Quantum Computing and AI connected with Nuclear Physics

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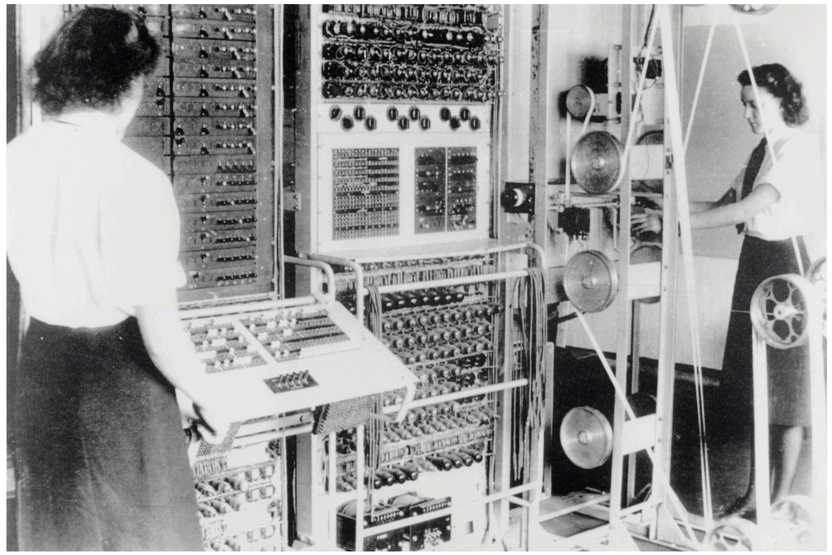
中国物理学会高能物理分会第十二届全国会员代表大会暨学术年会

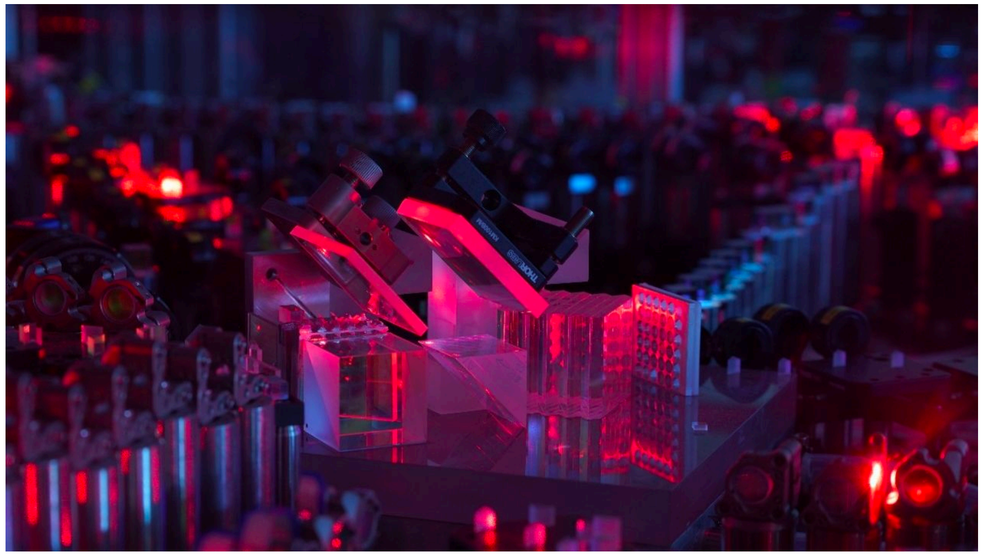
Outline

- Quantum simulation of Schwinger mechanism
- Phase transition in large language model
- Summary

Current State of Quantum Hardware

- Noisy intermediate-scale quantum (NISQ) devices
  - Error rate: 1%~0.1%
  - Number of qubits: 100 ~1000





Current State of Quantum Hardware

- Noisy intermediate-scale quantum (NISQ) devices
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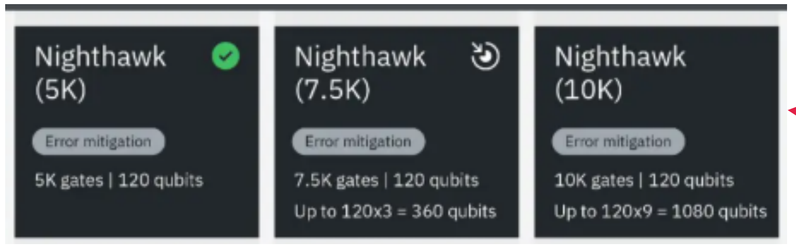
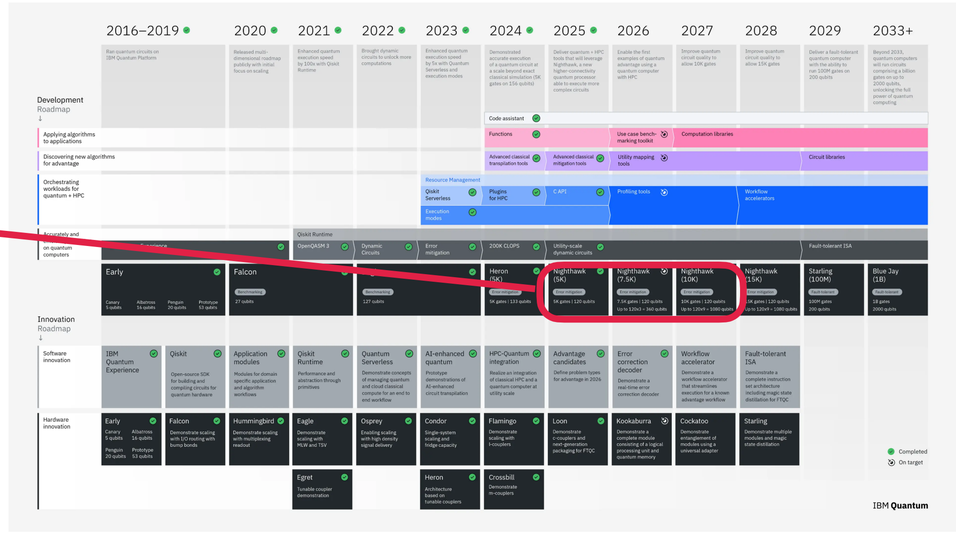
  - Number of qubits: 100 ~1000
  - Simulation of 2+1D systems is becoming reasonable

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





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Current State of Quantum Hardware

- Noisy intermediate-scale quantum (NISQ) devices
  - Error rate: 1%~0.1%
  - Number of qubits: 100 ~1000
  - Simulation of 2+1D systems is becoming reasonable
- What meaningful study can we do now?
  - Search for effective, applicable algorithm
  - Meaningful topics with small, simple systems

Gauge Theory in 1+1D

- Schwinger Model:

$$H = -\bar{\psi}(i\gamma^1 \mathrm{D}_1 + m_\alpha)\psi + \frac{1}{2}E^2$$

- Gauss's law:

$$\partial_x E = Q(x) \longrightarrow E(x) = E_0 + \int_0^x \mathrm{d}Q(y)$$

- The remaining gauge link can be eliminated by a gauge transformation.
- Pure fermionic Hamiltonian:

$$H = \frac{1}{2a}\sum_{n=1}^{N-1}\left(\phi_n^\dagger \phi_{n+1} + H.c.\right) + m\sum_{n=1}^{N}(-1)^n \phi_n^\dagger \phi_n + \frac{g^2 a}{2}\sum_{n=1}^{N-1}\left[\varepsilon + \sum_{l=1}^{n}\left(\phi_l^\dagger \phi_l - \frac{1-(-1)^l}{2}\right)\right]^2$$

Schwinger Mechanism

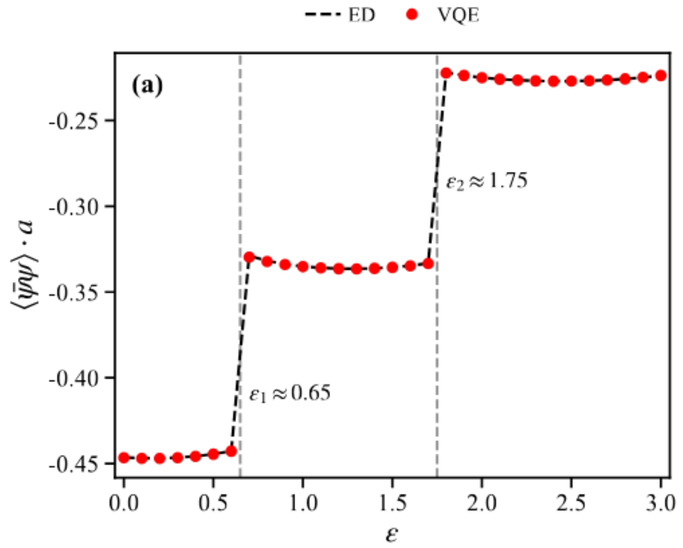
- Pair production under strong electric field.
- Strong field effect: no traditional perturbation method.
- Dynamical evolution: well-established in quantum simulation.
  - Trotterization
- State preparation: VQE + VQD

$$\langle\varphi(\theta)|H|\varphi(\theta)\rangle \qquad \langle\varphi(\theta)|H|\varphi(\theta)\rangle + \lambda\langle\varphi(\theta)|\varphi_0\rangle$$

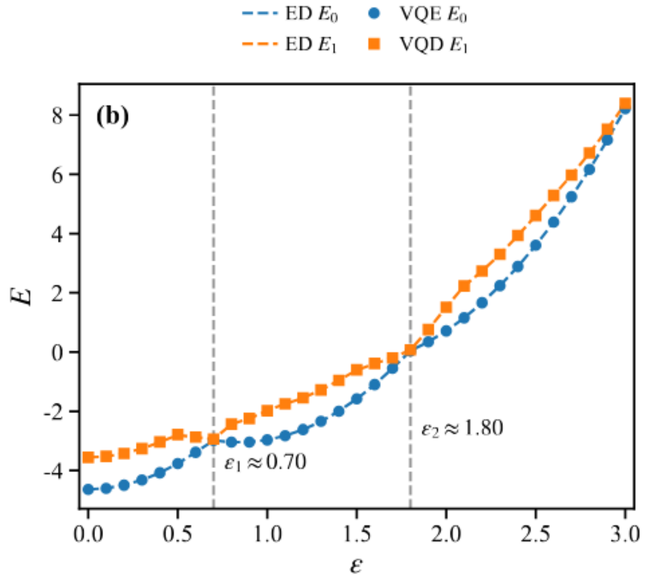
H. Chen, L. Cheng, XG, arXiv:2607.02894

Vacuum State with External Field

- “Jump” of the ground state.
  - First order phase transition at zero temperature.
- But there is no jump in the spectrum.



Chiral condensate of ground state

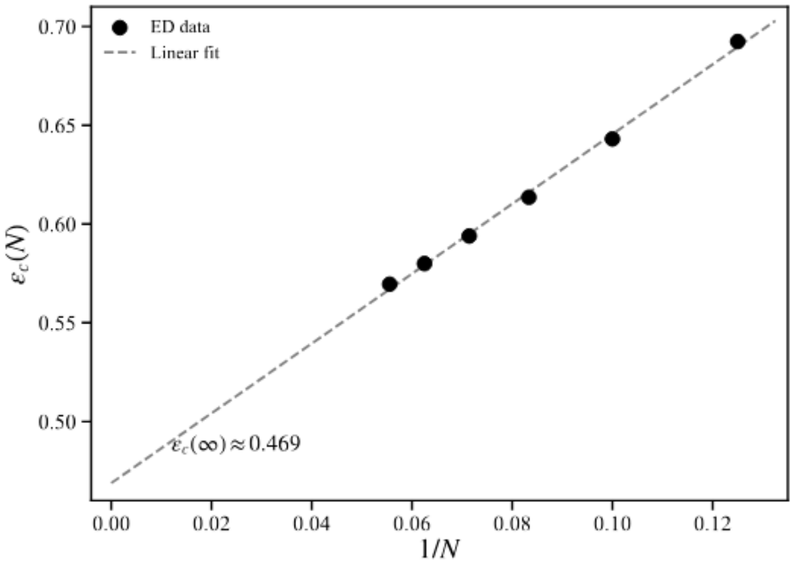


Energy of ground and first excited state

H. Chen, L. Cheng, XG, arXiv:2607.02894

Vacuum State with External Field

- The critical field strength $\epsilon_c \sim 1/N + \epsilon_c(\infty)$.
- $\epsilon_c(\infty)$ is smaller than the theoretical prediction: 0.5.
- Open boundary effect: $\langle H_k \rangle$ gives a negative contribution.



Fitting of the critical field strength

H. Chen, L. Cheng, XG, arXiv:2607.02894

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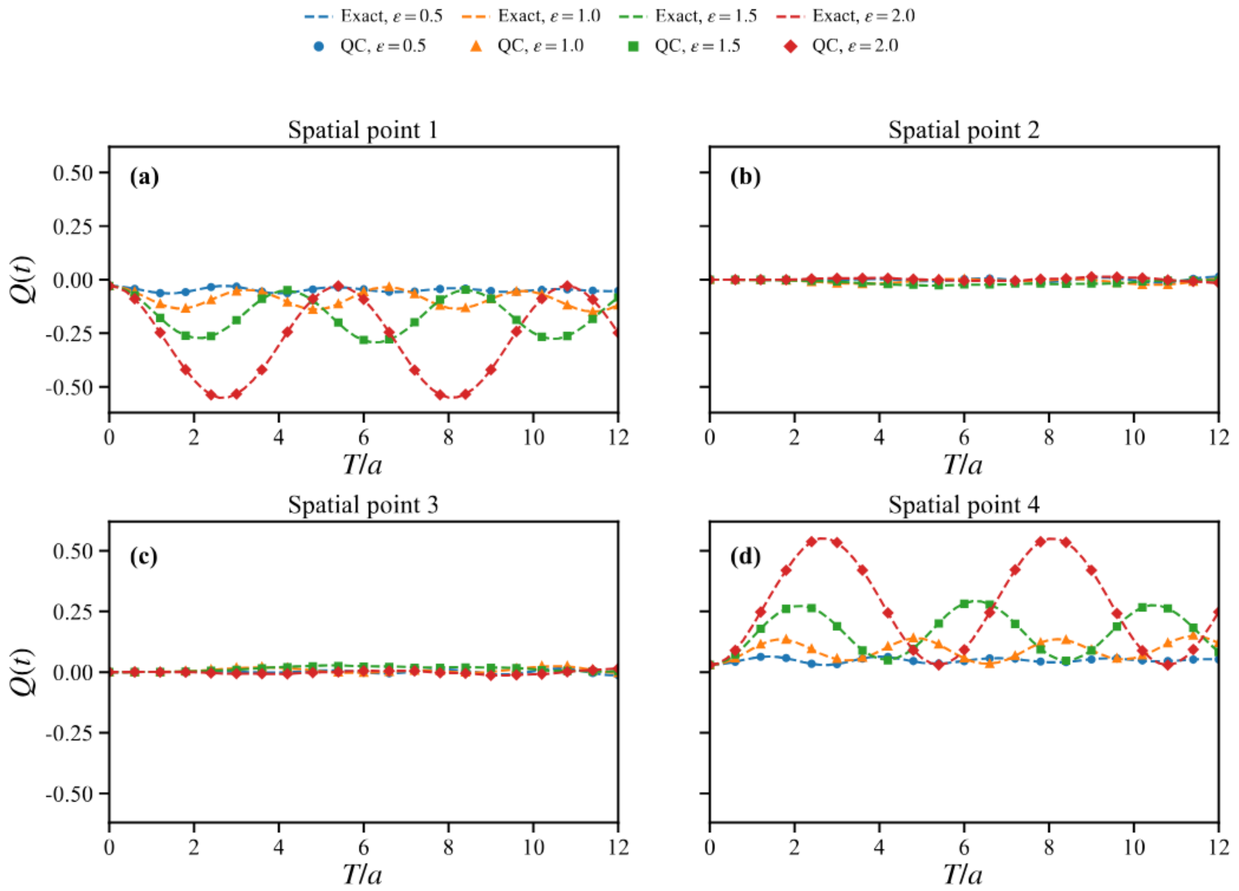
Spatial Charge Distribution

- A pair of charge is periodically produced at the boundary.
- No critical field strength observed.
- Consistent with theoretic prediction.



Time evolution of spatial charge density

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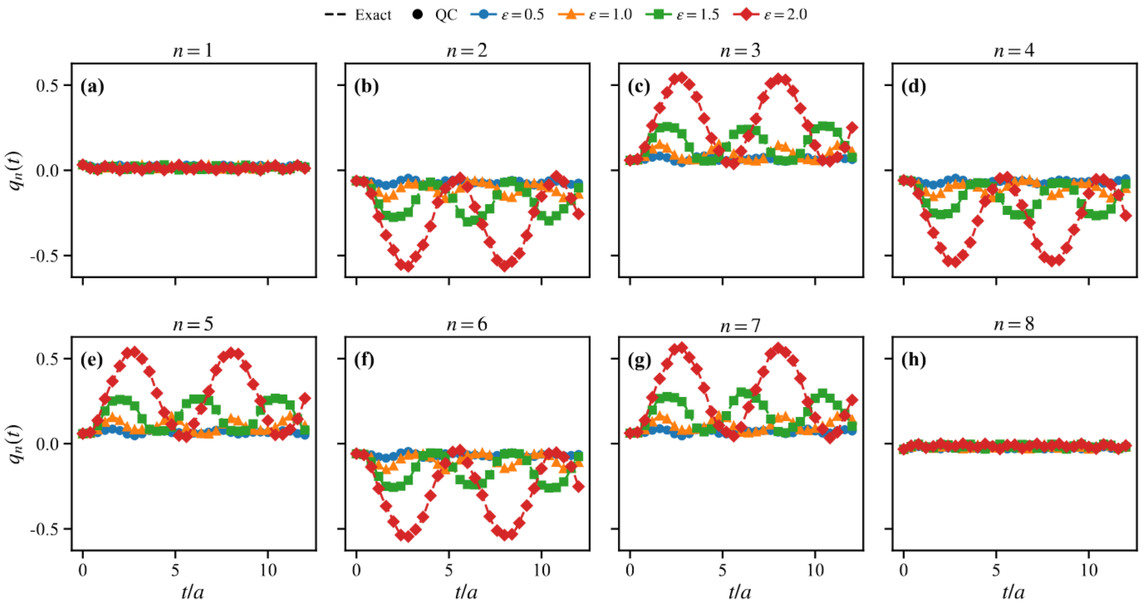
Lattice Particle Distribution

- Particle-antiparticle pairs are also produced in the middle.
- Deviation simple periodic behavior.
  - Contributions from higher modes.



Time evolution of charge density on each lattice site

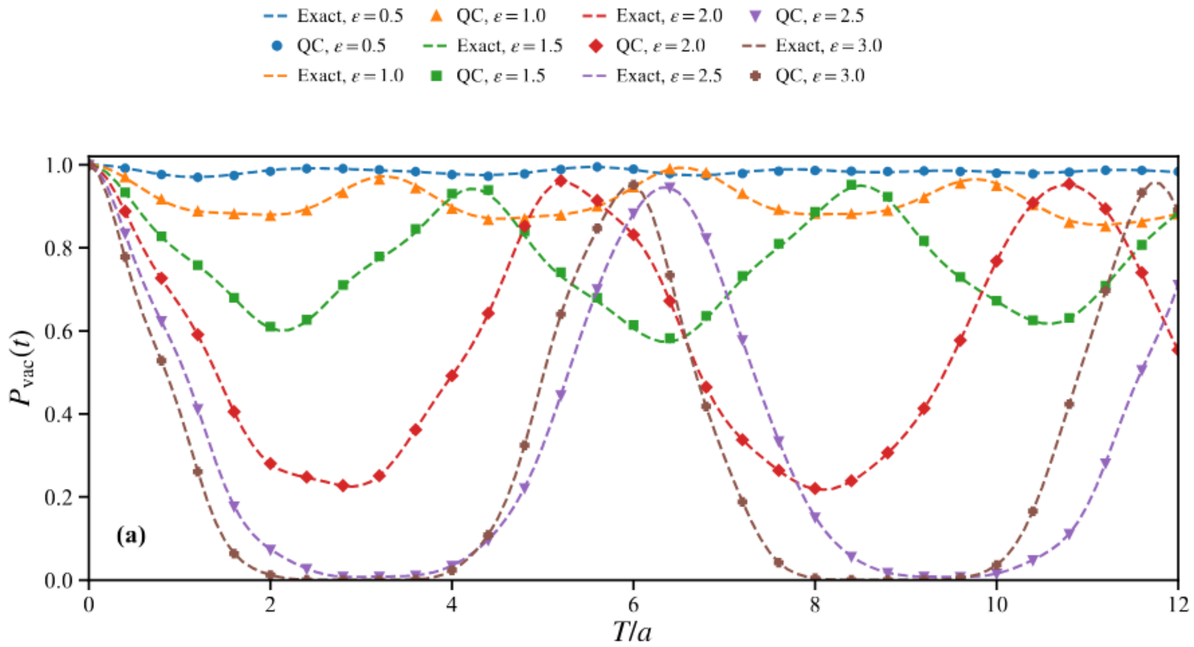
H. Chen, L. Cheng, XG, arXiv:2607.02894

Vacuum State Fidelity

- Vacuum state fidelity

$$P_{\mathrm{vac}}(t) = |\langle \psi_0 | \psi(t) \rangle|^2$$

- Describes how far the system deviates from the initial state.



Time evolution of vacuum state fidelity

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Vacuum State Fidelity

- Vacuum state fidelity

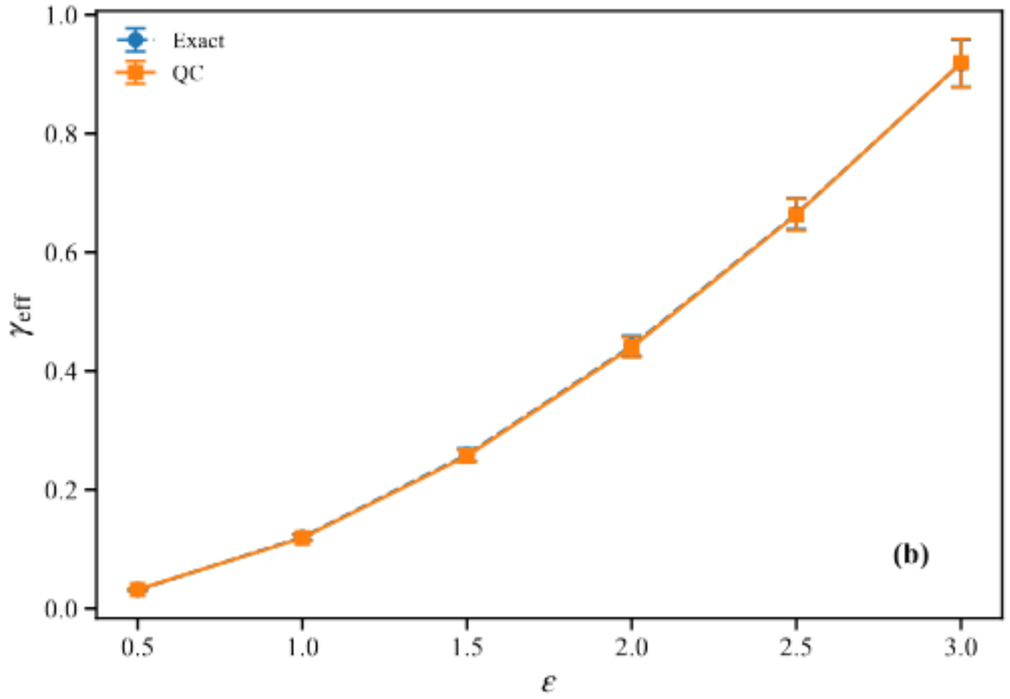
$$P_{\text{vac}}(t) = |\langle \psi_0 | \psi(t) \rangle|^2$$

- Describes how far the system deviates from the initial state.
- Fitting ($0 \leq T/a \leq 1.0$):

$$P_{\text{vac}}(t;\varepsilon) \simeq A(\varepsilon)\exp\left[-\gamma_{\text{eff}}(\varepsilon)t\right]$$

- In theory, pair production rate:

$$\Gamma \sim E^2 \exp(-a/E)$$



Fitted value of γ_{eff}

H. Chen, L. Cheng, XG, arXiv:2607.02894

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LLMs as Physical Models

- Language → tokens (high-dimension vectors).

$$\text{“I am a robot.”} \rightarrow \{t_i \,|\, i = 0,1,2,3,4\}$$

- Softmax probability $p_i = \dfrac{\exp(z_i/T)}{\sum_j \exp(z_j/T)}$: temperature?
- Attention mechanism $z_i = \sum_j Q(t_i)K(t_j)$: interacting between tokens?
- Prompt: external field / crystallization nuclei
- LLM: a system of interacting “spins”, with a temperature?
  - Does LLM have phase transition?

H. Ruan, J. Li, XG, L. Wang, arXiv:2606.06238

Phase Transition in LLMs

- Susceptibility:

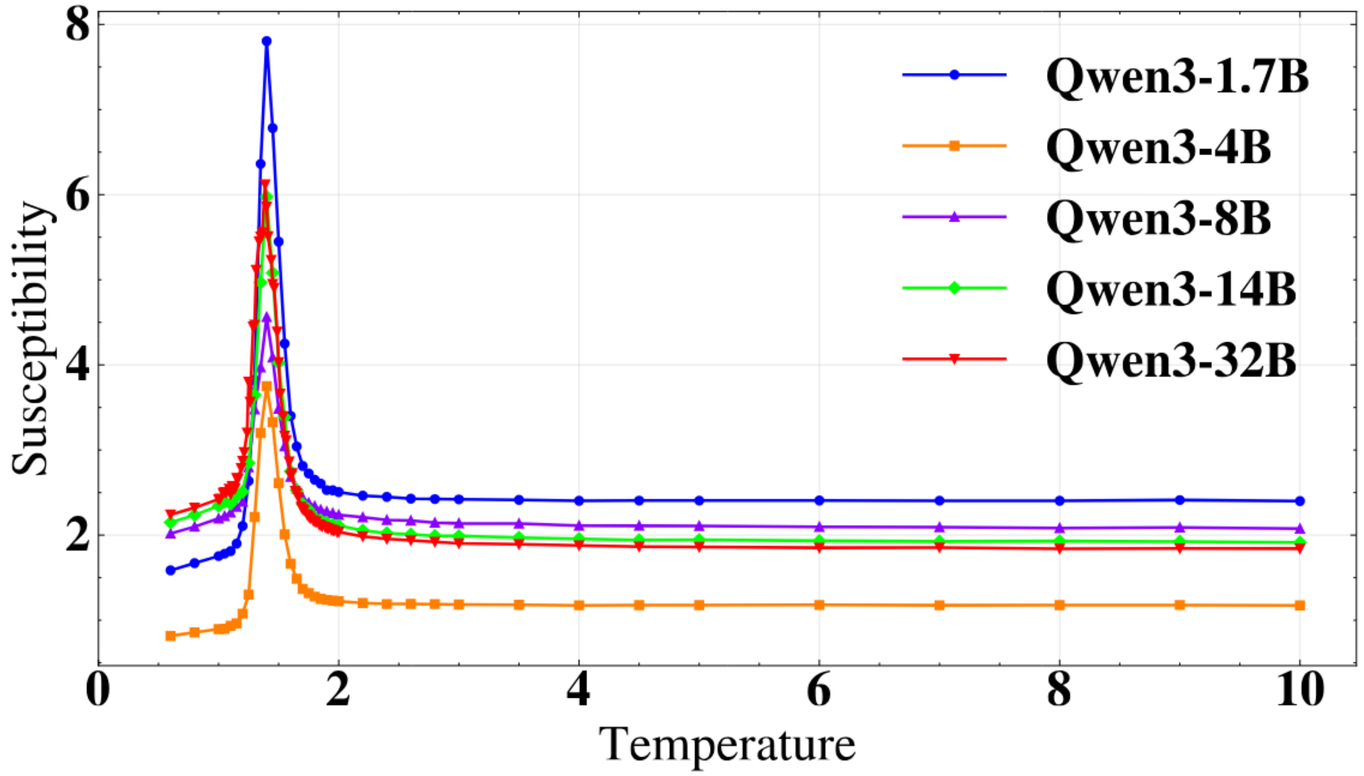
$$\chi = \frac{1}{L}\sum_{\sigma,\tau}\left[\frac{1}{N_s}\sum_i t_\sigma^{(i)}\cdot t_\tau^{(i)} - \frac{1}{N_s^2}\sum_i t_\sigma^{(i)}\cdot\sum_j t_\tau^{(j)}\right]$$

- Principle component analysis (PCA) of average t
- Intrinsic dimension I_d of t distribution
  - Two-NN method

H. Ruan, J. Li, XG, L. Wang, arXiv:2606.06238

Phase Transition in LLMs: Susceptibility

- Clear peak in susceptibility.
- Consistent through different number of parameters.



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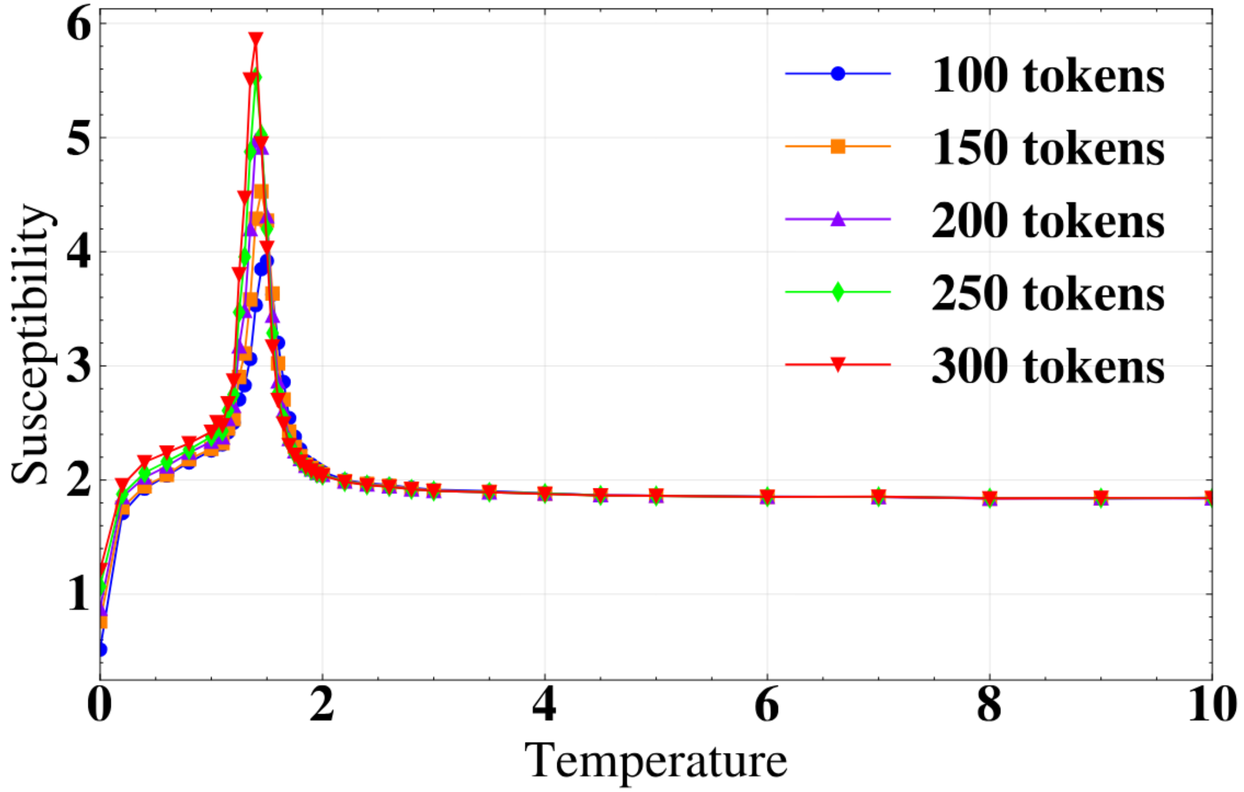
Phase Transition in LLMs: Susceptibility

- Shift of peak with number of tokens (system size)?
  - Finite volume effect?
  - External field vs. interaction?
  - Structure of language itself?



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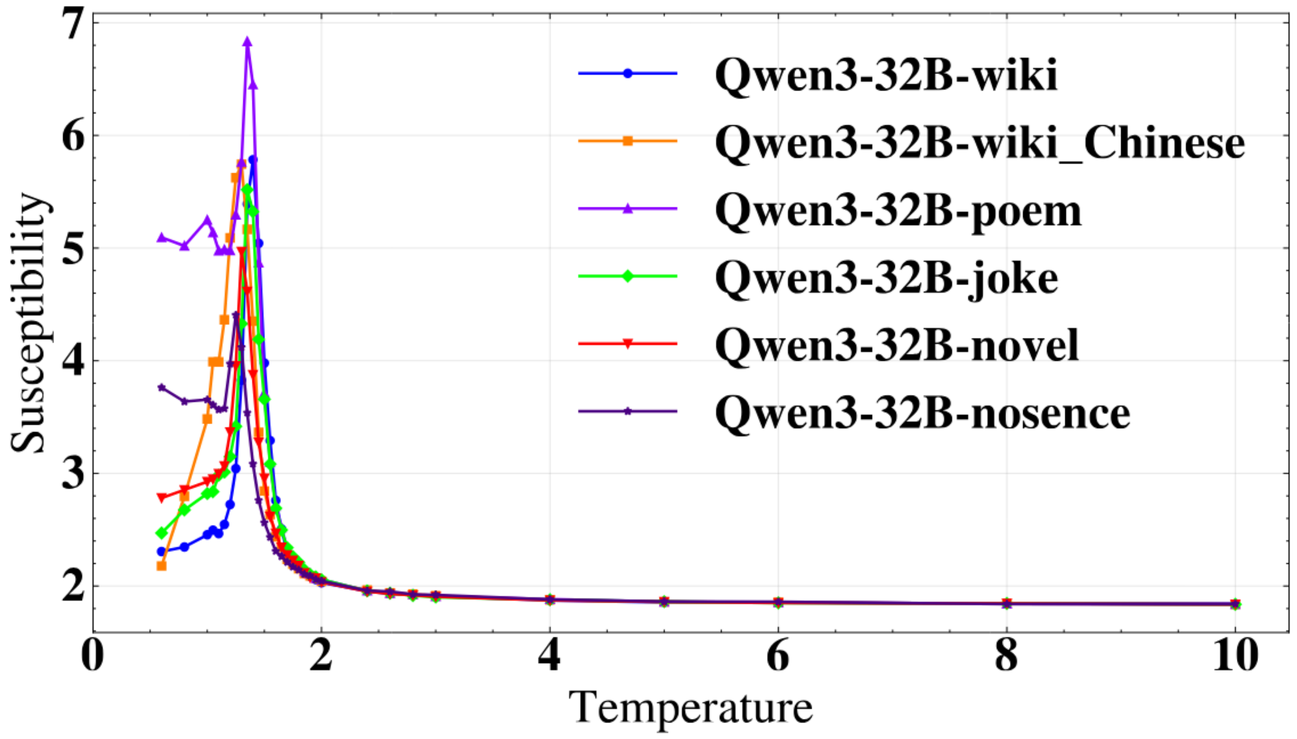
Phase Transition in LLMs: Susceptibility

- Prompt (external field) strongly affect properties at low “temperature”.
- High temperature behavior remains robust.
- Peak position seems to be affected.



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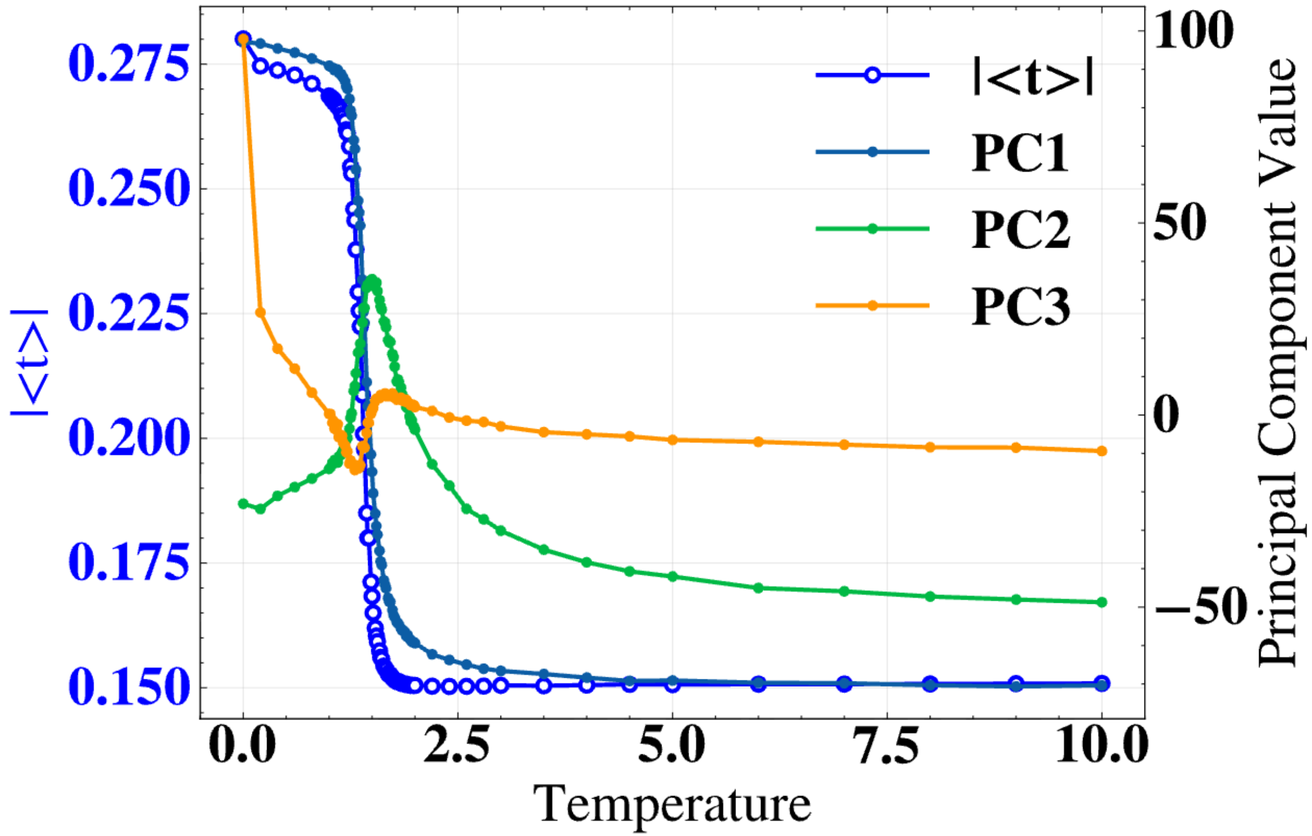
Phase Transition in LLMs: PAC

- $|\langle t \rangle|$ can be viewed as an order parameter?
  - Spontaneous magnetization?



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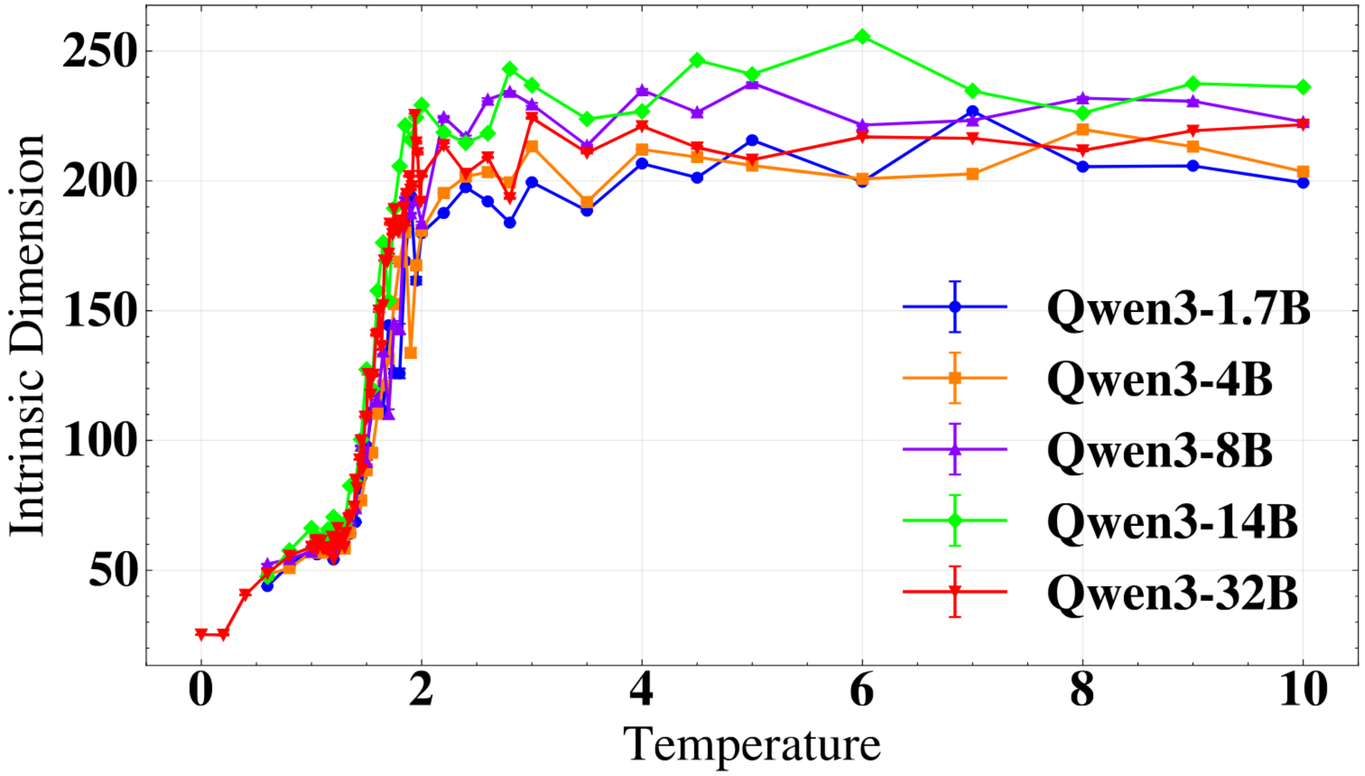
Phase Transition in LLMs: I_d

- Sharp increasing of intrinsic dimension near "T_c".
- Still different from typical phase transition behavior.
- More investigation in progress.



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Summary

- We studied Schwinger mechanism with Schwinger model, showing that quantum algorithm can effectively simulation strong-field dynamics.
- We also studied LLMs from the aspect of phase transition and found strong signals suggesting a phase transition in LLMs.

Thank you for your attention!