CCAT pathfinder kSZ science case: Probing the transition between gravity and dark energy dominated regimes

Characterizing galaxy cluster velocities provides a new and complementary way to investigate the nature of dark energy, to test gravity on large scales, and to constrain neutrino masses [1, 2, 3]. Measuring peculiar velocities is a challenging task. A promising approach is to use the kinetic Sunyaev-Zeldovich (kSZ) effect [4]: cosmic microwave background (CMB) photons passing through a cluster interact with electrons in the intra-cluster medium and are Doppler shifted due to the cluster's peculiar velocity relative to the CMB rest frame. As a consequence the CMB blackbody spectrum is shifted towards higher (lower) frequencies if the cluster is moving towards (away from) the observer. This process is directly proportional to the cluster line of sight velocity and optical depth. The kSZ signal amplitude in massive clusters is small compared to the thermal Sunyaev-Zel'dovich effect (tSZ) [5] (Fig. 1), which was first used to discover new clusters in 2009-10 [6, 7].

Using the kSZ as a cosmological probe requires a strong detection of the kSZ signal for a large number of clusters. At present the only direct kSZ detections are in merging cluster systems with particularly large velocities (e.g. [9]). A different approach that has recently been successful is to combine CMB data and optical redshift surveys and employ a pairwise statistic, collecting the clusters in bins of comoving separation at 10 Mpc – 500 Mpc scales and measuring the average relative motions of optically selected clusters [10]. This pairwise statistics approach is less affected by foregrounds and appears promising; however, it is limited to low redshifts by the available optical data and extracting competitive cosmological constraints will require additional constraints on cluster optical depths to convert the kSZ measurements into velocities. Moreover, kSZ measurements are only made between pairs of clusters rather than for each single cluster. For these reasons a direct detection of the kSZ effect for a large sample of clusters would be extremely valuable and would enable probing dark energy and modified gravity in a new and complementary way.

The main obstacles for direct kSZ measurements are the difficulty of characterizing and removing the CMB, tSZ, bright sub-mm galaxies, and radio sources. Measurements are needed with more frequencies and better sensitivity than current or upcoming experiments offer. The only observatory with sufficient frequency coverage has been Planck, but it did not have sufficient sensitivity or resolution. The shortest wavelength planned for upcoming CMB surveys is 1.4 mm, while several sensitive channels at shorter wavelengths are necessary to remove the thermal SZ effect and sub-mm galaxy emmission. The 6 m CCAT pathfinder telescope

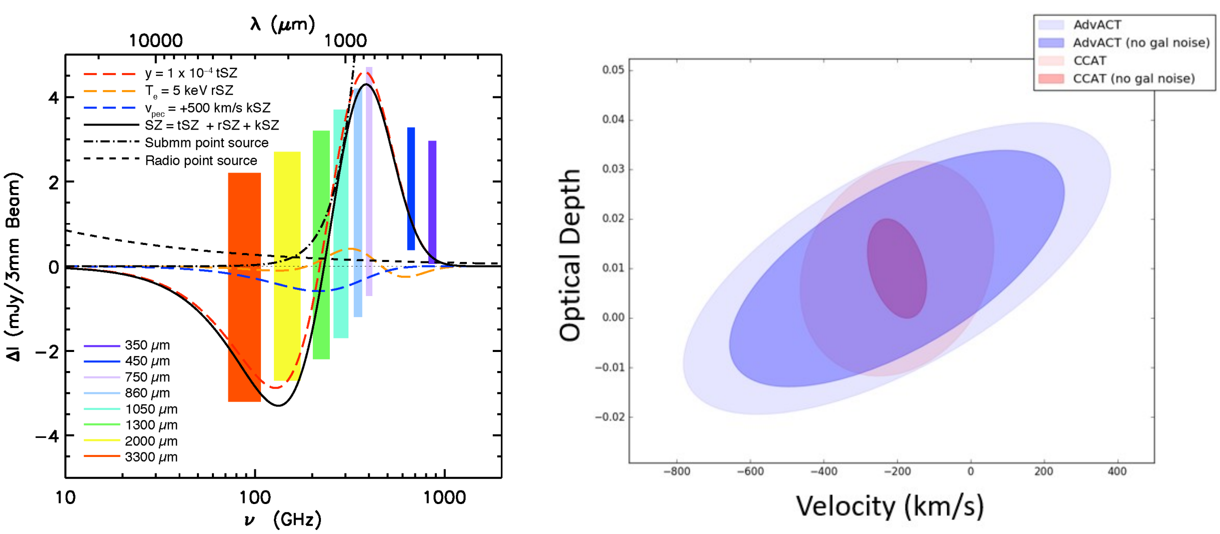

Figure 1: *Left:* Change in CMB intensity from the thermal SZ (red dashed) and kinetic SZ (blue dashed) along with several CCAT observing bands (colored bars). *Right:* Constraints on the velocity and optical depth of galaxy clusters from the CCAT Pathfinder (pink) compared with those from the upcoming Advanced ACTPol (blue) [8]. CCAT will significantly improve the velocity measurements due to the higher frequency channels. The "no gal noise" cases (dark pink and dark blue) show the constraints achievable if the sub-mm emission from star-forming galaxies was perfectly subtracted. Preliminary forecasts (not shown here) suggest that a 350 um or 450 um channel in the CCAT Pathfinder would enable removing the majority of this galaxy noise term. (Forecasts done with Avirukt Mittal.)

is an excellent instrument for these measurements as it offers the angular resolution and sensitivity required to separate all of the components. We forecast the expected constraints on peculiar velocities and optical depths from direct measurements of the kSZ effect with the CCAT pathfinder using a Fisher matrix approach similar to [11]. We assume a survey area of $\sim$ 1000 sq deg and 3000 hours of observation. We find that CCAT pathfinder measurements will substantially improve on upcoming CMB surveys (Fig. 1), and improve on current constraints by an order of magnitude. The forecasts described in [11] assume that emission from sub-mm galaxies will substantially increase the velocity uncertainty. Our preliminary analysis suggests that having a 350 um or 450 um band on the CCAT pathfinder in addition to 6 longer wavelength bands will enable accurate characterization of emission from sub-mm galaxies, enabling even greater improvement on velocity constraints (Fig. 1).

Figure 2 shows forecast dark energy and modified gravity constraints based on measuring one thousand clusters with $\sigma_V = 100$ km/s precision, which is consistent with the forecasts above. These compare well with forecasts for the upcoming SPT-3G project [12]. Velocity uncertainties of the order of $\sim$ 100 km/s could also enable a measurement of the sum of neutrino masses with a 1σ uncertainty of $\sim$ 0.03 eV, a precision that could allow ruling out the inverted mass hierarchy [3] and will complement other approaches.

Brief CMB science case

Measurements of the CMB are one of the pillars of modern cosmology. A practical consideration for kSZ science is that some of the most mature detector technologies for a kSZ instrument also provide CMB polarization sensitivity (e.g. [8]). Using polarization-sensitive detectors in a kSZ optimized instrument could enable the best ground-based measurements of CMB foregrounds at the higher frequencies required to understand the galactic dust observed by BICEP2 and Planck [13]. These measurements will characterize dust and magnetic fields in our galaxy and might turn out to be essential for advancing searches for gravitational waves from inflation.

Beyond the first generation CCAT pathfinder instruments, a 6 m telescope at the CCAT site with sufficient throughput could be used for a range of science, including cosmology via improved galaxy cluster velocities and precision CMB polarization measurements, or a wide range of spectroscopic science.

A new high-throughput telescope design was recently developed that will enable mapping the CMB 10x faster than the upcoming generation of CMB observatories [14] and is being considered for the CCAT pathfinder. This telescope could be used for the next generation "Stage IV" CMB observatory being planned by the community to probe inflationary gravity waves at tensor-to-scalar ratios as low as 0.001 and make a high-significance measurement of the neutrino mass sum, in addition to a wide range of large-scale structure science [15, 16].

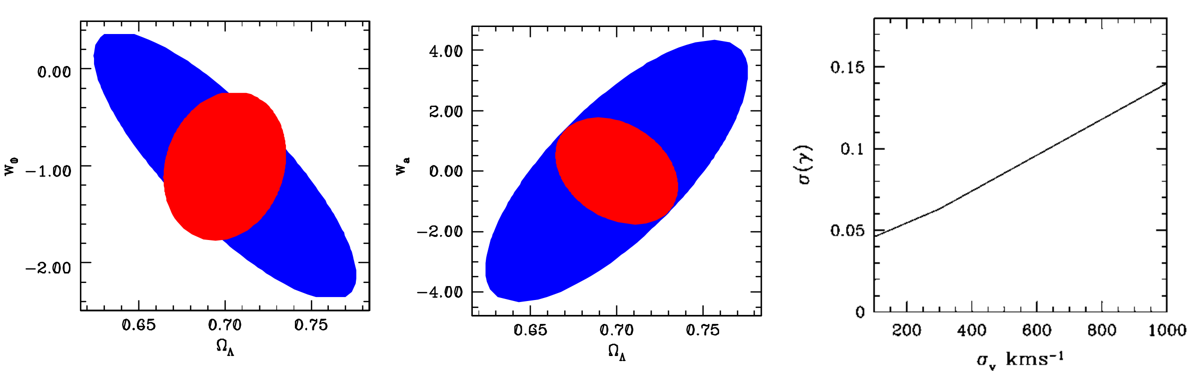

Figure 2: Cosmological parameter constraints from cluster peculiar velocity measurements (from 2013 CCAT cosmology memo). *Left:* This pair of plots show the expected dark energy parameter constraints. The red ellipses are obtained from the mean pairwise velocities of clusters assuming 1000 clusters with $\sigma_V = 100$ km/s. The blue ellipses are based on cluster number counts as a function of redshifts obtained from a SZ cluster survey that detects 4000 clusters (SPT-3G expectation). *Right:* Expected constraint on the cosmological growth index γ from a survey of 4000 clusters to the given velocity precision. A survey of 1000 clusters to 100 km/s will yield $\sigma(\gamma) \sim 0.05$, sufficient to discriminate at 2σ confidence between DGP extra-dimensions braneworld theories of modified gravity with $\gamma = 0.68$ from general relativity ($\gamma = 0.55$). Figure from [17]. Both calculations assume priors of $H_0 = (74.2 \pm 3.6)$ km/s and Planck measurements of the CMB power spectrum.

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