White Paper ID Number W050

Title of White Paper CMB Science in Canada

ID of Associated Expression of Interest E022

Topic Area of White Paper new facilities, experiments and missions

Executive Summary of White Paper (5000 character limit)

The previous decade of CMB science has led to incredible new discoveries and key science results including the detection of CMB lensing from temperature and polarization measurements, constraints on light relics and primordial non-Gaussianity and the measurements of Sunyaev-Zel'dovich signals by leveraging the CMB as a backlight to astrophysical objects between us and the last scattering surface. With significant improvements to detector and cryogenic technologies, the coming decade promises to be just as rich scientifically. We discuss fundamental science with CMB fluctuations, including the search for primordial B-modes on large scales to constrain the inflation through the tensor-to-scalar ratio, the dark sector through neutrino mass and light relics with the small-scale CMB power spectrum. We highlight current and planned advances in sensitivity of the CMB facilities and describe international collaborations with significant Canadian participation, including the Atacama Cosmology Telescope, the South Pole Telescope, SPIDER, BICEP-Keck, CGEM, the Simons Observatory, CCAT-p, TAURUS, CMB Stage-4, and LiteBIRD, and the Canadian involvement in the international CMB landscape. In a separate paper, we will highlight the science possible with wide surveys at submm-to-mm wavelengths, including measurements of the Sunyaev-Zel'dovich effect from galaxies, the Cosmic Infrared Background, and cross-correlations with other probes to learn about astrophysics at intermediate redshifts. Our white paper will outline the complementarity of various Canadian CMB efforts on the ground, in balloons and in space. We will address the need for Canadian support of these projects, to leverage the significant expertise in both theoretical and experimental cosmology within Canada. Canadians have been supported through traditional funding mechanisms (NSERC, CFI) for their ground-based efforts. As the community coalesces around LiteBIRD as the major satellite-based observatory for CMB polarization, dedicated mission-level funding is needed from the Canadian Space Agency for Canadians to realize their global leadership--this funding is the most challenging aspect of CMB science for the next decade.

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LRP2020 White Paper

CMB Science in Canada

THEMATIC AREAS (SCIENCE): Cosmology, Dark Energy & Dark Matter; Cosmic Microwave Background; Inflation

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1 Introduction

The cosmic microwave background (CMB) is one of the cleanest probes of cosmology and much remains to be learned from continued measurement and analysis of it. The fluctuations in the temperature and polarization pattern of the CMB yield a wealth of information about both the early and the late time Universe. CMB measurements on large scales probe primordial gravitational waves and the inflationary epoch, while measurements on smaller angular scales give insight into the matter distribution of the cosmos and insight into dark matter and dark energy. Measurements of the temperature fluctuations of the CMB are now close to the limit of cosmic variance on intermediate scales. Improvements in detector technologies will allow cosmic-variance limited measurements of the polarization anisotropies which, in principle, contain even more information than the temperature maps do. We will briefly describe the history of CMB observations, and the planned future missions, before discussing the relevance of CMB science to Canadian research and the need for continued investment in Canadian CMB science.

The CMB community (represented by the paper co-authors) has chosen to submit one unified white paper for the Long Range Plan, rather than many, and highlight our main priorities in terms of *CMB facilities* for the coming decade. These priorities include **a role in the international Simons Observatory Collaboration, a builder role in the CMB Stage IV collaboration, and Canadian leadership and participation in LiteBIRD**.

1.1 Science results from Canadian CMB facilities

CMB experiments from the ground, from space and from stratospheric balloons (all of which have significant Canadian leadership and participation) have led to significant scientific results over the past 10 years. A subset of these results include the detection of the lensing of the CMB on small scales (Das et al., 2011; van Engelen et al., 2012), the detection of the signature of dark energy from CMB measurements alone (Sherwin et al., 2011), the detection of small-scale B-mode polarization from gravitational lensing (Hanson et al., 2013; Polarbear Collaboration et al., 2014), and through cross-correlation between CMB maps and tracers of large scale structure (e.g. Baxter et al., 2018; Madhavacheril et al., 2015; Miyatake et al., 2017) and the many cosmological constraints from *WMAP* (**?**) and *Planck*, (e.g. Planck Collaboration et al., 2018). CMB science has delivered the first (and subsequently many) detection of the signature of the kinetic Sunyaev-Zeld'ovich effect (e.g. Hand et al., 2011; Schaan et al., 2016), constraints on cosmic non-Gaussianity (Crawford et al., 2014; Planck Collaboration et al., 2019). These CMB survey facilities have typically made their maps and products available for use by the community after a short latency[1], generating many additional papers and results beyond the main science publications of any given collaboration.

The next decade will usher in another significant improvement in detector and readout technology, and optical design, broadening the scope of scientific questions that can be answered with CMB data.

[1]The data are often released on NASA's LAMBDA site: https://lambda.gsfc.nasa.gov/

1.2 Fundamental physics from the CMB

The two main classes of scientific questions that one can answer using the CMB are:

- what can we learn about the earliest moments in the lifetime of the Universe by searching for inflationary signatures on the largest scales?
- what can we learn about the distribution of matter in the Universe, from small-scale measurements of the temperature and polarization of the CMB and how it is distorted by structures along the line of sight?

In addition to these fundamental cosmological questions, the microwave sky provides a wealth of information on astrophysics at intermediate cosmic epochs through measurements of the Sunyaev-Zeldovich (SZ) effect from galaxy clusters, the clustering of the cosmic infrared background and by cross-correlating mm- and sub-mm maps with other traces of matter in the Universe, like galaxy clusters. We leave discussion of these physics to a separate white paper (led by D. Scott).

1.2.1 Inflation physics

The polarization signature of the CMB gives a window into the primordial Universe through the tensor-to-scalar ratio r. Cosmic inflation is the current leading scenario for the origin of structure in the Universe, as quantum fluctuations are imprinted on all scales, later to 'grow' into the structures we see today. Inflation also naturally predicts the presence of primordial gravitational waves. Detecting these gravitational waves is one of the most important contemporary cosmological tasks; a detection of gravitational waves would reveal new physics at high energies and give us insights into quantum gravity. Different inflationary models predict different values for r, and CMB experiments in the coming decade will finally achieve sensitivities that will enable a significant detection of $r \sim 0.001$, within the bounds of many plausible models. Figure 1 illustrates how future CMB missions will be able to rule out large portions of model space, narrowing the window on allowed inflationary models and giving us insight into these first few moments in the life of the Universe.

Furthermore, the CMB has already provided vital constraints on the behavior of the early universe. The series of peaks and troughs in the temperature power spectrum, and large-angle anti-correlations between temperature and polarization anisotropies, are strong evidence that cosmic density fluctuations were generated at very early times rather than by cosmic strings at later times. The tilt of the power spectrum has already ruled out several inflationary models, and measurements of multi-point correlations in observed maps have also helped to constrain the space of models. Combinations of future CMB datasets with other cosmological probes will be essential for bringing these constraints below 'theoretical thresholds' that will enable us to rule out large classes of models for the early universe.

1.2.2 The dark Universe

In the simplest cosmological model consistent with today's data, 95% of the total energy budget of the Universe is made of dark matter and dark energy. In order to understand the nature of these mysterious cosmological components, we need to constrain the physical properties of these dark components and how they interact with the other ingredients in our cosmological model. Measurements of the CMB on small angular scales are sensitive to the diffusion damping of the CMB, which gives us insight into the number of neutrino species when the CMB photons decoupled from the baryons. Structures along the line of sight between us and the surface of last scattering deflect CMB photons, so small-scale CMB measurements enable us to probe the dark-matter power spectrum through the signature of lensing of the microwave sky. Through this lensing signature we will be able to probe additional components of our cosmological model. For example, we would be able to constrain non-standard dark matter models or the neutrino mass through the lensing signature, and would be able to constrain models with different effective degrees of freedom, as shown in Figure 2.

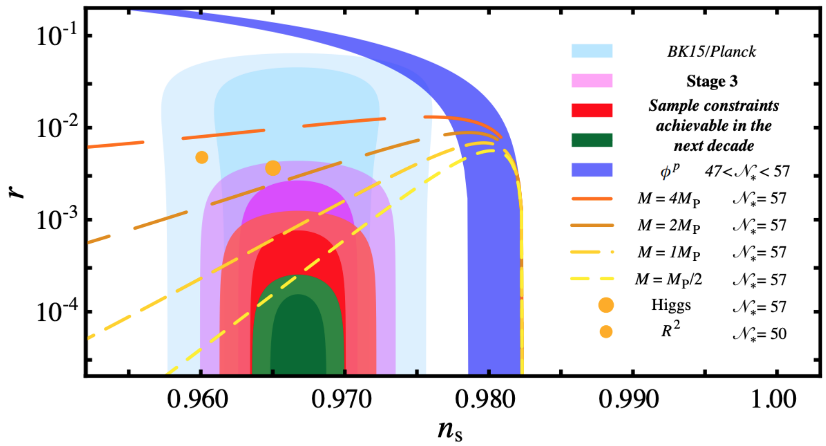

Figure 1: Model constraints from future CMB missions. Example forecasts of constraints with future ground- and space-based missions illustrate how powerful the next decade will be in testing inflation. Figure reproduced from Shandera et al. (2019).

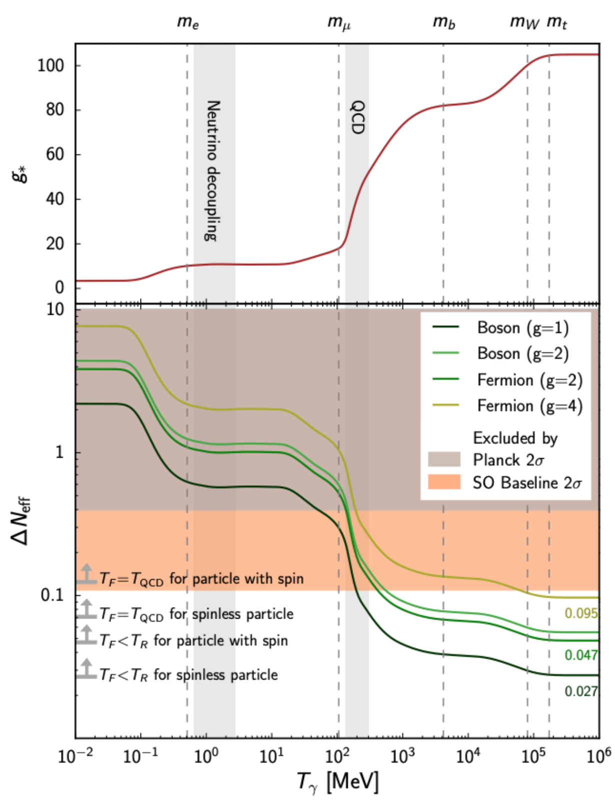

Figure 2: Constraints on light relics from CMB measurements. Future CMB experiments (here the forecast is for the SO baseline configuration) will be able to achieve errors on the effective relativistic degrees of freedom $N_{\rm eff}$ that will allow us to distinguish different models of the evolution of these effective relativistic species as a function of the photon temperature in the early universe, T_γ. Figure reproduced from Ade et al. (2019).

1.3 The future of CMB science

Canadian scientists have played very prominent roles in most of the major breakthroughs in CMB science despite only very modest funding. There has been no national funding for examples, for WMAP, ACT or the SPT and very little funding for *Planck* and others compared to their costs, and yet Canadians have played leading roles in experimental design, data analysis and scientific exploitation of these major missions.

Multiple international CMB telescope collaborations are planned for the coming decade, in addition to the improvements on existing facilities. All have Canadian involvement, and we list the main ones below.

1.3.1 ACTPol and AdvACT

The Atacama Cosmology Telescope (ACT), a Gregorian telescope with a 6-m primary mirror and a 2-m secondary mirror operated from 2007 to 2010 with the Millimeter Bolometer Array Camera (MBAC) as its primary science receiver. The detectors were upgraded in 2010 to feedhorn-coupled, polarization-sensitive detector arrays, to polarization-sensitive ACTPol, which continued to observe the CMB sky with arcmin resolution over about $2000\,\mathrm{deg}^2$ using dichroic detectors. The subsequent upgrade, Advanced ACTPol (AdvACT), commenced in 2016 and is ongoing, with observations in three bands, 90, 150 and 220 GHz over 40% of the sky. AdvACT will continue observations until the Simons Observatory sees first light. Canadian scientists at UBC, UofT, CITA and McGill have been active members of the ACT Collaboration since it began operations in 2007, and remain a driving force behind scientific analysis of the ACT data. ACT engagement has been supported in part by continued funding for computation from Compute Canada, enabling Toronto to be a site for much of the map-making and analysis of ACT data.

1.3.2 SPT

The South Pole Telescope (SPT) is a 10-m diameter telescope located at the Amundsen–Scott South Pole Station in Antarctica. The first SPT survey completed in 2011 and a new polarization-sensitive camera was installed on SPTpol in 2012. SPTpol operated from 2012 to 2016, scanning hundreds of square degrees on the sky to arcminute resolution. SPTpol was itself upgraded to the third generation SPT-3G in 2017, resulting in an order-of-magnitude improvement in mapping speed over SPTpol. The SPT-3G camera consists of 16,000 detectors across three frequency bands (90, 150 and 220 GHz). The SPT-3G survey began in 2018 and will cover $1500\,\mathrm{deg}^2$ to a depth of roughly $3\,\mu$K-arcmin at 150 GHz. Canadian scientists at Toronto and McGill actively contribute to the detector readout system for SPT, and a large fraction of the SPT analysis is performed in Canada, leading to some of the significant results mentioned in the introduction to this white paper.

1.3.3 Bicep-Keck

Bicep Array is the newest multi-frequency instrument in the Bicep/Keck Array program. It is comprised of four refractive telescopes observing the polarization of the cosmic microwave background (CMB) at 30/40, 95, 150 and 220/270 GHz with over 30,000 detectors. The Bicep Array follows Bicep3 's modular focal plane concept, and upgrades to 6” wafers to allow higher detector count per module. The first receiver at 30/40 GHz is expected to start observing at the South Pole during the 2019-20 season. By the end of the planned Bicep Array program, we project $\sigma(r) \approx 0.003$, assuming current modeling of polarized Galactic foreground and depending on the level of de-lensing that can be achieved with higher resolution maps from the South Pole Telescope.

1.3.4 Simons Observatory

The Simons Observatory (SO) is currently under construction in the Chajnantor Science Preserve in the Atacama Desert in Chile and will begin observations in the early 2020s. SO will be sensitive to both the temperature and polarization CMB anisotropies and will operate in six bands, namely 27, 39, 93, 145, 225 and 280 GHz in two separate telescope configurations: three small-aperture 0.5-m telescopes (SATs) to map the sky on large angular scales; and one large-aperture 6-m telescope (LAT) for high-resolution CMB science. SO will have a total of 60,000 cryogenic bolometers. This has been made possible by a combined USD $40.1M grant from the Simons Foundation and US participating institutions, namely Princeton University, The University of California at San Diego, The University of California at Berkeley, The University of Pennsylvania and the Lawrence Berkeley National Laboratory as well as the Heising-Simons Foundation. Canadian involvement in SO is currently not supported by national grants. Going forward, the ability to significantly contribute to SO development, analysis and science **will be greatly enhanced by support for students and postdocs, who are not funded by any infrastructure grants from the participating institutions.** SO has members from many Canadian institutions focused on CMB research, including UBC, SFU, McGill, the Dunlap Institute, CITA and Perimeter.

1.3.5 CCAT-p

The Cerro Chajnantor Atacama Telescope-prime (CCAT-prime) is a 6-m, off-axis, low-emissivity, large field-of-view submillimetre telescope also under construction on Cerro Chajnantor and scheduled for first light in the last quarter of 2021. Built at 5,600 m, CCAT-p will be the highest permanent, ground-based telescope in the world. The CCAT-p camera, PrimeCam can support up to seven modules or optics tubes, which will operate at five different frequencies, namely 220, 270, 350, 410 and 860 GHz, in parallel with spectroscopic measurements (with $R = 100$ between 210 and 420 GHz). The CCAT-prime spectrometer modules require low-temperature Fabry-Perot Interferometer optics that will be installed at the Lyot stop in the relevant modules. Designed as a submillimetre observatory, the first generation of CCAT-p will lead to characterization of secondary CMB anisotropies, including the SZ effects, gravitational lensing, and Rayleigh scattering. Many of these are discussed in a companion LRP White paper. The second generation of CCAT-prime will be optimised for science in synergy with SO and as input for the CMB-S4 design. CCAT-p is applying for funding for Canadian participation through the Canada Foundation for Innovation (CFI) grant program.

1.3.6 SPIDER

SPIDER is a balloon-borne experiment consisting of 6 telescopes, each coupled to a polarization-sensitive transition-edge bolometer array cooled to 300 mK. SPIDER was designed to operate at 95 100, 150 and 280 GHz with degree-resolution, to measure polarized CMB fluctuations on large angular scales. The first SPIDER balloon flight was in January 2015 from McMurdo Station, Antarctica, with support from NASA's Columbia Scientific Balloon Facility, and lasted for 17 days, mapping 12% of the full sky at 95 and 150 GHz. The second SPIDER launch is slated for winter 2020 and will fly three 280 GHz telescopes in addition to 2 telescopes at 95 GHz and 150 GHz. Canadian participation is currently supported through the Canadian Space Agency (CSA).

1.3.7 CGEM

The Canadian Galactic Emission Mapper is an experimental program to map polarized foregrounds to the CMB at 10 GHz. It is funded by the CFI and will operate from the radio-protected site of the DRAO. CGEM consists of a low noise receiver coupled to a spinning 4m aperture telescope and it will survey 2/3 of the sky with this WMAP-like scanning strategy. The maps it produces will provide templates of polarized galactic emission, essential for cleaning the CMB maps anticipated from direct CMB polarization experiments. CGEM is part of the global effort to measure primordial gravitational radiation.

1.3.8 TAURUS

The next-generation balloon experiment is the proposed TAURUS CMB telescope. TAURUS is designed as three SPIDER-like telescopes, two telescopes measuring the 90- and 150-GHz bands, and another telescope measuring 280 and 350 GHz, with 10,000 detectors cooled to 100 mK. TAURUS is proposed to observe 75% of the sky with FWHM of 0.5–1° and will reach the depth of *Planck* in 10 days. The science goal of TAURUS is to measure the optical depth to reionization, τ to a precision of $\sigma_\tau = 0.004$.

1.3.9 CMB-S4

CMB Stage Four (CMB-S4) is a proposed CMB experiment that was recently awarded Concept Design-0 status by the United States Department of Energy (DOE). CMB-S4 is envisioned to be the ultimate ground-based cosmic microwave background experiment, as a collaboration between experimental efforts and groups at the South Pole and the Atacama Desert, bringing together previously competitive groups to begin science operations in 2026. Additionally, it is largely funded through partnerships between the US National Science Foundation (NSF) and DOE, with the construction phase to be funded as an NSF MREFC project and a DOE HEP MIE project. **The same modality of small, personal research funding for development and analysis on large projects is no longer feasible.** In order to become a builder participant in CMB-S4, which is led by the US DOE, we will need significant funding in Canada for the development of infrastructure, and to fund a dedicated pipeline team. Such funding could be generated through CFI funding in the 2022/2023 cycle.

1.3.10 LiteBIRD

LiteBIRD is a planned millimetre-wavelength space telescope scheduled for launch in the 2020s for three years of observations at a Sun-Earth Lagrangian point L2. LiteBIRD is a Japanese-led project with collaboration between Japanese, US, European and Canadian groups, and was recently selected as the Japanese second large strategic mission. LiteBIRD is enabled by key technology breakthroughs that have been demonstrated on the ground including a novel Transition Edge Sensor (TES) multiplexed readout system developed in Canada, and this Canadian technological contribution that is already baselined for the mission, enabling Canadian access to LiteBIRD data, which is being studied through Science Maturation Studies and Mission Contribution Studies from the Canadian Space Agency. LiteBIRD was ranked as the top priority for Canadian CMB science in the LRP 2010 Mid Term Report. It will provide polarization measurements of the entire sky on large scales and will definitively hunt for the signals of inflation, complementing ground-based studies. This project has entered Phase 0, and **in order to ensure Canadian participation in this collaboration it requires a funding commitment from the CSA.**

2 Connection or relevance to Canada

CMB cosmology remains one of the great strengths of Canadian astronomy, with Canadians playing key roles in nearly every major CMB science result in the past 40 years, both in technological hardware development and theoretical analysis. The continued investment in expertise in the CMB fields (four recent faculty hires in the past 5 years have extensive expertise in CMB experiment and theory) means that Canada continues to ‘punch above its weight’ internationally in this field. This must remain a priority for the coming decade, as we become more firmly ensconced in the era of CMB polarization measurements. Ambitious balloon-, ground- and space-based missions provide a program that has extensive support well into the 2020s and will ensure continued development of HQP in this area going forward. These projects are balanced between those that are Canadian-led and proposed (e.g., CCAT-p) and those where Canadian scientists are key partners in an international collaboration (e.g., LiteBIRD).

3 Timeline

The timeline for future CMB experiments are shown in Figure 3. The Canadian involvement in future CMB missions builds on the significant historical involvement of Canadian scientists in international CMB collaborations. While Canadian scientists have been able to support involvement in large collaborations, the cost of future missions is becoming such that strategic national funding for projects is necessary to ensure continued participation and leadership in these next-generation facilities.

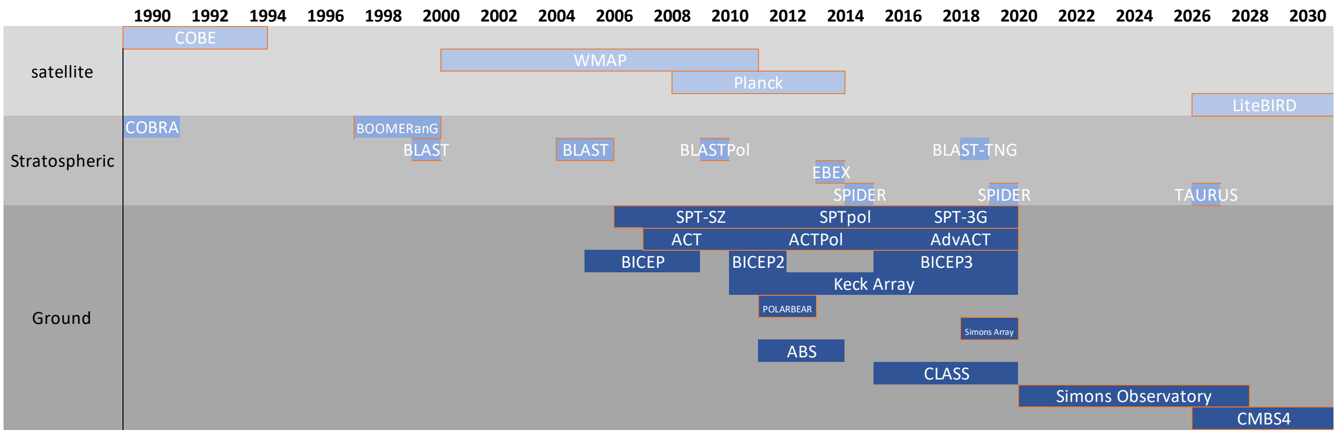

Figure 3: Timeline of past and future missions. Those with Canadian scientific leadership are outlined in orange. As the size of projects grows in the coming decade, Canadian participation will be limited to our ability to contribute financially to hardware and analysis of missions from the ground, balloons and in space.

4 Cost

In Table 1, we present the estimated costs for ongoing and upcoming CMB missions, and the cost of Canadian involvement. Those not slated for specific cost include those where the Canadian engagement has been through NSERC-supported research and small grants, or where participation on a national level has not yet been obtained.

Name	Project Cost (CAD Million)	Estimated Cost of Canadian involvement (CAD Million)
CCAT-p	30	30
SPT-3G	40	-
ACTPol/AdvACT	35	-
LiteBIRD	750	30
Simons Observatory	150	1-2
CMB-S4	800	4-7

Table 1: Cost estimates of current and future CMB missions. Funding for CCAT-p is being proposed under the current CFI (2019/2020) call. Future contributions to SO or CMB-S4 could potentially be funded from CFI calls, or seed funding, while support for LiteBIRD requires national agency funding.

5 Description of risk

1: How does the proposed initiative result in fundamental or transformational advances in our understanding of the Universe?

CMB science addresses some of the most fundamental questions about the early Universe, the nature of dark matter and dark energy, and the distribution of matter throughout cosmic time. It remains one of the cleanest cosmological probes of physics in the early universe, and has already resulted in many fundamental science results. As measurements of polarization improve to the level of temperature constraints today, and wide areas of the sky are mapped that allow cross correlations with other probes of large scale structure, we will see many additional key results from CMB science. Using the CMB as a 'backlight' has led to a significant number of new discoveries, which are outlined in the Scott *et al.* white paper.

2: What are the main scientific risks and how will they be mitigated?

Canadian involvement in CMB science is across a wide range of scales (e.g., large scales with LiteBIRD, small scales with SO and CMB-S4, high resolution and frequency with CCAT-p), mitigating the risk of focusing effort on only one telescope project. Involvement in each of the telescope collaborations will typically be at the intermediate level (few to tens of millions of dollars), with **significant return on investment** given the capacity for scientific leadership within Canada. A significant risk would be to remain in the previous modality where little to no investment was made in most CMB missions, relying on individual grant funding to support computation, hardware and analysis. The costs of current and future facilities is such that a lack of funding for CMB missions will remove the ability of Canada to provide scientific and technical leadership in these projects.

3: Is there the expectation of and capacity for Canadian scientific, technical or strategic leadership?

Canadian leadership is at all levels: experimental design and development; observation and data analysis; and theoretical modeling and understanding. The proposed involvement in CMB projects leverages a significant Canadian scientific strength. Canadian expertise is already valued in these projects, and Canadians have already been identified for leadership (e.g. hardware development and analysis for LiteBIRD, science working group leadership in SO).

4: Is there support from, involvement from, and coordination within the relevant Canadian community and more broadly?

There is significant coordination within the Canadian community. Many of the relevant faculty members and PIs are collaborators on more than one experiment; those collaborations will continue and grow. New partnerships have been developed through proposals for involvement in proposed telescopes (e.g. LiteBIRD). Almost all Canadian CMB institutions are engaged in the SO collaboration and similarly, most Canadian CMB scientists are engaged in planning for CMB-S4.

5: Will this program position Canadian astronomy for future opportunities and returns in 2020-2030 or beyond 2030?

The projects proposed are either forecast to begin taking data in the 2020s (e.g., Simons Observatory, CCAT-p, TAURUS) or will start in the late 2020s and ensure continued Canadian participation in the 2030s (CMB-S4, LiteBIRD). Continued (and increased) national funding for Canadian involvement in future missions will extend the legacy of Canadian involvement in CMB science.

6: In what ways is the cost-benefit ratio, including existing investments and future operating costs, favourable?

Canadian investment in CMB science has generated scientific results with a highly favourable cost-benefit ratio, and the spectrum of proposed scientific investment ensures both Canadian participation in international collaborations. Space-based missions like LiteBIRD build on the legacy of the *Planck* mission and the scientific and technical development work for SPT. Canadian-led ground-based projects such as CCAT-p will enable astrophysical science with millimeter-wave observations, complementing other multi-wavelength efforts. Continued investment in analysis support of Canadian participation in collaborations like SPT-3G, SO and CMB-S4 will also be essential for ground-based science to ensure that Canada remains a strategic partner in the coming decade.

7: What are the main programmatic risks and how will they be mitigated?

The upcoming five years are crucial for CMB science, to ensure that the investment of the previous decades are leveraged for the future. **A failure to invest in projects like CCAT-p and LiteBIRD will delay or endanger these projects and as a result will remove the momentum of the CMB science community in answering some of the most fundamental cosmological questions.** This proposal has highlighted the main CMB missions for the next decade, and **Canada has a leadership role in all of them.**

The current mode is for CMB scientists to use their own funds (e.g. NSERC Discovery) to fund research related to these collaborations. The lack of funding resources, particularly for postdoctoral researchers, but also for travel restricts the ability of Canadians to contribute fully to these groups, and will become an even greater risk as the scope of projects increases. The main risk is that **should funding for CMB science remain at a low level, Canadians will not be able to take leadership roles in data analysis and science results, nor will they be able to be a large stakeholder in these missions.**

8: Does the proposed initiative offer specific tangible benefits to Canadians, including but not limited to interdisciplinary research, industry opportunities, HQP training, EDI, outreach or education?

CMB science requires a multitude of skills, including experimental development and theoretical analysis. Through detector technology development, meaningful partnerships with industry have been established and will be strengthened through continued investment. In addition, a lasting relationship with vendors which includes HQP transfer from the academic to the industrial sector has been established. The coming decade presents an exciting opportunity to strengthen those contacts and relationships. Science with the CMB is inherently interdisciplinary, with engineering coupled to theoretical analysis. The HQP that are trained on CMB experiments have a broad range of skills and those skills are readily transferred to data science (both in the various Canadian 'tech corridors' and internationally). Finally, Canadians have played and continue to play a role in outreach and training more broadly. Chilean researchers in partnership with Canadian scientists have produced and continue to plan educational initiatives like summer schools and program[a], and outreach events through public engagement and access. One example is the upcoming 2020 Eclipse in Chile, which will be used as an opportunity to engage Chilean high school students and the public and discuss the role of Chile in uncovering the secrets of the Universe.

[a] e.g., CosmoAndes2018 and the CMB Analysis Summer School Notes

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