Snowmass2021 - Letter of Interest

CMB Spectral Distortions: A new window to fundamental physics

Thematic Areas: (check all that apply □/■)

■ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
■ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (TF09) Astro-particle physics & cosmology

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Abstract: Following the pioneering observations with *COBE* in the early 1990s, studies of the cosmic microwave background (CMB) temperature and polarization anisotropies have greatly advanced our understanding of the Universe. However, *CMB spectral distortions* – tiny departures of the CMB energy spectrum from that of a perfect blackbody – provide a second, independent probe of fundamental physics, with a reach deep into the primordial Universe. Spectral distortions probe the *thermal history* of the Universe providing insight into processes within the cosmological standard model[i] (CSM) as well as new physics beyond. As highlighted in this LOI, spectral distortions are an important tool for understanding inflation and the nature of dark matter. The range of signals is vast: *many orders of magnitude of discovery space* can be explored by detailed observations of the CMB energy spectrum. In addition, several CSM signals are predicted and provide clear experimental targets that are observable with present-day technology. A detection of these signals would anchor our understanding of the CSM over orders of magnitude in physical scales. *Their absence would pose a huge theoretical challenge, immediately pointing to new physics.* With dedicated experimental approaches, we have the unique opportunity to open this new observational window in the decades to come.

[i]When referring to the CSM we assume the ΛCDM parametrization, supplemented by the Standard Model (SM) of particle physics, admitting that the presence of dark matter and dark energy requires physics beyond the latter.

Formation of CMB spectral distortions: Spectral distortions are created by processes that drive matter and radiation out of equilibrium after thermalization becomes inefficient at redshift $z \lesssim 2 \times 10^6$. Examples are energy-releasing mechanisms that heat the baryonic matter, inject photons or other electromagnetically-interacting particles. The associated signals are usually characterized as μ- and y-type distortions, formed by energy exchange between electrons and photons through Compton scattering [1–6]. While y-type distortions can be formed at late times ($z \lesssim 5 \times 10^4$), a μ-distortion is a clear witness of processes occurring deep into the pre-recombination era ($5 \times 10^4 \lesssim z \lesssim 2 \times 10^6$). This classical picture has been refined in recent years, and we now understand that the transition between μ- and y-type distortion is gradual and that the signal contains valuable time-dependent information in residual r-type distortion [7–9]. Additional information can be imprinted by non-equilibrium processes in the pre-recombination plasma [10–12], free-free emission [13–17] or by non-thermal particles in high-energy particle cascades [12;18–22]. Spectral distortions thus provide more than just a simple integral constraint for cosmology. They are a unique and powerful probe of a wide range of interactions between particles and CMB photons, reaching from the present all the way back to a few months after the Big Bang and allowing us to access information that cannot be extracted in any other way. Broad overviews of the CMB spectral distortion science case can be found in [7;23–31].

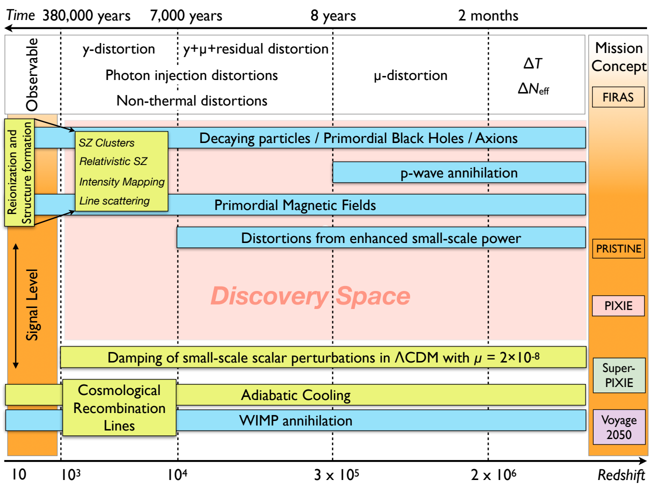

Figure 1: Science thresholds and mission concepts of increasing sensitivity. Guaranteed sources of distortions and their expected signal levels are shown in yellow, while non-standard processes with possible signal levels are presented in turquoise. Spectral distortions could open a new window to the pre-recombination Universe with a vast *discovery space* to new physics that is accessible on the path towards a detection and characterization of the μ-distortion from the dissipation of small-scale acoustic modes set by inflation and the cosmological recombination radiation. The figure is adapted from this reference [23].

Dark Matter: The search for dark matter (DM) is one important example of how spectral distortions probe fundamental physics. Non-baryonic matter constitutes $\simeq 25\%$ of the energy density of the Universe, but its nature remains unknown. The long-favored WIMP-scenario is under increasing pressure [32–37], and emphasis is gradually shifting focus towards alternatives, prominent examples being axions, sterile neutrinos, sub-GeV DM or primordial black holes [38–44]. Measurements of the CMB anisotropies themselves have clearly helped to establish the presence of DM on cosmological scales [45;46;46] and also provided tight constraints on DM annihilation and decay [47–55] as well as DM-SM-interactions [56–60]. *CMB spectral distortions offer a valuable complementary probe to search for DM* [7;12;61–67] *and its interactions* [68–70]. For decaying particle scenarios, distortions are sensitive to particles with lifetimes $t_X \simeq 10^6 - 10^{12}$ s, *providing direct measurement of particle lifetimes via r-type distortions* [65;71]. Similarly, annihilating particles can be constrained using distortions: the μ-distortion is sensitive to light particles ($m \lesssim 100$ keV) and complements γ-ray searches for heavier particles, being sensitive to s- and p-wave annihilation [71–73]. The rich spectral information added by various non-thermal processes [10–12;19–21;74] will allow us to glean even more information about the nature of DM, placing limits on the importance of different decay or annihilation channels.

Axion-like particles and dark photons: Axions or Axion-Like Particles (ALPs) are predicted in multiple particle physics scenarios [75–80], and their discovery would mark a paradigm shift in the framework of the standard models of cosmology and particle physics. Several particle physics experiments [81] such as CAST [82], ALPS-II [83], MADMAX [84], ADMX [85], CASPER [86] are looking for the signatures of axions or ALPs over a wide range of masses. *Spectral distortion bring a complementary cosmological avenue to probe ALPs (even* *if they are only a fraction of the DM) by studying their coupling with photons in the presence of an external magnetic field and other plasma effects*[87–95]. CMB distortions are a probe for detecting ALPs and dark photons. The signatures of non-gravitational interactions of ALPs with photons distort their energy spectrum and thus can be detected robustly if the energy spectrum of the source is well-known. The radiation field of CMB provides us with an excellent source which can be used to detect the distortions due to ALPs. The ALPs distortion[93–95] (α-distortion) is imprinted on the CMB while it is passing through the external magnetic field of the intergalactic medium, inter-cluster medium, voids and Milky Way. In this way, we can explore a new parameter space of the coupling strength and ALP masses, which are currently beyond the reach of particle-physics experiments. The discovery space is enormous and provides a direct cosmological window into the string axiverse[79].

Probe of inflation: A central question in modern cosmology is the origin of the observed primordial density perturbations. *Spectral distortions provide a unique new probe of primordial density perturbations.* Inflation may or may not actually describe the early Universe, but the existence of primordial density perturbations is uncontested; regardless of their origin, the dissipation of these perturbations through photon diffusion ($\leftrightarrow$ Silk damping) in the early Universe will distort the CMB spectrum at observable levels[96–100]. The signal ($\mu+y+r$-distortion) can be accurately calculated using simple linear physics and depends on the amplitude of primordial perturbations at scales with wavenumbers $k \simeq 1-10^4\,\mathrm{Mpc}^{-1}$, some ten e-folds further than what can be probed by CMB anisotropies. Measurements of μ-distortions are directly sensitive to the power spectrum amplitude and its scale dependence around $k \simeq 10^3\,\mathrm{Mpc}^{-1}$[65;101–104]. Within the slow-roll paradigm, this provides a handle on higher-order slow-roll parameters (often accounted for as running of the tilt or running of the running), benefiting from a vastly extended lever arm[65;105–108]. Outside of standard slow-roll inflation, large departures from scale-invariance are well-motivated and often produce excess small-scale power (e.g., features[109–112], inflection points[113–118], particle production[119–123], waterfall transitions[124–128], axion inflation[129–132], heavy fields[133;134], etc. [135]), implying the presence of new physical scales that can be probed with spectral distortions. Spectral distortions furthermore depend on the perturbation-type (i.e., adiabatic vs. iso-curvature)[136–139], and are also created by tensor perturbations[140;141], primordial non-Gaussianity[142–148], as well as cosmic bubbles and textures[149–151], thus providing additional ways to test inflation scenarios in uncharted territory. Low-energy cosmological recombination lines[24;152–157] could provide additional constraining power to inflationary models[158] as well as allow exploring explicit temporal variations of fundamental constants[157;159].

Primordial black holes: CMB spectral distortions can also place stringent limits on the abundance of primordial black holes (PBHs) e.g.,[43;160–163]. There is good motivation to study these scenarios, because PBHs with masses of $m_{\rm PBH} \simeq \mathcal{O}(10)M_\odot$ may indeed explain the gravitational wave signals[164–167] emitted in the merger events of (primordial) binary black holes reported by LIGO / Virgo[168]. PBHs with masses in the range $m_{\rm PBH} \simeq 10^{-17}M_\odot - 10^{-11}M_\odot$[43;169] can furthermore still constitute $\simeq 100\%$ of cold DM (see also[126;161;170]). Lastly, PBHs with masses $m_{\rm PBH} \simeq 3\times 10^3 M_\odot - 10^5 M_\odot$ may form the seeds for super-massive black holes (SMBHs) that grow to their current sizes merely by continuous (sub-)Eddington accretion, solving a long-standing problem in cosmology[171–174]. CMB spectral distortions are also sensitive to PBHs with masses $m_{\rm PBH} \simeq \mathcal{O}(10)M_\odot$[161;175].

Summary: The seminal measurements of the CMB blackbody spectrum by *COBE*/FIRAS in the early 1990s cemented the Hot Big Bang model by ruling out any energy release greater than $\Delta\rho_\gamma/\rho_\gamma \simeq 6\times 10^{-5}$ of the energy in CMB photons[176–178]. Technological advances since then allow us to drill deeper into the signal by four orders of magnitude or more (e.g., with experimental concepts like *PIXIE*[179;180], *PRISM*[26], COSMO, *CMB-Bharat*[181], *PRISTINE*[182], *BISOU*, *Super-PIXIE*[183] or *Voyage 2050*[23;184]), opening an enormous discovery space for both predicted distortion signals and those caused by new physics. Along with the vast discovery space in fundamental physics, spectral distortions are also going to probe many astrophysical phenomena at late times[1;185–190], hence embracing a wide range of processes waiting to be explored.

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