Astro2020 Science White Paper

“SZ spectroscopy” in the coming decade: Galaxy cluster cosmology and astrophysics in the submillimeter

Thematic Areas:

PRIMARY: Cosmology and Fundamental Physics
SECONDARY: Galaxy Evolution

Corresponding Author:
Name: Kaustuv Basu
Institution: University of Bonn
Email: kbasu@astro.uni-bonn.de
Phone: +49 228 735 658

Co-authors: Jens Erler (Bonn), Jens Chluba (Manchester), Jacques Delabrouille (APC Paris), J. Colin Hill (IAS/Flatiron Institute), Tony Mroczkowski (ESO), Michael D. Niemack (Cornell), Mathieu Remazeilles (Manchester), Jack Sayers (Caltech), Douglas Scott (UBC), Eve M. Vavagiakis (Cornell), Michael Zemcov (RIT), Manuel Aravena (UDP Santiago), James G. Bartlett (APC Paris/JPL), Nicholas Battaglia (Cornell), Frank Bertoldi (Bonn), Maude Charmetant (Bonn), Sunil Golwala (Caltech), Terry L. Herter (Cornell), Pamela Klaassen (UK ATC), Eiichiro Komatsu (MPA), Benjamin Magnelli (Bonn), Adam B. Mantz (KIPAC/Stanford), P. Daniel Meerburg (KICC/Groningen), Jean-Baptiste Melin (IRFU Saclay), Daisuke Nagai (Yale), Stephen C. Parshley (Cornell), Etienne Pointecouteau (IRAP Toulouse), Miriam E. Ramos-Ceja (Bonn), Mateusz Ruszkowski (Michigan), Neelima Sehgal (Stony Brook), Gordon G. Stacey (Cornell), Rashid Sunyaev (MPA/IKI)

Abstract: Sunyaev-Zeldovich (SZ) effects were first proposed in the 1970s as tools to identify the X-ray emitting hot gas inside massive clusters of galaxies and obtain their velocities relative to the cosmic microwave background (CMB). Yet it is only within the last decade that they have begun to significantly impact astronomical research. Thanks to the rapid developments in CMB instrumentation, measurement of the dominant thermal signature of the SZ effects has become a routine tool to find and characterize large samples of galaxy clusters and to seek deeper understanding of several important astrophysical processes via high-resolution imaging studies of many targets. With the notable exception of the Planck satellite and a few combinations of ground-based observatories, much of this “SZ revolution” has happened in the photometric mode, where observations are made at one or two frequencies in the millimeter regime to maximize the cluster detection significance and minimize the foregrounds. Still, there is much more to learn from detailed and systematic analyses of the SZ spectra across multiple wavelengths, specifically in the submillimeter (\(\gtrsim 300\) GHz) domain. The goal of this Science White Paper is to highlight this particular aspect of SZ research, point out what new and potentially groundbreaking insights can be obtained from these studies, and emphasize why the coming decade can be a golden era for SZ spectral measurements.
1 Introduction to the SZ landscape

Galaxy clusters stand at the crossroads between astrophysics and cosmology. By forming the most massive end of the dark-matter halo mass function, their number counts deliver effective constraints on the composition and growth history of the Universe [1–3]. At the same time, galaxy clusters provide unique laboratories to test several astrophysical phenomena – from massive galaxy evolution and the role of AGN feedback, to particle acceleration in Mpc-scale shocks [4–6]. Quite naturally, studies of galaxy clusters and the associated large-scale structures have been one of the most productive areas of research in the last few decades, collecting huge amounts of data from ground and space based observatories across the entire electromagnetic spectrum.

Among the various methods to find and characterize galaxy clusters, one of the newest and most rapidly developing is the Sunyaev-Zeldovich effect [7–13]. It has two main variants: the thermal (tSZ) and the kinematic (kSZ) effects. They arise from inverse Compton scattering of the CMB photons by hot intracluster electrons and have several desirable properties: the signals are practically redshift independent (only limited by the telescope beam), have unique spectral signatures, and the amplitudes connect directly to total cluster thermal energy and line-of-sight momenta. From the first blind tSZ detection of clusters only a decade ago [14, 15], catalogs now exist with over a thousand confirmed objects and an order-of-magnitude more are expected from the next-generation CMB experiments [16–18], transforming cosmological quests such as the nature of dark energy and neutrino masses. Another rapidly developing field is the high angular resolution SZ imaging [13] that is opening up new windows on cluster astrophysics (see white papers by Mroczkowski et al. and Sehgal et al.). Our aim in this paper is to highlight some of the unique science that can be addressed from detailed measurements of the SZ spectra and how those results can shape our view of the Universe within the decade 2020–2030 and beyond.

![Figure 1: Left: tSZ (solid) and kSZ (dashed) spectra including relativistic corrections from high-energy thermal electrons. Two extreme temperatures highlight the spectral shapes, also for the kinematic effect. The dotted curve is the unscattered CMB scaled down by a factor of 2000 (figure from Ref. [13]). Right: tSZ spectral distortions once again, with a more representative set of temperatures and a varying Compton-\(y\) that cause the spectra to match at the minima of the tSZ decrement. This panel illustrates the importance of high frequency observations to break the \(y - T_e\) degeneracy. The vertical grey bands are Planck frequency channels, many of which are also accessible from a good ground site, e.g., in Atacama or Antarctica.](image)

The importance of submillimeter data to separate the kSZ effect was realized early on [19, 20]. This effect carries information about the electron bulk motion relative to the CMB rest frame and
promises to be an important cosmological probe [21–25], yet successful applications have been limited, most notably for identifying strong internal bulk motions in merging clusters [26–28] and detecting the kSZ-galaxy bispectrum via pairwise subtraction [29–31]. Terrestrial CMB experiments have mostly used the “photometric mode” for SZ science: focusing on 1–2 bands in the millimeter to maximize tSZ detection significance and using the 220 GHz channel to subtract the CMB, which also eliminates the kSZ signal. This has kept the focus on a static view of the universe to perform number count cosmology similar to X-ray or infra-red surveys. Now, after the Planck data release, the real potential of multi-frequency SZ observations is coming into perspective, from kSZ measurements and the search for the missing baryons [32–34], to extracting cluster properties from the tSZ spectrum [35, 36]. The next decade will see a full realization of these scientific quests when large format ground-based cameras will improve upon the resolution and sensitivity of past satellite probes, including in the submm, while at the same time new space missions will offer unprecedented spectral sampling and sky coverage to complement the results from the ground.

2 Galaxy cluster temperatures from the rSZ effect

What will change if we can measure galaxy cluster temperatures across cosmic time?

Figure 2: Left: Spectral modeling result from a stacked sample of 772 Planck clusters, with red and blue lines denoting the best-fit tSZ and thermal dust emission spectra. The mean cluster temperature is measured only at $2.2\sigma$ significance ($4.4^{+2.1}_{-2.0}$ keV), but the result shows the importance of accurate dust modeling using high-frequency data (figure from Ref. [36]). Right: rSZ temperature measurement uncertainties on individual clusters as expected from an “optimized CCAT-prime” camera concept [37] with 10,000 deg$^2$ survey area. The errors actually improve with redshift, in complete contrast with X-ray observations, enabling us to stack and calibrate cluster masses out to the epoch of their formation. Furthermore, future surveys can improve these predictions by employing additional frequency bands or using priors from X-ray data.

Just as with the X-ray Bremsstrahlung spectrum, the full, relativistic spectrum of the tSZ effect (referred also as the relativistic SZ, or rSZ, effect) carries information about the mean temperature of the scattering electrons [38–41]. As shown in Fig. 1 (right panel), mm-wave observations alone cannot distinguish this effect from a change in the Comptonization parameter, and only by adding high-frequency observations it is possible to break this $y - T_e$ degeneracy and extract the temperature information (unless other priors on electron densities are used). The current best constraints on the tSZ spectrum and the associated $T_{rSZ}$ value comes from Planck satellite data (Fig. 2 left), which
provide a marginal detection after stacking hundreds of clusters [36, 42]. But next-generation CMB experiments with submm capabilities will push the noise down to levels where similar detection significance can be achieved on *individual* massive clusters [36, 37]. When measured via stacking (which will eliminate the kSZ contribution) the accuracy of $T_{\text{rSZ}}$-based mass calibration will be similar to what is expected from CMB lensing and other methods, hence providing an important tool to model the thermodynamic history of galaxy clusters from a very early epoch.

An example is shown in Fig. 2 (right), where $T_{\text{rSZ}}$ errors are computed for an SZ survey with three submm bands [37] and realistic foregrounds, yielding temperature accuracies above $6\sigma$ in stacked cluster samples at $z \sim 1$. This will be a significant step forward, since the temperature determination from forthcoming X-ray surveys such as SRG/eROSITA will be limited mostly to $z \lesssim 0.2$ clusters [43, 44]. $T_{\text{rSZ}}$ is further interesting as it is pressure ($n_e T_e$) weighted [45, 46], as opposed to roughly $n_e^2$ weighting of the X-ray temperature [47], hence it is a low-scatter mass proxy suitable for cosmological modeling of the halo mass function. Accounting for the relativistic corrections will also improve the accuracy of cosmological modeling from tSZ power spectra and possibly alleviate some of the current tensions between CMB and cluster cosmology results [48].

*Planck* satellite data in the present decade have also provided unmistakable signs of thermal emission from dust within galaxy clusters themselves [49–51], which will be a critical component for SZ spectral modeling. The origin of this cluster-centric FIR emission is currently unknown; it could be from individual star-forming galaxies (i.e. a component of the cosmic infrared background) but could also be diffuse dust, accumulated from galaxy stripping [52] or AGN-uplifting of the central cold gas [53]. Its impact will be even more significant for high-$z$ proto-clusters or for the study of the circumgalactic medium (CGM) in low-mass halos, where the relative dust contribution could be higher. It has already been shown that, for modeling AGN feedback in galaxy halos from the associated tSZ signal, not accounting for the dust emission can lead to incorrect conclusions [54]. If our goal is to calibrate cluster masses across cosmic time using the rSZ effect, then accurate modeling of their dust emission using submm data is going to play a central role.

### 3 SZ component separation and the measurement of cluster velocities

*How can we ensure unbiased kSZ measurements and what will be the scientific impact?*

The issue of dust contamination will enter the study of the kSZ effect – and hence the determination of the cosmic velocity field on large scales – in two ways. First, similar to the rSZ temperature measurement, it will bias the line-of-sight velocity estimation for individual halos. This problem is illustrated in the left panel of Fig. 3, where an instrument that has only low-frequency (mm-wave) coverage returns biased estimates for temperature and velocities by ignoring dust emission, while having no discernible bias on the Comptonization parameter. Even though statistically not the most powerful technique, measuring the velocity (and hence optical depth) of selected individual high-mass halos will be extremely important for calibrating the galaxy-electron density power spectrum and breaking the so-called “optical depth degeneracy” [55, 56]. Such measurements will also be important in the search for missing baryons from stacked electron density profiles [32, 34].

The second case of dust contamination will be within CMB maps themselves, which are the templates for kSZ signal in every kSZ bispectrum or cross-correlation analyses (at small angular scales the primordial CMB power is mostly replaced by kSZ). The origin of this bias is incorrect/insufficient use of foreground information in map making. An illustrative example is shown in Fig. 3 (right), where all of the four publicly-released *Planck* CMB maps from 2015 show strong
residuals in the direction of known clusters. This residual comes from not explicitly accounting for the tSZ signal in the foreground model and minimizing that contribution [58]. For the high-precision CMB imaging in the coming decade, a simple non-relativistic tSZ template will not suffice, but one will need its relativistic corrections as well [48], necessitating submm data. The same will be true with dust, whose correlation with large-scale structure is already proven [49], thereby also requiring the leverage of high-frequency data for unbiased CMB map extraction.

The impact of kSZ measurements on cosmology, via both direct and statistical methods, will be immense (see white paper by Battaglia et al.). It will help to identify the time evolution of dark energy from large-scale velocity correlations [59], search for missing baryons at low redshifts [60], and provide constraints on the energy feedback within galaxy halos [61], to list a few. High-frequency ($\gtrsim 300$ GHz) CMB observations will be a critical ingredient for building this dynamical view of the Universe, together with the next-generation infra-red, optical, and X-ray surveys.

4 ntSZ effect for the cosmic ray energy budget of clusters

What role does the nonthermal population play in determining large-scale structure growth?

Exploration of the SZ spectral distortions will not be complete without taking into account the non-thermal SZ (ntSZ) effect [62–64]. As shown in Fig. 4, the high-frequency bands are again important in disentangling its contribution, but the spectral shapes are more uncertain due to the wide variety of non-thermal populations (cosmic rays) that can contribute. Typically, the overall cosmic ray pressure in galaxy clusters is very low ($\lesssim 1\%$; [65–67]) so ntSZ studies will be critical only within specific cluster regions, such as AGN bubbles for understanding the feedback mechanism [68, 69], or near cluster cores for finding the signature of annihilating dark-matter particles [70].
At the same time, sensitivities of the next generation CMB survey experiments can enable stacking analyses of the global ntSZ effect for an important class of objects: the radio halo clusters. These host Mpc-scale diffuse synchrotron emissions that are thought to be the signature of GeV-energy electrons energized by major mergers [71–74], however this correspondence is highly uncertain and the determination of merger energetics via synchrotron emission is complicated by the unknown magnetic field strengths and topology. In the coming decade, all-sky radio surveys are expected to increase the number of radio halo clusters from ~ 50 currently known objects to several hundreds [75–77]. A determination of their volume-averaged ntSZ signature will provide direct constraints on the energy dissipation and particle acceleration processes following major mergers, complementing the picture of a dynamical Universe as will be established by other probes.

5 The path forward in the coming decade

What are the instrumental requirements for the next generation to make significant progress?

The mm/submm community will move toward realizing the promises of SZ spectral science from both space and the ground. New generation CMB and spectral intensity mapping surveys will carry on the rapid developments in microwave detector technology that are occurring right now, e.g., kinetic inductance detector (KID) based cameras coupled with imaging interferometers like CONCERTO [78] and more sensitive future cameras with significantly higher optical throughput like Prime-Cam [79] (the latter hosting multichroic detectors with an imaging Fabry-Pérot interferometer [57]). Efficient instantaneous sampling of the spectrum can be possible with broadband multichroic focal planes consisting of multimoded feeds [80], multi-scale antenna arrays [81], and direct detection spectrometers like TIME [82], Wspec [83], Micro-Spec [84] and DESHIMA [85].

CCAT-prime, located at 5600 m altitude in the Atacama, will be among the first survey telescopes in the coming decade to scan a large fraction of the sky in the submm for CMB science [86]. It will also provide ample scope for future generation instruments to take advantage of this excellent site. Other locations with comparable atmospheric transmission are at the South Pole or Dome-C in Antarctica, where for example the current 10-m SPT dish is already used for submm VLBI [87]. Future developments in the Atacama desert will likely include the CSST [88] and lead up to AtLAST [89–91], a 50-m class submm telescope that will revolutionize SZ spectral science. Looking from space, future CMB missions like PICO [92] and CMB-Bharat [93] – building upon the scientifically compelling mission concepts of PRISM [94] and CORE [95] – will provide full-sky coverage with angular resolution similar to Planck’s, but with more spectral channels and much better sensitivity. Those will be complemented by infra-red missions like SPICA [96], to deliver THz-frequency data with similarly high-precision for modeling the thermal dust emission.
References

[1] S. W. Allen, A. E. Evrard, and A. B. Mantz. Cosmological Parameters from Observations of Galaxy Clusters. ARAA, 49:409–470, September 2011. arXiv:1103.4829, doi:10.1146/annurev-astro-081710-102514.

[2] A. V. Kravtsov and S. Borgani. Formation of Galaxy Clusters. ARAA, 50:353–409, September 2012. arXiv:1205.5556, doi:10.1146/annurev-astro-081811-125502.

[3] D. Nagai. Cosmology and astrophysics with galaxy clusters. In American Institute of Physics Conference Series, volume 1632 of American Institute of Physics Conference Series, pages 88–106, November 2014. doi:10.1063/1.4902845.

[4] C. L. Sarazin. X-ray emission from clusters of galaxies. Reviews of Modern Physics, 58:1–115, January 1986. doi:10.1103/RevModPhys.58.1.

[5] J. Kormendy and S. Djorgovski. Surface photometry and the structure of elliptical galaxies. ARAA, 27:235–277, 1989. doi:10.1146/annurev.aa.27.090189.001315.

[6] A. M. Bykov, H. Bloemen, and Y. A. Uvarov. Nonthermal emission from clusters of galaxies. A&A, 362:886–894, October 2000.

[7] R. A. Sunyaev and Y. B. Zeldovich. The Spectrum of Primordial Radiation, its Distortions and their Significance. Comments on Astrophysics and Space Physics, 2:66, March 1970.

[8] R. A. Sunyaev and Y. B. Zeldovich. The Observations of Relic Radiation as a Test of the Nature of X-Ray Radiation from the Clusters of Galaxies. Comments on Astrophysics and Space Physics, 4:173, November 1972.

[9] R. A. Sunyaev and Y. B. Zeldovich. The velocity of clusters of galaxies relative to the microwave background. The possibility of its measurement. NASA STI/Recon Technical Report N, 80, 1975.

[10] R. A. Sunyaev and I. B. Zeldovich. Microwave background radiation as a probe of the contemporary structure and history of the universe. ARAA, 18:537–560, 1980. doi:10.1146/annurev.aa.18.090180.002541.

[11] M. Birkinshaw. The Sunyaev-Zel’dovich effect. Phys. Rep., 310:97–195, March 1999. arXiv:astro-ph/9808050, doi:10.1016/S0370-1573(98)00080-5.

[12] J. E. Carlstrom, G. P. Holder, and E. D. Reese. Cosmology with the Sunyaev-Zel’dovich Effect. ARAA, 40:643–680, 2002. arXiv:astro-ph/0208192, doi:10.1146/annurev.astro.40.060401.093803.

[13] T. Mroczkowski, D. Nagai, K. Basu, J. Chluba, J. Sayers, R. Adam, et al. Astrophysics with the Spatially and Spectrally Resolved Sunyaev-Zeldovich Effects. A Millimetre/Submillimetre Probe of the Warm and Hot Universe. Space Sci. Rev., 215:17, February 2019. arXiv:1811.02310, doi:10.1007/s11214-019-0581-2.

[14] Z. Staniszewski, P. A. R. Ade, K. A. Aird, B. A. Benson, L. E. Bleem, J. E. Carlstrom, et al. Galaxy Clusters Discovered with a Sunyaev-Zel’dovich Effect Survey. ApJ, 701:32–41, August 2009. arXiv:0810.1578, doi:10.1088/0004-637X/701/1/32.

[15] F. Menanteau, J. González, J.-B. Juin, T. A. Marriage, E. D. Reese, V. Acquaviva, et al. The Atacama Cosmology Telescope: Physical Properties and Purity of a Galaxy Cluster Sample Selected via the Sunyaev-Zel’dovich Effect. ApJ, 723:1523–1541, November 2010. arXiv:1006.5126, doi:10.1088/0004-637X/723/2/1523.
[16] The Simons Observatory Collaboration, P. Ade, J. Aguirre, Z. Ahmed, S. Aiola, A. Ali, et al. The Simons Observatory: Science goals and forecasts. arXiv e-prints, August 2018. arXiv:1808.07445.

[17] K. N. Abazajian, P. Adshead, Z. Ahmed, S. W. Allen, D. Alonso, K. S. Arnold, et al. CMB-S4 Science Book, First Edition. arXiv e-prints, October 2016. arXiv:1610.02743.

[18] J.-B. Melin, A. Bonaldi, M. Remazeilles, S. Hagstotz, J. M. Diego, C. Hernández-Monteagudo, et al. Exploring cosmic origins with CORE: Cluster science. JCAP, 4:019, April 2018. arXiv:1703.10456, doi:10.1088/1475-7516/2018/04/019.

[19] J. M. Lamarre, M. Giard, E. Pointecouteau, J. P. Bernard, G. Serra, F. Pajot, et al. First Measurement of the Submillimeter Sunyaev-Zeldovich Effect. ApJL, 507:L5–L8, November 1998. arXiv:astro-ph/9806128, doi:10.1086/311678.

[20] E. Komatsu, T. Kitayama, Y. Suto, M. Hattori, R. Kawabe, H. Matsuo, et al. Submillimeter Detection of the Sunyaev-Zeldovich Effect toward the Most Luminous X-Ray Cluster at Z = 0.45. ApJL, 516:L1–L4, May 1999. arXiv:astro-ph/9902351, doi:10.1086/311983.

[21] S. DeDeo, D. N. Spergel, and H. Trac. The kinetic Sunyaev-Zel’dovich effect as a dark energy probe. arXiv Astrophysics e-prints, November 2005. arXiv:astro-ph/0511060.

[22] S. Bhattacharya and A. Kosowsky. Dark energy constraints from galaxy cluster peculiar velocities. Phys/ Rev. D, 77(8):083004, April 2008. arXiv:0712.0034, doi:10.1103/PhysRevD.77.083004.

[23] E.-M. Mueller, F. de Bernardis, R. Bean, and M. D. Niemack. Constraints on Gravity and Dark Energy from the Pairwise Kinematic Sunyaev-Zel’dovich Effect. ApJ, 808:47, July 2015. arXiv:1408.6248, doi:10.1088/0004-637X/808/1/47.

[24] E. Schaan, S. Ferraro, M. Vargas-Magaña, K. M. Smith, S. Ho, S. Aiola, et al. Evidence for the kinematic Sunyaev-Zel’dovich effect with the Atacama Cosmology Telescope and velocity reconstruction from the Baryon Oscillation Spectroscopic Survey. Phys/ Rev. D, 93(8):082002, April 2016. arXiv:1510.06442, doi:10.1103/PhysRevD.93.082002.

[25] N. S. Sugiyama, T. Okumura, and D. N. Spergel. Will kinematic Sunyaev-Zel’dovich measurements enhance the science return from galaxy redshift surveys? JCAP, 1:057, January 2017. arXiv:1606.06367, doi:10.1088/1475-7516/2017/01/057.

[26] T. Mroczkowski, S. Dicker, J. Sayers, E. D. Reese, B. Mason, N. Czakon, et al. A Multi-wavelength Study of the Sunyaev-Zel’dovich Effect in the Triple-merger Cluster MACS J0717.5+3745 with MUSTANG and Bolocam. ApJ, 761:47, December 2012. arXiv:1205.0052, doi:10.1088/0004-637X/761/1/47.

[27] J. Sayers, T. Mroczkowski, M. Zemcov, P. M. Korngut, J. Bock, E. Bulbul, et al. A Measurement of the Kinetic Sunyaev-Zel’dovich Signal Toward MACS J0717.5+3745. ApJ, 778:52, November 2013. arXiv:1312.3680, doi:10.1088/0004-637X/778/1/52.

[28] R. Adam, M. Arnaud, I. Bartalucci, P. Ade, P. André, A. Beelen, et al. Mapping the hot gas temperature in galaxy clusters using X-ray and Sunyaev-Zel’dovich imaging. A&A, 606:A64, October 2017. arXiv:1706.10230, doi:10.1051/0004-6361/201629810.

[29] N. Hand, G. E. Addison, E. Aubourg, N. Battaglia, E. S. Battistelli, D. Bizyaev, et al. Evidence of Galaxy Cluster Motions with the Kinematic Sunyaev-Zel’dovich Effect. Physical Review Letters, 109(4):041101, July 2012. arXiv:1203.4219, doi:10.1103/PhysRevLett.109.041101.
[30] Planck Collaboration, P. A. R. Ade, N. Aghanim, M. Arnaud, M. Ashdown, J. Aumont, et al. Planck intermediate results. XIII. Constraints on peculiar velocities. A&A, 561:A97, January 2014. arXiv:1303.5090, doi:10.1051/0004-6361/201321299.

[31] B. Soergel, A. Saro, T. Giannantonio, G. Efstathiou, and K. Dolag. Cosmology with the pairwise kinematic SZ effect: calibration and validation using hydrodynamical simulations. MNRAS, 478:5320–5335, August 2018. arXiv:1712.05714, doi:10.1093/mnras/sty1324.

[32] Planck Collaboration, P. A. R. Ade, N. Aghanim, M. Arnaud, M. Ashdown, E. Aubourg, et al. Planck intermediate results. XXXVII. Evidence of unbound gas from the kinetic Sunyaev-Zeldovich effect. A&A, 586:A140, February 2016. arXiv:1504.03339, doi:10.1051/0004-6361/201526328.

[33] J. C. Hill, S. Ferraro, N. Battaglia, J. Liu, and D. N. Spergel. Kinematic Sunyaev-Zel’dovich Effect with Projected Fields: A Novel Probe of the Baryon Distribution with Planck, WMAP, and WISE Data. Physical Review Letters, 117(5):051301, July 2016. arXiv:1603.01608, doi:10.1103/PhysRevLett.117.051301.

[34] S. Lim, H. Mo, H. Wang, and X. Yang. The detection of missing baryons in galaxy halos with kinetic Sunyaev-Zel’dovich effect. arXiv e-prints, December 2017. arXiv:1712.08619.

[35] G. Hurier and C. Tchernin. Mapping the temperature of the intra-cluster medium with the thermal Sunyaev-Zel’dovich effect. A&A, 604:A94, August 2017. arXiv:1702.03711, doi:10.1051/0004-6361/201629993.

[36] J. Erler, K. Basu, J. Chluba, and F. Bertoldi. Planck’s view on the spectrum of the Sunyaev-Zeldovich effect. MNRAS, 476:3360–3381, May 2018. arXiv:1709.01187, doi:10.1093/mnras/sty327.

[37] A. Mittal, F. de Bernardis, and M. D. Niemack. Optimizing measurements of cluster velocities and temperatures for CCAT-prime and future surveys. JCAP, 2:032, February 2018. arXiv:1708.06365, doi:10.1088/1475-7516/2018/02/032.

[38] E. L. Wright. Distortion of the microwave background by a hot intergalactic medium. ApJ, 232:348–351, September 1979. doi:10.1086/157294.

[39] E. Pointecouteau, M. Giard, and D. Barret. Determination of the hot intracluster gas temperature from submillimeter measurements. A&A, 336:44–48, August 1998. arXiv:astro-ph/9712271.

[40] S. Nozawa, Y. Kohyama, and N. Itoh. Study on the solutions of the Sunyaev-Zeldovich effect for clusters of galaxies. Phys/ Rev. D, 79(12):123007, June 2009. arXiv:0904.3811, doi:10.1103/PhysRevD.79.123007.

[41] J. Chluba, D. Nagai, S. Sazonov, and K. Nelson. A fast and accurate method for computing the Sunyaev-Zel’dovich signal of hot galaxy clusters. MNRAS, 426:510–530, October 2012. arXiv:1205.5778, doi:10.1111/j.1365-2966.2012.21741.x.

[42] G. Hurier. High significance detection of the tSZ effect relativistic corrections. A&A, 596:A61, December 2016. arXiv:1701.09020, doi:10.1051/0004-6361/201629726.

[43] K. Borm, T. H. Reiprich, I. Mohammed, and L. Lovisari. Constraining galaxy cluster temperatures and redshifts with eROSITA survey data. A&A, 567:A65, July 2014. arXiv:1404.5312, doi:10.1051/0004-6361/201322643.

[44] F. Hofmann, J. S. Sanders, N. Clerc, K. Nandra, J. Ridl, K. Dennerl, et al. eROSITA cluster
cosmology forecasts: Cluster temperature substructure bias. A&A, 606:A118, October 2017. arXiv:1708.05205, doi:10.1051/0004-6361/201730742.

[45] S. H. Hansen. Cluster temperature profiles and Sunyaev-Zeldovich observations. MNRAS, 351:L5–L8, June 2004. arXiv:astro-ph/0401391, doi:10.1111/j.1365-2966.2004.07920.x.

[46] S. T. Kay, L. C. Powell, A. R. Liddle, and P. A. Thomas. The Sunyaev-Zel’dovich temperature of the intracluster medium. MNRAS, 386:2110–2114, June 2008. arXiv:0706.3668, doi:10.1111/j.1365-2966.2008.13183.x.

[47] P. Mazzotta, E. Rasia, L. Moscardini, and G. Tormen. Comparing the temperatures of galaxy clusters from hydrodynamical N-body simulations to Chandra and XMM-Newton observations. MNRAS, 354:10–24, October 2004. arXiv:astro-ph/0404425, doi:10.1111/j.1365-2966.2004.08167.x.

[48] M. Remazeilles, B. Bolliet, A. Rotti, and J. Chluba. Can we neglect relativistic temperature corrections in the Planck thermal SZ analysis? MNRAS, 483:3459–3464, March 2019. arXiv:1809.09666, doi:10.1093/mnras/sty3352.

[49] Planck Collaboration, P. A. R. Ade, N. Aghanim, M. Arnaud, J. Aumont, C. Baccigalupi, et al. Planck 2015 results. XXIII. The thermal Sunyaev-Zeldovich effect-cosmic infrared background correlation. A&A, 594:A23, September 2016. arXiv:1509.06555, doi:10.1051/0004-6361/201527418.

[50] Planck Collaboration, R. Adam, P. A. R. Ade, N. Aghanim, M. Ashdown, J. Aumont, et al. Planck intermediate results. XLIII. Spectral energy distribution of dust in clusters of galaxies. A&A, 596:A104, December 2016. arXiv:1603.04919, doi:10.1051/0004-6361/201628522.

[51] J.-B. Melin, J. G. Bartlett, Z.-Y. Cai, G. De Zotti, J. Delabrouille, M. Roman, et al. Dust in galaxy clusters: Modeling at millimeter wavelengths and impact on Planck cluster cosmology. A&A, 617:A75, September 2018. arXiv:1811.05477.

[52] M. Vogelsberger, R. McKinnon, S. O’Neil, F. Marinacci, P. Torrey, and R. Kannan. Dust in and around galaxies: dust in cluster environments and its impact on gas cooling. arXiv e-prints, November 2018. arXiv:1811.05477.

[53] N. Werner, A. Simionescu, E. T. Million, S. W. Allen, P. E. J. Nulsen, A. von der Linden, et al. Feedback under the microscope-II. Heating, gas uplift and mixing in the nearest cluster core. MNRAS, 407:2063–2074, October 2010. arXiv:1003.5334, doi:10.1111/j.1365-2966.2010.16755.x.

[54] B. Soergel, T. Giannantonio, G. Efstathiou, E. Puchwein, and D. Sijacki. Constraints on AGN feedback from its Sunyaev-Zel’dovich imprint on the cosmic background radiation. MNRAS, 468:577–596, June 2017. arXiv:1612.06296, doi:10.1093/mnras/stx492.

[55] N. Battaglia. The tau of galaxy clusters. JCAP, 8:058, August 2016. arXiv:1607.02442, doi:10.1088/1475-7516/2016/08/058.

[56] S. Flender, D. Nagai, and M. McDonald. Constraints on the Optical Depth of Galaxy Groups and Clusters. ApJ, 837:124, March 2017. arXiv:1610.08029, doi:10.3847/1538-4357/aa60bf.

[57] G. J. Stacey, M. Aravena, K. Basu, N. Battaglia, B. Beringue, F. Bertoldi, et al. CCAT-Prime: science with an ultra-widefield submillimeter observatory on Cerro Chajnantor. In Ground-based and Airborne Telescopes VII, volume 10700 of Society of Photo-Optical Instrumentation Engineers
[58] T. Chen, M. Remazeilles, and C. Dickinson. Impact of SZ cluster residuals in CMB maps and CMB-LSS cross-correlations. MNRAS, 479:4239–4252, September 2018. arXiv:1803.08853, doi:10.1093/mnras/sty1730.

[59] D. Alonso, T. Louis, P. Bull, and P. G. Ferreira. Reconstructing cosmic growth with kinetic Sunyaev-Zel’dovich observations in the era of stage IV experiments. Phys/ Rev. D, 94(4):043522, August 2016. arXiv:1604.01382, doi:10.1103/PhysRevD.94.043522.

[60] C. Hernández-Monteagudo and R. A. Sunyaev. Missing baryons, bulk flows, and the E-mode polarization of the Cosmic Microwave Background. A&A, 490:25–29, October 2008. arXiv:0805.3702, doi:10.1051/0004-6361:200810204.

[61] N. Battaglia, S. Ferraro, E. Schaan, and D. N. Spergel. Future constraints on halo thermodynamics from combined Sunyaev-Zel’dovich measurements. JCAP, 11:040, November 2017. arXiv:1705.05881, doi:10.1088/1475-7516/2017/11/040.

[62] Y. Rephaeli. Cosmic microwave background comptonization by hot intracluster gas. ApJ, 445:33–36, May 1995. doi:10.1086/175669.

[63] T. A. Enßlin and C. R. Kaiser. Comptonization of the cosmic microwave background by relativistic plasma. A&A, 360:417–430, August 2000. arXiv:arXiv:astro-ph/0001429.

[64] S. Colafrancesco, P. Marchegiani, and E. Palladino. The non-thermal Sunyaev-Zel’dovich effect in clusters of galaxies. A&A, 397:27–52, January 2003. arXiv:arXiv:astro-ph/0211649, doi:10.1051/0004-6361:20021199.

[65] F. Zandanel, C. Pfrommer, and F. Prada. On the physics of radio haloes in galaxy clusters: scaling relations and luminosity functions. MNRAS, 438:124–144, February 2014. arXiv:1311.4795, doi:10.1093/mnras/stt2250.

[66] R. Bartels, F. Zandanel, and S. Ando. Inverse-Compton emission from clusters of galaxies: Predictions for ASTRO-H. A&A, 582:A20, September 2015. arXiv:1501.06940, doi:10.1051/0004-6361/201525758.

[67] A. Pinzke, S. P. Oh, and C. Pfrommer. Turbulence and particle acceleration in giant radio haloes: the origin of seed electrons. MNRAS, 465:4800–4816, March 2017. arXiv:1611.07533, doi:10.1093/mnras/stw3024.

[68] Z. Abdulla, J. E. Carlstrom, A. B. Mantz, D. P. Marrone, C. H. Greer, J. W. Lamb, et al. Constraints on the Thermal Contents of the X-ray Cavities of Cluster MS 0735.6+7421 with Sunyaev-Zel’dovich Effect Observations. ArXiv e-prints, page arxiv:1806.05050, June 2018. arXiv:1806.05050.

[69] M. Lacy, B. Mason, C. Sarazin, S. Chatterjee, K. Nyland, A. Kimball, et al. Direct detection of quasar feedback via the Sunyaev-Zeldovich effect. MNRAS, 483:L22–L27, February 2019. arXiv:1811.05023, doi:10.1093/mnrasl/sly215.

[70] S. Colafrancesco. SZ effect from Dark Matter annihilation. A&A, 422:L23–L27, July 2004. arXiv:astro-ph/0405456, doi:10.1051/0004-6361:20040175.

[71] R. Cassano, S. Ettori, S. Giacintucci, G. Brunetti, M. Markevitch, T. Venturi, et al. On the Connection Between Giant Radio Halos and Cluster Mergers. ApJL, 721:L82–L85, October 2010. arXiv:1008.3624, doi:10.1088/2041-8205/721/2/L82.

[72] G. Brunetti and T. W. Jones. Cosmic Rays in Galaxy Clusters and Their Nonthermal Emission.
[73] M. W. Sommer and K. Basu. A comparative study of radio halo occurrence in SZ and X-ray selected galaxy cluster samples. MNRAS, 437:2163–2179, January 2014. arXiv:1307.3049, doi:10.1093/mnras/stt2037.

[74] R. J. van Weeren, F. de Gasperin, H. Akamatsu, M. Brüggen, L. Feretti, H. Kang, et al. Diffuse Radio Emission from Galaxy Clusters. Space Sci. Rev., 215:16, February 2019. arXiv:1901.04496, doi:10.1007/s11214-019-0584-z.

[75] Z. S. Yuan, J. L. Han, and Z. L. Wen. The Scaling Relations and the Fundamental Plane for Radio Halos and Relics of Galaxy Clusters. ApJ, 813:77, November 2015. arXiv:1510.04980, doi:10.1088/0004-637X/813/1/77.

[76] R. Norris, K. Basu, M. Brown, E. Carretti, A. D. Kapinska, I. Prandoni, et al. The SKA Mid-frequency All-sky Continuum Survey: Discovering the unexpected and transforming radio-astronomy. Advancing Astrophysics with the Square Kilometre Array (AASKA14), page 86, April 2015. arXiv:1412.6076.

[77] K. Knowles, A. Baker, K. Basu, V. Bharadwaj, R. Deane, M. Devlin, et al. MERGHERS: An SZ-selected cluster survey with MeerKAT. arXiv e-prints, September 2017. arXiv:1709.03318.

[78] G. Lagache. Exploring the dusty star-formation in the early Universe using intensity mapping. In V. Jelić and T. van der Hulst, editors, IAU Symposium, volume 333 of IAU Symposium, pages 228–233, May 2018. arXiv:1801.08054, doi:10.1017/S1743921318000558.

[79] E. M. Vavagiakis, Z. Ahmed, A. Ali, K. Basu, N. Battaglia, F. Bertoldi, et al. Prime-Cam: a first-light instrument for the CCAT-prime telescope. In Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX, volume 10708 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, page 107081U, July 2018. arXiv:1807.00058, doi:10.1117/12.2313868.

[80] B. R. Johnson, D. Flanigan, M. H. Abitbol, P. A. R. Ade, S. Bryan, H.-M. Cho, et al. Development of Multi-chroic MKIDs for Next-Generation CMB Polarization Studies. Journal of Low Temperature Physics, 193:103–112, November 2018. arXiv:1711.02523, doi:10.1007/s10909-018-2032-y.

[81] C. Ji, A. Beyer, S. Golwala, and J. Sayers. Design of antenna-coupled lumped-element titanium nitride KIDs for long-wavelength multi-band continuum imaging. In Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VII, volume 9153 of Proc. SPIE, page 91532I, July 2014. doi:10.1117/12.2056777.

[82] A. T. Crites, J. J. Bock, C. M. Bradford, T. C. Chang, A. R. Cooray, L. Duband, et al. The TIME-Pilot intensity mapping experiment. In Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VII, volume 9153 of Proc. SPIE, page 91531W, August 2014. doi:10.1117/12.2057207.

[83] S. Bryan, J. Aguirre, G. Che, S. Doyle, D. Flanigan, C. Groppi, et al. WSPEC: A Waveguide Filter-Bank Focal Plane Array Spectrometer for Millimeter Wave Astronomy and Cosmology. Journal of Low Temperature Physics, 184:114–122, July 2016. arXiv:1509.04658, doi:10.1007/s10909-015-1396-5.

[84] E. M. Barrentine, G. Cataldo, A. D. Brown, N. Ehsan, O. Noroozian, T. R. Stevenson, et al. Design and performance of a high resolution µ-spec: an integrated sub-millimeter spectrometer. In
[85] A. Endo, P. Werf, R. M. J. Janssen, P. J. Visser, T. M. Klapwijk, J. J. A. Baselmans, et al. Design of an Integrated Filterbank for DESHIMA: On-Chip Submillimeter Imaging Spectrograph Based on Superconducting Resonators. Journal of Low Temperature Physics, 167:341–346, May 2012. arXiv:1107.3333, doi:10.1007/s10909-012-0502-1.

[86] S. C. Parshley, J. Kronshage, J. Blair, T. Herter, M. Nolta, G. J. Stacey, et al. CCAT-prime: a novel telescope for sub-millimeter astronomy. In Ground-based and Airborne Telescopes VII, volume 10700 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, page 107005X, July 2018. arXiv:1807.06675, doi:10.1117/12.2314046.

[87] J. Kim, D. P. Marrone, C. Beaudoin, J. E. Carlstrom, S. S. Doeleman, T. W. Folkers, et al. A VLBI receiving system for the South Pole Telescope. In Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX, volume 10708 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, page 107082S, July 2018. arXiv:1805.09346, doi:10.1117/12.2301005.

[88] S. Padin. Inexpensive mount for a large millimeter-wavelength telescope. Appl. Opt., 53:4431–4439, July 2014. doi:10.1364/AO.53.004431.

[89] F. Bertoldi. The Atacama Large Aperture Submm/mm Telescope (AtLAST) Project. In Atacama Large-Aperture Submm/mm Telescope (AtLAST), page 3, January 2018. doi:10.5281/zenodo.1158842.

[90] Carlos De Breuck. Site considerations for atlast, January 2018. URL: https://doi.org/10.5281/zenodo.1158848, doi:10.5281/zenodo.1158848.

[91] T. Mroczkowski and O. Noroozian. AtLAST Instrumentation Considerations and Overview. In Atacama Large-Aperture Submm/mm Telescope (AtLAST), page 26, January 2018. doi:10.5281/zenodo.1159053.

[92] B. M. Sutin, M. Alvarez, N. Battaglia, J. Bock, M. Bonato, J. Borrill, et al. PICO - the probe of inflation and cosmic origins. In Space Telescopes and Instrumentation 2018: Optical, Infrared, and Millimeter Wave, volume 10698 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, page 106984F, July 2018. arXiv:1808.01368, doi:10.1117/12.2311326.

[93] Tarun Souradeep et al. CMB Bharat: Assessing the prospects for frontier CMB space experiments from India. http://cmb-bharat.in/, 2018. [Online].

[94] PRISM Collaboration, P. Andre, C. Baccigalupi, D. Barbosa, J. Bartlett, N. Bartolo, et al. PRISM (Polarized Radiation Imaging and Spectroscopy Mission): A White Paper on the Ultimate Polarimetric Spectro-Imaging of the Microwave and Far-Infrared Sky. arXiv e-prints, June 2013. arXiv:1306.2259.

[95] J. Delabrouille, P. de Bernardis, F. R. Bouchet, A. Achúcarro, P. A. R. Ade, R. Allison, et al. Exploring cosmic origins with CORE: Survey requirements and mission design. JCAP, 4:014, April 2018. arXiv:1706.04516, doi:10.1088/1475-7516/2018/04/014.

[96] H. Kaneda, D. Ishihara, S. Oyabu, M. Yamagishi, T. Wada, M. Kawada, et al. SPICA Mid-infrared Instrument (SMI): technical concepts and scientific capabilities. In Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave, volume 9904 of Proc. SPIE, page 99042I, July 2016. doi:10.1117/12.2232442.