The non-zero mass of the neutrino has been puzzling physicists for decades. It is the first confirmed physics beyond the standard model, but has proven impossible to measure in the lab. However, neutrinos make up a significant fraction of the mass in the universe (up to 1%). Due to their very low, but non-zero, mass, they have a distinct effect on the growth of large scale structure. At early times, neutrinos behaved as "hot" dark matter but became "cold" dark matter as the universe expanded. Hot dark matter is able to stream freely through potential wells created by massive objects, pulling them apart while cold dark matter becomes trapped and enhances the structure. The formation of galaxy clusters, which are the most massive gravitationally bound objects in the universe, is highly sensitive to the neutrino mass. More massive neutrinos become cold earlier, leading to a larger number of high-mass clusters. Through the Sunyaev-Zel'dovich Effect, high-resolution microwave telescopes are able measure the abundance of clusters over cosmic time.

The SZE is the result of photons in the Cosmic Microwave Background (CMB) interacting with high-energy electrons in a galaxy cluster. When CMB photons scatter off the electrons, they are shifted in frequency. At low frequencies (below $\sim$220 GHz), this results in a reduction of the CMB intensity. These relatively small "shadows" are used to detect galaxy clusters in high resolution CMB surveys. The amplitude of the effect can be used to estimate the cluster mass. Current cluster cosmology studies are limited by systematic biases of the cluster masses, some of which comes from emissive sources in the clusters themselves. Dust emission due to start formation in the member galaxies is a potentially important bias of cluster mass.

In 2015, the Planck Collaboration released a paper exploring the correlation between the SZE and the Cosmic Infrared Background (CIB) [1]. The CIB is emitted by hot gas in star forming galaxies. Unfortunately, the Planck cluster catalog only extends to redshift of $\sim$1.0, and the CIB primarily comes from redshift $>$1.0. For cluster surveys with higher angular resolution (such as those produced by data collected from the South Pole Telescope and the Atacama Cosmology Telescope), this effect has not been quantified for most of their clusters.

I will probe the emission from dust in galaxy clusters out to redshift ~ 1.5, using clusters found in data from the South Pole Telescope (SPT) and CIB maps from Planck. Following [1], there are two methods for performing this correlation. The first is a stacking analysis. I will make small cutouts of the Planck CIB maps and SPT CMB maps at the locations of SPT-selected clusters. Stacking the cutouts and using aperture photometry to extract the signal strength will reveal the average correlation between the SZE and CIB in each frequency band. The second method uses Fourier techniques to account for both the clusters detected at high signal to noise and lower significance clusters that are below the detection threshold. I will create an angular power spectrum of the correlation of each band with the SZE signal. These two methods are complementary. The first is a very direct probe of known clusters. The second includes lower significance sources of SZE signal, which leads to higher signal to noise. Both of them require careful modeling of the SZE and CIB in order to distinguish the two terms.

Extending this work by the Planck team will probe a region of redshift that is more important to the systematic bias of cluster mass. The star formation rate is increasing over the range that I will probe, so the emission from dust is more significant. Furthermore, mapping out the correlation as a function of redshift will allow me to probe how it changes over the history of the universe. Of course, this comes with additional analysis challenges, most of which have to do with the extreme distance of the high redshift clusters in the SPT catalog. Since the CIB is emitted by hot compact objects, its amplitude decreases with distance (unlike the SZE, which is a spectral distortion of the CMB). Pushing to higher redshift will mean some loss in signal, simply from the distance. On the other hand, the surface brightness (amplitude at the source) of the CIB is higher in the redshift range I will probe. This is due to the increased star formation rate. The expansion of space effectively shifts the Planck bands into a higher intensity region of the emission spectra, further countering this effect.

My previous work with SPT has prepared me well for this project. I have been running a search for clusters using data collected by the SPT in 2012 and 2013. Through this work, I have become accustomed to working with CMB maps through both my low level analysis tasks, and the high level work to produce a cluster catalog from SPT data. Furthermore, I have been exposed to many more analysis techniques through collaborative work with my colleagues. Finally, as part of the SPT collaboration, I will have access to all of the resources I need to complete this project: SPT CMB maps filtered appropriately to isolate the SZE, Planck CIB maps (which are publicly available) and minimal computing resources.

This work will address a significant unknown in the systematic error budget of cluster masses. Even if I find significant contamination of the SZE by the CIB, that is simply the first step in accounting for the error. Since cluster cosmology is currently limited by systematic errors on cluster mass, caused by effects like this, understanding and eliminating them will have lead to significant improvements in cosmological constraints from cluster surveys. Beyond the impact on future cluster cosmology surveys, the results of this correlation probe several other astrophysical phenomena. The Butcher-Oemler Effect [2] predicts that star formation is suppressed in galaxy clusters, relative to a similar galaxy outside a cluster. Since the CIB traces star formation, this correlation would determine if there is statistical evidence for the Butcher-Oemler Effect. Furthermore, the correlation can be binned in redshift to determine if the star formation in clusters is time-dependent. The stacking method also includes spatial information, which allowed Planck to determine that the star formation in low redshift clusters is primarily in the outskirts of the cluster. This analysis would extend our knowledge to older clusters.

The results of this work also have appeal outside of the scientific community. They help us to understand star formation in the largest objects in the universe. Using SPT-selected clusters allows us to look back in time, when the star formation rate was highest. I will present this knowledge to the general public through several outlets. There are multiple local astronomical societies (the Eastbay Astronomical Society and the Mount Diablo Astronomical Society, for example) that are very interested in having graduate students speak about their work. I will be giving talks to some of them in the near future on my current work with the SPT, so when this work is done, it will be easy for me to return and present our new findings. My research group is also starting a collaboration with the Chabot Space and Science Center. I will work with then to create a standalone exhibit detailing my work, and arrange talks for the public.

References

[1] Planck Collaboration et al. Planck 2015 results. XXIII. The thermal Sunyaev-Zeldovich effect–cosmic infrared background correlation. *ArXiv e-prints*, September 2015.

[2] H. Butcher and A. Oemler, Jr. The evolution of galaxies in clusters. I - ISIT photometry of C1 0024+1654 and 3C 295. *Astrophysical Journal*, 219:18–30, January 1978.