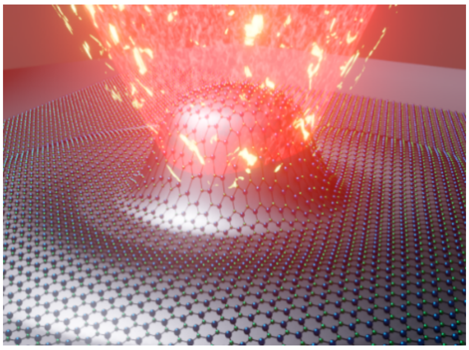
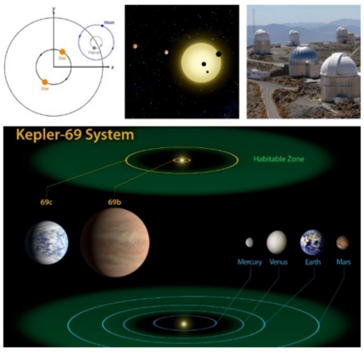
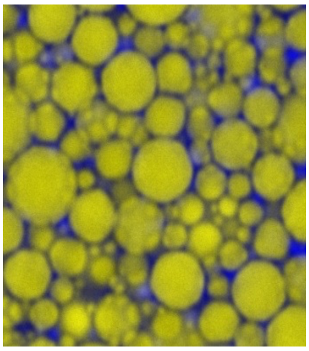
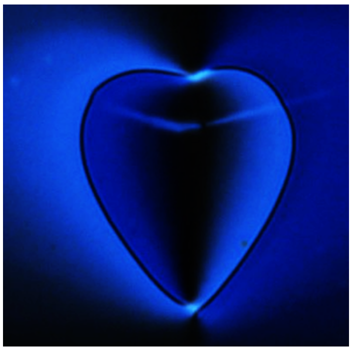


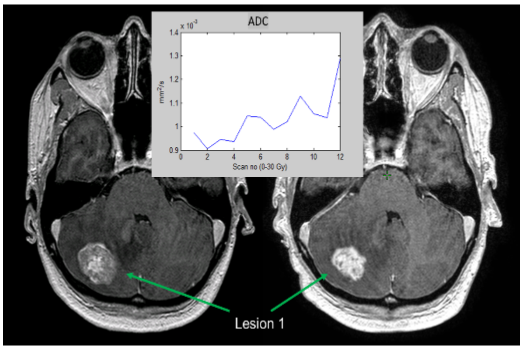


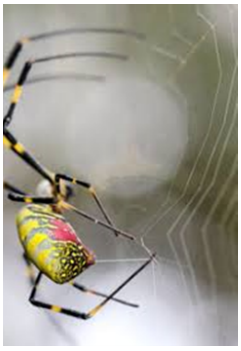


Physics thesis topics
- inspirational catalogue

Get your first glimpse at world-class research during your bachelor project, and get fully involved in it during your master project! Whether you are interested in the physics of cells and membranes, light and photons, gravity and black holes, particles and fundamental forces or many other areas – there is a project for you at SDU!







Contents

At SDU, you can find physicists at many different departments belonging to several different faculties. This catalogue intends to point out some of possible people you can work with, and thereby areas in which you can specialize, during your studies at SDU.

NB: There is a rule, that there must be a supervisor from the relevant education on bachelor and master projects, to make sure that the project has enough physics in it and that relevant rules are followed. This is usually not a major issue but should be remembered when you are discussing projects with someone that do not teach courses on the natural science physics education. Usually, the issue is solved by involving an extra supervisor on the project, but the actual involvement of this person can be minimal.

Associate Professor Manuel Meyer

Email: mey@sdu.dk

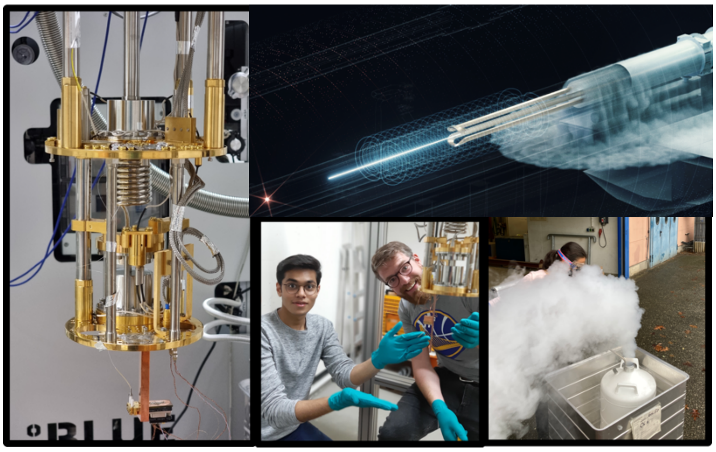
Webpage: https://axion-alp-dm.github.io/

Project types: Bachelor and Master

Research topics:
Particle and astroparticle physics, single photon detection

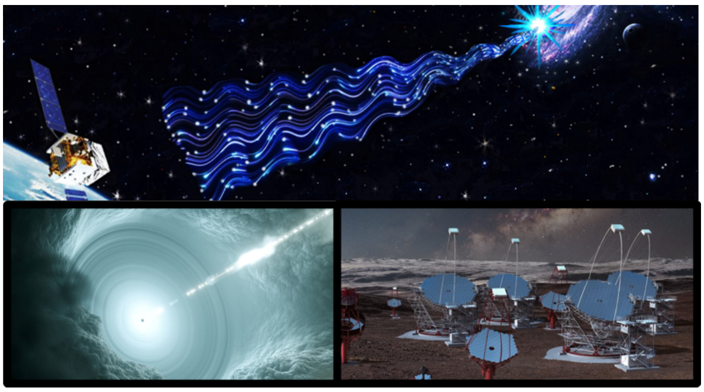
Research methods:
Experimental (detector component characterization, working with infrared lasers / optical fibers, quantum sensors), Theoretical (data analysis and interpretation, simulations)

Introduction to my research:



Using both laboratory experiments as well as observations of galaxies and other astrophysical sources, I try to understand the nature of the mysterious dark matter. Dark matter makes up roughly 85% of all matter in the Universe and could consist of yet-undiscovered elementary particles. Theory predicts that dark matter could possibly reveal itself in very weak interactions with light. In the experiments I'm involved in, we try to look for this interaction by shining light through walls and by searching for features in spectra of distant galaxies and supernova explosions.

Examples of thesis projects:



I can offer a variety of thesis topics depending on the courses you have attended and if you rather like to work "hands-on" in the lab or with data analysis. The projects can either be related to the ALPS II large-scale laboratory experiment or to astrophysical high-energy gamma-ray observations. Please reach out via email if you are interested!

Example project: Characterization of optical filter and improvement of the signal and background discrimination

The ALPS II experiment aims to produce hypothetical particles, so-called axions, by sending a powerful infrared laser beam into an optical cavity and through a magnetic field. Laser photons could convert to axions in the magnetic field, leave the cavity, and re-convert into photons in a second magnetic field. The number of reconverted photons will be tiny (we expect at most around one photon per day). Therefore, we need sensitive single photon detectors and an effective suppression of any potential background. One investigated detector technology is a superconducting transition edge sensor that counts photons at a temperature close to absolute zero. Here at SDU, we are investigating ways to reduce the number of spurious photons reaching the detector. One possibility is to use an optical filter inside the cryostat which we are currently building in our lab. We are also looking into using machine-learning algorithms to achieve a better discrimination between signal and background events registered with the detector. We are always looking for students to help us with these projects.

Example project: Searching for physics beyond the standard model with gamma-ray observations

Charged particles like electrons can be accelerated to almost the speed of light in extreme environments in the Universe, for example in remnants of supernova explosions or close to supermassive black holes. These particles can produce gamma rays, i.e., photons one million times more energetic than X-rays. The gamma-ray spectra of these sources could be affected by beyond-the-standard-model physics. For instance, certain theories that try to combine General Relativity and the Standard Model predict that Lorentz Invariance breaks down above a certain energy. This could lead to observable features such as a suppression of the gamma-ray flux. In this project, we will model the broad-band emission of the Crab nebula, one of the brightest gamma-ray sources in the sky. Using this model, we will make predictions for gamma-ray observations in the presence of Lorentz Invariance Violation and confront our predictions with data from Imaging Air Cherenkov Telescopes and the *Fermi* satellite.

Professor Martin Snoager Sloth

Email: sloth@sdu.dk

Webpage: http://universe-origins.dk/sloth/

Project types: Bachelor and Master

Research topics: Particle cosmology

Research methods: Bachelor and Master

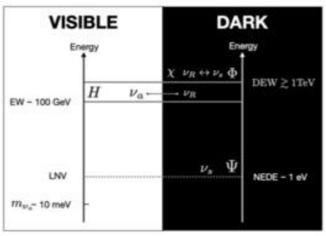
Introduction to my research:

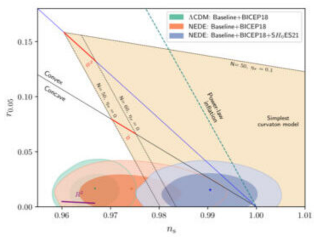
I am working on understanding the most fundamental problems pertaining to our understanding of the Universe; the origin of the Universe, the evolution of the Universe, the matter contents, and the forces which govern the Universe.

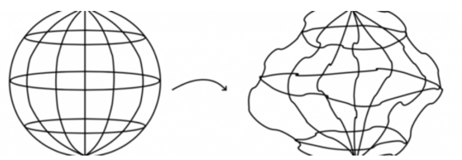
You can find more information here: http://universe-origins.dk/sloth/?page_id=64

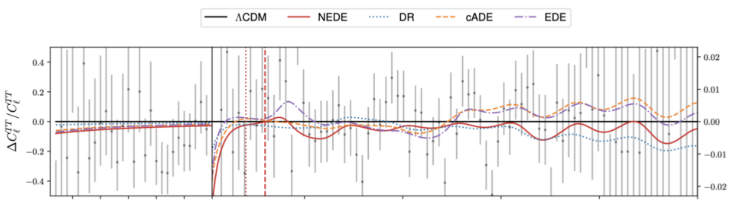
Examples of thesis projects:

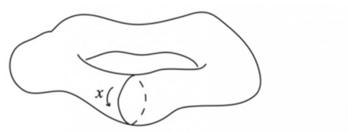
Cosmological tensions (Hubble tension and S8 tension), Dark Matter models, Dark Energy and string theory, physics of primordial inflation, the origin of cosmic magnetic fields, perturbative quantum gravity and consistency relations of cosmological correlation functions, primordial black holes and gravitational waves, the black hole information paradox, quantum cosmology.











Assistant Professor Sofie Marie Koksbang

Email: koksbang@cp3.sdu.dk

Webpage: https://arxiv.org/search/?query=koksbang
&searchtype=all&source=header

Project types: Bachelor and Master

Research topics:
Cosmology, general relativity

Research methods:
Theoretical (numerical and/or analytical)

Introduction to my research:
My research is within the field of *inhomogeneous cosmology*. Cosmology is the study of the Universe as a whole. According to the standard model of cosmology, 95% of the current content of the universe is dark matter (25% of the content) and dark energy (70%). These substances have entirely unknown physical natures, making the standard model unsatisfyingly phenomenological. The standard model is nonetheless generally considered successful. But inconsistencies between observations and the model have appeared and are now statistically significant at around 5 sigma. This indicates that the model is somehow incorrect or incomplete.

In *inhomogeneous cosmology* the aim is to study how structures (from tiny particles to huge galaxy clusters) affect our understanding of the Universe and to what extent this can explain the apparent discrepancies between observations and our standard model.

Examples of thesis projects:

(Machine learning) Cosmic Backreaction, Bachelor level
Background: A hypothesis called *the backreaction conjecture* posits that dark energy does not exist and that the apparent late-time accelerated expansion of the universe (which dark energy is supposed to explain) is an artifact due to the non-linearity of Einstein's equations (the mathematical foundation for general relativity): The non-linearity means that Einstein's equations give different results for the large-scale dynamics of the Universe depending on whether one plugs in average density fields etc. into Einstein's equations or instead plugs in the inhomogeneous density field (describing a universe with galaxy clusters, voids etc.) and averages afterwards (to get a set of equations describing the large-scale/smooth universe). The former is manifestly incorrect but it is what is done in standard cosmology. The latter is formally correct and gives extra terms (cosmic backreaction) sourcing the expansion of the Universe, including a term which can lead to accelerated expansion. A realistic quantification of cosmic backreaction of the real universe is still missing.

In these projects, the aim is to understand and describe the concept of backreaction. A core element is working with a toy-model to gain physical intuition for backreaction and how it can lead to accelerated expansion. The project can then develop in different directions depending on the student's interest. It could, for instance, be mainly analytical and thus aim at deriving the dynamical equations for an inhomogeneous universe including backreaction terms. The project can also be mainly computational and numerically study exact solutions to Einstein's equations in terms of their prediction for cosmic backreaction. The project can also be aimed at using open source software for doing symbolic regression (machine learning) for learning about the behavior of backreaction.

Master's theses:
The following is a list of examples of projects suitable for a master's thesis. All projects rely heavily on numerical work but will also necessarily include some analytical work.

1) **Optical drift:** I have identified an observational "smoking gun" for cosmic backreaction (described in the bachelor projects above) which we will be able to measure within 30-100 years….The observable is called redshift drift and an important concept related to redshift drift is *optical drift* which is the apparent change of position of an object on the sky. In this project you will use a family of solutions to Einstein's equation known as *Szekeres models* for studying the optical drift effect in the presence of anisotropic structures (a void surrounded by galaxy clusters/walls).
2) **Reproducing Szekeres models with Gadet-2**: Structure formation in cosmology is traditionally studied using Newtonian N-body simulations and thus not by using the more correct general relativity. In this project you will see if it is possible to reproduce exact, inhomogeneous solutions to Einstein's equations with an open source Newtonian N-body code (e.g. Gadget-2). A big obstacle is how to relate the coordinates used for Szekeres models to those of the N-body simulation.
3) **Observations in a universe with opaque baryonic matter**: Different types of observations in cosmology such as CMB and supernova data is usually compared with model predictions by using open source *Monte Carlo* codes. In this project you will modify the open source *Monte Python* code in order to do cosmological parameter extraction under the assumption that ordinary (baryonic) matter is opaque i.e. by introducing the assumption that light we observe in our telescopes only includes light which has not propagated through ordinary matter and see if this removes current inconsistencies between theory and observations in cosmology.
4) **Observations in a tilted universe:** Observations are beginning to indicate that we may live in an anisotropic universe, i.e. a universe that looks fundamentally different in different directions. In this project you will look at the standard cosmological spacetime, but in a *tilted* frame where observations become anisotropic. You will use the model to study different types of observations (e.g. redshift drift mentioned earlier) to identify signals of anisotropy that we might be able to use in the future to learn about the possible anisotropy of our universe.

Cosmic backreaction from symbolic regression: A main goal in *inhomogeneous cosmology* is to learn how to relate cosmic backreaction to observables (see the bachelor project described above regarding cosmic backreaction). In this project you will compare different open source symbolic regression codes in terms of their ability to faithfully extract information about the behavior of backreaction in toy cosmological models.

Assistant Professor Tobias Cornelius Hinse

Email: toch@sdu.dk

Webpage:
https://portal.findresearcher.sdu.dk/da/persons/toch

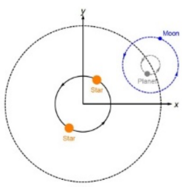
Project types: Bachelor and Master. Topics: Extrasolar planets, celestial mechanics, astrodynamics, planet dynamics, numerical celestial mechanics, solar system dynamics, non-linear dynamics, moons and small-body dynamics, photometry, transiting planets, classic astrophysics data modeling, meteor observations, astrometry, circumbinary extrasolar planets, image processing, observational astronomy, spectral energy distribution (SED) modeling of single stars, astrobiology, binary stars, didactical experiments for STEM classroom.

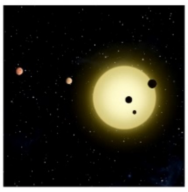
Research topics:
Dynamics and physical properties of extrasolar planets, binary star systems, observational astronomy.

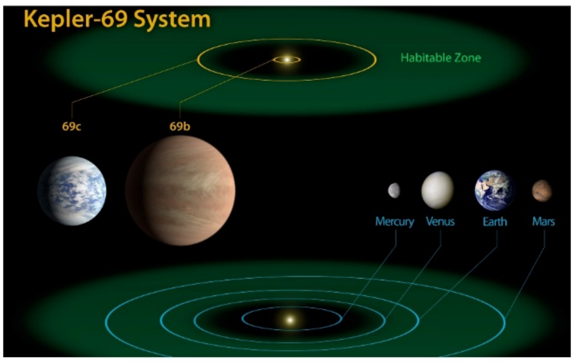
Research methods:
Numerical / computer simulations, image processing, model building, data time-series analysis, Fourier analysis, aperture / differential photometry, statistical hypothesis testing (F-test).

Introduction to my research:

I started my research by looking at the three-body problem considering the orbital stability and habitability of an Earth-mass planet considering gravitational perturbations from a Jupiter-like planet orbiting a solar mass star. This was the starting point towards celestial mechanics and planet dynamics. In parallel I developed interest in observational astronomy and data modeling with focus on high-precision photometry of transiting extrasolar planets. My research demands plugging information from various astrophysical catalogs and work with well-defined tools (like SED modeling for stellar characterization). However, recently I also developed an interest in didactics of STEM science experiments in the laboratory suitable for classroom demonstration.







Examples of thesis (BSc & MSc) projects:

Analysis of a transiting planet, planet dynamics and solar system planet evolution from numerically long-term integration of the equations of motion, small-body dynamics and dynamics of a moon. Stellar characterization via spectral energy distribution modeling. However, I am also open to topics that combine data science and astrophysics. I do not have much experience with this, but looking towards the future this is where modern astronomy will head towards with upcoming large sky survey like Rubin Observatory (formerly LSS telescope), EUCLID and PLATO space telescopes and ELT. This is the field of 'Astrostatistics'. Finally, if you would like to write a thesis project in developing and testing a well-defined didactical science/lab activity, please contact me: We could work on projecting Brownian motion on the classroom wall and bring Einstein's thoughts and ideas about nature's small-scale structure and physical processes vividly available to students with quantitative measurements of Avogadro's constant.

Associate Professor Michael Andersen Lomholt

Email: mlomholt@sdu.dk

Webpage: https://phylife.sdu.dk/michael-lomholt

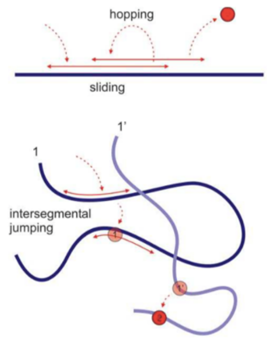
Project types: Bachelor and Master

Research topics:
Statistical physics, biophysics, soft matter, data analysis, random walks and stochastic processes

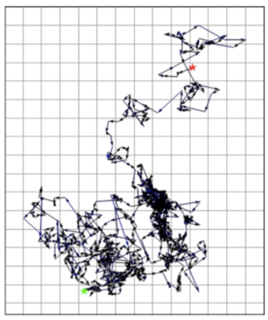
Research methods:
Theoretical (analytical, numerical, simulations and data analysis)

Introduction:
I am a theoretical physicist that does both pure theory as well as modelling and analysis of experimental data. Projects with me can be tailored according to interests, and involve purely analytic studies, as well as studies that are heavy on programming, numerical analysis or simulations. Projects that involve modelling and data analysis can be done in collaboration with experimentalists, for instance my colleagues at PhyLife - Center for Physical Life Sciences. Send me an e-mail, and we can set up a meeting to discuss the possibilities.

A few examples of projects to illustrate potential topics:



Random walks and dynamics of DNA-protein interactions
Random walks occur in many natural processes. For instance, a protein in a cell searching for a specific binding site on DNA. This gives rise to a complicated random walk that switches between movement in 3D around the cell with occasional binding to the DNA molecule. When bound to DNA the motion is then in 1D along the DNA.



Is diffusion in cells Brownian or anomalous?
Given a complicated trajectory of a diffusing particle like the one to the left, how does one find a theoretical model that describes the data well, or just determine which of a given generic set of models that best fits the trajectory? My preferred framework for answering these kinds of questions is Bayesian inference.

Computational methods
To help answer questions such as thus above, I also develop and study computational algorithms. A key computational method is Monte Carlo simulations, where random numbers are used to greatly speed up computations.

Associate Professor Francesca Serra

Email: serra@sdu.dk

Webpage: https://sites.google.com/view/serralab-sdu-jhu/home

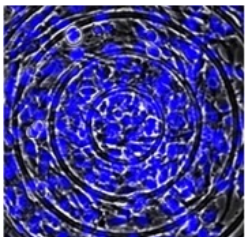
Project types: Bachelor, Masters, PhD

Research topics:
Soft matter, liquid crystals, collective behavior of cells, topological defects

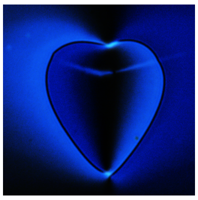
Research methods:
Experimental (Optical microscopy)

Introduction to my research:
What do computer displays and layers of living cells have in common? We try to answer: liquid crystals! These fascinating materials share some properties of liquids and solids: they can flow like liquids but their molecules are aligned, like in solids. Moreover, some kinds of living cells are elongated and align with each other, just like liquid crystals. This alignment helps cells communicate better and move more easily.
Liquid crystals are familiar to all of us for their use in computer displays. However, while liquid crystals in displays are usually well ordered, interesting properties emerge when liquid crystals are forced to mis-align and form disordered regions called topological defects. Our goal is to control and study topological defects both in molecular systems and in cell systems, to draw analogy and study their fundamental properties.

Examples of thesis projects (can be adapted for bachelor and master):



Topological defects in cells on a curved surface
Layers of cells that align with each other form topological defects. We discovered that cells near defects behave differently from other cells: they express different proteins, they divide more often, they become more dense and more spherical (as in the photo). Our and others' experimental evidence suggests that the formation of topological defects is responsible for determining the shape of organs and tissues in the body, the so-called "morphogenesis", or the "origin of shapes". If confirmed, this will open a whole new understanding of biology through physics.
One simple mechanism to form defects is to create a surface with bumps, holes and obstacles, but it is important to understand what defects are induced and how. In this work, you will learn to fabricate substrate for cells, observe cells with optical microscopy (phase contrast, fluorescence, confocal), analyze their position, orientation and order parameter and identify the defects, in order to establish a correlation between defects and substrate curvature.



Controlling topological defects with photo-alignment

There are various strategies to control the orientation of liquid crystals. The most promising and versatile is through "photo-alignment", using a thin layer of light-sensitive material that changes orientation according to the polarization of light and guides in turn the orientation of liquid crystal. Thanks to photo-alignment, one can control defects in liquid crystals and effectively "draw" arbitrary patterns of defects (like the heart in the photo), which can then be used to trap small particles or as optical devices. In this work, you will set-up a new photo-alignment system with lenses and polarizers, test it with simple patterns in liquid crystal materials and, finally, design complex pattern to create arbitrary defects.

Associate professor Adam Cohen Simonsen

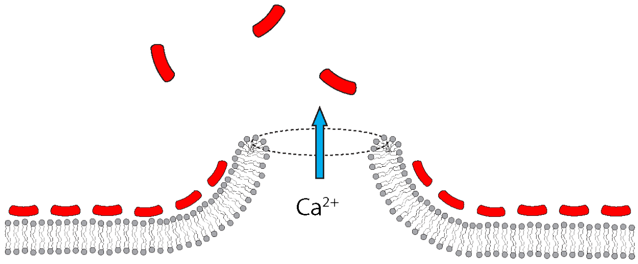
Email: adam@sdu.sdk
Webpage: https://phylife.sdu.dk/adam-cohen-simonsen/
Project types: Bachelor, Master, ISA
Research topics: Biophysics, Biomembranes, Food Physics

Research methods: Experimental models of biological systems. Atomic Force Microscopy (AFM). Fluorescence microscopy. Image Analysis. Method development.

Introduction:
My research is broadly focused on understanding the physics of interfaces in biological systems. One main interest is understanding biological membranes, their structure, and their dynamics during processes such as plasma membrane repair. We use experimental methods to fabricate model membrane systems and study them with advanced microscopy tools and image analysis. I collaborate with e.g. the Danish Cancer Society and with colleagues at PhyLife (SDU) and outside SDU. Another interest concerns the structure of dairy and plant-based food materials which we study using microscopy in collaboration with major companies such as Arla and IFF.

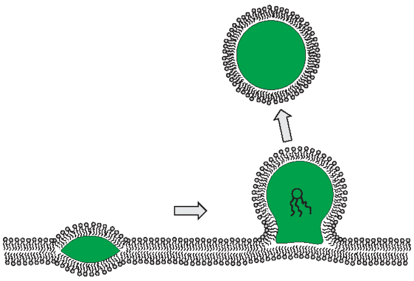
Examples of thesis projects which can be tailored to your background and specific interests (from bachelor level and up):

Mechanism of plasma membrane repair



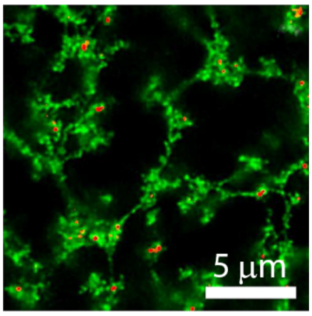
The plasma membrane of cells is a lipid bilayer barrier of only 5 nm between the cell interior and its surroundings. During the life cycle of a cell, the barrier can be damaged which will lead to cell death within minutes if the hole is not sealed again. Cells have developed sophisticated repair mechanisms involving proteins that bind to the membrane and modify its shape after damage. This project will use artificial model membranes to investigate with microscopy, image analysis and theory how repair proteins interact with membranes and modify their shape with the end goal of understanding the repair mechanism.

Membrane inclusions



Lipid bilayers can because of natural processes or interactions with the environment absorb molecules or particles which are only partly soluble in the membrane structure. This can lead to nucleation of aggregates inside the bilayer and potential formation of new structures. One important example in cells is the formation of lipid lenses and lipid droplets which are formed when fats (triglyceride) are up-concentrated in the bilayer. Another less studied example is the interaction of micro and nano-plastics in the environment with lipid bilayer membranes. In the project we will study the physical mechanisms behind the formation of membrane inclusions, using experimental model membranes.

Microscopy of food systems. Possibility for collaborations with companies



Food systems are fascinating soft materials basically consisting of proteins, carbohydrates and lipids in water. Foods often have a complex structure at the micro and nanoscale which is coupled to their macroscopic properties. At PhyLife we measure food microstructures using high-resolution confocal fluorescence microscopy and quantify them with image analysis. There is a growing interest in developing and understanding foods based on plant ingredients. In collaboration with companies (e.g. Arla), we use microscopy to study plaint/dairy hybrid foods. As a student you will have the opportunity to participate in these studies and/or collaborate with companies as part of your project.

Professor Daniel Wüstner

Email: wuestner@bmb.sdu.dk
Webpage: https://dwlab.sdu.dk
Project types: Bachelor and Master

Research topics:

Membrane biophysics, lipid and protein transport in cells in relation to human diseases

Research methods:
Quantitative live-cell imaging, fluorescence spectroscopy, membrane systems, X-ray microscopy, image analysis and modeling

Introduction to my research:
I am a biophysicist combining experimental work on subcellular trafficking with image analysis and modeling. Our research is also increasingly using machine learning to analyze and interpret image data. We develop and use advanced fluorescence imaging methods, as well as correlative microscopy based on soft X-ray tomography (SXT). We apply such methods to study intracellular transport processes and their alterations, as they occur in brain disorders, atherosclerosis and other diseases.

Examples of thesis projects:
Correlative imaging of intracellular organelles and their interactions:
We combine single particle tracking (SPT) with SXT to study the dynamics and ultrastructure of cellular organelles and their interactions. X-ray microscopy is an ultrastructural imaging method, which allows one to assess the cellular mesoscale, i.e., structures of the size of about 30-50 nm, not being possible with light microscopy. We develop image analysis programs to analyze live-cell imaging data, for example SpatTrack, a MatLab based program for for quantification of organelle dynamics. We also collaborate extensively with colleagues from PhyLife, for example with Michael Lomholt on advanced analysis of tracking data. Here, students can learn to perform SPT experiments and analyze the obtained trajectory data. The project also allows for analyzing X-ray tomograms and eventually to acquire SXT data on a synchrotron facility.

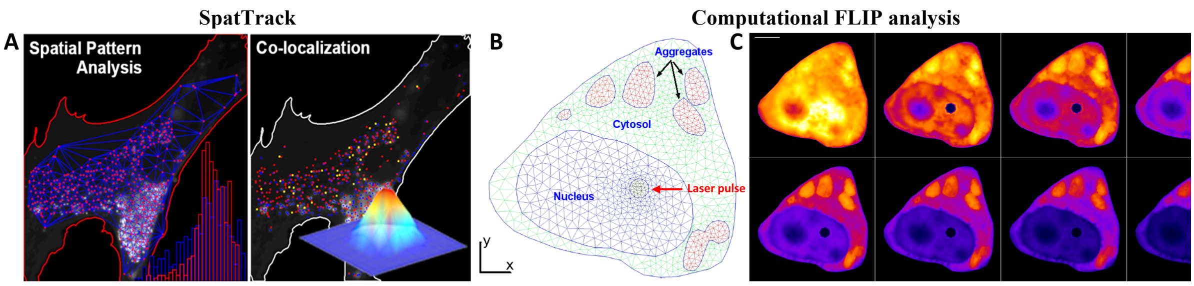


Figure 1. SpatTrack is a MatLab based software suite for spatiotemporal analysis of endo-lysosomes and other organelles in cells (A). Computational FLIP allows for dynamic analysis of protein aggregates based on a discretized cell geometry (B). Selected snapshots of a FLIP simulation of mutant Huntingtin (**C**).

Computational imaging of toxic protein aggregates in cells:

A variety of neurodegenerative diseases, such as Alzheimer's, Parkinson and Huntington disease are characterized by formation of toxic protein aggregates in cells. In collaboration with colleagues at IMADA, we develop quantitative imaging methods to study the formation and dynamics of such aggregates. For example, we developed a novel quantitative form of fluorescence loss in photobleaching (FLIP) for analysis of intracellular transport rates and diffusion parameters. In FLIP, repeated photobleaching of a small portion of the cell with interleaved confocal imaging allows to follow protein dynamics and thereby to study protein turnover in aggregates. In this project, students can learn to perform live-cell imaging including single molecule tracking with 10-nm resolution (MinFlux microscopy), FLIP experiments and to analyze and model such data using various approaches.

Biophysical studies of drug interactions with model and cellular membranes:

Natural products, such as polyene macrolides produced by certain bacteria, bear huge potential for treating infections and protecting food against molds. This is very important, as some fungal species develop drug resistance and thereby can spread without control in hospitals, making the quest for new drug molecules an important endeavor. In a collaborative effort, we combine spectroscopic analysis with live-cell imaging and molecular simulations to study the mechanisms underlying the antifungal activity of polyene macrolides, such as nystatin and natamycin. In this project, the students can learn to work with model membrane systems and with yeast cells and employ fluorescence spectroscopy and various imaging techniques to understand how these molecules disturb membrane function.

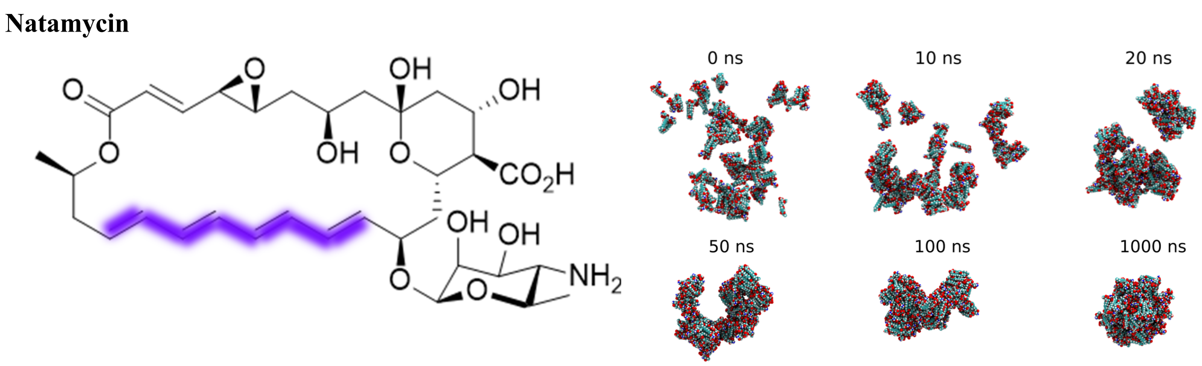


Figure 2. Left: natamycin structure with conjugated double bonds giving the molecule its fluorescence in violet. Right, snapshots from molecular dynamics simulation of self-aggregation of natamycin in water carried by Jacob Kongsted's team from FKF at SDU.

Advanced Bioimaging Group

Jonathan R. Brewer email: brewer@bmb.sdu.dk

The group is focused on the use and development of advanced Bioimaging and image analysis techniques to answer fundamental questions in biological systems. The group has worked on development of skin cancer models, tissue bioprinting and developing an organ on a chip-based system for artificial skin. We also work with development of novel bioimaging and image analysis techniques and are presently developing an image-based method to quantify expression, and spatial organization of RNA in single cells and tissue. JB is also the Director of the Danish Molecular Biomedical Imaging Center (www.DaMBIC.dk). DaMBIC is a bioimaging facility at the forefront of bioimaging in Denmark.

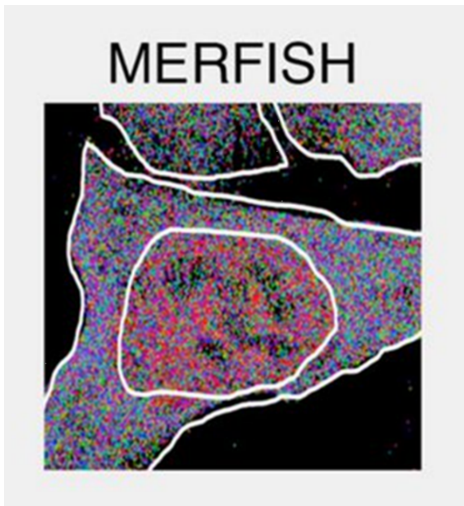
Example projects

Spider silk as a model for the synthesis of superior biomaterials: (Learn skills such as microfluidics, imaging, and image analysis.)

An interesting set of materials which nature offers are the extremely strong and tough biomaterials such as spider silk. Spider dragline silk is exceptionally strong and elastic, being up to three times tougher than Kevlar, despite being exceptionally light and biodegradable. Due to low yield and the cannibalistic and territorial nature of spiders, mass production of silk from spiders is not possible. Thus, for mass production, synthesis of artificial spider silk is necessary. However, fabrication of artificial silk with the same properties as spider silk has not yet been achieved. In this project we propose to create new methods to fabricate artificial spider silk which will provide an environment friendly and strong substitute material. This will be done by developing a biomimetic silk spinning method and by using bacteria strains which can produce eco-friendly artificial silk.

Characterization of skin on a chip using spatial transcriptomics (Learn skills such as, advanced imaging, image analysis, microfluidics and machine automation.)

In this project, bioimaging is to be combined with spatially resolved transcriptomics, in order to study the mechanical regulation of cell renewal in skin tissue and artificial skin. A skin-on-a-chip model, which combines cell biology with microsystem biology to create a more realistic artificial skin model, is currently under development. In a project, different time points of skin-on-a-chip models and traditionally grown skin models can be compared using immunohistochemistry, smFISH and MERFISH. Single-molecule Fluorescent In Situ Hybridization (smFISH) is a technique allowing the detection of RNA species at a single molecule level. Multiplexed Error-Robust Fluorescent In Situ Hybridization (MERFISH) is a new technique, allowing the simultaneous imaging of several hundred RNA species in just a few hours. These techniques enable us to draw comparisons between artificially grown skin and real human tissue and improve the culturing process of organotypically grown cultures. In another project, the regulation of mRNA species during wound healing will be investigated using the previously mentioned techniques.



Associate Professor Himanshu Khandelia

Email: hkhandel@sdu.dk

Webpage: hkgroup.sdu.dk

Project types: Bachelor and Master

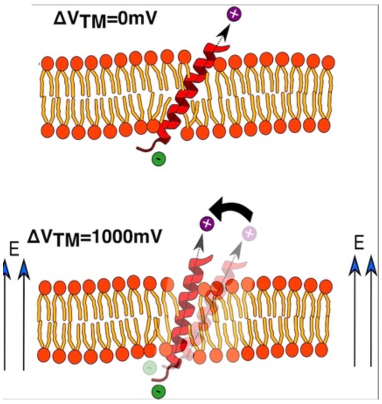
Research topics:
Molecular dynamics simulations of biomolecular systems, Electromechanical coupling in lipid membranes, ion transport across membranes, psychedelic compounds, membrane repair mechanisms.

Research methods:
Molecular dynamics simulations, Free energy calculations.

Introduction:
My research group develops and employs chemical and physical computational methods to investigate fundamental molecular scale biomolecular phenomena, with specific focus on lipid membranes, and membrane-associated biological processes, including transport across membrane proteins, membrane repair mechanisms in cancer and the molecular basis of diseases. Research in my group is highly interdisciplinary and strides the fields of physical chemistry, biology, biochemistry, biophysics, data science and computation. We actively collaborate with leading research groups all around the world. We are housed in the interdisciplinary Center PHYLIFE: Physical Life Science.

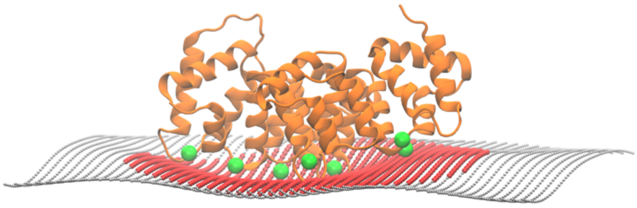
Examples of Thesis Projects

Novel Mechanisms of Voltage Sensing



The coupling between transmembrane electrical potential and mechanical properties in lipid membranes gives rise to many interesting phenomena. One of these is the possibility to sense the transmembrane electrical potential using small hydrophobic peptides which will re-orient in response to an electric field. The reorientation of the peptide is driven by the dipole-electric field coupling, but opposed by hydrophobic mismatch. We use simulations to investigate the phenomena and design peptides which can better sense voltage sensors. (with M. Lomholt)

Mechanisms of Membrane Repair

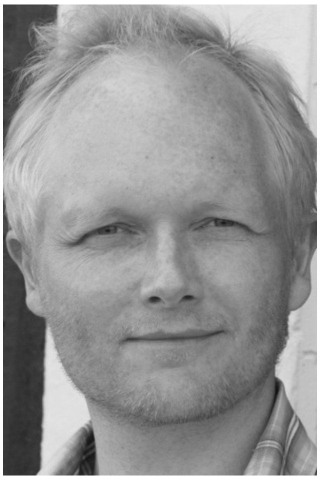


Cancer cells are subject to frequent membrane rupture when they metastasize or grow uncontrollably. To seal the ruptured membrane, cells express a class of proteins called Annexins, which are known to trimerize on the membrane, and induce significant local curvature. We use molecular simulations, in combination with biophysical (with A. Simonsen) experiments to investigate the mechanism by which these proteins repair membranes, and how repair is linked to the ability of the proteins to modify the mechanical properties of the membrane.

Compartments in Molecular Simulations (involves Programming)

The analysis of molecular simulations often involves looking into compartments in 3D space such as pores in proteins, or a domain of a membrane. The contents of these compartments, as well as their boundaries are dynamic, and useful analysis necessitates accurate book-keeping and unique methods to track the contents and boundaries of the compartments. We want to develop some techniques to be able to do so for specific protein-membrane systems.

Associate Professor Carsten Svaneborg



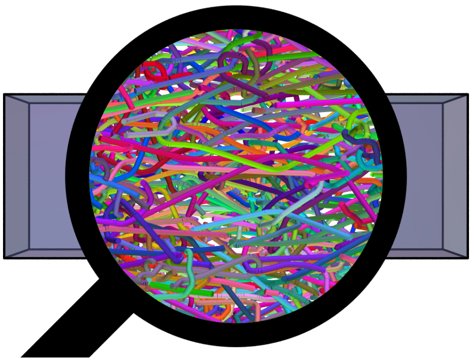
Email: zqex@sdu.dk
Webpage: http://zqex.dk
Project types: ISA, Bachelor and Master projects
Research topics: Soft matter, polymer physics, biophysics.
Research methods: Computational and theoretical, statistical physics.

Introduction to my research:

What is soft condensed matter? This field of physics studies the vast array of materials, that are neither simple solids or liquids. Most of the materials in our body are soft-matter as is most of the foods we eat. Other examples are paints, foams, glues, gels, emulsions, cell membranes, plastics, lubricants, soaps, and tires. As physicists, we want to learn how these materials works and how to make them better.

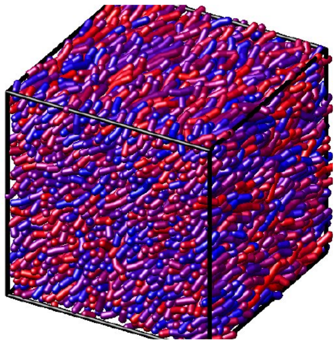
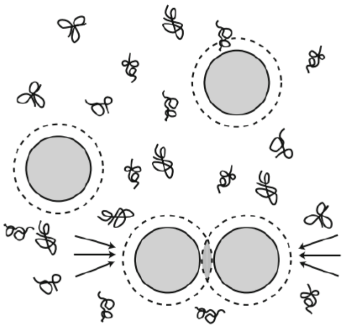
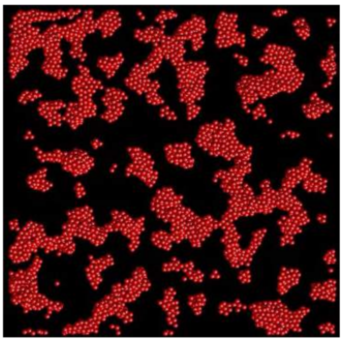
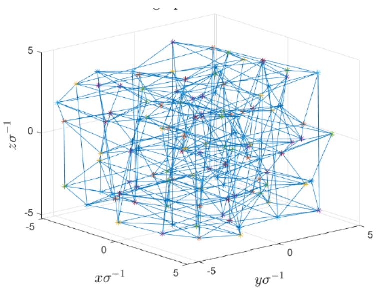
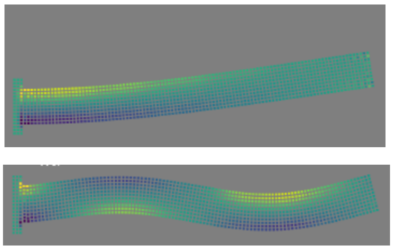
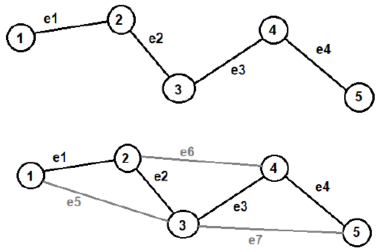
Where does these materials get their properties from? At the molecular or mesoscopic scale, they can be made of colloids, polymers, lipids or liquid crystals. These building blocks exhibit thermal motion and self-organize into complex mesoscopic structures, such as fluctuating strings, membranes or spatial domains. The material properties are due to these emergent structures and their dynamics. Hence to understand these materials, we apply the whole tool box of physics, such as classical mechancs, field theory, and statistical mechanics.

How can we study soft-matter at the various scale? Macroscopic viscoelastic properties can be characterized by rheological technique, effective mesoscopic interactions measured with AFM, while the mesoscopic structures can be characterized e.g. confocal microscopy or small-angle scattering techniques. However, I prefer to use computer simulations. On the computer, we can build large systems and study their physics on molecular, mesoscopic and macroscopic scales simultaneously. A key problem is how to define computationally efficient models that captures the relevant physics. Performing large scale simulations provide data like just like an experiment, except we can also tune the laws of nature to produce more information than an experiment can. By careful analysis of the data, we can critically test and improve theoretical models as well as experimental analysis methods.



My reseach focuses on polymer melts and rubbers. At the molecular scale they are made of polymers, which are string-like molecules with random walk conformations. Due to topological interactions with neighbouring polymers, a single polymer finds its thermal fluctuations localized into a tube, which itself is a coarse random walk. We develop analytic theory to understand the thermal motion of a random walk string along a random walk. We perform large scale simulations on supercomputers to study model systems. By analyzing the data, we can infer the tube structure and the spectrum of thermal fluctuations inside tubes. Hence we can study how viscoelasticity emerges due to topology. Cross-linking the polymers turns the material an elastic rubber, what happens to the molecules when we stretch a rubber, and how does that explain elasticity? This is fundamental science, but done in collaboration with Continental Tires.

Examples of past projects:

 Andreas: Simulations of stiff rods that form liquid crystalline phases. What is the phase diagram as function of length of the rod. (with Francesca Serra)	 Henrik: Spherical colloids in a gas of polymers. How can we infer the attractive depletion interactions between the colloids induced by the polymers?	 Jens: Developing a model of casein micelles in skimmed milk. Can the model reproduce the structures observed with confocal microscopy on yoghurt? (with Adam Cohen Simonsen / ARLA)
 Lau: Describing a rubber as a 3D graph of springs. Implement a program to predict the resulting stress-strain curve. Does it match a more realistic model that includes topological interactions?	 Tobias: Benchmarking the SPH approximation of continuum elasticity theory. How accurately can we simulate the vibrations modes of an elastic rod fixed at a wall. Can such models predict stress-strain relations? (with LEGO)	 Emilie: The simplest model of a polymer is a linear chain of springs. What happens if we add non-local springs along the chain. Can we analytically derive the what springs are required to describe stiff polymer molecules such as DNA.

Project options:

A good project is one where we go boldly where nobody has gone before by combining aspects of one or more of the following

- Inventing a new analytical model and deriving its physics predictions.
- Applying existing theory to a practical problem to understand it better.
- Developing new simulation models or methods to study new problems.
- Appy methods from computational physics to produce simulation data.
- Develop analysis techniques turning data into knowledge.
- Implementing new codes to enable new physics / models to be simulated.

Are your interests primarily in studying a specific system, developing analytic theory, running simulations and analyzing results, in implementing code or new analysis techniques, or in everything? In either case you are interested in doing a project, contact me and we can invent a project together.

Professor Jacob Kongsted

Email: kongsted@sdu.dk

Webpage: https://www.sdu.dk/da/forskning/kemi-farmaci/forskere/biologisk/jacob-kongsted

Project types: Bachelor and Master

Research topics:
Quantum chemistry method developments and applications, Quantum computing, Quantum biology, Molecular simulation of biological systems, Computational biophysics

Research methods:
Theoretical and computational (analytical, numerical, simulations and data analysis)

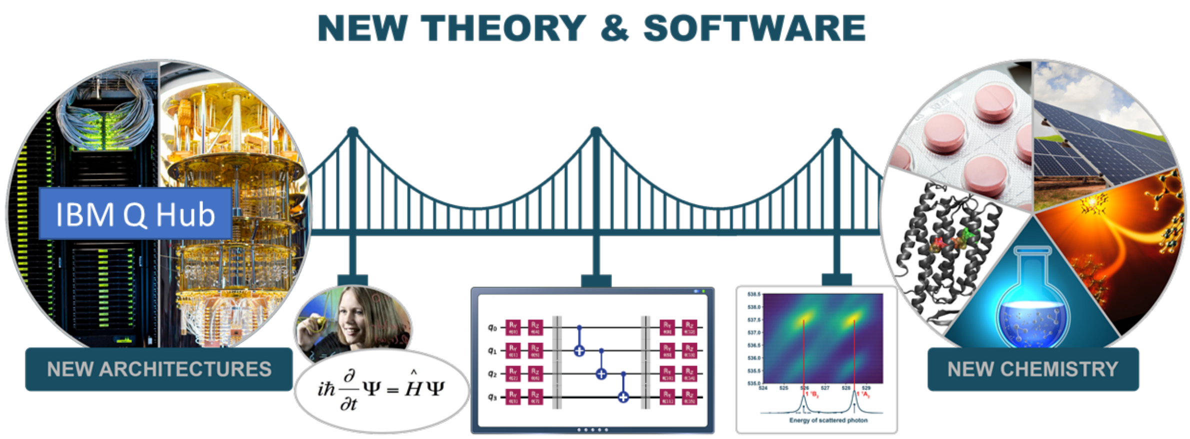
Introduction:
I am a theoretical chemist with a strong background in theoretical and computational molecular physics working in the cross-field between chemistry and theoretical/computational biophysics. My main research field is development and application of quantum chemical methods to explore (molecular) biological systems. My method development relies both on traditional computing algorithms and more recently on quantum computing. In some projects I work closely together with experimentalists, for instance my colleagues at PhyLife, aiming at analyzing and rationalizing results of advanced biophysical experiments based on mechanistic calculations.

A few examples of projects to illustrate potential topics:

Development of quantum chemistry methods for biological systems
We develop novel quantum chemistry methods in order to provide mechanistic insight into biological processes and functions. Application of quantum chemistry to biologically relevant molecules is hampered by the big size of such molecules (e.g. proteins). To overcome this barrier, we develop advanced embedding theories relying on an integration of classical and quantum mechanics. We apply such embedding methods to obtain mechanistic and/or spectroscopic insight to functional biomolecules.

Development of quantum chemistry algorithms for quantum computers
Recently, we have started a new project aiming at development of quantum chemistry methods to run on quantum computers. Our focus in this project is very fundamental, and consists of a reformulation of conventional quantum chemistry methods in order to take advantage of the possibilities offered by quantum computing. In this project we have access to state-of-the-art quantum computers through a newly established Danish IBM quantum Hub.

Quantum biology
Based on our method developments, we have a number of specific projects where we seek to understand the potential role played by quantum mechanics to drive fundamental biological processes. Such projects usually rely on a combination of quantum chemistry calculations coupled to molecular dynamical simulations.



Associate Professor Erik Donovan Hedegård

Email: erdh@sdu.dk

Webpage: https://erikh.gitlab.io/erikhgroup/

Project types: Bachelor and Master

Research topics:
Quantum mechanical method development, Simulation of properties and energetics of bio-inorganic systems,
Relativistic quantum mechanics, Computational biophysics

Research methods:
Theoretical and computational (analytical, numerical, simulations and data analysis)

Introduction:
I am a theoretical chemist with a strong background in theoretical molecular physics. I work interdisciplinary between molecular physics, inorganic/bio-inorganic chemistry, and theoretical/computational biophysics.
My main research concerns the development of quantum mechanical methods for molecular systems. With our methods we aim to understand the function of bio-molecular systems containing transition metals, e.g., how a metal is used by a protein to transform energy or transport electrons. We develop our methods for high-performance computing facilities all over the world.
In some projects, I work closely with experimentalists, for instance, crystallographers and spectroscopists at the University of Copenhagen and Lund University/MAX-IV (Sweden), where we attempt to match their experimental results with our simulations.

A few examples of projects to illustrate potential topics:

Development of quantum chemistry methods for strong electron correlation
Molecules with transition metals typically display strong-electron correlation effects due to the half-filled d-shells. Most theoretical models in use today cannot handle this scenario, leading to large errors for this class of molecules. Yet, transition metals are ubiquitous in nature and theoretical methods to handle them are required.
We develop novel quantum mechanical methods that can handle strong correlation and transition metals. We employ these methods to understand the function and mechanism of metals in biological systems. In dealing with biological systems, the system sizes often become huge. Therefore, we also combine the electronic structure methods for strong correlation with classical embedding theories to handle large biological environments (otherwise, the calculations become unfeasible). An example of an application of our methods is shown in Figure 1: This figure shows how O2 is bound to a metal atom in a protein that can degrade biomass efficiently (for biofuel generation). The binding of O_2 is critical to ensure that biomass is degraded efficiently; showing this was a paradigm change for biomass breakdown, which was believed not to require oxygen in nature.

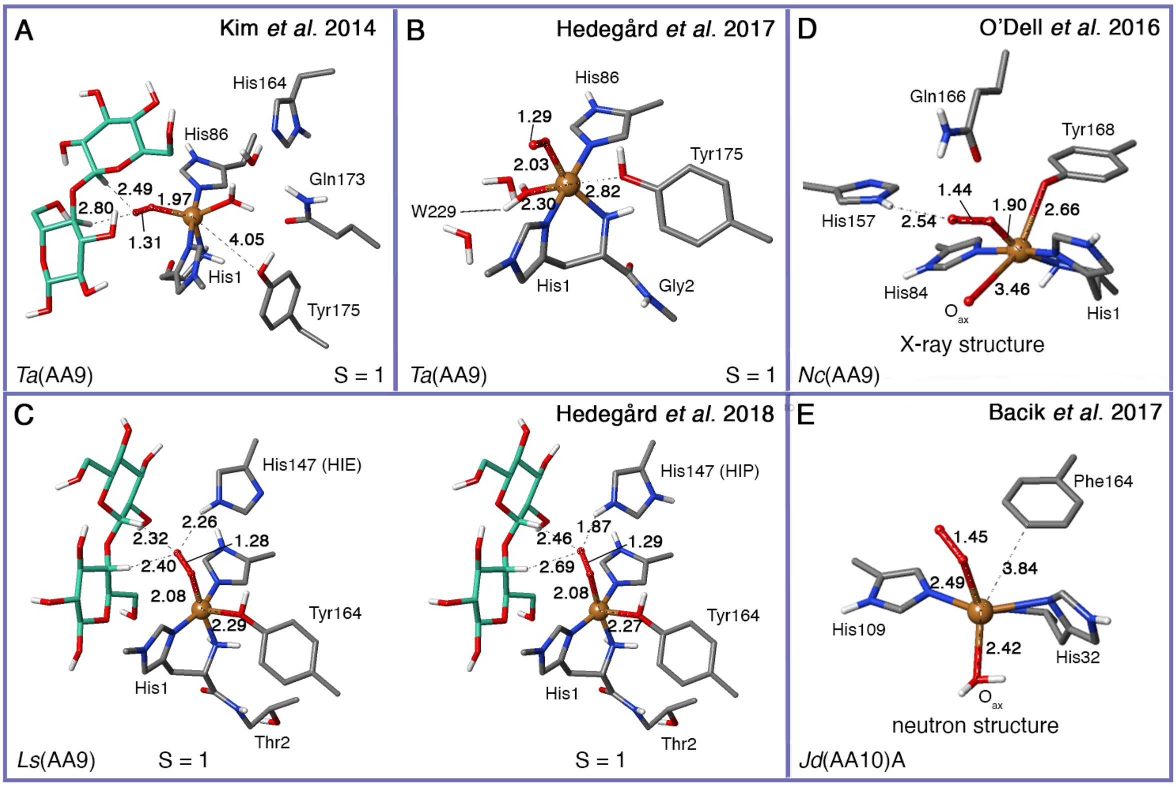


Figure 1. *Transition metal (in gold) surrounded by different proteins and a bound O_2 molecule. The proteins (LsAA9, TaAA9, NcAA9 and JdAA110) can boost breakdown of biomass in biofuel reactors. We also show calculated versus neutron/X-ray structures.*

Development of theory and algorithms for interaction of electromagnetic radiation with large, open-shell systems

In many cases, our only possibility to observe a biological process on the molecular level is through interaction with electromagnetic radiation. We, therefore, combine electronic structures methods with models that describe interactions with electromagnetic radiation – both the electric and magnetic components of the radiation are of interest since the different components provide complementary spectroscopic insight to understand the mechanism of the (bio)molecules.

Development of quantum chemistry algorithms for light-activated cancer medicine

Light can be exploited to induce reactions in heavy-atom-containing molecules that selectively can destroy cancer cells. This has the potential to become a much milder cancer treatment with fewer side effects than traditional chemotherapy. Unfortunately, key details of the light-molecule interaction are unknown, preventing us to control it. We develop theoretical models and algorithms that allow us to explore light interaction with molecules containing heavy metals. A key ingredient is to include relativistic effects in the models and this theory will be introduced as part of the project.

Bertil F. Dorch, associate professor of astrophysics / Library Director

Email: bfd@bib.sdu.dk / dorch@nbi.ku.dk

Webpage:
https://portal.findresearcher.sdu.dk/da/persons/bertil-dorch

Project types: Bachelor's Thesis, Master's Thesis, Ph.D. Thesis.

Research topics:
Topic 1) Astrophysical plasmas and magneto-hydrodynamics, in particular in the Sun and stars.
Topic 2) Historical Astronomy and Astrophysical Information Science.

Research methods:
1) Computational Astrophysics.
2) Systematic Reviews and data archive mining.

https://youtu.be/wGewXPLWCf8?si=I 1

Introduction to my research:
On the one hand, my main field of research is the evolution and dynamics of magnetic fields in astrophysical objects with a focus on the magneto-hydrodynamical regime, i.e. the magnetized plasmas of e.g. the Sun and stars leading to well-known observable effects such as sunspots and starspots, solar and stellar winds, and a wide range of energetic phenomenon that results from solar and stellar dynamos etc. Besides magnetism being interesting in its own right, the magnetic activity of astrophysical objects influences several other fields of astrophysics, and the understanding of magnetic phenomenon impacts a wide range of topics from computing realistic stellar models, over the discovery of exoplanets, to dealing with the space weather of the Solar System. On the other hand, I also research on historical scholarly communication, mainly within the natural sciences with a focus on astronomical history and heritage.

Examples of a Thesis projects:
1) MHD plasma phenomenon in stellar atmospheres: What is the role of magnetism in the dynamics and energy budget of astrophysical objects?
2) When and how are fully convective stars magnetically active?
3) Stellar dynamos across the HR diagram: Can we predict magnetic activity based on stellar parameters?
4) Collaborative theses with other supervisors.

Professor Francesco Sannino

Director of the Quantum Field Theory Center
PI for Mathematical Modeling for Infectious Diseases
Affiliations:
Danish IAS, IMADA, University of Southern Denmark,
Scuola Superiore Meridionale, Dipartiment di Fisica, Federico II Univeristy, INFN, Napoli, Italy

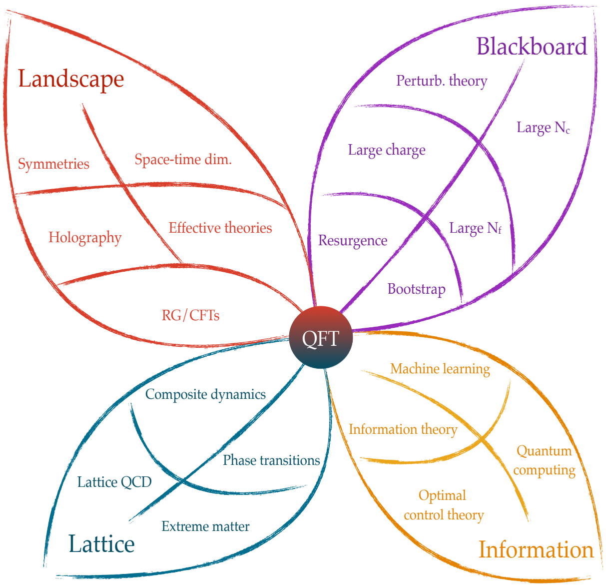
Email: sannino@qtc.sdu.dk

Webpage: https://www.sdu.dk/en/forskning/dias/researchers/chairs/francesco-sannino

Project types: Bachelor and Master

Research topics:
Quantum field theory, quantum black holes, gravity, particle physics, cosmology, information theory, mathematical modeling of epidemiology, population dynamics and viruses' genetic variations.

Research methods:
Quantum Field Theory, both analytical and numerical



Introduction to my research:
Bohr's quantum mechanics and Einstein's theory of special relativity revolutionized our understanding of nature from the atomic world to how rays of light propagate. These theories are at the heart of the quantum information and computing technological revolutions as well as the working of the Global Position System. Yet, when fusing quantum mechanics and special relativity the resulting theory is incompatible with the most elementary concepts such as causality, i.e. that the cause must precede its effect. Quantum Field Theory (QFT) is the only known way to reconcile quantum mechanics and special relativity. It has allowed mankind to achieve the most profound understanding of the laws of the Universe, from the Standard Model to cosmology and condensed matter physics. Yet much is still left to be understood about QFTs, especially in regimes where theories are strongly interacting, and standard calculations methods fail. Quantum chromodynamics (QCD), the theory responsible for the existence of protons and neutrons, is the most celebrated example of a strongly interacting QFT. Quantum gravity itself becomes strongly coupled at the Planck scale. Similar strongly coupled systems are encountered in condensed matter, particle physics and string theory.

The goal of my research is to map and solve Quantum Field Theory dynamics by exploiting different regimes that allow for controlled investigations and precise results.

My present and future research work is organized around the following themes:

Quantum Field Theory landscape: We map the QFTs landscape and identify scale-invariant theories acting as signposts among possible QFTs. We construct effective metric descriptions of quantum black holes thereby mapping the landscape of quantum gravity theories.

Quantum Field Theory on the blackboard: We employ and extend semiclassical approaches, from the large quantum number limits to resurgence, to compute physical quantities to all orders in the coupling strengths.

Quantum Field Theory on supercomputers: We use first-principle numerical simulations on larger supercomputers to determine the critical behaviour of QCD and QCD-like theories at high temperatures and/or density, including quantum phase transitions.

More recently I have been using powerful methodologies borrowed from theoretical physics and mathematics to investigate and curb the dynamical evolution of epidemics and understand population dynamics.

A major strength of my research ambition is the combined use of complementary approaches from the renormalization group to semiclassical and numerical simulations. Breakthroughs in any part of the proposed program can lead to paradigm shifts in our understanding of nature.

Examples for thesis projects: Depending on the level of detail we go to and the courses you have already attended, the following projects are already suitable for a bachelor thesis project.

Physical applications of effective metric descriptions of quantum black

Borrowing from our novel approach to universally classify quantum gravity corrections to extended gravitating objects such as black holes, interesting research topics gravitate around the applications of these model-independent metrics for black hole phenomenology from gravitational waves to imaging.

Projects suitable for master thesis only:

Heavy and Defect Conformal Field Theory

It has recently been understood that the best way to characterize Quantum Field Theories is as renormalization group flows among different Conformal Field Theories that have a higher degree of symmetries. We are now developing a way to probe near conformal field theories, such as Quantum Chromodynamics at large number of flavors, via the introduction of heavy quarks. The master thesis work would revolve around computing interesting correlators to be investigated, for example, via first principle high performance lattice computations.

Effective metric descriptions for cosmology

Help generalize the approach for effective metric descriptions for static and stationary extended objects such as black hole to time dependent metrics like the one employed in cosmology, to quantify and constrain in a model independent way quantum gravity corrections to the expansion of the Universe.

Associate Professor Benjamin Jäger

Email: jaeger@sdu.dk

Webpage:
www.sdu.dk/da/forskning/dias/researchers/fellows/benjamin-jager

Project types: Bachelor and Master. Theoretical / Computational (at the interface to Lattice QCD)

Research topics: Finite Temperature Effects of QCD, QCD Phase Diagram, Machine Learning Methods for Spectral Reconstruction, Simulating Physics Beyond the Standard Model

Research methods: Computational / Numerical simulations / Data analysis

Introduction to my research:

I mainly study Quantum Chromodynamics (QCD), but also venture into areas beyond the Standard Model. My roots are in theory but I aim to do my research close to computational science. I regularly use European supercomputers to run large simulations.

Examples of thesis projects:

1) Data Analysis of Monte Carlo Simulations in Lattice Quantum Chromodynamics (Bachelor/ Master)

This project focuses on analyzing Monte Carlo data from Lattice Quantum Chromodynamics simulations. The student will employ statistical and machine learning techniques to interpret the behavior of quarks and gluons. The goal is to gain insights into the strong force and the properties of the quark-gluon plasma. This project provides hands-on experience with computational physics and advanced data analysis methods.

2) Enhancing Lattice QCD Simulations with Machine Learning
(Bachelor/ Master)

This project involves applying Machine Learning (ML) methods to preconditioners in Lattice Quantum Chromodynamics simulations. The aim is to simplify the numerical inversions of the Dirac operator, a key challenge in QCD computations. The project offers hands-on experience with ML algorithms and high-performance computing in the context of theoretical physics.

Associate Professor Matthias Wilhelm

Email: mwilhelm@imada.sdu.dk

Webpage: https://www.sdu.dk/staff/mwilhelm

Project types: Bachelor and Master

Research topics: Quantum Field Theory, Feynman Integrals, Particle physics, Gravitational waves

Research methods: Theoretical, machine learning

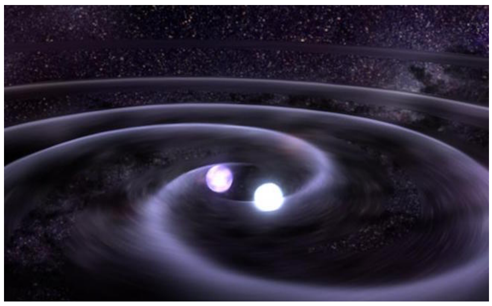
Introduction to my research:

The research of the Scattering Amplitudes Group is focused on precision calculations in Quantum Field Theory (QFT). Quantum Field Theory combines Albert Einstein's theory of Special Relativity with Quantum Mechanics. It has given a hugely successful framework for describing Nature across a vast range of scales. A key quantity for calculating precision predictions in Quantum Field Theory are Scattering Amplitudes, with applications ranging from particle physics to classical gravity.

The discovery of the Higgs particle at the Large Hadron Collider (LHC) at CERN in 2012 was a huge success and confirmation of the Standard Model of Particle Physics. The upcoming high-luminosity upgrade to the LHC will allow us to probe the Standard Model to unprecedented precision and discover potential signs of New Physics in the form of tiny deviations between high-precision experimental measurements and high-precision theoretical predictions. However, this requires us to first calculate those theoretical predictions to high precision.

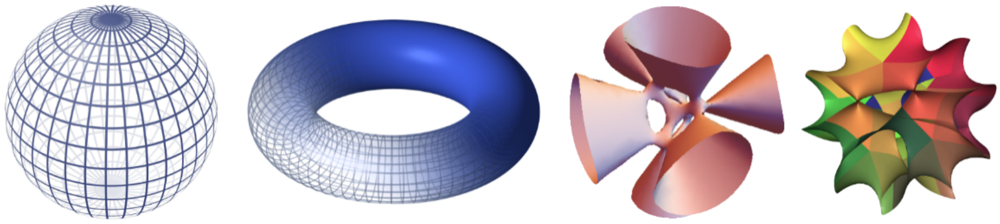
The LHC at CERN (Image credit: CERN)

The discovery of gravitational waves from inspiralling and coalescing pairs of black holes at the Laser Interferometer, Gravitational-Wave Observatory (LIGO) in 2015 was a huge confirmation of Einstein gravity. With the advent of the third generation of gravitational-wave observatories such as the Einstein telescope, Cosmic Explorer and LISA, also this field is quickly moving towards precision physics. Techniques from quantum Field Theory and Scattering amplitudes can be successfully used to predict the form of gravitational waves during the long inspiralling phase of such a merger.



Artist's impression of gravitational waves from inspiralling neutron stars (Image credit: NASA/Goddard Space Flight Center)

What both cases have in common is that the results of high-precision calculations show surprising simplicity and rich mathematical structure. At high precision, Feynman integrals arise that contain intricate geometries and that integrate to new classes of transcendental functions. Understanding these functions is in particular a key towards reaching the desired precision for the upcoming experiments.



Selected geometries in Feynman integrals: Riemann sphere (Image credit: CC BY 3.0 Geek3), elliptic curve (Image credit: Public domain Lucas Vieira), K3 surface (Image credit: CC BY SA 4.0 BTotaro) and Calabi-Yau varieties (Image credit: CC BY SA 3.0 Ronhjones).

The research of the Scattering Amplitudes Group combines techniques from theoretical physics and pure mathematics, such as complex analysis, algebraic geometry and number theory, as well as machine learning.

Examples of thesis projects:

1. Classification of Feynman-integral geometries for gravitational waves at fifth post-Minkowskian order
2. Special function for two-loop integrals in Quantum Chromodynamics
3. Machine learning for analytic calculations in theoretical physics

Associate Professor Joel D. Cox

Email: cox@mci.sdu.dk

Webpage: https://www.sdu.dk/en/forskning/polima

Project types: Bachelor and Master

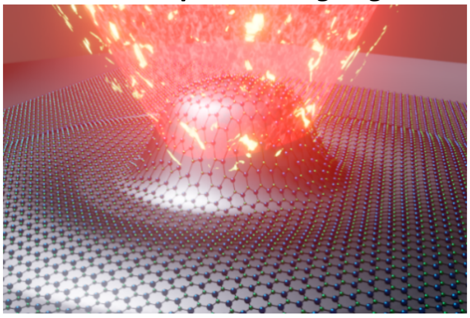
Research topics:
Nanophotonics, quantum optics, nonlinear optics, polaritons, atomic physics, two-dimensional materials, atomically-thin materials, condensed matter physics

Research methods:
Theoretical (analytical, numerical, simulations)

Introduction to my research:
In general, my research interests are in the theoretical description of light-matter interactions in nanostructures and quantum mechanical systems (e.g., atoms, photons). I enjoy working on problems that can explain or motivate experimental efforts to develop photonic devices with active functionalities on the nanoscale. I am particularly interested in the study of hybrid light-matter excitations known as *polaritons*, which can focus light down to nanometer length scales for exploring the boundaries of classical and quantum physics or developing next-generation photonic devices.

Examples of thesis projects:

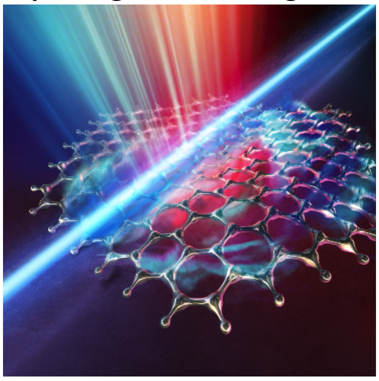
Controllable quantum light generation with two-dimensional materials



Single photon sources (SPS) that can generate streams of indistinguishable photons are crucial resource for quantum optical technologies. In this context, 2D materials present intriguing possibilities to develop on-chip SPS through their ability to tailor the photonic environment of nearby quantum light emitters (e.g., few-level atoms) or by engineering defects that emit photons directly in a 2D material.

The aim of this project is to theoretically explore extrinsic and intrinsic quantum light emitters with 2D materials to reveal new quantum optical functionalities in engineered nanoscale platforms. There are several interesting possibilities that could be theoretically explored in the project and readily probed in experiment: Control of chiral quantum light emission by patterned anisotropic 2D materials, or spontaneous emission enhancement produced by controlled laser-written deformations in a substrate supporting a 2D layer.

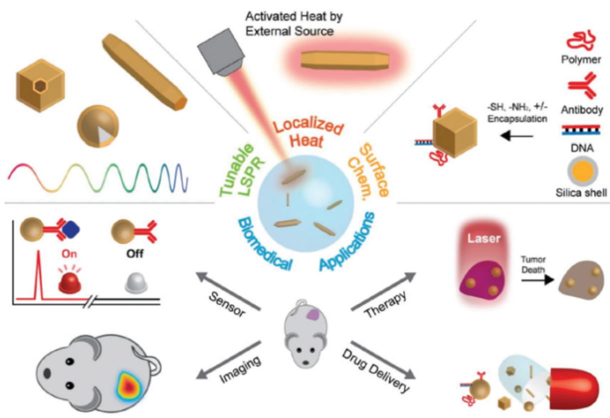
Exploring nonlinear light-matter interactions with swift electrons



Energetic free electrons offer precise spatial and spectral characterization of subwavelength optical excitations supported in a wide range of nanophotonic platforms. The objective of this project is to theoretically explore nonlinear optical phenomena, such as high-harmonic generation and saturable absorption, triggered by intense light pulses and swift electrons interacting with optical resonances in low-dimensional condensed matter systems (metals, semiconductors, and topological insulators).

The project involves developing simple atomistic simulations that can be used to describe experiments where ultrashort light pulses are used to excite a nanostructure and electron beams probe the induced electromagnetic near fields; the reverse process where an energetic electron excites a nanostructure and the optical pulse excites high-energy electromagnetic radiation may also be studied.

Thermo-optical phenomena in plasmonic nanostructures



Metal nanoparticles support plasmons—collective oscillations of free electrons—which concentrate light on length scales well-below the optical diffraction limit. The extreme light concentration provided by plasmons in a metallic nanoparticle is associated with significant heat generation within the particle that diffuses into its immediate surroundings. Use of plasmonic nanoparticles as nanoscale heat sources is attracting interest in diverse fields including nanomedicine, solar energy, and photocatalysis.

The objective of this project is to theoretically explore the thermo-optical properties of metallic nanostructures in various configurations, and to consider the impact of quantum mechanical effects, such as spill-out of electronic wave functions at the edge of a particle, on its thermo-optical response. A starting point is standard Mie theory for spherical particles, which constitutes an efficient, accurate, and computationally inexpensive tool to study light absorption and scattering. Nonlocal effects in the optical response can then be incoroporated through quantum-informed models for plasmonics, including hydrodynamic models for screening and damping, and surface-response models that adopt phenomenological parameters obtained from quantum mechanical calculations.

Associate Professor Christos Tserkezis

Email: ct@mci.sdu.dk

Webpage: https://www.sdu.dk/en/forskning/polima/people/faculty-members/christos-tserkezis

Project types: Bachelor and Master

Research topics:
Nanophotonics, polaritons, light—matter interactions, quantum plasmonics, electromagnetic scattering, optical chirality

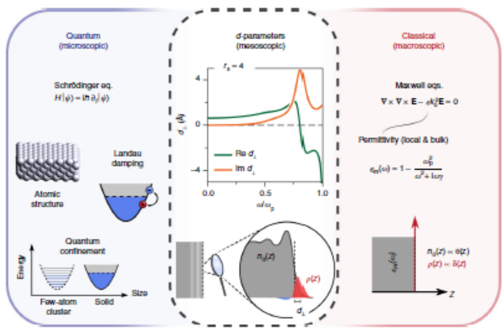
Research methods:
Theoretical (analytical and numerical)

Introduction to my research:

I am a theoretical physicist working on nano- and quantum optics, on topics that combine applied electromagnetism with condensed-matter physics. Examples include the area of quantum plasmonics, where information from the solid-state physics of the metal is implemented in otherwise classical-electrodynamic calculations, and polaritonics, where the electrons, excitons, phonons, or spins of the material respond collectively to an external light excitation. These complex interactions have the potential to enable applications in optical communications, imaging and superresolution microscopy, quantum optics, or sensing and biophysics. My theoretical work is mainly focused on understanding the fundamental physics governing light—matter interactions, and exploring new effects.

Examples of thesis projects:

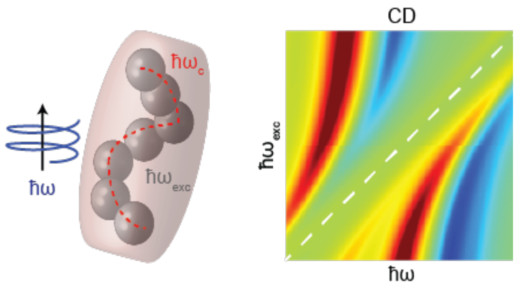
Quantum corrections in the optical response of cylindrical objects
Among the various new effects that can be observed when the wavelength of light is comparable to the size of the objects illuminated, collective free-electron oscillations in metallic nanoparticles, so-called plasmons, attract tremendous interest, because such structures provide unprecedented confinement and enhancement of the electromagnetic. When pushing this response to its limits through plasmonic nanostructures with sub-nm geometric details, a theoretical description that goes beyond the local response approximation of classical electrodynamics is needed, to account for effects such as screening, electron spill-out and surface-enabled Landau damping.



One approach to tackle these issues is based on the Feibelman surface-response functions. The aim of this project is to implement these response functions to the case of cylindrical objects (first analytically and then in an appropriate code), and study how spill-out affects the response of long but extremely thin metallic wires.

Analysis and design of reconfigurable chiral polaritonic environments

Chirality, i.e. the property of an object not being superimposable onto its mirror image, relates to all kind of biological samples, where a simple difference in handedness (whether the sample has a left- or a right-handed orientation) can lead to significantly different properties and (bio)compatibilities. One of the most important techniques for identifying the handedness of an object is circular dichroism (CD) spectroscopy, where the object interacts with left- or right- circularly polarised light, and the difference in absorption between the two polarisations provides the desired information. The ability to enhance and accurately control the chiroptical response of nanostructures acquires wide interdisciplinary importance. This kind of control can be achieved by the interaction of chiral objects with resonant achiral environments, such as organic molecules supporting collective excitonic resonances. The interaction of the different optical modes supported by the two components (chiral object/excitonic matrix) leads to hybrid half-light—half-matter states, known as polaritons, which are accompanied by the splitting of resonances in the spectra of any observable into two hybrid resonances that maintain the properties of the original one. The aim of this project is to explore, theoretically and numerically, optimal architectures for this hybridisation.



Nicolas Ubrig
Assistant professor, Quantum Optoelectronics Group @POLIMA

Email: ubrig@mci.sdu.dk

Webpage: https://www.sdu.dk/en/forskning/polima
https://arxiv.org/a/ubrig_n_1.html

Project types: Bachelor and Master

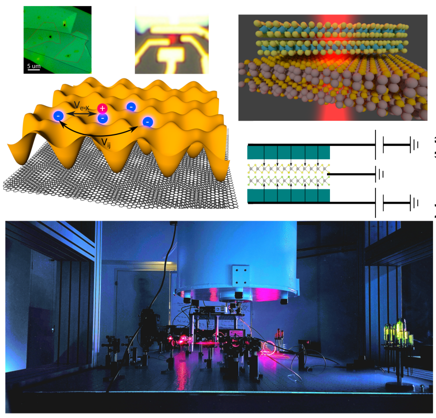
Research topics: Optics and optoelectronics, Optical spectroscopy, Quantum transport, Magnetism, Semiconductor physics, Two-dimensional materials (e.g., graphene), Correlated states of matter

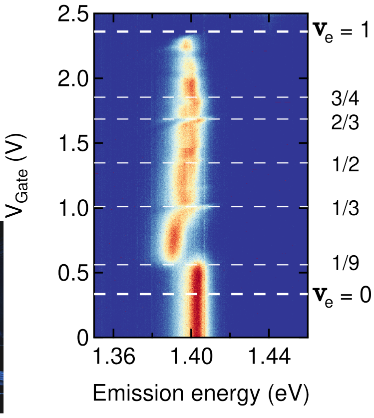
Methods: Experimental physics, Quantum optics, Magneto-optics

Introduction
In the trajectory of technological advancements, each epoch has been intricately tied to a specific class of materials; from the Stone Age with its reliance on stones to the Information Age dominated by silicon. In the imminent era of quantum science and technology, the foundation of this revolution is anticipated to rely on a novel class of materials: quantum materials. The avatars of this class of materials are yet to be discovered. However, they are expected to feature low-dimensional characteristics, facilitating the emergence of quantum effects, and possess nanoscale dimensions, that render them high tunability. Our challenge resides in identifying this new class of materials and controlling their physical properties at the design stage.

Examples of projects

Optoelectronics of 2D semiconductor heterostructures



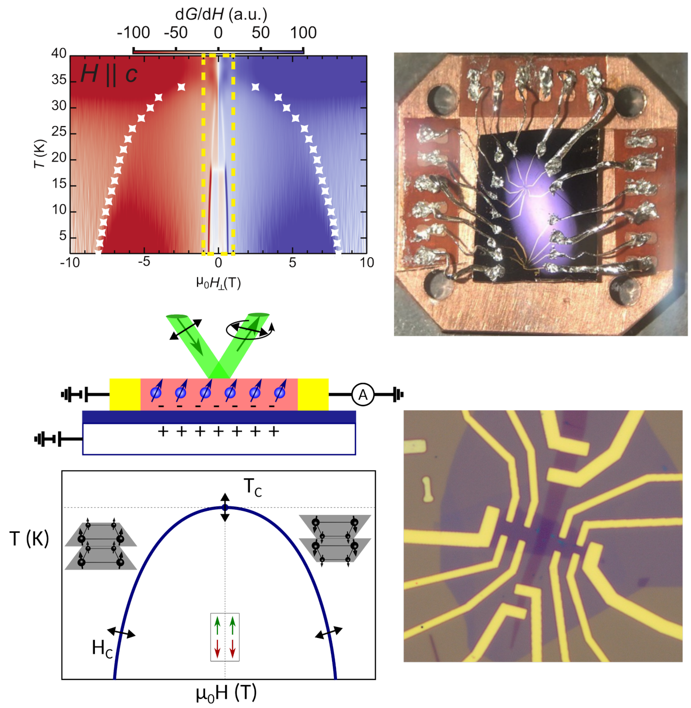


One of the most remarkable advantages of 2D materials lies in their unparalleled versatility: they can be seamlessly stacked layer by layer, free from the usual constraints of lattice matching or chemical compatibility. This opens the door to engineering entirely new artificial materials, structures that nature never conceived, featuring properties radically different from their individual components. With nothing more than a crystal, a substrate, and scotch tape, you obtain atomically thin layers and form heterostructures with extraordinary optoelectronic characteristics, enabling you to understand interactions at the atomic scale.

In such a project you will design and fabricate your own custom structure based on 2D semiconductors. Using advanced nanofabrication techniques, you will integrate these atomically thin materials into functional electronic devices such as a field-effect transistor. Through a combination of electronic transport measurements and optical spectroscopy, we will explore their fundamental physical properties. Our goal is to generate excitons, bound electron-hole pairs, via optical excitation, and probe their interactions with surrounding charge carriers. These delicate quantum effects can give rise to unexpected and exotic electronic phenomena, including superconductivity and magnetism.

Optoelectronics of 2D semiconductor heterostructures

The discovery of long-range magnetic order in atomically thin 2D materials has seeded an entire new field of research. At its core lies the van der Waals magnetic spin paradigm with a rich scientific potential of systems built from van der Waals magnets. For the first time, researchers have access to a vast and expanding database of compounds with tunable properties, enabling easy exploration and functionalization.



This project sets out to address some of the key challenges still facing the field of 2D magnetism, notably the efficient detection of magnetism in atomically thin materials. Traditional tools like neutron scattering or magnetization measurements, designed for micron-sized crystals, simply lack the sensitivity and scale. Two powerful alternatives are illustrated in the figure: quantum transport measurements and magneto-optical techniques. Both approaches require the integration of these materials into carefully designed device architectures. This necessary step not only enables detection of magnetic interactions, but also brings us closer to the overarching goal of our research: to electrically tune and map the magnetic phase diagram of van der Waals magnets.

Assist. Prof. P. André D. Gonçalves

Email: padgo@mci.sdu.dk

Webpage: https://sites.google.com/view/padgoncalves

Project types: Bachelor & Master

Research topics:

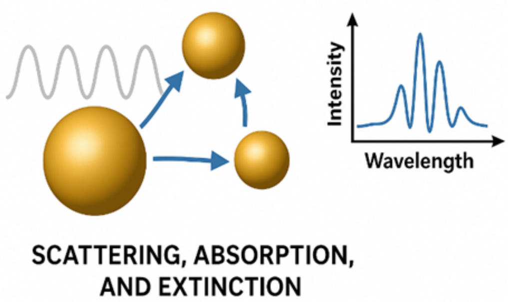
- Quantum nanophotonics and nanoplasmonics
- Two-dimensional & atomically thin materials (e.g., graphene, transition metal dichalcogenides, etc.)
- Light–matter interactions at the nanoscale
- Quantum optoelectronics of advanced quantum materials

Research methods:
Theoretical; from analytical and semi-analytical techniques to numerical and computational methods (most projects can be tailor to the students' preference, i.e., either more analytical or more computational).

Introduction to my research:
I am an Assistant Professor of Theoretical and Computational Physics at the Center for Polariton-driven Light-Matter Interactions (POLIMA). My research focuses on fundamental investigations of light–matter interactions at the nanoscale and on the theoretical modeling of the optoelectronic properties of complex nanostructures. My interests span a wide range of topics, including nanophotonics with atomically thin materials and related van der Waals heterostructures, quantum nanoplasmonics, polariton-enhanced phenomena, as well as novel electron–light–matter interactions in various spectromicroscopies. Besides the fundamental aspects of my research, I strive to leverage the created knowledge toward the control of light–matter interactions in the few-nanometer regime toward improved or entirely new optoelectronic devices.

Examples of thesis projects:

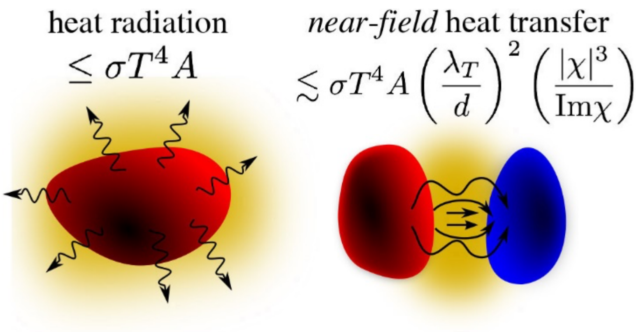
Quantum corrections in the optical response of coupled plasmonic nanoparticles
Metallic nanoparticles (e.g., Au, Ag, Al) exhibit strong optical resonances—localized surface plasmons—that enable them to efficiently scatter and manipulate light at dimensions far below the wavelength of conventional light (photons in homogeneous media). When multiple nanoparticles are involved, their optical responses become strongly coupled, giving rise to hybridized plasmonic modes, directional scattering, and collective resonances relevant for sensing, nanoantennas, and metasurfaces. This thesis project focuses on modeling such multi-particle systems using the T-matrix approach, a powerful semi-analytical method for solving electromagnetic scattering problems, augmented by quantum surface response



formalism capable of incorporating the salient quantum-mechanical effects in the optical response of nanosystems. The student will either develop a custom computational code or generalize an open-source T-matrix code to account for such quantum effects impacting the system's optical response. The work will involve computing scattering, absorption, and extinction spectra; analyzing near-field enhancements; and visualizing coupled plasmonic modes.

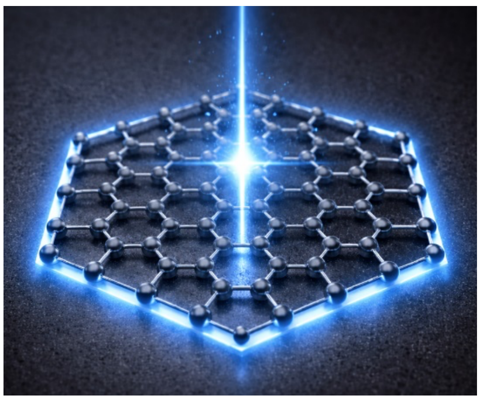
Quantum surface response effects in plasmon-mediated near-field radiative heat transfer

Near-field radiative heat transfer (NFRHT) between nanostructures is strongly influenced by evanescent electromagnetic modes, including surface plasmons that significantly speed up the energy exchange between two bodies beyond the conventional blackbody limit. However, when gaps shrink below ~5–10 nm, classical electrodynamics breaks down: nonlocality (spatial dispersion), electron spill-out/spill-in, and Landau damping modify the optical response and thus the energy flow. The Feibelman *d*-parameter formalism offers a powerful, efficient, and scalable way to incorporate such quantum-mechanical effects directly into electrodynamical processes governing NFRHT. This project aims to explore how nonclassical corrections, incorporated via *d*-parameters, impact the near-field heat transfer in plasmonics nanostructures such as planar gap configurations, nanoparticle dimers, or tip–surface geometries involving metals and/or 2D-material–metal hybrid platforms. Using analytical models or numerical simulations, the student will compute NRHT spectra and compare classical and quantum-corrected predictions.



Interaction of Fast Electrons with 2D Nanostructures: Limits of Continuum Models

Fast electrons interacting with nanostructures form the basis of electron beam spectroscopies such as electron energy-loss spectroscopy (EELS), which provide nanoscale insight into electronic and optical properties of materials. For extended 2D materials like graphene, these interactions are often described using a continuum model based on a homogeneous surface conductivity. While this approach is successful for "large" structures, its validity at scales ≲10–20 nm breaks down. The goal of this project is to determine the size threshold below which the continuum surface-conductivity description of a 2D material breaks down and a fully atomistic treatment becomes necessary. The student will study the interaction of fast electrons with finite 2D nanostructures and compare predictions from continuum electrodynamics with atomistic models such as tight-binding combined with linear-response theory. By analyzing electron energy-loss spectra as a function of nanostructure size, shape, and electron trajectory, the project aims to identify qualitative and quantitative signatures of the breakdown of homogeneous models. The results will provide guidance on when atomistic descriptions are required for interpreting EELS experiments on 2D materials.



Assistant Professor Chun Yuen Ho

Email: chuh@sdu.dk

Webpage: https://www.sdu.dk/en/forskning/cape

Project types: Bachelor and Master

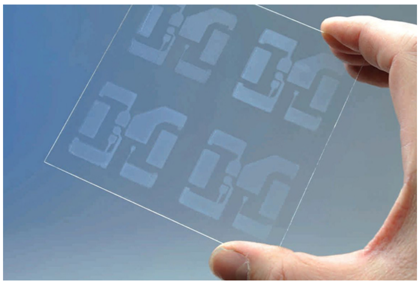
Research topics:
Semiconductors, thin films, metal oxides, defects, materials physics

Research methods:
Experimental (Thin film deposition and characterization, optoelectronic device integration)

Introduction to my research:
My research activities are in semiconductor physics and materials physics in thin films. I am especially interested in how electronic, electrical and optical properties of semiconductors can be tailored by alloying, doping and manipulating point defects. My current interests are primarily on basic research of the design, synthesis and characterization of novel compound semiconductors, but with a focus on their applications in solar cells and other optoelectronic devices.
At the Centre for Advanced Photovoltaics and Thin-Film Energy Devices (SDU CAPE), I have been working on the development of oxide materials for their integration in photovoltaics, aiming to bridge the gap between materials and devices development using high-throughput thin films synthesis and characterization methodologies for fully automated exploration of novel functional materials and devices.

Examples of thesis projects:

Indium-free transparent conducting oxides



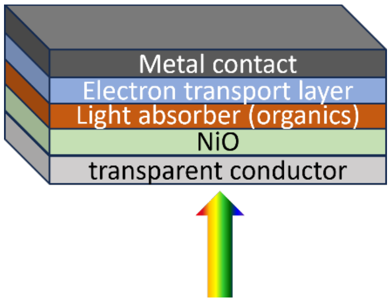
Transparent conducting oxides are a class of materials that combine high electrical conductivity and optical transparency, and are used in consumer electronics and optoelectronic devices, see for example figure on the right. Currently, indium tin oxide dominates the transparent conductor market, and accounts for ~60% of global indium use, causing the price of indium to rise dramatically in recent years. In this project, we will explore novel resonant doping of zinc oxide to realize indium-free alternatives as transparent conducting oxides with excellent electrical conductivity and optical transparency that can be used in various optoelectronic devices, including solar cells and light emitting diodes.

Thermal annealing of semiconductor alloys
Properties of semiconductors can be tailored by alloying two distinct materials. The electronic, structural, electrical and optical characteristics depend heavily on the chemical composition of the alloys. Alloying two semiconductors that crystallize in different crystallographic structures provides an additional freedom to control the materials, but in

most cases results in thermal instability, limited by fundamental thermodynamics. In this project, we will investigate a specific alloy semiconductor system – $Zn_{1-x}Mn_xO$ – to map out the region where the materials remain structurally stable. Additionally, the effects of annealing atmosphere, i.e. either reducing or oxidizing, on the electrical and optical properties will be revealed. This will allow a deeper understanding of the structure-property relationship, as well as defects physics of this material that has great potential in solar cells and other optoelectronic devices.

NiO as hole transport layer in organic solar cells

Nickel oxide, NiO, is a wide gap *p*-type semiconductor that can be used as a hole transport layer to facilitate selective charge extraction in solar cells, particularly in emerging perovskite solar cells. However, its use in organic solar cells is still limited, despite its potential to replace the more commonly used PEDOT (a conductive polymer) that induces instability in the device. In this project, we will deposit NiO by magnetron sputtering. NiO thin films with tuned electrical and optical properties will be obtained by varying the deposition conditions and post-deposition thermal annealing. Optimized NiO will be integrated directly into organic solar cells (see device configuration in figure below) to evaluate the performance and stability of the entire devices. Up scaling using roll-to-roll facilities is also envisioned.



Associate Professor Mathias Porsmose Clausen

Email: mpc@igt.sdu.dk

Webpage:
https://portal.findresearcher.sdu.dk/en/persons/mathias-porsmose-clausen

Project types: Bachelor and Master

Research topics: Gastrophysics, Edible Soft Matter, Biophysics, Bioimaging, Rheology, Image analysis

Research methods: Experimental

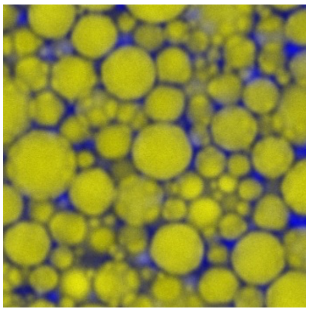
Introduction to my research:
I am originally a biophysicist, working for many years with development and application of advanced microscopy methods such as super-resolution microscopy and label-free imaging methods. Now, I apply physical and chemical concepts to understand the biological systems that we eat – food. This is a new branch of physics inspired by gastronomy: Gastrophysics. I am fascinated by how food in the kitchen undergo transformations that result in changes of taste, aroma, and texture and how these transformations can be understood scientifically to develop new culinary methods and food products for the future.
Pedersen, Hansen, Clausen, *Gastronomy Unravelled by Physics: Gastrophysics,* 2021

Examples of thesis projects:

Exploring jellyfish for gastronomic use

Jellyfish is an unlikely food. Yet, the oceans are filling up with jellyfish and they contain many functional molecules and have interesting properties, e.g., they can be turned into crunchy or crispy structures (significant physical transformation from a very soft gel) or used as a functional ingredient to structure emulsions.
https://videnskab.dk/naturvidenskab/saadan-bliver-vandmaend-en-knasende-spise/

Microscopy tools for studying plant-based food



The need for changing our diets to more sustainable ones is clear. What is unclear, is how to achieve it. I believe it will not happen without offering appealing tastes and textures. Here, we will develop microscopy techniques to look at structures in plant-based foods to give insight on how microstructures determine the structural properties of the food materials. The project will be in collaboration with Novozymes.
https://aktuelnaturvidenskab.dk/fileadmin/Aktuel_Naturvidenskab/nr-6/AN6-2015mad.pdf

Image analysis tools to quantify food structures

An image says more than 1000 words, yet the information in an image is difficult to compare to other parameters if not quantified. In this project we will develop image analysis tools based on machine learning to segment food microscopy images of e.g., emulsions (blobs) or protein networks (mesh).
Bonilla et al., Quantitative image analysis of protein foam microstructure and its correlation with rheological properties: Egg white foam, 2022

Associate Professor Eva Arnspang Christensen

Email: arnspang@igt.sdu.dk

Webpage:
https://portal.findresearcher.sdu.dk/da/persons/arnspang

Project types: Bachelor and Master

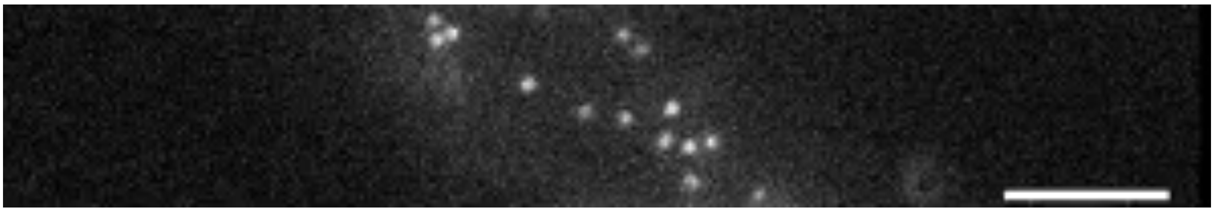
Research topics: Single Particle Tracking, Quantum Dots, Membrane Proteins, Biophysics, Bioimaging, Image analysis

Research methods: Experimental

Introduction to my research:
I am originally a biophysicist, working for many years with development and application of advanced microscopy methods such as super-resolution microscopy and label-free imaging methods along with advanced image analysis. Now, I apply these tools to understand the biology of the mammalian cell. I am particularly focused on membrane proteins, lipids and cell organelles. I am fascinated by how different drugs affect proteins in the cell and how these proteins have impact in diseases. To understand the different paths proteins take in the cells can be novel and valuable information and can allow for novel medical products for the future.

Examples of thesis projects:

Exploring membrane proteins at the single particle level
It is possible to stain single proteins with quantum dots and follow these while the cells are still alive. We will do microscopy together and analyze the movies afterward to get information about the localization and diffusion of the proteins. In the image below is a cell with stained membrane proteins. The bright dots are quantum dots.



Assistant Professor Orkun Furat

Email: ofu@mmmi.sdu.dk

Webpage:
https://portal.findresearcher.sdu.dk/en/persons/ofu/

Project types:
Bachelor and Master

Research topics:
Materials Science, Process Engineering, Applied Mathematics, Energy Science, Mechanics

Research methods:
Artificial Intelligence, Applied Mathematics, Data-driven Probabilistic Geometry Models, Statistical Image Processing

Introduction to my research:
I am an applied mathematician working at the interface of artificial intelligence, stochastics, physics, materials science and engineering sciences. My research focuses on developing data-driven modeling methods to understand and virtually design the microstructures of functional materials. Using microscopic image data, I combine AI and stochastic geometry to train interpretable 3D models that can generate virtual, but realistic microstructures. These models can be deployed to investigate how material microstructures influence macroscopic (functional) properties. Moreover, the 3D models can be deployed for statistically reconstructing 3D microstructures from lower-dimensional measurements (e.g., 2D image sections): This can reduce experimental efforts for the acquisition of 3D image data. My methods are applied to a broad range of material systems, including cathode materials in conventional and all-solid-state batteries, metallic alloys and nanostructured components for optical devices. By enabling virtual materials testing and inverse design, these methods can accelerate innovation in energy storage, advanced manufacturing and photonic technologies.

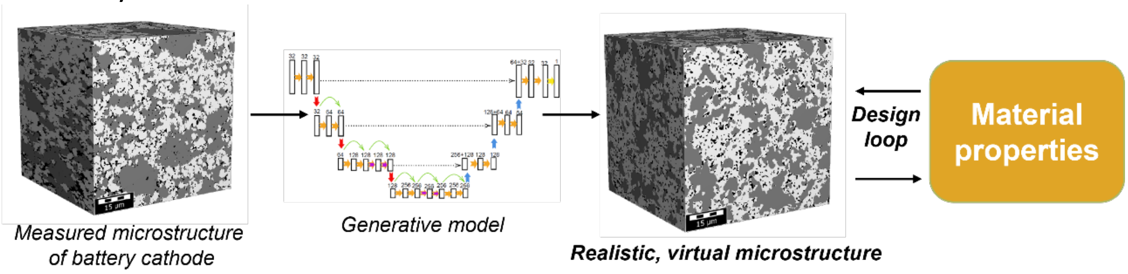
Some examples of thesis projects:
Projects typically rely on at least one of the following: image processing, machine learning, statistical analysis and computational modeling to extract and interpret information from experimental data. For each project: While code or published methods typically already exist, they usually need to be adapted, extended or customized to address the specific scientific problem and material system under investigation. Below are some possible thesis projects:

AI-driven design of virtual microstructures
Thesis projects in this field explore the prospects of AI-driven microstructure design (e.g., in battery materials) by

- performing statistical image analysis on experimentally acquired microscopy data
- training generative adversarial networks (GANs) or interpretable generative models to create realistic virtual 3D materials

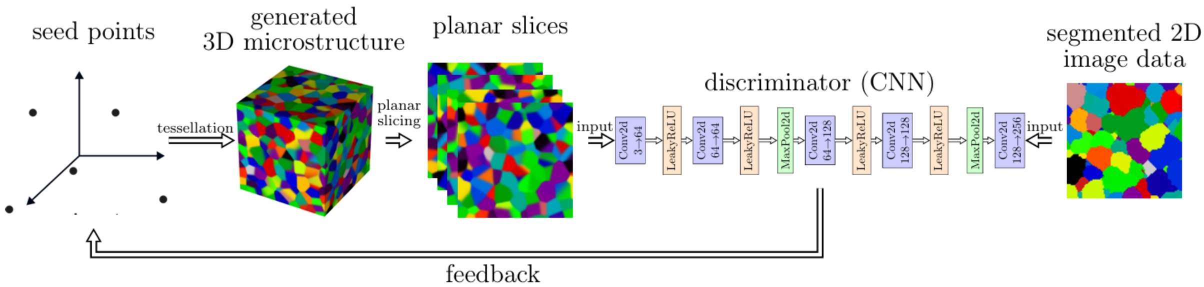
- designing structures with desirable properties (e.g., microstructures with improved electronic conductivity).

By combining structure modeling and AI, this project can help to create new materials more efficiently.



AI for 3D reconstruction from 2D images

Thesis projects in this field deal with the adaptation of computational methods in Python that can reconstruct 3D structures from 2D projectional images. Models from generative AI will be trained to generate virtual 3D structures that exhibit realistic simulated 2D projections ⇒ reduction of experimental measurement efforts. Applications can range from remote sensing and microscopy to computer vision, where understanding of 3D structures is crucial.



Data-driven modeling of crystallographic orientations

Thesis projects in this area investigate how crystallographic orientations of grains in polycrystalline materials can be quantified and modeled using modern data-driven tools. These orientations are of interest as they significantly influence macroscopic properties (e.g., mechanical properties of alloys). Typical projects involve

- extracting crystallographic orientations from experimental diffraction-based image data and determining suitable embeddings of orientations that facilitate statistical learning
- applying machine-learning methods or probabilistic generative models to learn complex orientation distributions from image data
- correlating the orientations of grains with their size and shape

Probabilistic characterization of particle separation processes

Thesis projects in this field combine microscopy-based particle analysis with probabilistic modeling to understand how size, shape and composition of particles influence their behavior during mechanical separation processes such as sedimentation or filtration. The work involves developing probabilistic descriptions of how particle properties change throughout separation. By linking particle descriptors with separation outcomes, these projects help improve process design (e.g., recycling processes) and raw material utilization.

Faisal Mahmood
Associate professor and medical physicist

Email:
Faisal.mahmood@rsyd.dk

Webpage:
https://portal.findresearcher.sdu.dk/da/persons/fmahmood

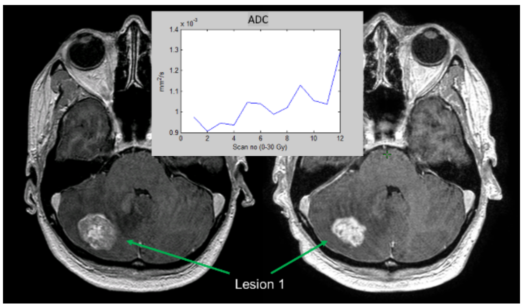
Project types: Master's

Research topics: Medical physics. Magnetic resonance imaging (MRI) in Radiotherapy. Imaging biomarkers from diffusion MRI, MRI relaxometry and other parametric imaging techniques.

Research methods: Experimental (clinical systems), computer analyses. Existing data or new data.

Introduction to my research:
I am a biophysicist and work within the field of medical physics at the Department of Oncology, Odense University Hospital. My research focus is on the use of Magnetic Resonance Imaging (MRI) in radiation therapy, for treatment of cancer. With MRI, soft-tissue (non-bony) anatomy can be imaged with high contrast and thus cancer can be differentiated from healthy tissue, potentially increasing precision of radiotherapy. Furthermore, parametric MRI can characterize the tissue micro-structure and give more detailed information about the underlying biology. The aim of most of my research is to investigate how information from MRI can be used to tailor radiotherapy for the patients.

Examples of thesis topics (other MRI related topics could be decided with the student):
Diffusion properties of tumours



Diffusion weighted MRI (DWI) probes the Brownian motion of water inside the tissue being scanned. Proper modelling of the data can reveal tissue properties such as the apparent diffusion coefficient and the capillary circulation of blood, both believed to be markers for the radio-sensitivity of the tumour. A project within this topic may help improving the analyses of DWI data for better characterization of tumours.

Geometrical distortion of magnetic resonance images
MRI is prone to geometrical distortion, due to the steps involved in MRI acquisition. It starts with excitation of hydrogen spins (within the tissue) to induce a net magnetization, followed by an application of magnetic gradients to resolve the location of the spins from the sampled radiofrequency signal emitted during the relaxation process. Assessment, impact and possible correction of the images is important and the main focus of this topic.