Quantum Physics & Quantum Information

Recent research progress on Experimental quantum simulation: Simulating many-body physics on a NMR quantum simulator

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September 18, 2014

“凝聚态物理-北京大学论坛” @ University of Beijing

Outline

I. Introduction
– Why quantum simulation (QS)
– Basic principle of QS

II. Operations Interpreted for Experimental QS
– Mapping the system
– Initialization
– Hamiltonian engineering
– Measurement

III. Towards Simulating Many-Body Physics
– Quantum information and many-body systems
– Quantum "baby" phase transition (Simulating Quantum magnets)
– Simulating Exotic quantum many-body physics: Topological orders in Wen-plaquette model

V. Conclusion

Why QS?

Simulating of quantum systems

- **Classical computers**

  Exponential growth of Hilbert space

Computational basis

$$|\Psi\rangle = \sum_{i_1=1}^{2} \cdots \sum_{i_n=1}^{2} c_{i_1 \ldots i_n} \, | i_1 \ldots i_n \rangle$$

System with 50 qubits

$2^{50} \approx 10^{15}$ complex amplitudes ~ 32 x 10^{15} bytes of information

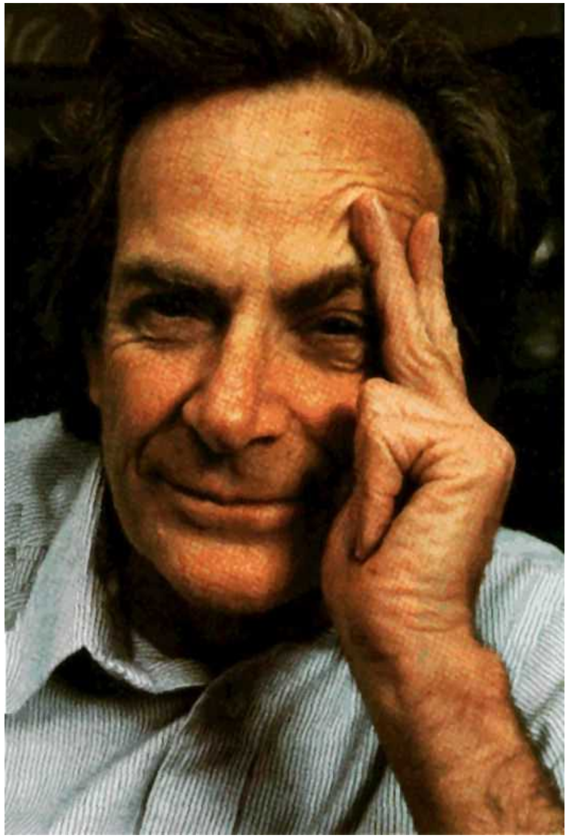
well beyond the capacity of existing computers

The Puzzle: Feynman's main thesis was quantum systems could not be efficiently imitated on classical systems.

Why QS?

Simulating of quantum systems

- **Quantum computers - Universal quantum simulators**



1982 Richard P. Feynmann

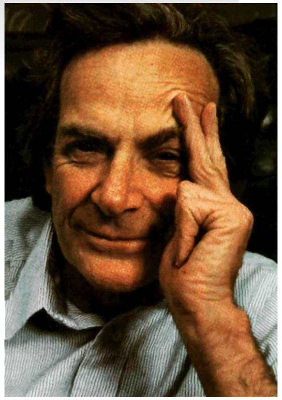
R.P. Feynman, "Simulating Physics with Computers", *Int. J. Theor. Phys.* **21**, 467-488, 1982

Can we do it with a new kind of computer – a quantum computer? Now it turns out, as far as I can tell, that you can simulate this with a quantum system, with quantum computer elements. […] I therefore believe it's true that with a suitable class of quantum machines you can imitate any quantum system, including the physical world.

量子计算

主要应用

经典难题
量子算法



量子系统
量子模拟

N = p*q

分解一个300位的整数所需时间比较

	经典计算机	量子计算机
算法	二次筛法	Shor算法
步数	10^{24}	10^{10}
CPU频率	1 THz	1 THz
时间	15万年	1秒

$$|\Psi\rangle = \sum_{i_1=1}^{2}\cdots\sum_{i_n=1}^{2} c_{i_1\ldots i_n}\,|i_1\ldots i_n\rangle$$

n= 50

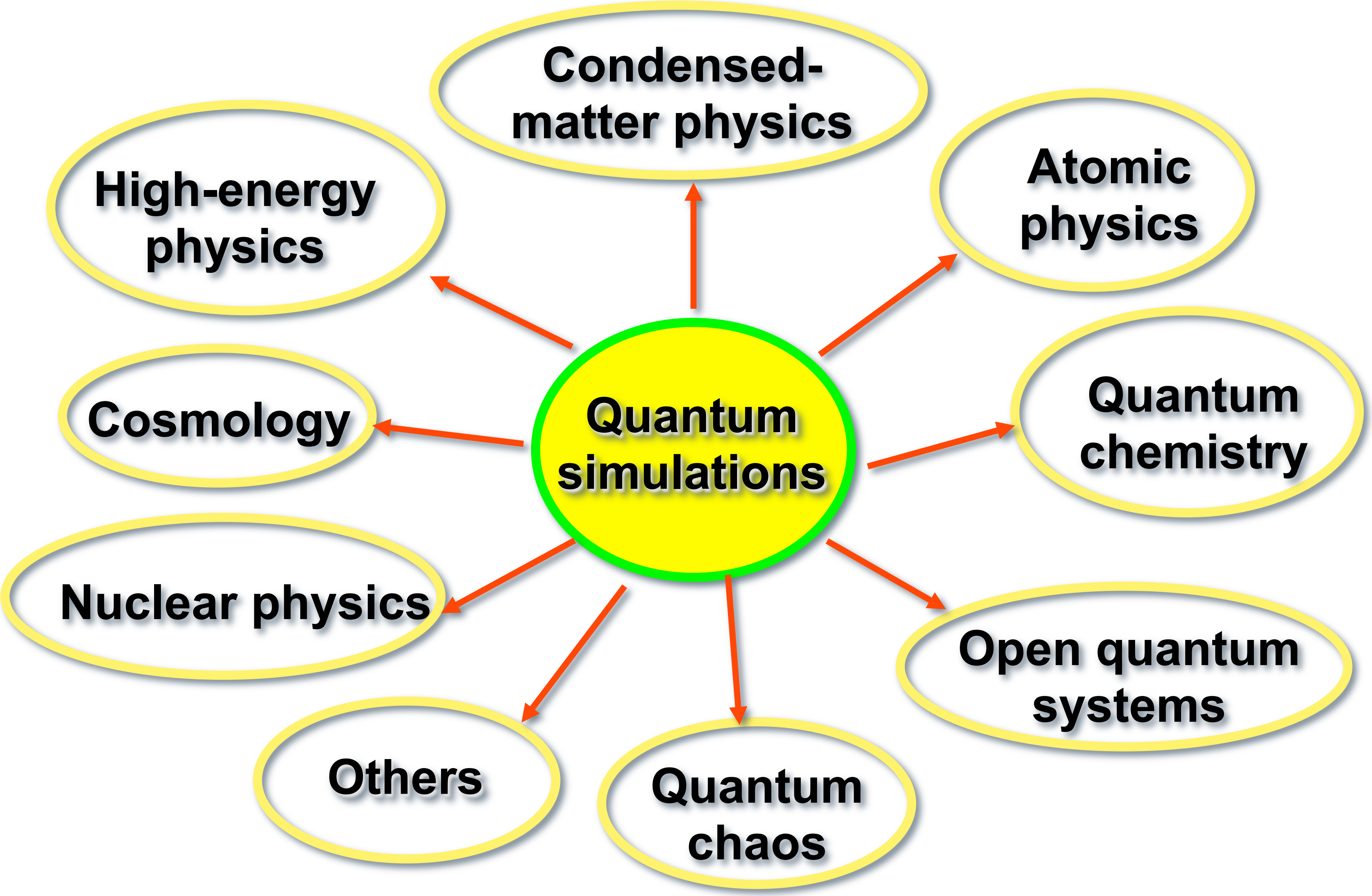
~ 32 x 10^{15} 字节经典信息

50位量子比特信息

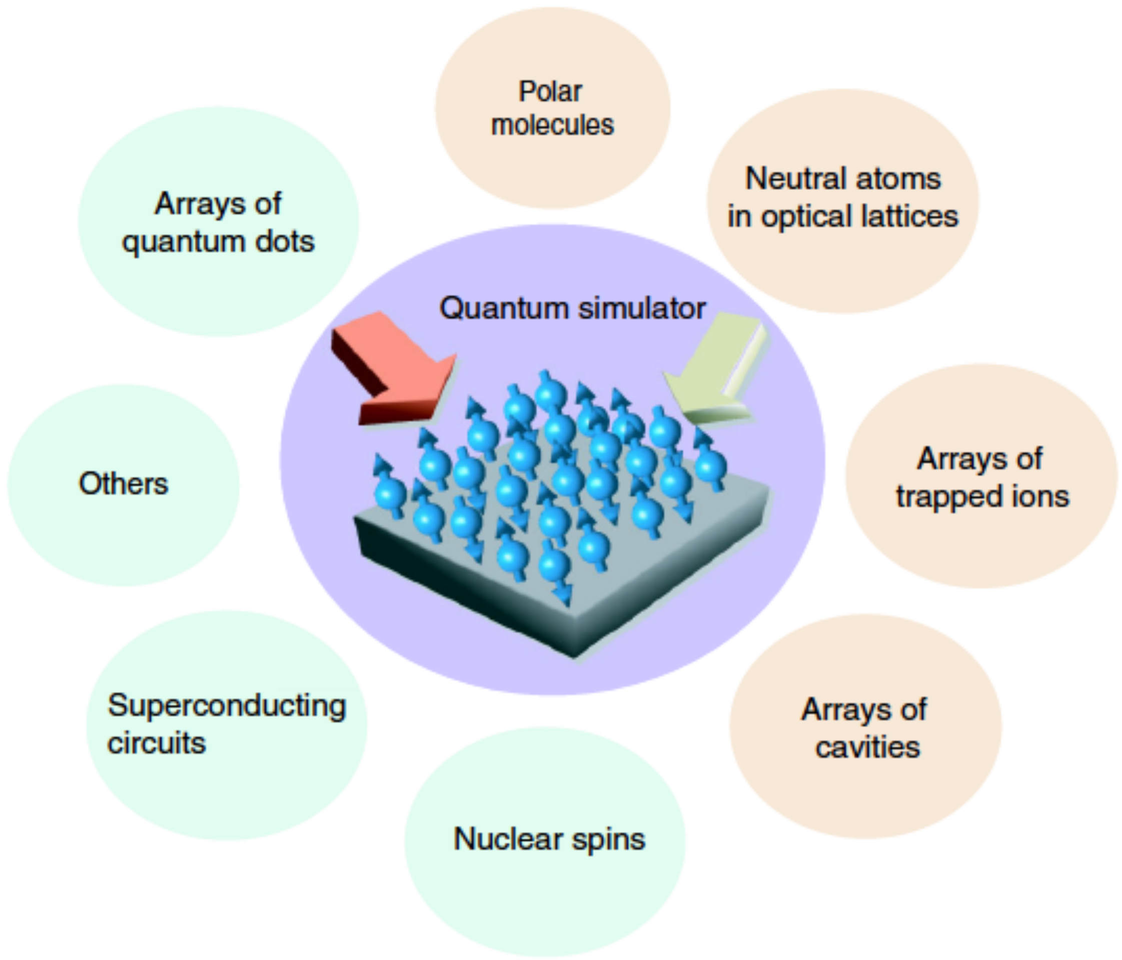
中等规模的量子仿真即有可能超越经典计算的极限，在实际问题的解决中展现量子计算的优势！

Quantum simulator ≠ Universal quantum computer

Applications of QS



Physical implementations of QS



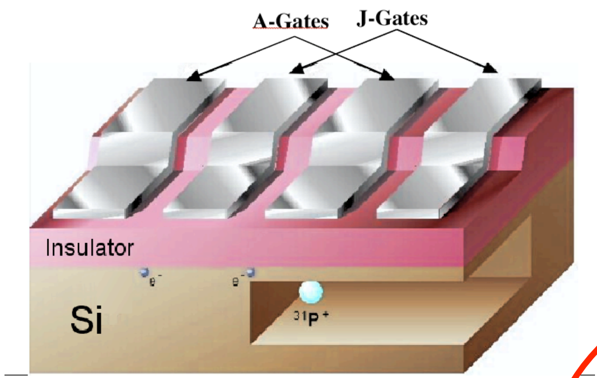
核自旋体系

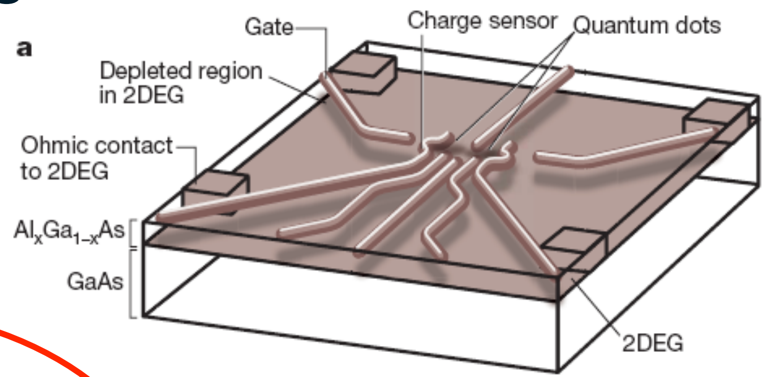
- 核自旋具有较长的消相干时间
- 相当成熟的磁共振技术
- 很好的测试平台

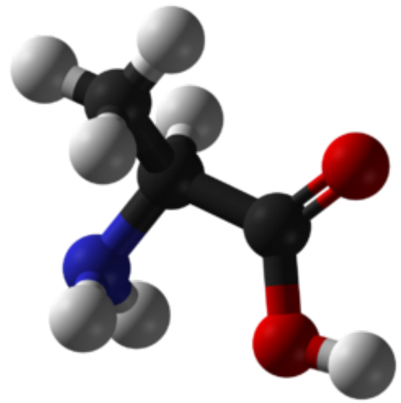
Spin-based QIP

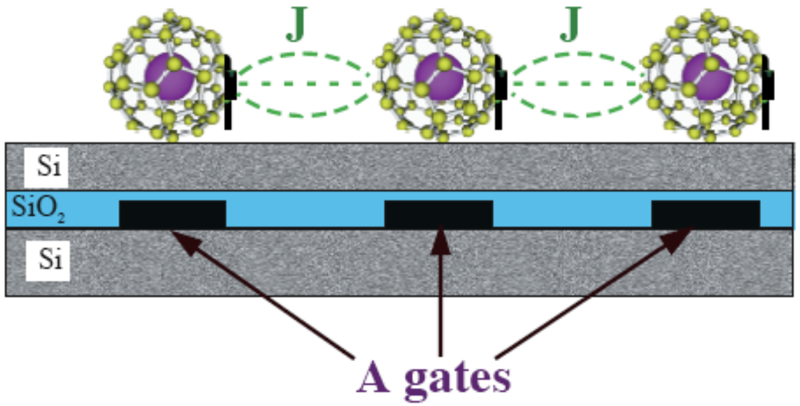
Spintronics

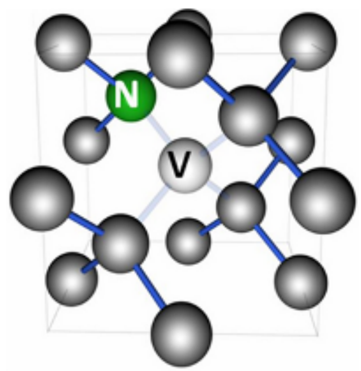
Proposal: *B.E. Kane, Nature 393, 133-137 (1998).*





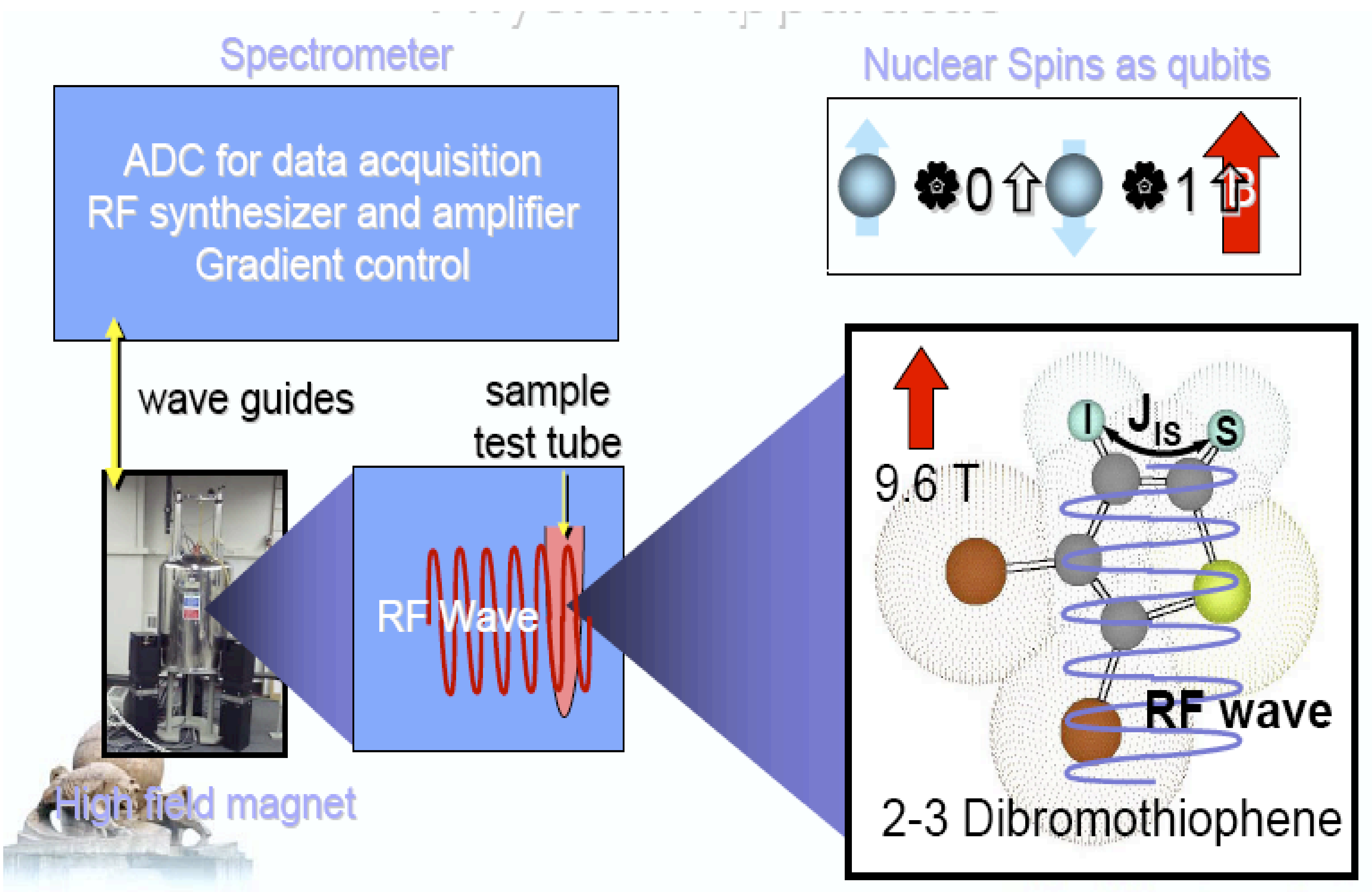






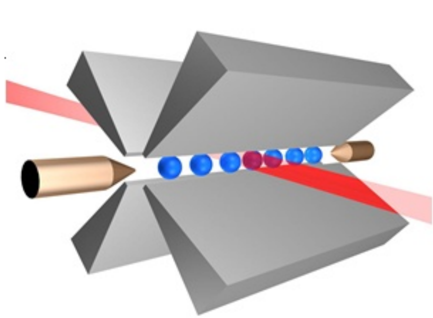
Nuclei + electrons

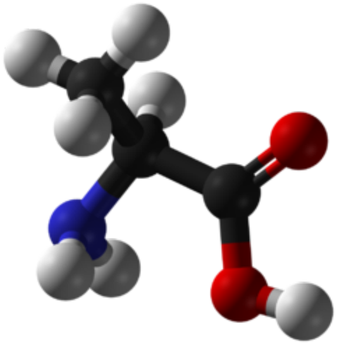
NMR QIP

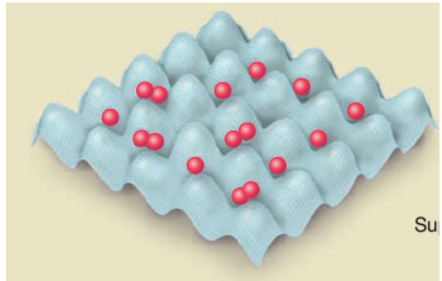


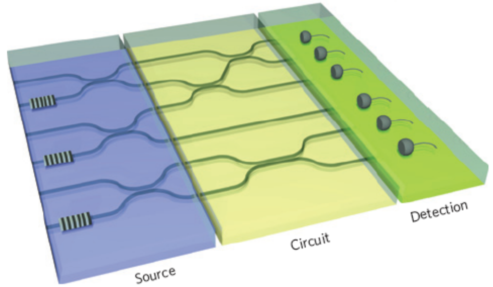
Spectrometer
ADC for data acquisition
RF synthesizer and amplifier
Gradient control
wave guides
sample
test tube
RF Wave
High field magnet
Nuclear Spins as qubits
0
1
B
9.6 T
I
J_{IS}
S
RF wave
2-3 Dibromothiophene

Different classes of quantum simulations









- **explore new physics (perhaps even trackable classically)**
- **outperform classical computation (address the classically non-trackabkle)**

Quantum harmonic and anharmonic oscillators

Many-fermion system

Quantum spin model (quantum phase transition)

Localization effects by decoherence

Quantum walk

Quantum chemistry

Quantum chaos

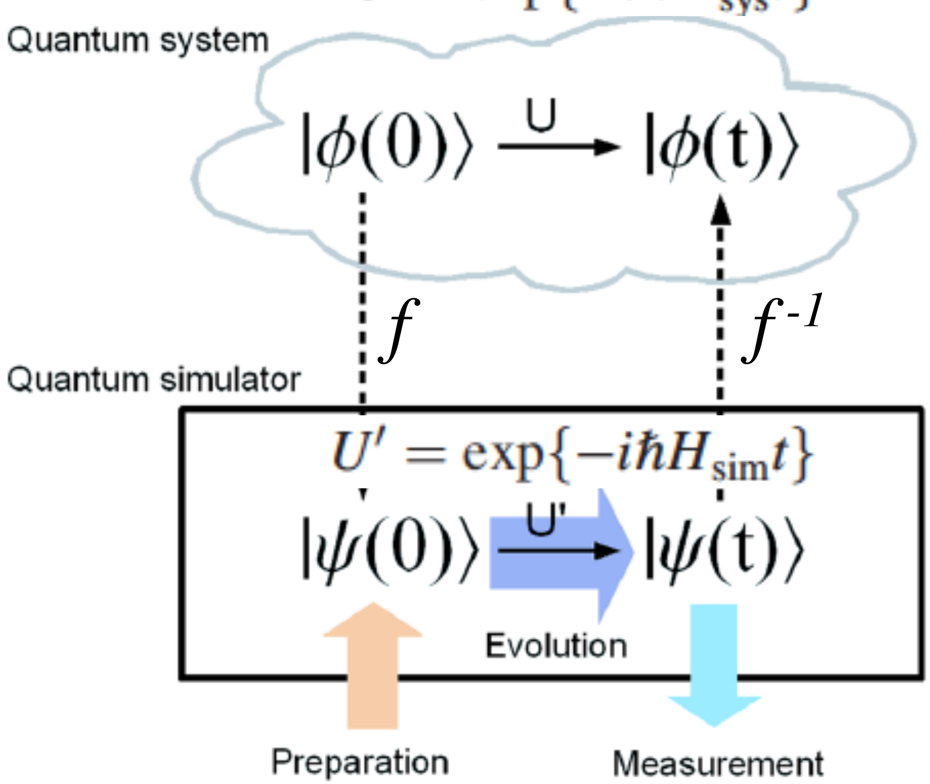
Paring Hamiltonian

Quantum Tunneling

Entropy 2010, *12*, 2268-2307

Basic principle of QS

QS: a controllable quantum system used to simulate or emulate other quantum systems



$$H_{sim} = f H_{sys} f^{-1}$$

Two types:

Digital quantum simulation: to use qubits to encode the state of the quantum system, "translate" its unitary evolution in terms of elementary quantum gates, and implement them in a circuitbased quantum computer.

Analog quantum simulation: to map the evolution of the system to be simulated onto the controlled evolution of the quantum simulator

$$H_{sys} \leftrightarrow H_{sim}.$$

I. M. Georgescu et al., Rev. Mod. Phys., Vol. 86, No. 1, January–March 2014

Basic principle of QS

Main steps

- ***Mapping***
- ***Initialization***
    - Direct state construction
    - Adiabatic quantum state preparation
- ***Hamiltonian engineering***
    - Lloyd's method (Average Hamiltonian theory)
    - Quantum network
- ***Measurement***
    - Quantum state tomography (full characterization)
    - Phase estimation algorithm (Energy spectrum and eigenstates)
    - Specialized measurement scheme to extract the desired observables (e.g., correlation functions)

Mapping

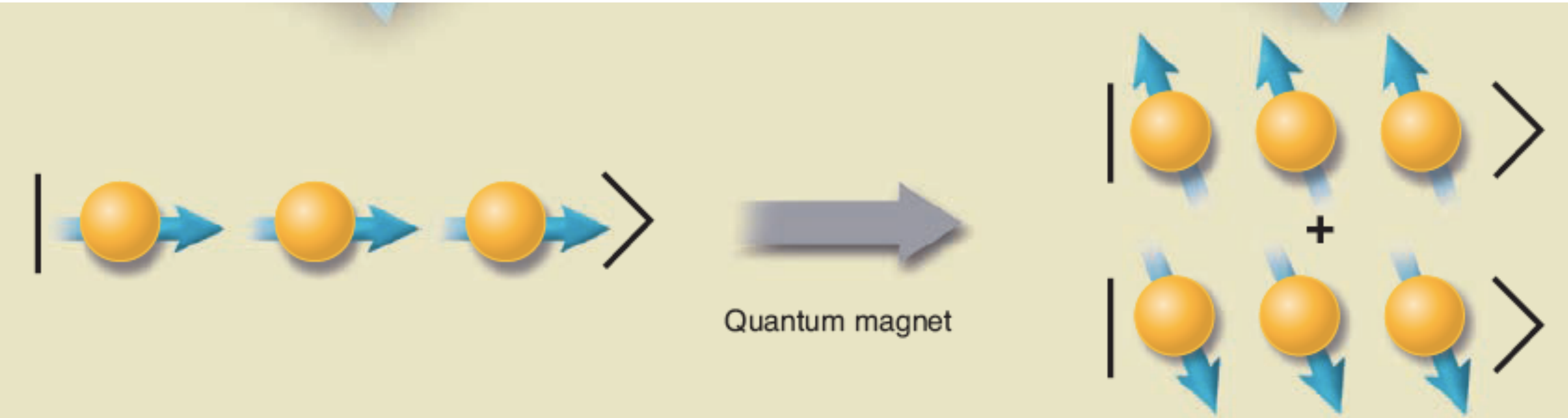
Quantum spin model (Quantum magnets)

$$H = \sum_{i=1}^{n} B_i \sigma_{iz} + \sum_{i<j=1}^{n} \left(J_{ij}^{x} \sigma_{ix} \sigma_{jx} + J_{ij}^{y} \sigma_{iy} \sigma_{jy} + J_{ij}^{z} \sigma_{iz} \sigma_{jz} \right)$$

External fields **Heisenberg couplings**

Heisenberg isotropic, Ising, XX, XY, XYZ model

Mapping: A more realistic model in that it treats the spins quantum-mechanically, by replacing the spin by a quantum operator (Pauli spin-1/2 matrices at spin 1/2).



Hamiltonian Engineering

- **Quantum Control Model**

$$U = e^{-iH_I T} \xleftrightarrow{\overline{H}_p = \phi H_I \phi^{-1}} V_T = e^{-i\overline{H}_p T} = \prod_k e^{-iH_p t_k} V_k$$

- **Lloyd's method** $\hat{H} = \sum_{j=1}^{n} \hat{H}_j$

  Trotter-Suzuki formula

$$\hat{U}(t) = e^{-iHt} = (e^{-iH_1(t/m)} e^{-iH_2(t/m)} \dots e^{-iH_k(t/m)})^m + \sum_{i<j} [H_i, H_j] \frac{t^2}{2m} + \dots . \quad ($$

the number of operations $Op_{\mathrm{Lloyd}} \propto t^2 n g^2 / \epsilon$ Polynomial scaling

S. Lloyd. Universal Quantum Simulators. Science, 273(5278):1073–1078, 1996.

Hamiltonian simulation

Example: Simulating many-body interactions

$$H^{(2)}_{\text{3spin}} = \Omega_x(I^1_x + I^2_x + I^3_x) + 4J_3 I^1_z I^2_z I^3_z$$

Trotter-Suzuki formula

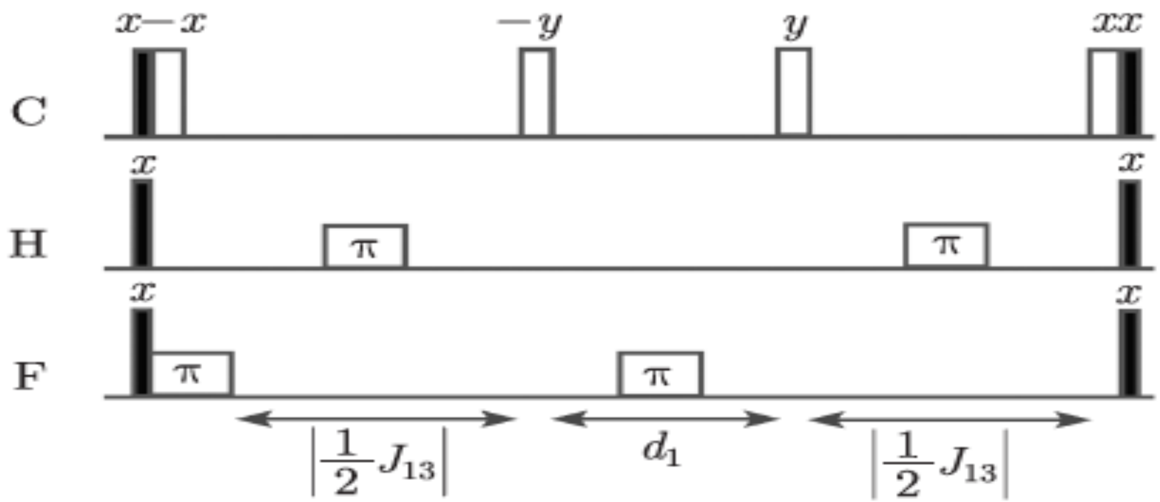
$$U^{(2)}_{\text{3spin}}(\Delta t) = \mathrm{e}^{-\mathrm{i}H^{(2)}_{\text{3spin}}\Delta t}$$

$$\approx \mathrm{e}^{-\mathrm{i}H^{\text{3spin}}_x \frac{\Delta t}{2}} \mathrm{e}^{-\mathrm{i}H^{\text{3spin}}_{zzz}\Delta t} \mathrm{e}^{-\mathrm{i}H^{\text{3spin}}_x \frac{\Delta t}{2}}$$

$$\mathrm{e}^{-\mathrm{i}H^{\text{3spin}}_{zzz}\Delta t} = R^1_x\left(\frac{\pi}{2}\right)\mathrm{e}^{-\mathrm{i}I^1_z I^3_z \pi/4} R^1_y\left(\frac{\pi}{2}\right)\mathrm{e}^{-\mathrm{i}2J_3 I^1_z I^2_z \Delta t}$$

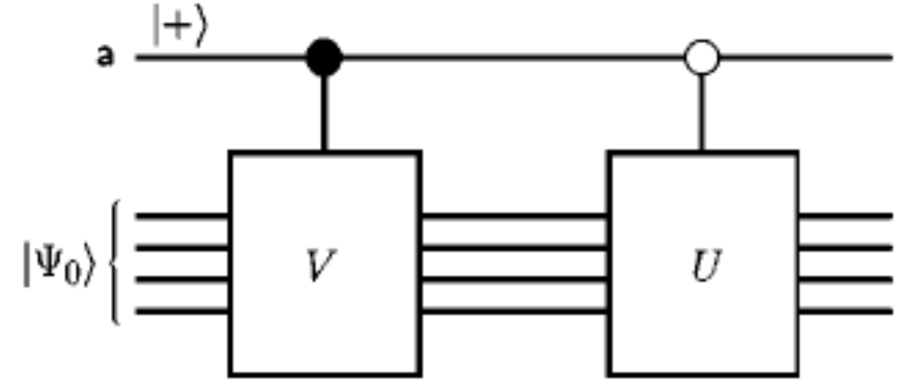
$$\cdot R^1_{-y}\left(\frac{\pi}{2}\right)\mathrm{e}^{\mathrm{i}I^1_z I^3_z \pi/4} R^1_{-x}\left(\frac{\pi}{2}\right)$$

C. H. Tseng et al., Phys. Rev. A, 61:012302 (1999)

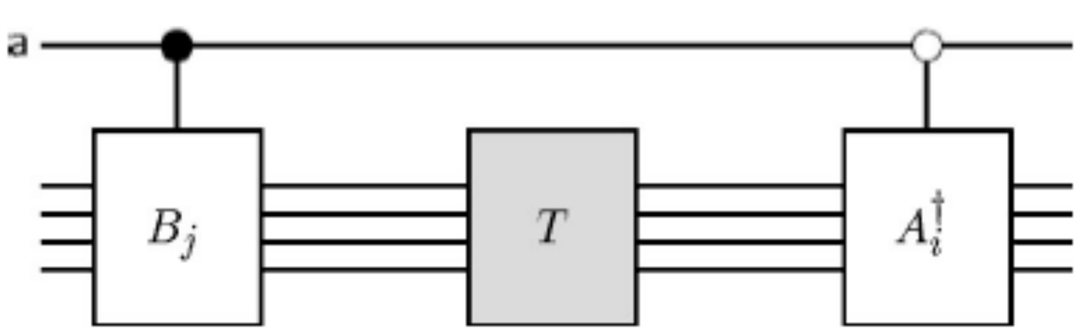


Measurement

Obtaining some properties of the state

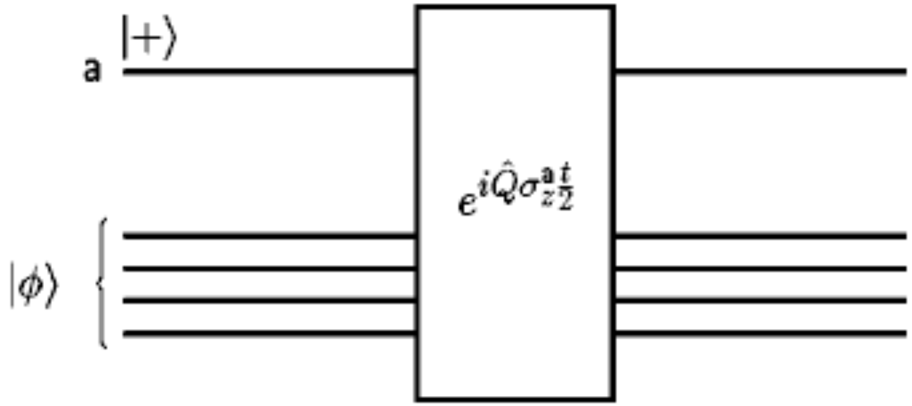


$\langle 2\sigma_+^{a} \rangle = \langle \Psi_0 | U^\dagger V | \Psi_0 \rangle$



$\langle 2\sigma_+^{a} \rangle = \langle T^\dagger A_i T B_j \rangle$

correlation functions



$\langle 2\sigma_+^{a} \rangle = \langle \phi | e^{-i\hat{Q}t} \phi \rangle$

the spectrum of an Hermitian operator

SOMMA et al., PRA 65 042323

Quantum information and many-body physics

- Quantum many-body systems on a lattice

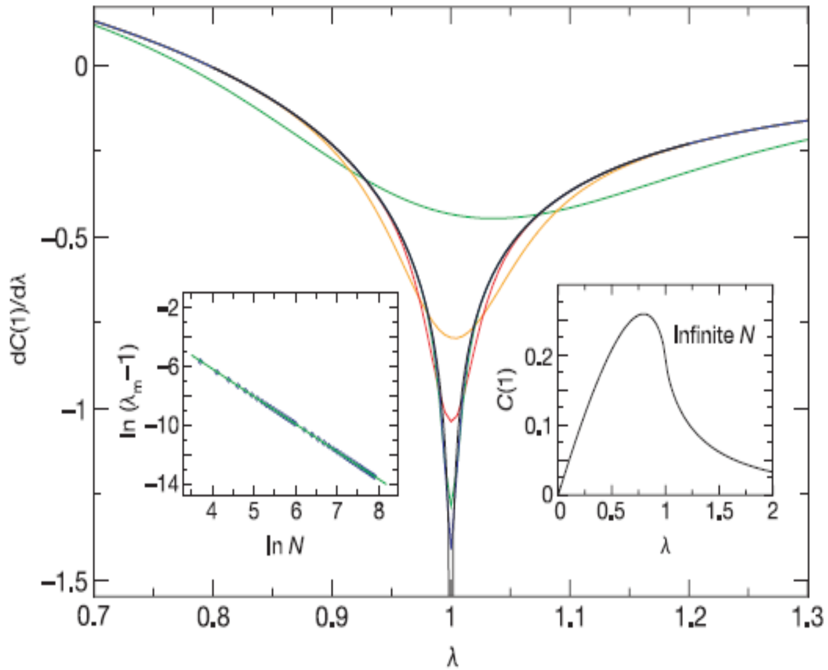
Hilbert space: $\mathcal{H} = \bigotimes_{x \in L} \mathcal{H}_x$

Hamiltonian: $\hat{H} = \sum_{x \in L} \hat{h}_x$

Quantum degree of freedom per lattice site

How much entanglement is contained in the ground state?

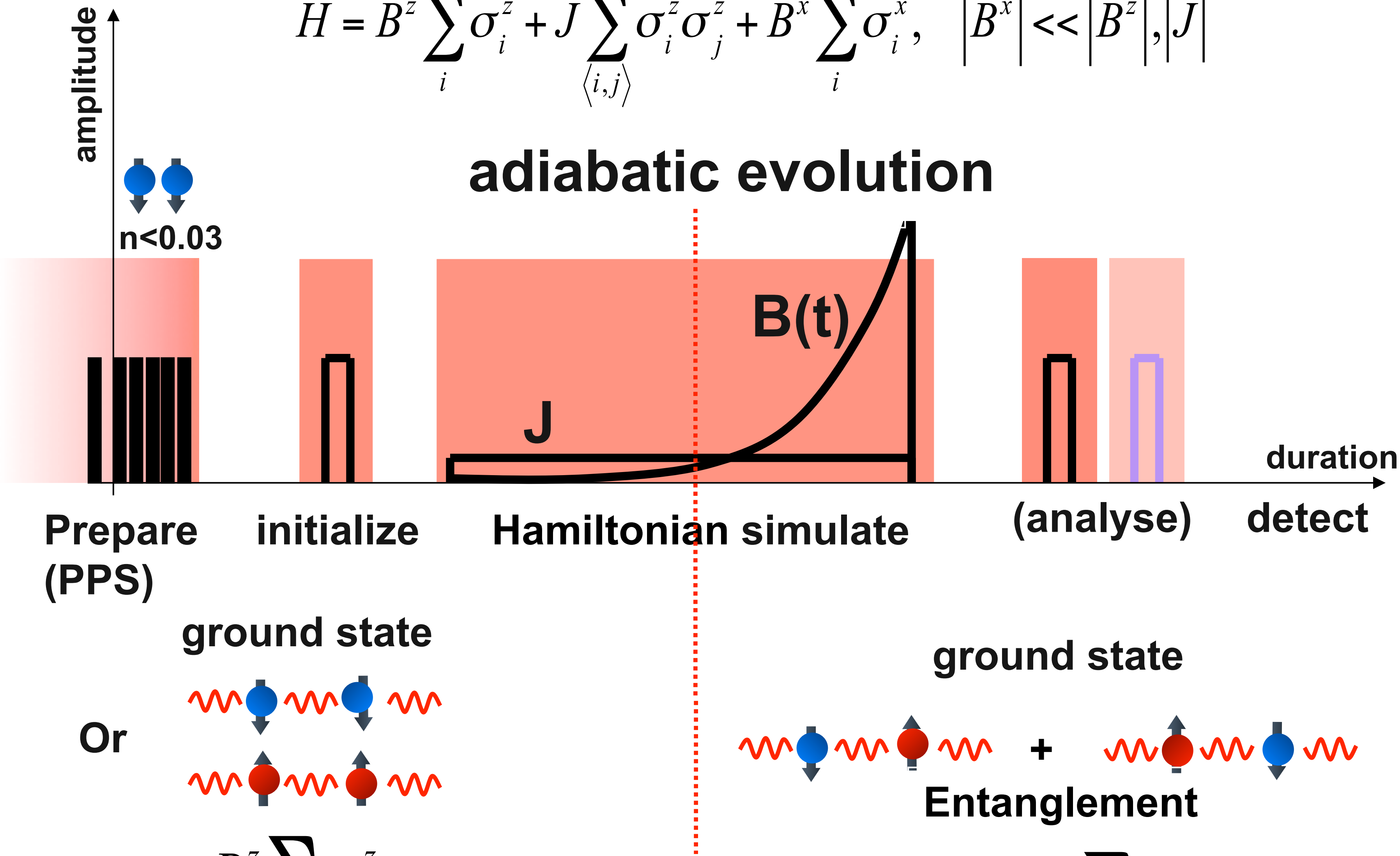
Scaling of ground state entanglement and Quantum phase transition



A. Osterloh et al., Nature 416, 609 (2002)

Quantum “baby” phase transition

$$H = B^z \sum_i \sigma_i^z + J \sum_{\langle i,j \rangle} \sigma_i^z \sigma_j^z + B^x \sum_i \sigma_i^x, \quad |B^x| << |B^z|,|J|$$



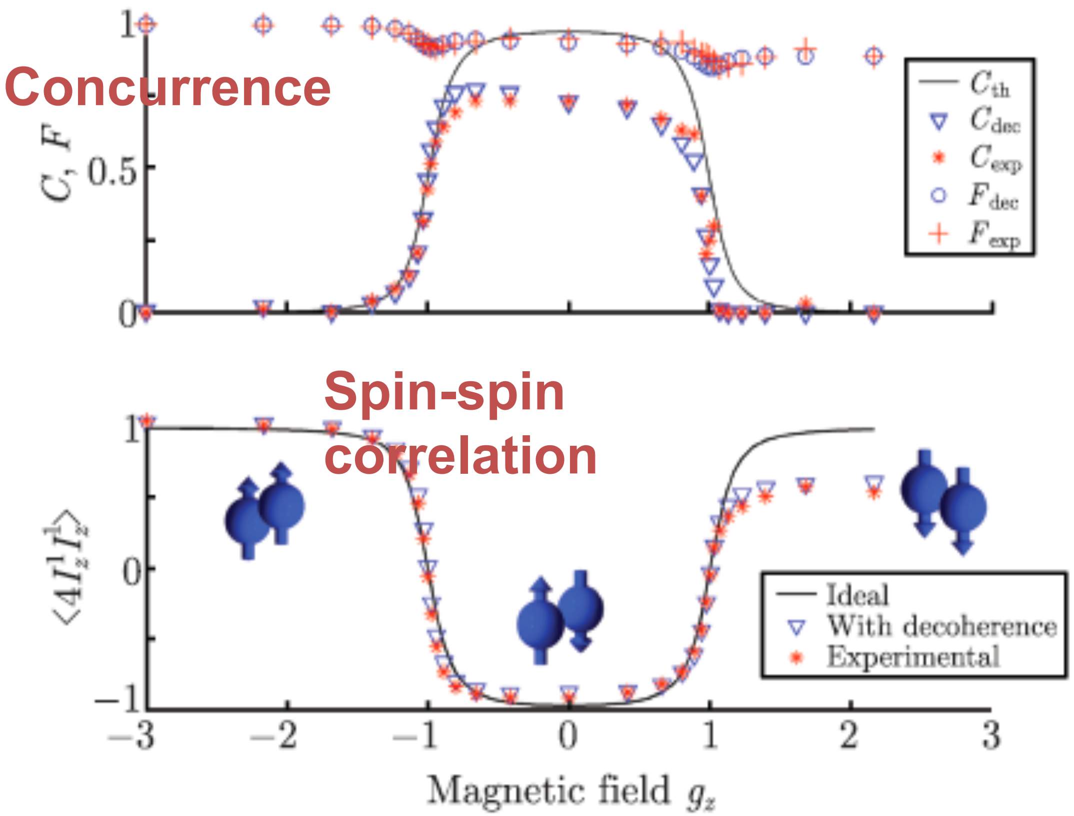
$$B^z \sum_i \sigma_i^z$$

$$|J / B^z| = 1$$

$$J \sum_{\langle i,j \rangle} \sigma_i^z \sigma_j^z$$

Entanglement and QPTs

Change in the ground-state wavefunction in the critical region: the concurrence as a function of **λ.**



XH Peng et al., PRA 72, 052109 (2005)

simulating a quantum magnet

32自旋Ising链的压缩量子模拟

- 使用压缩量子模拟方法，将n自旋链的模拟过程压缩至log(n)比特空间，大大减少计算资源

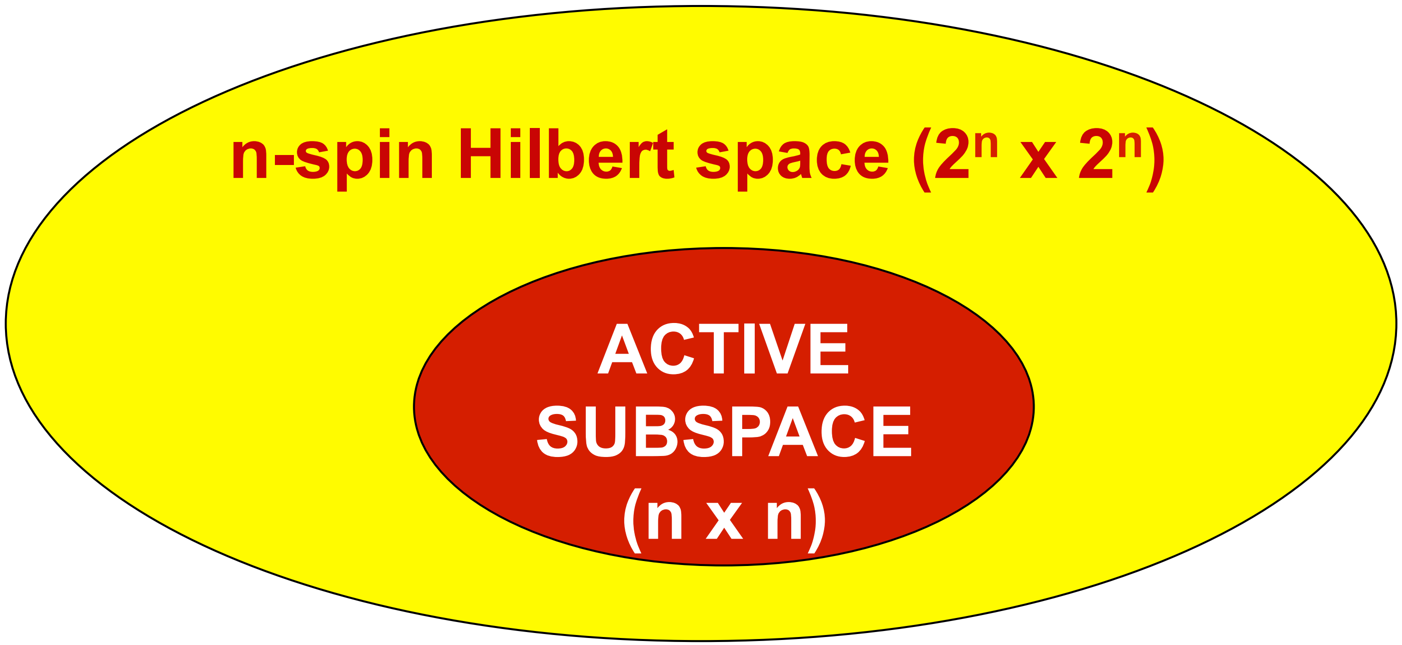
经典
- 原始
- 2^{32}

→

量子
- 指数
- 32

→

压缩
- 双指数
- 5



32自旋Ising链的压缩量子模拟

- Quantum matchgate circuits

$$G(A,B)=\begin{pmatrix} p & 0 & 0 & q \\ 0 & w & x & 0 \\ 0 & y & z & 0 \\ r & 0 & 0 & s \end{pmatrix}, \quad A=\begin{pmatrix} p & q \\ r & s \end{pmatrix}, \quad B=\begin{pmatrix} w & x \\ y & z \end{pmatrix}$$

Theorem 2.1. Consider any matchgate circuit of size N and width n, such that:
(i) the matchgates G(A,B) act on n.n. qubit lines only;
(ii) the input state is any computational basis state |x1 · · · xn>;
(iii) the output is a final measurement in the computational basis on any single qubit line.
Then the output may be classically efficiently simulated

R. Jozsa, et al., Proc. R. Soc. A 466, 809 (2009)
B. Kraus, PRL 107, 250503 (2011)

32自旋Ising链的压缩量子模拟

- Quantum Ising spin chain

$$H(J) = \sum_i \sigma_z^i + J\sum_i \sigma_x^i \sigma_x^{i+1}$$

- Jordan–Wigner transformation

Fermionic operators

$$a_k = Z \ldots Z \sigma_k^- \mathbb{1}$$
$$a_k^\dagger = Z \ldots Z \sigma_k^+ \mathbb{1}$$
$$\{a_i, a_j\} = 0 \text{ and } \{a_i, a_j^\dagger\} = \delta_{ij} \mathbb{1}$$

$$c_{2k-1} = a_k + a_k^\dagger, \quad c_{2k} = (a_k - a_k^\dagger)/i, \quad k = 1, \ldots, n$$

$$\{c_j, c_l\} \equiv c_j c_l + c_l c_j = 2\delta_{j,l} I, \quad j, l = 1, \ldots, 2n$$

Quadratic Hamiltonian

$$H = \mathrm{i} \sum_{\mu \neq \nu = 1}^{2n} h_{\mu\nu} c_\mu c_\nu,$$

hmn is a 2n x 2n matrix of coefficients

32自旋Ising链的压缩量子模拟

Theorem: Let H be any quadratic Hamiltonian *H* and $U = e^{iH}$

$$U^\dagger c_\mu U = \sum_{\nu=1}^{2n} R_{\mu\nu} c_\nu,$$

$R \in SO(2n)$ R is a real orthogonal matrix of 2n × 2n associated with U.

$$U_N \ldots U_1 \Longrightarrow R_N \ldots R_1$$

2^n x 2^n **2n x 2n**

Symmetry of the Ising model ⟹ **n x n**

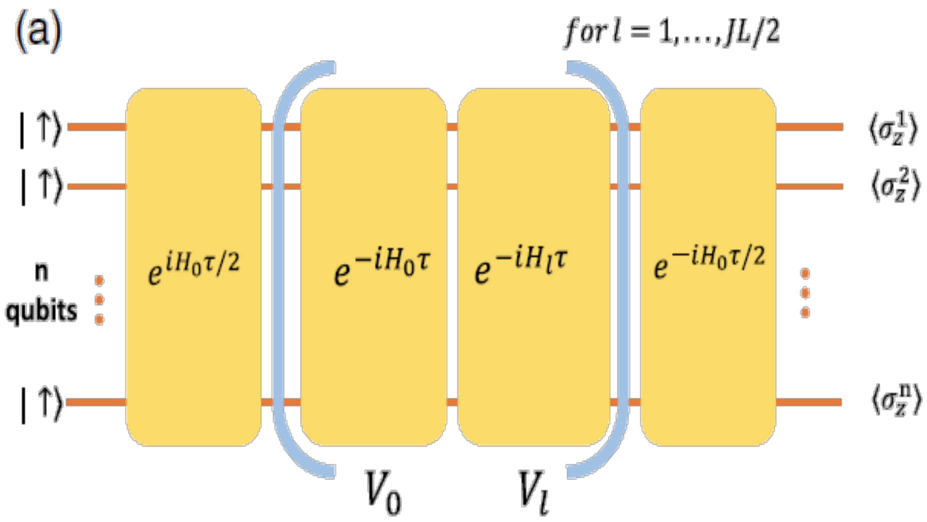
Log(n) qubits

Key idea:

$$R_0, R_l, S, \text{ and } \rho_{in} \xrightarrow{\textit{Unitary } V} |0\rangle\langle 0| \otimes O_1 + |1\rangle\langle 1| \otimes O_2$$

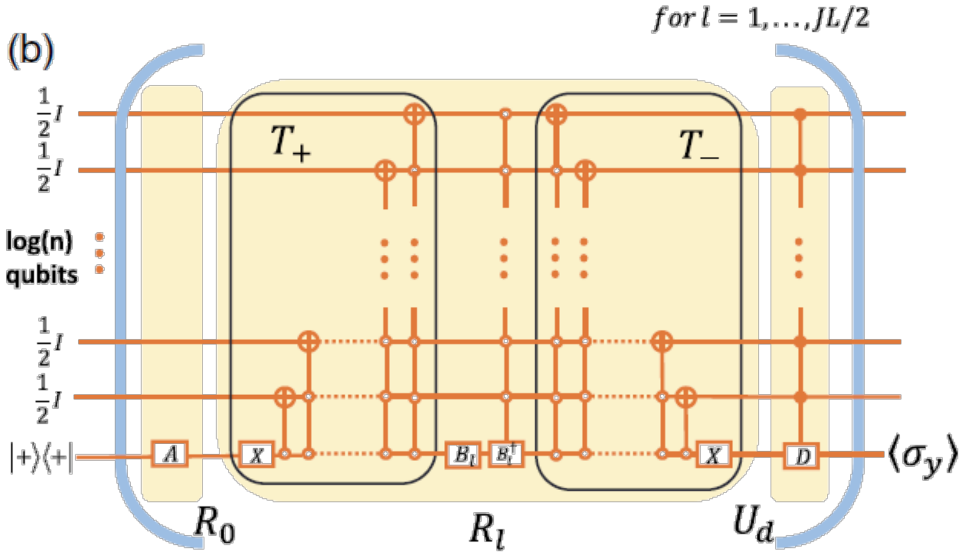
block-diagonal matrices

32自旋Ising链的压缩量子模拟



$$U(J) = \sqrt{V_0}\prod_{l=1}^{L(J)} U_l \sqrt{V_0}^{\dagger},$$

Traditional quantum simulation (n qubits)

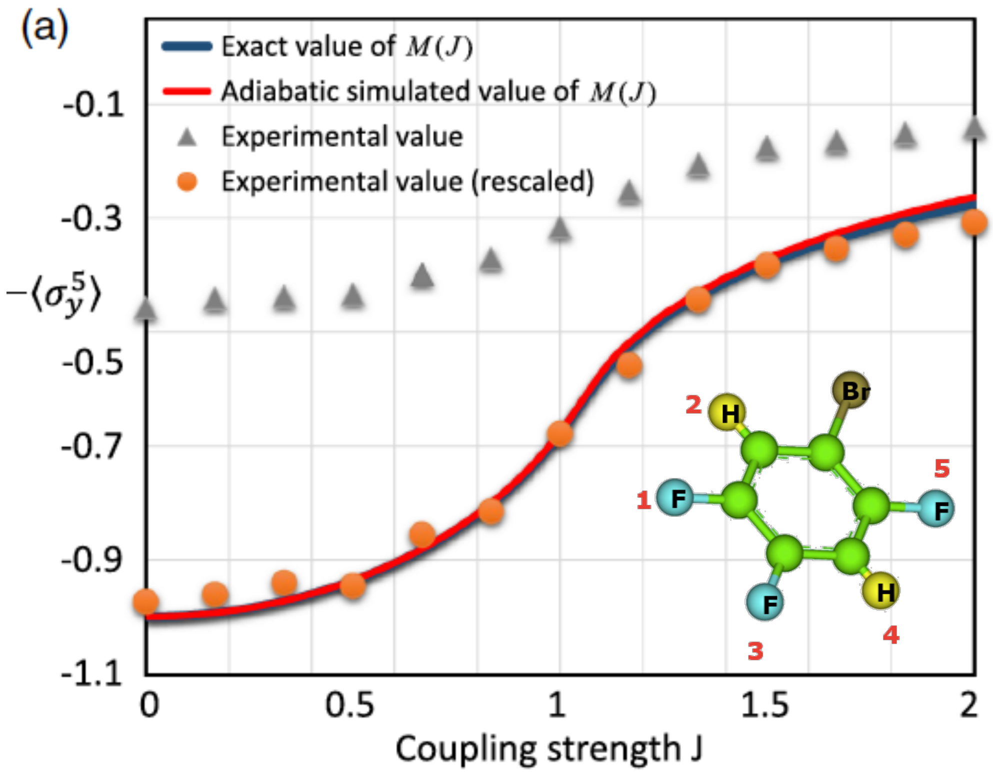


$$R(J) = \sqrt{R_0}\prod_{l=1}^{L(J)} T_l \sqrt{R_0}^{-1}$$

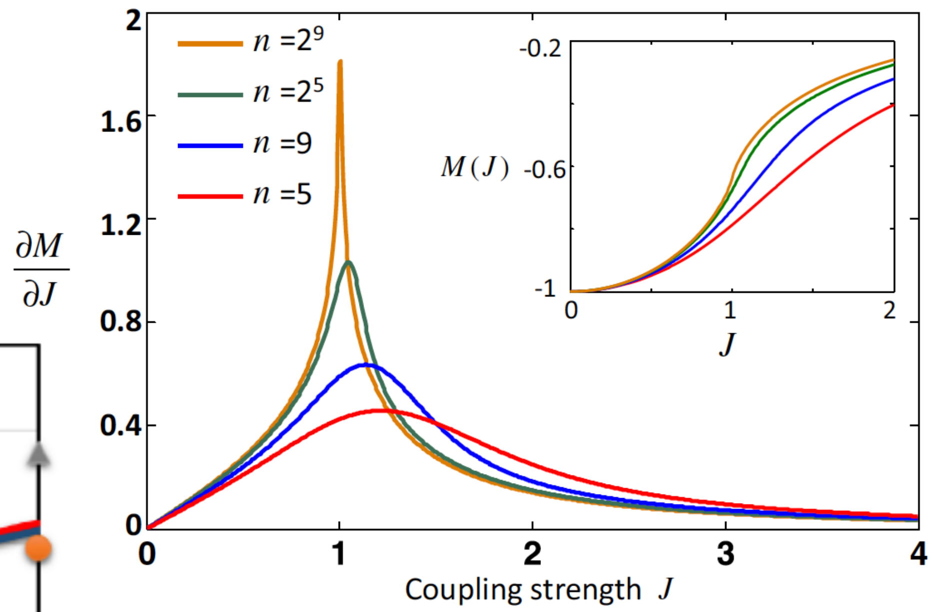
Compressed quantum simulation (log(n) qubits)

32自旋Ising链的压缩量子模拟

- 利用5量子比特的32自旋链的基态性质模拟



Ground-state magnetization

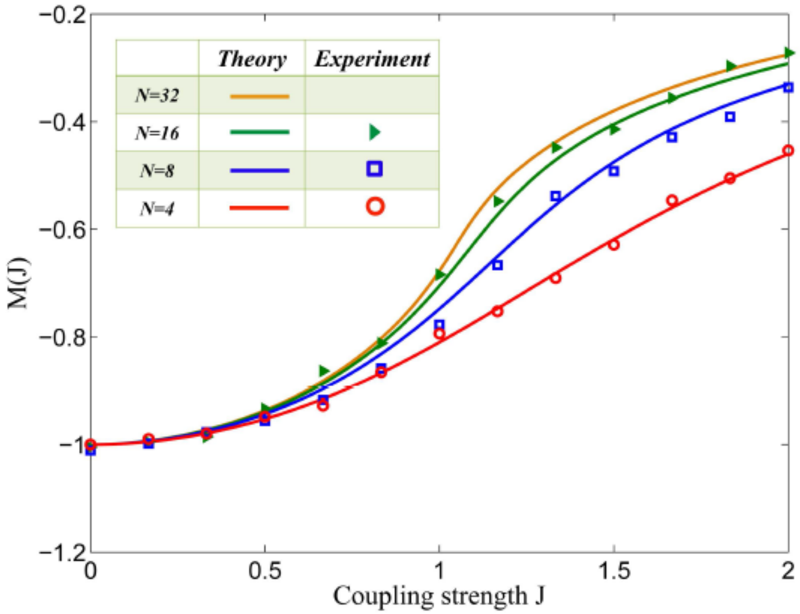


$$M(J) = -\mathrm{tr}[\hat{R}(J)\rho_{\rm in}\hat{R}(J)^T \mathbb{1} \otimes Y_m],$$

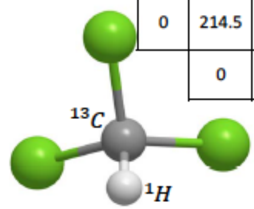
Z. Li et al., Phys. Rev. Lett. 112, 220501 (2014)

32自旋Ising链的压缩量子模拟

- 使用不同样品，研究不同尺度自旋链的基态性质

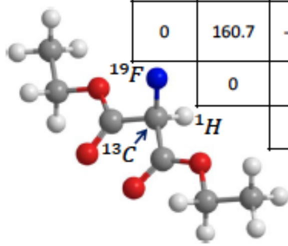


(A)



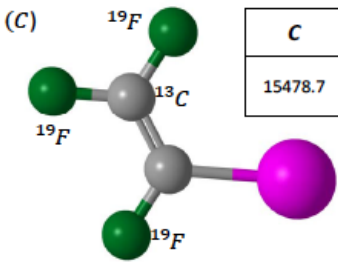
C	H		T_2(s)
0	214.5	C	0.35
	0	H	3.3

(B)



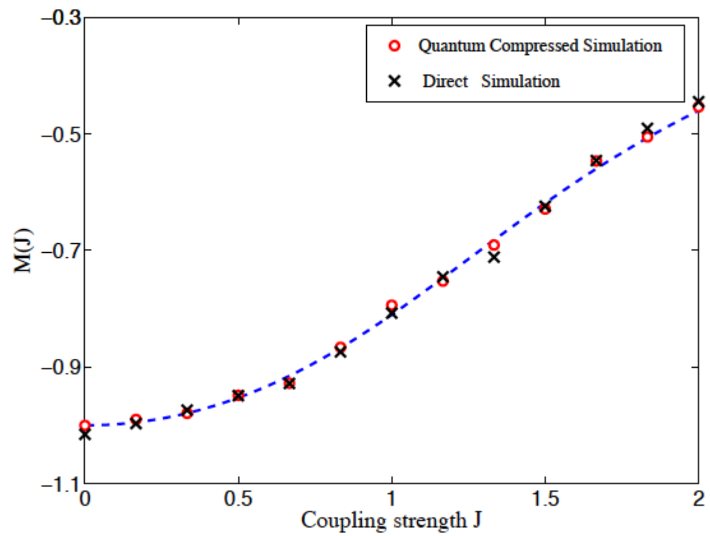
C	H	F		T_2(s)
0	160.7	-194.4	C	1.1
	0	47.6	H	1.2
		0	F	1.3

(C)



C	F_1	F_2	F_3		T_2(s)
15478.7	-297.6	-257.6	39.1	C	7.9
	-33114.5	64.6	51.4	F_1	4.4
		-42674.9	-129.1	F_2	6.8
			-56450.7	F_3	6.8

- **Comparison of traditional simulation to compressed simulation**



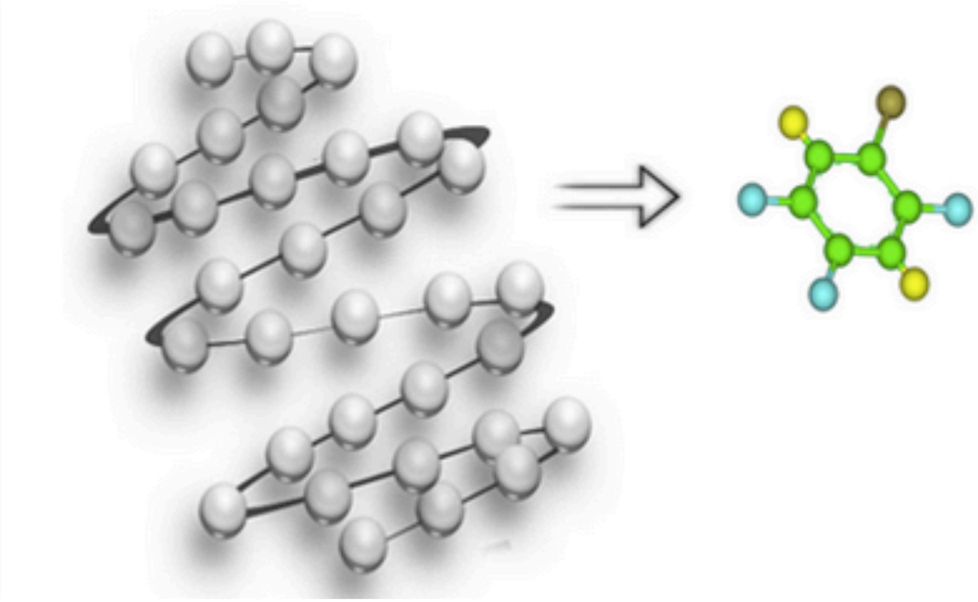
《Phys. Rev. Lett.》 Highlight Article.

PRL Editors' Suggestion 2014年6月6号

Experimental Realization of a Compressed Quantum Simulation of a 32-Spin Ising Chain

Zhaokai Li, Hui Zhou, Chenyong Ju, Hongwei Chen, Wenqiang Zheng, Dawei Lu, Xing Rong, Changkui Duan, Xinhua Peng, and Jiangfeng Du

Phys. Rev. Lett. **112**, 220501 – Published 2 June 2014

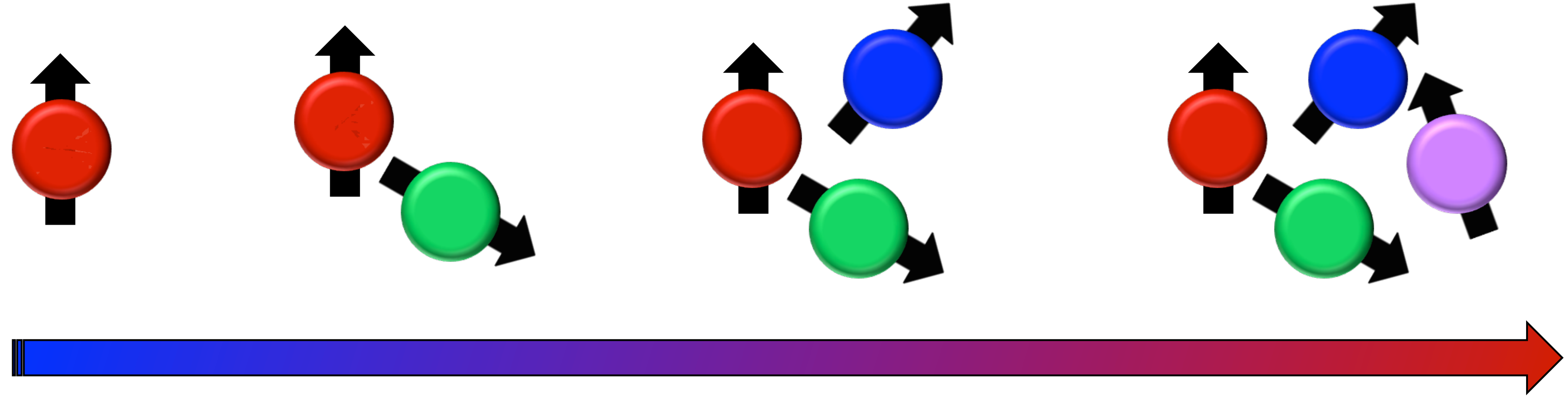


Using a quatum simulator with only five qubits, the simulation of a 32-spin Ising chain is experimentally demonstrated.

Z. Li et al., Phys. Rev. Lett. 112, 220501 (2014)

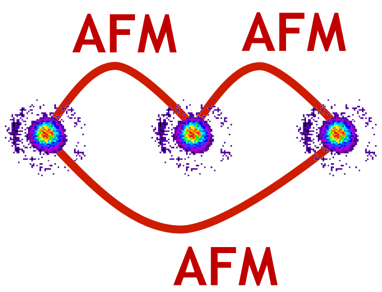
Exotic quantum many-body physics

Spin Chain (complex interaction)

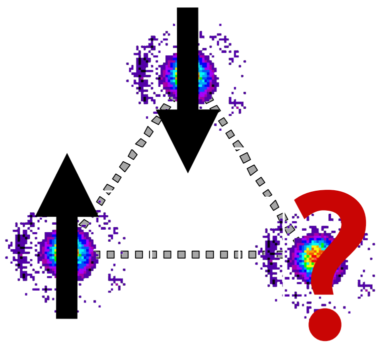


Many-body interaction

New Physics?



$J_{12}=J_{13}=J_{23} > 0$



Degenerated ground state

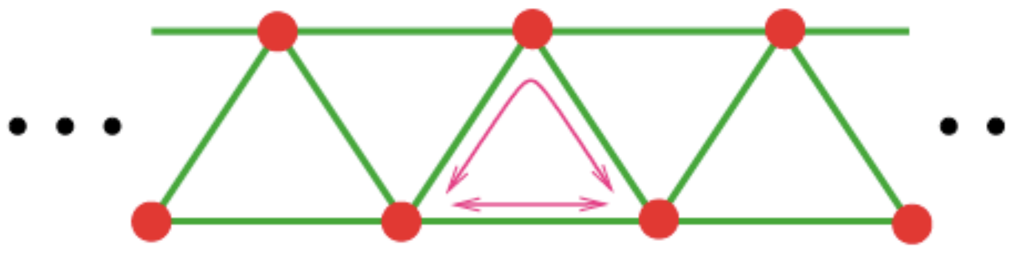
Frustration

Entanglement

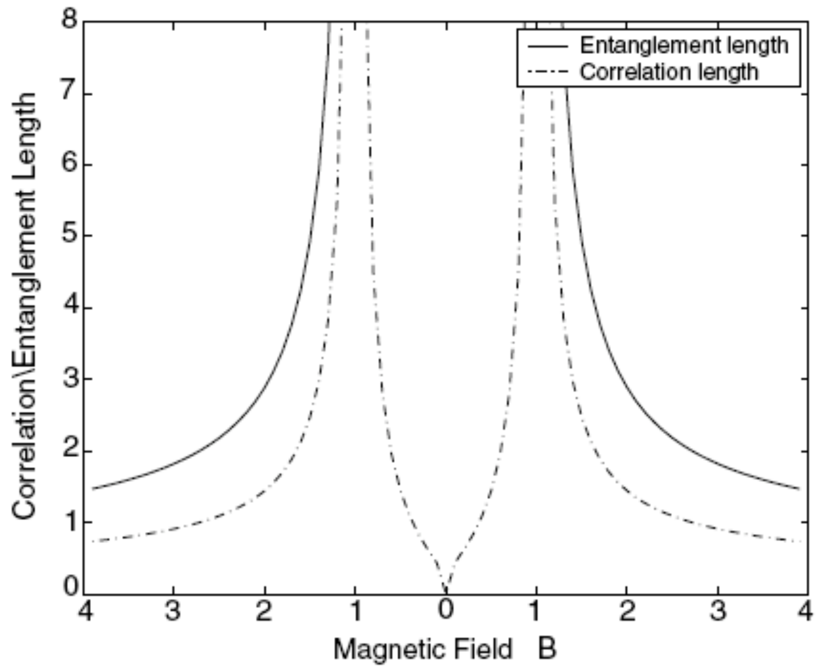
Exotic quantum many-body physics

New Physics: New critical phenomena

One-dimensional chain constructed out of equilateral triangles



$$H = \sum_i (-\sigma_{i-1}^x \sigma_i^z \sigma_{i+1}^x + B\sigma_i^z),$$



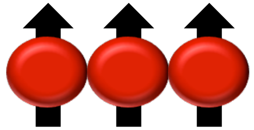
A three-spin cluster Hamiltonian that exhibits a novel kind of critical behavior that is not revealed by the traditional approach -- two-point correlation functions.

Pachos and Plenio, PRL 93, 056402 (2004)

Experimental demonstration

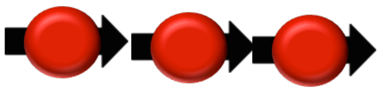
ground state

$$B^z \sum_i \sigma_i^z$$



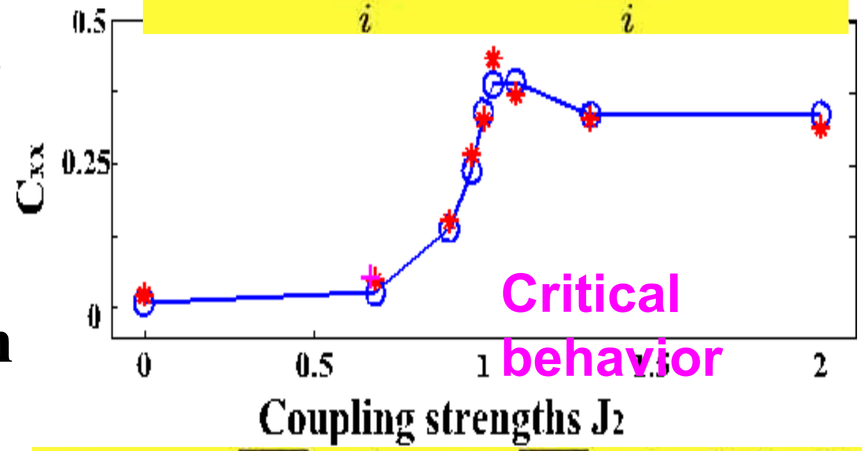
Standard two-spin correlation

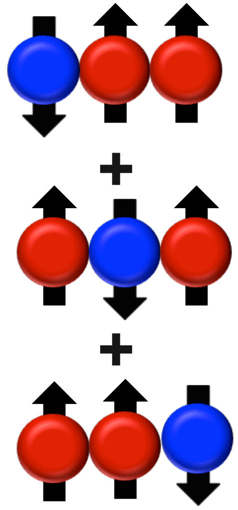
$$C_{xx} = \sum_{i \neq j} \langle \sigma_x^i \sigma_x^j \rangle / 3$$



$$B^z \sum_i \sigma_i^x$$

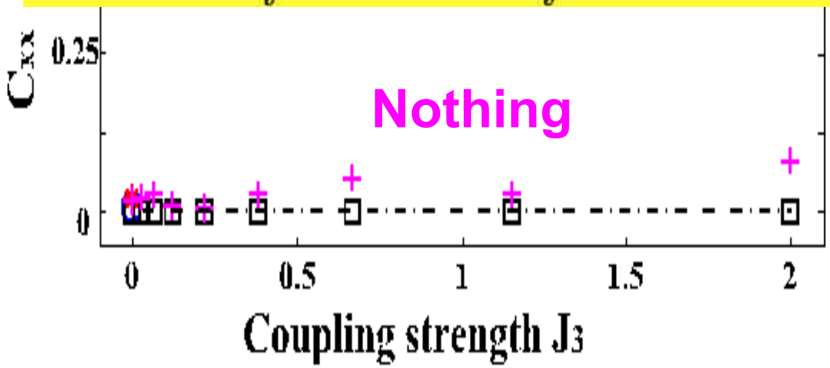
$$\mathcal{H} = \omega_z \sum_i \sigma_z^i + J_2 \sum_i \sigma_z^i \sigma_z^{i+1}$$

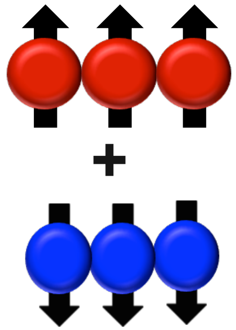




$$J \sum_{\langle i,j \rangle} \sigma_i^z \sigma_j^z$$

$$\mathcal{H} = \omega_x \sum_i \sigma_x^i + J_3 \sum_i \sigma_z^i \sigma_z^{i+1} \sigma_z^{i+2}$$

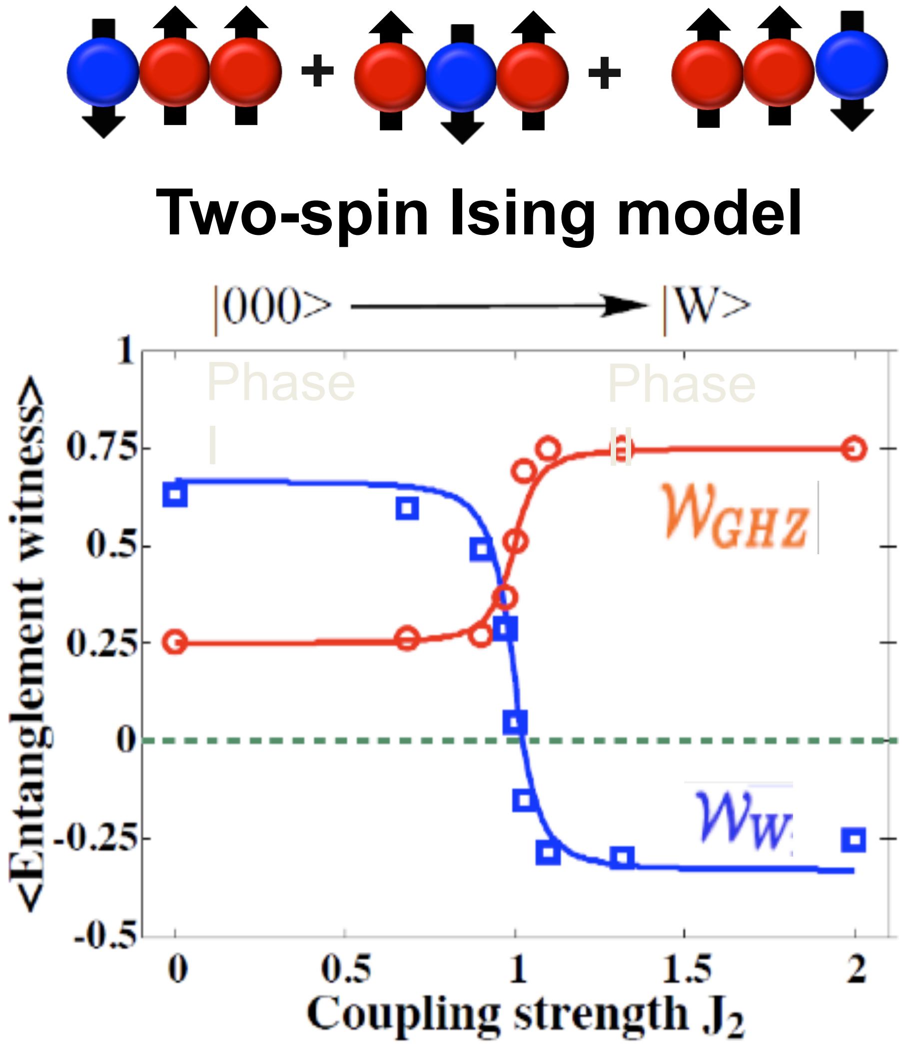


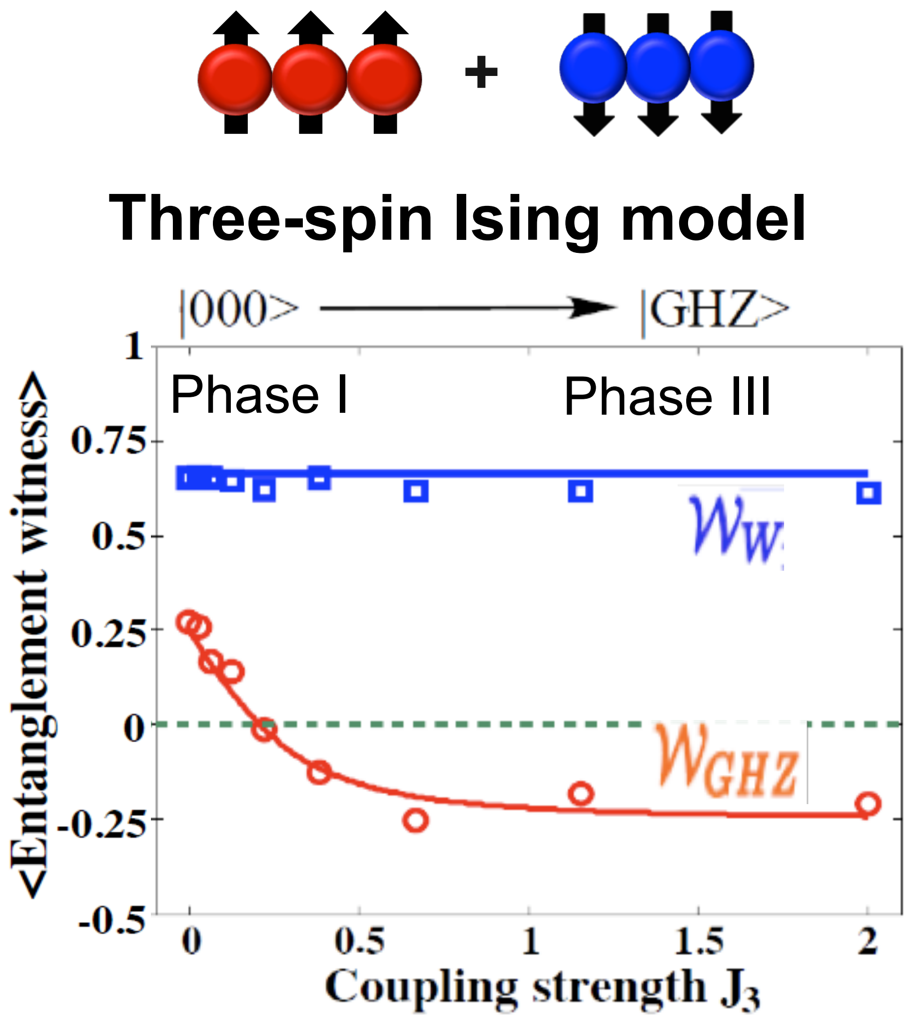


$$J \sigma_1^z \sigma_2^z \sigma_3^z$$

New critical phenomena induced by three-body interaction cannot be detected by the standard two-spin correlation.

Entanglement witness operators





XH Peng et al., Phys. Rev. Lett. 103, 140501(2009)

Exotic quantum many-body physics

New Physics: Topological orders (new quantum orders)

Kitaev's toric code model

$$H = -\sum_s A_s - \sum_p B_p$$

$$A_s = \sigma^x_{sa}\sigma^x_{sb}\sigma^x_{sc}\sigma^x_{sl}$$

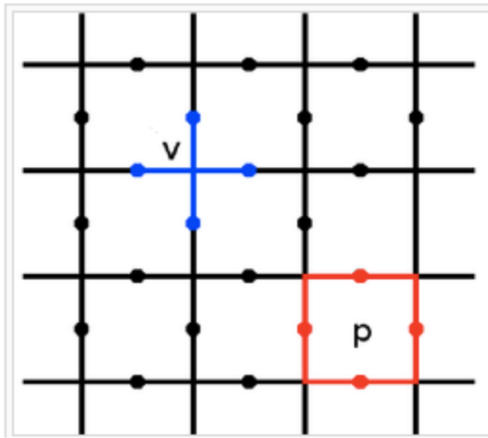
$$B_p = \sigma^z_{ij}\sigma^z_{jk}\sigma^z_{kl}\sigma^z_{li}$$

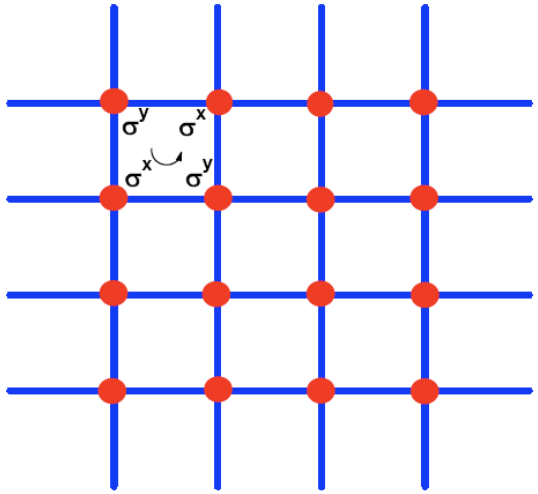
Wen-plaquette model

$$H = -J\sum_i \hat{F}_i,$$

$$\hat{F}_i = \sigma^x_i \sigma^y_{i+\hat{e}_x} \sigma^x_{i+\hat{e}_x+\hat{e}_y} \sigma^y_{i+\hat{e}_y}$$

Z2 topological orders





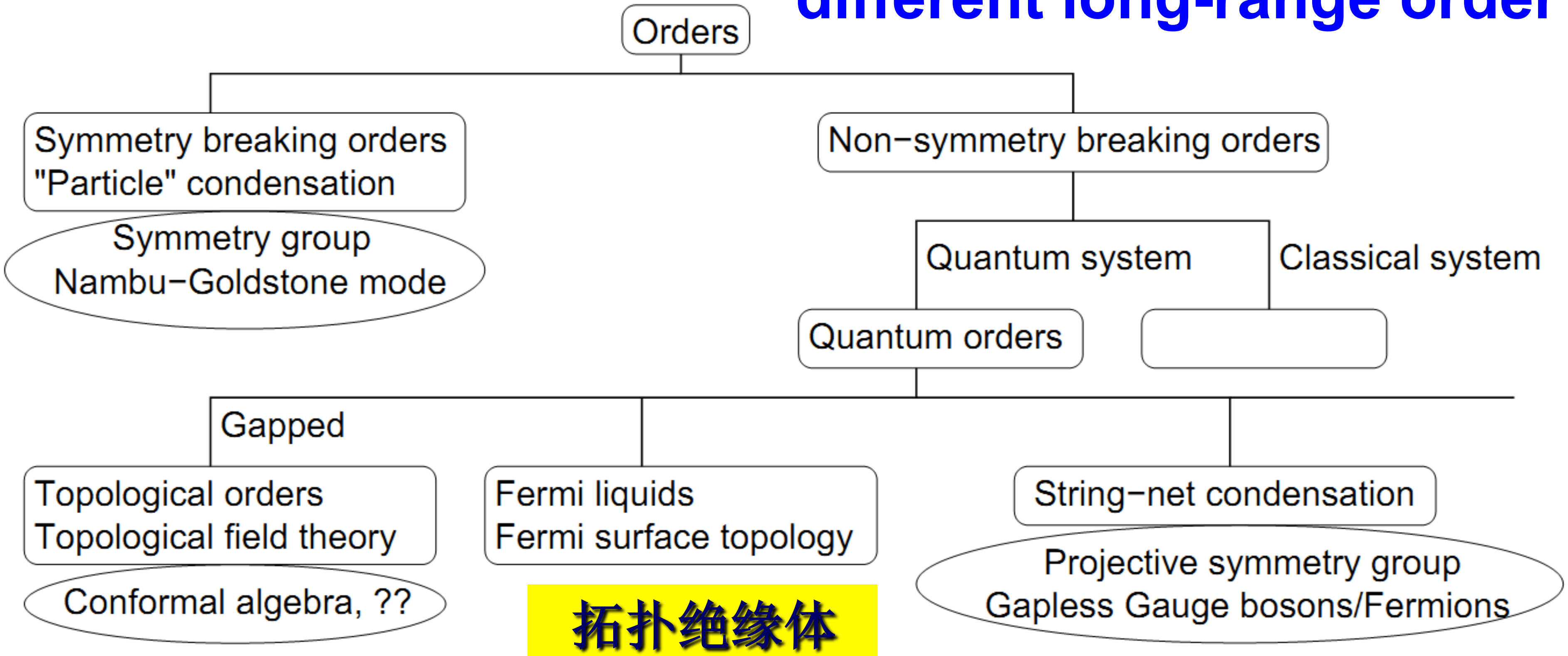
Topologic orders = pattern of quantum entanglements

A. Kitaev, Ann. Phys. 303, 2 (2003); X. G. Wen, PRL. 90, 016803 (2003)

Topological orders (TO)

新物态可能的分类

Different phases = different long-range order



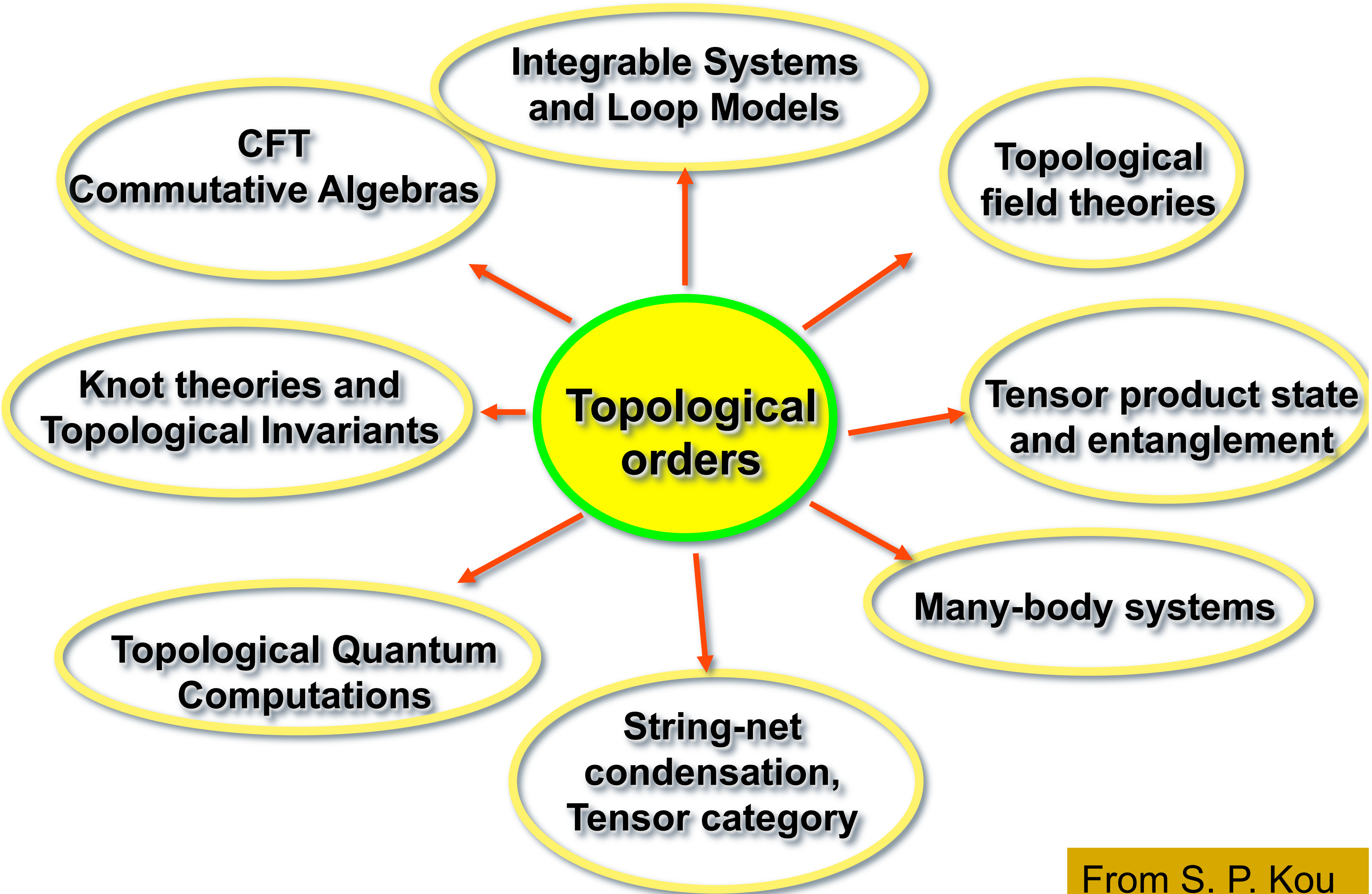
拓扑绝缘体

自旋液体、拓扑超导
分数量子霍尔态

自旋液体

X. G. Wen, Quantum Field Theory of Many-Body Systems

Topological orders (TO)



From S. P. Kou

Problems and challenges

- Fractional quantum Hall (FQH) systems is the physical ones naturally existing topological orders.

- Instead of naturally occurring physical systems, two-dimensional spin-lattice models, including the toric-code model, the Wen-plaquette model, and the Kitaev model on a hexagonal lattice, were found to exhibit Z2 topological orders.

- The study of such systems therefore provides an opportunity to understand more features of topological orders and the associated topological QPTs.

Problems and challenges

- Previous experiments for the toric-code model:

  Photon systems [Nature 482, 489-494 (2012), PRL 102, 030502 (2009), New. J. Phys 11, 083010 (2009)]

  NMR systems [PRA 88, 022305 (2013); arXiv:0712.2694v1 (2007)]

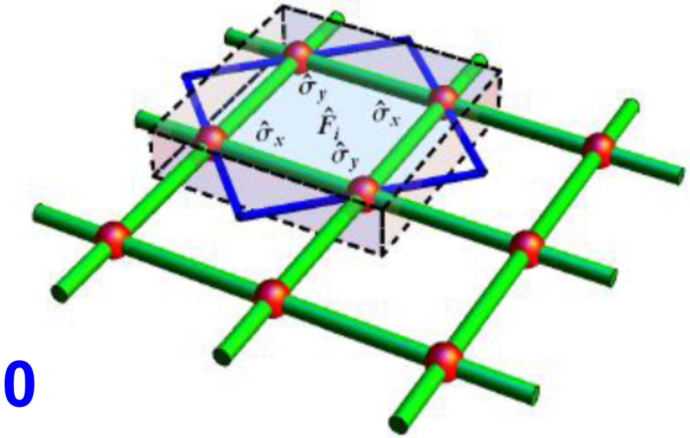
  not really realized quantum spin models, rather than directly prepared some specific entangled states with TO

- Two major challenges:
  - to engineer and control experimentally complex quantum systems with four-body interactions
  - to detect efficiently the resulting topologically ordered phases which is different from symmetry-breaking phase transition.

Wen-plaquette model

An exact soluble quantum spin model with Z2 topological orders

$$H = -J\sum_i \hat{F}_i, \quad \hat{F}_i = \sigma_i^x \sigma_{i+\hat{e}_x}^y \sigma_{i+\hat{e}_x+\hat{e}_y}^x \sigma_{i+\hat{e}_y}^y$$



- For J >0, the ground state is

$$F_i = 1$$

Z2A projective symmetry groups

J = 0

- For J < 0, the ground state is

$$F_i = -1$$

Z2B projective symmetry groups

A new kind of QPT
Different quantum orders
Same symmetry

Beyond Landau's symmetry breaking theory

Question: How to observe in the experiment?

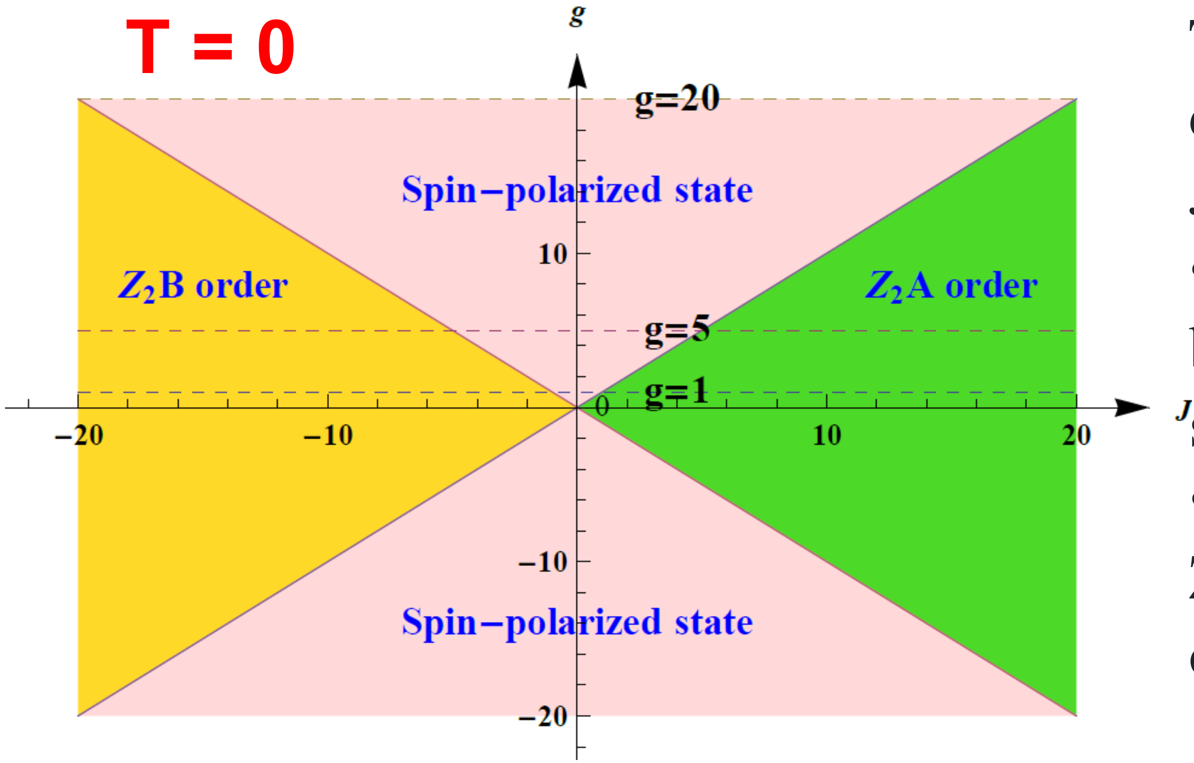
X. G. Wen, PRL. 90, 016803 (2003)

Phase diagram

Transverse Wen-plaquette model

$$\hat{H}_{tol} = \hat{H}_{Wen} - g\sum_i \hat{\sigma_i^x}$$

T = 0



The transition region depends on the value of |J/g|:

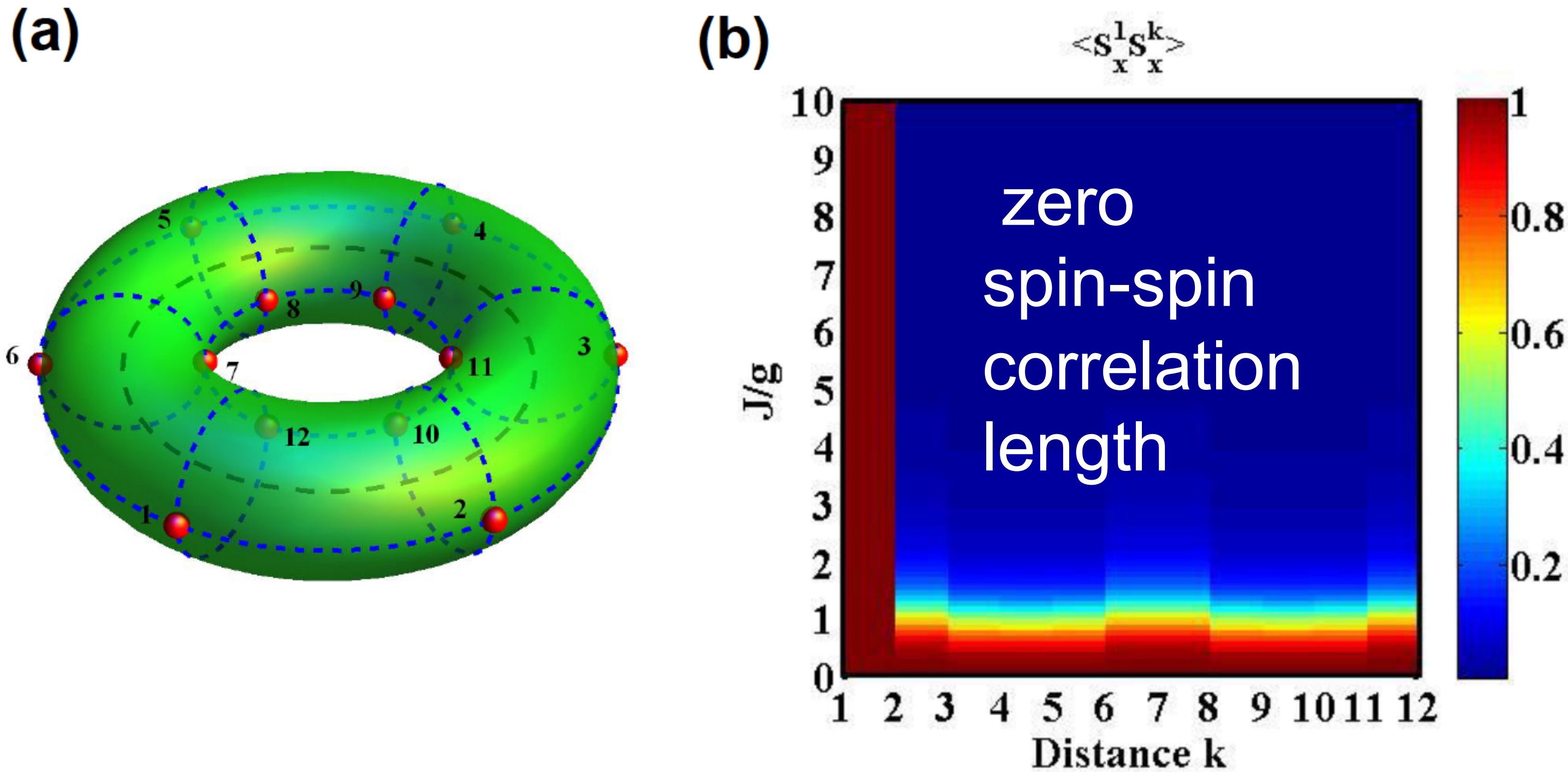
- The transition becomes narrower and sharper as g decreases.
- When g ➔0, Z2B ➔Z2A topological order @ J = 0.

Analogy quantum simulation

Validity of TQPT in the small finite-size system

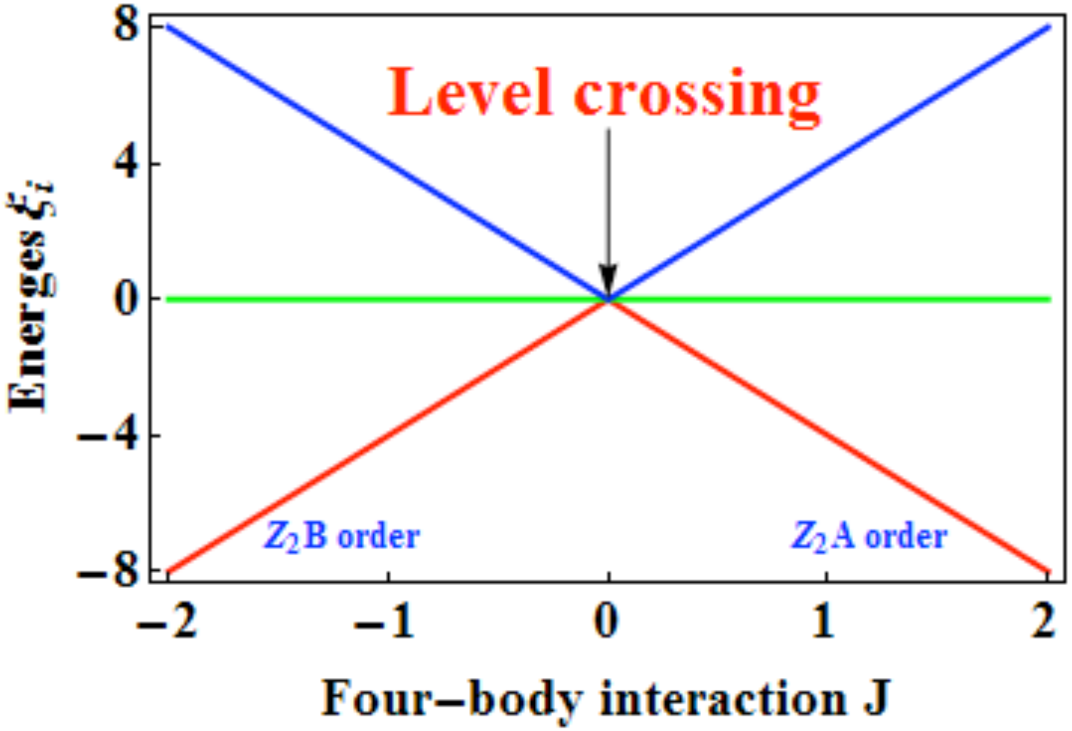
TOs exist in the Wen-plaquette model with periodic lattice of nite size   X. G. Wen, PRL. 90, 016803 (2003)

Spin-spin correlations



Validity of TQPT in the small finite-size system

g = 0 Wen-plaquette model



a first-order phase transition which can occur in a finite-size system [Rep. Prog. Phys. 66, 2069 (2003)]

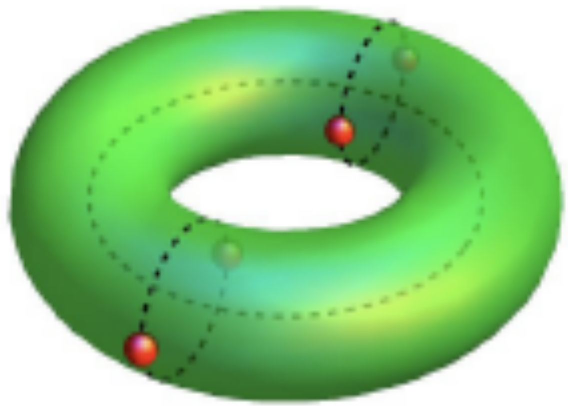
Transverse Wen-Plaquette model: second-order phase transition at J/g = 1 in the thermodynamic limit. In finite-size systems, the sharp quantum phase transition is smoothed into a graduate change in the properties of the ground state, but its effect can still be visible.

Wen-plaquette model

2x2 lattice: the simplest finite system to present such a TQPT

$$H_{Wen}^{4} = -2J(\hat{\sigma}_1^x \hat{\sigma}_2^y \hat{\sigma}_3^x \hat{\sigma}_4^y + \hat{\sigma}_1^y \hat{\sigma}_2^x \hat{\sigma}_3^y \hat{\sigma}_4^x)$$

Ground state has four-fold degeneracy



Transverse Wen-plaquettte model :

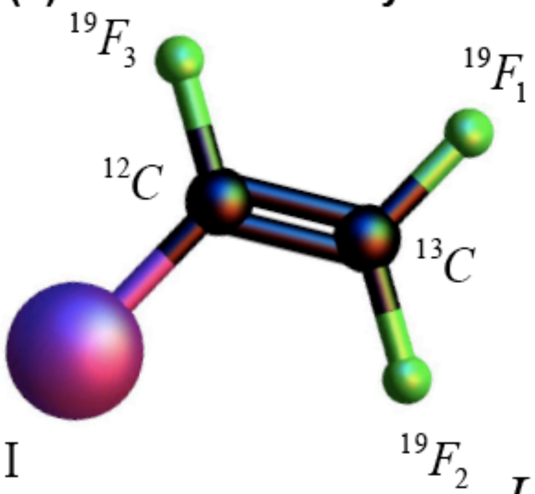
$$H_{tol} = H_{Wen}^{4} - g\sum_{i}^{Ns=4} \hat{\sigma}_i^x$$

Ground state:

$$|\psi_g\rangle \approx \begin{cases} |\psi_{Z2B}\rangle = |\Phi^+\rangle_{13}|\Phi^+\rangle_{24}, & J \ll -g < 0 \\ |\psi_{SP}\rangle = |++++\rangle, & J = 0 \\ |\psi_{Z2A}\rangle = |\Psi^+\rangle_{13}|\Psi^+\rangle_{24}, & J \gg g > 0 \end{cases}$$

Experiment

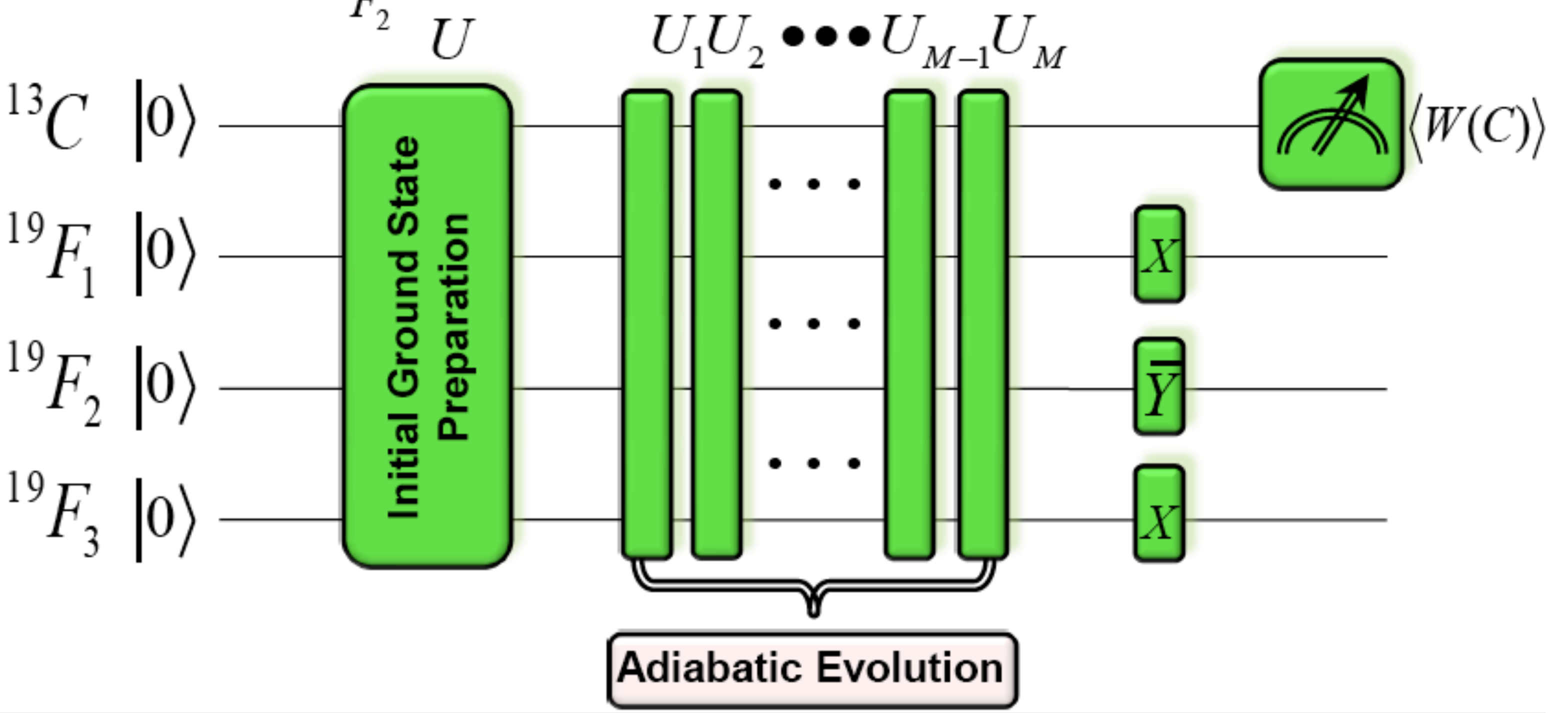
(a) Iodotrifluoroethyene



(b)

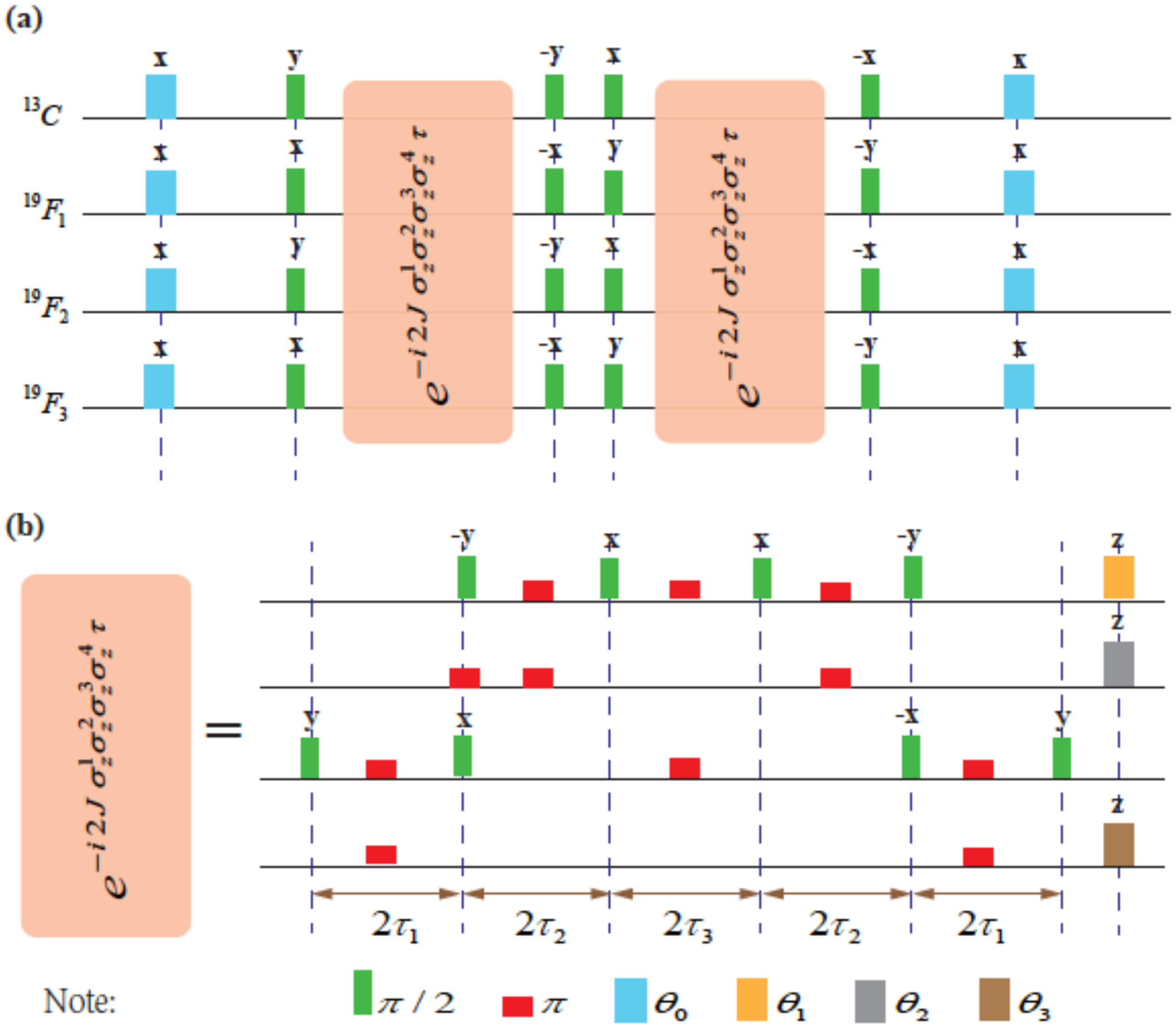
	^{13}C	$^{19}F_1$	$^{19}F_2$	$^{19}F_3$	$T_2(s)$
^{13}C	15478.7				7.9
$^{19}F_1$	-297.6	-33114.5			4.4
$^{19}F_2$	-275.7	64.6	-42674.9		6.8
$^{19}F_3$	39.1	51.4	-129.1	-56450.7	4.8

(c)



Hamiltonian simulation

$$H_{tol} = H_{Wen}^{4} - g\sum_{i}^{Ns=4}\hat{\sigma}_i^x$$



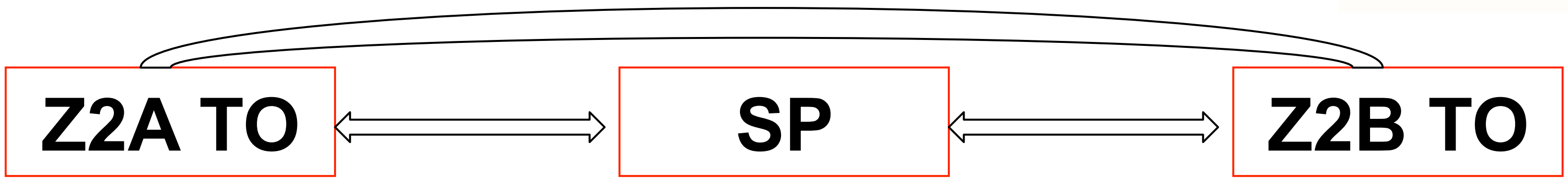
Measurement

What is the order parameter?

- Standard QPT detectors:
  - derivative of the ground state energy,
  - Block entanglement
  - ground state fidelity
- Non-local order parameters
  - Topological entanglement entropy
  - Wilson loop $\hat{W}(C) = \prod_C \hat{\sigma}_i^{\alpha_i}$

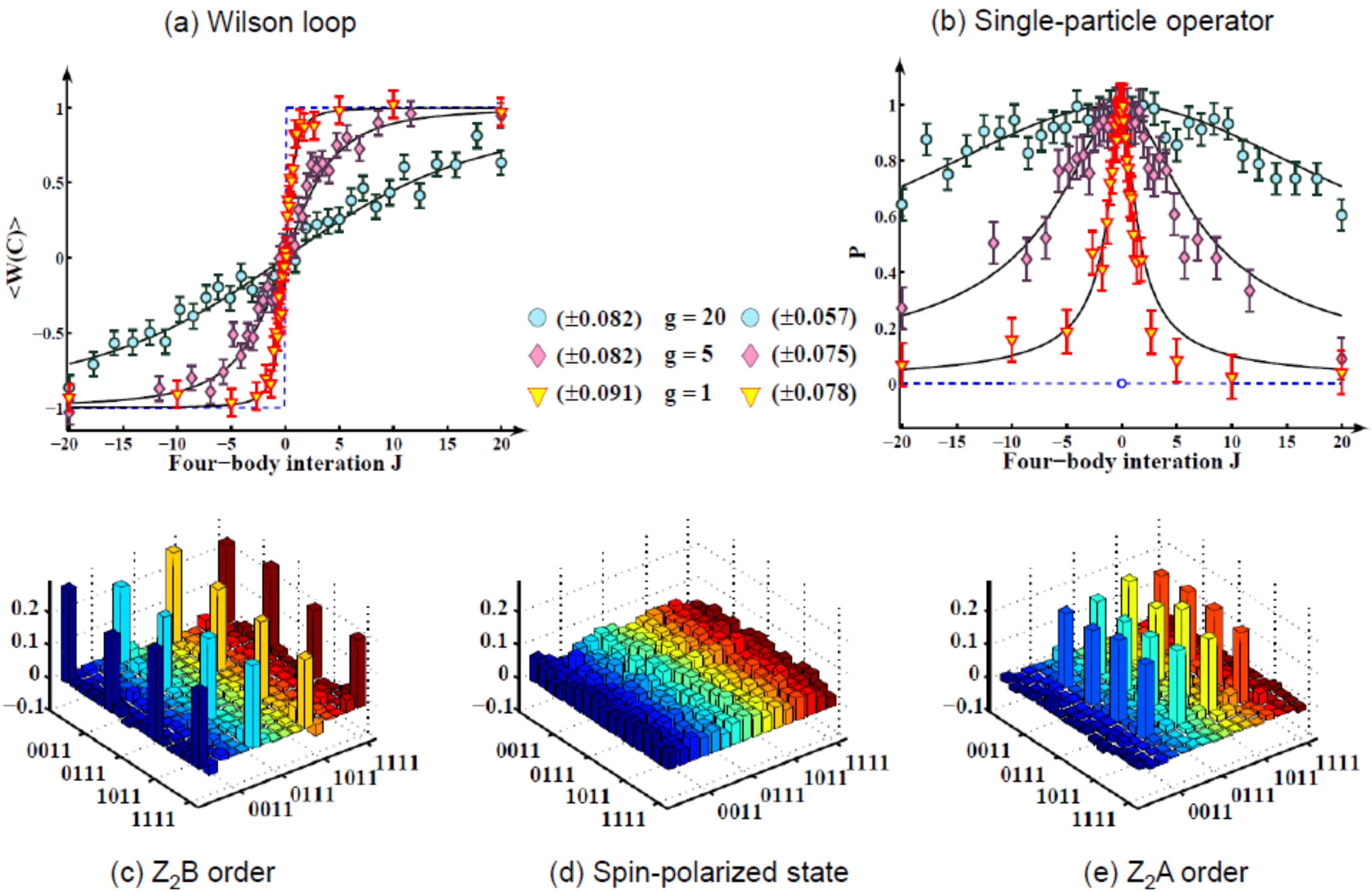
For the ground state, the closed-strings are condensed

$\langle W(C) \rangle \neq 0$



A. Hamma et al., Phys. Rev. B 77, 155111 (2008)

Experimental results



Entanglement, complementarity and TQPT

Complementarity: $$C^2_{k(ij\ldots n)} + S^2_k = 1$$

A conjecture: $$\sum_{m=2}^{n} \tau_m^{(k)} + S_k^2 = 1$$

Cases (g=1)	$C^2_{1(234)}(\rho^{exp})$	$C^2_{12}(\rho^{exp})$	$C^2_{13}(\rho^{exp})$	$C^2_{14}(\rho^{exp})$	$\tau_2^1 = \sum_{j\neq 1} C^2_{1j}(\rho^{exp})$
$\|\psi_{Z_2B}\rangle$	0.98	0	0.80	0	0.80
$\|\psi_{SP}\rangle$	0.038	2.9×10^{-4}	0	0	2.9×10^{-4}
$\|\psi_{Z_2A}\rangle$	0.99	0	0.80	0	0.80

Cases (g=1)	$C^2_{2(134)}(\rho^{exp})$	$C^2_{12}(\rho^{exp})$	$C^2_{23}(\rho^{exp})$	$C^2_{24}(\rho^{exp})$	$\tau_2^2 = \sum_{j\neq 2} C^2_{2j}(\rho^{exp})$
$\|\psi_{Z_2B}\rangle$	0.99	0	0	0.80	0.80
$\|\psi_{SP}\rangle$	0.049	2.9×10^{-4}	0	0	2.9×10^{-4}
$\|\psi_{Z_2A}\rangle$	0.99	0	0	0.80	0.80

Larger QS for TO

- From the theoretical view: explore more interesting physical phenomena, such as lattice-dependent topological degeneracy (even x even;even x odd; odd x odd), robust ground state degeneracy, quasiparticle fractional statistics, protected edge states, topological entanglement entropy and so on.

- From the experimental view: our experimental methods are universal for larger number of qubits; for the larger systems, quantum simulators will perform more powerfully than classical computers in the research of topological orders and their physics, which cannot be efficiently simulated on classical computers.

Remarks

- **The first experimental implementation of adiabatic transitions between different topological orders by simulating the quantum spin model. This provides an experimental tool for further studies of complex quantum systems.**

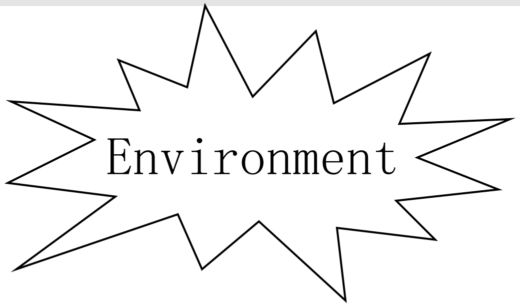
- **Our experiments demonstrate the feasibility of small quantum simulators for strongly correlated quantum systems, and the usefulness of the adiabatic method for constructing and initializing a topological quantum memory.**

X. H. Peng et al., Phys. Rev. Lett. 113, 080404 (2014)

Collaborate with Prof. S. P. Kou

summary: novel physics

#1



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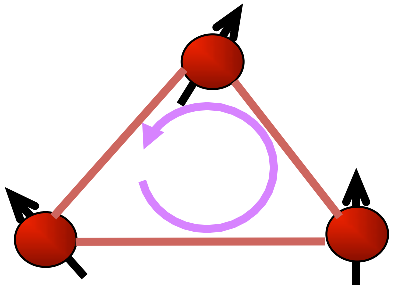

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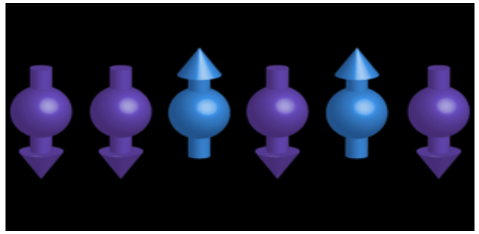

Decoherence ≠ error

➔ how to mitigate it
how to exploit it
(quantum control)

➔ how to investigate
(mesoscopic)
decoherence

scaling quantum simulations

➔ proof of principle on spins

bridging the gap
(proof of principle studies and "useful" QS)

➔ outperforming classical computation
➔ deeper understanding of quantum dynamics
➔ new physical phenomena

investigate the impact on:

- Solid state physics (magnets, ferroelectrics, quantum Hall, high T_c)
  (quantum phase transitions, spin frustration, spin glasses,…)
- quantum information processing / quantum metrology
- …

Thanks to ……

Collaborators:
Prof. Jiangfeng Du
Prof. S. P. Kou
Prof. Dieter Suter
Prof. C. K. Duan

Funding:
USTC， CAS， NNSFC……

NMR group (Graduate student):

Zhihuang Luo

Zhaokai Li

Jun Li

Wenqiang Zheng

Hui Zhou

……

Spin Magnetic Resonance Lab
自旋共振实验室

Thanks for your attention!

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