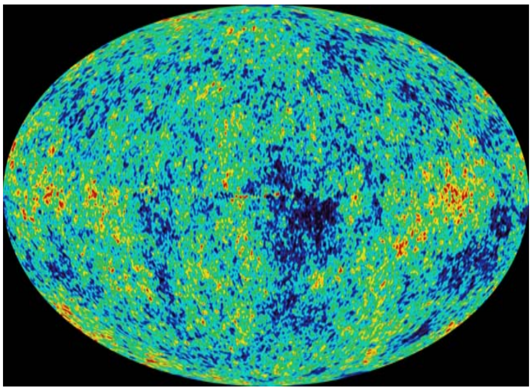
1. Studying Galaxy clusters with the cosmic microwave background radiation - *observational project* (Dr Yin-Zhe Ma)



The Planck satellite and WMAP satellite are the two most important CMB experiments of the day, and have been providing precise measurements on the cosmic microwave background (CMB) radiation, which have pinned down the cosmological parameters to an unprecedented precision. Not only can these two satellites precisely map the primordial CMB fluctuations, but also measure the secondary anisotropic fluctuations which reflect the properties of galactic clusters and dark matter halos.

The CMB photons traveled from the last scattering surface, can act as a "back light" and be re-scattered by the hot electrons in the Galaxy clusters. This is known as the "Sunyaev-Zel'dovich effect", which describes the distortion of CMB black-body spectrum by the hot electrons in the galaxy clusters. Recently, Planck has released its full-sky CMB maps in nine different frequency bands, of which 4 of the bands have arcmin level of beam size and lower noise level, and therefore detect the SZ effect for each cluster at 2-3 sigma level.

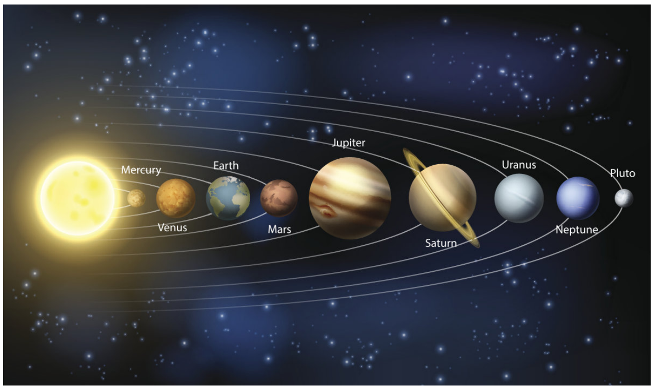
In this project, by using the Meta Catalogue of X-ray detected Clusters of galaxies (MCXC), we will cross-correlate the Planck with WMAP satellite' maps, and test their consistency on galaxy cluster scales. We will use the 94 GHz WMAP map, with the 100, 143, 217 and 353 GHz Planck maps, and calculate the Compton Y-parameter (value of distortion of temperature fluctuations of CMB) of each maps. Since two satellites have different beams in different frequency channels, we first convolve the Planck maps with WMAP beam and WMAP map with Planck beam, and then matched-filter both the WMAP and Planck maps. We then use the MCXC catalogue to locate the source of galaxy clusters, and calculate the Compton Y-parameter of distortion in each map. In this way, we can calculate the $Y_{\rm Planck}$ and $Y_{\rm WMAP}$ for each galaxy clusters and therefore obtain a one-to-one correspondence of the two. One can do a variety of tests: (1) One can stack the maps with around the galaxy clusters and therefore obtain the stacking detection of SZ clusters in WMAP, which has not yet calculated before; (2) One can compare $Y_{\rm Planck} - Y_{\rm WMAP}$ and therefore test the consistency between the two observations (The estimates of Y should be unbiased for two maps, but have different measurement errors due to different noise levels); (3) Further one can investigate the shape of the galaxy clusters by using these filtered maps and therefore shed some lights on clusters density profile and gas distribution.

This project will involve analytical and numerical modeling, as well as data analysis. There will be a small analytic component to this project, but the bulk of the work will be working with the maps on a computer. As such, a significant part of the project will be spent becoming comfortable in a high-level programming language like python or Fortran.

Interested students should contact Dr Yin-Zhe Ma (ma@ukzn.ac.za).

2. Measuring the motion of our solar system with respect to the cosmic microwave background radiation - *observational project* (Dr Yin-Zhe Ma)

The cosmic microwave background (CMB) has a 3.4 mK dipole anisotropy which can naturally be explained as being due to the motion of the solar system with respect to the CMB rest frame. An interesting consistency check of this is to evaluate the solar system motion from peculiar velocity surveys.



SNe luminosity measurements provide an accurate probe of peculiar velocities. Using observed correlations between SNe light curves, we can estimate the SNe absolute magnitudes and thus obtain accurate distance estimates to the SNe. Combined with spectroscopic measurements of the host galaxies' redshifts, this can be used to estimate the peculiar velocity of each SNe's host galaxy. The motion of the solar system will then show up as a dipole anisotropy in the SNe derived peculiar velocities. It is interesting to compare the estimates of the solar system motion from the SNe with those derived from the CMB. If they turn out to be inconsistent then it may be an indication that there is a significantly large intrinsic temperature dipole on the CMB surface of last scattering, which could be caused by a double inflation model for example.

In this study, we will use the state-of-the-art peculiar velocity field catalogue, named as CosmicFlow-2 catalogue, to calculate the speed of our solar system with respect to the CMB frame, by calculating the dipole anisotropy shown in the peculiar velocity field catalogue. This project will involve analytical and numerical modeling, as well as data analysis. The bulk of the work will be working with the catalogue on a computer. As such, a significant part of the project will be spent becoming comfortable in a high-level programming language like python or Fortran.

Interested students should contact Dr Yin-Zhe Ma (ma@ukzn.ac.za).

3. Studying the shape of dark matter halo with kinetic Sunyaev-Zeldovich effect - *observational project* (Dr Yin-Zhe Ma)

The kinetic Sunyaev-Zeldovich effect is the distortion of the black body spectrum of the cosmic microwave background radiation photons, which is produced by the re-scattering of the moving electron. The effect is proportional to the line-of-sight velocity of the galaxy cluster.

A recent study (Cunnama et al. 2009, MNRAS) shows that the velocity field of galaxy cluster is correlated with the elongation direction of the dark matter halo. Therefore, the elongation direction of each dark matter halo should be correlated with the measured kinetic Sunyaev-Zeldovich (kSZ) effect.

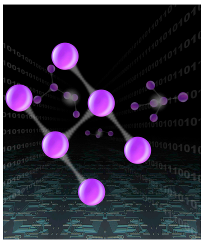
In this work, we will use two data sets to find such correlation signal. We will use the kSZ map produced from the Planck satellite, and the reconstructed tidal field catalogue from Slogan Digital Sky Survey. Then we will make a cross-correlation between the two and see how much signal is there. We will also do the same computation but with simulation and compare the results from simulation with real data. This study allows us to access how much baryons there are to source the kinetic Sunyaev-Zeldovich effect.

Interested students should contact Dr Yin-Zhe Ma (ma@ukzn.ac.za).

4. Quantum Teleportation of Multi-Dimensional Systems - *theory project* (Prof. Thomas Konrad)

We will compare two teleportation schemes with photons that can carry superpositions of many basis states (qudits) with respect to the resources they need and the feasibility to implement them in the lab. The schemes are based on encoding quantum information into the spatial modes of the photons. So far only the smallest unit of quantum information - one qubit - has been teleported. The project is 80% literature review and 20% development of own ideas.

5. Quantum Optimization Algorithm - *theory project* (Prof. Thomas Konrad)

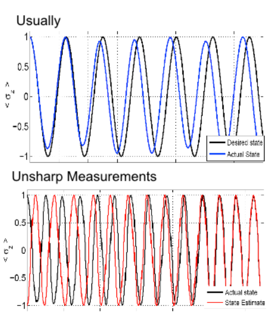


Quantum Computers promise unprecedented power of parallel processing. This project is to look at the possibility of using quantum parallelism in order to find the extrema of functions on a plane. We will review the literature and ideas developed by Prof Konrad in collaboration with Prof Hans Briegel from Austria to find a quantum version of a simple classical method.

6. Quantum Computation with Classical Light II? - *experimental project* (Profs Andrew Forbes and Thomas Konrad)

Certain quantum information processing tasks (quantum walks) can be implemented using different degrees of freedom of laser pulses (for example polarization and orbital angular momentum). The project is to theoretically and experimentally check aspects of the implementation of simple quantum algorithms (e.g. Deutsch-Josza) using laser pulses. This is the third project in a sequence after the Deutsch Algorithm (published) was successfully implemented in the framework of an Honours project in 2015 and a theoretical scheme was developed for the Deutsch-Jozsa Algorithm (a corresponding publication is in preparation).

7. Towards a New Atomic Clock - *theory project* (Prof. Thomas Konrad)



The measurement and control of a single quantum system is tricky because of the sensitivity of quantum superpositions to the leakage of information to the outside. Particularly, if it comes to stabilizing dynamical processes, the usual sharp measurements disturb the system too much. As the example of a trapped ion oscillating in a microwave field we study methods to detect and control the microwave frequency by so-called unsharp measurements of the energy of the ion.

8. The Twin Paradox revisited - *theory project*
(Prof. Thomas Konrad)

The twin paradox in special relativity tells the story of a twin A who travels with a rocket at high speed to Alpha Centauri and finds his twin brother B after his return to be older than him. From B's point of view A left and returned but in A's rest frame B left and returned. So why should B be older and not A? The answer is because A accelerated to come back and B did not. We look at a new version of the story, where the state of A's clock is teleported back to B and thus A and B's clock's can be compared without a change of A's motional state. Which clock runs slower in this situation or are they still in sync?

Prof Thomas Konrad is currently on a research visit abroad and only returns end of February. Students interested in one of his projects should contact him via email (konrad@ukzn.ac.za).

9. Observational cosmology in the radio and/or microwave - *observational project*
(Dr Cynthia Chang)

There are opportunities to work in observational cosmology using a variety of radio and microwave telescopes: HIRAX, HERA, SCI-HI, C-BASS, SPIDER. The range of work spans instrumentation development, field work (calibrations and observations), data analysis, and computational methods. The specific details of the project will be tailored to the student's interests. Programming experience (python preferred) is highly recommended but not required.

Interested students should contact Dr Cynthia Chang (cynthia@physicschick.com).

10. Finding the Biggest Things in the Universe - *observational project*
(Prof Jonathan Sievers)

Clusters of galaxies are the most massive gravitationally bound objects in the universe. Large ones can weigh as much as a thousand Milky Ways. Nevertheless, the seeds of their formation were planted in the first tiny fraction of a second after the Big Bang. As such, we can use clusters to learn about the birth of the universe, along with how it has grown with time. However, to be useful in studying cosmology, we need to measure the masses of clusters with as little systematic error as possible. The goal of this project is to use maps of the Cosmic Microwave Background (CMB) to find new clusters of galaxies and work on improving estimates of their masses.

The CMB is relic radiation from the Big Bang and gives us a snapshot of the universe when it was just 400,000 years old. Several experiments, such as the Planck Satellite and the Atacama Cosmology Telescope (ACT), have mapped the CMB over the sky with varying sensitivity and angular resolution. Clusters sit between us and the CMB, and leave a characteristic signature on the CMB. The large majority of the normal matter in clusters is not tied up in galaxies but instead is in the form of hot gas that fills the cluster. The cluster gas is many millions of degrees, while the CMB is 2.73 degrees above absolute zero. As the CMB photons pass through the gas, energy flows from hot to cold, and some of the cold CMB photons get a boost in energy. This boosting - the called the Sunyaev-Zeldovich (SZ) effect - makes a characteristic signal in the CMB where clusters look bright at high frequency but show up as holes at low frequencies. Simulations predict that the SZ effect should be the most precise way of measuring cluster masses, but the field is still young (the first surveys with enough sensitivity and resolution to discover clusters through the SZ effect only appeared within the last 5 years). Both Planck and ACT have published catalogs of clusters but to date they have not been combined to search for clusters. This combination should be more powerful than either survey alone.

This project will start by taking publicly available Planck maps at different frequencies and splitting the cluster signal from other contaminating signals like radio sources, distant dusty galaxies, and the CMB itself. When this part of the pipeline has been checked against known results, the combined ACT and Planck maps will be searched for clusters. The benefits of this are twofold - first, clusters already discovered by ACT will get improved measurements, including of their masses, and second, the combination should be able to discover many clusters that each experiment individually missed. If time permits, the new combined SZ measurements will be used to help constrain models for the physics of clusters and measure basic parameters of the universe.

There will be a small analytic component to this project, but the bulk of the work will be working with the maps on a computer. As such, a significant part of the project will be spent becoming comfortable in a high-level programming language like python or Matlab.

Interested students should contact Prof. Jonathan Sievers (sieversj@ukzn.ac.za).

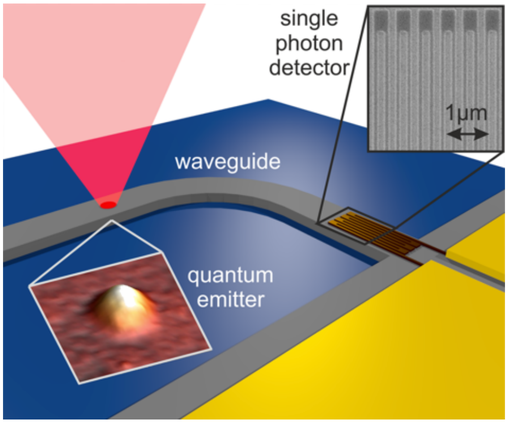
11. Can We Find the First Stars? - *experimental project* (Prof Jonathan Sievers)

We think we know that the first generation of stars lit up the universe when it was just a few hundred million years old. However, we have never directly seen these first stars, and what they looked like is still a mystery. One signal they leave is on the all-sky brightness of hydrogen. The rest frequency of hydrogen emission is 1.4 GHz, but the first stars were so early that the expansion of the universe has stretched out that light to around 100 MHz. You may recognize 100 MHz from places like your FM radio dial, and so searching for this signal is very difficult due to interference from radio stations and the like.

To get around the radio interference, experiments searching for the first stars need to be very far from people. A group at Carnegie-Mellon in the US deployed an experiment to an island nearly 200 km off the coast of Mexico, but found that even that far away the radio emission from the mainland covered the light from the first stars. Consequently, we teamed up with them to deploy an experiment to Marion Island, a small volcanic island half-way between South Africa and Antarctica. We are now fully funded to run an experiment at Marion, and we expect to send the first version this year. We have several projects appropriate for honours students, including working on hardware that will be deployed to Marion, working on electronic controls and data systems that will run an instrument left for the winter, and preparing analysis techniques for the data that we will collect. Students can train on data from the northern hemisphere experiment, and we expect the first data from Marion by the end of May. There may be an opportunity for students who work on the hardware/instrument software to deploy to Marion Island next year.

Interested students should contact Prof. Jonathan Sievers (sieversj@ukzn.ac.za).

12. Quantum nanophotonics - *experimental project* (Prof Mark Tame)



This project will introduce the student to the study of nanoscale optical systems operating in the quantum regime. The physics of single-photon sources will be studied using silicon, gold and graphene nanowires integrated with emitter systems in the form of quantum dots and nitrogen-vacancy centres in diamond. Applications in both quantum and classical information processing will be investigated.

The work will be part theory (waveguide analysis and electromagnetic simulations) and part experiment (lasers, single-photon detectors and atomic force microscope).

Interested students should contact Prof. Mark Tame (tame@ukzn.ac.za).

13. Implementation of a fibre-based QKD system - *experimental project* (Prof Francesco Petruccione and Dr Yaseera Ismail)

The aim of this project is to implement a Quantum Key Distribution (QKD) scheme within a fibre based link.

Quantum communication or more specifically QKD is based on the sharing of a secure key for the encryption of sensitive data. QKD is implemented by transmitting single photons that are encoded through phase or polarisation, within a quantum channel that is either fibre or free-space.

A "plug and play" fibre based scheme demonstrated by Muller et al [1], has been realised in a commercial quantum communication system by ID Quantique from Switzerland, in the form of the first generation Clavis. This system implements a phase encoded QKD scheme and by default supports two QKD protocols, namely BB84 and SARG04.

The "plug and play" scheme uses phase encoding to enable communication between two parties. It features one party (Bob) sending a pulse to the second communicating party (Alice) using an unbalanced interferometer. Alice attenuates the signal to an average of a single photon per pulse, and encodes it before sending it back to Bob as a quantum signal.

This process leads to generation of a raw key which can undergo post-processing resulting a final key that can be utilised for encryption.

Objectives and Outcomes:

1. Establish a fibre based QKD link between to legitimate individuals.
2. Perform a BB84 and SARG04 protocol.
3. Obtain a raw key from the encoded single photons transmitted through the fibre channel.
4. A comprehensive written report of the project and findings.

Interested students should contact Prof Francesco Petruccione (petruccione@ukzn.ac.za) or Dr Yaseera Ismail (Ismaily@ukzn.ac.za).

[1] A Muller, T Herzog, B Huttner, W Tittel, H Zbinden, N Gisin, “"Plug and play" systems for quantum cryptography” Applied Physics Letters 70, 793–795 (1997).

14. Proving the existence of entanglement - *experimental project* (Prof Francesco Petruccione and Dr Yaseera Ismail)

The aim of this project is to verify the existence and quantify the quality of entanglement of a photon pair generation source.

The verification of entanglement lies in the violation of the CHSH inequality, which states that in local realistic theories the absolute value of a particular combination of correlations between two particles is bounded by 2, such that the violation is represented as follows:

$$S(\alpha,\alpha',\beta,\beta') = E[\alpha,\beta] - E[\alpha,\beta'] + E[\alpha',\beta] + E[\alpha',\beta'],$$

where α and α' and β and β' denote the local measurement settings of the two observers, each receiving one of the entangled particles. Here, a two-photon polarization entangled state will be used and the orientations of the measurement settings will be varied via polarisers placed in each arm of the source. The normalised expectation value for a fixed setting is given by

$$E[\alpha,\beta] = \frac{C(\alpha,\beta) - C(\alpha_\perp,\beta) - C(\alpha,\beta_\perp) + C(\alpha_\perp,\beta_\perp)}{C(\alpha,\beta) + C(\alpha_\perp,\beta) + C(\alpha,\beta_\perp) + C(\alpha_\perp,\beta_\perp)},$$

where $C(\alpha,\beta)$ denotes the coincidence count rate obtained for the combination of polariser settings (α,β). The statistical nature of the inequality requires that sufficiently long integration time for collecting the required coincidence rates. The quantum value of S should violate the inequality giving an ideal value of $2\sqrt{2}$, thus proving the existence of entanglement.

Objectives and Outcomes:

1. Set up the optical apparatus to verify entanglement of a photon generation source.
2. Gather data from the experimental setup to illustrate the existence of entanglement.
3. Vary parameters of the setup to understand what affects the quality of entanglement.
4. A comprehensive written report of the project and findings.

Interested students should contact Prof Francesco Petruccione (petruccione@ukzn.ac.za) or Dr Yaseera Ismail (Ismaily@ukzn.ac.za).

15. Quantum state tomography of an entanglement source - *experimental project*
(Prof Francesco Petruccione and Dr Yaseera Ismail)

The aim of this project is to use quantum state tomography to characterize the quality of an entanglement source.

Quantum state tomography is the process of reconstructing the quantum state for a source of quantum systems by measurements on the systems coming from the source. Balanced homodyne tomography is a reliable technique of reconstructing quantum states in the optical domain. This technique combines the advantages of the high efficiencies of photodiodes in measuring the intensity or photon number of light, together with measuring the quantum features of light by a clever set-up called the homodyne tomography detector.

An entanglement source generates two photons in a certain quantum state. One of the photons, known as the idler, is used to trigger the detector. The other photon, the signal, is directed into the homodyne detector, in order to reconstruct its quantum state. Since the signal and idler photons are entangled, it is important to realize, that the optical mode of the signal state is created non-locally only when the trigger photon impinges the photodetector and is actually measured.

The measurement is reproduced a large number of times in order to develop a density matrix and the Wigner function. This gives rise to the quantum state of the photon.

Objectives and Outcomes:

1. Set up the optical apparatus to generate a quantum state tomography.

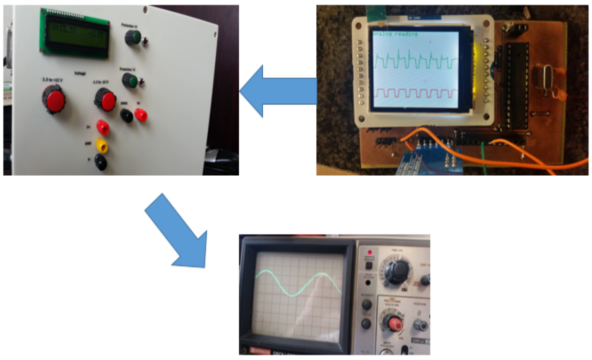
2. Gather data from the experimental setup to reproduce the quantum state tomography of the source.

3. Identify and vary the parameters of the setup to aim in improving the quality of the source.

4. A comprehensive written report of the project and findings.

Interested students should contact Prof Francesco Petruccione (petruccione@ukzn.ac.za) or Dr Yaseera Ismail (Ismaily@ukzn.ac.za).

16. Africhino laboratory tools - *experimental project* (Prof Francesco Petruccione and Dr Marco Mariola)



Many scientific experiments require the measurement of a physical quantity in form of electric signals in order to elaborate and control other processes. This research project aims to design a series of reliable, low-cost and open-source devices.

The devices will be integrated in a unique apparatus able to work as a classical personal computer or as an acquisition, elaboration and control system. In this work we intend to realise an Arduino based micro-controller board, generator functions and power control systems.

This project will give the candidate the necessary electronic design skills to be competitive in a world market and be self-sustaining in order to realize several electronic devices for their experiments as scientist.

Objective and Outcomes:

1. Design an Analog to Digital and Digital to Analog interface for an Open-Source Microcomputer.
2. Build a random generator function using the Direct Digital Synthesis.
3. Microcomputer interface for power systems control
4. A written report of the system comprensive for a physical experiment.

Interested students should contact Prof Francesco Petruccione (petruccione@ukzn.ac.za) or Dr Marco Mariola (MariolaM@ukzn.ac.za).

17. First steps in computational "Quantum Biology" - *theory project* (Dr Ilya Sinayskiy and Prof Francesco Petruccione)

The aim of this project is to familiarise the student with the Hierarchical Master Equation Approach - one of the main computational approaches in the newly emerging field of "quantum biology".

The student will learn the basics of the Theory of Open Quantum Systems, elements of quantum field theory and stochastic analysis. The student will learn about methods for the simulation of strongly interacting open quantum systems. For the computational part of the project, the student will learn methods of advanced programming in Mathematica or Python. The obtained results would be compared with known ones in the literature. Possibly, a publication could emerge from this project.

Interested students should contact Dr Ilya Sinayskiy (Sinayskiy@ukzn.ac.za) or Prof Francesco Petruccione (petruccione@ukzn.ac.za).

18. Many-body Computational Quantum Electrodynamics: Nonequilibrium Physics with Light - *theory project* (Dr Ilya Sinayskiy and Prof Francesco Petruccione)

In this project, the student will learn about light-matter interacting systems and the basics of the phase transition physics. The student will learn fundamentals of the theory of open quantum systems and the ways to simulate them.

In the computation part of the project the student will write a program to numerically simulate the dynamics of a dissipative-driven spin-boson system. The student will explore different parameter regimes and numerical observe phase transition in such a system. The obtained results will be compared with known ones in the literature. Possibly, a publication could emerge from this project.

Interested students should contact Dr Ilya Sinayskiy (Sinayskiy@ukzn.ac.za) or Prof Francesco Petruccione (petruccione@ukzn.ac.za).

19. Open Quantum Walks - *theory project* (Dr Ilya Sinayskiy and Prof Francesco Petruccione)

The aim of this project is to familiarise the student with open quantum walks (OQWs) and their properties. In particular, the student will focus on the microscopic derivation of particular OQWs and identify different behaviours of the "walker" with different thermodynamical parameters of the environment. Theoretical investigations would be illustrated by numerical simulations in Mathematica/Matlab packages.

Interested students should contact Dr Ilya Sinayskiy (Sinayskiy@ukzn.ac.za) or Prof Francesco Petruccione (petruccione@ukzn.ac.za).

20. Dissipative Quantum Computing with Open Quantum Walks - *theory project* (Dr Ilya Sinayskiy and Prof Francesco Petruccione)

The aim of the project is to familiarise the student with concept of quantum computing, especially its dissipative formulation and the formalism of Open Quantum Walks (OQWs). The student will learn about OQW formulation of the dissipative quantum computing (DQC) model. As an example of the DQC with OQWs, some simple quantum computing algorithms would be considered and numerically simulated in Mathematica/Matlab packages.

Interested students should contact Dr Ilya Sinayskiy (Sinayskiy@ukzn.ac.za) or Prof Francesco Petruccione (petruccione@ukzn.ac.za).

21. Dissipative Dynamics of a Driven Qubit - *theory project*
(Dr Ilya Sinayskiy and Prof Francesco Petruccione)

In this project the student will study the dynamics of a qubit interacting with an external magnetic field and a dissipative environment. The interaction with the heat bath will be treated as weak and we will use the Born-Markov approximation, which is perfectly justified for many situations in quantum optics. We will assume that the qubit interacts with the precessing magnetic field. We will be interested in the dynamics of the coherence and occupation probability in the qubit subsystem (Mathematica/Matlab numerical simulations will be used).

Interested students should contact Dr Ilya Sinayskiy (Sinayskiy@ukzn.ac.za) or Prof Francesco Petruccione (petruccione@ukzn.ac.za).

Other projects are available, as presented in this meeting or already agreed on with supervisors. For many of the projects, bursaries are available. Please check with your potential supervisor.