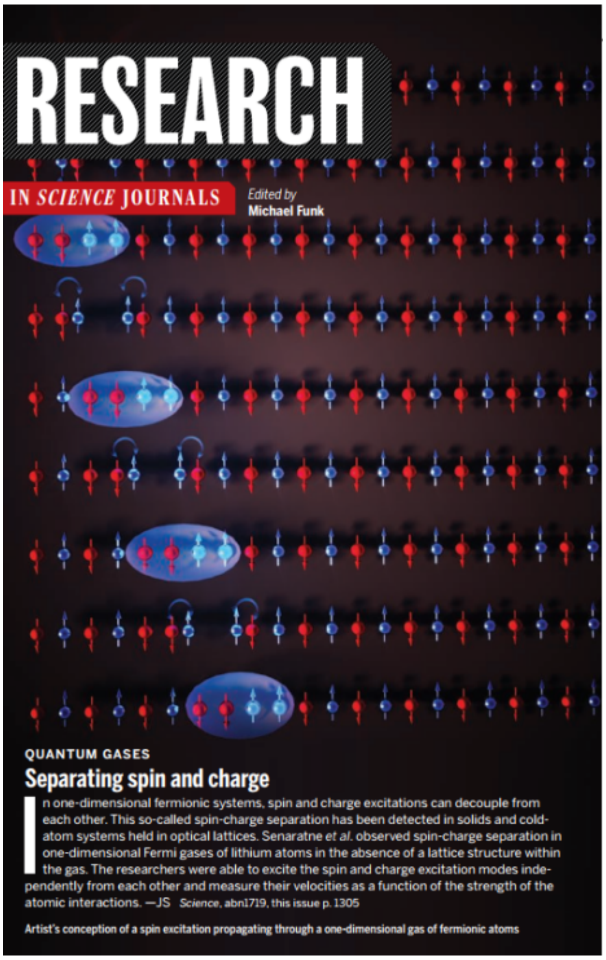
Xi-Wen Guan's Research Highlight



《Science》highlights our work on determinant observation of spin charge separation phenomenon

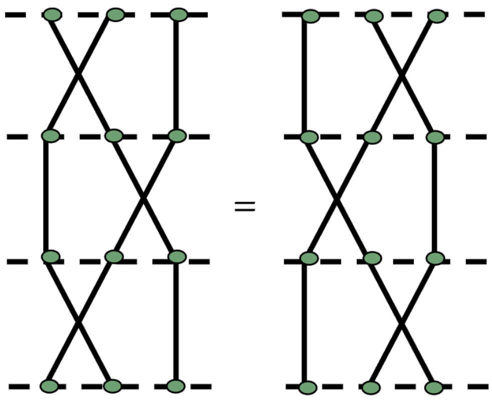
Please see the link：
[1], Phys. Rev. Lett. 125, 190401 (2020), https://doi.org/10.1103/PhysRevLett.125.190401
[2], Science 376, 1305 (2022), https://www.science.org/doi/10.1126/science.abn1719

Quantum Integrable models

Quantum integrable systems have a research history of over 80 years and have found extremely important applications in both physics and mathematics. Among their key developments, the discovery of the Yang-Baxter equation plays a crucial role in solving significant quantum many-body problems, studying two-dimensional statistical models, and advancing research on quantum groups and conformal field theory in mathematics. Particularly in recent years, the realization of one-dimensional ultracold Bose and Fermi gases, along with breakthrough experiments on quantum critical phenomena, has provided a new means to better understand quantum statistics and correlation effects in quantum many-body systems. In recent years, experimental results in one-dimensional quantum many-body physics have verified the predictions of Yang-Baxter exactly solvable models.

Guan Xiwen's Research and Academic Achievements

In January 2013, Guan established the Quantum Integrable Systems Research Group at the Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences. The group's research focuses on the exact solutions of low-dimensional quantum many-body systems and the applications of integrable systems in ultracold atomic gases, spin liquids, strongly correlated electron systems, Kondo physics, and statistical physics—covering studies on fractional statistics, Luttinger liquid theory, quantum critical phenomena, and related thermodynamic properties.



Yang-Baxter equation：facterization of a three-particle scattering matrix

In recent years, Guan has been engaged in cutting-edge research on quantum integrable systems, achieving significant results in exactly solvable models related to ultracold atomic gases, spin liquids, and strongly correlated electrons. He has applied mathematical physics models to address realistic problems in ultracold atomic physics and condensed matter physics, with several of his theoretical predictions validated by important experiments in recent years. These include predictions on super Tonks-Girardeau gases, novel Yang-Gaudin quantum pairing states, spin-charge separation, Luther-Emery liquid, 1D generalized hydrodynamics, measurements of dynamic response functions, quantum magnetism in 1D spin materials, integrable quantum field theory, non-equilibrium thermodynamics, and cavity QED systems. Additionally, another key research direction involves quantum criticality, and dynamic problems in one-dimensional systems.

In recognition of these important achievements, Guan, together with his collaborators Professor Murray T. Batchelor and Professor Chaohong Lee, was invited to publish a review article on one-dimensional integrable Fermi gas systems in the world-renowned journal *Reviews of Modern Physics* [Rev. Mod. Phys. 85, 1633 (2013)]. The article elaborates in detail on the novel quantum many-body phenomena described by exactly solvable models, providing crucial guidances and references for theoretical and experimental research in this field. To date, it has become one of the most influential review papers on quantum exact solution theory in the field.

Paper link：https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.85.1633

In addition, in 2022, Guan and Dr. Peng He were invited to publish a progress report titled "New Trends in Quantum Integrability: Recent Experiments with Ultracold Atoms" in Report on Progress in Physics. In this report, they elaborated in depth on the latest advancements in 1D experiments, including quantum holonomy, spin-charge separation, Luttinger liquids, critical phenomena, Haldane fractional quantum statistics, collective excitations, Fermi gases with SU(N) higher mathematical symmetry, and quantum impurities. The article also outlooked the potential applications of 1D ultracold atomic systems in future quantum technologies, such as their use in probing gravity, testing quantum many-body entanglement, and realizing quantum heat engines and refrigeration etc.

Paper link: https://iopscience.iop.org/article/10.1088/1361-6633/ac95a9/pdf

Integrable Models in Physics

Guan and his co-workers have achieved a series of important research results in these fields, which have been directly applied to the latest experimental breakthroughs in low-dimensional many-body physics. These include revealing the novel physics of many-body systems such as Heisenberg spin chains, spin ladder compounds, the 1D Hubbard model, the BCS model, Gaudin magnets, the Lieb-Liniger model, super Tonks-Girardeau gases, spin-1/2 interacting Fermi gases, and ultracold quantum spin Bose gases.

1. **Ultracold atoms:** Over the past two decades, the development of experimental preparation and manipulation techniques for degenerate ultracold atomic systems has provided a unprecedented platform for investigating quantum many-body phenomena and precision measurement methods. Guan with his research team has achieved a series of progress in Tomonaga-Luttinger liquids, spin-charge separation, and quantum critical phenomena in one-dimensional (1D) quantum many-body systems, revealing the microscopic mechanisms of 1D quantum many-body phenomena. These results serve as an important benchmark for understanding higher-dimensional quantum many-body phenomena and have attracted widespread attention from international peers, for example, platforms such as *Physics* (the online journal of the American Physical Society), *Physicsworld*(the website of the European Physical Society), and the Journal Club for Condensed Matter Physics have all published articles introducing their achievements.
   In the field of quantum gas research, anisotropically confined gases, formed by strong radial confinement and weak axial confinement, provide an ideal and pure system for studying integrable theories. Recently, experiments on super Tonks-Girardeau gases realized by Haller et al. in the strong attraction region of cesium atoms, published in Science 325, 1224 (2009) and Science 371, 296 (2021), respectively, have verified the predictions they predicted based on the integrable bosonic gas model.

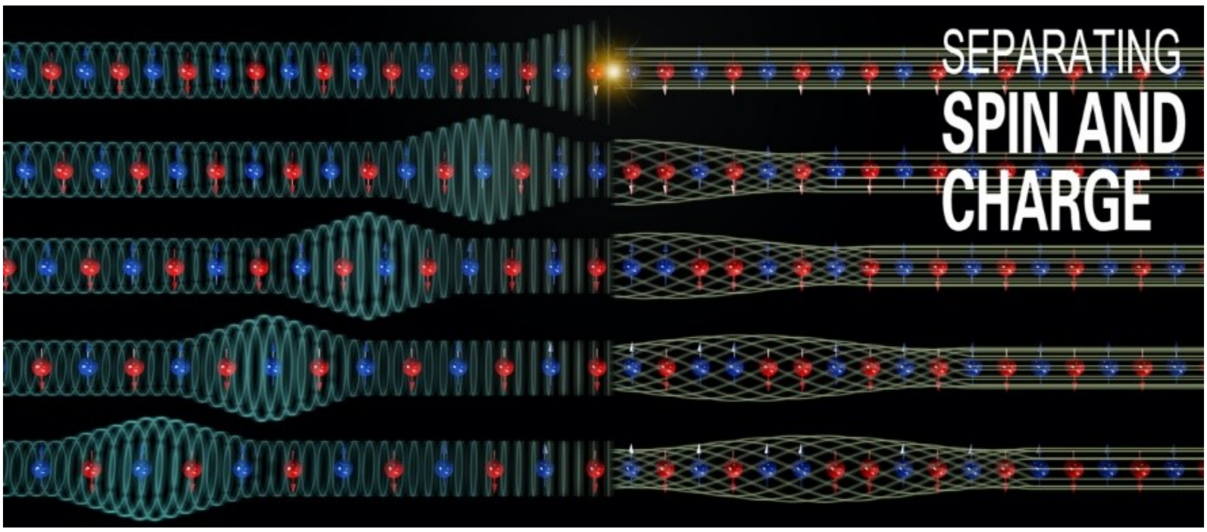
   Paper link：https://iopscience.iop.org/article/10.1088/1742-5468/2005/10/L10001/pdf;
   https://www.science.org/doi/epdf/10.1126/science.1175850
   https://www.science.org/doi/epdf/10.1126/science.abb4928

   In this regard, Xi-Wen Guan used exactly solvable models to predict the exotic Bardeen-Cooper-Schrieffer (BCS) and Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) Cooper pair states in the 1D Yang-Gaudin model at an early stage (Guan, et. al., Phys. Rev. B 76, 085120 (2007)). In 2010, Professor Hulet's group experimentally confirmed the FFLO pairing state in 1D attractive Fermi gases that they had predicted using the Bethe ansatz method. The low-energy excitations of 1D interacting fermions usually split into two independent Tomonaga-Luttinger liquids, which describe the collective motion of quasiparticles carrying either spin or charge, separately. This phenomenon is called spin-charge separation and is a unique universal law in 1D quantum many-body physics. Although the Tomonaga-Luttinger liquid theory was proposed more than 40 years ago, spin-charge separation has long lacked conclusive experimental verification. The reason lies in the complex interparticle interactions and rich internal degrees of freedom, which pose great challenges to the theoretical description of the system's physical properties. The Tomonaga-Luttinger liquid theory cannot meet the needs of experimental measurements, making the accurate theoretical characterization of spin-charge separation a recognized worldwide problem.

In 2020, Guan's team, through the theory of quantum integrable systems, calculated the low-energy fractional excitation spectrum of 1D cold Fermi atomic gases with precision for the first time, and discovered the exotic properties of collective spin and charge excitations at different temperatures. They also revealed the microscopic nature of spin-charge separation and spin-incoherent liquids (Phys. Rev. Lett. 125, 190401 (2020)). This article also took the lead in proposing an experimental scheme for the conclusive observation of this phenomenon in Fermi ultracold atomic systems using Bragg spectroscopy, providing theoretical guidance for solving the problem that this iconic physical phenomenon of the Tomonaga-Luttinger liquid theory has lacked convincing experimental verification for more than 40 years.

Paper link: https://doi.org/10.1103/PhysRevLett.125.190401

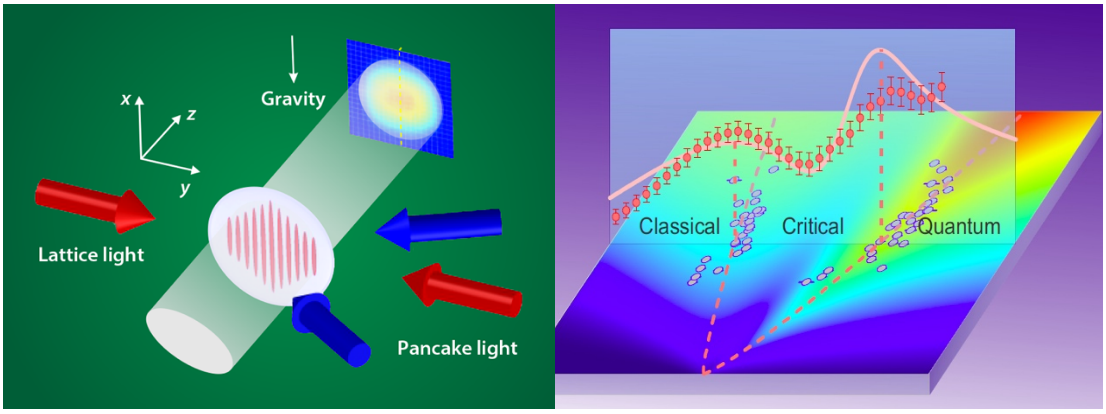
In subsequent work, Guan collaborated with the teams of Professor Randall G. Hulet and Professor Han Pu from Rice University (USA). They observed the exotic phenomenon of spin-charge separation for the first time with certainty by confining a 1D ultracold Fermi gas, and discovered the nonlinear Tomonaga-Luttinger liquid effect caused by spin backward scattering in this system. The achievement was published in Science and selected as a "Research Highlight" by the journal. Professor Thierry Giamarchi from the University of Geneva, a world-renowned physicist, commented on this work in a special feature of the international Journal Club for Condensed Matter Physics: "This is of course a remarkable result. ...This opens the door to using it in situations where the theory is much less well established."



The theoretical prediction of the spin-charge separation phenomenon has obtained conclusive experimental verification.

Paper link：https://www.science.org/doi/epdf/10.1126/science.abn1719

In 2017, in collaboration with Academician Jianwei Pan from the University of Science and Technology of China and his colleague, Professor Zhensheng Yuan, through quantum control and measurement of ultracold atoms in optical lattices, combined with the theory of quantum integrable systems, the collaborative research teams obtained, for the first time internationally, the quantum critical properties of the transition between a classical gas and a quantum liquid in a 1D finite-temperature many-body system. Moreover, by measuring its phase correlations, they observed the power-law correlation characteristics of Luttinger liquids, achieving significant progress in the field of low-dimensional quantum many-body system research. This research result was published in *Physical Review Letters* and selected as an "Editors' Suggestion". *Physics* invited Professor Giamarchi from the University of Geneva to comment on this research result in its "Viewpoint" column under the title "Theory of 1D Quantum Materials Verified in Cold Atom and Superconductor Experiments". Additionally, *Physicsworld*, the website of the European Physical Society, reported this achievement under the title "Atomic Systems and Josephson Junctions Simulate 1D Quantum Liquids".



Left: Schematic diagram of the experimental setup for ultracold atoms used to observe the 1D quantum many-body phase transitions and Luttinger liquids; Right: Phase diagram of the 1D quantum many-body ystem.

Paper link: **https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.119.165701**

Recently based on the newly developed multi-label algorithm, this study realizes high-precision calculation of all "relative excitations" of quantum integrable systems in both the ground state and finite-temperature states. For the first time, it accurately calculates the complete dynamic correlation function of the Lieb-Liniger model, obtains its full spectral function in the energy-momentum space, and reveals the singular power-law behavior at the threshold of the single-particle spectrum through the results of a large-scale system with 4000 particles. This achievement confirms, for the first time, the validity and applicable scope of the nonlinear Luttinger liquid theory, lays a foundation for dynamic studies such as non-equilibrium steady states, and further provides a quantitative basis for experimental detection of novel correlation effects.

Paper link: https://academic.oup.com/nsr/article/12/9/nwaf294/8209836

2. **Spin Systems:** In the study of quantum spin chains, long-range order in 1D antiferromagnets is disrupted, leading to rich quantum magnetic effects at low temperatures. We found that integrable spin-1 chains with strong single-ion anisotropy can well describe compounds such as NENC, NDPK, and NBYC. The thermodynamic and magnetic properties of these systems can be accurately calculated using sophisticated thermodynamic Bethe ansatz and quantum transfer matrix methods.

In the research on quantum spin ladder systems, which provide a simplified model for understanding the mechanism of high-temperature superconductivity in cuprates. We established the correspondence between integrable su(N) systems and spin ladders. These models successfully describe the physical properties of realistic ladder compounds such as B5i2aT and CHpC. In particular, the Luttinger liquid parameters obtained through integrable theory are in high agreement with the experimental results of compounds like $(5IAP)_2CuBr_4 \cdot H_2O$ (see the research paper published in Advances in Physics 87):

Paper link：https://www.tandfonline.com/doi/abs/10.1080/00018730701265383

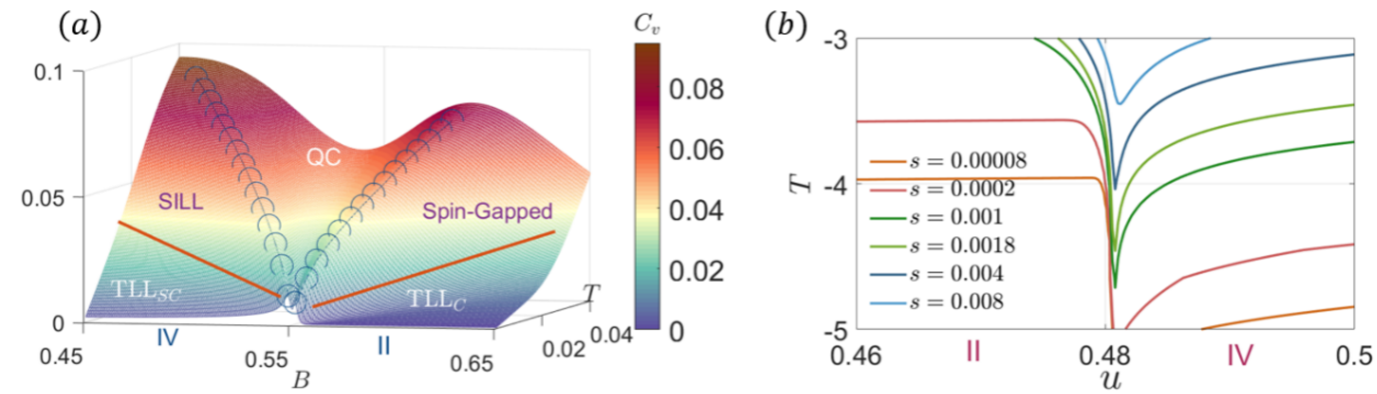
1D quantum spin systems in solids have long been a focus of experimental and theoretical attention. With the advancement of experimental techniques, the thermodynamic and magnetic properties of materials like CuPZn can now be well observed. However, the understanding of magnons, spinon excitations, and quantum critical properties remains incomplete. Guan with his collaborators has conducted in-depth studies on the issues related to 1D antiferromagnetic Heisenberg chains, obtaining analytical scaling functions for various physical quantities in the quantum critical region. They pointed out that the double-peak structure of specific heat can well determine the transition temperature of the quantum critical region, and proved that the Wilson ratio is proportional to the Luttinger parameter. Furthermore, through precise comparison with experimental results, we confirmed that the theoretical interpretation is completely correct, correcting misunderstandings in the determination of transition temperatures in the quantum critical region. This holds significant guiding significance for future theoretical and experimental research (see Phys. Rev. B 96, 220401 R (2017)). After the article was published, our results were immediately verified by experimental papers [Sci. Adv. 3, eaao3773 (2017)]. In particular, recent experiments published in PNAS perfectly validated the predictions regarding Luttinger liquids and critical phenomena:

Paper link： https://academic.oup.com/pnasnexus/article/3/9/pgae363/7739746

3. **1D Hubbard model**： For a long time, the Fermi-Hubbard model has been an important theoretical model for describing electron interactions in lattices. It plays a crucial role in characterizing universal strongly correlated electron phenomena and explaining numerous exotic properties of quantum materials. However, research methods for this model are rather limited: numerical calculations are constrained by the fermion sign problem, and many-body perturbation theory as well as mean-field theory cannot be practically applied. Consequently, the Fermi-Hubbard model is widely recognized as a world-renowned challenge. In relevant research, the exactly solvable 1D Fermi-Hubbard model has long been expected to provide a benchmark for describing many-body physical phenomena in strongly correlated electron systems. Recently, experimental physicists have realized ultracold atomic systems in optical lattices and successfully constructed the exactly solvable 1D Hubbard model. They observed the dynamic transport and superdiffusive behavior of spin and charge, which offers a new perspective for explaining the microscopic nature of superconductivity and superfluidity. Nevertheless, how to understand the influence of interactions between fermions on the quantum states of spin and charge, and how to rigorously establish interaction-driven quantum phase transitions, Mott insulators, and universal thermodynamic laws remain elusive. Although mathematical physics methods have made considerable progress over decades, the

universal laws of the 1D Hubbard model have not yet been obtained, which hinders in-depth understanding of many-body quantum phenomena.

Guan's research team and its collaborators have achieved a series of important advances in the theoretical study of the 1D repulsive Hubbard model, including investigations into the exotic quantum properties, thermodynamics, and dynamic correlations of the attractive Hubbard model. Recently, they derived a set of exact analytical solutions for the 1D repulsive Hubbard model, covering fractionalized spin and charge excitations, spin-coherent and spin-incoherent Luttinger liquids, interaction-driven quantum phase transitions, and quantum refrigeration. The research results were published on October 3, 2024, in *Reports on Progress*



Left: A 3D plot of specific heat in the temperature-magnetic field-specific heat coordinate system during the phase transition from Phase IV (partially filled, partially polarized phase) to Phase II (partially filled, fully polarized phase) in the 1D repulsive Hubbard model; Right: Isentrope diagram of the interaction-driven II-IV quantum phase transition in the temperature-interaction plane, demonstrating the interaction-induced entropy accumulation effect, which holds guiding for quantum heat engines and refrigeration.

Paper link：https://iopscience.iop.org/article/10.1088/1361-6633/ad7b70/pdf

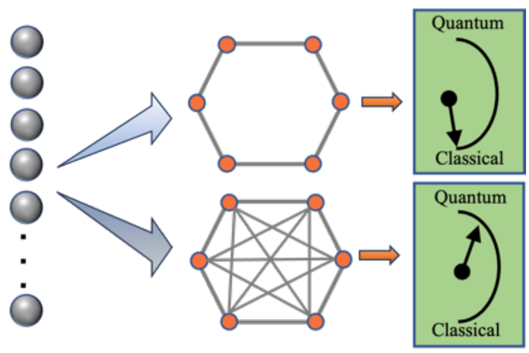
4. **Quantum Precision Measurement and Quantum metrology**：The latest frontier research in quantum many-body problems includes the study of quantum metrology at the many-body level, which also represents a key challenge in current quantum precision measurement. The research group led by Guan took deep investigation in proposing an interaction-driven quantum liquid heat engine and its corresponding experimental scheme. Their work, published in a Nature partner journal, has become a high-impact paper in this research field.

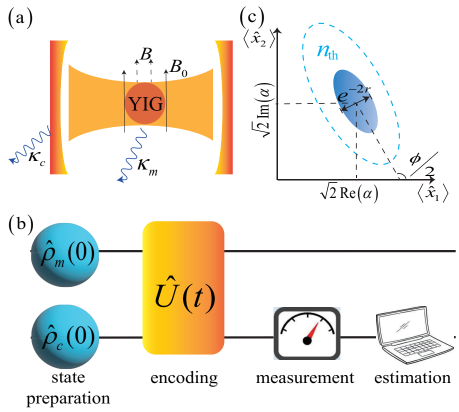
See link: https://www.nature.com/articles/s41534-019-0204-5.pdf

They have also achieved important new progress in the research on multiparticle quantum walks in one-dimensional (1D) lattice systems and their potential applications in high-precision gravity measurement. They revealed the microscopic mechanism of 1D three-particle quantum walks and proposed, for the first time, an experimental scheme to improve the accuracy of gravity measurement via quantum walks. The relevant research results were published on August 28, 2021, in the journal Physical Review Letters under the title "Multiparticle Quantum Walks and Fisher Information in One-Dimensional Lattices".

Paper link：https://link.aps.org/doi/10.1103/PhysRevLett.127.100406

Recently, Guan's research group and its collaborators demonstrated that in generalized phase estimation tasks, for non-entangled initial states, even if local many-body interaction Hamiltonians are used to encode parameters, it is impossible to make the measurement precision exceed the shot noise limit. Furthermore, this study revealed extensive connections between many-body physics, quantum control theory, quantum chaos, operator growth, and the application of quantum chaos in quantum metrology. The research results were published in 2024 in *Physical Review Letters* [132, 100803 (2024)]. In addition, they investigated the partial measurement estimation theory: targeting scenarios where only a part of the system is accessible in practical measure, they conducted an in-depth analysis of Gaussian state precision measurement tasks under such conditions. This study established an exact relationship between quantum Fisher information and bipartite entanglement, thereby clarifying the crucial role of bipartite entanglement in dynamic encoding. It also built a definitive connection between quantum entanglement and measurement precision in the theory of partial-measurement-based precision measurement. The article was published in [*Phys. Rev. B* 109, L041301 (2024)].





Left: In generalized phase estimation tasks, local interactions and long-range interactions have a substantial impact on the precision of phase estimation. For non-entangled initial states, even if local many-body interaction Hamiltonians are used to encode parameters, it can not make the measurement precision exceed the shot noise limit. This indicates that long-range interactions and initial state entanglement are important quantum resources for achieving Heisenberg measurement precision in parameter estimation. For more relevant information, please refer to the related articles in *Physical Review Letters*.
Paper link：https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.132.100803

5. **Anyons and Fractional Exclusion statistics：** Anyons and fractional quantum statistics have become one of the most important research directions in modern physics. In the field of 1D integrable anyon models, anyons--quasiparticles that describe fractional statistics—are gaining increasing importance in condensed matter physics and quantum computing. In particular, the fractional statistical characteristics recently observed in fractional quantum Hall effect experiments have opened up new avenues for researching fundamental issues such as quantum

computing and superconductivity. These advances also demonstrate the unique value of integrable models in revealing the intrinsic laws of quantum many-body systems.

Guan and his collaborators proved that 1D interacting anyonic gases—including interacting bosons and fermions—are equivalent to ideal particles that obey Haldane fractional statistics, see [PRL, 96, 210402, (2006)]. This provides profound insights into quantum statistics and dynamics in many-body physics. Theorists from many countries (the United States, France, Germany, the United Kingdom, China, etc.) have subsequently advanced theories in this area; this includes the recent discovery by Guan and his collaborators that non-mutual Haldane fractional statistics naturally emerge in the quantum critical region in 1D, 2D, and 3D interacting bosonic gases. This establishes a universal relationship between Haldane fractional statistics and symmetry breaking between particles and holes [see the paper in National Science Review: 9nwac027 (2022)].

Moreover, their recent study on the Haldane's fractional exclusion statistics in the spin-1/2 XXX chain by using advanced mathematical techniques and computer simulations initiatively identify the emergence of fractional exclusion statistics (FES) in this system, see [Phys. Rev. A 111, 033319 (2025)]. This result was remarked by the Science Archive as "Unlocking Quantum Secrets: Researchers Discover Hidden Statistics in Spin Chain Systems".

Paper link：https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.96.210402

https://academic.oup.com/nsr/article/9/12/nwac027/6535630?login=true