7. Public Summary

The Van Swinderen Institute for Particle Physics and Gravity (VSI) is an institute of the Faculty of Science and Engineering (FSE) of the University of Groningen (UG) that was formed in 2014. Its primary focus is on fundamental research in particle physics and gravity. In an interactive and collaborative atmosphere, the VSI scientists work towards an understanding of Nature at the smallest and the largest distance scales and how this is all connected. They study the fundamental forces of Nature, the building blocks of matter and their symmetries, and how these are related to the Universe as a whole. Modern research has shown close connections between the physics at the smallest distance scales (from sub-atomic scales down to the Planck-scale of quantum gravity) and cosmic distances. The goal is to gain a deeper understanding of the foundations of the Universe by searching for new physics beyond the Standard Models of particle physics and cosmology. Research at VSI on these topics is organised along three research lines or frontiers: the Cosmic Frontier, the High Energy frontier, and the Precision Frontier, which each have specific opportunities and objectives, but also have many connections to each other. In the Cosmic Frontier, the objective is to understand the physics of the early universe, its inflationary period and the imprint this has made in the Cosmic Microwave Background and in the Gravitational Wave spectrum. This is tied to astrophysical studies with satellites and earth-based telescopes. The High Energy Frontier is concerned with elementary particle physics and high-energy collider experiments, all aimed at improving our understanding of the Standard Model of elementary particles and to find out what lies beyond it at even smaller distances scales or, equivalently, at even higher energies. The Precision Frontier focuses on table top precision experiments with the aim to advance our knowledge of particle physics by performing low energy, extremely high precision experiments using cold atoms and molecules. Its objective is closely related to that of the HEF, in particular regarding theoretical studies. All this research is curiosity-driven and is carried out through close collaboration between theory and experiment in all three frontiers. There is also collaboration with astronomers and mathematicians at FSE in the context of the research theme the “Fundamentals of the Universe”.

VSI has an active and stimulating research environment formed by 14 scientific staff members, 3 honorary/special appointment professors, on average 35 PhD candidates and 5 to 8 postdoctoral researchers. VSI is a university partner of Nikhef, the Dutch National Institute for Subatomic Physics, which is a partnership between funding agency NWO and six Dutch universities. Through Nikhef, VSI participates in the LHCb experiment at CERN, and the main local experiment of the NL-eEDM collaboration, situated on the Zernike campus in Groningen, is an integral part of the Nikhef research portfolio. Besides the local and CERN-based experiments, VSI staff members also take part in collaborations of astrophysical observatories (both earth based detectors and satellites). VSI’s strong connection to long-term experiments ensures the viability of the research lines. Funding agency NWO is the main source of external funding of VSI. During the evaluation period, VSI staff members collectively acquired over 12 million euros in external research funding, which is a testimony to the quality and viability of the research.

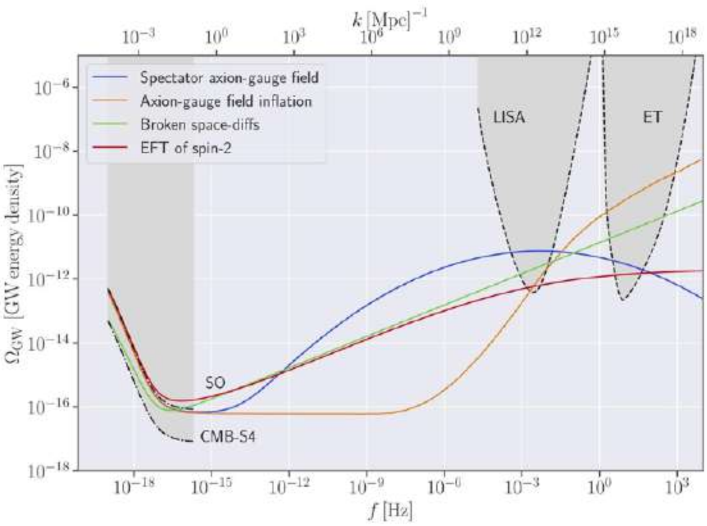
Scientists at VSI are all very dedicated to teaching in the Bachelor’s and Master’s Physics programmes of the Faculty, most notably the Particle Physics BSc track and the Quantum Universe MSc track. They also supervise a large share of the BSc and MSc students each year. Several VSI staff members have been elected or nominated “Teacher of the Year” and several hold key positions in the Faculty’s education management. VSI staff members are also very actively and enthusiastically engaging in outreach activities, especially the ones aimed at children and prospective students. Also, VSI aims to have a positive impact on society by providing the job market with highly skilled graduates with versatile transferable skills. VSI alumni have high employability and end up in a variety of jobs, especially jobs with a demand for computing skills tied to a high level of mathematical and analytical skills. Last but not least, open science and open access publications are the standard for VSI’s research. In all these ways VSI strives to contribute to society.

CASE STUDY 1
Multi-messenger Approach to the Primordial Universe

Our understanding of the composition and history of the Universe has made giant leaps in recent decades, resulting in a detailed understanding of the 13.8 billion years since its origin. However, the Big Bang itself poses an unanswered question: how did the Universe come into existence? Our best hypothesis for this phase is referred to as cosmic inflation. In order to test this phase, scientists are scouring the current Universe for evidence.

In this quest, members of VSI are focusing on two different observational probes of the early Universe: the cosmic microwave background (CMB) and primordial gravitational waves (GW). The CMB dates from an important transition only hundreds of thousands of years after the Big Bang. Prior to this transition, the Universe was opaque to light, and hence one must move from electromagnetic radiation to the much feebler primordial GW that have not yet been detected.

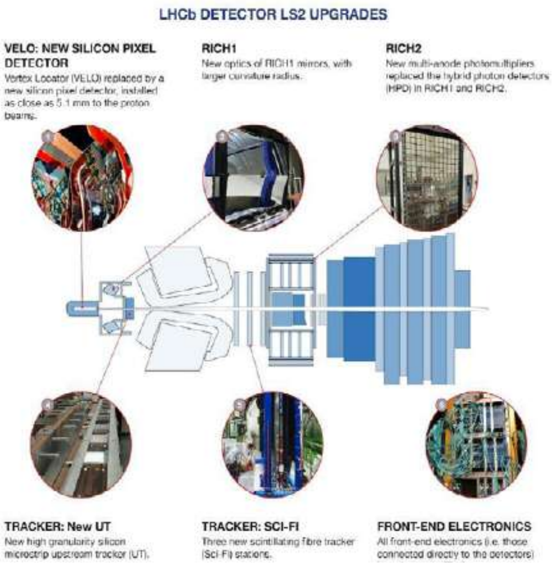
VSI has several experts on this topic. Daan Meerburg has made important contributions to the state-of-the-art constraints from CMB data, on the interactions during inflation, so-called primordial non-Gaussianities. As scientific leader of the first search for correlated features in the primordial power spectrum and bispectrum, he played a key role in the Planck satellite collaboration. Similarly, Emanuela Dimastrogiovanni is a leading member of the cosmology working group of the Laser Interferometer Space Antenna (LISA) consortium and of the cosmology division of the Einstein Telescope (ET). These are new generations of gravitational wave detectors, whose prime targets include GW from the primordial Universe. These new observational tools guarantee a vibrant field of investigation for decades to come.



A key strength of the Cosmic Frontier of VSI lies in the combination of CMB and GW expertise. This allows for a multi-messenger approach to the primordial Universe, exploiting data from both probes to provide much stronger constraints, as outlined by Dimastrogiovanni. This approach has since become a very active area of research in the GW community. A demonstration of this fruitful collaboration within VSI is the forecast to constrain the inflationary particle content, highlighting the complementary nature of the CMB and direct GW detectors in the search for new physics. This work, benefitting from both theoretical modelling and data analysis techniques, shows that a joint analysis has the potential to discover unique signatures that are otherwise inaccessible. This is nicely illustrated in the figure that shows the stochastic GW backgrounds as predicted from various inflationary models and the constraints present and future detectors (Simons Observatory, CMB-S4, LISA and ET) will be able to put on the models.

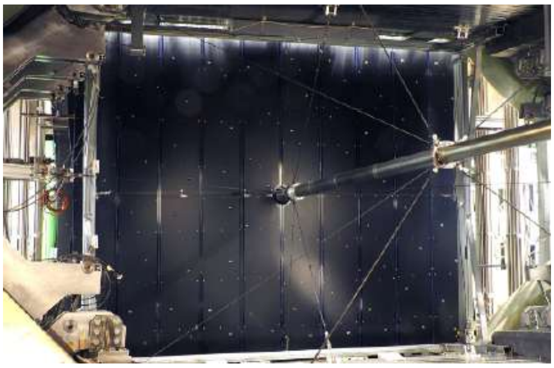
CASE STUDY 2
LHCb physics motivated upgrade and long term programme

"Cracking" the Standard Model (SM) of elementary particles must be a top priority on our way to understanding unexplained phenomena as the matter-antimatter asymmetry and neutrino masses, its relation with gravity, the nature of dark matter and dark energy, etc. The Large Hadron Collider beauty (LHCb) experiment, a state-of-the-art particle physics detector located at CERN (Geneva), is set to achieve this ambitious goal attacking the issues of matter-antimatter asymmetry and its apparent link with the existence of 3 "copies" (*flavours*) of each type of elementary particle we know (quarks and leptons).



Finding differences in the decay paths of rare particles containing a *beauty* quark into the three different lepton flavours would open a crack in the SM, which predicts instead *Lepton Flavour Universality (LFU)*. LHCb results showed puzzling discrepancies with SM predictions, which need to be explored further. To this end LHCb has just completed an ambitious upgrade, including state-of-the-art electronics, tracking and particle identification. All detectors and electronics have been installed and brought into operation in 2022 and will start taking physics data in 2023. The VSI group has played a prominent role in major parts of this upgrade: the VELO pixel, the Sci-Fi tracker and the Front-End electronics.

We are looking forward to new data with the upgraded detector to find deviations from LFU studying decays like $B \to l^+l^-$, $B \to K\, l^+l^-$ and $\Lambda_b \to \Lambda\, l^+l^-$ ($l=e,\mu,\tau$) with unprecedented precision and even measuring previously inaccessible decays like $B_c \to \tau\nu$, a measurement only possible at LHCb thanks to the new VELO pixel detector and in which VSI has a leading role.



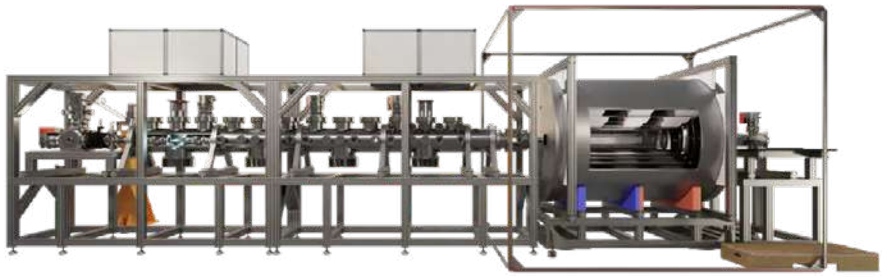
Pictures: (left) Front view of SciFi tracker once installation was completed in spring 2022 and its position carefully adjusted as close as possible (2mm) to the beam pipe. (right) Proposed 13 years ago, the VELO pixel detector installation marks a crucial milestone. The detector is movable and will come closer to the LHC beam than ever before.

The LHC is the ultimate tool for measuring extremely rare phenomena, with proton beams colliding 40 million times per second and with such intensity that, in every collision, hundreds of simultaneous interactions take place, but exploiting it fully requires detection and analysis techniques to disentangle more individual interactions per event than at present. While exciting physics can be done with the current upgraded LHCb detector, we therefore keep pushing for better detection systems and analysis tools and more exciting measurements. This continuous endeavour is vital for a successful research programme.

Concretely, the LHCb trackers will be upgraded to provide "*4D tracking*", i.e. to add to their already stunning position resolution very precise timing information, down to 30-40 trillionths of a second. The VSI team will be at the forefront of this challenge, in the upgrade of the silicon pixels. Funding for the *FASTER* project has been secured in 2022 and a PhD candidate has just been hired.

CASE STUDY 3
The NL-eEDM Collaboration of the Precision Frontier

This line of research in the precision frontier requires a joint effort of theory and experiment, via extremely precise measurements on atoms and molecules. We focus on testing fundamental symmetries and their breaking in particle physics at low energy, specifically the violations of parity, time-reversal invariance, baryon-number conservation, and Lorentz invariance. One current focus is the search for the electric dipole moment of the electron (eEDM). No permanent electric dipole moment of an elementary particle has ever been observed, but its discovery would have a high impact in particle physics. While the value of the eEDM predicted by the Standard Model of particle physics is far too small to be measured, extensions of the Standard Model have been proposed that predict a small but measurable eEDM.



The eEDM is accessible through precision measurements of the energy levels of molecules, specifically the diatomic molecule Barium monofluoride (BaF). We work on probing energy level shifts due to applied electric fields as sensitively as possible, which requires the development of new experimental techniques to cool and slow these molecules, to boost the sensitivity of our measurements. A key element in our approach to increase the eEDM sensitivity is the unique molecule decelerator that is designed, constructed and operated in the VSI labs. At 4,5 metres, it is the longest decelerator worldwide (visible in the figure above), capable of bringing beams of heavy molecules to rest. The quantum chemistry calculations at the highest level of theory by members of VSI supports the design and interpretation of these measurements. Furthermore, we study theoretically the impact of eEDM measurements on high-energy particle-physics observables. Teamwork is crucial in this programme. We have a long-standing collaboration between VSI and the VU in Amsterdam, and the local theory-experiment interaction is essential. Since 2023, also theory collaborators from the UvA have joined the team. Our team's approach has resulted in a number of significant contributions to the field, such as the first demonstration of the electrostatic deceleration of heavy molecules to a standstill and the most accurate calculation of the eEDM sensitivity of BaF molecules.

This programme has been able to attract significant funding. We started as a Nikhef research programme on the electron's EDM in 2016, kick-started with infrastructure from previous FOM programmes and a VIDI (Hoekstra). Soon after, we were awarded a 2.7 M€ FOM programme dedicated to the electron-EDM that ran from 2017 until 2023, with 7 PhD candidates. Borschevsky obtained an 800 k€ VIDI grant for method development and high accuracy calculations for fundamental research with atoms and molecules in 2019, and in 2022 we were able to secure a 2.7M€ NWO-XL programme, a 1.5 M€ VICI (Hoekstra) and a 700 k€ NWO-M2 grant (Borschevsky and Hoekstra). This research programme is a prime example of the power of team science. Through the synergy of these individual and consortium grants, our team can maintain the momentum to bring these low-energy table-top particle physics experiments to world-leading sensitivity.

CASE STUDY 4
Educating the scientists of the future

The VSI has always regarded outreach, in particular to the younger generations, as a crucial element in the societal part of its scientific mission. We feel that this is important both to foster the researchers of the future and to provide a realistic, bias-free view on science in general. VSI scientists have therefore often featured and taken the initiative in a multitude of outreach activities. These range from global and online, such as the recurring online events aimed at highschool students across the world, as well as local and onsite, such as Zpannend Zernike, the annual science festival on the Zernike campus in which VSI always actively participates, with demonstrations in the VSI labs, each year visited by hundreds of people, mostly families with kids.

Another important local venue is Noorderzon, the annual performance arts festival of Groningen, where a section is dedicated to scientific outreach activities, aimed at either all ages or specifically children. VSI researchers have played a leading role in many instances here. For example, Roest has led an "Einstein in a Wheelbarrow" experience in 2019, where hundreds of young visitors experienced the equivalence principle between acceleration and gravity (on which General Relativity is based) by being blindfolded and asked to tell the difference between the two.

An especially stimulating event happened while the Royal family was visiting Groningen on King's Day in 2019. As part of the *Kennis is Koning* science fair, VSI researchers hosted a 4m wide trampoline that emulated the fabric of space-time. On this single day, thousands of children simulated the solar system by throwing in marbles of different sizes, and finding out about attraction through curvature and the nature of gravity. Hoekstra and PhD candidates offered a host of demonstrations about supercon-ductivity, lasers and other appealing topics.

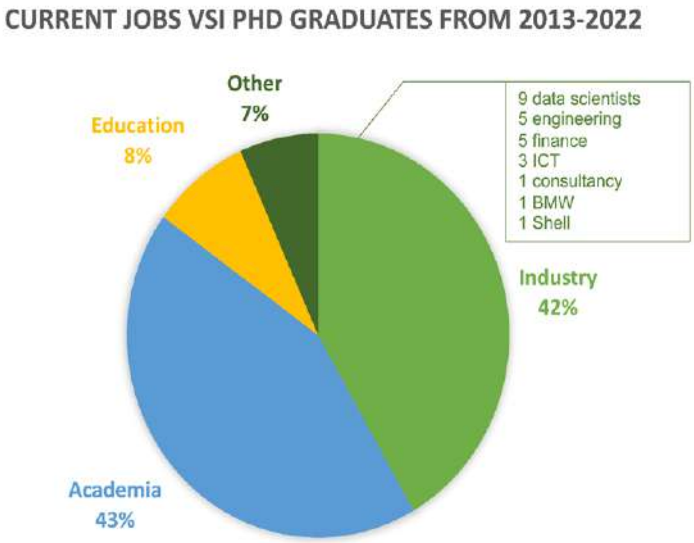
VSI researchers have also actively collaborated to reach the younger minds while they are at schools. Roest, together with UG researchers from other fields and with support from the UG Scholierenacademie, has created a Massive Open Online Course aimed at primary school classes, consisting of a number of videos and assignments on the role of the solar system in everyday life. Starting in 2016, this has been a massive success for a number of years now, and has been watched by more than 20.000 children.

In the same spirit, Bergshoeff and Pallante, together with two other researchers, have discussed their thoughts on their favourite equations - Newton's gravity law and the Dirac equation - with talented poets, who have composed a poem on this basis. With a beautiful design, these posters (see the picture for one example) have been distributed to 200 schools in the north of the Netherlands in 2019. This was part of the project *Poetry = mc^2* led by Roest and financially supported by the Young Academy Groningen and VSI.

CASE STUDY 5
Training highly skilled people with versatile transferable skills

VSI, together with the Kapteyn Astronomical Institute, forms the main driving force behind the successful Quantum Universe (QU) Master track, which started in the academic year 2013-2014. Soon after the start, its intake grew to a stable 35-40 master students per year. It is a unique Master programme that aims to provide students with the essential skills and tools to perform research at the interface of physics, astronomy, mathematics and cosmology. The programme offers courses in theoretical and experimental techniques and is aimed at directly connecting the educational programme with current research. Every year, the programme is reviewed and adjusted to improve courses and to incorporate new developments in the field, such as the recent addition of a course on Gravitational Waves. In this way, we prepare the students for a wide variety of research topics that they can pursue in their Master research projects, and possibly later in a PhD project. To further arouse the interests of young researchers and to connect education and research, a successful yearly series of Quantum Universe (QU) workshops has been launched.

Although all this is primarily aimed at training students for research, their acquired analytical, mathematical, computational and experimental skills are highly sought after outside academia. The students have highly advanced skills that can be applied in research for companies, in finance and in recent years increasingly in data science. As an illustration of this point, we list in which sectors the PhD graduates/alumni of VSI are currently working (our Master students and postdocs also often land good jobs in the same sectors). From the 60 people who obtained their PhD degrees in the 10-year period 2013-2022, 26 are still in academic research positions (from postdoc positions to academic staff members), 25 are working in industry (see pie chart for details), 5 in education (high school teachers or educational support staff) and 4 elsewhere/unknown.



The expectation is that the number of data scientists will grow in the coming years. The increasing demand for data scientists is the main reason why we hired an assistant professor with an education profile with a background in computational physics, who will start in October 2023. Specifically, the goal is to better cover machine learning and neural network aspects in the physics curriculum. This will be beneficial for the students who will remain in academia, but equally so for those who move to industry. In this way, we ensure that we keep on delivering highly trained people with versatile transferable skills suitable for the current job market.

CASE STUDY 6
VSI's open science

Our field of particle physics and gravity has been a trailblazer of open science. The first free scientific online archive was arXiv.org, which started in August 1991. Initially it was a physics archive, but it expanded to include astronomy, mathematics, computer science, quantitative biology and statistics. Posting preprints on this archive quickly became common practice in the field, as illustrated by this preprint by Bergshoeff & De Roo that was posted in December 1991. Another example from our field is the Journal of High Energy Physics, a monthly peer-reviewed scientific journal, founded in 1997 as one of the first open access (OA) journals. In our field, open access of research papers has thus been a long standing practice. 98% of the publications by VSI members in the period 2017-2022 are published green OA (the articles are available in a repository and in almost all cases the published version is OA) and 72% is published in fully or partly OA journals (gold and hybrid OA).

In case of hybrid journals, article publication charges (APCs) are often covered by the Sponsoring Consortium for Open Access Publishing in Particle Physics (SCOAP³), the world's largest disciplinary open access initiative which was established in 2014 and in 2022 has reached the milestone of over 50'000 research articles published. It is a partnership of over 3,000 libraries, funding agencies, and research organisations from 44 countries and 3 intergovernmental organisations, hosted at the European Organization for Nuclear Research (CERN). It has an agreement with 11 leading journals which cover the vast majority of research articles in the discipline.

All publications using CERN data are required to be open access as part of the CERN policy. Also, CERN collaborations strive to make their data available, allowing for citizen science. In 2022, the LHCb Collaboration has released the first 200 terabytes of the data via the CERN OpenData Portal, making it available to the public.

Computer codes of VSI members are increasingly being shared through public repositories, like github, as well. For example, VSI PhD graduate Florent Scarpa (supervisor D. Boer) has put his codes in a github repository (see picture) and VSI PhD graduate Elwin Dijk (supervisors K. Jungmann and L. Willmann) made his codes available on the RUG page of his PhD thesis.

As none of the research of VSI is of a sensitive nature, the aim is to share it openly. The advanced technical nature of the research does make it challenging to do this according to the FAIR (Findability, Accessibility, Interoperability, and Reusability) principle, but we ourselves also benefit from it, for instance when a PhD candidate wants to continue a certain line of research of a previous VSI member who however has left academia and is not available for a transfer of files and for explaining them. In this way, we ourselves also benefit from public codes and shared research data.