Frontiers in Ultracold Fermi Gases

90 years after the "birth" of fermions in Florence

Firenze (Italy), March 21st-23rd 2016

Conference Program

Monday 21st

9:00 – 9:45	Registration
9:45 – 10:00	Opening
10:00 – 10:45	**Rudolf Grimm** *Birth, life, and fate of a Fermi polaron*
10:45 – 11:15	Coffee break
11:15 – 12:00	**Gora Shlyapnikov** *Itinerant ferromagnetism in two-component Fermi gases*
12:00 – 12:45	**Martin Zwierlein** *Strongly Interacting Fermi Gases of Atoms and Molecules*
12:45 – 14:30	Lunch
14:30 – 15:15	**Carlo Di Castro** *From normal Fermi Liquid and its instabilities to its violations*
15:15 – 16:00	**Giacomo Roati** *Dynamics of strongly interacting atomic Fermi gases*
16:00 – 18:00	Coffee break + **Poster session**

Tuesday 22nd

Free morning	Those who are interested may attend the free public event "*Fermi a Firenze*" in Palazzo Vecchio, Salone dei Cinquecento, at 10:00. Talks (in Italian) by: **Roberto Casalbuoni** *Enrico Fermi: un genio del '900* **Massimo Inguscio** *Soffermiamoci sugli atomi più freddi dell'Universo*
13:30 – 15:00	Lunch
15:00 – 15:45	**Randy Hulet** *Quantum Magnetism with Ultracold Atoms*
15:45 – 16:30	**Jason Ho** *Realizing Non-Abelian Statistics with Ultra-cold Fermions*
16:30 – 17:00	Coffee break
17:00 – 17:45	**Hui Zhai** *Toward Majorana Fermions in Fermi Superfluids of Ultracold Alkali-Earth Atomic Gases*

Wednesday 23rd

9:45 – 10:30	**Tilman Esslinger** *Fermions in twisted lattices and quantum pinholes*
10:30 – 11:15	**Stefano Giorgini** *Dipolar systems of fermions: a quantum Monte-Carlo perspective*
11:15 – 11:45	Coffee break
11:45 – 12:30	**Giancarlo Strinati** *Vortex arrays in neutral trapped Fermi gases through the BCS–BEC crossover*
12:30 – 13:15	**Christophe Salomon** *Bose and Fermi Superfluids*
13:15 – 13:30	Concluding remarks
13:30 – 15:00	Lunch

Invited Talks

Rudolf Grimm (IQOQI & University of Innsbruck, Innsbruck, Austria)

Birth, life, and fate of a Fermi polaron

An impurity immersed in a Fermi sea is a very elementary situation in quantum many-body physics. The behavior of the resulting quasiparticles (Fermi polarons) lies at the heart of interesting phases of quantum matter, with broad interest ranging from strongly interacting Fermi gases in the normal phase and high-Tc superconductors to Kondo physics. A polaron's life strongly depends on the conditions of its interactions with its environment and exhibits a variety of intriguing phenomena.

Our model system is a small sample of K-40 atoms immersed in a large Fermi sea of Li-6 atoms. We control the interaction via an interspecies Feshbach resonance, with the additional possibility of extremely fast optical control. An interferometric detection scheme in the time domain enables us to unveil the full story of the polaron's life. The birth is observed on a short time scale of a few microseconds, directly set by the Fermi time. The polaron then lives with a well-defined quasiparticle energy, but undergoes a loss of coherence by thermal excitations. The polaron may finally decay into molecular excitations. A new chapter is opened by interpolaronic interactions mediated by the Fermi sea.

We briefly mention further new developments, like bosonic K-41 impurities in the Li-6 Fermi sea, and the creation of a novel Fermi-Fermi mixture of dysprosium and potassium atoms.

Gora Shlyapnikov (LPTMS, Orsay, France)

Itinerant ferromagnetism in two-component Fermi gases

I will discuss a one-dimensional two-component atomic Fermi gas with an infinite intercomponent contact repulsion. It will be shown that adding an attractive resonant odd-wave interaction breaking the rotational symmetry one can make the ground state ferromagnetic. A promising system for the observation of this itinerant ferromagnetic state is a 1D gas of 40K atoms, where 3D s-wave and p-wave Feshbach resonances are very close to each other and the 1D confinement significantly reduces the inelastic decay.

Martin Zwierlein (MIT, Cambridge, USA)

Strongly Interacting Fermi Gases of Atoms and Molecules

Ultracold Fermi gases of atoms realize the physics of strongly interacting fermions in a pristine environment, allowing for a microscopic view down to the resolution of one interparticle spacing and for the study of dynamics in real time. I will begin by reviewing several highlights in the study of Fermi gases near Feshbach resonances, in the crossover between Bose-Einstein condensation of tightly bound molecules and Bardeen-Cooper-Schrieffer superfluidity of long-range Cooper pairs. I will then describe the creation of homogeneous box potentials for Fermi gases and how one can directly obtain the equation of state of the homogeneous, unitary Fermi gas from such potentials. Another way to induce strong interactions in Fermi gases is their confinement into optical lattices. Here I will describe our Fermi gas microscope, allowing for the observation of fermions at the single-atom, single-site resolved level.

As a new direction I will present the creation of stable, dipolar fermionic molecules at ultralow temperatures, which hold great potential for quantum information applications and the realization of novel states of matter.

Carlo Di Castro (Università “La Sapienza”, Roma, Italy)

From normal Fermi Liquid and its instabilities to its violations

I will make an excursus on correlated eectron systems from normal Fermi Liquid and its instabilities (superconductivity, Anderson localization in the presence of interaction) to its violations (low dimensionality, singular interactions and coupling to soft critical modes).

The superconductive phase will be only recalled for some general features in relation with superfluidity and BEC.

The violation of Fermi Liquid by an effective interaction mediated by other critical fluctuations will be consdered in connection with the normal phase of high temperature superconductors.

Giacomo Roati (INO-CNR & LENS, Firenze, Italy)

Dynamics of strongly interacting atomic Fermi gases

We will present two paradigmatic and extreme experimental studies, exploiting strongly interacting ultracold Fermi gases of 6Li atoms confined in optical potentials.

In a first experiment, we create the analogous of a Josephson junction by bisecting BEC-BCS crossover superfluids with a thin optical barrier. We observe coherent dynamics in both the population and in the relative phase between the two superfluid reservoirs, extracting the Josephson coupling energy, which appears to be maximum for unitary superfluids. For critical parameters, we see how the Josephson dynamics is strongly affected by the presence of topological defects entering the superfluid bulk.

In a second experiment, we create an artificial ferromagnetic state by segregating degenerate spin mixtures into two initially disconnected reservoirs. We study the spin dynamics for different interaction strengths and temperatures. For sufficiently high values of the inter-spin repulsive interactions and at sufficiently low temperatures, we observe a time window during which spin diffusion is zeroed, that we interpret as signature of the Stoner instability in our system. Parallel to this, we reveal the ferromagnetic behaviour of the system by observing a softening of the spin dipole mode. At long evolution times, once the ferromagnetic state has relaxed onto lower energy states of the many-body system, our measurements provide exciting new insights into the behaviour of the spin drag coefficient within temperature regimes so far not accessed in previous experiments.

Randy Hulet (Rice University, Houston, USA)

Quantum Magnetism with Ultracold Atoms

Ultracold atomic gases confined to optical lattices have proven to be highly versatile and tunable systems for realizing novel quantum states of matter. We are using Fermi gases of 6Li atoms in our laboratory to explore several goals related to the strong correlations that arise in these systems. We have realized the Hubbard model, which has long been suspected of containing the essential ingredients of high temperature superconductivity. We measured the compressibility of the Mott insulating phase that occurs near half filling (1 atom/site), thus demonstrating the excitation gap of the Mott insulator [1]. Progress in this field, however, has been hampered by an inability to cool to low enough temperatures to achieve the most ambitious goals. To address this problem, we have developed the compensated optical lattice method to enable evaporative cooling in the lattice. With this method, we have cooled the Mott insulator sufficiently far to observe short-range antiferromagnetic correlations using Bragg scattering of light [2]. We are currently exploring new methods for entropy storage and redistribution to achieve even lower entropy in the antiferromagnetic phase.

[1] P. M. Duarte, R. A. Hart, T.-L. Yang, X. Liu, T. Paiva, E. Khatami, R. T. Scalettar, N. Trivedi, and R. G. Hulet, Physical Review Letters 114, 070403 (2015).

[2] Russell A. Hart, Pedro M. Duarte, Tsung-lin Yang, Xinxing Liu, Thereza Paiva, Ehsan Khatami, Richard T. Scalettar, Nandini Trivedi, David A. Huse, and Randall G. Hulet, Nature 519, 211 (2015).

Jason Ho (Ohio State University, Columbus, USA)
Realizing Non-Abelian Statistics with Ultra-cold Fermions

Non-abelian statistics is a higher dimensional generalization of the familiar statistics of bosons and fermions. It has been demonstrated theoretically to exist for the excitations of some exotic quantum systems. It is of great interests for fundamental reasons and for its possible applications to quantum computation. However, realization of these states remains difficult in solid state systems. I shall give a simple and explicit demonstration of the working of non-abelian statistics using ultra-cold fermions, and point out that fast rotating fermions in the quantum Hall regime is an ideal platform to realize this fascinating phenomenon.

Hui Zhai (Tsinghua University, Beijing, China)
Toward Majorana Fermions in Fermi Superfluids of Ultracold Alkali-Earth Atomic Gases

Spin-orbit coupling and fermion superfluidity are two essential ingredients toward topological superfluid and Majorana fermions. Spin-orbit coupling has been simulated by using the Raman process in alkali atoms, but it suffers from the heating problem due to spontaneous emission. Using very precise clock transition, spin-orbit coupling can also be realized in alkali-earth atoms between the ground and the clock state, in which hopefully the heating problem can be greatly suppressed. While to realize Fermi superfluid in alkali-earth atoms, Feshbach resonance is a necessary tool. Recently proposed and experimentally observed " orbital Feshbach resonance " (OFR) changes the conventional view that there is no magnetic field tunable resonance between these states, and makes the realization of Fermi superfluid in alkali-earth system possible. We further show that OFR has a flavor of narrow resonance because of which the Fermi superfluid transition temperature is even higher. Combining these two developments, we argue that it is quite promising to achieve topological Fermi superfluid with Majorana edge state in alkali-earth atomic gases.

Tilman Esslinger (ETHZ, Zurich, Switzerland)
Fermions in twisted lattices and quantum pinholes

The remarkable advances in cooling and manipulating atomic gases have opened up new avenues to explore fundamental ideas in quantum many-body physics. Control over parameters at a microscopic level makes it possible to tailor the properties of the experimental systems almost at will. In my talk I will illustrate the recent progress in creating topologically non-trivial systems and show how time-reversal symmetry can be broken in an optical lattice of honeycomb geometry. This enabled us to realize the topological Haldane model [1,2]. I will also report on a new generation of experiments in which the conduction of neutral atoms through a pinhole, - or quantum point contact -, is studied in normal and strongly correlated regimes [3-6].

[1] F.D.M. Haldane, Phys. Rev. Lett. 61, 2015 (1988).
[2] G. Jotzu, M. Messer, R. Desbuquois, M. Lebrat, T. Uehlinger, D. Greif, and T. Esslinger, Nature 515, 237 (2014).
[3] J.-P. Brantut, J. Meineke, D. Stadler, S. Krinner, and T. Esslinger, Science 337, 1069 (2012).
[4] S. Krinner, D. Stadler, D. Husmann, J.-P. Brantut, and T. Esslinger, Nature 517, 64 (2015).
[5] D. Husmann, S. Uchino, S. Krinner, M. Lebrat, T. Giamarchi, T. Esslinger, and J.-P. Brantut, Science 350, 1498 (2015).

Stefano Giorgini (University of Trento, Trento, Italy)
Dipolar systems of fermions: a quantum Monte-Carlo perspective

The physics of quantum degenerate gases with dipolar interactions is emerging as an active area of research in the field of ultracold atoms. Experimental efforts are following both the route of cooling atomic species with a large magnetic moment, such as Dysprosium and Erbium, and the one of producing heteronuclear molecules in their ground state which exhibit a large electric dipole moment. From the theoretical point of view, very peculiar and interesting many-body effects are expected in the regime where dipolar interactions dominate. I will review some recent work carried out using quantum Monte Carlo methods on the various phases of dipolar fermions in single and bilayer geometries. In particular, I will discuss in some details the Fermi liquid to Wigner crystal transition of a Fermi gas in two dimensions and the novel type of BCS-BEC crossover of fermions in a bilayer geometry.

Giancarlo Strinati (University of Camerino, Camerino, Italy)

Vortex arrays in neutral trapped Fermi gases through the BCS–BEC crossover

Vortex arrays in type-II superconductors reflect the translational symmetry of an infinite system. There are cases, however, such as ultra-cold trapped Fermi gases and the crust of neutron stars, where finite-size effects make it complex to account for the geometrical arrangement of vortices. We self-consistently generate these arrays of vortices at zero and finite temperature through a microscopic description of the non-homogeneous superfluid based on a differential equation for the local order parameter, obtained by coarse graining the Bogoliubov–de Gennes (BdG) equations. In this way, the strength of the inter-particle interaction is varied along the BCS–BEC crossover, from largely overlapping Cooper pairs in the Bardeen–Cooper–Schrieffer (BCS) limit to dilute composite bosons in the Bose–Einstein condensed (BEC) limit. Detailed comparison with two landmark experiments on ultra-cold Fermi gases, aimed at revealing the presence of the superfluid phase, brings out several features that make them relevant for other systems in nature as well [1].

[1] S. Simonucci, P. Pieri, and G. Calvanese Strinati, Nature Phys. 11, 941945 (2015).

Christophe Salomon (LKB ENS & CNRS, College de France, Paris, France)

Bose and Fermi Superfluids

As pioneered by Bose, Einstein, Fermi, and Dirac about 90 years ago, quantum statistics play a central role in establishing properties of matter. Many-body theories describe atoms, molecules, gases, liquids, and solids from the very high temperature case of neutron stars to the low temperature domain of liquid helium and dilute quantum gases.

Thanks to the tunability of the atomic interactions offered by magnetic Feshbach resonances, Bose and Fermi gases can be brought to the quantum degenerate strongly interacting regime. Using lithium isotopes, we have recently produced and studied a novel mixture of Bose and Fermi gases where both species are in the superfluid regime, one of the remaining challenges in Helium 4 -Helium 3 mixtures [1]. We probe the collective dynamics of this system by exciting center-of-mass oscillations (dipole modes) that exhibit extremely low damping below a certain critical velocity. Using high precision spectroscopy of these low-lying modes we observe coherent energy exchange and measure the coupling between the two superfluids. We have also measured the critical velocity for superfluid counterflow in this Bose-Fermi mixture as a function of interaction strength between fermions and temperature [2]. Near unitarity, in the phonon-dominated regime we find a critical velocity close to the speed of sound of the Fermi gas i.e much higher than the Bose gas speed of sound. We compare our findings with the recent prediction made for homogeneous Bose and Fermi gases and for weak Bose-Fermi coupling [3]. In this situation the critical velocity is predicted to be given by the sum of the sound velocities in the Bose gas and in the Fermi gas. Finally, raising the temperature of the mixture slightly above the superfluid transitions reveals an unexpected phase- locking of the Bose and Fermi center of mass oscillations. We interpret this phenomenon by mapping this system onto a Caldeira-Leggett model of two quantum harmonic oscillators coupled to a thermal excitation bath.

[1] I. Ferrier-Barbut, M. Delehaye, S. Laurent, A.T. Grier, M. Pierce, B.S. Rem, F. Chevy, C. Salomon, A Mixture of Bose and Fermi Superfluids, Science 345, 1035 (2014)

[2] M. Delehaye, S. Laurent, I. Ferrier-Barbut, S. Jin, F. Chevy, and C. Salomon, Critical Velocity and Dissipation of an ultracold Bose-Fermi Counterflow, Phys. Rev. Lett., 115, 265303, (2015)

[3] Y. Castin, I. Ferrier-Barbut, and C. Salomon, the Landau critical velocity for a particle in a Fermi superfluid, Comptes-rendus Physique 16, 241, (2015)

Posters

Matteo Archimi (Università di Pisa, Pisa, Italy)
Effects of strong interactions in cold Rydberg atoms

Gianluca Bertaina (Università di Milano, Milano, Italy)
One-dimensional liquid ^{4}*He and hard-core systems: dynamical properties beyond Luttinger liquid theory*

Alessia Burchianti (INO-CNR, Firenze, Italy)
Josephson effect and dissipative phase-slips in a fermionic superfluid

Giacomo Cappellini & Marco Mancini (Università di Firenze, Firenze, Italy)
Observation of orbital Feshbach resonances and chiral edge states in ultracold fermions

Vincent Corre (IQOQI, Innsbruck, Austria)
Toward Fermi Fermi mixtures of ultracold dysprosium and potassium atoms

Luca Dell'Anna (Università di Padova, Padova, Italy)
Combined effects of disorder and interactions in 2D fermionic systems and enhancement of critical temperatures

Marco Di Liberto (INO-CNR BEC Center, Trento, Italy)
Topological Varma superfluid in optical lattices

Lucia Duca (LMU, Munich, Germany)
Probing Bloch band geometry with ultracold atoms in a honeycomb lattice

Nick Flaeschner (Institut of Laser Physics, Hamburg, Germany)
Experimental Reconstruction of the Berry Curvature in a Floquet Bloch Band

Camille Frapolli (Laboratoire Kastler Brossel, Paris, France)
Two-step condensation in a spin-1 gas of sodium atoms

Isabella Fritsch (University of Innsbruck & IQOQI, Innsbruck, Austria)
Fermi-Bose Mixture of ^{6}*Li and* ^{41}*K*

Stefano Gherardini & Matthias Müller (LENS, QSTAR & Università di Firenze, Firenze, Italy)
Stochastic quantum measurements, Zeno and ergodicity on an atom chip

Emil Kirilov (University of Innsbruck, Innsbruck, Austria)
A new quantum gas apparatus for ultracold mixtures of K and Cs and KCs ground-state molecules

Luca Lepori (Università di Padova, Padova, Italy)
Rabi-coupled ultracold Fermi mixtures

Cosimo Lo Vecchio (LENS, Firenze, Italy)
Atom chip for Quantum Control

Guido Masella (INO-CNR, Pisa, Italy)
Progress towards the realization of a quantum degenerate gas of atomic Dysprosium

Nick Proukakis (Joint Quantum Centre & Newcastle University, Newcastle, UK)
Bose-Bose and Bose-Fermi Superfluid Mixtures

Liang Qi (Atominstitut - TU Wien, Wien, Austria)
Calorimetry of a Bose-Einstein Condensed Photon gas

Chunlei Qu (INO-CNR BEC Center, Trento, Italy)
Domain walls in coherently coupled Bose-Einstein condensates

Simona Scaffidi Abbate (Università di Firenze, Firenze, Italy)
Evidence of Quantum Phase Slips in 1D Atomic Superfluids

Giulia Semeghini (INO-CNR, Firenze, Italy)
Quantum phase transition with parity symmetry breaking and hysteresis

Luca Taddia (Scuola Normale Superiore & INO-CNR, Pisa, Italy)
Laughlin pumping with earth-alkaline-like ultracold fermions

Andreas Trenkwalder (INO-CNR, Firenze, Italy)
A new $^{6}Li^{53}Cr$ experiment

Andrea Trombettoni (CNR-IOM & SISSA, Trieste, Italy)
Fixed Points Structure & Effective Fractional Dimension for O(N) Models with Long-Range Interactions

Giacomo Valtolina (LENS & INO-CNR, Firenze, Italy)
Itinerant ferromagnetism in strongly repulsive atomic Fermi gases

RuGway WU (Atominstitut - TU Wien, Wien, Austria)
Towards phase measurement and quantum back-action in a double-well system