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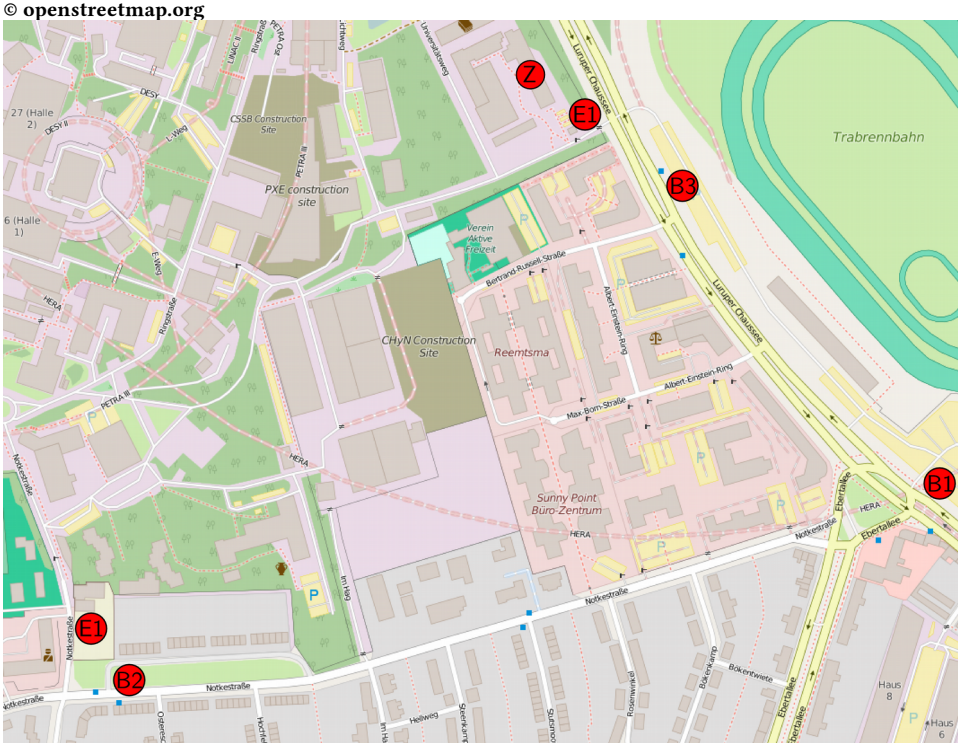
CUI Young Researchers Workshop 2020

# Frontiers in nonequilibrium dynamics of multicomponent systems in the few- to many-body crossover

February 10 - 12, 2020
Center for Optical Quantum Technologies
University of Hamburg

# Directions






Z: Center for Optical Quantum Technologies (building 90, ZOQ), Luruper Chaussee 149, 22761 Hamburg
B1: Bus stop *Trabrennbahn Bahrenfeld*, lines 1,2,3
B2: Bus stop *Zum Hünengrab (DESY),* line 1
B3: Bus stop *Luruper Chaussee/DESY,* line 2
E1: Main entrance to the DESY campus
E2: Side entrance to the DESY campus

**Coming from the airport or Altona train station:**
Take the train S1 to *Othmarschen* and then the bus 1 to *Zum Hünengrab* (B2). For more information on directions and the Hamburg public transport, please contact us or check www.hvv.de.

# Schedule

## Monday 10/02

8:30 *Welcome and introduction to the workshop*

9:00 Bo Huang (Innsbruck) [p. 5]
*Impurities in a Fermi sea: from BEC to single bosons*

10:00 *Coffee Break*

10:30 Magnus Graf Skou (Aarhus) [p. 5]
*Dynamics of quantum impurities towards formation of the Bose polaron*

11:30 Georgios M. Koutentakis (Hamburg) [p. 6]
*Orthogonality catastrophe of the repulsive 1D polaron*

12:30 *Lunch*

14:30 Artem G. Volosniev (IST Austria) [p. 7]
*Impurity-impurity interactions induced by one-dimensional quantum gases*

15:30 *Coffee Break*

16:00 Luis A. Peña Ardila (Hannover) [p. 7]
*From single to interacting polarons in Bose-Einstein condensates*

17:00 *Lab Tour*

## Tuesday 11/02

9:00 Quentin Bouton (Kaiserslautern) [p. 8]
*Single-atom quantum probes for ultracold gases boosted by nonequilibrium spin dynamics*

10:00 *Coffee Break*

10:30 Fabian Grusdt (LMU Munich) [p. 9]
*Dynamical meson formation in strongly correlated quantum matter*

11:30 Gerhard Zürn (Heidelberg) [p. 9]
*Glassy dynamics in a disordered Heisenberg quantum spin system*

12:30 *Lunch*

14:30 Arturo Camacho-Guardian (Aarhus) [p. 10]
*Strongly interacting polaron-polaritons*

15:30 *Coffee Break*

16:00 Kristian Knakkergaard Nielsen (Aarhus)[p. 11]
*Superfluid flow of polaron-polaritons above Landau's critical velocity*

17:00 *Poster Session*

18:00 *Pizza*

## Wednesday 12/02

9:00 Christof Weitenberg (Hamburg)[p. 11]
*Prospects for engineering anyons in atomic few-body systems*

10:00 *Coffee Break*

10:30 Panos Giannakeas (Max-Plank Dresden) [p. 12]
*Efimov physics in strongly mass-imbalanced ultracold gases*

11:30 Maximilian Prüfer (Heidelberg)[p. 13]
*Universal dynamics and the quantum effective action for ultracold gases far from equilibrium*

12:30 *Lunch*

14:00 Miguel Ángel García-March (Valencia)[p. 13]
*Open quantum systems approach to Bose polaron problems and applications in quantum sensing and phononics*

15:00 *Departure*

## Monday 10/02

8:30 am - 9:00 am ***Welcome and introduction to the workshop***

9:00 am – 10:00 am

**Bo Huang**
**Institute for Quantum Optics and Quantum Information (IQOQI) and Institute for Experimental Physics and Center of Quantum Physics, University of Innsbruck**

***Impurities in a Fermi sea: from BEC to single bosons***

Ultracold quantum gases offer a well-controllable environment to study the phases and dynamics of multicomponent mixtures. The intra- and interspecies scattering lengths can be conveniently tuned from the weak to the strongly interacting regime with the aid of Feshbach resonances. In our Bose-Fermi mixture experiment on K-41 and Li-6, we study the properties of a small cloud of bosons immersed in and interacting with an extended Fermi sea. Here, we first present our results on the limit of high boson density, where bosons form a BEC in the Fermi sea. By measuring the K-K-Li three-body loss rate for varying interspecies repulsion, we observe phase-separation and analyze the remaining overlap between components [1]. We further study the dynamics of phase-separated Bose-Fermi mixtures by measuring the breathing mode frequency of the BEC across the phase transition [2]. In the second part of the talk, I will discuss our ongoing research involving reduced boson densities, which finally connect to polaron physics in the limit of single-impurity.

[1] Lous, *et al.*, Phys. Rev. Lett. **120**, 243403 (2018).
[2] Huang, Fritsche, *et al.*, Phys. Rev. A **99**, 041602 (2019).

10:00 am - 10:30 am ***Coffee Break***

10:30 am - 11:30 am

**Magnus Graf Skou**
**Institute for Physics and Astronomy, University of Aarhus**

***Dynamics of quantum impurities towards formation of the Bose polaron***

The non-equilibrium impurity dynamics in an ultra-cold bosonic gas constitutes a challenging and fundamental question. We employ a novel interferometric scheme to investigate such dynamics using spin impurities interacting with a 39K Bose-Einstein condensate. This grants access to the quantum coherence of the impurity and allows for its ultrafast dynamical evolution to be resolved below the degeneracy time scale. With the versatile tool of Feshbach resonances the dynamics are measured from weak-coupling to strong interactions and across unitarity. We observe an initial universal evolution governed by unitarity limited scattering between the impurity and the medium. For weak interactions this is followed by a dynamical crossover to a weak-coupling regime. Both of these regimes can be described using simple power laws with different exponents despite the complexity of the system. Furthermore, we observe the emergence of many-body physics signalling the onset of Bose polaron formation. The results are compared with pertubative predictions in the weak-coupling regime and a rigorous model valid for short times for all interactions, obtaining excellent agreement.

11:30 am - 12:30 am

**Georgios Koutentakis**
**Center for Quantum Optical Technologies and CUI: Advanced imaging of matter, University of Hamburg**

***Orthogonality catastrophe of the repulsive 1D Bose Polaron***

We unravel the dynamical response of one-dimensional Bose-Einstein Condensates (BEC) coupled to one or two impurities of either bosonic or fermionic flavor. By quenching the BEC-impurity repulsions to weak interaction strengths a stable polaronic excitation is revealed, that is well-described within an effective potential picture. However, as the interaction strength is increased the impurities are expelled from the spatial extent of their BEC environment and the time-evolved many-body state of the composite system becomes almost orthogonal to the initial one even for short times after the quench. This effect referred to as orthogonality catastrophe is theoretically studied in detail by employing Ramsay and pump-probe spectroscopy, shedding light on the dynamical formation, induced interactions and the fate of quasi-particle excitations.

12:30 pm - 2:30 pm ***Lunch***

2:30 pm – 3:30 pm

**Artem G. Volosniev**
**Institute of Science and Technology (IST) Austria**

***Impurity-impurity interactions induced by one-dimensional quantum gases***

Impurity particles in an environment experience modification of their bare interaction potentials. For instance, one can find systems in which electronic polarons, even in spite of their fermionic nature and Coulomb repulsion, form an in-medium bound state – bipolaron, the quasiparticle, which might play a role in the properties of high-temperature superconducting materials.

This talk focuses on induced interactions between impurities immersed in one-dimensional quantum gases. These interactions are used to interpret ground state energies of degenerate gases with two impurity particles, and the quench dynamics of two impurities in a Bose gas. It is shown that effective two-body models can be used to study many-body systems with two impurities, provided that the impurities interact weakly with the environment.

*3:30 pm - 4:00 pm* ***Coffee Break***

4:00 pm - 5:00 pm

**Luis A. Peña Ardila**
**Institute for Theoretical Physics, Leibniz University**

***From single to interacting polarons in Bose-Einstein condensates***

Mobile impurities in a Bose-Einstein condensate can form quasi-particles termed Bose polarons. Here, we show how these quasi-particles are originated when a single impurity is dressed by the excitations of the quantum bosonic bath. The most striking advantage of these polarons is the huge degree of controllability of the coupling strength between the impurity and the bosonic bath. Thus, one can realize polarons from weak all the way up to the strong interacting regime. Comparisons with experiments are shown. For strong interactions two polaron can bind together forming a two body-bound state: bipolaron. They emerge due to the induced nonlocal interaction mediated by density oscillations of the bath.

Polarons bound–state displays a more important role in low dimensions. In particular, polarons can form many-body bound states even at intermediate coupling. This feature is completely unique in two-dimensional geometries.

Here, we use exact QMC to study an impurity immersed in a 2D superfluid and to compute the polaron energy, the effective mass and the quasiparticle residue for arbitrary coupling strength. We find important deviations of the quasiparticle properties from perturbation theory even at very weak coupling strengths. Commonly, an unexpected feature for polarons at weak coupling. Instead, in the strongly interacting regime, the ground-state polaron loses the quasiparticle nature characteristic of weak interactions and forms a many-body bound state featuring a large effective mass, a vanishing wave-function residue and a size that extends over many healing lengths of the bath. Finally, we will show some novel features appearing in polarons featuring long range interactions. In particular we will introduce ionic polarons.

5:30 pm – 8:00 pm ***Lab Tour***

## Tuesday 11/02

9:00 am - 10:00 am

**Quentin Bouton**
**Department of Physics and Research Center OPTIMAS, Technical University of Kaiserslautern**

***Single-atom quantum probes for ultracold gases boosted by nonequilibrium spin dynamics***

Quantum probes are atomic-sized devices mapping information of their environment to quantum mechanical states. By improving measurements and at the same time minimizing perturbation of the environment, they form a central asset for quantum technologies. In the talk, I will first present our experimental realization of single-atom quantum probes for local thermometry based on the spin dynamic of individual neutral Cesium (probe) atoms immersed into an ultracold gas (bath) of Rubidium atoms. By controlling microscopic atomic collisions, we map thermal information about the gas onto the quasi-spin population of the probe. Our probe is not restricted to measure temperature, but it allows sensing any mechanism affecting the total collisional energy in a spin exchange collision such as the magnetic field, realizing also local magnetometry. Second, I will show that having access to the dynamics of the microscopic process of motion-spin mapping allows us optimizing the information flow. Quantifying the sensitivity of our probe by the Quantum Fisher information, we find that it can outperform the steady-state limits setting the Cramér-Rao bound by roughly one order of magnitude.

10:00 am - 10:30 am ***Coffee Break***

10:30 am - 11:30 am

**Fabian Grusdt**

**Department of Physics and Arnold Sommerfeld Center for Theoretical Physics (ASC), Ludwig-Maximilians University (LMU) Munich**

***Dynamical meson formation in strongly correlated quantum matter***

Quantum gas microscopy provides a new perspective on strongly correlated quantum matter. Instantaneous projective measurements can reveal quantum fluctuations on all time scales, which allows access to high-energy properties. In this talk I show how these unique capabilities can be used to search for universal constituents of strongly correlated quantum matter, analogous to the search of elementary particles in high-energy physics. Specifically, I will focus on non-equilibrium dynamics of mobile impurities which reveal spinons and chargons in the doped Fermi-Hubbard or t-J model. Non-equilibrium impurity problems in a BEC and relations to traditional spectroscopic probes will also be discussed.

11:30 am - 12:30 am

**Gerhard Zürn**
**Physical Institute, University of Heidelberg**

***Glassy dynamics in a disordered Heisenberg quantum spin system***

Out of equilibrium systems with disorder can show extremely slow dynamics as for example known from spin glasses where the magnetization relaxes over several orders of magnitude in time [1]. To determine whether such glassy behavior persists for quantum many-body spin systems is challenging as solving for the unitary dynamics of the underlying Hamiltonian is hardly possible.

We address this question using Rydberg atoms where the spin degree of freedom is encoded into two electronically excited states. Spin-spin interactions arise from the van-der-Waals interactions between Rydberg atoms, while the disorder originates from the random positions of each atom in the sample. This

allows us to realizes a 3D Heisenberg XXZ spin Hamiltonian with power-law interaction.

In this talk experiments will be presented in which we observe relaxation towards a randomized state through the build up of entanglement between pairs of atoms not predicted by classical equations of motion [2].
We find an anomalous slow dynamics of the magnetization following a stretched exponential function with an exponent independent of the strength of disorder up to a critical value.

Our experiments and supporting numerical simulations beyond mean-field [3] suggest that slow dynamics described by stretched exponential decay is a generic property of disordered quantum spin systems.

[1] J. Bouchaud, Journal de Physique I **2**, 1705-1713, (1992).
[2] A. Signoles, *et al.*, arXiv:**1909.11959** (2020)**.**
[3] J. Schachenmayer, *et al.*, Phys. Rev. X **5**, 11022, (2015).

12:30 pm - 2:00 pm ***Lunch***

2:30 pm - 3:30 pm

**Arturo Camacho-Guardian**
**Department of Physics and Astronomy, University of Aarhus**

***Strongly interacting polaron-polaritons***

We develop a theory for the interaction of light with superfluid optical media, describing the motion of quantum impurities that are created and dragged through the liquid by propagating photons. The resulting many-body correlations are shown to have profound effects on the optical properties of the light. This gives rise to an interesting cross-over between two quasiparticles, the polaron-polariton and the polariton carrying light for weak and strong light-matter coupling respectively, with a complex and lossy mixture of photons and matter in between. We show that the polaritonic quasiparticles can traverse the superfluid well above Landau's critical velocity without being slowed down by its surroundings.

*3:30 pm - 4:00 pm* ***Coffee Break***

4:00 pm - 5:00 pm

**Kristian Knakkergaard Nielsen**
**Department of Physics and Astronomy, University of Aarhus**

***Superfluid flow of polaron-polaritons above Landau's critical velocity***

In his seminal work [1], Landau argued that an object can move through a superfluid without friction as long as it is slower than a certain critical velocity, namely the speed of sound of the superfluid. Above this speed the object will generate Cherenkov radiation and decelerate. In this talk, I will describe to you how the interaction of light with superfluid optical media can substantially alters this situation. Specifically, I will show how quantum impurities [2, 3] created and dragged through the liquid by propagating photons [4, 5] can lead to the formation of a new quasiparticle state — the polaron-polariton — which can traverse the superfluid well above Landau's critical velocity without being slowed down by its surroundings.

[1] L. Landau, Phys. Rev. **60**, 356–358 (1941).
[2] N. B. Jørgensen, *et al.*, Phys. Rev. Lett. **117**, 055302 (2016).
[3] M.-G. Hu, *et al.*, Phys. Rev. Lett. **117**, 055301 (2016).
[4] L. V. Hau, *et al.*, Nature **397**, 594(1999).
[5] M. Fleischhauer, and M. D. Lukin, Phys. Rev. A **65**, 022314 (2002).

5:30 pm – 8:00 pm ***Poster Session***

## Wednesday 12/02

9:00 am - 10:00 am

**Christof Weitenberg**
**Institute for Laser Physics and CUI: Advanced imaging of matter, University of Hamburg**

***Prospects for engineering anyons in atomic few-body systems***

Anyons are exotic particles, which differ from bosons and fermions in their statistical phase under exchange of two particles. They arise as quasi-particle excitations in fractional quantum Hall systems, but their direct observation is still challenging. A promising approach for microscopic access to anyons is the quantum simulation of the fractional quantum Hall effect with ultracold atoms. In these system, the large magnetic field can be created via a

rapid rotation of a harmonic trap and the strongly-correlated states can be probed via single-atom resolved imaging. The preparation of Laughlin states by adiabatically rotation frequencies close to the centrifugal limit seems realistic in the regime of few-body systems. Different protocols to probe the fractional statistics of the quasihole excitations have been proposed, including a spectroscopic signature by removing an atom into a different internal state or an interferometric signature by manipulating two quasiholes with optical tweezers. An alternative approach is the realization of the anyon-Hubbard model via a mapping to bosons with density-dependent Peierls phases. In this talk, I will present these ideas and discuss the experimental challenges and requirements on the way to a direct observation of anyons.

10:00 am - 10:30 am ***Coffee Break***

10:30 am - 11:30 am

**Panos Giannakeas**
**Max-Plank Institute for Physics of Complex Systems**

***Efimov physics in strongly mass-imbalanced ultracold gases***

The main premise of this talk is to highlight the Efimovian idiosyncrasies of three colliding atoms which uniquely emerge in a two-species ultracold gas. In this particular system the magnitude and the sign intra- and inter-species scattering lengths can render an inherently different Efimovian landscape. For example, recent studies on mass-imbalanced three-body collisions have demonstrated that the opposite sign of the intra- and inter-species scattering lengths results into recombination spectra which exhibit Efimov resonances intertwined with Stueckelberg suppression effects. Our current studies exploit these unique attributes of Efimov physics in mass-imbalanced systems by investigating the relevant scattering processes in atom-dimer gases. In particular, our analysis shows that the corresponding atom-dimer collisions are strongly enhanced when an Efimov bound state from the energetically closed three-body channel lies in the atom-dimer continuum, i.e. energetically open channel. Namely, our study demonstrates that in mass-imbalanced atom-dimer gases exists a series of atom-dimer resonances which fulfill a Fano-Feshbach scenario. In addition, we highlight the pivotal role of Stueckelberg physics on the width of the atom-dimer resonances where by adjusting the intra-species scattering length the atom-dimer continuum fully decouples from the Efimov

states. Finally, our analysis addresses the universal aspects of this type of atom-dimer resonances, as well as, the importance of the Van der Waals physics.

11:30 am - 12:30 am

**Maximilian Prüfer**
**Kirchhoff Institute for Physics, University of Heidelberg**

***Universal dynamics and the quantum effective action for ultracold gases far from equilibrium***

The number of parameters needed to specify the state of a many-body quantum system grows exponentially with the number of its constituents - this prevents an exact description of dynamics on the microscopic level as this task becomes computationally intractable. In this talk I will present quantum field theory methods which provide efficient descriptions for emerging macroscopic phenomena. With these we experimentally characterize a $^{87}$Rb spinor Bose gas far from equilibrium. By employing a quantum quench we bring the system far from equilibrium and for long times after the quench we observe universal dynamics associated to the emergence of a non-thermal fixed point [1]. In this regime the correlation function of the angular orientation of the transversal spin features rescaling in time and space. The spatially resolved read-out of the complex valued transversal spin field [2] allows the extraction of one-particle irreducible correlation functions, the building blocks of the quantum effective action [3]. We find a strong suppression of the four-vertex at low momenta emerging in the highly occupied regime.

[1] M. Prüfer, *et al*., Nature **563**, 217-220 (2018).
[2] P. Kunkel, *et al.*, PRL **123**, 063603 (2019).
[3] M. Prüfer, *et al.*, arXiv:**1909.05120** (2019).

12:30 pm - 2:00 pm ***Lunch***

2:00 pm - 3:00 pm

**Miguel Ángel García-March**
**Institute for Photonic Sciences (ICFO), The Barcelona Institute for Science and Technology**

***Open quantum systems approach to Bose polaron problems and applications in quantum sensing and phononics***

I will discuss the dynamics of one and two impurities in a homogeneous or trapped Bose-Einstein condensate (BEC) when the problem is approached with the quantum Brownian motion theory [1-4]. I will show that the long-time behavior is superdiffusive, when the impurities are untrapped. In case they are trapped, I discuss the realistic conditions for the final equilibrium state to be squeezed or to present entanglement in the case of two impurities. I discuss two applications: i) for quantum non-demolition thermometry in a BEC [5]; and ii) in phononics, to construct a system that permits a heat current between two BECs, and evaluate this system as a thermal diode [6].

[1] A. Lampo, *et al.*, Quantum **1**, 30 (2017).
[2] A. Lampo, *et al.*, *Quantum Brownian Motion Revisited* (Springer, 2019).
[3] A. Lampo, *et al.*, Phys. Rev. A **98,** 063630 (2018).
[4] C. Charalambous, *et al.*, Sci. Post **6,** 10 (2019).
[5] M. Mehboudi, *et al.*, Phys. Rev. Lett. 122, 030403 (2019).
[6] C. Charalambous, *et al.,* arXiv:**1905.02016** (2019).

## List of participants

| Name | Talk | Poster |
|---|---|---|
| Peña Ardila, L. A. | Mon, 16:00 | No |
| Białończyk, M. | No | Yes |
| Bougas, G. | No | Yes |
| Bouton, Q. | Tue, 9:00 | No |
| Camacho-Guardian, A. | Tue, 14:30 | No |
| Dobrzyniecki, J. | No | Yes |
| García March, M. Á. | Wed, 14:00 | Yes |
| Giannakeas, P. | Wed, 10:30 | No |
| Graf Skou, M. | Mon, 10:30 | Yes |
| Grusdt, F. | Tue, 10:30 | No |
| Huang, B. | Mon, 9:00 | Yes |
| K. Mukherjee | No | Yes |
| Knakkergaard Nielsen, K. | Tue, 16:00 | Yes |
| Koutentakis, G. M. | Mon, 11:30 | No |
| Liu, Y. | No | No |
| Mikkelsen, M. | No | Yes |
| Prüfer, M. | Wed, 11:30 | No |
| Schiffer, S. | No | Yes |
| Volosniev, A. G. | Mon, 14:30 | No |
| Weitenberg, C. | Wed, 9:00 | Yes |
| Zürn, G. | Tue, 11:30 | No |

## Accommodation

We have booked a single room in the DESY guesthouse from 9th to 12th of February for you. The hostel keys can be collected at the DESY main gatehouse (E1) any time after 2:00 pm.

**DESY guest house**
Notkestraße 85, 22607 Hamburg
hostel@desy.de, phone: (+49)408998-2740
For more information on the DESY guest house, please contact us or check http://guest-services.desy.de/

## Schedule Overview

| Time | Monday | Tuesday | Wednesday |
|---|---|---|---|
| 08:30 | Welcome | | |
| 09:00 | Huang | Bouton | Weitenberg |
| 10:00 | Coffee Break | | |
| 10:30 | Graf Skou | Grusdt | Giannakeas |
| 11:30 | Koutentakis | Zürn | Prufer |
| 12:30 | Lunch | | |
| 14:30 | Volosniev | Camacho-Guardian | García-March |
| 15:30 | Coffee Break | | Departure |
| 16:00 | Ardila | Knakkergard Nielsen | |
| 17:00 | Lab tour | Poster Session | |

## Contact

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**Workshop homepage**
https://www1.physik.uni-hamburg.de/en/forschung/institute/ilp/forschung/schmelcher/workshops/young-researchers-2020.html

## Acknowledgements

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