

## 2025

**Integrability and its applications.** Over the past year the group has produced a body of work that combines deep theoretical physics with powerful mathematical methods. A common goal across all projects has been to understand complex quantum and gravitational systems in an *exact and predictive way*, rather than relying only on approximations. This has allowed the group to extract reliable results about strongly interacting quantum matter, spacetime, and holography—areas where conventional methods often fail.

**Strongly coupled quantum field theories.** Many of the most important theories in modern physics, including those describing elementary particles and their interactions, are *strongly coupled*: their components interact so intensely that ordinary perturbation theory breaks down. The group made major progress in this area by exploiting surprising connections between these quantum field theories and ideas from probability theory and statistics.

In particular, the group exploited that certain observables in supersymmetric gauge theories follow *universal statistical laws* that were originally discovered in random matrix theory, a field developed to describe nuclear spectra and complex systems. This means that highly complicated quantum dynamics can sometimes be captured by simple and universal mathematical patterns. As a result, quantities that were previously very hard to compute—such as correlation functions and spectral data—can now be obtained in a controlled and precise way [1].

**Exact methods in quantum many-body and field theory.** A second core achievement of the year is the systematic use of *integrability*, a powerful mathematical structure that makes certain interacting systems exactly solvable. Integrable models appear in particle physics, statistical mechanics, and condensed-matter theory, and they provide rare examples where full, non-approximate answers can be found.

The group developed new tools that make it possible to compute *exact physical quantities* in these models, including conserved charges, thermodynamic properties, and the way quantum fields interact at very short distances. Importantly, these results are not limited to idealized situations: they apply at finite temperature, with boundaries, and in regimes where both quantum and thermal effects are important.

One particularly significant outcome is a complete description of how subtle non-perturbative effects contribute to physical observables [2]. These effects are crucial for understanding the true behavior of quantum systems but are often invisible to standard methods. By organizing them into a single coherent framework, the group has provided a much clearer picture of how exact quantum field theories really work.

**Quantum dynamics and many-body state.** Another major line of research concerns the *dynamics of quantum many-body systems*, especially those driven far from equilibrium.

These problems are central to modern physics, from cold-atom experiments to quantum information processing, but they are notoriously difficult because the number of quantum states grows exponentially with system size.

The group achieved a breakthrough by deriving *exact formulas* for how certain highly structured quantum states overlap with the true energy eigenstates of interacting systems [3]. These results are essential for predicting how quantum systems evolve after being disturbed, a situation known as a “quantum quench.”

In parallel, the group showed that some apparently complicated interacting systems can be transformed into much simpler ones that behave like *free particles*. This makes it possible to compute their real-time evolution exactly, something that is usually impossible in strongly interacting systems. These advances provide powerful new tools for understanding thermalization, transport, and information flow in quantum matter.

**Gravity, holography, and spacetime.** The final major theme of the year connects quantum field theory to gravity through the principle of *holography*, which states that certain gravitational theories are equivalent to quantum systems without gravity living in fewer dimensions.

The group made an important conceptual advance by showing that the basic dictionary of holography can be derived purely from *symmetry principles*, without relying on specific models or equations of motion. This strengthens the theoretical foundations of holography and clarifies why it is such a robust framework for understanding quantum gravity.

Further work explored how strings, which are fundamental objects in many theories of quantum gravity, are related to the *causal structure of spacetime*—that is, the way events influence one another. This helps bridge microscopic quantum physics and large-scale geometry.

The group also studied *gravitational memory effects*, subtle permanent changes in spacetime caused by passing objects or radiation. These effects connect gravitational waves, scattering processes, and observable spacetime distortions, and they are of increasing interest in both theory and experiment.

### **References**

[1] [https://link.springer.com/article/10.1007/JHEP04\(2025\)005](https://link.springer.com/article/10.1007/JHEP04(2025)005)

[2] <https://www.sciencedirect.com/science/article/pii/S0003491625002349?via%3Dihub>

[3] <https://journals.aps.org/prl/abstract/10.1103/4vy2-8cnk>