ANOUAR MOUSTAJ

PostDoc in Computational/Theoretical Physics

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EDUCATION

Doctorate of Philosophy in Theoretical Physics
Utrecht University
October 2020 – December 2024 | Utrecht

- Focus on Condensed Matter Physics: Topological Phases in Aperiodic, Nonhermitian, and Correlated systems. Thesis Link

Master of Science in Theoretical Physics
Utrecht University
September 2018 – July 2020 | Utrecht

- Focus on Field Theoretical Methods in Physics (Condensed Matter and Particle Physics). Extra Courses: Quantum Information Theory, Complex Systems, and String Theory.

Bachelor of Science in Physics
Groningen University
September 2015 – June 2018 | Groningen

- Focus on Theoretical Physics with Advanced Mechanics, Relativistic Quantum Mechanics and Symmetries in Physics courses

WORK EXPERIENCE

PostDoc
Aalto University
May 2025 – Present | Espoo

- Research on Quantum-Inspired Computational Methods.
- Teaching a PhD Course on Quantum-Inspired and Machine Learning Computational Methods for Quantum Science
- Co-supervision of Student Projects on Machine Learning and Quantum-Inspired Classical Computations for Condensed Matter Physics

PhD Candidate
Utrecht University
October 2020 – December 2024 | Utrecht

- Research on topological phases of matter.
- Co-supervision of master and bachelor theses
- Seminar Organization

Teaching Assistant
Utrecht University
2019 – 2024 | Utrecht

- Classical Mechanics
- Multivariable Calculus and Linear Algebra
- Classical Field Theory
- Quantum Field Theory
- Statistical Field Theory
- Field Theory in Condensed Matter

RESEARCH INTERESTS

- Tensor networks and quantum-inspired computation
- Machine learning for quantum science
- Topological, aperiodic, non-Hermitian, and strongly correlated systems

PUBLICATIONS

Google Scholar
ORCID

LANGUAGES

English	6/6
French	6/6
Dutch	6/6
Arabic	6/6
Italian	3/6
Spanish	2/6
Finnish	1/6

GENERAL SKILLS

Analytical · Academic writing · Social and Organizational · Presentations

Python · Julia · HPC · LaTeX · Inkscape

HOBBIES

Fitness · Reading · Traveling · Motorbike

Extended CV

Anouar Moustaj

Publication Summary

1. **TENSOR-NETWORK METHODOLOGY FOR SUPER-MOIRÉ EXCITONS BEYOND ONE BILLION SITES** – arXiv:2603.02011 (2026).
   Full list of authors: Anouar Moustaj, Yitao Sun, Tiago V. C. Antão, Lumen Eek, and José L. Lado.
   Short description: In this work, we develop a tensor-network methodology for computing excitonic spectra in large-scale quasicrystal and super-moiré systems. The method encodes the real-space Bethe-Salpeter Hamiltonian as a tensor network and combines it with a Chebyshev tensor-network algorithm, allowing access to excitonic Hamiltonians with dimensions up to 10^{18}. This makes it possible to compute bound-exciton spectral functions in systems exceeding one billion lattice sites while retaining full real-space resolution. We demonstrate the approach in one- and two-dimensional super-moiré systems, revealing exciton miniband formation, moiré-induced spatial confinement, and the simultaneous resolution of atomistic and mesoscopic structures in the excitonic spectra.

2. **PARITY-DEPENDENT DOUBLE DEGENERACY AND SPECTRAL STATISTICS IN THE PROJECTED DICE LATTICE** – arXiv:2602.11844 (2026).
   Full list of authors: Koushik Swaminathan, Anouar Moustaj, José L. Lado, and Sebastiano Peotta.
   Short description: In this work, we investigate the spectral statistics of an interacting fermionic system obtained by projecting the Hubbard interaction onto the two lowest-energy degenerate flat bands of the dice lattice subjected to a π-flux. We show that the level-spacing and gap-ratio distributions depend on the parity of the particle number. For even particle numbers, the spectra follow the Gaussian Orthogonal Ensemble, consistent with a time-reversal-symmetric Hamiltonian. In contrast, the odd-particle sector exhibits exact double degeneracy of all eigenstates, even after resolving all known symmetries, with the spacing distribution between doublets described by the Gaussian Unitary Ensemble. This reveals the coexistence of distinct random-matrix ensembles within a single interacting flat-band system.

3. **TENSOR NETWORK APPROACH TO MOMENTUM-RESOLVED SPECTROSCOPY IN NON-PERIODIC SUPER-MOIRÉ SYSTEMS** – Phys. Rev. Research, accepted (2026).
   Full list of authors: Anouar Moustaj, Yitao Sun, Tiago V. C. Antão, and José L. Lado.
   Short description: In this work, we develop a tensor-network methodology to compute momentum-resolved spectral functions in large, non-periodic super-moiré systems at an atomistic level. The method encodes an exponentially large tight-binding problem as an auxiliary quantum many-body problem, which is then treated using a many-body kernel polynomial tensor-network algorithm combined with a quantum Fourier transform tensor network. We demonstrate the approach for one- and two-dimensional super-moiré systems, including cases with non-uniform strain, interactions treated at the mean-field level, and quasicrystalline super-moiré patterns. We also show that the method can compute spectral functions restricted to selected spatial regions, enabling the study of position-dependent electronic structure and minigaps relevant to quantum twisting microscope experiments.

4. **LATENT HALDANE MODELS** – Phys. Rev. B 111, 245106 (2025).
   Full list of authors: Anouar Moustaj, Lumen Eek, Malte Röntgen, and Cristiane Morais Smith.
   Short description: In this work, we explore how to construct a family of seemingly complicated two-dimensional models that result in energy-dependent Haldane models upon performing an isospectral reduction. In these models, we find energy-dependent latent Semenoff masses without introducing a staggered on-site potential. In addition, energy-dependent latent Haldane masses also emerge in decorated lattices with nearest-neighbor complex hoppings. Using the Haldane model's properties, we then predict the location of the topological gaps in the aforementioned family of models and construct phase diagrams to determine where the topological phases lie in parameter space.

5. **HIGHER-ORDER TOPOLOGY PROTECTED BY LATENT CRYSTALLINE SYMMETRIES** – SciPost Phys. 18, 061 (2025).
   Full list of authors: Lumen Eek, Malte Röntgen, Anouar Moustaj, and Cristiane Morais Smith.

Short description: We demonstrate that rotation symmetry is not essential for the existence of fractional corner charges in C_n-symmetric higher-order topological crystalline insulators. Instead, we show that a latent rotation symmetry, revealed through isospectral reduction, is sufficient. We introduce the concept of a filling anomaly for systems with latent crystalline symmetry and propose modified topological invariants. This generalizes the notion of higher-order topology in two dimensions, extending protection from explicit C_n symmetry to latent symmetry. Our findings are supported by model examples exhibiting non-trivial corner charges without C_n-symmetry, broadening the classification of topological crystalline insulators to include latent symmetries.

6. **ANOMALOUS POLARIZATION AND TOPOLOGICAL CHARGE PUMPING IN APERIODIC CHAINS** – Condens. Matter 2025, 10(1) (2025).
Full list of authors: Anouar Moustaj, Julius Krebbekx, and Cristiane Morais Smith.
Short description: In this work, we show that structural aperiodicity does not impede the ability to perform topological charge pumping in the insulating regimes of such systems. Depending on the pumping protocol, it seems like one can almost always pump charges across aperiodic 1D systems, except in a few cases. Additionally, we show that palindromic realizations of these systems exhibit anomalous polarization responses resulting from a bulk-boundary correspondence and a nontrivial quantized polarization. We probe various signatures such as the degeneracy of the entanglement spectrum and quantized Berry phases in different chains, each representing a distinct class of structural aperiodicity: the Fibonacci quasicrystal, the Tribonacci quasicrystal, the Thue-Morse chain and the Rudin-Shapiro chain.

7. **HALDANE MODEL ON A SIERPINSKI GASKET** – Phys. Rev. B 110, 245405 (2024).
Full list of authors: Zebedeus Osseweijer, Lumen Eek, Anouar Moustaj, Mikael Fremling, and Cristiane Morais Smith.
Short description: We study the topological phases of the Haldane model on a single Sierpi'nski gasket fractal. The fractal geometry generates multiple fractal gaps, a split flat band, and flux-induced gaps. Since conventional momentum-space invariants are inapplicable, we characterize the topology using a real-space Chern number and confirm the robustness of the topological states to disorder. Our phase diagrams reveal intricate patterns, contrasting with prior studies, and show that fractality significantly influences topological phases, offering a richer platform than conventional geometries.

8. **TOPOLOGICAL PHASES OF THE INTERACTING SU-SCHRIEFFER-HEEGER MODEL: AN ANALYTICAL STUDY** – Phys. Rev. B 110, 165145 (2024).
Full list of authors: Anouar Moustaj, Emanuele di Salvo, Chen Xu, Lars Fritz, Andrew Mitchell, Cristiane Morais Smith, and Dirk Schuricht.
Short description: In this project, we investigate the low-energy limit of the SSH chain near a phase transition to explore the impact of electron-electron interactions on the nontrivial phase, which is defined by a quantized, nonzero relative polarization density between sublattices. Since this is a 1D model, we can derive some exact results on the role played by interactions by using the properties of the Sine-Gordon model. We have derived the relationship between the fermionic field's scaling dimensions and the model's physical electric polarization.

9. **EMERGENT NON-HERMITIAN MODELS** – Phys. Rev. B 109, 045122 (2024).
Full list of authors: Lumen Eek, Anouar Moustaj, Malte Röntgen, Vincent Pagneux, Vassos Achilleos, and Cristiane Morais Smith.
Short description: In this work, we use recently developed graph-theoretical tools to design systems whose isospectral reduction – akin to an effective Hamiltonian – has the form of the Hatano-Nelson or non-Hermitian SSH models. In the reduced version, the couplings and on-site potentials become energy-dependent. We show that this leads to interesting phenomena such as an energy-dependent non-Hermitian skin effect, where eigenstates can simultaneously localize on either end of the systems with different localization lengths. Moreover, we predict the existence of various topological edge states pinned at non-zero energies with different exponential envelopes, depending on their energy.

10. **MULTIFRACTAL PROPERTIES OF TRIBONACCI CHAINS** – Phys. Rev. B 105, L180503 (2023).
Full list of authors: Julius Krebbekx, Anouar Moustaj, Karma Dajani, and Cristiane Morais Smith.
Short description: We introduce two one-dimensional tight-binding models based on the tribonacci substitution – the hopping and on-site tribonacci chains – which generalize the Fibonacci chain. A

perturbative real-space renormalization procedure is developed for both hopping and on-site models. We show that the two models are equivalent at the fixed point of the renormalization-group flow and that the renormalization procedure naturally gives the local resonator modes. Additionally, the Rauzy fractal, inherent to the tribonacci substitution, is shown to serve as the analog of conumbering for the tribonacci chain. The renormalization procedure is used to repeatedly subdivide the Rauzy fractal into copies of itself, which can describe the eigenstates in terms of local resonator modes. Finally, the multifractal dimensions of the energy spectrum and eigenstates of the hopping tribonacci chain are computed, from which it can be concluded that the tribonacci chains are critical.

11. **SPECTRAL PROPERTIES OF TWO COUPLED FIBONACCI CHAINS** – New J. Phys. 25 093019 (2023).
Full list of authors: Anouar Moustaj, Malte Röntgen, Christian V. Morfonios, Peter Schmelcher, and Cristiane Morais Smith.
Short description: We study two identical Fibonacci chains coupled to each other in different ways. We find that this setup allows for a rich variety of effects. Depending on the coupling scheme used, the resulting system (i) possesses an eigenvalue spectrum featuring a richer hierarchical structure compared to the spectrum of a single Fibonacci chain, (ii) shows a coexistence of Bloch and critical eigenstates, or (iii) possesses many degenerate eigenstates, each of which is perfectly localized on only four sites of the system. The latter is a realization of a perfectly flat band in a 1D quasiperiodic system.

12. **FIELD THEORETICAL STUDY OF DISORDER IN NON-HERMITIAN TOPOLOGICAL MODELS** – Phys. Rev. B 105, L180503 (2022).
Full list of authors: Anouar Moustaj, Lumen Eek, and Cristiane Morais Smith.
Short description: In this work, we provide a new method to analytically study the effect of disorder, using tools from quantum field theory applied to discrete models around phase-transition points. We investigate two different one-dimensional models, the paradigmatic non-Hermitian SSH model and a s-wave superconductor with imbalanced pairing. These analytic results are compared to numerical simulations in the discrete models. A universal behaviour is found for the two investigated models, namely that the systems are driven from a topological to a trivial phase for disorder strengths equal to about four times the energy scale of the model.

13. **EFFECTS OF DISORDER IN THE FIBONACCI QUASICRYSTAL** – Phys. Rev. B 104, 144201 (2021).
Full list of authors: Anouar Moustaj, Sander Kempkes, and Cristiane Morais Smith.
Short description: We study the properties of the one-dimensional Fibonacci chain, subject to the placement of on-site impurities. The resulting disruption of quasiperiodicity can be classified in terms of the renormalization path of the site at which the impurity is placed, which greatly reduces the possible amount of disordered behavior that impurities can induce. This means that a transition regime between quasiperiodic order and disorder exists, in which some parts of the system still exhibit quasiperiodicity while other parts start to be characterized by different localization behaviors of the wavefunctions.

Educational Activities

Course creation

I developed the PhD course *Machine Learning for and from Quantum Science* at Aalto University, supported by a local grant that I was awarded after proposing the course design. The course is project-based: students work in pairs to read a recent paper on a selected topic and reproduce some of its results, either in their original form or through a variation. They present their work through both an oral presentation and a fully reproducible computational report.

Student (co-)supervision

1. Summer internship of Jagoda Malag (Master in Theoretical Physics): *Time evolution of fractal structures with tensor networks* (2026).
2. Summer internship of Zeb Osseweijer (Master in Theoretical Physics): *Representing fractal structures with tensor networks* (2026).
3. Summer internship of Tafhimul Hasan (Bachelor in Quantum Technology): *Supervised learning of mobility edges* (2026).
4. Special Assignment of Milla Kolehmainen (Master in Applied Mathematics): *Representing aperiodic order with tensor networks* (2026).
5. Master thesis of Kasper Vespala (Master's in Engineering Physics): *Inferring Fermi surfaces from quasiparticle interference patterns in metals using generative diffusion models* (2025).
6. Bachelor thesis of Zeb Osseweijer (Physics and Chemistry double bachelor): *Topological phases of multiorbital electronic systems on a Sierpinski fractal lattice* (2024).
7. Master thesis of Julius Krebbekx (Theoretical Physics and Mathematics double master): *Multifractal Properties of Tribonacci Chains* (2023)
8. Master thesis of Lumen Eek (Theoretical Physics and Applied Physics double master): *Topology and disorder in non-Hermitian physics* (winner of the Lorentz prize for the best master thesis in theoretical physics in the Netherlands). (2022).

Teaching Assistance

1. Classical Mechanics (2019)
2. Multivariable Calculus and Linear Algebra (2020)
3. Field Theory in Condensed Matter (2021)
4. Quantum Field Theory (2021-2022)
5. Statistical Field Theory (2022-2023)
6. Classical Field Theory (2024)

Lecture Material

1. I replaced two professors to teach a series of lectures on topological insulators for a master course in condensed matter physics. The lectures and exercises were made from scratch.
2. I co-organized the CMES (Condensed-Matter Educational Seminar), where a PhD student gives a few lectures on a topic to their fellow PhD students and advanced master students. I lectured on topological insulators, focusing on the Haldane model as the "hydrogen atom" of topological matter.
3. I wrote a solution set for the general undergraduate physics book Mazur, E. (2022). *Principles and practice of physics*. Pearson.

Conferences, Workshops, and Seminars

Overview of Talks, Posters, and Conferences/Workshops/Seminars Attended

Name	Location/date	Presentation
NWO Physics	Veldhoven 2021 (online)	None
TOPCORE Meeting	Amsterdam 2022	Talk
CECAM topological phases in condensed matter and cold atom systems	Cargèse 2022	Poster
Topological connections between Japan & Netherlands	Utrecht 2023	Talk
Condensed-Matter Student Seminar	Utrecht 2023	Talk
NWO Physics	Veldhoven 2023	Poster
PLaNET	Utrecht 2023	Talk
DRSTP School	Callantsoog 2023	Talk
Current topics in the nonequilibrium physics of quantum many-body systems	Göttingen 2023	Poster
Topological Matter School	San Sebastian 2023	Poster
QuMat Meeting	Nijmegen 2023	None
NWO Physics	Veldhoven 2024	Talk
DRSTP – Trends in Theory	Wageningen 2024	Poster
Conference for the 60th birthday of Cristiane Morais Smith	Les Houches 2024	Talk
QuMat Meeting	Enschede 2024	Talk
Quantum-Inspired Algorithms vs Quantum Computers	Jyvaskyla 2025	None
International workshop on tensor networks	Grenoble 2025	Poster
Quantum Correlated Light and Matter	Espoo 2025	Poster
Quantum Materials in and out of Equilibrium	Bremen 2026	Poster
Aalto Physics Days	Espoo 2026	Talk
Interplay between neural and tensor networks	Grenoble 2026	Poster

Postgraduate Schools

- Galileo Galilei Institute's School for Statistical Field Theories – Florence 2022 (online)
- Dutch Research School for Theoretical Physics' Statistical Physics and Theory of Condensed Matter – Callantsoog 2022
- Galileo Galilei Institute's School for Statistical Field Theories – Florence 2023
- Dutch Research School for Theoretical Physics' Statistical Physics and Theory of Condensed Matter – Callantsoog 2023
- Topological Matter School – San-Sebastian 2023
- Quantum-Inspired Algorithms Versus Quantum Computers: New Computational Routes for Solving Chemistry, Atomic Physics and Correlated Matter Problems – Jyväskylä 2025

Organization of Seminars

- Member of the organizing committee of the bimonthly social gathering PLaNET (PhD Lunch and Non-Expert Talks), where a PhD student talks on a topic of his choice during lunch. On top of organizing it, I gave talks on two occasions: one was about the dark history of the Nobel-prize-winning physicist William Shockley, and one was about the development of the OpenAI company and its products, such as ChatGPT.
- Member of the organizing committee of the CMSS (Condensed-Matter Student Seminar), where we invite condensed-matter PhD students to give talks about their recent work. I presented our work on the spectral properties of coupled Fibonacci chains.

- Co-organized the TOPCORE meeting 2022 in Amsterdam: venue booking, catering, organization of talks, and invitation of external speakers.
- Co-organized the mini-symposium topological connections between Japan & Netherlands: organized talks and invited external speakers.