Scientific Advisory Committee
APPEC, June 18-19, 2019
CERN, Geneva, Switzerland

Draft Agenda

Meeting venue: CERN, Room C (61-1-009) which is located in the Main Building in the Pas perdus.

Part I: Tuesday 18 June 14.00-18.30 hrs (welcome from 13.30 hrs)

1. Adoption of the Agenda **5'**

2. Minutes SAC meeting 5 November 2018 (see doc 02.1) **5'**

3. Announcements from APPEC-GA **10'**

- Approved working plan 2018-2020 (December 2018, see doc 03.1)
- New requests from APPEC-GA (May 2019)
  APPEC-GA suggests to add to the working plan of the SAC the following items:
  - *Status CMB-developments and possible next steps*
  - *Feedback on Outline APP-GEO roadmap*
  - *Proposal for regular Town meetings (including role of SAC)*
  - *Assessment of the GWIC Science case report for 3G GW detectors*
- SAC composition renewal
  Before the summer break a call for nominations for 5 new SAC members will be sent to APPEC GA and APPEC SAC. A renewal proposal will be discussed in APPEC SAC and then be sent to APPEC GA for approval in December 2019.

4. Preparation mandate and composition for a DM committee **60'**

- Introduction, draft composition, comments on draft mandate (see doc 04.1)
- Draft mandate (see doc 04.2)
- Discussion and conclusions

Coffee and Tea Break **30'**

5. Status CMB-developments and possible next steps **45'**

- Latest draft white paper (see doc 05.1) and intro by Ken Ganga
  aim: to keep fostering the activities on CMB, to understand how APPEC can consolidate the roadmap for the community and to understand how to use what we achieved after the meetings series in Florence that where sponsored by APPEC.
- Discussion
- Conclusions and follow-up

6. Proposal APPEC Town meetings **30'**

- Proposal APPEC-GA for regular Town Meetings (see doc 06.1)
- Discussion
- Conclusions

7. Towards a APP-GEO roadmap? 30'

- Workshop on Observatory Synergies for Astroparticle Physics and Geoscience: summary and outlook (see doc 07.1)
- Outline for a common APP-GEO roadmap with GA request for SAC feedback (see doc 07.2)
- Discussion
- Feedback to GA

8. Assessment of the GWIC Science case report for 3G GW detectors 30'

Short presentation (De Kleuver) followed by discussion per topic:

- Draft GWIC Science case report for 3G GW detectors
  https://gwic.ligo.org/3Gsubcomm/documents/3G-observatory-science-case.pdfb
- Request for assessment by APPEC-GA and GWAC in the next months
- Discussion and follow-up actions

9. Other topics 20'

Short presentation (De Kleuver) and discussion:

- ATF topics: plans for 2019/2020
- EuCAPT: status update
- ….

Dinner 19.30 Pizzeria Restaurant de la Place, Route de Meyrin 286, Meyrin
http://www.pizzeria-restaurant-laplace.ch/

Part II: Wednesday 19 June 9.00-12.00 hrs

10. Draft report Neutrinoless double beta decay committee 60'

- Executive Summary (see doc 10.1) and Draft report (doc 10.2, will follow later)
- Presentation by Silvia Pascoli, chair of the committee
- Discussion
- Conclusions: input for final report and next steps

Coffee and Tea break 30'

11. Input/influence European PP strategy update 60'

- Impressions APPEC chair (doc 11.1, will follow later) and others
- Next steps
- Discussion
- Conclusions and follow-up

12. AOB 15'

- Next meeting Location and date next meeting: before GA meeting, or connected to GA?

Closing of the meeting (12:00)

Minutes
APPEC SAC meeting
November 5th 2018, 10:10-16:00
Zürich, Switzerland

Present
Laura Baudis (chair), Jocelyn Monroe (vice chair), Paula Chadwick, Ken Ganga, Sijbrand de Jong, Job de Kleuver (APPEC General Secretary, support to SAC), Ofer Lahav, Manfred Lindner, Antonio Masiero (APPEC chair), Mauro Mazzeto, Ramon Miquel, Marco Pallavicini, Sergey Troitsky, Marco Zito.

Apologies
We received apologies for their absence from Gisela Anton, Karsten Danzmann, Jo van den Brand.

Items		**To Do´s:**
1. Adoption of the Agenda	Laura Baudis opened the meeting. The agenda was adopted.	
2. Installation of the renewed SAC	On behalf of the APPEC-GA Job de Kleuver formally installed the renewed SAC. The APPEC-GA appreciates the efforts of the SAC members and hopes for a fruitful collaboration to strengthen the European Astroparticle Physics. A short tour the table was made.	
3. Short overview APPEC Roadmap	• Antonio Masiero gave an overview of the APPEC Strategy and the recommendations that are APPEC's focus in the coming years. • The money plot presents only the regular investments of the APPEC members (M€ 80/year). In addition there are opportunities for funding from regional funds, EU, Astro, PP, etc. Maybe APPEC could benefit from informal talks to align the agencies. CERN has good experiences with that. • Antonio stressed that the SAC is an scientific committee of experts, not a political body of countries. Advices and input from the SAC that is not biased by agencies and policy will be very helpful for the APPEC-GA.	
4. Draft mandate APPEC SAC	The first draft of the SAC mandate document was discussed. The document will be split in a SAC mandate/regulation and in a list of topics to be discussed in the coming years. Topics GA need a clear description and a deadline and can be added by GA (as suggested in the draft document) or SAC (in the meeting were mentioned various topics). Job will edit the document and send it around for last feedback before it will be sent to APPEC GA for approval in December.	Job

Items		To Do´s:
5. Draft input document APPEC for European PP strategy update	• A small committee of GA members is preparing a draft input document for the European PP strategy update. A first draft was discussed by the SAC. • It was agreed that SAC would check their comments once again and add via email additional comments if any within a week. The SAC will send these comments and suggestions to Antonio and Job (cc SAC) as soon as possible, but before 12 November • Antonio will include these comments in the new draft that will be sent to APPEC GA and SAC (again) for feedback. • The final draft will be sent to APPEC GA for approval on 14 December.	SAC < 12-11-18 Antonio Job
6. Draft mandate bb-committee	• The draft mandate for a bb-committee was discussed. It was agreed that the committee should be enlarged with at least a non-expert chair and not only have experts from each experiment. It was suggested to add to the aims to do a reality check for the future plans (TDR, budget, planning, support, etc.). A good relation and contact to the DOE committee is needed. • The SAC members will sent last comments on the draft mandate and suggestions for a chair or other additional members to Laura before 15 November. • Laura will prepare the final draft and composition of the committee and send it to Job for approval by APPEC GA in December.	SAC < 12-11-18 Laura Job
7. Preparation mandate for a DM committee	• It was decided to prepare a mandate for a DM committee, directly after finalizing the mandate for the bb-committee. The format of the bb-committee will be followed. • Laura will prepare the draft mandate. • SAC members will send suggestions for members and an non-expert chair before 1 December.	Laura SAC < 1-12-18
8. Discussion on other topics in the new SAC mandate	• Most of the topics were already discussed in agenda item 4. • The SAC was informed by Antonio about the EuCAPT Theory Center proposal. The aim is to coordinate and to prevent overlaps in the various APP theory meetings all over Europe. The SAC supports coordination and stimulation of collaboration of existing activities. • The SAC supports the idea to have a joint meeting with the APPEC GA in 2019.	Job
9. Practical organisation APPEC-SAC (meetings)	• The frequency of SAC meetings will be two per year and if necessary more. In between topics can be discussed by email. • The SAC prefers a noon-to-noon meeting, including an informal dinner. • The minutes of meetings will contain mainly conclusions and action items (no written report of all discussions and	

Items		**To Do´s:**
	details). • Part of the SAC will be renewed by the end of 2019. The GA will send a request for nominations for new members early 2019. The SAC will be consulted in that process too. • For the next meeting the chair of the bb-committee will be invited to discuss the draft report and progress of the committee. • Next time we will use Indico for the agenda of the meeting. • The next meeting will be in May or early June 2019. If possible it will be connected to the PP town meeting in Grenada. Job will contact Antonio Bueno. If this is no option the location will be Paris or London.	Laura/Job Job/Laura Job
10. AOB	• This was Antonio Masiero's last SAC meeting. His term as GA chair ends in December 2018. The SAC thanked Antonio for all his efforts as former chair of the SAC and as GA chair.	
Closing of the meeting	The meeting was closed at 16.00 hrs.	

APPEC-SAC working plan
concerning implementation roadmap and more..
December 2018

Introduction
The new APPEC strategy was launched in January 2018 and includes 21 recommendations of which 10 are focused on scientific topics. The APPEC SAC is an important advisory body of the APPEC General Assembly on these topics. The composition of the APPEC SAC is renewed (see below) and a new chair (Laura Baudis) and vice chair (Jocelyn Monroe) were appointed by the APPEC GA in June 2018.
In consultation with the SAC a renewed mandate was formulated (see below) and also a draft working plan. Both need approval by APPEC GA in December 2018.

SAC present composition
Laura Baudis, chair (until December 2020)
Jocelyn Monroe, vice chair (until December 2020)

Member until December 2021:
Sijbrand de Jong, Paula Chadwick, Karsten Danzmann, Marco Pallavicini, Ofer Lahav, Ken Ganga, Manfred Lindner, Sergey Troitsky

Member until December 2019:
Gisela Anton, Jo van den Brand, Marco Zito, Mauro Mezetto, Ramon Miquel

SAC is supported from the APPEC workforce by Job de Kleuver.

SAC composition renewal
Early 2019 a call for nominations for new SAC members will be sent to APPEC GA and APPEC SAC. A renewal proposal will be discussed in APPEC SAC and then be sent to APPEC GA for approval before summer 2019.

SAC mandate
A renewed mandate for APPEC-SAC is attached after consultation of the APPEC-SAC. This SAC mandate is sent to APPEC GA for approval in December 2018.

SAC working plan 2018-2020
Both APPEC GA and APPEC SAC can add items to the APPEC SAC working plan.

<u>Advice requests from APPEC GA:</u>
- Comments on APPEC document for European Particle Physics Strategy Update; deadlines: half November and 4 December 2018
- Gravitational Waves (scientific aspects of GW and 3rd generation detector developments); deadline: depends on developments in GWIC and for ESFRI proposal ET

- Neutrino less double beta decay;
  deadline mandate for bb-subcommittee: 1 December 2018
  deadline report: summer 2019
- Dark Matter searches;
  deadline mandate and composition sub-committee DM: early 2019
  deadline report: fall 2019
- Midterm review APPEC Roadmap
  deadline summer/fall 2020 => town meeting in 2nd half of 2020?

Topics mentioned by SAC that should probably also be on the action list

- Suggestions for new common call themes
- Suggestions for themes APPEC Technology For a
- Balance in APP between big projects, small projects, longterm R&D and Computing
- Topics for a joint GA-SAC meeting in 2019
- Computing and software technology
- Progress APP theory center organisation EuCAPT (cf. needs by theory community)
- ……

This working plan is sent to APPEC GA for approval in December 2018.

APPEC SAC - summer 2018

COUNTRY	Cosmic rays	High-Energy Photons	Ultra-High Energy neutrinos	Gravitational waves	Neutrino Properties	Neutrino Mass	Dark Matter	Dark Energy	Cosmology CMB	Theory
Belgium										
France					Marco Zito				Ken Ganga	
Germany			Gisela Anton	Karsten Danzmann						Manfred Lindner
Italy					Marco Pallavicini	Mauro Mezzeto				
Ireland										
Netherlands	Sijbrand de Jong			Jo van den Brand						
Poland										
Russia										Sergey Troitsky
Spain									Ramon Miquel	
Sweden										
Switzerland							Laura Baudis			
UK		Paula Chadwick					Jocelyn Monroe	Ofer Lahav		
China										
USA/Canada										
CERN										

Green	new member from June 2018
Black	current member (will be replaced in fall 2019)

DM committee: draft mandate and composition committee

May/June 2019

Introduction
In our last SAC meeting it was decided to prepare a mandate for a DM committee, after finalizing the mandate for the bb-committee. The format of the bb-committee will be followed. Laura and Jocelyn have prepared the draft mandate, following the format of the double beta mandate (see attachment doc 04.2) and also a draft proposal for the composition of a DM committee (see below).

The next steps are now 1) discussion and approval of the drafts by the SAC, 2) approval by APPEC General Assembly and then 3) start of committee.

Draft Mandate
The draft mandate was sent by email to you a few weeks ago and I collected your comments in the appendix to this document, hoping this stimulates the discussion.

Proposal composition DM committee
Here is the proposal for the committee composition:
1. is first person to invite, 2. is to invite if #1 declines.

<u>Chair:</u>
1. Leszek Roszkowski (Poland, UK), 2. Riccardo Catena (Sweden)

<u>Members:</u>
Axions: Bela Majorovits (Germany)
LAr: Giuliana Fiorillo (Italy)
LXe (Europe): Mark Schumann (Germany)
LXe (US programme): 1. Kimberly Palladino (US), 2. Asher Kaboth (UK)
Crystals: Susana Cebrian (Spain)
Germanium: 1. Federica Petricca (Germany), 2. Karolina Scheffner (Italy)
Silicon: Ben Kilminster (CH)
Theory: 1. Veronica Sanz (UK), 2. Laura Covi (Germany)

APPENDIX: email comments to the draft DM mandate

The idea of a DM taskforce seems a very good idea to me. The proposed members seems to me ok, but I am not a DM expert, so this is a somewhat superficial opinion.

I have some problems with the mandate. Although it obviously lists many important angles to look at the issue, for me it lacks precision.

Just some of the shorter ones:
"Examine the systematic errors, including uncertainties due to nuclear physics." which technically could render the valid answer: *"we examined them"*.
It would be better to ask what you want to know: what are the systematic errors or each type of experiment ? Are they limiting the ultimate performance ? How could they be improved in present methods, or which new methods could be devised with smaller uncertainties ?

Maybe a bit a naive question: why should we not strive to have a sensitivity under the so called neutrino floor? Finally something that could be measured and used to experimentally test de predicted sensitivity of the apparatuses.
Can't the neutrino background not be subtracted to get a sensitivity below the neutrino floor?

The last sentence in the but-last paragraph seems to reveal an agenda:
"It should become evident that the dark matter physics program plays an important role in attracting highly qualified researchers to the field."
What if this is not the case? Has the committee then failed?

On general grounds, I think that both document and proposed list of members are somewhat too much WIMP oriented. If I see a good reason to have such a high level committee at work, is that of exploring options out of the well established mainstream.
Besides, DAMA result should be an element of the debate, until it is proved to be wrong or its signal is credibly explained by a non-dark-matter-related phenomena (which both are not the case, so far).

Do we all believe that this committee could have a significant impact on the DM search strategy in coming years? If yes, then I fully agree with Manfred that (1) it deserves a more detailed discussion and (2) it should contain more independent experts and not representatives of particular experimental projects.

In addition, we are witnessing a very complicated phase in DM searches, with WIMPs becoming a good option but not the one singled out among a plethora of other possibilities. I was glad to discover that many people in the community share, to various extents, this opinion and some even publish it as a short review in Nature [A new era in the search for dark matter, by G. Bertone and T.M.P.Tait, Nature 562 (2018) no.7725, 51-56, DOI: 10.1038/s41586-018-0542-z]. The same point was mentioned by someone also at the previous APPEC SAC meeting in which I participated by Skype. I expect that in future this might become even more important. In this context, there are two points to discuss:

(1) shall the mandate be concentrated on direct searches only, or include all the approaches, including indirect, collider, and astrophysics;
(2) shall the committee personal composition be less WIMP-oriented?

I would propose to invite more theoretical physicists to the committee, here are a few potential candidates:
Malcolm Fairbairn (King's College, London)
https://inspirehep.net/search?ln=en&p=find+a+fairbairn%2C+m
Sergei Sibiryakov (CERN+EPFL, Lausanne)
https://inspirehep.net/search?ln=en&ln=en&p=find+a+sibiryakov%2C+s
Gianfranco Bertone (GRAPPA, Amsterdam)
https://inspirehep.net/search?ln=en&ln=en&p=find+a+bertone%2C+g
Dmitry Gorbunov (INR, Moscow)
https://inspirehep.net/search?ln=en&ln=en&p=find+a+gorbunov%2C+d
Of course I did not discuss with them whether they would agree or not.

It is a good draft, but it is also important and I would recommend therefore that we have a good in person discussion with all SAC members in the upcoming SAC meeting at CERN. Or is there an urgency that would not allow to wait until then? There are various aspects which deserve good attention to get the best scientific advice. Examples are if if it is optimal to ask for advice from a collection of proponents of projects or if it is better to include wider advice from topical experts that are more independent. We should also discuss and agree what the report of such a committee implies for the work of the SAC. There are a number of other aspects that deserve to be discussed a bit more such that we arrive at the best scientific advice.

I don't have much to add (or subtract) from the draft. I would, however, ask that the first sentence be "tweaked" a bit. I would suggest changing from
While there is ample indirect evidence for dark matter via its gravitational interaction with visible matter, its nature at the microscopic level remains unknown.

to something more like
While there is ample indirect evidence for dark matter via its gravitational interaction with matter on astrophysical scales, its nature at the microscopic level remains unknown.

The reason being that the CMB is (at least formally) just about the best indication of matter, and it's not visible. Similar arguments can be made for galaxy lensing now. So the easiest thing is just to figure out an elegant way to remove the word "visible".

I support the idea of setting up a DM committee, I approve the draft mandate and the draft list of candidates for the committee.

If you need a second option for the LXe (Europe) expert I would propose Christian Weinheimer from Munster University, Germany.

APPEC SAC Document, April 18, 2019

Mandate to the dark matter detection committee

While there is ample indirect evidence for dark matter via its gravitational interaction with visible matter, its nature at the microscopic level remains unknown. The goal to discover non-gravitational interactions of dark matter (DM) is by now a global effort, and many avenues are being pursued. Direct detection experiments which look for low-energy scatters of Weakly Interacting Massive Particles (WIMPs) off nuclei, as well as scatters and absorption of dark photons and axion-like particles, have reached ever increasing sensitivities and are operated in underground laboratories around the world.

Europe is leading the search with experiments covering both low-mass and the high-mass DM region. Worldwide, the current sensitivity of searches at masses above 6 GeV is probed by liquid xenon experiments such as LUX, PandaX-II, and XENON1T, and by liquid argon detectors such as DEAP-3600 and DarkSide-50. The lower DM mass region is mostly explored with experiments using crystals operated at mK temperatures (CRESST, EDELWEISS, SuperCDMS) and silicon CCDs (DAMIC, SENSEI). Recently it was realised that direct detection experiments, including argon detectors such as DarkSide-50, as well as xenon detectors, can probe much lower DM masses via DM-electron interactions. Near-future and next-generation liquefied noble gas TPCs using argon (such as DarkSide-20k) and xenon (such as LZ, XENONnT and DARWIN) will probe the WIMP parameter space with unprecedented precision, while also being sensitive to light dark matter particles via DM-electron scattering, and to ALPs and dark photons via the axio-electric effect. Europe is also leading experiments to look for solar axions and galactic axion-like particles, uich as ALPs at DESY, CAST at CERN, and the proposed MADMAX and IAXO projects.

The new APPEC roadmap mentions the search for non-gravitational interaction of dark matter particles with high-priority. To aid in the future discussions and devise more concrete recommendations, the APPEC GA has appointed a committee of experts in the field[1], with expertise covering the various technologies. Here we draft a mandate for this committee, with the goal of defining: aims, expectations, deliverables, deadlines and a chair of the committee.

The Dark Matter Search APPEC Committee (DMSAC) should advise APPEC on the European (and international) programme in dark matter search physics. It should report to the APPEC SAC, providing an assessment of the current and future scientific opportunities in non-accelerator dark matter searches over the next 10 year period. The concrete aims are:

- A SWOT analysis of various technologies with the potential to surpass current sensitivities by a non negligible factor in few years; an assessment on how existing, planned and proposed technologies and how these compare with one another. The committee should thus first assess the status of ongoing and planned experiments, including major technical challenges and a comparison of their discovery potential. Then the committee should assess the potential of proposed and future technologies, assess their challenges and risks and upgradability and their potential to probe the parameter space down to the so-called neutrino floor, and eventually beyond. The status of ongoing R&D for next-generation experiments should also be discussed.
- Examine the systematic errors, including uncertainties due to nuclear physics.
- Synergies with other experiments of indirect, accelerator and cosmology dark matter searches should be considered, including possible technical and R&D synergies, e.g with CERN.

[1]The committee members are: xxx, yyy, zzz, etc

- Critical examination of the resources vs schedule that would ensure the due scientific advancement and discovery potential.
- Assessment of the required infrastructure in Europe, including maintenance and upgrades of existing facilities.
- Assessment of other physics channels that can be explored with future direct detection detectors.

We ask that the recommended programs should be implementable under reasonable assumptions. The report should also provide a discussion about possible international partnerships, and how the European programme may be complemented with experiments outside of APPEC. We would also appreciate if the report can inform the scientific discussions and questions that drive the dark matter field in a fashion which is accessible to non-specialists, mention the broader impacts of low-background physics and rare-event searches, and the relevance of the programme in the training of next-generation of researchers. It should become evident that the dark matter physics program plays an important role in attracting highly qualified researchers to the field.

The APPEC SAC would appreciate the committee's comments by end of November 2019 (?), and a final report by mid-May 2020. The report will be an essential input to planning within APPEC of the European future in dark matter physics.

European Cosmic Microwave Background Studies: Context and Roadmap

A list of contributors can be found in the appendix.

September 17, 2018

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1 Introductory Summary

The Cosmic Microwave Background has been one of the primary drivers behind the advent of so-called precision cosmology. Europe in general, and the Planck Satellite in particular, has recently played a large role in the field. But as with any endeavor, planning and investment must be maintained in order to ensure that the European CMB community continues to thrive. The European CMB Co-ordinators have taken it upon themselves to proselytize for such planning. With this *Florence Process*, we attempt to inventory the community's priorities and to clearly present them in order to help with resource prioritization.

There are *at least* three broad CMB science axes, which here we'll call the Primordial Universe, Large-Scale Structure, and Spectroscopy. While we can do all these different things with the CMB, to do each well does take some specialization and differentiation. For example, he first two targets are (usually) done with imaging, and can be attempted from the ground. The third, is something that may ultimately be necessary, but which can only be done well from space.

In this document we have underlined larger, ground-based, European-wide projects. We recognize the importance of smaller projects but note that smaller projects don't need European-wide coordination of efforts. Similarly, considerable expertise exists in Europe in the conception and implementation of space-based CMB missions. In fact, the 2017-2026 APPEC roadmap endorsed a European-led satellite mission to map the CMB from space (APPEC 2017). However, there are a number of agencies already intimately involved in the CMB, with well-defined programs and for which a proposal and deliberation process already exists. We hence accentuate sub-orbital CMB, briefly mentioning in space-based initiatives that contribute to the CMB landscape.

We take as our long-term horizon roughly a decade from now, 2027, which is the timescale for new satellite missions being launched as well as first light for the ground-based CMB Stage 4 project.

In section 2 we present the science that can be done with the CMB. In section 3 we present the state of the field. In section 4 we present the "Road Map".

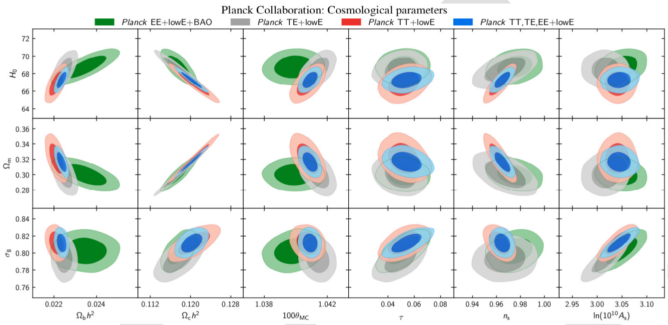

Figure 1: Constraints on parameters of the base-ΛCDM model from the separate *Planck* EE, TE, and TT high-l spectra combined with low-ℓ polarization (lowE), and, in the case of EE also with BAO, compared to the joint result using Planck TT,TE,EE+lowE. Parameters on the bottom axis are sampled MCMC parameters with flat priors, and parameters on the left axis are derived parameters (with H_0 in km s^{-1}Mpc^{-1}). Contours contain 68 % and 95 % of the probability. From Planck Collaboration et al. (2018)

2 Science

While a satellite such as Planck, with an approximately 1.7 m mirror and an orbit at the second Sun-Earth Lagrange point (L2) could address a number of different science subjects (see figure 1), it is difficult to address the same range of topics from the ground. So here we separate the main science drivers for the CMB into three separate science topics, which while inter-related, also demand different technological trade-offs.

Below we discuss three "headline" science targets for the CMB – each of which would merit dedicated efforts, even individually. In the interest of succinctness, we don't mention here the myriad "ancillary" CMB science possible, all of which merits significant investment as well; we will often get these results "for free". Such topics include cosmic birefringence, hot gas in the Universe probed by the Sunyaev-Zeldovich (SZ) effect, spatial variations of deviations from CMB's Planck spectrum, tests of the so-called "anomaly" in temperature data with polarization, Galactic science, and much more.

2.1 The Primordial Universe and Inflation

Often called the Holy Grail of cosmology, detection of a divergent-free "B-Mode" component of primordial CMB polarization is often held up as a possible "smoking gun" for the Inflationary model of the Universe. Were it to be detected, it would immediately transform our vision of

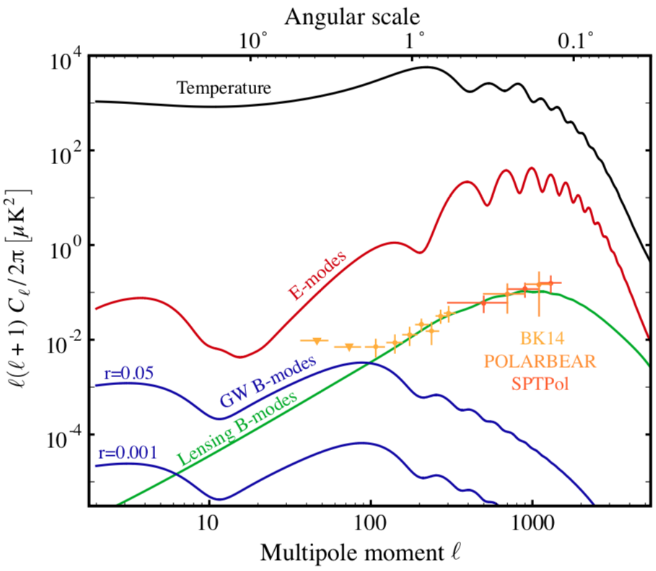

Figure 2: Theoretical predictions for the temperature (black), E-mode (red), and tensor B-mode (blue) power spectra. Primordial B-mode spectra are shown for two representative values of the tensor-to-scalar ratio: r=0.001 and r=0.05. The contribution to tensor B modes from scattering at recombination peaks at l∼80 and from reionization at $\ell < 10$. Also shown are expected values for the contribution to B modes from gravitationally lensed E modes (green). Current measurements of the B-mode spectrum are shown for BICEP2/Keck Array (light orange), POLARBEAR (orange), and SPTPol (dark orange). The lensing contribution to the B-mode spectrum can be partially removed by measuring the E and exploiting the non-Gaussian statistics of the lensing. From Abazajian et al. (2016).

the creation of the Universe and launch new investigations into what *caused* the Big Bang and *how* it transpired.

The most unambiguous signal indicating that Inflation might have occurred would be a polarized B-Mode signal with correlations of order a degree or larger (the blue curves at the lower/left of figure 2). While ancillary data will be necessary to address astrophysical contaminants, the relatively large angular scales at which these features appear mean that one does not need a large telescope to measure these signals – relatively small instruments can suffice. Additionally, because we are simply looking for a detection in the first instance, rather than a statistical characterization of the signal on multiple scales, the optimal strategy seems to be to integrate deeply on a limited sky area, and then to “open” the sky coverage after detection, in order to verify foreground removal, assure oneself that the statistics, are understood, and so on.

2.1.1 Foregrounds

While raw sensitivity is still important to the CMB, in recent years it has become clear that understanding the so-called “foregrounds” will also be crucial for digging out the low-laying primordial signals we search (BICEP2/Keck Collaboration et al. 2015). Observations at “neighboring” frequencies will be important for future results. In addition, nearby structure will “scramble” primordial signals to some extent via *lensing*. This is an exciting prospect, as it gives us a way to probe the difficult-to-observe *Dark Matter*, but it also means that complementary observations with larger telescopes, such as those described in the next section, will also be necessary.

2.2 Large-Scale Structure and Neutrinos

As the Universe evolved from its initial hot, dense, homogeneous state just after the Big Bang, the *structure* we see in the Universe today – the galaxies, the clusters of galaxies, and the pattern of the *Cosmic Web* in general – began to form under the effects of gravity. The result is sensitive to a number of things, including Dark Energy, Dark Matter, and the numbers and masses of light particles, such as neutrinos, present in the Universe at early times. We therefore use this structure to test for the presence of and to characterize these phenomena.

This structure appears at small angular scales – on the order of arc-minutes – and thus requires larger telescopes to measure. Calculations indicate that 6 m telescopes will suffice given the wavelengths of interest for the CMB (CMB-S4 CDT 2017). In addition, in order to get the statistics required – that is, in order to measure enough examples of structure formation – we will need to do these measurements over a large fraction of the sky. It is, it should be noted, essentially impossible to observe the full sky from a single location on the Earth.

2.3 Spectroscopy

The confirmation of the Blackbody nature of the CMB was one of the keys to general acceptance of the Standard Model of Cosmology. A number of processes that occur at different points along the history of the Universe do change this spectrum, and there is therefore a wealth of information which can be gleaned from precise measurements of the CMB’s spectrum. From the physical processes that occur during the so-called phase of recombination, where the CMB is last scattered, to relatively more recent processes such as the reionization of the Universe and the Sunyaev-Zeldovich effect in clusters and in general, the myriad processes that inject any sort of energy into the photons of the CMB can be probed with its spectrum.

Tantalizingly, the decades-old *COBE*/FIRAS measurement is still our most sensitive spectroscopic measurement of the CMB. But we are now capable of making much more sensitive instruments than this venerable experiment.

3 Experimental Landscape

Successive generations of experiments have recently been categorized in four stages based on the number of detectors they host in their focal planes. Recently completed experiments have been Stage 1 ($\sim 10^2$ detectors) or Stage 2 ($\sim 10^3$ detectors), while some coming on line now are Stage 3 ($\sim 10^4$ detectors). As an example, the BICEP2 and Keck Array are Stage 2, while BICEP3 and BICEP Array are Stage 3. The ultimate plan is to reach a Stage 4 (and thus the name “CMB-Stage 4”), with focal planes of order ($\sim 10^5$ detectors). Figure 8 shows the corresponding sensitivity progression, assuming no impact from systematic effects and no significant penalty from foregrounds or the atmosphere.

In the recent past, CMB studies using such detectors have had significant contributions from ground-based, balloon-based, and satellite-borne experiments. Here we review the status of each of these in turn. It is obviously difficult to do justice to the enormous quantities of work that have been done in a brief space, so we also supplement the three sections here in appendix 4.3.3.

3.1 Ground

As noted above, the US CMB community has been developing a major coordination effort to lead existing and planned ground-based polarization experiments towards an ambitious plan called "CMB Stage 4". First light is anticipated in 2027. The plan involves university-based groups, national laboratories, large US funding agencies, and private donations.

The CMB-S4 project is conceived not as a single instrument, but as multiple, dedicated telescopes operating from the South Pole and the Chilean Atacama plateau (CMB-S4 CDT 2017). The plan is to consider a combination of small aperture and large aperture telescopes, to probe degree and sub-degree scales, respectively. *One of the primary goals of this White Paper is to explore if and how Europe can fit into or complement this program.*

The ground-based CMB B-mode experimental landscape is summarized in Table 1. These experiments cover a wide range in angular resolution and sky coverage.

3.1.1 Small Aperture (Large Angular Scales) Experiments

Experiments like BICEP, CLASS, QUBIC and LSPE are designed to map large sky areas at moderate $\sim 0.5°$ angular resolution in order to probe the spectra of CMB polarization generated in a fiducial, early-Universe epoch of Inflation.

AliCPT or the Ali CMB Polarization Telescope is a Sino-American program designed to observe Primordial Gravitation Waves from the Tibetan Plateau (and thus the Northern Hemisphere) at 95 and 150 GHz with a 70 cm aperture at a 5,250 m site. A first version will have 7000 TES detectors and a second would complete 3 years of observations with 20,000 detectors by 2025 (Li et al. 2017).

BICEP/Keck is a small-aperture (0.25–0.5 m) system, which started taking data in the 2006 at the South Pole. As the project has grown, the number of telescope platforms, as well as cameras and frequency bands has also grown. It targets 30,000 detectors in the coming years.

CLASS (figure 5) will be a four-telescope system to measure CMB polarization at large angular scales between 40 and 220 GHz from the Atacama site in Chile. The goal is to observe 70 % of the sky targeting both the reionization and recombination peaks of the E- and B-mode spectra.

GroundBIRD is a fast-spinning ($\sim$20 rpm), small-aperture ($\sim$30 cm) telescope with cooled optics (Otani et al. 2016) with array of $\sim$450 MKIDs at 145 and 220 GHz. The mirror has an aperture of 30 cm and is cooled to 3.4 K to suppress photon noise. It will observe from the Teide Observatory in the Canary Islands.

Polarbear and the Simons Array is a project using intermediate-sized telescopes, in principle allowing it to target both primordial and lensing B-Modes at frequencies of 90–220 GHz (and so might have been put in either this section or in section 3.1.2). The ACT project is fusing with the Simons Array project to form the Simons Observatory.

QUBIC is based on bolometric interferometry which, if validated, will afford more spectral resolution across wide bolometer spectral bands via what is being called "Spectro-Imaging". It will be fielded at the Alto de Chorillos site near Salta in the Argentine Andes in 2019. QUBIC targets primordial B-Modes at 150 and 230 GHz, while a second module in W band to be developed later. See Aumont et al. (2016).

QUIJOTE is comprised of two 2.5 m, fully spinning, off-axis telescopes to measure CMB polarization at 10–40 GHz. QUIJOTE uses coherent receivers based on HEMT LNAs and will make a polarized map of half the sky at 10–20 GHz and deep integrations of three regions covering one-eighth the full sky with a sensitivity $\sim 1\,\mu$K at one degree resolution across all its bands (Table 1). It observes from the Teide Observatory. See Rubiño-Martín et al. (2012).

LSPE/STRIP, the ground-based LSPE partner of the higher-frequency balloon-borne SWIPE, will deploy a 1.5 m, fully rotating, cross-Dragone telescope coupled to an array of 49 HEMT-based coherent polarimeters at 42 GHz, plus 6 channels at 90 GHz as atmospheric monitor. The aim is to cover about 25 % of the sky with sub-degree resolution from Tenerife. The LSPE sky area also overlaps with the deep regions observed by QUIJOTE at lower frequencies.

3.1.2 Large Aperture (Small Angular Scales) Experiments

Large aperture instruments such as ACT or SPT, which reach arc-minute scales, are capable of measuring the B-modes generated through the lensing of E-modes by large scale structures, and may provide insight into Galactic emission and the Sunyaev-Zel'dovich effect.

Atacama Cosmology Telescope (ACT) is a 6-meter, off-axis telescope (Swetz et al. 2011). It measures both temperature and polarization and covers (or will cover) frequencies from 28 to 280 GHz with thousands of detectors. The ACT project fuses with the Simons Array project to form the Simons Observatory. These instruments observe from the Atacama site in Chile.

South Pole Telescope (SPT) is the largest of all experiments discused here. The 10-meter telescope has been operational at the South Pole since 2011, producing SZ data and CMB anisotropy data from arcminute to degree angular scales (Figure 6). Its most recent incarnation, SPT-3G uses a total of 16, 400 detectors distributed at 95, 150, and 220 GHz (Table 1).

3.1.3 Observation Sites

The tendency in the past decade has been to concentrate experiments in a few high-altitude observing sites, partly motivated by their high quality and partly by the convenience of sharing accessibility and infrastructures in very isolated locations. As Table 1 shows, most projects (with a few notable exceptions) are located in three sites, the Atacama Desert, Antarctica, and the Canary Islands.

Atacama Desert, Chile at an elevation of 5200 m, hosts the ACT and Simons Array telescopes, including the Polarbear telescope. These experiments are in the process of merging into the Simons Observatory. In addition, the CLASS experiment is also located on this site. See section .1.2 for more detail about these projects.

Alto de Chorillos, near Salta in the Argentine Andes and roughly 150 km from the Simons site in Chile, will host QUBIC.

Gandisê Mountain Range in Tibet is the planned home for AliCPT. A 5,250 m site is to be initially used, with the possibility of a nearby 6,000 m site being developed in the future (Li et al. 2017).

The South Pole, at an elevation of 2,900 meters and with very stable atmosphere, has hosted CMB experiments for decades. It is now the home of the South Pole telescope and the BICEP/Keck array of cameras.

The Teide Observatory (OT) is located on the island of Tenerife, at an altitude of 2,400 m above the sea level, on the Canary Islands, Spain. Of the three sites intensively used by CMB experiments, Tenerife is the only one in the Northern Hemisphere. The characteristics of the site, at moderate altitude and easily accessible, are favorable for low frequency observations (Figure 7).

3.1.4 Related experiments at other sites and other wavelengths

While not directly observing the CMB, some of the "sister" experiments which are important for the CMB, either because of technology or understanding of foregrounds, are:

C-BASS is an ongoing project to make a full-sky map in temperature and polarization at 5 GHz with $\sim 0.7^\circ$ resolution, mainly for better maps of polarized foreground synchrotron radiation. Two instruments are operated from two low altitude sites, one in each hemisphere. The Northern survey was completed and data are being analyzed, while the Southern instrument completed commissioning in late 2016 and is currently taking data. See Irfan et al. (2015) and Jones et al. (2018).

CCAT-Prime (CCATp) is a 6-meter aperture submillimeter telescope under construction for a 5600 meter elevation site on Cerro Chajnantor in northern Chile, anticipating first light in 2021. Though not observing at CMB frequencies, it will use a 6 m telescope similar to those used by the Simons Observatory, and is forging a collaboration with that team.

CONCERTO is a wide-band (125-360 GHz), low spectral resolution (R=300) spectrometer with 5000 KIDs that will be installed at the APEX telescope Atacama site in 2021. CONCERTO will be dedicated to intensity mapping of carbon lines at high redshift as well as to the detection of the kinetic and thermal SZ effect in clusters of galaxies. It will also serve as a test-bench for large arrays of KIDs in background conditions similar to those of current CMB experiments.

KISS is a low-spectral-resolution (1-3 GHz) large band (120-261,GHz) spectrometer made of 632 KIDs that will be installed at the Teide Observatory in the fall of 2018. KISS is dedicated to spectral observations of low redshift clusters of galaxies to measure their mass and temperature via the SZ effect, and constitutes a test-bench for the development wide field-of-view ground-based millimeter spectrometers.

NIKA2 is a high-resolution (11-18"), large FOV (6.5'), polarised dual band, millimeter camera with 2896 Kinetic Inductance Detectors (KIDs) operating at 150 and 260 GHz. It is installed at the IRAM 30 m telescope (Pico Veleta, Spain). NIKA2 is an open facility and a technology demonstrator for large arrays of KIDs and polarisation setups that is particularly well adapted to SZ observations of distant clusters (Adam et al. 2018).

S-PASS (S-band Polarization All Sky Survey) is a polarization survey at 2.4 GHz, of relevance for synchrotron foreground removal (Carretti et al. 2010; Krachmalnicoff et al. 2018). The full Southern sky has been mapped in 2007-2019 with Parkes radio telescope with 9 arcmin resolution and SNR>5. The plan is to complete the survey in the Northern hemisphere using the Sardinia Radio Telescope in the same frequency band.

3.2 Balloons

The primary advantage of balloon-based experiments is the opportunity to observe from above the bulk of the Earth's atmosphere, thereby significantly reducing the experimental noise. It has been, in fact, one of the few ways of taking data above around 250 GHz. In the past, ARCADE, ARCHEOPS, ARGO, BAM, BEAST, BOOMERANG, EBEX, FIRS, MAX, MAXIMA, MAXIPol, MSAM, QMAP, and TopHat have all exploited this fact in order to publish cutting-edge CMB results.

Traditional balloon flights, however, are limited to around a day of observations, and like satellites have limitations on their size. The PIPER program aims to surmount this difficulty by making multiple flights per year, drastically reducing the time between flights. To date they have had one successful test flight, and are targeting three flights in 2018 (in the past, most balloon experiments have flown once per year at most), with a total of eight flights over the life of the program.

BOOMERANG, EBEX, and TopHat, on the other hand, increased the amount of observation time by flying "long-duration" flights, staying aloft and taking data continuously for up to two weeks while circumnavigating Antarctica. The *Spider* experiment took data at 100 and 150 GHz during a Winter, 2014-15 long-duration flight, and will have one more flight, adding a 280 GHz channel. Similarly, IDS, an evolution of EBEX program, is also being proposed to NASA's long-duration balloon (LDB) program. In Europe, the *Olimpo* program recently finished a multi-day flight from the northern hemisphere.

As ground-based experiments become larger and continue to observe longer, pressure remains on balloons to continue to increase their observation time. The proposed BFORE program seeks to address this by flying an "Ultra-Long-Duration" balloon (ULDB; `https://www.csbf.nasa.gov/balloons.html`) flight. This program is in its infancy – there have only been a few test flights – but has a goal of a 100-day flight. None of the handful of flights to date have targeted the CMB, but with a goal of 100 days aloft, this may ultimately allow balloon experiments to have similar post-detection (i.e., integrated over the life of the program) sensitivities to those of ground based instrument. And in the absence of another satellite mission, it may be the only way to get higher frequency data.

3.3 Space

The absence of atmosphere in space allows measurements over the entire frequency range of interest and greatly reduces experimental noise. This unique environment, especially at L2, provides very stable conditions and also is not affected by any electromagnetic contamination from human activity. These stable conditions allow, in particular, better control and characterization of systematic effects. It is perhaps the only way to make the very largest-scale measurements of the polarized sky, which may be necessary, for example, to measure the cosmological reionization parameter, τ.

LiteBIRD, programmatically the most advanced of the possible future space missions, is designed to measure the full-sky distribution of temperature and polarization anisotropies of the CMB in the multipole range of $2 \leq \ell \leq 200$. To this end it will map the entire sky in 15 frequency bands from 34 to 448 GHz (with the band centers from 40 to 402 GHz), which are required to reduce effects of Galactic foreground emission on the CMB map. The baseline design of *LiteBIRD* consists of two telescopes: Low Frequency Telescope (LFT) and High Frequency Telescope (HFT), both of which will use half-wave plates as the first optical elements for polarization modulation (Sugai et al. 2016). The focal planes will be cooled to 0.1 K and filled with a few thousand transition-edge sensor (TES) bolometers (Matsumura et al. 2016; Suzuki et al. 2018).

LiteBIRD was proposed to JAXA as a Strategic Large Mission in February 2015, and is currently in JAXA's Phase A1. The final selection by JAXA is expected to be announced no later than the end of March 2019. The planned launch date is 2027. While no firm decisions have been taken for the moment, the LiteBIRD European collaboration already gathers 9 partners with about 130 persons. France and Italy have already entered in Phase A. France has been identified to be responsible of the sub-Kelvin stage, while Europe has been asked by JAXA to take the responsibility of the HFT. Discussions with ESA have also started in 2018, in the frame of a CDF-Study to investigate the possibility of an ESA Mission of Opportunity to contribute to the HFT.

Pristine, like its intellectual predecessor *PIXIE*, would use a polarizing Fourier Transform Spectrometer to measure both the linear polarization and spectral energy distribution of the millimeter sky. Both build upon *COBE*/FIRAS technology, but would promise orders of magnitude gains in sensitivity. A "Fast Mission" proposal to ESA is being prepared which foresees a launch along with *Ariel* in the 2027 time frame (`https://www.cosmos.esa.int/web/call-for-fast-mission-2018`).

More ambitious, but still less certain programmatically, the *CMB-Bharat* and *PICO* concepts, like the earlier *CORE* proposal, would modulate polarization only by scanning, hence avoiding moving parts and thereby minimizing systematic effects. The earliest possible launch date for such polarization imagers might be around 2030.

CMB-Bharat, being discussed with the Indian Space Agency, ISRO, is designed to observe with about $\tilde{2}0$ frequency bands and a 1.5 m telescope. Two options are considered that might extend the scientific capability of the mission: (1) a mode for deep observations of selected sky regions at the end of the mission; and/or (2) a small spectrometer instrument, similar to *PIXIE* or *Pristine*, that would measure the absolute spectrum of the CMB from 60 to 3000 GHz.

PICO, which is currently under study in the US with European and international participation, would target a sensitivity sufficient to detect $r \simeq 10^{-4}$. *PICO* would have 21 frequency channels ranging from 20 to 800 GHz, with over 13,000 detectors at the focus of a 1.4 m telescope. It is hoped that NASA will open a suitable mission opportunity after the next US Decadal Survey.

4 Proposed Roadmap

We assert that in order for the European CMB community to be involved in cutting-edge CMB research, it must be a significant part of the flagship efforts – in the long term, these will include the ground-based CMB-S4 experiment, a next-generation satellite mission, and possibly a ULD Balloon experiment. CMB-S4 is slated to begin observations in 2027. Similarly, *LiteBIRD*, presumably the next CMB satellite, targets launch in the same time frame. We therefore take 2027 as the target date for this road-map.

We begin by defining our long-term goals, covering the period from 2027 onward, as our schedules for the short-term are constrained and because as CMB experiments get larger and larger, they take more time to put in place. These long-term goals then drive the so-called mid-term (2022–2026) and short-term (today–2021) road-maps.

In defining the European road-map, we should of course, lever European interests, expertise, and production capabilities. While a full survey of European expertise is beyond the scope of this document, we highlight the following aspects of current European activity as being particularly relevant in this context:

- **Detection & Optics**: A number of groups in Europe have put significant resources into developing detectors such as Kinetic Inductance Devices (KIDs, in addition to competence in more traditional transition-

edge sensors), multiplexed readouts and quasi-optical components such as Half-Wave-Plates. Europe has also led the development of more novel detection concepts such as bolometric interferometry and has the capacity to make transition-edged sensor and high-electron mobility detectors.
- **High- and Low-Frequency Studies**: The CMB community in Europe has traditionally had a "broad" interest in the CMB, meaning that it is interested in the CMB itself, but also in the astrophysics accessible at "neighboring" frequencies. The community has developed experiments to study lower frequencies in general and Galactic synchrotron as it affects the CMB in particular, in addition to strong balloon and space programs to study the ISM and other processes involving the heating and emission of dust in our neighborhood and further away.
- **Telescopes**: Europe has a world-leading industrial capability for fabricating radio telescopes and many European-made telescopes are already being used to study the CMB. Few of them, however, are currently owned and operated by Europeans.
- **Balloon program**: Europe already has an active and ongoing CMB balloon program, with particularly relevant experience in fielding northern-hemisphere balloon experiments.
- **Existing collaborations**: Many European CMB scientists are already embedded in US-led Stage 3 experiments, and are actively working on plans for their future extensions, and incorporation into CMB-S4.

4.1 Long-term (2027–)

In the long-term, Europe should aim to maintain a major role in all three CMB experimental arenas, i.e. in future ground-based, balloon-borne and satellite missions.

4.1.1 Ground

As noted in Section 3, CMB-S4 is anticipated to begin operations in 2027. With an estimated budget of 412 million US dollars (CMB-S4 CDT 2017), it will be a centerpiece of future CMB studies, and one in which Europe should actively participate in or coordinate with, as opposed to trying to compete with. In order to achieve this, we make the following headline, long-term recommendations.

- By 2027, European-built instrumentation should form a major component of the CMB-S4 receiver hardware. This should be in the form of **complete optical modules (tubes)**, suitable for mounting on both small aperture and large-aperture CMB-S4 telescopes.
- By 2027, Europe should be taking observations at multiple sites to allow creation of an **$\sim$15 GHz map of the full sky.**
- The CMB-S4 experiment should include both **small-aperture and large-aperture telescopes** that are designed, built and operated by European-led teams as contributions to the CMB-S4 effort.

4.1.2 Balloons

Integration time is of the utmost importance for future CMB experiments. For a future balloon experiment to be competitive, (perhaps multiple) ULD flights will be required.

- If practical, by 2027, Europe should field an **independent ULD Balloon experiment**, concentrating on northern hemisphere coverage, and on frequencies $>$ 100 GHz.
- Europe should be making significant **contributions to a future major US-led ULDB experiment**. Such a contribution could consist of complete optics tubes, contributions to the flight module and/or operations.

4.1.3 Space

Building on Planck experience (as well as on the proposals to ESA for CORE and PRISM), Europe should continue to prepare for a major role in a future CMB space missions. Contacts with potential international partners should be initiated or pursued.

- The *LiteBIRD* mission concept is currently in a Phase A study, with a final decision on selection expected by March, 2019. Europe should pursue a major role in *LiteBIRD*. If selected, Europe should provide cooling elements and should take a leading role in developing the ***LiteBIRD* High Frequency Telescope**.
- Potential European contributions to *PICO* and/or *CMB-Bharat* should be pursued, in preparation for the next opportunity to either participate in these missions if selected, or to propose a joint mission if such an opportunity arises through ESA.

4.2 Mid-term (2022–2026)

The post-2026 goals define the mid-term (2022–2026) goals. The specific recommendations are designed to position the European CMB community, by 2026, for realizing the long-term ambitions described above.

First, we highlight a pressing need for a coordinated, joint approach for developing Europe's data analysis capabilities. To address this need, we make the following recommendation:

- Development of a European **CMB data analysis center** (or distributed network).

We envisage that such a center or network would serve as a facility for all of Europe's CMB researchers, and would support European data analysis contributions to all experiments in which Europe is involved, such as *Euclid*.

4.2.1 Ground

To enable a major European role in CMB-S4, we make the following recommendations for the European ground-based program in the mid-term:

- Installation and operation of a **European 6-meter telescope** at the South Pole site.

- Installation and operation of one or more **European small aperture telescopes**, including European-built **KIDs-based receivers**, at the Atacama site, in Chile.
- Installation and operation of a **Low Frequency telescope**, covering the frequency range between 5 & 20 GHz, at the Atacama Site, in Chile.
- Development of **"Bolometric Interferometer in a Tube"** technology for deployment in CMB-S4 telescopes, if determined to be feasible.

4.2.2 Balloons

The direction that the future European balloon program will take will be determined during the mid-term phase of the road-map. The following objectives should be pursued:

- Completion of the European balloon programs currently in development/operation (i.e. **OLIMPO** and **LSPE/SWIPE**).
- Development and implementation of a **European ULDB capability** if determined to be feasible.
- Coordination with international partners on **concepts for a next-generation ULDB** CMB experiment, in the CMB-S4 era.

4.2.3 Space

Our recommendations for space are less precise, as this process is driven by well-defined processes led by the European Space and national space agencies. They should, however, lead to **significant participation in a major CMB satellite mission** to be launched towards the end of the decade. In addition to large missions, space also affords opportunities for smaller "Mission of Opportunity"-type experiments, which can potentially be launched on a shorter timescale. We therefore identify the following additional recommendation for the mid-term road-map.

- The European CMB community should pursue opportunities for proposing or contributing to spectral space mission concepts (such as a re-submission of the *PIXIE* concept), if *Pristine* is not selected.
- Europe should pursue the best exploitation of ground-based CMB data in conjunction with European experimental data such as that of Euclid.

4.3 Short-term (2018–2021)

In order to be able to realize the above goals, there are a number of tasks that must be completed on a shorter timescale. Most of these short-term goals are associated with establishing and refining the plan for Europe's future contributions and securing the necessary funding. In some cases, we will also need to finalize (and formalize) arrangements for international collaborations.

4.3.1 Ground

We identify the following, pressing, tasks, that need to be addressed in the short term, in order to secure a healthy future for European participation in ground-based CMB:

- Agreement on **instrument concept** and **funding** for a **European 6-m telescope** at the South Pole.
- Agreement on **instrument concept** and **funding** for European small-aperture KIDS-equipped telescope(s) in Chile (or even elsewhere if the requisite additional funding were available).
- Agreement on **funding** and **instrument concept** for a European low-frequency telescope at the Atacama, Chile.
- Agreement on access to SPT and/or Simons small-scale data for comparisons with *Euclid* data.
- Studies of the **feasibility** of **bolometric interferometry in a tube**.

4.3.2 Balloons

The short-term tasks for the Balloon program are concerned with getting the current generation of experiments up and running. Assesment of the viability of a future European-led ULDB experiment should also begin within the next 3 years:

- Successful deployment and operation of the **OLIMPO** and **LSPE/SWIPE** balloon experiments.
- Study of the **feasibility** of developing a **European-led ULDB northern hemisphere experiment** on a ∼2025 timescale.

4.3.3 Space

Our short-term recommendations for space involve completing the final Planck data release and identifying/formalising Europe's role in a future experiment:

- Consolidation and archiving of ***Planck*** data, deliverables, software and derived products.
- Finalization of proposed participation in ***LiteBIRD***, if it is selected.
- Pursue opportunities for **"small" space missions** (e.g. the ***Pristine*** mission concept for a CMB spectrometer satellite), that can potentially be launched on shorter timescales.
- Discussions with **world-wide space agencies** regarding the next satellite mission, imaging *or* spectroscopic, including participation in the **US Decadal Survey**.

References

Abazajian, K. N., Adshead, P., Ahmed, Z., et al. 2016, ArXiv e-prints [arXiv:1610.02743]

Adam, R., Adane, A., Ade, P. A. R., et al. 2018, A&A, 609, A115

Anjalimarar. 2018

APPEC. 2017, European Astroparticle Physics Strategy 2017–2026, http://www.appec.org/wp-content/uploads/Documents/Current-docs/APPEC-Strategy-Book-Proof-19-Feb-2018.pdf

Aumont, J., Banfi, S., Battaglia, P., et al. 2016, ArXiv e-prints [arXiv:1609.04372]

Bennett, C. L., Halpern, M., Hinshaw, G., et al. 2003, ApJS, 148, 1

BICEP2/Keck Collaboration, Planck Collaboration, Ade, P. A. R., et al. 2015, Physical Review Letters, 114, 101301

Carretti, E., Haverkorn, M., McConnell, D., et al. 2010, Mon. Not. of the Royal Ast. Soc., 405, 1670

CMB-S4 CDT. 2017, REPORT TO THE AAAC, Tech. rep.

Hazumi, M., Borrill, J., Chinone, Y., et al. 2012, in Proceedings of the SPIE, Vol. 8442, Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave, 844219

Irfan, M. O., Dickinson, C., Davies, R. D., et al. 2015, Mon. Not. of the Royal Ast. Soc., 448, 3572

Ishino, H., Akiba, Y., Arnold, K., et al. 2016, in Proceedings of the SPIE, Vol. 9904, Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave, 99040X

Jones, M. E., Taylor, A. C., Aich, M., et al. 2018, Mon. Not. of the Royal Ast. Soc., 480, 3224

Krachmalnicoff, N., Carretti, E., Baccigalupi, C., et al. 2018, ArXiv e-prints [arXiv:1802.01145]

Li, H., Li, S.-Y., Liu, Y., et al. 2017, ArXiv e-prints [arXiv:1710.03047]

Matsumura, T., Akiba, Y., Arnold, K., et al. 2016, Journal of Low Temperature Physics, 184, 824

Matsumura, T. et al. 2014, J. Low. Temp. Phys., 176, 733

Peebles, P. J. E., Page, L. A., & Partridge, R. B. 2009, Finding the Big Bang (Cambridge)

Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2016, A&A, 594, A13

Planck Collaboration, Aghanim, N., Akrami, Y., et al. 2018, ArXiv e-prints [arXiv:1807.06209]

Rubiño-Martín, J. A., Rebolo, R., Aguiar, M., et al. 2012, in Proc. of the SPIE, Vol. 8444, Ground-based and Airborne Telescopes IV, 84442Y

Smoot, G. F., Bennett, C. L., Kogut, A., et al. 1992, ApJ, 396, L1

Sugai, H., Kashima, S., Kimura, K., et al. 2016, Proc. SPIE Int. Soc. Opt. Eng., 9904, 99044H

Suzuki, A. et al. 2018, 17th International Workshop on Low Temperature Detectors (LTD 17) Kurume City, Japan, July 17-21, 2017

Swetz, D. S., Ade, P. A. R., Amiri, M., et al. 2011, ApJS, 194, 41

Thornton, R. J., Ade, P. A. R., Aiola, S., et al. 2016, ApJS, 227, 21

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High-Level Questions

- What, if any, contribution should Europe be making to existing S3/S4 plans?
- To what extent do we extend frequency coverage on both the low and high ends of the spectrum and if so, how far?
- One of our “big” questions was: Do we need Northern coverage and if so, how do we address it?
- Do we need spectral distortion measures and if so, what is the process?

Detailed Experimental Landscape

.1 Ground

Ground-based measurements have played a major role in the progress of CMB science. In spite of the effects of the Earth's atmosphere and of limited observable sky, experiments from the ground still produce outstanding results. Thanks to progress in millimeter-wave technology and to the relatively low impact of the atmosphere on millimeter-wave polarization, new generations of ground-based CMB experiments are being planned to probe primordial gravitational waves through polarization B-modes. These will be carried out from selected high-quality sites, in atmospheric windows in the 10–300 GHz range.

In addition to polarization and lensing, ground-based observations are also carried out to measure the SZ effect (e.g. SPT, ACT, AMIBA) and in the past have been used to measure the Rayleigh-Jeans portion of the CMB frequency spectrum (see Peebles et al. 2009, for a review).

.1.1 Summary

The ground-based CMB B-mode experimental landscape is summarized in Table 1. These experiments cover a wide range in angular resolution and sky coverage. Large aperture instruments, such as ACT or SPT, reach arcminute scales and are capable of measuring the B-modes generated through the lensing of E-modes by large scale structures, and may provide insight into Galactic emission and the Sunyaev-Zel'dovich effect. Experiments like BICEP, CLASS, QUBIC and LSPE are designed to map large sky areas at moderate $\sim 0.5^\circ$ angular resolution in order to probe both the recombination and the reionization bumps of the E- and B-mode spectra.

The tendency in the past decade has been to concentrate experiments in a few high-altitude observing sites. As Table 1 shows, most projects (with a few notable exceptions) are located in three sites, the Atacama Desert, Antarctica, and the Canary Islands.

.1.2 Experiments from Atacama Desert, Chile

Here we outline the existing and planned instruments at the James Ax Observatory, Atacama Desert, Chile, at an elevation of 5200 m, as well as QUBIC, which is nearby in Argentina.

Atacama Cosmology Telescope (ACT). This is a 6-meter, off-axis telescope (Swetz et al. 2011) initially used for high resolution temperature anisotropy measurements (see Figure 3). The upgraded receiver, called ACTpol, is sensitive to polarization with arrays operating at 97 GHz and 148 GHz, and has been taking data since 2014. The instrument uses feedhorn-coupled, polarization-sensitive TES arrays cooled to 100 mK with continuous cooling (Thornton et al. 2016). The angular coverage is from degree to arcminute scales, allowing de-lensing as well as Sunyaev-Zel'dovich measurements. A future incarnation, called AdvACTpol, foresees a focal plane incorporating a few thousands detectors in the range 28–230 GHz.

Polarbear. POLARBEAR-I has been observing from Atacama since 2011 using an off-axis 2.5 m telescope (see Figure 4). The receiver consists of an array of ∼1300 polarization-sensitive TES bolometers cooled to 300 mK with lenslet-coupled, double-slot, dipole antennas (Arnold et al. 2012, Kermish et al. 2012). A cold half-wave plate is used to modulate the observations and to mitigate systematics. The next generation focal plane, POLARBEAR-II, incorporates ∼ 7600 TES detectors and will use a novel dichroic pixel architecture yielding simultaneous data at 95 and 150 GHz (Suzuki et al. 2015).

CLASS. CLASS is a four-telescope system (supported by two mounts, fig. 5) to measure CMB polarization at large angular scales. The goal is to observe 70 % of the sky targeting both the reionization and recombination peaks of the E- and B-mode spectra. Each of the four telescopes will be dedicated to specific frequencies: one telescope at 38 GHz, two at 93 GHz, and one (using a dichroic plate) at 145/217 GHz. When completed, CLASS will have about 70 detectors at 38 GHz; 500 at 95 GHz; and 2000 at 147 and 217 GHz. The focal plane arrays use TES detectors and a rapid front-end polarization modulator.

Simons Array and Observatory. The Simons Array is a project to further increase sensitivity by deploying three POLARBEAR-II-type telescopes and receivers (Suzuki et al 2015). The Simons Array will increase by an order of magnitude the number of detectors, reaching overall ∼23000 elements divided in the frequency bands 95, 150 and 220 GHz. The ACTpol and the Simons Array teams will soon join to form the Simons Observatory Collaboration.

QUBIC. An innovative instrumental approach, based on bolometric interferometry, is proposed by QUBIC to control and self-calibrate systematics (QUBIC Collaboration 2016). Since systematic effects are likely to be the ultimate limiting factor of future super-sensitive polarization arrays, the effort is particularly valuable. The signals from 400 back-to-back dual-band horns will produce interference fringes imaged on a cooled array of 1024 TES bolometers. A rotating half-wave plate and polarizers will synthesize the IQU signals. Validation of the concept in hardware is required and will be carried out in a technical demonstrator test within 2018. The QUBIC angular sensitivity will be optimized around $\ell \approx 100$ to probe the recombination peak. The plan foresees deployment of a first module at Alto Chorillo, Argentina (5000 m) in 2019, covering 150 and 230 GHz, while a second module in W band will be developed later.

Others. The CCAT-prime (CCAT-p) is a 6-meter aperture submillimeter telescope under construction for a 5600 meter elevation site on Cerro Chajnantor in northern Chile. It is being built by a Cornell-led consortium of US universities and a German consortium, and is scheduled for first light in 2021. The unique Cross-Dragone optical design of CCAT-p delivers a wide and diffraction-limited field-of-view (FoV), which enables unchallenged mapping speed and surface brightness sensitivity.

The first-light instrument includes the "Prime-Cam", arrays of polarization-sensitive, TES bolometers that simultaneously image in four bands (230, 270, 350 and 410

Table 1: On-going and planned ground-based CMB polarization experiments

Project	Lead Institution	Year	Site[1]	Multipole range	Frequency bands [GHz]	Detectors	References	Notes
ACTPol (Atacama Cosmology Telescope — Polarization)	Princeton University	2014–	A	225-8725	90, 146	TES	Thornton et al. 2016	AdvACTpol: 88 detectors at 28 and 41 GHz; 1712 at 95 GHz; 2718 at 150 GHz; 1006 at 230 GHz
POLARBEAR (POLARization of Background microwave Radiation)/Simons Array	U.C. Berkeley	2012–	A	50–2000	150/90, 150, 220, 280	TES	Keating et al. 2011/Suziki et al. 2015	POLARBEAR-II focal plane will include 1500 pixels; Simons Array 22, 764 detectors
CLASS (Cosmology Large-Angular Scale Surveyor)	John Hopkins University	Future	A	2–200	38, 95, 147, 217	TES	Chuss et al. 2016; Harrington et al. 2016	When completed: 72 detectors at 38 GHz; 1036 at 95 GHz; 2000 at 147 and 217 GHz.
QUBIC (QU Bolometric Interferometer for Cosmology)	APC/Paris	Future (2019)	ARG	$\sim$100	97, 150, 230	Bolom. interferometer	QUBIC Collaboration, 2016	A second module is planned for deployment in Antarctica.
SPTpol (South Pole Telescope – Polarization)	University of Chicago	2012–	SP	500–5000	95, 150	TES	Benson et al. 2014	SPT-3G: Total of 16, 400 detectors at 95, 150, 220 GHz
BICEP (Background Imaging of Cosmic Extragalactic Polarization)/Keck Program	Caltech, Harvard, U. Minnesota, Stanford	2006—	SP	20–330	95/95, 150,220/35–270	TES	Grayson et al 2016	2560 detectors at 95 GHz. BICEP3/KECK program: over next several years will include over 30, 000 detectors in 5 frequency bands in 35–270 GHz range.
QUIJOTE (Q U I JOint Tenerife Experiment)	IAC	2012–	TO	10–300	11, 13, 17, 19, 30, 40	HEMT	Rubino-Martin et al. (2012)	40 GHz receivers in commisioning phase (2018)
LSPE/STRIP (Large Scale Polarization Experiment)	University of Milano	Future (2018)	TO	5–250	40, 90	HEMT	Bersanelli et al. 2012	Coordinated with LSPE/SWIPE (Balloon) at 120–140 GHz (De Bernardis et al. 2012)
GroundBIRD	RIKEN, KEK	Future (2018)	TO	6–300	145, 220	MKIDs	Otani et al. 2016	440 detectors; Rotating telescope at 20 rpm.

Notes. The notation for the sites is: A (Atacama Desert, Chile, 5200 m); SP (South Pole, Antarctica, 2800 m); TO (Teide Observatory, Tenerife, 2400 m); ARG (Alto Chorillo, Argentina, 5000 m); OV (Ovro, Ca); ZA (South Africa); WM (White Mountain, 3800 m).

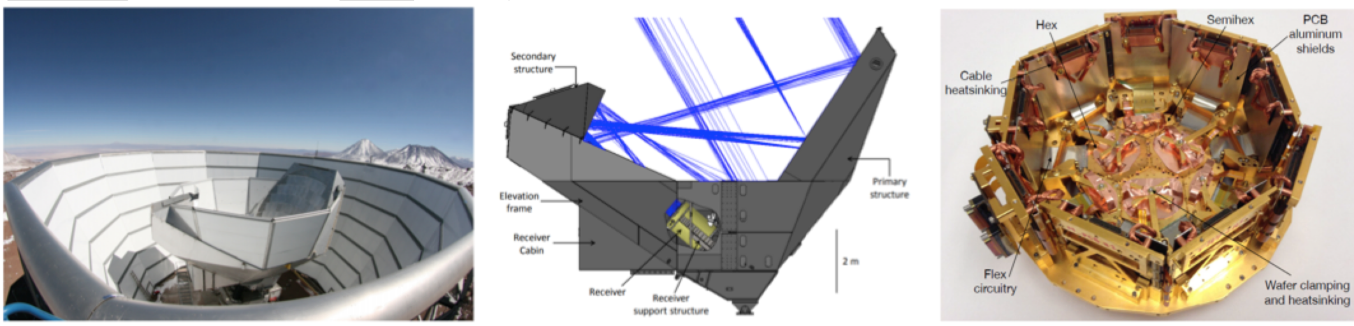

Figure 3: The ACT system. Left: inside its ground screen with static and co-moving ground screens. From the ground to the top of the telescope is 12 m. Center: Ray trace of ACT's primary and secondary mirrors up to the entrance of the receiver. Right: fully assembled. Adapted from Thornton et al. (2016).

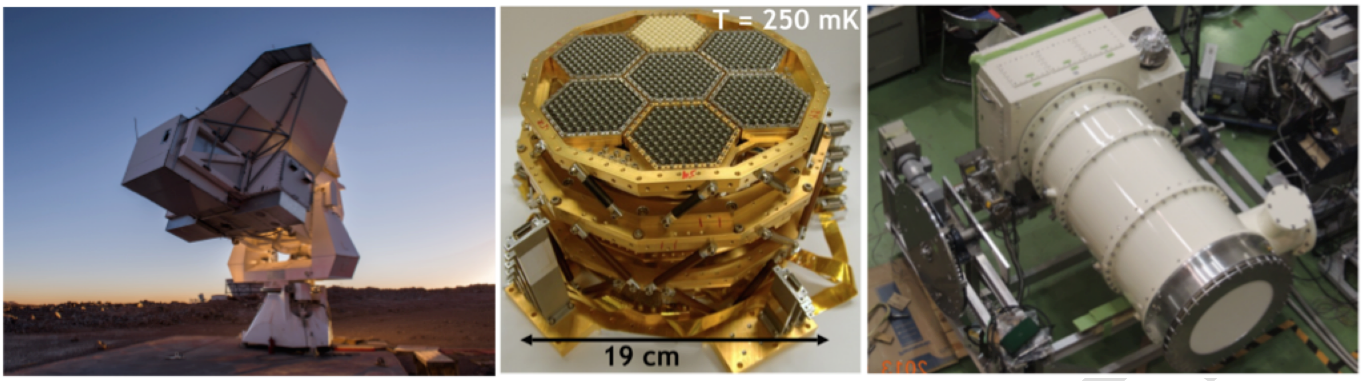

Figure 4: Polarbear. Left: the 2.5 m telescope at Atacama. Center: The POLARBEAR-I array with 637 dual polarization pixels cooled to 250 mK. The TES bolometers use digital frequency-domain multiplexing readout. Right: POLARBEAR-II will have approximately 7 times more channels.

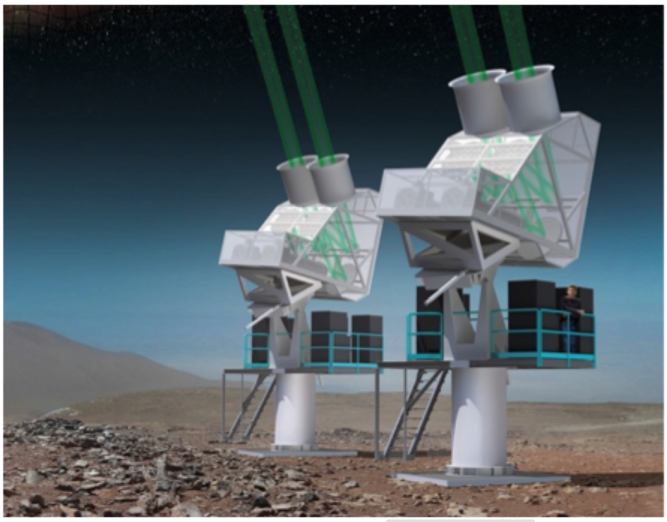

Figure 5: Conceptual rendering of the future CLASS (left) and Simons Array (right) instruments.

GHz); the spectrometer will be a 1-degree FoV imaging Fabry-Perot based on superconducting mirrors optimized for broad-band spectroscopy that spectroscopically multiplexes in these four telluric windows. The 860 GHz camera will use KID technologies.

CCAT-p is a potential telescope platform for CMB-S4, and it also offers unique capabilities for important advances in high-frequency polarization science before CMB-S4.

.1.3 Experiments from South Pole, Antarctica

In this section we describe experiments carried out at the South Pole, near the Amundsen-Scott US Station, at an elevation of 2900 meters.

South Pole telescope (SPT). The 10-meter SPT telescope has been operational since 2011, producing SZ data and CMB temperature anisotropies at arcmin-to-degree scales (Figure 6). The 2012 SPTpol camera has ∼1500 TES bolometers paired in polarization-sensitive pixels at 90 and 150 GHz. The two arrays use different technologies. The 150 GHz pixels are corrugated-feedhorn-coupled TES polarimeters; while the 90 GHz pixels are individually packaged dual-polarization absorber-coupled polarimeters coupled to the optics through individually machined contoured feedhorns. SPT-3G, now installed, uses a total of 16, 400 detectors distributed at 95, 150, and 220 GHz (Table 1). The SPT-3G receiver will increase by a factor of ∼20 the mapping speed over the earlier SPTpol (Benson et al 2012).

BICEP/Keck. This is an evolving, small-aperture (0.25–0.5 m) system, which started taking data in the 2006. BICEP2, operated in 2012-2014, was a 26 cm, two-lens refractor telescope coupled with an array of ∼250 polarization-sensitive TES pixels (500 bolometers) at 150 GHz with 0.52° resolution. The Keck Array was made as a system of five BICEP2-class receivers at 95 and 150 GHz, sharing a common boresight. The Keck Array, currently in its fifth observing season. Results from BICEP2/Keck (in combination with Planck, BAO, and other data) currently set the tightest (model dependent) limits on r of 0.07 (Keck & BICEP Collaborations, 2016). BICEP3 was installed in January 2015 in the same site as BICEP2, and began collecting data in May 2016. It includes a 220 GHz channel to monitor polarized dust. The 52 cm compact refractor telescope is coupled to a focal plane of modularized tiles of antenna-coupled TESs (∼2500 bolometers). Both the telescope and the detectors are similar to those of BICEP2 and the Keck Array. The next step will be to deploy a "Bicep Array" with multiple receivers, evolved from BICEP3, spanning 35 to 270 GHz with a total detector number of order tens of thousands.

.1.4 Experiments from Teide Observatory (Tenerife, Canary Islands)

The Teide Observatory (OT) is located on the island of Tenerife, at 28°18′00" N, 16°30′35" W, and an altitude of 2, 400 m above the sea level. The OT has a tradition of more than 30 years in the study of CMB anisotropies, with experiments like the Tenerife radiometers (1984-2000), the IAC-Bartol (1994-1997), the JBO-IAC two-element 30 GHz interferometer (1997-2002), the COSMOSOMAS experiment (1998-2007) and the Very Small Array interferometer (2000-2008). The OT will soon host three different instruments for CMB polarization, one of them (QUIJOTE) being operational already. Of the three sites intensively used by CMB experiments, Tenerife is the only one in the Northern Hemisphere. The characteristics of

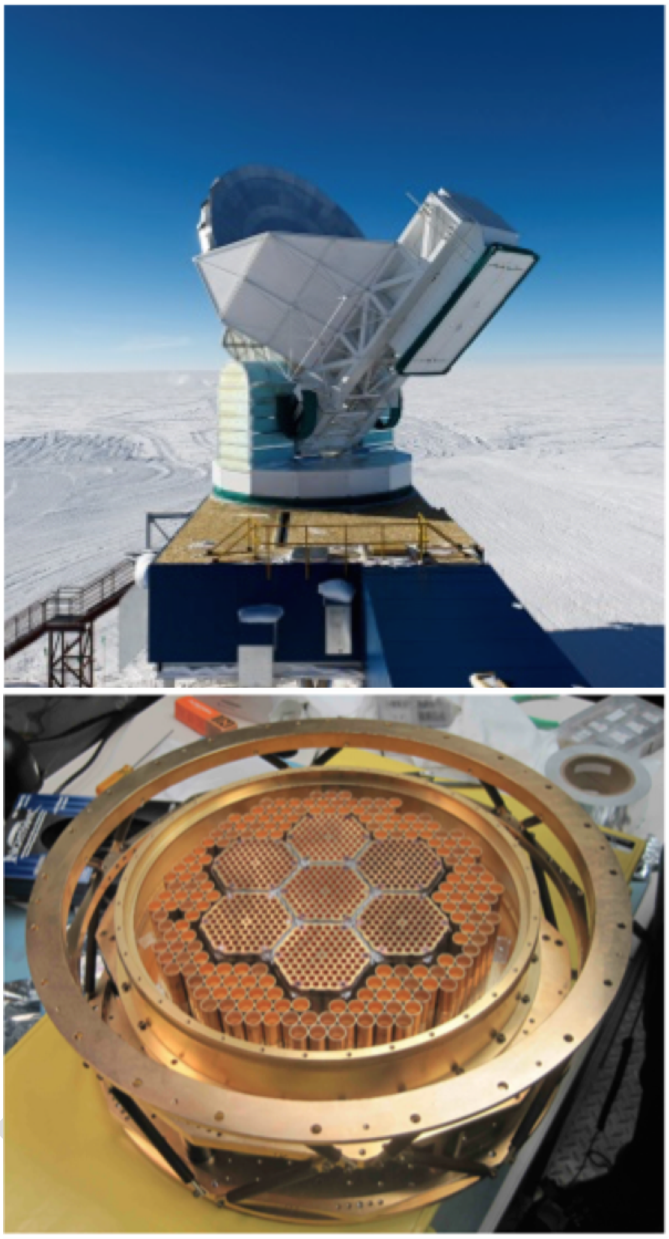

Figure 6: The South Pole Telescope (top) and the SPT-3G focal plane (bottom).

Figure 7: Experiments in operation (QUIJOTE) and planned to be deployed (LSPE/STRIP and GroundBIRD) at the Teide Observatory, Tenerife.

the site, at moderate altitude and easily accessible, are favorable for low frequency observations (Figure 7).

QUIJOTE. QUIJOTE (Rubino-Martin et al. 2012) comprises two 2.5 m, fully spinning, off-axis telescopes to measure CMB polarization at low frequency. Both telescopes are operating now. The telescopes are equipped with three instruments: the MFI (10–20 GHz), TGI (30 GHz) and FGI (40 GHz). The two main goals of the project are to provide northern sky maps ($20,000\,\mathrm{deg}^2$) of the polarized emission in the 10–20 GHz range, and also to carry out deep integration in three regions covering a sky area of $\sim 5000\,\mathrm{deg}^2$, with a sensitivity $\sim 1\,\mu$K at one degree resolution in 6 frequency bands in the range 10–40 GHz (Table 1). QUIJOTE uses coherent receivers based on HEMT LNAs. The polarization detection is done using mechanical modulation of a polarizer (half-wave plate) a cryogenic temperatures in the MFI instrument (10–20GHz), while the TGI and FGI instruments use phase switches. The MFI has been in operation since November 2012. The TGI instrument has 31 polarimeters at 30 GHz, while the FGI will deploy 31 polarimeters at 40 GHz. Both instruments share the same cryostat, so simultaneous observations with some receivers at 30 GHz and some others at 40 GHz are possible.

LSPE/STRIP. In 2018, STRIP will deploy a 1.5 m, fully rotating, cross-Dragone telescope coupled to an array of 49 coherent polarimeters at 42 GHz, plus 6 channels at 90 GHz as atmospheric monitor. The HEMT-based polarimeters are cooled to 20 K and use a pseudo-correlation design, each directly producing the Q and U signals. The aim is to cover about 25 % of the sky with sub-degree resolution. STRIP is the ground based partner of the balloon-borne SWIPE in the LSPE project. SWIPE will observe the same sky area of STRIP, covering 140 and 220–240 GHz bands with TES bolometers. The combination of the two LSPE instruments will provide good leverage to remove polarized dust and synchrotron. The LSPE sky area also overlaps with the 3 "deep regions" observed by QUIJOTE at lower frequencies.

GroundBIRD. GroundBIRD is a fast-spinning (∼20 rpm), small-aperture (∼30 cm) telescope with cooled optics (Otani et al. 2016). The focal plane houses an array of ∼450 pixels at 145 and 220 GHz, using microwave kinetic inductance detectors (MKIDs) cooled to 210 mK. The mirror has an aperture of 30 cm and is cooled to 3.4 K to suppress photon noise. The instrument employs a rotary joint to pass through the high-pressure He gas while allowing fast rotation.

All three Tenerife projects (QUIIJOTE, LSPE and GroundBIRD) aim at measuring large sky areas at degree scales. While no formal collaboration is currently in place between different instruments, there is potential for synergy, as a large portion of the Northern sky will be observed at several bands in the 10–220 GHz range, including useful redundancy for systematics cross-checks.

.1.5 Experiments at other sites and other wavelengths

C-BASS is an ongoing project to make a full-sky map in temperature and polarization at 5 GHz with ∼0.7° resolution, mainly to improve control of polarized foreground synchrotron radiation. Two instruments are operated from two low altitude sites, one in each hemisphere. The Northern instrument uses an on-axis 6.1-m telescope at Owens Valley Radio Observatory (OVRO), California. The Northern survey was completed and data are being analysed (early results in Ifran et al 2015), while the Southern instrument completed commissioning in late 2016 and is currently taking data. We also report on the S-PASS (S-band Polarization All Sky Survey) a polarization survey at 2.4 GHz, of relevance for synchrotron foreground removal (Carretti et al 2010, Krachmalnicoff et al 2018). The full Southern sky has been mapped in 2007-2019 with Parkes radio telescope with 9 arcmin resolution and SNR>5. The plan is to complete the survey in the Northern hemisphere using the Sardinia Radio telescope (SRT) in the same frequency band.

.1.6 Coordination in the US for ground-based efforts

Since 2013, the US CMB community has been developing a major coordination effort to lead the main existing and planned ground-based polarization experiments towards an ambitious plan, called "CMB-S4", to be deployed around 2025. The plan involves university-based groups, national laboratories, all main US funding agencies and private donations. Successive generations of experiments are categorized in four stages based on the typical number of detectors they host in their focal planes. Typically, the ongoing experiments described above are Stage 1 (∼10^2 detectors) or Stage 2 (∼10^3 detectors), while those planned are Stage 3 (∼10^3 detectors). As an example, in figure 2.7 the Bicep2 and Keck Array are Stage 2, while BICEP3 and BICEP Array are Stage 3. The ultimate plan is to reach a Stage 4 ("CMB-S4"), with focal planes of order (∼10^5 detectors). Figure 8 shows the corresponding sensitivity progression, assuming no impact from systematic effects and no significant penalty from foregrounds or the atmosphere; it also shows a few figures of merit in terms of scientific capabilities (limits on tensor-to-scalar ratio,

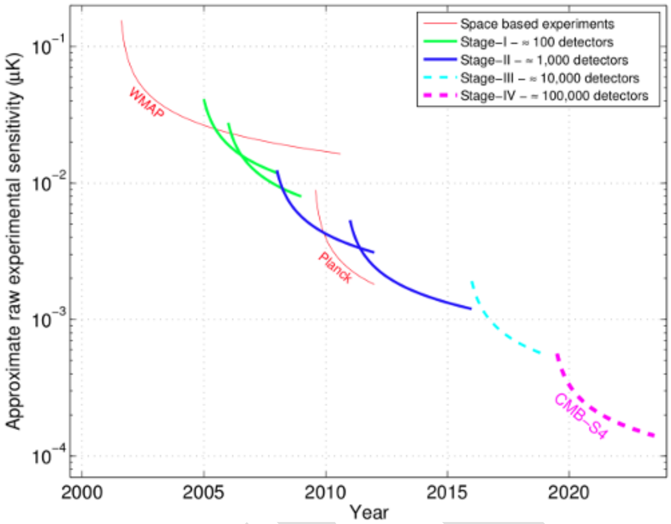

Figure 8: Different stages of future ground-based polarization experiments according to the S4 program. The predicted sensitivities assume white-noise of photon-noise-limited detectors (from CMB-S4 Collaboration 2016a). The CMB-S4 sensitivity corresponds to 1 μK·arcmin with 4 years survey of ∼50 % of the sky.

$\sigma(r)$; on number of neutrino species $\sigma(N_{\rm eff})$; on neutrino mass, $\sigma(\Sigma m_\nu)$, and dark energy).

The CMB-S4 project is conceived not as a single instrument, but as multiple dedicated telescopes operating from the South Pole, the high Chilean Atacama plateau and possibly a northern hemisphere site, to provide the required sky and spectral coverage (CMB-S4 Collaboration 2016a). The plan is to consider a combination of small aperture and large aperture telescopes, to probe several-degrees and sub-degree scales, respectively. The primary objective will be checking the reionization peak down to $\ell < 20$. The recombination peak is more likely accessible by complementary space or balloon experiments. In any case Stage 3 should verify the feasibility of probing down to $\ell \sim 2$–3 with ground-based observations and possibly pushing that for CMB-S4.

.2 Balloon

Balloon-borne instruments have also played an important role in the development of the field of CMB measurements. The primary advantage of a balloon-based experiment is the ability to observe from above the bulk of the Earth's atmosphere, thereby significantly reducing the experimental noise. It has been, in fact, one of the few ways of taking data above around 250 GHz. In the past, ARCADE, ARCHEOPS, ARGO, BAM, BEAST, BOOMERANG, EBEX, FIRS, MAX, MAXIMA, MAX-IPol, MSAM, QMAP, and TopHat have all exploited this fact in order to publish cutting-edge CMB results. As mentioned above, SWIPE is being developed to observe, in conjunction with STRIP, at frequencies between 140 and 230 GHz.

Traditional balloon flights, however, are limited to around a day of observations, and like satellites have limitations on their size. The PIPER program aims to surmount this difficulty by making multiple flights per year, drastically reducing the time between flights. To date they have had one successful test flight, and are targeting three flights in 2018 (in the past, most balloon experiments have flown once per year at most), with a total of eight flights over the life of the program.

BOOMERANG, EBEX, and TopHat, on the other hand, increased the amount of observation time by flying "long-duration" flights, staying aloft and taking data continuously for up to two weeks while circumnavigating Antarctica. The *Spider* experiment took data at 100 and 150 GHz during a Winter, 2014-15 long-duration flight, and will have one more flight, adding a 280 GHz channel. Similarly, IDS, an evolution of EBEX program, is also being proposed to NASA's long-duration balloon (LDB) program.

As ground-based experiments become larger and continue to observe longer, pressure remains on balloons to continue to increase their observation time. The proposed BFORE program seeks to address this by flying an "Ultra-Long-Duration" balloon (ULDB; `https://www.csbf.nasa.gov/balloons.html`) flight. This program is in its infancy – there have only been a few test flights – but has a goal of a 100-day flight. None of the handful of flights to date have targeted the CMB, but with a goal of 100 days aloft, this may ultimately allow balloon experiments to have similar post-detection (i.e., integrated over the life of the program) sensitivities to those of ground based instrument. And in the absence of another satellite mission, it may be the only way to get higher frequency data.

.3 Space

There are clear advantages in going to space. The absense of atmostphere allows measurements in the whole frequency range of interest and greatly reduces the experimental noise. This unique environment, specially at L2, provides very stable conditions and also is not affected by any electromagnetic contamination from human activity. Those stable conditions allow, in particular, a better control and characterization of systematic effects. Space-based experiments have achieved outstanding results in the measurement of the CMB temperature and polarization anisotropies. The NASA *COBE/DMR* instrument discovered the CMB temperature anisotropies and measured its spectrum at low multipoles (Smoot et al. 1992). A decade later, the *WMAP* satellite, also from NASA, provided the most precise measurement of the temperature spectrum at that time and started the era of precision cosmology (Bennett et al. 2003). More recently the ESA *Planck* mission has measured the temperature spectrum with a precision only limited by cosmic variance up to multipoles $\ell \approx 1500$. This measurement together with that of the porization power spectra are extremely well described by the spatially flat six parameters ΛCDM model, allowing the determination of the cosmological parameters with unprecedented precision (Planck Collaboration et al. 2016). At present there are several initiatives to measure CMB polarization from space with a sensitivity orders of magnitud better than Planck and with the main aim of detecting the polarization B-mode: *LiteBIRD* (JAXA), *CMB Bharat* (ISRO) and *PICO* (NASA). Among them *LiteBIRD* is in the most advanced stage.

The *LiteBIRD* spacecraft Hazumi et al. (2012); Matsumura et al. (2014); Ishino et al. (2016) is designed to measure the full-sky distribution of temperature and polarization anisotropies of the CMB in the multipole range of $2 \leq \ell \leq 200$. To this end it will map the entire sky in 15 microwave frequency bands from 34 to 448 GHz (with the band centers from 40 to 402 GHz), which are required to reduce effects of Galactic foreground emission on the CMB map.

LiteBIRD was proposed to JAXA as a Strategic Large Mission in February 2015, and is currently in JAXA's Phase A1. The final selection by JAXA is expected to be announced no later than the end of March 2019. The planned launch date is 2026.

The baseline design of the *LiteBIRD* consists of two telescopes Sugai et al. (2016): Low Frequency Telescope (LFT) and High Frequency Telescope (HFT), both of which will use half-wave plates as the first optical elements for polarization modulation. The focal planes Matsumura et al. (2016); Suzuki et al. (2018) will be cooled to 0.1 K and filled with a few thousand transition-edge sensor (TES) bolometers. Each pixel contains a sinuous antenna coupled by a lenslet, and is sensitive to multi colors.

Full-sky maps in 15 microwave bands offer rich data sets, which enable many exciting science topics including primordial gravitational waves from inflation and their detailed characterization, reionization of the Universe, cosmic birefringence, hot gas in the Universe probed by the SZ effect, spatial variations of deviations from CMB's Planck spectrum, tests of the so-called "anomaly" in temperature data with polarization, and Galactic science. In addition, cross-correlating *LiteBIRD* data with other data sets such as the distribution of galaxies will yield a richer set of results, which maximize scientific impacts of *LiteBIRD*.

There is keen interest in a successor to FIRAS, as well as an anisotropy experiment with a larger aperture than that of *LiteBIRD*.

CMB Bharat (Anjalimarar 2018) might exist, and an American concept, *PICO*, will be presented to the decadal survey.

A proposal towards regular **APPEC-Town Meetings**

Status: idea supported by APPEC-GA, advice requested from APPEC-SAC.

Introduction

APPEC has made great progress in coordination at European level in recent years. The highlight is the development of the recent roadmap. Supporting the implementation of the roadmap will continue to be one of APPEC's tasks in the coming years.

The implementation of the roadmap has two sides. One side points towards the funding agencies to be taken care of by the APPEC functional center(s). The other side points to the scientific community. APPEC must strengthen its acceptance of the scientific community in order to obtain the mandate to represent the interests of all scientists on the European level. The scientific community must have the confidence to talk openly with APPEC about ideas and plans for the future.

Towards Regular Town Meetings

Regular Town Meetings organized by APPEC could be an important means to support the strategic discussion in European Astroparticle Physics.

- The Town Meetings can be used as summaries of the strategic discussions in the different research fields of Astroparticle Physics.
- On the basis of a Town Meeting every 2-3 years, strategic developments could be discussed in a larger circle and new initiatives launched.
- The Town Meetings would be a good way to involve a large part of the European Astroparticle Physics community directly in the discussions and also to offer a cross-field forum.
- The Town Meetings should focus on strategic issues and clearly not be understood as a scientific conference. Input on the topics should come from the GA, SAC and from the scientific community.

The Town Meeting in Paris 2016 as part of the development of the current roadmap is a very good example of how these meetings could be organized. There are similar regular strategic meetings on a national basis in many countries. In addition to the strategic discussion, these meetings are also an excellent tool for further networking Astroparticle Physics and thus gaining greater coherence and momentum. And last not least the Town Meetings could be recognized as a trademark of APPEC.

The focus of the Town Meeting should be on the recommendations of the roadmap. The central questions should be:

1) Where do we stand in the implementation of the roadmap?
2) What are the developments that could lead to a change in the strategic recommendations?
3) What are the new developments in Astroparticle Physics but also in neighbouring fields?

It seems sufficient if the Town Meeting lasts 2 days.

Town Meeting preparation and organization

The preparation of a Town meeting should be done along two ways. On the one hand, the SAC should inform itself about the scientific developments in the various research fields and identify strategically relevant topics for discussion. On the other hand, national Astroparticle Physics communities should be informed about the preparation of the Town Meeting, so that they can bring in topics to the SAC.

A possible timetable would be: One year before a Town Meeting, the scientific communities and the national communities would be informed about the start of the organisation of the next Town Meeting. Six months before the Town Meeting, the SAC will determine the topics in consultation with the GA and then concretely prepare the meeting. This would give both the national committees and the scientific communities sufficient time to prepare for the Town Meeting.

At the same time, the accompanying organisational steps, such as the determination of the location, etc., are being carried by the APPEC workforce/functional center.

This proposal was supported by APPEC-GA in May 2019. It was decided to send it to the APPEC-SAC with a few comments:

- *Is the SAC willing to take up the important role in the organisation of the Town Meetings?*
- *Can the SAC together with the APPEC Workforce decide on a good month in the fall for the planning of the Town Meetings?*
- *In the schedule should be plenty of time for discussions and not too many talks*
- *The location of the Town Meeting will rotate; a call to host the next Town Meeting will be organised.*

Workshop on Observatory Synergies for Astroparticle Physics and Geoscience

11-12 February 2019, Institut de Physique du Globe, Paris

Summary and Outlook

On February, 11-12 2019 the European Alliance for Earth Sciences – GEO.8, the Astroparticle Physics European Consortium – APPEC and the Academia Europaea organized the Workshop on Observatory Synergies for Astroparticle Physics and Geoscience at the Institut de Physique du Globe de Paris (IPGP) (https://indico.in2p3.fr/event/18287/)

More than 60 scientists and representatives of funding agencies and companies from 11 European countries gathered together. The aim was to discuss the scientific and technical overlapping topics of the two communities and to promote a common strategy for the future.

It is also important to note that in the framework of the EU-funded ASPERA ERANET, precursor of APPEC, three workshops in the period 2011-2012 had been organized and a brochure had been prepared in order to address and develop synergies between astroparticle physicists and geoscientists.

At IPGP, many overlapping aspects concerning science, technology/methodology and societal impacts have been identified. Some of the highlights are mentioned in the following.

Neutrinos covering a broad energy spectrum and detected by different astroparticle underground, underwater and under-ice observatories have the potential to additionally give precious information about the Earth's mantle and core.

Cosmic ray muons, are a very promising tool to complement to geophysical imaging techniques such as gravimetry to investigate underground structures, with many applications ranging from volcano monitoring to archaeology and underground structure prospection.

Methodologies developed in the context of gravitational wave research, e.g. for the monitoring of micro-seismic noise and/or stronger seismic incidents can have applications ranging from Earthquake Early Warning systems to the monitoring and risk evaluation of large civil infrastructures. Inversely, geoscientific techniques and algorithms realized for subsoil mapping and assessment of the seismic noise have a return to gravitational wave environmental noise hunting issues.

Ocean imaging is another example of measurements that geoscientists and deep ocean neutrino observatories commonly perform, e.g. through the deployment of acoustic sensors. They can give precious information on seismic activity as well as hints about biological formations and the behavior of deep ocean life.

More generally, astroparticle physicists and geoscientists working with underground or underwater facilities/instrumentation can reveal with unprecedented detail the characteristics and the geological role of "deep-life" in Earth or Ocean.

An overview of recent discoveries on life in the deep Earth attracted much attention and confirmed the needs of investigations in extreme environment.

On the technical front, the innovations concerning large distributed seismic and gravimetry networks based on very new technologies have an impact on both sides of the astro-geo-synergy. A common interest arose thus on the recent developments using optical fibers as distributed acoustic or strain sensors monitoring large areas as well as means of implementation of precise timing and synchronization.

Last but not least, a geoscience observatory in preparation, the Krafla Magma Testbed (KMT, www.kmt.is) was presented as an example of a possible locus of development of synergies around a large infrastructure.

In the discussion that followed the presentation of the above characteristic but certainly not exhaustive list of synergies, the gathered agencies and leading scientists decided to pursue and enhance the work along the following lines:

i. The sustainable institution of yearly meetings on these common topics of synergy, eventually opening them to the global community. The effort to implicate ESFRI and Other World Class (OWC) infrastructures, from both fields in order to assess synergies has to be enhanced. The participants demanded therefore that next meetings could be organized close to large infrastructures of either field. The European Gravitational Observatory (EGO), host of the VIRGO gravitational-wave detector close to Pisa, in Italy, will thus be the location of the next workshop in 2020. It was also recommended to involve already existing overlapping communities, such as the geoneutrino one, already engaged in the organization of conferences and summer schools on shared topics.
ii. The common future demands concerning computing and IT technology, already the subject of COST actions (e.g. COST CA17135 on Machine Learning in Geoscience and Gravitational Waves) have not been deeply treated in the workshop in Paris but should be considered in the near future and included in a dedicated event and/or in the planned conference of 2020.
iii. In order to realize ambitious collective projects, the APPEC and GEO.8 representatives recommended to summarize the shared demands and aims in a roadmap for the upcoming years. An *ad hoc* working group for the preparation of this document will be soon established. The different funding agencies and organizations involved in APPEC, GEO.8, EGU and AGU – the European and American Geoscience Unions, could be then more easily engaged in joint activities involving for instance the realization of large infrastructures such as those proposed by the KMT Consortium.
iv. Concerning the consortia links, the Chair of the Executive Board of GEO.8 will be invited to the General Assembly meetings of APPEC as an observer and vice-versa.
v. The Earth and Cosmic Sciences section of the Academia Europaea can provide the framework for further discussing and exploring synergies between astroparticle physicists and geoscientists.
vi. Last but not least, the EU framework programs Horizon 2020 and the future Horizon Europe are an opportunity to finance joint activities in different categories e.g. FET, ERC synergy, MSCA- COFUND/ ITN/ RISE, without excluding possible options in the pillars Industrial Leadership and Societal Challenges, and the respective successors in FP9.

This document is signed by the organizing team, the representative of Academia Europaea, the chair of APPEC and the Executive Secretary of GEO.8: Michel Diament, Stavros Katsanevas, Francesca Moglia, Paolo Papale, Teresa Montaruli and Alexander Rudloff.

GEO8 European Alliance for Earth Sciences · Academia Europaea · APPEC

APPEC-GA proposal

Towards a common APP-GEO roadmap

May 2019

Introduction: the recent convergence between geosciences and astroparticle physics

There are many areas of natural synergy between geosciences (GEO) and astroparticle physics (APP). These two fields share a mutual scientific culture based on common objects of study, methods and approaches. The geosphere, is a direct object of study of the geosciences and also the target and detecting medium for astroparticle observatories. Additionally, APP and GEO both deal with complex natural systems also of very large dimensions with respect to human ones, with large sensor networks in sometimes hostile environments (sea, desert, underground, space), and also require long series of precise observations acquired over various time scales, and models relying on the state of the art in fundamental physics, chemistry, biology and informatics. Radioactive dating is a common tool and they both use large data manipulation and worldwide networking, including the distribution of alerts, based on new monitoring techniques. Furthermore, the proper understanding of the Earth environment and its climatic changes, impact of scientific infrastructures on the environment has become an urgent societal task. Additionally, the GEO-APP fields have high innovation potential in introducing new "smart" technologies. Both communities are highly involved in education with goals to teach scientific methodology and spread critical thinking on societal issues, promoting citizen's science and participation.

For these reasons, on February 11-12, 2019 APPEC, GEO.8 and Academia Europaea organized the Workshop on observatory synergies for astroparticle physics and geoscience in Paris. From the published conclusions of the event (doc 11.1) emerges the clear aim expressed by the community and the organizations present in Paris of institutionalizing this collaboration with the realization of a roadmap (point iii).

In the present proposal, we sketch the structure of this document from APPEC side, before approaching the colleagues from GEO.8 and Academia Europaea, and a possible action plan for the upcoming months.

A first scenario of work packages (WPs)

For the future of the collaboration between APP and GEO, we foresee 7 WPs.

The first 3 WPs treat directly 3 main families of experiments, where the interests of the two joint communities are presented. Between them, WP3 considers 3 sub-topics covering 3 environments: earth surface, atmosphere and space. WPs 4-6 cover technological and societal interests common to the two scientific communities, either as independent technologies or applicable to present and upcoming experiments.

WP7 is the one looking at the future, for the realization of joint projects.

1) **WP1: Deep and shallow underground science**
    a. APP concerned infrastructures: Underground labs (Gran Sasso, Modane etc); dark matter and neutrino detectors; present and future gravitational-wave detectors (Virgo, ET)

b. GEO Concerned infrastructures: KMT, EPOS
c. Common themes: seismicity and Newtonian noise, understanding the earth's core and mantle, develop low radioactivity techniques, infrastructure challenges, monitor geological strata for long times, extreme biology and geomicrobiology, earthquake early warning.

2) **WP2: Deep sea/ice science**
   a. APP concerned infrastructures: KM3NET, IceCube
   b. GEO concerned infrastructures: EMSO, ARGO
   c. Common themes: deep sea and ice monitoring, core and mantle measurements, acoustic detection, deep sea biology, environmental monitoring (CO_2, O_2, radioactivity), earthquake and tsunami early warning, muons for measurements of temperature variations (eg for South Pole).

3) WP3: Space and atmospheric science and experiments on earth-surface
   a. APP concerned infrastructures: CTA, AUGER, LISA, CMB experiments
   b. GEO concerned infrastructures: EISCAT, IAGOS
   c. Common themes: understand and monitor the atmosphere, Newtonian noise for Gravitational detectors, cloud formation, cosmic rays, atmospheric monitoring satellites (TARANIS, cubesats, ESA plane network), GPS/Lidar atmospheric monitoring

4) WP4: Instruments and technology
   a. Muon tomography
   b. Innovative gravimetry
   c. Fiber sensing
   d. Acoustic imaging
   e. Distributed and/or robotic sensors
   f. Network synchronization and time distribution
   g. Early warning systems
   h. Large Civil Infrastructure issues

5) **WP5: Data acquisition, computing and analysis**
   a. Low latency acquisition
   b. Distribution of alerts
   c. Machine learning
   d. Massive computing issues
   e. Open data issues

6) WP6: societal impact
   a. Early warnings
   b. Citizen's science
   c. Outreach, education and engagement
   d. Critical thinking on Earth and Universe

7) **WP7: Coordination and next generation of large infrastructures**
   a. Agency coordination
   b. Community building
   c. EU and International coordination (e.g. common calls in Horizon Europe)
   d. Communication with national/global instances on societal issues (e.g. climate change)

A straw calendar

In blue are the APPEC independent actions and in black the APP-GEO ones.
Proposal to GA is to conduct the following activities together with GEO.8/Academia Europaea.

I. Nomination of the roadmap committee: mid-June 2019
II. First feedback from SAC in their meeting: mid-June 2019
III. A first meeting of the roadmap committee and finalization of the work-package content:early September 2019
IV. Second feedback from SAC: November (?) 2019
V. Reporting to APPEC GA and GEO-8: December 2019
VI. First Town meeting: July 2020 (to be discussed: inclusion in APPEC Town Meeting plan)
VII. Proposals to Horizon Europe

Questions to the General Assembly:

(1) Do you have comments on the scientific and technical content?
(2) Do you have comments on the sustainability of the plan?
(3) How can this plan be integrated with the other APPEC activities?

Double Beta Decay APPEC Committee
Executive Summary

Version 1

June 11, 2019

Panel: Andrea Giuliani, J.J. Gomez Cadenas, Silvia Pascoli (Chair), Ezio Previtali, Ruben Saakyan, Karoline Schäffner and Stefan Schönert

The discovery of neutrino masses and mixing, implied by neutrino oscillations, is so far the only particle physics evidence of physics beyond the Standard Model (SM). It has opened new key questions, among which establishing the nature of neutrinos is arguably the most important. The latter is intrinsically related to the conservation of lepton number, which is related to the fundamental symmetries of nature, the origin of neutrino masses in theories beyond the Standard Model and the generation of the observed matter-antimatter asymmetry in the Universe via the leptogenesis mechanism. Generically, neutrinoless double beta decay is the most sensitive probe of lepton number violation.It is mediated by the 3 light massive neutrinos, if they are of Majorana type, with half-lives which may be at reach in current and future experiments. The theoretical predictions depend on the values of neutrino masses, whether they are with normal ($m_1 < m_2 < m_3$) or inverted ($m_3 < m_1 < m_2$) ordering, and on the CP violating phases. They can also receive contributions from other lepton number violating processes, e.g. sterile neutrinos, in extensions of the SM.

Recommendation 1. The search for neutrinoless double beta decay is a top priority in particle and astroparticle physics.

Key technologies in the search for neutrinoles double beta decay have been conceived, developed and demonstrated in Europe: germanium diodes operated in liquid argon with high energy resolution and multi-site event rejection; pure and scintillating bolometers capable of studying at least four different isotopes with high energy resolution and particle identification; gaseous Xenon TPC capable of joining good energy resolution with topological reconstruction of the events and, in future, final state identification. Other developments regard the use of room temperature semiconductor detectors and the synergies between dark matter search and double beta decay searches in Xe-based experiments. The most promising searches based on these technologies should be supported in order to ensure the international leadership of the experiments with European direction and located in European laboratories.

Recommendation 2. A sustained and enhanced support of the European experimental programme is required to maintain the leadership in the field and exploit the broad range of expertise and infrastructure.

The current objective of the experimental search for neutrinoless double beta decay (DBD0ν) is to explore deep into the inverted ordering region of the neutrino mass pattern. Several proposed next-generation projects aim at this goal. Some of them can in principle fully cover this region and detect DBD0ν even in case of direct ordering, provided that the lightest neutrino mass is larger than 10–20 meV.

Future projects can be broadly classified into two categories: experiments using a fluid-embedded DBD0ν source (featured by large sensitive masses and easy scalability) and experiments using a crystal-embedded DBD0ν source (featured by high energy resolution and efficiency). In the first class we have Xe-based TPC projects like nEXO (evolution of the closed EXO-200), NEXT-HD (evolution of imminent NEXT-100), and PandaX-III-1t (evolution of the foreseen PandaX-III-200). This class includes also experiments which dissolve the source in a large liquid-scintillator matrix exploiting existing infrastructures like KamLAND2-Zen (evolution of the current KamLAND-Zen-800) and SNO+-phase-II (evolution of the imminent SNO+-phase-I). In the second class we have experiments based on germanium diodes like LEGEND-1t (evolution of the current GERDA and MAJORANA and of the planned LEGEND-200) and those which exploit the bolometric technique, like the multi-step AMoRE program (AMoRE-I and AMoRE-II, which represent the evolution of the current AMoRE pilot), and CUPID, which is based on the large experience gathered by CUORE and the demonstrators CUPID-Mo and CUPID-0, which are all collecting data.

In this rich landscape, the most prominent projects with a strong European component are CUPID, LEGEND-1t and NEXT-HD. Featured by a planned 3 σ discovery sensitivity that, at least for some matrix element calculations, reaches below 20 meV for $m_{\beta\beta}$, these projects can ensure Europe a forefront position in the international scenario. They study three different isotopes (^{100}Mo, ^{76}Ge and ^{136}Xe respectively) with quite different approaches, offering a large complementarity that is a bonus for such a challenging research.

A multi-technology approach is necessary to mitigate the risks of individual experiments and to corroborate the findings, given the experimental challenges posed. The use of multiple isotopes may allow to identify the mechanism behind the process, whether mediated by light neutrino masses or due to some exotic physics.

Recommendation 3. A multi-isotope program at the highest level of sensitivity should be supported in Europe in order to mitigate the risks and to extend the physics reach of a possible discovery.

If the neutrino mass ordering is normal and the lightest neutrino mass is below 10-20 meV, only experiments with zero background in the tens of tons scale have a chance to detect neutrinoless double beta decay if the light neutrino mass mechanism is dominant. This poses a formidable challenge that no technology is capable of facing at the moment. However, extensions of the present approaches or totally new ideas could in principle achieve this elusive target if supported by an adequate R&D program. These R&D activities should be funded in order to prepare right now the medium term future of double beta decay search. Of course, the required large scale enrichment remains by itself a major challenge, which could probably be overcome only by developing a dedicated international facility as a part of the research program itself.

Recommendation 4. A programme of R&D should be devised on the path towards the meV scale for the effective Majorana mass parameter.

In order to establish a multi-technology and multi-isotope DBD0ν physics program extensive underground space to host the DBD0ν-experiments is necessary. Facilities, not only in Europe, are encouraged to support this rich physics strategy by providing the necessary underground space (including upgrading existing facilities) as well as onsite expertise in low-background techniques to guarantee an effective and timely implementation of the experiments. Close coordination between the European underground laboratories for hosting prototype detectors and low-background screening is mandatory.

Recommendation 5. The European underground laboratories should provide the required space and infrastructures for next generation double beta decay experiments and coordinate efforts in screening and prototyping.

Last but not least, once a positive signature is found, lepton number violation will be established and a key question will be to determine the physics mechanism behind it. A strong theoretical effort should be devoted to continue to explore different theoretical models behind neutrinoless double beta decay and its complementarity with other experimental searches e.g. for heavy sterile neutrinos, left-right models at colliders, leptoquarks etc. Consequently, this will allow to extract the information from the measurement of the half life. Most interestingly, in the case of the simplest mechanism of light neutrino exchange, this would give information on neutrino masses and, at least in principle, on Majorana CP violation, with a strong complementarity with the determination of neutrino masses from cosmology. Such plan requires to extract the effective Majorana mass parameter with high precision, for which nuclear matrix elements need to be evaluated. The computation of nuclear matrix elements is challenging and currently is affected by an uncertainty which is typically quantified in a factor of 2-3. New developments are very promising and exploit ab-initio computations. An enhanced effort is required and a stronger interactions between the particle physics and nuclear community would be highly beneficial.

Thanks to the large mass, low background and high detector performances, the new generation double beta decay experiments will be also sensitive to a certain number of other physical processes that allow experimental investigation with unprecedented sensitivities. Alternative double beta decay modes, some exotic processes predicted by the extensions of the Standard Model, validation of fundamental physics principles and, most important, the search for Dark Matter candidates could be analyzed with great precision. The investigation of all these possible physics channels indicates that the designed approaches could be considered as multipurpose experiments, for which neutrinoless double beta decay is the main goal, but also other important achievements could be also considered of extreme scientific importance.

Recommendation 6. A strong theoretical effort should proceed in order to understand the particle physics implications of a positive observation, to achieve a more accurate determination of the NMEs and to exploit the broader physics reach of these experiments.