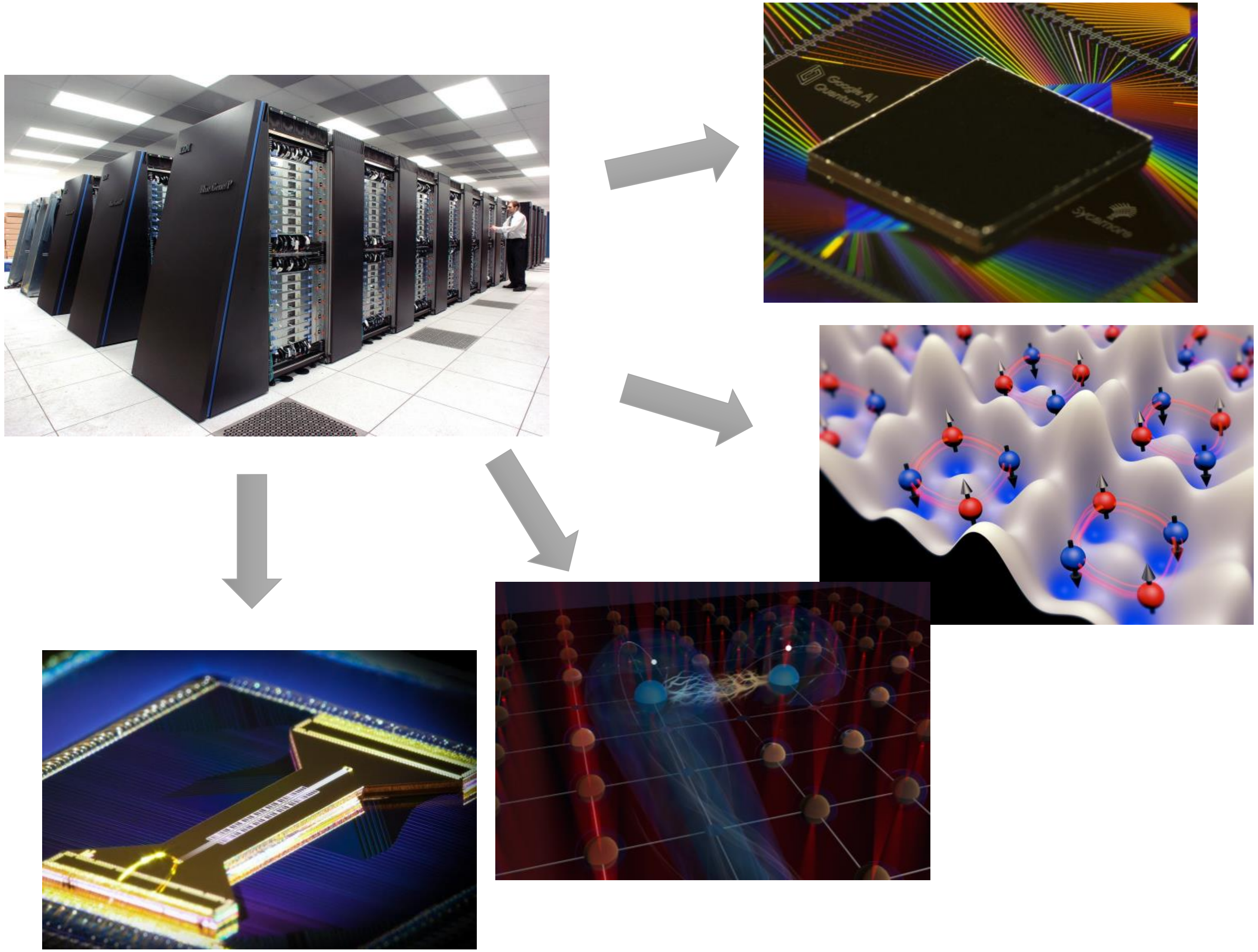
$$Z(\lambda) = \int dx \, \exp(-x^2 + i\,\lambda\,x)$$





Quantum simulation?

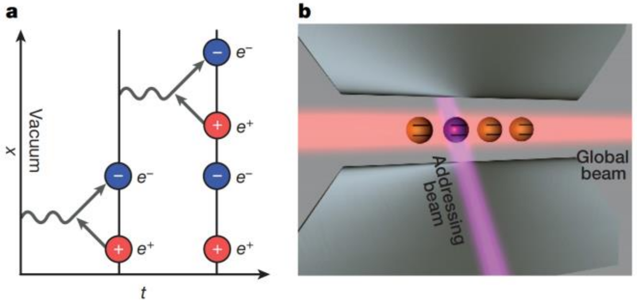




LETTER
doi:10.1038/nature18318

Real-time dynamics of lattice gauge theories with a few-qubit quantum computer

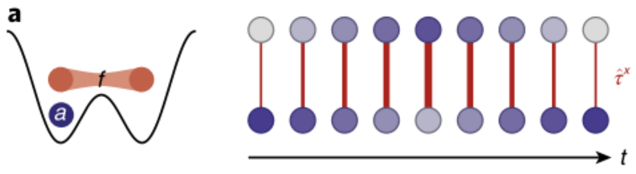
Esteban A. Martinez[1]*, Christine A. Muschik[2,3]*, Philipp Schindler[1], Daniel Nigg[1], Alexander Erhard[1], Markus Heyl[2,4], Philipp Hauke[2,3], Marcello Dalmonte[2,3], Thomas Monz[1], Peter Zoller[2,3] & Rainer Blatt[1,2]



ARTICLES
https://doi.org/10.1038/s41567-019-0649-7
nature physics

Floquet approach to $\mathbb{Z}_2$ lattice gauge theories with ultracold atoms in optical lattices

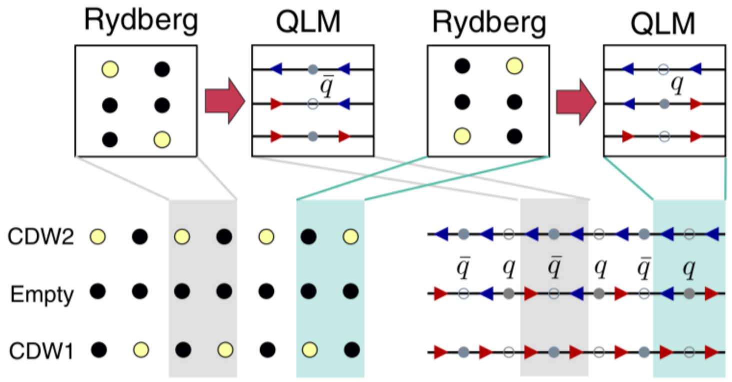
Christian Schweizer[1,2,3], Fabian Grusdt[3,4], Moritz Berngruber[1,3], Luca Barbiero[5], Eugene Demler[6], Nathan Goldman[5], Immanuel Bloch[1,2,3] and Monika Aidelsburger[1,2,3]*



PHYSICAL REVIEW X 10, 021041 (2020)

Lattice Gauge Theories and String Dynamics in Rydberg Atom Quantum Simulators

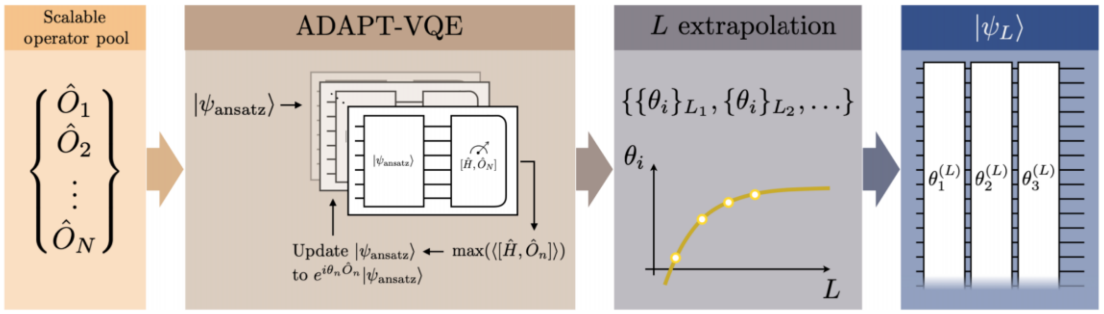
Federica M. Surace,[1,2] Paolo P. Mazza,[1,3] Giuliano Giudici,[1,2,3] Alessio Lerose,[1,3] Andrea Gambassi,[1,3] and Marcello Dalmonte[1,2]



PRX QUANTUM 5, 020315 (2024)

Scalable Circuits for Preparing Ground States on Digital Quantum Computers: The Schwinger Model Vacuum on 100 Qubits

Roland C. Farrell,* Marc Illa,† Anthony N. Ciavarella,‡ and Martin J. Savage§



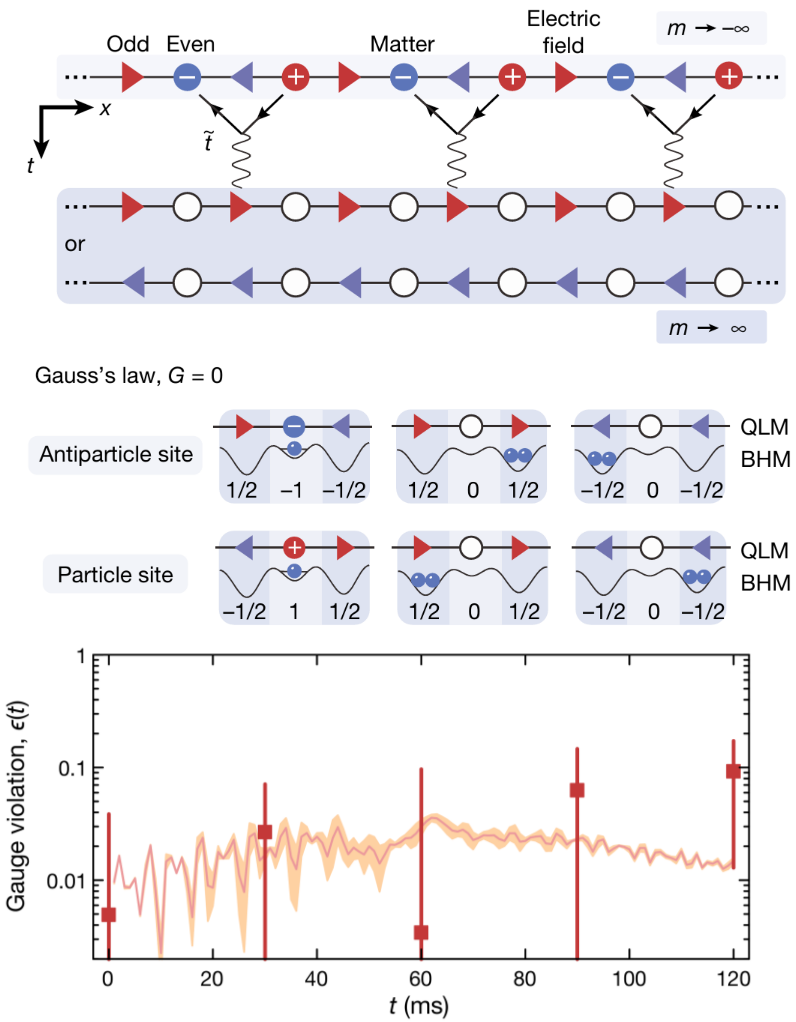
Article

Observation of gauge invariance in a 71-site Bose–Hubbard quantum simulator

https://doi.org/10.1038/s41586-020-2910-8

Received: 19 March 2020

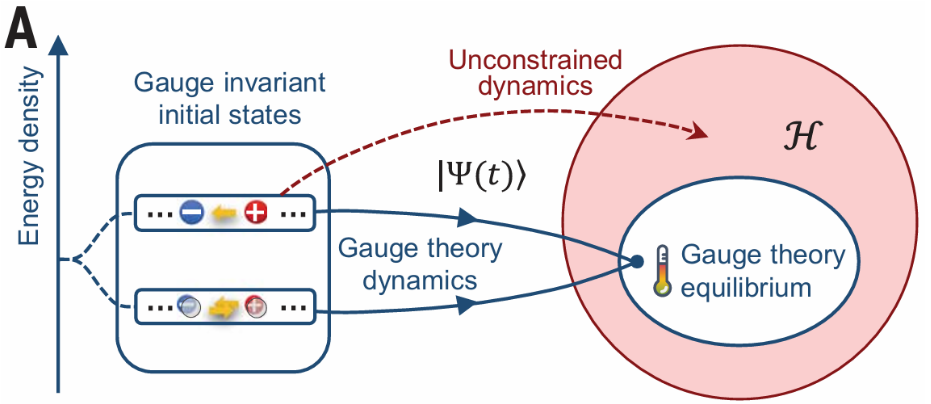
Bing Yang[1,2,3,4,8], Hui Sun[1,2,3,4], Robert Ott[5], Han-Yi Wang[1,2,3,4], Torsten V. Zache[5], Jad C. Halimeh[5,6,7], Zhen-Sheng Yuan[1,2,3,4]✉, Philipp Hauke[5,6,7]✉ & Jian-Wei Pan[1,2,3,4]✉

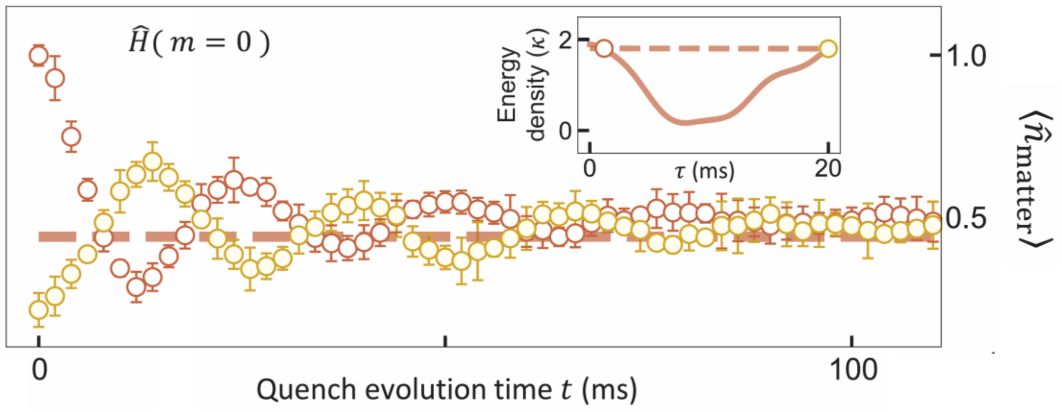


QUANTUM SIMULATION

Thermalization dynamics of a gauge theory on a quantum simulator

Zhao-Yu Zhou[1,2,3,4]*†, Guo-Xian Su[1,2,3,4]†, Jad C. Halimeh[5], Robert Ott[6], Hui Sun[1,2,3,4], Philipp Hauke[5], Bing Yang[3,7]‡, Zhen-Sheng Yuan[1,2,3,4,8], Jürgen Berges[6], Jian-Wei Pan[1,2,3,4,8]



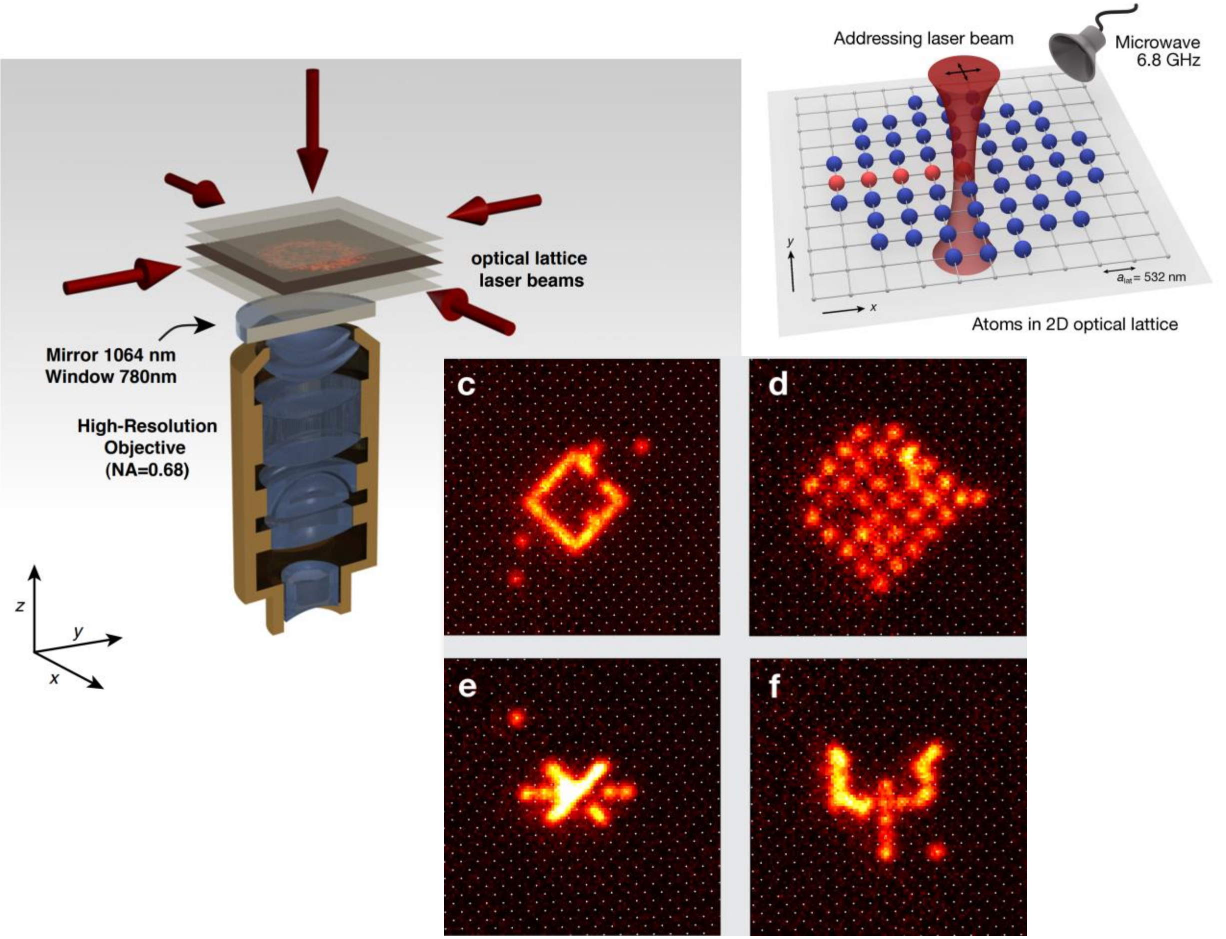


ARTICLE

doi:10.1038/nature09827

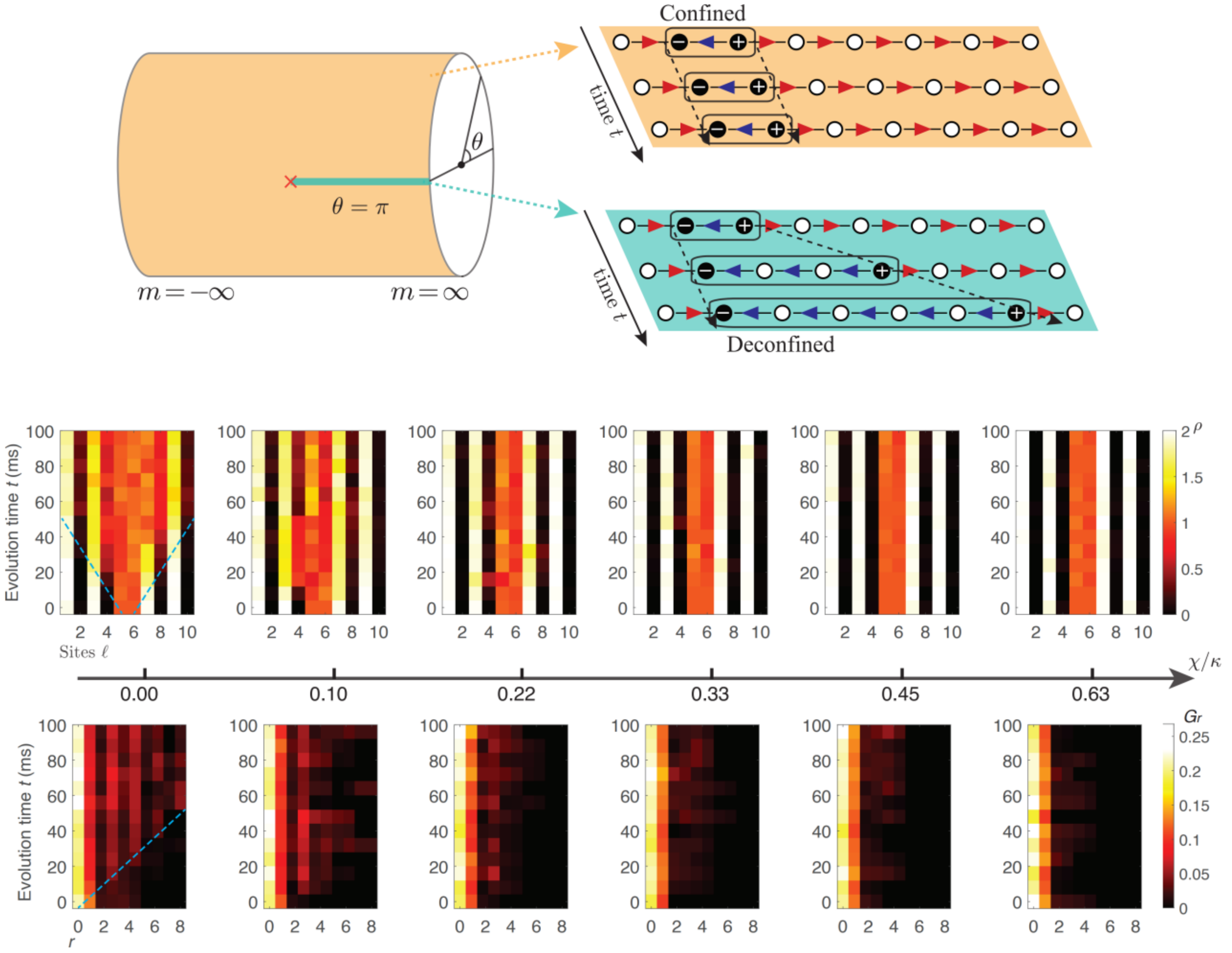
Single-spin addressing in an atomic Mott insulator

Christof Weitenberg[1], Manuel Endres[1], Jacob F. Sherson[1]†, Marc Cheneau[1], Peter Schauß[1], Takeshi Fukuhara[1], Immanuel Bloch[1,2] & Stefan Kuhr[1]



Observation of microscopic confinement dynamics by a tunable topological θ-angle

Wei-Yong Zhang,[1,*] Ying Liu,[1,*] Yanting Cheng,[2,*] Ming-Gen He,[1] Han-Yi Wang,[1] Tian-Yi Wang,[1] Zi-Hang Zhu,[1] Guo-Xian Su,[1] Zhao-Yu Zhou,[1] Yong-Guang Zheng,[1] Hui Sun,[1] Bing Yang,[3] Philipp Hauke,[4,5] Wei Zheng,[1,6,7] Jad C. Halimeh,[8,9] Zhen-Sheng Yuan,[1,6,7] and Jian-Wei Pan[1,6,7]



PHYSICAL REVIEW D VOLUME 55, NUMBER 10 15 MAY 1997

Scattering processes in the massive Schwinger model

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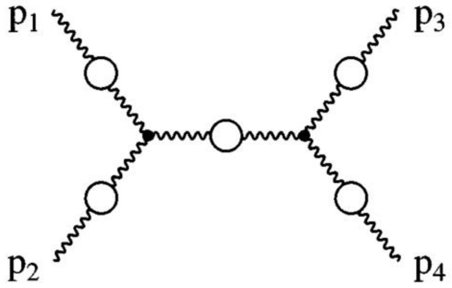
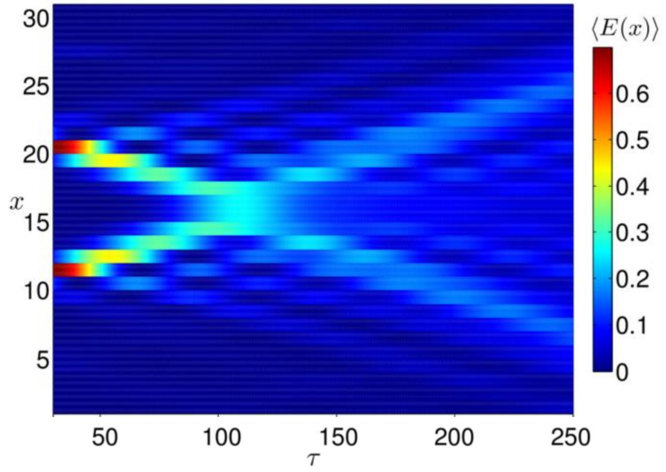
Center for Theoretical Physics, Laboratory for Nuclear Science, and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
and Institut für theoretische Physik d. Universität Wien, Boltzmanngasse 5, 1090 Wien, Austria



PHYSICAL REVIEW X 6, 011023 (2016)

Real-Time Dynamics in U(1) Lattice Gauge Theories with Tensor Networks

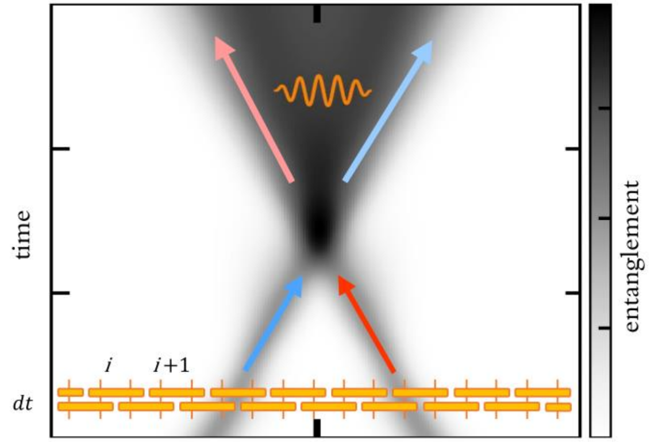
T. Pichler,[1] M. Dalmonte,[2,3] E. Rico,[4,5,6] P. Zoller,[2,3] and S. Montangero[1]



PHYSICAL REVIEW D 104, 114501 (2021)

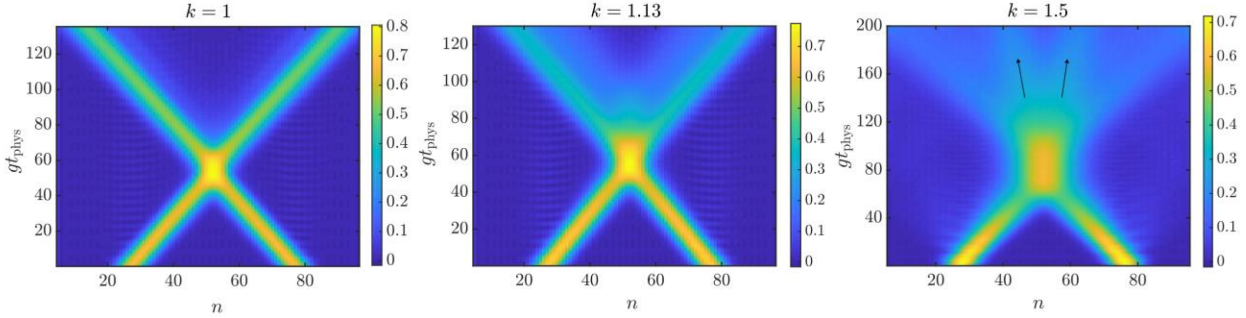
Entanglement generation in (1+1)D QED scattering processes

Marco Rigobello,* Simone Notarnicola, Giuseppe Magnifico, and Simone Montangero



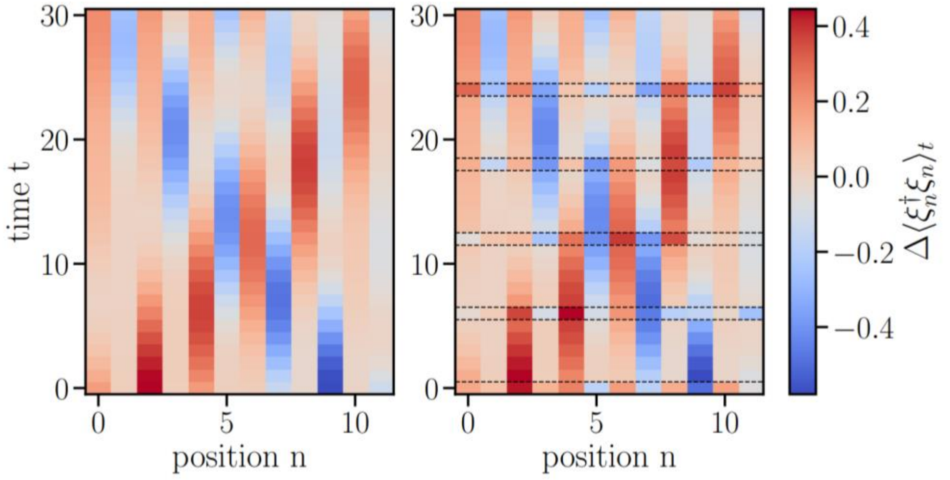
Real-time scattering in the lattice Schwinger model

Irene Papaefstathiou,[1,2] Johannes Knolle,[3,2,4] and Mari Carmen Bañuls[1,2]



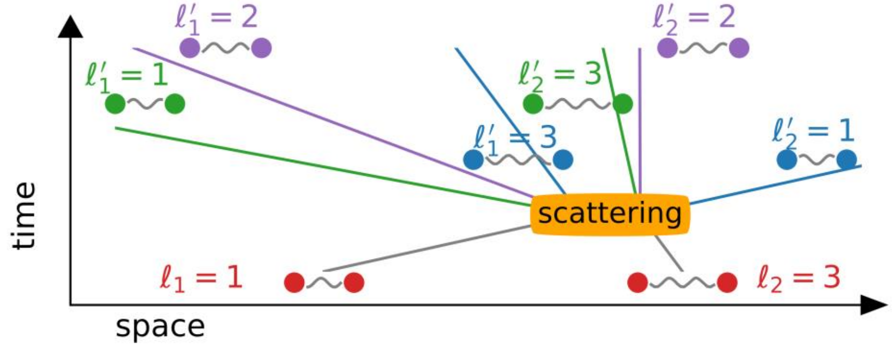
Fermionic wave packet scattering: a quantum computing approach

Yahui Chai,[1,*] Arianna Crippa,[1,2] Karl Jansen,[1,3] Stefan Kühn,[1]
Vincent R. Pascuzzi,[4,†] Francesco Tacchino,[5] and Ivano Tavernelli[5]



Scattering of mesons in quantum simulators

Federica Maria Surace[1,2,*] and Alessio Lerose[3,*]

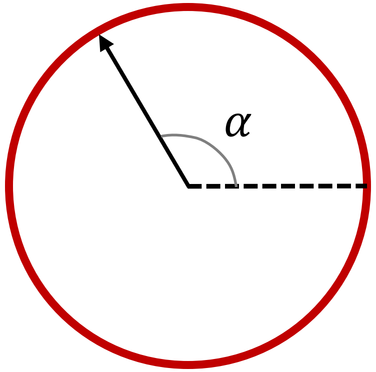


The U(1) quantum link model

Gauge invariance: Gauss's Law

Kogut, Susskind, *Phys. Rev. D* (1975)
Hauke. *et al*. *Phys. Rev. X* (2014)
Wiese *Ann. Phys.* (2013)

$\hat{H}_{\mathrm{QED}}$ of fermionic fields $\hat{\psi}(x)$



Local U(1) gauge transformation

$\hat{\psi}(x) \rightarrow e^{ie\alpha(x)}\hat{\psi}(x), \alpha(x) \in (0,2\pi]$

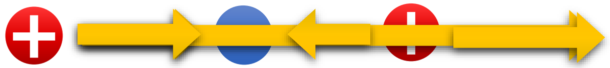
$\hat{H}_{\mathrm{QED}}$ Invariant

Kinetic · Rest mass · Gauge field

$$\hat{H}_{\mathrm{QED}} = \int dx \left(\overbrace{i\hat{\psi}^{\dagger}(x)\gamma_0\,\gamma_1\left(\partial_\mu + ie\hat{A}_\mu\right)\hat{\psi}(x) + \mathrm{H.c.}}^{\text{Kinetic}} \right) + \overbrace{m\hat{\psi}^{\dagger}(x)\gamma_0\hat{\psi}(x)}^{\text{Rest mass}} + \overbrace{\frac{1}{2}\hat{E}^2}^{\text{Gauge field}}$$

$$\begin{cases} \hat{\psi}(x) \rightarrow e^{ie\alpha(x)}\hat{\psi}(x), \alpha(x) \in (0,2\pi] \\ \hat{A} \rightarrow \hat{A} - \partial_\mu \alpha \end{cases} \Rightarrow \left(\partial_x E - e\hat{\psi}^{\dagger}\gamma^0\hat{\psi}\right)|\Psi_{\mathrm{phy}}\rangle = 0$$

Local gauge invariance



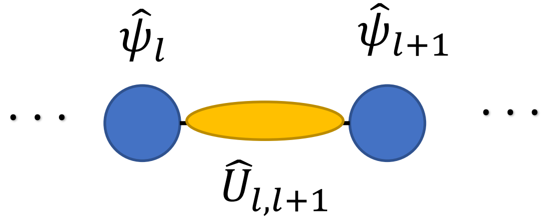
Gauss's Law $(\nabla \cdot \vec{E} - \rho)|\Psi_{\mathrm{phy}}\rangle = 0$

Lattice QED $\hat{G}_l|\Psi\rangle = (\hat{E}_{l,l+1} - \hat{E}_{l,l-1} - e\,\hat{\psi}_l^{\dagger}\hat{\psi}_l)|\Psi\rangle = 0, \quad [\hat{H}_{\mathrm{lat-QED}}, \hat{G}_l] = 0$

Kogut, Susskind, *Phys. Rev. D* (1975)
Hauke. *et al*. *Phys. Rev. X* (2014)
Wiese *Ann. Phys.* (2013)
Yang. *et al. Nature* (2020)

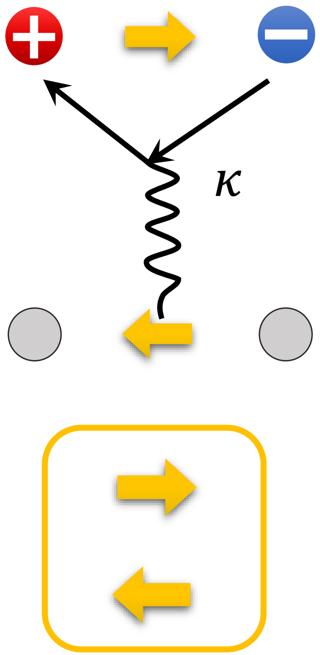
The quantum link model

Dynamical gauge fields couple
Fermionic matter fields by “spin flip”

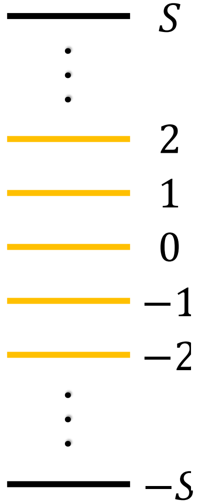


$H_{\text{lat-QEI}}$

$\hat{A}$



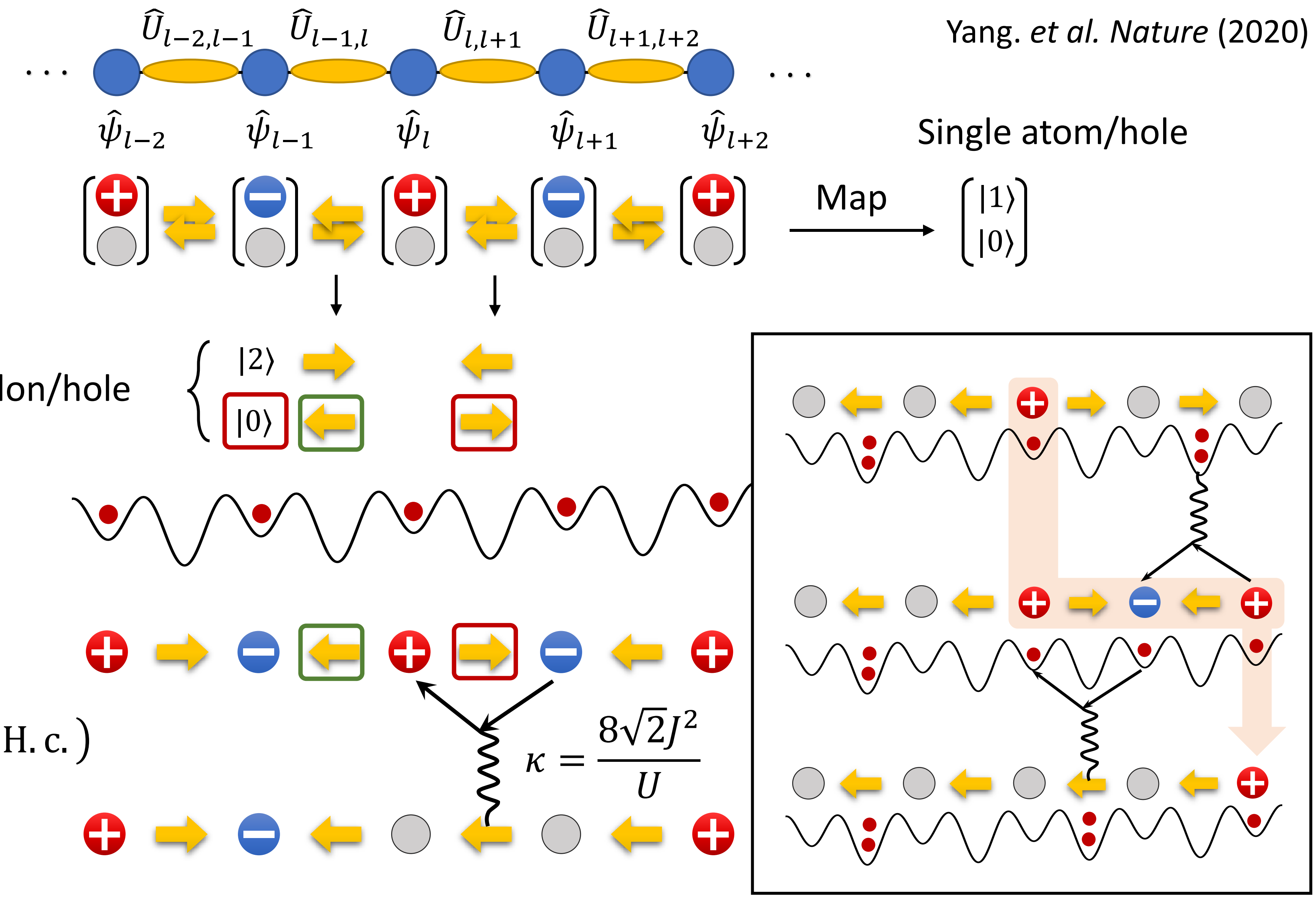
“Quantum link



Realization on the quantum simulator

Mapping onto Bose-Hubbard quantum simulator

Kogut, Susskind, *Phys. Rev. D* (1975)
Hauke. *et al. Phys. Rev. X* (2014)
Wiese *Ann. Phys.* (2013)
Yang. *et al. Nature* (2020)



Staggered Fermions

Gauge links —Map→ Doublon/hole

Bosons in staggered optical superlattice

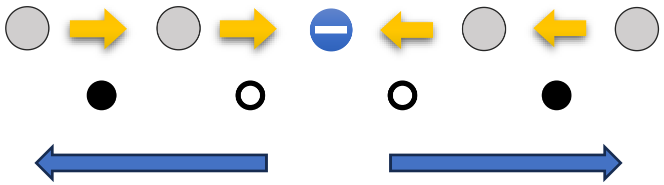
Kinetic $\frac{\kappa}{2}\left(\hat{\psi}_l \hat{U}_{l,l+1} \hat{\psi}_{l+1} + \mathrm{H.c.}\right)$

Preparing a moving wavepacket

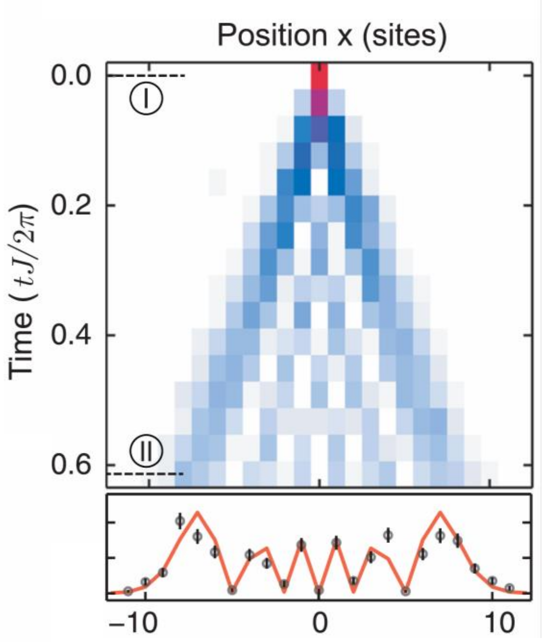
Low-energy effective theory:

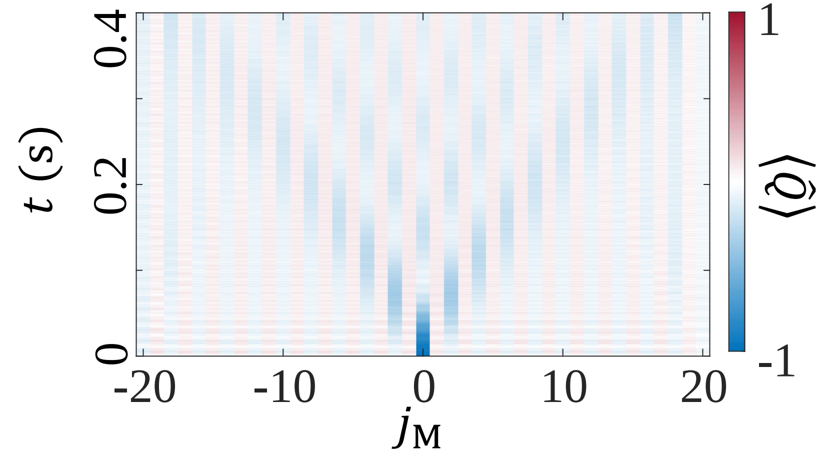
Two-component Fermi-Hubbard Model

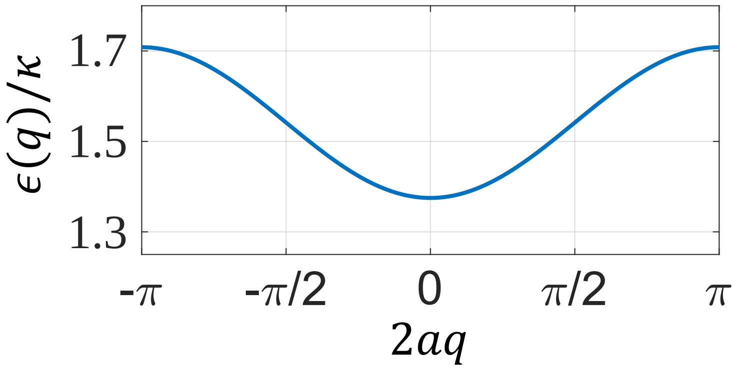
$$H_{\text{gauge}} = \frac{\kappa}{2}\sum_l (\hat{\psi}_l \hat{S}^+_{l,l+1}\hat{\psi}_{l+1} + \text{H.c.}) + m\sum_l \hat{\psi}^\dagger_l \hat{\psi}_l \quad \xrightarrow[\tilde{t} = \kappa^2/(8ma^2)]{m \gtrsim \kappa} \quad \hat{H}_{(\text{A})\text{P}} = -\tilde{t}\sum_{\ell_{(\text{A})\text{P}}} (\hat{\psi}^\dagger_{\ell_{(\text{A})\text{P}}} \hat{\psi}_{\ell_{(\text{A})\text{P}}+1} + \text{H.c.})$$



The particle propagates both ways





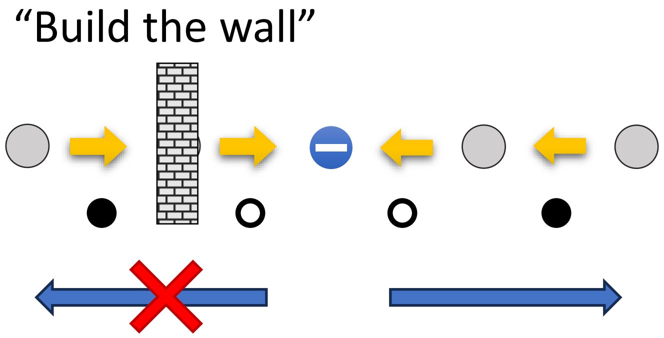


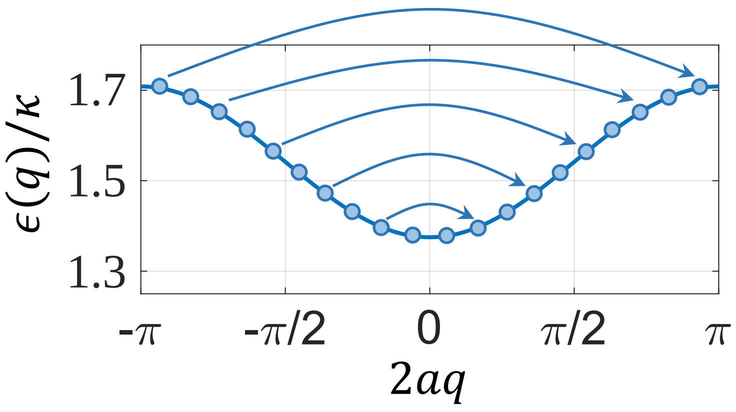
QUANTUM WALKS

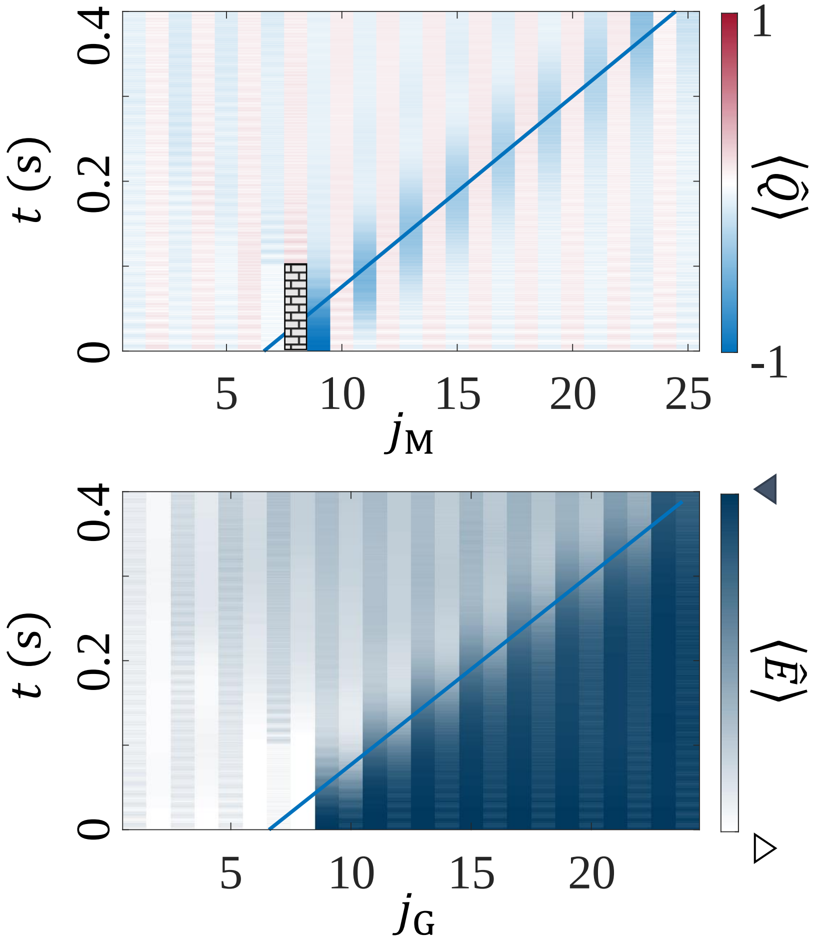
Strongly correlated quantum walks in optical lattices

Philipp M. Preiss,[1] Ruichao Ma,[1] M. Eric Tai,[1] Alexander Lukin,[1] Matthew Rispoli,[1] Philip Zupancic,[1*] Yoav Lahini,[2] Rajibul Islam,[1] Markus Greiner[1]†

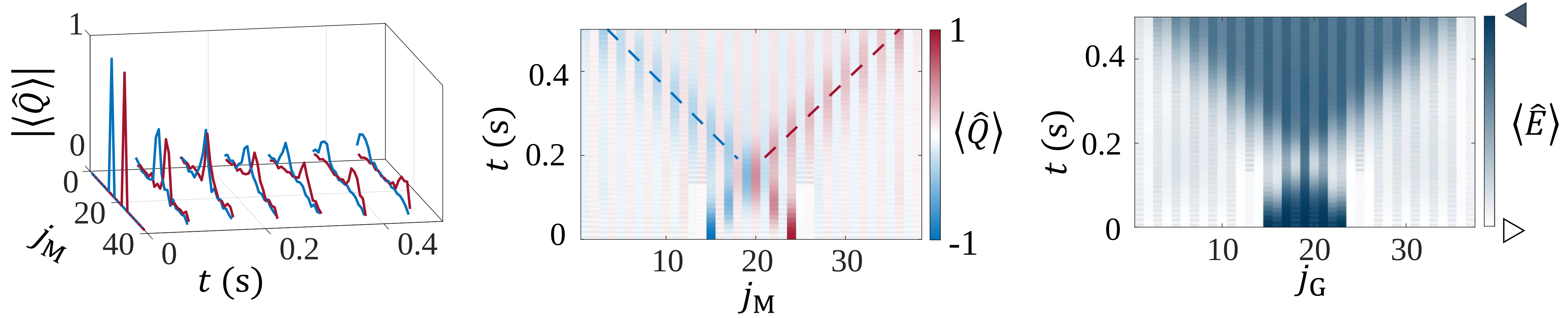
Preparing moving wave packets of an elementary (anti)particle







Particle-antiparticle collision

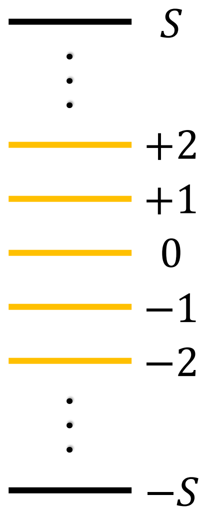


Confinement dynamics

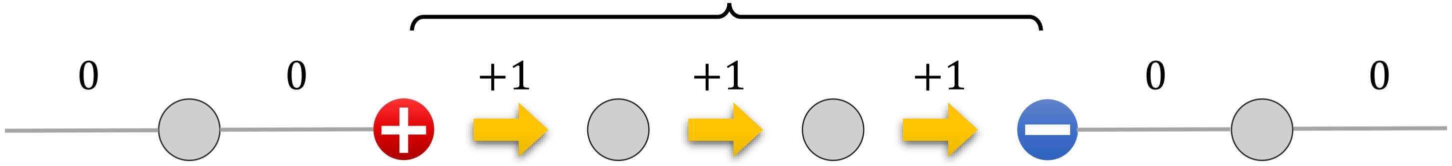
Confinement in (1+1)D QED

$$H_{\text{lat-QED}} = \frac{\kappa}{2}\sum_l \left(\hat{\psi}_l^\dagger \hat{U}_{l,l+1}\hat{\psi}_{l+1} + \text{H.c.}\right) + m(-1)^l\left(\hat{\psi}_l^\dagger\hat{\psi}_l\right) + \frac{1}{2}E_{l,l+1}^2$$

Spin-S Quantum link model



String tension from the gauge coupling term

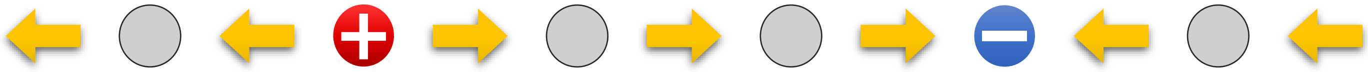


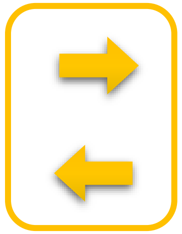
But...

No string tension!

Gauge coupling is a overall energy shift $\left(+\frac{1}{2}\right)^2 = \left(-\frac{1}{2}\right)^2$

Spin-1/2 Quantum link model

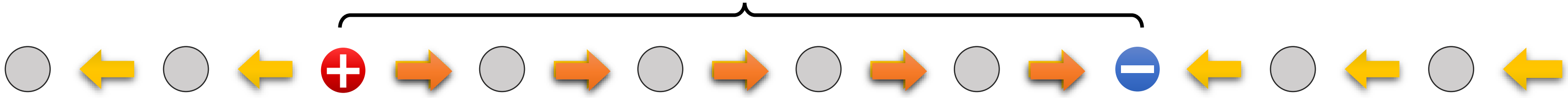




$$H_{\mathrm{Lat-QED}} = \sum_l -\frac{\kappa}{2a}\left(\hat{\psi}_l \hat{S}^{+}_{l,l+1}\hat{\psi}_{l+1} + \mathrm{H.c.}\right) + m\,\hat{\psi}_l^{\dagger}\hat{\psi}_l + a\chi(-1)^l \hat{S}^{z}_{l,l+1}$$

String energy $E \sim \chi L$

Gauge theory

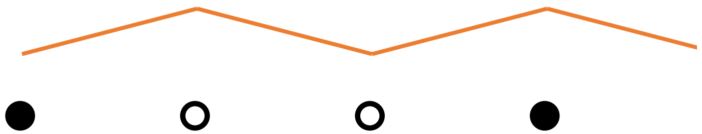


“background field”

Break degeneracy
between the two vacua!

Staggered potential χ

Spin Model



(1+1)D QED

Toy model

Charge Shielding and Quark Confinement in the Massive Schwinger Model*

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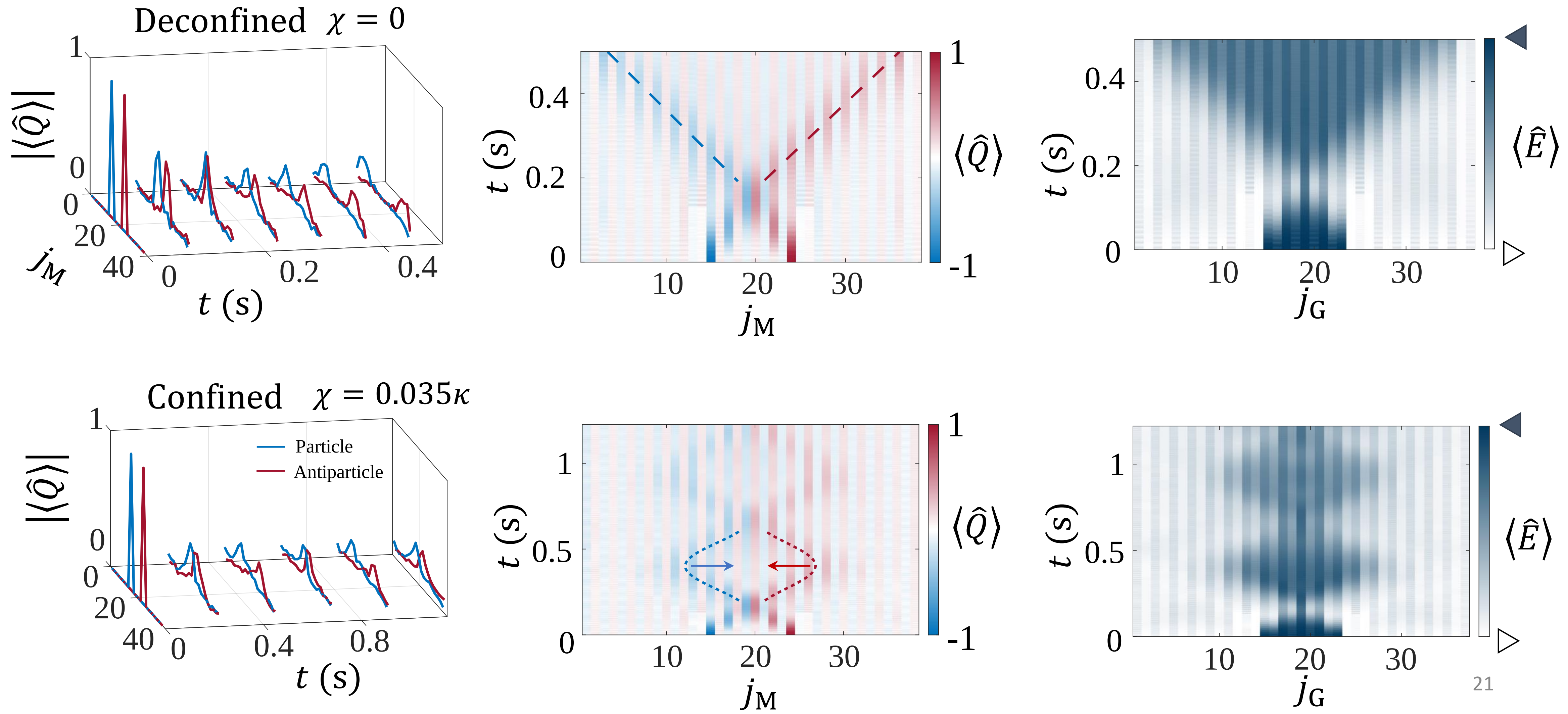
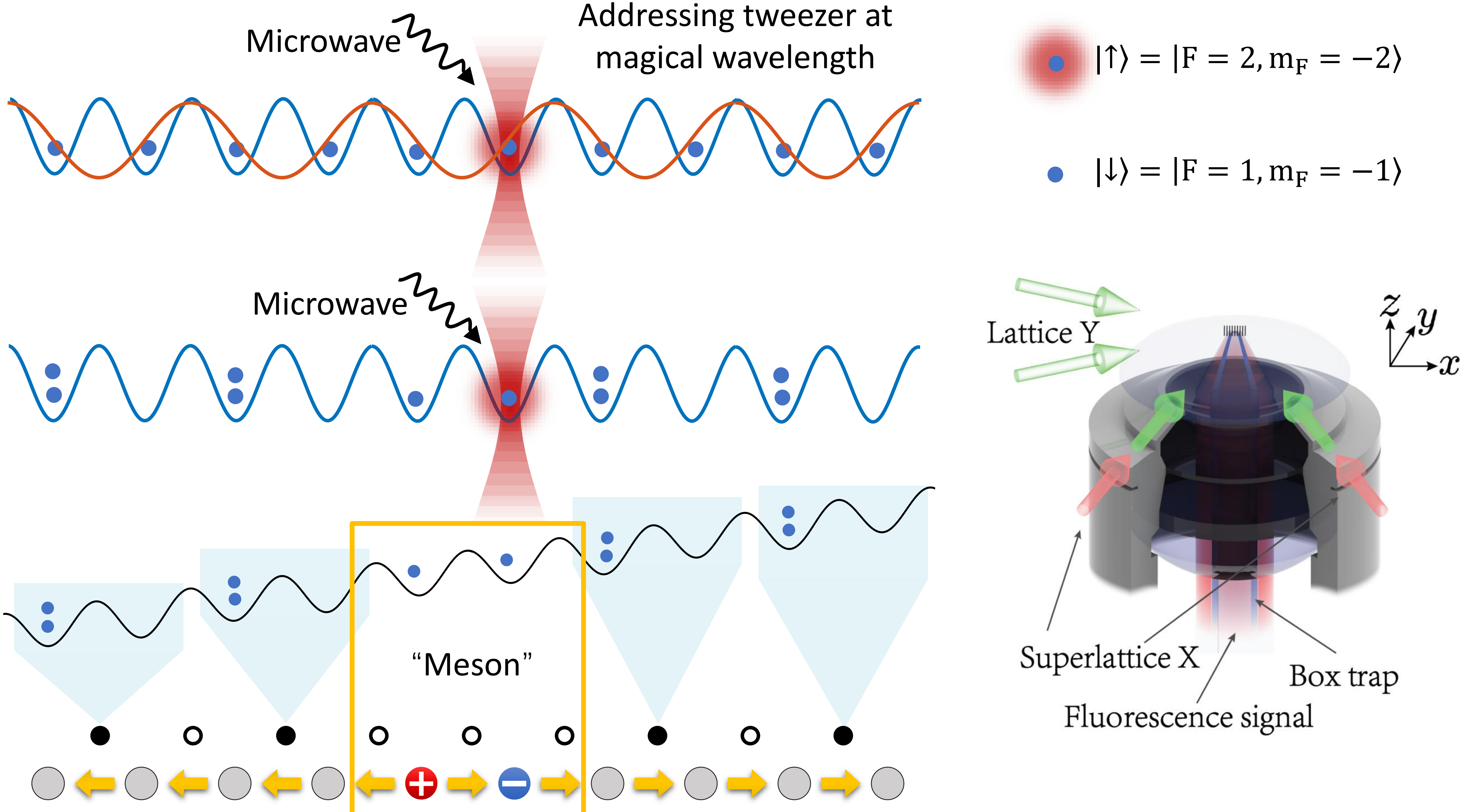
Received May 8, 1975

Particle-antiparticle collision and confinement dynamics



Zhang. *et al.* arXiv:2306.11794
(Accepted in Nature Physics)

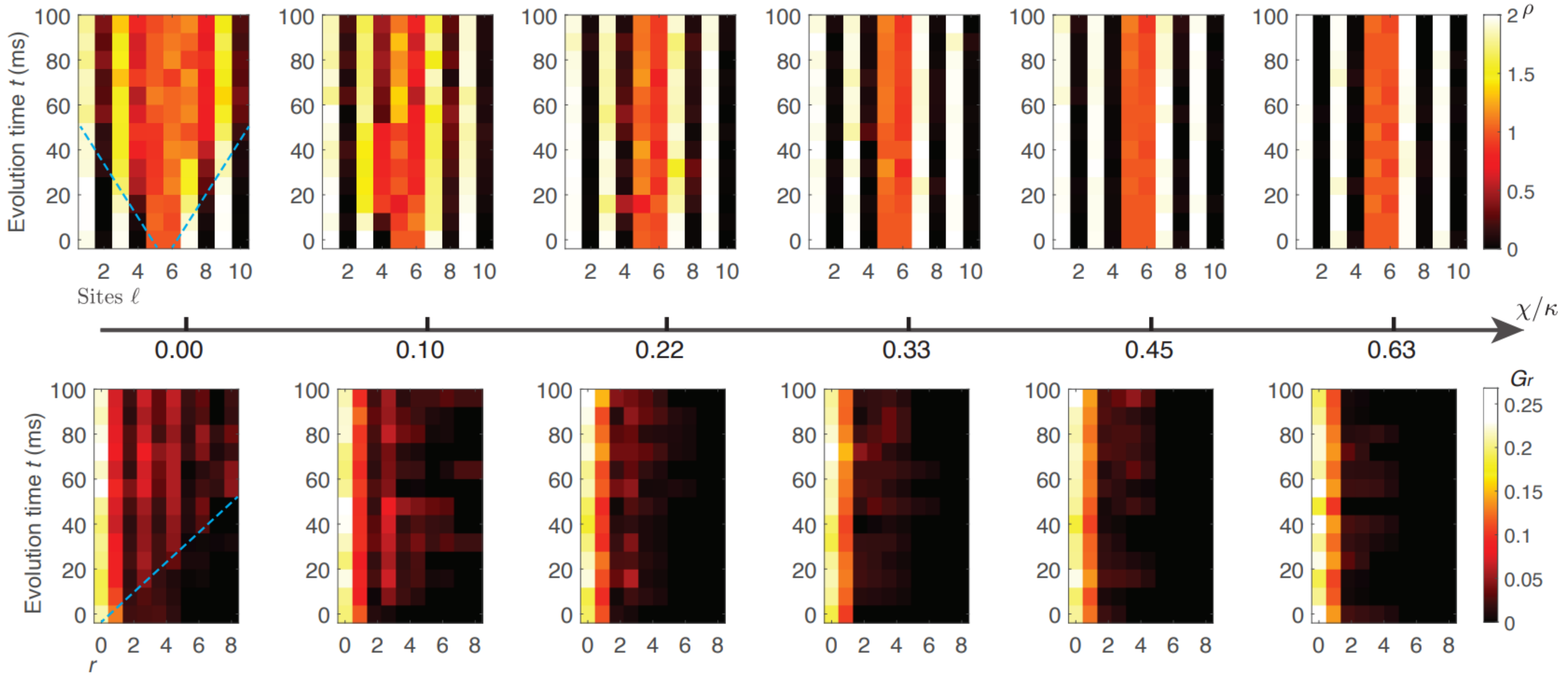
Experimental observation of confinement



Zhang. *et al.* arXiv:2306.11794
(Accepted in Nature Physics)

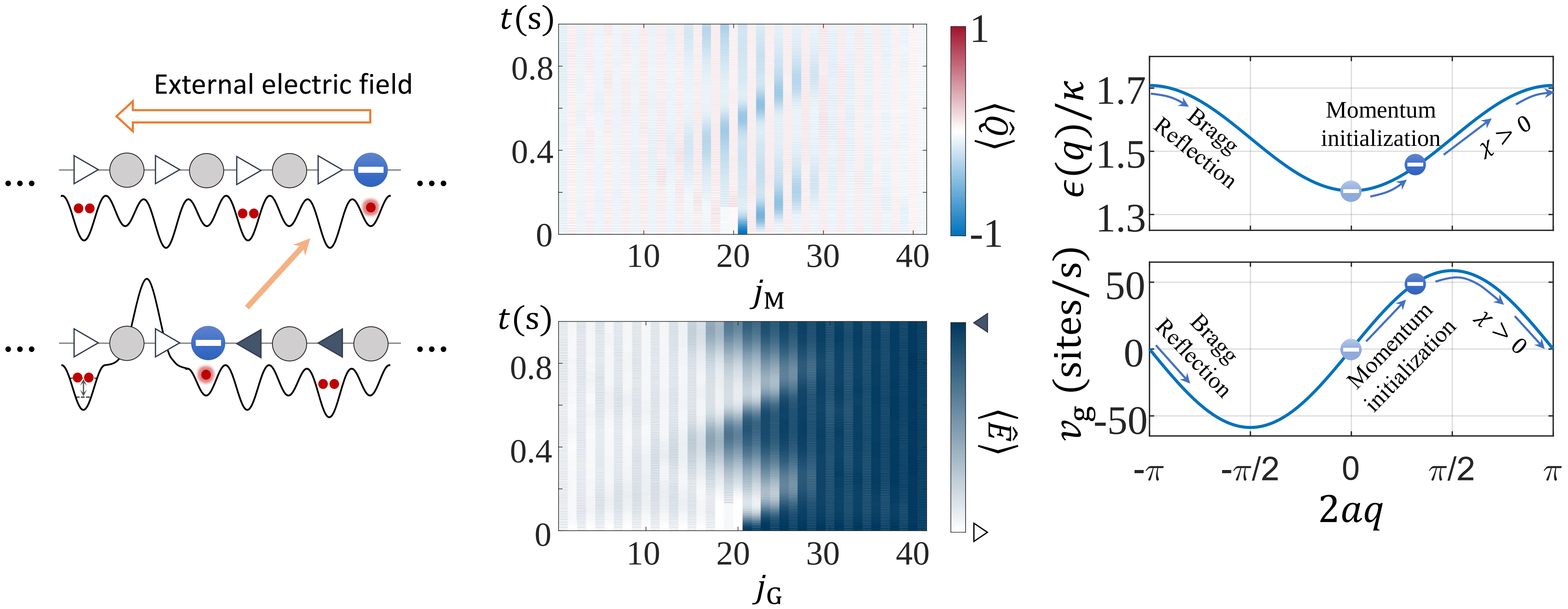
Experimental observation of confinement

$$H_{\text{Lat-QED}} = \sum_{l} -\frac{\kappa}{2a}\left(\hat{\psi}_l \hat{S}^{+}_{l,l+1}\hat{\psi}_{l+1} + \text{H.c.}\right) + m\,\hat{\psi}^{\dagger}_l\hat{\psi}_l + a\chi(-1)^l \hat{S}^{z}_{l,l+1}$$



Particle acceleration

Particle acceleration



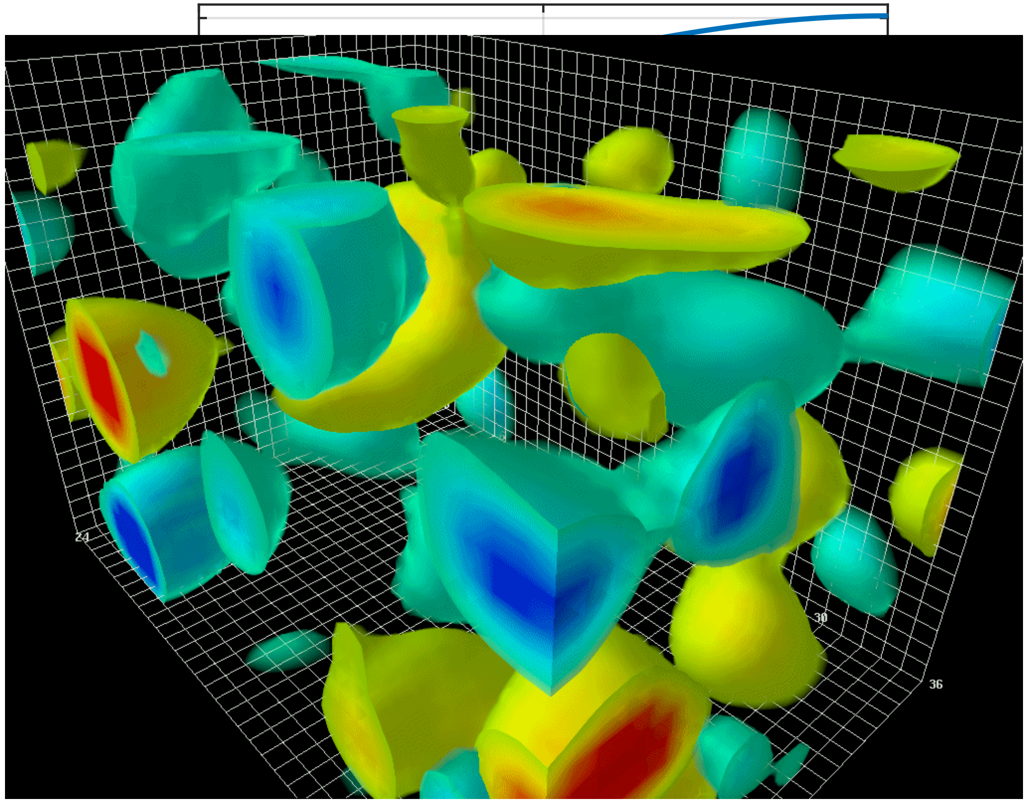
Particle acceleration

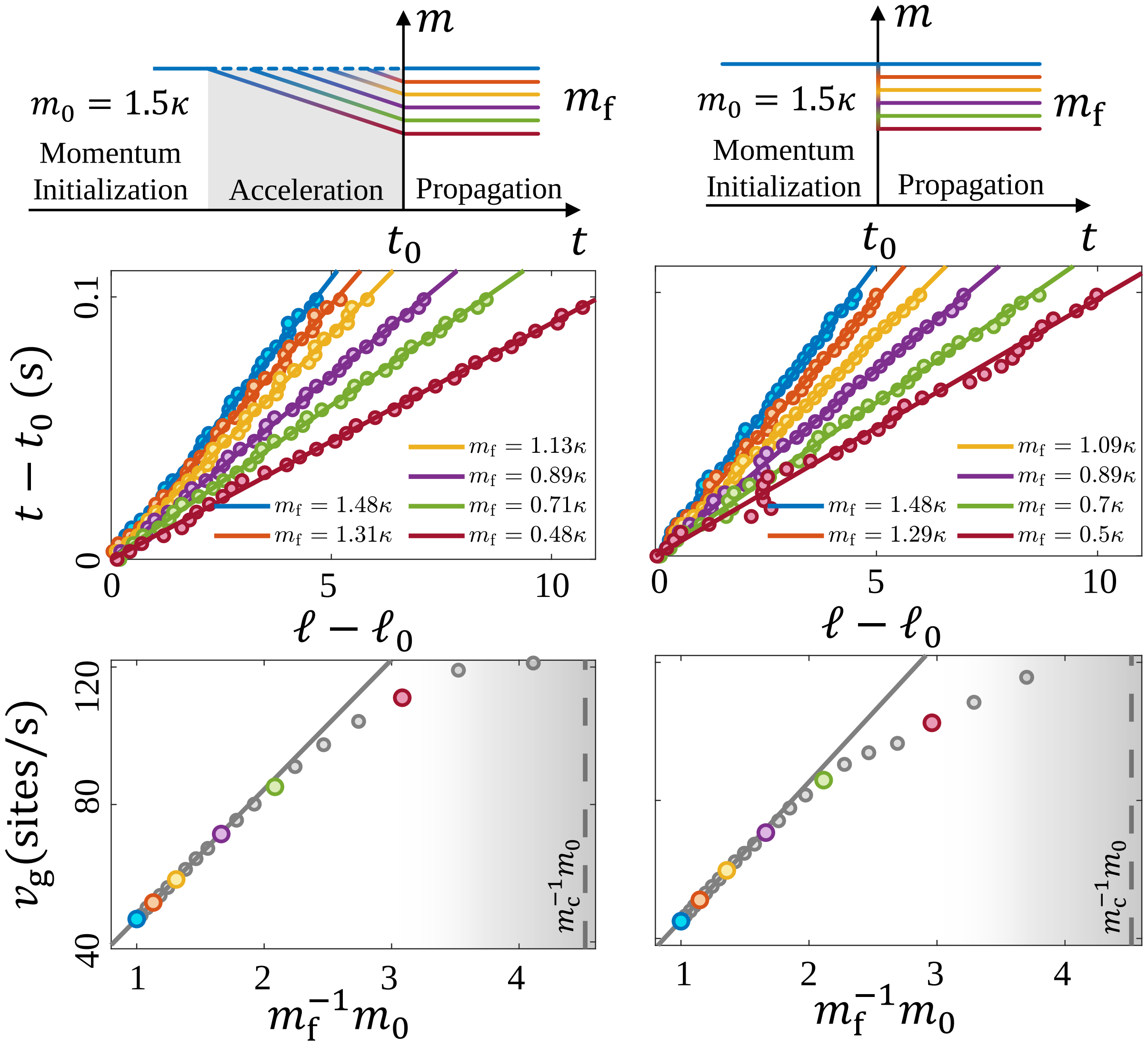
$$H_{\text{Lat-QED}} = \sum_{l} -\frac{\kappa}{2a}\left(\hat{\psi}_l \hat{S}^{+}_{l,l+1}\hat{\psi}_{l+1} + \text{H.c.}\right) + m\,\hat{\psi}_l^{\dagger}\hat{\psi}_l$$

$$\hat{H}_{\text{(A)P}} = -\,\tilde{t}\sum_{\ell_{\text{(A)P}}}\left(\hat{\psi}^{\dagger}_{\ell_{\text{(A)P}}}\hat{\psi}_{\ell_{\text{(A)P}}+1} + \text{H.c.}\right)$$

$$\tilde{t} = \kappa^2/(8ma^2)$$

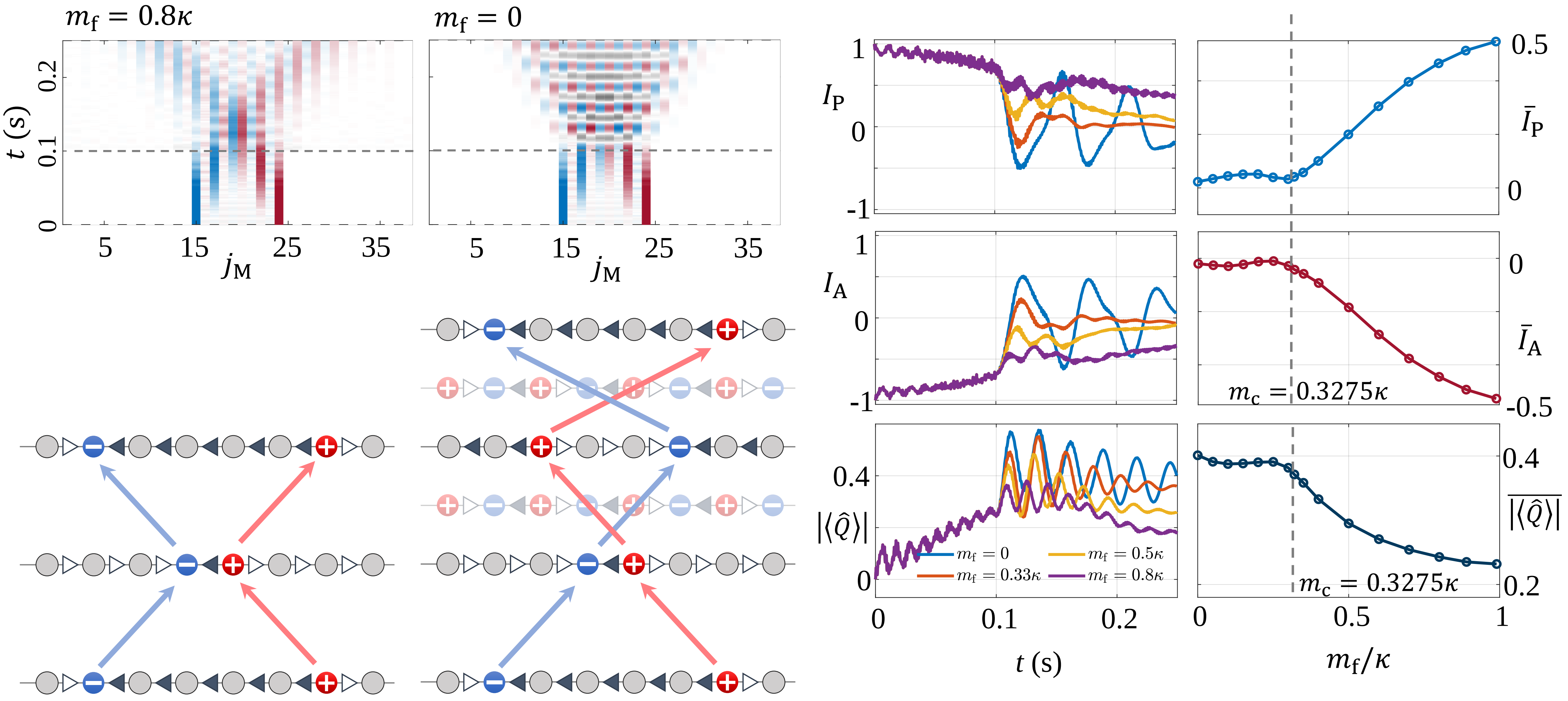
$\chi = 0$





Su. *et al.* arXiv:2401.05489

String inversion



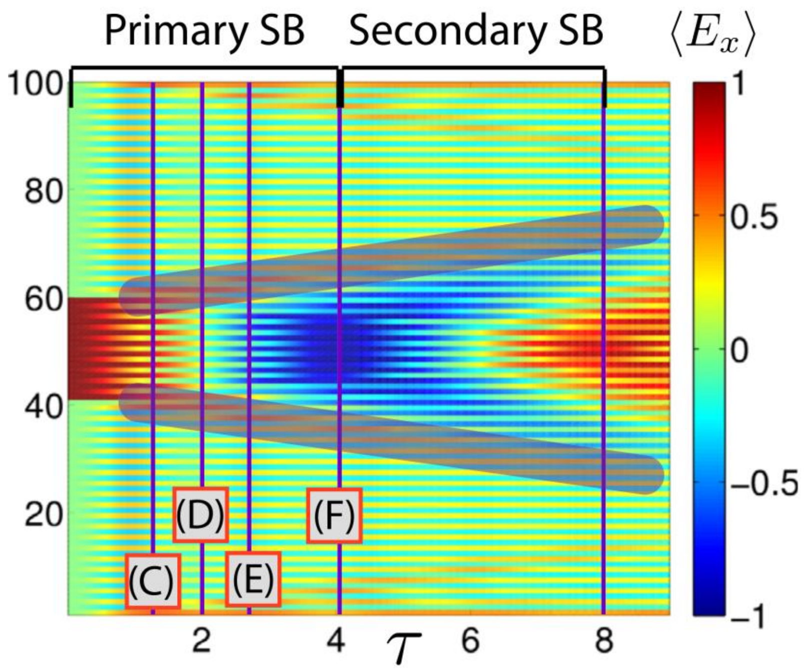
String inversion

Spin-1 quantum link model

PHYSICAL REVIEW X **6,** 011023 (2016)

Real-Time Dynamics in U(1) Lattice Gauge Theories with Tensor Networks

T. Pichler,[1] M. Dalmonte,[2,3] E. Rico,[4,5,6] P. Zoller,[2,3] and S. Montangero[1]

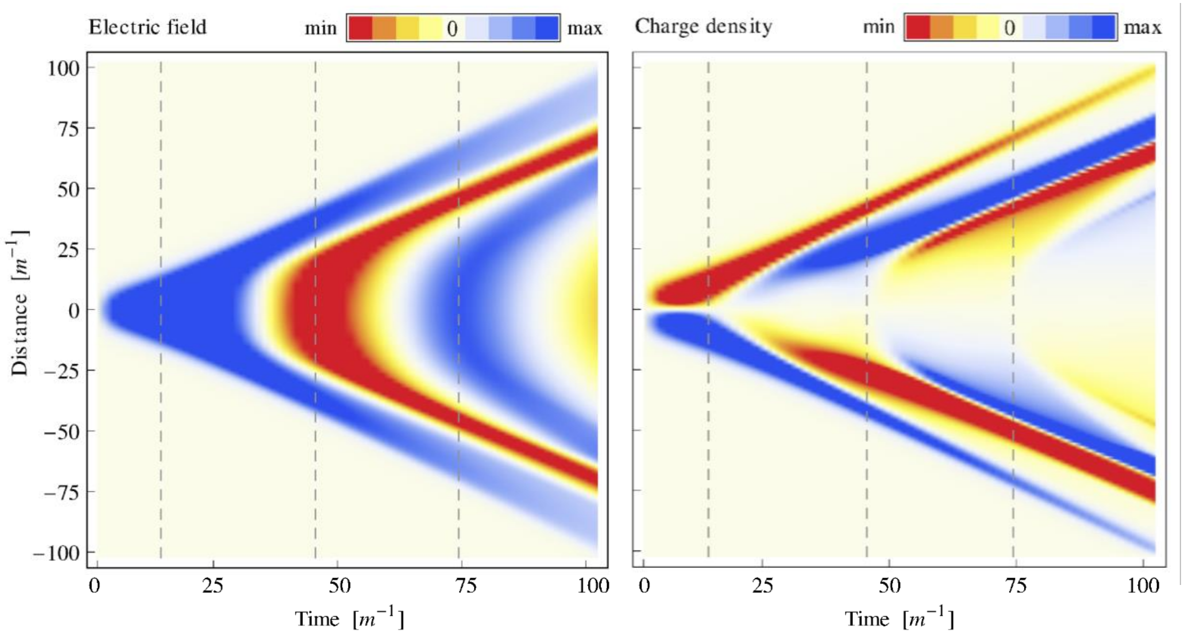


Full (1+1)D QED

PRL **111,** 201601 (2013) PHYSICAL REVIEW LETTERS week ending 15 NOVEMBER 2013

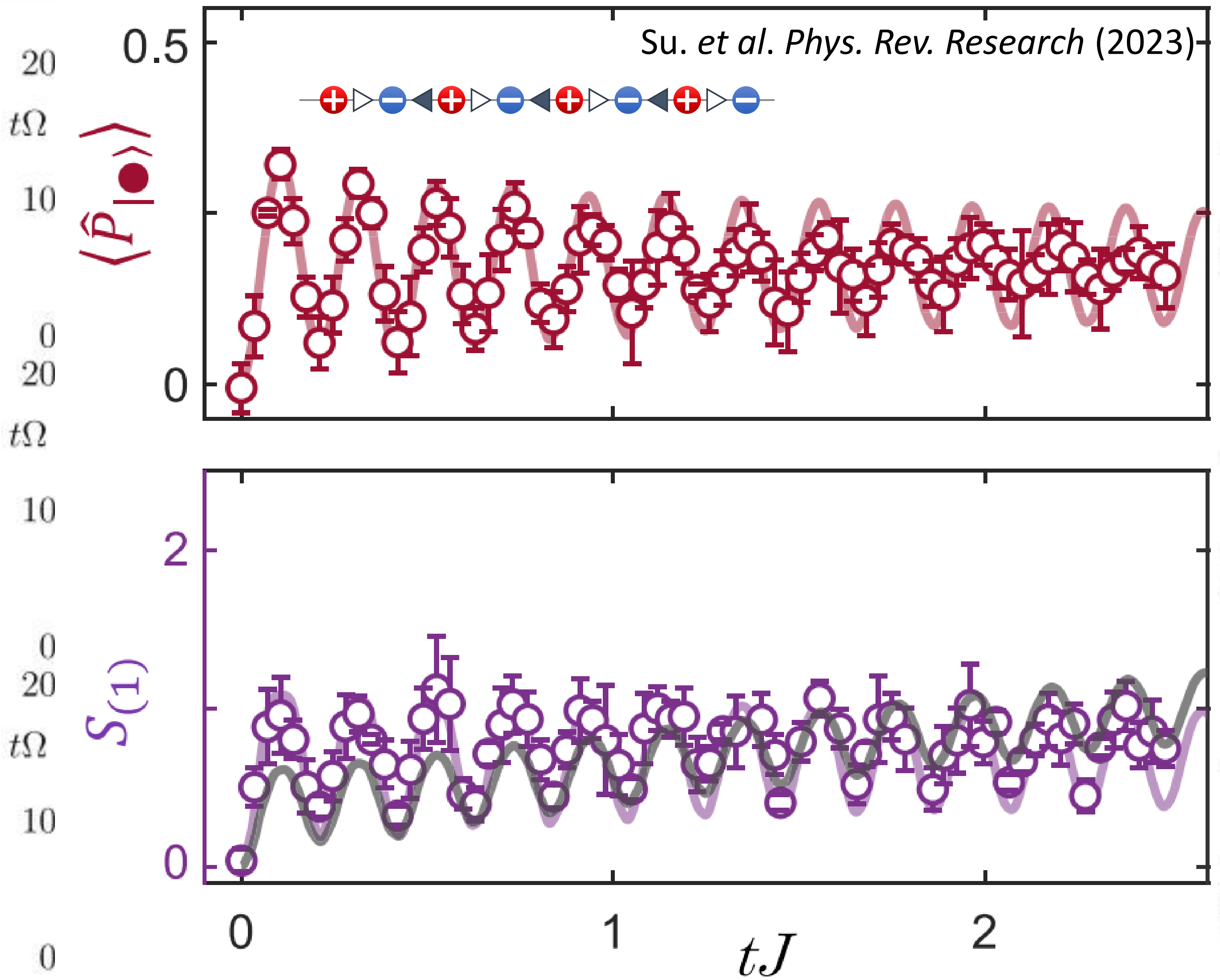
Real-Time Dynamics of String Breaking

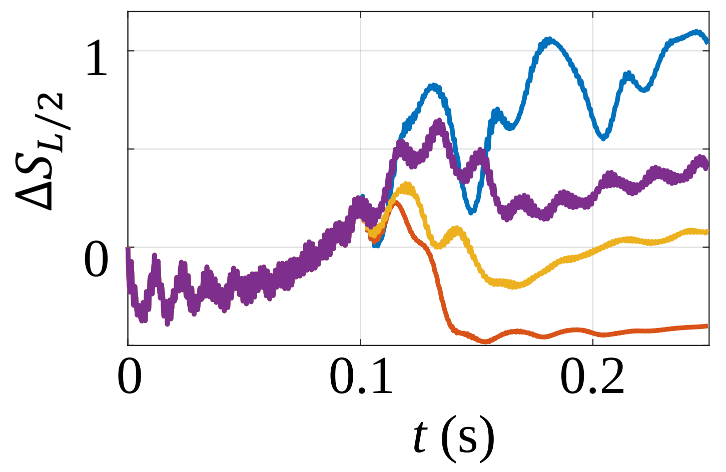
F. Hebenstreit,[1] J. Berges,[1,2] and D. Gelfand[1]

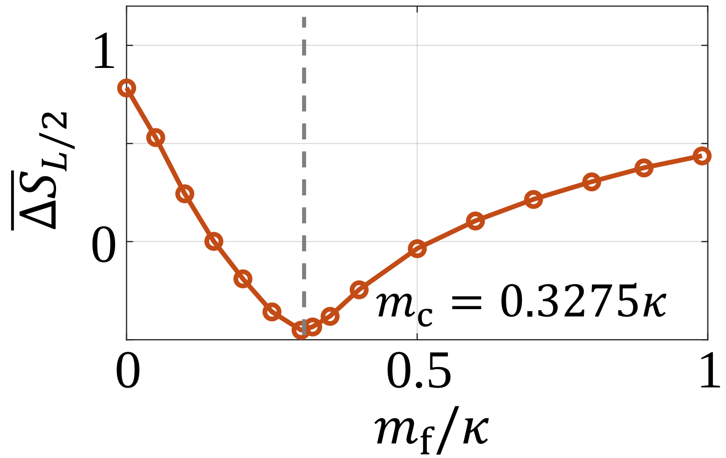


Entropy production

Surace. *et al. Phys. Rev. X* (2020)



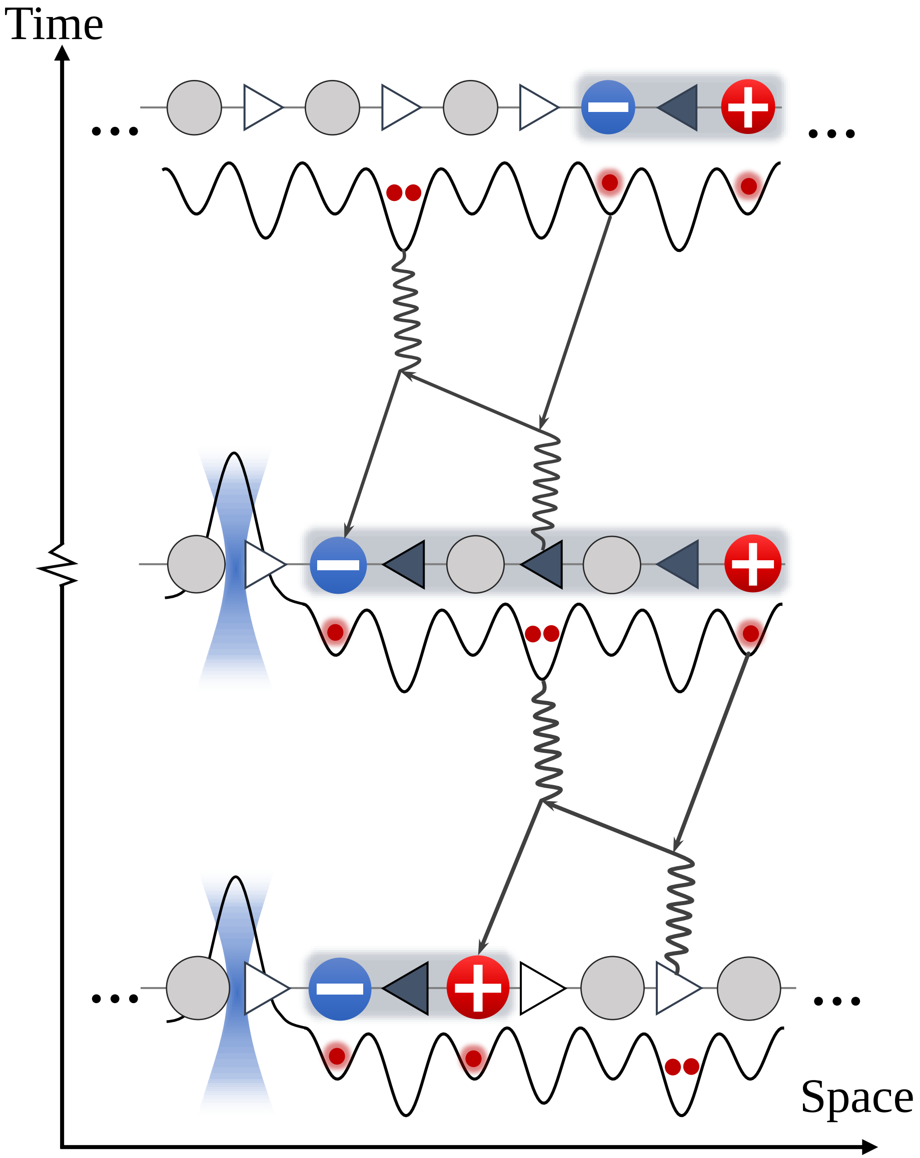


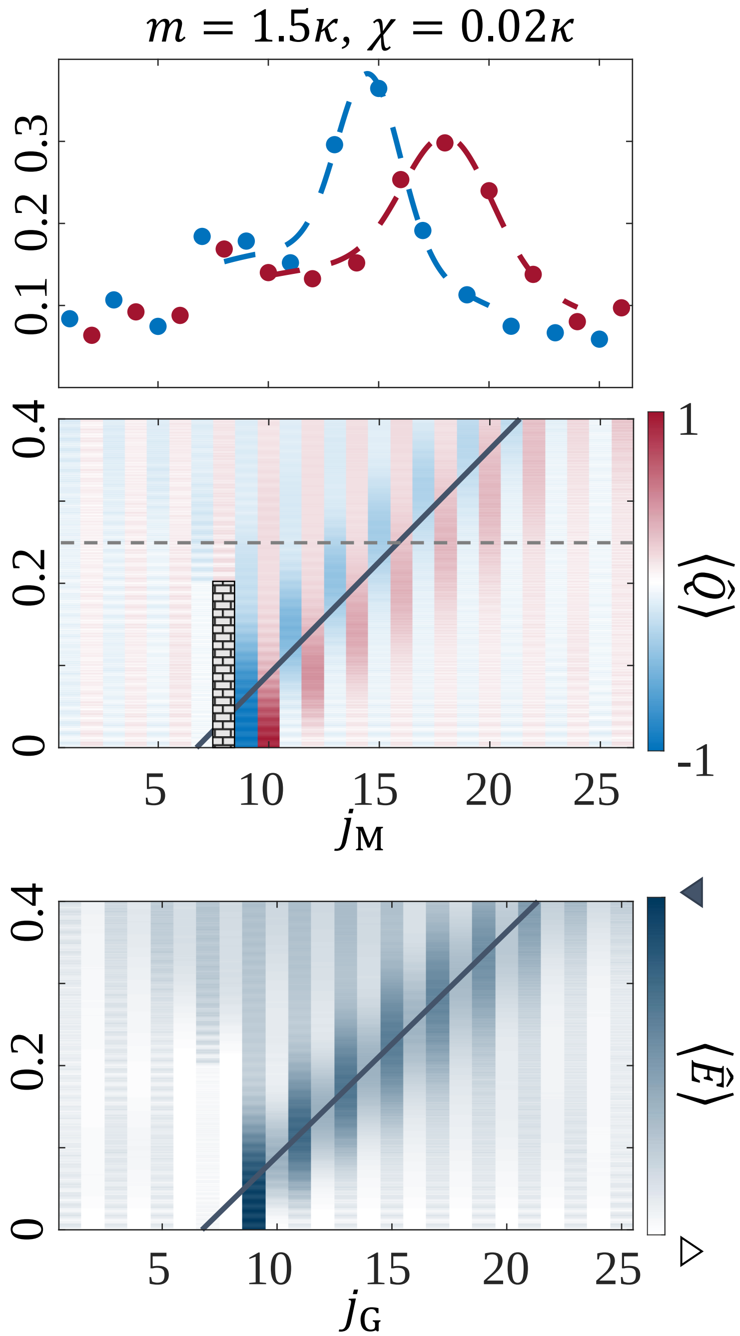


Meson collisions

Su. *et al.* arXiv:2401.05489

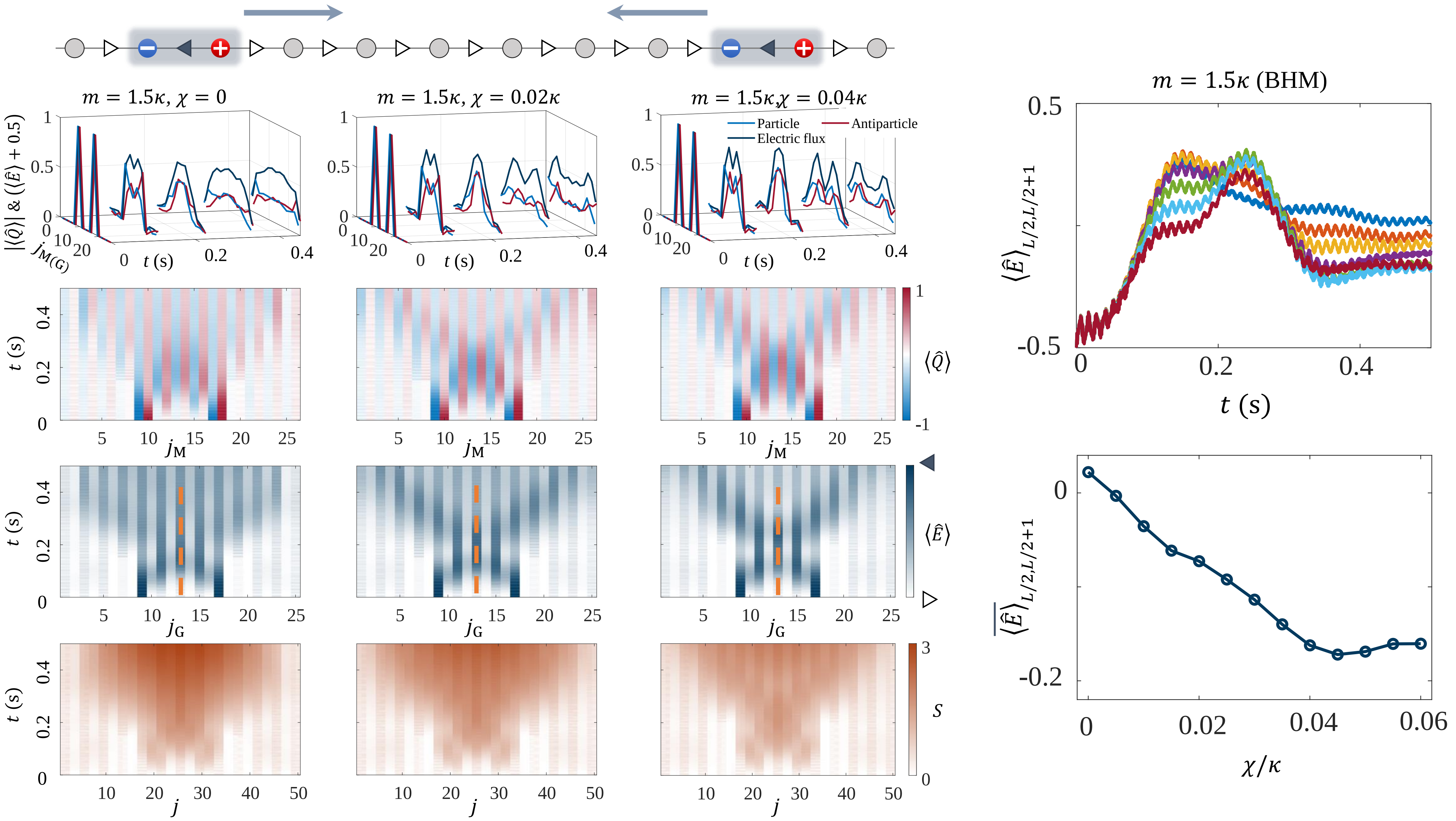
Meson scattering



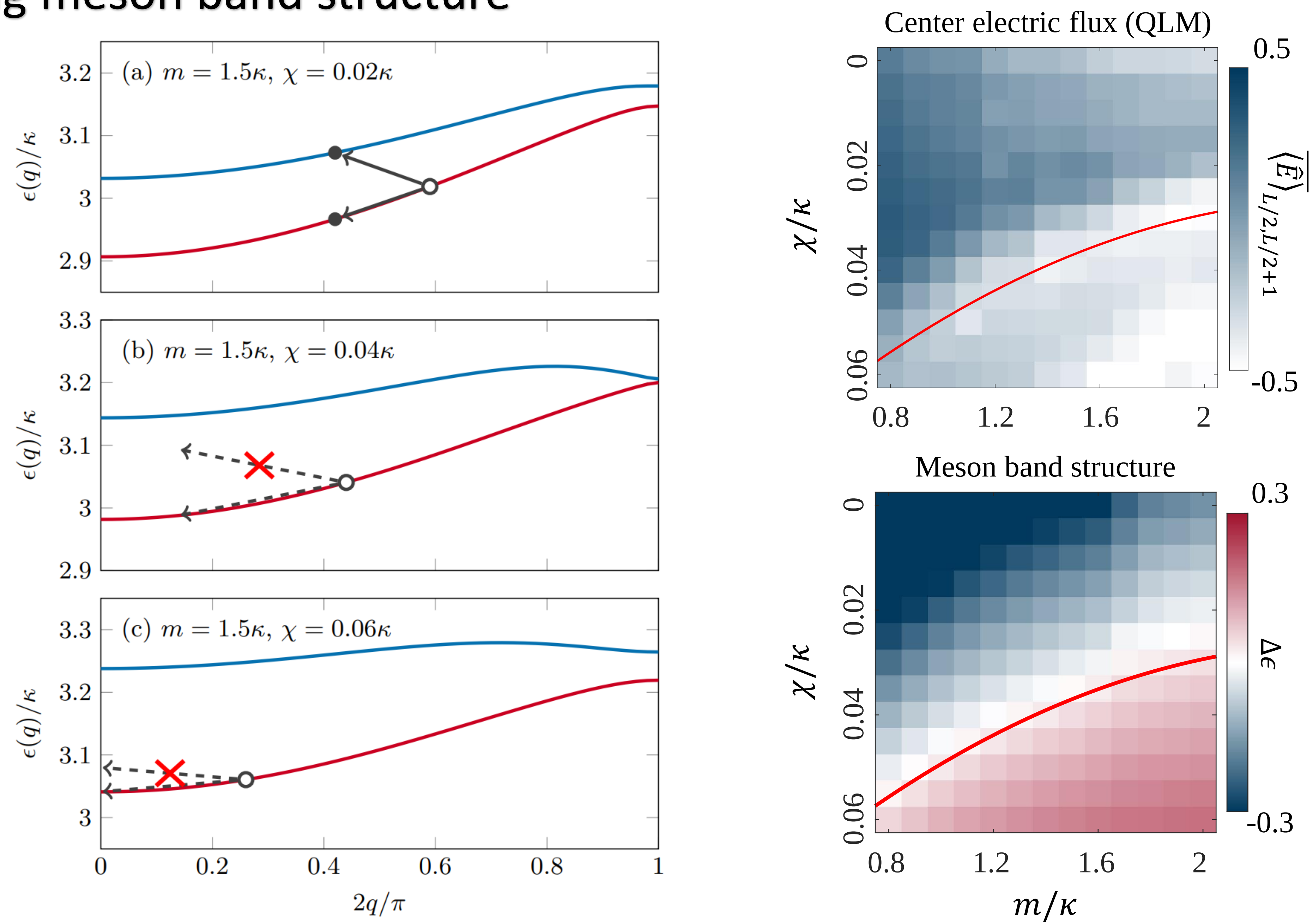


Su. *et al.* arXiv:2401.05489

Meson scattering



Probing meson band structure



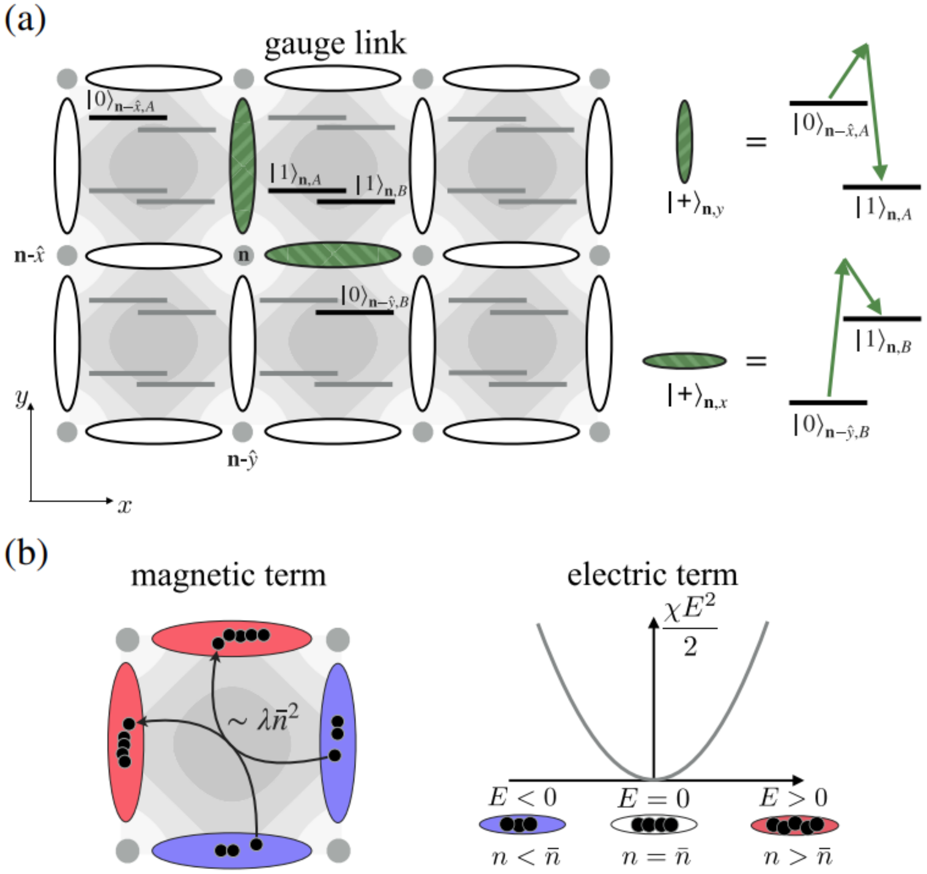
Summary

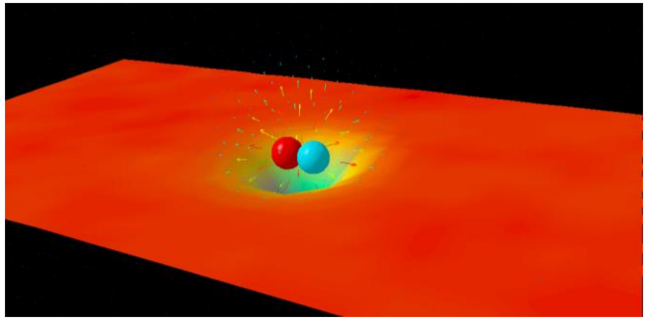
- A cold-atom quantum simulator for lattice QED
- Preparation of moving wave packet in the quantum simulator
- Low-energy collisions and confinement dynamics
- String inversion in the strong coupling limit
- Probing meson band structure via collision dynamics

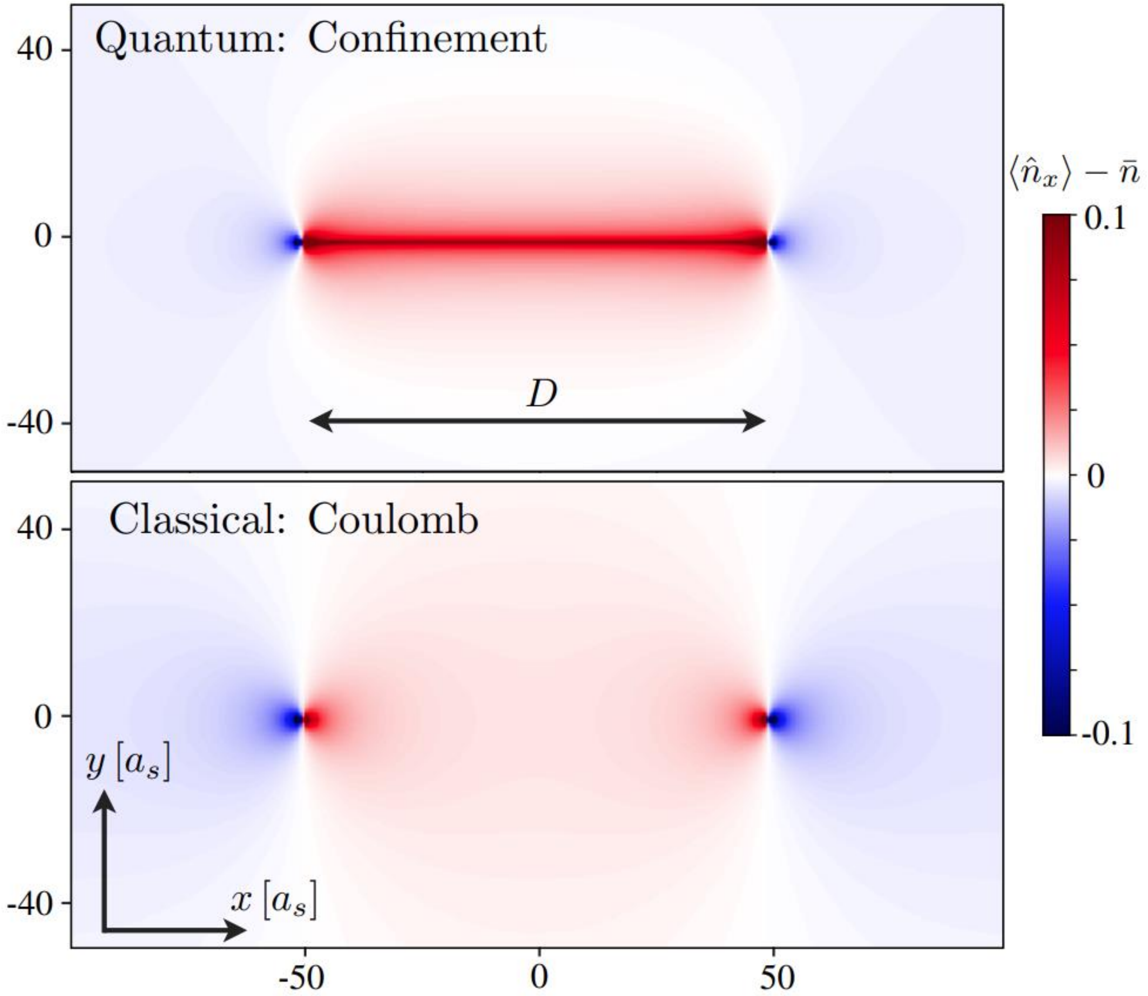
PHYSICAL REVIEW LETTERS **127,** 130504 (2021)

Scalable Cold-Atom Quantum Simulator for Two-Dimensional QED

R. Ott,[1,*] T. V. Zache,[1,2,3] F. Jendrzejewski,[4] and J. Berges[1]







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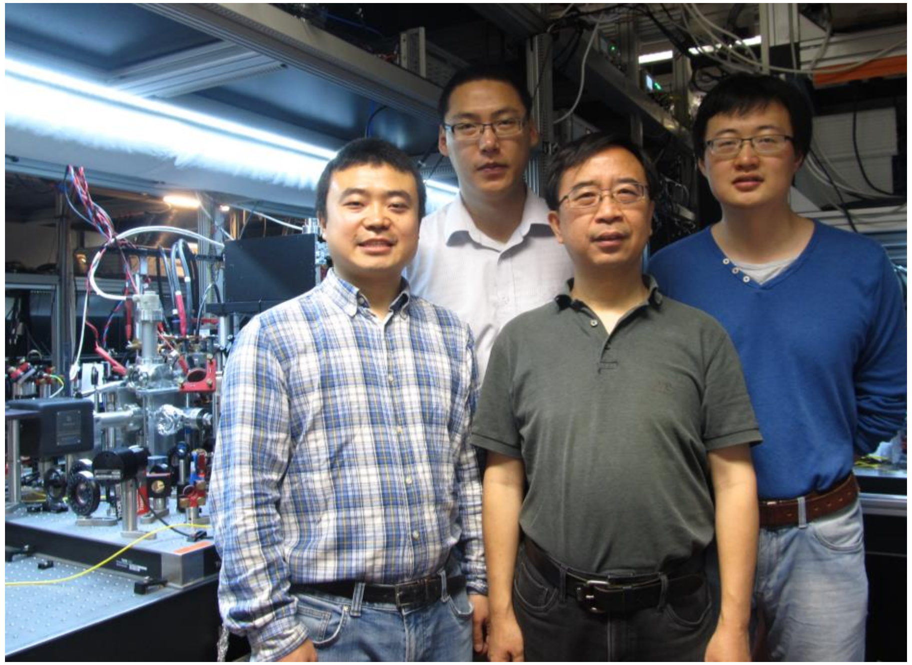

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Philipp Hauke (Trento)

Wei-Yong Zhang (USTC)

Hui Zhai (Tsinghua)

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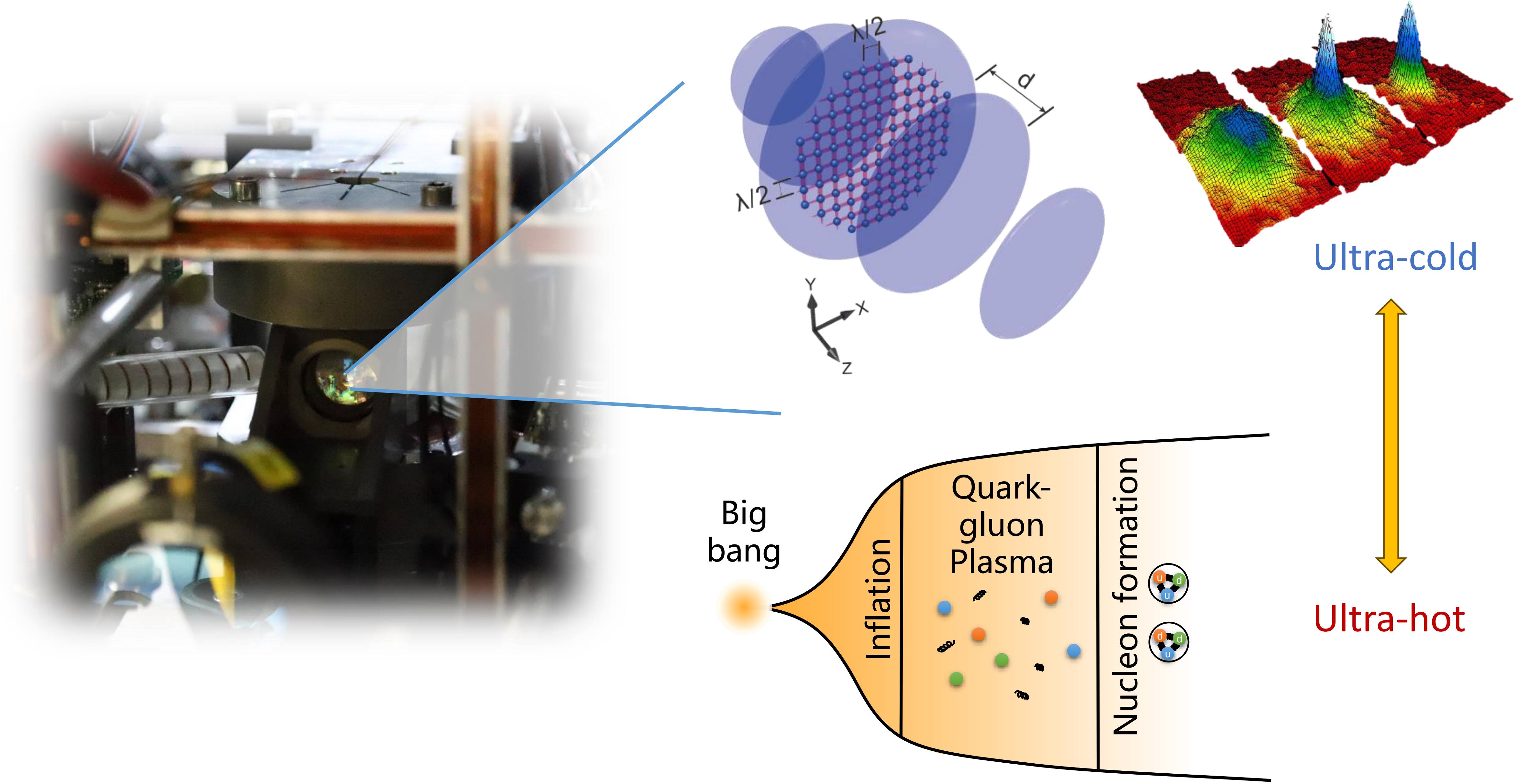

λ/2
λ/2
d
Y
X
Z
Ultra-cold
Ultra-hot
Big bang
Inflation
Quark-gluon Plasma
Nucleon formation