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**Executive Summary of White Paper (5000 character limit)**

Canada has thriving communities in CMB (cosmic microwave background) studies, cosmology and submillimetre (submm) astronomy, with involvement in many facilities that featured prominently in previous Astronomy Long Range Plans. The standard cosmological model continues to be well fit using a small number of parameters. No one expects this model to be complete and so we need to continue to challenge it with data; moreover, it does not explain how galaxies and other structures form. So, how do we improve the precision of our understanding of structure formation within this model?

Wavelengths from the microwave to the submm will be particularly fruitful for answering this question. That's because, in addition to the CMB anisotropies, there are other signals that can be extracted from large maps at these wavelengths - particularly the cosmic infrared and submm backgrounds, the thermal and kinetic Sunyaev-Zeldovich effects, and CMB lensing. Such signals carry a wealth of information about the cosmological model, as well as how dust, gas and star-formation evolve within dark-matter halos. Cross-correlations between these signals and those coming from the radio, optical and X-ray surveys, will provide even more information. Canadians are already members of teams for several related facilities and are working to be involved in others. In order for Canada to be fully engaged in exploiting the detailed information coming from these cosmological signatures, it is crucial that we find the resources to participate competitively in a combination of projects currently being planned. Examples include CMB-S4, CCAT-prime, AtLAST, a new camera for JCMT, balloon projects such as BFORE and a future ambitious CMB satellite.

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1 Introduction

Canadian astronomers have a particular interest and expertise in wide-field surveys. Among such surveys, the most ambitious ones are carried out as major collaborative efforts with astronomers from other countries. The widest (and perhaps highest impact) of these surveys have come from the WMAP satellite at microwave frequencies (e.g., Bennett et al., 2013), and from the Planck satellite covering microwave-to-submm frequencies (e.g., Planck Collab. 2018 I, 2018). Although the beamsizes are modest, these data sets cover the entire sky in 14 bands from 20 to 900 GHz.

We all know that these maps can be used to extract the primary cosmic microwave background (CMB) signal, sometimes called the “baby picture” of the Universe, whose statistical properties are currently the dominant way of constraining the parameters that describe our Cosmos – this is discussed in a separate white paper (Hlozek et al., 2019). To get to the “background” we must first extract the “foregrounds”, which mostly come from the Milky Way Galaxy, from the inside of which we observe the CMB. It is also well known that these foreground signals can teach us about the large-scale properties of our Galaxy (e.g., Planck Collab. 2018 XII, 2018, and references therein), another science area in which Canadians excel.

What is perhaps less well known is that there are several “secondary” signals in these CMB maps, which are of growing interest. For many CMB experiments these give ancillary science motivations; however, for some surveys planned at similar wavelengths such “secondary” signals are in fact the primary science goals. The CMB anisotropies (in both temperature and polarisation) were largely formed at the last-scattering epoch for CMB photons, which was at a redshift $z \approx 1100$, when the Universe was about 400,000 years old. However, there are several signals that arose at lower redshift, when structure was forming in earnest. These additional cosmological signatures come from gravitational lensing, scattering processes and emissivity in sources. With sufficient frequency discrimination, CMB experiments can produce several distinct maps of these “non-CMB” signatures (see Fig. 1).
Determining the cosmological information content from Gaussian fluctuations is just a matter of counting modes. Any map that is constructed up to a resolution corresponding to multipole $\ell_{\text{max}}$ contains $\sim \ell_{\text{max}}^2$ modes. The usual divergence-type (or $E$-mode) polarisation thus effectively doubles the number of modes that are probed by CMB experiments that have polarisation sensitivity (more if we can also measure $B$ modes; Scott et al. 2016). The “non-CMB” maps are currently noise-dominated (rather than cosmic-variance-dominated), but that will change with more sensitive mapping. Hence the sheer amount of information telling us about cosmology and structure formation will grow by at least a factor of a few. However, not all information has equal value and we can expect explicit new kinds of information to come from some of these additional modes that are being probed – for example in constraints on dark-energy evolution, dark-matter properties, feedback processes in structure formation, etc. In addition these secondary signals are not Gaussian, and hence we can extract more than just the power spectrum. Indeed by combining with other probes of the same low-redshift Universe, we can simultaneously constrain the cosmological model and learn about how the baryonic components – stars, star formation, cold gas, hot gas and dust – occupy dark-matter halos.

Figure 1: CMB surveys will map large fractions of the sky in several distinct frequency channels (potentially including Stokes $Q$ and $U$ polarization, as well as $I$), indicated schematically here. These can be combined to yield maps of Galactic foregrounds (not shown), together with the primary CMB temperature and polarisation $E$-mode maps. In addition it is possible to extract several other signatures of structure formation at redshifts much lower than the CMB last-scattering epoch, in particular from CMB lensing, the cosmic infrared background, and the thermal and kinetic Sunyaev-Zeldovich effects.

2 CMB experiments

There are many new and planned projects to map the sky at wavelengths from the microwave to the submm. A (non-exhaustive) list of currently ongoing experiments includes ACTPol, BICEP/Keck, CLASS, SPIDER and SPTPol. In terms of future wide-field surveys that will provide valuable information on CMB “secondaries”, there is AdvACT and SPT-3G, with Simons Observatory (SO Collab., 2019) being an ambitious ground-based program that is currently under construction, and then there is the even more ambitious CMB-Stage 4 (CMB-S4
Science Case, 2019) project that is in the planning stages. Large cameras on single-dish mm and submm telescopes (like IRAM or the LMT) perform surveys that are effectively like CMB mapping at higher angular resolution – opportunities here include a new detector array for JCMT, the CCAT-prime project (Aravena et al., 2019) and plans for ATLAST (Klaassen et al., 2019). There are also ideas for surveys from balloons (which can go to even higher frequencies), like BFORE (Bryan et al., 2018). And the ultimate concept is a very powerful future satellite, such as the “Backlight” idea (Basu et al., 2019).

To pick on one example here, AtLAST is a concept for a 50-m single-dish submm telescope on the Atacama Plateau, with a continuum camera having a thousand times the mapping speed of current facilities. By adding powerful spectroscopic capabilities it will be possible to produce a “submm SDSS”, revolutionising our understanding of the evolution of star-formation in the Cosmos.

CCAT-prime, being at a higher altitude even than ALMA, can extend surveys to higher frequencies, with a telescope that is largely dedicated to wide surveys. CCAT-p is a 6-m telescope that is currently being built, for completion in 2023. Its first-light camera will cover five bands in the mm-to-submm range, enabling much of the science discussed here. Canadians are already part of the project, and trying to secure funding to make significant contributions (see the white paper by Chapman et al., 2019).

Another dimension in such imaging surveys is the inclusion of polarimetry. Canadians have already been involved in such instruments, through POL-2 on JCMT, the Planck satellite and BLAST-pol (the polarisation-sensitive version of the successful BLAST balloon project). A new camera envisioned for JCMT would have polarimetric capability, in addition to dramatically increased mapping speed. Many of the current and future CMB experiments (for example the LiteBIRD satellite) are focusing on polarisation because of the high-priority search for primordial curl (or “B”) modes in the polarisation pattern. This means that we will have extremely deep intensity maps, with complementary polarisation information.

Let us turn to an example of such a future CMB experiment. “CMB-S4 is envisioned to be the ultimate ground-based cosmic microwave background experiment, crossing critical thresholds in our understanding of the origin and evolution of the Universe, from the highest energies at the dawn of time through the growth of structure to the present day” (Abazajian et al., 2019). This so-called “Stage 4” experiment has as its main science goals a measurement or upper limit on the amplitude of primordial $B$ modes at the $10^{-3}$ level and constraints on light-relic particles that contribute at the level of only a few percent of a standard-model neutrino. In order to achieve these goals, CMB-S4 will make an extraordinarily deep map of about $1000 \text{deg}^2$, as well as a wide map of about half of the sky. These regions will be covered in several bands between 30 and 300 GHz (1 cm to 1 mm in wavelength), with a large fraction of the detectors being around 150 GHz (2 mm), where the beamsize will be about 1 arcmin. This means that in addition to the inflationary and dark-Universe science goals, CMB-S4 will make exquisite maps of the CMB secondary signals, thus tracking how structure forms at relatively low redshifts.

The ultimate project currently being discussed is a large-aperture CMB telescope in space, with a huge number of detectors, where a large part of the science goals are exactly what we are describing here – extracting the cosmological signals that lie in front of the CMB. A plan for this “CMB Backlight” mission was submitted to ESA’s “Voyage 2050” process (Basu et al., 2019).

### 3 Signals in front of the CMB

So what are these “secondary” signals that come out of CMB surveys, and what can they be used to tell us about structure formation?

#### 3.1 Gravitational lensing

The CMB provides the oldest photons that we can detect. The paths of these photons are diverted by the gravitational influence of the matter that they pass through on their journey towards us. This induces correlations in the maps of CMB $T$ and $E$ modes, which can be extracted and used to produce a map of the large-scale lensing potential (e.g., Planck Collab. 2018 VIII, 2018, and references therein). Polarisation maps will be particularly powerful
in future, since, as the sensitivity continues to be enhanced, they are lacking most of the foreground signals that can contaminate temperature maps.

The statistics of CMB lensing maps contain information that can be exploited to constrain dark energy and modified gravity, as well as the sum of the masses of the neutrino species (e.g., CMB-S4 Science Book, 2016). The lensing map produced by CMB experiments gives an image of the dark matter along the line of sight to the last-scattering surface. The main contributions come from structures at $z \sim 1–3$, which are also probed in wide-field surveys in other wavebands (optical, radio, etc.). Since lensing traces the effect of all the matter, then comparisons with surveys that are sensitive to the baryons (stars, gas, etc.) can help us understand the relationship between baryonic matter and dark matter.

As well as weak lensing, there are strong-lensing signals to extract. The steep slope of the flux distribution of submm galaxies means that it is an efficient waveband for finding strong lenses. Such studies have already begun, using Herschel Negrello et al. (2010), Planck (Cañameras et al., 2015) and SPT (Vieira et al., 2013), for example, but with relatively modest sample sizes. There should be many thousands in future surveys. Investigating the abundance of such lenses can in principle measure background cosmology, while detailed studies of substructure can be used to constrain dark-matter properties (Hezaveh et al., 2016).

### 3.2 Thermal Sunyaev-Zeldovich effect

The thermal Sunyaev-Zeldovich (or tSZ) effect is the upscattering of CMB photons as they pass through hot, ionised gas, in particular in the halos of galaxy clusters. The effect is essentially redshift independent, and hence can be used to find clusters at higher redshifts than other techniques. Catalogues of SZ-detected clusters already contain $>1,000$ objects (Planck Collab. 2016 XXVII, 2016), new surveys will find $>10,000$, and eventually surpass $100,000$ (for CMB-S4) or even $1,000,000$ (for the Backlight).

The counts of clusters are a sensitive probe of background cosmology, and hence parameters (including dark-energy and neutrino physics) can be constrained through estimation of $N(M > M, z)$. Of course this can only be done effectively if we fully understand the selection effects, which means it is necessary to model cluster physics as well. This is in fact where combining surveys becomes particularly powerful, since we can measure the density and temperature profiles of clusters (as well as groups, and even galaxies) through comparing with X-ray and optical data.

Determining the masses of clusters is perhaps the greatest challenge here, but that can be tackled using detailed studies of individual objects using everything we can bring to bear. For example this can be done with instruments such as MUSTANG (Romero et al., 2019) on the Green Bank Telescope (and similar instruments on IRAM and the LMT), as well as with the VLA, and eventually using ALMA in Band 1 (its lowest frequency band; Di Francesco et al. 2013).

### 3.3 Kinetic Sunyaev-Zeldovich effect

The kinetic SZ (or kSZ) effect is much ($\sim 10$ times) weaker than tSZ, and comes from a combination of optical depth and line-of-sight velocity. Despite its inherent weakness, it is potentially extremely powerful in giving us an unbiased tracer of the peculiar velocity field (see e.g., Ma & Scott, 2014). It is effectively tracing the radial peculiar momentum of the gas field and has been detected through various cross-correlation methods (e.g., Hand et al., 2012). In fact there are several ideas for statistically extracting kSZ signals that rely on comparison with other data sets, and these are all essentially different kinds of 3-point functions of maps and catalogues (Smith et al., 2018).

Both the kSZ and tSZ effects can be used to trace the (sometimes called “missing”) baryons that exist in the warm-hot intergalactic medium, which are hard to detect otherwise (e.g., Van Waerbeke et al., 2014). It is also possible to trace the gas in the filaments of the cosmic web (Tanimura et al., 2019). Furthermore a combination of kSZ+tSZ+lensing will enable us to test feedback models for galaxy formation (Battaglia et al., 2019).

On top of all that, the kSZ effect also yields new ways to probe the epoch of reionisation, which are very complementary to the information expected to come from redshifted 21-cm studies and searches for the high-$z$ sources of ionization (Smith & Ferraro, 2017).
3.4 Cosmic infrared background

About half of the light emitted by stars is absorbed by dust and reradiated in the thermal infrared and then redshifted to longer wavelengths (see e.g., Hill et al., 2018). Thus the far-IR/mm regime allows us to track star-formation (or $\dot{M}_\star$), to complement the direct stellar light (or $M_\star$) that we see in the optical/near-IR. All of the star-forming galaxies in the Universe combine to give the cosmic infrared background (CIB). The contributions to the CIB can be studied using its statistics, specifically the 1-point (i.e., histograms Patanchon et al., 2009) and 2-point (i.e., power spectra Viero et al., 2013) functions of the maps. The CIB power spectrum carries particularly valuable information about the clustering and redshift distribution of the sources. With multi-band measurements of the CIB one can extract tomographic information (and more can be extracted by cross-correlating with other probes).

The CIB anisotropies have already been measured with much higher S/N than generally appreciated, using BLAST, Herschel, Planck, ACT and SPT, in many mm-to-submm bands (Viero et al., 2019). With improved measurements (and models) we will be able to trace how dark-matter halos turn their baryons into stars and at the same time constrain background cosmological models.

Peaks in the CIB can be identified as clumps of star-forming galaxies, which are candidates for “proto-clusters”. Huge surveys at these wavelengths enable the discovery of large numbers of these objects, as has already been carried out with Planck Planck Collab. Int. XXXIX (2016) and SPT Miller et al. (2018). But future surveys will generate well-understood statistical samples containing thousands of objects, which can be studied in surveys from other wavebands, and will be targets for pointed observations with JWST, TMT, etc.

3.5 Cross-correlations

It seems likely that there will be an explosion of activity in comparing wide-field surveys at disparate wavelengths. The coming of SKA, LSST, Euclid, eROSITA and other huge-scale efforts will make this inevitable (see white papers by Spekkens et al. 2019 and McConnachie et al. 2019). There are several different statistical approaches that can be used here, including “stacking” (i.e., the covariance between a map and a catalogue), cross-correlations between maps and bispectra (between three data products). The available data products will include maps and catalogues, in both 2 and 3 dimensions. But it is important to point out that exactly what will come out of such cross-correlation studies is not known!

Combination of tSZ, X-ray and lensing data will yield the density and temperature profiles around clusters – statistically for large samples of objects and in more detail for brighter (or closer) individuals. This means we have the ability to look at the effects of feedback (from AGN or SNe, for example) on the IGM. This may be the best way to understand the relationship between galaxy formation and large-scale structure.

21-cm and other intensity-mapping surveys are another area of expertise for Canada, particularly with CHIME (Bandura et al., 2014). Cross-correlations of intensity-mapping data-cubes with the CMB secondary signatures will be particularly interesting for understanding how neutral hydrogen is related to other baryonic components.

3.6 Further science directions

Galactic foreground signals will need to be extracted before these cosmological signals can be investigated. Then, of course, such signals can be used to learn more about our Galaxy, including dust, gas and magnetic field structures. There are other diagnostics of the Universe in front of the CMB that can be extracted from CMB surveys.

With huge swaths of sky scanned continuously, the cadence of such surveys could be nearly daily. As an example, at a wavelength of 2 mm, CMB-S4 could provide 2-mJy rms maps of half the sky every 2 days. CCAT-prime could provide similar monitoring at higher frequency. This would give us monitoring of known sources such as: GRBs; AGN; blazars; XRBs; novae; protostars; and asteroids. Additionally, the mm and submm sky could also be searched for other time-variable phenomena, such as FRBs, GW sources, SNe, extra planets, and (of course) things we haven’t even thought of yet! Ambitious CMB-like experiments will thus play a role in multi-messenger astronomy, bringing the mm waveband into the mix for the first time, which will be particularly important for obscured sources that could be hard to detect in the optical or X-ray bands.
With the right frequency channels, it will be possible to extract catalogues of both virialised clusters (through the tSZ effect) and proto-clusters (i.e. peaks in the CIB). Of particular interest will be understanding how these populations are related, and whether we can find the intersection, where clumps of star-forming galaxies turn into actual clusters.

Changes in the CMB anisotropies at high frequencies could indicate the effects of Rayleigh scattering or resonant line scattering, giving information on high-redshift modes that could further constrain cosmological parameters. Beyond the tSZ and kSZ effects, one can also try to use the relativistic and non-thermal SZ effects to measure gas temperatures and feedback within clusters, while the polarized SZ effect can measure transverse velocities (see Basu et al., 2019, for more discussion).

This white paper has focused on broad-band detectors of continuum radiation. However, spectroscopic capability at these same wavelengths allows for several new directions, e.g. intensity mapping of CO or CII lines, blind redshift surveys and tomography of other signatures, as well as studies of individual extragalactic sources over a wide range of redshifts with space observatories such as SPICA and Origins (see the white paper by Johnstone et al., 2019).

4 Conclusions

The science described here is very well aligned with major interests among Canadian astronomers. The example projects given are generally open to involvement by any interested Canadian researcher, and indeed there are many who are already involved. As a nation of astronomers, we are particularly good at dealing with wide-field surveys, and the relatively small size of our community means that we are quite familiar with the benefits of multi-waveband approaches. We therefore have some advantages that make it natural for us to tackle science questions that come from the combination of signatures from many different components of our Universe. Those that are extracted from CMB-type experiments are new and growing in importance.

Despite our advantages as Canadians, the major challenge is competing with well-funded teams among our collaborators in other countries. It is important that there are opportunities for securing sufficient funding for hardware, software and data analysis contributions to these projects. This is the only way that we will be able to play leadership roles in the scientific exploitation of these enormously exciting data sets.
1: How does the proposed initiative result in fundamental or transformational advances in our understanding of the Universe?

Tracing structure at relatively low redshifts will enable us to understand how the baryonic components of the Universe – stars, gas and dust in various forms – occupies dark matter halos, a critical step in understanding how the initially very smooth Cosmos developed into what we see around us today. At the same time these same measurements can constrain fundamental physics, such as the evolution of dark energy and the masses of neutrinos.

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

The main risk is that we don’t have the resources to contribute meaningfully to these projects.

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

Canadians are already acknowledged experts in the hardware, data analysis and scientific interpretation of these kinds of data. Because of this, Canadians are often invited to be members of international collaborations in this science area.

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

The relevant (cosmology, CMB, etc.) communities are well engaged in some of these projects already. Many of the most active people are members of several different collaborations, meaning that coordination is happening.

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

Canadians have been involved in many high-profile CMB-related projects in the past, playing strong leadership roles in several of them, and this is expected to continue to be the case with the next generation of facilities. But only if Canadians can find the financial resources to make meaningful contributions.

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

Note that the references given in this white paper cover a wide range of relevant topics, and essentially all of them were either led by or had strong involvement of Canadians. This is a research area where Canada excels.
7: What are the main programmatic risks and how will they be mitigated?

All of the projects described here are large international collaborations. There is acknowledged Canadian expertise in these science areas, and so it will be easy for Canadians to contribute – however, in order to play leading roles it will be necessary to find the resources to compete with colleagues in the US, Europe and elsewhere. Particularly critical is the support for postdoctoral researchers, as well as travel funds (for international collaboration meetings). There is currently no obvious source of support of this kind for a group of Canadians, of the sort that is readily available for our main international partners.

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?

HQP involved in these projects learn either hardware skills, which are directly transferable to industry, or “big data” type analysis skills, which also make them extremely employable. There are many individual success stories that can be pointed to. We should always be striving to improve EDI; however, the HQP who have previously worked on these projects represent a diverse group, and one can easily point to role models to encourage future diversity.

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