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Neutron star are one of the most exciting, and certainly exotic, nuclear physics laboratories in the universe. These incredibly dense objects are born when a massive star exhausts its nuclear fuel and dies, exploding as a supernova. The core that survives the explosion is no longer supported by nuclear processes and collapses under its own gravity. If the original star was very massive (more than thirty times the mass of our sun) it will continue collapsing all the way to form a black hole, but if it's less massive eventually the interior components will be squeezed together so tightly that there is no more space to squeeze them any further, and the collapse halts, forming a 'dead' star. For the least massive stars quantum mechanical effects deriving from the electrons being pushed close to each other are sufficient to halt the collapse and a White Dwarf is born. For more massive stars the collapse continues until neutrons are pushed together far enough that their quantum mechanical pressure can support the star, and one has a Neutron Star.

These objects are so extreme that their interior density is higher than the interior density of a standard nucleus: they have a mass approximately one and half times that of the sun compressed in a 10 km radius, the same as if the mass of the sun were compressed into a space the size of Warsaw.

Radio astronomy offers a glimpse of the interior of these objects, as we can observe the radio signal emitted by magnetised, rotating neutron stars. These emit a beam of radio waves that sweeps past the Earth as the stars rotate, very much like a lighthouse. Careful timing of these signals reveals that occasionally there are 'jumps' in the rotation rate of the star, which are thought to be due to interior components of the star that are 'superfluid'. Superfluidity is well known from laboratory experiments with gasses such as helium, which, cooled close to absolute zero, can flow for long times without viscosity. The interior of the neutron star behaves like such a cold object and allows for complex flows that can give rise to glitches and oscillations of the star. This is extraordinary as a superfluid does not rotate as an ordinary fluid, but is rather a 'quantum' fluid, that rotates by forming an array of microscopic vortices that behave like quantum objects. Radio pulsar glitches are thus a large scale, macroscopic, consequence of small scale quantum behaviour.

We are also on the verge of a revolution in astronomy that will forever change our view of the sky and allow us to unlock the secrets hidden in neutron star interiors: we are about to witness the birth of gravitational wave astronomy.

Gravitational waves are a prediction of Einstein's theory of General Relativity, which states that violent astrophysical events, involving extreme objects such as black holes and neutron stars, will produce ripples, 'waves' in fabric of space time that could propagate to us and cause the distance between objects to oscillate. The effect on Earth is, however tiny: a standard gravitational wave would lead to the distance between two objects several kilometres apart changing by much less the the diameter of a nucleus. It is thus not surprising that gravitational waves have never been directly detected.

A massive engineering feat has, however, been performed in the last 20 years, which has resulted in us now having, for the first time in history, the technology to directly detect gravitational waves.

Three large scale detectors have been built, two in the United States, known as Advanced LIGO, and one in Italy, Virgo. These are interferometers, devices that shoot laser light down two arms several kilometres long, reflecting it on a mirror and measuring how long it takes to come back. If a gravitational wave passes through the instrument it will deform each arm differently, and lead to a difference in the time the two laser beams take to complete their paths. In practice several sources of noise, from thermal fluctuations, to seismic noise due to traffic close to the laboratory, will be much stronger than the signal and mask it. It is thus necessary to work in a vacuum, with huge suspensions and very carefully crafted materials and lasers.

The Advanced LIGO and Virgo team, of which the Polish POLGRAW consortium is an important part, will begin observations in September 2015 and will bring about a revolution in our understanding of the universe unlike any that has taken place since the first telescope was pointed to the sky.

Neutron stars are one of the main targets for these detectors, however the signals will be very weak and theoretical models are needed to help extract the data from the noisy output of the detector, in very much the same way that we can understand what a person is saying in a very noisy background if we can see subtitles.

This project will undertake cutting edge theoretical work to perform three-dimensional computer simulations of superfluid neutron stars, and produce models that will aid gravitational wave detection and help make use of radio and X-ray data to understand fundamental physics in extreme conditions.

This project will develop a computational framework to connect three different tools: a 3 dimensional superfluid hydrodynamics code, based on the established astrophysics code LORENE, to study the star on large scales and model the expected signals, a 3 dimensional heat transport code to model heating and its feedback on fluid motion, and a 3 dimensional vortex filament code, that models the complex dynamics of superfluid 'vortices' on microscopic scales. All this will be done using the state of the art nuclear physics models for neutron star interiors developed at the Nicolaus Copernicus Astronomical Centre in Warsaw.

We will use our models to study radio pulsar glitches, gravitational waves, and fluid oscillations of the star. This is particularly interesting, as detecting and interpreting a gravitational wave signal from a neutron star oscillation (i.e. detecting waves in the fluid interior) would allow us to probe the structure of the star with great detail, as is routinely done with our sun, in the same way as the motion of waves on the surface of a lake or sea can be used to deduce the presence and size of sunken obstacles.

This work will thus contribute materially to the success of huge and revolutionary project that involves more than a thousand scientist in Poland and all over the world, and that will herald a new and exciting age for astronomy and physics.