QLUSTER
Quantum and Classical Ultrasoft Matter

Dear Reader,

This third project year 2025, was the year of the last QLUSTER trainings and overall less collective student group activities. We finally recruited our tenth doctoral candidate, who is now at the University of Vienna working with Prof. Christos Likos.

This year students had to gain independence and each work in their respective fields. It was, however, also the year with many secondments, so individual collaborations between various nodes. Some of our students are now close to finishing their third year, some others still have many months to go, but there is a general feeling the project is now in an advanced stage.

The last training courses, that were celebrated this past year at HighFinesse, together with the industrial workshop, were the *industrial environment and applications training* and a *project management training*. The CECAM workshop was held in Vienna, as foreseen, and the our final QLUSTER international workshop has been programmed for November 30 – December 4, 2026. This is a mayor event to which we are all looking forward.

Best Regards,

Team QLUSTER

(Fig.) Left the QLUSTER computational work, organized through the CECAM. Right QLUSTER's tenth doctoral candidate Panagiotis Ilia now working at the University of Vienna node.

QLUSTER activities

This third year of our project was less packed with collective activities, because well, it takes a lot of work and effort to pass a thesis on a very specialized subject. Our students have been working hard to get their research going.

This Project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101072964.

We started this year with the consortium meeting on February 27 in San Sebastian. It was a mixed presential-online event. The day started of with a general introduction to the state of the project, followed by a discussion. This was continued after coffee, until lunch. After lunch the students each gave a presentation about the progress of their work.

For 2025, the only training events that were still on the to-do list for this year were the industrial training and the management skills course. Those were organized by our partner HighFinesse and held in Tübingen, their headquarters. Both activities were one-day events, thereby making up two very intense days with a long program for each day. The industrial training was composed of six 40 minutes talks, a 1:30 hour class and a poster session. The day ended 18:10 with a collective discussion and was followed by a group dinner at 19:30. The management course was a one-day course, where theory and practical exercises were combined.

(Fig.) The two training days at HighFinesse in Tübingen.

These days the consortium is looking into organizing the yearly consortium meeting – that will probably be held online – because it is easier to fit in everybody's busy schedule. Now that part of the students is in the final phase of their thesis, some need the time to do final simulations, experiments or just to start writing.

Scientific highlights

This third year there were multiple papers that came out within the context of the QLUSTER project. Some of those are highlighted here; for more, check out our webpage as specified below.

Collective cluster nucleation dynamics in 2D Ising quantum magnets

Philip Osterholz, Fabio Bensch, Shuanghong Tang, Silpa Baburaj Sheela, Igor Lesanovsky, Christian Groß, arXiv:2512.04656.

Strongly interacting many-body systems often show collective properties that are non-trivially related to the microscopic degrees of freedom. Collectivity is responsible for intriguing ground state properties, for example, in superconductors. However, collective effects may also govern the non-equilibrium response of quantum systems, not only in condensed matter physics but also in quantum field theories modeling the properties of our universe. Understanding emergent collective dynamics from first principles, in particular in non-perturbative regimes, is

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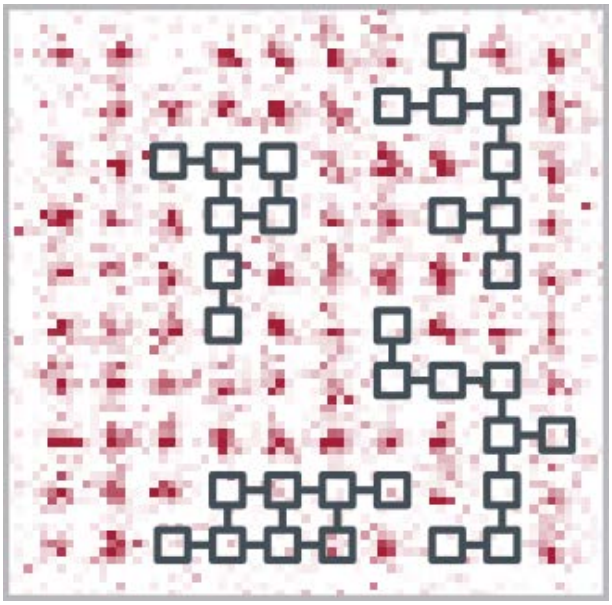
therefore one of the central challenges in quantum many-body physics. Here we report on the observation of collective cluster nucleation in 2D quantum Ising systems realized in an atomic Rydberg array. We observe a confined regime in which the steady-state cluster size is energy-dependent and a deconfined regime characterized by kinetically constrained dynamics of cluster nucleation. Our results mark a qualitative leap for quantum simulations with Rydberg arrays and shed light on highly collective non-equilibrium processes in one of the most important textbook models of condensed matter physics with relevance from quantum magnets and the kinetics of glass formers to cosmology.



The team at the University of Tübingen has experimentally observed large spin-clusters in a two-dimensional quantum Ising magnet. The Ising magnet is formed by potassium Rydberg atoms in a 2d optical tweezer array. The observed collective clusters composed of up to 15 individual spins behave as one object identified by their size-dependent resonance frequency. Additionally, the team has studied the avalanche-like nucleation dynamics of unconfined spin clusters. The picture shows a single experimental image of the 2d array. Each red blob is the fluorescence of an atom in on spin state. Four clusters are found in this image and they are marked by the connected black squares. On the raw image, clusters are connected regions of flipped spins, that is, sites of missing fluorescence in the underlying spare-lattice. The distance between the lattice sites is 7 micrometers.

Coarse-Graining of Slit-Confined Star Polymers in Solvents of Varying Quality

Reyhaneh A. Farimani and Christos N. Likos, Macromolecules 2025, **58**, 21, 11827–11840.

We investigate star polymers with varying functionalities and under varying solvent conditions confined within a slit geometry. Our approach involves accurately estimating and validating the effective interaction by directly computing the force between a pair of star polymers and comparing the radial distribution function from monomer-resolved molecular dynamics simulations with that obtained through Monte Carlo simulations using the effective interaction. Our findings reveal significant sensitivity in the radial distribution function to subtle variations in the tail of the interaction potential, particularly in dilute regimes. Furthermore, we employ a morphological model to analyze the interpenetration of the star polymers. We establish that solvent quality has minimal impact on the degree of interpenetration, whereas the star functionality affects it markedly, leading to enhanced faceting and reduced interpenetration for the number of arms grows. These results are particularly relevant for enhancing our understanding of polymeric materials' rheological and mechanical properties.

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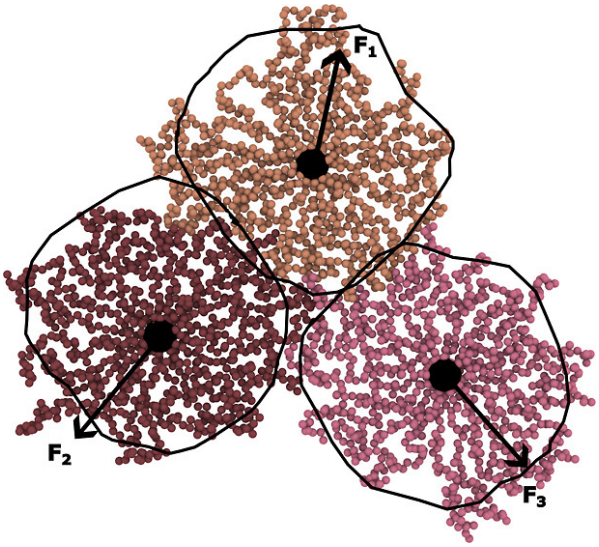
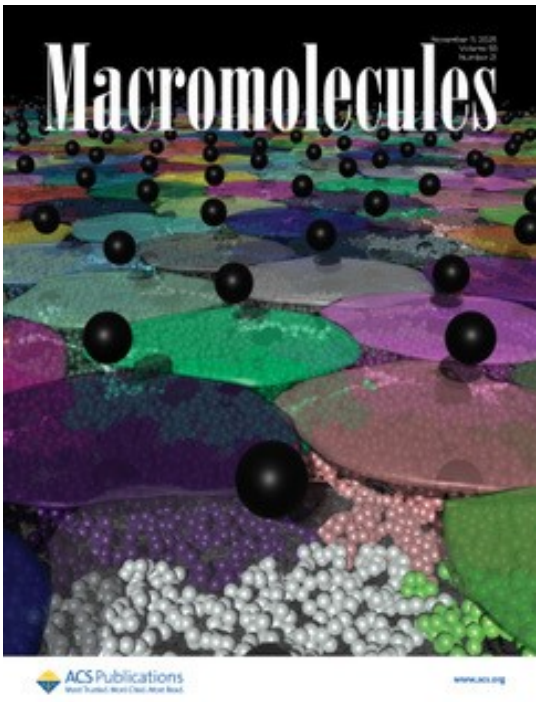


Three slit-confined star polymers. Star polymers confined within a slit are investigated across various solvent qualities and numbers of arms using a two-level coarse-graining approach. The image features: monomer-resolved configurations that reveal confinement-induced conformations; a morphological coarse-graining that simplifies the monomer configuration into a simple shape/surface mesh, emphasizing interpenetration and faceting in dense solutions; and, finally, a pair potential representation that encapsulates thermodynamic and structural information while omitting details related to deformation and overlap.



Cover art of the article appeared on this volume's cover: artists impression of slit-confined star polymers.

Numerical insights on the volume phase transition of thermoresponsive hollow microgels,

Leah Rank and Emanuela Zaccarelli, Soft Matter 2025, **21**, 3979.

Hollow microgels, consisting of a pNIPAM polymer network with a central cavity, have significant potential due to their tunable softness and encapsulation capabilities. Using molecular dynamics simulations, we thoroughly characterise the swelling behaviour of neutral hollow microgels across the volume phase transition (VPT) upon varying crosslinker concentration, shell thickness, and size. In particular, we examine in detail the onset of cavity filling and its relation to the VPT, detecting the presence of a discontinuity in the radius of gyration of the microgels, if an appropriate balance between shell stiffness and thermo-responsiveness is reached. The discontinuity is, however, absent in the behaviour

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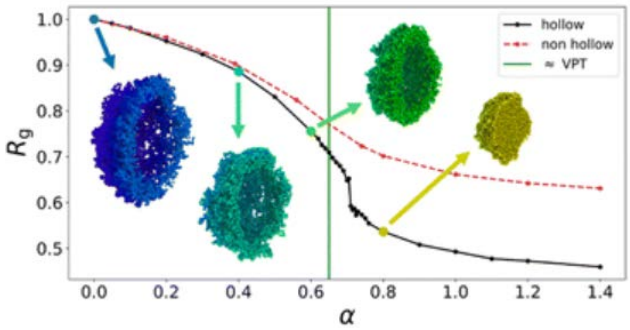
of the hydrodynamic radius, in agreement with experimental observations. We then test our numerical model by direct comparison of form factors with available measurements in the literature and also establish a minimal-size, stable hollow microgel for future computationally feasible bulk investigations. Overall, our findings provide valuable insights into the fundamental swelling properties of hollow microgels that can be useful to control the opening and closing of the cavity for application purposes.



Radius of gyration as a function of effective temperature parameter (alpha) for hollow and non-hollow microgels. The Volume Phase Transition (VPT) is indicated by the green line.

All QLUSTER's publications can be found on the website of Digital CSIC dedicated to the project: https://digital.csic.es/cris/project/pj00278

All news on activities can be found on our News page: https://www.qluster-horizon.eu/blog

You're always welcome to send us an email at qluster.project@gmail.com

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