Past research

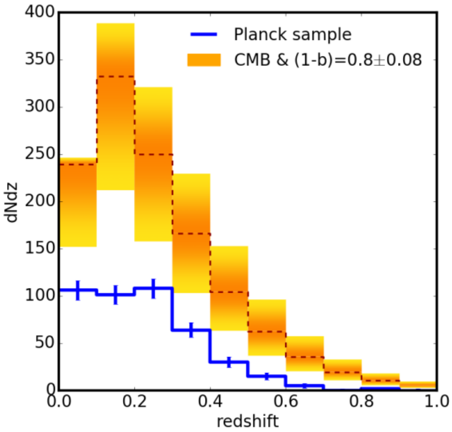
Hideki Tanimura

I have developed complementary expertise on galaxy clusters and cosmic filaments in the large-scale structure of the Universe, using both observational data and hydrodynamical simulations. My research expertise also covers a simulation of CMB polarization and its foreground emissions for future observations and a gamma-ray telescope construction for astronomical observations.

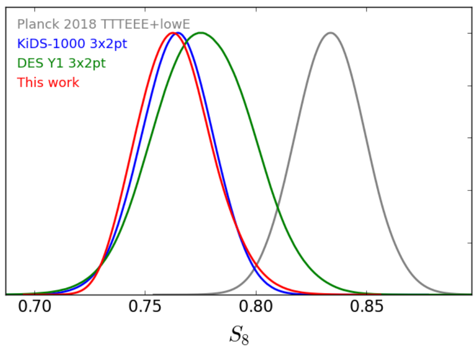
1 Constraints on cosmological parameters with galaxy clusters

The current standard cosmological model, called the ΛCDM model, has been supported by many observational results at different epochs. However, the model's validity is being reexamined, particularly due to a discrepancy in the $S_8(\equiv \sigma_8(\Omega_m/0.3)^{0.5})$ parameter: the amplitude of matter density fluctuations, σ_8, scaled by the square root of the matter density, Ω_m. Especially, $S_8 = 0.830 \pm 0.013$ was measured with the cosmic microwave background (CMB) anisotropies ($z \sim 1100$) by *Planck* [1]. However, low-redshift ($z \sim 0-1$) cosmological probes such as the abundance of galaxy clusters by *Planck* [2, 3] and gravitational lensing by Kilo Degree Survey (KiDS) [4] and Dark Energy Survey (DES) [5] indicate a preference for $S_8 \sim 0.76-0.78$, representing a $\sim 3\sigma$ tension with the CMB constraints; for example, as shown in Figure. 1a, this lower S_8 value results in a lower population of galaxy clusters by a factor of three than the standard model prediction based on *Planck*'s CMB measurement. These results indicate that the growth rate of cosmic structure is less than expected from the CMB measurement at the early universe and **may demand modifications to the standard model (i.e., new physics), while the tension was not statistically significant.**

To investigate the S_8 tension, I have used the Sunyaev-Zel'dovich (SZ) effect. The SZ effect is a direct tracer of the thermal energy in baryons in the Universe and is highly sensitive to the σ_8 and Ω_m cosmological parameters. To improve the former *Planck* 2015 analyses with the SZ effect [6], I constructed a new all-sky SZ map using the latest *Planck* data released in 2020 and performed a cosmological analysis with the new SZ map in collaboration with Dr. Guillaume Hurier, Dr. Matthieu Tristram at the Laboratoire de l'Accelerateur Lineaire, and Dr. Reijo Keskitalo at the Lawrence Berkeley National Laboratory. The analysis showed that the S_8 value was fully consistent with recent KiDS and DES weak-lensing low-redshift observations, **confirming the S_8 tension with the CMB** [7], as shown in Figure. 1b. **(Note that solving this S_8 tension by extending the ΛCDM model is my current research goal.)**



(a) Blue: Observed number of galaxy clusters by *Planck* as a function of redshift. Yellow: Predicted number in the ΛCDM model based on the *Planck* CMB measurement [8].



(b) Probability distribution of the S_8 parameter obtained from the *Planck* CMB (gray), KiDS-1000 3x2pt (blue), DES Y1 3x2pt (green), and my result with the SZ power spectrum (red) [7].

Figure 1

2 Detections of missing baryons

During the past years, I have mainly focused on one of the important cosmological problems called the missing baryon problem. Baryon density is ~4.9% of the energy density of the Universe, and the value is well constrained by CMB observations [1]. However, for decades, observations of the late-time Universe did not find ~30-40% of the baryons [9]. Hydrodynamical simulations predict that most of the missing baryons are located in filamentary structures in the cosmic web as a form of Warm and Hot Intergalactic Medium (WHIM) with temperatures of $10^5 < T < 10^7$ K [10]. Despite this prediction, detections of the missing baryon have been prevented due to its low density and complex source morphology.

I challenged this cosmological problem by developing new statistical data analysis tools and finally **achieved the first detection** via the SZ effect. I also performed the same analysis in simulations and constrained the physical states, such as the gas density and temperature. This research was conducted in collaboration mainly with Prof. Ian McCarthy at Liverpool John Moores University and Prof. Ludovic Van Waerbeke at the University of British Columbia. My result was published in [11], and it received a lot of attention **(89 citations since 2019)**, including from public media [12, 13, 14].

I continued my study of the missing baryons after joining the ByoPiC project (https://byopic.eu/) in France. I took charge of one of the main goals of this project, i.e., detecting and characterizing missing baryons with multi-wavelength data. For this purpose, **I managed a small group in the team and achieved the goal**. Our work resulted in three publications [15, 16, 17], including my first-author publication [15]. In this new study, I extended my research to the analysis of the *Planck* CMB lensing data [18], which allowed me to further constrain the amplitude of underlying dark matter density fluctuations in the cosmic web. In addition, my observational result was compared with numerical simulations in [19], resulting in a ByoPiC Ph.D. work I contributed.

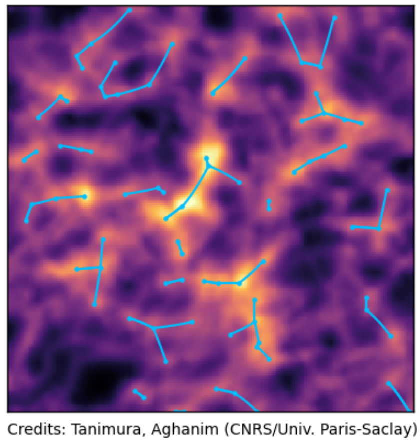


Figure 2: *ROSAT* image of diffuse X-ray emissions from the cosmic filaments detected in my analysis [20]. The overlaid filaments (cyan) are identified with SDSS galaxies.

Recently, other detections of the missing baryons have been reported; however, they are still limited to "indirect" detections through the absorption of X-ray photons or the SZ distortion of CMB photons. On the other hand, my further research **succeeded in the first "direct" detection of the missing baryons** in the cosmic filaments via X-ray emissions, as demonstrated in Figure. 2. Combined with my previous detections with the SZ effect, my multiwavelength detections allowed me to constrain the physical state of the detected missing baryon, resulting in a new publication [20]. This work was advertised in a press release of the Centre National de la Recherche Scientifique (CNRS) in France [21], highlighted by "Nature Astronomy" [22], and featured by French science magazines [23, 24].

3 Baryonic effects in galaxy clusters

The intracluster medium (ICM) in galaxy clusters is known to have a complex dynamical evolution, regulated not only by gravity but also by non-gravitational processes due to the relativistic plasma ejected by active galactic nuclei (AGN), called AGN feedback [25]. The AGN feedback has a wide range of impacts on the evolution of galaxies and galaxy clusters; however, it is not well understood.

To constrain AGN feedback models, I focused on low-mass halos ($\sim 3 \times 10^{13} M_{\odot}$), in which the impact of non-gravitational processes should be more noticeable than in massive halos. I statistically detected the SZ signal around the low-mass halos with a standard stacking analysis. Then, I **initiated a collaboration** with Prof. Ian McCarthy and compared my detected signals with his cosmo-OWLS simulations [26] with three different AGN feedback models, as shown in Figure. 3. This comparison supported one particular AGN model and **successfully constrained the AGN model**. This result was published in [27] and also reflected in the implementation of the AGN feedback model in newer BAHAMAS simulations [28]: an extension of the cosmo-OWLS simulations. During this study, I also built international collaborations with researchers from Brazil, Canada, South Africa, and the UK, and contributed to three publications by providing my expertise in the SZ data analysis to the multiwavelength analysis [29], the cross-correlation analysis [30], and the SZ analysis [31].

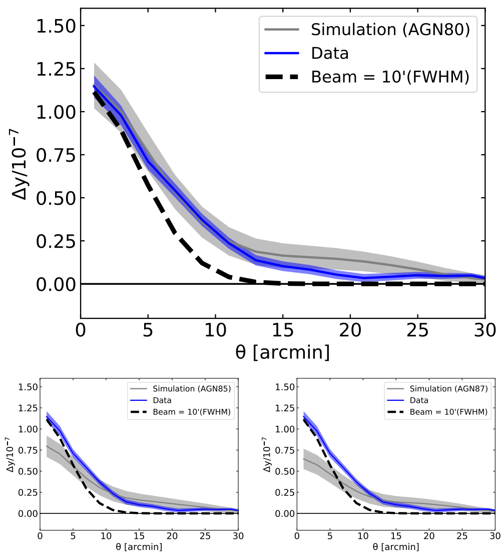


Figure 3: My detected SZ signal from low-mass halos (blue) compared with three different AGN feedback models (gray) in the cosmo-OWLS simulations: AGN80 (upper), AGN85 (lower left), and AGN87 (lower right).

Moreover, I **initiated a collaboration in the international LSS2LSS workshop** with Prof. Saleem Zaroubi at the University of Groningen and at the Technion and developed my new idea in measuring the kinetic SZ (kSZ) effect in galaxy clusters. The kSZ effect is the Doppler shift of CMB photons due to the hot plasma in galaxy clusters and can be used to probe the gas density and the velocity field around galaxy clusters. My analysis successfully detected the kSZ signal in galaxy clusters and found that the gas distribution extends over their virial radius, indicating the importance of baryonic effects over gravity. It resulted in a new publication [32].

4 Microwave sky simulation for detecting CMB B-mode polarization

The ΛCDM model is successful in predicting many phenomena observed in the Universe. However, this model raises new questions: Why is the Universe so homogeneous and isotropic on large scales? Why is the Universe geometrically flat? Inflation theory offers solutions to these problems, but no direct evidence has been observed yet. The CMB polarization is a key observable to support the inflation theory, which predicts a specific polarization pattern (B-mode) in the CMB caused by gravitational waves in the inflationary period of the Universe. However, galactic foreground emissions also have the same type of polarization and are much stronger than CMB polarization. In order to remove the foreground emissions efficiently and obtain the CMB more precisely, Prof. Gary Hinshaw designed a project (Canadian Galactic Emission Mapper) to produce the map of linear polarization by the ground-based observation at 10 GHz. In the project, I simulated skies at five frequency bands of WMAP (available data then) using available template maps of foreground emissions, the CMB, as well as expected detector and atmosphere noises, and estimated the improvement by adding the 10-GHz band. I optimized the telescope configuration and confirmed that the CMB polarization is extracted more precisely by a factor of $\sim$3. **This result was included as a main prediction in the new project proposal, and the project is now accepted and funded as the Canadian Galactic Emission Mapper (CGEM) in Canada.** This study built up my theoretical background in cosmology and deep understanding of data at microwave frequencies used for cosmological analyses.

5 Hardware construction for CANGAROO gamma ray telescope

Before my Ph.D., I started my research career in the CANGAROO group in Japan. The CANGAROO group used an imaging atmospheric Cherenkov telescope to measure the direction and energy of the gamma rays and to explore the spatial structure and energy spectrum of astronomical objects such as supernova remnants and AGNs. The spatial and energy resolution can be improved by observations with multiple telescopes, called stereo mode. I tested the data-acquisition system for the CANGAROO 3rd telescope and the triggering system that brought stereo capability to this telescope as the primary operator. In the end, **I successfully installed the system in the telescope in Australia, analyzed the first data of a well-known bright source, and confirmed the signal detection.** It was the first big success in my research career, and the project enabled me to understand both the hardware and software to operate the telescope. I also conducted remote support for onsite observers when there is trouble in telescope operation.

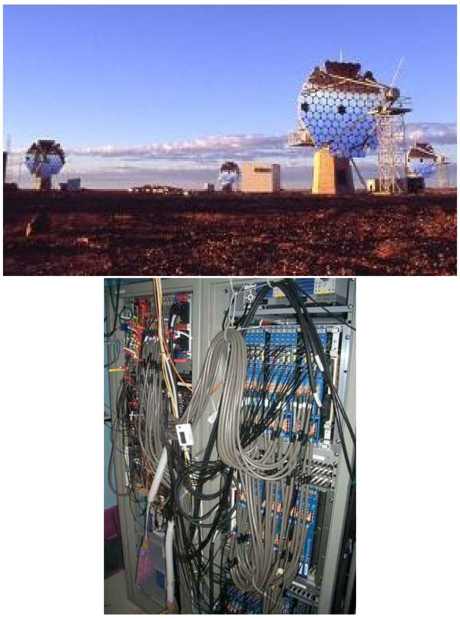


Figure 4: Four cherenkov telescopes of the CANGAROO III project in south Australia, and the data-taking system including ADCs, TDCs and Front-end modules I installed in the 3rd telescope.

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