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Measuring Reionization, Neutrino Mass, and Cosmic Inflation with BFORE

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Abstract BFORE is a NASA high-altitude ultra-long-duration balloon mission proposed to measure the cosmic microwave background (CMB) across half the sky during a 28-day mid-latitude flight launched from Wanaka, New Zealand. With the unique access to large angular scales and high frequencies provided by the balloon platform, BFORE will significantly improve measurements of the optical depth to reionization τ , breaking parameter degeneracies needed for a measurement of neutrino mass with the CMB. The large angular scale data will enable BFORE to hunt for the large-scale gravitational wave B -mode signal, as well as

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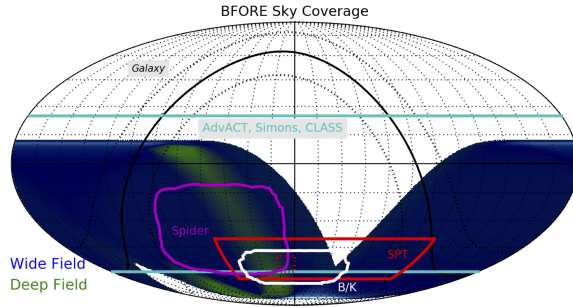


Fig. 1 Simulated sky coverage for a 28-day BFORE ULDB flight launched from New Zealand on April 15th, 2021. The wide field is shown in blue in the top panel and covers 50% of the sky, overlapping with the Simons Observatory and the current generation of ground-based CMB experiments,^{2,3,4,5,6} as well as the Spider balloon instrument.^{7,10} The 2500 deg² deep field (green) is away from the Galactic plane (black solid and dashed lines).

the degree-scale signal, each at the $r \sim 0.01$ level. The balloon platform allows BFORE to map Galactic dust foregrounds at frequencies where they dominate, in order to robustly separate them from CMB signals measured by BFORE, in addition to complementing data from ground-based telescopes. The combination of frequencies will also lead to velocity measurements for thousands of galaxy clusters, as well as probing how star-forming galaxies populate dark matter halos. The mission will be the first near-space use of TES multichroic detectors (150/217 GHz and 280/353 GHz bands) using highly-multiplexed mSQUID microwave readout, raising the technical readiness level of both technologies.

Keywords Cosmic Microwave Background, Reionization, Neutrinos, Inflation, Scientific Ballooning, TES detectors, microwave SQUID

1 Introduction

The temperature and polarization anisotropies of the Cosmic Microwave Background (CMB) encode a wealth of information about reionization, cosmic inflation, and the large-scale structure of the universe. Precision large-scale structure measurements with the CMB are moving towards a detection of the sum of the neutrino masses m_ν , a major outstanding question in particle physics. These and other science goals¹ are the context for the recently funded Simons Observatory, the proposed CMB-S4 project, as well as the current generation of ground-based^{2,3,4,5,6} and balloon-borne^{7,8,9} CMB instruments.

BFORE is a proposed CMB polarization experiment designed to be flown on a NASA ultra-long duration balloon (ULDB) launched from Wanaka, New Zealand. A key advantage of ULDB, compared with conventional NASA Antarctic flights, is a dramatic increase in available sky coverage. During the nighttime portions of the flight, BFORE will spin to map 50% of the sky (20,000 deg², shown in Figure 1) in four bands (150, 217, 280, and 353 GHz). This sky coverage, as well as the stability of the TES detectors and balloon platform, will allow the instrument to reconstruct the large angular scale modes needed to make a significantly improved

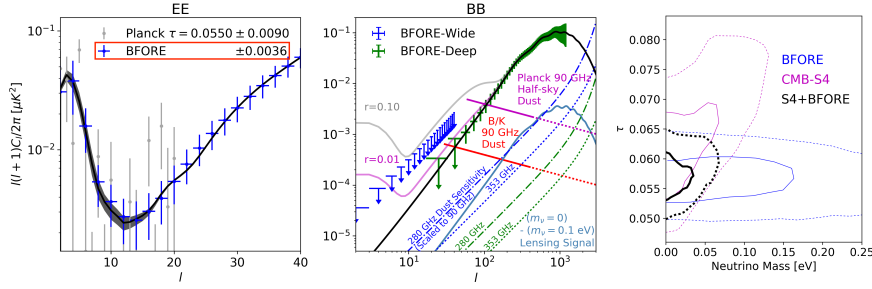


Fig. 2 **Left:** BFORE E -mode data alone will improve the error on the optical depth to reionization τ by nearly a factor of 3 over the *Planck* 2016 τ measurements.¹¹ **Center:** The BFORE half-sky B -mode data (blue points) will constrain the large angular scale gravitational wave signal, and the 2,500 deg² deep field data (green points) will constrain the degree-scale signal, each at the $r \lesssim 0.01$ level. BFORE data alone will measure neutrino mass to 0.166 eV (1σ), and will yield foreground data over half the sky at 280 GHz (dashed blue and green lines) and 353 GHz (dotted blue and green lines) of unprecedented sensitivity. **Right:** Ground-based CMB measurements that lack sensitivity to large angular scales due to atmospheric fluctuations suffer from a degeneracy between τ and neutrino mass. The BFORE τ measurement will break this degeneracy. Forecasting¹ shows that Simons Observatory and/or CMB-S4, τ constraints better than available from *Planck* but at the level BFORE will provide, plus DESI-like BAO measurements, are all necessary to detect the minimal 0.058 eV neutrino mass at more than 3σ .

measurement of the optical depth to reionization τ , breaking degeneracies needed for a detection of neutrino mass. The data will also set an improved upper limit on large angular scale gravitational wave B modes from inflation. The similar angular resolution and overlapping sky coverage with current and upcoming ground-based CMB experiments means that the higher frequency bands of BFORE will play an important role in dust foreground cleaning. During the daytime portions of the flight, the instrument will map a 2,500 deg² deep field to set an independent upper limit on neutrino mass and degree-scale gravitational wave B modes, and also to study lensing, galactic dust, galaxy cluster properties and star formation.

2 Science Goals

2.1 Neutrinos and Reionization

The CMB is sensitive to neutrino mass because when neutrinos are relativistic they free stream and damp the clustering of matter. Their mass therefore imparts a scale at which the gravitational lensing power spectrum is suppressed. This lensing signal is reconstructed from the CMB temperature and polarization maps using B -modes and higher-order statistics. However, as illustrated in Figure 2, in ground-based CMB measurements limited by atmospheric fluctuations to angular scales smaller than a few degrees, there is a degeneracy between neutrino mass and τ . This arises because the apparent amplitude of lensed B -modes depends on the neutrino mass, but it also depends on the amplitude of primordial perturbations A_s . However, small-angular-scale CMB measurements observe the damped perturbations, meaning they measure the parameter combination $A_s e^{-2\tau}$. This causes a

Table 1 BFORE Instrument Parameters and Calculated Map Depths

Telescope:	Temperature	250 K (Primary), 4.2 K (Secondary)			
	Primary diameter	1.35 m, emissivity ≤ 0.005			
Detectors:	Central frequencies	150	217	280	353 GHz
<i>mSQUID</i>	Number of TESs	2400	2400	2880	2880
<i>readout</i>	Detector NEP	6	8	10	12 aW/ $\sqrt{\text{Hz}}$
	Background power	1.0	1.5	2.0	2.5 pW
<i>100 mK fridge</i>	Background NEP	17	23	31	37 aW/ $\sqrt{\text{Hz}}$
Half-sky map:	$\Delta Q/U$ (RJ)	13	11	18	12 $\mu\text{K-arcmin}$
<i>28 nights</i>	$\Delta Q/U$ (CMB)	22	34	101	158 $\mu\text{K-arcmin}$
<i>w/ 90% obs. eff.</i>	$\Delta Q/U$ (Dust scaled to 150 GHz)	22	10	13	9 $\mu\text{K-arcmin}$
Deep map:	$\Delta Q/U$ (RJ)	4.1	3.6	5.7	3.8 $\mu\text{K-arcmin}$
<i>28 days</i>	$\Delta Q/U$ (CMB)	7.1	11	32	54 $\mu\text{K-arcmin}$
<i>w/ 90% obs. eff.</i>	$\Delta Q/U$ (Dust scaled to 150 GHz)	7.1	3.2	4.2	3.2 $\mu\text{K-arcmin}$
Beam:	FWHM	6.1	4.2	3.3	2.6 arc-minutes

degeneracy^{12,13} between τ and the lensed B -mode amplitude, and therefore also a degeneracy with neutrino mass.

In 2016, the *Planck* team published constraints on reionization with improved treatment of large angular scale systematics and noise, yielding $\tau = 0.0550 \pm 0.0090$ from the SimBaL simulation-based estimator¹¹, and $\tau = 0.0580 \pm 0.0120$ from the Lollipop cross-spectrum estimator.¹⁴ These uncertainties on τ leave enough of a degeneracy to preclude¹ a 3σ detection of the minimal neutrino mass, even if a future ground-based experiment like CMB-S4 achieves an 1 $\mu\text{K-arcmin}$ map noise and even if CMB-S4 combines with DESI-like measurements of large-scale structure. This means that the current instrument-noise-limited precision of the *Planck* τ constraints will limit the science reach of the Simons Observatory, CMB-S4, and potentially current generation experiments.

As illustrated in Figure 2, BFORE will break this τ - m_ν degeneracy by precisely measuring the CMB E -modes on large angular scales, yielding an independent measure of τ with nearly 3 times better error than *Planck*. The projected BFORE error on τ of ± 0.0036 is powerful enough to combine¹ with DESI and Simons Observatory (or CMB-S4) to yield a 3σ or better detection of the minimal 0.058 eV neutrino mass. The BFORE τ measurement will be within a factor of 2 of the all-sky CMB cosmic-variance limit of ± 0.0020 . In general, the angular scales relevant for τ ($\ell < 20$, i.e. $\gtrsim 9^\circ$) are difficult to access from the ground, especially at higher frequencies where atmospheric emission increases. Moreover, these angular scales are difficult to reach from the limited sky area available to Antarctic balloon-based measurements, showing that a ULDB mission like BFORE is uniquely powerful for this measurement.

2.2 Inflation

Cosmic inflation is a paradigm that naturally explains the observed gaussianity and scale-invariance of cosmological perturbations. A key additional prediction of inflation is a background of gravitational waves that would imprint a B -mode signal onto the CMB at roughly degree scales at recombination, and also at large angular scales at reionization. A major science goal of the current and next generation of CMB experiments is to definitively detect these inflationary B -modes. However, their amplitude (quantified by r) is constrained to be small; for exam-

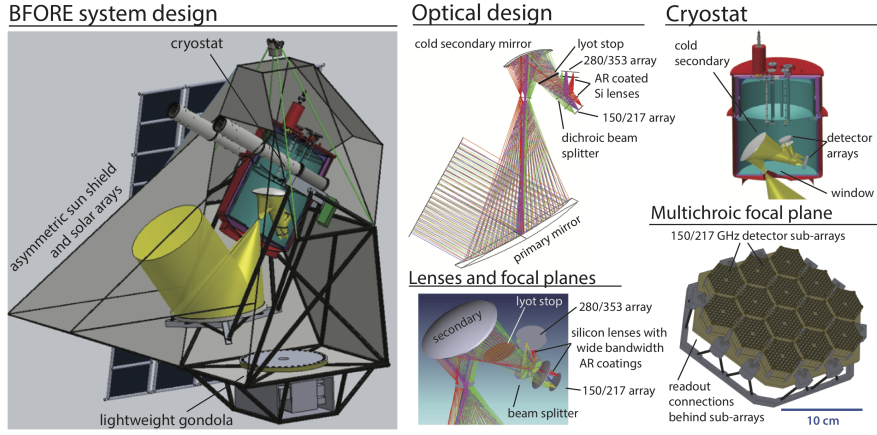


Fig. 3 **Left:** BFORE gondola with solar panels, star cameras, and partially-shown sun shields. **Middle:** The BFORE optical design uses anti-reflection coated silicon lenses to illuminate a 1.35 m effective diameter on the primary mirror. **Top Right:** Cutaway view of the cryostat showing the 4-K secondary mirror and 100-mK focal plane array. The cryostat holds 500 liters of liquid helium. **Bottom Right:** The BFORE 150/217-GHz focal plane consists of 10 sub-arrays, each with 120 feed horns, for a total of 4800 TESs. The 280/353-GHz array has a similar sub-array architecture, but with 5760 TESs.

ple, GUT-scale inflation¹⁵ suggests $r \sim 0.01$, which is the target for the current generation of ground-based CMB experiments.

As illustrated in Figure 2, BFORE will use its unique access to large angular scales from the ULDB platform to measure or constrain the large angular scale B -mode signal with $r \sim 0.01$ sensitivity. It will also measure the degree scale signal to a similar level. Being above the atmosphere means that BFORE will measure galactic dust foreground emission in the 280- and 353-GHz bands to improve foreground removal from its own maps and complementary ground-based data. In the event of a detection of a potential inflationary gravitational wave signal by BFORE or another experiment, the large sky coverage of BFORE will be important in evaluating whether or not the signal is isotropic and scale-invariant, and the 280- and 353-GHz maps will be important for verifying that the signal is not contaminated by dust foregrounds.

3 Instrument Approach

The sky coverage needed to achieve the science goals of BFORE leads naturally to a mid-latitude flight. The current NASA ULDB program has a stricter weight budget than the Antarctic program, which the instrument has been designed to meet. The weight budget in turn limits available power from batteries and solar panels, and drives the design of the cryogenic receiver to an efficient liquid helium system. The instrument will use TES detectors with a highly multiplexed microwave SQUID readout. The gondola and pointing systems are based on high heritage systems flown recently on Spider.^{16,10}

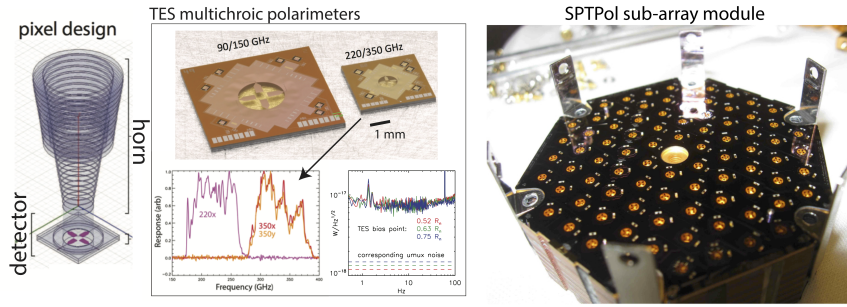


Fig. 4 Left/Middle: Horn-coupled TES multichroic polarimeters at 90/150 GHz and 220/350 GHz, similar to those currently used in ACTPol and SPTPol. Measured 220/350-GHz passbands are also shown. The noise measurement shows that the bolometers deliver better NEP than required for BFORE.¹⁹ The current noise of the microwave mux has been measured to be $17 \text{ pA}/\sqrt{\text{Hz}}$, much lower than the TES noise. **Right:** The full arrays depicted in Figure 3 consist of sub-arrays similar to this 84-feedhorn SPTPol module.²⁰ The photo shows the back side of the module with the detector wafer exposed before the backshort was installed on top of the wafer.

The optical system uses a single ambient temperature mirror to increase the angular resolution over what is feasible with all-cryogenic optics, while minimizing the loading contribution. Following the cryogenic secondary mirror and the Lyot stop, there is a dichroic to split the 150/217 and 280/353 bands, and a single cold lens forming an image onto each focal plane. The cryostat window has a diameter smaller than 20 cm, so we are able to use a thin polypropylene window. This reduces loading on the detectors and cryogenic system, and eliminates the need for a complex mechanical retractable window cover.

The high-heritage NIST-fabricated multichroic detector arrays in BFORE will combine the proven performance of TES detectors with new low-dissipation mSQUID microwave readout. The arrays will be cooled to 0.1 K to take full advantage of the low-background balloon environment. As illustrated in Figure 3 and Table 1, the detector arrays have a total of 10,560 bolometers across two arrays of multichroic horn-coupled polarization-sensitive pixels, operating in the 150/217 and 280/353-GHz bands. Similar dichroic pixels have been used in two seasons of observations on the ACTPol experiment with a 90/150 GHz array^{17,18} and one season (so far) with a 150/220-GHz array on Advanced ACTPol.²

Polarization modulation is often used in CMB experiments to reduce the impact of detector $1/f$ noise and reduce the impact of some beam systematics. This comes at the expense and complexity of additional moving parts and payload weight. Also, if a modulator is used in a large diameter optical system such as BFORE, it is not practical to make the modulator the first optical element, which reduces its ability to mitigate systematics. The BFORE detectors and readout have demonstrated a low enough $1/f$ knee to reconstruct modes on the sky over an entire gondola rotation, meaning that as with Spider²¹, rapid modulation is not needed for BFORE. On degree and larger angular scales (for τ and primordial B -mode science), beam systematics should be negligible due to the small primary beam. For dust foreground mapping and other high ℓ science, the mid-latitude

flight provides more than 45° of sky rotation, enough to completely switch Q to U without a modulator. Modern optimal mapmaker software^{22,23} uses this rotation between the sky and instrument to separate beam systematics from true sky signal. Since there are proven strategies to address detector stability and beam systematics without a modulator, to reduce payload weight and system complexity, BFORE will not include a modulation subsystem. The focal planes have interleaved Q and U pixels for further consistency checks on beam and polarimetric systematics, a technique used successfully by SPTPol.²⁴

4 Conclusions

Studying reionization to move towards a detection of neutrino mass, large angular scale B -modes from gravitational waves, and high frequency CMB dust foregrounds, are all important science goals that naturally point towards a mid-latitude ULDB balloon experiment such as BFORE. The payload architecture has been designed with the ULDB weight and power constraints in mind, with reductions in system complexity based on previous experience with balloon- and ground-based CMB measurements. Because the mission would be the first sub-orbital use of the multichroic TES pixels and microwave SQUID multiplexing, the flight would raise the NASA technical readiness level (TRL) of these technologies, paving the way for their use in future satellite programs.

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