

Cume #474
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Welcome to your Thanksgiving appetizer cume! You will have received the corresponding paper, [Das et al. \(2023\)](#) prior to the receiving this exam. Herein, you will find questions on that paper and related topics.

There are 14 questions/subquestions with 47 points possible. A score of 33 points or more will warrant an automatic pass.

In reading the paper, I do not suggest that you read it linearly from front to back. First, focus most on the main text and not the Appendices. For this particular paper, I might suggest reading the Abstract; peruse the figures and read the captions, keeping an eye out for which figures might include key results highlighted in the Abstract; read Section 4; skim Section 2 without getting too bogged down in the equations; and then focus on Section 3.

As a reminder, references beyond this paper, notes, or communication (other than with me) are NOT permitted during this exam. **Online resources, including AI-driven tools such as ChatGPT, are strictly forbidden.** You are permitted to use the basic functions of a calculator, i.e., not graphing or information stored prior to the exam. If you need a calculator that is not on your, please ask to borrow one; we have them available and phones should be turned off and put away during the exam.

Please make sure your writing is legible. As a general rule, I try to assign partial credit for good efforts, but I *cannot if the writing is illegible*. Also, please show all work and do attempt each problem, showing your thought process even if you can't solve it completely. Note that most questions have multiple parts, so make sure you answer the entire problem.

If anything needs clarification, please drop by my office in AY 205 or email me (jnb@nmsu.edu).

Possibly relevant information:

$$\begin{aligned}k_B &= 8.6 \times 10^{-5} \text{ eV/K} = 1.38 \times 10^{-16} \text{ erg / K} \\m_p &= 1.673 \times 10^{-24} \text{ g} \\M_\odot &= 1.988 \times 10^{30} \text{ kg} \\G &= 6.674 \times 10^{-11} \text{ m}^3 / (\text{kg s}^2) \\1 \text{ pc} &= 3.08 \times 10^{16} \text{ m}\end{aligned}$$

1) (**Remember**) This paper attempts to measure the thermal Sunyaev-Zel'dovich effect. In 1-2 sentences *plus* a drawing, describe what is meant by thermal Sunyaev-Zel'dovich effect *without* using the phrase 'inverse Compton scattering'. (4 pts)

The thermal Sunyaev-Zel'dovich effect is caused by photons from the CMB (1 pt) being upscattered to higher energies by energetic particles of hot gas (1 pt).

Drawing should show both motions of gas particles (1 pt) and photons coming in and somehow leaving with higher energy than upon entering the parcel of gas (1pt).

2. The measurements herein employ stacking techniques to measure the Compton y parameter.

2a) (Understand) In what situations is it useful to ‘stack’ a signal (in 1-2 sentences)? (2 pts)

Stacking is done to try and detect a signal (1 pt) among data where any potential is below the noise level (1 pt). Alternatively, one could analyze the ensemble properties of objects where individual detections may be significant, but the stacked signal is more so. (Accept either)

2b) (Understand) Describe, in 1-2 sentences, one method of stacking either used in this paper or in another work you are familiar with. (2 pts)

In this study, the authors average the Compton y signal in regions projected on the sky around locations of known galaxies, which are in turn binned by their stellar mass. (1 pt for averaging a signal; 1 pt for the binning; most stacking experiments are variations on this theme)

2c) (Remember/Apply) Das et al. use a sample of galaxies with photometric redshifts for their stacking experiment. What is a typical error on z_{phot} and how (qualitatively) do errors in z_{phot} impact the stacking experiment results? (Hint: What happens if z_{phot} is an overestimate? What about an underestimate?) (5 pts)

A typical error on photometric redshifts is $\sigma(z_{\text{ph}}) = 0.1$. (1 pt for an attempt; 1 pt for something less than 1 and greater than 0.001) Errors in z_{phot} primarily affects the angular diameter distance assigned to each galaxy and, thus, the angular size on the sky corresponding to physical distances around the galaxies. Inferred physical properties of the galaxies, such as stellar mass and halo mass, are also affected. (2 pts for physical distances; physical properties not required) For the results, overestimates in the redshifts translate to increased angular diameter distances and decreased θ_i in Equations 1, 2, and 3. In this case, smaller regions around these galaxies would be averaged in Compton y for some fixed physical radius. (1 pt) These stacks would be interpreted as representing a larger physical distance than they should. If the general trend shown in the bottom-left panel of Figure 5 is valid, this would boost the signal at larger radii in the stack. (1 pt)

The reverse would be true for underestimates.

2d) (Apply) The angular diameter distance may be approximated as follows:

$$d_A \approx \frac{c}{H_0} z \left(1 - \frac{3 + q_0}{2} z \right)$$

Where $q_0 = \Omega_{r,0} + \frac{1}{2}\Omega_{m,0} - \Omega_{\Lambda,0}$.

Given your typical error quoted for part (c) above, what would be the corresponding error in angular diameter distance at the median redshift (see Figure 3) of their galaxy sample? You may

use either concordant cosmological parameters or those adopted and provided in the paper. (5 pts)

Propagation of error (2 pts):

$$\sigma(d_A) = \frac{c}{H_0} \sigma(z_{ph}) - \frac{c(3 + q_0)}{H_0} z \sigma(z_{ph})$$

Value of q_0 for concordant cosmological parameters ($\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$): -0.55 (1 pt for reasonable values; 1 pt for plugging in)

Median $z_{ph} \sim 0.2$, so $\sigma(d_A) \sim 228$ Mpc. (1 pt for follow-through)

2e) (Analyze/Evaluate) How might the results shown in Figure 5 be affected by such errors? Hint: one approach might be to calculate the angular diameter distance and then the fractional error. (3 pts)

Given that $d_A \sim 700$ Mpc at $z=0.2$, this is a fractional error of ± 0.3 , which means points at $1 R_{200}$ would be contaminated by signal between 0.7 and $1.3 R_{200}$. Given the bin sizes of their annuli, redshift uncertainty is likely not a major issue with the analysis unless some very large systematic bias to higher or lower redshifts is present. (1 pt for some quantitative statement relating error to physical distances plotted there; 2 pts for assessment backed by logic)

3a) (Analyze) Referring to the authors' main conclusions in Section 4, in which panel of which figure can we see the corresponding data leading to their Conclusion 2 (deviation from self-similarity)? Describe specifically what we should look for to see the result described, such as points at particular values and data included on the plot for comparison. (3 pts)

This result is shown in the right panel of Figure 6. (1 pt) The two fits to their data (green and red lines) each have steeper slopes than that implied by the self-similar model (blue dotted line). (2 pts).

3b) (Analyze) Referring to the authors' main conclusions in Section 4, in which panel of which figure can we see the corresponding data leading to their Conclusion 3? Describe specifically what we should look for to see the result described, such as points at particular values and data included on the plot for comparison. Note that two results are described here: 1) the baryon-sufficiency of certain galaxies and 2) a nonmonotonic trend. (3 pts)

This result is shown in the Figure 7. (1 pt) The 'sufficiency' result apparently comes from the fact that the error bars of their measurement at $\sim 10^{11} M_\odot$ extend beyond the horizontal dotted line, which corresponds to the cosmic baryon fraction. (1 pt). The 'nonmonotonic' result arises from the black circles going up then down. (1 pt)

4) (Evaluate) Focusing now on Figure 7, the authors report a 'nonmonotonic behavior' of baryon fraction as function of stellar mass. What is your assessment of the robustness of this claim? (3 pts)

First off, one could draw a horizontal line through the data that was contained well within all of the vertical error bars. Second, the errors are certainly correlated, as the horizontal error bars have substantial overlap, so galaxies are being double counted across the bins. I am highly skeptical of this claim. (1 pt for something about error bars; 2 pts for some logical assessment; deduct 1 pt if they do not make a definitive judgement either way)

5a) **(Create)** If you were trying to build upon this study, what different observational datasets would you desire to improve upon its results, e.g., the parameter space covered or the significance of certain measurements? Note, you don't have to name particular surveys, just the salient desired features of the datasets and, importantly, how they translate to better measurements of the tSZ effect (i.e., looking for a bit more precise language here than occurs in the last paragraph of the paper). (4 pts)

For one the sky coverage of ACTPol is fairly small, so an all-sky survey survey like Planck would be ideal if it had the resolution of ACTPol or better. This would enable us to leverage wide-field spectroscopic surveys, such as the SDSS or DESI, from which to select many, many more galaxies to stack. This will greatly increase the significance of SZ signal detection. In addition, such spectroscopic surveys provide much higher redshift precision, enabling better constraints on physical distances. Lastly, improving the angular resolution of these CMB maps enable us to stack on smaller regions around, e.g., less massive galaxies with smaller virial radii. (2 pts for each feature; 2 features named for full credit)

5b) **(Apply/Analyze)** The authors mention angular resolution of the SZ map as an important attribute of the mm-wave data. What angular resolution (in arcsec) would be desired to have multiple (say 3) sampling bins within R_{200} of a galaxy in the lowest mass bin from the Das et al. study? Note that Table 1 lists the R_{200} for each mass bin, and you can use your angular diameter distance from Question 2e. (4 pts)

From Table 1, $R_{200} = 185$ kpc for the lowest mass bin (centered on $10^{9.9} M_{\odot}$). Since $d_A \sim 700$ Mpc at $z=0.2$, $1 R_{200} \sim 0.00024$ rad. At 206,265 arcsec/radian, $1 R_{200}$ corresponds to ~ 50 arcsec. For a beam size of $1/3 R_{200}$, one would like an angular resolution of ~ 17 arcsec. (1 pt for knowing to calculate d_A ; 1 pt for finding a value for R_{200} ; 1 pt for dividing R_{200} by d_A ; 1 pt for converting to arcsec)

6. The concept of 'baryon sufficiency' is somewhat subjective, and researchers from different communities have come to different conclusions about what baryon content might be deemed 'sufficient'.

6a) **(Understand)** What is meant by 'baryon sufficiency' in the context of this Das et al. 2023 study? Please include both what components 'baryons' comprises here and what makes them 'sufficient'. (2 pts)

In this study, 'baryon sufficiency' means that the baryon content measured in the study, which includes the stellar mass and hot gas mass derived from SZ measurements and some

assumptions, normalized by the halo mass is equal to or exceeds the cosmic baryon fraction. (1 pt for hot gas and stellar mass; 1 pt for cosmic fraction)

6b) **(Apply)** What is the virial temperature (see Equation 10b) corresponding to the mass bin with the peak baryon fraction in Figure 7? Assume values for the physical constants as given above and mean molecular mass $\mu = 1.3$ for ionized, metal-enriched gas. (3 pts)

The paper gives the following equation for virial temperature (1 pt for finding it):

$$T_{vir} = \frac{\mu m_p G M_{200}}{2 k_B R_{200}}$$

The mass bin with peak baryon fraction in Figure 7 is centered on $M_* = 10^{11} M_\odot$. (1 pt) Plugging in the corresponding M_{200} and R_{200} from Table 1 and the relevant constants gets a $T_{vir} \sim 3.3 \times 10^6$ K. (1 pt)

6c) **(Remember/Evaluate)** Observational studies using ultraviolet spectra of background quasars have reported detections of Mg II and H I around equally massive galaxies. What are the implications of these observations? What potential tensions would arise with the results and conclusions presented by Das et al. 2023? (4 pts)

Observations of Mg II and H I in the CGM might suggest the presence of cooler gas phases down to 10^4 K. (2 pts) If the full cosmic share of baryons is accounted for by the hot gas and stars alone, this would mean that cooler phases present would push galaxies ‘super-baryonic’ relative to the expected cosmic fraction. Furthermore, this complicates the assumption of all the gas being at the virial temperature in the halos, as the multiphase medium will likely contain a complicated mix of temperatures and densities. (2 pts for some reasoning stemming from a multiphase medium)