**Note:** The research proposals do not have to be one of the titles provided in this List, but it is recommended that the research is supported by experts available within the faculty of the Nazarbayev University School of Engineering and School of Science and Technology. Candidates may wish to generate their own titles. We also encourage the PhD candidates to contact potential Faculty Members for additional information on the following PhD topics.

Prof. Michael R.R. Good michael.good@nu.edu.kz

Topics of Interest: Quantum cosmology, quantum fields in curved spacetime, thermodynamics, general relativity.

1). **End-state of black holes and the hot vacuum; Hawking Effect and Unruh Effect**

Current black hole evaporation models need modification so that a finite amount of total energy is emitted. This project involves studying the differences between finite energy models with and without a left-over black hole remnant. It involves sewing together the spacetimes inside and outside a black hole so that continuity is maintained while the radiation process eventually shuts down as the black hole completely evaporates. In the Unruh effect, thermality is found by exploiting the conformal anomaly between Rindler-Minkowski coordinates. Rindler coordinates represent a rectilinearly accelerated observer in flat spacetime. There is a need to calculate, in a similar manner, the spectrum for Letaw-Minkowski coordinates, where Letaw coordinates refer to a uniformly accelerated observer that is neither circular nor straight-line. The spectrum for Letaw is of particular interest because it is exactly solvable using an excited detector formalism. Letaw acceleration is a peculiar cusp like motion, where for low accelerations, the light emitted is hotter than Unruh radiation.

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"On horizonless temperature with an accelerating mirror”, Good, M.R.R., Yelshibekov, K., Ong, Y.C.

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2) **Cosmological particles production and accelerated boundary conditions; Casimir Effect and Parker Effect**

There is a need to investigate particle production in an expanding spacetime which may be explicitly mapped to black hole light. A massless scalar quantum field embedded in a warping spacetime can produce particle and energy which may be more deeply connected to black holes and accelerated boundary conditions. This project also involves solving the
Bogolubov formulism in simple dynamic cosmology models. This project involves investigating the tiny light emitted by an accelerated mirror and its intimate connection to the death of stars. The dynamical Casimir effect can soon be detected via new laser-plasma proposals. Of particular interest is investigating a new solution where the boundary drifts to the speed of light.


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Prof. Daniele Malafarina daniele.malafarina@nu.edu.kz

1. Gravitational collapse (analytical models)
Investigate the behaviour of gravity in the strong field by solving analytical toy models for gravitational collapse. In particular the possible formation of horizon and singularity in black hole space-times and the possible occurrence of bounces where matter is re-ejected after the collapse phase and periodic solutions. In this context we aim to study:
(a) The role played by matter models in the formation of black holes, naked singularities or bouncing scenarios. What kind of repulsive effect appear in collapse once the density reaches a critical threshold? What kind of matter models would allow for the formation of non central singularities during collapse? What are the consequences of time-like naked singularities for far away observers?
(b) Small scale modifications to the classical relativistic framework for collapse due to quantum-gravity effects. These may prevent the formation of the singularity and produce a bounce or a periodic solution. What kind of matter models are necessary to produce the bounce? How does matter behave at very high densities? These projects require good mathematical skills.

2. Gravitational collapse (numerical models)
Extend the models for gravitational collapse to include more realistic physical effects such as rotation, hydrodynamics equations and dissipative effects such as neutrino or radiation transport. This project requires good computational skills. 


### 3. Exotic compact objects

Studying the motion of test particles in the field of exotic compact objects, as possible alternatives to black holes. Circular geodesics in the equatorial plane representing the path of particles in the accretion disk around a compact object. Gravitational lensing of light coming from distant sources and passing in the vicinity of the compact object. One possible outcome would be the construction of a computer simulated image of the object as seen by distant observers, to be compared with the black hole shadow.

This project requires a mix of analytical and computational skills.


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**Prof. Ernazar Abdikamalov ernazar.abdikamalov@nu.edu.kz**

### 1. Supernova Explosions as Cosmic Laboratories for New Physics

Supernovae are powerful explosions of massive stars at the end of their lives, leaving behind neutron stars or black holes. Supernovae are responsible for the production of elements heavier than iron throughout the universe. Neutron stars contain matter under extremely high density. Some of the most pressing open questions in astrophysics, nuclear and neutrino physics are posed in the context of supernovae. How do stars explode? Which elements are synthesized? What are the properties of nuclear matter and neutrinos at high densities? Supernovae are unique cosmic laboratories that can help answer these questions. Neutrinos, gravitational waves, and photons from the next supernovae are on their way to Earth. The international networks of observatories are poised to observe them in detail. In this project, we develop new models of supernovae and study their observational signatures. We will study how those signatures can be used to probe the physics of nuclear matter and neutrinos. These efforts will involve collaboration on an international level with recognized institutions around the world such as Caltech, Oak Ridge National Laboratory, and Princeton University, among others.

### 2. New computational approaches to radiation transport
Radiation plays a key role in a wide range of critically-important phenomena. Its behavior is described by the Boltzmann transport equation, which is a notoriously difficult to solve. In the last several decades, two different classes of computational methods has been developed, each with advantages and drawbacks: the deterministic and the Monte Carlo (MC) approaches. Despite this effort, the solution techniques suffer from severe drawbacks that limit their accuracy, efficiency, and scalability. In this project, we aim at developing novel approaches to radiation transport that address these drawbacks. We plan to construct a new hybrid scheme that combines MC and deterministic methods, which will result in a highly efficient and accurate technique that will find applications in a wide range of areas of science and engineering.

Prof. Zhandos Utegulov, email: zhutegulov@nu.edu.kz, phone: +7 7172 70 65 54

1) Laser-based material science of fast high-temperature thermo-mechanical phenomena in refractory materials & advanced optical instrumentation development

To evaluate stability of materials operating in harsh operational conditions (e.g. high temperatures & stresses, high rates of straining & heating experienced by nuclear reactor fuels, advanced armors, supersonic jets, rocket engines, plasma-arc electrodes and cutting tools, components of the fusion and accelerator devices), it is extremely important to perform optically controlled thermomechanical tests on these materials with high spatial and temporal resolution to qualify these material for the actual operation. These high-precision tests will play extremely important role in the development of reliable and economical materials withstandin aggressive environmental conditions pertinent in diverse industrial and research applications. PhD students will be offered interdisciplinary research opportunities in the applied physics area of nanosecond pulsed laser - matter interaction to investigate opto-acoustic and fast thermo-mechanical phenomena during heating, melting and ablation regimes in mechanically stressed refractory metals and ceramics. Students will have unique hands-on experience with optical design and instrument construction, data acquisition and measurement automation, signal analysis pertinent to materials property measurement, analytical and computational modeling. This PhD project pursues two-fold objectives: fundamental science of laser-matter interaction at small spatio-temporal scale, as well as development of highly innovative instrumentation for laser-pulse, remote, crucible-free, high-speed and localized melting of refractory materials under different stress levels with real-time determination of their mechanical, thermal, chemical and microstructural properties with high spatial and temporal resolutions. Collaboration with key international and national R&D partners will be offered.

2) Advanced optical techniques for nanometer-scale thermal transport across materials and interfaces

A diverse variety of technology drivers such as radiation resistive nuclear materials, value-added thermal barriers, higher efficiency thermoelectric energy conversion, phase-change memory, heat-assisted magnetic recording, thermal management of nanoscale electronics, and nanoparticles for thermal medical therapies are appealing studies of the applied physics of thermal transport at the nanoscale. The knowledge of radiation-induced thermal transport degradation in engineering materials is of paramount importance for nuclear and fusion reactor system design and validation. Most of corresponding experimental data on this subject concerns neutron irradiation and almost nothing is known about high energy heavy ion irradiation simulating fission fragment impact. At the same time such data are of considerable practical interest especially for number of insulators recommended as candidate materials for inert matrix fuel hosts due to large number of fission track recoil in reactor fuels. Laser pump beam’s modulation frequency- and corresponding heat penetration depth-dependent thermal transport properties of relevant insulator materials will be studied in terms of contribution of phonon scattering from ion-induced defects in crystalline, nanocrystalline and amorphous phases. PhD students will have interdisciplinary research opportunities in the applied physics area of modulated picosecond time-domain thermoreflectance, Raman spectroscopy and photoacoustic cell techniques to investigate thermal transport in ion-induced damaged structures, have hands-on experience with ultrafast optics & electronics design, data acquisition, measurement automation, data analysis and modeling. This PhD project will focuses on developing a microscopic understanding of thermal transport at the nanoscale, fundamental studies of thermal transport across dissimilar solid-state structures with nanometer-scale spatial resolution as a result of radiation damage imparted to materials. Collaboration with key international and national research partners will be offered.


3. Brillouin laser light scattering spectroscopy of complex liquids and biomaterials for visco-elastic property measurement & optical sensor development

This PhD topic will be focused on spontaneous and stimulated Brillouin laser light scattering spectroscopies for investigation of elastic and rheological properties of complex viscoelastic soft matter in non-contact, localized and non-destructive manner with high spatio-temporal resolution. The ultimate goal of this project will be not only fundamental science of photon-
phonon interaction linked to visco-elastometry and opacity of soft matter, but also development of highly innovative instrumentation for laser-pulse, remote, real-time diagnostics of viscoelastic properties of complex fluids and soft matter in various industrial settings pertinent for oil & gas, chemical, pharmaceutical, biomedical and food industries. PhD students will have interdisciplinary research opportunities in the applied physics area of laser - matter acousto-optic interaction, GHz visco-elastometry, molecular hydrodynamics, optical design, data acquisition, measurement automation, data analysis and modeling. Collaboration with key international and national R&D partners will be offered.


Prof. Aikaterini Mandilara aikaterini.mandilara@nu.edu.kz

1. Bound entangled states: characterization and applications

Since their discovery [1], bound entangled states have attracted a lot of attention in the community of quantum information. These states have the peculiar characteristic of requiring non-local resources for their preparation but being at the same unstillable in terms of EPR pairs. While different classes of PPT [2] bound states have been identified during the last decades, a global characterization of their intrinsic properties is still missing. In addition, there is a long standing open question whether NPT bound states do exist. Recently, an algorithm [3] has been proposed for analyzing the entanglement characteristics of mixed multipartite entangled states, being able to identify with high accuracy bound entangled states. The aim of this project is to apply and extend this algorithm for analyzing the global properties of PPT bound entangled states but also for searching for NPT bound ones. At second step of this project, the researcher based on the obtained results should be able to identify applications for bound entangled states in quantum information and also study their role in physical processes as open quantum dynamics, quantum phase transitions etc.

1. Reverse Engineering of Photonic Structures

Introducing novel designs of photonic components such as photovoltaic cells and invisibility cloaks is a fascinating process useful in numerous scientific branches from Electrical Engineering to Physics and Chemistry. One should first select the correct metric for the performance of the component by taking into account the interaction with other parts of the device. Then such a metric should be maximized into the multi-dimensional parametric space defining the configuration of the component. Knowledge of the physical effects occurring in wave integrations along with mastering of analytical techniques and numerical methods is essential for obtaining optimal designs. Such a reverse engineering approach has been employed in [1] for an electromagnetic shield and in [2] for an energy-efficient absorber.


2. Manipulating the Light with Graphene and 2D Metamaterials

The radical concept of metamaterials is related to the design of artificial molecules and atoms (on the scale of the operating wavelength) placed in two or three dimensions in order to change the macroscopic electromagnetic properties of the surrounded area in an exotic, non-natural way. This idea can be expanded at the atomic level when stacking one-atom-thick layers of more than one material to produce new two-dimensional (2D) media. A typical example of such a case is graphene: a hexagonal lattice of carbon atoms (common graphite) extending over two dimensions which exhibits huge electrical conductivity and shape durability. The same approach can be extended to obtain other two-dimensional (2D) media (such as black phosphorus, molybdenum sulfides or boron nitrides) with even more fascinating properties. Use of suitable 2D media for modeling highly efficient photonic devices has been made in the perfect lens of [1] and in the filtering (ENZ) structure of [2].

3. Guessing the Texture of Electromagnetic Samples

An inverse problem is by itself a challenging topic since it concerns the guessing of the characteristics of objects based on imperfect external measurements. The applications span from scanning the subsoil and identifying underground mineral/oil deposits (ground penetrating radar, GPR) to estimating non-invasively the texture of inorganic or biological samples. Making the correct system modifications and selecting the suitable materials used together with the corresponding illumination, will render the inversion procedure easier and more noise-immune. At the post-processing stage, well-developed algorithms which may increase the quality of the data, will be implemented. A similar approach has been followed in [1], where ground penetrating radar techniques have been refined with use of thin passive layers; furthermore, in [2] quantum Aharonov-Bohm measurements assist the inverse scattering from bio-chemical samples.


Prof. Vasileios Kovanis vassilios.kovanis@nu.edu.kz

1. Fast, Tunable and Low Noise Photonic Oscillators

Combining an optically injected diode laser and properly feeding back a polarization-rotated signal we can induce self-referenced robust limit cycle microwave output that is widely tunable, spanning across 100GHz bandwidth, by simply varying the dc-bias points of the master and DFB slave lasers diode. We observed feedback-induced reduction of the pulsation peak linewidth by more than two orders of magnitude relative to the injection-only case. The nonlinear dynamics of the optically injected semiconductor laser can be used to minimize sensitivity to fluctuations in the operating points. Theoretical analysis of these experimental recordings is performed using a new stochastic delay third order Adler phase equation with good agreement with the experimental findings. The student will write code for delay differential equations, attempt to draft a more sophisticated stochastic version and perform a massive set of simulations to compare with analytical results as well experimental findings. Possible collaborative visits to the University of New Mexico and The Free University of Bruxelles may occur during the duration
of the project, Possible outcomes well be a manuscript in IEEE as well conference contributions to CLEO and OSA.


2. Chimera States in Arrays of next Generation Lasers
Semiconductor laser arrays have been investigated experimentally and theoretically from the viewpoint of temporal and spatial coherence for the past forty years. In this work, we are focusing on a rather novel complex collective behavior, namely chimera states, where synchronized clusters of emitters coexist with unsynchronized ones. For the first time, we find such states exist in large diode arrays based on quantum well gain media with nearest-neighbor interactions. The crucial parameters are the evanescent coupling strength and the relative optical frequency detuning between the emitters of the array. By employing a recently proposed figure of merit for classifying chimera states, we provide quantitative and qualitative evidence for the observed dynamics. The corresponding chimeras are identified as turbulent\(^2\) according to the irregular temporal behavior of the classification measure. Such studies may be the springboard for designing next generation photonic emitters providing on demand diverse waveforms. The student will write code for a large set of ordinary differential equations modeling ring semiconductor lasers and use the Yannis Kevrekidis\(^3\) measure to dissect the numerical findings. Possible collaborative visits to the University of Crete and University of Central Florida may occur during the duration of the project. And outcomes will be a manuscript in Physical Review as well conference contributions to CLEO, OSA and or Dynamic Days.


3. From Bloch Oscillations to Bloch Oscillators
A charged capacitor which is placed with a semiconductor in a closed loop will normally discharge in a characteristic time . In the past we showed, that if a semiconductor of high purity is subjected to a RF bias with frequency , discharge does not occur if the voltage across the capacitor is proportional to an integer multiple of . Thus a RF frequency may be converted to a dc voltage. The ac to dc conversion is made possible by the interplay between Bloch oscillations induced by the electric field of the external RF source and those induced by the field from the charge residing on the capacitor. The process resembles the frequency-to-voltage conversion by a hysteretic Josephson junction, except that the evolution of the Josephson phase is replaced by the evolution of the crystal momentum of conduction electrons in the semiconductor. We discuss
Twisted Light in Nonlinear Photonics

We learn in geometrical optics that light propagates along straight lines, which is a good approximation in optically homogeneous medium and at the spatial scale much larger than the wavelength. A closer look at the wavelength and sub-wavelength scales reveals that light can be actually twisted around “threads of darkness” – dark core lines of optical vortices.

This project is part of the research program at Physics Department of Nazarbayev University, developing the concept of twisted light in nonlinear photonics, a branch of photonics focusing on the novel physical phenomena that emerge by tailoring the topology of light, the structure of matter, and the nonlinear light-matter interaction [1]. Smart engineering of photonic media and devices requires deep understanding of physics of structured light as well as elaborate experimental techniques for its generation and control. This cross-disciplinary research will provide novel physical basis and functionalities to the next generation devices in optical integrated circuits, sensors, classical and quantum logic elements, switches and spin-memory elements.

1. *Conical intersections for light and matter waves*, Daniel Leykam and Anton S. Desyatnikov

Two (2) PhD Positions in the Department of Chemical Engineering, on the topic of “Structure-Property interactions in multi-scale composites”
Contact: Professor Athanasios Paphanasiou
Head of Chemical Engineering
athanasios.paphanasiou@nu.edu.kz
The aim of the proposed research is to take advantage of recent advances in computing and microstructural characterization and, by utilizing a combination of advanced computing and experimentation in specimens of precisely defined and complex microstructure, derive quantitative relationships between microstructure and properties. We plan to apply this approach to two categories of composite materials, namely fibrous materials with reference to the liquid molding and pultrusion processes and flake-reinforced composites [1-3]. In the first category, the property of interest is the hydraulic permeability of the fibrous medium. In the second, the focus is to develop barrier materials (with respect to humidity, CO2 etc.) and the property of interest is the diffusion coefficient. Experimentally, specimens of precisely controlled microstructure will be generated using 3D Printing.


PhD thesis proposals (SST, Physics department)

Principal Investigator: Prof Jean-Jacques Zondy (SST – Physics, NU)
Co-PI’s: Prof Emeritus Claude Fabre (University of Paris-Sorbonne, Universite Pierre et Marie Curie (UMPC/Laboratoire Kastler-Brossel, Ecole Normale Superieure), Quantum Optics group, Paris ); Prof Zhan Zheng, Center for Optics and Optoelectrics Research, College of Science, Zhejiang University of Technology, China ; Prof Dmitry Kolker, Institute of Laser Physics SB-RAS/Novosibirsk State University, Russia.

Keywords: Nonlinear optics and Photonics, Experimental Laser optics, Optical Parametric Oscillators (OPOs).

1) Classical and quantum information technologies based on self-phase-locked, subharmonic frequency divide-by-3 optical parametric oscillators
Sub-harmonic divide-by-n phase-locked oscillators, consisting of n oscillators (with frequencies \( n\omega, (n - 1)\omega, \ldots, \omega \)) coupled by nonlinear self-injecting mechanisms that tightly lock their phases, are intriguing complex devices exhibiting novel physical properties compared to classical non-phase-locked oscillators. One peculiar feature of such subharmonic oscillators is...
the existence of $n$ possible deterministic phase states spaced by $\Delta \varphi = 2\pi / n$ for a single vibrational intensity state. In the optical domain, they can be experimentally implemented with the so-called frequency divide-by-$n$ ($n = 2$ or $3$) optical parametric oscillators (OPOs). A frequency-divide-by 2 (2:1) self-phase-locked OPO (2:1 SPL-OPO) is a nonlinear optical frequency down-conversion device in which pump photons with frequency $2\omega$ from a laser beam interacting with a $\chi^{(2)}$ nonlinear optical crystal are split into two sub-harmonic photons of frequency $\omega$. Such a 2:1 OPO oscillating at frequency degeneracy is naturally self-phase-locked, exhibiting two possible phase states $\Delta \varphi = \pm \pi$ for the same intensity state for the $\omega$ degenerate sub-harmonic waves [1]. While 2:1 SPL-OPO has been widely investigated for its quantum noise and quantum entanglement properties, frequency-divide-by-three (3:2:1) SLP-OPOs ($3\omega \rightarrow 2\omega, \omega$), exhibiting 3 possible equidistant locked phase-states (spaced by $\Delta \varphi = 2\pi / 3$) have received less attention due to their difficult experimental implementation, because an additional nonlinear interaction self-injecting the two non-degenerate subharmonics ($2\omega \leftrightarrow \omega$) [1]. Preliminary classical and quantum optics theoretical investigations of this nonlinear device have shown that it can exhibit much richer nonlinear dynamics (such as 3-phase patterned vortex spiral waves or cavity solitons) and quantum properties (such as the unprecedented demonstration of phase noise squeezing or novel photon entanglement properties [3]) much richer than in the 2:1 SPL-OPO. The PhD proposal aims to unveil experimentally and theoretically all these new physical properties that have potential applications in classical/quantum information processing and in phase-encoded information storage.


2) Widely wavelength tunable optical parametric oscillators for applications in non-invasive, real-time trace gas sensing in the mid-infrared (MIR) molecular fingerprint spectral range

Probing molecular species via fundamental or overtone rovibrational spectroscopic signatures using sensitive (such as photoacoustic spectroscopy, PA) or ultra-sensitive spectroscopic techniques (such as Cavity Ring Down Spectroscopy, CRDS [1], with sensitivity ranging from 1 part per million – ppmv – up to one part per trillion – pptv) has many practical applications in real life (real-time breath analysis of disease-specific biomarkers for early disease detection, pollutants or explosives trace detection, industrial chemical residues analysis, mid-IR LIDAR ranging, real-time monitoring of hydrocarbon leak in oil plants or pipelines etc…). The advantage of using coherent MIR laser sources for the detection and quantification of molecular
species lies in the 100-to-1000 fold oscillator strengths of rovibrational transitions compared to electronic transitions in the visible or near-IR range, leading to higher detection sensitivity. Because no widely tunable commercial conventional laser is available in the 5 – 20 microns MIR range, optical parametric oscillators (OPOs) based on the down-conversion of, e.g. a near-IR laser such as Nd:YAG at 1.064 microns, is the most convenient way to build such widely tunable MIR (nonlinear) laser sources [2]. The principle of operation of an OPO is based on the spontaneous splitting of the pump laser photon (due to second-order nonlinearity of a quadratic nonlinear chalcogenide material) into two child photons of lower energies called signal and idler photons, such that the total photon energy and momentum are conserved (phase-matching condition). Typical single-crystal nonlinear material for the MIR are, e.g., silver gallium selenide (AgGaSe₂), zinc germanium phosphide (ZnGeP₂), lithium seleno-inate (LiInSe₂) etc…, that are hosted inside standing-wave or ring resonators designed to obtain parametric oscillation of the signal wave while the MIR idler wave escapes from the resonator. OPOs can be implemented as continuous-wave (cw) laser sources [3] or pulsed (nanosecond -ns, picosecond -ps or femtosecond -fs) laser sources.

The experimental PhD work will consist of constructing from scratch such OPOs either in the ns or cw regime of lasing, using a high-power or high-pulse energy Nd:YAG laser sources (1.064 μm) and obtaining wavelength-tunable signal (1.2 – 3 μm) and idler waves (5 – 20 μm). Various novel ternary or quaternary chalcogenide crystals grown in Russia, such as barium gallium selenide (BaGa₄Se₇) will be used as nonlinear crystal [4]. This table-top experiment in optics and lasers will also allow metrological characterization of the physical properties of the tested materials (linear and nonlinear properties, thermo-optical and laser damage properties etc…). The MIR OPO developed will be applied to spectroscopic trace gas detection of various molecular species (hydrocarbons or pollutant species) using one of the numerous single-pass, multi-pass, or cavity-enhanced available spectroscopic methods.