Coherence of confined matter in lattice gauge theories at the mesoscopic scales

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Quantum Research Centre, Technology Innovation Institute Abu Dhabi

Centre for Quantum Technologies
National University of Singapore

Quantum Research Centre

Technology Innovation Institute

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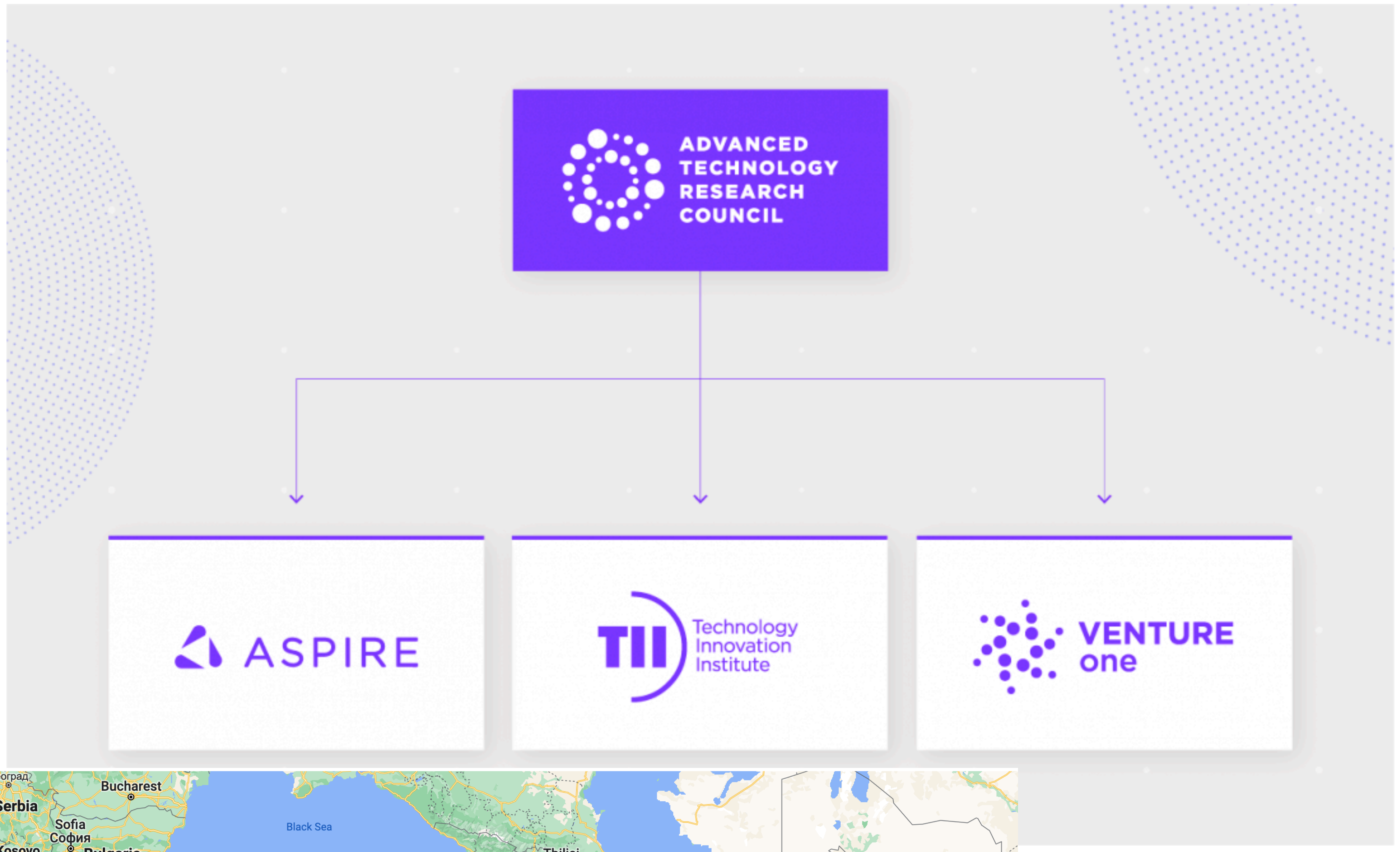

About 850 researchers; about 60 nationalities

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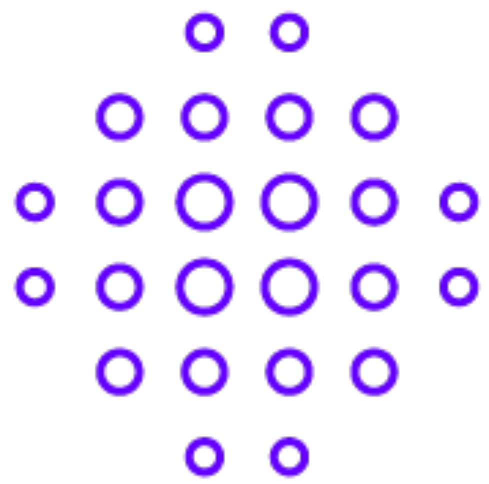
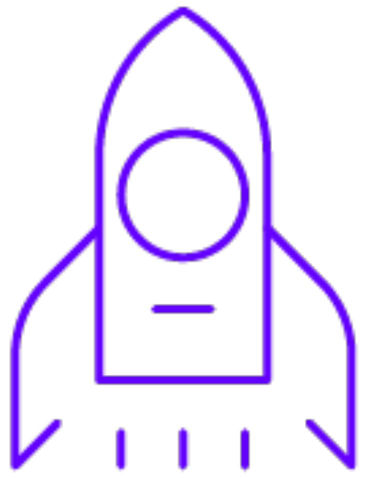
EL2 Communities:





Quantum
Research Center

Quantum physics

Quantum computing

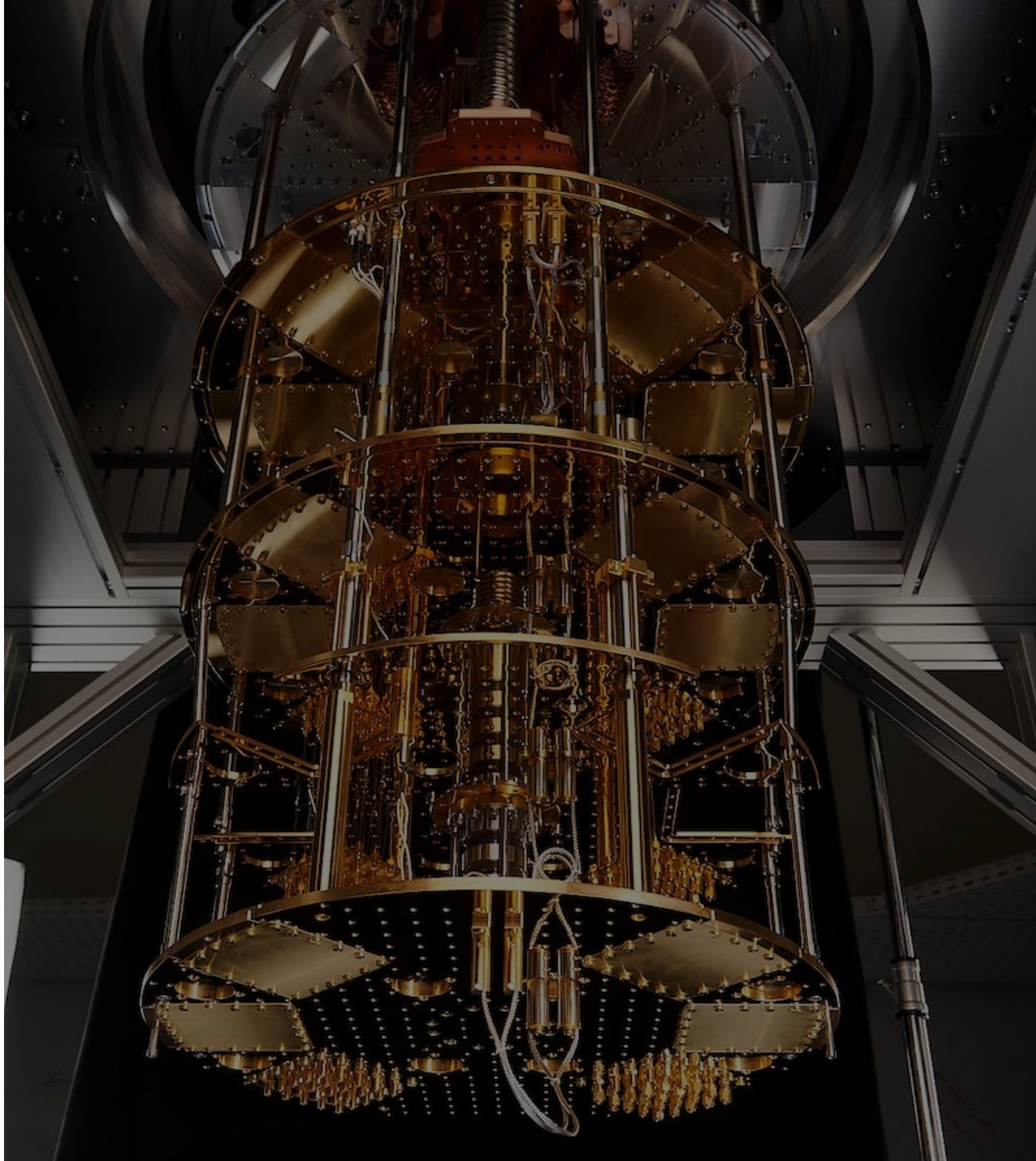
Quantum algorithms

Quantum sensing

Quantum middleware

Quantum communications

~70 Researchers; 6 permanents,~30 Postdocs, ~30 Ph.D students



People

Atomtronics

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Executive Director

Superconducting

Dr. Juan Polo
Lead Researcher

Dr. Andreas Osterloh
Senior Researcher

Dr. Vijay Singh
Postdoctoral Researcher

Dr. Gianluigi Catelani
Lead Researcher

Dr. Giampiero Marchegiani
Postdoctoral Researcher

Prof. Frederico Brito
Senior Researcher

Philip Kitson
JSF PhD student

Wayne Chetcuti
Junior Researcher

Francesco Perciavalle
Junior Researcher

Enrico Domanti
Junior Researcher

Abbas Hirkani
ICTP-TII PhD student

Ben Blain
Junior Researcher

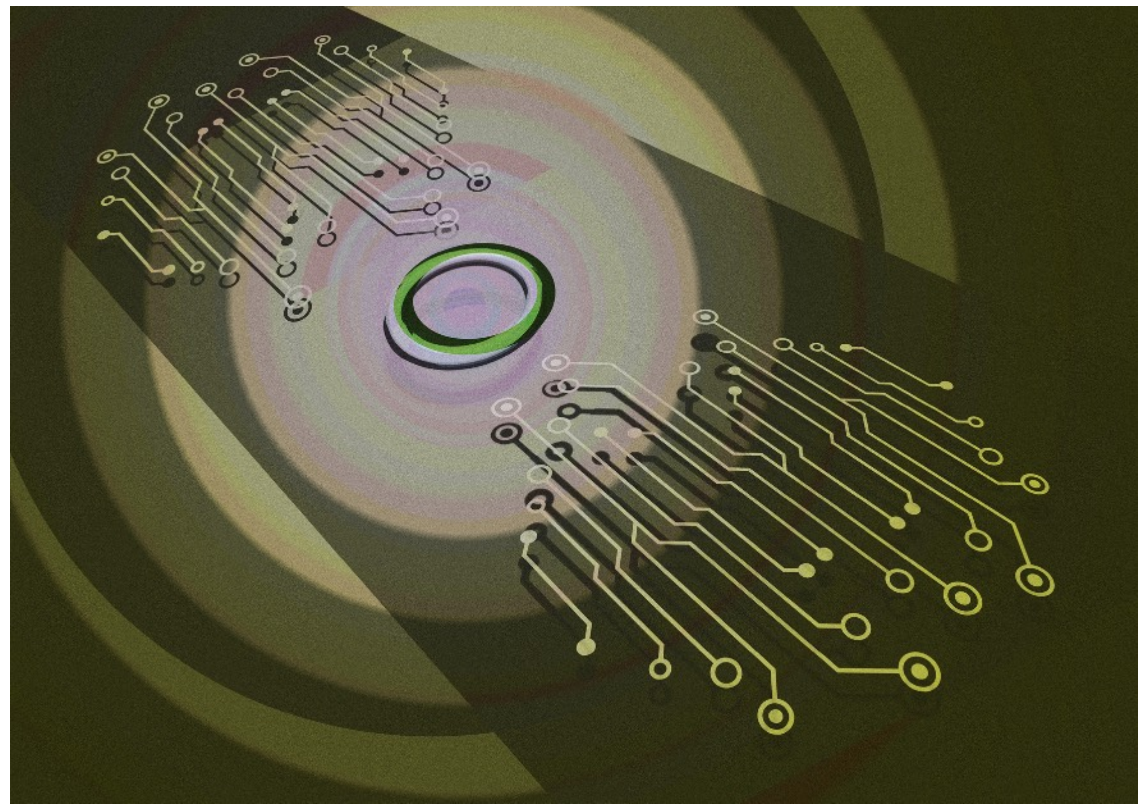
Guglielmo La Magna
Intern Student

Atomtronics

Atomtronics is an emerging field in *quantum technology* seeking to realize atomic circuits exploiting ultra-cold atoms manipulated in micro-magnetic or laser-generated micro-optical traps or circuits.

Cold atom circuits: ‘Quantum many particles in ring-shaped potentials’, Amico, Osterloh, Cataliotti, PRL 2005.

“Atomtronics: Ultracold-atom analogs of electronic devices.”, Seaman, Kramer, Anderson , Holland, PRA (2007).



Amico, Anderson, Boshier, Brantut, Minguzzi, Kwek, Rev. Mod. Phys. 2022

Some goals

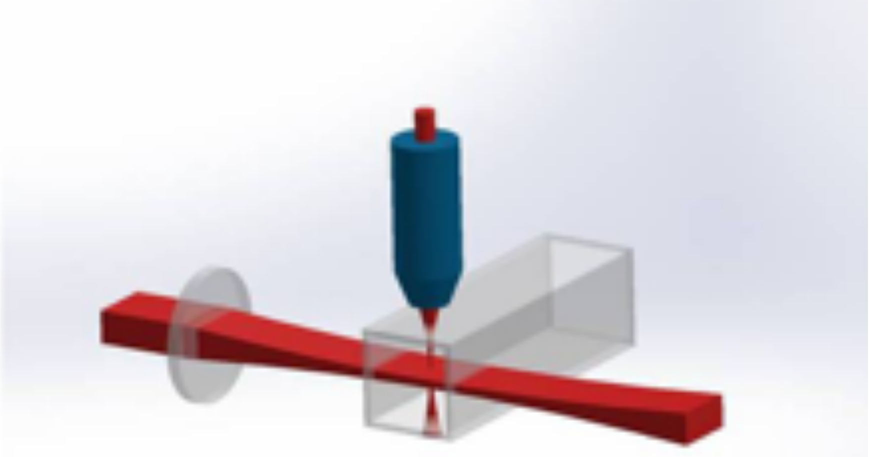
- Enlarge the scope of cold atoms quantum simulators (currents).
- Many-body physics (exotic quantum phases of matter: topological order..)
- Bridging mesoscopic and cold-atoms physics.
- Insights in foundational aspects of quantum science.
- New quantum devices.
- Quantum sensing.
- Hybrid systems.
- ……..

“Roadmap on Atomtronics: state of the art and perspectives’, Amico, Boshier, Birkl, Kwek, Miniatura, Minguzzi et al, AVS Quantum Science 2021, arXiv:2008.04439.

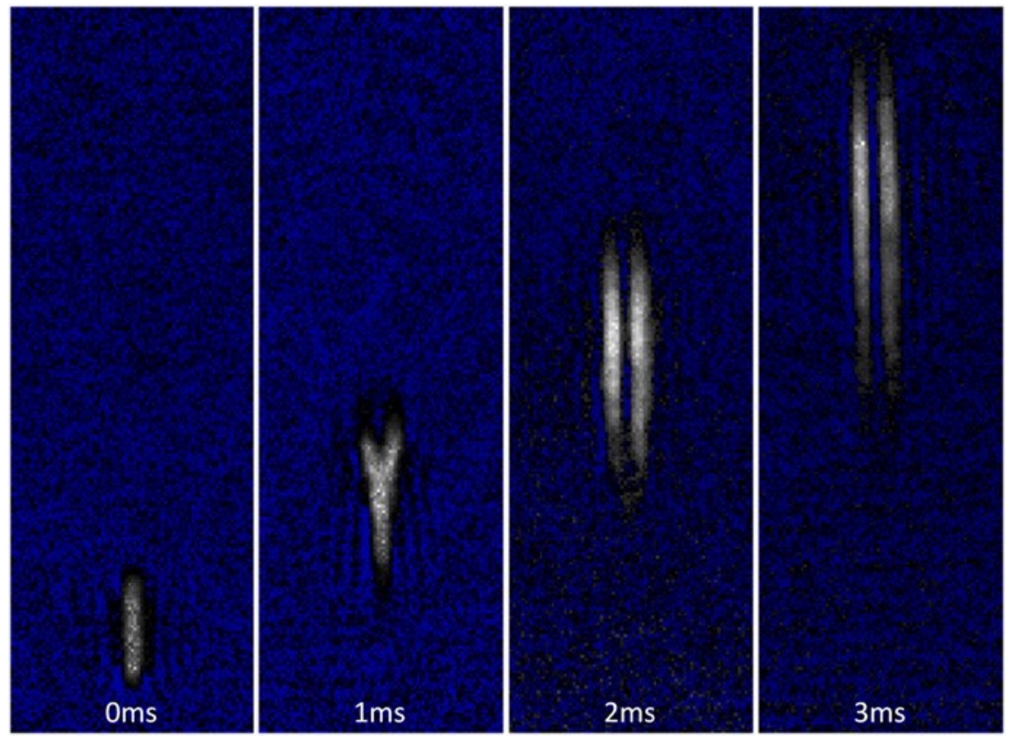
‘Roadmap on quantum optical systems’, Amico, Boshier ‘Atomtronics’ J.Optics 2016

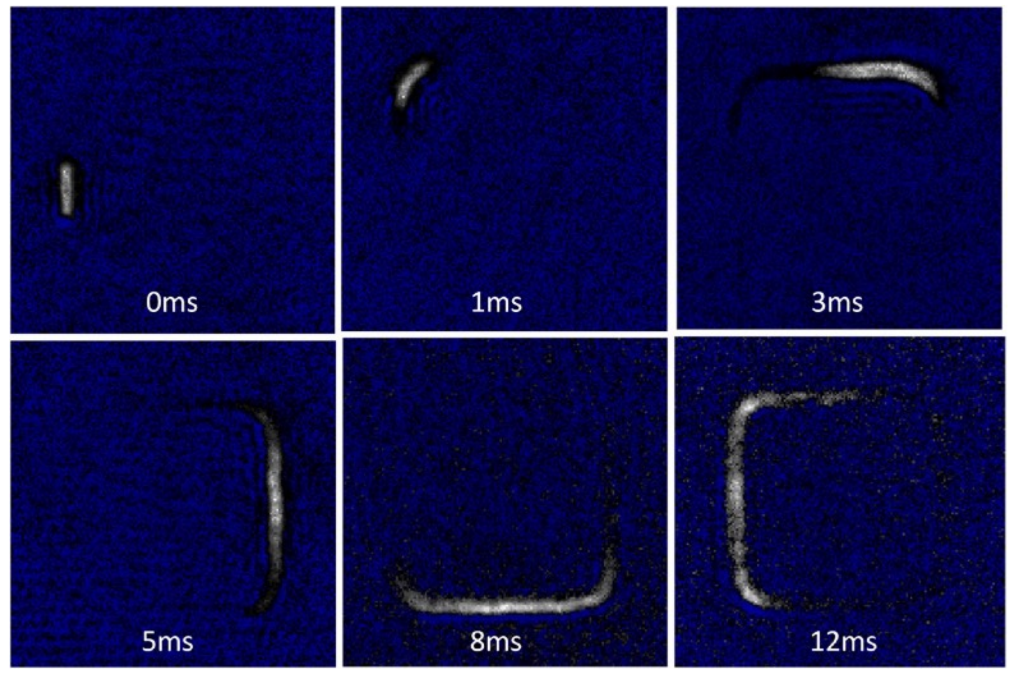
New J. Phys. Focus on ‘Atomtronics enabled quantum technology’ 2015, Amico, Birkl, Boshier, Kwek Eds.

Sculpted light

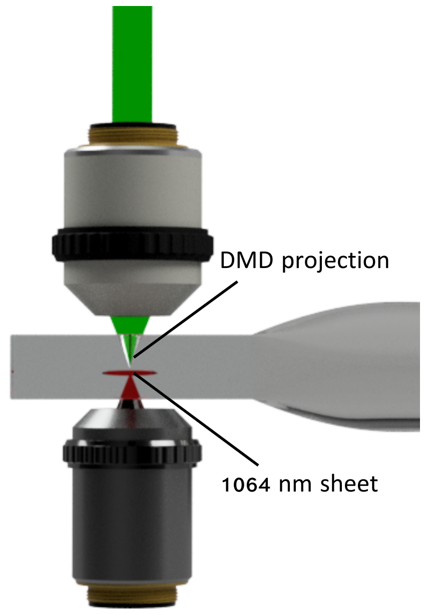


Painting



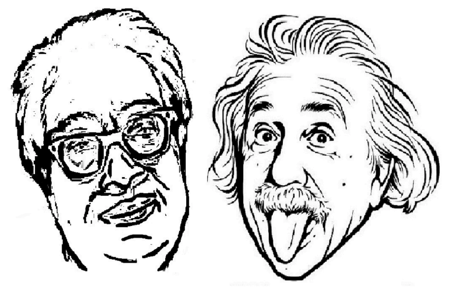


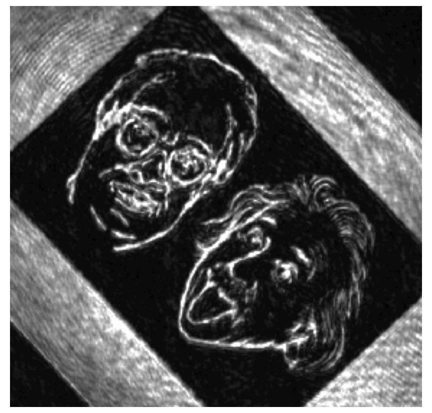
Boshier@LANL 2014 -

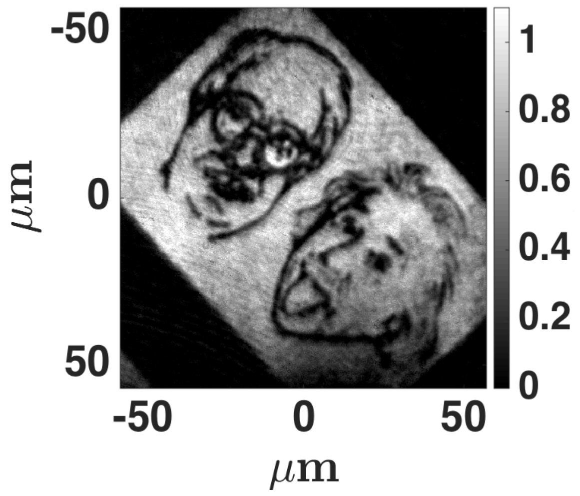


Digital micromirror device

Spatial light modulator

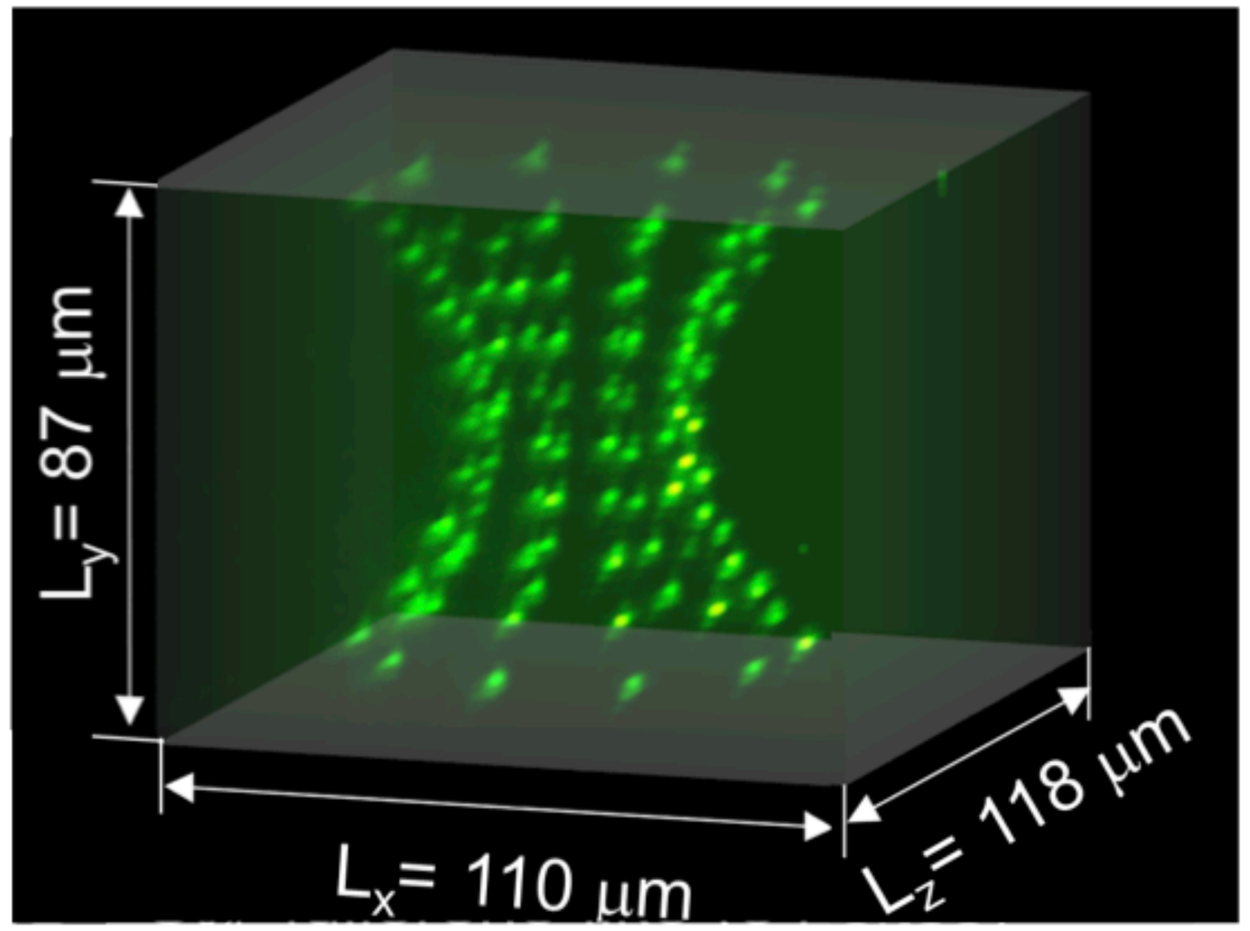






Input binary **Projected light** **Trapped BEC**

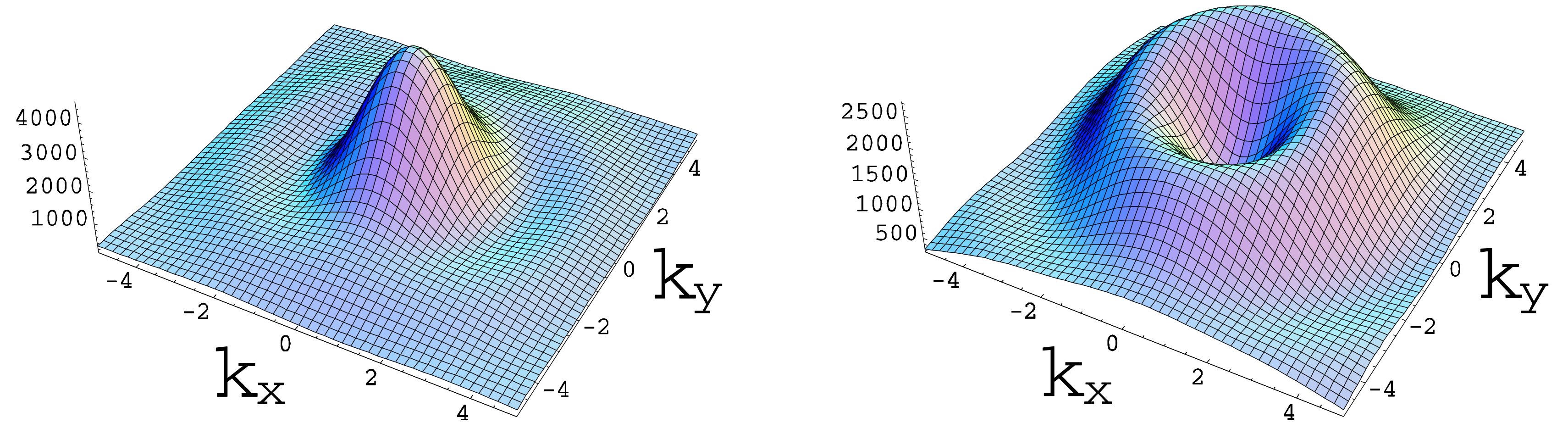
Rubinsztein-Dunlop & Baker @ Queensland 2016-2019
Cassettari St. Andrews (UK) 2018-2019
.....



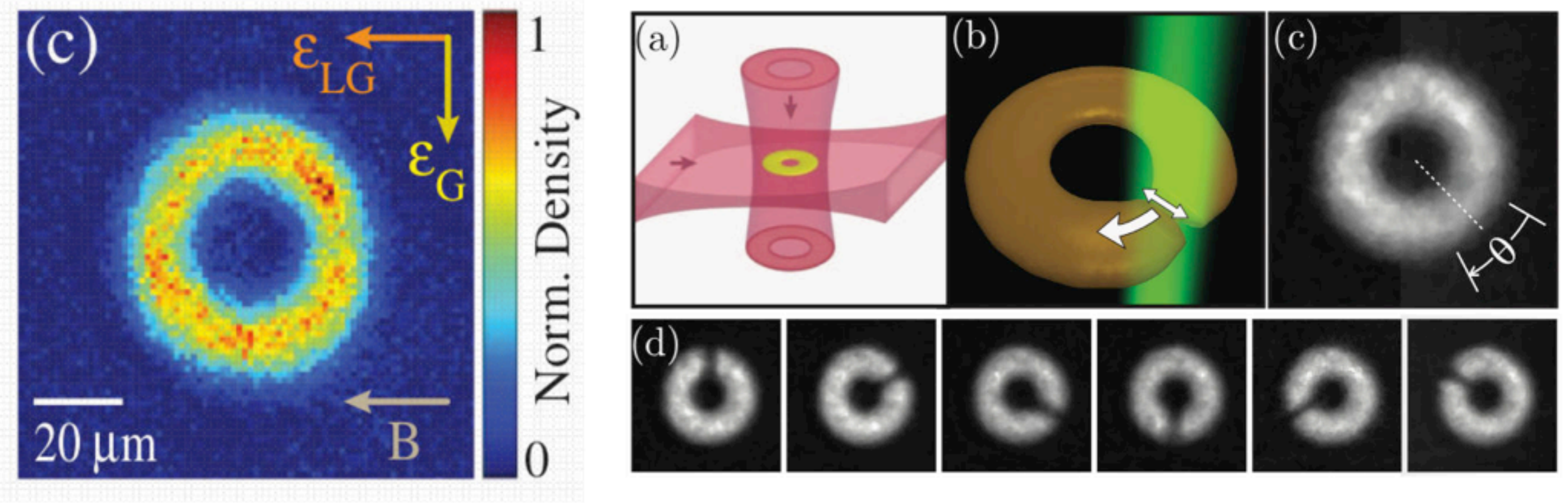
Barredo, Lienhard, de Léséleuc, Lahaye, Browaeys, Nature 561, 79 (2018)

Ring circuits

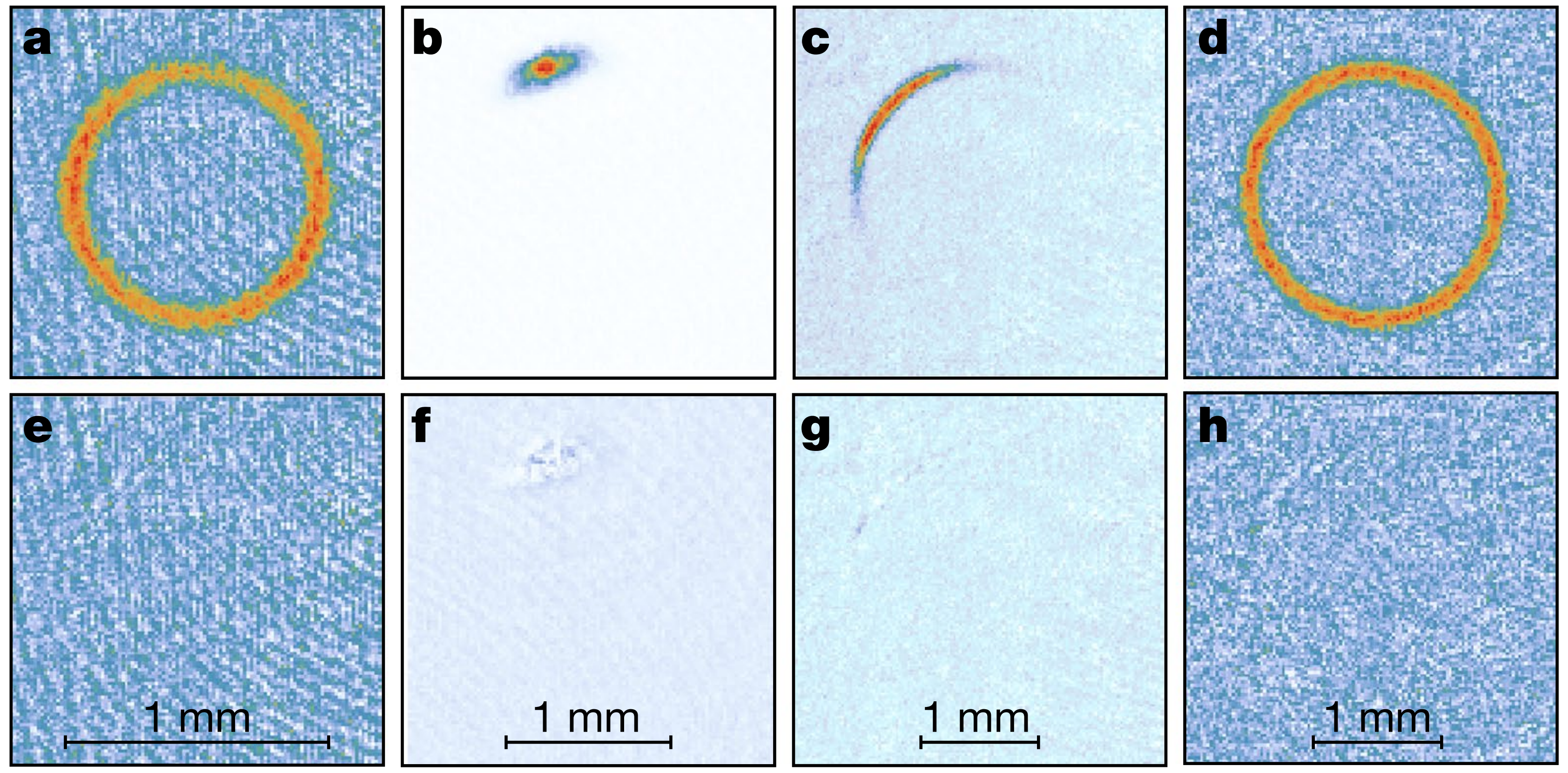
Persistent current in interacting many-body systems in ring shaped potentials (ex Laguerre-Gauss)



Amico, Osterloh, Cataliotti PRL 2005



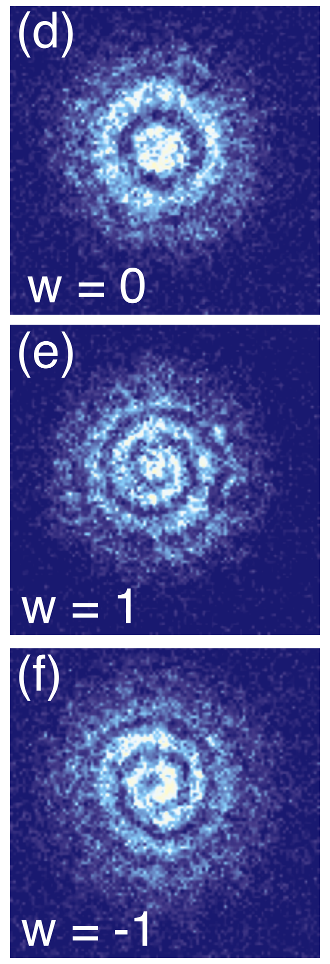
G. Campbell, W. Phillips, C. Clark and co-workers@NIST, (2013–2015)



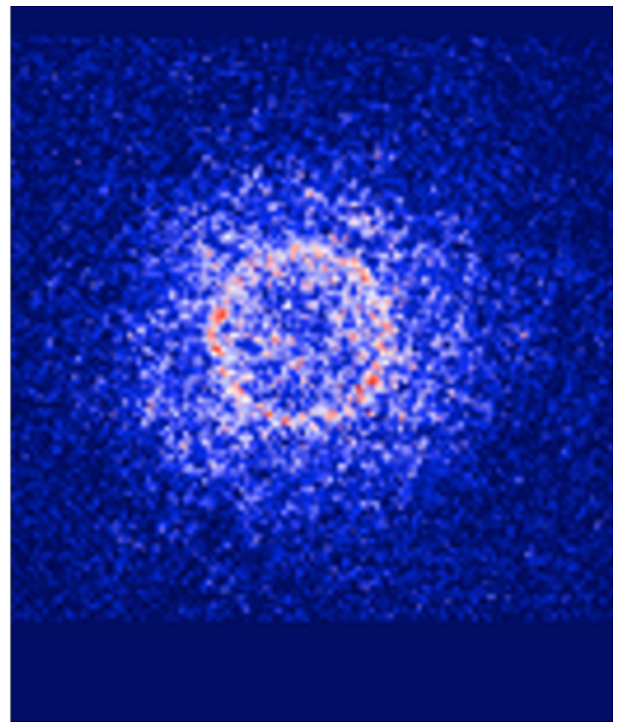
von Klitzing group@Heraklion, Nature 2019

Perrin group@Paris, PRL 2019

Fermionic rings



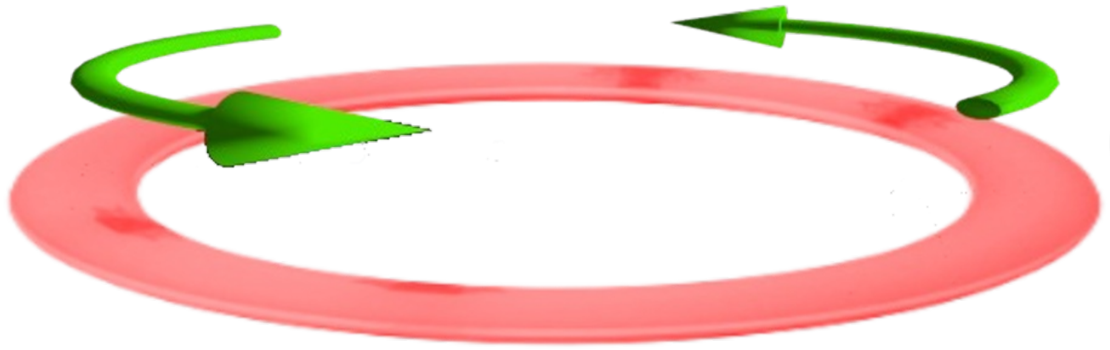
G. Roati group PRX 2022 @Florence



PRL 2022 Kevin Wright group@Darthmouth

Lines of research in Atomtronics @TII:

- **Rotation sensors: Bose gases**
  - Interferometry
  - Qubits made out of currents
  - Shapiro steps
- **SU(N) fermions**
  - Persistent currents and correlations
  - Interferometry
- **Rydberg Atomtronics**
  - Flow of excitations
- **Quantum analogues**
  - Lattice gauge theories
  - QCD



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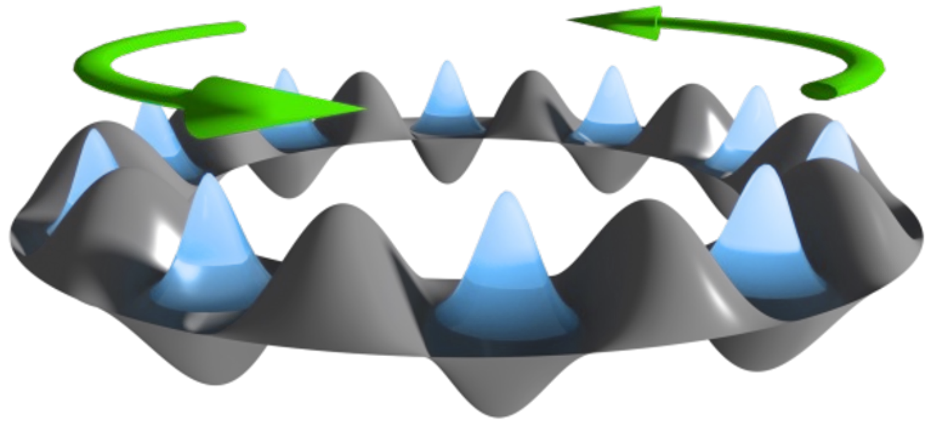
Dr. Vijay Singh



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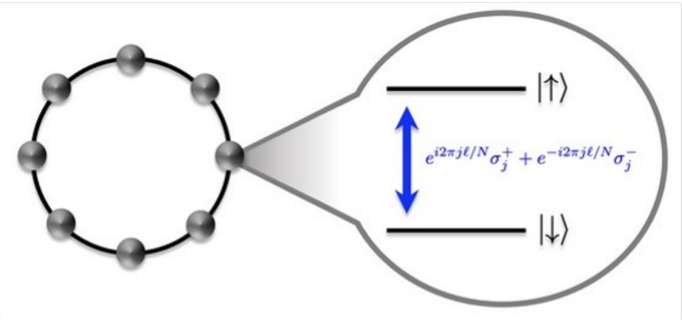

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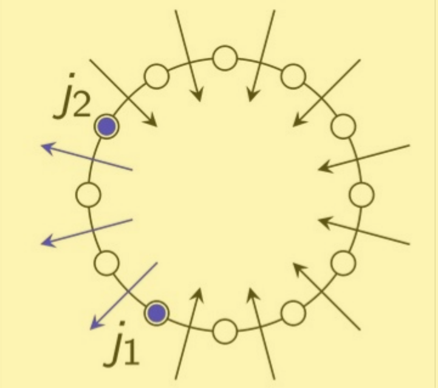

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State of the art

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*]

ARTICLES
https://doi.org/10.1038/s41567-021-01194-3
nature physics
Check for updates

Domain-wall confinement and dynamics in a quantum simulator

W. L. Tan[1,3✉], P. Becker[1,3✉], F. Liu[1], G. Pagano[1,2], K. S. Collins[1], A. De[1], L. Feng[1], H. B. Kaplan[1], A. Kyprianidis[1], R. Lundgren[1], W. Morong[1], S. Whitsitt[1], A. V. Gorshkov[1] and C. Monroe[1]

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Confined Phases of One-Dimensional Spinless Fermions Coupled to Z_2 Gauge Theory

Umberto Borla, Ruben Verresen, Fabian Grusdt, and Sergej Moroz
Phys. Rev. Lett. **124**, 120503 – Published 26 March 2020

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Lattice Gauge Theories and String Dynamics in Rydberg Atom Quantum Simulators

Federica M. Surace, Paolo P. Mazza, Giuliano Giudici, Alessio Lerose, Andrea Gambassi, and Marcello Dalmonte
Phys. Rev. X **10**, 021041 – Published 21 May 2020

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Simulating 2D Effects in Lattice Gauge Theories on a Quantum Computer

Danny Paulson, Luca Dellantonio, Jan F. Haase, Alessio Celi, Angus Kan, Andrew Jena, Christian Kokail, Rick van Bijnen, Karl Jansen, Peter Zoller, and Christine A. Muschik
PRX Quantum **2**, 030334 – Published 25 August 2021

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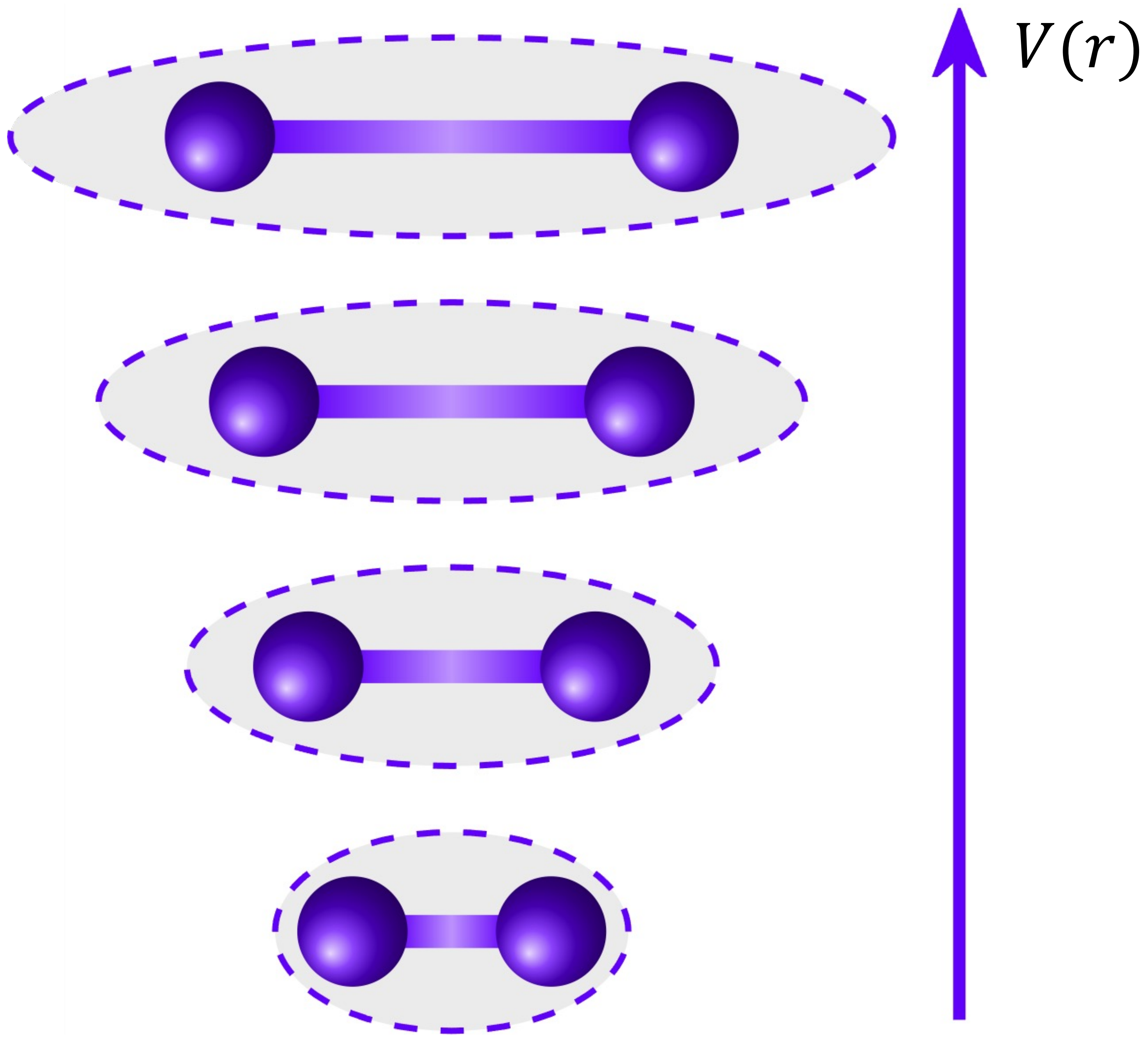
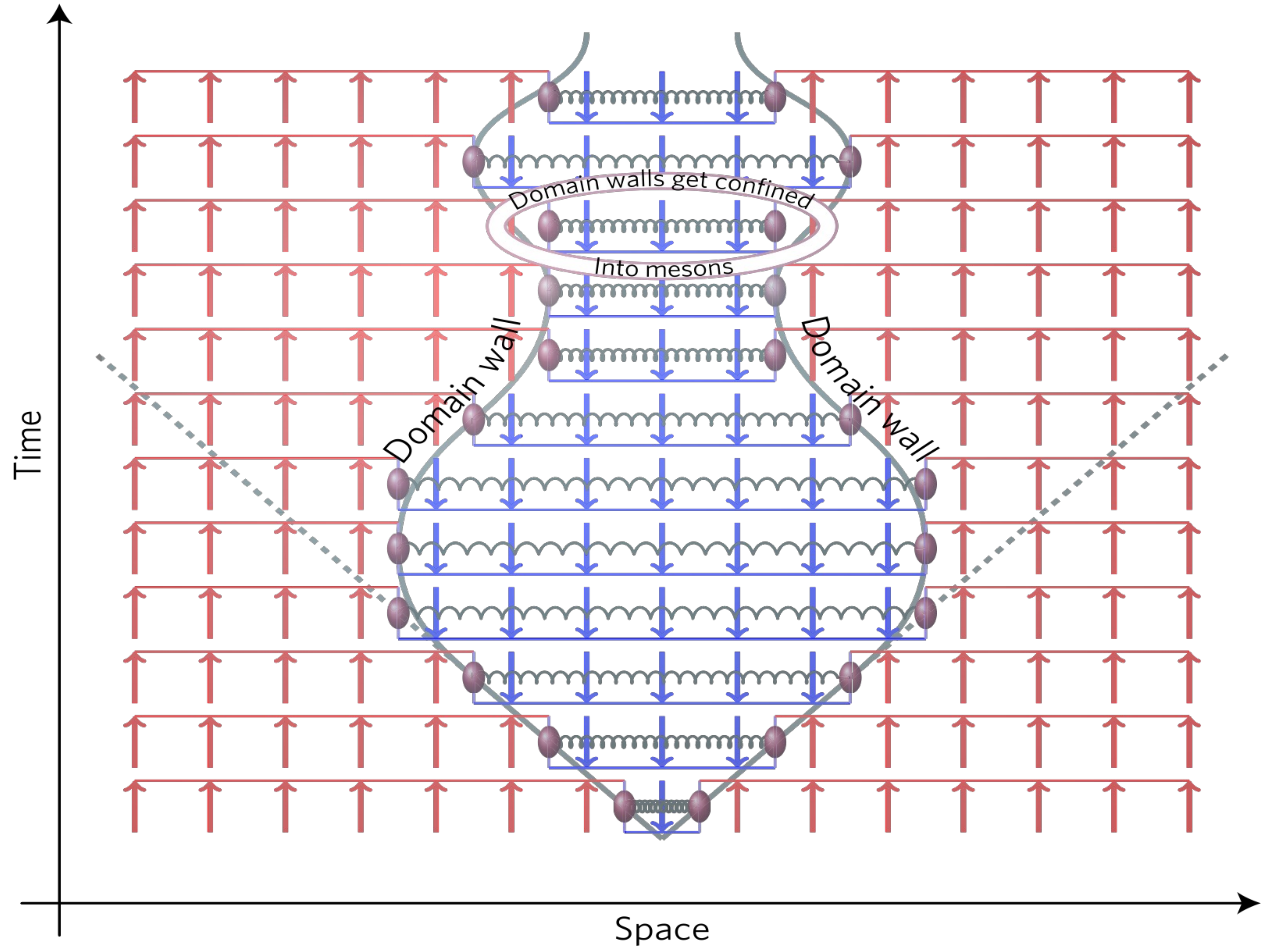
Digital Quantum Simulation of the Schwinger Model and Symmetry Protection with Trapped Ions

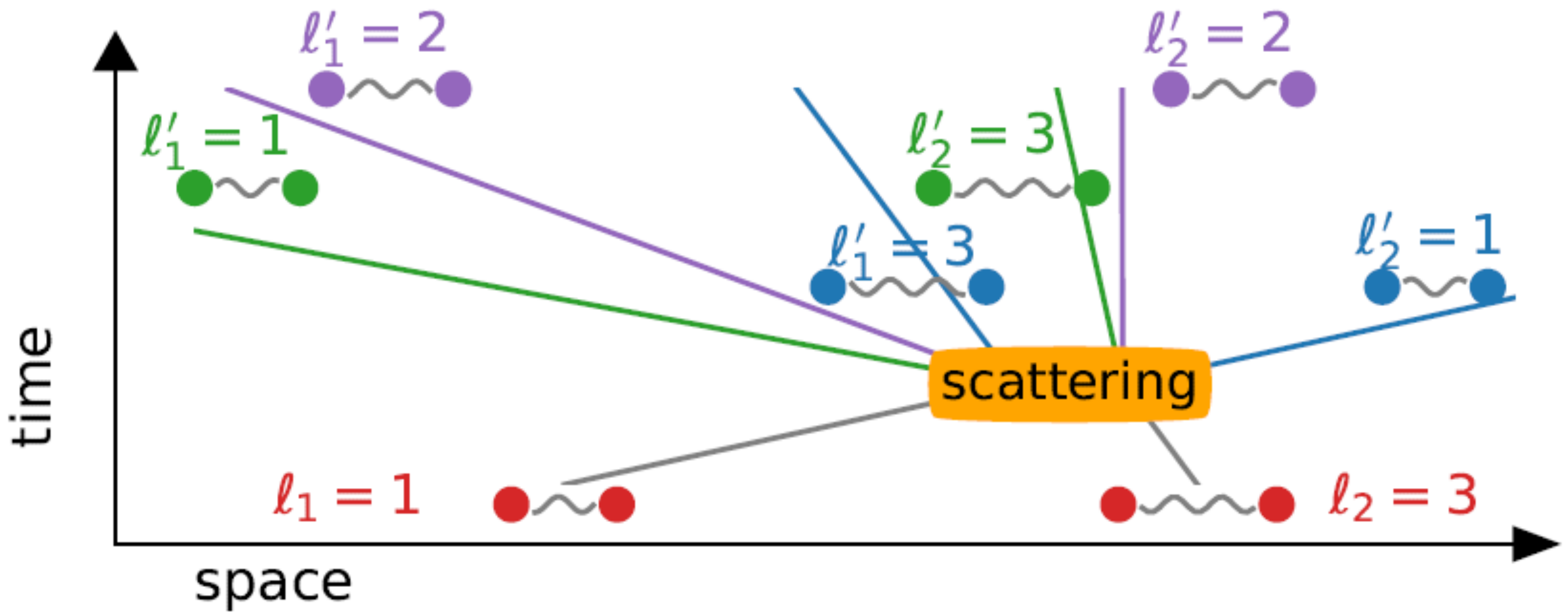
Nhung H. Nguyen, Minh C. Tran, Yingyue Zhu, Alaina M. Green, C. Huerta Alderete, Zohreh Davoudi, and Norbert M. Linke
PRX Quantum **3**, 020324 – Published 4 May 2022

Mesons





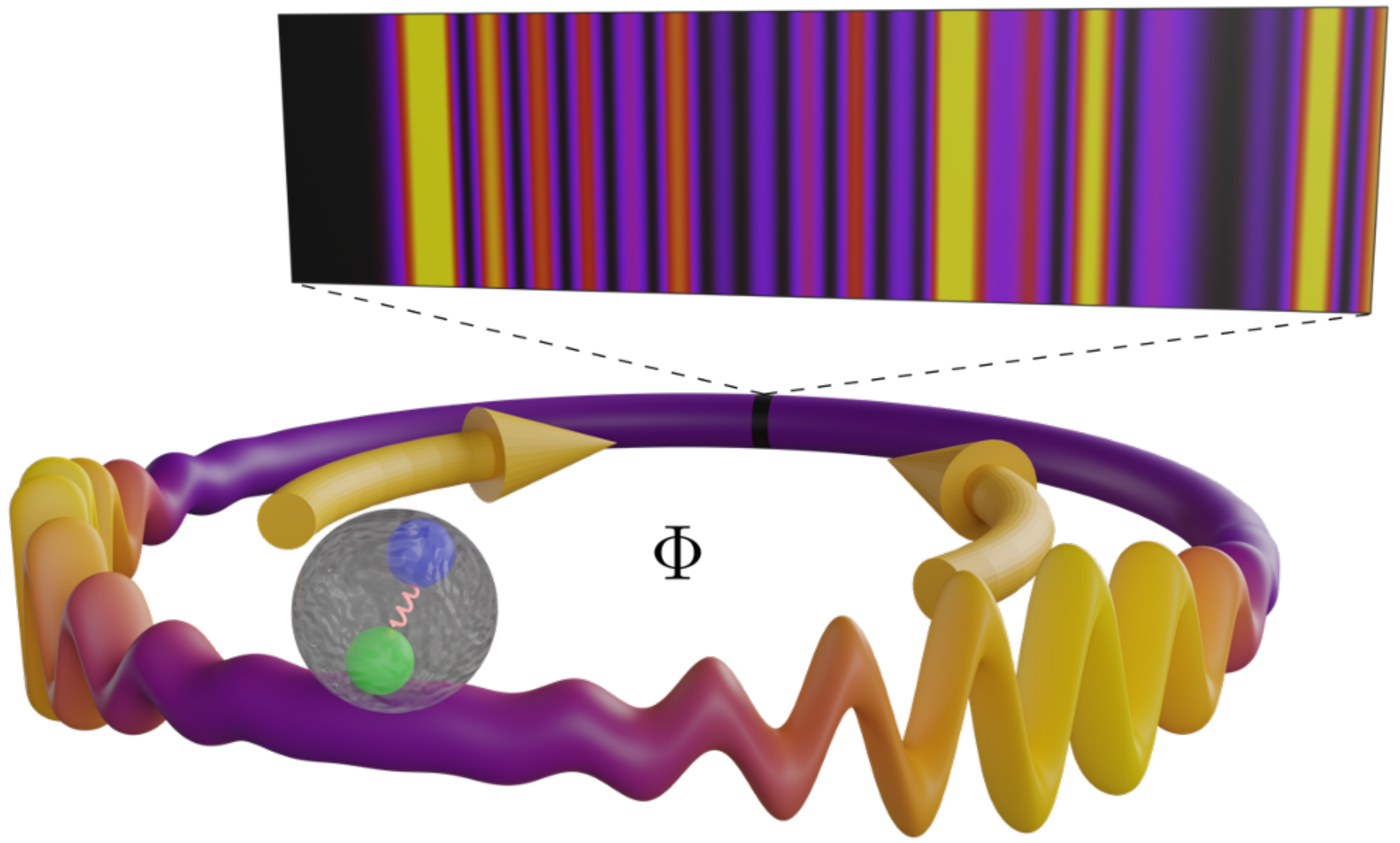
Kormos, M., Collura, M., Takács, G. *et al.* Real-time confinement following a quantum quench to a non-integrable model. *Nature Phys* 13, 246–249 (2017).



Federica Maria Surace and Alessio Lerose 2021 *New J. Phys.* 23 062001.

Coherence of confined matter in lattice gauge theories at the mesoscopic scales

E. C. Domanti, P. Castorina, D. Zappalà, L. Amico (2023) - arXiv:2304.12713

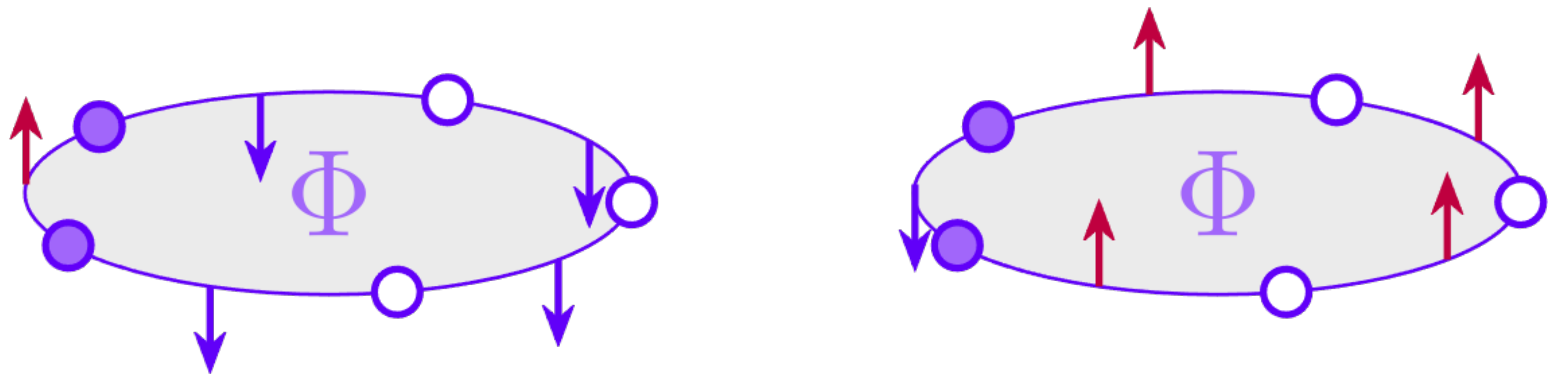


1d Z_2 lattice gauge theory

$$\mathcal{H} = \sum_j \left[w \left(e^{i\,(2\pi/L)\,\Phi/\Phi_0}\, c_j^\dagger c_{j+1} + h.c. \right) \sigma^x_{j+\frac{1}{2}} + \frac{\tau}{2} \sigma^z_{j+\frac{1}{2}} \right]$$

$$G_j \;=\; \sigma^z_{j-\frac{1}{2}} (-1)^{n_j} \sigma^z_{j+\frac{1}{2}}$$

- Generator of local $\mathbb{Z}_2$ transformations $G_j : [\mathcal{H}\,, G_j] = 0 \implies$ gauge sectors
- Neutral gauge sector: $G_j = 1 \;\forall j$



Implementation: Driven matterwave

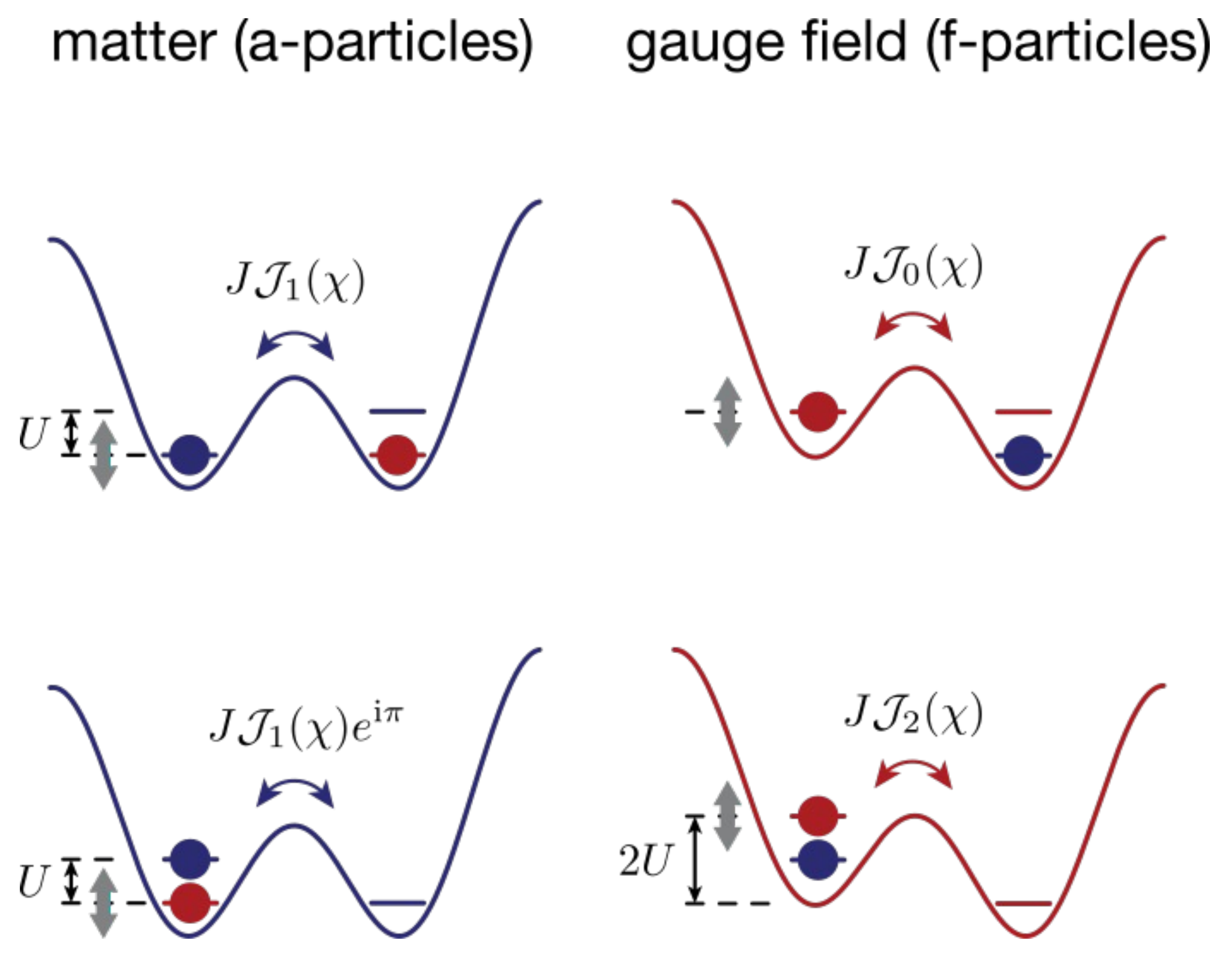
- Two atomic species, obtained from the internal levels of ^{87}Rb, are trapped in a species dependent double well potential

$$H = -J(a_2^\dagger a_1 + f_2^\dagger f_1 + h.c.) + U\sum_{j=1}^{2} n_j^a n_j^f + \Delta_f\, n_1^f + A\, cos(wt+\phi)(n_1^a + n_1^f)$$

- Tunneling processes are suppressed by large interaction U
- High frequency driving with $w \sim U$ restore the tunnelings, that acquire a density dependence

$$H_{eff} = -J_a\, \tau^z (a_2^\dagger a_1 + h.c.) - J_f\, \tau^x$$

$$\tau^z = n_2^f - n_1^f \qquad \tau^x = f_2^\dagger f_1 + f_1^\dagger f_2$$

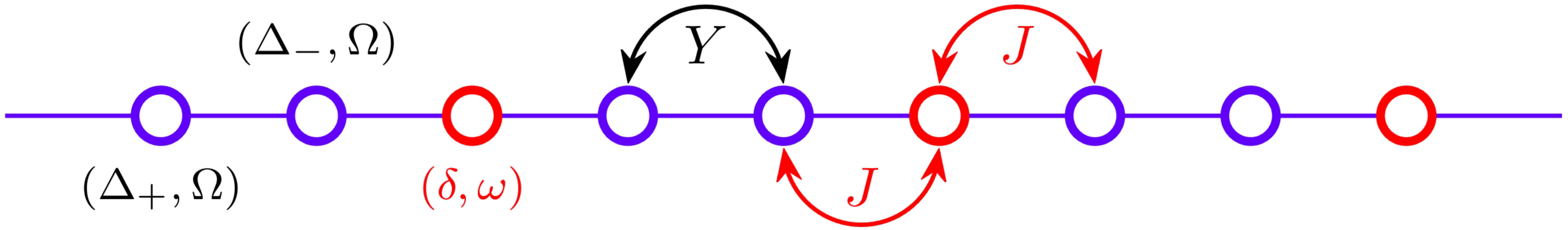


Schweizer, C., Grusdt, F., Berngruber, M. *et al.* Floquet approach to $\mathbb{Z}_2$ lattice gauge theories with ultracold atoms in optical lattices. *Nature Phys* 15, 1168–1173 (2019).

L. Barbiero, C. Schweizer, M. Aidelsburger, E. Demler, N. Goldman, F. Grusdt, Coupling ultracold matter to dynamical gauge fields in optical lattices: From flux attachment to Z_2 lattice gauge theories, Sci. Adv. (2019)

Implementation: Rydberg atoms

$$H = \sum_j \left[J_j \left(\sigma_j^+ \sigma_{j+1}^- + h.c. \right) + \frac{\Omega_j}{2} \sigma_j^x + \frac{\Delta_j}{2} \sigma_j^z \right]$$



- Purple sites = matter sites: alternating detunings $\Delta_\pm = \Delta \pm m$ and Rabi frequency Ω
- Red sites = gauge field links: detuning δ and Rabi frequency ω
- In the limit of very large Δ and for $\delta = \frac{2J^2}{\Delta}$ we obtain an effective lattice gauge theory

$$H_{LGT} = \sum_j \left[\frac{\omega}{2} \tau_j^x + \frac{J\Omega}{2\Delta} (s_j^z + \gamma_{j+1}^z) \tau_j^x + \frac{m}{2} (\gamma_j^z - s_j^z) + Y (\gamma_j^+ s_j^- + h.c.) - \frac{J^2}{\Delta} (s_j^+ \tau_j^z \gamma_{j+1}^- + h.c.) \right]$$

$$\gamma_j, s_j \rightarrow \text{matter variables}$$

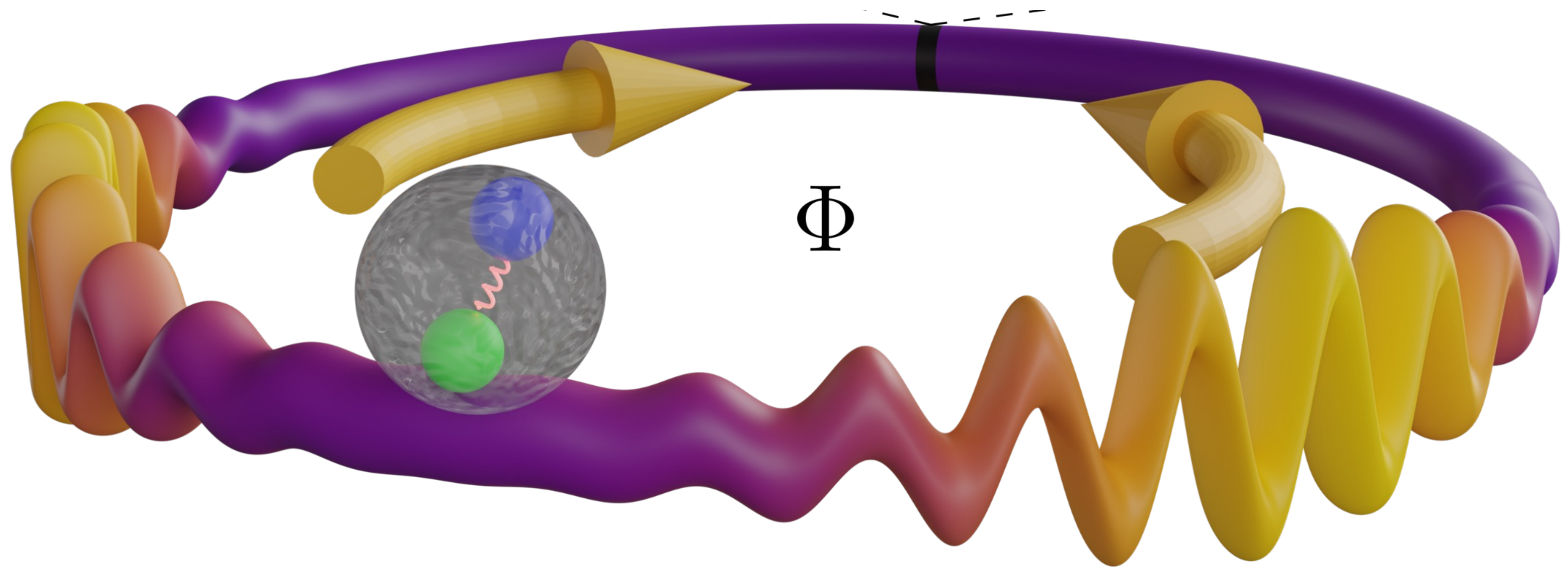
$$\tau_j \rightarrow \text{gauge variables}$$

Meson on a ring

$$\psi_E(s,r) = \mathcal{N}\, e^{iKs}\, \phi_E(K,r)$$

$$\phi_E(K,r) = \frac{\mathcal{J}_{E/\tau - r}\left[w(K,\Phi)\right]}{\mathcal{J}_{E/\tau}\left[w(K,\Phi)\right]} - \frac{\mathcal{Y}_{E/\tau - r}\left[w(K,\Phi)\right]}{\mathcal{Y}_{E/\tau}\left[w(K,\Phi)\right]}$$

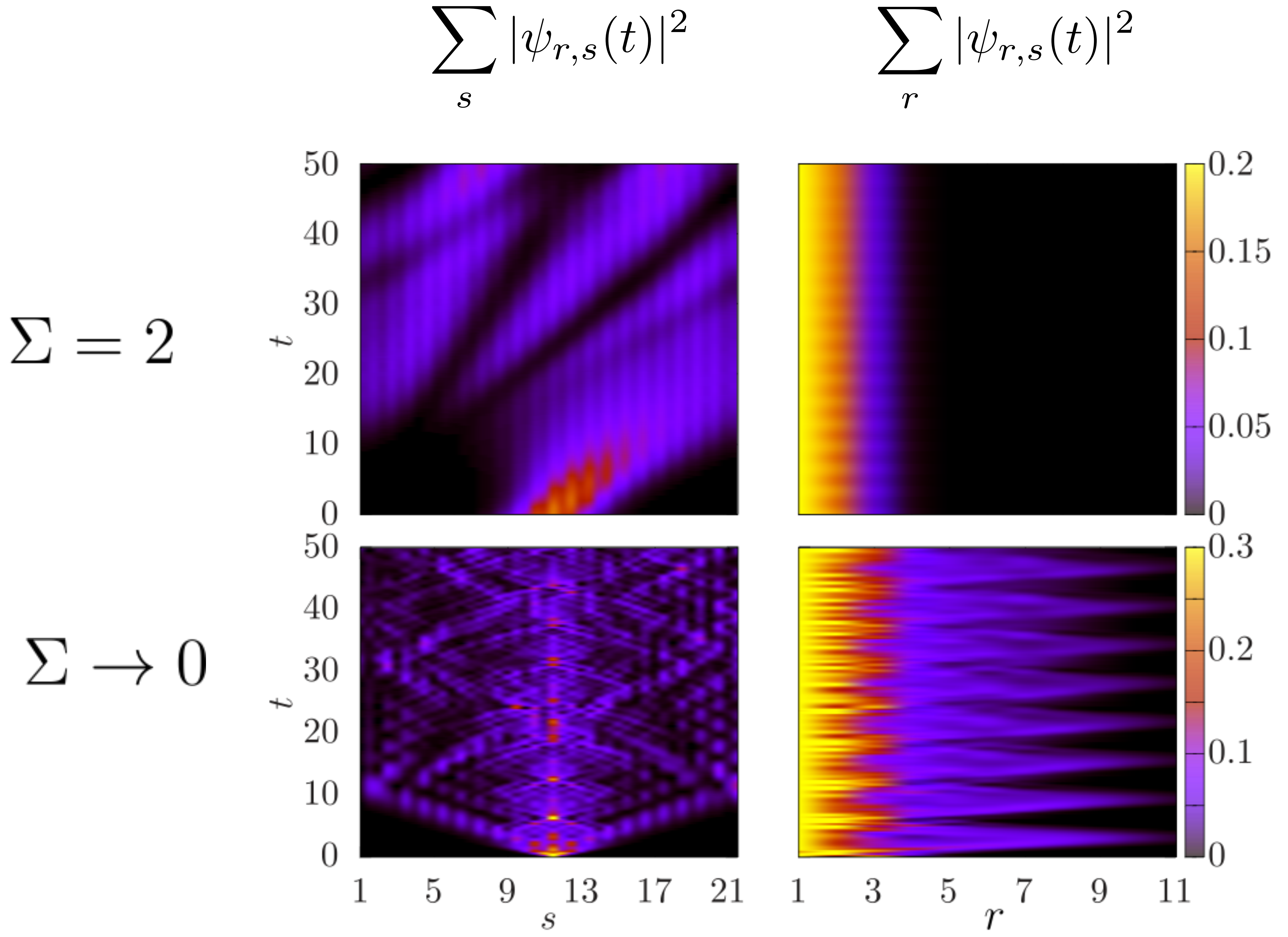
$$w(K,\Phi) = 2\, w\, cos\left(\frac{K}{2} + \frac{2\pi\Phi}{L\Phi_0}\right)\,,\; K = \frac{2\pi}{L} n$$

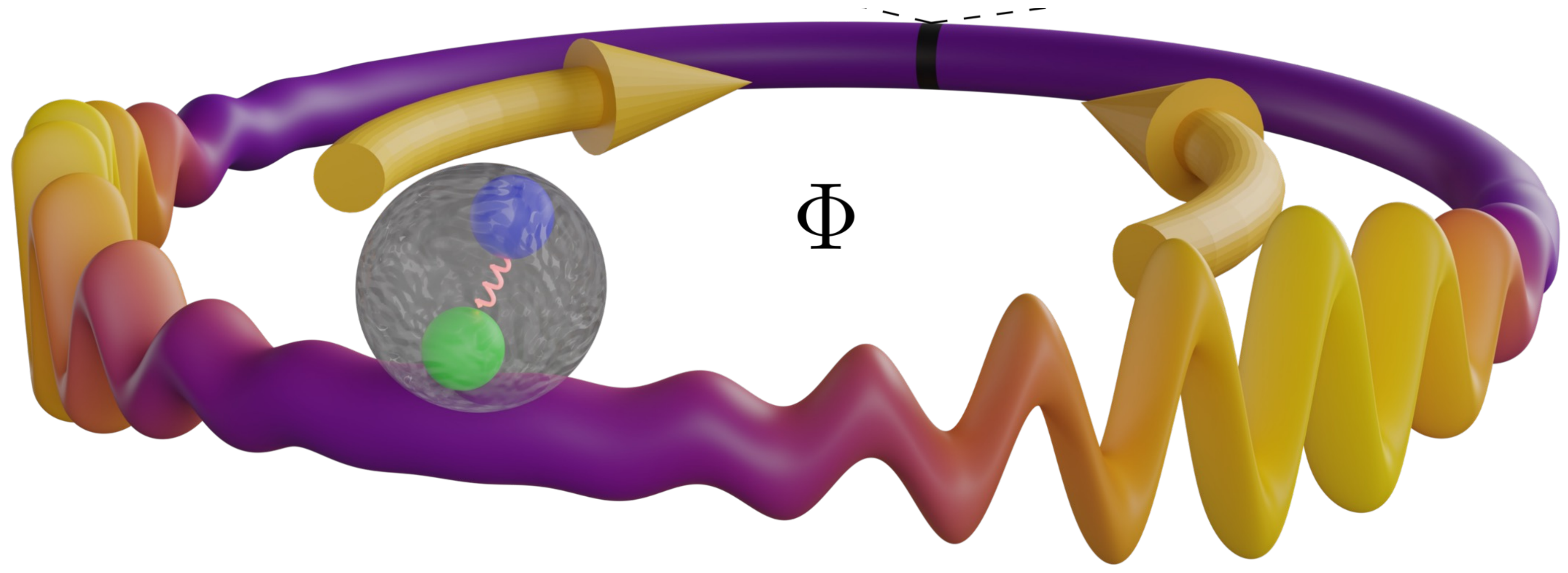


As a lattice effect, coupling between center of mass and relative coordinate dynamics

E. C. Domanti, P. Castorina, D. Zappalà, L. Amico (2023) - arXiv:2304.12713

Quench dynamics: $\Phi = 0 \rightarrow \phi \neq 0$



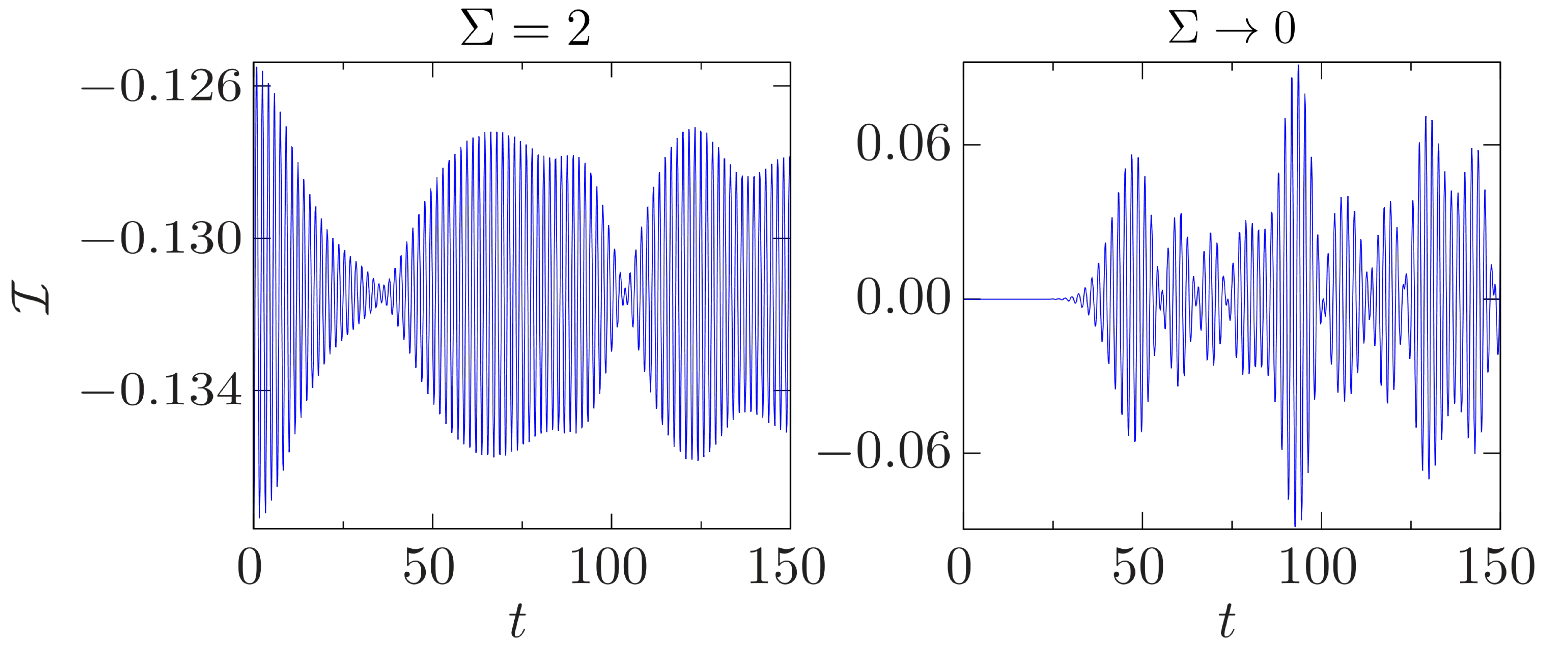


$$\psi^{\sigma}_{\Phi}(t) = e^{-iH(\Phi)t}\psi^{\sigma}_{0}(t=0)$$

$$\psi^{\sigma}_{0}(t=0) = e^{-(s+L/2\,\delta_{\sigma,\downarrow}-s_0)^2/(2\,\Sigma)}\,\psi^{\sigma}_{K=0,l=1}(s,r)$$

E. C. Domanti, P. Castorina, D. Zappalà, L. Amico (2023) - arXiv:2304.12713

Quench dynamics: current

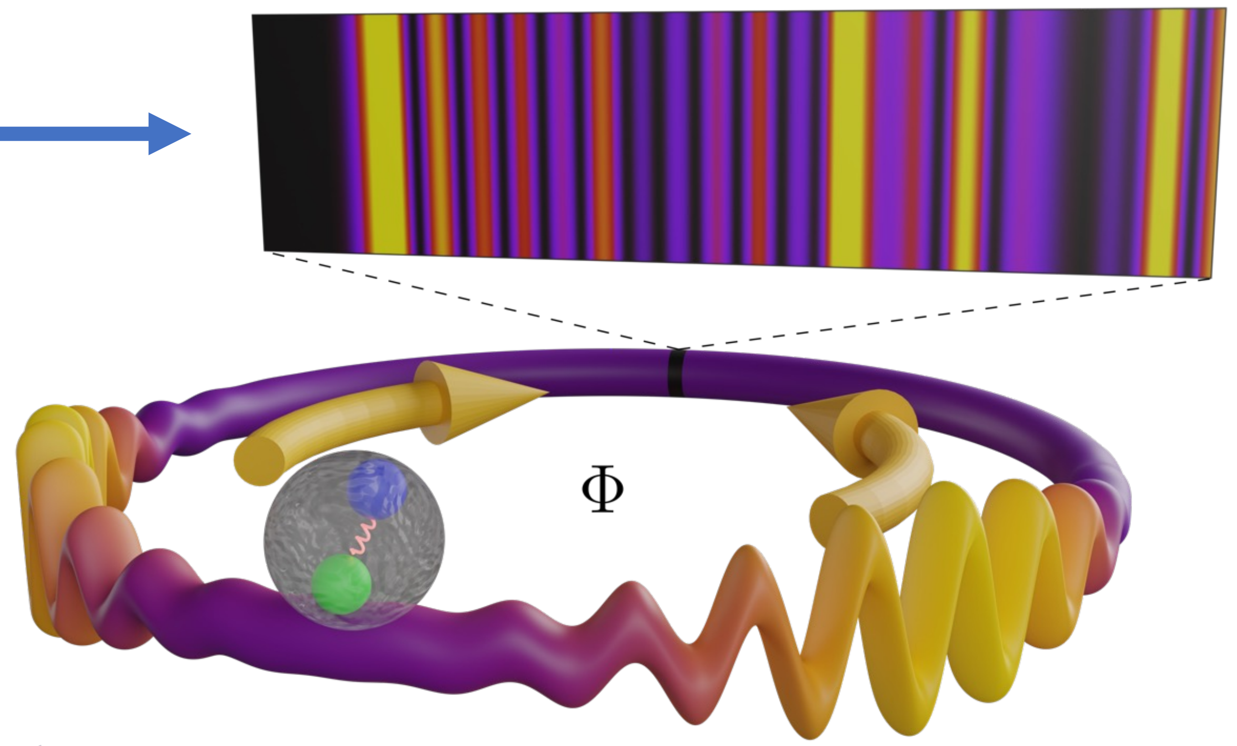


E. C. Domanti, P. Castorina, D. Zappalà, L. Amico (2023) - arXiv:2304.12713

Quench dynamics: Aharonov-Bohm

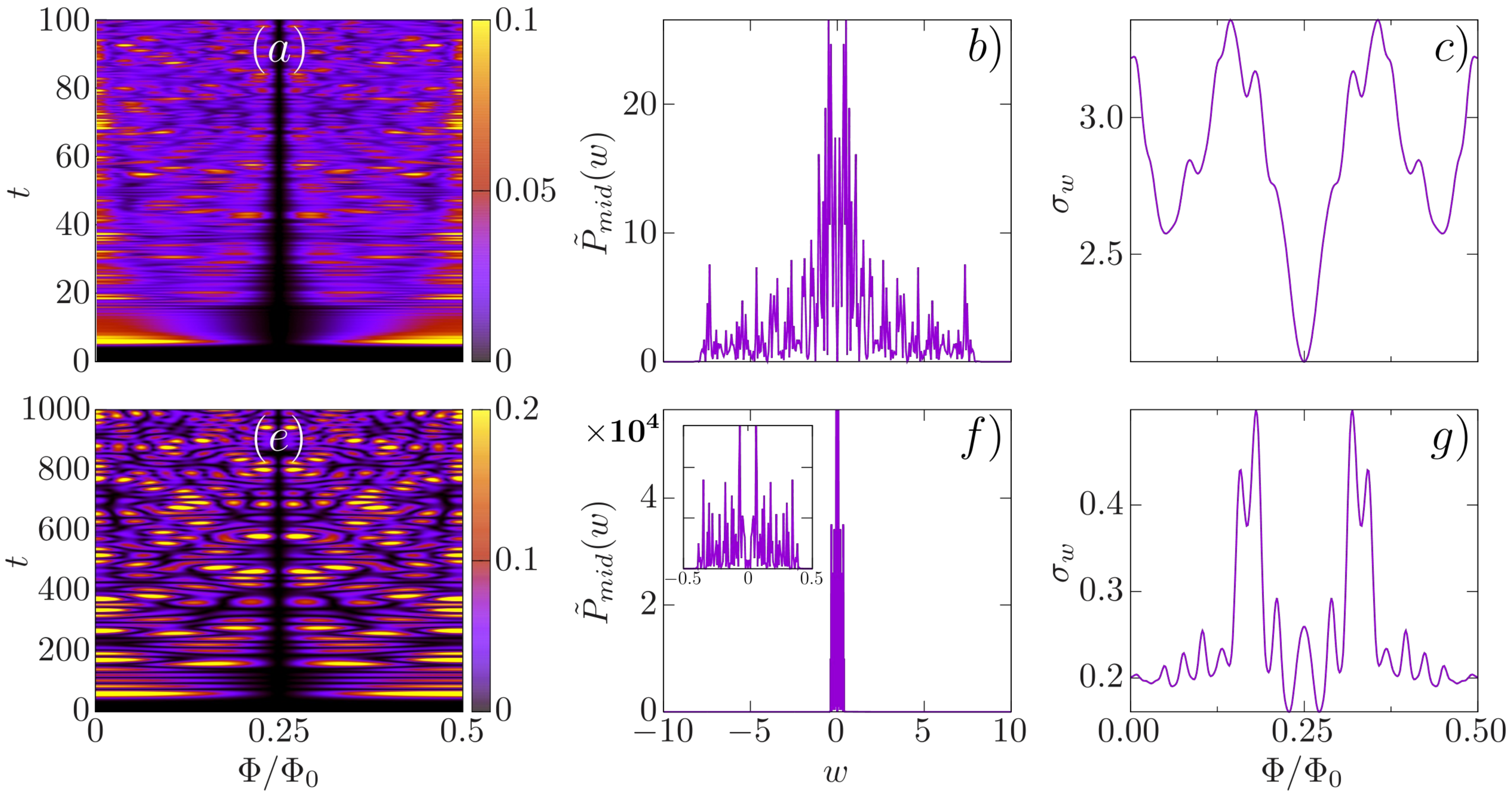
E. C. Domanti, P. Castorina, D. Zappalà, L. Amico (2023) - arXiv:2304.12713

$$P(s_0 + L/2) = \sum_r |\psi(s_0 + L/2, r)|^2$$



$\tau = 0.1$

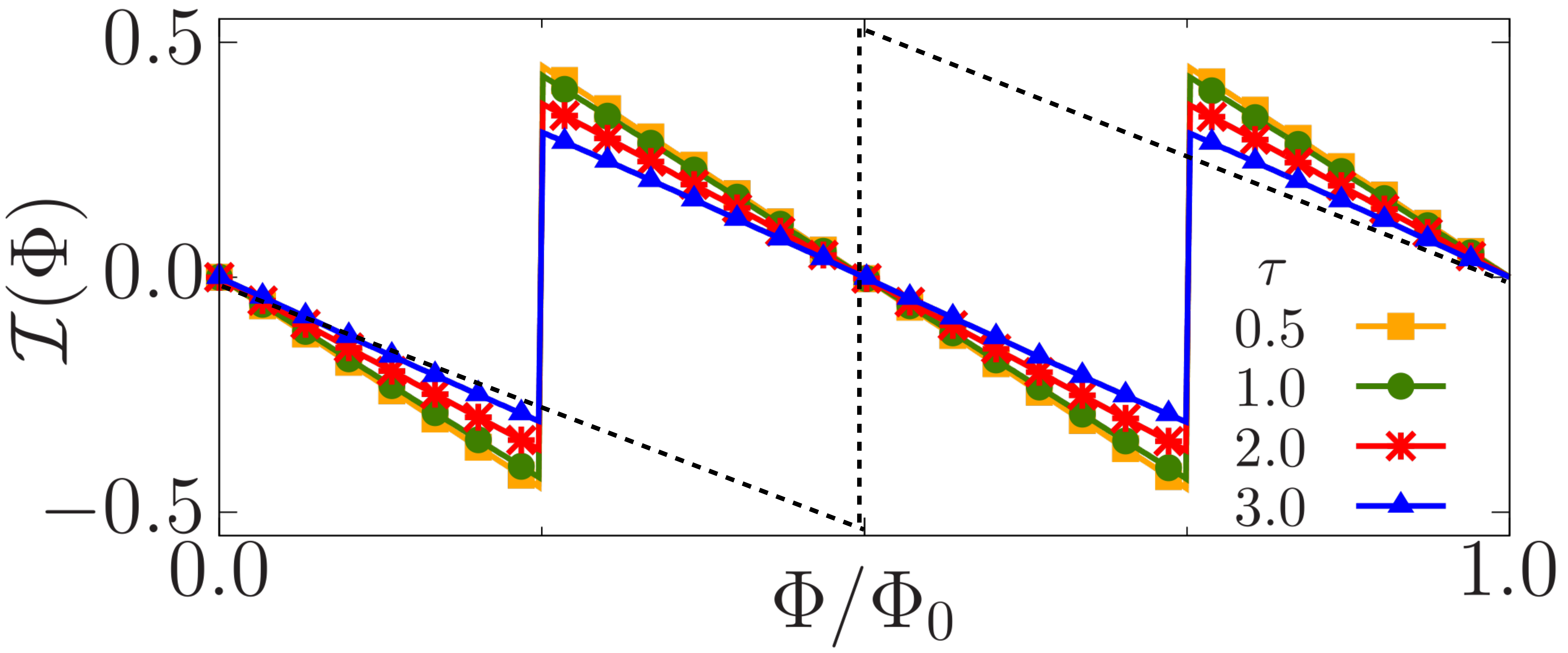
$\tau = 10$

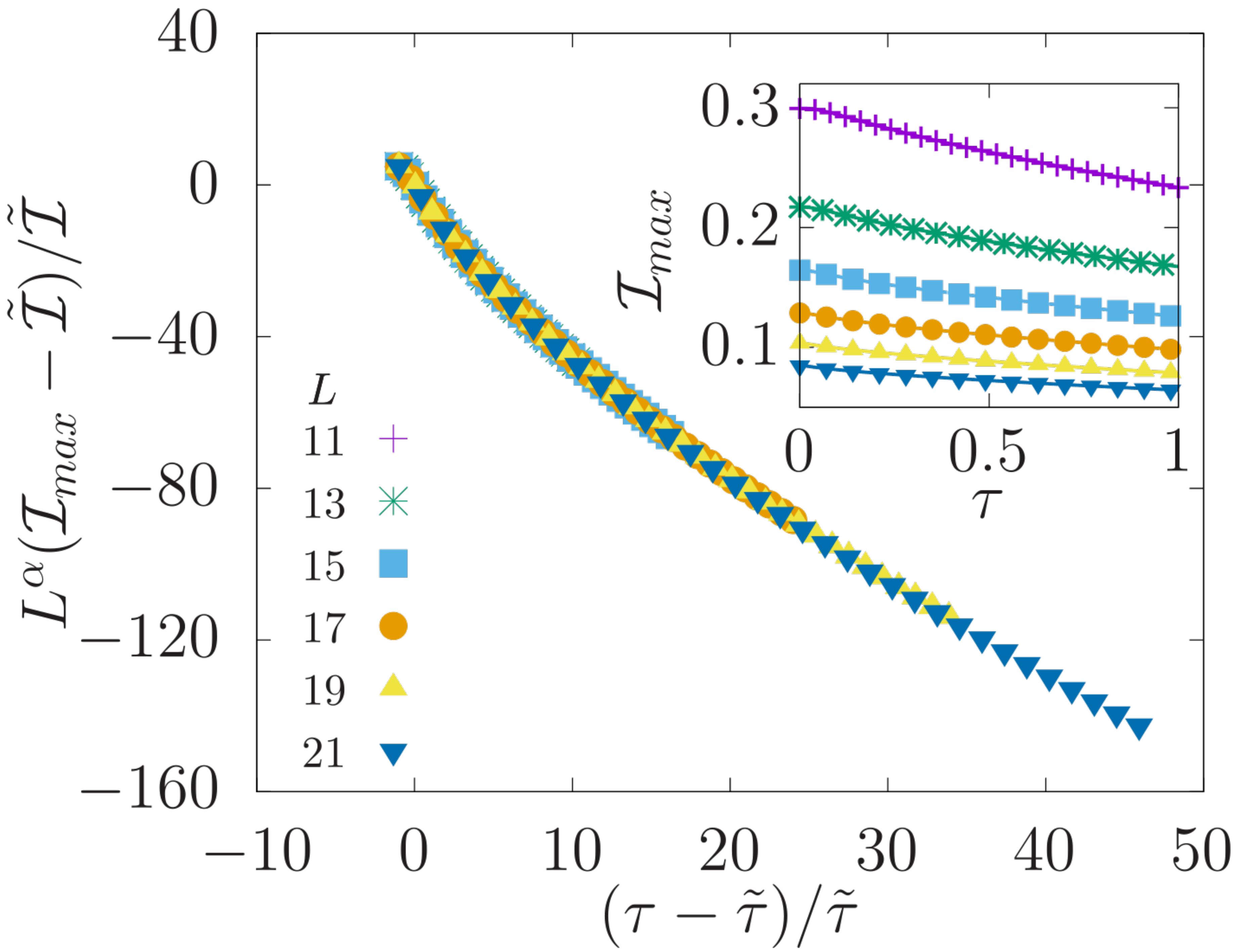


The relative coordinate dynamics is coupled with the magnetic field!

Ground state current

$$\mathcal{I}(\Phi) = -i\frac{2\pi w}{L\Phi_0}\sum_j \left(e^{i\frac{2\pi}{L}\Phi/\Phi_0} c_j^\dagger \, \sigma^x_{j+\frac{1}{2}} \, c_{j+1} - h.c.\right)$$





E. C. Domanti, P. Castorina, D. Zappalà, L. Amico (2023) - arXiv:2304.12713

Conclusions

◆Atomtronics-enabled quantum simulation of lattice gauge theories: able to resolve features of the theory that are very hard (if not impossible) to access through particle accelerators.

- The dynamics of the current reflects the coupling between the center of mass and the relative motion of confined particles
- Mesoscopic properties of confined matter can be accessed through the meson current
- Aharonov-Bohm oscillations