Many-Particle Cavity Quantum Electrodynamics

Dr. Farokh Mivehvar
Prof. Helmut Ritsch
https://www.uibk.ac.at/th-physik/cqed/

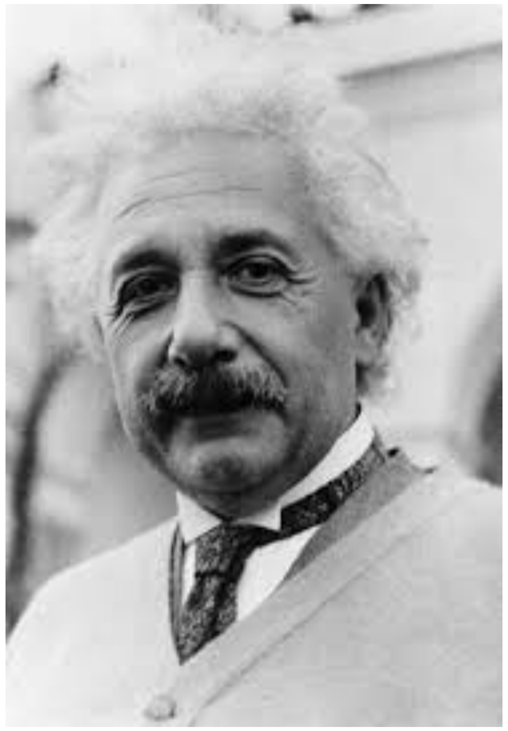
Institute for Theoretical Physics

universität innsbruck

Electromagnetic Fields (Light): Wave or Particle?

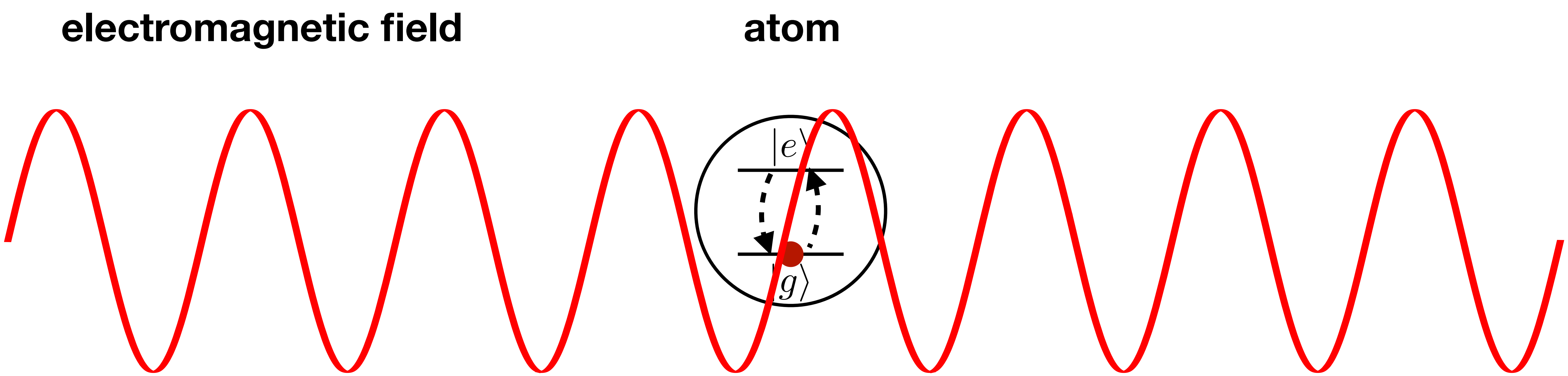
Maxwell: Electromagnetic fields are wave.

Einstein: Electromagnetic fields are composed of particles called “photons”.



Light-Matter Interaction in Free Space

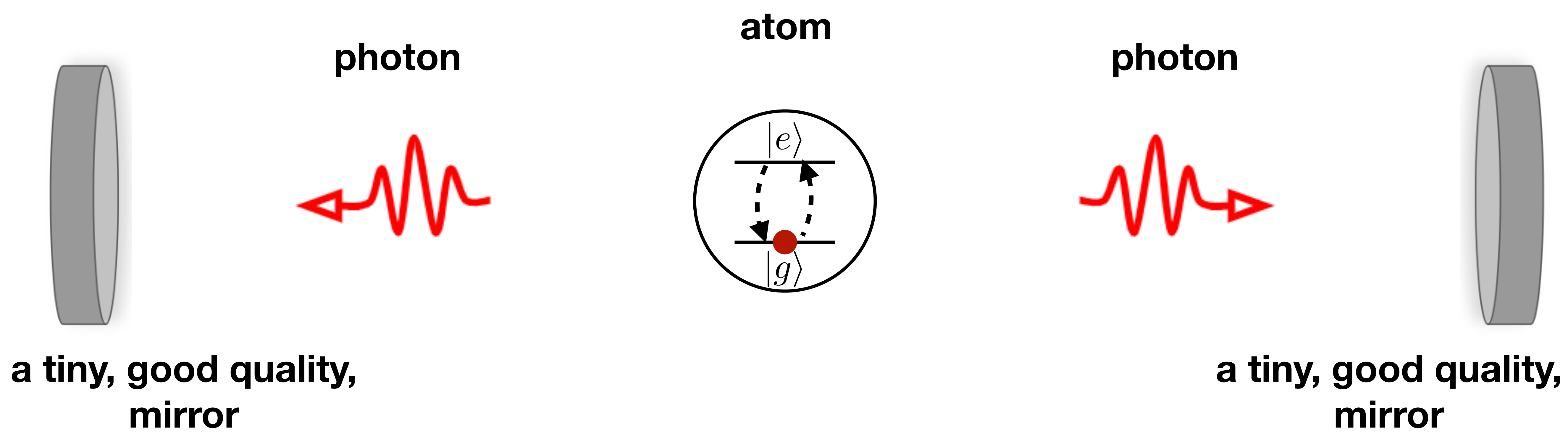
- An atom interacting with electromagnetic fields in free space:



Electromagnetic fields behave as waves!

Light-Matter Interaction inside Cavities

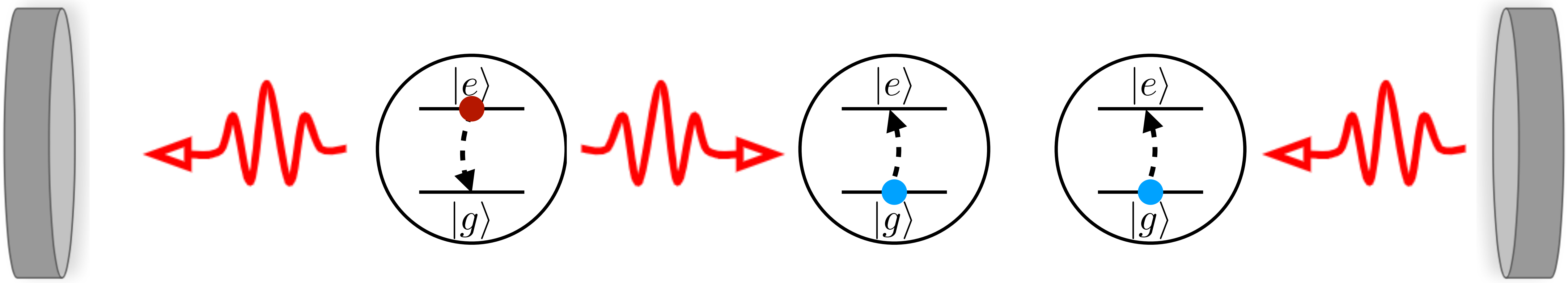
- An atom interacting strongly with electromagnetic fields confined between two high-quality mirrors, which is called a “cavity”:



Electromagnetic fields behave as particles!

Light-Matter Interaction inside Cavities

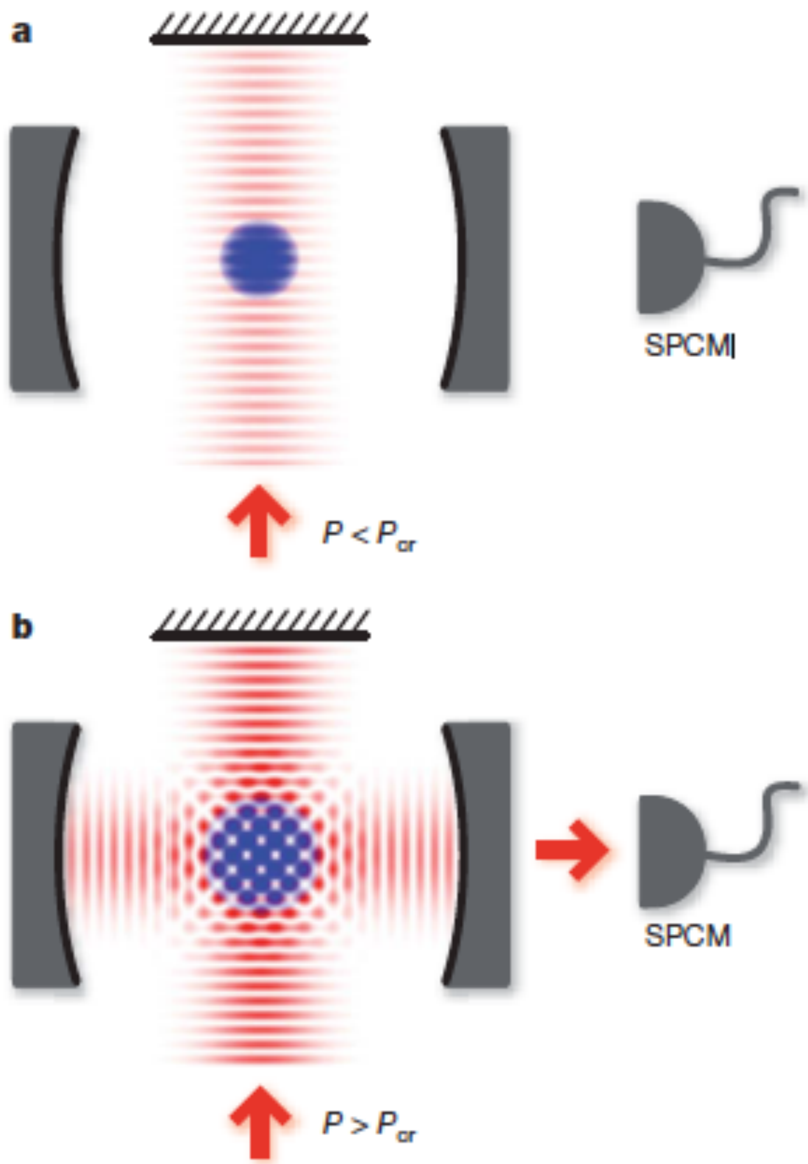
- Many atoms interacting strongly with electromagnetic fields inside a cavity:

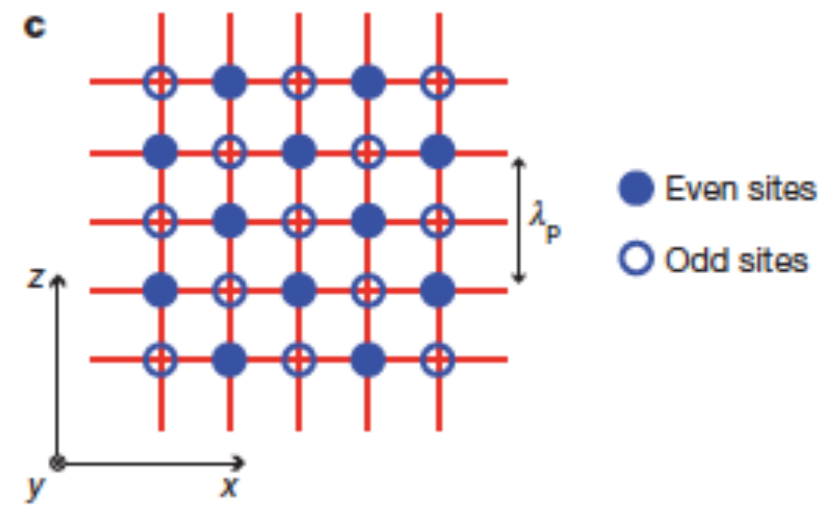


photon-induced long-range interactions between atoms

Photon-Induced Crystallization

- Self-ordering of atoms in crystalline order





discrete $\mathbb{Z}_2$ symmetry

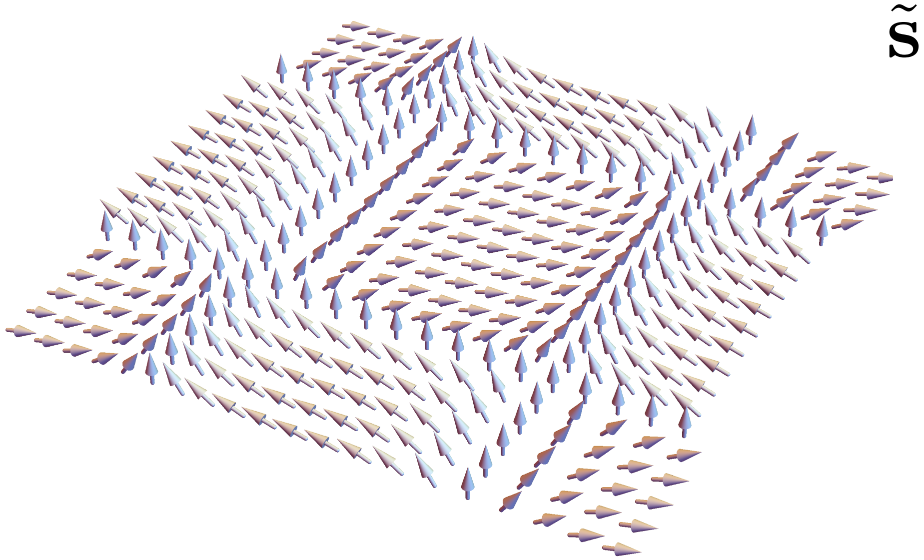
Theory: Innsbruck group
Domokos and Ritsch, PRL (2002)

Experiment: ETH group, Shanghai group, EFPL group
Nature **464**, 1301 (2010)
Science **373**, 1359 (2021)
arXiv:2212.04402 (2022)

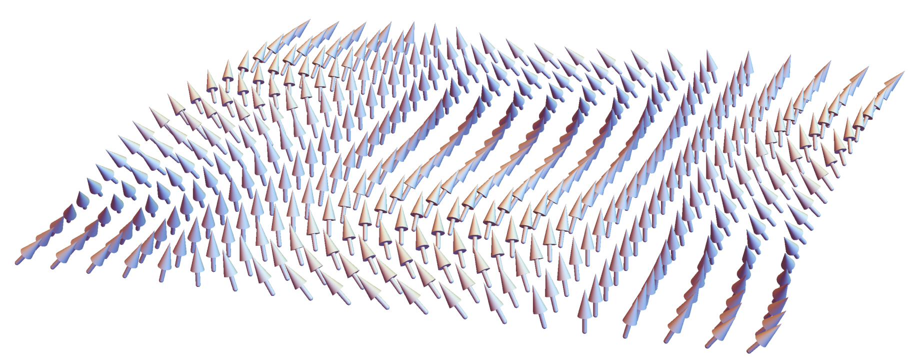
Photon-Induced Magnetization

- Emergence of various spin orders

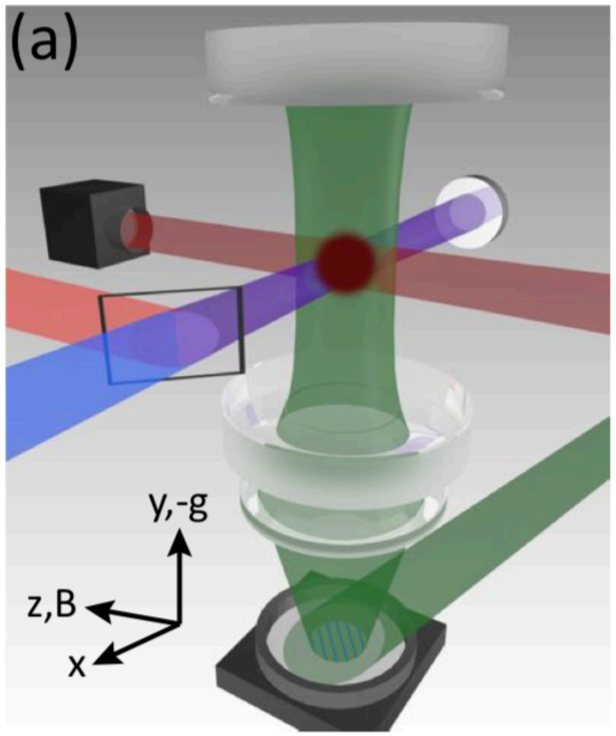
$\tilde{\mathbf{s}}(\mathbf{r})$



antiferromagnetic order



spin-spiral order

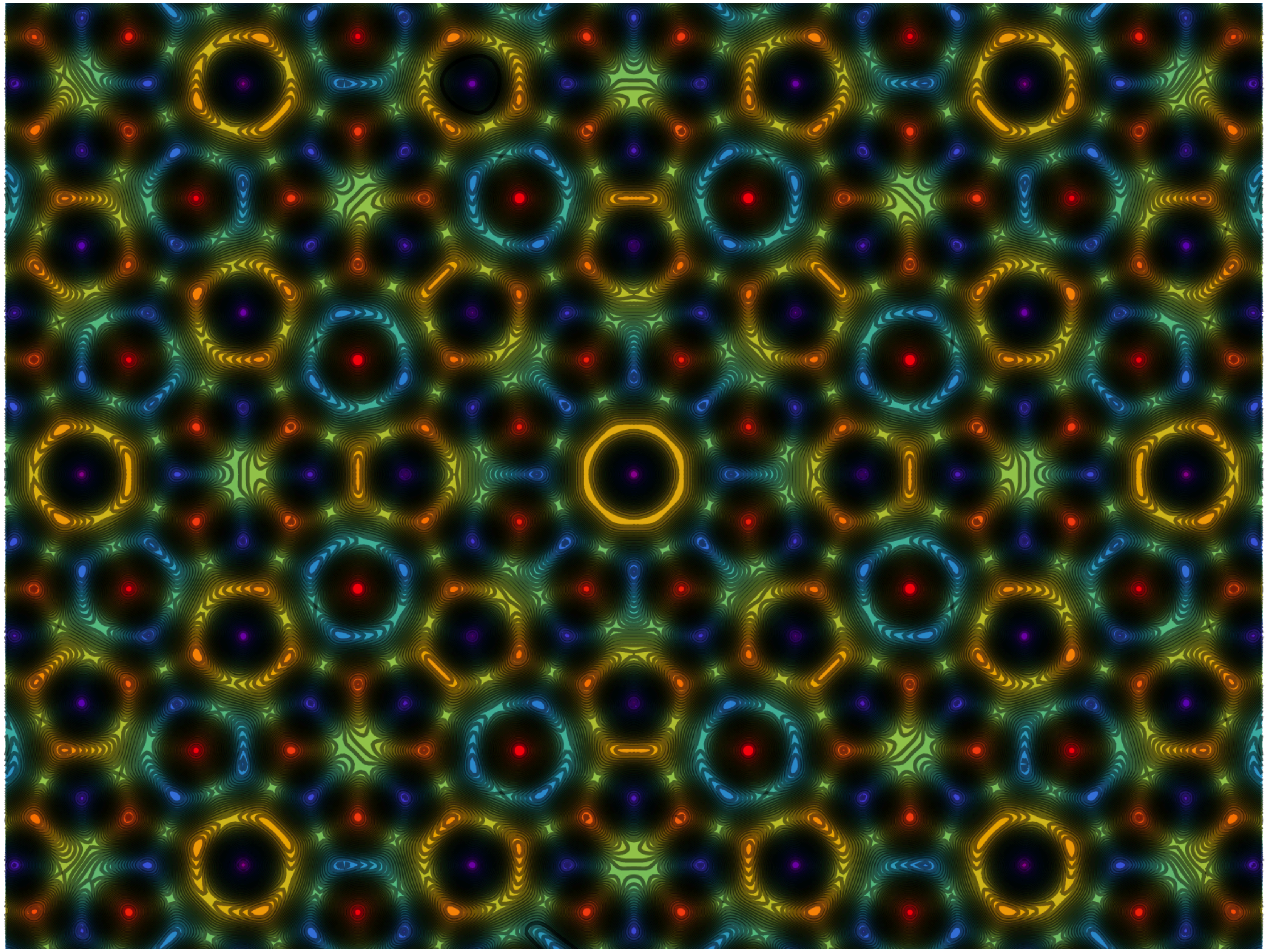


Theory: Innsbruck group
Mivehvar, Piazza, Ritsch, PRL **119**, 063602 (2017)
Mivehvar, Ritsch, Piazza, PRL **122**, 113603 (2019)

Experiment: Stanford group, ETH group
Phys. Rev. Lett. **121**, 163601 (2018)
Phys. Rev. Lett. **120**, 223602 (2018)
Phys. Rev. Lett. **123**, 160404 (2019)

Photon-Induced Quasicrystallization

- Self-ordering of atoms in quasicrystalline order

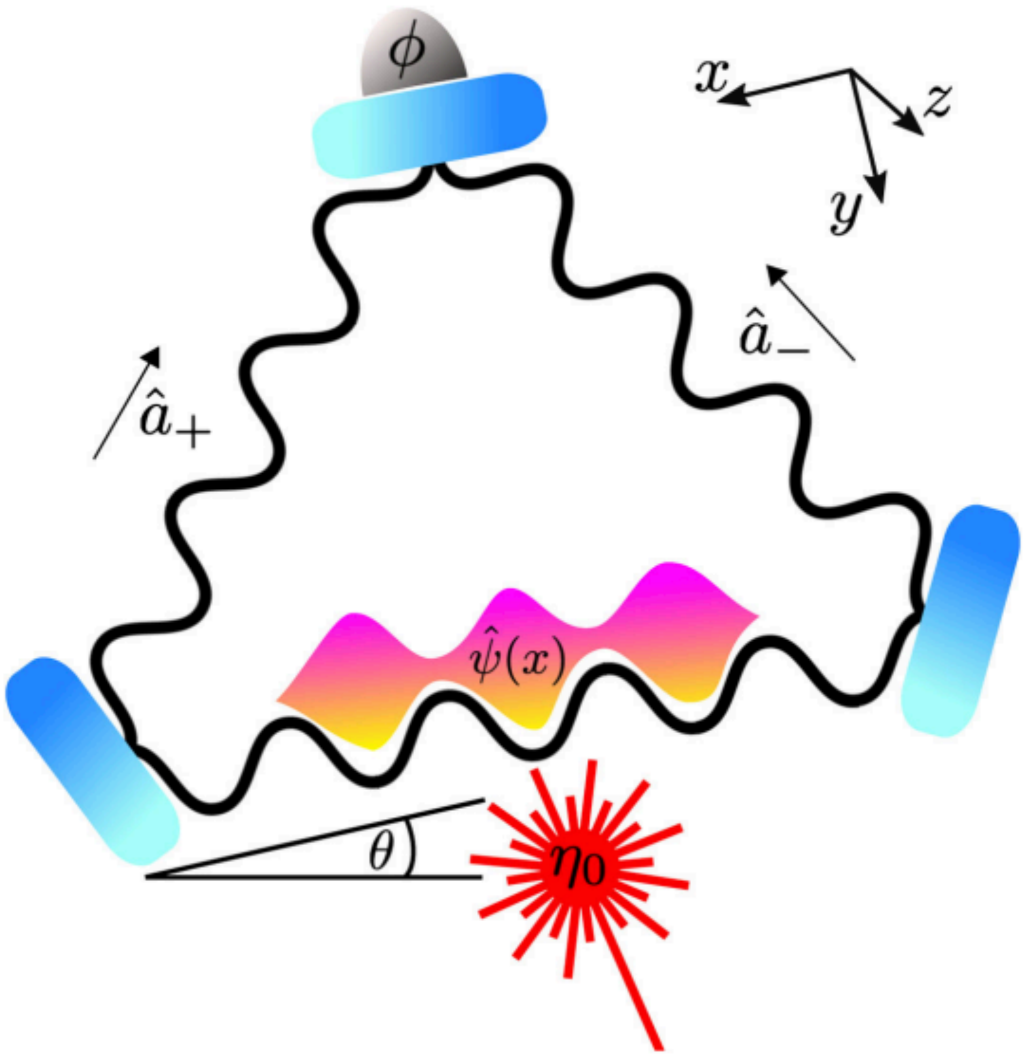


C_8=45°

Theory: Innsbruck group
Mivehvar, Ritsch, Piazza, PRL **123**, 210604 (2019)

Cavity-Enhanced Quantum Measurements

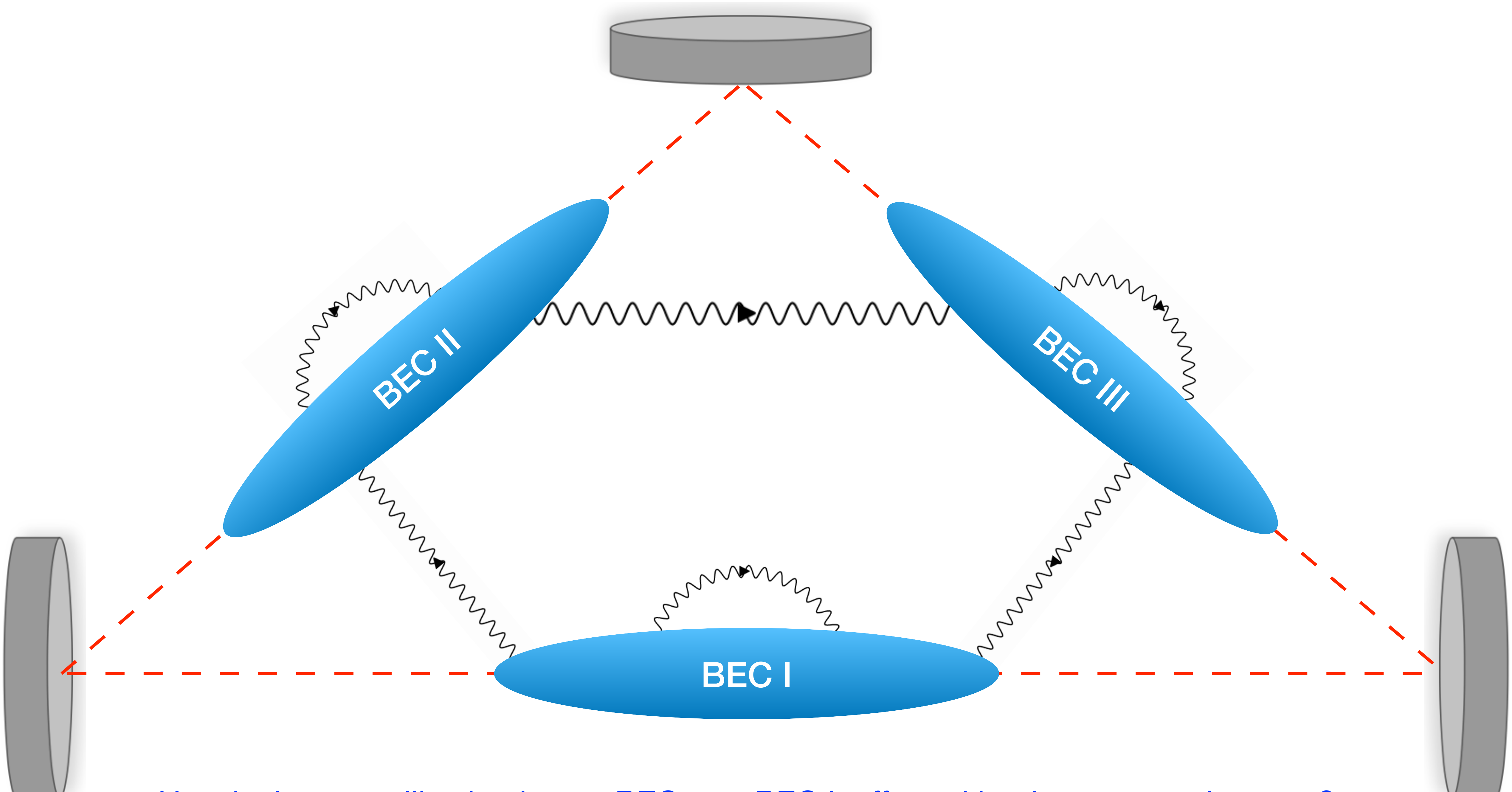
- A precise gravimeter (a device which measures the gravitational acceleration g)



Theory: Innsbruck group
Gietka, Mivehvar, Ritsch, PRL **122**, 190801 (2019)

Project 1

- Photon-induced entanglement among distant Bose-Einstein condensates (BECs)?

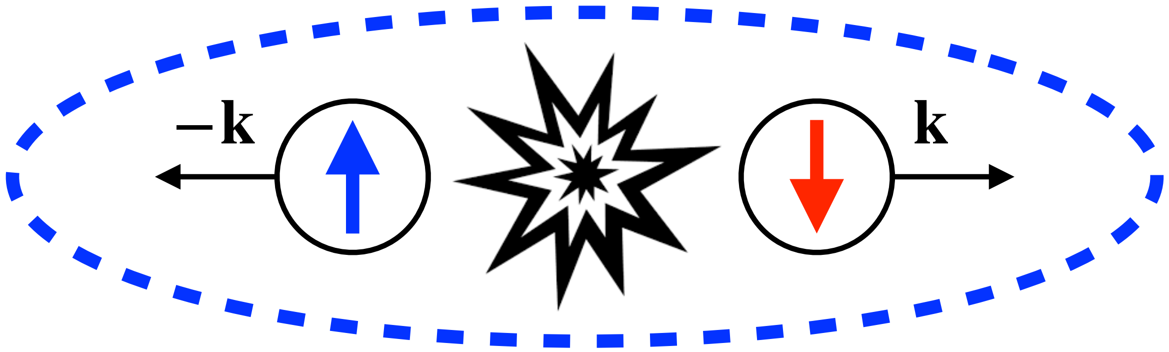


How is the crystallization in one BEC, say BEC I, affected by these entanglements?
And in turn, how does it affect the crystallization in the other BECs?

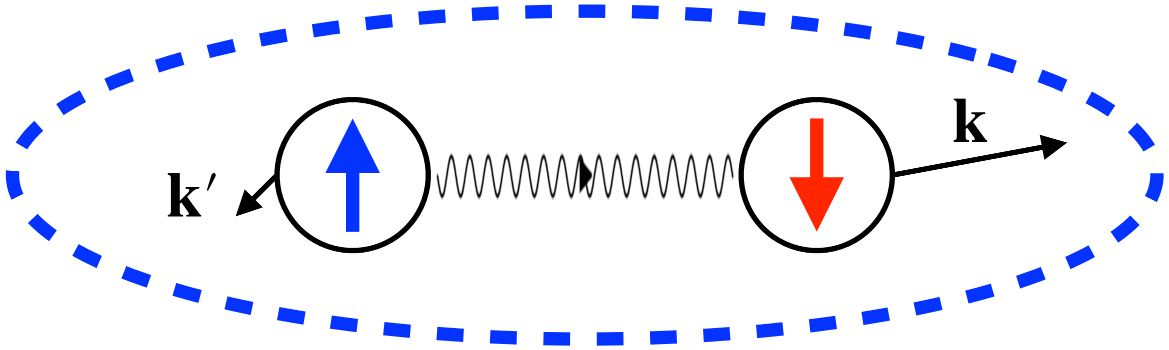
Project 2

- Photon-induced superfluid (superconducting) pairing?

interaction/phonon-induced
Cooper pairing



photon-induced
Cooper pairing with non-zero
CM momentum?



Project 3

- Including rotation: effect of photon-induced interaction on rotating molecules?

Is it possible to align molecules rotationally with photon-induced interactions?
And, is it possible to detect the degree of the molecular alignment *non-destructively* through cavity output?

Even More Projects

- Thesis with computational focuses

QuantumOptics.jl

v1.0.1 released

A Julia Framework for Open Quantum Dynamics

https://qojulia.org/

Farokh.Mivehvar@uibk.ac.at
Helmut.Ritsch@uibk.ac.at

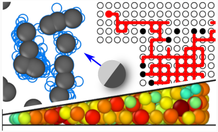
Theoretische Bio-Nano Physik

Prof. Thomas Franosch, Michele Caraglio, Alessio Squarcini

10. Jänner, 2023

Vorstellung Arbeitsgruppen

Institut für Theoretische Physik
Universität Innsbruck (UIBK)

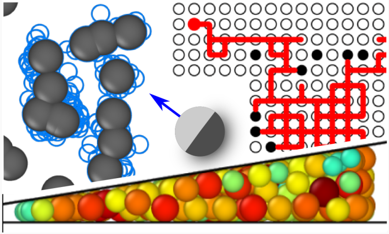


Soft matter / Statistical Physics

Active particles

Complex transport

Proposal 1



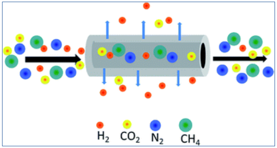
Glass transition

Polymer Physics

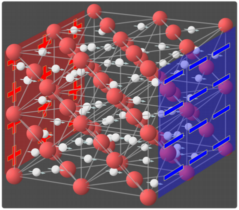
Proposal 2

Complex transport

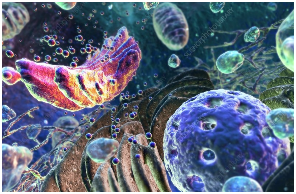
Molecular sieve



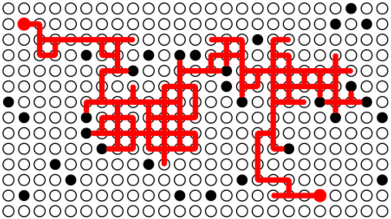
Ion-conductor



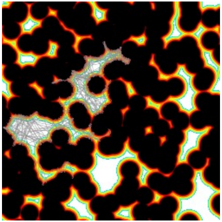
Interior of cells



Lattice Lorentz Gas

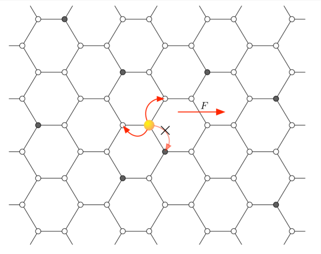


Lorentz Model



Complex transport: Bachelor Proposal 1

Goal: Investigate the transport properties of a lattice Lorentz gas with a driving force.

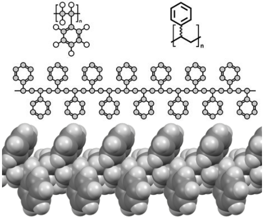


Learning objectives:

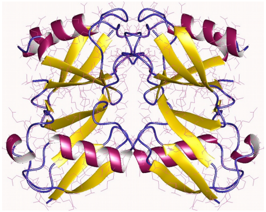
- Implement stochastic simulations for the study of the dynamics in a complex environment;
- Analyze the transport properties through the basic concepts of stochastic processes and probability theory;
- Interpret the results and compare them to those obtained by following analytical approaches.

Polymers

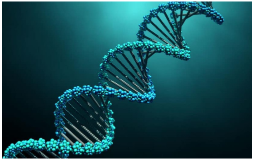
Polysterene

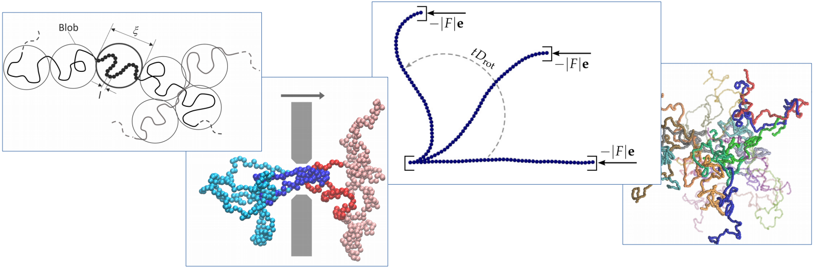


Proteins



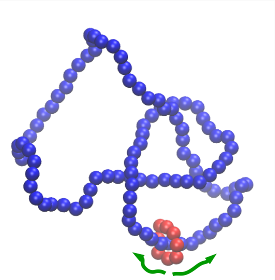
DNA and RNA





Polymers: Bachelor Proposal 2

Goal: Investigate the sliding dynamics of rings along polymeric chains whith non-trivial topology.

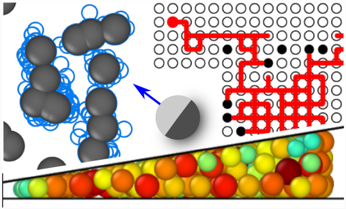


Learning objectives:

- Learn how to simulate polymeric systems through computer simulations;
- Learn basic notions of polymer topology (knots and links);
- Analyze the motion of the ring through the basic concepts of stochastic processes.

Potential Master theses available in various topics

- Glass transition
- Active particles
- Complex transport



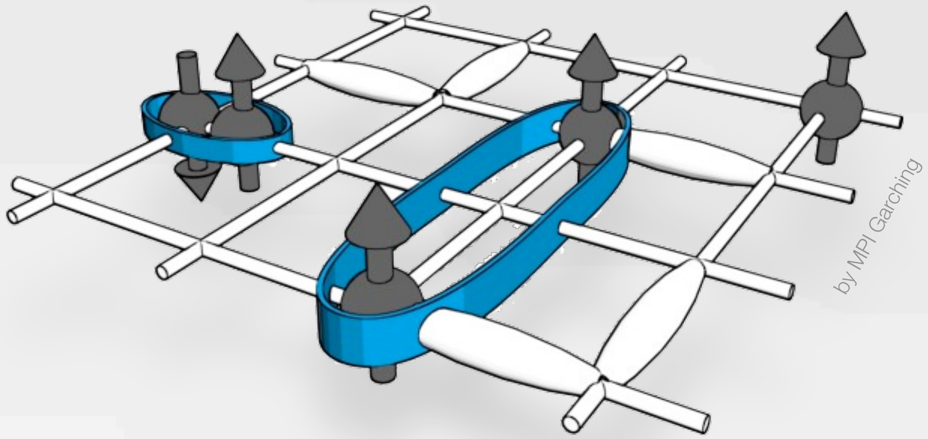
If you are interested, please just approach us!

Thank you for your attention!

Theoretical condensed matter & Computational physics

Bachelor & Master thesis projects

We numerically investigate strongly correlated quantum many body systems in crystalline materials, optical traps and models, where two or more interactions are competing against each other at the same energy scale.

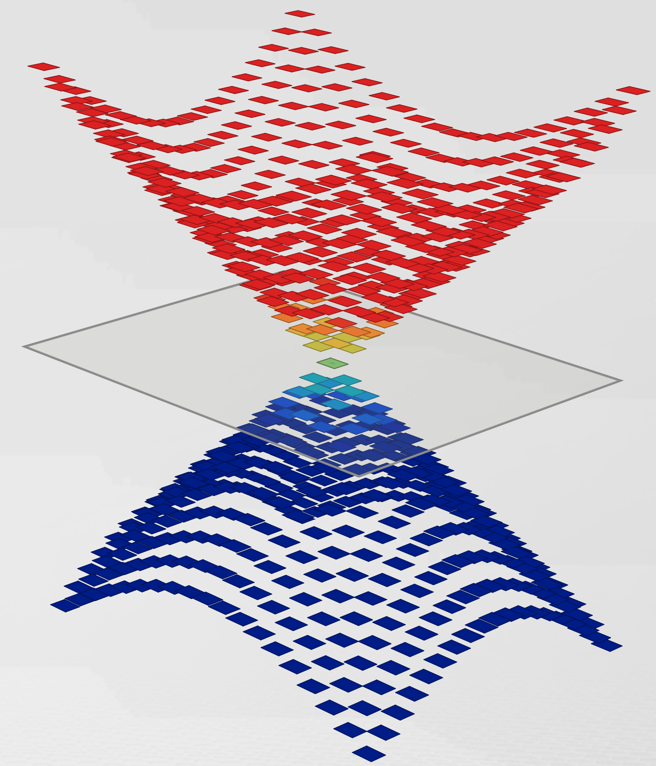


Research in this area attempts to model and simulate existing materials, as well as to predict the properties of designer materials and models.

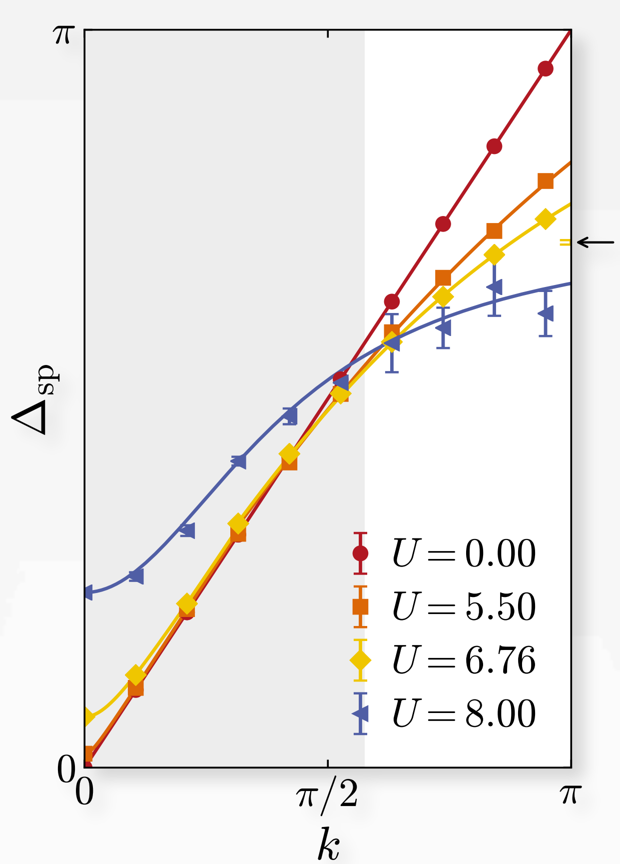
Our challenge is to understand the fundamental, complex interplay of many degrees of freedom, which can lead to exotic states of matter.

Dirac fermions on the lattice

Relativistic Dirac fermions constitute the fundamental starting point and building block for a vast host of modern physics topics, from twisted multilayer graphene to topologically protected surface states.



Implementing an effective relativistic energy-momentum relation for Dirac fermions in computer simulations remains however a technical challenge, which haunts high energy physics, condensed matter physics, but also cold atom experiments.

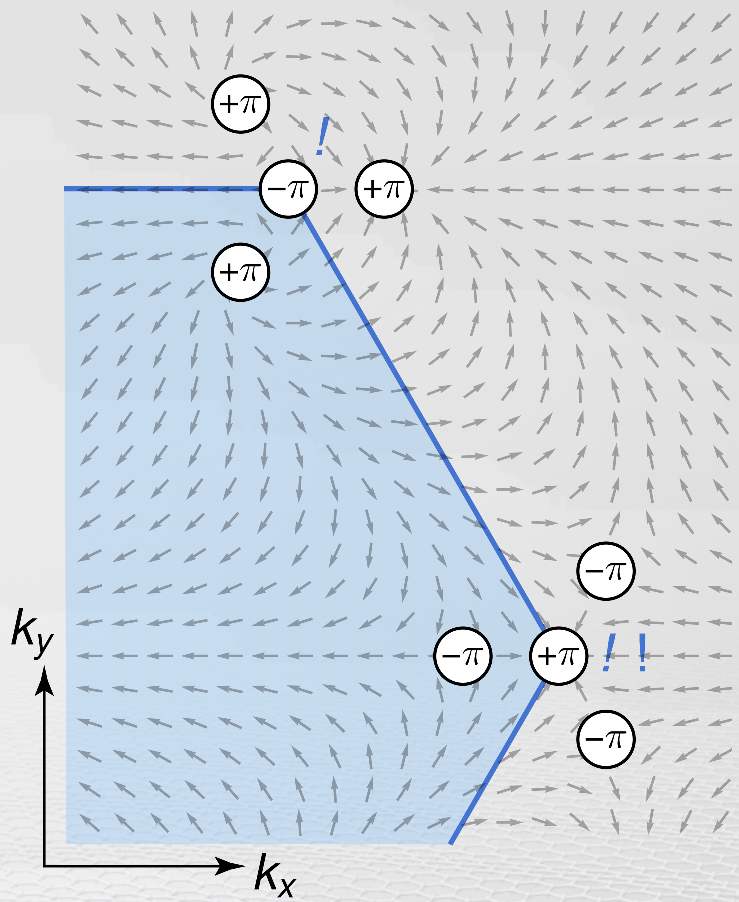


In most implementations violate at least one of the presumably necessary physical properties of *real* Dirac fermions, such as the conservation of chirality, or a local representation.

Certain versions of lattice Dirac fermions preserve the most important properties, but are a technical nightmare, i.e., numerically expensive to work with.

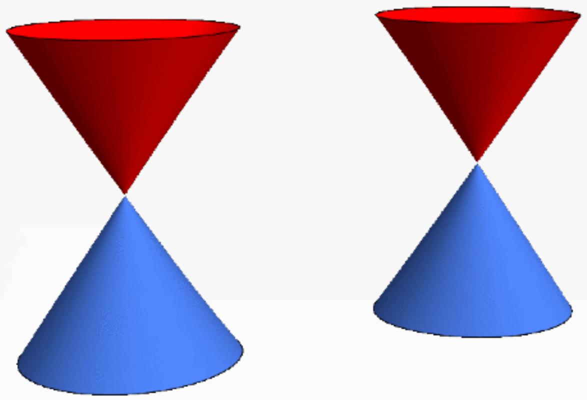
Dirac fermions on the lattice

Recently, new simulations and implementations have been put forward and claim to alleviate known problems of numerical simulations, such as ghost states, fermion doubling and the alteration of universality classes.



Kronfeld, arXiv:0711.0699 (2007)
T. C. Lang, A. M. Läuchli, Phys. Rev. Lett. **123**, 137602 (2019)
M. J. Pacholski *et al.*, SciPost Phys. **11**, 105 (2021)
A. Donis Vela *et al.*, arXiv:2201.02235 (2022)

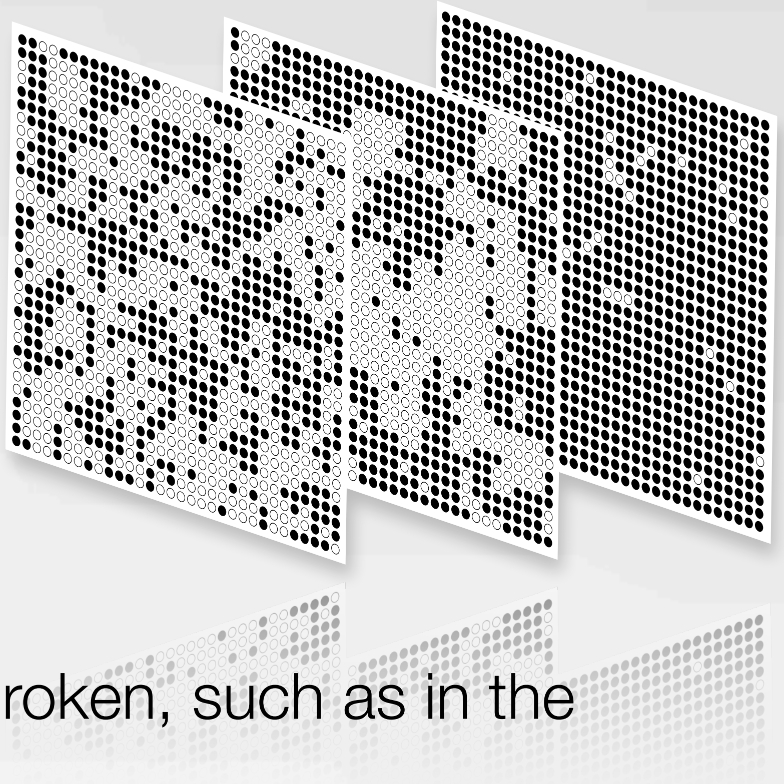
The topological properties of these lattice fermions are of particular interest to their application in moire systems, such as twisted multilayer graphene.



This project's objective is to test and compare different implementations of lattice Dirac fermions, their topological properties and protections against perturbations and evaluate their practical applicability in future computer simulations.

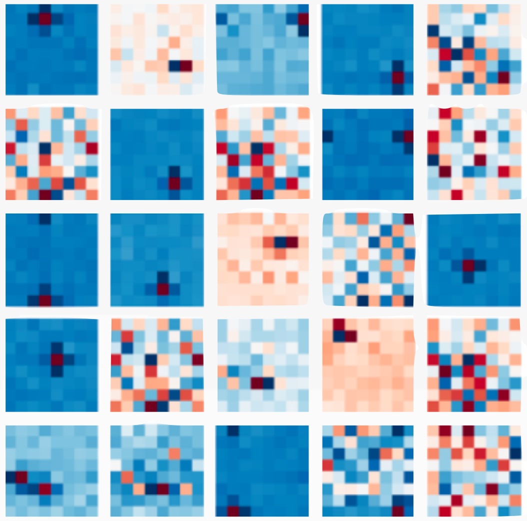
Machine learning, the inverse Ising problem & non-local Monte Carlo updates

Large scale simulations of classical and quantum models have only been made possible by the introduction of non-local (cluster) updates.



No matter how much brute force computing power one invests - you cannot beat a clever algorithm!

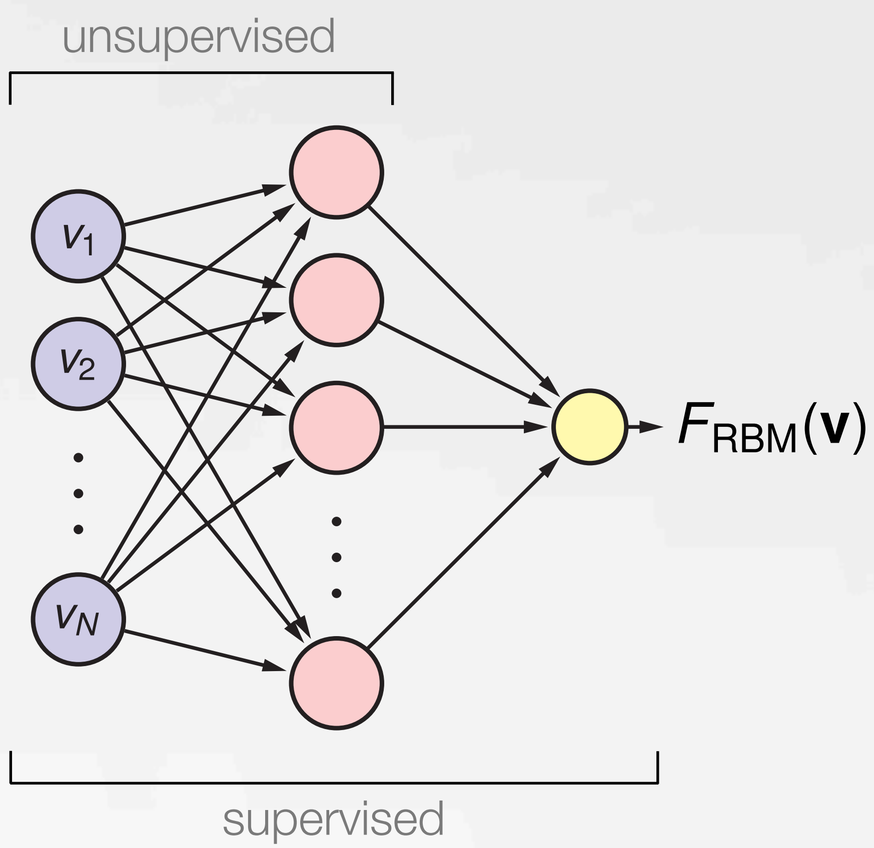
This holds true in particular for simulations close to (quantum) critical points, but also models with complex, or non-local interactions, or systems where symmetries are broken, such as in the presence of external fields.

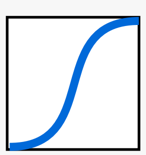


Non-nocal update algorithms rarely exist, as most of the known ones rely on simple conserved symmetries and simple interactions. Recently, alternatives based on the generation of effective models as sampling basis in Monte Carlo simulations have been proposed.

The applicability of such an algorithm appears promising, but remains unexplored.

Machine learning, the inverse Ising problem & non-local Monte Carlo updates





Alternatively, machine learning introduced the basic neural networks, which allow to be quickly and inexpensively trained with complex input.

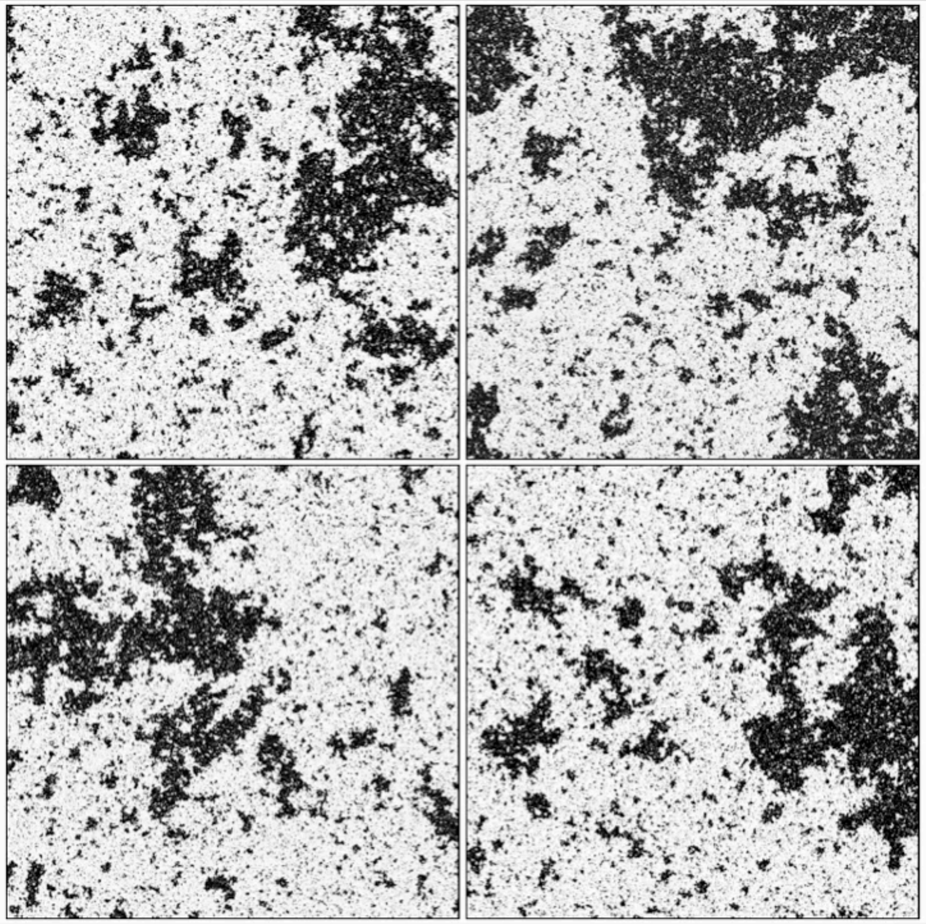
Reversing/activating these trained networks allows to generate configurations suitable for updates in (quantum) Monte Carlo simulations, which are almost exempt from autocorrelations.

L. Wang, Phys. Rev. E **96**, 051301(R) (2017)
L. Huang, L. Wang, Phys. Rev. B **95**, 035105 (2017)
Liu *et al.*, Phys. Rev. B **95**, 041101(R) (2017)
Carrasquilla, Torlai, Phys. Rev. X Quantum **2**, 040201 (2021)

This project investigates the competitiveness of non-local updates derived from a trained neural network in classical and quantum models.

Finite-Size Scaling at fixed RG-invariant

The study of (quantum-) phase transitions and critical theories are at the heart of physics. Investigating phase transitions allows us to unify and classify seemingly disparate physical systems. They represent the junction between phases and as such allow to research the proliferation of excitations, which drive the system into either phase.



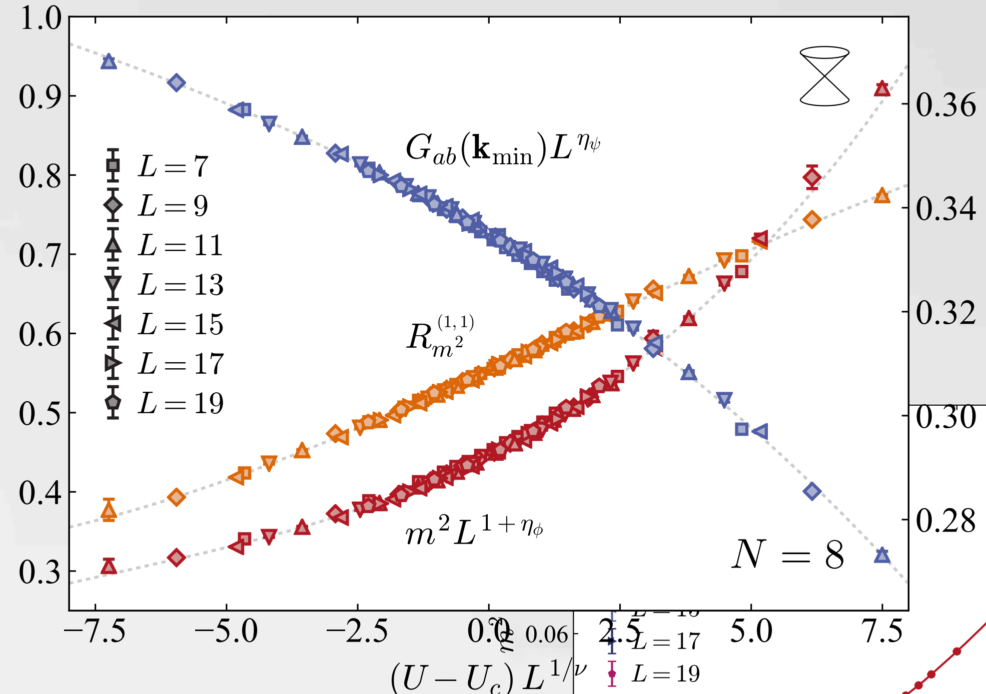
By Douglas Ashton

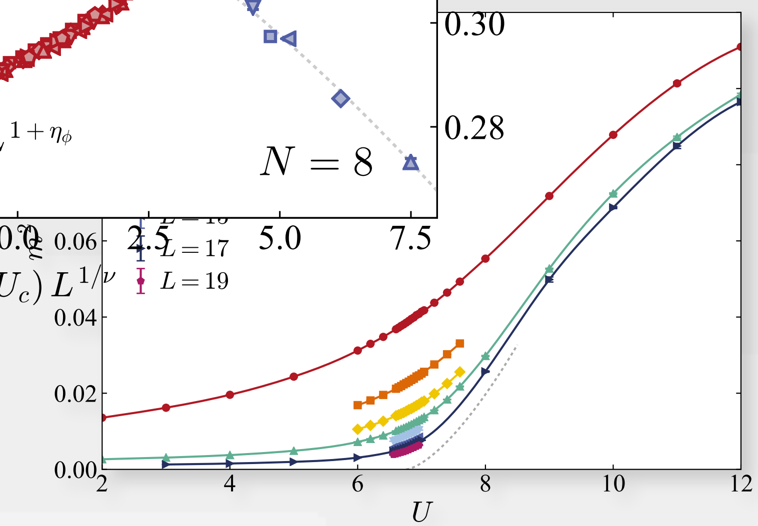
Numerical simulations are restricted to seemingly small finite size systems. Yet, we are interested in the emerging physical properties in the thermodynamic limit, i.e., the macroscopic level.

The finite size scaling ansatz constitutes the most reliable framework to extract critical properties such as the universal exponents at continuous (quantum-) phase transitions from numerical finite size simulations. Based on the concept of scale invariance the physical properties can be cleverly fitted by a scaling function close to criticality.

Finite-Size Scaling at fixed RG-invariant

A newly modified scaling ansatz suggests to expand the scaling function around so called renormalisation group invariant quantities (points).





The numerical analysis is then afflicted by the statistical fluctuations of said quantities rather than those of the usual order parameter.

This yields significant improvement of statistical accuracy as compared to a standard analysis!

F. Parisen Toldin, Phys. Rev. **E** 105, 034137 (2022)
M. Campostrini *et al.*, Phys. Rev. B **89**, 094516 (2014)

This project scrutinises a recent suggestion to drastically improve the numerical finite size scaling analysis at classical and quantum critical points, which promises to pin down the critical properties of controversial phase transitions.

Contact

Thomas C. Lang
Institut für Theoretische Physik
ICT Gebäude, Raum 4S21
thomas.lang@uibk.ac.at

Please don't hesitate to contact me for details!

- Dirac fermions on the lattice
- Machine learning, the inverse Ising problem and non-local Monte Carlo updates
- Finite-Size scaling at fixed renormalization-group invariant

Also, if you already have a certain project, or specific topic in the field of computational condensed matter physics in mind - your suggestions are very welcome!

Programming experience is helpful, but not required!

AG Lechner

Institute for Theoretical Physics

Quantencomputing

Research topics

- Solving Optimization Problems on Quantum Computers

Translating mathematical problems to quantum algorithms
Developing novel methods for near term and error-corrected quantum computers

- Statistical mechanics and thermodynamics of adiabatic quantum computing

Executing Quantum Gates is an adiabatic or non-adiabatic process and thus thermodynamics. We study the energy consumption of computation and investigate its limits.

References

A quantum annealing architecture with all-to-all-connectivity from local interactions,
Wolfgang Lechner, Philipp Hauke and Peter Zoller,
Science advances 1, e1500838 (2015).

Parity Quantum Optimization: Compiler,
Kilian Ender, Roeland ter Hoeven, Benjamin E. Niehoff, Maike Drieb-Schön, Wolfgang Lechner
arxiv:2105.06233 (2021).

Parity Quantum Optimization: Constraints,
Maike Drieb-Schön, Younes Javanmard, Kilian Ender, Wolfgang Lechner
arxiv:2105.06235 (2021).

Parity Quantum Optimization: Benchmarks,
Michael Fellner, Kilian Ender, Roeland ter Hoeven, Wolfgang Lechner
arxiv:2105.06240 (2021).

Universal Parity Quantum Computing,
Michael Fellner, Anette Messinger, Kilian Ender, Wolfgang Lechner
arXiv:2205.09505 (2022).

The Quantum Nanophysics, Optics and Information / Oriol Romero-Isart Group

Presenter: Thomas Agrenius

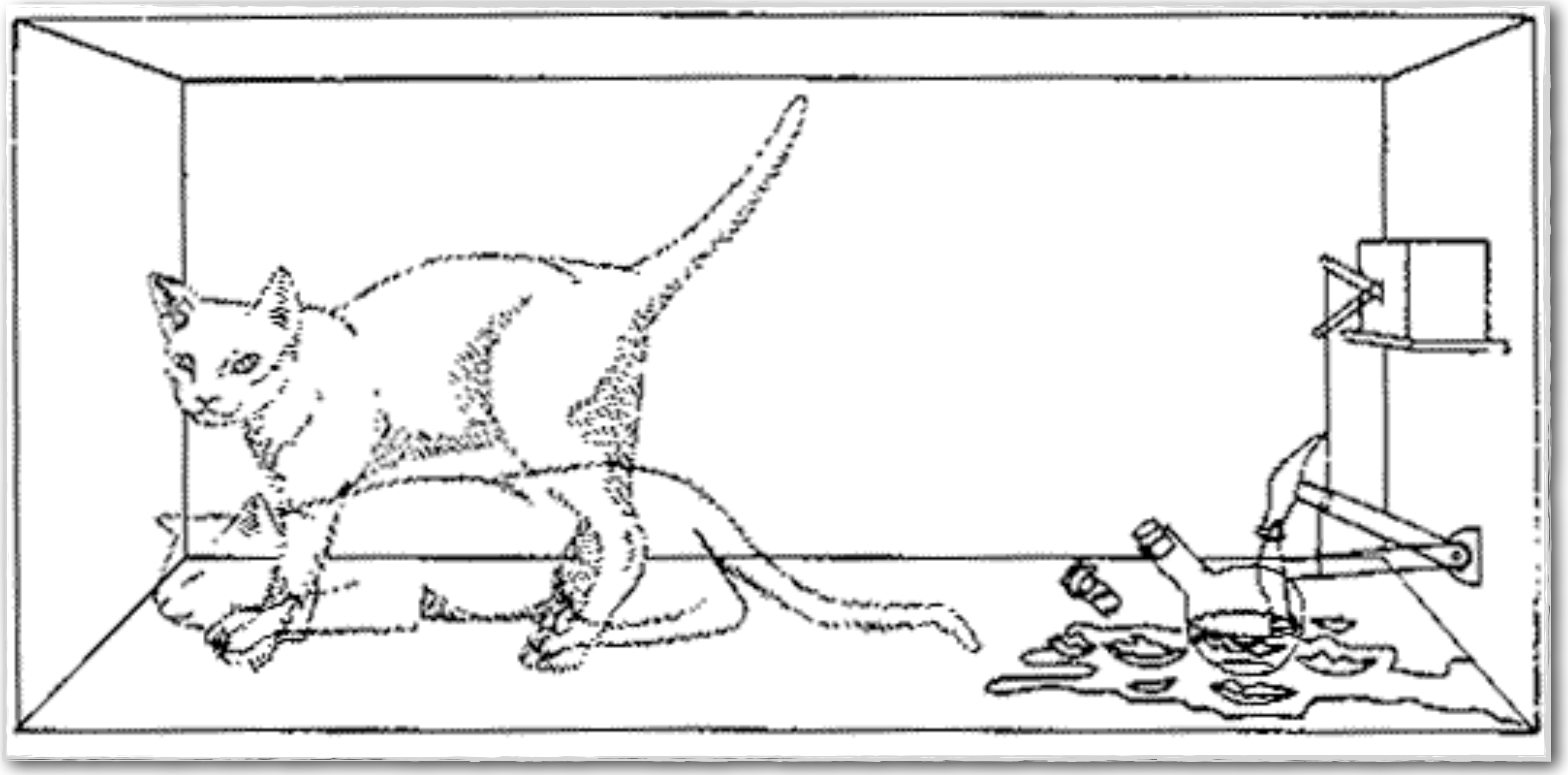
IQOQI - Institute for Quantum Optics and Quantum Information
ITP - Institute for Theoretical Physics, University of Innsbruck

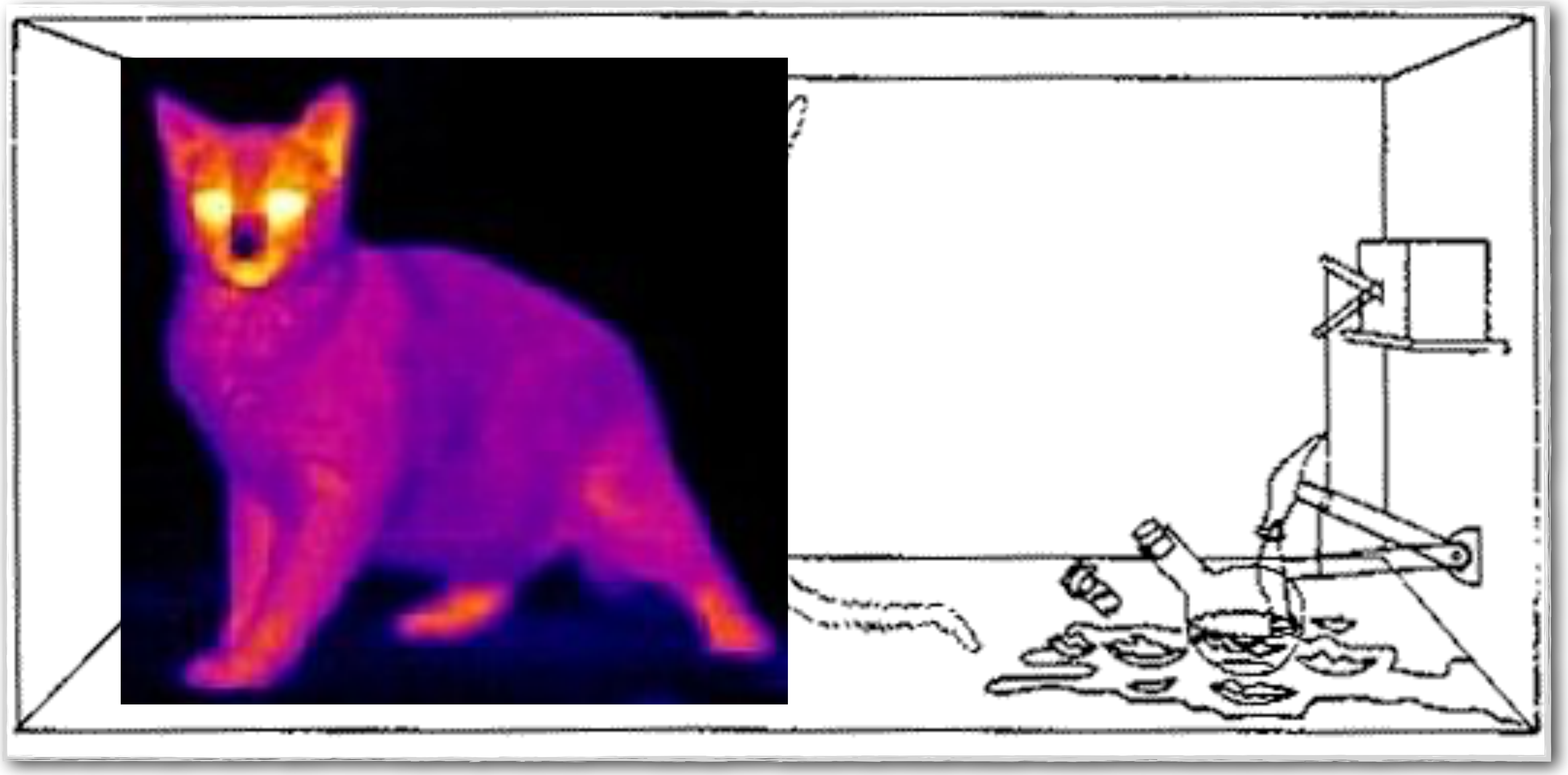
Seminar mit Bachelorarbeit 11.1.2023

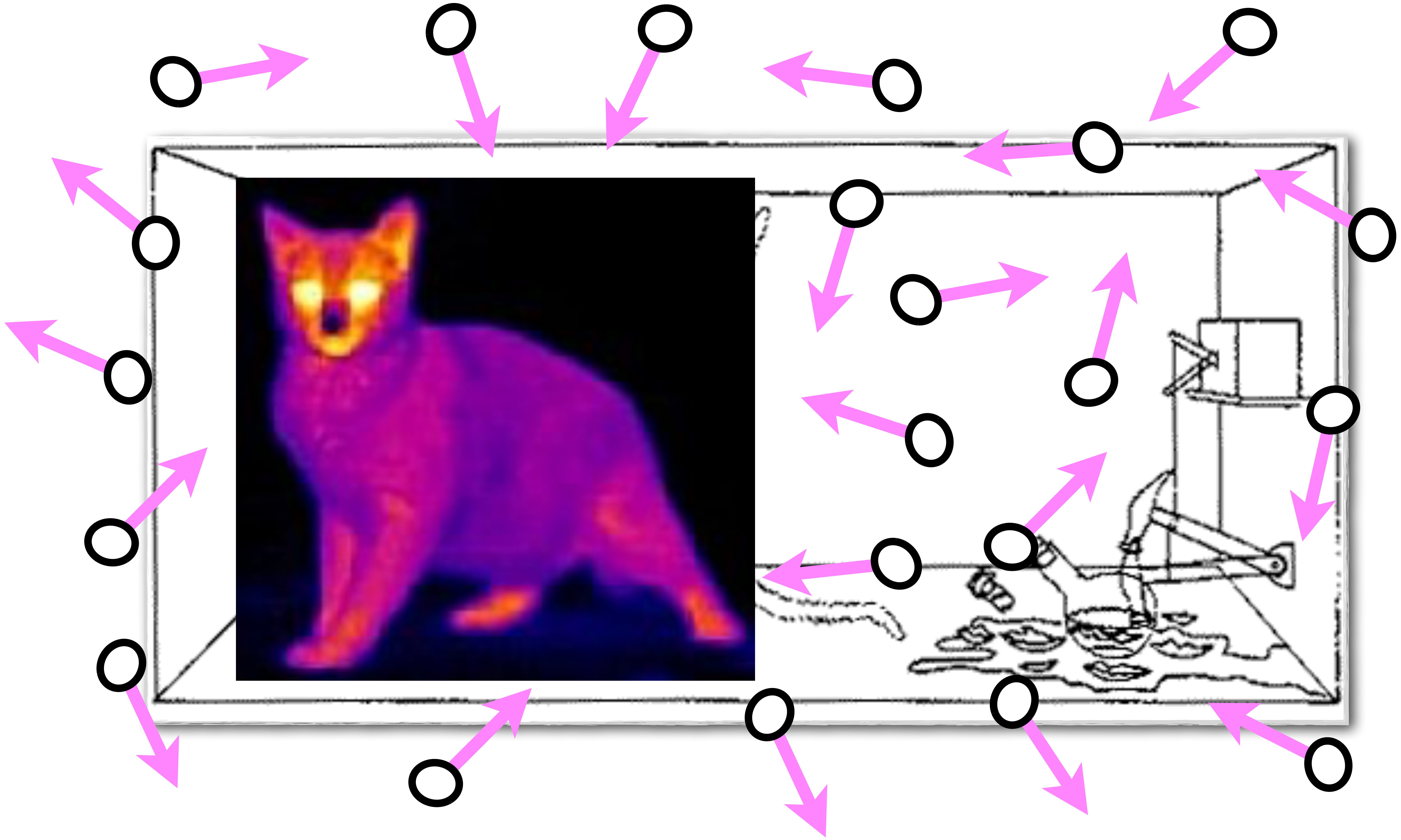
Toward quantum superposition of living organisms

Oriol Romero-Isart[1,4], Mathieu L Juan[2], Romain Quidant[2,3] and J Ignacio Cirac[1]

New Journal of Physics **12** (2010) 033015 (16pp)
Received 4 January 2010
Published 11 March 2010
Online at http://www.njp.org/
doi:10.1088/1367-2630/12/3/033015







Toward quantum superposition ~~of living organisms~~

Oriol Romero-Isart[1,4], Mathieu L Juan[2], Romain Quidant[2,3] and J Ignacio Cirac[1]

Toward quantum superposition ~~of living organisms~~

Oriol Romero-Isart[1,4], Mathieu L Juan[2], Romain Quidant[2,3] and J Ignacio Cirac[1]

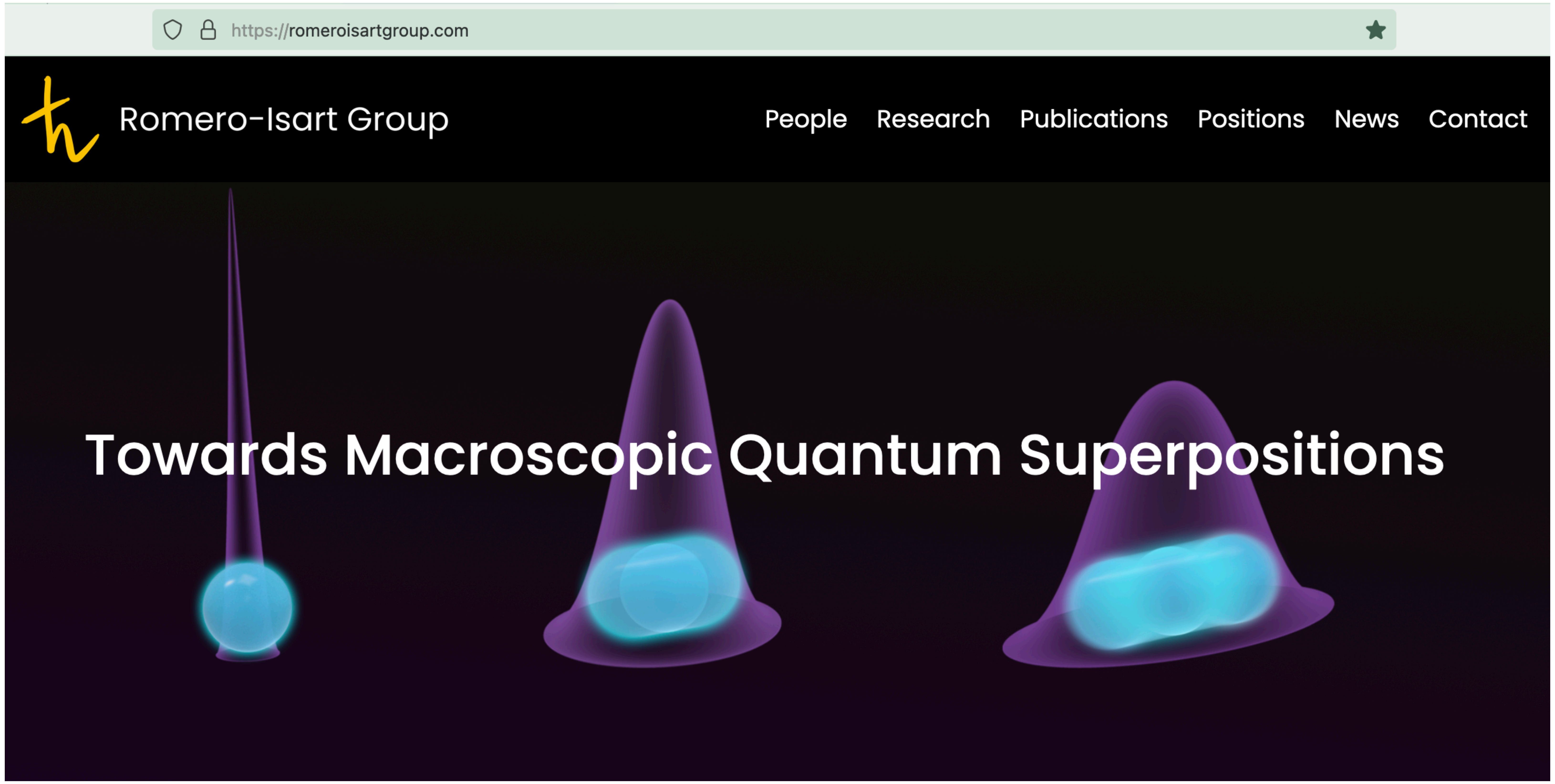
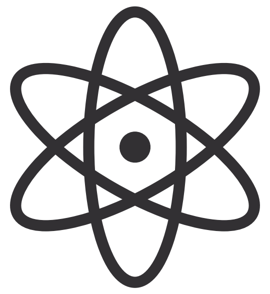


Image: Novotny Lab, ETH Zurich
Micrograph: Uros Delic, U. of Vienna

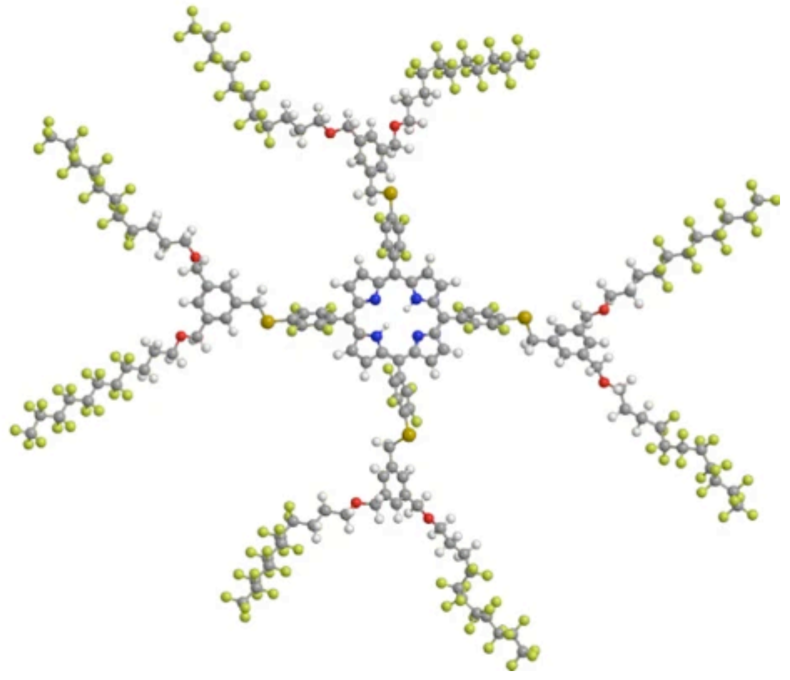
Current World Records of Quantum Superpositions

Longest distance ~1 m
mass 87 u



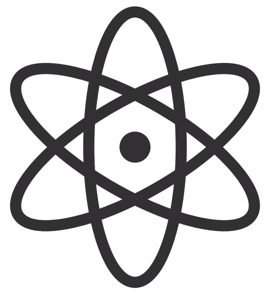
Rb-87

Heaviest object:
mass ~27 000 u
distance 300 nm



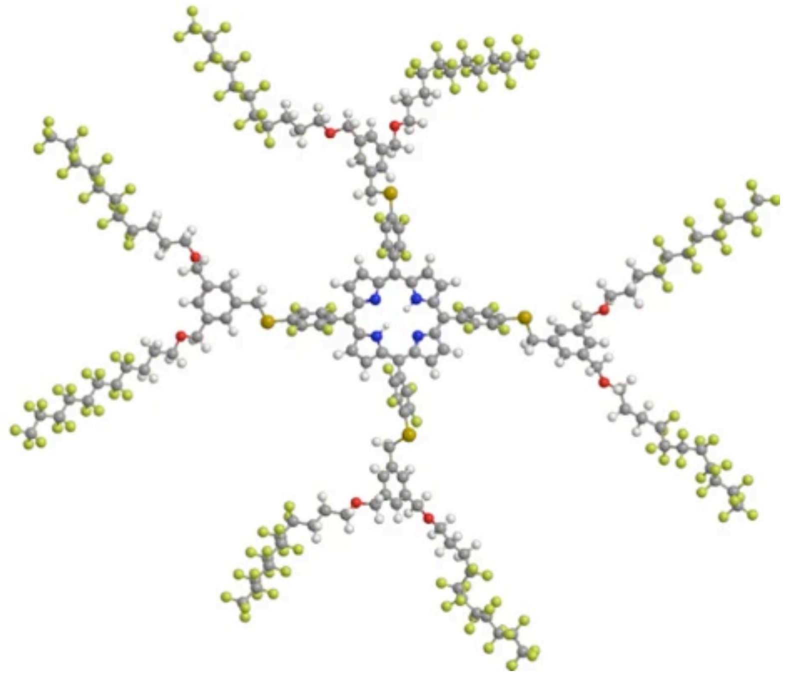
Current World Records of Quantum Superpositions

Longest distance ~1 m
mass 87 u

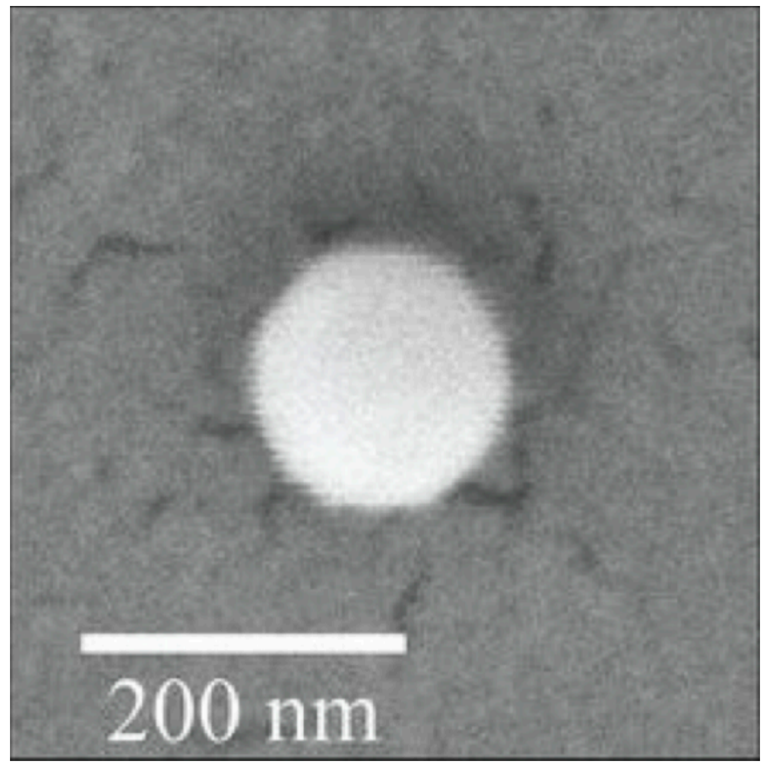


Rb-87

Heaviest object:
mass ~27 000 u
distance 300 nm



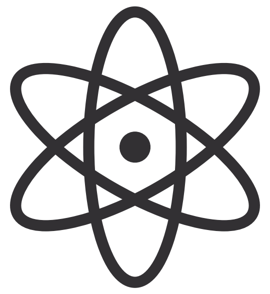
Our goal:



glass nanoparticle
mass 5 billion u
superposition distance: as far as possible

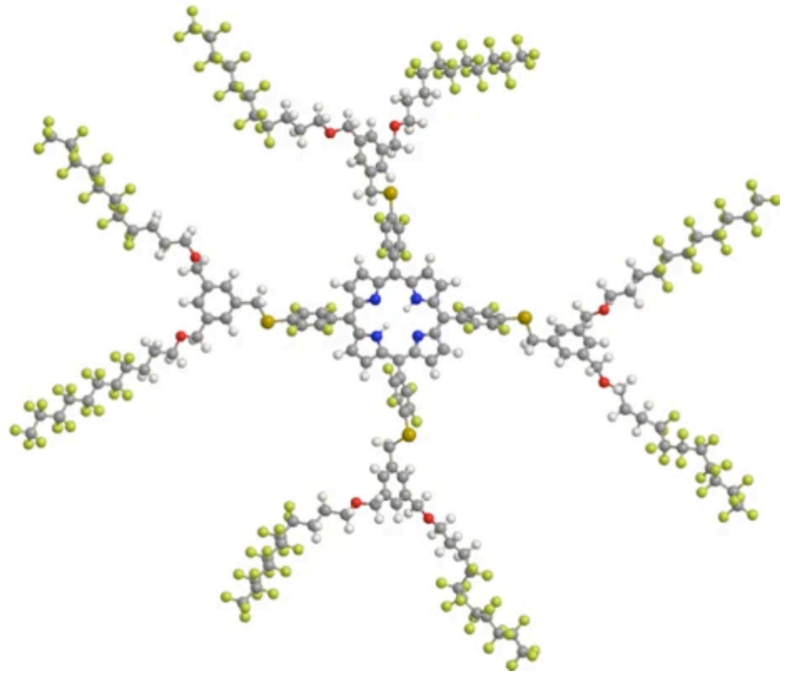
Current World Records of Quantum Superpositions

Longest distance ~1 m
mass 87 u

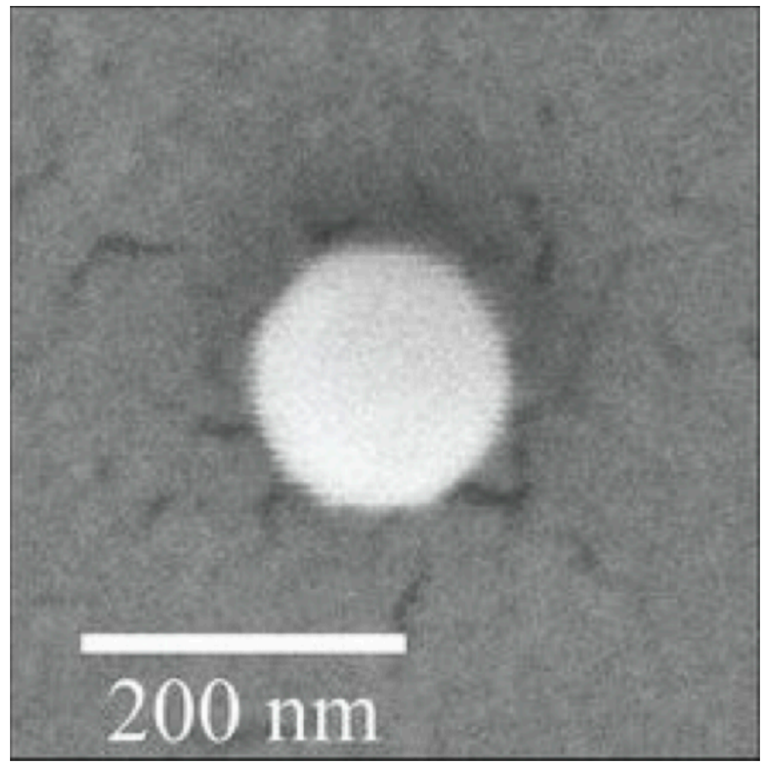


Rb-87

Heaviest object:
mass ~27 000 u
distance 300 nm

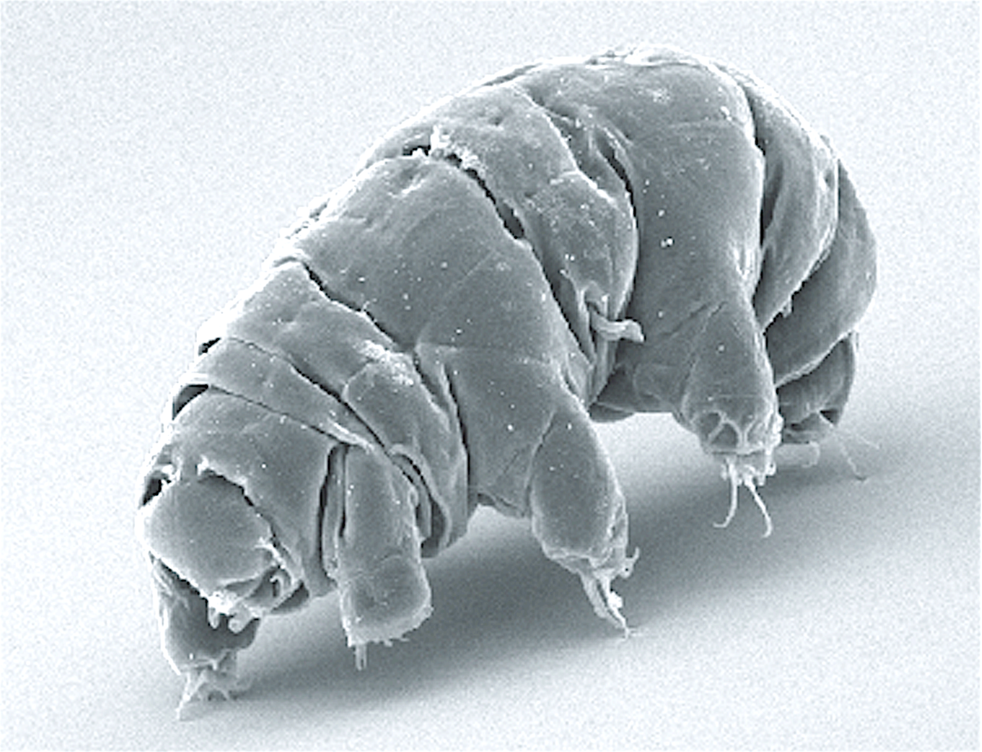


Our goal:



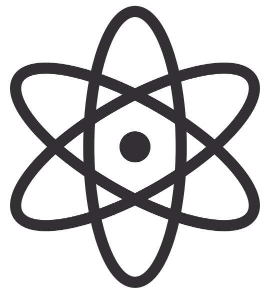
glass nanoparticle
mass 5 billion u
superposition distance: as far as possible

~~Living organisms~~
Dielectric material



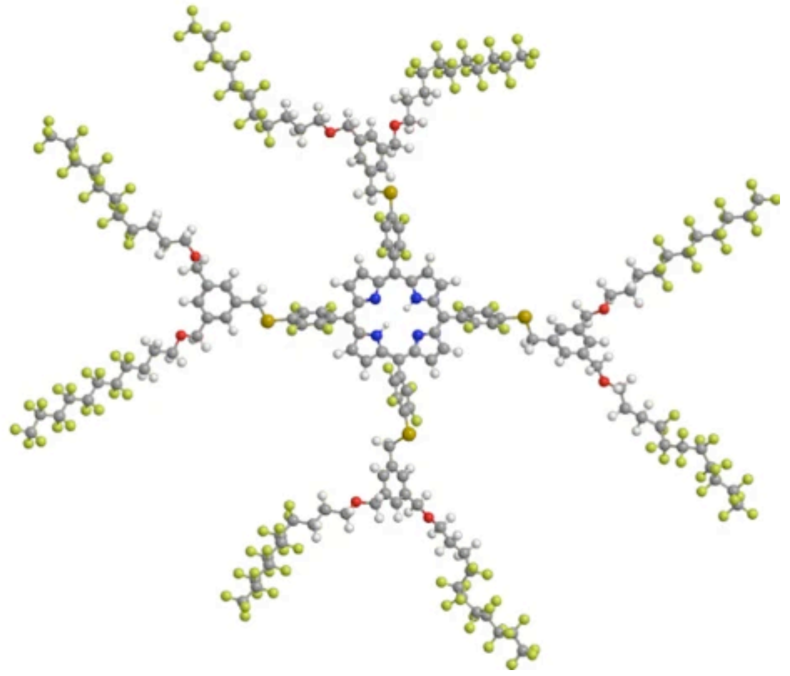
Current World Records of Quantum Superpositions

Longest distance ~1 m
mass 87 u

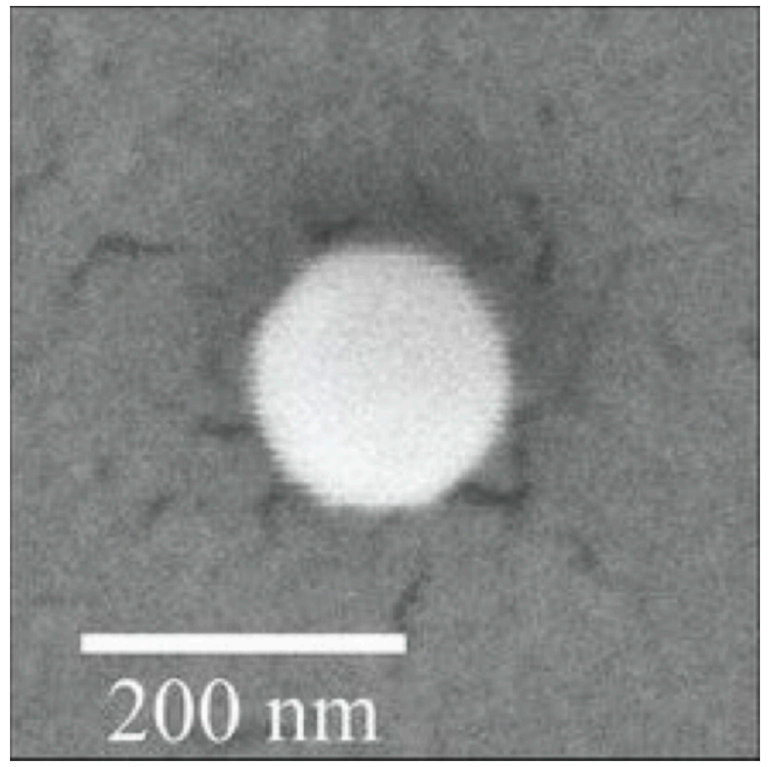


Rb-87

Heaviest object:
mass ~27 000 u
distance 300 nm



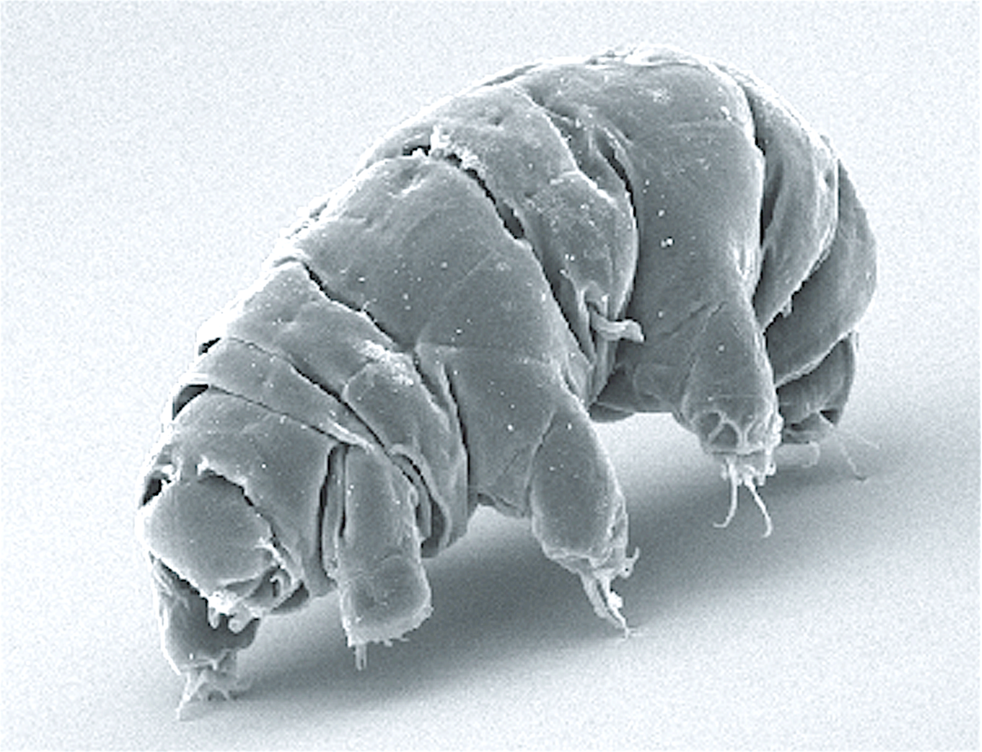
Our goal:



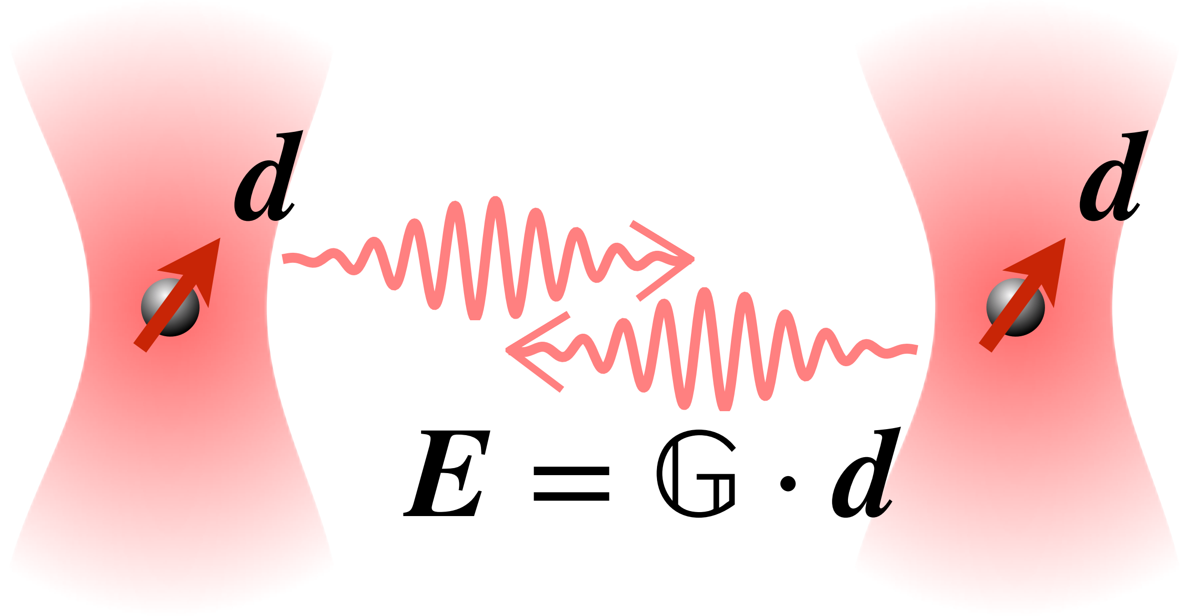
glass nanoparticle
mass 5 billion u
superposition distance: as far as possible

~~Living organisms~~
Dielectric material

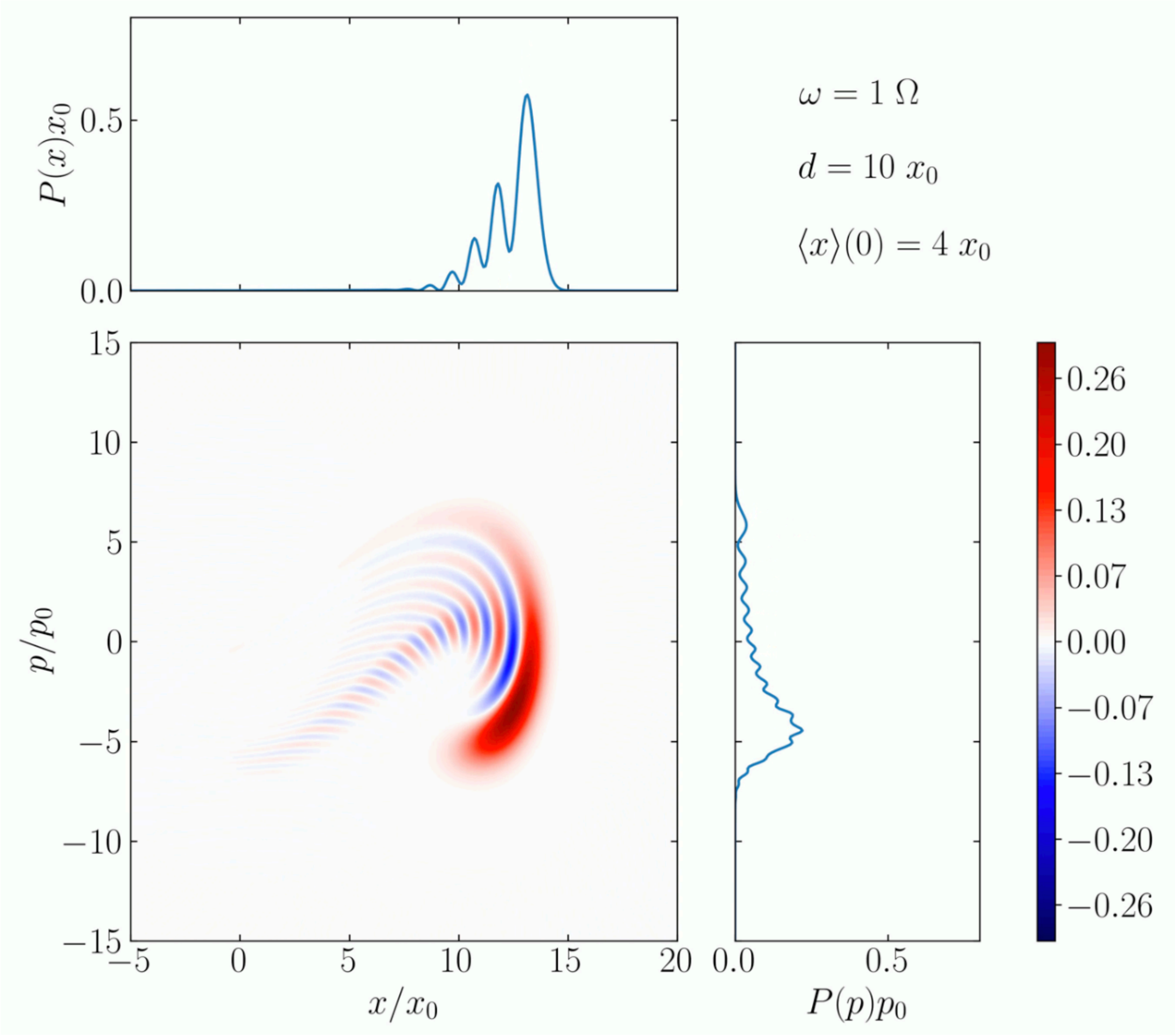
See Oriol's paper!



Physics of optical and magnetic levitation



Macroscopic quantum mechanics



Quantum mechanics with noise

$$\mathrm{d}\,|\psi\rangle = -\frac{\mathrm{i}}{\hbar}\hat{H}\,|\psi\rangle\,\mathrm{d}t + (\hat{U} - 1)\,|\psi\rangle\,\mathrm{d}W$$

Analytics, numerics, machine learning - whatever you like!

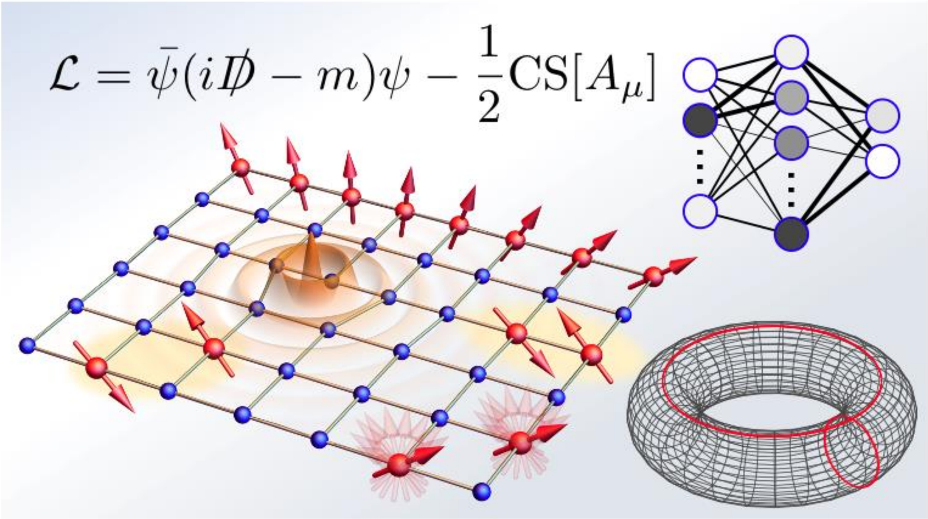
```python
def iperp(u):
    EPS = 0.1   # cutoff
    fullfunc = lambda v : numpy.sin(v)/v + 4 * numpy.cos(v) / numpy.power(v, 2) - 12 * numpy.sin(v) / numpy.power(v,3) - \
        24 * numpy.cos(v) / numpy.power(v, 4) + 24 * numpy.sin(v) / numpy.power(v, 5)          # the full function
    maclaurin2 = lambda v : 1/5 - numpy.square(v)/14                  # maclaurin expansion
    return piecewise_func(u, maclaurin2, fullfunc, EPS)
```


Patrick
Callum
Katja
Davide
Oriol
Thomas
Marc
Piotr
Silvia
Andreu
Leonarda
Judith
Master students
PhD students
Postdocs
Professor
Admin
www.romeroisartgroup.com

Quantum condensed matter theory

Mathias S. Scheurer
Institute for Theoretical Physics
Office: 2S11
Mathias.Scheurer@uibk.ac.at

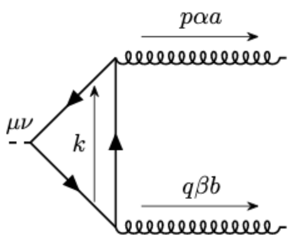
University of Innsbruck
Wed, 01/11/2023



Group site: https://www.uibk.ac.at/th-physik/mscheurer/

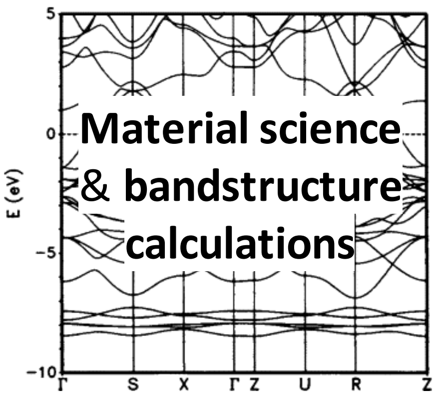
“Spectrum” of condensed matter theory

or: the slide I should have seen earlier



Quantum field theory
e.g., non-Abelian gauge theories, Higgs mechanism, dualities, …

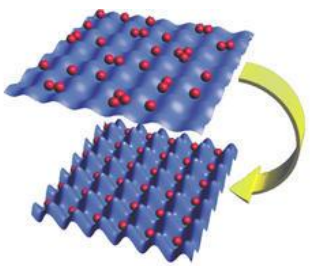
Interesting math:
e.g. topology and group theory



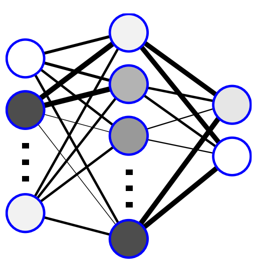
Material science & bandstructure calculations

Condensed Matter Theory

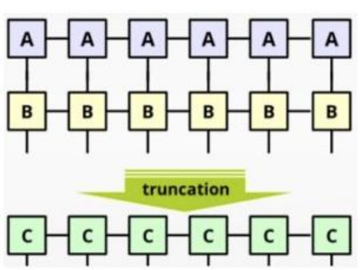
Quantum information & simulation



Data Science/ Machine Learning

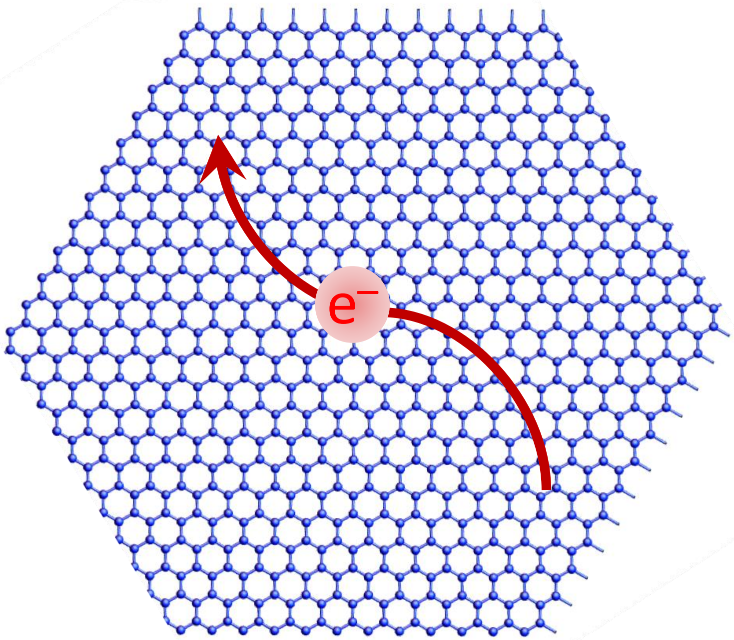


Computational physics



Topic I: Electrons in moiré graphene

Dirac equation: $E(\boldsymbol{k}) \sim v|\boldsymbol{k}|$
(emergent relativitics)



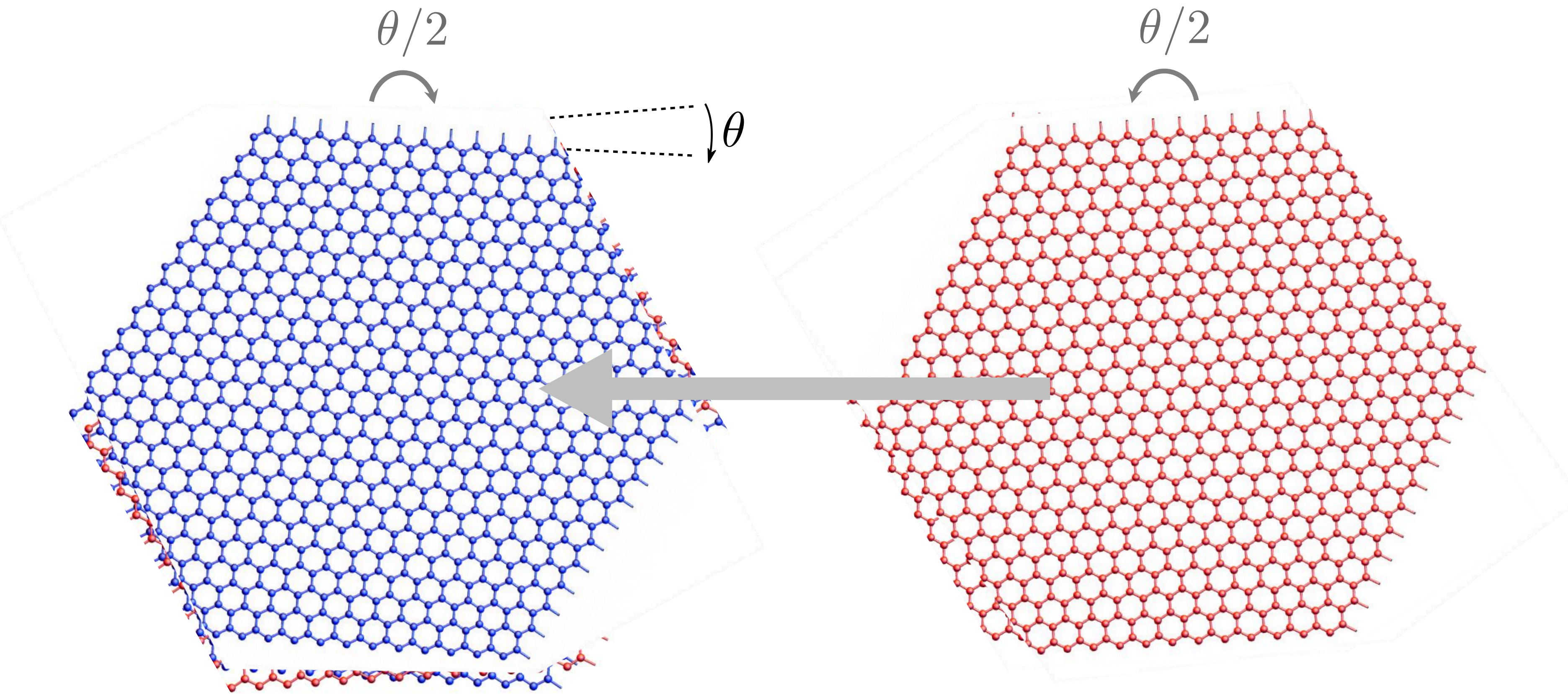
Graphene

"… they move through the graphene as a wave."

for groundbreaking experiments regarding the 2D material graphene

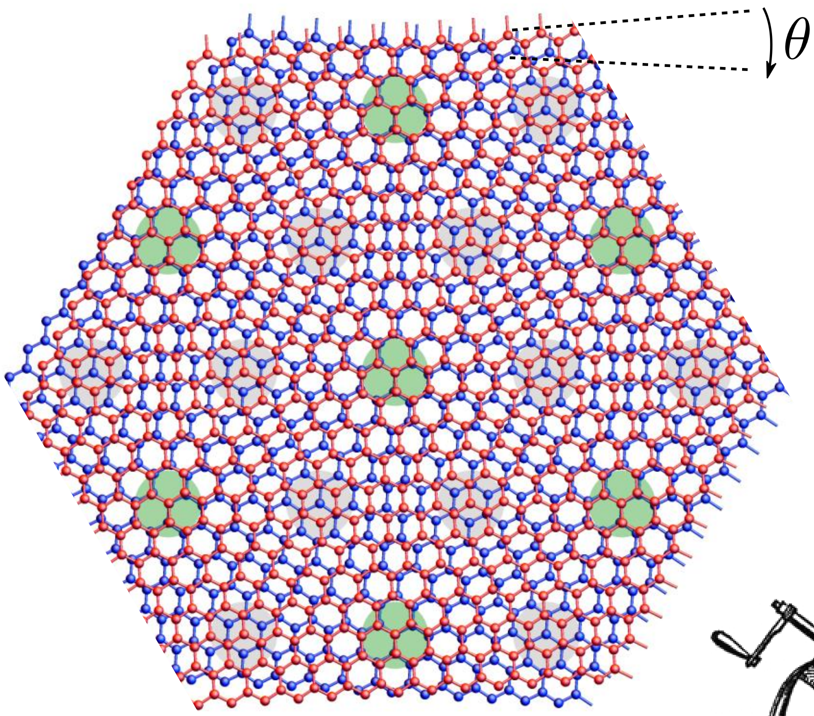
Geim & Novoselov, 2010

Topic I: Electrons in moiré graphene



Graphene **Graphene**

Topic I: Electrons in moiré graphene

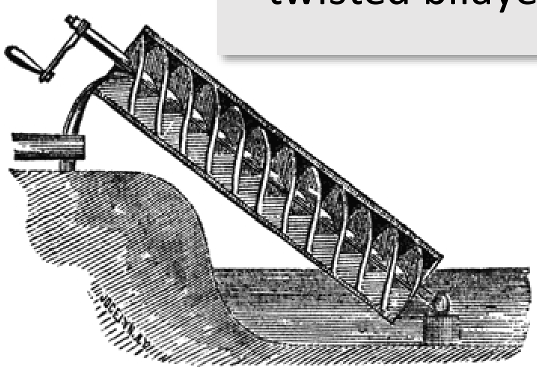


Twisted bilayer graphene

- ➢ ”Magic angle” $\theta \simeq 1°$: $E(\boldsymbol{k}) \approx$const.
- ➢ becomes superconductor or magnet

In this bachelor thesis:

“**Thouless Pump**” in a toy model of twisted bilayer graphene

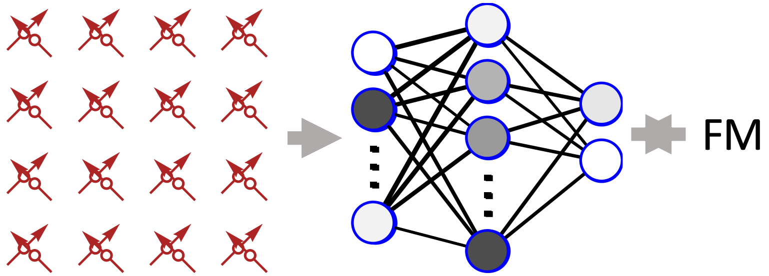


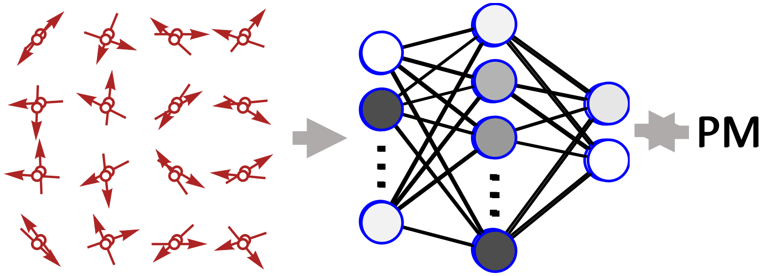
The quantum analogue of a screw pump

Topic II: Machine learning of phase transitions

Basic idea:

Carrasquilla & Melko, Nat. Phys. **13**, 431 (2017).





In this bachelor thesis:

- ➢ Learn how to train a **neural network** with TensorFlow
- ➢ Apply it to a **problem in physics**, like the Schrödinger equation