QPT 2025

Guilin, China

Quantum Simulations in High Energy Physics and Beyond

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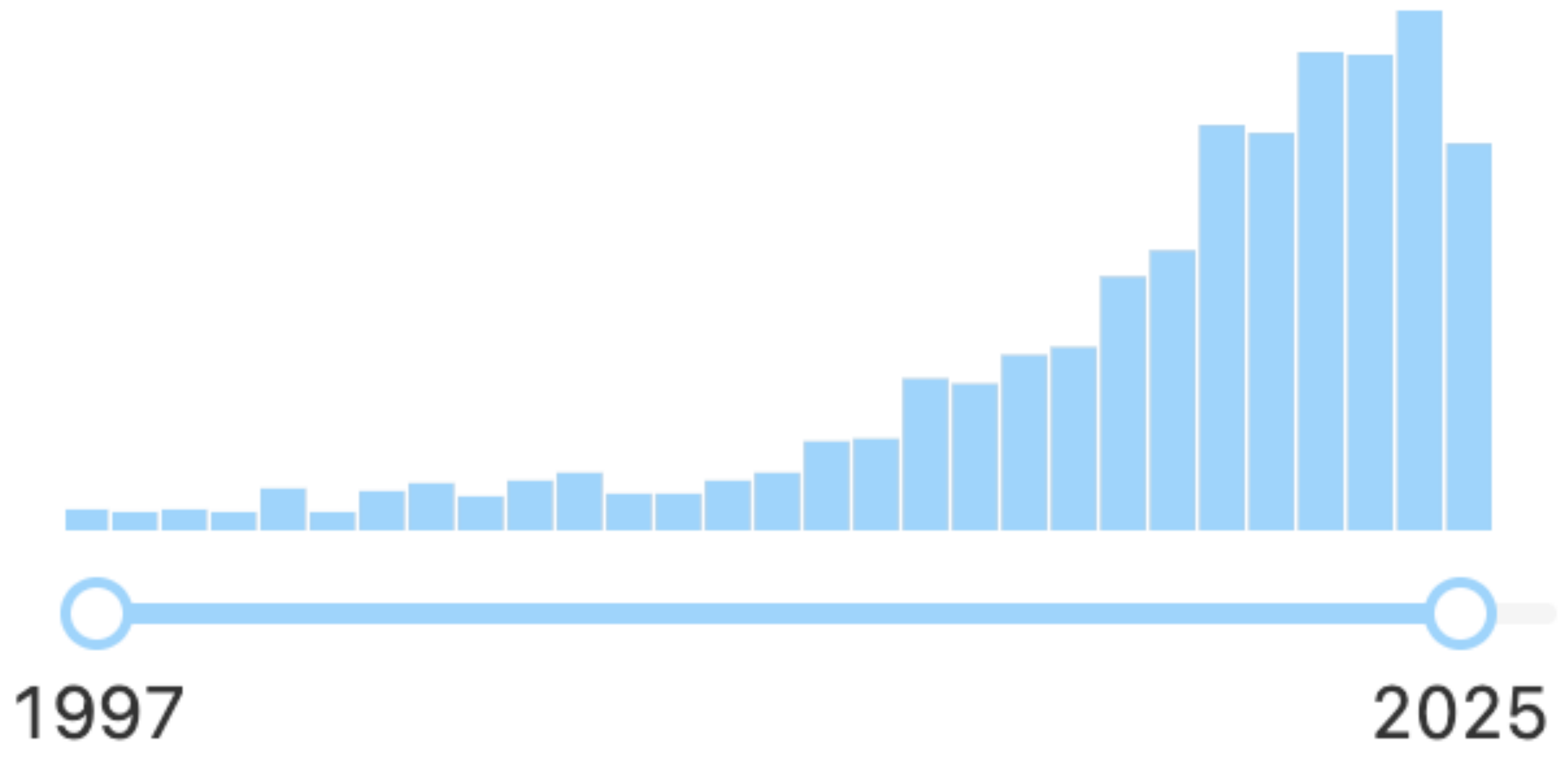
South China Normal University

the 16th Workshop on QCD Phase Transition and Relativistic Heavy-Ion Physics

24-28, October

Quantum Computing

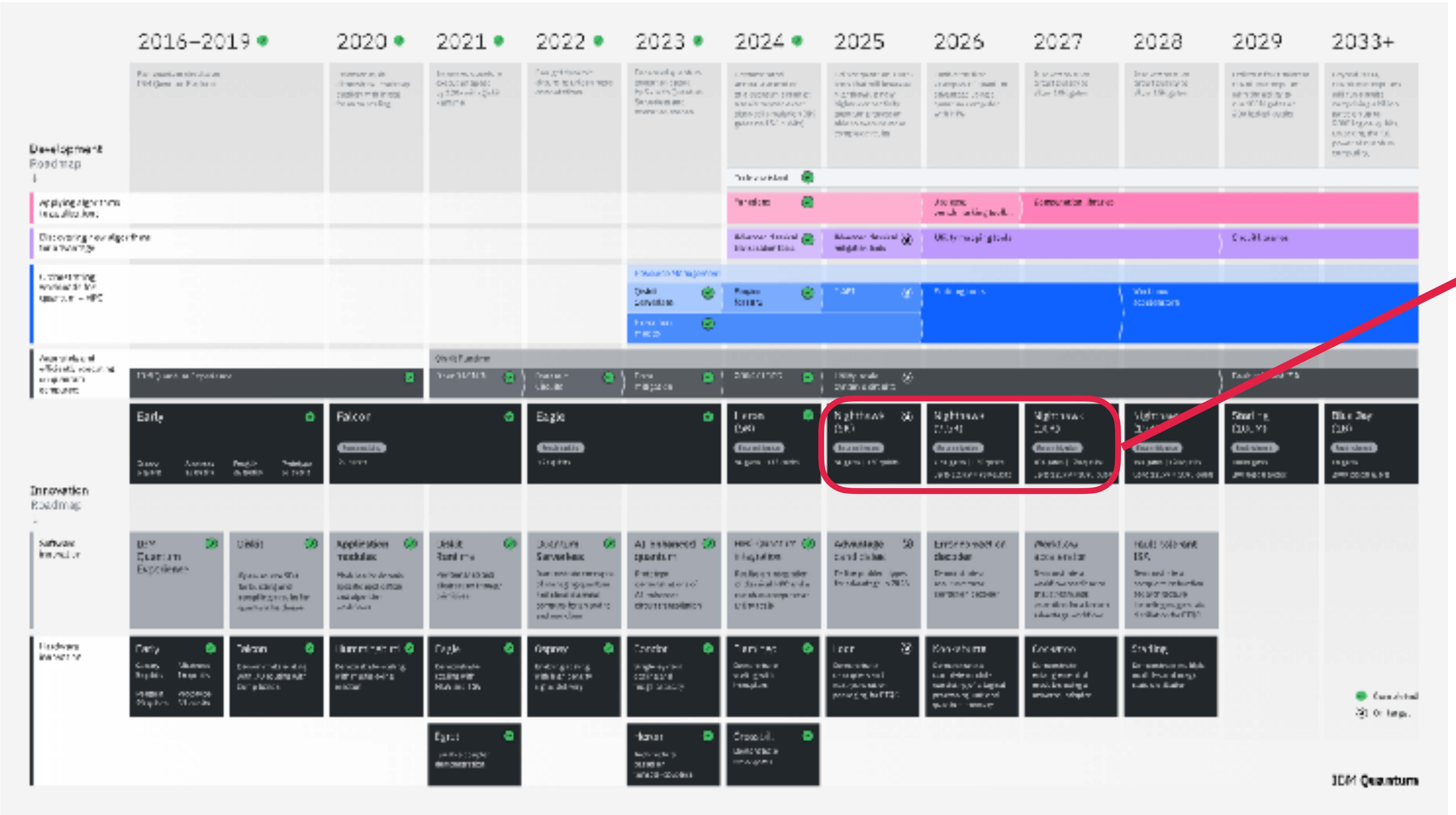
- Quantum computing: a promising new method
  - Possible exponential acceleration
  - Quantum effect: superposition, entanglement, …
  - Quantum simulation: directly simulation physical systems on a quantum computer
- Topics of interest in HEP:
  - Real-time evolution
  - Non-perturbative physics
  - Non-Abelian gauge theory
  - Thermal states
  - …

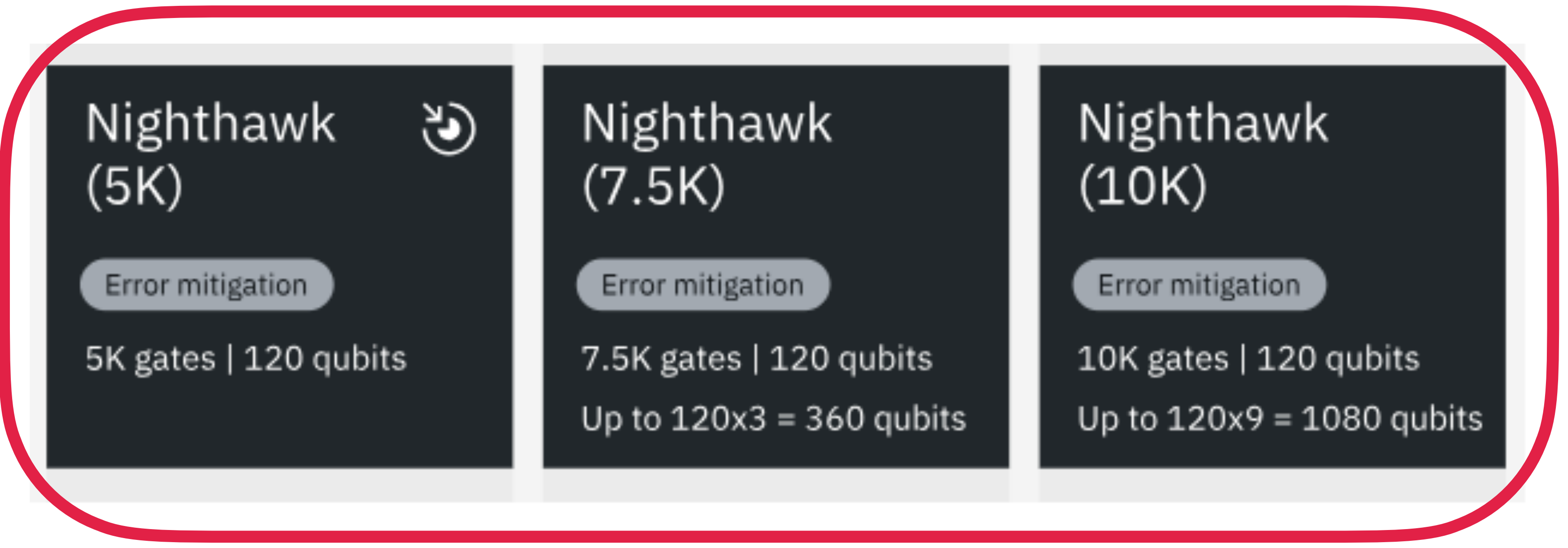


Search "quantum computing" in hep-th

Quantum Hardware

- Quantum computing: current status
  - Noisy intermediate-scale quantum (NISQ) devices
    - Error rate: 1%~0.1%
    - Number of qubits: ~100





$1080 \sim 4 \times 16^2$, $10K \sim 120 * 100$

Simulation of 2+1D systems may be reasonable in 2 years!

https://www.ibm.com/quantum/technology#roadmap

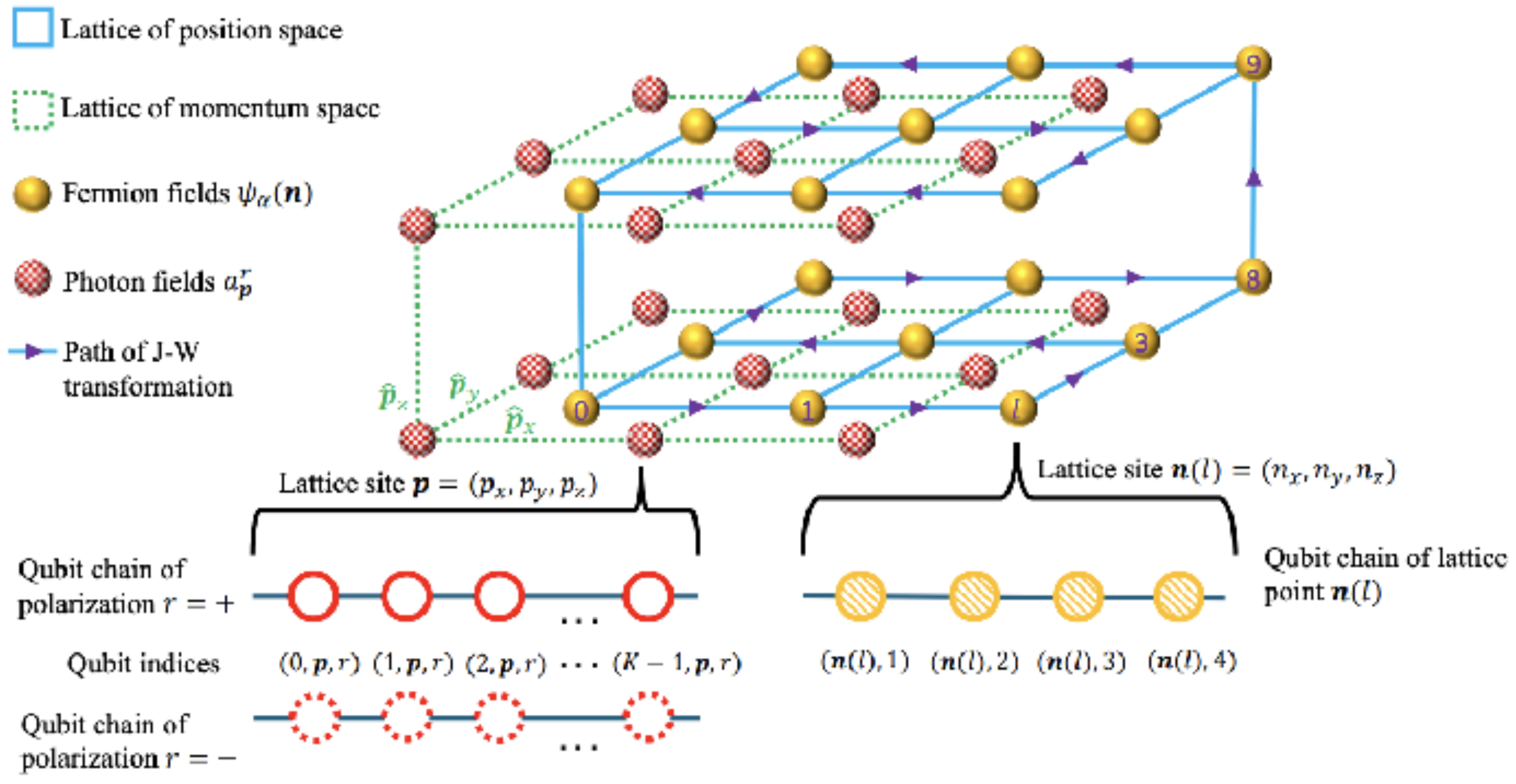
Quantum Hardware

- Quantum computing: current status
  - Noisy intermediate-scale quantum (NISQ) devices
    - Error rate: 1%~0.1%
    - Number of qubits: ~100
- What we can do now
  - Small, simple system
  - Effective, applicable algorithm

Quantum Simulation of Gauge Theory

- 1+1D: Gauge field eliminated
- >1+1D: Challenging
  - Gauge d.o.f
    - Fix: choice of gauge
    - Exploit: encoding
  - Discritization
  - Truncation

Coloumb gauge QED
preserves Gauss's law



Li, *Phys.Rev.D* 112 (2025) 5, 054512

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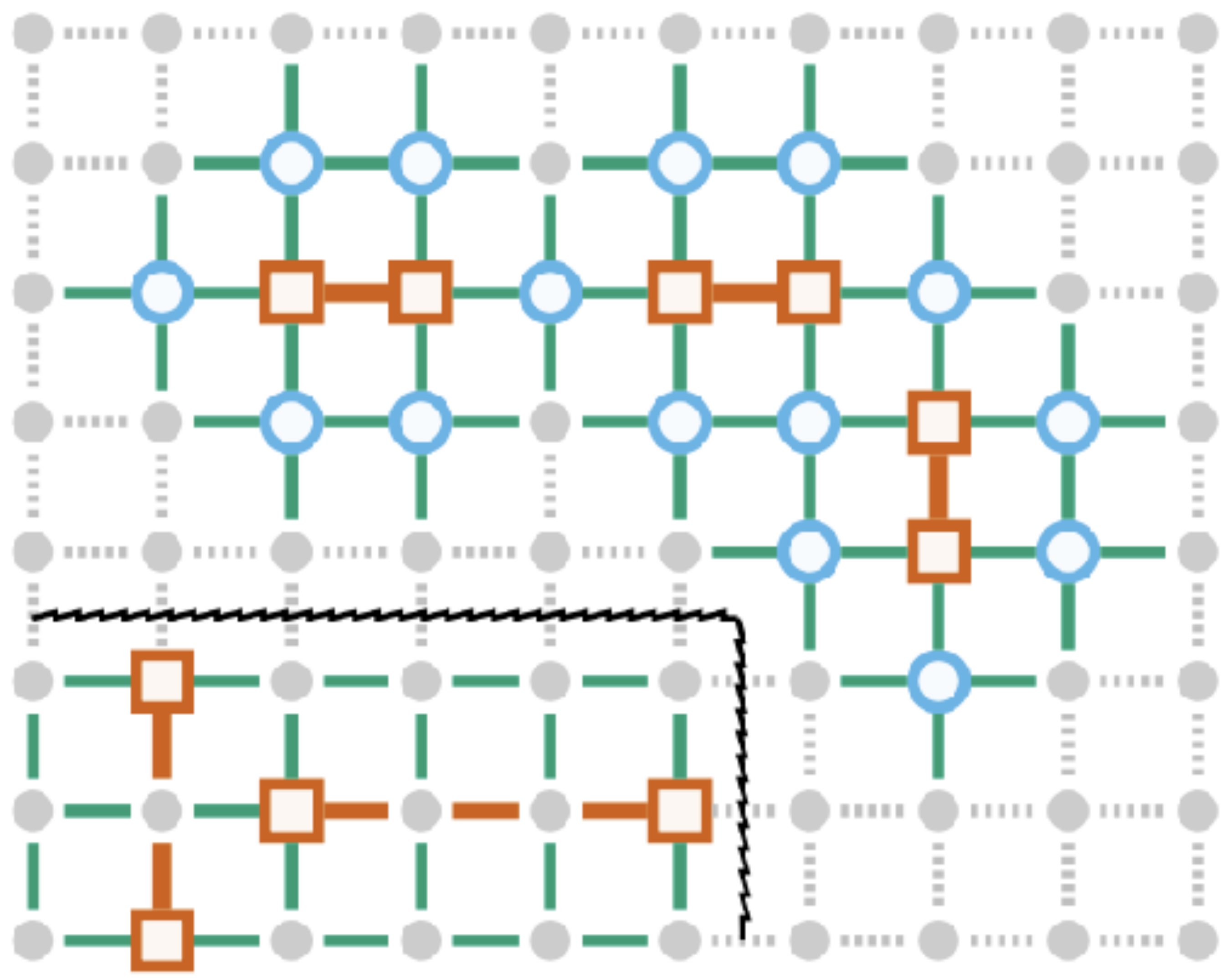
Use gauge redundancy as error correction code



Carena, Lamm, Li, Liu, *Phys.Rev.D* 110 (2024) 5, 054505

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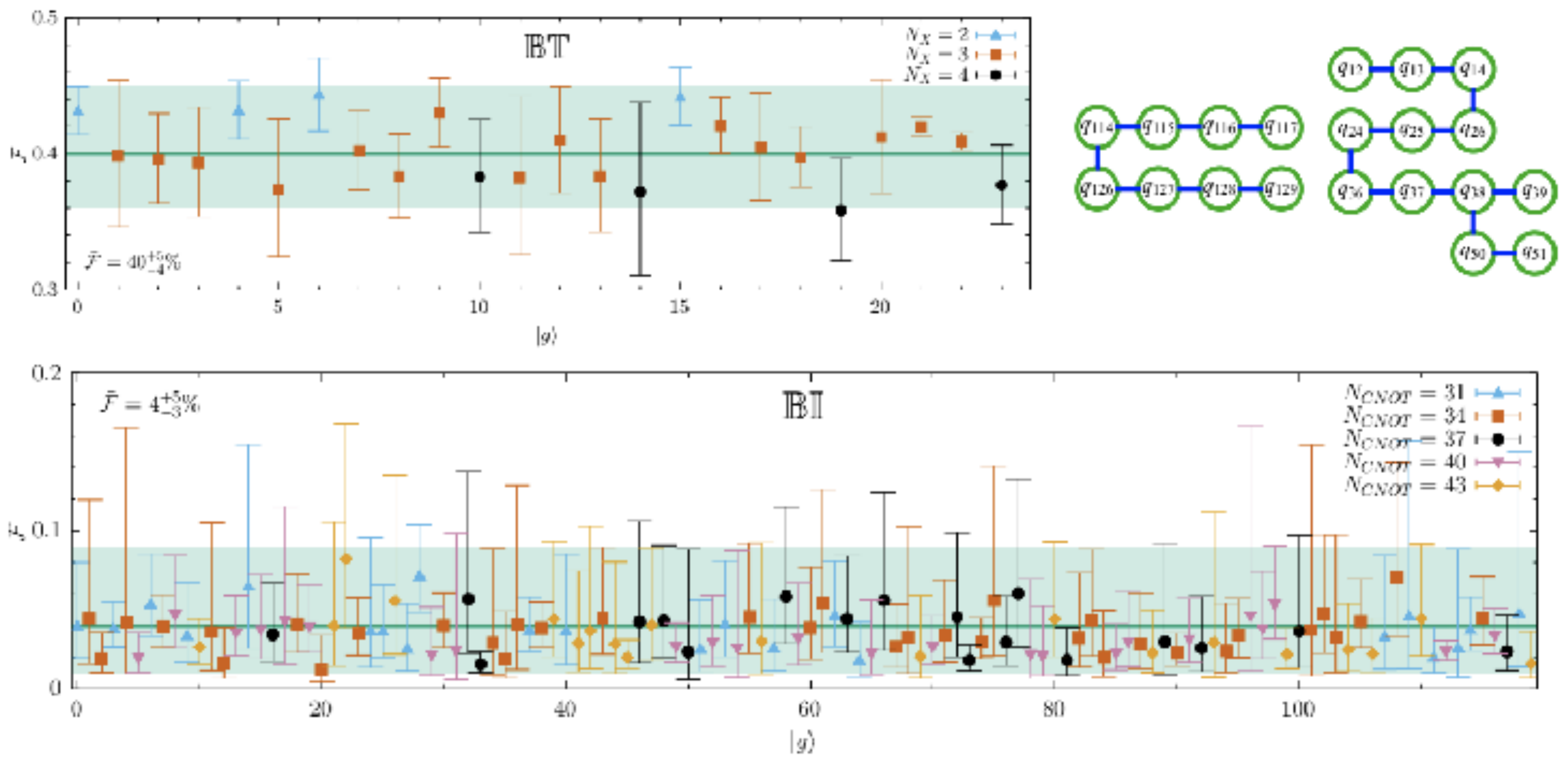
Gate realization of SU(2) and SU(3)’s subgroup



Lamm, Li, Shu, Wang, Xu, *Phys.Rev.D* 110 (2024) 5, 054516

State preparation

- Variational method

$$|\varphi(\theta)\rangle = U(\theta)|\varphi_0\rangle$$

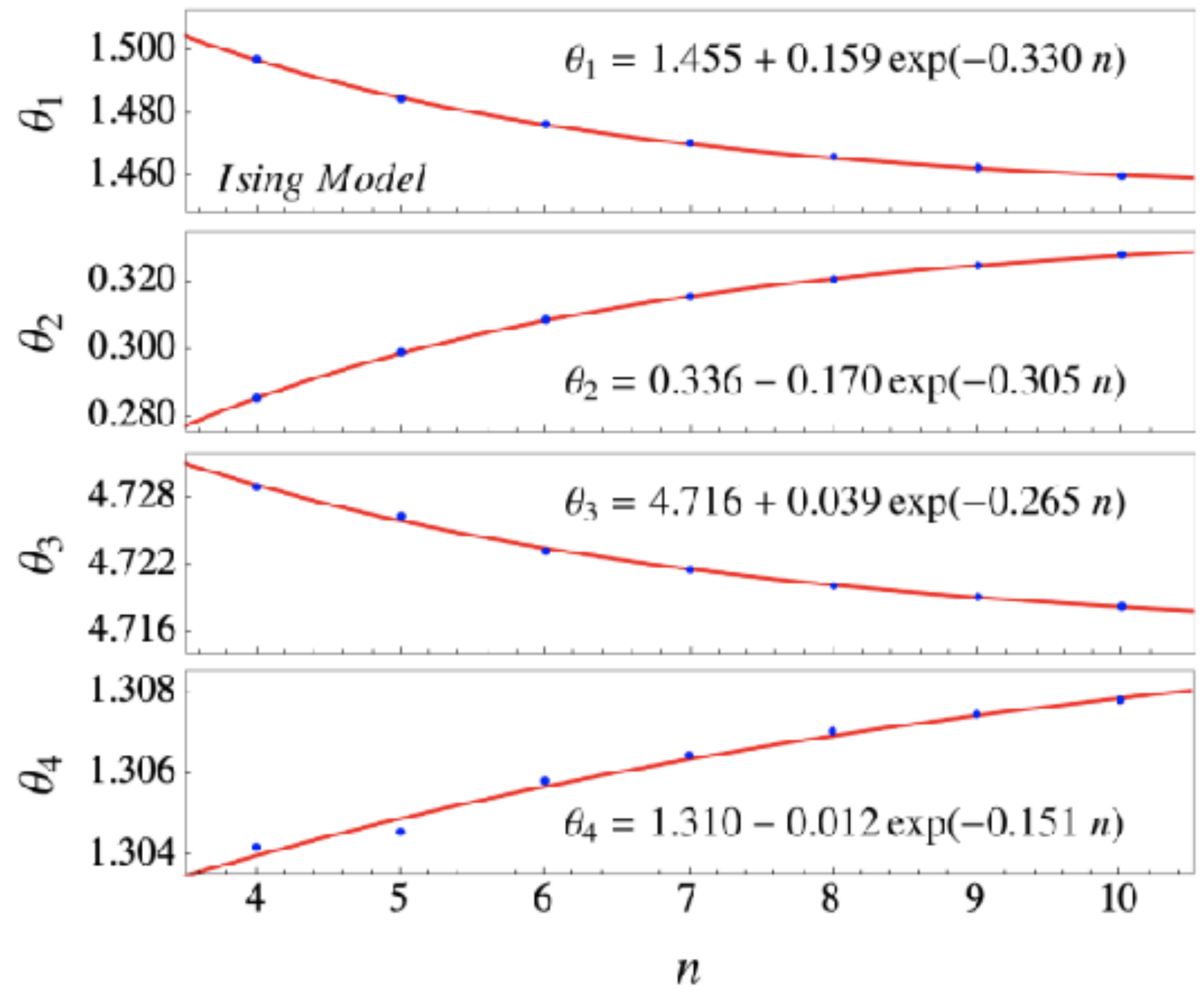
  - Ansatz: construct $U(\theta)$ in terms of quantum gates

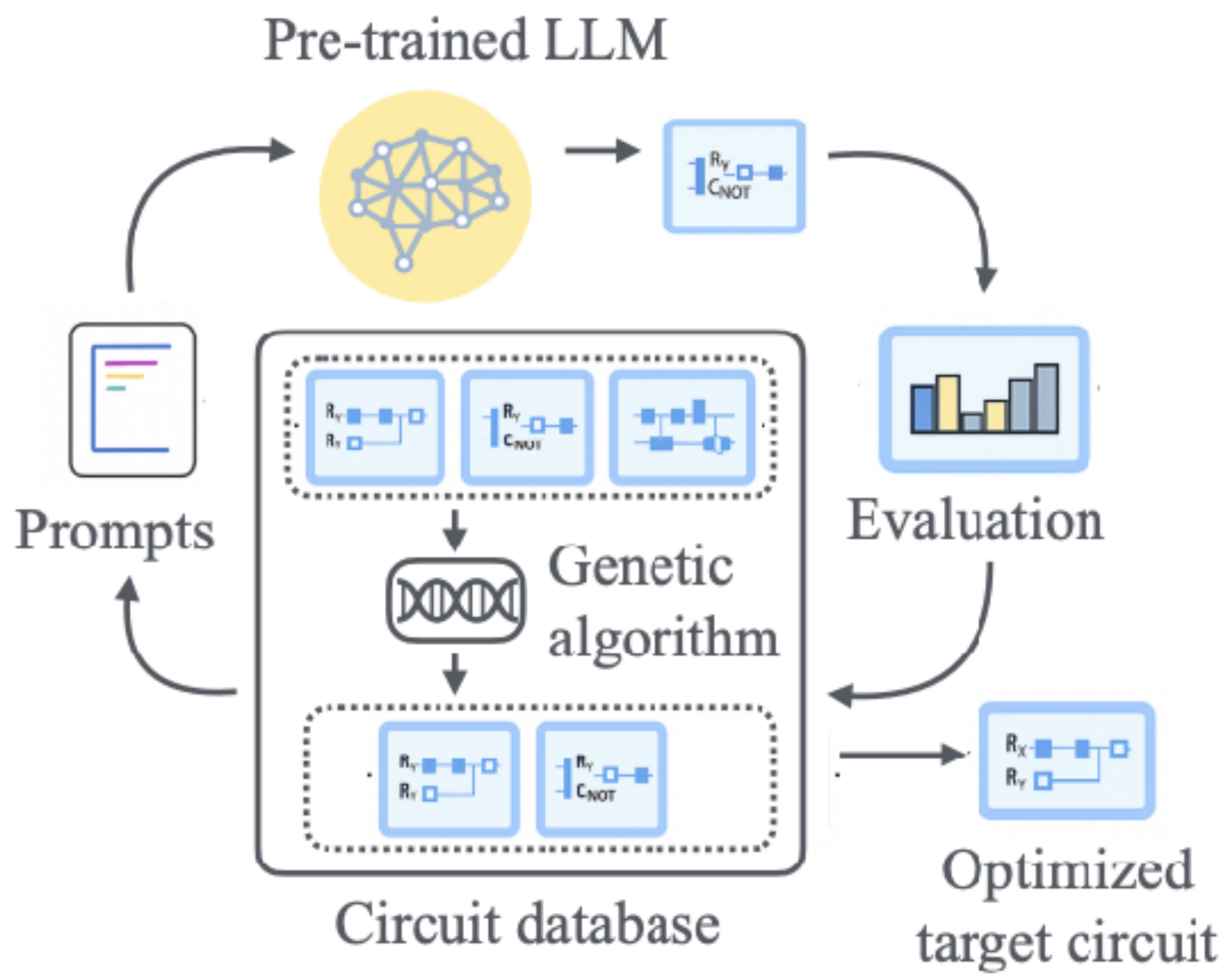
$$U(\theta) = \Pi_i \hat{G}_i(\theta_i)$$

  - Expressibility
  - Optimization difficulty
  - Conservation laws — Quantum numbers
  - Length of circuit

State preparation

- State preparation via LLM
- Scalability
  - Const # of parameters
  - Continuous evolution of parameters





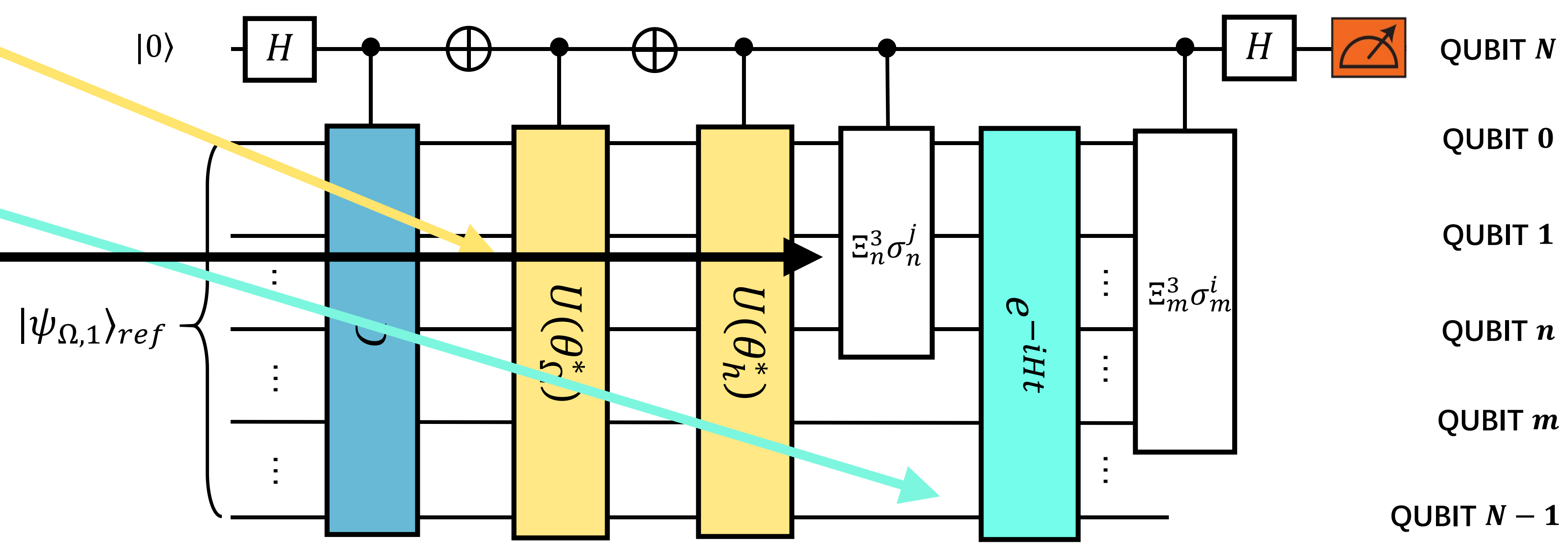
Cao, Hou, Li, Liu, Song, Zhang, Zhang, Zhao, arxiv:2505.06347

Real Time Dynamics

- Calculation of time-dependent observables

$$\langle\alpha|\Pi_i\left[\hat{O}_i(t_i)\right]|\beta\rangle$$

- State preparation
- Time Evolution
- Measurement



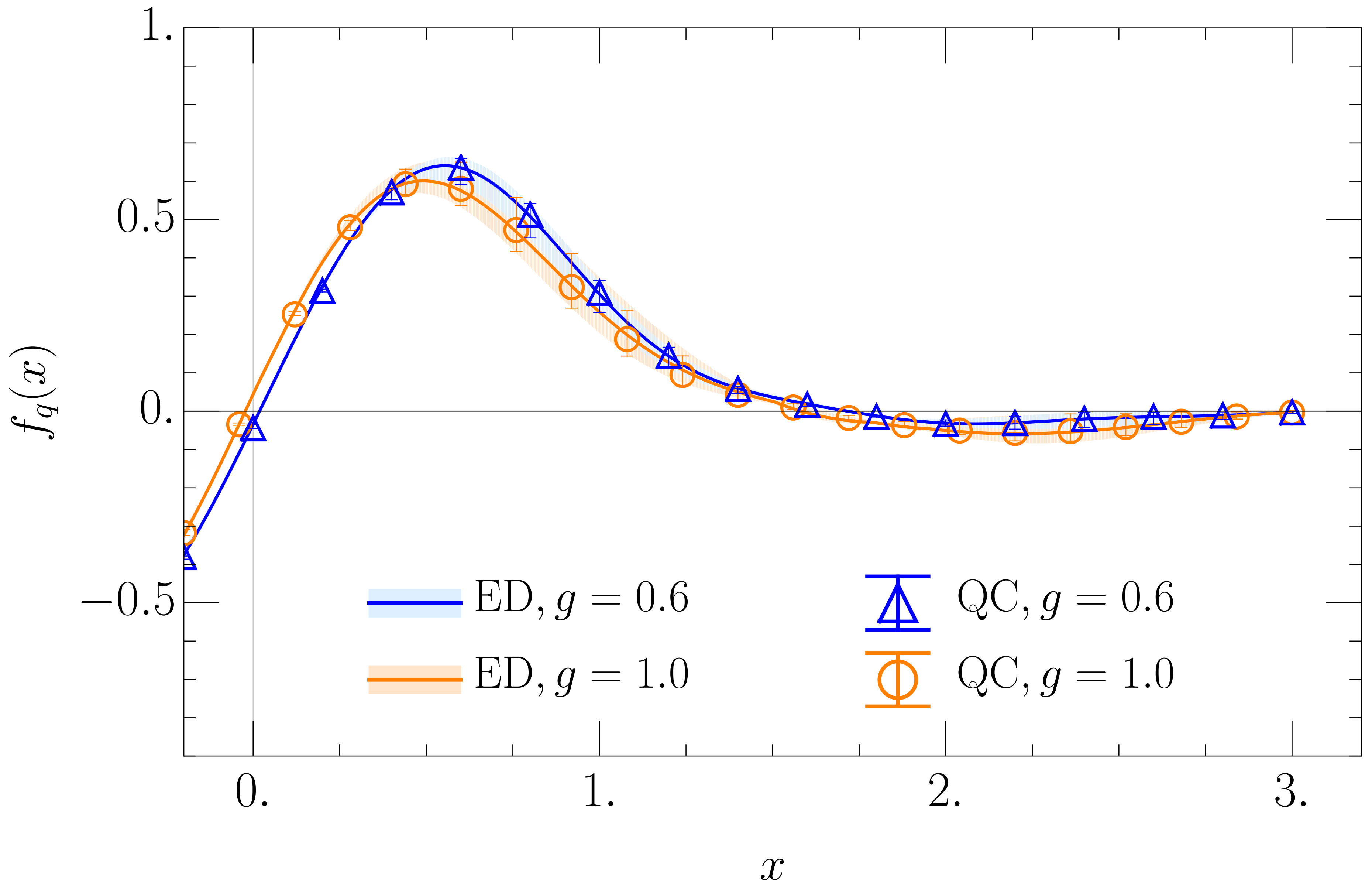
- Scalable
- Applicable to various problems

Li, XG, Lai, Liu, Wang, Xing, Zhang, Zhu,
Phys.Rev.D 105 (2022) 11, L11150
Sci. China Phys. Mech. Astron. 66(2023) 8, 281011

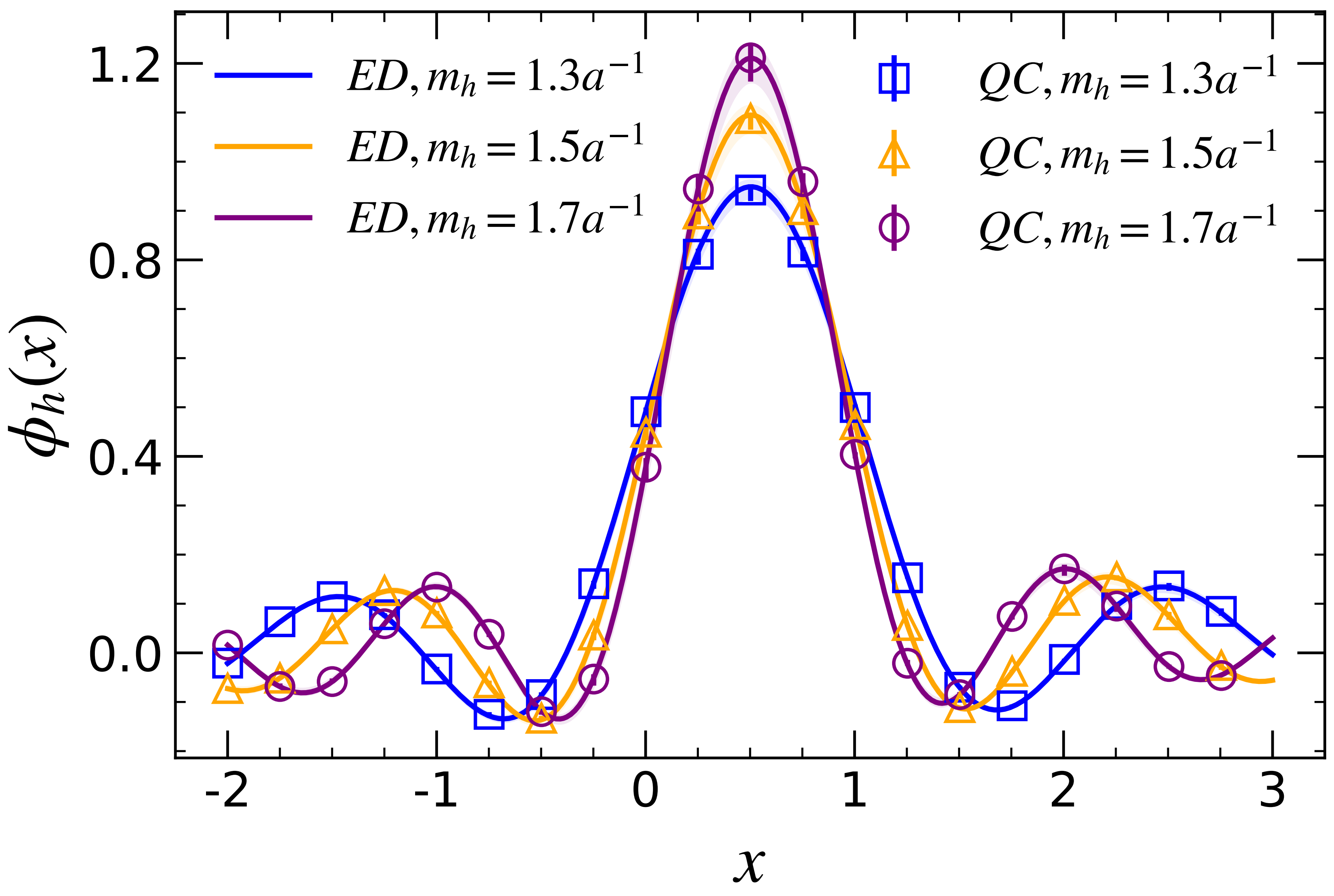
Hadron Structure

1+1D NJL model, classical simulation

Meson PDF



Meson Light Cone Distribution Amplitude



Li, XG, Lai, Liu, Wang, Xing, Zhang, Zhu,
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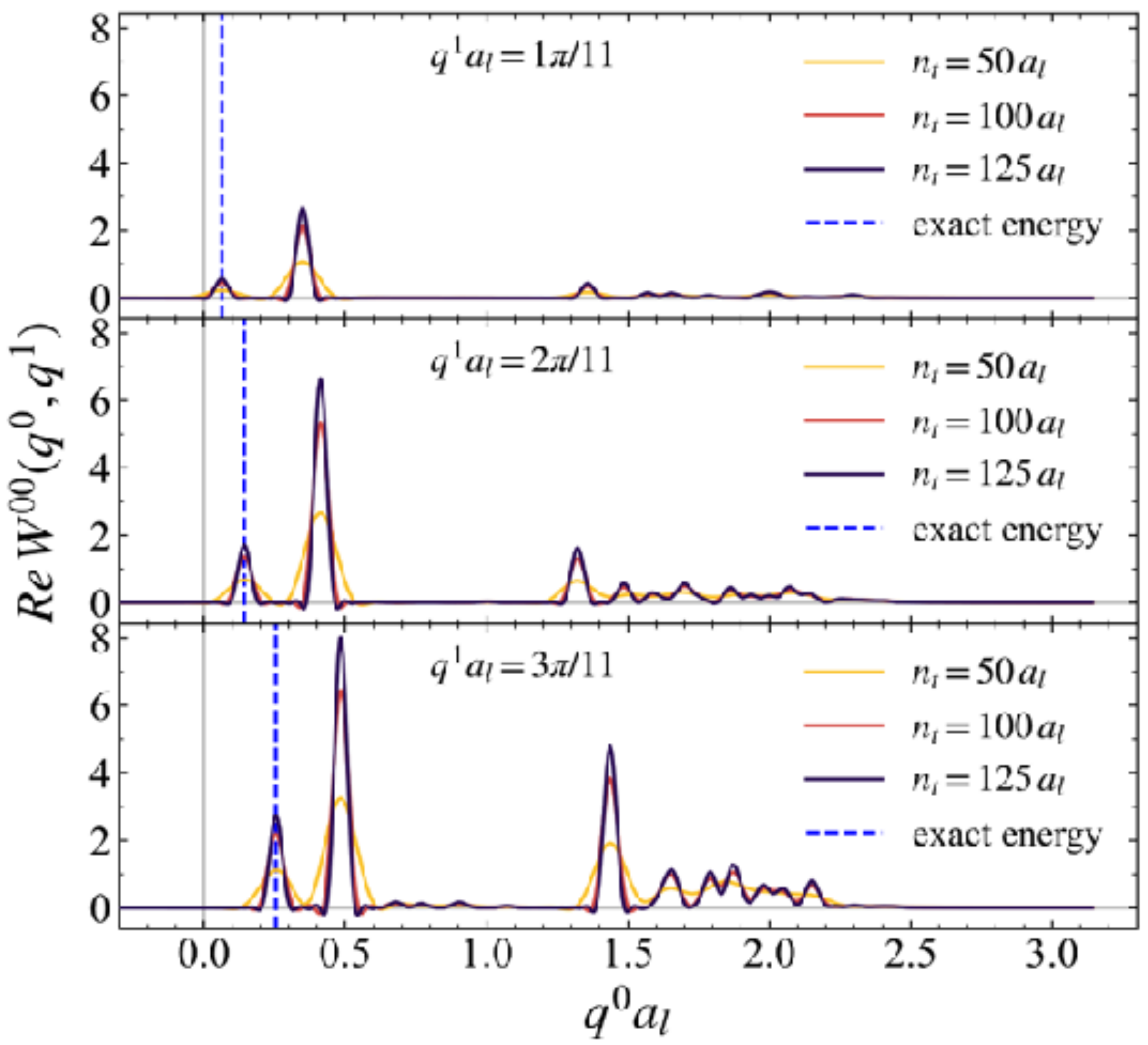
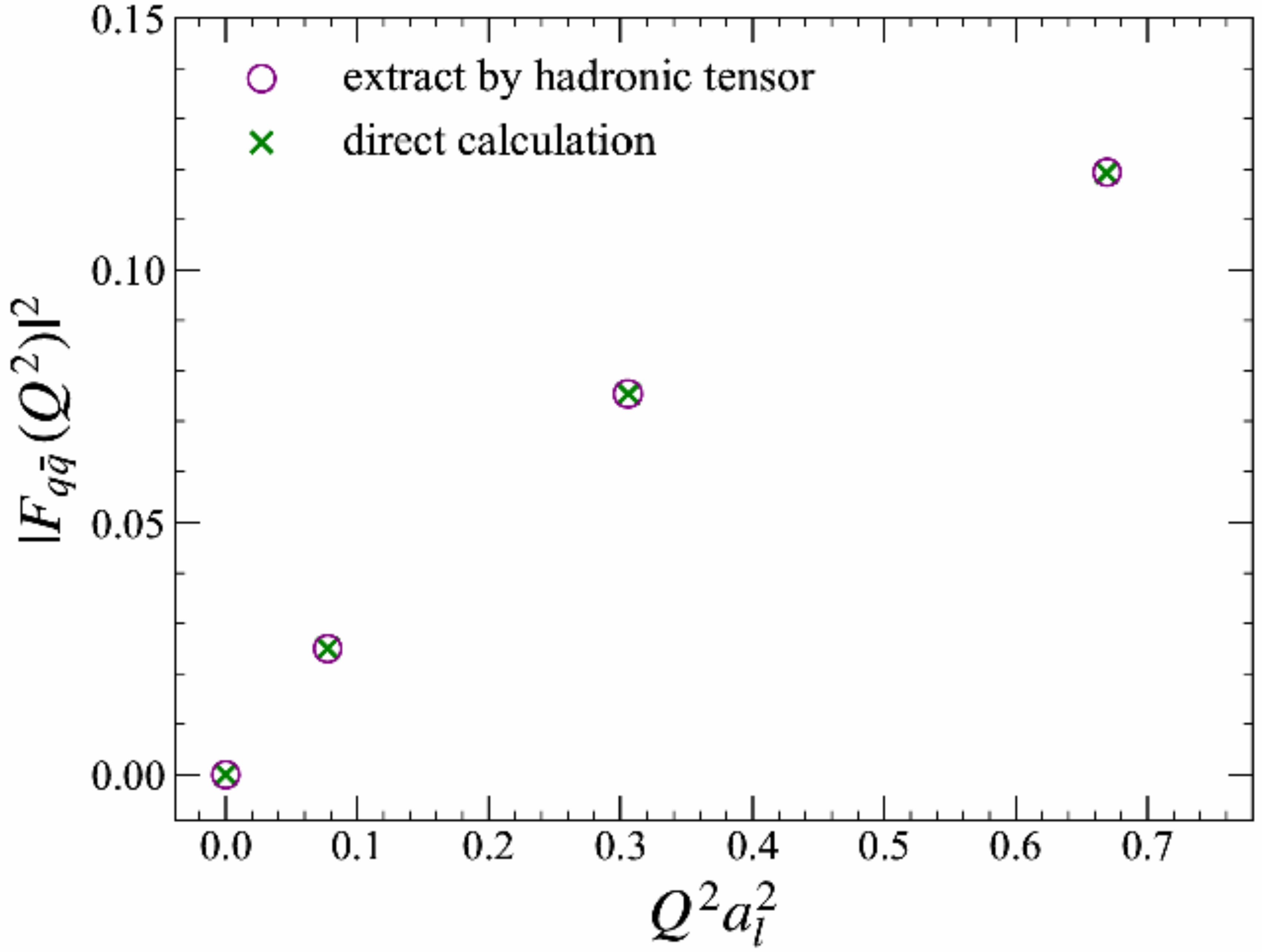
Hadronic Tensor and Form Factor





Dairui Zou’s Poster (E9)

Thermal Systems

- Calculation of temperature-dependent observables

$$\mathrm{tr}\left[\rho(T)\hat{O}\right]$$

  - It is challenging to handle non-unitary operators / mixed states in QC
    - Purification: more qubits
    - Imaginary time evolution: non-unitary
    - Monte Carlo: evaluation of probability
    - Complexity: space vs. time

Thermal State Preparation

- Finite temperature: the Gibbs state

$$\rho(\beta) = \frac{1}{Z(\beta)} e^{-\beta H}, \quad Z(\beta) = \mathrm{Tr}(e^{-\beta H})$$

$$\rho(\alpha) = \sum_i \boxed{P_i(\beta)} \boxed{|\varphi_i\rangle\langle\varphi_i|}$$

Eigenstate of H
independent of β

Analytically solvable

$$P_i = \frac{e^{-\beta E_i}}{\left(\sum_n e^{-\beta E_i}\right)}$$

- Variational method
  - Parametrization

$$\rho(\alpha) = \sum_i P_i(\beta) U(\alpha) | i \rangle \langle i | U^\dagger(\alpha)$$

$$E_i = \langle i | U^\dagger(\alpha) H U(\alpha) | i \rangle$$

Thermal State Preparation

- Loss Function : Free energy

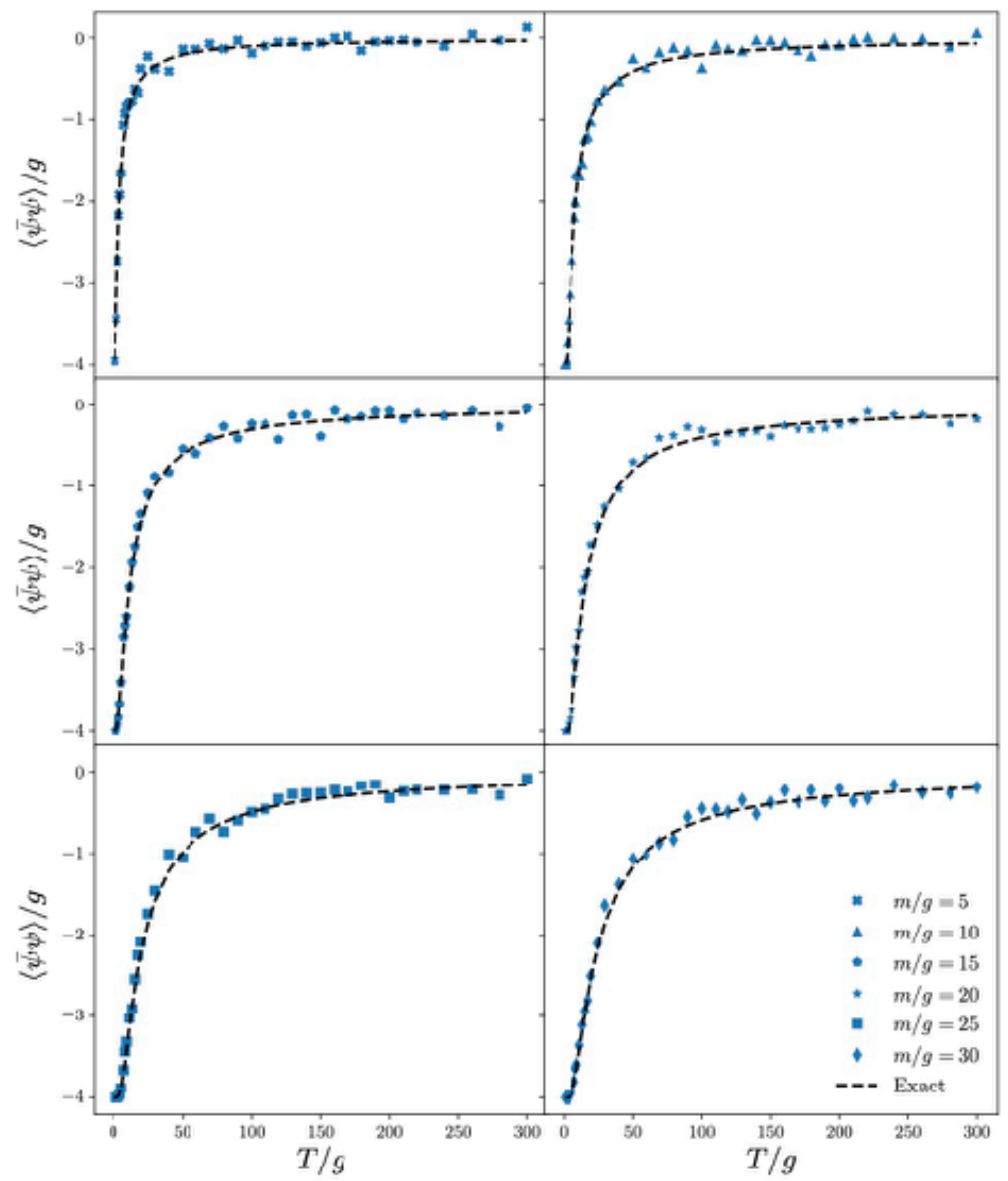
$$
\begin{aligned}
F &= E - TS \\
&= \mathrm{Tr}\left[\rho H\right] + T\,\mathrm{Tr}\left[\rho \log \rho\right] \\
&= \sum_i P_i \left[E_i + T \ln P_i\right]
\end{aligned}
$$

- The variational method is only used once for all different temperatures.
- Many part of the calculation is analytical.
- A Monte-Carlo sampling is then used for measurement.

Efficiency of Monte-Carlo

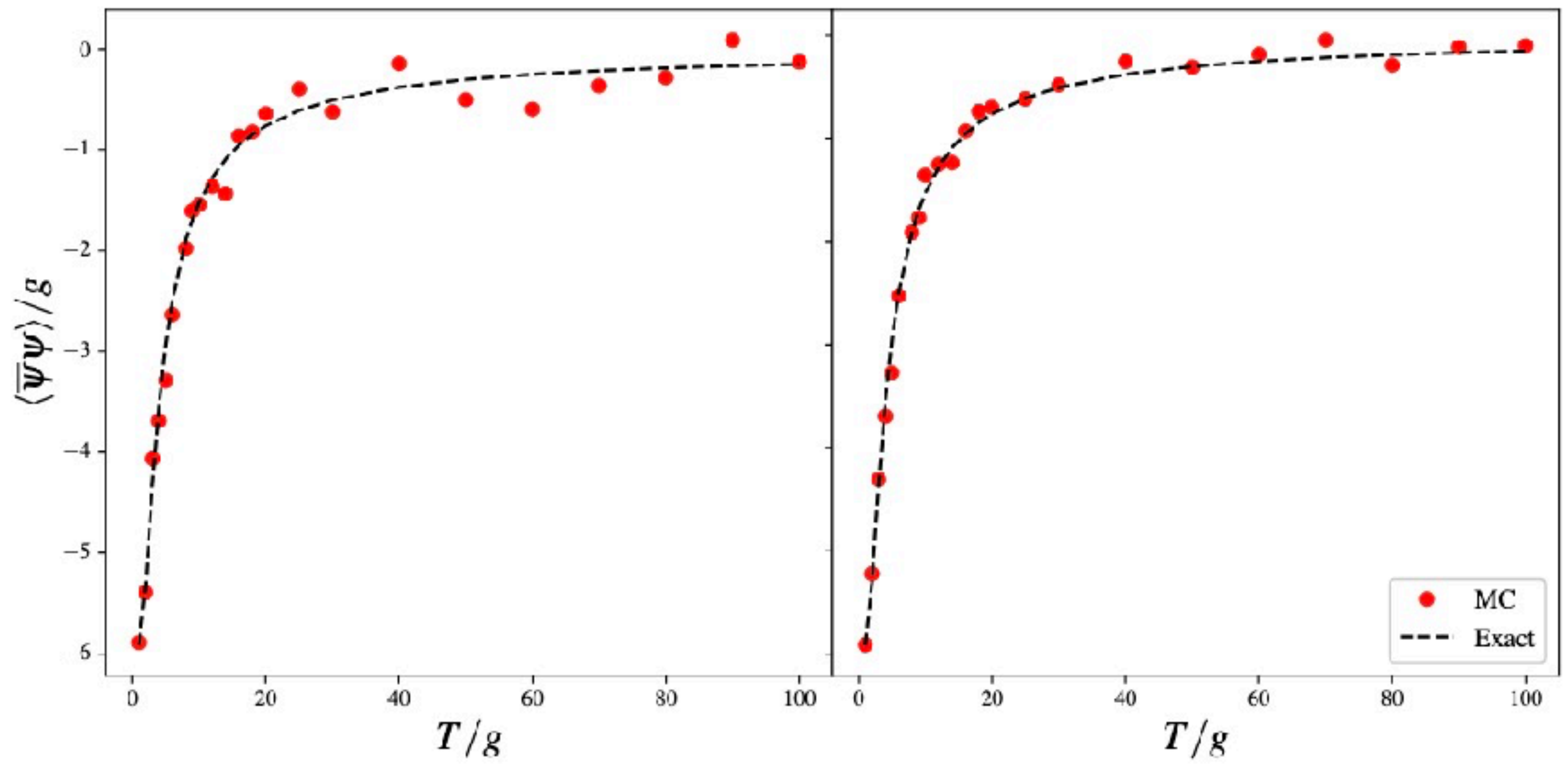
1+1D SU(2) model

8 qubits, 1000 states



16 qubits, 1000 states

16 qubits, 2000 states



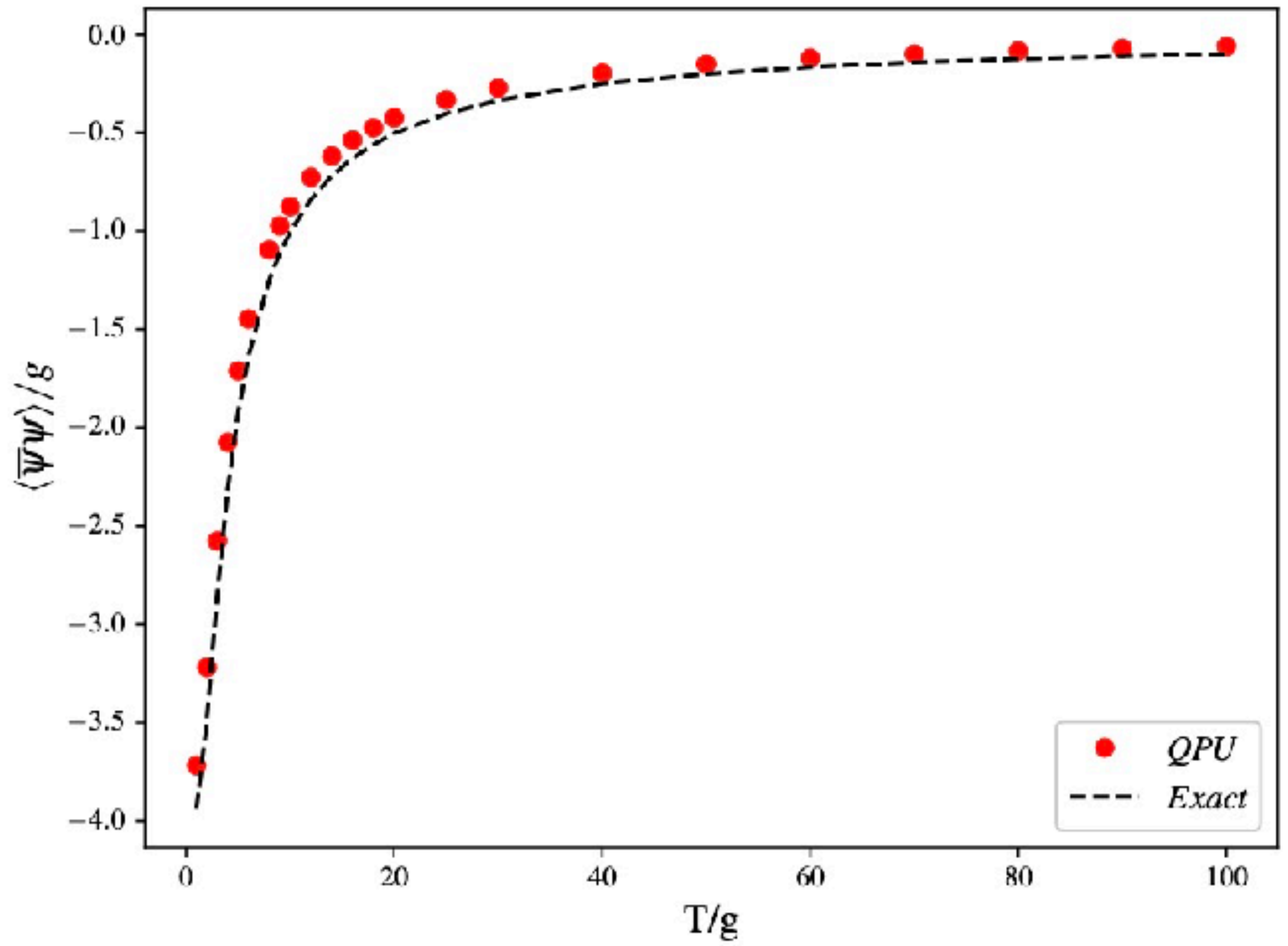
Zhang, XG, Wang, Xing, Phys.Rev.D 111 (2025) 5, 056031

- Required number of sampling increases only as power law of number of qubits.

Real QC results

- Optimization on classical simulater
- Measurement of σ on IBM quantum computer
  - No error mitigation
  - A simpler ansatz

8 qubits, 1000 states

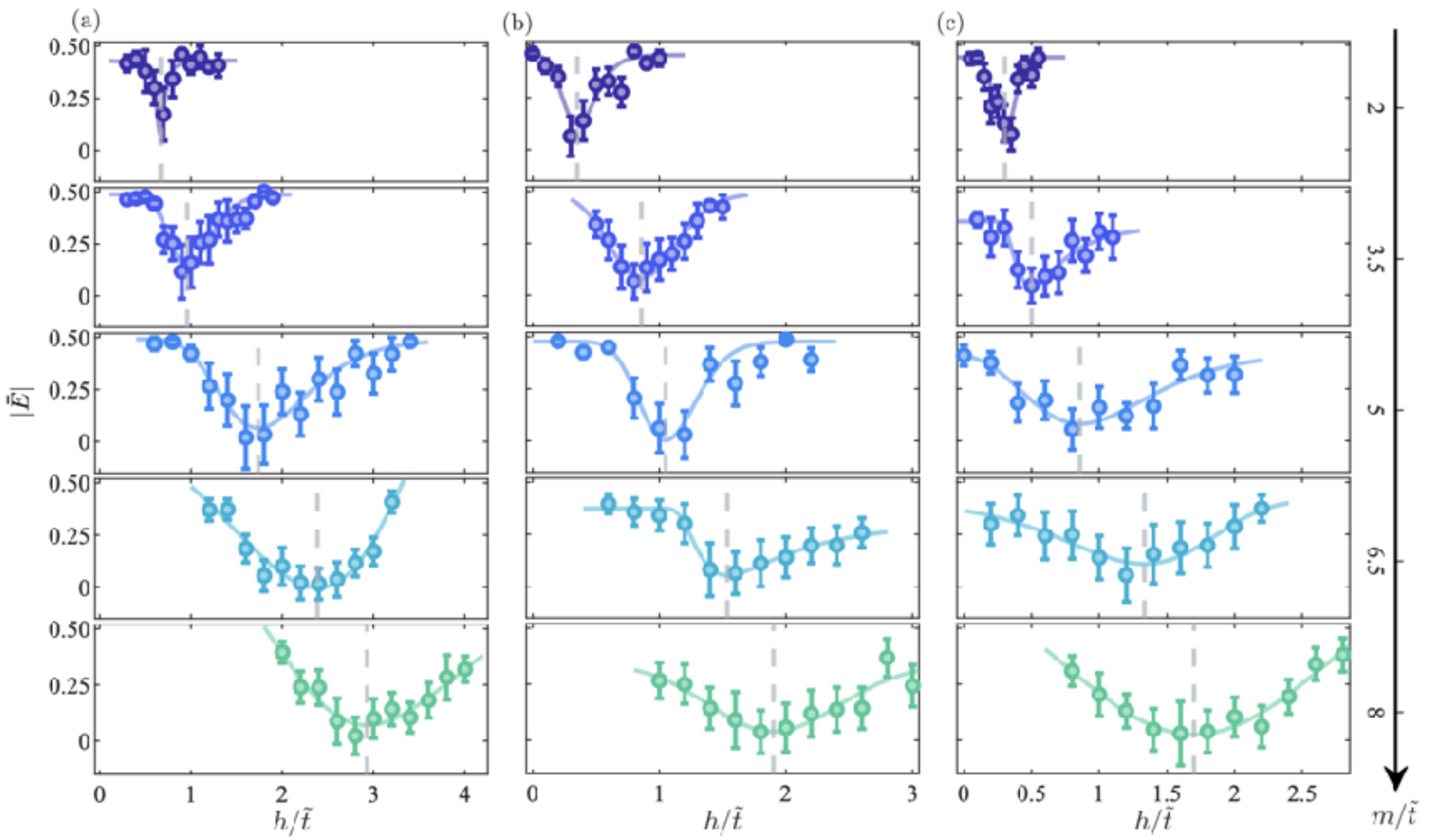


Zhang, XG, Wang, Xing, Phys.Rev.D 111 (2025) 5, 056031

Confinement

- 1+1D gauge theory exhibits confinement
  - They can be used to simulate QCD
- String tension:
  - Opposite changes on boundary / External field
  - Formation of fermion pair: string breaking
  - Ground state
  - Finite temperature
  - Dynamical (Schwinger mechanism?)

String breaking with different field strength and mass



Liu, Zhang, Zhu, He, Yuan et al. *Phys.Rev.Lett.* 135 (2025) 10, 10190 2

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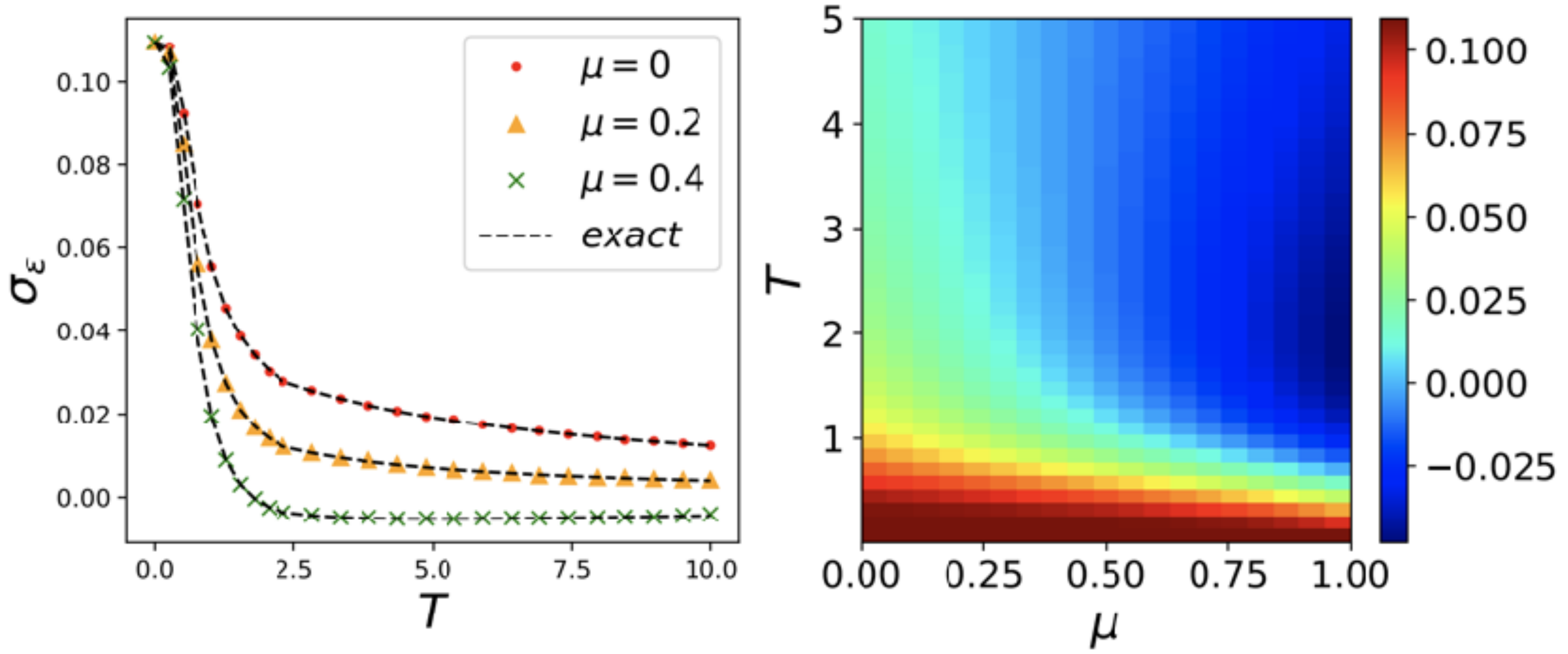
String breaking with different temperature and chemical potential



Xie, XG, Xing, Xue, Zhang, Zhu, *Phys.Rev.D* 106 (2022) 5, 054509

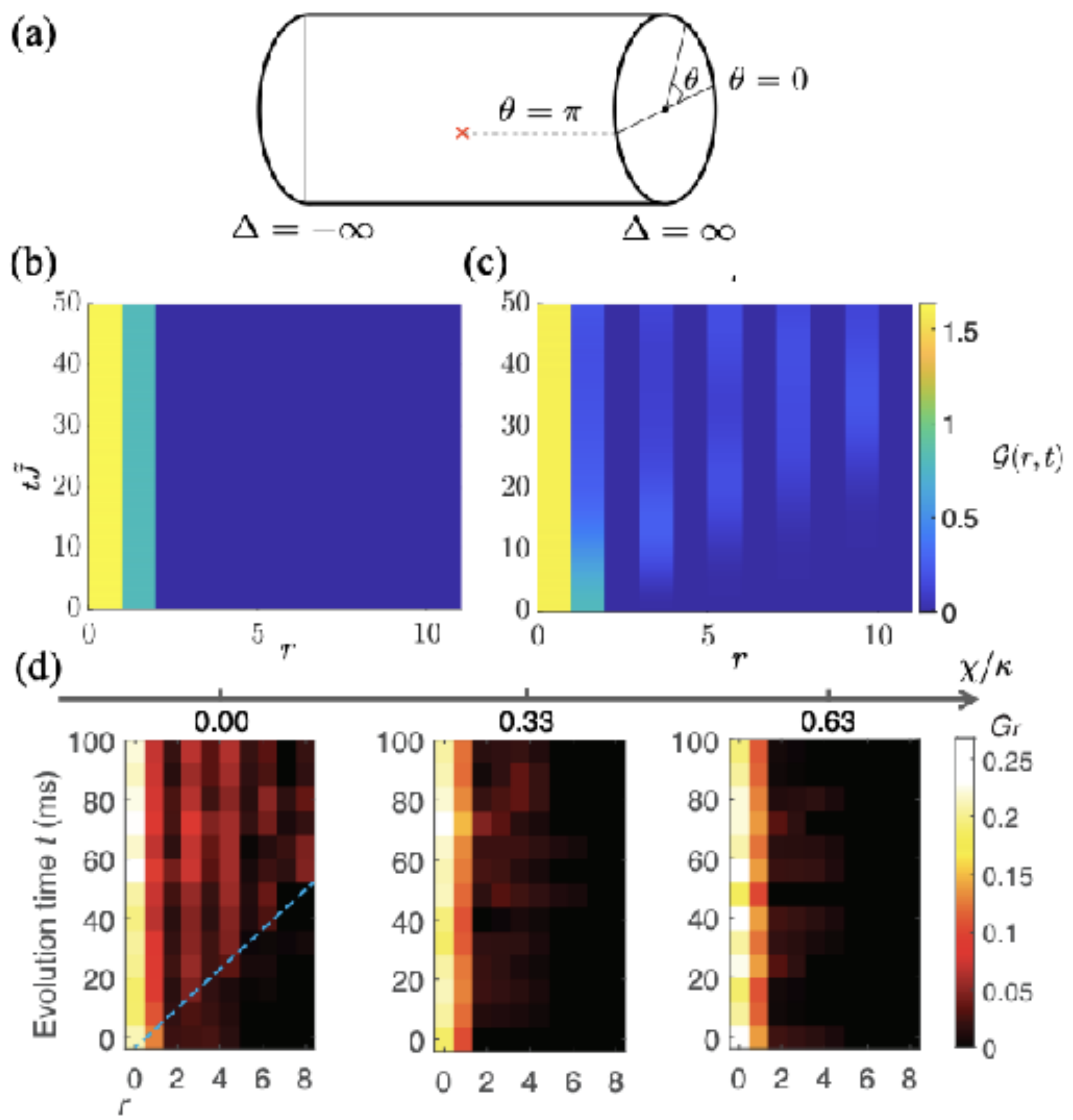
Confinement with Topological Angle

- 1+1D topological theta term

$$H_\theta = \frac{\theta}{4\pi}\epsilon_{\mu\nu}F^{\mu\nu} = \frac{\theta}{2\pi}E$$

$$F_{\mu\nu}F^{\mu\nu} + \frac{\theta}{4\pi}\epsilon_{\mu\nu}F^{\mu\nu} \sim (E + \frac{\theta}{2\pi})^2$$

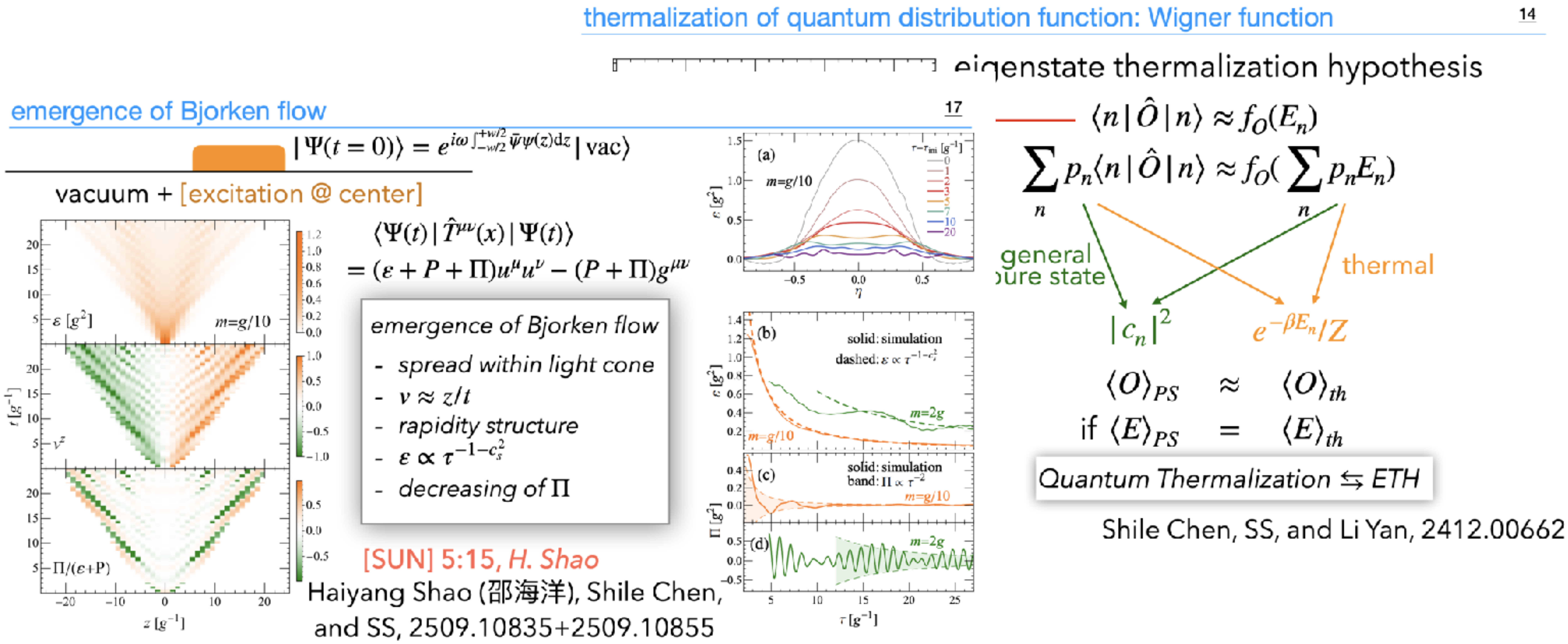
- Deconfinement at $\theta = \pi$



Cheng, Zhai, *Nature Rev.Phys.* 6 (2024) 566-576

Thermalization

- Ther
- Eige
- Qua



Please refer to Shuzhe's talk on Saturday!

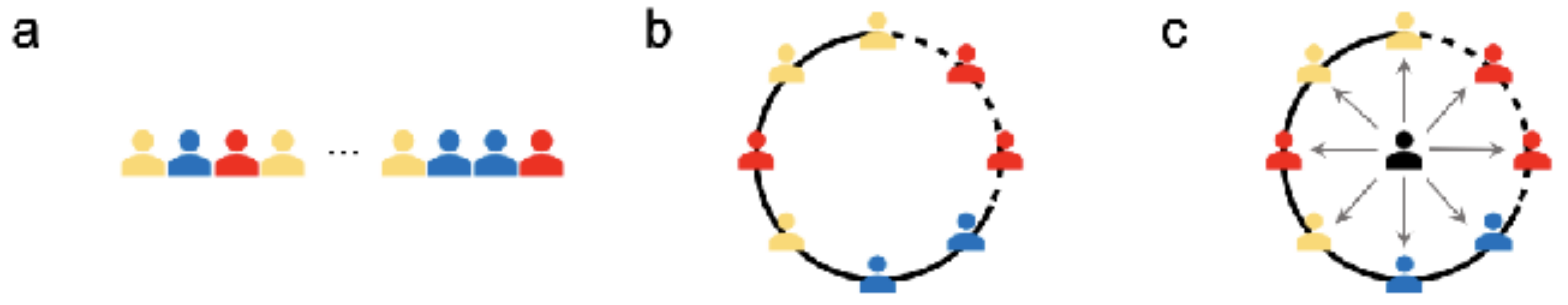
Beyond HEP: Opinion Dynamics

- Opinions → spins

$$H_0 = \sum_i a_i \left(Z_i \cos \theta_i + X_i \sin \theta_i \right)$$

- Exchange of opinions: spin-spin interaction

$$H_I = \sum_{\langle i,j \rangle} - c_{ij} \left(Z_i Z_j + X_i X_j \right)$$

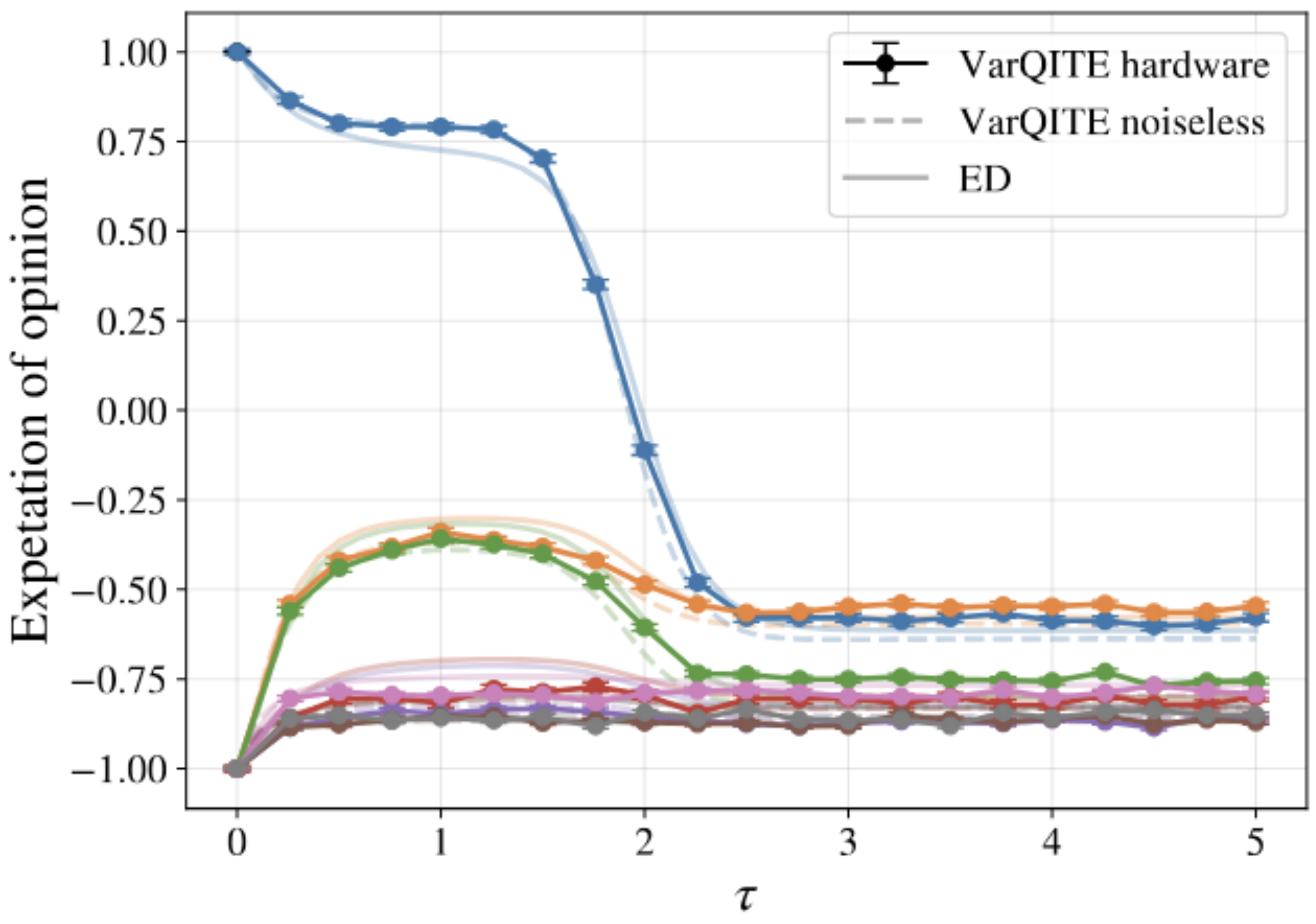


  - Leader → Background field

- Opinion dynamics → <u>imaginary</u> time evolution

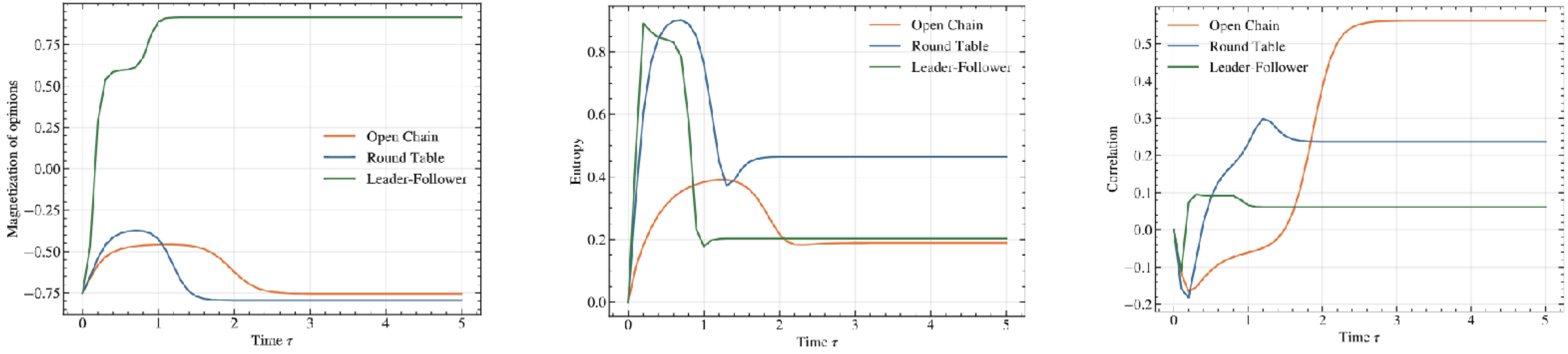
Beyond HEP: Opinion Dynamics

- A metastable state corresponding to the first excited state of H.
  - Temporary stalemate of opinions
- Real QC, classical simulation and ED results match quite well.



XG, Wang, Wang, in preparation

Beyond HEP: Opinion Dynamics



XG, Wang, Wang, in preparation

- Persistence of metastable state.
- Non-classical features:
  - Entanglement
  - Correlation of opinions

Summary and Outlook

- Quantum simulation of HEP is a new research field with reasonable potential.
- Development of various algorithms and also their applications.
- Connected to a wide range of topics across and outside of HEP.
- Contemporary QCs already have good performance on simplified models.

Thank you!