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OECD Global Science Forum

REPORT OF THE ASTROPARTICLE PHYSICS INTERNATIONAL FORUM (APIF)

Authors of this report are Members of the Astroparticle Physics International Forum (annex 1).

Contacts: Carthage Smith (carthage.smith@oecd.org) and Qian Dai (qian.dai@oecd.org).

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TABLE OF CONTENTS

LIST OF ACRONYMS

ACT	Atacama Cosmology Telescope
AGN	Active Galactic Nuclei
AMS	Alpha Magnetic Spectrometer
ANTARES	Astronomy with a Neutrino Telescope and Abyss environmental RESearch
APIF	Astroparticle Physics International Forum
ApPEC	Astroparticle Physics European Consortium of Funding Agencies
ApPIC	Astroparticle Physics International Committee
ARA	Askaryan Radio Array
ArDM	Argon Dark Matter
ARIANNA	Antarctic Ross Ice-Shelf ANtenna Neutrino Array
ASPERA	Astro Particle European Research Area network for funding agencies
ATLAS	A Toroidal LHC ApparatuS
BAO	Baryon Acoustic Oscillations
BICEP	Background Imaging of Cosmic Extragalactic Polarization
BOREXINO	Italian Diminutive of BOREX (Boron Solar Neutrino Experiment)
BOSS	Baryon acoustic Oscillation Spectroscopic Survey
CCD	Charge-coupled Device
CDM	Cold Dark Matter
CEA	French Alternative Energies and Atomic Energy Commission
CERN	European Organization for Nuclear Research
CHIME	Canadian HI Mapping Experiment
CLASS	Cosmology Large Angular Scale Surveyor
CMB	Cosmic Microwave Background
CMS	Compact Muon Solenoid
CNES	French Space Agency
CO2	Carbon Dioxide
COBE	Cosmic Background Explorer
COrE+	Cosmic Origins Explorer +
CP	Charge-parity
CTA	Cherenkov Telescope Array
CTIO	Cerro Tololo Inter-american Observatory
CUORE	Cryogenic Underground Observatory for Rare Events
DECam	Dark Energy camera
DES	Dark Energy Survey
DESI	Dark Energy Spectroscopic Instrument
DM	Dark Matter

DOE	Department of Energy
DUNE	Deep Underground Neutrino Experiment
EBEX	E and B Experiment
eBOSS	Extended Baryon acoustic Oscillation Spectroscopic Survey
EC	European Commission
EGO	European Gravitational Observatory
ESA	European Space Agency
ESSENCE	Equation of State: SupErNovae trace Cosmic Expansion
ETHZ	Swiss Federal Institute of Technology in Zurich
EUSO	Extreme Universe Space Observatory
EXO	Enriched Xenon Observatory
Fermi-LAT	Fermi Large Area Telescope
GSF	Global Science Forum
GUT	Grand Unified Theories
GWIC	Gravitational Wave International Committee
H.E.S.S.	High Energy Stereoscopic System
HAWC	High Altitude Water Cherenkov Telescope
IceCube	IceCube Neutrino Observatory
IHEP	Institute of High Energy Physics
INFN	National Institute for Nuclear Physics
IUPAP	International Union of Pure and Applied Physics
JAXA	Japanese Space Agency
JEM	Japanese Experiment Module
JPARC	Japan Proton Accelerator Research Complex
KAGRA	Kamioka Gravitational Wave Detector
KamLAND	Kamioka Liquid Scintillator Antineutrino Detector
KIMS	Korea Invisible Mass Search
KM3NeT	Cubic Kilometre Neutrino Telescope
LAMOST	Large Sky Area Multi-Object Fibre Spectroscopic Telescope
LBNF	Long-Baseline Neutrino Facility
LHAASO	Large High Altitude Air Shower Observatory
LHC	Large Hadron Collider
LIGO	Laser Interferometer Gravitational-Wave Observatory
LISA	Laser Interferometer Space Antenna
LiteBIRD	Lite (Light) satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection
LNS	National Laboratories of Southern Italy
LSPE	Large-Scale Polarization Explorer

LSST	Large Synoptic Survey Telescope
MACE	Major Atmospheric Cerenkov Experiment Telescope
MAGIC	Major Atmospheric Gamma-Ray Imaging Cherenkov
MINOS	Main Injector Neutrino Oscillation Search
NASA	National Aeronautics and Space Administration
NIKA	New IRAM KIDs Array
NOnA	NuMI Off-Axis ne Appearance
NSF	National Science Foundation
OECD	Organization of Economic Co-operation and Development
OLIMPO	A High Resolution Balloon-borne Telescope
OPERA	Oscillation Project with Emulsion-tRacking Apparatus
PAMELA	Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics
PIPER	Primordial Inflation Polarization Explorer
PIXIE	Primordial Inflation Explorer
POLARBEAR	POLARization of the Background millimEter bAckground Radiation
QIJOTE	Q-U-I JOint Tenerife
QUBIC	Q and U bolometric Interferometer
RENO	Reactor Experiment for Neutrino Oscillations
RETB	Radio Electronic Token Block
RSD	Redshift Space Distortions
SDSS	Sloan Digital Sky Survey
SM	Standard Model
SNeIa	Type “Ia” Supernovae
SNLS	Supernova Legacy Survey
SNO	Sudbury Neutrino Observatory
T2K	Tokai to Kamioka
TA	Telescope Array
TW	Terawatt
UK	United Kingdom
USA	United States of America
VERITAS	Very Energetic Radiation Imaging Telescope Array System
VIRGO	A gravitational wave detector based near Pisa
VLT	Very Large Telescope
WFIRST	Wide-Field Infrared Survey Telescope
WGAP	Working Group on Astroparticle Physics
WIMP	Weakly Interacting Massive Particle
WMAP	Wilkinson Microwave Anisotropy Probe

About this report

This report has been compiled by members of the Astroparticle Physics International Forum (APIF). It is a final report to the Organisation of Economic Co-operation and Development (OECD) Global Science Forum (GSF), which established APIF in 2011. The report serves a standard accountability function and aims primarily to illustrate the value of APIF in the period up to the end of 2016, during which it has been convened under the aegis of OECD-GSF, and to support the case for its continuation, as an independent structure, beyond 2016. With these aims in mind, what to include in such a report was not immediately obvious. APIF is essentially a forum for strategic discussions and astroparticle physics is a specialised field of interdisciplinary research, with its own complex concepts and scientific language. Communicating the value of these strategic discussions, whilst at the same time conveying the excitement and challenges of the scientific area, is not a straightforward task.

After much deliberation, the APIF members decided to structure their report in three sections: 1. a review of APIF activities, 2011-2016; 2. a review of recent scientific progress; and 3. illustrative cases of the spill-over benefits of astroparticle physics for other areas of science and society. Readers who are not specialists in astroparticle physics may struggle to understand all of the details in section 2, whilst specialists may find that it over-simplifies some of the issues. Likewise, the selection of examples in section 3 may be criticised by some readers and there are undoubtedly many more cases that could have been included. Whilst section 1 can be read as a stand-alone report, the subsequent sections are designed to give substance, context and meaning to what APIF is about: the scientific challenges that APIF is tackling, the scale of international collaboration and investment and the importance of astroparticle physics for innovation and society. With this in mind, hopefully there is something in all three sections of interest both for specialists and non-specialists alike.

In many ways, astroparticle physics is a good example of the opportunities and challenges facing many areas of science. It is a relatively new field combining historically separated scientific disciplines. It is increasingly dependent on very large and expensive infrastructure and it generates and analyses huge amounts of ‘big data’. Thus, it requires extensive international coordination and collaboration. These are the reasons why APIF is necessary and, by extrapolation, one could ask the question whether similar strategic international forums might be beneficial in other new and emerging areas of science?

Preface

APIF grew out of the OECD Global Science Forum Working Group on Astroparticle Physics (WGAP) whose report, published in March 2011, summarised the status of this emerging interdisciplinary field. The report had one recommendation - that a venue be created for consultations of the officials of the funding agencies for the purpose of facilitating a globally coherent response to the scientific opportunities in astroparticle physics. The body would be called the Astroparticle Physics International Forum or APIF and its delegates would be funding agency officials nominated by the delegations to the OECD Global Science Forum. The group decided that the APIF Chair should be super partes and not a national delegate. In late 2010 I was contacted by Stefan Michalowski to see if I would be willing to be nominated as Chair. While I had little idea of what APIF would do and what the Chair's job would entail, I was compelled to say yes because of the exciting scientific opportunities and my belief that global cooperation and coordination have become crucial for scientific progress in almost every field.

Beginning in 2011, APIF has met twice a year, each time for 1.5 days; the first two meetings were held in Paris. In 2012 the group switched to a format where the meetings were hosted by its members; the first such meeting was in London. The group then added an optional trip (sometimes requiring an additional day) to an astroparticle physics facility to the meeting agenda: in 2012, Sudbury Neutrino Observatory (SNO) Lab in Sudbury, Canada; in 2013, the European Gravitational Wave Observatory (EGO) in Pisa, Italy and Kamioka Lab in Japan; in 2014, the French Alternative Energies and Atomic Energy Commission (CEA) in Saclay/Paris and the Laser Interferometer Gravitational-Wave Observatory (LIGO) in Livingston, Louisiana in US; in 2015 the Institute of High Energy Physics (IHEP) and the Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST) in Beijing and Gran Sasso in Rome; in 2016, the Korea Invisible Mass Search (KIMS)/Yangyang Site in Seoul.

The 1.5-day meeting format has allowed for the exchange of information, science updates, strategic discussions and occasionally a more specific work item. As I discovered, the most important agenda item has been the free and very frank exchange of information among science managers and agency representatives, outside the presence of scientists who might be tempted to lobby for their areas or projects. This exchange has included updates on national priorities and roadmaps, national policies (e.g., open access in publishing and data sharing policies), best practices (e.g., management of intermediate to large international facilities), and important funding decisions. There were periodic science updates to the 2011 report prepared by the members as well as occasional talks by invited scientists and even the Chair.

While I had little idea of what I was getting involved in when I said yes to being Chair in 2010, after 12 meetings I have come away firm in the belief that APIF has been very valuable in helping to create a more coherent global program in astroparticle physics and that my time has been well spent. The best testimony to the value of APIF is the high level and high quality of participation, the willingness of the members to host APIF meetings, and now the great effort put forth to find a new mechanism for the continued existence of APIF.

Professor Michael Turner
Kavli Institute for Cosmological Physics
University of Chicago
APIF Chairman, 2011-2016

1. APIF ACTIVITIES, 2011-2016, AND BEYOND

1.1 Background and Overview

APIF was established by OECD GSF, for an initial three year period, in response to the main policy recommendation in the OECD GSF Report of the Working Group on Astroparticle Physics, March 2011 (OECD, 2011). It was agreed at the 29th GSF meeting in October, 2013 that APIF would continue for a second 3-year mandate period and that if APIF wished to continue beyond 2016, it should do so as an independent body, or under the aegis of another organisation.

The original Working Group recommended that APIF operate as a venue for consultation among officials of relevant funding agencies to address policy and coordination challenges in astroparticle physics as the next generation of infrastructures in this growing field were recognised as requiring increased international coordination due to their potential size and cost (see Appendix 1 for the APIF Terms of Reference). Astroparticle physics was defined as covering 6 main scientific domains: dark matter (DM), dark energy, high-energy messengers, gravitational waves, proton decay and neutrino mixing, and neutrino mass (more recently, the cosmic microwave background (CMB) was also added as a key scientific domain). APIF's overall goal was to ensure that, during the next 10-15 years, progress in these interdisciplinary areas of physics would be a globally coherent response to the scientific challenges, using an optimal set of national, regional, and international projects.

It was agreed that APIF should be made up of government or funding agency officials nominated by the delegations to the GSF, and interested non-OECD member countries. Nominations were reviewed and approved by the GSF Bureau. APIF was expected to meet at least once per year, elect its own Chair and other officers, define its own rules and procedures, establish subsidiary bodies as needed, and be self-financing. APIF was established with an independent chair - Professor Michael Turner, from the Kavli Institute for Cosmological Physics, University of Chicago.

APIF has increased its membership base since the 1st meeting, although not all members have been present at all meetings. APIF members have been nominated by national funding agencies or ministries with responsibilities for astroparticle physics in OECD and interested non-OECD member countries. Gaps in geographic representation were discussed at the 8th meeting, which identified several countries with appreciable research activities and/or infrastructures in astroparticle physics including Argentina, Brazil, Canada[1], Chile, China, India and South Africa. Subsequently, China, India, Brazil and South Africa have participated in APIF, Israel also has renewed its participation and active efforts have been made to encourage other countries to join APIF.

The value provided to us by APIF, as an international science policy forum, is very high compared to other bodies. ***In fact it is unique on the global scale in the domain of astroparticle physics.*** *We have appreciated the membership policy where interested countries nominate representatives, who are senior funding agency or ministry officials with responsibility for the planning and implementation of astroparticle physics projects.*

We have exchanged information about the processes, plans and priorities of funding agencies. National roadmaps have been periodically presented and updated. This has provided first hand and timely information. Analysis of governance issues for new large global research infrastructures have been of high interest.

Inviting additional countries to join the forum would strengthen our activities.

- Maurice Bourquin, University of Geneva, Switzerland

By July 2016, APIF had 33 listed participants from 20 countries and regions[2], who were nominated by national funding agencies or ministries with responsibilities for astroparticle physics. It had held 11 meetings biannually on a rotating regional basis[3]. To improve understanding of the international capabilities, visits to major astroparticle physics facilities have been routinely included in the meetings. Consistent with the aims proposed by the original GSF Working Group, the major activities of APIF since 2011 have included:

- Exchange of information;
- Exploration of the prospects for joint actions;
- Consultation on science policy issues applicable to astroparticle physics;
- Discussion on the future development of APIF (since 2014).

APIF was very informative and useful. ***APIF provided a good opportunity to gather a global view of the present and future of astroparticle physics.*** *It was also important to know the prioritization processes and decision-making processes in different countries.*

It is valuable to continue APIF in future. Many big projects in astroparticle physics are expected to be international and therefore continuous exchange and sharing of information will be even more useful and important. It is also desirable to get more involvement of a wider set of countries.

- Yoichiro Suzuki, Kavli Institute for the Physics and Mathematics of the Universe, the University of Tokyo, Japan

APIF's relationship with other relevant international organisations has been a recurrent theme. There have been discussions with the Astroparticle Physics European Consortium of Funding Agencies (ApPEC) and the Astroparticle Physics International Committee (ApPIC) of the International Union of Pure and Applied Physics (IUPAP). APIF members welcomed an invitation from ApPEC for dialogue and potential collaboration. A number of the members of APIF are also ApPEC members and there is an informal liaison through these members. It was agreed that both APIF and ApPEC might propose joint activities as needed in the future. APIF members welcomed the establishment of ApPIC, an international scientific interest group. It was agreed with ApPIC that APIF might propose names of scientists for consideration as ApPIC members and that, in the future, APIF could seek information, analysis or advice from ApPIC, whose members might be invited to participate in APIF discussions on an ad hoc basis.

An APIF webspace was established online on the OECD web site: http://www.oecd.org/sti/sci-tech/theastroparticlephysicsinternationalforumapif.htm and on the OECD Innovation Policy Platform: https://www.innovationpolicyplatform.org/astroparticle-physics-international-forum-oecd-project, where papers and summaries of meetings could be accessed in a password protected space for members only.

> *The benefit of APIF has been the ability to share information with other funders about developments and priorities in the field, and to identify areas where we need to coordinate, either globally or possibly on a multilateral basis.* ***The forum has facilitated informal information sharing in a confidential environment that helps to build trust between potential partners.*** *It has enabled us to understand the planning processes and roadmap activities taking place in each region, and given us access to the background behind decisions. Through sharing information at an international funding agency level, we are able to hear directly about progress, policy and potential strategy changes to inform our own decision making processes.*
>
> - Janet Seed, Science and Technology Facilities Council, UK

1.2 APIF Activities

1.2.1 Exchange of information

APIF is recognised among its members as a critical global venue to exchange information. In this regard, APIF activities have included regular reviews and updates on relevant national and international developments, plans and priorities, and developments in specific domains of astroparticle physics. There have also been ad hoc consultations with external experts on specific topics, and exchanges of information with other relevant organizations, such as the European Commission (EC).

In the course of the early meetings, comprehensive overviews of national processes, plans, priorities and perspectives in astroparticle physics of APIF member countries were presented by members. Subsequently, shorter updates on national developments have been provided by established members at each meeting. New members have been invited to present an in-depth overview of national activities in astroparticle physics upon attending APIF meetings for the 1st time.

An important aspect of information sharing has been the consideration of national and regional road-mapping exercises. The Japanese astroparticle physics roadmap (2013), the European strategy for particle physics (2013) and the progress of the Particle Physics Project Prioritization Panel (P5) report of the United States (2014) were presented and the implications discussed.

Visits to major astroparticle physics facilities of the hosting country have been incorporated in the meeting agendas (see Appendix 3) and have helped promote shared understanding of different national investments and strategies.

International developments in astroparticle physics have been closely followed at APIF meetings. This has included scientific updates from the Gravitational Wave International Committee (GWIC) and ApPIC. At the European level, the activities of the Astro Particle European Research Area network for funding agencies (ASPERA) and ApPEC have been reported.

Substantive discussions of progress in the key scientific domains that were identified in the OECD GSF Working Group report, including dark matter, dark energy, high-energy messengers, gravitational radiation, proton decay and neutrino mixing, and neutrino mass were conducted at the early meetings, with subsequent meetings including updates on significant developments in these scientific domains (see ahead, section 2).

As suggested in the OECD GSF Working Group report, APIF has occasionally invited scientific experts to attend its meetings. Experts were invited to make presentations on key topics including gravitational waves, dark matter, the Euclid mission of the European Space Agency (ESA) and Wide-Field

Infrared Survey Telescope (WFIRST) mission of the USA National Aeronautics and Space Administration (NASA).

1.2.2 Exploration of the prospects for joint actions

It was suggested in the OECD GSF Working Group report that APIF might explore the prospects for joint actions with special emphasis on large programmes and projects. Members agreed that it would not be appropriate to develop a new funding scheme but that the legal, administrative and managerial dimensions of establishing and operating mid- and large-scale international cooperative projects should be discussed. As a result, a short guide/check list that would be useful for proponents of new and existing projects in astroparticle physics was prepared. This document, entitled *Guide/checklist for proposers of new projects in particle astrophysics* (available at the APIF site on the OECD Innovation Policy Platform), was approved by APIF in 2013. It enumerates the issues that should be considered by project proposers, taking into account the the different phases of a project lifecycle, including conceptualisation/preparatory, construction, operation, and decommissioning.

1.2.3 Consultation on science policy issues

The OECD GSF Working Group report suggested that APIF could be a venue for consultation on generic science policy issues, such as access to research facilities and to data, or contributions to operating costs of facilities by users. There were a number of discussions at APIF meetings on the policy issues related to data access in astroparticle physics. At the same time, a scoping study of issues relating to access to scientific publication in astroparticle physics was initiated.

APIF members considered data access policies in astroparticle physics within the overall context of such policies across multiple scientific domains. Sessions on practices, activities and trends in data access andpolicies on access to facilities,and scientific publications were held. Due to the importance of these issues, one meeting was devoted to national and project policies on access to facilities, data and scientific publications. Extensive discussions focussed on both national examples, from the USA and the UK, and projects and facilities, including the IceCube Neutrino Observatory, the Large Synoptic Survey Telescope (LSST), LIGO and the Cherenkov Telescope Array (CTA). The main OECD activities on open science and open data were also introduced. The diversity of existing policies and its implications for international collaboration was discussed by members, Invited presentations on the activities of the Research Data Alliance and on access to experimental data at the Chinese Institute of High Energy Physics were made at subsequent meetings and members have continued to share and exchange information on data access as a routine part of their updates.

> *We have been participating in APIF since its beginning, as well as its previous incarnation, the WGAP. The APIF has been a successful forum for us to participate, coordinate and keep on top of the international particle astrophysics efforts. We feel it is worthwhile to continue participating in the group under a new structure.*
>
> - Kathy Turner, Office of High Energy Physics, Department of Energy, USA

Along with discussions on data access, consideration was given to access to scientific publications in astroparticle physics. APIF members agreed on a proposal for exploratory work to track astroparticle physics publications using bibliometrics.

1.2.4 Discussion on the future development of APIF

Securing the future of APIF became an important objective for its members following the GSF decision in 2013 to extend the mandate for 3 years and then cease support at the end of 2016. Discussions around the future of APIF began in earnest in 2014 and have covered: the mission and role; priorities and activities; membership; relationship with other relevant organizations; and the legal status and structure beyond 2016.

To further define the priorities for the future a survey was conducted among APIF members, focussing on the following questions:

- What were their expectations at the creation of APIF?
- What have they already got from APIF membership?
- What would be their expectations for the future and how should APIF evolve to fulfil them?

Outcomes of this survey were used to carry out a preliminary SWOT (strengths, weaknesses, opportunities and threats) analysis for APIF. All members recognised APIF as a unique global forum for the exchange of information, in confidence, between funding agencies. While specific tangible APIF outputs were difficult to define, these were generally considered to be less important than exchanging information and increasing understanding between the participants. Members were aware of the gaps in geographic representation, as well as the opportunities to do more, for instance on coordination and access to facilities and data. It was pointed out that APIF could also play an important role in identifying and bridging the gaps between national and international strategies. This analysis paved the way for further positive discussions on membership expansion and the prospects, role and structure of APIF beyond 2016.

> *I think the main justifications for the future activities of APIF are:*
>
> - *sharing the future prospect of astroparticle physics with the global community,*
> - *allowing in return the global community to access the information in order to participate,*
> - *thus creating a sustainable and progressive research field of astroparticle physics.*
>
> *For Korean astroparticle physics community which is small in number and low in voice even within the Korean Physical Society,* ***international collaborations are crucial.*** *In order to maintain strong competences, domestically as well as internationally, it has managed to establish a few large-scale experiments in recent years. However, it is inevitable and essential as well that the Korean community should take part in international collaborations.*
>
> *For this, APIF is very helpful as it has discussed the up-to-date information on the prospects in the field of astroparticle physics: What experiments are planned, being organised, and going on in what parts of the world and who and which countries are participating there.*
>
> *These sorts of information are very important for a middle-sized country like Korea which tries to keep its research strength in order to stay in the mainstream of the S&T achievements.*
>
> - Sun Kun Oh, Konkuk University, Korea

1.3 Future APIF structure and hosting arrangements

The members of APIF agreed that APIF should continue its activities beyond 2016. To establish arrangements for continuing the activities, the "Astroparticle Physics International Forum Agreement" (see Appendix 2) was drafted and agreed by the members.

APIF's past and future goal is to ensure that progress in astroparticle physics will be a globally coherent response to the scientific opportunities through an optimal set of national, regional and international projects. To achieve this goal, APIF will continue to provide a forum for exchange of information.

APIF will have a light administrative structure and elected chairperson. The chairperson will normally serve for three years. Any APIF member can make a nomination for this position, which will entail also a commitment to provide the secretariat if one's nominee is elected. The function of the secretariat will be to cover the organisational and logistical issues related to meetings, compilation and dissemination of any reports, and maintenance of a dedicated website.

The first hosting proposals, from France and the USA, were submitted, considered and decided upon by participants at the 12th APIF meeting in October 2016. Both proposals were considered as being well above the threshold for acceptance. A consensus was reached to accept the proposal from the USA with Roger Blandford as the chairperson.

2. PROGRESS IN KEY SCIENTIFIC DOMAINS IN ASTROPARTICLE PHYSICS

The 6 key scientific domains identified in the 2011 Working Group report (dark matter, dark energy, high-energy messengers, gravitational waves, proton decay and neutrino mixing, and neutrino mass) are among the principal topics for the discussions of APIF. With reference to the strategic vision of large infrastructures for astroparticle physics in the Working Group's report, updates since 2011 are given in this section on each of the 6 domains. In addition, there is an update on the CMB, a key related scientific domain.

There are 3 overarching scientific questions, which astroparticle physics research is addressing.

1. What is the Universe made of? This focuses on Dark Matter, Dark Energy and the Cosmic Microwave Background.

2. What is the role of high-energy phenomena in the Universe? This focuses on High-Energy Messengers (Charged Particles, Gamma Rays, Neutrinos) and Gravitational Waves.

3. What is the nature of matter and interactions at the highest energy scale? This focuses on Neutrino Mixing and Proton Decay and Neutrino Mass.

In the coming years, many experiments that address these questions will be moving to much larger scales that require global scientific expertise and collaboration as well as global contributions and coordination. APIF can play an important role as a venue for informing the agencies on the status, planning and coordination of these experiments.

2.1 What is the Universe made of?

The studies of dark matter, dark energy and the CMB provide complementary information on the properties of the Universe, including what it is made of, what it was like at the beginning and how it will end. Astrophysical observations to date support a picture in which the Universe is flat and its composition is about 27% cold dark matter (CDM), 68% dark energy and 5% "normal" matter, along with a tiny fraction of relic neutrinos. The name dark matter refers to the fact that it doesn't interact with light, or any electromagnetic radiation. Dark energy is responsible for the acceleration of the expansion of the Universe. The CMB is the thermal radiation leftover from the time when neutral atoms first formed in the early universe, and provides a "window" to investigate the Universe's properties when it was approximately 380,000 years old. That most of the present mass and energy of the Universe is dark matter and dark energy provides overwhelming evidence that there must be physics beyond our current best description of the 'normal' matter in the Universe, termed the "Standard Model" of the physics of elementary particles and fields (For a discussion of the Standard Model see the report of the Working Group on Astroparticle Physics (OECD, 2011)).

2.1.1 Dark Matter

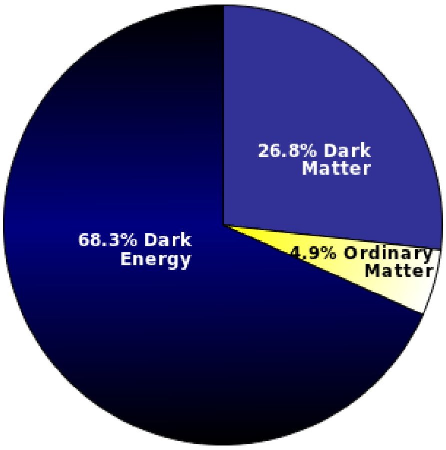
Introduction and background:

We know Dark Matter (DM) is out there. Astrophysical observations of gravitational effects provide evidence of its existence at all times, from the time of nucleosynthesis (a few minutes after the big bang) to the moment in which the CMB radiation was released (about 380,000 years later), all the way to the present Universe. DM pervades all length scales, from the Universe as a whole to individual galaxies, including our Milky Way, and even to some smaller structures. The question is not, does dark matter exist?

The question is, what is dark matter made of? We have compelling evidence that it is an entirely new form of matter, beyond the known particles, and that these novel particles move slowly and hence are called CDM. However, as of yet, we have no experimental proof.

Since a significant part (about 27%) of the composition of the Universe (Figure 1) is estimated to be CDM, an understanding of the properties of CDM is essential to determine how galaxies formed and how the Universe evolved.

Figure 1. Composition of the Universe



Source: Adapted from ESA, 2013

Direct DM Searches: one of the most compelling candidates for CDM is a Weakly Interacting Massive Particle (WIMP). Direct detection searches are designed to find evidence for WIMPs interacting with ordinary matter in a massive detector placed underground to reduce backgrounds that might simulate such an interaction.

Indirect Detection: another approach is to observe that WIMPs might annihilate (or decay) in a dense region of the Universe to yield known particles, in particular gamma rays, charged leptons and neutrinos. Unlike gamma or cosmic rays, which can have several astrophysical origins, high-energy neutrinos emerging from the centre of the sun could be produced only in DM annihilations. Experiments such as the High Energy Stereoscopic System (H.E.S.S.), the Very Energetic Radiation Imaging Telescope Array System (VERITAS), the Major Atmospheric Gamma-Ray Imaging Cherenkov (MAGIC), Fermi and the IceCube Neutrino Observatory (IceCube) have each set upper limits on such processes.

Production at the Large Hadron Collider (LHC): in the effective operator approach, the bounds on a given WIMP mass can be converted to bounds on cross sections that describe WIMP–nucleon scattering at a very low momentum transfer, of the order of a keV. Depending on the type of interaction, contributions to spin-dependent or spin-independent WIMP–nucleon interactions are expected. The ongoing A Toroidal LHC ApparatuS (ATLAS) and Compact Muon Solenoid (CMS) experiments at the European Organization for Nuclear Research (CERN) have, to date, only set upper limits on such particle production.

Axions: the axion is a hypothetical elementary particle postulated by the Peccei–Quinn theory to resolve the strong charge-parity (CP) problem in quantum chromodynamics. If axions exist, have a low mass within a specific range and were produced abundantly in the early universe, they are of interest as a possible CDM candidate. Most experimental searches for the axion are based on their interaction with two photons. Consequently, axions can transform into photons and vice-versa when subject to strong external electric and magnetic fields, in what is known as the Primakoff process.

Recent scientific progress

Laboratory experiments searching for galactic Dark Matter particles scattering off nuclei have so far not been able to establish a discovery. While there have been several reports of possible DM interactions, there have also been a number of other experiments which claim to rule out these observations; however significant progress is being made in the search. Several searches are also underway for dark matter axions.

Several studies claim to have found hints of the existence of DM in gamma rays, but not all scientists are convinced. Planck's latest publication (February 2015) put constraints on the properties of hypothetical WIMPs that are in conflict with the interpretation of data from the space experiments, Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA), Alpha Magnetic Spectrometer (AMS) and Fermi Large Area Telescope (Fermi-LAT). No DM signal has yet been reported by the LHC Collider experiments.

The upper limits on the axion-photon coupling constant have been reduced.

Future plans & challenges

Experiments under construction now will lower the limits on the DM search and may provide hints or first discoveries of the DM particles. These experiments are increasing in size and now involve more global collaborations. It is also planned that the types of technologies needed to search for dark matter particles will be narrowed down and will be used for a future large-scale global collaboration experiment or experiments.

2.1.2 Dark Energy

Introduction and background:

The scientific community prior to 1998 expected that the expansion of the Universe would be slowing down due to the gravitational attraction of matter. However, in 1998 two scientific teams (who won Nobel Prizes for this work in 2011) discovered that the expansion of the Universe is accelerating, using ground-based and space-based measurements of distances to type "Ia" supernovae (SNeIa). The previously-unknown energy in the Universe causing this acceleration has been dubbed "dark energy". The discovery has subsequently been confirmed by a number of methods and experiments, such as measurements of the CMB and of large scale galaxy clustering from the Sloan Digital Sky Survey (SDSS) and other experiments. Higher redshift supernovae found with the Hubble Space Telescope showed that, while the Universe is now accelerating, it was decelerating at earlier times.

The fundamental nature of dark energy remains a mystery. To date, there are no compelling theoretical explanations and observational exploration is the focus of the effort. Understanding its nature will change the way we view the Universe and have profound implications for fundamental physics. Distinguishing between competing hypotheses to determine the nature of dark energy, including if it is a cosmological constant, a breakdown in Einstein's General Relativity, or something else, requires precise measurements using complementary data sets and a combination of techniques. Current experiments are either photometric imaging or spectroscopic surveys and may be optimised for one technique, but typically use several others. The primary targets and techniques currently are SNeIa, weak gravitational lensing, baryon acoustic oscillations (BAO), galaxy clusters, and redshift space distortions (RSD). Each has its particular strengths and different sources of errors.

A staged program of experiments has been developed, with a complementary suite of imaging and spectroscopic surveys, focusing on ever-increasing precision measurements of the acceleration of the Universe over time from the current epoch to approximately 10 billion years ago. Some of the major experiments are described below. In addition, the infrastructure for all of these experiments will be used by a wider community for other astronomical measurements.

Recent scientific progress

In the few years following the discovery of Dark Energy, two large supernovae surveys were launched: Equation of State: SupErNovae trace Cosmic Expansion (ESSENCE), which used the Mayall 4m telescope in Arizona, and the Supernova Legacy Survey (SNLS), which used the Canada-France-Hawaii telescope on Mauna Kea. Both surveys relied on using the 8m Gemini, Keck and very large telescope (VLT) telescopes for spectroscopy. These surveys, which observed the sky for 5-6 years, discovered hundreds of high-redshift supernovae and developed new and improved techniques to analyse supernovae light-curves and control systematic uncertainties.

The Baryon acoustic Oscillation Spectroscopic Survey (BOSS) experiment used an upgraded spectrograph installed on the Apache Point Observatory in New Mexico, USA. BOSS was the flagship survey in the SDSS-III and completed data taking in July 2014. The final analysis is being completed in 2016. The extended Baryon acoustic Oscillation Spectroscopic Survey (eBOSS) survey on SDSS-IV started observations at higher redshifts in 2014.

Combined with measurements from CMB or other techniques, the supernovae surveys and BOSS could reach precisions of about 5% in measuring the equation of state of Dark Energy.

The Dark Energy Survey (DES) is primarily a Department of Energy (DOE) and National Science Foundation (NSF) partnership with private and international contributions. A new Dark Energy camera (DECam) was fabricated and is now operating on the Blanco telescope at Cerro Tololo Inter-american Observatory (CTIO) in Chile. Four primary techniques provide complementary measurements of the nature of dark energy include galaxy angular clustering, weak lensing tomography, galaxy cluster counts, and supernovae. The five-year imaging survey started in 2013, and initial precision cosmology results are expected in 2016, including constraints on the time variation of the equation of state of dark energy.

Future plans & challenges

The complementary ground-based projects currently under construction are the LSST and the Dark Energy Spectroscopic Instrument (DESI) project. The LSST consists of a new 8.4 m telescope facility and associated instrumentation on Cerro Pachon, Chile. Its imaging survey will provide data for weak lensing studies as well as other dark energy techniques. NSF and DOE developed a partnership for the LSST project, with significant private contributions. Full science operations are planned to start in 2022.

The DESI survey will provide precision spectroscopic measurements, with the BAO and RSD as the primary methods for studying dark energy. The DESI project is being led by DOE with NSF, international and private contributions. It consists of 10 new spectrographs and a robotic fiber positioner system to be installed and operated on NSF's Mayall telescope on Kitt Peak in Arizona. Full science operations are expected to start in 2020. Both the DESI and LSST dark energy science collaborations have significant European and other international membership.

The next-generation, complementary space missions are the ESA-led Euclid satellite and the USA NASA WFIRST. Euclid is a 1.2-meter optical/near infrared telescope, visible charge-coupled device (CCD) imager and near infrared photometer instruments. NASA is a significant partner, with hardware and data responsibilities, along with a science team. Euclid will do a redshift survey of galaxies. The dark energy program focuses on the weak gravitational lensing and H-alpha galaxy clustering techniques. It is currently under construction, with a launch planned for 2020.

For the future, the global community continues to explore the development of other methods and wavelengths to study the nature of dark energy. CMB measurements continue to provide critical constraints on dark energy. Neutral hydrogen emission in the redshifted 21cm line as a cosmological probe is untested, but the Canadian HI Mapping Experiment (CHIME) array of radio telescopes is deploying in 2016. Future space-based X-ray and gravitational wave missions are being studied.

Efforts to develop technologies towards future experiments, such as massively multi-object spectroscopy, large arrays of superconducting detectors, suppression of infrared emission when observing through the Earth's atmosphere, and efficient adaptive optics, are underway.

2.1.3 Cosmic Microwave Background

Introduction and background:

After being accidentally discovered more than half a century ago, the CMB was shown to exhibit small fluctuations of its temperature in 1992 by the Cosmic Background Explorer (COBE) satellite (this observation warranted the Nobel Prize to G. Smoot and J. Mather in 2006). During recent years, the Wilkinson Microwave Anisotropy Probe (WMAP) and Planck satellites and an array of ground-based and balloon-borne experiments have given us high precision measurements of such CMB temperature fluctuations.

These measurements, as well as the measurement of the fluctuations in the polarisation modes E and B, are of utmost relevance since they allow i) for precision measurements of the cosmological parameters; ii) for precise measurements of the number of neutrino species and of the sum of neutrino masses; and iii) for the first complete map, through gravitational lensing, of the clusters of matter (including dark matter) intervening between the primordial fluctuation recombination era and the present era of the Universe.

The post-Planck CMB research program in the short/medium-term future finds its main goal in the measurement of the B-modes of the CMB polarisation (at large and small angles) with the same type of ultimate precision as obtained in the temperature (scalar) fluctuations.

The cosmological gravitational waves that were produced during the primordial inflationary epoch are predicted to have left crucial imprints of their tensor modes on the large-angle B-modes. Hence measuring these latter quantities may allow accessing the oldest of all the cosmic messengers, namely the primordial gravitational waves. Moreover, measuring the ratio of the amplitudes of the tensor to scalar modes would enable us to establish the energy scale at which primordial inflation set in. Putting together precise measurements of specific relations among various, relevant cosmological parameters would finally shed light not only on the existence of a primordial inflationary era, but also on the major physical features (energy scale, scalar potential triggering inflation, etc.) characterising that crucial phase for the entire subsequent evolution of the Universe.

The measurement of the B-modes at small angles is also of utmost relevance, providing a precious insight into the large scale distribution of matter (including the dark matter), the number and sum of the masses of neutrinos and/or possible exotic particles. In particular, the combination of earth-bound and cosmic experiments exploring neutrino masses and properties should lead to conclusive results on these crucial issues in the next 10-15 years.

Recent scientific progress

Space-borne and ground-based CMB experiments are complementary. Europe has been leading on CMB space experiments thanks, in particular, to the Planck mission, which also has significant NASA contributions. On the other hand, USA has a clear leadership on ground and balloon-borne experiments with a large number of USA-led projects, many with international contributions, already taking data or planned in the near future in the Southern hemisphere, e.g. Atacama Cosmology Telescope (ACT), Cosmology Large Angular Scale Surveyor (CLASS), POLARization of the Background millimEter bAckground Radiation (POLARBEAR), South Pole Telescope, Background Imaging of Cosmic Extragalactic Polarization (BICEP2/BICEP3), Keck Array, the E and B Experiment (EBEX), SPIDER, the Primordial Inflation Polarization Explorer (PIPER). There are also ambitious third generation CMB programs driven by European collaborations: the Q and U bolometric Interferometer (QUBIC), the Q-U-I JOint TEnerife (QIJOTE) and the New IRAM KIDs Array 2 (NIKA2) and the balloons, the Large-Scale Polarization Explorer (LSPE) and OLIMPO. To date the B-mode signal from gravitational lensing of E-mode polarisation and from foreground dust has been detected and a limit on the ratio of tensor to scalar fluctuations has been set at the level of 0.07.

Future plans & challenges

For the future, the emphasis will be on understanding the B-modes in detail to gain information on the inflationary epoch of the Universe and on neutrino properties. The next generation of experiments should aim at greater sensitivities for the tensor to scalar ratio r and also at the largest coverage of the angular spectrum. On the ground, the recent P5 strategic plan in the USA has strengthened the prospects for financing a unique “Stage IV” experiment in the years 2020-2025 (CMB-S4) aiming at establishing greater precision on r. At the same time, CMB-S4 plans to reach an unprecedented precision on the sum of the masses of light neutrinos. It is expected that the current ground-based collaborations will coalesce into the CMB-S4 collaboration to accomplish the “Stage IV” experiment. In space, the most ambitious common European effort in this field is the proposal for a new ESA mission the Cosmic Origins Explorer + (COrE+), submitted in the call for the next medium (M5, 2029-2030) mission of the ESA Cosmic Vision programme. In parallel, the space project Lite (Light) satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection (LiteBIRD) is in phase A in the Japanese Space Agency (JAXA), with NASA contributions, and the space project the Primordial Inflation Explorer (PIXIE), that includes the possibility to measure deviations from the CMB black-body spectrum, is under consideration by NASA.

2.2 What is the role of high-energy phenomena in the Universe?

From the initial inflation and big bang blasts to the explosion of supernovae, from the collision and merger of giant black holes to the gamma ray bursts, from active galactic nuclei (AGN) centres to pulsars and quasars, the Universe is known to go through events of an extraordinary violence. While the observation of a beautiful night sky with so many stars apparently immutable would let us believe that we live in a quiet universe and an eternal cosmos, those violent events lasting from a few days to sometime less than a second are showing us that everything we live in evolves and dies, including the Universe. These events are so violent that even from very far away they are bombarding the earth with highly energetic radiations.

Even if the first observation of such violent events can be traced back to the very ancient times with the antique observation of a sudden apparition of a newly born star as brilliant as a whole Galaxy, a phenomenon today known under the name supernova and related to the collapse of a massive star into a neutron star or a black hole, those violent events are still today largely not understood and probably not even all known. Not only is it thus important to observe them and to understand their nature and properties, it is important to explore their role in the Universe. Why do galaxies have a gigantic black hole in their centre - the famous AGN? Is the shock wave of a supernovae explosion the origin of new star formations? What is the origin of inflation? These are some examples of the essential questions raised by the high-energy phenomena in the Universe. Moreover, in such energetic events the laws of nature are pushed toward their limit and are fantastic laboratories to test our understanding of the Universe. In particular, high-energy phenomena produce intense accelerating fields, far stronger than those created in the laboratory, and these fields can propel particles to extremely high energies. The study of these phenomena provides a unique testing ground for the study of deviations from known fundamental physical laws, including gravitation.

These high energy phenomena are powerful enough to produce very energetic radiations, photons far beyond visible light and other particles and waves such as neutrinos or gravitational waves. Therefore, they are studied by detecting these unconventional "messengers": very high-energy photons and charged cosmic ray particles, neutrinos, and gravitational waves. Since those detections are very difficult and require innovative and large detection systems this field is young and in constant development. In order to reach the required sensitivity to make discoveries or even to become real observatories the new generations of experiment are becoming global. This is one of the fields in which the APIF has been useful to bring the discussion to the global scale. Many discoveries have been achieved in recent years, the major one being the first detection and discovery of gravitational waves by a community now organised at the global level. Major projects are being started at the global level, the most emblematic being CTA, a gamma ray observatory project with a site in each hemisphere and with members or partners from all continents.

2.2.1 High-Energy Messengers

Introduction and background:

The fact that the cosmos is permanently bombarding us with radiations was discovered a century ago, leading to the new concept of cosmic rays. Following their discovery, these radiations were the principal source of progress in understanding elementary particles; then, for many years, research shifted to experiments performed at energy-frontier accelerator laboratories. In recent years, however, cosmic rays have attracted renewed attention, due in part to the enormous energies that they can attain. Basic questions about them remain unanswered: where do they originate? Can the known laws of physics account for their acceleration and propagation through space? What is their composition? There is the intriguing possibility that some of the particles are decay products of dark matter, antimatter, or other exotic entities. Can they be used as a new window to observe the Universe, a new type of observatory? What bodies are emitting them? What do those violent and transient events tell us about the Universe and its evolution?

It is typical of astroparticle physics that finding the answers to these questions would advance both astronomy and elementary particle physics. Research in this domain has been, and will continue to be, complementary to that carried out using the traditional tools and methods of these neighbouring fields, such as optical and radio telescopes, X-ray satellites, and particle accelerators.

Recent scientific progress

The 2011 OECD report on astroparticle physics stressed that "nearly all of the advanced second-generation projects have been implemented as international collaborations". Since 2011 these projects have entered scientific exploitation and produced an enormous amount of results and progress in our understanding.

Neutrinos: One of the most striking results is the real start of neutrino astronomy with the discovery by IceCube, an experiment using the earth as a target to transform neutrinos into muons and the ice of the

South Pole as a muon detector, of several 100TeV-PeV range cosmic neutrinos. The 54 reported IceCube events do not show any clear clustering pattern making their origin an open question. A study of a proposed upgrade of IceCube is ongoing to increase the sensitivity. A twin project, the Cubic Kilometre Neutrino Telescope (KM3NeT) using the water of the Mediterranean Sea instead of the ice, is implementing a first phase, after the success of a demonstrator called the Astronomy with a Neutrino Telescope and Abyss environmental RESearch (ANTARES). Both experiments are modifying their network in order to be sensitive to neutrinos produced in the atmosphere with the aim to use them to study the neutrino mass. In addition, the Askaryan Radio Array (ARA) and the Antarctic Ross Ice-Shelf ANtenna Neutrino Array (ARIANNA) detectors are being developed to be more sensitive at the EeV range using the radio detection of the Askaryan effect.

High-energy gamma rays: A second highlight is provided by the space gamma ray observatory, the Fermi satellite, which has revolutionised our vision of the whole high-energy sky by publishing huge catalogues of transient and violent cosmic sources; a lot of them being of an unknown type.

A third important development is the upgrade of the H.E.S.S. experiment in Namibia in which a very large telescope (24m) has been added to the four 12m telescopes. This experiment uses the atmosphere as a target to transform high-energy gamma rays into a shower of energetic particles. Then, the network of telescopes observes the atmosphere to see the light emitted by the shower and deduce the origin and energy of the initial gamma ray. This observatory is paving the way for the much larger high energy gamma ray observatory, the Cherenkov Telescope Array (CTA). This third generation instrument will be a network of about a hundred telescopes of different sizes deployed at both a southern site (specialising in galactic observation) and a northern one (specialising in extragalactic observations), with partners from Europe, North and South America, Asia, and Africa and with 1200 scientists from 32 countries. CTA will cover all sky with an unprecedented sensitivity. The preconstruction phase has been successfully implemented and an interim legal international organisation has been created. North and south sites have been selected, the pre-production of telescopes started in 2016 and the partial operation of telescopes in the CTA sites is scheduled for 2018.

A complementary space mission, the Extreme Universe Space Observatory onboard Japanese Experiment Module (JEM-EUSO), has been delayed. However a Russian-led mission, Klypve-EUSO, has been under negotiation by space agencies as an interim mission. It will measure the spectrum and anisotropy of ultra-high energy cosmic rays with a uniform exposure across both hemispheres. A first balloon flight of the EUSO design was successfully conducted in 2014 from Timmins Canada by the French Space Agency (CNES). A ultra-long duration EUSO flight by a super pressure balloon is planned for 2017 by NASA, aiming at the first detection of airshowers by fluorescence from above.

The High-Altitude Water Cherenkov (HAWC) telescope was inaugurated in 2015. It is now in full operation and already showing impressive results for galactic and extragalactic gamma ray sources. In parallel, complementary efforts in India (project Major Atmospheric Cerenkov Experiment Telescope-MACE) and in China (project Large High Altitude Air Shower Observatory-LHAASO) will cover the lower and higher parts of the spectrum, respectively.

Charged Cosmic Rays: In 2015, using 109 highest-energy cosmic-ray events with energies greater than 5.7×10^{19} eV, the Telescope Array (TA) experiment reported on a cluster of cosmic-ray events with a statistical significance of 5.1σ (pre-trial). A four-fold TA extension, called TAx4, is planned to confirm this “hot spot” in the northern sky. The surface detector part of this proposal was approved in April, 2015. Its construction is planned to finish in 2017, and about 300 highest-energy cosmic rays are expected to be accumulated in total by 2020. The Pierre Auger Observatory upgrade was recently funded for the study of the composition and muon content of showers at ultra-high energies.

2.2.2 Gravitational Waves

The hundred-year quest to detect gravitational waves, to test a key prediction of General Relativity and to open a new window on the Universe successfully ended in February 2016. The LIGO detectors in Hanford, Washington and Livingston, Louisiana measured the tiny change in distance (about 10^{-15} cm) between two mirrors separated by 4 km caused by the coalescence of two, 30-solar-mass black holes about one billion light years away. In June, the LIGO Collaboration announced a second detection of gravitational waves from a binary-black-hole coalescence. Given that the first detection came during an engineering run of the recently upgraded LIGO detectors and the second detection came from a short science run with the LIGO interferometers still a factor of 3 or 5 from their ultimate sensitivity, the future for gravitational-wave astronomy looks very bright indeed. In 2017, the European VIRGO interferometer should come back on-line after an upgrade, with a similar sensitivity as the LIGOs; and in a few years the Kamioka Gravitational Wave Detector (KAGRA) interferometer in the Kamioka Mine should begin operating. LIGO-India is planning to construct an interferometer similar to the USA LIGOs. Within a few years, these earth-based interferometers should be detecting tens if not hundreds of events every year from neutron star and black hole mergers and doing gravitational-wave astronomy.

NASA and ESA are making plans for a space interferometer – the Laser Interferometer Space Antenna (LISA) – that would operate at much lower frequencies (mHz vs. hundreds to thousands of hertz for the ground based detectors), where the expected sources are stellar mass binaries in the Milky Way Galaxy and supermassive black hole collisions.

Currently, two other searches for gravitational waves are underway at even lower frequencies: pulsar timing arrays, which are sensitive at the nanohertz range and CMB polarisation experiments, which are sensitive to frequencies down to 10^{-16} Hz. The pulsar timing arrays use a network of radio telescopes to very accurately monitor the arrival times of radio pulses from the most stable pulsars to see the effect of gravitational waves from supermassive black hole mergers and other sources. The CMB experiments are looking for the signal of inflation-produced gravitational waves on the polarisation of the CMB. The sought-after signal is the odd parity polarisation pattern (so called B-mode). Its amplitude is very small – at most tens of nanokelvin – and there are “foregrounds”, polarised dust emission and the effects of gravitational lensing which can transform the ordinary even parity mode (E mode) into B-mode polarisation. In 2015, the BICEP2 experiment detected B-mode polarisation; however, it is now generally agreed that, most, if not all, of the detected signal is from polarised dust emission. More than ten experiments are taking data or are being mounted to detect the B-mode signature of inflation. If detected, it would reveal the time (around 10^{-36} sec) and energy scale (trillions of times larger than that of the LHC) of inflation.

2.3 What is the nature of matter and interactions at the highest energy scale?

In the Big Bang scenario, for a brief moment the Universe was extremely hot corresponding to energies well beyond anything that can be realised by particle accelerators. As it cooled, particles and matter formed. Questions concerning the properties of the neutrino and the predominance of matter over antimatter in the Universe (as observed today) are among the outstanding problems in particle physics and cosmology. Neutrino masses and mixings and the possibility of proton decay are some of the phenomena that enable us to study that early epoch of the Universe: How matter was created and has developed.

2.3.1 Neutrino Mixing and Proton Decay

Introduction and Background:

Neutrino oscillations are a clue to the physics beyond the Standard Model of elementary particles and may reveal the secret of the creation of the matter in the Universe. Atmospheric and solar neutrino oscillations were discovered in 1998 and in 2001, respectively. The existence of neutrino oscillations, transitions in flight between the three different types (flavour) of neutrinos (ν_e, ν_μ, ν_τ and their antineutrinos), is caused by non-zero neutrino masses and neutrino mixing, and may provide the answer to the preponderance of matter over anti-matter in the Universe. The tiny, yet finite, neutrino mass indicates the existence of the large energy scale and requires an extension beyond the Standard Model.

Recent scientific progress

The studies of neutrino oscillations have made significant progress in our understanding of neutrinos over the last 4 years and many new efforts are currently being employed/planned. Precision experiments at Daya Bay (China), Tokai to Kamioka (T2K) and SuperKamiokande (Japan), Double Chooz (France) and Reactor Experiment for Neutrino Oscillations (RENO) (Korea) have elucidated many characteristics of the neutrino oscillation process. In June 2011, the T2K experiment in Japan indicated ν_e appearance in the high intensity ν_μ beam produced at the Japan Proton Accelerator Research Complex (JPARC), indicating a positive θ_{13} with a 2.5σ excess. During 2011-15, a series of reactor and accelerator experiments, Daya Bay (China), Double Chooz (France), and RENO (Korea), established the non-zero $\sin^2 2\theta_{13}$. Daya Bay in 2012 provided initial strong evidence of non-zero θ_{13}. The best measurement to date is $\sin^2 2\theta_{13} = 0.084 \pm 0.005$ (Daya Bay), yielding $\theta_{13} \approx 8^o$. In 2013, the Main Injector Neutrino Oscillation Search (MINOS) (USA) observed the appearance of ν_e and NuMI Off-Axis ν_e Appearance (NOνA) (USA) obtained their first results on ν_μ disappearance and ν_e appearance in 2015. Seeing the same θ_{13}-driven effects with different sources of neutrinos at very different energies and baselines is a strong proof of non-zero θ_{13}.

By combining all the experimental data, we get some indication on the mass hierarchy and the CP phase, δ, the remaining missing information on the neutrino sector. Those analysis results demonstrate the importance of the future experiments. The current T2K experiment measures a combination of θ_{13} and δ while reactor experiments measure pure θ_{13} effects. The combination favours $\delta = -\pi/2$.

In addition, Super-Kamiokande (Japan) observed a day/night flux difference of the solar neutrinos that is direct evidence of the matter effect on neutrinos propagating through the earth and two experiments, Super-K and the Oscillation Project with Emulsion-tRacking Apparatus (OPERA) (Italy), have detected the evidence of tau-neutrino appearance. These measurements have strengthened our understanding of neutrino oscillations.

Future plans and challenges

Significant efforts are being made to plan for a next generation long baseline neutrino oscillation experiment. The proposed Long-Baseline Neutrino Facility (LBNF) / Deep Underground Neutrino Experiment (DUNE) experiment would comprise a 34 kilo-ton liquid Argon detector as a far detector at the Homestake mine in South Dakota with a high intensity beam over 1300 km from Fermilab, near Chicago. This USA-based, international, experiment is being developed in collaboration with CERN in Europe. In addition, the Japanese-led project, Hyper-Kamiokande, a 1 mega-ton water Cherenkov detector, using known technology and employing the high intensity beam from JPARC, 295 km away, is potentially ready to begin development.

Proton decay is expected to happen in most grand unified theories (GUTs) and so it is essential to search for it. A certain class of GUTs, for example, predicts that a proton should decay into $e^+\pi^0$ with a lifetime of about 10^{31} years. Experiments have already ruled out this possibility. Since long baseline neutrino experiments require large "far" detectors, it is not surprising that the current/future proton decay detectors are mostly those used as far detectors of long baseline experiments.

2.3.2 Neutrino Mass

Introduction and Background:

The result of the Big Bang should be a symmetric Universe with equal amounts of matter and anti-matter, yet that is clearly not the case. It is possible that neutrinos are their own anti-particles and determining if this is the case could explain the mass asymmetry of the Universe and even shed light on the masses of the neutrinos and how they acquire that mass.

Several questions relate to neutrinos:

- Is Charge Parity (CP) violated in the neutrino sector? (That may explain why there is more matter than antimatter.)
- What is the neutrino mass ordering?
- What is the absolute mass scale?
- Are neutrinos their own antiparticles?
- Are there unknown types of neutrinos, such as sterile neutrinos?

Neutrinoless Double Beta Decay: several even-even nuclei are stable against ordinary β decay but are unstable for ββ decay in which two neutrons are changed into two protons simultaneously. This decay can proceed through several modes. The allowed process, the two-neutrino mode ($2\nu\beta\beta$), is completely described by known physics. The neutrinoless decay ($0\nu\beta\beta$) is forbidden in the Standard Model (SM) since it violates conservation of the total lepton number. Its observation would constitute proof that neutrinos are Majorana leptons and would provide a clear indication of new physics beyond the SM. The detection of a nucleus undergoing ββ decay without producing any neutrinos is the only practical way to establish if the neutrino is its own antiparticle.

Sterile neutrinos are hypothetical particles (neutral leptons – neutrinos) that do not interact via any of the fundamental interactions of the Standard Model except gravity. Since these additional neutrinos cannot couple to neutral elementary particles or Z bosons, they must lack weak interactions. The number of sterile neutrino types is unknown. They may, however, be responsible for a number of unexplained phenomena in physical cosmology and astrophysics, including dark matter, baryogenesis or dark radiation. Several "neutrino anomalies" have been reported, some of which might be compatible with sterile neutrinos but no positive identification has been claimed.

Recent scientific progress

It is known that neutrinos possess a small, yet finite, mass. Previous experiments place the mass at less than 2 eV, while limits from oscillation experiments place a lower bound of 50 meV on the neutrino mass. The effects of neutrino mass within this scale will have a direct impact on galaxy evolution and cosmology. The sum of the neutrino masses has been determined from Planck 2015 results: combining

Planck with other astrophysical data they find $N_{eff} = 3.15 \pm 0.23$ for the effective number of relativistic degrees of freedom and the sum of neutrino masses is constrained to < 0.23 eV.

To date, no positive identification of Neutrinoless Double Beta decay has been confirmed. The most recent results from experiments come from the Cryogenic Underground Observatory for Rare Events (CUORE) (Italy), the Enriched Xenon Observatory (EXO)-200 (USA) and the Kamioka Liquid Scintillator Antineutrino Detector (KamLAND)-Zen (Japan). These have established the most stringent half-life limits to date. Using a range of nuclear matrix element estimates, this can be interpreted as a limit on the effective Majorana neutrino mass

"Neutrino anomalies" have been observed in several experiments. Intriguingly, these results come from a wide range of experiments covering neutrinos and anti-neutrinos with different flavours and different energies. Short baseline accelerator neutrino oscillation experiments, short baseline reactor experiments, and even the radioactive source experiments, have all observed anomalies that can be interpreted as due to one or more sterile neutrinos but no positive identification has yet been claimed.

Future plans and challenges

The search for sterile neutrinos is an active area of particle physics. Since sterile neutrinos have mass, and at low energies act just like regular Standard Model neutrinos, they can participate in neutrino flavour oscillations through their sub-dominant mixing with the familiar active neutrinos. It is through this subtle effect that we hope to find sterile neutrinos if they exist. In experiments involving energies larger than their mass they would participate in all processes in which ordinary neutrinos take part, but with a quantum mechanical probability that is suppressed by the small mixing angle. They would also interact gravitationally due to their mass, however, and if they are heavy enough, they could explain CDM or warm dark matter.

Concluding comments

Over the past 6 years, during the lifetime of APIF, there has been major progress in many areas of astroparticle physics that brings us a little bit closer to really understanding the origins and nature of the Universe. This progress has been made because of major investment in research facilities, advances in digital technologies and most of all because of the collective ingenuity of human minds, working together in international collaborations. Major breakthroughs, such as the detection of gravitational waves, have opened up new and exciting areas of research and discovery but these will require even greater international cooperation and making difficult choices on major strategic investments. APIF can potentially play a significant role in promoting this cooperation and exploring some of these strategic options.

3. BENEFITS OF ASTROPARTICLE PHYSICS TO OTHER SCIENCES AND SOCIETY

As presented in section 2, astroparticle physics addresses fundamental questions about the Cosmos, but it also excites public interest in science, motivates global coordination through the scale and the complexity of its large research infrastructures, and promotes new technologies and high level quality assurance procedures.

This section provides a few examples of the synergies that exist between astroparticle physics on one hand and other scientific disciplines and society in general on the other. Examples of applications of knowledge and instruments, as well as other benefits from astroparticle physics projects collected from various sources are given, with particular consideration to the following questions:

1. What is the impact on technology transfer?

2. What is the impact on other scientific disciplines?

3. What is the impact on society beyond science and technology?

3.1 Examples of impact on technology transfer

Extraction of Underground Argon and Helium (USA)

From a 2007 R&D award originally designed to search for underground argon which might be depleted in the radioactive argon isotope, ^{39}Ar, a unique new plant for extracting helium, ^{4}He, has been realised. The R&D effort, ongoing since 2008 for the collection of underground argon by the **DarkSide Dark Matter** collaboration at the carbon dioxide (CO_2) extraction plant owned by Kinder Morgan in Cortez, Colorado, resulted in the provision to Kinder Morgan of a 7-year monitoring of noble gases in the CO_2 stream. The monitoring results identified the presence of a valuable new source of helium. In June 2015, Air Products commenced production at its new Doe Canyon helium production facility in Colorado. Air Products Doe Canyon helium plant is the only one in the world extracting helium from a gas stream composed primarily of carbon dioxide. The plant is expected to produce up to 230 million standard cubic feet of helium per year, replacing more than 15 percent of the current United States Bureau of Land Management reserve helium supply as that system continues to decline.

Radiation Detectors based on Noble Gas (Switzerland)

Radioactive materials outside of regulatory control are an increasing threat to health (radioactive consumer goods, polluted neighbourhoods), business (endangered supply chain, plant shut-downs for decontamination, liability claims), and freedom (nuclear terrorism, dirty bomb threats). The Arktis Radiation Detectors Ltd Company has developed mobile radiation detection systems and radiation portal monitors based on noble gas detectors for homeland security (Arktis, 2016). The work started from the **Liquid Argon Dark Matter (ArDM)** project at the Swiss Federal Institute of Technology in Zurich (ETHZ).

Cyclotron Development (USA and Italy)

The development of high-power cyclotrons, such as that used for the **IsoDAR** project, which when coupled to the antineutrino detector, **KamLAND**, can be used for research on sterile neutrinos, is of great interest also for medicine and industry. This evolving research area provides an excellent example of synergy between the goals of fundamental physics research and the needs of society. Isotope production at hospitals and other facilities is an important and necessary resource for medical imaging and treatment.

This has motivated a close collaboration between laboratories, universities, and industry. As an example, the National Laboratories of Southern Italy, National Institute for Nuclear Physics (INFN-LNS), Catania, Italy, test-stand is drawing substantial support from the private sector. Best Medical Italy is actively contributing to the collaboration. The value to medical isotope production arises from two aspects of the test-stand. The first is the development of high-current proton beams which ultimately enhance the production rate of isotopes. The second is that the system being developed can accelerate any ion with the same charge-to-mass ratio as H_2^+, including He^{++} and deuterons. In particular, ^{211}At, a very powerful therapeutic agent, is optimally produced by 28 MeV alpha (He^{++}) beams. Its widespread clinical use is limited today only by the availability of production capacity. The test cyclotron developed in this project, coupled with an existing commercial ion source for doubly stripped helium ions, can immediately be applied to the production of this isotope (Aberle, et al., 2013; Alonso, 2012).

3.2 Examples of impact on other scientific disciplines

Seeing through the Earth's Interior with Cosmic Ray Muons (Japan)

What goes on in the Earth's interior? Geophysicists have taken advantage of cosmic ray muons to image the inside of an active volcano. A team at the **Earthquake Research Institute, University of Tokyo,** placed muon detectors on the side of Mt Asama and has recently succeeded in producing dynamic muographic images of the ascent and descent of magma during a volcano eruption. The detector captures magmatic movements inside a volcano, necessary for taking animated muographs. The research team proposes that this new animated muography technique will enable the development of a new volcano eruption monitoring system that improves on the accuracy of existing eruption prediction methods by real-time dynamic processing of data gathered using muography to create a three-dimensional visualisation of the volcanic interior (Tanaka, et al., 2009; Tanaka H. , 2012).

Atmospheric Monitoring (Argentina and Namibia)

The **Pierre Auger Observatory** and the **H.E.S.S. experiment** aim at understanding the nature and origin of ultra-high energy cosmic rays. Their instruments allow one to perform a number of studies on aerosols in the atmosphere. Modeling of aerosols in climate models is a challenging task, due to the lack of a complete global coverage of long-term ground-based measurements.

At the PAO, several facilities have been installed to monitor the aerosol component of the atmosphere. One uses laser tracks generated by the Central Laser Facility. The measured aerosol concentrations depict two notable features: a seasonal trend with a minimum reached in Austral winter and a quick increase occurring yearly just after August. The first feature can be explained by air masses transported from the Pacific Ocean and travelling above snowy soils to the observatory. The peak in September and October could be interpreted as air mass transport from biomass burning occurring in the north of South America (mainly in northern Argentina and Bolivia) during the dry season. However, another cause, such as air pollution transported from closer urban areas located north of the observatory, cannot yet be excluded.

In order to make the most efficient use of observational time, a smart scheduling scheme has been implemented in H.E.S.S.. In this scheme, two separate observation schedules are defined for observations that require excellent atmospheric conditions and those that do not (Collaboration & Curci, 2014; Hahn & Reyes, 2015).

Earth's Interior-geoneutrinos (Japan and Italy)

Geo-neutrinos are electron anti-neutrinos produced in the β decays of ^{40}K and several nuclides in the chains of the long-lived radioactive isotopes ^{238}U and ^{232}Th, which are naturally present in the Earth.

Information about the Earth's interior composition has so far come exclusively from indirect probes: seismology only constrains the density profile, while geochemistry offers previsions based on the chemical composition of rocks from the upper Earth layers, chondritic meteorites, and the photosphere of the Sun. Geo-neutrinos are unique direct messengers of the abundances and distribution of radioactive elements within our planet's interior. By measuring their flux and spectrum it is possible to assess the radiogenic contribution to the total heat balance of the Earth. These pieces of information are critical in understanding complex processes such as the generation of the Earth's magnetic field, mantle convection, and plate tectonics and of crucial importance for geophysical and geochemical models.

Measurements by the liquid scintillator detectors **BOREXINO** (Italy) and **KamLAND** (Japan) of geo-neutrinos provide direct evidence that radioactivity within the Earth is a major contributor to its internal heating. Preliminary evidence for the relative abundance of U and Th and the relative amounts of radioactivity in the mantle and crust will help geologists explain the history of the Earth.

These new techniques in neutrino detection opened a door into a new inter-disciplinary field of Neutrino Geoscience. The first indications of measurements of geo-neutrinos from the mantle, the indicative exclusion of the fully radiogenic Earth model, the invalidation of the geo-reactor in the Earth's core with power greater than a few terawatts (TW) and the indication of chondritic Th/U ratio are examples of the first geologically important results of this new inter-disciplinary field. All of these measurements need further confirmation with higher statistical significance. The awareness of the potential to study the inner parts of our planet with geo-neutrinos is increasing within both the geological and physical scientific communities (Araki, et al., 2005; Borexino cooperation, et al., 2015; Sinev, 2010).

3.3 Examples of impact on society beyond science and technology

Railway Safety (Argentina and UK)

One of the challenges faced in creating the **Pierre Auger Observatory** was how to collect data from more than 1600 water-Cherenkov detectors deployed on a 1500 m grid in a remote part of Argentina’s Mendoza Province. It was necessary to identify occurrences of cosmic-ray signals within a few microseconds of each other at three or more adjacent detectors with a 3 W power budget at each station. The communication between the data centre and the individual detectors and the readout of the detectors required purpose-built instrumentation. A cutting-edge system was developed by a group of electronic engineers and physicists from the University of Leeds (UK) using ideas adapted from mobile-phone technology.

Building upon the success of the communication system for cosmic-ray research, one of the leaders of the effort, Paul Clark, set up his own company, Comms Design Ltd. Its first contract with Network Rail used the concepts developed for the Pierre Auger Observatory to make the single-track rail lines in the Scottish Highlands safer and more reliable. The outdated Radio Electronic Token Block (RETB) system then in use was upgraded and since November 2010 the new RETB radio system has been deployed over more than 700 km of track in rural areas following extensive tests and after gaining the necessary approval certificates. The total potential benefit is hard to quantify, but the cost of the new RETB system is approximately 10% of that of conventional signaling. The new design is “infrastructure-light” in terms of trackside equipment and cabling, and also sidesteps the growing problem of cable theft that plagues modern railways. This may make an RETB-like system attractive for all railway lines – not only the remote, single-line tracks. The new hardware will also likely be used in other areas of the UK, and might well become the standard for the next 30 years (Institute of Physics, 2015).

Collection, Study and Use of Ancient Lead (Italy)

The National Laboratory of Gran Sasso (Italy) recently received 120 lead bricks that are about 2000 years old and were recovered undersea 20 years ago. The Roman lead is already employed to shield experiments of extreme precision such as **the Neutrinoless Double Beta Decay CUORE experiment**.

Due to its high atomic number, reasonable cost, good mechanical properties and low activation cross section for environmental neutrons, lead is an excellent shielding material. However, ^{210}Pb represents an important component of environmental radioactivity via its beta decay. In common lead used in underground experiments this contamination is normally around 200 Bq/kg. ^{210}Pb is expected to be totally absent in ancient lead such as found in wrecks of Roman ships sunk in the Mediterranean Sea or near Britain.

The CUORE lead is from a Roman “navis oneraria magna” ship specialised in the transport of lead and sunk between 50 and 80 B.C. off the coast of Sardinia. On the basis of an agreement between the Archaeological Superintendence of Cagliari and INFN, about 1000 ingots of lead of 33 kg each were extracted in a campaign of diving expeditions funded by INFN in collaboration with the archaeological heritage ministry. Each of the lead ingots has a unique stamp that records some of its manufacturing history: the name of the Roman who cast it. These inscriptions are priceless archaeological sources, and are being studied at the National Archaeological Museum in Cagliari, southern Sardinia. They were given to INFN with the requirements to save the beautiful Roman inscription (“cartiglio”) on their top and to apply advanced instrumentation to determine the archeological origin of the Roman lead. The bolometric analysis of the content of ^{210}Pb in Roman lead shows that its contribution to radioactivity is less than a few mBq, five orders of magnitude lower than in common lead and two orders lower than for the best specially prepared commercial lead (Nosengo, 2010).

Concluding comments

Astroparticle physics is fundamental discovery research, whose motivation is to expand our knowledge and understanding. However, it is also at the frontier of technological development and, whilst this is primarily motivated by experimental needs, there are significant spill-overs for industry, society and other areas of research. This is illustrated by the few examples that have been highlighted here by APIF members but there are many, many more that could have been selected. By definition, these beneficial spill-overs are hard to predict beforehand but they can be encouraged by building good international and inter-agency relationships. APIF has a potentially important role to play in strengthening these relationships and the associated exchange of knowledge and experience.

APPENDIX 1. TERMS OF REFERENCE FOR APIF, 2011-2016

The original terms of reference for APIF are defined in the following extract from the Report of the OECD-GSF Working Group on Astroparticle Physics (OECD, 2011):

To address the policy challenges enumerated above in each of the six scientific domains of astroparticle physics, the Working Group recommends the establishment of a venue for consultations among officials of funding agencies that make significant investments in the field. The overall goal should be to ensure that, during the next 10-15 years, progress in astroparticle physics will be a globally coherent response to the scientific challenges, using an optimal set of national, regional, and international projects. The new consultative group would be called the Astroparticle Physics International Forum (APIF), and would be a subsidiary body of the OECD Global Science Forum. Funding agency officials would be nominated by the delegations to the GSF, and by the governments of interested non-OECD member countries. Once the nominations were accepted by the GSF, all members of APIF could participate in the activities with identical rights and standing. APIF would be created for a period of three years. It would meet at least once per year, elect its own Chair and other officers, define its own rules and procedures, establish subsidiary bodies as needed, and be self-financing. The members of APIF would report to their respective agencies, and the APIF Chair would report annually to the Global Science Forum. When necessary, APIF could request a modest level of in-kind support from the GSF secretariat.

The activities of APIF could include, inter alia:

1. Exchange information about relevant national and regional developments, plans and priorities. Regularly review and update the strategic vision described in the OECD report.
2. Explore the prospects for joint actions (for example, design studies for experiments, research and development) with special emphasis on large programmes and projects.
3. Study options and solutions for governance structures and mechanisms for potential new international collaborative projects.
4. Consult on relevant generic science policy issues, such as access to research facilities and to data, or contributions to operating costs of facilities by users.
5. Analyse the needs and requirements for rare resources such as isotopes for detectors and, if appropriate, promote sharing or joint procurements. Discuss the optimal utilisation of infrastructures (observatories, antennas, underground laboratories).
6. Engage in a collective dialogue with governmental and non-governmental entities in areas that have a strong impact on astroparticle physics, for example, space agencies, and agencies that are responsible for research in high-energy physics, nuclear physics, astronomy and astrophysics.
7. Develop strategies and procedures for promoting transfer of technology and other benefits to industry and to society in general. Jointly develop educational and outreach materials.

The activities of APIF would not pre-empt or interfere with national or regional mechanisms for planning, prioritising, authorising, funding or overseeing specific research projects. Negotiations for new international collaborations could begin in APIF, but would be pursued in other venues.

As needed, APIF would seek information and advice from the international scientific community. It could invite individual experts, spokespersons of projects or members of scientific bodies (e.g., scientific unions or national advisory groups) to attend APIF meetings or to participate in subsidiary activities. It could commission analyses and reports from scientific groups.

APPENDIX 2. THE ASTROPARTICLE PHYSICS INTERNATIONAL FORUM AGREEMENT, 2017 ONWARDS

Whereas, the Astroparticle Physics International Forum (hereafter APIF) was established by the Global Science Forum (hereafter GSF), a subsidiary body of the Organisation for Economic Cooperation and Development (hereafter OECD), in response to one of the policy recommendations in the OECD GSF Report of the Working Group on Astroparticle Physics of 31 March 2011;

Whereas, as of October 2016, APIF has held 12 meetings biannually on a rotating regional basis, since the first meeting in Paris, April 2011;

Whereas, hosting and support from the GSF to APIF will end on 31 December 2016;

The APIF participants (see Annex) have agreed, as follows:

ARTICLE 1 – SCOPE OF THE AGREEMENT

1. The purpose of this agreement is to establish arrangements for continuing the activities of APIF beyond 2016 on an independent basis.

ARTICLE 2 – OBJECTIVES OF APIF

2. APIF serves as a venue for exchange of information and consultation on astroparticle physics, including, inter alia, dark matter, dark energy, cosmic microwave background, high-energy messengers (including charged particles, gamma rays and neutrinos), gravitational waves, proton decay and neutrino mixing, and neutrino mass.

3. To that effect, APIF serves as a venue for:

Sharing information on the priorities, programs and constraints of different countries, including strategic goals, budgets and project status;

Making information available to national funding agencies and responsible national bodies on scientific progress, new opportunities and R&D in astroparticle physics;

Improving the possibilities for international cooperation by understanding the planning processes, roadmaps and interests of national funding agencies and responsible national bodies in different countries;

Promoting knowledge of the applications of the techniques developed for large astroparticle physics facilities, both in other scientific areas and in industry; and

Considering science policy issues relevant to astroparticle physics, such as access to facilities and data, publishing of results, and management of large facilities.

ARTICLE 3 – ACTIVITIES OF APIF

4. APIF's activities include, inter alia:

Meetings: APIF will normally meet twice yearly on a rotating regional basis, and visit major astroparticle physics facilities at the meetings, where feasible and appropriate.

Reports: APIF may issue occasional reports on matters of importance to astroparticle physics.

5. The activities undertaken in the framework of APIF shall not pre-empt or interfere with national, regional or international mechanisms for planning, prioritising, authorising, funding or overseeing specific research projects.

ARTICLE 4 – PARTICIPATION IN APIF

6. Participation in APIF is open to individuals nominated by national funding agencies or ministries with responsibility for astroparticle physics.

7. The initial APIF participants are those individuals who actively participated as national representatives in the meetings of APIF under the framework of the OECD GSF, as attached in the Annex.

8. With respect to new APIF participants, national funding agencies or ministries may nominate individuals on their own initiative or on the invitation of the APIF participants acting by consensus. Such nominees must be approved by the APIF participants by consensus. Approved nominees shall become participants upon their signature/endorsement of the present agreement. Endorsement shall be communicated to the chairperson in writing who shall inform all participants.

9. In exceptional circumstances, substitutes for individual meetings may be approved by the chairperson.

10. APIF participants should have a good knowledge of strategies, policies and programmes in astroparticle physics in their countries.

11. The number of nominees of each country will depend on respective administrative structures, division of responsibilities and scale of investment in astroparticle physics and will be agreed by consensus of APIF participants. A maximum of three participants per country is normally allowed.

12. Any APIF participant, after consultation with his/her national nominating agency or ministry, may terminate his/her participation by advising the chairperson and secretariat in writing of the intention to do so three months prior to the next APIF meeting.

13. Participation in APIF is voluntary with no dues being requested. It is expected that the costs of participation in APIF activities for APIF participants will be covered by their nominating national funding agencies or ministries.

14. APIF participants may define collectively their operating rules and procedures as necessary.

ARTICLE 5 – APIF CHAIRPERSON AND SECRETARIAT

15. APIF will elect its chairperson. Any APIF participant can make a nomination for chairperson, which will entail also a commitment to provide the secretariat if one's nominee is elected. The chairperson will normally serve for three years.

16. The function of the secretariat will be to cover the organisational and logistical issues related to meetings, compilation and dissemination of any reports, and maintenance of a dedicated website.

ARTICLE 6 – OBSERVERSHIP IN APIF

17. International organisations or entities, with significant investments or interests in astroparticle physics, may be invited to nominate representatives to attend APIF meetings as observers. Observers shall be agreed by consensus among APIF participants.

18. Individual experts, members of scientific bodies or programmes may be invited as guests to attend specific APIF meetings or for specific agenda items.

ARTICLE 7 – STATUS OF THE AGREEMENT

19. This agreement is not legally binding, and does not create enforceable rights and obligations. The participants undertake to use reasonable efforts to perform and fulfil promptly, actively and on time all necessary actions to realise the purpose of this agreement, always subject to the availability of resources.

20. This agreement will enter into effect on 1 January 2017 for participants included in the Annex. Thereafter, the agreement will enter into effect for new participants after acceptance by the existing APIF participants of their nomination and endorsement of the agreement.

21. This agreement may be modified at any time by a consensus of APIF participants, and will be reviewed every 3 years.

22. This agreement may be terminated at any stage by a two thirds vote of APIF participants.

ANNEX. LIST OF THE INITIAL 2017 APIF PARTICIPANTS

Country	**Name**	**Organization**
Brazil	Ronald Cintra Shellard	Brazilian Center for Research in Physics
China	Hesheng Chen	Institute of High Energy Physics, Chinese Academy of Science
European Commission*	Keji Adunmo	Directorate-General Research & Innovation, European Commission
France	Philippe Chomaz	Fundamental Research Division, Alternative Energies and Atomic Energy Commission (CEA)
	Reynald Pain	The CNRS National Institute of Nuclear and Particle Physics (IN2P3)
Germany	Marc Hempel	Projektträger, German Electron Synchrotron (DESY), Federal Ministry of Education and Research (BMBF)
	Hans-Jürgen Donath (or replacement tbc)	German Electron Synchrotron (DESY), Federal Ministry of Education and Research (BMBF)
India	Naba Mondal	Tata Institute of Fundamental Research
Israel	Fadil Salih	Applied Physics and Mathematics, Ministry of Science, Technology and Space
Italy	Antonio Masiero	National Institute for Nuclear Physics (INFN)
Japan	Yoichiro Suzuki	Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo
	Toshikazu Ebisuzaki	Computational Astrophysics Laboratory, Rikagaku Kenkyūsho (RIKEN)
	Kunihiko Sasaki	Scientific Research Institutes Division, Ministry of Education, Culture, Sports, Science and Technology (MEXT)
Korea	Yeongduk Kim	Center for Underground Physics
	Sun Kun Oh	Konkuk University
Netherlands	Stan Bentvelsen	National Institute for Subatomic Physics (Nikhef)
Spain	Manel Martinez	Institute for High Energy Physics
Sweden	Mats Johnsson	Ministry of Education and Research
Switzerland	Maurice Bourquin	University of Geneva
	Bruno H. Moor	Federal Department of Economic Affairs, Education and Research
South Africa	Lerothodi Leeuw	University of South Africa
United Kingdom	Janet Seed	Science and Technology Facilities Council
United States	Vernon Jones	National Aeronautics and Space Administration
	Kathy Turner	Department of Energy
	Jim Whitmore	National Science Foundation

*As observer

APPENDIX 3. A LIST OF APIF MEETINGS AND VENUES, 2011-2016

	Date	**Venue**	**Research Infrastructures Visited**
1st APIF Meeting	April 4-5, 2011	OECD Headquarters, Paris, France	/
2nd APIF Meeting	October 10-11, 2011	OECD Headquarters, Paris, France	/
3rd APIF Meeting	April 26-27, 2012	Institute of Physics, London, UK	/
4th APIF Meeting	October 15-17, 2012	Sudbury, Canada	Sudbury Neutrino Observatory and Science North
5th APIF Meeting	April 19-20, 2013	Pisa, Italy	VIRGO, European Gravitational Observatory
6th APIF Meeting	October 28-29, 2013	Toyama, Japan	Kamioka Laboratory and Japan Proton Accelerator Research Complex
7th APIF Meeting	May 15-16, 2014	Paris and Saclay, France	Installations relevant to Astroparticle physics and Cosmology in Saclay
8th APIF Meeting	December 3-4, 2014	Baton Rouge and Livingston, USA	Laser Interferometer Gravitational Wave Observatory
9th APIF Meeting	May 11-12, 2015	Institute of High Energy Physics, Beijing, China	Large Sky Area Multi-Object Fiber Spectroscopic Telescope
10th APIF Meeting	November 19-20, 2015	Rome and Gran Sasso, Italy	Gran Sasso National Laboratory
11th APIF Meeting	May 9-11, 2016	Seoul, Korea	Korea Invisible Mass Search, Yangyang site
12th APIF Meeting	October 10-12, 2016	OECD Headquarters, Paris, France	The Astroparticle and Cosmology (APC) laboratory, CEA Saclay and IAS.

NOTES

1. Canada was one of the original members but withdrew in 2013.
2. Argentina, Belgium, Brazil, China, European Commission, France, Germany, India, Israel, Italy, Japan, Korea, Netherlands, Poland, South Africa, Spain, Sweden, Switzerland, United Kingdom, United States.
3. Including Paris, London, Sudbury, Pisa, Toyama, Paris and Saclay, Baton Rouge and Livingston, Beijing, Rome and Seoul. A list of APIF meetings and venues is included in Appendix 3.

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