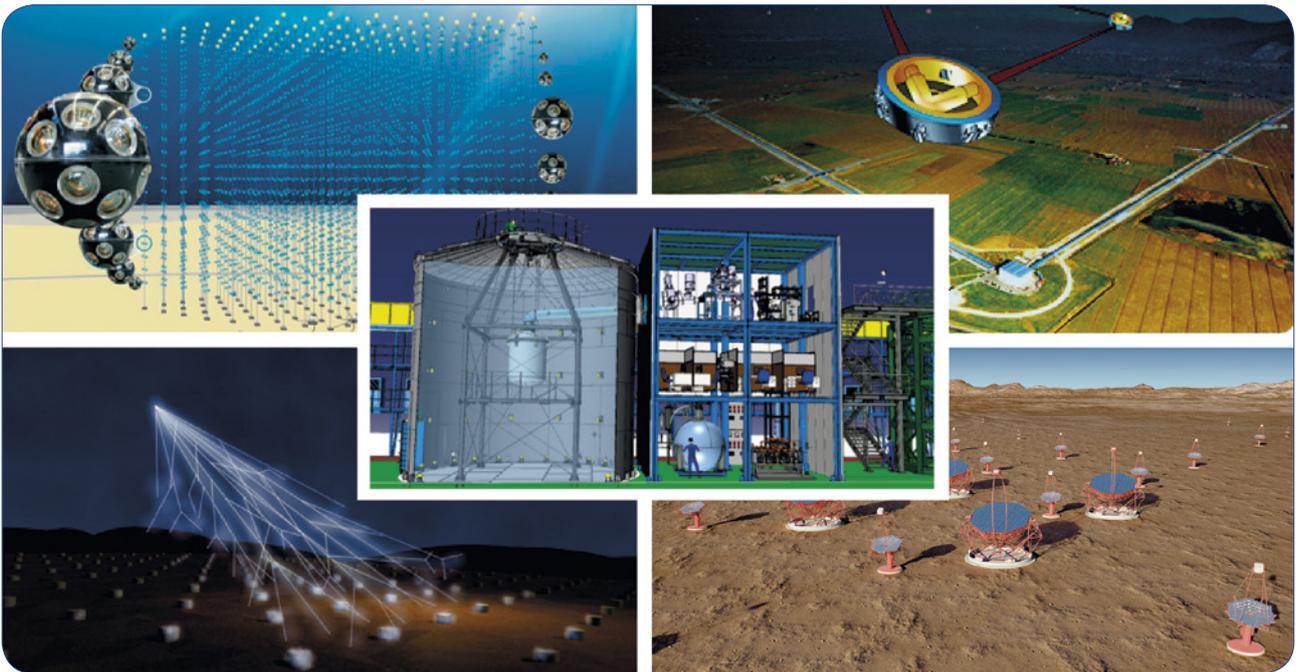


# Strategic plan for Astroparticle Physics in the Netherlands

# 2014-2024



# Strategic Plan for Astroparticle Physics in the Netherlands 2014–2024



Committee for Astroparticle Physics in the Netherlands (CAN)  
March 2014

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## Executive Summary

Astroparticle Physics is an interdisciplinary field at the interface of Physics, Astronomy, and Cosmology. For ages, there has been a strong cross-fertilization between these fields, but at the core of Astroparticle Physics are questions regarding the limits of our current understanding of the fundamental laws of nature. These questions concern the nature of the biggest matter component in the Universe (dark matter), the nature of the biggest energy component in the Universe (dark energy), the origin of the highest energy particles in the Universe (cosmic rays), and the nature of space-time and its dynamics.

We are currently on the verge of answering these major questions within the period covered by this Strategic Plan for Astroparticle Physics in the Netherlands. And with a growing community of astroparticle physicists in the Netherlands, we are well positioned to play an important role in the essential, big, infra-structural projects that will answer these outstanding questions. With some confidence we can say that these projects will bring us the first detection of gravitational waves, the first detection of dark matter in the laboratory, if indeed super-symmetry is the correct description of particles in nature. Concerning the origin of the highest energy cosmic rays several experiments are tackling this problem using various messengers that carry information from the location of origin to Earth: on the one hand the energetic particles themselves, where composition measurements at the highest energies, and the direction from which they are coming, provide complementary information on the origin and acceleration mechanisms for these particles, on the other hand we have the signals coming from interactions of the highest energy particles with matter located near the sites of acceleration: very high energy neutrinos and gamma-rays. Together, these multiple messengers will point out the sites of the origin of the highest-energy cosmic rays.

The Netherlands are in an ideal position to participate in these Astroparticle Physics quests. The reasons are: the Dutch research infrastructure and excellence in particle physics, with a world class institute like Nikhef, and a world-wide recognized excellence in astronomy, with the Netherlands being united in the NOVA research school for astronomy. In addition, Dutch theoretical physics is at a high level participating with experts in quantum gravity and super-symmetry theory.

The active Astroparticle Physics community has sprung from this group of researchers, and is organized in the Committee for Astroparticle Physics in the Netherlands (CAN). The CAN represent more than 40 senior staff and faculty members, working at the universities of Amsterdam (UvA and VU), Groningen (RUG), Leiden (UL), and Nijmegen (RUN) as well as at the national research centres ASTRON, Nikhef, and SRON. The CAN was responsible for the first roadmap (2005), which formed the national community, and which was also influential in setting up centres of excellence/teaching programs in Astroparticle Physics, such as GRAPPA (UvA/Nikhef), IMAPP (RUN), and the Quantum Universe (RUG), which also lead to new faculty hires in the fields of Astroparticle Physics. This growing involvement

of the Netherlands in Astroparticle Physics has resulted in a high Dutch international visibility in this field, and resulted in participation in leading international experiments in Astroparticle Physics, in some cases in a leading role.

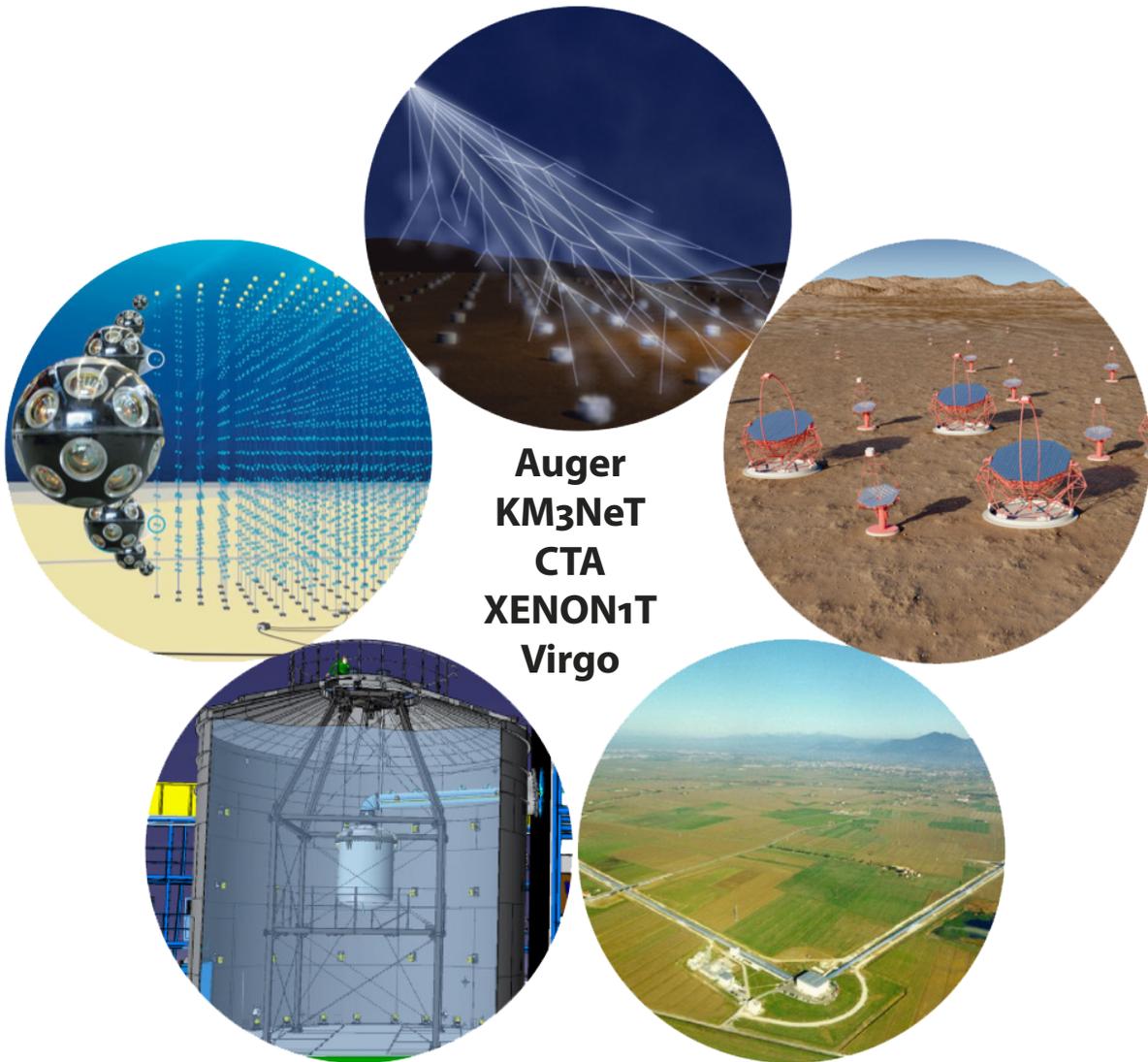
In this roadmap we express the CAN's strategy for Astroparticle Physics in the coming decade. This strategy consists in consolidating some projects that have been initiated as a result of the previous road map, such as **continuing support** for the **Pierre Auger Observatory** for cosmic rays, the European gravitational wave detector **Virgo**, and a major involvement in the **KM<sub>3</sub>NeT** neutrino detector in the Mediterranean Sea, for which the Netherlands host now the organisational centre. The Pierre Auger Observatory has already delivered first-class results, by proving that the highest energy cosmic-rays are not coming from uniformly over the sky. Continuing observations should establish whether they point at well known astrophysical sources and what types (of nuclei) these particles are. KM<sub>3</sub>NeT is preparing the construction, the US-led experiment IceCube has recently proven the importance of neutrino detections, by detecting the first very high energy neutrinos that are of cosmic origin. This breakthrough is proof that neutrinos provide a new window on the Universe that is at the point of being explored.

On the other hand, we **support** major **future** experiments that have emerged during the last decade, and that have strong international support in the form of endorsements from European Astroparticle Physics roadmaps<sup>1</sup>. These are the **Cherenkov Telescope Array (CTA)**, a new very high energy gamma-ray telescope array that will improve the sensitivity of the current telescope arrays by a factor ten, and **XENON1T**, a direct dark matter detection experiment. CTA will be essential to pin point the sources that are accelerating particles to very high energies, both in the Galaxy and in the nearby Universe. For Galactic sources it will provide accurate images of the sources, directly pin-pointing where the particles are accelerated, and by measuring energy spectra also establishing the maximum energies particles can be accelerated to. In addition it will function as a sensitive telescope to search for indirect signatures of dark matter. XENON1T is the successor of the currently most sensitive dark matter experiment XENON100, XENON1T will be ten times more sensitive.

There are interesting synergies between the various research facilities mentioned (Auger, KM<sub>3</sub>NeT, Virgo, CTA, XENON): The sources of cosmic rays, gamma rays, neutrinos, and gravitational waves are expected to be the same energetic astrophysical objects. The direct search for dark-matter particles with dedicated detectors will be complemented through indirect searches with gamma-ray telescopes.

Apart from participating in the internationally established infra-structural projects mentioned above, it is important to realize that Astroparticle Physics also has an important theoretical basis, to which Dutch scientist contribute. On the physics side,

<sup>1</sup> <http://www.aspera-eu.org/images/stories/files/Roadmap.pdf>



**Auger**  
**KM3NeT**  
**CTA**  
**XENON1T**  
**Virgo**

this consists of theoretical physicists working on fundamental theories of nature, whereas on the astrophysical side this includes scientist working on understanding particle acceleration and propagation, and on accretion physics and relativistic outflows, which provide the power for particle acceleration.

To realize the potential and ambitions of Astroparticle Physics, as detailed in the current roadmap, the budget for Astroparticle Physics is required to be of the order of ten to twelve million Euro per annum. More than half of this amount is to cover the salary costs of faculty/staff members of the research institutes as well as PhD students and postdoctoral scientists. A large fraction is for participation in research facilities. This fraction will increase somewhat as new research facilities enter the construction phase.

The participation in research facilities invariable means that the Netherlands are involved in new technical developments, needed to stay on the forefront in science. As a result, participation in international infrastructure not only means scientific

access to the forefront facilities, but also that the Netherlands are involved in high-tech innovations necessary for state-of-the-art research facilities.

The resources necessary for maintaining an internationally competitive Astroparticle Physics community in the Netherlands, is partially provided by the participating research institutions, as well as national and European funding bodies (including NWO, FOM, NOVA, ERC). Since Astroparticle Physics falls in between the NWO divisions of physics on the one hand, and physical sciences on the other hand, we recommend **to establish a long-term, structural, dedicated, interdisciplinary funding line for Astroparticle Physics in the Netherlands.**

## 1 Introduction

A new interdisciplinary research domain has emerged at the interface of physics, astronomy, and cosmology. This field of research, which is known as “Astroparticle Physics”, is addressing issues that may revolutionize our scientific and philosophical views on the Universe.

A significant fraction of the energy content of the high-energy Universe is made up by relativistic particles, such as ionized atomic nuclei, neutrinos, or gamma rays. These cosmic-ray particles have energies which exceed the energies available at human-made accelerators, such the Large Hadron Collider (LHC) by factors of thousands. Presumably, the origins of the different particle types are closely related to each other. Understanding the origin of cosmic rays and their role in the Universe is an important aspect of Astroparticle Physics.

Furthermore, Astroparticle Physics deals with fundamental questions to understand the Universe, such as dynamics of space time and the detection of gravitational waves. The properties of elementary particles are well described by the standard model of particle physics. However, there are experimental hints for physics beyond the standard model. A key role play the properties of neutrinos. Astroparticle Physics opens a unique opportunity to address this issue through astrophysical observations, which are complementary to accelerator based investigations. While so far most scientific endeavours have addressed the nature of normal matter, of which stars, planets, and human beings are composed, one of the key subjects of Astroparticle Physics is the nature of unknown types of matter, which are labelled dark matter.

For the next decade (2014–2024) the Dutch groups involved in Astroparticle Physics are seeking for answers to the following scientific key questions:

- What is the origin of cosmic rays?
- Do we detect gravitational waves and what is the dynamics of space time?
- What is the nature of dark matter?
- What is the origin of the large-scale structure of the Universe?
- Is there physics beyond the standard model and what role do neutrinos play in it?



Figure 1. Participants attending a session on Astroparticle Physics, organized by the CAN during the FOM Veldhoven annual meeting of Dutch Physics in 2014.

### Symposia on Astroparticle Physics in the Netherlands

The CAN is organizing regular symposia to strengthen the connections and synergies between the Dutch groups.

Meetings to date include

- APP1 — 26 April 2004, Amsterdam
- APP2 — 24 September 2004, Nijmegen
- APP3 — 21 January 2005, Leiden
- APP4 — 22 April 2005, Groningen
- APP5 — 14 October 2005, Utrecht
- APP6 — 3 February 2006, Amsterdam
- APP7 — 13 October 2006, Nijmegen
- APP8 — 8 February 2007, Dwingeloo
- APP9 — 12 October 2007, Groningen
- APP10 — 5 March 2008, Amsterdam
- APP11 — 20 March 2009, Leiden
- APP12 — 4 December 2009, Amsterdam
- APP13 — 19 March 2010, Nijmegen
- APP14 — 19 April 2011, Groningen
- APP15 — 3 November 2011, Leiden
- APP16 — 10–11 May 2012, Amsterdam
- APP17 — 30 May 2013, Nijmegen
- APP18 — 23 October 2013, Leiden
- APP19 — 27–28 March 2014, Beekbergen

The first three are in the focus of the present plan (Sections 2.1–2.3), the remaining two (Sections 2.4 and 2.5) are addressed in close collaboration with the astronomy and high-energy physics communities, which implies that resources are shared with those communities.

With the present document the CAN intends to give an overview on the present activities (year 2014) and to plan the activities for the next decade, building on the heritage of the 2005 strategic plan<sup>[2]</sup>. Objective of the present document is to continue a strong research program on Astroparticle Physics in the Netherlands.

### National organization

The interest of the Dutch groups in the field of Astroparticle Physics is represented by the *Committee for Astroparticle Physics in the Netherlands (CAN)*, which has been established in 2004. It comprises members, representing the different sub-fields and the institutions involved in Astroparticle Physics in the Netherlands. Objective of the committee is to strengthen and further develop the field of Astroparticle Physics in the Netherlands in research and teaching. The CAN has regular meetings, typically at least twice a year. The CAN is organizing regular symposia for the Dutch Astroparticle Physics community since 2004. In March 2014 we will already have the 19<sup>th</sup> *Symposium on Astroparticle Physics in the Netherlands*. These symposia are typically attended by 50 to 100 people, indicating the strong interest in Astroparticle Physics in the Netherlands.

Astroparticle Physics is an interdisciplinary field at the interface of Physics, Astronomy, and Cosmology. In the Dutch scientific landscape the present strategic plan on Astroparticle Physics

<sup>2</sup> Strategic Plan for Astroparticle Physics in the Netherlands, The Committee for Astroparticle Physics in the Netherlands (CAN) <http://www.astroparticlephysics.nl/> (2005)

has common borders with the Dutch high-energy physics strategic plan<sup>[3]</sup> and the astronomy strategic plan<sup>[4]</sup>. Due to the interdisciplinary character of Astroparticle Physics, both documents also contain chapters on Astroparticle Physics, which are aligned with the present document. This underlines the strong connections between the scientific communities.

### International embedding

Also internationally, Astroparticle Physics represents an important growth area in fundamental research. Many leading European countries have already allocated substantial budgets to this interdisciplinary research field. ASPERA<sup>[5]</sup> has prepared a roadmap for Astroparticle Physics in Europe.

The present document is well congruent with the European strategy as outlined by ASPERA. The ASPERA roadmap mentions seven types of projects of strategic relevance, the “Magnificent Seven”. The Dutch community focuses on five of them, namely:

- Cosmic rays: A large next-generation array for the detection of charged cosmic rays, a follow-up on the Pierre Auger Observatory.
- Gamma rays: A large array of Cherenkov Telescopes for detection of cosmic high-energy gamma-rays (CTA).
- High energy neutrinos: A cubic kilometer-scale neutrino telescope in the Mediterranean Sea (KM<sub>3</sub>NeT).
- Dark matter search: Ton-scale detectors that probe a large part of the favoured parameter space of Minimal Supersymmetric Models (*i.e.* reach a sensitivity range of  $10^{-47}$  cm<sup>2</sup> for the spin-independent cross section).
- Gravitational waves: A third-generation underground gravitational antenna (Einstein Telescope).

ESFRI, the European Strategy Forum on Research Infrastructures<sup>[6]</sup> has established a roadmap for large-scale infrastructure, which includes in the field of Astroparticle Physics CTA, KM<sub>3</sub>NeT, (and SKA).

## 2 Science questions for the next decade

For the next decade (2014–2024) Dutch researchers aim to answer the following scientific key questions in the field of Astroparticle Physics.

### 2.1 What is the origin of the highest energy particles in the Universe?

The Earth atmosphere is continuously being bombarded by highly energetic particles, called cosmic rays. Discovered in 1912 by Viktor Hess, we now know that cosmic rays can

comprise protons, atomic nuclei and electrons, among others. Which sources are responsible for these ultra-high energy particles is still a major scientific question, as well as how they are capable of accelerating particles to energies surpassing those achieved by CERN’s Large Hadron Collider by many orders of magnitude.

The energy spectrum of cosmic rays spans a wide range, from about  $10^6$  to beyond  $10^{20}$  eV (Fig. 2), and is well fit by a broken power-law distribution with a spectral index at lower energies  $\sim -2.7$ , steepening at higher energy to around  $-3.3$ . At energies below ( $\sim 10^{10}$  eV) the cosmic ray spectrum is modulated by the solar wind, which hinders lower energy particles to enter the solar system. At the highest energies there appears to be a steep decline in particle flux above  $6 \times 10^{19}$  eV. Such a cut-off was in fact predicted in 1966, from potential interactions of the highest energy cosmic rays with cosmic microwave background photons. A consequence of this effect is that the highest energy particles must originate from within a distance of  $\sim 100$  Mpc from the Sun. The cut-off at the highest energies could also be related to the maximum energies attained in the respective sources during the acceleration processes. Cosmic rays with energies below  $10^{17}$  to  $10^{18}$  eV are considered to be of Galactic origin, whereas particles of higher energies are assumed to have an extragalactic origin.

Over the last decades significant progress has been made in understanding particle acceleration in both Galactic and extragalactic sources. However, some key questions have remained unanswered for several decades:

- **Which extragalactic sources are responsible for the highest energy cosmic rays observed ( $\sim 10^{20}$  eV)?** In order to achieve very high energies, particles need to be contained within their sources for sufficiently long time to be continually accelerated. This requirement is fulfilled only if the magnetic gyroradius of the particle is smaller than the typical source sizes  $R$ , *i.e.*  $R < E/qB$ , with  $E$  the particle energy,  $q$  the charge of the particle and  $B$  the typical magnetic field strength in the astrophysical source. This is the so-called Hillas criterion<sup>[7]</sup>, which is illustrated in Fig. 3. The diagram indicates the main sources that might be the sources of the highest energy particles: active galactic nuclei (AGN), gamma-ray bursts (GRBs), the large-scale intergalactic medium (IGM), and, recently reconsidered, some subset of neutron stars. However, there is still lively debate over which of these sources are the most likely origin of extragalactic cosmic rays.
- **At which energy is the transition from cosmic rays of Galactic origin to extragalactic origin?** The strength of Galactic magnetic fields implies that particles with energies in excess of  $\sim 10^{17}$  eV have a gyroradius larger than the thickness of the Galactic disc and, thus, cannot be magnetically bound any more to the Galaxy. This is close to a feature in the cosmic-ray spectrum called the ‘Ankle’ (Fig. 2). Another feature is the so-called ‘Knee’ at  $4 \times 10^{15}$  eV. Both spectral features have at some time been associated with the transition between cosmic rays of Galactic and ex-

3 FOM Institute for Subatomic Physics, Strategic Plan 2011–2016, document FOM-11.0937.

4 Strategic Plan for Astronomy in the Netherlands 2011–2020, Netherlands Committee for Astronomy (NCA) on behalf of NOVA, SRON, ASTRON, and NWO-EW.

5 ASPERA is a network of national government agencies responsible for coordinating and funding national research efforts in Astroparticle Physics, <http://www.aspera-eu.org/>

6 <http://ec.europa.eu/research/infrastructures/>

7 A. Hillas, The Origin of Ultrahigh-Energy Cosmic Rays *Ann. Rev. Astron. Astrophys.* **22** (1984) 425–444.

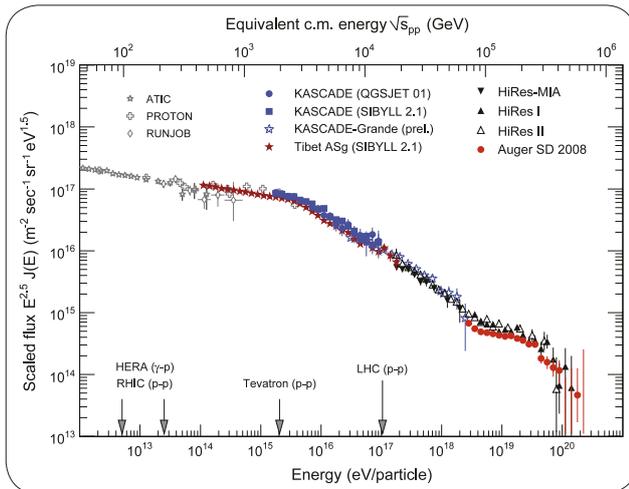


Figure 2. The energy spectrum of cosmic rays. From: J. Blümer, R. Engel, J. Hörandel Cosmic Rays from the Knee to the Highest Energies, *Prog. Part. Nucl. Phys.* 63 (2009) 293–338.

tragalactic origin. This question is intimately connected to the question of what are the dominant sources of Galactic cosmic rays. The leading hypothesis is that the dominant sources of Galactic cosmic rays are supernova remnant shocks. Indeed, over the last decade there has been growing observational evidence that supernova remnants can accelerate particles to above  $10^{13}$  eV. However, there is no evidence yet that particles can accelerate up to the ‘Knee’, let alone up to the ‘Ankle’. Several alternative sources for Galactic cosmic rays have therefore been proposed (e.g., OB stellar associations, pulsars, microquasars).

- **What is the origin of the recently discovered fractional positron increase above  $10^{10}$  eV?** Recently, space-based cosmic-ray detectors (PAMELA, AMS, Fermi) detected that above  $10^{10}$  eV the positron-electron ratio increases. This increase could be a result of local dark matter decay (Section 2.3). However, also nearby particle accelerators, like pulsar wind nebulae are considered. Given the interest for both cosmic-ray and dark-matter research, this is a question that needs to be solved in the near future.
- **What are the particle acceleration mechanisms?** Even identifying the sources of Galactic and extragalactic cosmic rays, leaves the question open of how these particles are being accelerated. Astrophysical particle acceleration is usually associated with some form of shock acceleration (the so-called Fermi-mechanism), and/or acceleration of particles in the presence of magnetic reconnection. These mechanisms have been invoked to explain acceleration in a wide variety of sources, from solar-flare to highly relativistic GRB shocks. Particle acceleration is a rich subject of active theoretical research, coupling the more macroscopic magnetohydrodynamics with more microscopic electrodynamics in ways that currently challenge the best computational and semi-analytical methods. Theoretical models of the various processes can be put to test with current and next generation radio through x-ray telescopes<sup>[8]</sup> and gamma-ray observatories.

8 They are summarized as “complementary signals” in the present document.

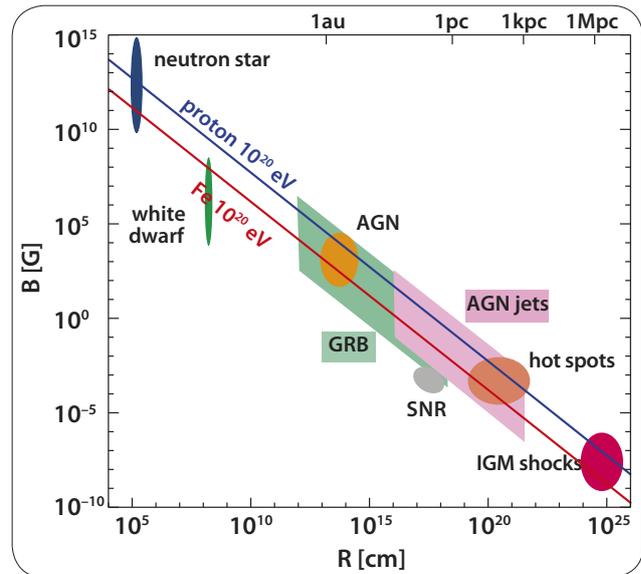


Figure 3. A graphical representation of the acceleration constraints in terms of source size  $R$  and magnetic field  $B$  that allows particles to be accelerated up to  $10^{20}$  eV. From: K. Kotera, A. V. Olinto, *The Astrophysics of Ultrahigh Energy Cosmic Rays* *Ann. Rev. Astron. Astrophys.* 49 (2011) 119–153.

The above questions are thus addressed both theoretically and by using several experiments with which we study cosmic rays directly or through the signals they produce. All the available signals together fall under the umbrella of so-called multi-messenger physics, which include cosmic-ray detections, electromagnetic signals, and neutrino detection.

The Netherlands are currently involved in the Pierre Auger Observatory, located in Argentina. This observatory investigates the energy, mass, and directional distribution of the highest energy cosmic-rays.

The electromagnetic signals associated with cosmic-ray acceleration span all electromagnetic energy bands, from radio to gamma-ray. However, most of the radiation is associated with accelerated electrons/positrons, but only in gamma-rays can one obtain electromagnetic signals from the energetically more important protons and atomic nuclei. This gamma-ray signal is caused by decay of secondary neutral pions, produced during hadronic collisions of accelerated particles with surrounding gas or photon fields. These gamma-rays are targeted by for example the Fermi satellite, which covers the  $10^8$ – $10^{10}$  eV band, and ground-based Cherenkov telescopes like H.E.S.S., which cover the highest energy gamma-rays ( $10^{11}$ – $10^{14}$  eV). The key upcoming facility for this field is the Cherenkov Telescope Array (CTA), which will be an order of magnitude more sensitive than H.E.S.S.

The cosmic-ray collisions close to the sources produce roughly equal numbers of charged pions that eventually decay into neutrinos and other particles. This means that cosmic-ray accelerators must also be sources of high energy neutrinos. Detecting high-energy neutrinos from a cosmic-ray source is an indisputable indication that hadronic particles are acceler-

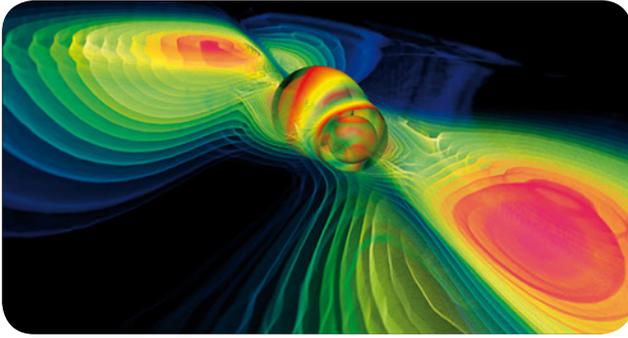


Figure 4. A numerical simulation showing the rich dynamics associated with the merger of two black holes. Detecting the gravitational wave signals will give us empirical access to the dynamical self-interaction of pure spacetime.

ated there. The detection of these neutrinos are the main objective of current and future neutrino telescopes, such as Antares, KM<sub>3</sub>NeT.

## 2.2 What is the nature of spacetime?

Even at the classical level, the genuinely strong-field dynamics of general relativity have never been explored empirically. This is a highly unsatisfactory situation: The most interesting aspect of any field theory is its dynamics, and this is especially true of a strongly non-linear theory such as general relativity. Moreover, string theory and other approaches to quantum gravity naturally lead to modifications of gravity, such as scalar-tensor models and gravitational parity violation. In the foreseeable future, the only way to gain reliable access to the strong-field dynamics of general relativity is by the direct detection of gravitational waves (GWs), ripples in the curvature of spacetime, caused by some of the most violent events in the Universe, such as colliding black holes and the Big Bang itself.

Astrophysical predictions for detection rates with upcoming ground-based detectors such as Advanced Virgo and LIGO range from a few to hundreds of binary neutron star mergers per year, with similar numbers for neutron star-black hole and binary black hole collisions. This will enable a census of black holes and neutron stars in binaries, yielding invaluable information on the evolution and fate of very massive stars. If at least one neutron star is involved in a merger then there will be an electromagnetic counterpart, enabling fruitful complementary observations; for example, a *single* GW observation can suffice to confirm or refute the current paradigm that short, hard gamma ray bursts are caused by colliding compact objects. GWs from merging binary neutron stars can also be used to strongly constrain the elusive neutron star equation of state, about which little is currently known. Finally, binary black hole mergers are exquisite laboratories for probing the strong-field dynamics of spacetime.

GW observations allow us to study the large-scale structure of spacetime. Inspiring binaries are self-calibrating cosmic distance markers, which will allow us to do cosmology without any need for a cosmic distance ladder. With only 15 sources observed by a network of Advanced Virgo/LIGO detectors, even without electromagnetic counterparts, the Hubble constant

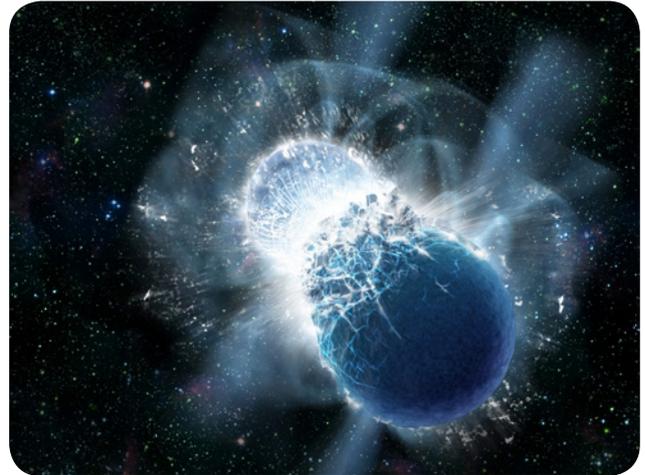


Figure 5. Collisions of two neutron stars are believed to cause short, hard gamma ray bursts, and they will be strong sources of gravitational waves. By studying the GW signals, we will be able to strongly constrain the behaviour of bulk nuclear matter. Merging compact binaries are also self-calibrating cosmic distance markers, enabling the independent study of the large-scale structure and evolution of the Universe.

could be measured with an accuracy rivalling that of existing techniques, but without being subject to the usual systematics. The future Einstein Telescope (ET), to be built around 2025, will be able to see binary black holes out to redshifts  $z > 10$ , with a detection rate of  $10^3$ – $10^6$  yr<sup>-1</sup>. The rich dynamics occurring in black hole binaries will be laid bare in exquisite detail. Again using inspiraling binaries as standard sirens for cosmology, we will be able to determine the equation of state of dark energy, including its time evolution, in a way that is completely independent from any other method.

Another exciting possibility is that a primordial GW background would be detected, possibly having originated just  $10^{-32}$  seconds after the Big Bang. The *existing* Virgo and LIGO data have already put stronger constraints on the parameter space of cosmic string networks than any other method. The Advanced Virgo/LIGO network will do the same for the string theory inspired Pre-Big-Bang model; see Fig. 6. At a frequency of  $\sim 10$  Hz, ET will be sensitive to gravitational wave energy densities that are four orders of magnitude smaller than with Advanced Virgo/LIGO.

Nikhef is a significant contributor to the construction of Advanced Virgo (an effort led by Van den Brand) and to the development of data analysis techniques for its scientific exploitation (Van Den Broeck); it is also an important player in the research and development efforts for Einstein Telescope. The GW group at Nijmegen (Groot, Nelemans) will be designing and building BlackGEM, a dedicated array of optical telescopes for electromagnetic follow-up of GW detections made by Advanced Virgo and LIGO.

Whereas ground-based detectors are sensitive from a few Hz to 10 kHz, space-borne interferometers, due to their much larger size, would probe much lower frequencies, between  $10^{-4}$  Hz and 1 Hz. Stellar mass objects in compact binaries will

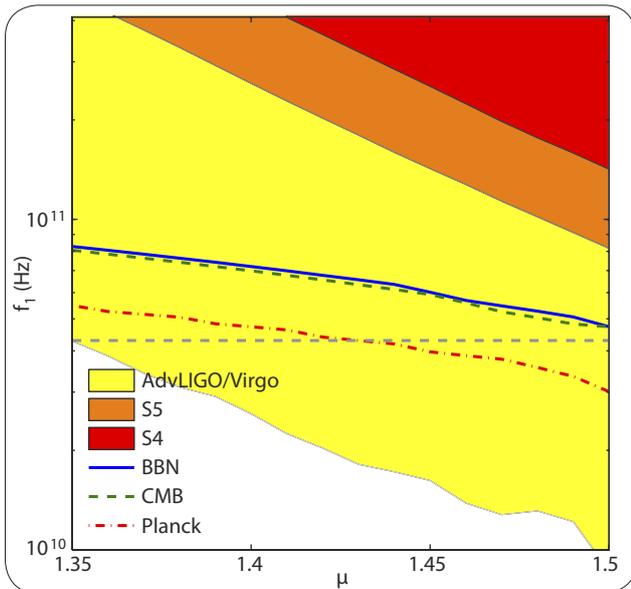


Figure 6. In the near future, Advanced Virgo/LIGO will put stronger constraints on the parameter space (characteristic frequency  $f_1$  and string tension  $\mu$ ) of the string theory inspired Pre-Big-Bang model than any other method—or confirm the model.

be detected in abundance throughout our own Milky Way, putting constraints on their evolution. Other prime sources are the mergers of super massive black holes in the centres of galaxies, which trace the merger history of galaxies and thus directly test the current concordance model for cosmological structure formation. Small compact objects falling into super massive black holes allow for precision tests of the celebrated ‘no hair theorem’. Dutch activities related to space-based GW detectors are led by the Nijmegen group.

Regarding super massive black holes we also note the Event Horizon Telescope, a very long baseline array of millimetre/sub-millimetre facilities to be constructed on a 2020 time scale. This will allow probing the event horizon of Sgr A\*, a likely super massive black hole in the centre of the Milky way containing some 4 million solar masses.

GWs with frequencies in the range  $10^{-9}$ – $10^{-5}$  Hz can be detected by monitoring radio pulses emitted by millisecond pulsars that are distributed over the sky. Likely sources are super-massive black hole binaries long before they merge, and primordial GWs from immediately after the end of inflation. Observing the latter would give us access to physics at energies well beyond collider scales, and might allow for direct tests of quantum gravity. Researchers at SRON/ASTRON/UvA (notably Hessels) currently have a strong involvement in the European Pulsar Timing Array and LOFAR, and in the future they will utilize the Square Kilometre Array of radio telescopes. In addition to pulsar timing, Dutch radio astronomers monitor tight binaries to perform precision tests of general relativity.

Thus, ground-based observatories, possible future space-based detectors, and pulsar timing arrays together will allow us to observe gravitational waves in an extremely wide range of frequencies, from  $10^{-9}$  Hz all the way to  $10^4$  Hz, enabling

optimal use of the gravitational wave spectrum for astrophysics, cosmology, and the fundamental physics of spacetime.

### 2.3 What is the nature of Dark Matter?

A large body of astrophysical and cosmological data points to the existence of dark matter—a substance that contributes about a quarter to the total energy balance of the Universe and has no detectable interaction with electromagnetic radiation (it is not seen or ‘dark’). The nature of dark matter is among the most intriguing questions of modern physics. If dark matter is made of particles, this particle is not part of the Standard Model of elementary particle physics. To be a viable dark matter candidate it must be stable or cosmologically long-lived, very weakly interacting with ordinary matter, produced in the early Universe in sufficient amounts, and consistent with existing astrophysical and cosmological bounds.

Natural candidates would be neutrinos. However, cosmological observations, such as galaxy rotation curves together with the measurements of anisotropies in the cosmic microwave background, rule out the possibility that a significant fraction of dark matter particles remained relativistic up to the matter-dominated epoch, *i.e.* are neutrinos.

The dark matter particle hypothesis necessarily implies an extension of the Standard Model and any solution of this puzzle will have a profound impact on particle physics. By constraining properties of dark matter particles one can differentiate among extensions of the Standard Model and learn about the fundamental properties of matter.

One of the most popular dark matter candidates are weakly interacting massive particles—WIMPs. These stable particles interact with Standard Model particles with roughly electroweak strength. The interest for these candidates is due to their potential relation to the electroweak symmetry breaking, which is being tested at the LHC. For example, supersymmetric models predict the existence of such massive particles that are subject only to the weak nuclear force. Transporting this possible solution of a subatomic puzzle to cosmology, WIMPs can account for the missing dark matter. To give a correct dark matter abundance, these particles should have a mass in the range  $10^9$  to  $10^{12}$  eV. WIMPs are searched for directly by their interactions with ordinary matter in dedicated so-called direct detection experiments. The Netherlands (Nikhef & GRAPPA/UvA) is participating in the XENON project. WIMPs can also be searched for indirectly through *e.g.* the search for gamma-rays from WIMP dark matter annihilations (as done in FERMI and in the future by CTA).

However, WIMPs are not the only possible dark matter candidates. Many particles were suggested in attempts to combine an explanation for the mystery of dark matter with other profound problems of particle physics, with their masses ranging from micro-eV to  $10^{22}$  eV. For example, an attempt to provide a solution of the so-called ‘strong CP problem’ leads to a prediction of axions—an example of a bosonic dark matter particle.

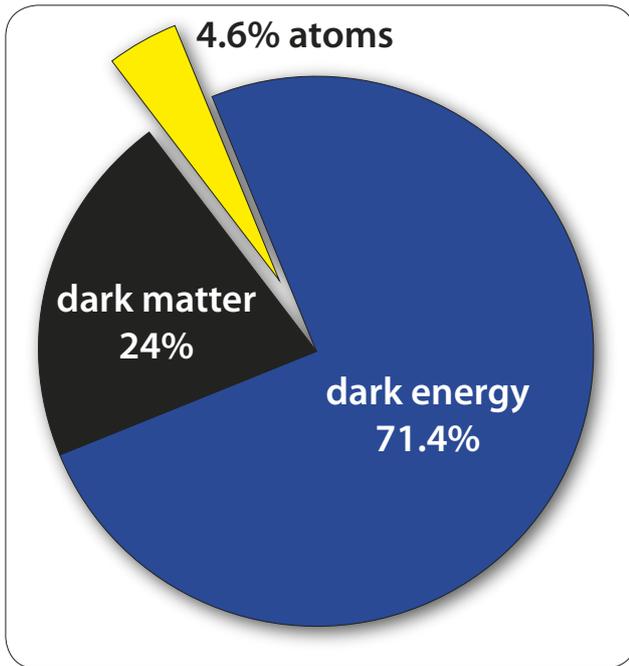


Figure 7. Content of the Universe.

Another model extends the neutrino sector to provide a dark matter candidate. If one adds three right-handed (sterile) neutrinos to the usual (active) neutrinos of the Standard Model, it is possible to explain simultaneously neutrino oscillation data, the dark matter in the Universe, and generate the correct baryon asymmetry of the Universe without introducing any new physics above the electro-weak scale. This model is called the Neutrino Minimal Standard Model. The lightest sterile neutrino can have a mass in the  $10^3$  eV range and can be coupled to the rest of the matter weakly enough to provide a viable dark matter candidate. An important property of the Neutrino Minimal Standard Model is that its parameter space is bound on all sides and it is testable already with existing experimental means. Sterile neutrinos, predicted by the Neutrino Minimal Standard Model, are searched for at accelerators.

Not much is known phenomenologically about the properties of dark matter particles, such as their mass, primordial velocities, and strength and character of their interactions with other particles and with themselves. Important bounds on primordial velocities are given by observational cosmology and astrophysical studies of galaxy formation. At the largest distances, modern cosmological and astronomical observational data are successfully described by the simplest Cold Dark Matter model, that assumes that dark matter particles were created non-relativistically and rule out the possibility that a significant fraction of dark matter particles remained relativistic until the recombination epoch. At smaller scales (below  $\sim$  Mpc), the data are compatible with both Cold Dark Matter and Warm Dark Matter models. In the latter, particles are created relativistically in the early Universe but became non-relativistic long before matter-radiation equality.

The main methods to probe the structure formation at these scales are Lyman- $\alpha$  forest data and weak lensing surveys: the currently running KiDS survey (led by the Leiden Observatory), as well as the forthcoming EUCLID and LSST surveys. The warm dark matter particles might have been created out-of-equilibrium in the early Universe and have a complicated non-thermal spectrum of primordial velocities, a property that would be imprinted into the shape of the matter power spectrum at the corresponding scales. An important role in probing for Warm dark matter signatures is played by (LOFAR) measurements, exploring the reionization history of the Universe and formation of the first stars.

As for the interaction of dark matter particles with ordinary matter, they can either be stable (but can annihilate with each other into Standard Model particles), or decaying (in which case their lifetime should exceed that of the Universe by many orders of magnitude). In searching for an annihilation signal, neutrino telescopes, cosmic ray experiments (measurements of anti particles), as well as  $\gamma$ -ray and x-ray observations are 'indirect detection experiments' providing important information, complementary to the direct detection experiments. For decaying dark matter the situation is different. The decay signal is proportional to the column density along the line of sight. As a result a vast variety of astrophysical objects of different nature would produce a comparable decay signal. The decaying dark matter particle often possesses a 2-body decay channel, producing a photon with an energy of half the rest mass of the dark matter particle. The search for decaying dark matter by looking for a monochromatic decay line in the spectra of dark matter dominated objects is very promising, as the dark matter origin of any 'suspicious' line can be unambiguously checked. Therefore, one has the freedom of choosing the observational targets, avoiding complicated astrophysical backgrounds.

An extensive program of search for a decaying dark matter signal has already been realized. ESA's XMM-Newton satellite delivers, thanks to its large collecting area, the best searching capabilities for the weak extended signal of decaying dark matter; Chandra, Suzaku and Integral have also been used. In the near future the launch of the Japanese Astro-H satellite will be important as it will have a much higher spectral resolution for extended sources than any of the current instruments. In the far future, this type of resolution will be combined with high spatial resolution and large collecting area with the Athena mission, which is the only contender for a large mission for the 2028 ESA launch slot. All the aforementioned missions have an open observing time policy, and in many cases the Netherlands (SRON) were leading part of the instrumentation (XMM-Newton, Chandra, Astro-H, Athena).

#### 2.4 What is the origin of the large-scale structure of the Universe?

Our view of the Universe has changed dramatically over the past century: not even a hundred years ago it was believed to consist of only our own Galaxy. Einstein's General Theory of Relativity is the cornerstone for our modern understanding of

cosmology. Its premise of a dynamical spacetime formed the framework for an expanding Universe. Encapsulated in the Friedmann-Robertson-Walker-Lemaitre equations, it found a dramatic confirmation in the discovery of cosmic expansion by Edwin Hubble. Cosmology turned into a truly physical science with the discovery of the cosmic microwave background by Penzias and Wilson in 1965, which formed the ultimate proof of the fact that the Universe had commenced in a hot and dense Big Bang. In the subsequent decades, our detailed understanding of the physical processes that have been at work in shaping the structure and infrastructure of the Universe has increased by orders of magnitude.

With the discovery of the accelerating Universe towards the end of the 20th century, a concordance cosmological model started to emerge. Managing to describe an ever increasing array of cosmological observations by a relatively small number of parameters, it also is based on the perplexing realization that 96% of the energy content of the Universe has an unknown and unidentified identity. Dark matter, the dominant gravitationally attractive component responsible for the formation of structure in the Universe, is presumed to exist of as yet unidentified particles. Even more elusive is the dark energy that dominates the expansion and fate of our Universe.

Cosmology research in the Netherlands centres around four topics, which are strongly interrelated:

- The first is the nature of Dark Matter (see also Section 2.3), of principle importance for the formation of structure in the Universe. Probes of dark matter range from the largest cosmic scales, the cosmic microwave background, down to galactic scales.
- An even larger riddle concerns the nature of Dark Energy. This component represents more than 70% of the Universe, and is the agent behind the accelerated expansion of the Universe. For the discovery of this cosmic acceleration, in 1998, Perlmutter, Schmidt and Riess have been awarded the Nobel prize Physics in 2011. Dark energy has been dominating the dynamics of the Universe since the last 6–7 billion years, and determines the ultimate fate of our Universe. The name Dark Energy reflects our ignorance on this mysterious medium, as well as the assumption it should be identified with an as yet unidentified energy. It is considered to be one of the biggest questions in fundamental physics, and may hold the key towards our understanding of the very first moments after the Big Bang and a quantum theory of gravity.
- The third question is that of the formation of cosmic structure, ranging from the first stars and galaxies to that of the clusters of galaxies and the Cosmic Web (Athena). This involves issues such as the end of the Dark Ages and the Epoch of Reionization, which is one of the major science drivers behind LOFAR. It also includes a wide range of projects directed towards searching for high redshift galaxies, and understanding the processes behind the formation and evolution of galaxies. An important aspect is that of the structure and dynamics of the Universe on scales of a few

up to hundreds of Megaparsecs, which contains a wealth of directly inferable information on the primordial Universe.

- The fourth component of cosmological interest deals with the physics of the very early Universe. It involves interests in the origin of matter-antimatter asymmetry of the Universe, the origin and nature of primordial perturbations and inflationary scenarios, the theory of production of dark matter and other remnants of the early Universe, the nature of cosmological singularity. This is closely related to the research on the physics of fundamental forces and constituents of nature, including particle physics and (ultra) high energy physics, quantum gravity, (super)string and brane theories.

In the Netherlands these questions are addressed by the Astroparticle Physics community in close collaboration with scientists from the neighbouring fields Astronomy, Cosmology, and Theoretical (High-Energy) Physics, with the first and the last question having the closest relation to Astroparticle Physics.

## 2.5 What is the structure of the physics beyond the Standard Model?

The Standard Model of particle physics is an extraordinarily successful theory. It has been extensively tested in numerous experiments and the agreement between the measurements and the theory is spectacular. Nevertheless, there are presently several phenomena in particle physics, astrophysics, and cosmology which the Standard Model in its original form cannot explain:

The Standard Model does not provide a quantum mechanical description of the fourth fundamental force of nature: gravity. What is the origin of transitions between neutrinos of different flavours? Neutrino oscillations only occur when neutrinos are massive, whereas the Standard Model only contains massless left-handed neutrinos.

What ensures that there is much less anti-matter than matter in the Universe today?

What accounts for some 24% of the total matter density in the present Universe? What particle is the Dark Matter made of? The Standard Model does not contain a viable Dark Matter candidate.

If the homogeneity and flatness of the Universe is explained by a period of the rapid accelerated expansion, the Inflation —what is the mechanism that drives it?

What is the nature of Dark Energy? Is accelerated expansion of the Universe caused by a small cosmological constant or by some other, yet to be discovered substance?

Astroparticle Physics provides a unique opportunity (alternative and complementary to accelerator experiments) to access physics beyond the Standard Model. This includes:

- Efforts in particle physics (e.g. searches for new physics at accelerator experiments and, in particular, at the LHC).
- Systematic studies of the properties of Dark-Matter particles (to constrain their possible masses, strength and type of their interaction with ordinary matter, and their primordial velocity distribution).

- Theoretical work on the properties of neutrinos (explaining “why neutrinos are so light?” and the whole pattern of neutrino flavour oscillations).
- Exploring generic features of a putative theory of quantum gravity and the possible imprints this could leave on the Cosmic Microwave Background, with a particular focus on the data of the Planck satellite.
- Development, testing, and constraining extensions to the Standard Model that can accommodate the above mentioned beyond-the-standard-model phenomena. This requires a theory of the early Universe for such models, including a mechanism of generation of matter-antimatter asymmetry, models of inflation and consequent re-heating of the Universe, description of primordial synthesis of elements in the presence of hypothetical new particles etc.

Constraining physics beyond the standard model is an important part of Astroparticle Physics, as it requires combined analyses of the data from various astronomical observations, particle physics and Astroparticle Physics experiments, and corresponding theoretical work. Various aspects of this work are done by Dutch groups (Amsterdam, Groningen, Leiden, Nikhef, Utrecht).

### 3 Achievements since 2005 — Astroparticle Physics: a strongly increasing field in the Netherlands

All major objectives outlined in the Dutch Astroparticle Physics plan from 2005<sup>1</sup> have been achieved, the Netherlands have been established as an international partner in Astroparticle Physics, and the international role of the Netherlands in this field is being continuously strengthened. Since 2005 the Dutch activities in Astroparticle Physics are continuously growing, new staff members have been hired at the universities and the national research institutions. New interdisciplinary entities have been founded, such as IMAPP in Nijmegen, the GRAPPA institute in Amsterdam, or the Quantum Universe in Groningen. These resources form a solid pedestal for the further development of Astroparticle Physics in the Netherlands during the next decade.

The excellence of Dutch scientists in the field of Astroparticle Physics is also underlined by the awarding of national and international high-level personal grants and prizes, such as the Spinosa award, ERC advanced grants, and NWO VICI grants.

The success is manifested in particular in the following achievements:

#### 3.1 Measurement of cosmic rays

Dutch groups (Groningen, Van den Berg, Scholten; RU Nijmegen, De Jong, Falcke, Hörandel; Nikhef, Timmermans) have established a new technique to measure the properties of air showers induced by high-energy cosmic rays: the radio detection of air showers. This includes activities in the LOFAR

radio telescope<sup>[9]</sup> and the Pierre Auger Observatory<sup>[10]</sup>. This technique has been pioneered by the LOPES experiment<sup>[11]</sup>, in which RU Nijmegen (Falcke, Hörandel) plays a key role.

Objective of the LOFAR key science project cosmic rays (lead by RU Nijmegen) is to measure the radio emission from air showers with unprecedented precision. To enable the air shower detection RU Nijmegen has installed a scintillator array in the LOFAR core. A breakthrough has been achieved in 2013: the first measurement of the type of the primary cosmic ray, inducing an air shower, based on the radio technique.

Dutch groups play a leading role in the Auger Engineering Radio Array (AERA). They have significantly contributed to the construction of the set-up and play a leading role in the data analysis. A significant increase in the understanding of the radio emission mechanism has been achieved through measurements of the polarization of the radio signal. This resulted in a measurement of the Askaryan effect and an estimate of its strength relative to the geomagnetic mechanism.

Since 2005, Dutch groups (De Jong, Falcke, Hörandel, Timmermans, Van den Berg) play an important role in the Pierre Auger collaboration to measure the properties of the highest-energy particles in the Universe at energies exceeding  $10^{17}$  eV. Key observables are the energy spectrum, the mass composition, and the arrival direction of cosmic rays. It turns out that a precise measurement of the elemental composition of cosmic rays at the highest energies will be crucial in the future.

In addition, RU Nijmegen (Hörandel) plays a significant role in the exploration of the properties of Galactic cosmic rays since 2007, namely: Measurements of the elemental composition of cosmic rays with the balloon experiment TRACER in the energy range  $10^9$  to  $10^{14}$  eV. These measurements improve our understanding of the propagation of cosmic rays in our Galaxy. And the investigation of the properties of cosmic rays with the KASCADE-Grande air shower experiment in the energy range  $10^{13}$  to  $10^{18}$  eV. In particular, Nijmegen is involved in the study of high-energy hadronic interactions in air showers. RU Nijmegen is official member of the KASCADE-Grande collaboration since 2011.

Since 2011 RU Nijmegen (Haverkorn) is working on Galactic magnetic fields. This is crucial for the understanding of the propagation of cosmic rays in the Galaxy and, in particular, for the understanding of the arrival directions of the highest-energy cosmic rays measured with the Auger Observatory.

#### 3.2 Neutrino astronomy

The primary aim of neutrino astronomy is the discovery of high-energy neutrino sources in the Universe. The detection principle is based on the observation of the Cherenkov effect in water or ice. Dutch groups are involved in the ANTARES<sup>[12]</sup> and KM<sub>3</sub>NeT<sup>[13]</sup> projects in the Mediterranean Sea.

<sup>9</sup> <http://www.lofar.nl/>

<sup>10</sup> <http://www.auger.org/>

<sup>11</sup> <http://www.astro.ru.nl/lopes/>

<sup>12</sup> <http://antares.in2p3.fr/>

<sup>13</sup> <http://www.km3net.org/>

The Dutch groups joined the ANTARES collaboration in an early stage and co-founded KM<sub>3</sub>NeT. Amongst other things, they have developed the data acquisition system for the ANTARES detector including a new approach of bringing all data to shore for further filtering. Data are being continuously taken since 2007. The Dutch groups continue to carry the responsibility for the operation of the detector. Some maintenance is provided for the repair of detector elements and upgrades of the soft- and hardware in the shore station.

The first analysis on point sources was led by the Dutch groups (Heijboer, Nikhef) and subsequently continued towards the current analysis of six years of data. Also in many other analyses the Dutch groups were leading contributors. A memorandum of understanding for the operation of the ANTARES detector until 2016 (followed by a possible decommissioning) was approved in 2012.

In 2006, a design study (EU FP6) was initiated by a joint venture of the ANTARES, NEMO, and NESTOR groups for a cubic kilometre scale neutrino detector in the Mediterranean Sea concluding that for a total cost of about 220 M€, a detector with 50 times the sensitivity of ANTARES and about five times the sensitivity of IceCube can be realized. From 2009 to 2012 a preparatory phase study (EU FP7) was performed which led to the formation of the KM<sub>3</sub>NeT collaboration for which Maarten de Jong (Nikhef) was elected spokesperson in January 2013. A Memorandum of Understanding for the first phase was agreed on in October 2013 funded from regional, national and European sources. The final infrastructure will be installed at three different sites, namely Italy, France, and Greece. The collaboration has shown that the construction and operation of a distributed research infrastructure does not compromise the science goals.

Nikhef has contributed several cost-effective design innovations which have been adopted in the final technical solution for the telescope. For safe deployments and reliable operation of detector units in the deep sea, a collaboration between Nikhef and NIOZ, the Dutch institute for oceanographic research, was set up. As a result, a complete design of a detection unit has been worked out and several deployment tests were successfully performed.

Following the establishment of yearly meetings of all neutrino telescope collaborations, a Memorandum of Understanding for a Global Neutrino Network has recently been signed (October 2013) by ANTARES, Baikal, IceCube, and KM<sub>3</sub>NeT which now also formalizes the support for exchange of know-how and preliminary results within the worldwide community.

### 3.3 Gamma ray astronomy

The major future facility to explore gamma rays with energies exceeding 50 GeV will be the Cherenkov Telescope Array (CTA)<sup>[14]</sup>. Gamma ray observations are an essential ingredient to understand the origin of cosmic rays, as already present-day

<sup>14</sup> <http://www.cta-observatory.org/>

stereoscopic TeV telescopes have the capability to localize and image cosmic-ray sources. The gamma-ray field has rapidly evolved over the last decade; gamma-ray sources can now be detected with high sensitivity and arc-minute resolution, which allows one to detect gamma rays and resolve the structure of extended sources like supernova remnants and galaxies with high statistics. Dutch groups (Markoff, Vink) are involved in the CTA project since its beginnings and have played a minor, but visible role, within the CTA consortium. One of the first CTA physics meetings and the May 2012 consortium meeting were hosted in the Netherlands.

In 2013 a major step towards a bigger contribution of the Netherlands to CTA has been achieved. Groups in Amsterdam (Berge) and Nijmegen (Hörandel) are now developing new technology and prototypes for Cherenkov light cameras for the CTA project in collaboration with groups at ASTRON and in Groningen.

This manifests a revival of this field in the Netherlands, which were in the past an important contributor via SRON to the Compton Telescope (COMPTEL), onboard NASA's Compton Gamma-ray Observatory (CGRO), as well as ESA's INTEGRAL satellite, exploring gamma rays in the MeV energy range.

### 3.4 Gravitational wave detection

Virgo<sup>[15]</sup> is a large interferometer located in Cascina, Italy, which has been operational since 2008. The Nikhef group (Van den Brand, Bertolini, Bulten, Van Den Broeck) joined the Virgo collaboration in 2007 and became a member of the EGO Council in 2009. Its contributions to Virgo included angular alignment of optical components and an optical system for the input mode cleaner (end mirror). Virgo reached its design sensitivity, with the ability to measure relative length changes of  $\Delta L/L < 10^{-22}$ . Right now the instrumental activities are focused on a major upgrade to the second-generation Advanced Virgo, which is poised to make first detections as part of a global network of detectors.

Nikhef is also strongly involved in the development of data analysis techniques. It is a dominant player in two out of four of Virgo's analysis groups. The RU Nijmegen group (Nelemans, Groot) recently also became a full member of the Virgo collaboration and is working on the astrophysical interpretation of upcoming detection events.

In 2011 an EU-funded conceptual design study was concluded for an underground, cryogenic, third-generation ground-based observatory, the Einstein Telescope<sup>[16]</sup>. This is envisaged to be a large (~ 10 km) facility housing up to six interferometers, whose joint sensitivity would be a factor of 10 better than that of the Advanced Virgo/LIGO network. Nikhef has led the effort in site selection and infrastructure, and made major contributions to the science case.

<sup>15</sup> <http://www.virgo.infn.it/>

<sup>16</sup> <http://www.et-gw.eu/>

An independent method for direct detection which is approaching maturity is via systematic monitoring of pulsars in so-called pulsar timing arrays. The Westerbork and LOFAR radio telescopes are part of the European Pulsar Timing Array, with involvement of ASTRON (Hessels, Smit).

eLISA is a future space-based detector that is needed in order to detect individual sources with sizes larger than several km, such as super-massive black hole mergers, stars captured by super massive black holes, and Galactic binaries. It is the prime candidate for the L3 Gravitational wave mission that has been selected by ESA. The RU Nijmegen group is the world-leading group for Galactic binaries and is part of the European eLISA consortium. A strategic partnership between SRON, Nikhef, NOVA, TNO, and various university groups has been set-up (the eLISA-NL consortium) to ensure a strong Dutch contribution to this mission.

The activities are embedded in the traditionally strong fundamental physics and astrophysics community in the Netherlands. The connection between gravitational waves, inflation, string theory, and cosmic defects is studied by Postma (Nikhef); new techniques for the calculation of waveforms are pursued by van Holten (Nikhef and Leiden); gravitational wave emission by neutron stars is studied by Watts (UvA); and Nelemans (RU Nijmegen) works on progenitors of compact binaries and the complementarity of electromagnetic observations.

### 3.5 Dark matter detection

The Netherlands has become a strong participant in one of the leading direct detection dark matter experiments. Nikhef (Decowski) joined two noble-liquid dark matter efforts in 2010: the XENON collaboration<sup>[17]</sup> and the DARWIN<sup>[18]</sup> design study. The XENON collaboration is operating the running 100-kg XENON100 experiment, which has published the most stringent limits for spin-independent WIMP-nucleon cross sections, down to  $\sigma_{SI} \sim \times 10^{-45} \text{ cm}^2$  (for a WIMP of 50 GeV mass). The collaboration is also presently constructing the next-generation XENON1T ton-scale experiment at the Gran Sasso underground laboratory in Italy. Both experiments use dual-phase xenon time-projection chambers, searching for possible signals from dark matter particles (e.g. WIMPs) colliding with xenon nuclei. While XENON100 only had about 150 kg of the target material, XENON1T will have 3.5 tons of xenon. The experiments require extraordinary low levels of radioactivity in their detector as to not obscure the potential signal.

The DARWIN design study, which was funded through the ASPERA EU framework, aims to design a multi-target experiment with both a 20 ton xenon target and a 30 ton argon target.

In the running XENON100 experiment the Amsterdam/Nikhef group is contributing to operation and maintenance of the detector and to the dark matter analysis, which is an essential preparation for XENON1T analysis. For the XENON1T-phase,

the group works on Monte Carlo background studies, builds the vibration-free cryostat support structure, and the trigger and event builder for the XENON1T data acquisition system. Engineers at Nikhef also have essential consulting/advising roles for the XENON1T detector cryostat and related items.

For the DARWIN design study, Nikhef is performing detector R&D by testing the Nikhef-developed GridPix detector in liquid xenon and argon and participates in the background and science impact work packages. Lastly, there is a significant local effort at Nikhef to build up a xenon R&D laboratory allowing for the testing of new detector ideas and the study of xenon properties in order to improve the analysis of dark matter data.

## 4 Dutch priorities 2014–2024

For the next decade (2014–2024) the Dutch Astroparticle Physics community should continue and strengthen the interdisciplinary research program in the Netherlands on the subject of Astroparticle Physics. Scientists in the Netherlands have developed unique detection concepts that put the Dutch scientific community in a unique position to play a leading role in several front-line international experiments in Astroparticle Physics. Together with the strong theoretical efforts this allows Dutch scientists to address forefront scientific key questions.

One of the fundamental questions of Astroparticle Physics is addressed in a multi-messenger approach, in which the same astrophysical objects are studied by means of cosmic-ray, neutrino, gamma-ray, and gravitational wave detectors. As it is commonly believed that cosmic rays originate in (or close to) very energetic compact objects (such as Active Galactic Nuclei, Black Holes, or Supernovae) it is very important to study the same objects with different means. To understand the structure of the Universe, the detection of gravitational waves will be pushed forward and the properties of the dark matter particles will be studied.

### 4.0 Theoretical research

The strong experimental activities must be accompanied by theoretical Astroparticle Physics on all levels. Dutch theoretical physicists are involved in studying the most fundamental aspects of nature, and are trying to answer questions like: What is gravity? What were the initial conditions of the Universe? And what physical processes played a role in how the Universe was formed? And what lies beyond the standard model and what does this imply for the physics of the early Universe and the nature of dark matter? These questions are of interest for theoretical physics, but often the ideas cannot be tested in laboratories and have to rely on studying the Universe at large to test new ideas.

Theory also plays a key role in allowing the accurate interpretation of phenomena that we observe in astrophysical settings. For Astroparticle Physics, in particular, important theoretical research tries to understand the processes by which particles are accelerated to very high energies, how these particles are

<sup>17</sup> <http://xenon.astro.columbia.edu/>

<sup>18</sup> <http://darwin.physik.uzh.ch/>



Figure 8. A detector station of AERA at the Pierre Auger Observatory to measure the radio emission from extensive air showers.

transported, and how these particles interact with plasma, radiation fields, and magnetic fields. Another important aspect is to understand the behaviour of matter under extreme conditions, including the generation and governing physics of accretion flows and outflows associated with compact objects. These relativistic outflows are thought to be the source of cosmic rays both within the Galaxy and beyond, yet their formation and internal physics is far from understood. While some aspects of the problem can be tackled semi-analytically, the physics of magnetized plasma in strong gravity and subsequent radiation transfer is too complex to handle without extensive computer simulations. Such computational methods are particularly necessary for understanding the processes rooted near the event horizon of black holes, or close to neutron star surfaces, and allowing their multi-messenger signals to be properly interpreted. Compact objects are also expected to be the most important source of gravitational waves, both when they are formed in a supernova explosion, as well as when two of these objects merge. Theoretical studies are also needed to understand the expected population of gravitational wave sources, and to understand what other multi-messenger signals may accompany gravitational waves from merging objects.

The above examples show that involvement in international research infrastructures is closely interwoven with complementary theoretical efforts, in which Dutch groups are traditionally very active. Several initiatives in the Netherlands GRAPPA at the UvA, IMAPP at the RU, and the Quantum Universe at the RUG, bring together theorists and experimentalists under the roof of a focused program. These theoretical efforts also require infrastructure in the form of facilities like shared computational clusters.

#### 4.1 Measurement of cosmic rays — Pierre Auger Observatory

The main scientific question for the next decade is to clarify the origin of the highest-energy particles in the Universe. This necessitates the measurement of their properties —arrival

direction, energy, and particle type/mass— with high accuracy. Present results of the Pierre Auger Observatory indicate that the capability to measure the mass of the particles, *i.e.* to identify the particle type needs to be improved. The present findings are hampered by **1.** the low number of observed cosmic rays with an identified mass at the highest energies due to the low duty cycle of the existing state-of-the-art method to measure the longitudinal development of the air showers with fluorescence light telescopes; and **2.** the limited understanding of hadronic interactions (in the atmosphere) at high energies which constrain the interpretation of the observed quantities.

We plan to address both issues by **1.** increasing the mass sensitivity of the Auger observatory, in particular by utilizing the radio detection of air showers as a tool to determine the mass/particle type of the highest-energy cosmic rays with a duty cycle close to 100% and by participating in an upgrade of the Pierre Auger Observatory to increase the muon sensitivity; and **2.** use the air shower data itself to improve our understanding of hadronic interactions at energies well beyond the energy range of man-made accelerators.

Main activities for the next decade include:

We will use the data from the Pierre Auger Observatory to study hadronic interactions at high energies. Of great importance for the development of air showers are hadronic interactions with low momentum transfer. In such interactions most events are emitted in forward direction. Therefore, it is difficult to study such interactions at colliders. Detailed investigations of air shower observables allow to constrain hadronic interaction models. Among others, we will use our experience from the KASCADE experiment on this topic.

A full exploration of the potential of existing set-ups for radio detection. We will complete the installation of the AERA antenna array (see Fig. 8) at the Pierre Auger Observatory. Radio measurements of air showers with AERA and the LOFAR radio telescope are complementary. At LOFAR we have a high antenna density which will yield precision measurements of the radio signals emitted in air showers. This data will enable us to clarify the emission mechanisms and to disentangle the different contributions: synchrotron radiation, Askaryan effect, and Cherenkov effects. AERA, being part of the Pierre Auger Observatory allows us to cross calibrate the radio technique with established techniques to observe air showers. In particular, we will establish an absolute energy scale and mass sensitivity for the radio technique. Finally, the experience with AERA and LOFAR will improve our knowledge on how to build a next-generation experiment based on radio detection to measure elemental composition of cosmic rays. Objective is to complement the Auger Observatory with a 300 km<sup>2</sup> radio detector.

Dutch groups also seek participation in a next-generation cosmic-ray experiment. This will be an international effort, comprising of members of the Auger Collaboration and addi-

**Synergies** The coherent work of Dutch groups in Astroparticle physics yields synergies between the different approaches and experimental techniques to study the Universe.

Charged cosmic rays are investigated with the Pierre Auger Observatory, but will also be studied through their Cherenkov radiation in the atmosphere with CTA. Neutrinos will be observed with dedicated telescopes, such as ANTARES or KM<sub>3</sub>NeT, but are also measured via the observation of horizontal air showers with the Pierre Auger Observatory.

Dark matter is searched for with dedicated experiments like XENON (or at the LHC), but indirect hints can be obtained from studies of TeV gamma ray emission with CTA, the measurements of x rays, the investigation of the large-scale structure of the Universe, or the measurement of positrons in cosmic rays.

General relativity and the structure of space time are studied through the detection of gravitational waves, the observation of the event horizon of black holes with radio telescopes, but also the observation of highest-energy cosmic rays can be used to constrain fundamental physics, such as Lorentz invariance.

The connection of the different experimental efforts to the key science questions is illustrated below.

	<i>Origin of cosmic rays</i>	<i>Nature of dark matter</i>	<i>Nature of space time</i>
<i>Cosmic ray measurements</i>	•••		•
<i>Gamma ray astronomy</i>	•••	••	•
<i>Neutrino astronomy</i>	•••	•	
<i>Direct dark matter detection</i>		•••	
<i>Gravitational wave detection</i>	•		•••

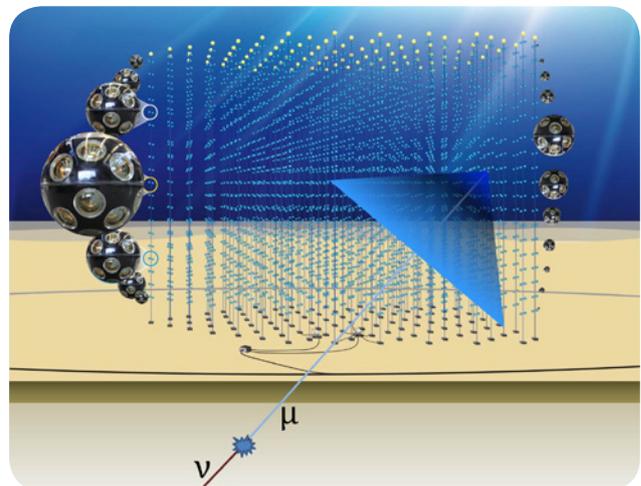
*Relation between experimental efforts (as described in Section 4) and the scientific key questions (as outlined in Section 2). The number of dots indicates the impact of a method on the respective scientific topic.*

tional international partners. Objective of this experiment will be to determine the mass composition of cosmic rays at the highest energies and to clarify the origin of cosmic rays. Radio detection of air showers has a great potential to play a key role in such a next-generation experiment.

#### 4.2 Neutrino astronomy — KM<sub>3</sub>NeT

Recent observations by IceCube in 2012 gave tantalizing first evidence for extraterrestrial high-energy neutrinos. Due to the lack of statistics and angular precision, information on the origin of these events is so far limited and an independent confirmation of the discovery is desired. Though the current observations are consistent with an isotropic flux there are speculations on potential clustering around the galactic centre, suggesting a galactic origin. The size of the Antares detector will not allow for a follow up on this signal but it will continue to deliver competitive data with a better angular resolution and complementary field of view on the sky to IceCube. The KM<sub>3</sub>NeT detector yields a superior angular resolution and sensitivity. KM<sub>3</sub>NeT will thus provide a unique opportunity to follow up on the IceCube discovery and widen this exciting new window to the Universe. With a field of view including our Galaxy, it is optimally positioned to scrutinize the evidence for possible emission from galactic sources. As an example, a 5-sigma detection of neutrinos from the supernova remnant RXJ1713 is obtainable within 5 years. This will allow to conclude on the so far highly debated acceleration mechanisms of cosmic sources, as neutrino fluxes are an unambiguous evidence for an acceleration mechanism for hadronic particles.

The Dutch groups are well positioned to continue their leading role in the event reconstruction and data analyses. A new technical concept by Nikhef using many small photomultipliers in a sphere instead of large photomultipliers enables new ways of background identification and enhances the information available to the reconstruction in the single photon counting. Developments have started to optimally use the additional information in the reconstruction and analyses. The new design with multi-PMT spheres has also already raised the interest of IceCube for upgrades. The KM<sub>3</sub>NeT detector is the first instruments with this new concept, which has the potential to become the new standard for future observatories.



*Figure 9. Detection principle of the KM<sub>3</sub>NeT neutrino telescope.*

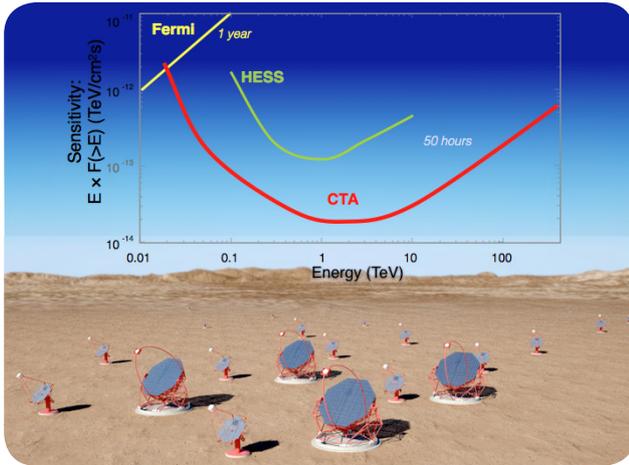


Figure 10. A montage of an artist's impression of CTA together with the sensitivity curve of CTA in comparison with H.E.S.S. and Fermi. Note the different telescopes that make up CTA: small-sized (4–7 m), medium-sized (~ 12m), and large-sized telescopes (~ 24m). The large-sized telescopes are in the core of CTA, whereas the small-sized telescopes are spread out over a large area in order to ensure a large effective area for the highest energy photons (>10 TeV). (Figure courtesy Richard White.)

The relations that are currently being developed and formalized between Antares and various other observatories like the gravitational wave observatories LIGO and VIRGO and also optical observatories like TAROT or ROTSE for further exchange and combination of the data will be expanded for KM<sub>3</sub>NeT for an optimal use of multi-messenger information. KM<sub>3</sub>NeT will be optimally positioned to harvest on this exciting new field of research using neutrinos as the cosmic messengers.

#### 4.3 Gamma ray astronomy — CTA

The international CTA consortium aims to construct an array of telescopes in both the Southern and Northern hemispheres, where each array will employ a suite of more than 40 telescopes to reach a sensitivity that is a factor ten better than H.E.S.S. The telescope array will have telescopes of different diameters to detect both the weak Cherenkov light of the numerous gamma ray photons below 100 GeV, which require few, but large-sized telescopes, and the rare but bright Cherenkov showers from gamma rays above 10 TeV (Fig. 10).

On an international level the development of CTA is strongly progressing. CTA is a well recognized future large scale facility, and features in the relevant astroparticle and astrophysical roadmaps of Europe (ESFRI, ASPERA, and Astronet) and the US (US astronomy and astrophysics decadal review, 2010). In the 2011 edition of the ASPERA Roadmap CTA was listed as the top priority in the category “large-scale infrastructures”. In the recent report “A high level expert group on the assessment of the project on the ESFRI roadmap” the CTA project is ranked in group two: “research infrastructures which might be able to achieve maturity by 2015”.

The Dutch groups are full members of the consortium and represented in the consortium board. In the immediate future groups in Amsterdam and Nijmegen will develop new



Figure 11. The French-Italian-Dutch Virgo interferometer near Pisa is part of a worldwide network of ground-based detectors.

techniques and prototypes for Cherenkov light cameras. Dutch groups also aim for a significant contribution to the construction and the operation of the telescope (from 2015 onward).

#### 4.3 Detection of gravitational waves — Virgo, Einstein Telescope

Advanced Virgo, whose construction started in 2011, will reach strain sensitivities of a few times  $10^{-24}$  Hz<sup>-1/2</sup>. After commissioning starting in 2015, it is likely to make first detections. In terms of instrumentation, the Nikhef group (Van den Brand) is responsible for a number of systems and components that are critical to the success of the project, notably cryolinks for diminishing phase noise, seismic attenuation, angular alignment, and phase cameras. The data analysis group at Nikhef (Van Den Broeck) is currently the world leader in developing techniques to use gravitational wave signals to test the predictions of general relativity in the strong-field, dynamical regime of gravity, and it aims to be ready to measure the neutron star equation of state with gravitational-wave observations of binary neutron star mergers. The RU Nijmegen group (Groot, Nelemans) is poised to become the leading partner in Virgo for complementary electromagnetic observations through the construction of BlackGEM, a dedicated array of optical telescopes in Chile.

The Einstein Telescope is envisaged to be a large-scale, third-generation facility for gravitational-wave detection. Now that a conceptual design study has been successfully concluded, the next step should be to conduct a technical design study for the Einstein Telescope. Nikhef aims to be a major contributor regarding site selection and infrastructure as well as seismic attenuation.

With the launch of the space-based eLISA projected for 2034, the Nijmegen group will, together with SRON, coordinate the eLISA-NL consortium activities focussed on identifying possible hardware contributions together with industry, on having major participation in preparations for eLISA data analysis led by Nikhef and on enable scientific exploitation for the Dutch community.

As part of the European (and International) Pulsar Timing Array, the ASTRON / University of Amsterdam pulsar group are working towards direct detection of nano-Hertz gravitational waves. This includes using LOFAR to monitor the interstellar

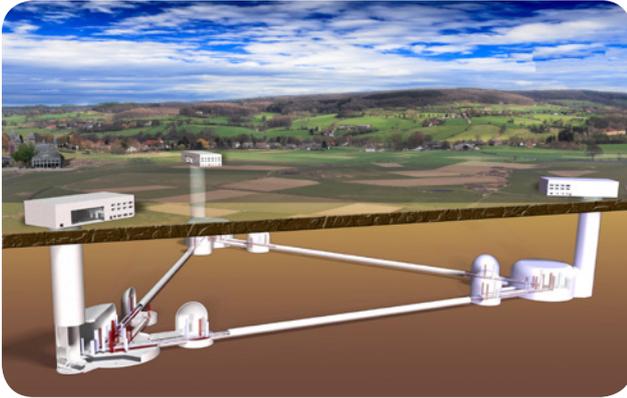


Figure 12. An impression of the Einstein Telescope, a future underground observatory, consisting of multiple interferometers to form a third-generation gravitational wave detector.

weather that affects pulsar signals. This work will likely be pushed into the detection regime once the full collecting area of the SKA is available, with the prospect of directly measuring the stochastic gravitational background of the Universe. At the same time, the Dutch pulsar group is actively surveying for new precision pulsar laboratories in which we can test the nature of gravity and dense matter. This includes, *e.g.*, the recent discovery of a pulsar in a triple stellar system, which we are studying to make a uniquely powerful test of the strong equivalence principle.

#### 4.5 Direct detection of dark matter — XENON

The Amsterdam group (Nikhef and UvA) is participating in the XENON collaboration, operating the XENON100 detector and preparing the next-generation XENON1T experiment, which will improve the sensitivity by more than two orders of magnitude. The goal for XENON1T is to reach a spin-independent WIMP-nucleon cross section sensitivity of  $\sim 2 \times 10^{-47} \text{ cm}^2$ .

The construction of XENON1T started in August 2013 at LNGS. It is expected to start taking science data in early 2015. The Amsterdam group is heavily involved in the design and construction of XENON1T. They are responsible for the cryostat support structure and the trigger farm which will allow low-energy thresholds and flexible data taking schemes. At the same time, they are also participating in the analysis of existing XENON100 data, focusing on the low-mass WIMP analysis. This will position them well for the analysis of XENON1T data. The XENON1T detector was designed with an upgrade option in mind. Many of the components will be reusable for the XENONnT detector, with roughly twice the amount of xenon target material and double the number of PMT readout channels. It is envisaged that this detector could be operational by 2017–2018. All the hardware components that Nikhef is responsible for are already fully prepared for XENONnT use.

Looking further ahead, Nikhef is also participating in the DARWIN design-study which aims to build a large multi-target dark matter detector. The present plan is to employ large, unsegmented target masses (about 20 t of liquid xenon and/or 30 t of liquid argon) capable of fiducialization. The cryostats containing the noble liquids are immersed in large water



Figure 13. Rendering of the XENON1T direct detection dark matter experiment in construction at the Gran Sasso underground laboratory (LNGS) in Italy.

Cherenkov shields to suppress the background originating from cosmic muons and muon-induced neutrons to negligible levels. The goal of DARWIN is to produce world-leading dark matter search results independent of the future landscape of experimental results. Therefore DARWIN will either probe WIMP-nucleon cross sections down to  $10^{-48} \text{ cm}^2$ , or, ideally, yield a high-statistics measurement of WIMP-induced nuclear recoils. The other two main physics goals of DARWIN are the first real-time detection of solar *pp*-neutrinos with high statistics and the search for the neutrino-less double beta decay of  $^{136}\text{Xe}$ . DARWIN could be located at LNGS or at the recently approved extension of the Laboratoire Souterrain de Modane, DOMUS and run until at least 2025. Nikhef has a xenon R&D laboratory and is presently engaged in studying non-PMT-based readout schemes for a DARWIN-sized detector.

Finally, Dutch groups are leading many important directions in the direct, indirect and accelerator searches for dark matter particles and their phenomenology. Through various programs, Dutch groups have started to collaborate on a number of related scientific topics in order to combine results and extract as much information regarding dark matter as possible.

#### 4.6 Complementary Activities

In addition to the activities described above, Dutch scientists also play a key role in instruments build by other communities, but with high relevance for Astroparticle Physics.

##### Event Horizon Telescope

The general theory of relativity has been confirmed in the weak-field regime in many cases, using a variety of astronomical observations. However, the most interesting regime is the strong-field regime. As the strong-field regime cannot be sampled in laboratory conditions, we need astrophysical sources, ideally black holes, which will be investigated in detail with the Event Horizon Telescope (EHT).

The EHT<sup>[19]</sup> uses the technique of Very Long Baseline Interferometry (VLBI) to synthesize an Earth-sized telescope in order to achieve the highest resolution possible using ground-based instrumentation. The target source is observed simultaneously at all telescopes. The data are recorded at each of the sites

<sup>19</sup> <http://www.eventhorizontelescope.org/>

and later brought back to a processing facility where they are passed through a special purpose supercomputer known as a correlator. Dutch groups (Falcke, Markoff) are involved in the science case and development of the instrument.

### Square Kilometre Array

The ultimate radio observatory for the next decade will be the Square Kilometre Array (SKA)<sup>[20]</sup> in which Dutch scientists (ASTRON, Amsterdam, Groningen, Leiden, Nijmegen) play a leading role through their involvements in the LOFAR telescope. The total collecting area of the SKA will be one square kilometre. To achieve this, the SKA will use several thousand dishes (high frequency) and many more low frequency and mid-frequency aperture array telescopes, with the several thousand dishes each being 15 meters in diameter. The telescopes will be arranged in multiple spiral arm configurations, with the dishes extending to vast distances from the central cores, creating what is known as a long baseline interferometer array.

### X-ray telescopes

X-ray emission is of interest for Astroparticle Physics for three main reasons: 1. To detect the highest energy cosmic-ray electrons (> TeV) emitting X-ray synchrotron emission, complementing gamma-ray emission from the same electrons caused by inverse Compton scattering. 2. To search for the decay from a potential dark matter candidate, massive ( $mc^2 > \text{keV}$ ) sterile neutrinos. 3. For the source physics of potential sources of cosmic rays (supernova remnants, pulsars and AGN) and dark matter (e.g. clusters of galaxies).

Currently several important X-ray missions are operating: NASA's Chandra, ESA's XMM-Newton, and Japan's Suzaku missions. Chandra and XMM-Newton may continue to operate for another decade. Japan will launch in 2015 a successor to Suzaku, named Astro-H, which has hard X-ray capabilities and a high spectral resolution imager. ESA's contribution to Astro-H is led by SRON. The Russians will launch in 2015 Spectrum X-gamma, which contains among others the German X-ray imager eRosita, which will survey AGN and clusters of galaxies.

As for the more distant future. ESA has selected as the science theme "*The Hot and Energetic Universe*" for the large mission to be launched in 2028. This theme foresees the launch of a sensitive advanced X-ray telescope (Athena).

## 5 Financial roadmap

The CAN has identified priorities for the research in Astroparticle Physics in the next decade, as outlined in this document. To achieve the outlined objectives requires resources of the order of about ten to twelve million EUR per year. The interdisciplinary character of Astroparticle Physics necessitates collaborative efforts of different funding bodies. The CAN recommends to fund the activities through a combination of national and European institutions. Funding sources include:

<sup>20</sup> <http://www.skatelescope.org/>

- the participating research institutions, namely the University of Amsterdam, the Free University Amsterdam, Leiden University, Radboud University Nijmegen, the University of Groningen and the national research laboratories ASTRON, Nikhef, and SRON;
- Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO);
- Stichting voor Fundamenteel Onderzoek der Materie (FOM, NWO-N);
- Netherlands Research School for Astronomy (NOVA);
- the European Research Council (ERC).

It is vital that the relevant funding bodies continue to support Astroparticle Physics. Due to the interdisciplinary character of Astroparticle Physics, applications often fall in between the responsibilities of the Dutch high-energy physics (FOM, NWO-N) and astronomy (NOVA, NWO-EW) funding schemes. To sustain the further development of Astroparticle Physics in the future it is desired to establish an own (NWO) funding line for Astroparticle Physics in the Netherlands<sup>[21]</sup>. This should evolve into a structural long-term commitment, providing a solid and substantial basis for the future.

The annual budget for the sub-fields of Astroparticle Physics is illustrated in Fig. 14 and listed in Table 1. Numbers till 2013 are actual expenditures, while numbers for future years are estimates, based on this plan. Several present projects reach the end of their life cycle around the year 2020, this results in an apparent decline of funds after 2020. However, it is expected that new innovative projects will be started in the next years and the required funds are expected to be at least constant.

The costs for the senior staff and faculty members are covered by the participating universities and research laboratories. Additional funds are required to hire PhD students and post-doctoral scientists. Finally, the large-scale research infrastructures necessitate investments for R&D, construction, and operation. The resulting spending profile for these cost categories is depicted in Fig. 15. Some activities already have substantial investment money secured, this applies in particular to the KM3NeT project.

The CAN expects that the remaining necessary funds will be obtained through national NWO Middle Groot (NWO-M) and NWO Groot (NWO-G) grants, the NOVA instrumentation program and personal grants from e.g. the VICI and ERC initiatives.

Funding of the Einstein Telescope as an international large-scale, top-level research facility, will require funds beyond the order of magnitude of the regular Astroparticle Physics research program in the Netherlands. To establish the Einstein telescope in the Netherlands will require direct funding on government level.

<sup>21</sup> At the time of writing of this document, the CAN is in contact with NWO-EW to establish an interdisciplinary research program "Astroparticle Physics".

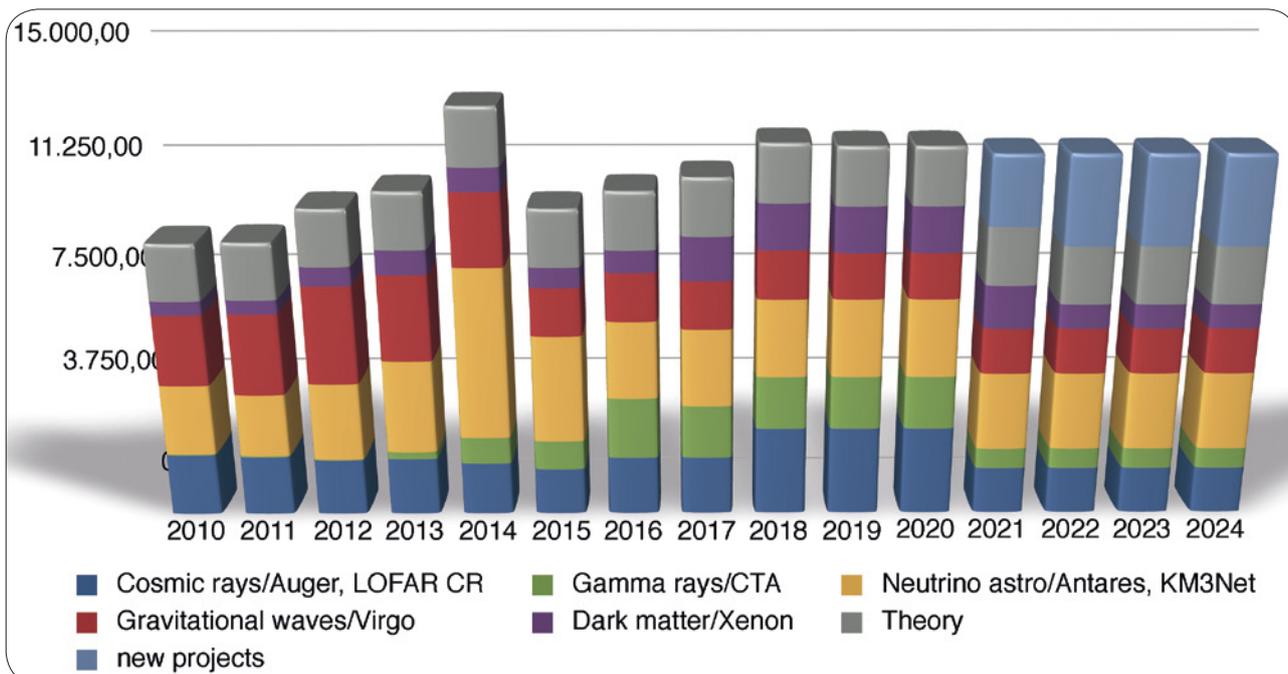


Figure 14. Annual expenses for Astroparticle Physics in the Netherlands, indicating the distribution over the sub-fields. Numbers till 2013 are actual expenditures, future values are based on assumptions.

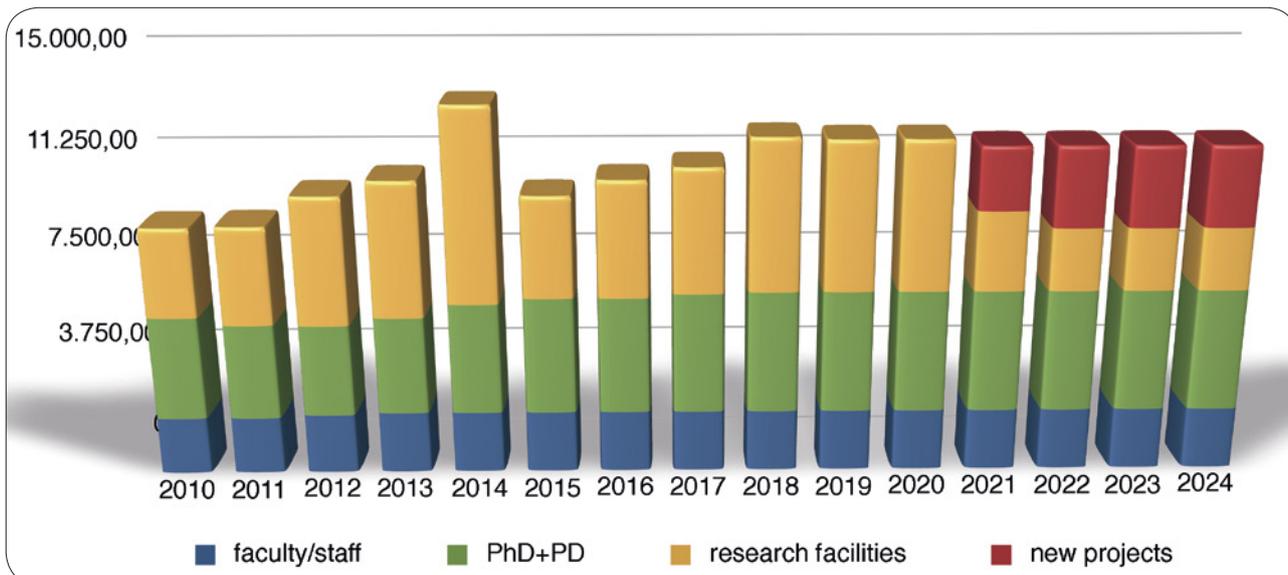


Figure 15. Annual expenses for Astroparticle Physics in the Netherlands, indicating the distribution over the cost categories: faculty/staff members, PhD students and postdoctoral scientists, as well as costs for R&D, construction, and operation of the large-scale research facilities. Numbers till 2013 are actual expenditures, future values are based on assumptions.

## 6 Education and Outreach

Courses on Astroparticle Physics and related fields are offered in the regular curricula of the universities in Amsterdam, Groningen, Leiden, and Nijmegen. In particular, courses in the master education help to attract students into this exciting field of research. Students are embedded in the daily work of the research groups through their activities for their respective bachelor and master projects.

Education of PhD students is conducted in close collaboration with high-energy physics and astronomy, thus underlining the interdisciplinary character of the field of Astroparticle

Physics, in particular through participation in the Nikhef topical lectures and the NOVA autumn schools. Both, lecturers and students from Astroparticle Physics participate in these schools. Dutch scientists also organize regularly an International Summer School on Astroparticle Physics. Schools to date include:

Nijmegen 03, 17–29 August 2003,  
 Nijmegen 06, 29 August–8 September 2006,  
 Nijmegen 09, 19–28 August 2009,  
 Nijmegen 12, 25 July–3 August 2012.

The next school is planned for 2015. High-profile international researchers are lecturing at these schools. The schools are

year	cosmic rays	gamma rays	neutrinos	gravitational waves	dark matter	theory	new projects	total
2010	2,070	37	2,359	2,373	456	1,876		9,173
2011	2,000	37	2,106	2,735	456	1,876		9,212
2012	1,877	37	2,605	3,279	622	1,876		10,297
2013	1,923	248	3,115	2,869	807	1,876		10,840
2014	1,759	904	5,721	2,241	768	1,896		13,491
2015	1,559	979	3,577	1,608	668	1,896		10,288
2016	1,959	2,048	2,597	1,608	733	1,896		10,842
2017	1,959	1,780	2,597	1,608	1,439	1,896		11,280
2018	2,959	1,780	2,597	1,608	1,500	1,896		12,341
2019	2,959	1,780	2,597	1,508	1,500	1,896		12,241
2020	2,959	1,780	2,597	1,508	1,500	1,896		12,241
2021	1,559	681	2,597	1,508	1,435	1,896	2,323	12,000
2022	1,559	681	2,597	1,508	805	1,896	2,953	12,000
2023	1,559	681	2,597	1,508	805	1,896	2,953	12,000
2024	1,559	681	2,597	1,508	805	1,896	2,953	12,000

Table 1. Annual expenditures for the different sub-fields of Astroparticle Physics in the Netherlands (in thousand EUR). Numbers till 2013 are actual expenditures, future values are based on assumptions.

internationally recognized and well attended by PhD students from abroad, underlining the international role of Dutch Astroparticle Physics.

Topics in Astroparticle Physics are also well suited for the education of high school students. A cosmic-ray module for NLT (Nature Life and Technology) has been developed and is certified for use in the highest classes in Dutch high schools. The HiSPARC (High School Project in Astrophysics Research with Cosmic rays) experiment has been running successfully for more than ten years, producing many high school projects (profielwerkstukken). Dutch institutes start to participate in the international cosmic day, organized since 2012. Furthermore, scientists from the field of Astroparticle Physics are giving guest lessons in high schools and other occasions<sup>[22]</sup>.

## 7 Concluding remarks

This roadmap presents the case for continuing and intensifying Dutch research in the field of Astroparticle Physics. This roadmap succeeds the roadmap published in 2005. In the mean time the Dutch physics and astronomy communities recognized the importance of this multidisciplinary fields and the science opportunities it provided. As a result several Universities (UvA, RU, RUG) have now institutes or centres of excellence in the field of Astroparticle Physics, and have hired new faculty to strengthen Astroparticle Physics in their institutes.

These efforts paid off, the Netherlands play highly visible roles in international Astroparticle Physics research infrastructures, such as the Pierre Auger Observatory and in KM<sub>3</sub>NeT.

With this roadmap we lay out the future strategy of the Dutch Astroparticle Physics community. Some of the science themes

<sup>22</sup> The CAN web page <http://www.astroparticlephysics.nl/> will reflect our own activities as well as the outreach activities of the international experiments, in which we participate.

and infrastructure propagated are a continuation of what was established between 2005 and 2013. But compared to 2005 also new initiatives are being advocated, such as direct dark matter detection (XENON1T), very high energy gamma-rays (CTA), as well as pointing out the road ahead in gravitational wave research (Einstein Telescope). These new initiatives are well aligned with the international roadmaps, such as the ASPERA (European Astroparticle Physics network) and the ESFRI (European Research Infrastructures) roadmaps. This ensures broad support for our choices internationally, as well as guaranteeing that the Dutch Astroparticle Physics community maintains its high international profile, and that it will have access to first class research infrastructure.

Our expectation is therefore that the strategy laid out here will turn out to be as successful, as the results of our previous roadmap.

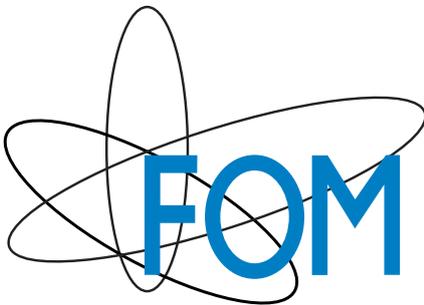
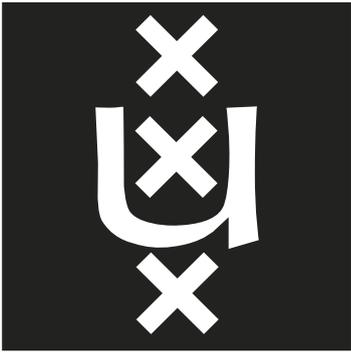
## Appendix: Staff/faculty members and institutes

Name	cosmic rays	neutrino astronomy	gamma rays	gravitational waves	dark matter	theory	neighbouring fields
<b>UvA Amsterdam</b>							
S. Ando						•	
D. Berge			•				
G. Bertone					•	•	
J. de Boer						•	
A.P. Colijn					•		
M.P. Decowski					•		
B. Freivogel						•	
M. van der Klis							•
P. Kooijman		•					
S.B. Markoff			•			•	•
J.P. van der Schaar						•	
J. Vink			•			•	•
A. Watts						•	•
R. Wijers			•			•	•
R. Wijnands							•
E. de Wolf		•					
<b>VU Amsterdam</b>							
J.F.J. van den Brand				•			
H.J. Bulten				•			
<b>U Groningen</b>							
A.M. van den Berg	•	•					
E. Bergshoeff						•	
L. Koopmans							•
M. Mendez						•	
D. Roest						•	
O. Scholten	•						
R. van den Weygaert						•	
<b>U Leiden</b>							
A. Achúcarro							•
A. Boyarsky					•		•
J. Brinchmann							•
H. Hoekstra							•
K. Kuijken							•
S. Portegies Zwart							•
E. Rossi						•	
H. Röttgering							•
D.F.E. Samtleben		•					
K. Schalm						•	
J. Schaye							•
<b>RU Nijmegen</b>							
A. Achterberg						•	
H. Falcke	•					•	•
P.J. Groot				•			•
M. Haverkorn	•						•
J.R. Hörandel	•		•				
S.J. de Jong	•						
E. Körding							•
G. Nelemans				•			•

Name	cosmic rays	neutrino astronomy	gamma rays	gravitational waves	dark matter	theory	neighbouring fields
<b>Nikhef</b>							
A. Bertolini				•			
A.J. Heijboer		•					
M. de Jong		•					
M. Postma						•	
J.J.M. Steijger						•	
C.W.J.P. Timmermans	•						
C.F.F. Van Den Broeck				•			
<b>ASTRON</b>							
J. Hessels				•			•
G. Janssen				•			
<b>SRON</b>							
J. In 't Zand							•
P.G. Jonker							•
J. Kaastra							•

Table 1. Staff and faculty members, active in Astroparticle Physics at Dutch institutions. They participate in research at large-scale infrastructures for cosmic rays, neutrino astronomy, gamma ray astronomy, gravitational wave detection, dark matter search, as well as on theoretical aspects. Also indicated are scientists, working in neighbouring fields, having overlap with Astroparticle Physics.

Astroparticle Physics in the Netherlands is supported by



ASTRON

SRON

NIKHEF



