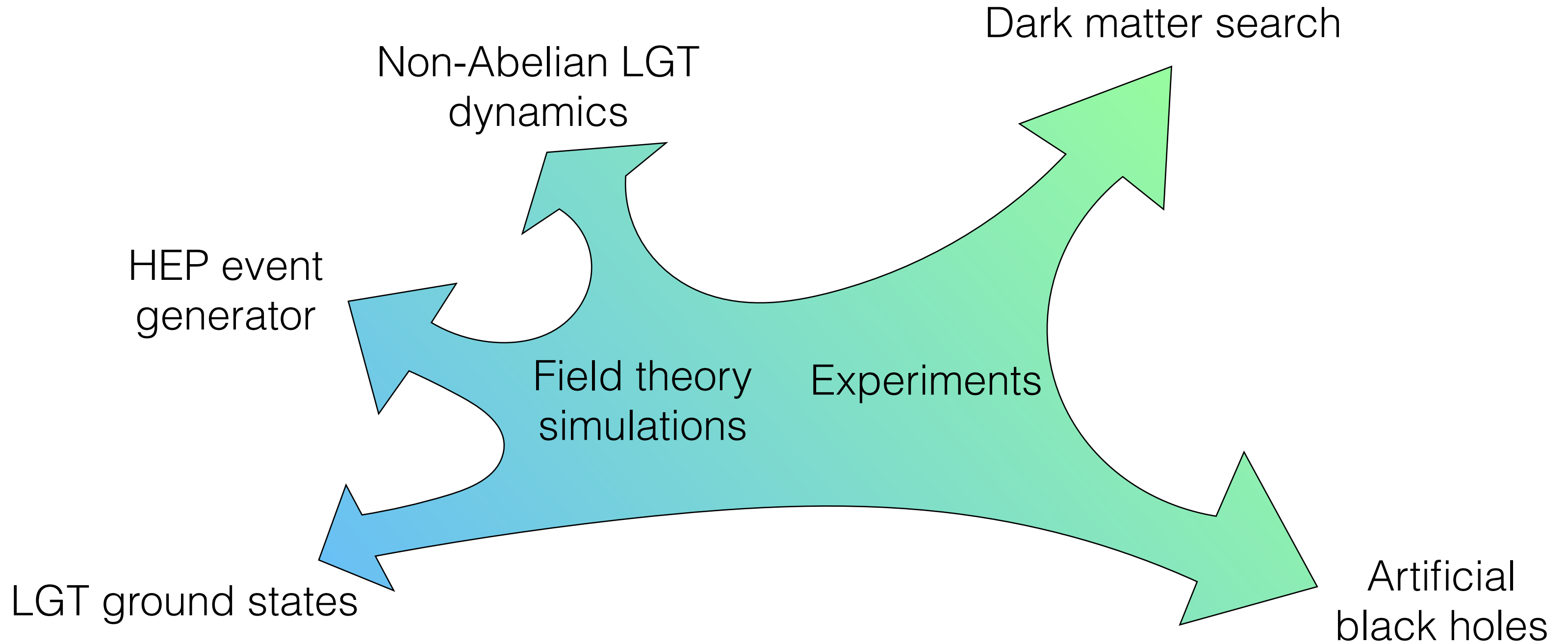


A Multi-Front Approach to Advancing High-Energy Physics with Quantum Technologies

Yutaro Iiyama
ICEPP, The University of Tokyo

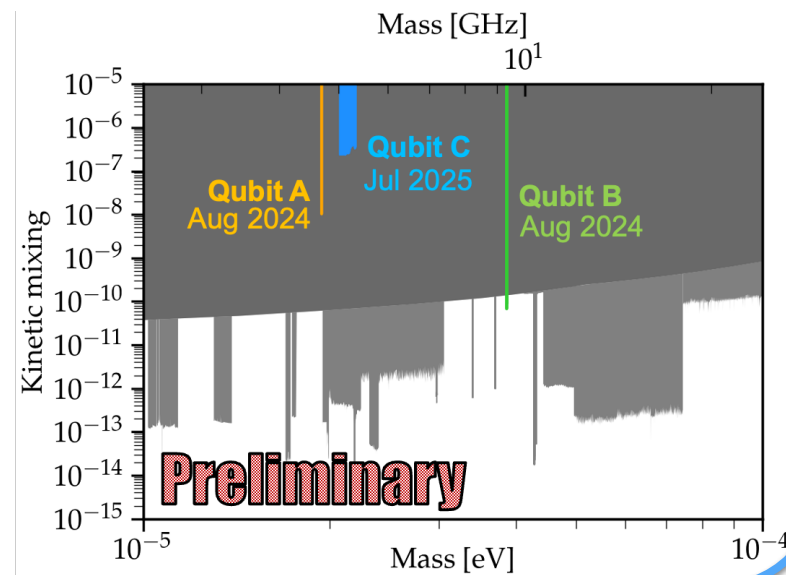
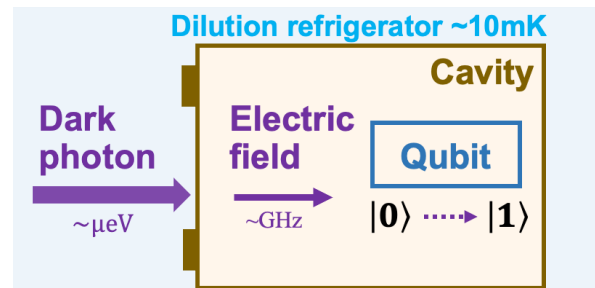
Multiple Quantum+HEP fronts at ICEPP



Dark matter search using qubits (DarQ)

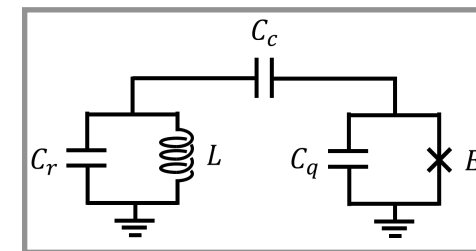
DarQ-Direct

Chen+, PRL 131 (2022)
 Chen+, PRL 133 (2023)
 Chen+, PRD 110 (2024)
 Watanabe+, Patras 2024

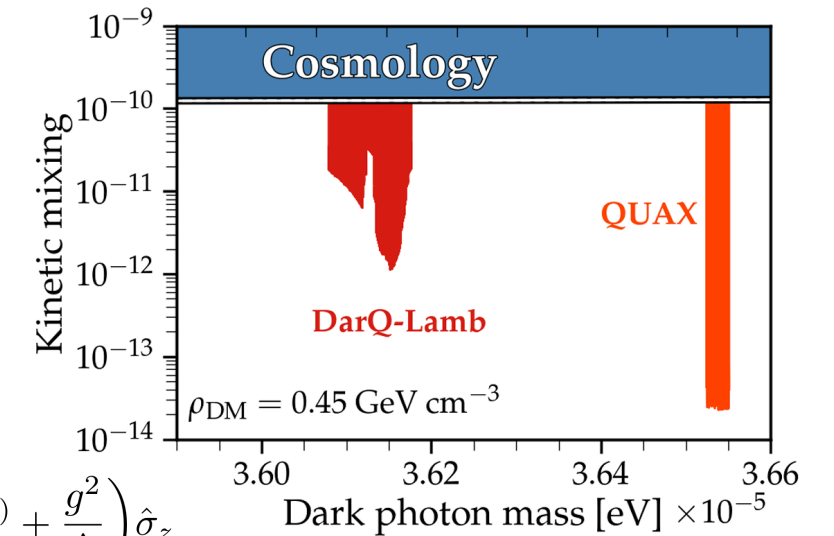


DarQ-Lamb

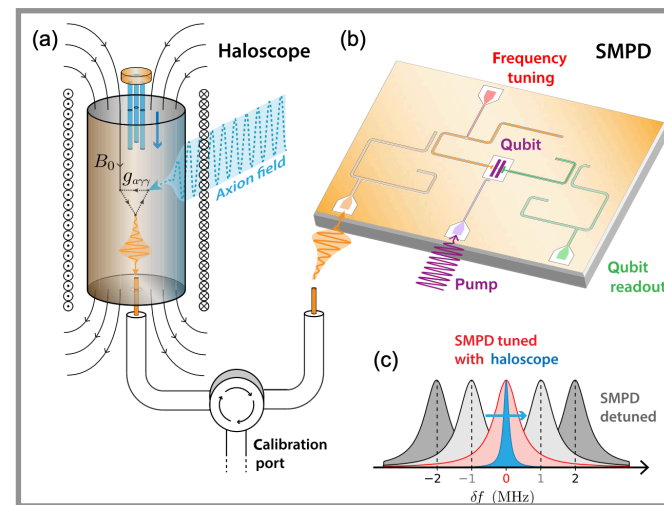
Nakazono+, 2505.15619



$$\hat{H}_{JC} = \hbar \left(\omega_c + \frac{g^2}{\Delta} \hat{\sigma}_z \right) \hat{a}^\dagger \hat{a} + \frac{\hbar}{2} \left(\omega_q^{(0)} + \frac{g^2}{\Delta} \right) \hat{\sigma}_z$$

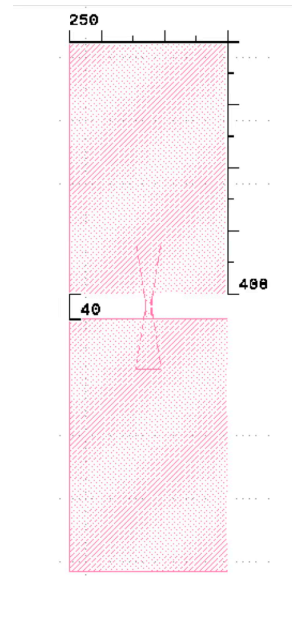


DarQ-SPC

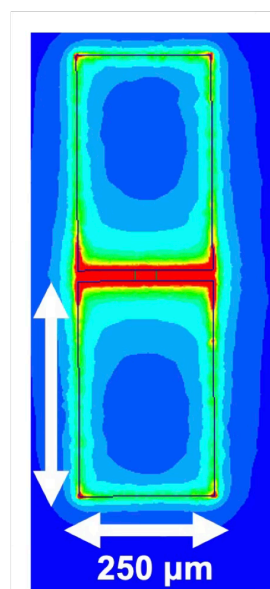


Braggio+ 2025

Design



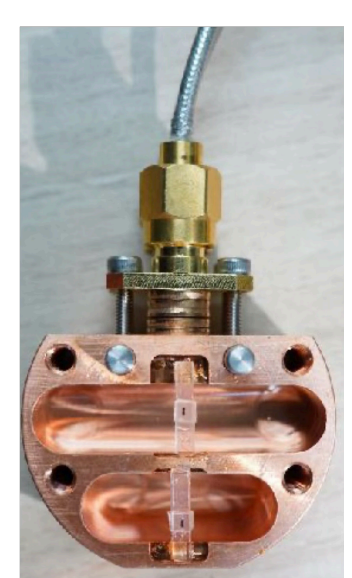
Simulation



Fabrication

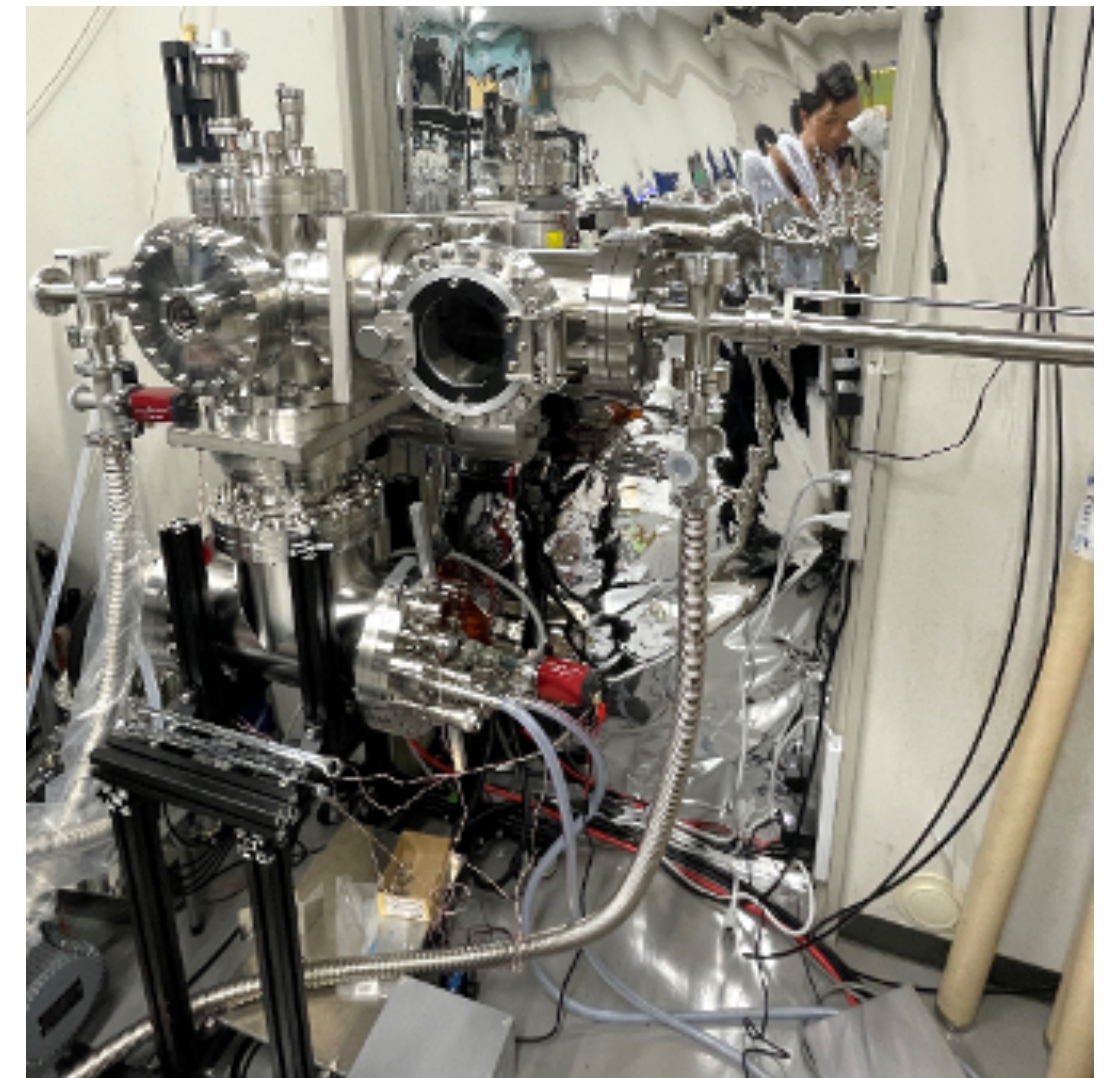
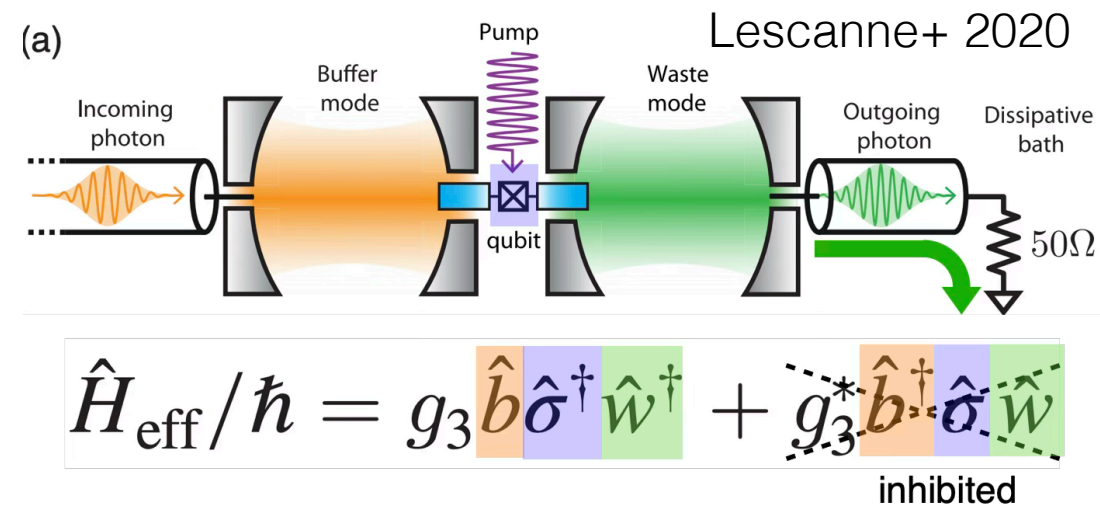
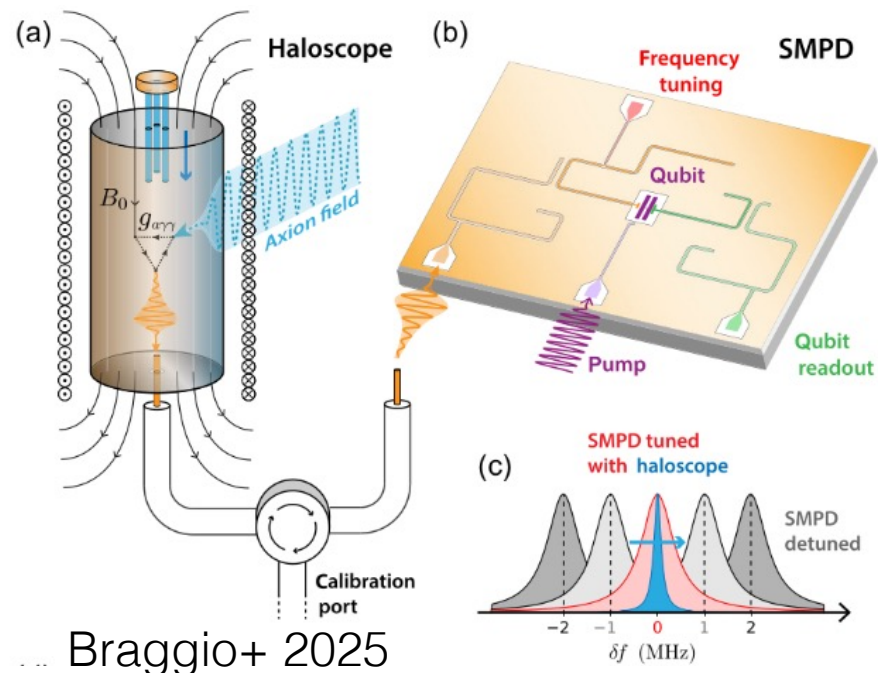


Packaging

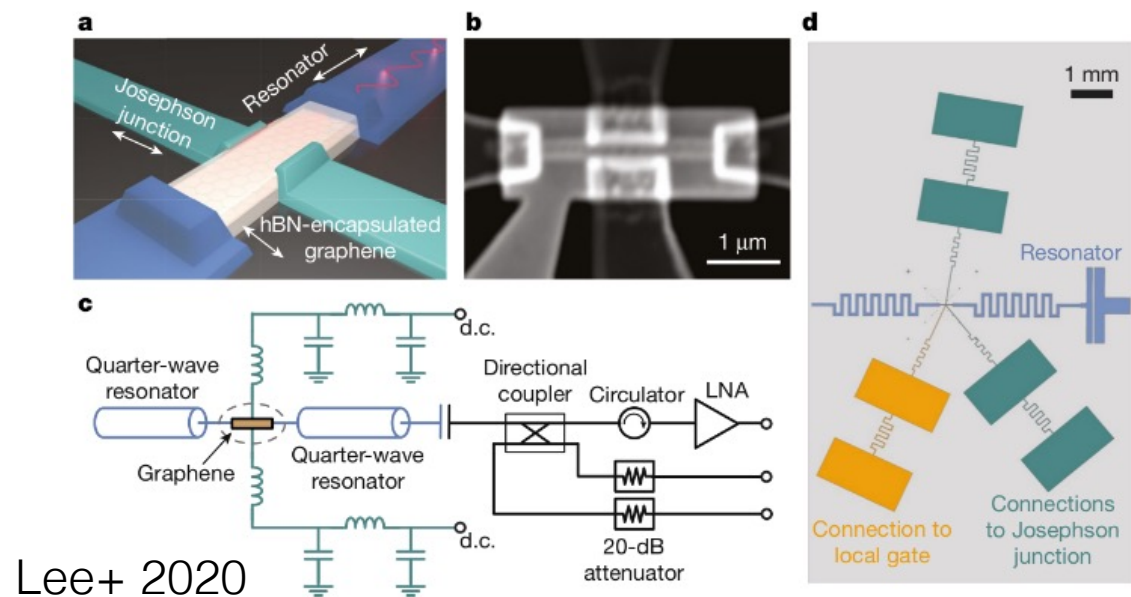


Device R&D for dark matter detection

- Single microwave photon detector



- Graphene superconducting bolometer



Building an in-house shadow evaporation chamber (Josephson junction fab)

Artificial black hole experiments

“Black hole” = event horizon analogues

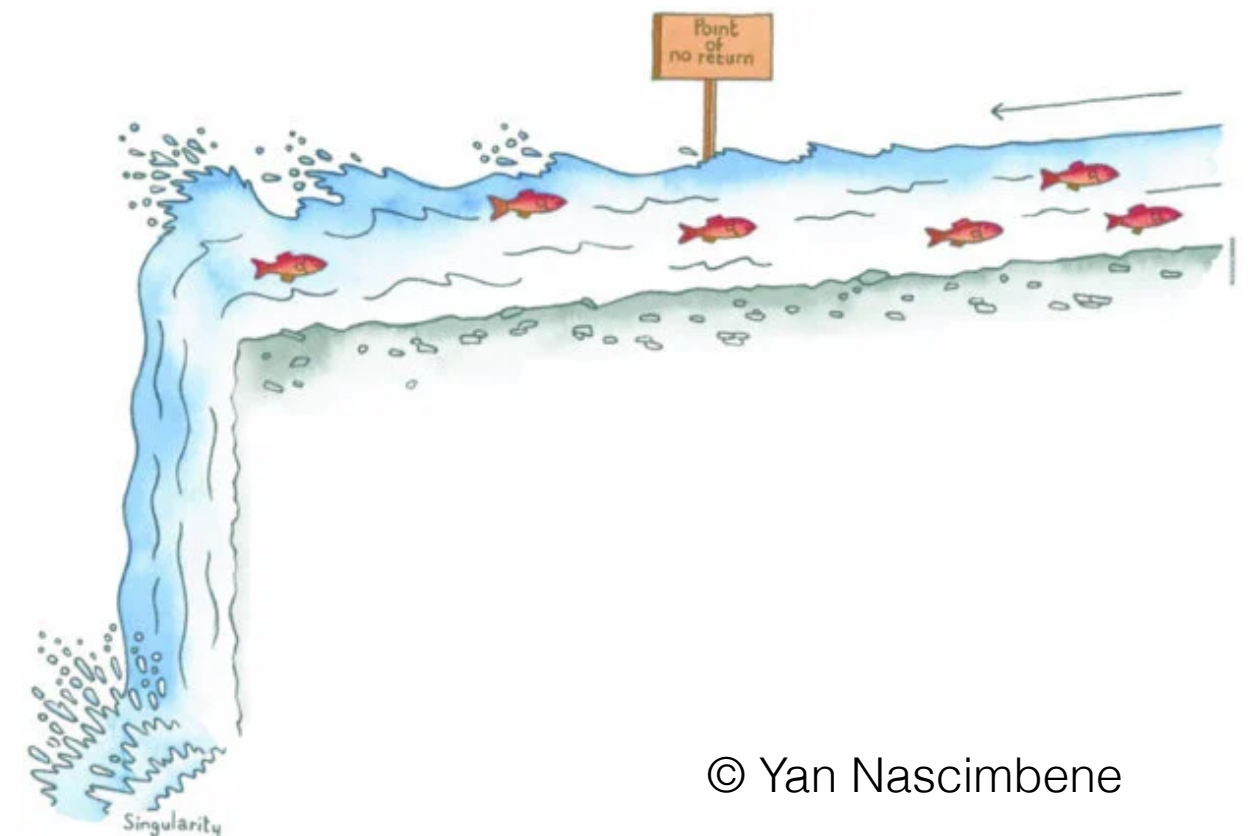
Aim: to realize waves in a background flow with

$$v_{\text{flow}} > v_{\text{wave}}$$

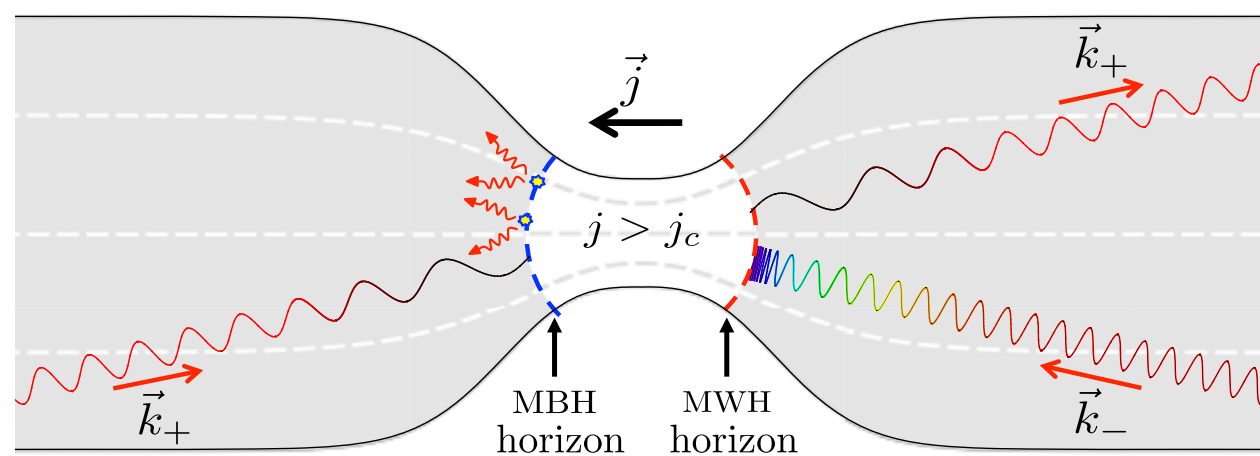
→ Observe Hawking radiation analogues

Two systems in use at ICEPP:

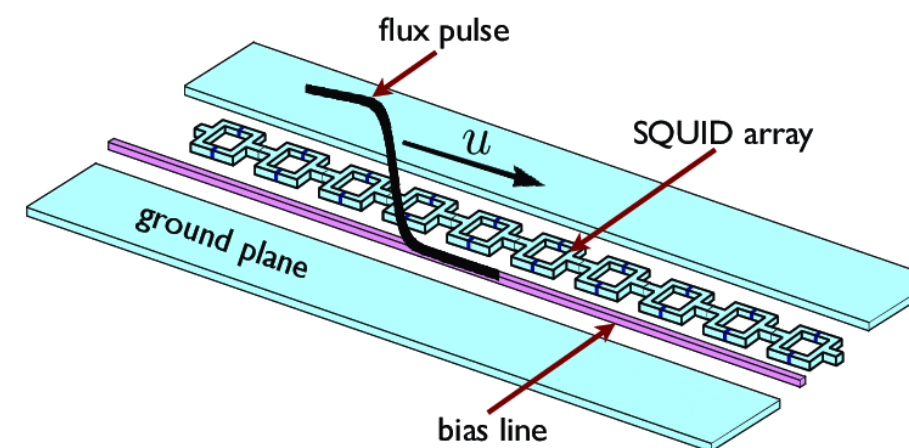
- Magnon (spin wave) in spin current
- RF in SQUID array



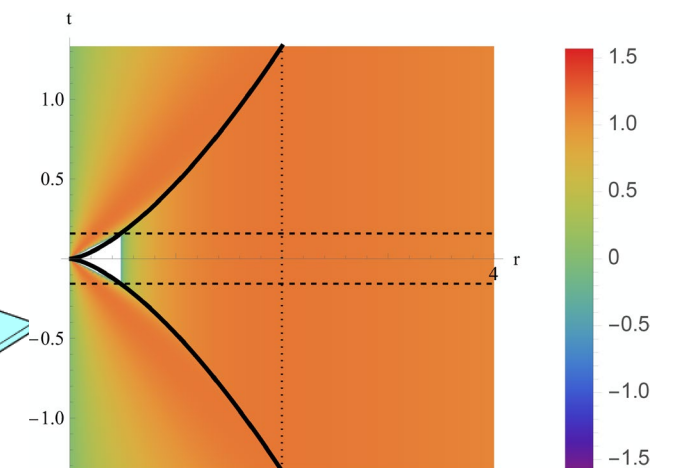
© Yan Nascimbene



Roldán-Molina+ 2017

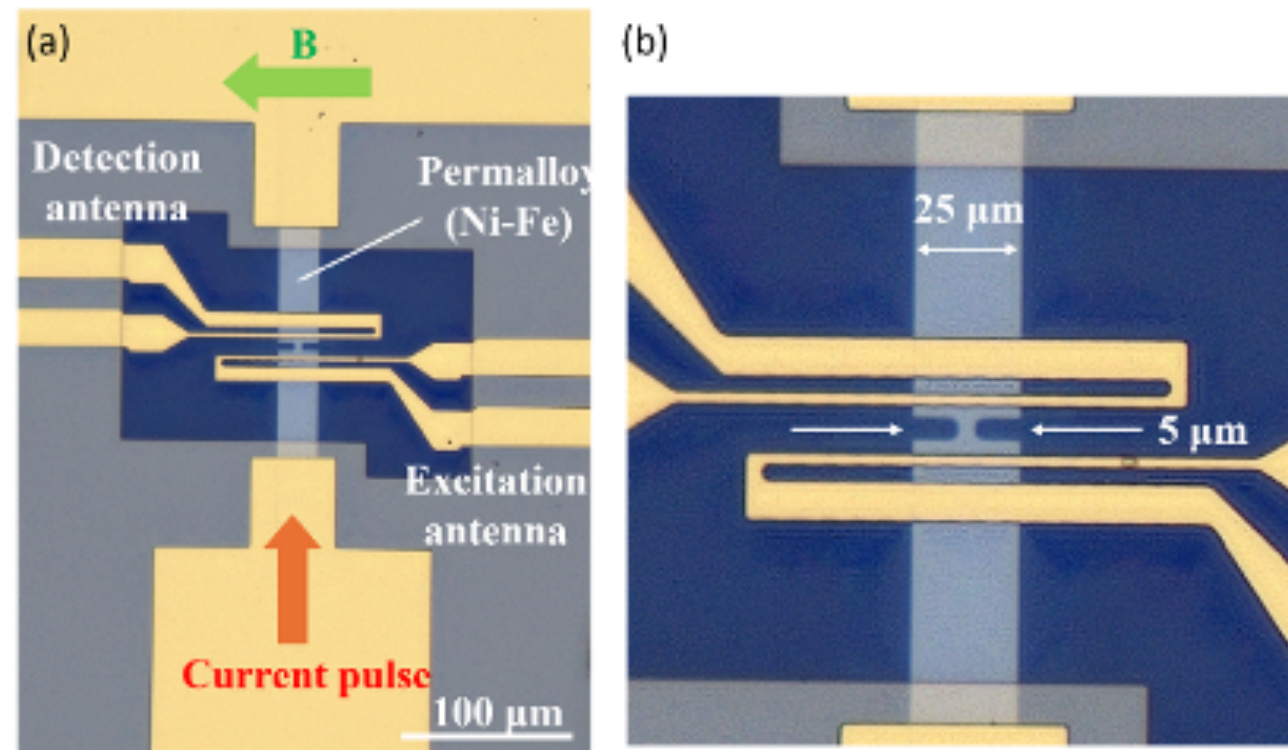


Nation+ 2009

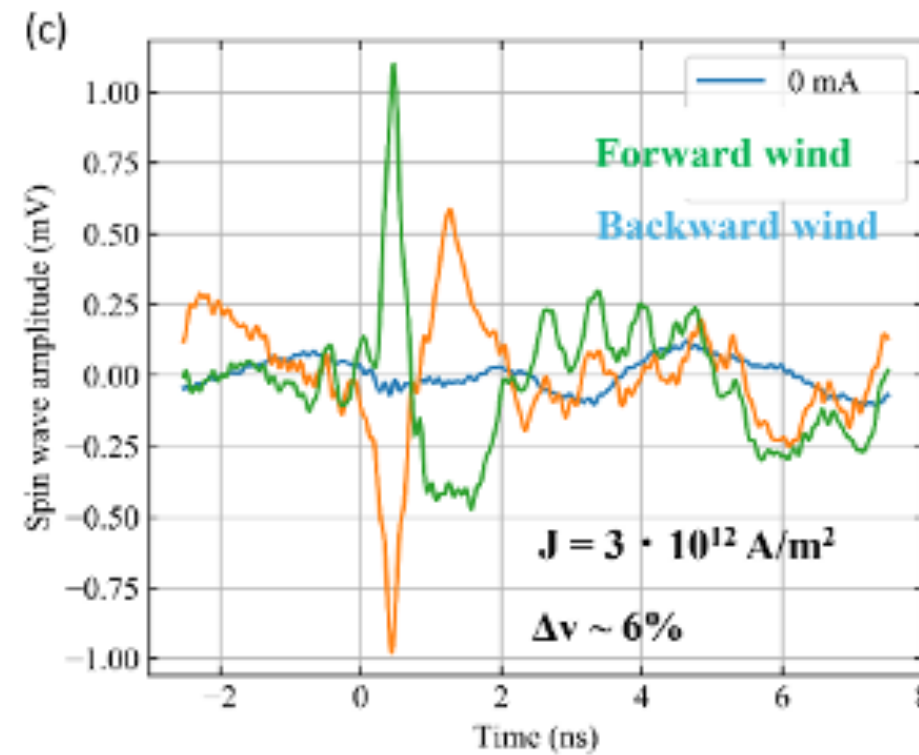


Maceda+ 2025

Spin wave event horizon

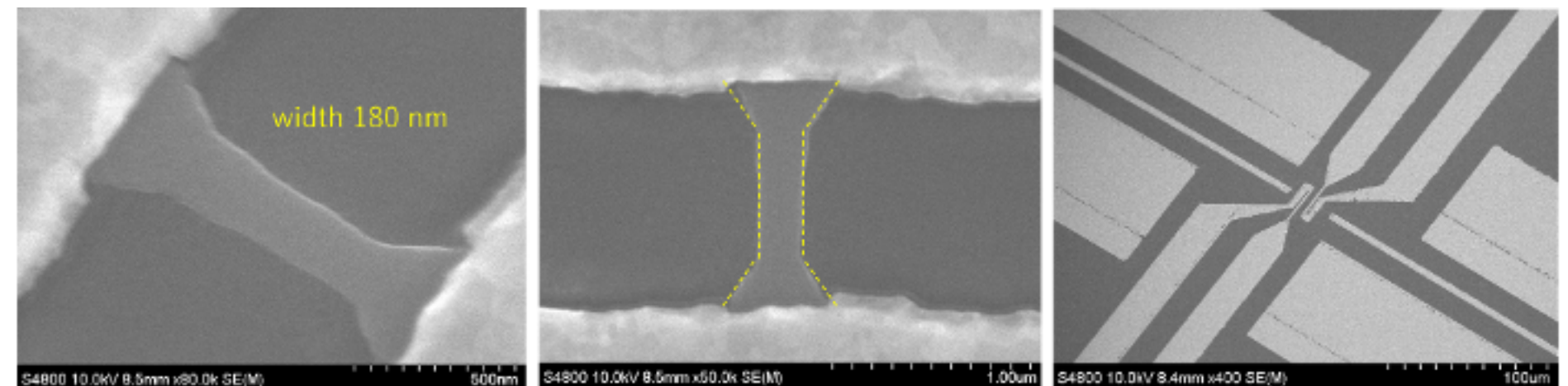
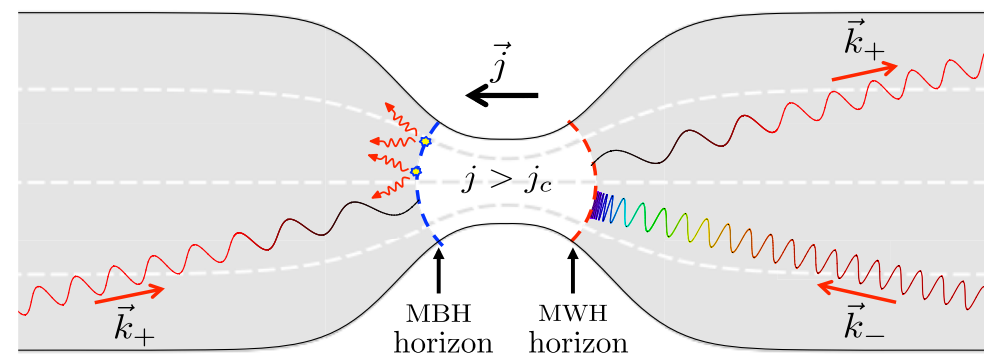


Microscope image of the experiment setup

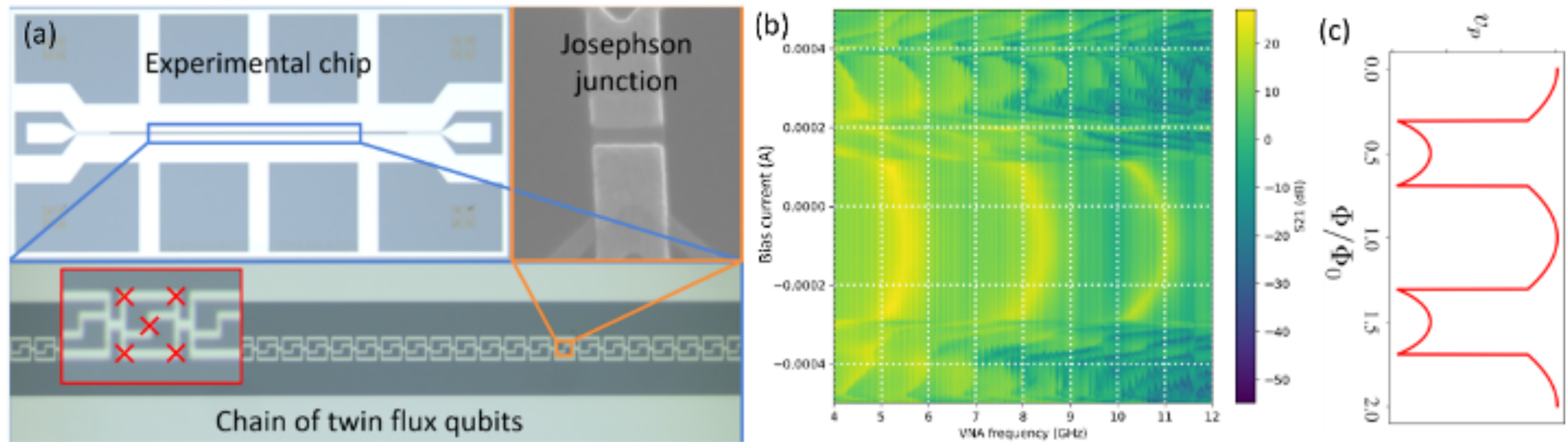


Realized 6% Doppler shift of spin waves
(Previous world record 0.4%)

Width of the bottleneck determines the current density
→ Fabricated sub-μm bottleneck



SQUID array



Array of 300 twin-flux qubits

Transmission spectrum
dependency on bias current

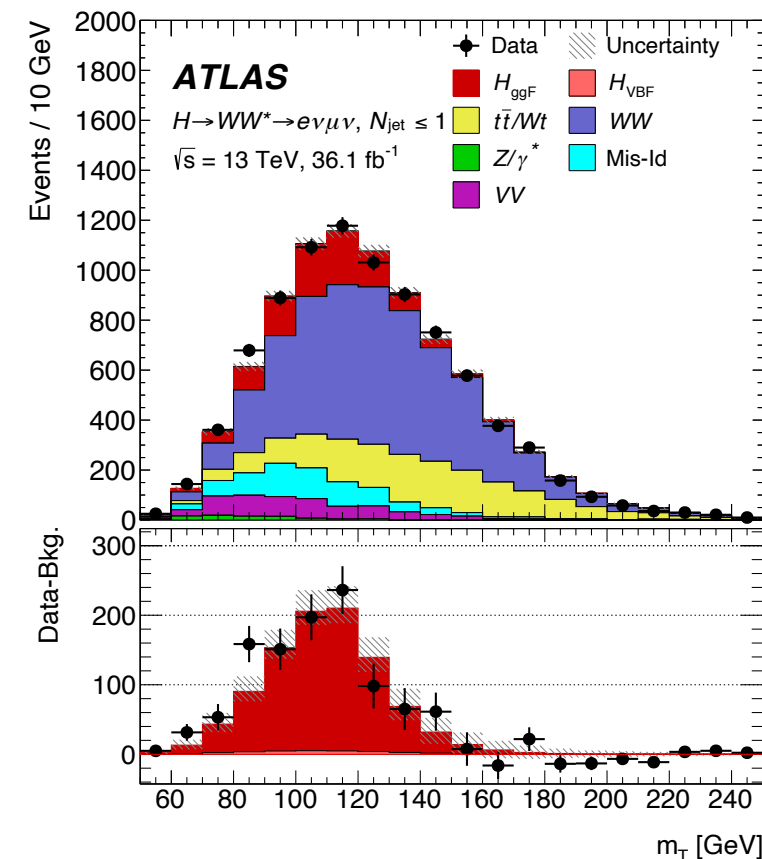
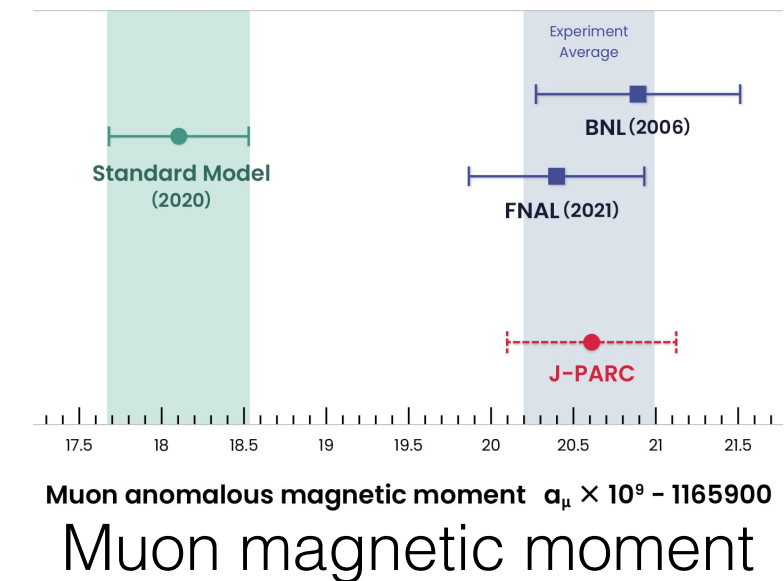
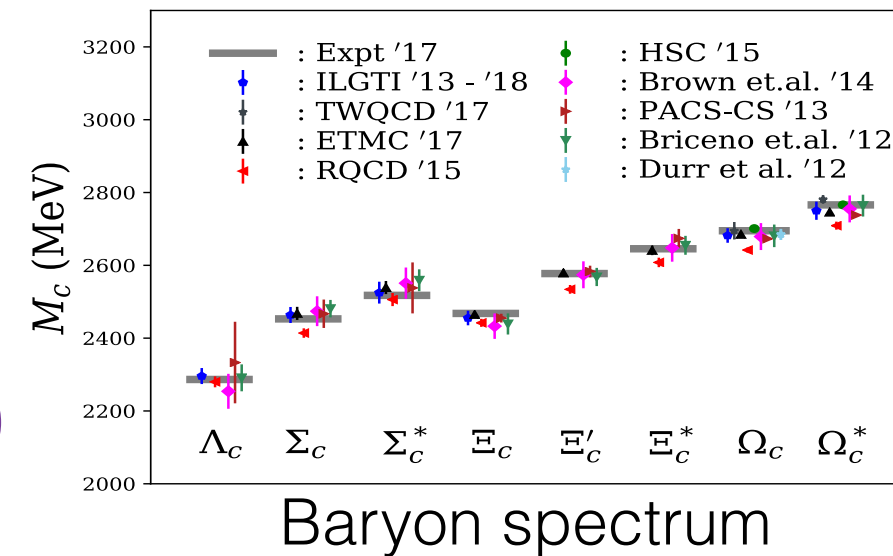
Simulation: fundamental pillar of particle physics

Theoretical:

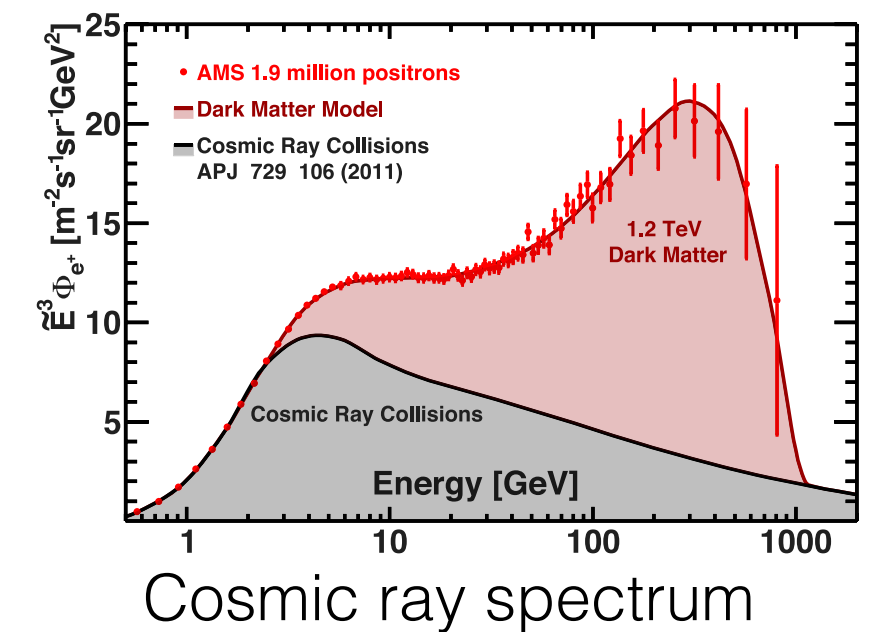
- Quarks and gluons become strongly coupled at low energy
→ Numerical simulation (lattice QCD) essential for quantitative predictions

Experimental:

- No “control systems”
→ Simulation often the only reference
- QFT is a well-defined framework
→ Can add / subtract fields to make alternative universes

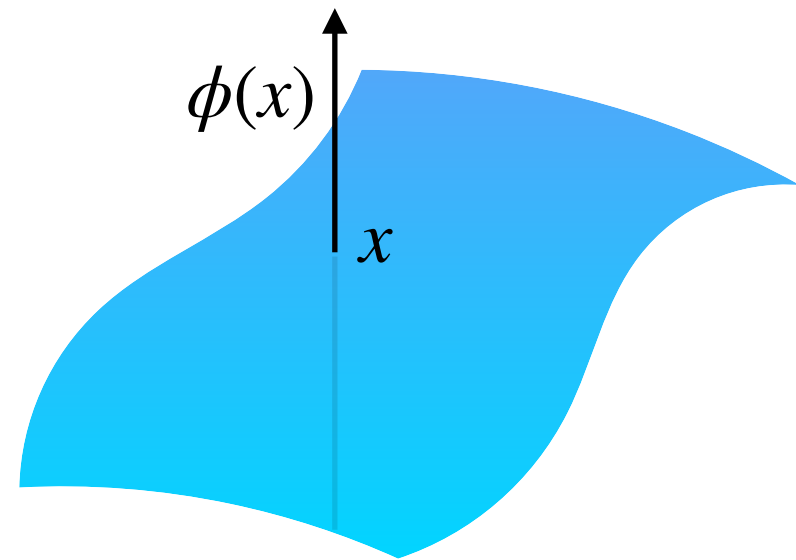


Higgs boson detection

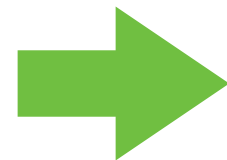


Lattice simulation on quantum computers

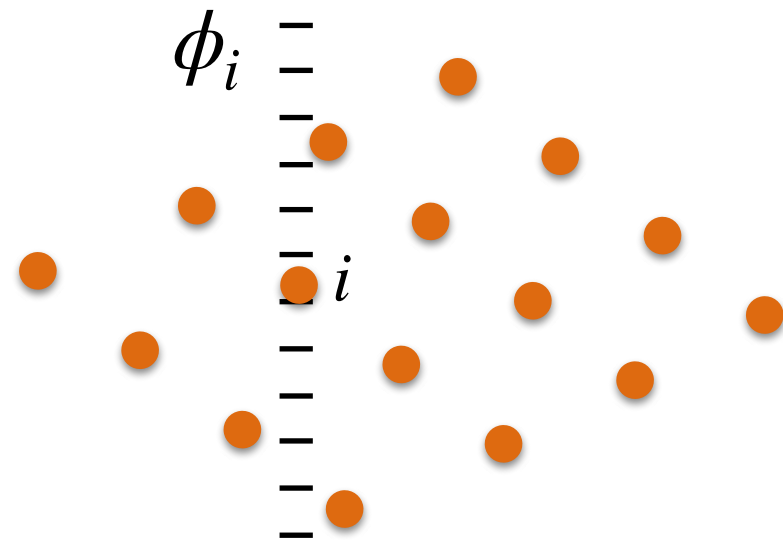
Quantum field theory



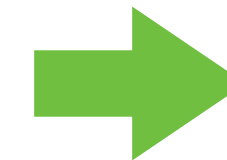
Continuous space
Unbounded field strengths



Lattice field theory



Discrete space
Truncated & discretized field strengths

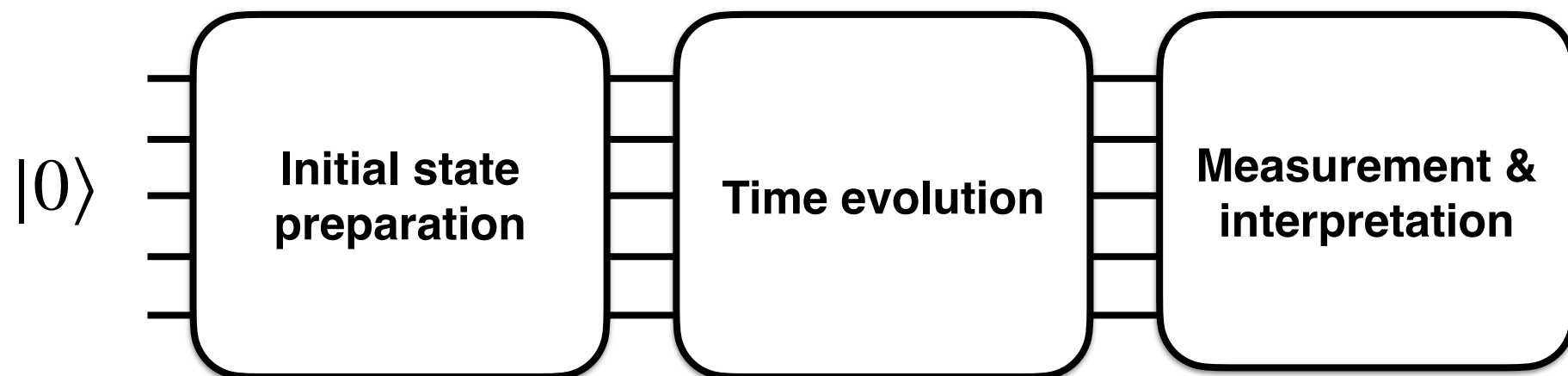


On a quantum computer

$$|\phi\rangle = |\phi_1\rangle \otimes \cdots \otimes |\phi_{Nd}\rangle$$

\uparrow Field value at site 1 \uparrow Field value at site N^d

Binarily represented field values



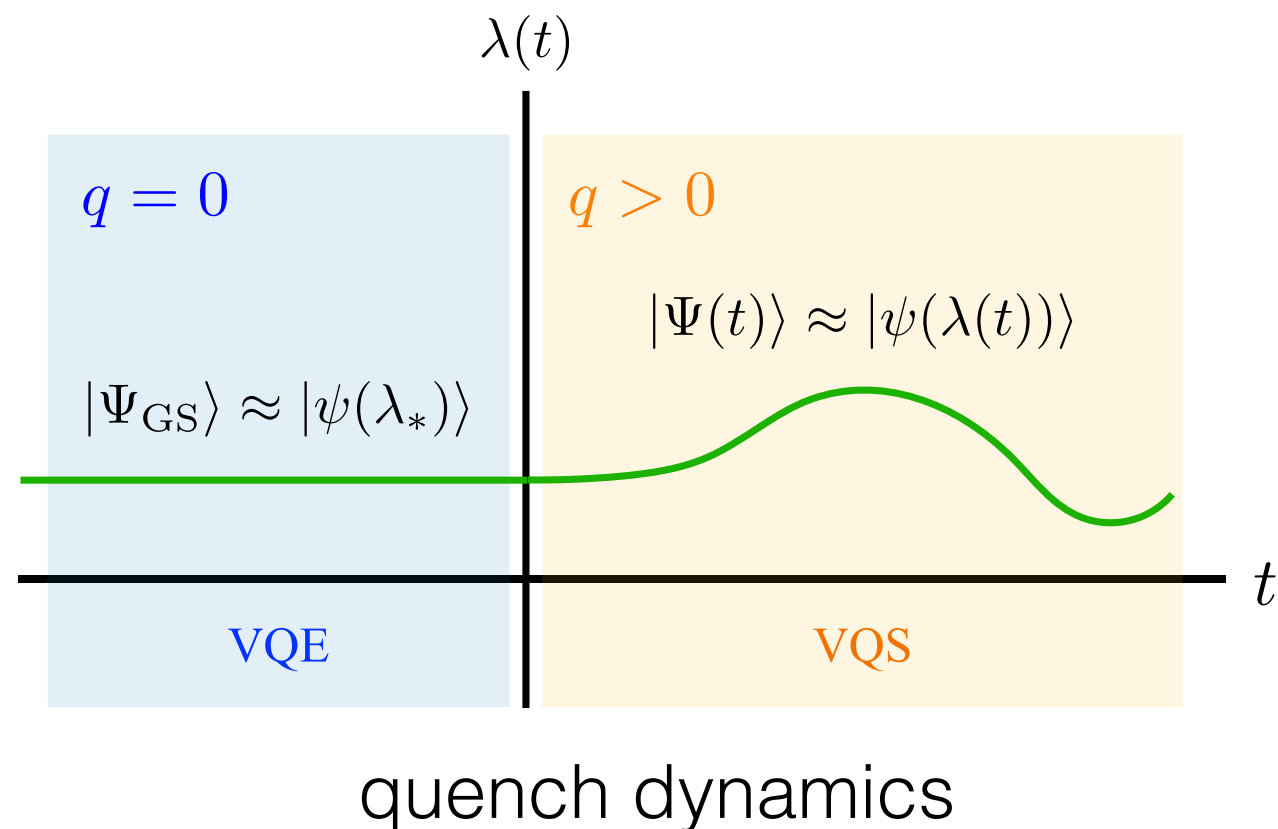
Prototypical problem: real-time evolution of the field state

Early-FTQC application: variational simulation

Nagano+, PRD 108, 034501 (2023)

- Time evolution (Trotter, QSP, ...) may be infeasible until full FTQC
 - Initial state preparation is also often costly
- ⇒ Explored performing both **variationally**

Tested on Schwinger model (1+1d electrodynamics) → Toy model of 3+1d QCD



McLachlan's variational principle

Given a parametrized state $|\psi(\vec{\theta}(t))\rangle$,

$$-iH|\psi(\vec{\theta}(t))\rangle = \frac{d}{dt}|\psi(\vec{\theta}(t))\rangle \quad (\text{Schrodinger equation})$$

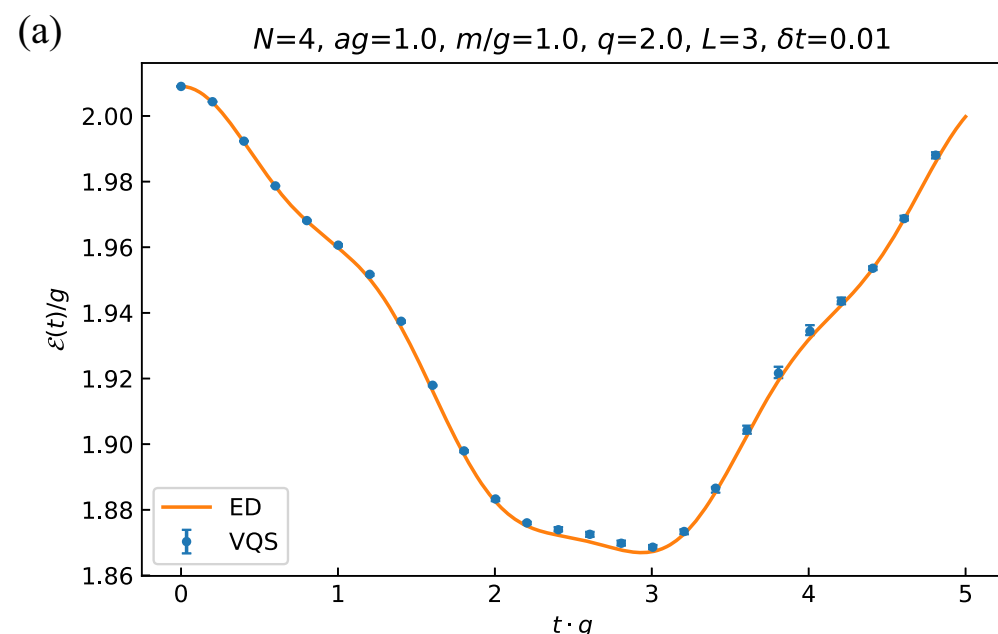
$$= \sum_j \dot{\theta}_j \frac{\partial}{\partial \theta_j} |\psi(\vec{\theta})\rangle$$

$$\Rightarrow \text{True trajectory minimizes } \left\| \left(\sum_j \dot{\theta}_j \frac{\partial}{\partial \theta_j} + iH \right) |\psi(\vec{\theta}(t))\rangle \right\|$$

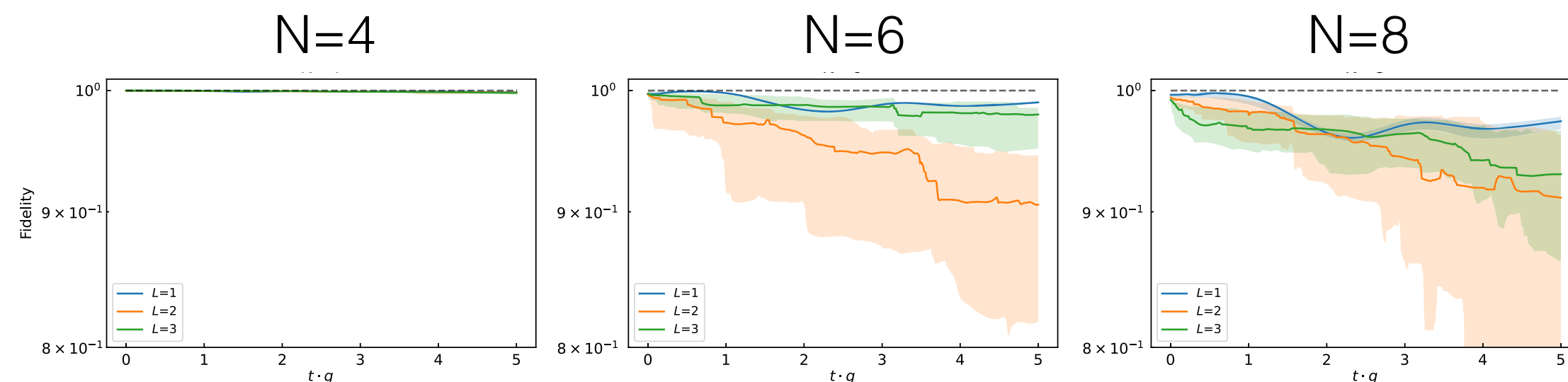
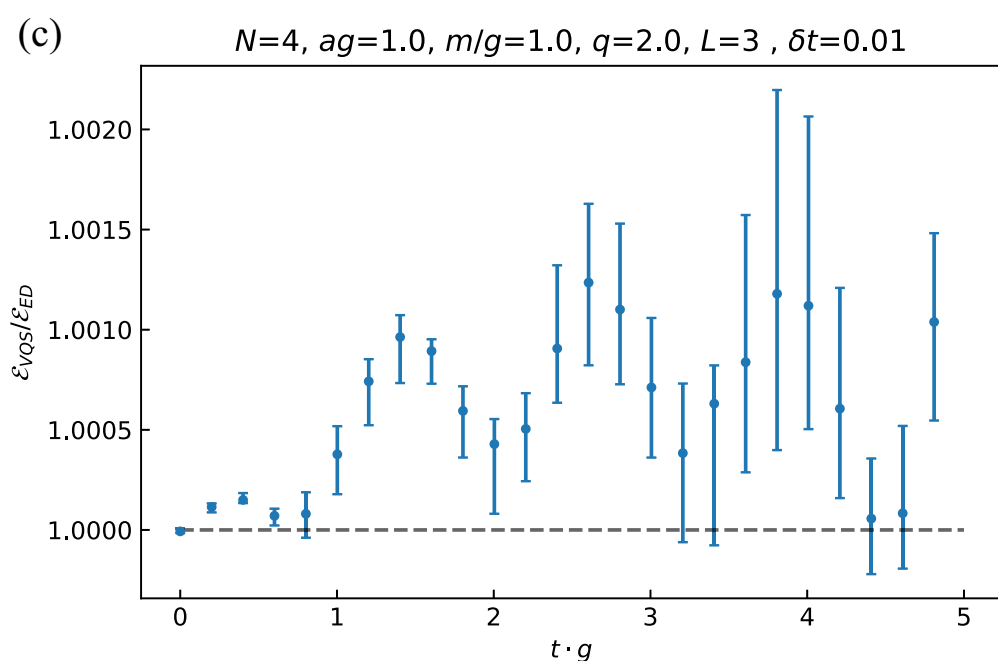
Early-FTQC application: variational simulation

Nagano+, PRD 108, 034501 (2023)

Electric field density evolution



- Initial ground state with VQE + variational time evolution produces **accurate simulation for very small systems**
- Accuracy drops with system size** for the considered ansatz & optimization algorithm
→ Room for improvement



Fidelity with respect to exact diagonalization

1+1d SU(2) LGT simulation

How do we encode non-Abelian LGT?

- “Holy grail” = real-time simulation of QCD (SU(3) LGT)
- The standard (Kogut-Susskind) framework is not practical
 - Non-commuting constraints (Gauss's law)
 - Binary representation of bosonic quantum numbers is unnatural

→ **Loop-string-hadron formulation** [Raychowdhury+ 2020]

- *Pure gauge loop operators.*— $\mathcal{L}^{\sigma,\sigma'}$:

$$\mathcal{L}^{++} = a(R)_\alpha^\dagger a(L)_\beta^\dagger \epsilon_{\alpha\beta} \quad (34a)$$

$$\mathcal{L}^{--} = a(R)_\alpha a(L)_\beta \epsilon_{\alpha\beta} = (\mathcal{L}^{++})^\dagger \quad (34b)$$

$$\mathcal{L}^{+-} = a(R)_\alpha^\dagger a(L)_\beta \delta_{\alpha\beta} \quad (34c)$$

$$\mathcal{L}^{-+} = a(R)_\alpha a(L)_\beta^\dagger \delta_{\alpha\beta} = (\mathcal{L}^{+-})^\dagger \quad (34d)$$

- *Incoming string operators.*— $\mathcal{S}_{\text{in}}^{\sigma,\sigma'}$:

$$\mathcal{S}_{\text{in}}^{++} = a(R)_\alpha^\dagger \psi_\beta^\dagger \epsilon_{\alpha\beta} \quad (35a)$$

$$\mathcal{S}_{\text{in}}^{--} = a(R)_\alpha \psi_\beta \epsilon_{\alpha\beta} = (\mathcal{S}_{\text{in}}^{++})^\dagger \quad (35b)$$

$$\mathcal{S}_{\text{in}}^{+-} = a(R)_\alpha^\dagger \psi_\beta \delta_{\alpha\beta} \quad (35c)$$

$$\mathcal{S}_{\text{in}}^{-+} = a(R)_\alpha \psi_\beta^\dagger \delta_{\alpha\beta} = (\mathcal{S}_{\text{in}}^{+-})^\dagger \quad (35d)$$

- *Outgoing string operators.*— $\mathcal{S}_{\text{out}}^{\sigma,\sigma'}$:

$$\mathcal{S}_{\text{out}}^{++} = \psi_\alpha^\dagger a(L)_\beta^\dagger \epsilon_{\alpha\beta} \quad (36a)$$

$$\mathcal{S}_{\text{out}}^{--} = \psi_\alpha a(L)_\beta \epsilon_{\alpha\beta} = (\mathcal{S}_{\text{out}}^{++})^\dagger \quad (36b)$$

$$\mathcal{S}_{\text{out}}^{+-} = \psi_\alpha^\dagger a(L)_\beta \delta_{\alpha\beta} \quad (36c)$$

$$\mathcal{S}_{\text{out}}^{-+} = \psi_\alpha a(L)_\beta^\dagger \delta_{\alpha\beta} = (\mathcal{S}_{\text{out}}^{+-})^\dagger \quad (36d)$$

- *Hadron operators.*— $\mathcal{H}^{\sigma,\sigma'}$:

$$\mathcal{H}^{++} = -\frac{1}{2!} \psi_\alpha^\dagger \psi_\beta^\dagger \epsilon_{\alpha\beta} \quad (37a)$$

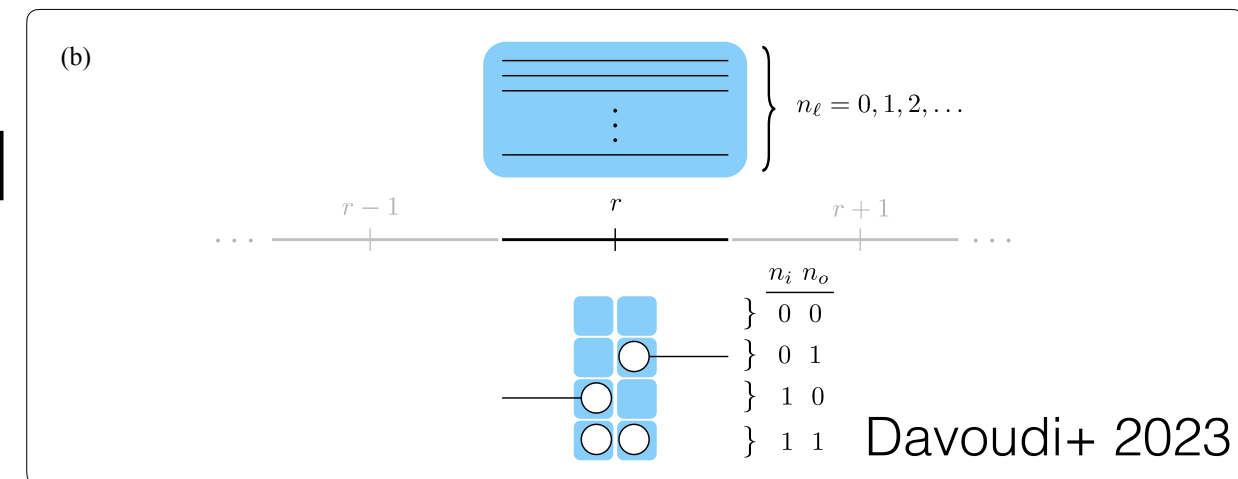
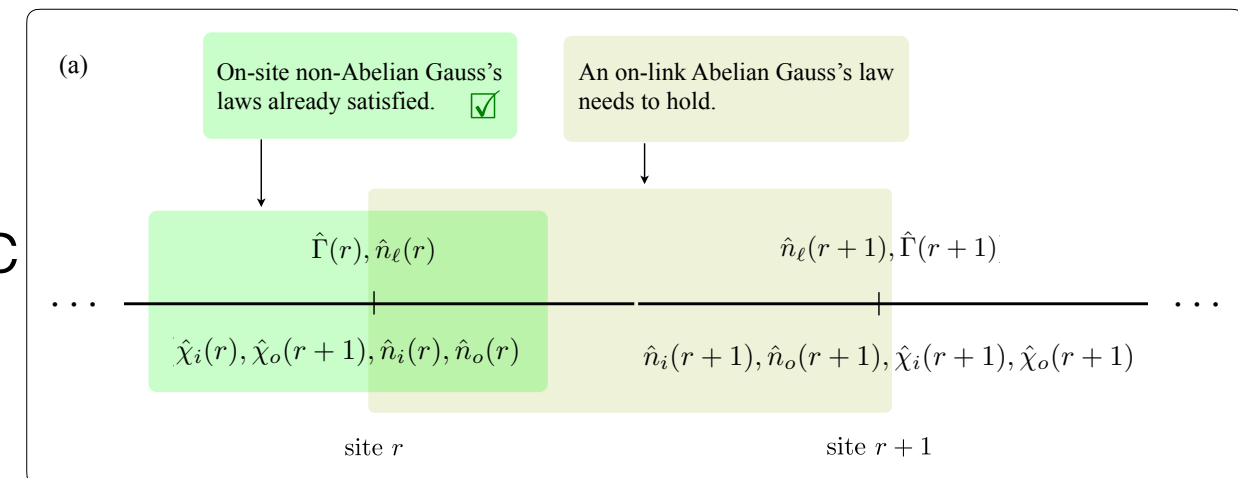
$$\mathcal{H}^{--} = \frac{1}{2!} \psi_\alpha \psi_\beta \epsilon_{\alpha\beta} = (\mathcal{H}^{++})^\dagger \quad (37b)$$

- *Gauge flux, quark number operators.*— $\mathcal{N}_{L/R}, \mathcal{N}_\psi$:

$$\mathcal{N}_L = a(L)_\alpha^\dagger a(L)_\alpha \quad (38a)$$

$$\mathcal{N}_R = a(R)_\alpha^\dagger a(R)_\alpha \quad (38b)$$

$$\mathcal{N}_\psi = \psi_\alpha^\dagger \psi_\alpha \quad (38c)$$

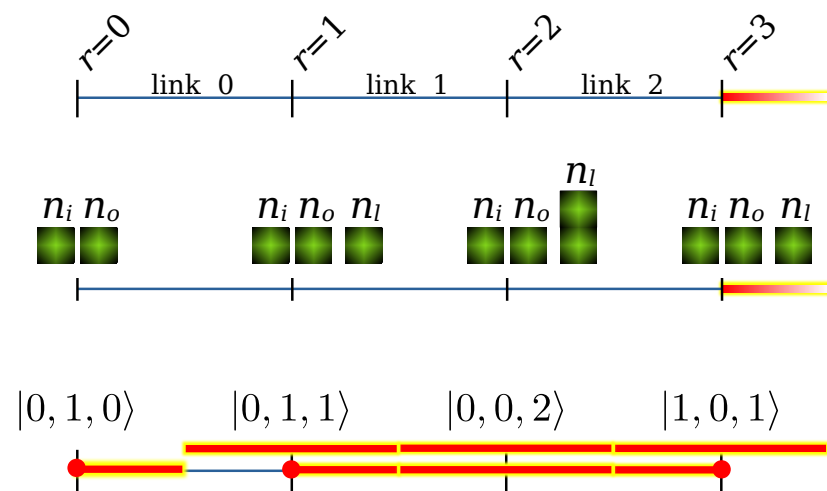


Express the Hamiltonian through SU(2) singlet operators

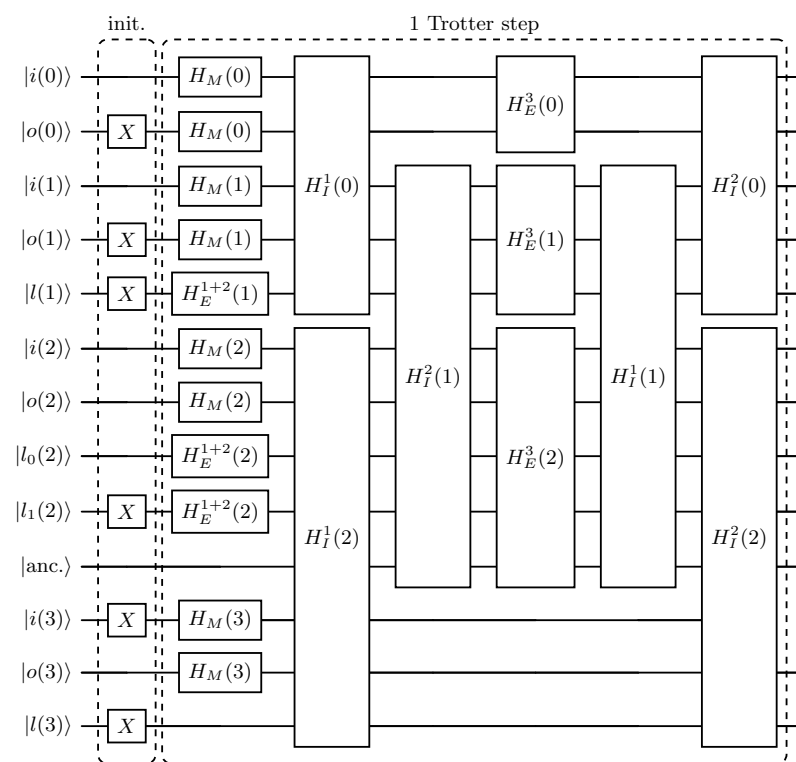
→ Basis = number states of commuting singlets

1+1d SU(2) LGT simulation

Manuscript in preparation

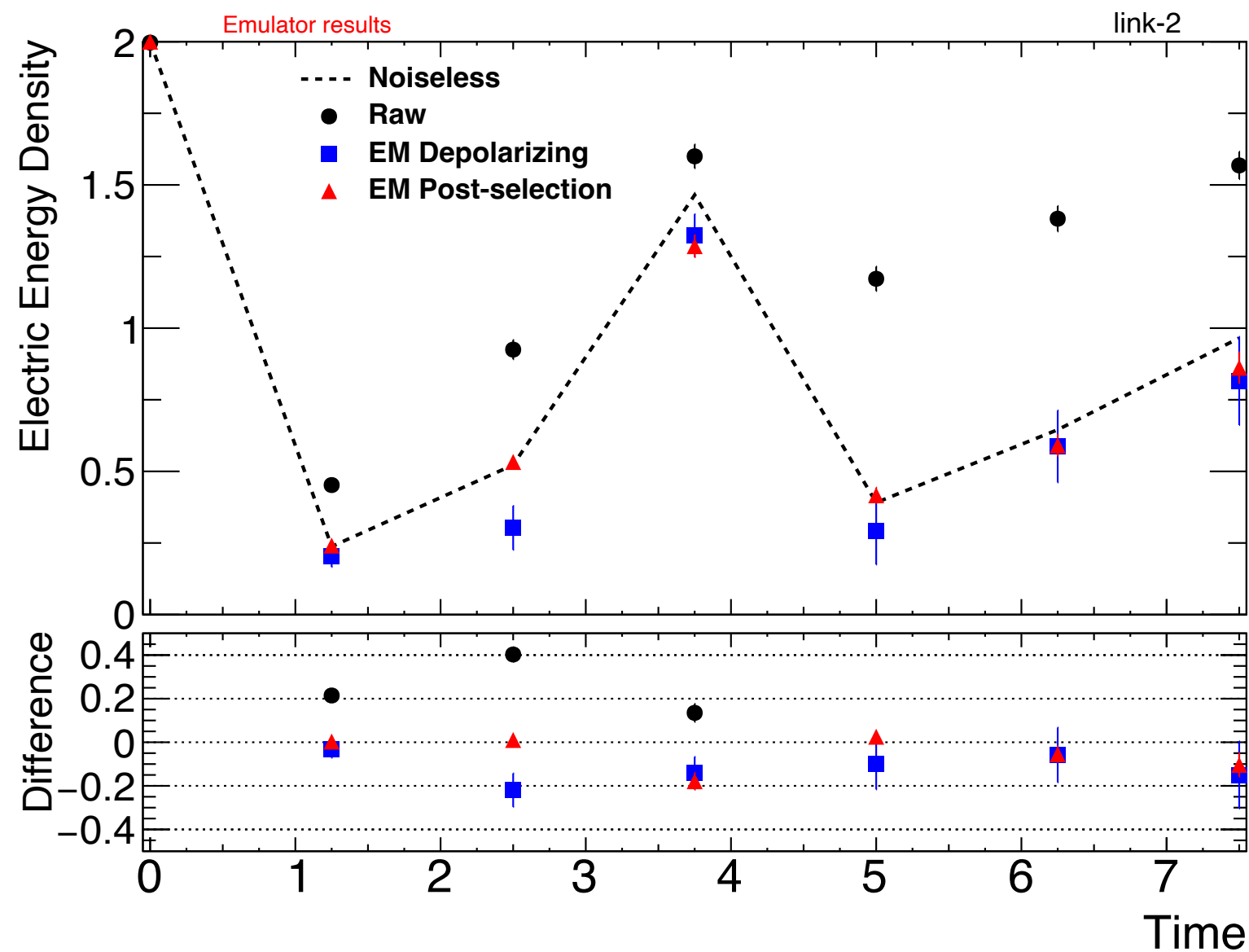


4-site setup and qubit assignments



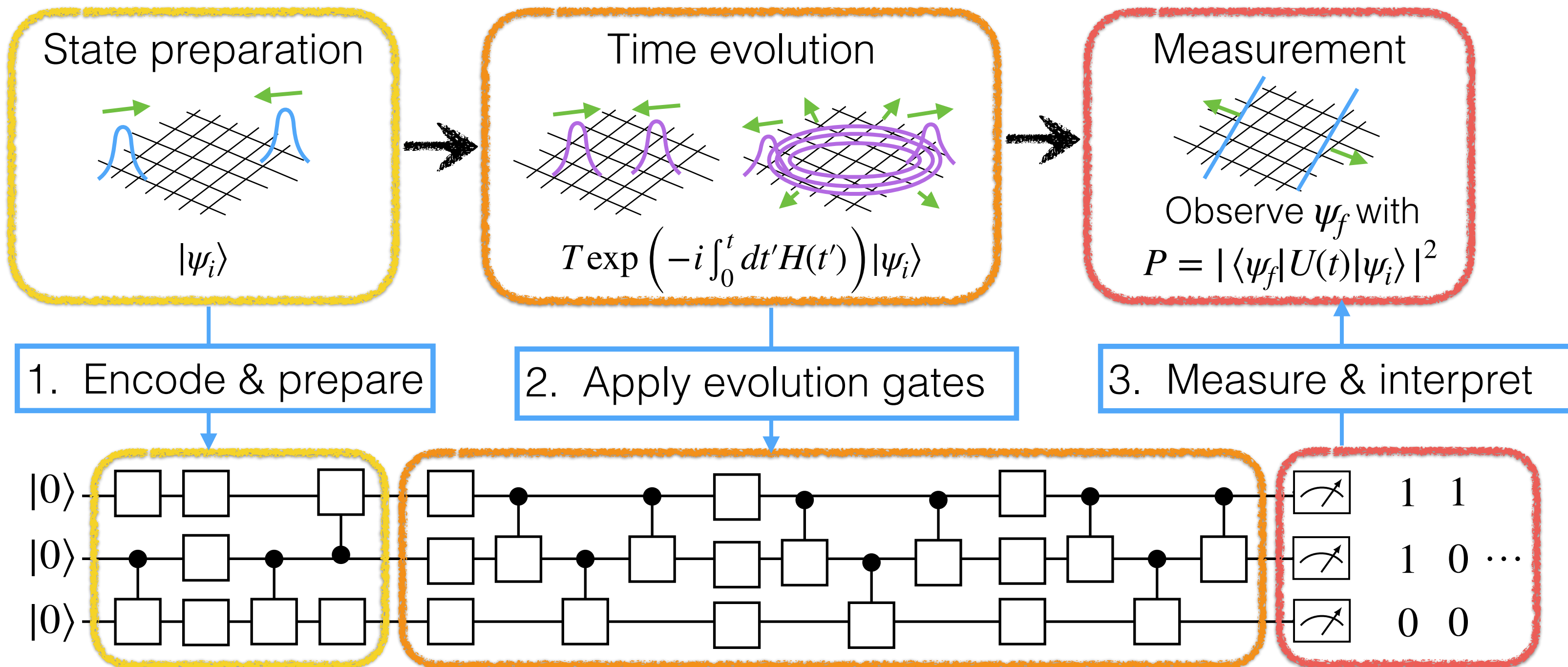
Circuit for 1 Trotter step

Expected simulation result with Quantinuum H2



Quantum event generator

Real-time dynamics simulation + shot-by-shot sampling:



High-energy scattering on lattice is impractical

Use an n -bit quantum register **per lattice point** per field:

$$|\text{system}\rangle = |j_1\rangle \otimes |j_2\rangle \otimes \cdots \otimes |j_N\rangle \quad (j_i = 0, \dots, 2^n - 1)$$

Field value at site 1

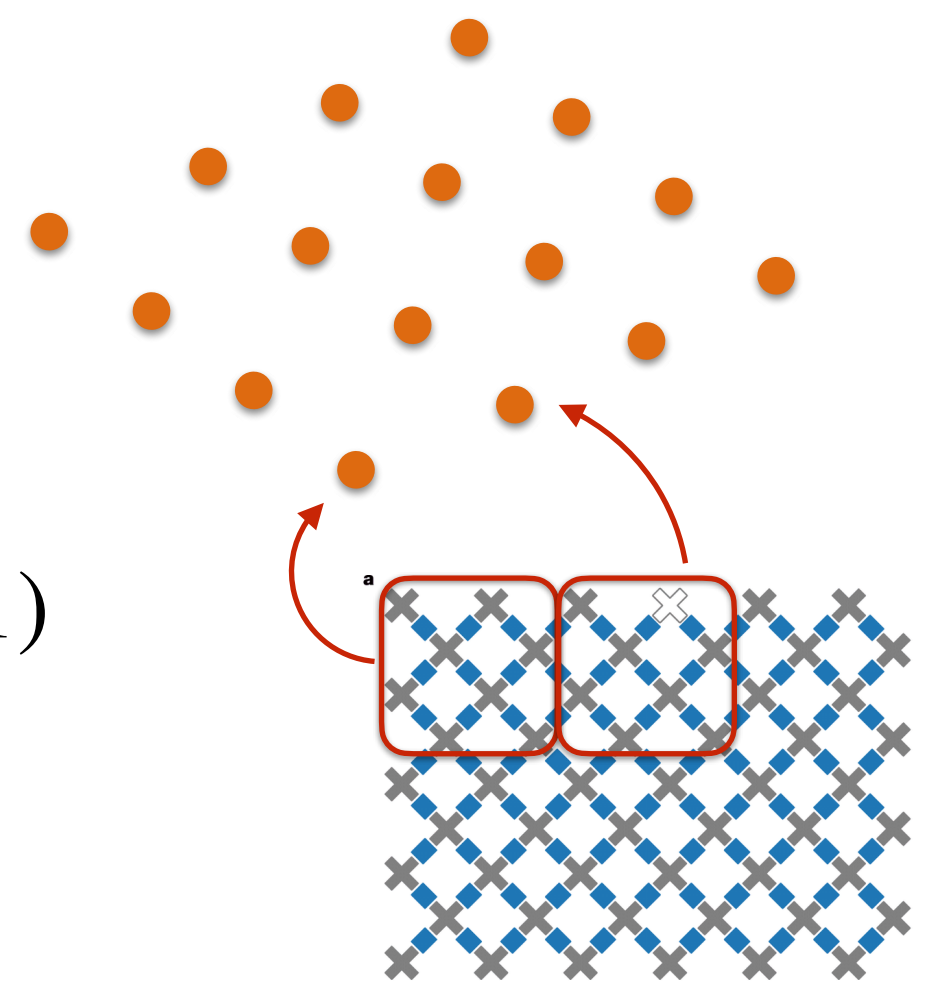
Can also encode a Fock representation:

$$|\text{system}\rangle = |k_{p_1}\rangle \otimes |k_{p_2}\rangle \otimes \cdots \otimes |k_{p_N}\rangle \quad (k_{p_i} = 0, \dots, 2^n - 1)$$

Number of excitations of mode p_1

⇒ **Qubit count:** nL^d

For $p_{\max}/p_{\min} = 10 \text{ TeV} / 100 \text{ MeV} = 10^5$ and $d = 3$ we need $\sim 10^{15}n$ qubits



Sparse Fock encoding

Assign a quantum register to **each particle**, maximum M particles

→ Field theory as multi-body quantum mechanics

$$|\text{system}\rangle = \mathcal{S} |p_1 \dots p_J \Omega \dots \Omega\rangle$$

J occupied slots M-J unoccupied slots

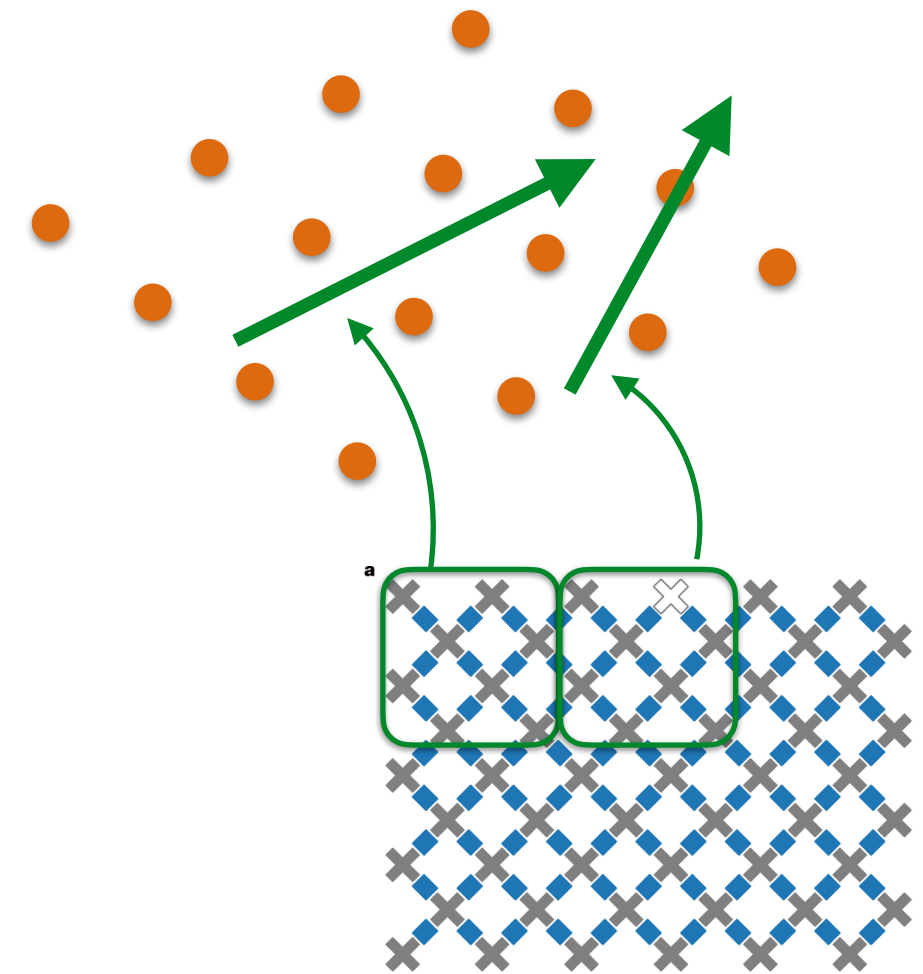
Symmetrization (bosons) or
antisymmetrization (fermions)

Slater determinant

Essentially, a sparse Fock representation

⇒ **Qubit count:** $M(d \log_2 L)$

For $p_{\max}/p_{\min} = 10^5$ and $d = 3$ we need $\sim 50M$ qubits



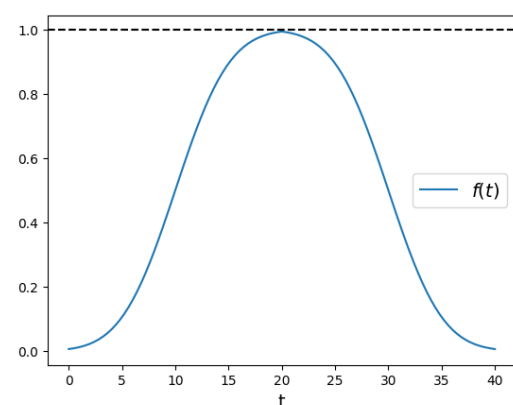
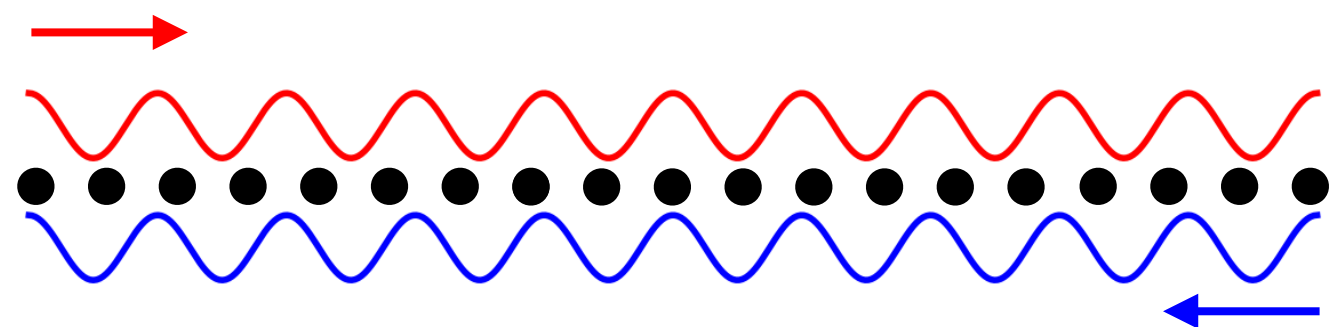
First steps in a long game

Goal: Build a quantum event generator for HEP experiments

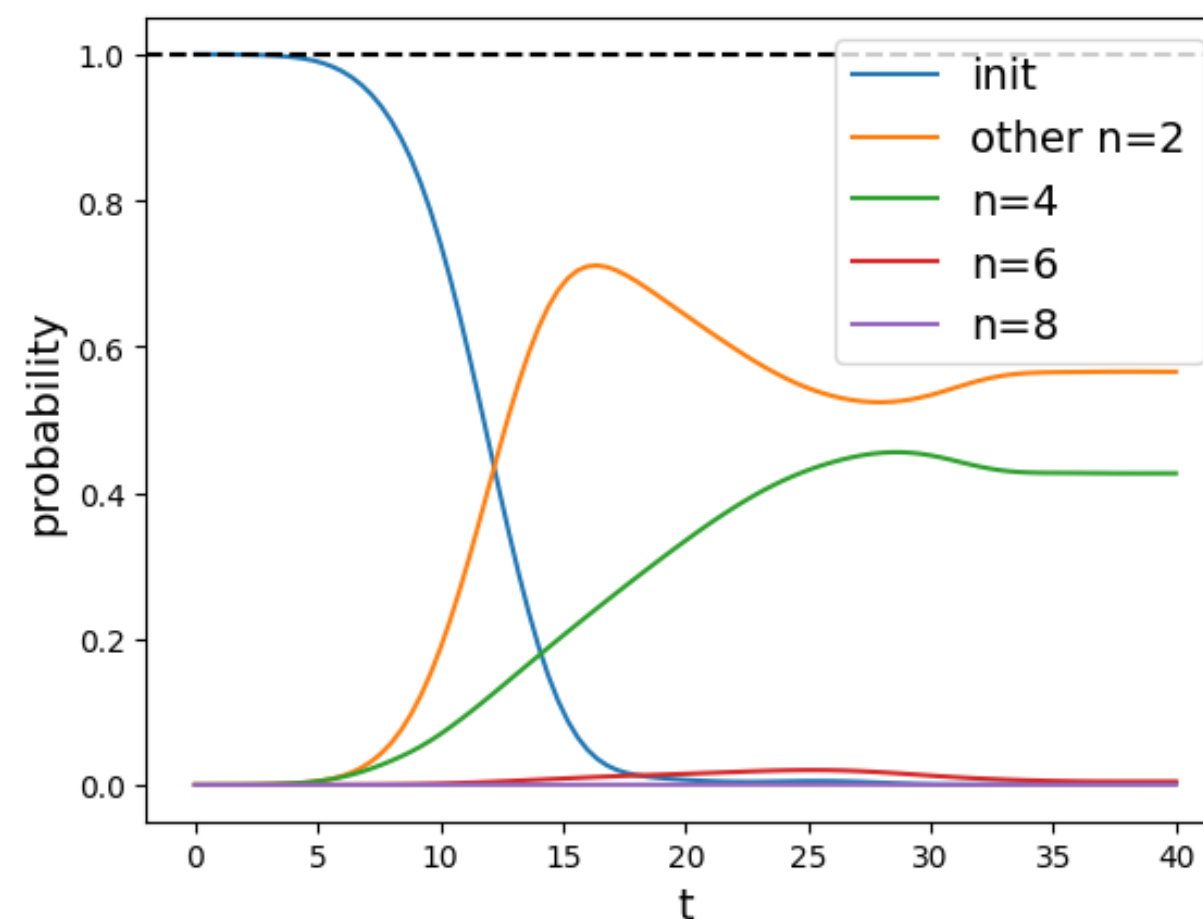
As a first step, verify validity of sparse representations in toy systems

Schwinger model on a 20-site lattice

$$\mathcal{H}(x) = \frac{1}{2} \left[-i\bar{\psi}(x)\gamma^1(\partial_1 - iA_1)\psi(x) + \text{h.c.} \right] + m\bar{\psi}(x)\psi(x) + \frac{1}{2g^2}E^2$$



Initial: particle & antiparticle plane waves
 Adiabatically modulate the interaction term
 → Track how excitation numbers evolve

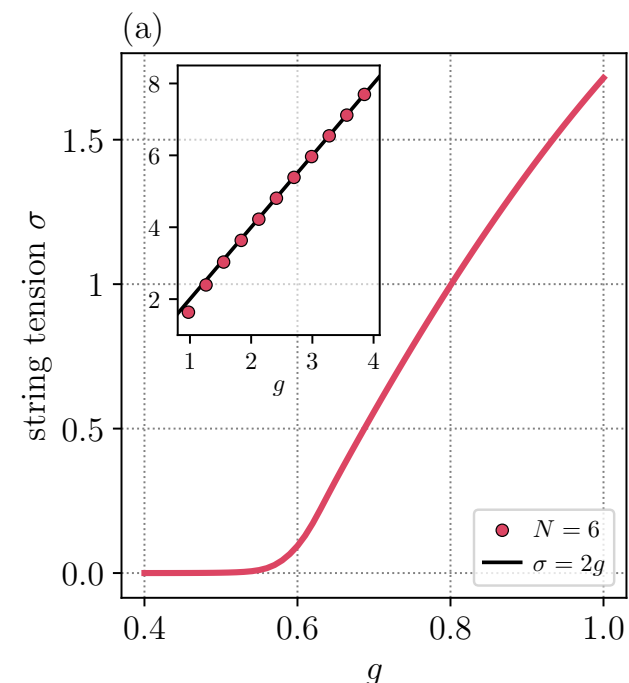
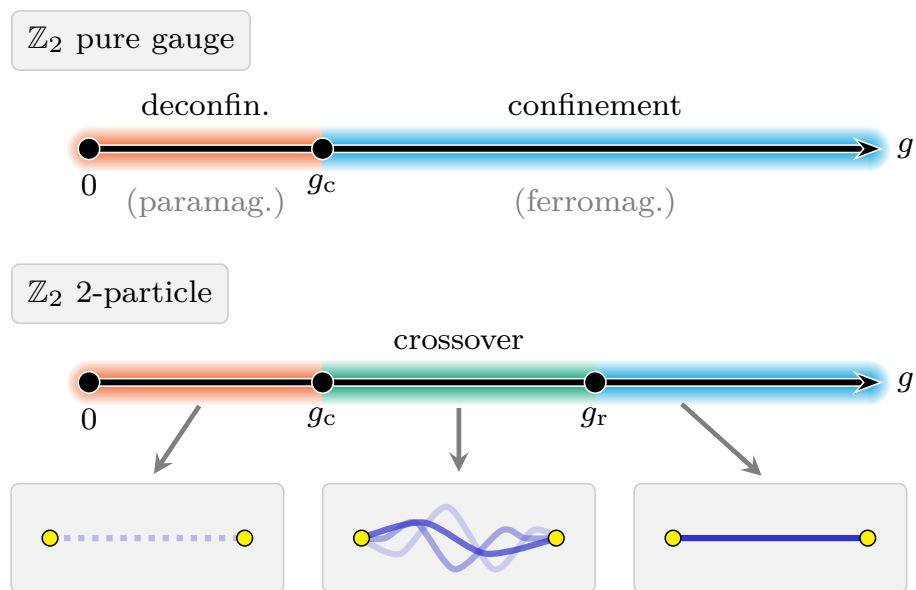


Manuscript in preparation

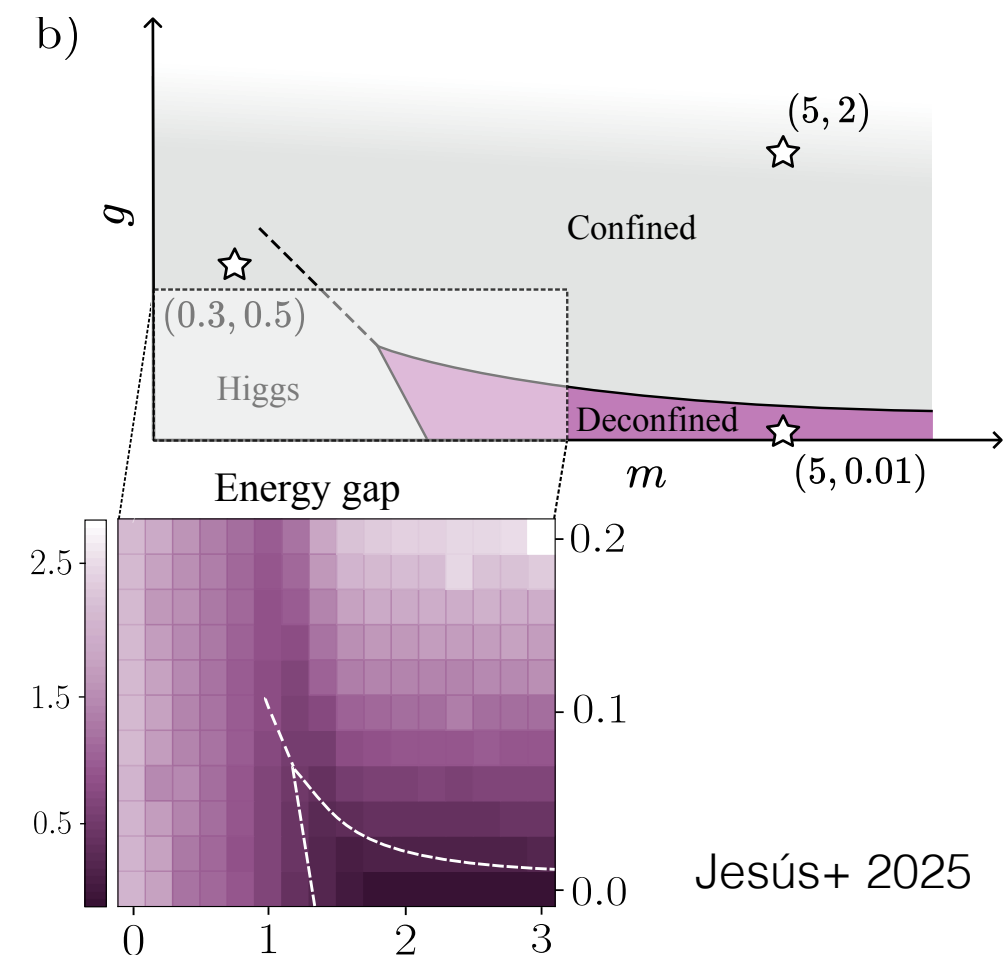
Lattice gauge theory ground state

Using quantum computers to study
Vacuum (ground state) properties & spectra of field theories

- Symmetry breaking, phase diagram
- Potential curve
- As a state preparation routine
- etc.



Di Marcantonio+ 2025



Jesús+ 2025

Vacuum from imaginary time evolution

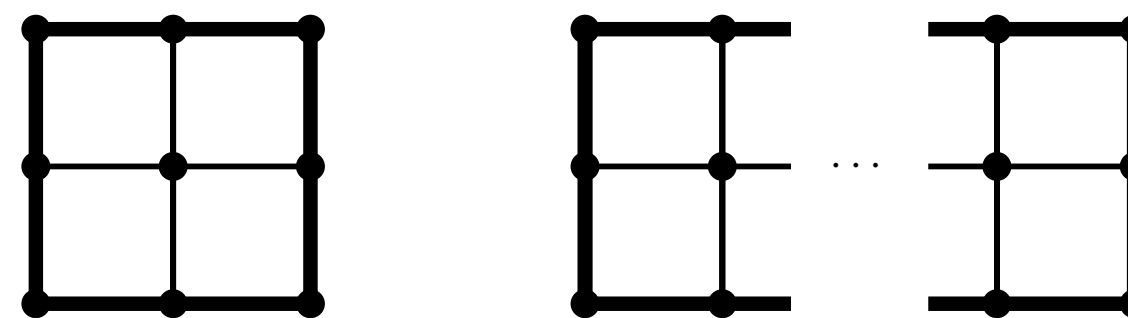
Imaginary time evolution (QITE): $|\Omega\rangle = \lim_{\tau \rightarrow \infty} \frac{e^{-H\tau} |\psi\rangle}{|e^{-H\tau} |\psi\rangle|}$ [Sekiyama & Nagano, 2604.17874](#)

→ Approximate with unitary operations (Trotter decomposition)

$$\frac{e^{-H\tau} |\psi\rangle}{\mathcal{N}} \sim \frac{\left(\prod_k e^{-H_k \Delta\tau} \right)^N |\psi\rangle}{\mathcal{N}} \sim \left(\prod_j \prod_k \exp(-i A_k^j \Delta\tau) \right) |\psi\rangle$$

Must be determined tomographically
→ Exponential cost at worst case

$N_{\text{site}}^y = 3$




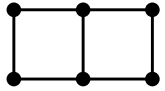
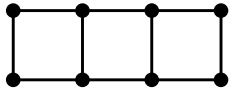
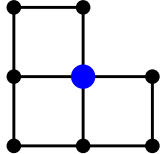
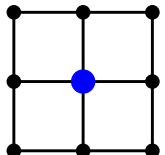
$N_{\text{site}}^x = 3$

$3 \leq N_{\text{site}}^x \leq 7$

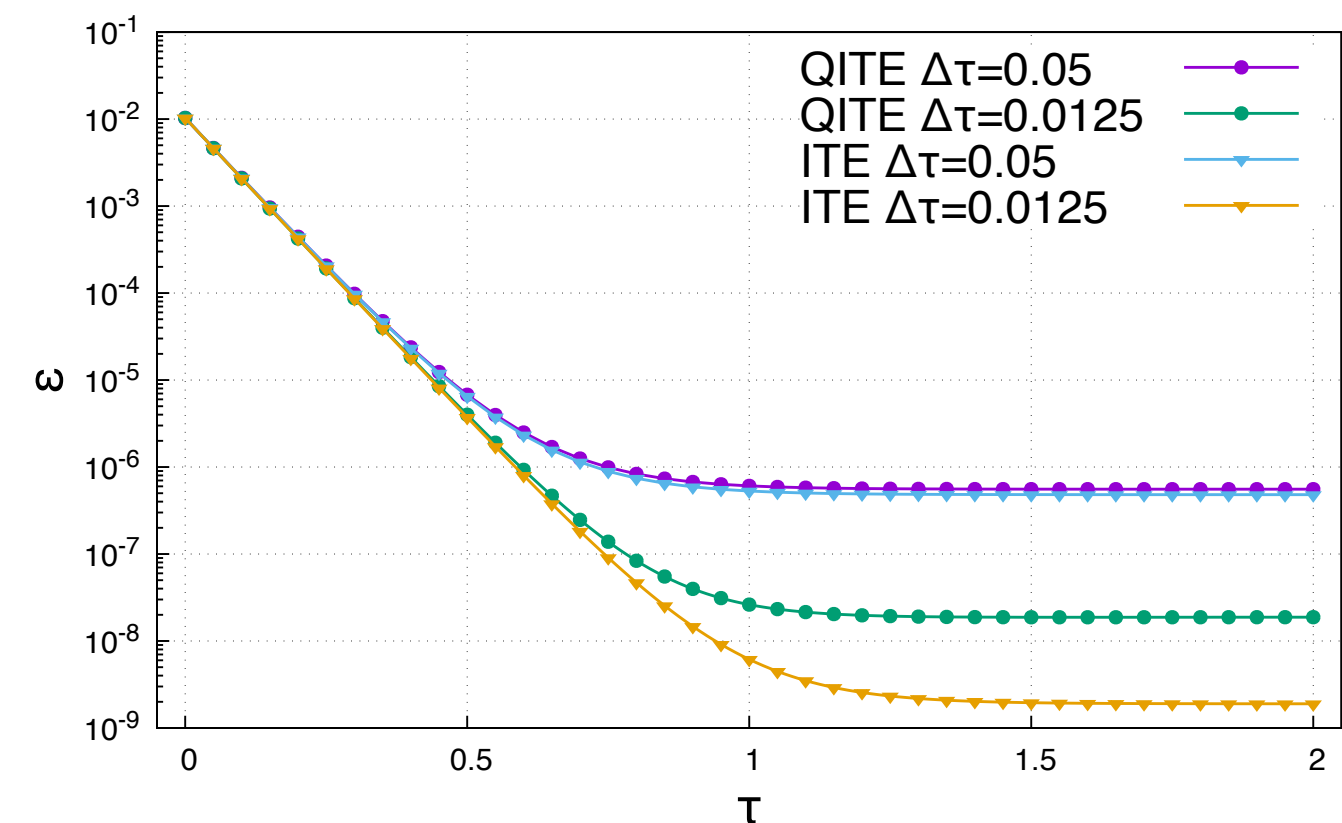
System: 1.5D \mathbb{Z}_2 LGT

Vacuum from imaginary time evolution

Sekiyama & Nagano, 2604.17874

support \mathcal{D}	weight $D = \mathcal{D} $	$ \mathcal{P} \setminus I^{\otimes D} $	$ \mathcal{P}_{\mathcal{G},\text{odd}} $	$ \mathcal{P}_{\mathcal{G},\text{odd}}/\mathcal{G} $
	4	255	8	8
	7	16383	192	192
	10	1048575	2048	2048
	10	1048575	2048	1024
	12	16777215	30720	15360

Main contribution:
Exploit the Hamiltonian structure & symmetries
to drastically reduce the tomography cost



High accuracy achieved in QITE

Vacuum from subspace diagonalization

Idea:

Reduce the dimension of Hamiltonian



Numerically diagonalize (on HPC)

- Many-body Hamiltonian projected onto subspace containing the ground state
- Use quantum computer to identify the subspace
- Gives strict upper bound on ground-state energy
- Several approaches exist (sample-based, Krylov, sample-based Krylov)

SCIENCE ADVANCES | RESEARCH ARTICLE

CHEMISTRY

Chemistry beyond the scale of exact diagonalization on a quantum-centric supercomputer

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A universal quantum computer can simulate diverse quantum systems with electronic structure for chemistry

offering challenging problems for processors have reached this size, for quantum computers in isolation but an intrinsically quantum computing processor and the sub-ground state properties of [2Fe]-proposed algorithm processes quantum sparse approximations to the ground quantum-centric supercomputing to exact diagonalization.

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Krylov diagonalization of large many-body Hamiltonians on a quantum processor

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Implicit Solvent Sample-Based Quantum Diagonalization

Published as part of *The Journal of Physical Chemistry B special issue "Molecular Simulation and Computational Chemistry: The Legacy of Peter A. Kollman"*.

Danil Kaliakin, Akhil Shaikh, Fanorhuan Lian, and Kenneth M. Merz, Jr.*

Quantum-Centric Algorithm for Sample-Based Krylov Diagonalization

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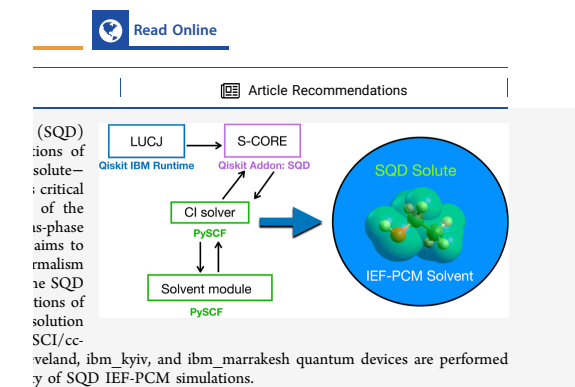
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Approximating the ground state of many-body systems is a key computational bottleneck underlying important applications in physics and chemistry. The most widely known quantum algorithm for ground state approximation, quantum phase estimation, is out of reach of current quantum processors due to its high circuit-depths. Subspace-based quantum diagonalization methods offer a viable alternative for pre- and early-fault-tolerant quantum computers. Here, we introduce a quantum diagonalization algorithm which combines two key ideas on quantum subspaces: a classical diagonalization based on quantum samples, and subspaces constructed with quantum Krylov states. We



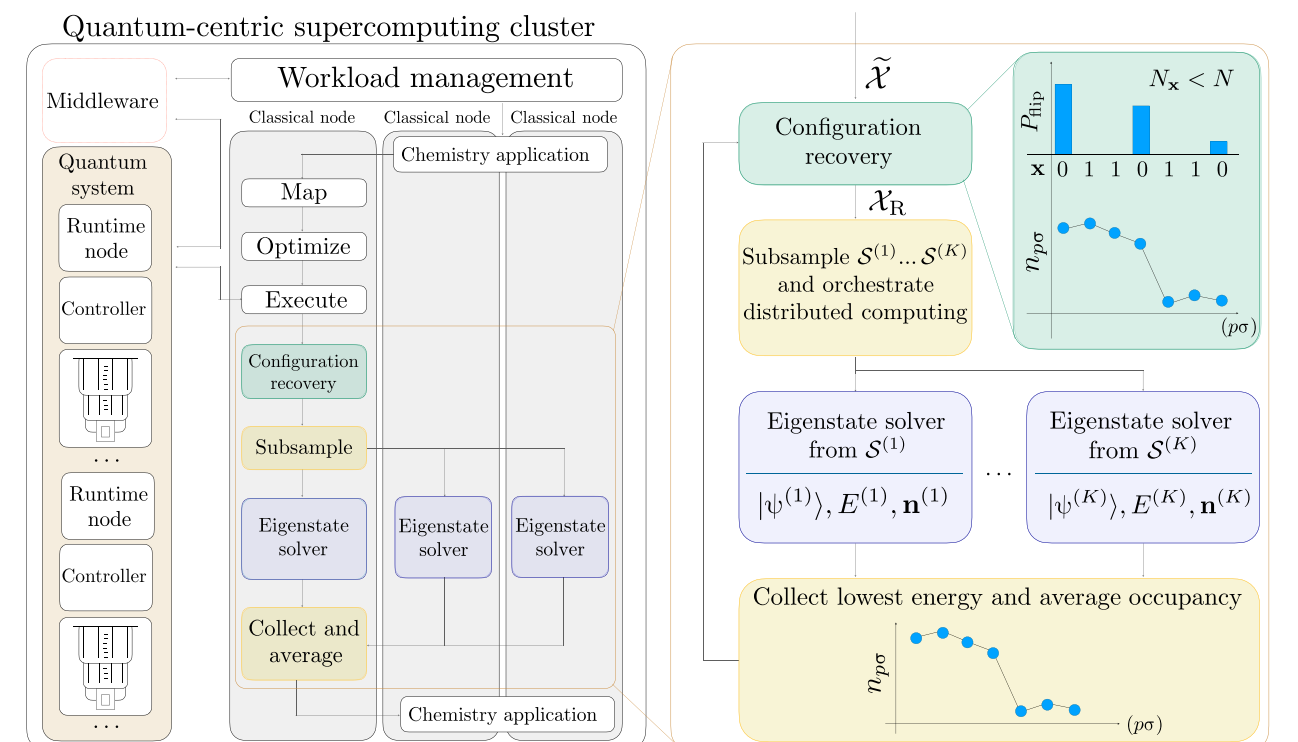
Sample-based Krylov diagonalization

If $\left(\begin{array}{cccccccc} \color{green}{\square} & \color{magenta}{\square} & \color{orange}{\square} & \color{blue}{\square} & \color{purple}{\square} & \color{green}{\square} & \color{cyan}{\square} & \color{red}{\square} \\ \color{green}{\square} & \color{cyan}{\square} & \color{purple}{\square} & \color{orange}{\square} & \color{green}{\square} & \color{magenta}{\square} & \color{blue}{\square} & \color{red}{\square} \\ \color{purple}{\square} & \color{green}{\square} & \color{blue}{\square} & \color{magenta}{\square} & \color{orange}{\square} & \color{cyan}{\square} & \color{red}{\square} & \color{purple}{\square} \\ \color{orange}{\square} & \color{purple}{\square} & \color{cyan}{\square} & \color{blue}{\square} & \color{magenta}{\square} & \color{green}{\square} & \color{red}{\square} & \color{orange}{\square} \\ \color{blue}{\square} & \color{orange}{\square} & \color{magenta}{\square} & \color{cyan}{\square} & \color{green}{\square} & \color{blue}{\square} & \color{red}{\square} & \color{blue}{\square} \\ \color{purple}{\square} & \color{orange}{\square} & \color{cyan}{\square} & \color{blue}{\square} & \color{magenta}{\square} & \color{green}{\square} & \color{red}{\square} & \color{purple}{\square} \\ \color{orange}{\square} & \color{purple}{\square} & \color{cyan}{\square} & \color{blue}{\square} & \color{magenta}{\square} & \color{green}{\square} & \color{red}{\square} & \color{orange}{\square} \\ \color{blue}{\square} & \color{orange}{\square} & \color{magenta}{\square} & \color{cyan}{\square} & \color{green}{\square} & \color{blue}{\square} & \color{red}{\square} & \color{blue}{\square} \\ \color{purple}{\square} & \color{orange}{\square} & \color{cyan}{\square} & \color{blue}{\square} & \color{magenta}{\square} & \color{green}{\square} & \color{red}{\square} & \color{purple}{\square} \\ \color{orange}{\square} & \color{purple}{\square} & \color{cyan}{\square} & \color{blue}{\square} & \color{magenta}{\square} & \color{green}{\square} & \color{red}{\square} & \color{orange}{\square} \end{array} \right) \begin{array}{c} \blacksquare \\ \square \\ \square \\ \square \\ \square \\ \square \\ \square \\ \square \\ \square \\ \square \end{array} = E_0 \begin{array}{c} \blacksquare \\ \square \\ \square \\ \square \\ \square \\ \square \\ \square \\ \square \\ \square \\ \square \end{array}$ then  $\begin{pmatrix} \color{green}{\square} & \color{magenta}{\square} & \color{orange}{\square} & \color{blue}{\square} \\ \color{orange}{\square} & \color{purple}{\square} & \color{cyan}{\square} & \color{blue}{\square} \\ \color{blue}{\square} & \color{orange}{\square} & \color{magenta}{\square} & \color{cyan}{\square} \\ \color{purple}{\square} & \color{orange}{\square} & \color{cyan}{\square} & \color{blue}{\square} \end{pmatrix} \begin{array}{c} \blacksquare \\ \square \\ \square \\ \square \end{array} = \tilde{E}_0 \begin{array}{c} \blacksquare \\ \square \\ \square \\ \square \end{array}$

where $\tilde{E}_0 \gtrsim E_0$

Steps

- Simulate time evolution for several t
- Measure each snapshots and obtain sample bitstrings
- Project the Hamiltonian onto the sample subspace and diagonalize

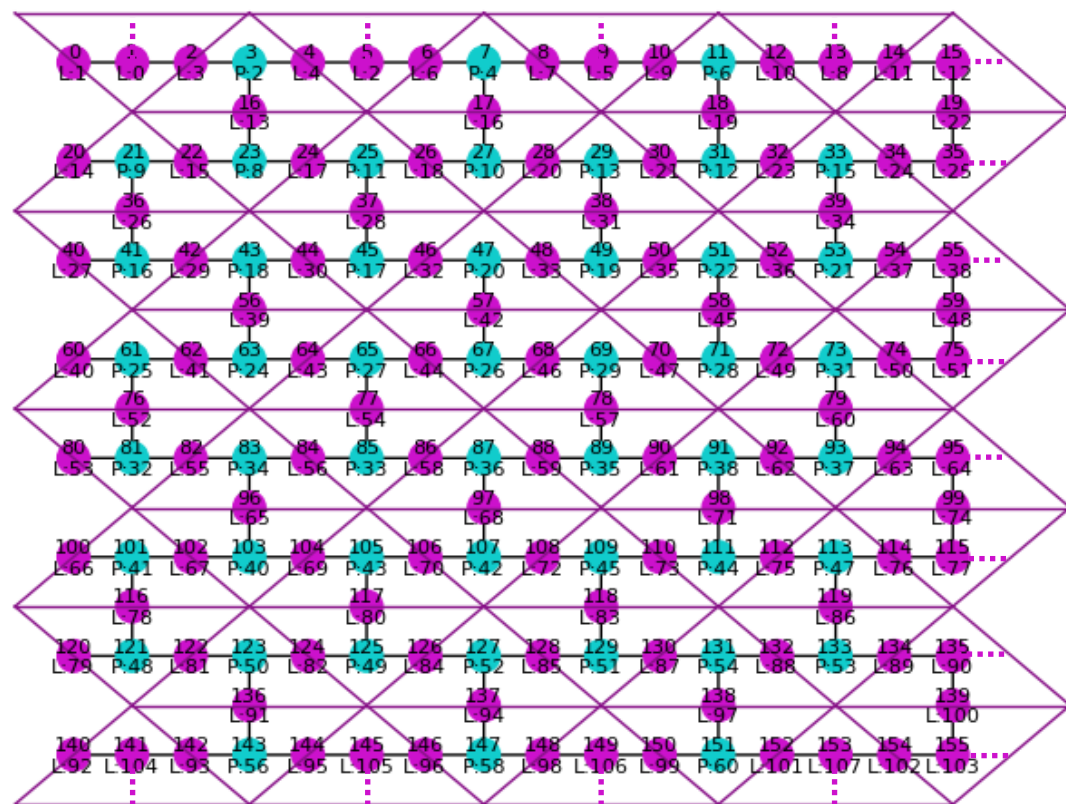
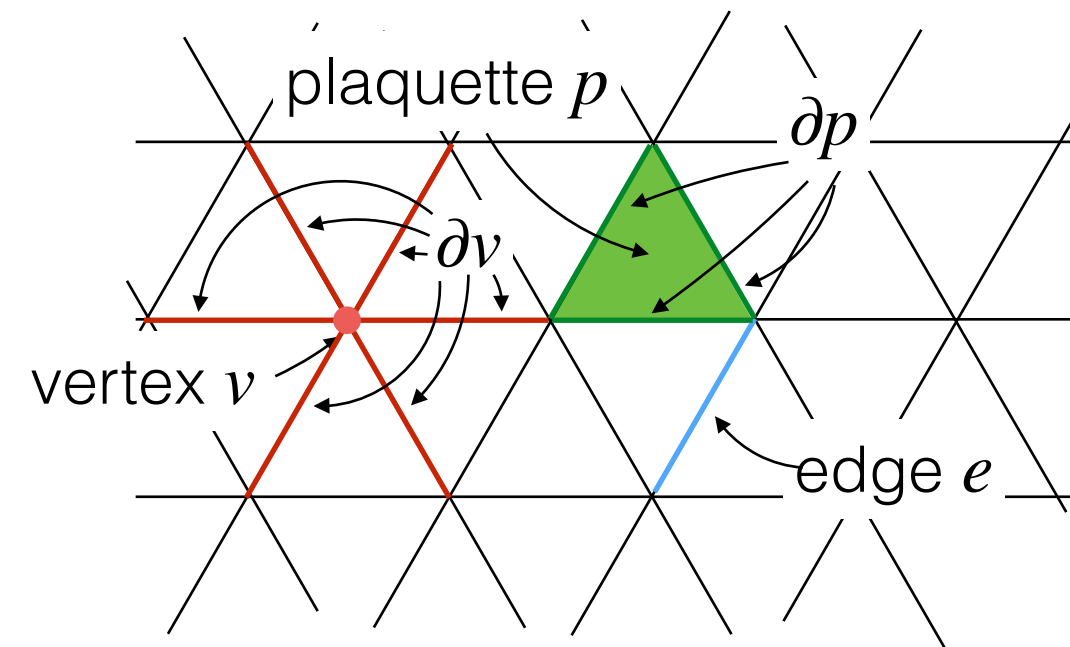


Ground state of 2D triangular pure \mathbb{Z}_2 LGT

Pure 2D \mathbb{Z}_2 lattice gauge theory:

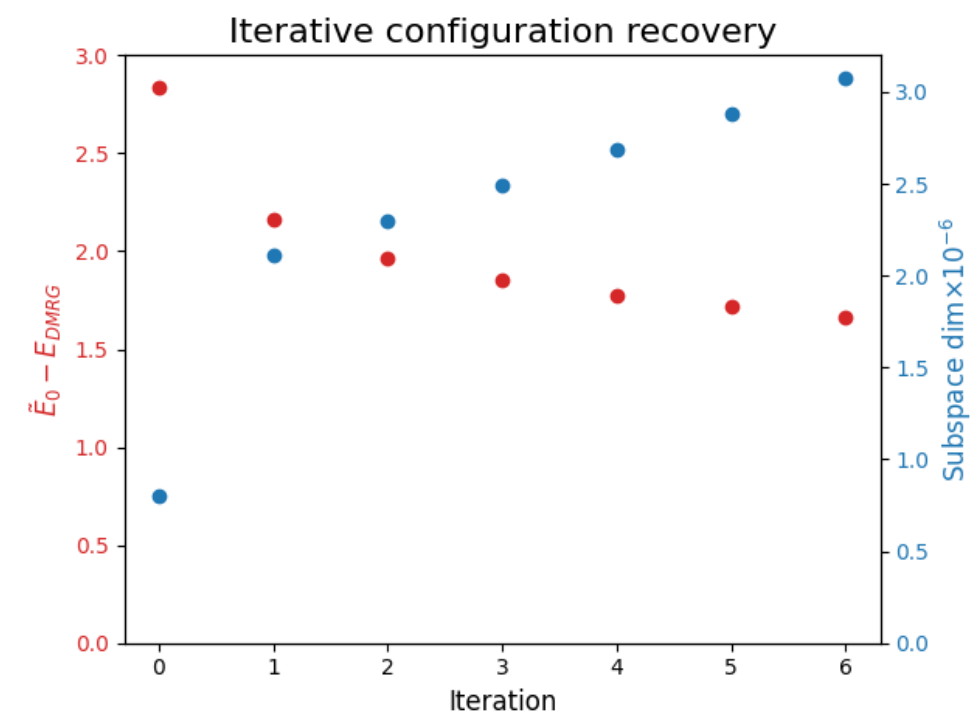
$$H_{\text{LGT}} = - \sum_{e \in \mathcal{E}} Z(e) - \lambda \sum_{p \in \mathcal{P}} \prod_{e \in \partial p} X(e)$$

edges \curvearrowright plaquettes \curvearrowright edges bounding p



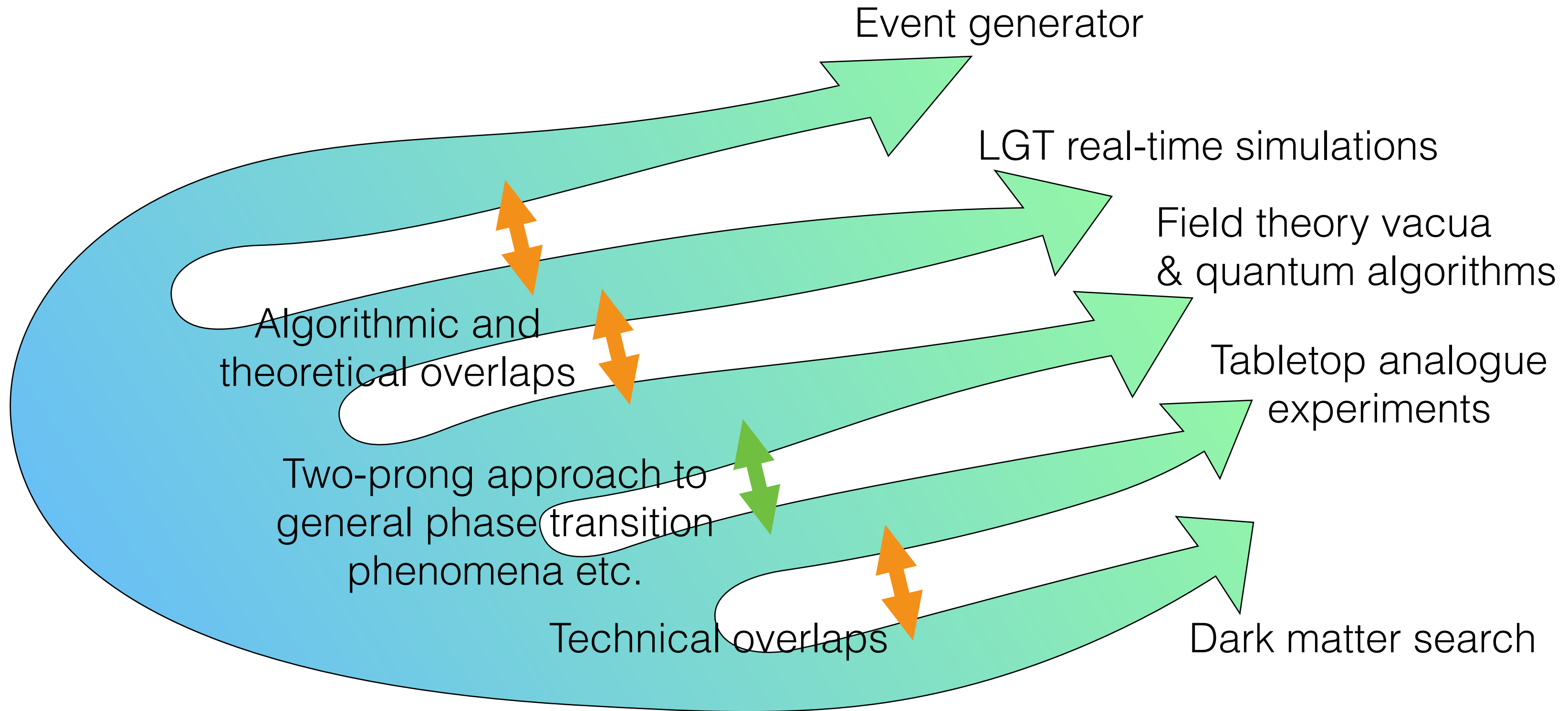
Utilizing the full IBM Heron chip for time evolution circuits

Increasing the projection subspace size improves the energy estimate



Manuscript in preparation

Going forward



Members



Toshiaki Inada



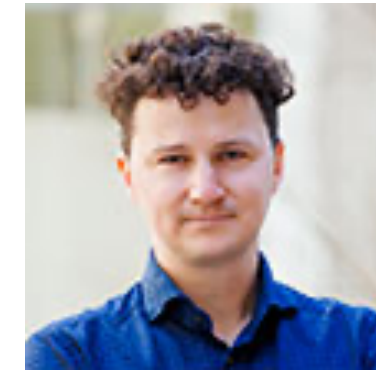
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Kazuyuki Nakayama



Chikara Kawai



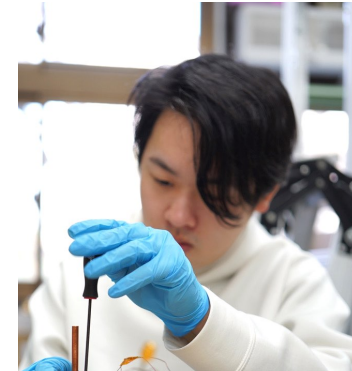
Kirill Shulga



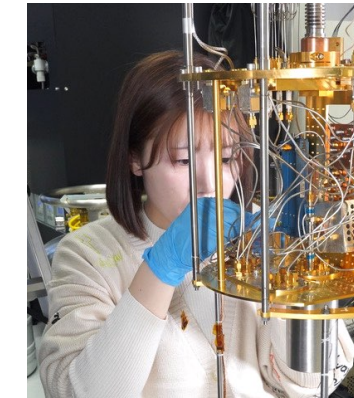
Fumika Suzuki



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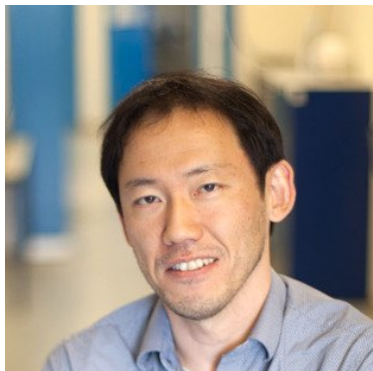
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Ryu Sawada



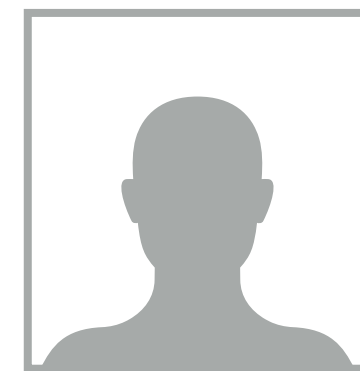
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