

ULTRACOLD ATOMS, QUANTUM OPTICS AND QUANTUM INFORMATION

QOT group of Maciej Lewenstein



ACTIVITIES

Quantum gauge theories
and ultracold atoms

Anomalous diffusion in
biological systems

Disordered
ultracold atoms

Ultracold dipolar gases

Frustrated
spin systems

Ultracold atoms and
quantum optics

Nano-optics and quantum
many-body physics

Quantum engineering

preparation, manipulation, and detection
of challenging states of matter

2D excitons gases

Attosecond physics

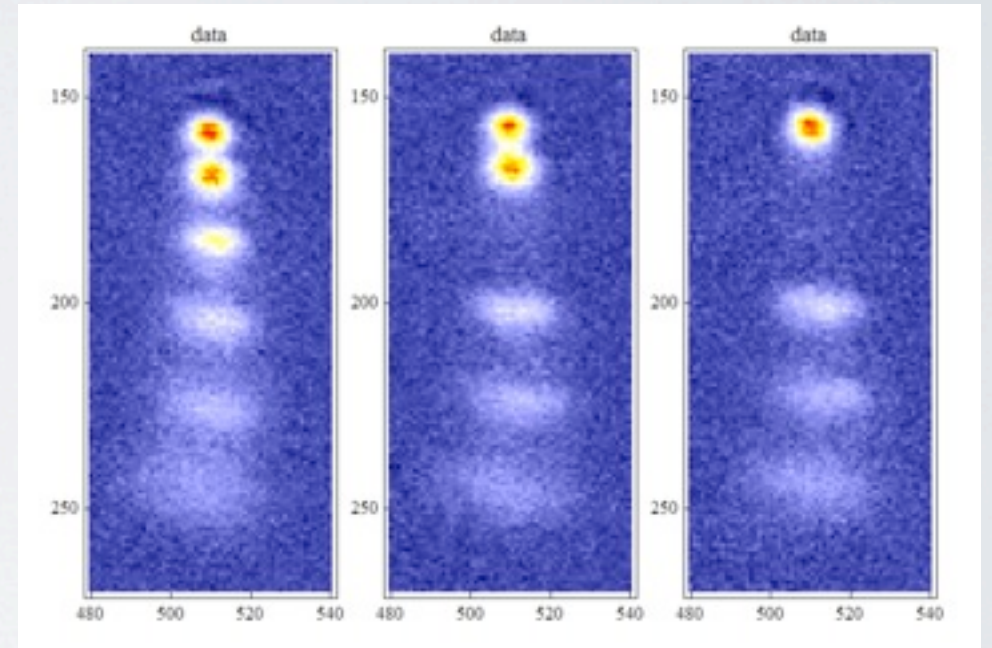
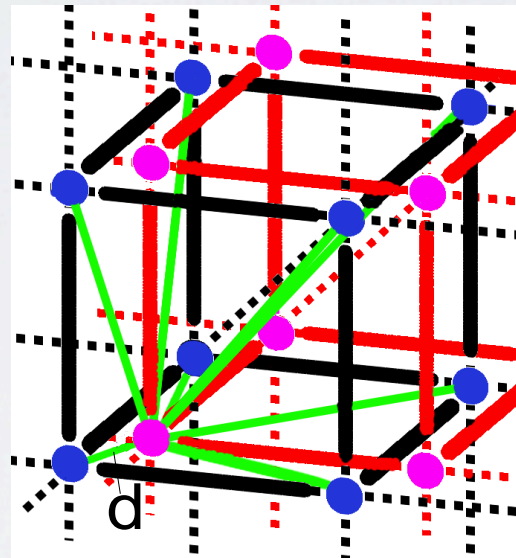
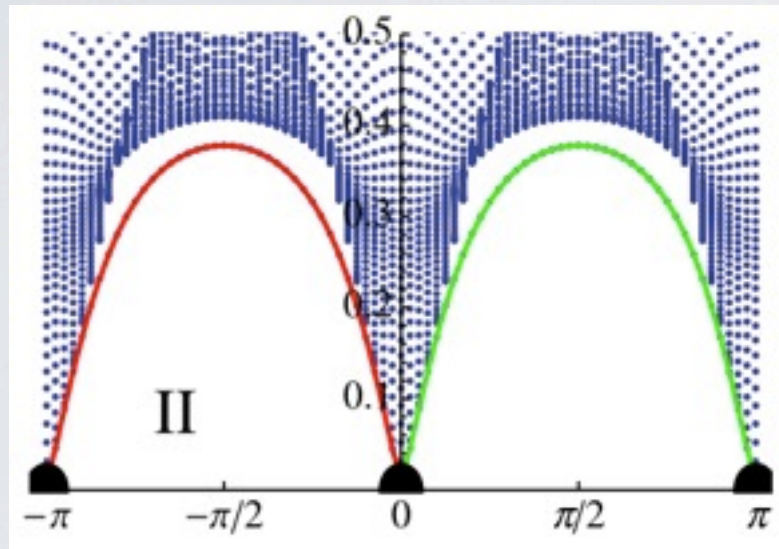
Spin-tonics
(spin-tronics with atoms)

Quantum information
theory

QUANTUM GAUGE THEORIES AND ULTRACOLD ATOMS

Synthetic gauge fields

- dynamic matter in static gauge fields (complex hoppings, but fixed from outside)
- IQH, FQH and QSH states
- relativistic dispersion relations (Dirac Hamiltonians), edge states, and Topological Insulators
- extra-dimensions: open, closed, and twisted b.c. in the spin



future directions:

- ▶ experimental realization of extra-dims
- ▶ quantum magnetism and spin liquids

(collaboration with LENS group)

relevant papers:

● *Fractional quantum Hall states of few bosonic atoms in geometric gauge fields*, B. Juliá-Díaz, T. Graß, N. Barberán, and M. Lewenstein, *New J. Phys.* 2012

● *Quantum simulation of an extra dimension*, O. Boada, A. Celi, M. Lewenstein, and J. I. Latorre, *PRL* 2012

● *Non-Abelian gauge fields and topological insulators in shaken optical lattices*, Philipp Hauke, Olivier Tieleman, Alessio Celi, Christoph Ölschläger, Juliette Simonet, Julian Struck, Malte Weinberg, Patrick Windpassinger, Klaus Sengstock, Maciej Lewenstein, and André Eckardt, *Phys. Rev. Lett.* 2012

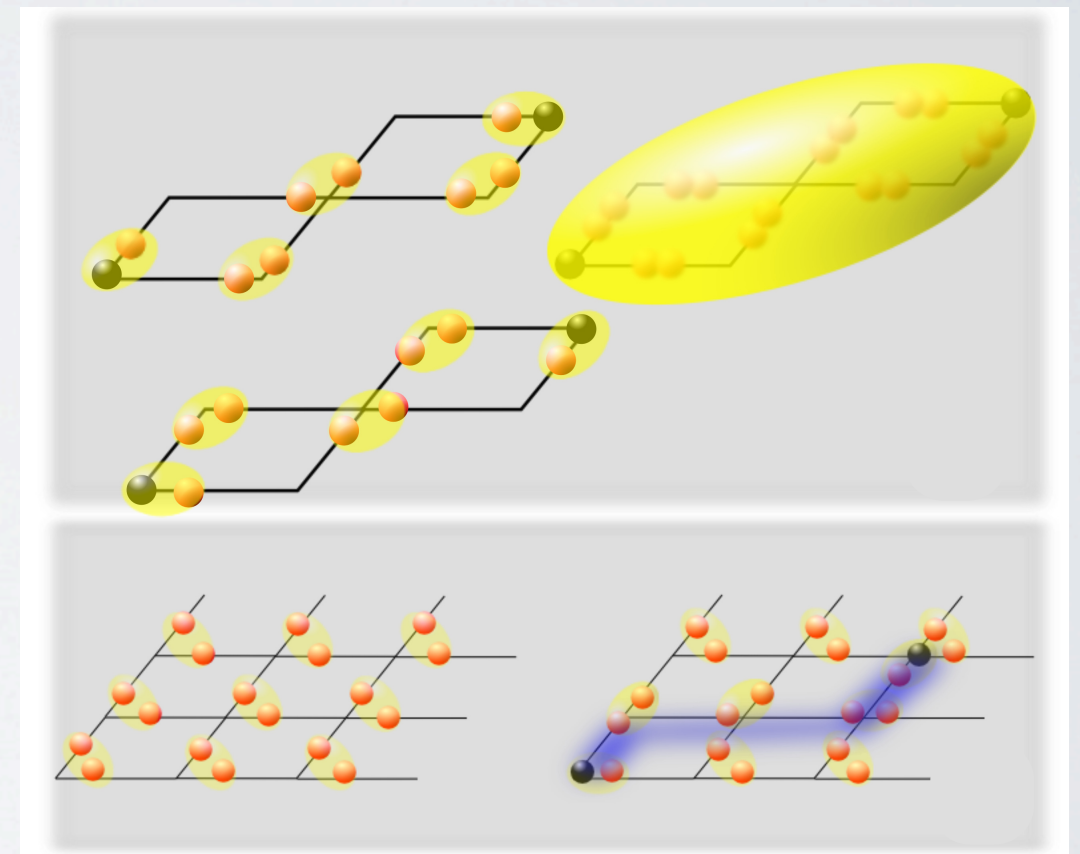
QUANTUM GAUGE THEORIES AND ULTRACOLD ATOMS

Dynamical gauge theories

- dynamic gauge fields with static matter/charges:
proposals for protocols to simulate Abelian and non-Abelian pure gauge theories with ultracold atoms in optical lattices
- emulate confinement of charges with ultra-cold atoms

future directions:

- ▶ implementation with trapped ions
- ▶ engineer dynamics for both gauge and matter fields



(collaboration with M. Mitchell)

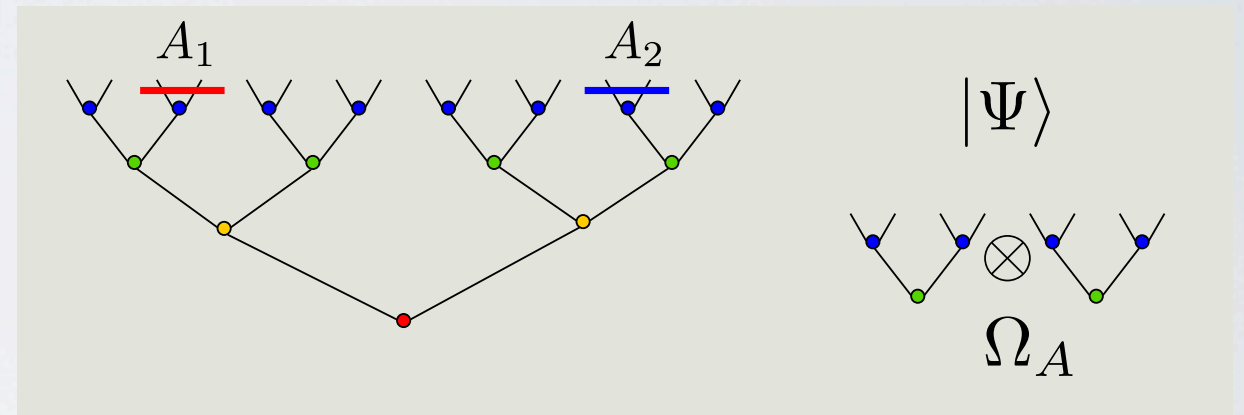
relevant papers:

- *Optical Abelian lattice gauge theories*, L. Tagliacozzo, A. Celi, A. Zamora, and M. Lewenstein Ann.Phys. 2013
- *Simulations of non-Abelian gauge theories with optical lattices*, L. Tagliacozzo, A. Celi, P. Orland, and M. Lewenstein, arXiv 2012

QUANTUM GAUGE THEORIES AND ULTRACOLD ATOMS

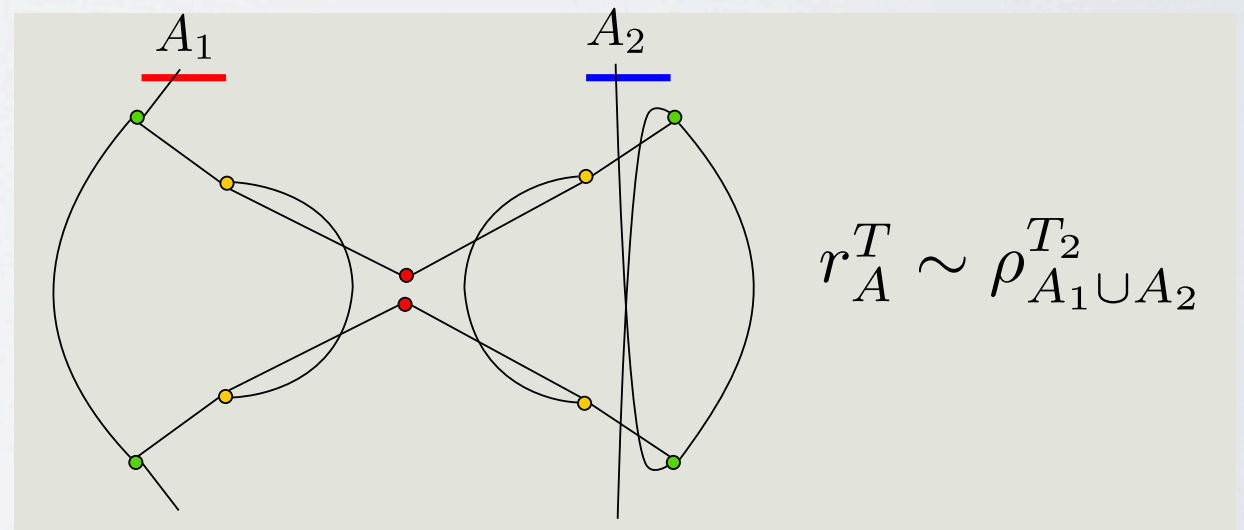
Tensor network techniques for many-body systems

- sophisticated numerics to investigate phase diagrams of interesting physical systems
- scaling of the negativity at quantum critical points
- out-of-equilibrium dynamics



future directions:

- ▶ characterize states obtained at equilibrium
- ▶ implement exact symmetries



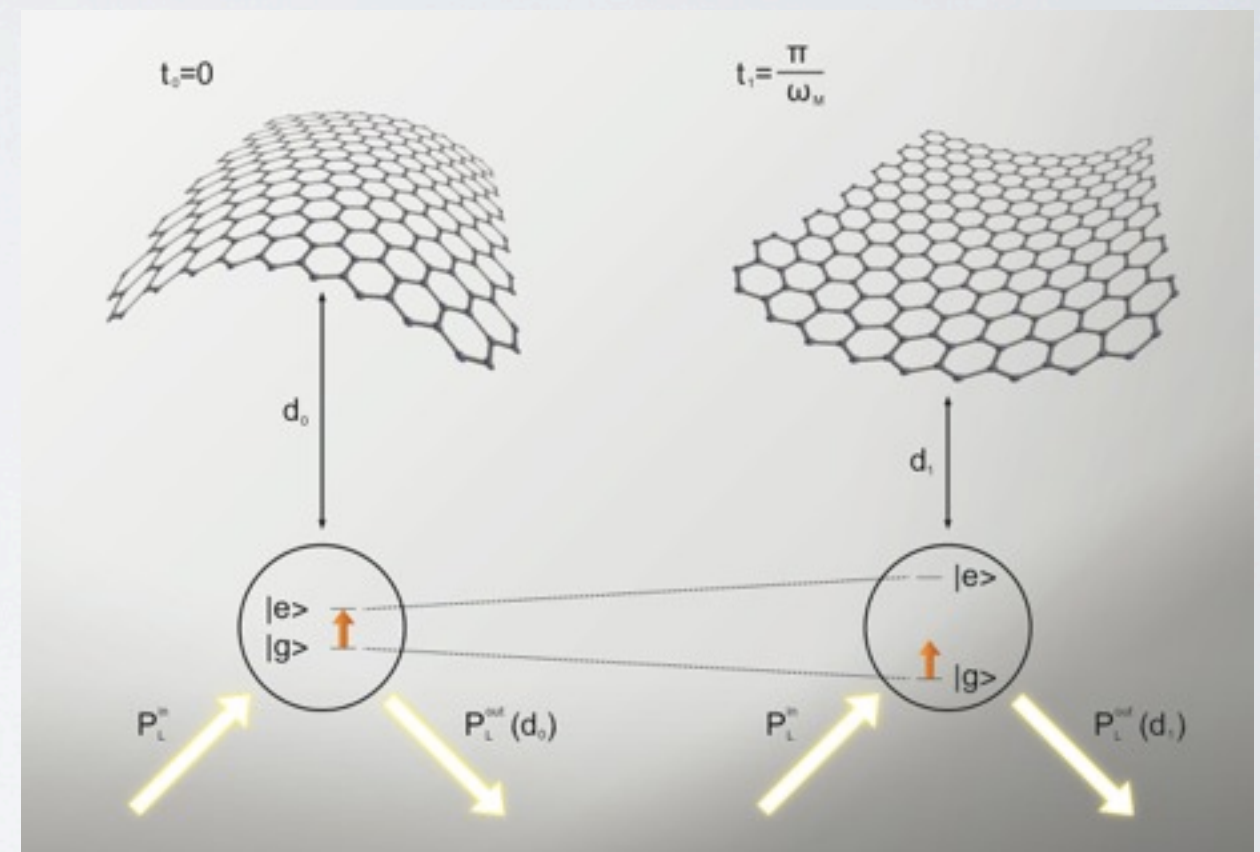
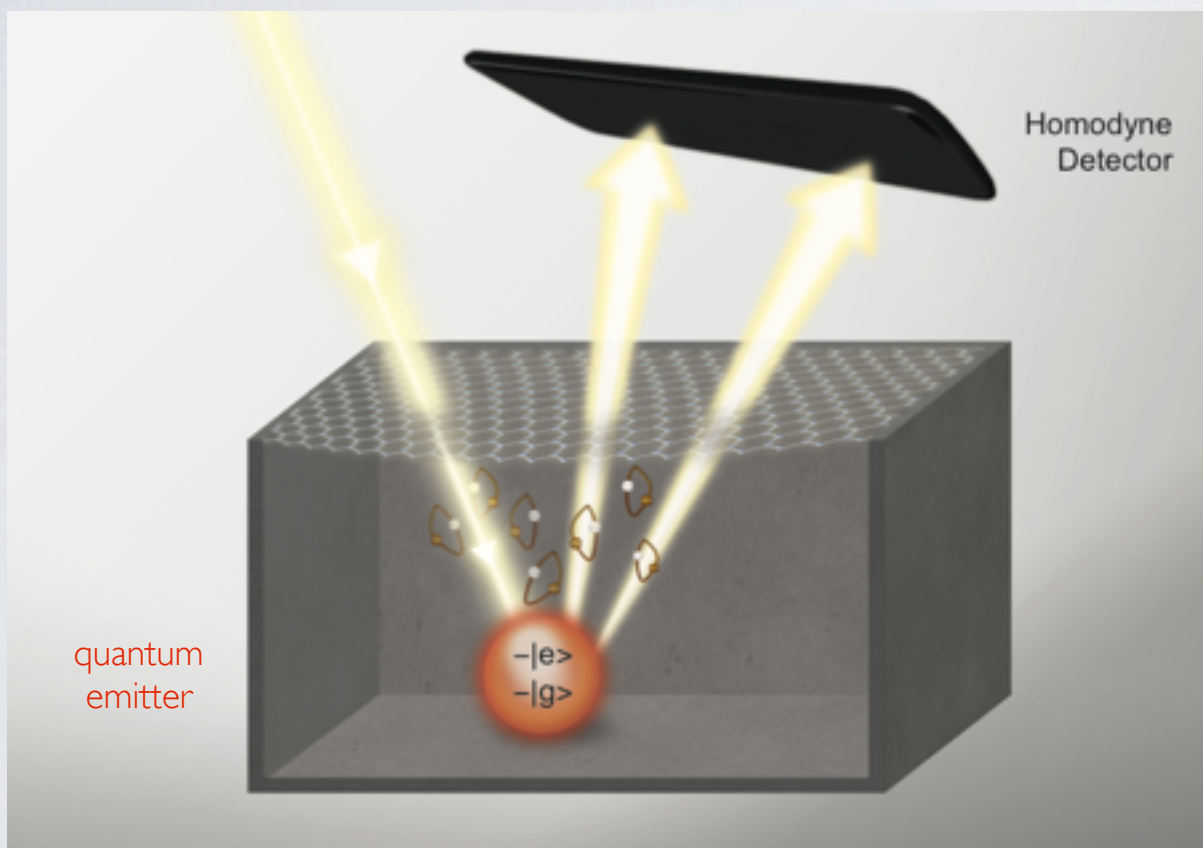
relevant papers:

- *Entanglement entropy for the long range Ising chain*, T. Koffel, M. Lewenstein, and L. Tagliacozzo, PRL 2012
- *Entanglement negativity in the critical Ising chain*, P. Calabrese, L. Tagliacozzo, and E. Tonni, arXiv 2013

NANO-OPTICS

Quantum sensing of graphene motion

- use vacuum forces for fast and precise position measurements of graphene
(none of the existing methods applies to graphene)
- position squeezed states of a graphene sheet: a valuable resource for quantum metrology
- useful scheme for a precise study of Casimir and vacuum forces



- ▶ vacuum forces are extremely strong at short distances. Turn a nuisance (it leads to “stiction” and prevents trapping of atoms close to surfaces) into an opportunity.
- ▶ experiment to be performed at ICFO (collaboration with F. Koppens and A. Bachtold)

relevant papers:

© C. Muschik, S. Moulieras, M. Lewenstein, F. Koppens and D. Chang, in preparation

SPIN-TOMICS

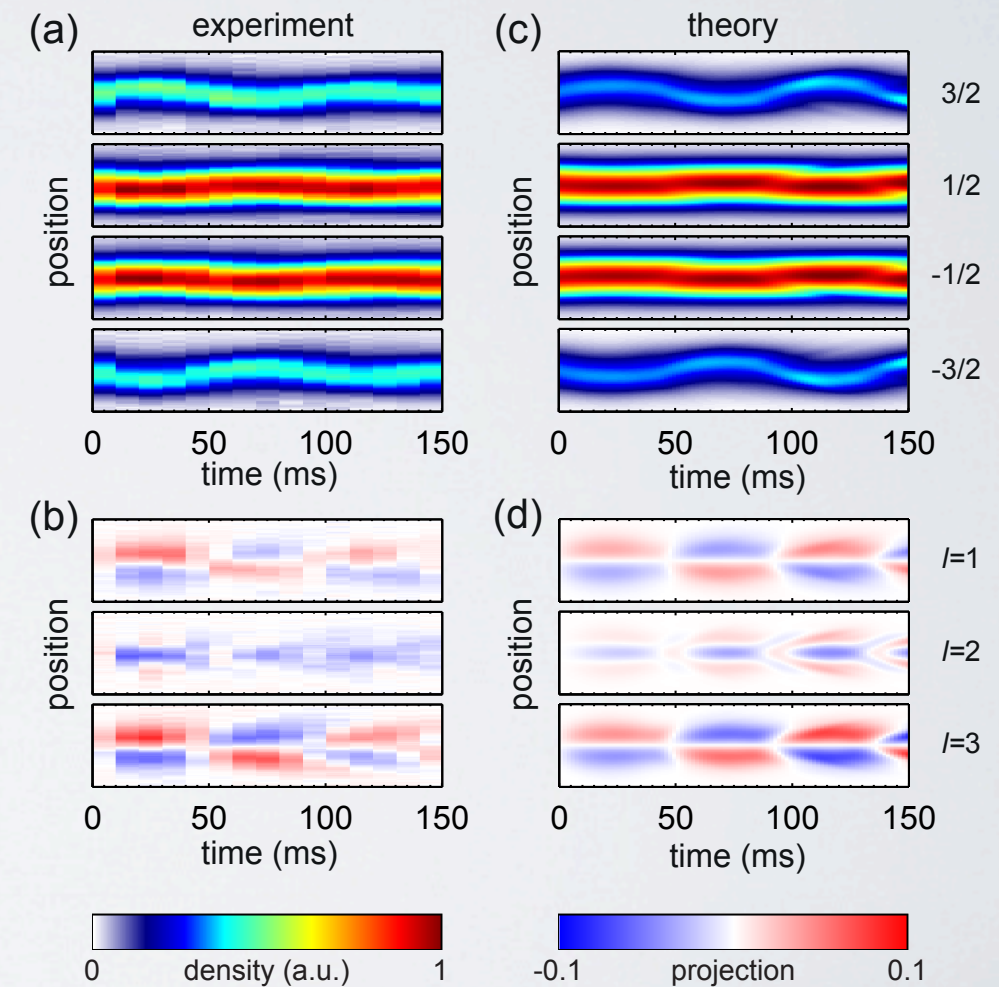
(SPIN-TRONICS WITH ATOMS)

Spinor dynamics in ultracold gases with large spin

- kinetic theory describing the time-evolution of fermions with $\text{spin} > 1/2$
- exotic symmetries [$SO(5)$ with $S=3/2$] and multipole spin waves
- great agreement with experiments (collaboration with Hamburg group)

future directions:

- ▶ expand present theory to include superfluidity and pairing
- ▶ include optical lattices



relevant papers:

- *Dynamically created long-range interaction and spin segregation with ultracold fermionic atoms*, U. Ebling, A. Eckardt and M. Lewenstein, PRA 2011
- *Engineering spin-waves in a high-spin ultracold Fermi gas*, J. Heinze, J. S. Krauser, N. Fläschner, K. Sengstock, C. Becker, U. Ebling, A. Eckardt, M. Lewenstein, arXiv 2013

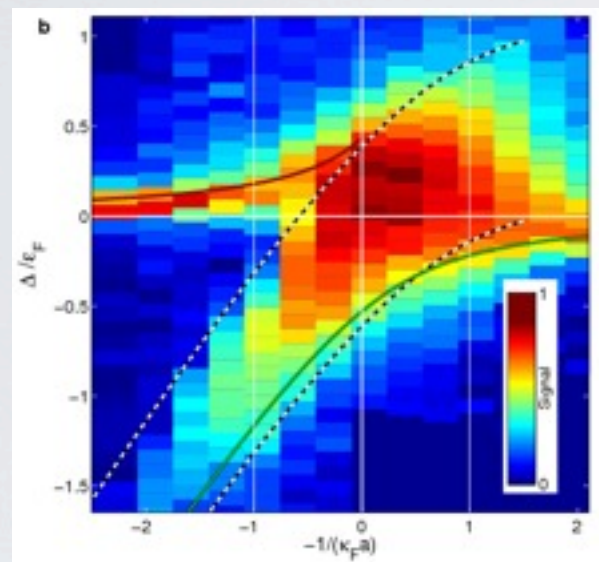
SPIN-TOMICS

(SPIN-TRONICS WITH ATOMS)

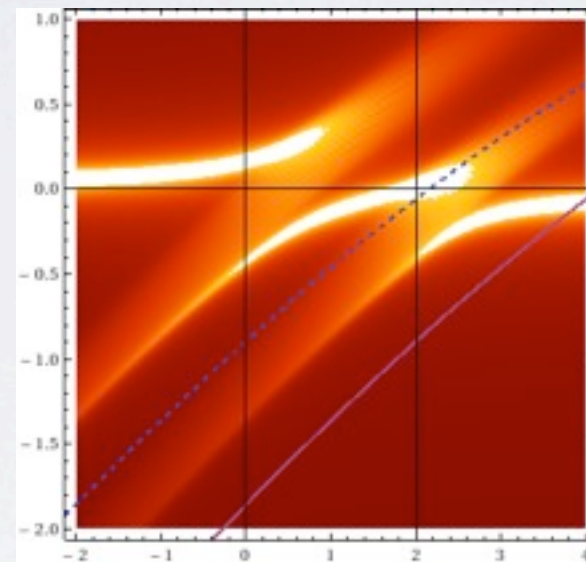


Ultracold quantum mixtures

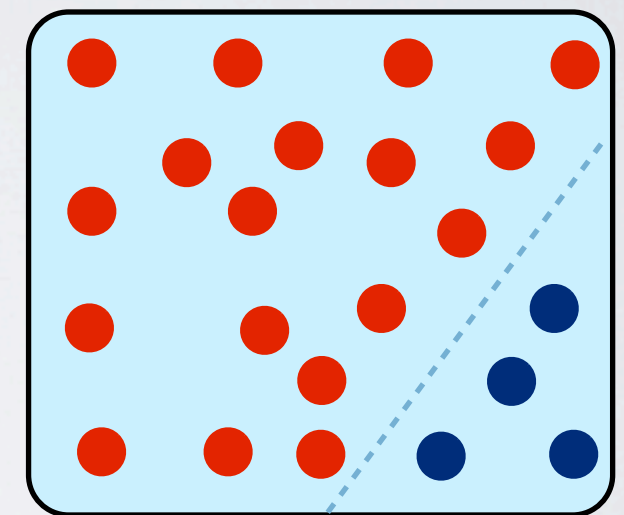
- statics and dynamics of impurities in Fermi gases



s-wave



p-wave



IFM

future directions:

- ▶ few-body states in dimensional cross-over

relevant papers:

● *Metastability and Coherence of Repulsive Polarons in a Strongly Interacting Fermi Mixture*, C. Kohstall, M. Zaccanti, M. Jag, A. Trenkwalder, P. Massignan, G. M. Bruun, F. Schreck, and R. Grimm, Nature 2012

● *Polarons and dressed molecules near narrow Feshbach resonances*, Pietro Massignan, EuroPhys. Lett. 2012

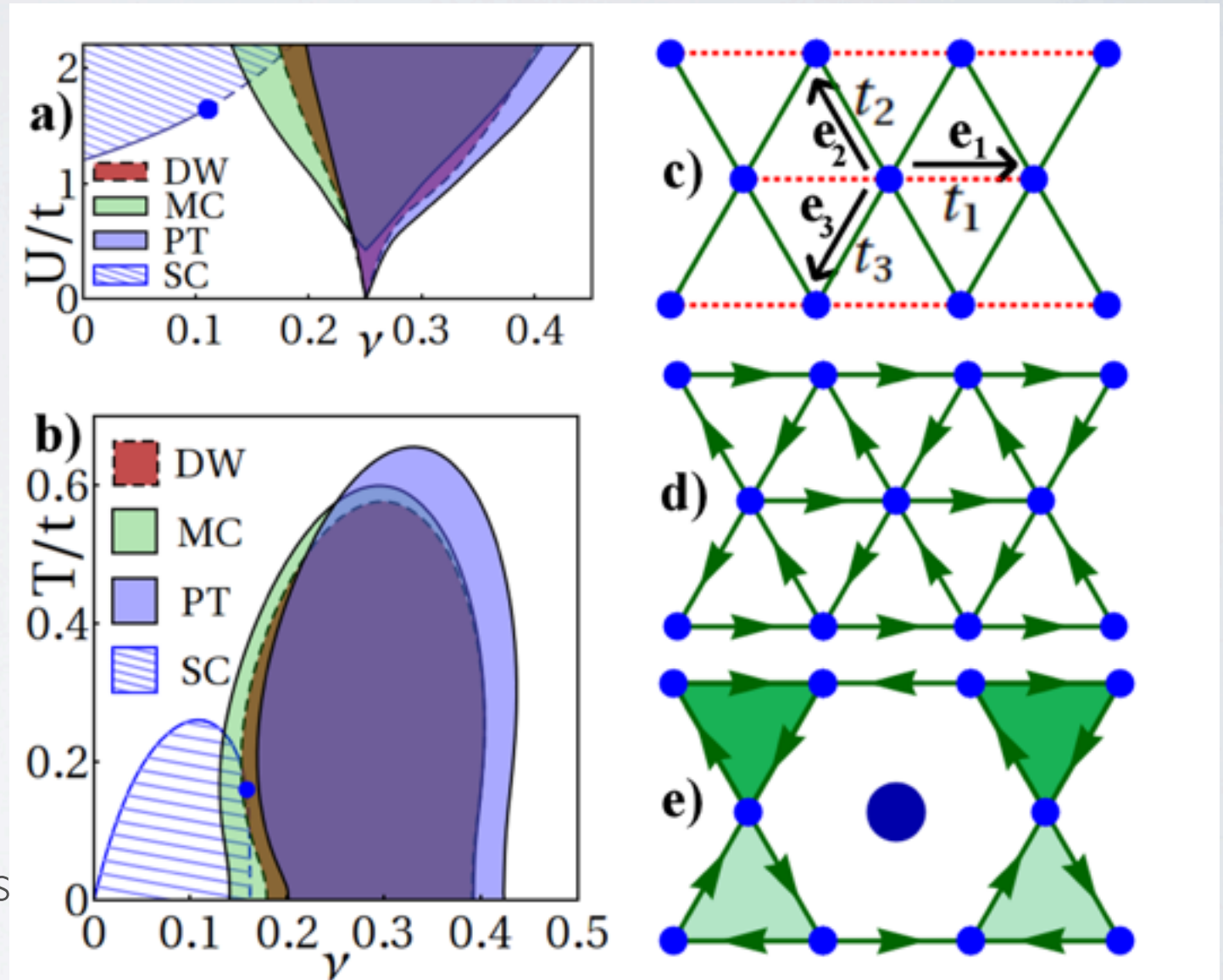
● *Itinerant Ferromagnetism in a polarized two-component Fermi gas*, P. Massignan, Z. Yu, G. M. Bruun, arXiv 2013

FRUSTRATED SPIN SYSTEMS

Spinless fermions on shaken triangular lattices (with alternating sign of tunneling)

- spontaneous generation of loop currents breaking time reversal symmetry
- multiple minima in the dispersion: generation of density waves

DW: density wave
 MC: modulated current
 PT: Peierl's trimerization
 SC: staggered loop current



future directions:

- interacting spinful fermions in shaken lattices
- effect of Peierls phase

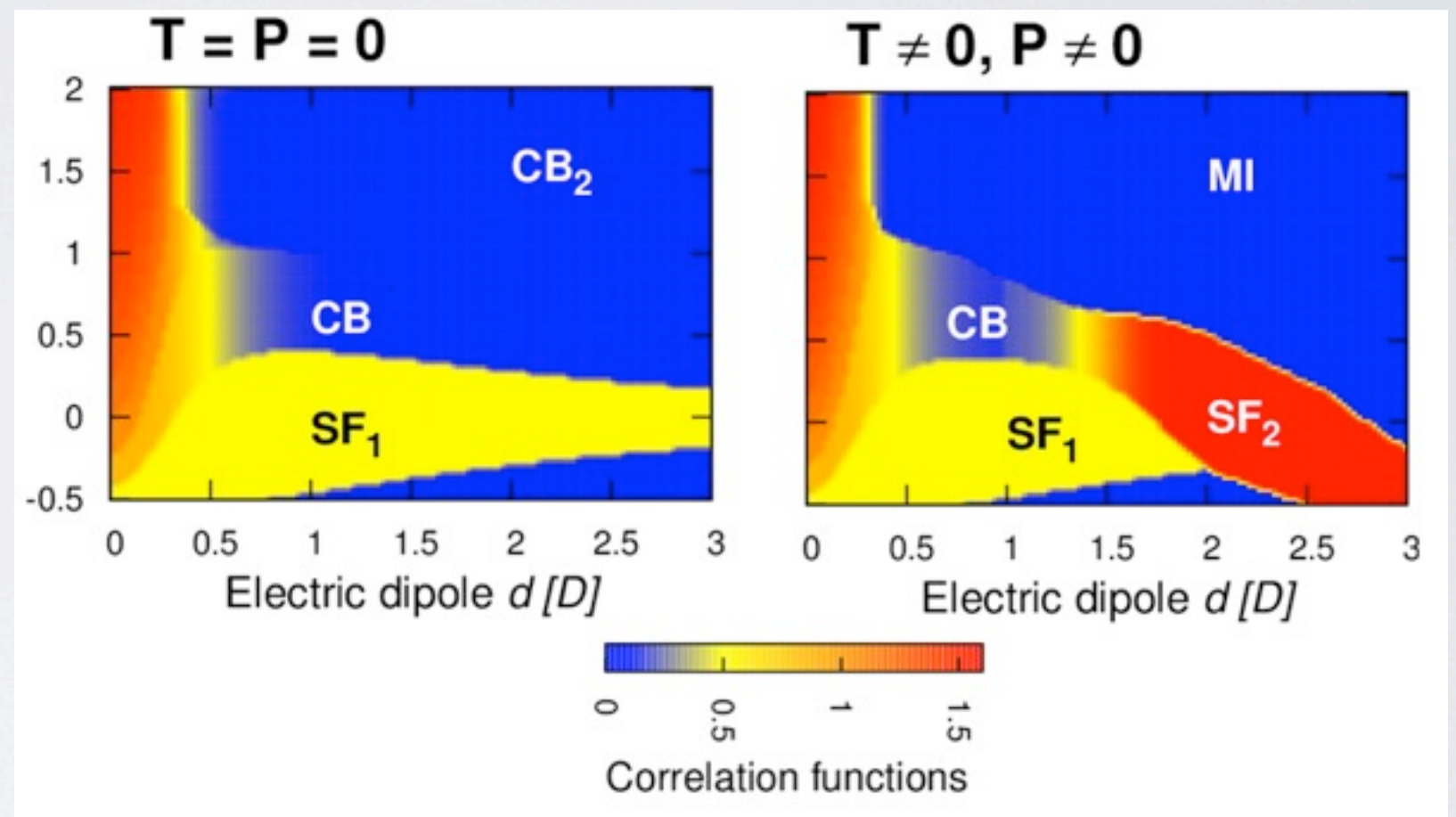
relevant papers:

• *Quantum simulation of frustrated magnetism in triangular optical lattices*, Julian Struck, Christoph Ölschläger, Rodolphe Le Targat, Parvis Soltan-Panahi, André Eckardt, Maciej Lewenstein, Patrick Windpassinger, and Klaus Sengstock, Science 2011

• *Spontaneous time-reversal symmetry breaking for spinless fermions on a triangular lattice*, Olivier Tieleman, Omjyoti Dutta, Maciej Lewenstein, and André Eckardt, PRL 2013

ULTRACOLD DIPOLAR GASES

- commonly neglected terms in the Bose-Hubbard model (occupation-dependent tunneling and pair tunneling) lead to interesting new phenomena (e.g., a pair-superfluid phase)
- multi-band description needed for studying interacting fermionic molecules in optical lattices
- novel quantum phases of dipolar gases in optical lattice induced by the Einstein-de Haas effect



future directions:

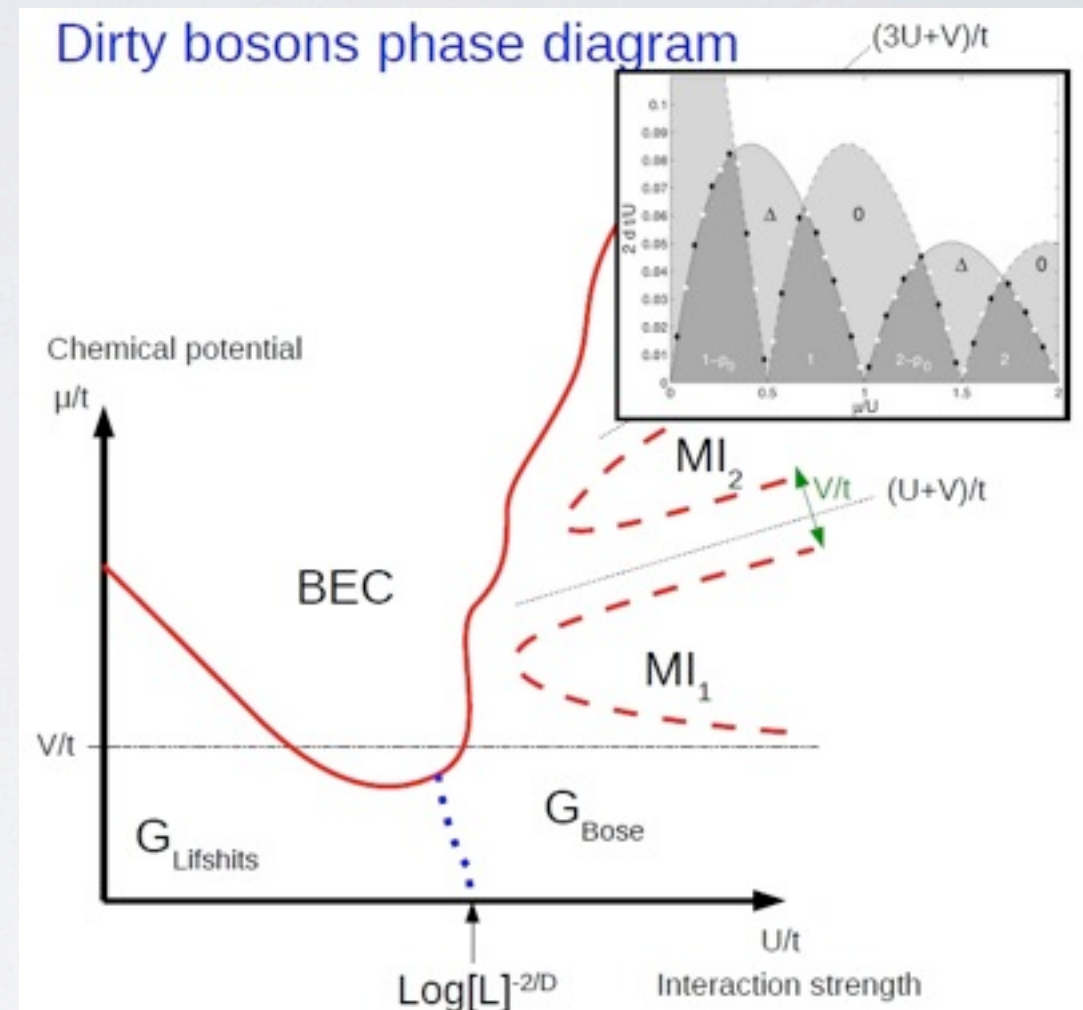
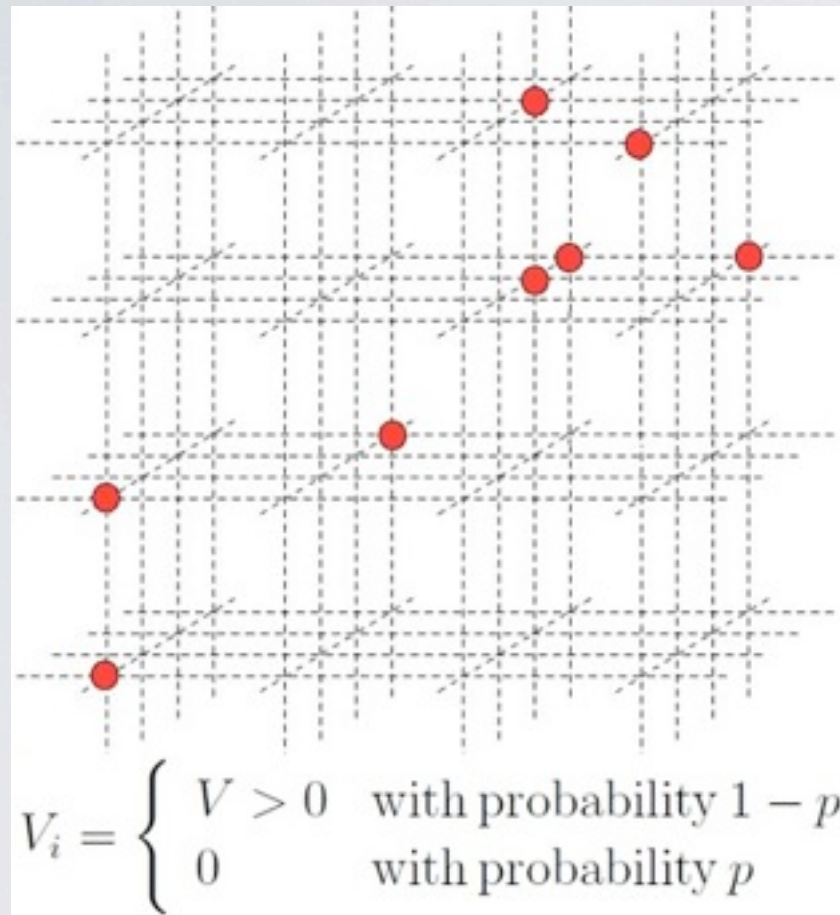
- ▶ experimental on-demand realization of orbital states in optical lattices

relevant papers:

- *Dipolar molecules in optical lattices*, T. Sowiński, O. Dutta, P. Hauke, L. Tagliacozzo, M. Lewenstein, PRL 2012
- *Orbital physics of polar Fermi molecules*, O. Dutta, T. Sowiński, M. Lewenstein, PRA 2013
- *Two component Bose-Hubbard model with higher angular momentum states*, J. Pietraszewicz, T. Sowiński, M. Brewczyk, J. Zakrzewski, M. Lewenstein, M. Gajda, PRA 2012

DISORDERED INTERACTING GASES

- Bose gas on a lattice in the presence of localized impurities (Bernoulli disorder)
- rigorous results for weak interactions: the particles occupy largest islands of zero potential



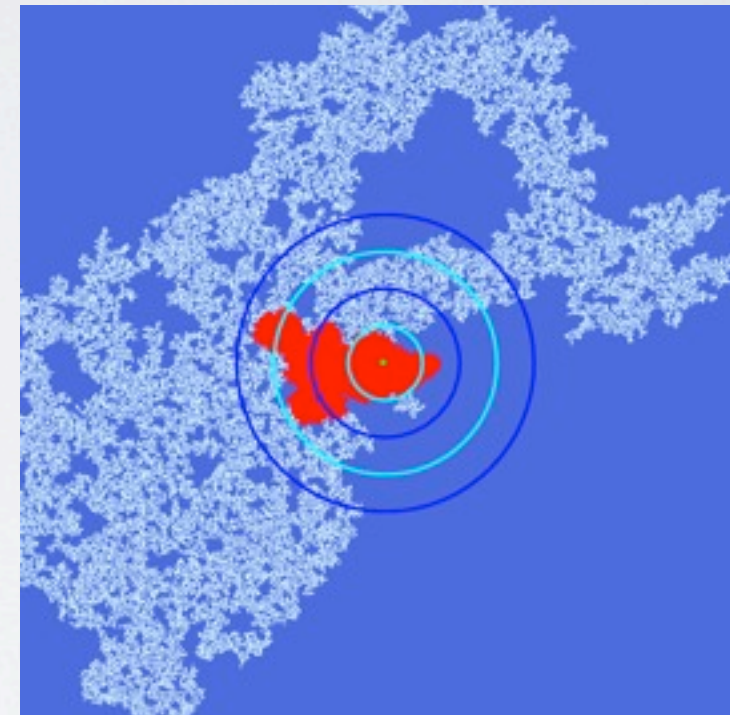
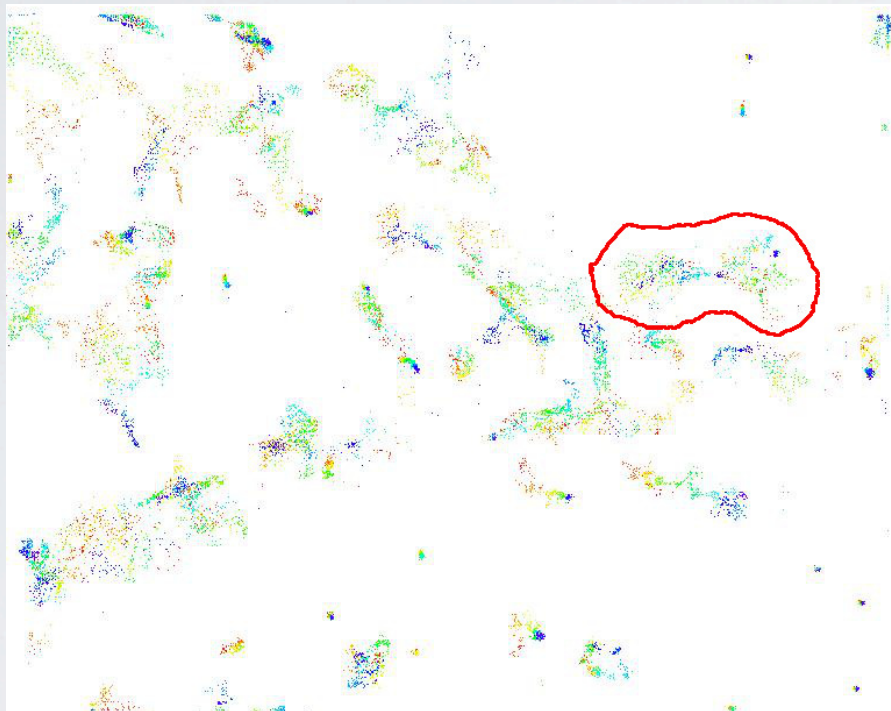
► generalized Bose-Hubbard model with impurities: proposal for realization of correlated disorder in tunneling, on-site interaction and chemical potential

relevant papers:

© *Glass to superfluid transition in dirty bosons on a lattice*, J. Stasinska, P. Massignan, M. Bishop, J. Wehr, A. Sanpera, and M. Lewenstein, New J. of Phys. 2012

ANOMALOUS DIFFUSION IN BIOLOGICAL SYSTEMS

- motion of receptors on the cell membrane is far from random:
 - subdiffusive and non-ergodic (energetic and geometric disorder)
 - non-isotropic (enhanced back-reflection)
- the space available for motion on the membrane is composed of spatial patches with $d_f < 2$



(collaboration with M. G. Parajo)

► develop theoretical models with minimal a-priori assumptions

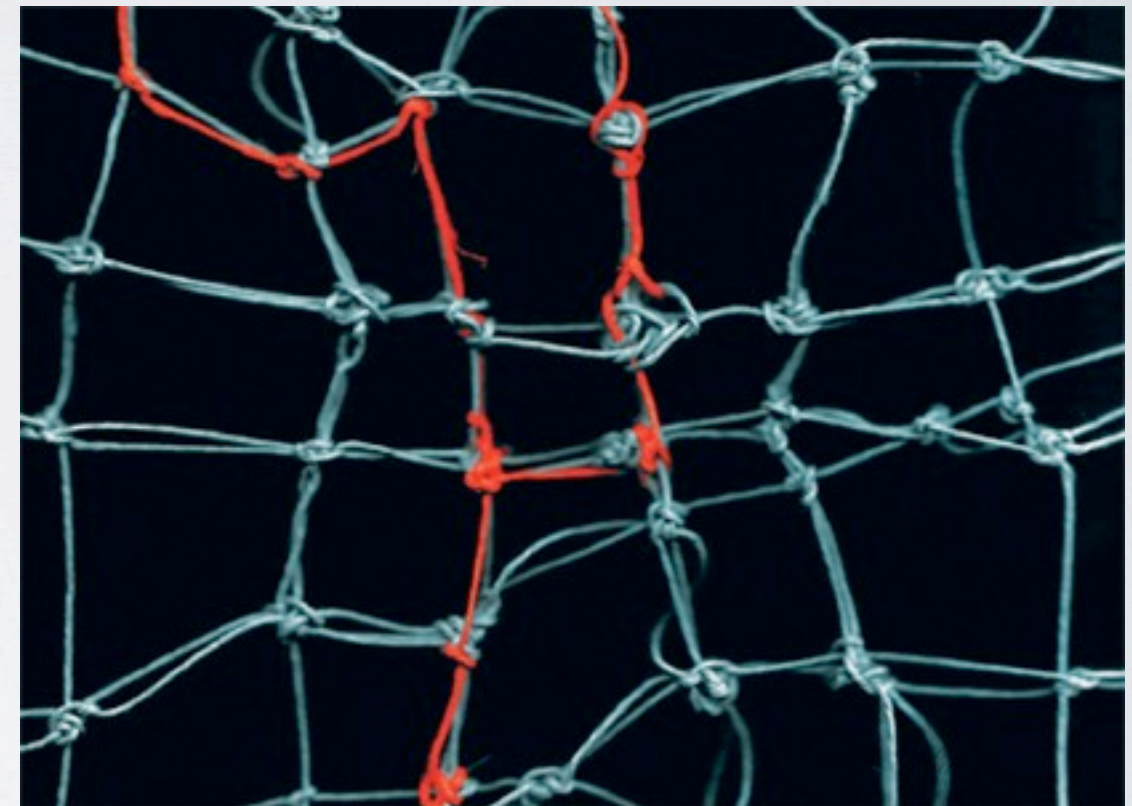
relevant papers:

© P. Massignan, J. Lapeyre, C. Manzo, J. Torreno, M. Lewenstein, and M. G. Parajo, in preparation

QUANTUM INFORMATION

recent results:

- quantum operations enhance desirable topological properties of complex networks
- two-body correlators are enough to detect nonlocality in physically relevant quantum systems (ground states of Hamiltonians realizable in the lab)
- general scheme for constructing distributed games in which quantum theory does not provide an advantage over classical correlations



future directions:

- ▶ characterization of entanglement and nonlocality in many-body systems
- ▶ searching for information-theoretic principles allowing to single out the set of quantum correlations

relevant papers:

● *Quantum complex networks*, S. Perseguers, M. Lewenstein, A. Acín, and J. I. Cirac, Nat. Phys. 2010

● *Bell inequalities with no quantum violation and unextendible product bases*, R. Augusiak, J. Stasińska, C. Hadley, J. K. Korbicz, M. Lewenstein, and A. Acín, PRL 2011

2D EXCITON GASES

recent results:

- optically programmed exciton traps
- observation of a fragmented exciton ring with spontaneous formation of macroscopic spatial coherence and spin-polarization

techniques:

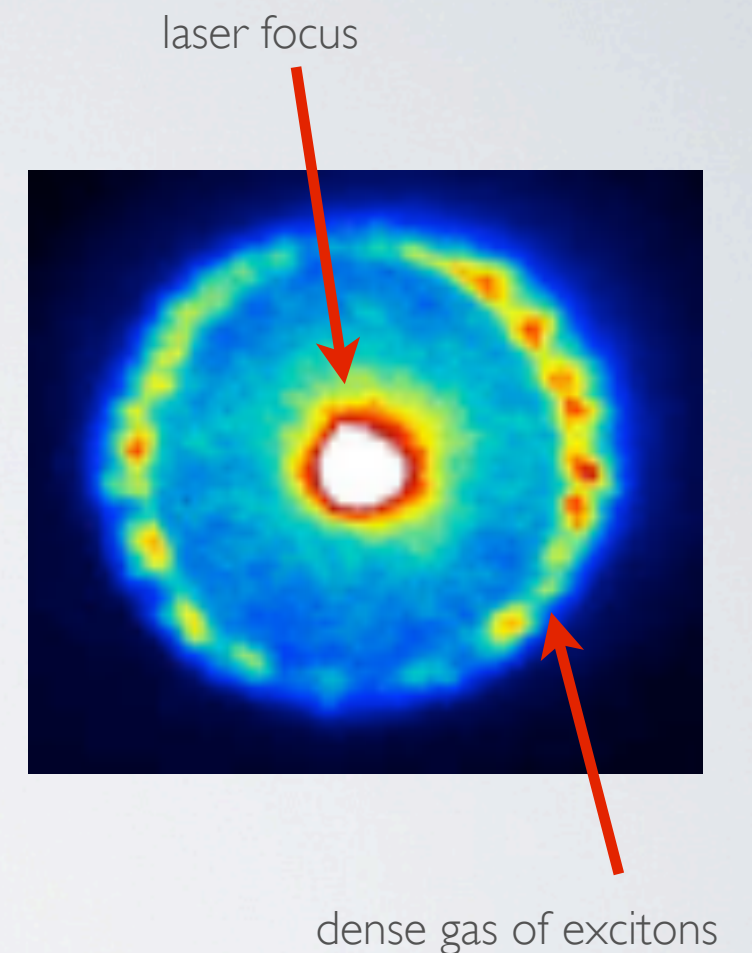
- optical microscopy at sub-Kelvin temperatures
- time and spatially resolved interferometry

future directions:

- ▶ unambiguous demonstration of the Bose-Einstein condensation of excitons

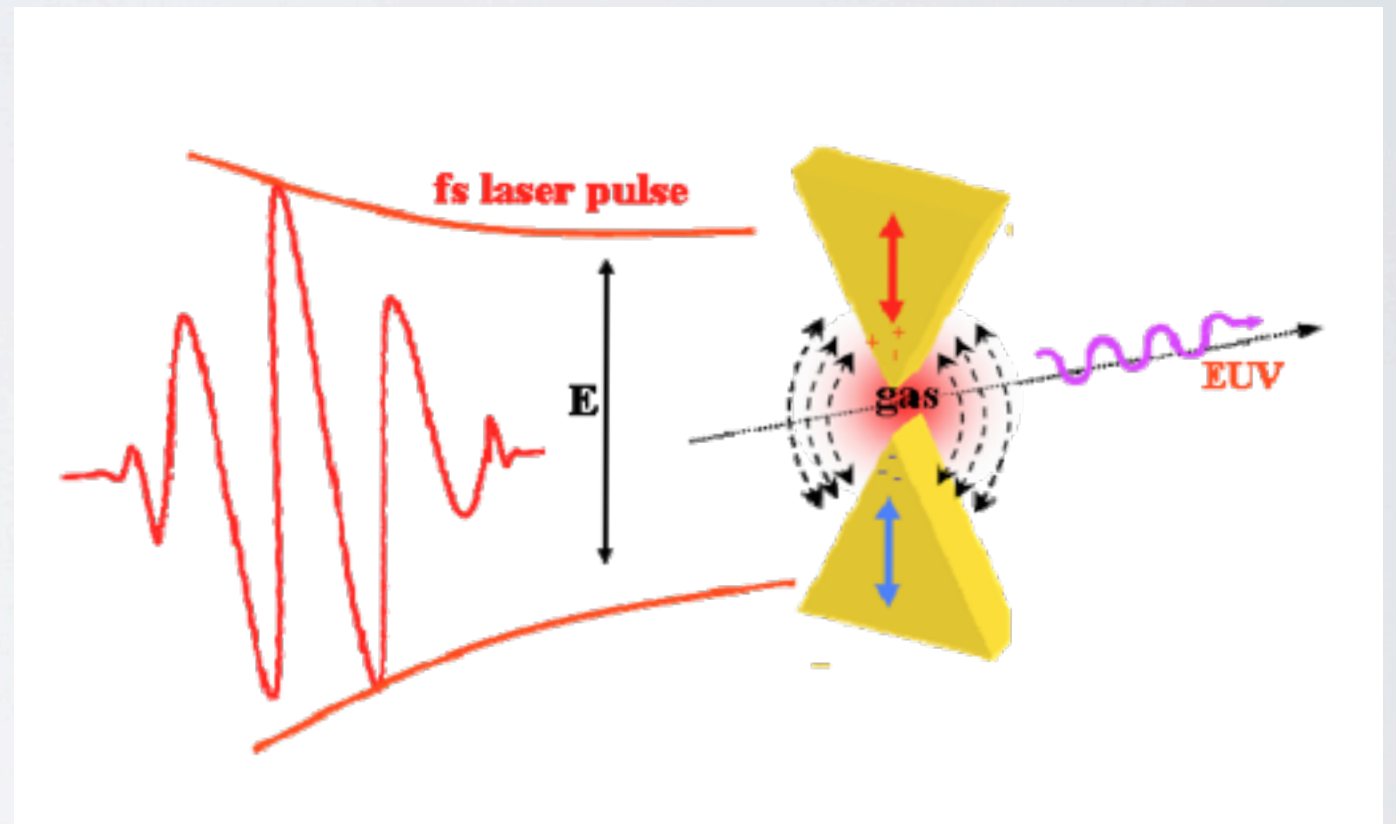
relevant papers:

- *Observation of macroscopic coherence in self-organized dipolar excitons*, M. Alloing, D. Fuster, Y. Gonzalez, L. Gonzalez, and F. Dubin, arXiv 2012
- *On-demand confinement of semiconductor excitons by all-optical control*, M. Alloing, A. Lemaitre, E. Galopin, and F. Dubin, arXiv 2012



ATTOSECOND PHYSICS

- higher-harmonic-generation and above-threshold ionization with spatially-inhomogeneous fields allow for:
 - shaping electron trajectories at the nanoscale
 - production of attosecond pulses



(collaboration with J. Biegert and R. Quidant)

relevant papers:

- *Beyond Carbon K-edge harmonic emission using spatial and temporal synthesized laser fields*, J. A. Pérez-Hernández, M. F. Ciappina, M. Lewenstein, L. Roso and A. Zair, PRL 2013
- *Enhancement of high harmonic generation by confining electron motion in plasmonic nanostructures*, M. F. Ciappina, Srdjan S. Acimovic, T. Shaaran, J. Biegert, R. Quidant and M. Lewenstein, Opt. Expr. 2012
- *Above threshold ionization by few-cycle spatially inhomogeneous fields*, M. F. Ciappina, J. A. Pérez-Hernández, T. Shaaran, J. Biegert, R. Quidant and M. Lewenstein, PRA 2012

PEOPLE

