MEASURING THE MASS OF MISSING BARYONS IN THE HALO OF ANDROMEDA GALAXY WITH GAMMA-RAY OBSERVATIONS

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ABSTRACT

One of the biggest mysteries in the modern cosmology and galaxy formation is the hideout of the “missing baryons”. The leading theory of galaxy formation predicts that a huge amount of baryons resides around galaxies extending out to their virial radii in the form of diffuse and hot gas of $10^6 - 10^7$ K, which is also known as the major component of the circumgalactic medium (CGM). Studies by various groups via different techniques, however, have not reached a consensus on the role of CGM in accounting for the missing baryons, with the estimated contribution ranging from a minor fraction to enclosing the baryon budget of the galaxy. In this work we attempt to measure the mass of missing baryons in CGM with a novel method based on the gamma-ray observations of the extended halo of the Andromeda Galaxy. Since cosmic-ray particles that are generated inside the galaxy will eventually escape to the CGM, they will produce gamma-ray emission via the proton-proton collision with CGM. Different from some traditional measurements which are sensitive only to gas in certain specific temperature range, the hadronic gamma-ray flux is sensitive to baryonic gases in all phases and does not rely on the metallicity in the halo. Our result suggests that the total baryon mass contained within the virial radius is less than $(1.4 - 5) \times 10^{10} M_\odot$ according to the gamma-ray observation. It implies that the CGM of Andromeda Galaxy may not account for more than 30% of the missing baryons, but the result is subject to uncertainties from the diffusion coefficient of the CRs in the halo as well as the stellar mass and dark matter halo mass of the galaxy. This method will become more constraining provided better understandings on these issues and more sensitive gamma-ray telescopes in the future.

1. INTRODUCTION

While baryons are measured to account for 16% of the total mass of the universe according to the observations of the cosmic microwave background [Planck Collaboration et al. \(2018\)](#), more than half of this ordinary matter that makes up almost everything familiar to us is yet to be localised. Decades of efforts have been dedicated to the hunt for missing baryons, and various studies have pointed to the existence of a gaseous halo extending out to at least 50 kpc around Milky Way and external galaxies with stellar luminosity similar to that of Milky Way, containing a total gas mass of a few times $10^9 M_\odot$ within 50 kpc ([Anderson & Bregman 2010](#); [Dai et al. 2012](#); [Fang et al. 2013](#); [Miller & Bregman 2013, 2015](#); [Li et al. 2017](#)). The gas density of the CGM $n(r)$ as a function of galactocentric radius r could be depicted by the so-called β model ([Cavaliere & Fusco-Femiano 1976](#), or a modified β model, see [Bogdán et al. 2013](#)), i.e., $n(r) \propto n_0(1 + (r/r_c)^2)^{-3\beta/2}$ where n_0 is a normalization factor, r_c is the core radius with

the typical value $\lesssim 5$ kpc, and β determines the slope of the distribution. The value of β within 50 kpc is found to be around 0.5 in many Milky Way-like galaxies ([Li et al. 2018](#); [Bregman et al. 2018](#)). The total CGM mass within the virial radius is mainly determined by the gas distribution at larger radius. If the slope for gas distribution within 50 kpc holds out to a much larger radius ([Li et al. 2018](#)) or even the virial radius, the CGM mass in the halo would be significantly less than that needed to account for the missing baryons ([Miller & Bregman 2015](#); [Bregman et al. 2018](#)). On the other hand, if a flattening is present in the density distribution at comparatively small radius with, e.g., $\beta \lesssim 0.3$, the entire halo could contain all the missing baryon ([Gupta et al. 2012](#); [Faerman et al. 2017](#); [Das et al. 2019](#)). Therefore, the key to evaluate the total missing baryon in CGM is to determine the density distribution slope beyond 50 kpc.

The halo of our Milky Way Galaxy has the most abundant observational data among all the galaxies and it has been ex-

tensively studied by various groups. However, the observable signals from different galactocentric radius of the halo all add up together along our line of sights, making it difficult to reveal its true gas distribution. The Andromeda Galaxy (M31), the nearest sibling of our Milky Way Galaxy, is probably the best target to study this issue. Unlike the halo of our Galaxy, we can observe Andromeda's halo from the side view and hence are, in principle, able to measure the baryon density as a function of the galactocentric radius. Moreover, Andromeda's halo is more detectable than other Milky Way-like external galaxies due to its proximity, provided that their intrinsic emissivities are similar. Indeed, evidence of a massive gaseous halo around Andromeda has already been discovered (Grcevich & Putman 2009; Lehner et al. 2015, 2020). The inferred baryon mass in cold and warm gas is about $4 \times 10^{10} M_\odot$ within the virial radius assuming a 0.3 solar metallicity for the CGM (Lehner et al. 2020). Nevertheless, many traditional methods of probing CGM such as those with UV/X-ray emission lines or absorption lines do not work well beyond 50 kpc because of the weak emission of the tenuous gas and the high Galactic foreground noise, as well as the large uncertainty from the metallicity of the CGM.

The Andromeda Galaxy has been detected in GeV gamma-rays by the *Fermi* Large Area Telescope (LAT) (Abdo et al. 2010). The gamma-ray signal mainly arises from the proton-proton collisions between cosmic-ray (CR) protons accelerated in the galaxy and the interstellar medium. Referring to the situation in our Galaxy, CRs typically leave the galaxy quickly on a timescale of ~ 10 Myr, losing only a minor fraction of their energies, and diffuse into the extended halo of the galaxy. Those wandering CRs will inevitably interact with CGM and produce gamma-ray emission via the proton-proton collision (Feldmann et al. 2013; Taylor et al. 2014; Kalashev & Troitsky 2016; Liu et al. 2019), same as that responsible for gamma rays from the galactic plane of our Galaxy. The expected gamma-ray flux is approximately proportional to the amount of the gas residing in the halo and thus the gamma-ray signal from the halo contains the information of the total mass of the baryonic matter therein.

The diffuse gamma-ray emission was detected recently extending out to 200 kpc from the Andromeda galaxy (Karwin et al. 2019). The intensity for $\lesssim 10$ GeV gamma-rays is at the level of $\sim 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, while no significant emission is detected above 10 GeV, which poses a quite constraining upper limit of 95% confidence level (C.L.) $\lesssim 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ at ≈ 35 GeV. Note that, in addition to CR interactions, other sources, such as termination shocks of a galactic wind (Zirakashvili & Völk 2006) and dark matter annihilation (Karwin et al. 2020), could also contribute to the diffuse gamma-ray emission of the halo, and thus the measured gamma-ray flux or upper limit should be regarded as a conservative upper bound for CR-generated gamma-ray emission. This would enable us to constrain the gas distribution beyond 50 kpc by comparing the measured intensity to

the predicted gamma-ray intensity from the pp collision under different assumptions of the slope (i.e., β), and test whether a flattening of the gas distribution is allowed by the gamma-ray data.

The rest of the paper is organized as follows: in Section 2, we model the CR distribution in the halo of M31 and the gamma-ray production via the pp collision. We compare the predicted gamma-ray intensity with the measured one and derive the constraints on the gas distribution beyond 50 kpc. We discuss the result obtained in this work in Section 4 and summarize the paper in Section 5.

2. COSMIC-RAY DISTRIBUTION IN THE HALO OF M31 AND THE PIONIC GAMMA-RAY FLUX

The transport equation of CRs injected from a single point source is (Berezinsky & Gazizov 2006)

$$\frac{\partial n}{\partial t} = D(E) \nabla_{\mathbf{r}}^2 n - v_w \nabla_{\mathbf{r}} n + \frac{\partial [b(\mathbf{r}, E, t)]}{\partial E} + Q(E, t) \delta^3(\mathbf{r} - \mathbf{r}_s), \quad (1)$$

where $n(\mathbf{r}, E, t)$ is the differential density of CRs at time t and position $\mathbf{r}(r, \alpha, \lambda)$. We use a spherical coordinate system with the original point at the center of M31 and the z -axis being the normal of the disk (see Fig. 1). The first term on the r.h.s of the equation describes the diffusion of CRs caused by magnetic field turbulence with the diffusion coefficient $D(E)$. The most constraining gamma-ray data is at 35 GeV, so the most relevant proton energy is at 350 GeV since the energy of gamma-ray photon generated by the pp collision generally carries 10% of the parent proton's energy. We thus denote the diffusion coefficient at 350 GeV by D_0 and assume the form of the diffusion coefficient to be $D(E) = D_0 (E/350 \text{ GeV})^{1/3}$. The power index 1/3 arises from the assumption of a Kolmogorov-type turbulence in the halo of M31. It should be noted that the turbulence is not necessary to be Kolmogorov-like, but it would not influence our result significantly because the diffusion coefficient at 350 GeV is mainly dependent on the value of D_0 . The value of D_0 depends on the property (such as strength) of the turbulence. It is important for the CR spatial distribution in the halo and will be discussed in the later section.

The second term describes the advection of CRs caused by large-scale galactic wind with a speed v_w . Given no evidence for a large scale galactic wind in the halo of M31, we set $v_w = 0$ in the later calculation. The third term represents the energy loss of CRs due to the pp collisions in CGM, which is given by $b(E, \mathbf{r}) = 6 \times 10^{-7} (E/10^{12} \text{ eV}) (n(r)/10^{-3} \text{ cm}^{-3}) \text{ eV s}^{-1}$ (Liu et al. 2019).

The last term in the r.h.s. describes the injection of CRs from a point source located at $\mathbf{r}_s$. $Q(E, t)$ can be decoupled into a term related to the CR injection history $S(t)$ and a term describing the CR injection spectrum $Q_0(E)$, i.e., $Q(E, t) = S(t)Q_0(E)$. By doing so, we implicitly assume that the shape of the injection spectrum does not evolve with time. The CR injection rate is generally proportional to the star formation

Figure 1. The diagrammatic sketch of M31 coordinate system and the geometry between M31 and Earth. The M31 coordinate system is symmetric with respect to the axis perpendicular with disk plane. The angle between the north pole and Earth is 103° . The shaded rectangle is the element volume in the integration with the coordinate (r, α, ψ) . ϕ is the open angle between the earth and the element volume. The spherical triangular highlighted by purple dashes is used to calculate ϕ . d is the distance between the element volume and Earth and θ is the viewing angle, which can be calculated from r, ϕ, R using simple geometric relationship.

rate (Kennicutt 1998). We here employ the star formation history of M31 derived by Williams et al. (2017), where four sets of the stellar evolution model are considered backtracking the star formation history of M31 to 14 Gyr ago. All the models show a common feature that most of the star formation occurred prior to 8 Gyr ago. Here we refer to the Padova model, as is shown in Fig. 2, and normalize the star-formation history with the present-day star formation rate (SFR_{M31}) so that we have $S(t=0) = 1$.

Following Liu et al. (2019), we approximate the galactic plane as a disk of negligible thickness (i.e., $\mathbf{r}_s = (r_s, \pi/2, \psi)$) and CRs are uniformly injected from the disk. The injection spectrum is assumed to be in the form of a power-law function, i.e., $Q_0(E) = N_0(E/1 \text{ GeV})^{-s}$, where N_0 is the normalization factor and s is the injection spectral index of CRs. Given the present CR luminosity in M31 $L_{\text{CR},0}$, we have $\pi R_{\text{gal}}^2 \int_{1 \text{ GeV}}^{\infty} E Q_0(E) dE = L_{\text{CR},0}$ with the radius $R_{\text{gal}} = 27 \text{ kpc}$ being the radius of galaxy disk of M31. $L_{\text{CR},0}$ can be normalized to the CR luminosity of our Galaxy $L_{\text{CR,MW}} = 10^{41} \text{ erg s}^{-1}$ by $L_{\text{CR},0} = L_{\text{CR,MW}} \frac{\text{SFR}_{\text{M31}}}{\text{SFR}_{\text{MW}}}$. The measured gamma-ray spectral index of M31 galaxy is 2.4 ± 0.1 (Abdo et al. 2010). It repre-

Figure 2. Star formation history for M31 from present to 14 Gyr ago from Padova stellar evolution models (Williams et al. 2017). The gray band shows the error region.

sents the spectral index of the steady-state CR spectrum in the galaxy, since the gamma-ray spectrum from pp collision generally follows the spectrum of the parent protons in the GeV energy range. Note that the energy-dependent escape of CRs from the galaxy leads to a softening in the steady-state spectrum with respect to the injection spectrum, with the spectral index being modified to $s + \Delta$ where Δ is the slope of the diffusion coefficient. In our Galaxy, $\Delta \approx 1/3$ is inferred from the measurement of the primary-to-secondary CR ratio (Aguilar et al. 2016). If the ISM in M31 has the similar property to that of our Galaxy, we may infer $s \gtrsim 2$ for the CR injection spectrum in M31, which is also consistent with the prediction of the canonical diffusive shock acceleration theory (Bell 1978; Blandford & Eichler 1987). In the following calculation, we consider s in the range of 2.0 – 2.2.

An analytical formulae for the distribution of CR injected from a point source at $\mathbf{r}_s$ can be given by (Berezinsky & Gazizov 2006)

$$n(\mathbf{r}, E, t; \mathbf{r}_s) = \frac{\pi^{3/2}}{(2\pi)^3} \int_{t_s}^t dt' Q(\mathcal{E}', t') \frac{\exp[-(\mathbf{r} - \mathbf{r}_s)^2 / 4\lambda(E, t')]}{\lambda(E, t')^{3/2}} \times \exp\left[\int_{t'}^t dt'' \frac{\partial b(\mathcal{E}'', t)}{\partial \mathcal{E}''}\right]. \quad (2)$$

We assume the CR sources homogeneously distributed throughout the disk and integrate over the contribution of each point sources in the disk to obtain the present-time ($t = 0$) CR density at $\mathbf{r}$ by

$$N(\mathbf{r}, E) = \int n(t = 0, \mathbf{r}, E; \mathbf{r}_s) r_s dr_s d\psi \quad (3)$$

After obtaining CR distribution, the gamma-ray emissivity can be calculated by (Kelner et al. 2006),

$$J_\gamma(E_\gamma, \mathbf{r}) \equiv \frac{dN_\gamma}{dE_\gamma dt} = cn_s(\mathbf{r}) \int_{E_\gamma}^{\infty} \sigma_{pp} N(\mathbf{r}, E) F_\gamma\left(\frac{E_\gamma}{E}, E\right) \frac{dE}{E}, \quad (4)$$

where F_γ is the spectrum of the secondary gamma-ray in a single collision, $n_g(r)$ is the gas density distribution in the halo. The gas density distribution within 50 kpc is more or less known according to previous studies. The gas density of the halos of our Galaxy and Andromeda at a galactocentric radius ≈ 50 kpc is measured to be $\approx 10^{-4} \text{ cm}^{-3}$ through modelling the ram-pressure on the clouds and satellite galaxies (Salem et al. 2015; Grcevich & Putman 2009). We consider $n_0 \equiv n(50 \text{ kpc}) = 10^{-4} \text{ cm}^{-3}$ and $\beta_{\text{in}} = 0.5$ as the benchmark parameters. To include the uncertainties of parameters, we vary β_{in} in the range of $0.4 - 0.6$ and n_0 in the range $(0.5 - 1.5) \times 10^{-4} \text{ cm}^{-3}$. Additionally, following Anderson et al. (2013); Bregman et al. (2018) and etc, we limit the total CGM mass within 50 kpc in the range of $(2 - 5) \times 10^9 M_\odot$ by choosing appropriate combinations of β_{in} and the normalisation density n_0 (see Fig. 3). On the other hand, for the gas distribution beyond 50 kpc, a possible flattening or steepening in the distribution is taken into account. In other words, for $r \gg r_c$, we have the gas density distribution

$$n(r) = n_0 \begin{cases} \left(\frac{r}{50 \text{ kpc}}\right)^{-3\beta_{\text{in}}}, & r < 50 \text{ kpc} \\ \left(\frac{r}{50 \text{ kpc}}\right)^{-3\beta_{\text{out}}}, & r \geq 50 \text{ kpc} \end{cases} \quad (5)$$

Figure 3. The parameters of gas density profile within 50 kpc. The gray and purple region marks different constraints on parameters from observation. The darkest region with black border marks the final employed parameter region.

M31 is approximately 785 kpc away from Earth and the observation of its gamma-ray halo radius extends out to 200 kpc from the galactic center. Denoting the coordinate of Earth by $\mathbf{r}_E$, the distance between Earth and certain point in the halo $\mathbf{r}$ can vary markedly from place to place. We therefore need to consider the geometry of the system to calculate the distance $|\mathbf{r} - \mathbf{r}_E|$ and the gamma-ray flux received at Earth. As shown in the top panel of Fig. 1, for certain point (marked as the gray rectangular) in the halo, we set its coordinate as (r, α, ψ) . Utilizing the spherical triangle highlighted with purple dashed curve, we find out the open angle ϕ between Earth

and the point as $\cos \phi = \cos 103^\circ \cos \alpha + \sin 103^\circ \sin \alpha \cos \psi$, and obtain $|\mathbf{r} - \mathbf{r}_E|$ by $\sqrt{(\mathbf{r} - \mathbf{r}_E)^2} = \sqrt{r^2 + r_E^2 - 2rr_E \cos \phi}$. Now we can calculate the average gamma-ray flux intensity within an angular radius θ_c with respect to the center of M31 viewed from Earth in the celestial plane by

$$\Phi_\gamma(E_\gamma) = \frac{1}{2\pi(\cos 0.4^\circ - \cos \theta_c)} \int \frac{J_\gamma(E_\gamma, \mathbf{r})}{4\pi(\mathbf{r} - \mathbf{r}_E)^2} dV. \quad (6)$$

with $dV = r^2 \sin \alpha d\alpha d\psi dr$. The integration variables range in $r \in (5.5 \text{ kpc}, 250 \text{ kpc})$, $\alpha \in (0, \pi)$ and $\psi \in (0, 2\pi)$ with the restriction $\theta \in (0.4^\circ, \theta_c)$, where $\sin \theta = r \sin \phi / (\mathbf{r} - \mathbf{r}_E)$ (see the lower panel of Fig. 1). To average over the radiation within 100 kpc around M31, for instance, we have $\theta_c = 100 \text{ kpc} / 785 \text{ kpc} \approx 7.3^\circ$. The lower limit 0.4° for θ corresponds to a projected size of 5.5 kpc at a nominal distance of 785 kpc, which is the radial extension of M31 viewed by *Fermi*-LAT (Ackermann et al. 2017). In the analysis of the halo's diffuse gamma-ray emission by Karwin et al. (2019), they remove the emission within 0.4° (i.e., the emission of the galaxy itself) so we also exclude it from our calculation as well.

3. CONSTRAINT ON THE BARYON MASS IN THE HALO OF M31

Karwin et al. (2019) have obtained the average gamma-ray intensity of two annulus regions of $0.4^\circ - 8.5^\circ$ and $8.5^\circ - 14^\circ$ with respect to M31 center, corresponding to, namely, the spherical halo of radius 5.5 – 120 kpc and the far outer halo of radius 120 – 200 kpc respectively. The observed intensities of the two regions above 10 GeV are comparable. However, considering that the CR density and the baryon gas density are lower at larger radius, the expected pionic gamma-ray emissivity in the spherical halo is larger than that in the far outer halo. Therefore, the gamma-ray intensity of the spherical halo is more constraining and we will perform our analysis based on it. Note that although the projected size of the spherical halo is 120 kpc, the measured gamma-ray intensity also contains the information of the gas density beyond 120 kpc because the measured gamma-ray emission results from the superposition of all the emission in the line of sight passing through the entire halo (see Fig. 1).

Bearing in mind that the theoretical gamma-ray intensity should not exceed the measured one, we adjust the value of β_{out} to search the flattest gas density distribution from 50 kpc to 250 kpc allowed by the gamma-ray data. To do this, we scan the entire parameter space of β_{in} , β_{out} and n_0 for a given diffusion coefficient. Note that the gamma-ray emissivity is dependent not only on the gas density but also on the CR density. As mentioned earlier, the value of the diffusion coefficient at 350 GeV (i.e., D_0) is crucial to the latter. The standard nonlinear theory for CR diffusion (Yan & Lazarian 2008) predicts a diffusion coefficient of $10^{29} \text{ cm}^2 \text{ s}^{-1}$ at several hundreds GeV for the inner halo ($r \sim 10 \text{ kpc}$) of our Galaxy, which is comparable to that in the Galactic disk (e.g. Ptuskin 2006;

Figure 4. Predicted hadronic gamma-ray intensity from the spherical halo with different β_{out} . The purple band and circles are the observational result given by Karwin et al. (2019) for the spherical halo of M31. We take $s = 2.1$, $D_0 = 6 \times 10^{30} \text{ cm}^2/\text{s}$, $n_0 = 6.3 \times 10^{-5} \text{ cm}^{-3}$ and $\beta_{in} = 0.6$.

Strong et al. 2010; Genolini et al. 2015; Huang et al. 2020). The diffusion coefficient in the outer halo ($r \sim 100 \text{ kpc}$) is probably different given different environmental conditions such as the plasma density and the magnetic field strength. From an energetic point of view, the turbulence in the halo might be advected from the galactic disk, or might be driven locally by the differential rotation of the CGM of M31 as observed by XMM-Newton (Hodges-Kluck et al. 2016) and Planck (Tahir et al. 2019), or the proper motion of satellite galaxies in the halo of the galaxy with a velocity of a few $\times 100 \text{ km/s}$ (van der Marel et al. 2019; Grcevich & Putman 2009; Watkins et al. 2010). A further investigation on the property of the turbulence in M31’s halo is beyond the scope of this work, but we note that in some previous literature, the authors generally considered a roughly 10 – 100 times larger diffusion coefficient for the halo than that of the Galactic disk (Feldmann et al. 2013; Kalashev & Troitsky 2016; Liu et al. 2019). We follow this treatment and consider D_0 ranging from $10^{29} \text{ cm}^2 \text{ s}^{-1}$ up to $10^{31} \text{ cm}^2 \text{ s}^{-1}$ and note that a larger D_0 might be also possible if the turbulence in the halo is very weak and it would relax the obtained constraint.

The critical value of β_{out} is obtained when the theoretical gamma-ray intensity touches the lowest data point (i.e., the data point at 35 GeV) in the $E_\gamma - \Phi_\gamma$ plot. The obtained β_{out} corresponds to the maximum allowable baryon mass in the halo for each D_0 considered. In Fig. 4, we show an example that how the predicted gamma-ray intensity changes with the value of β_{out} . As listed in Table 1, for D_0 smaller than $2 \times 10^{30} \text{ cm}^2 \text{ s}^{-1}$, the gamma-ray flux generated within 50 kpc already exceeds the data point. This result may imply that the CR diffusion in the halo cannot be too slow and in turn put a constraint on the diffusion coefficient (and consequently the properties of the turbulence) in the halo. A flattening of the density profile beyond 50 kpc would be allowed only if a

Figure 5. Constraint from gamma-ray observation on the mass of the missing baryon related to M31 that can be explained by CGM. The blue band shows the influence of uncertainties in the model parameters of the gas distribution within 50 kpc. The pink band represents the uncertainties caused by the CR injection spectral index. The gray band shows the uncertainties caused by SFH. The blue solid curve shows the median value of the constraint.

Table 1. Constraints on the β_{out} for gas distribution beyond 50 kpc and the total baryon mass enclosed in the halo.

D_0 (cm ² /s)	β_{out}		$M_{<250 \text{ kpc}}$ ($M_{\odot}$)	
	a	b	a	b
2×10^{30}	∞	∞	$< 2 \times 10^9$	$< 2 \times 10^9$
3×10^{30}	∞	2	2.5×10^9	2.8×10^9
6×10^{30}	2	0.6	6.9×10^9	1.4×10^{10}
10^{31}	0.8	0.27	2.1×10^{10}	3.9×10^{10}

NOTE—The first column is the employed diffusion coefficient for 350 GeV CR protons. The second column shows the largest values of β for the gas density profile outside 50 kpc allowed by gamma-ray observation under different diffusion coefficients. The sub-column a and b indicate the parameters derived by setting $M_{<50 \text{ kpc}} = 5 \times 10^9 M_{\odot}$ and $2 \times 10^9 M_{\odot}$ respectively. The third column presents the corresponding baryon mass within 250 kpc given each β .

large diffusion coefficient $\gtrsim 6 \times 10^{30} \text{ cm}^2 \text{ s}^{-1}$ for the halo is employed. By translating the value of β_{out} to the mass of CGM, we find that, as presented in Table 1 and Fig. 5, the mass of CGM cannot exceed $(1.4 - 5) \times 10^{10} M_{\odot}$ baryons even with a quite large diffusion coefficient $D_0 = 10^{31} \text{ cm}^2 \text{ s}^{-1}$. The total mass of M31’s dark matter halo is likely in the range of $M_h = (1 - 2) \times 10^{12} M_{\odot}$ (Watkins et al. 2010; Veljanoski et al. 2014; Kafle et al. 2018), while the total stellar mass in An-

dromeda is about $M_* = (1 - 1.5) \times 10^{11} M_\odot$ (Tamm et al. 2012; Williams et al. 2017). If we take the median value of all the quantities, we will arrive at that the CGM can only explain no more than 30% of the missing baryon for $D_0 = 10^{31} \text{ cm}^2 \text{ s}^{-1}$. The result is consistent with the studies on the baryon fraction in Milky Way's halo by various authors (Miller & Bregman 2015; Salem et al. 2015; Li et al. 2017). If this conclusion can be generalized to other galaxies, it implies that a considerable fraction of the missing baryons probably resides somewhere beyond the virial radius of galaxies, such as in the filaments of the cosmic web (Eckert et al. 2015; de Graaff et al. 2019) or in the intracluster medium of galaxy groups (Lim et al. 2020). However, given the uncertainties of the estimation of M_h , M_* as well as the gas distribution within 50 kpc, the maximum percentage of missing baryons that the CGM of M31 can account for, constrained from the gamma-ray observation, ranges in (6 – 100)%. This prevents us from drawing a robust conclusion.

We note that Fig. 5 could be also regarded as a constraint on the diffusion coefficient or the property of the turbulence in the extended halo. Provided that the baryon budget in M31 could be well determined with other methods, it then implies that the diffusion coefficient cannot be too small or the turbulence cannot be too strong in the halo.

4. SUMMARY

To summarize, we attempted to utilize gamma-ray observations as a novel and independent probe of missing baryons in this work. Different from some traditional measurements through UV/X-ray observation which are sensitive to gas in certain specific temperature range, the hadronic gamma-ray flux is sensitive to baryonic gases in all phases and does not rely on their chemical composition. We pointed out that the constraint obtained with this method is dependent on the CR diffusion coefficient in the extended halo of the galaxy which is not clearly known at present. Considering a wide range of the diffusion coefficient (up to two orders of magnitude larger than the one of the Galactic plane), we arrived at that the total mass of baryons concealed in the halo of the Andromeda Galaxy could be at most $(1.4 - 5) \times 10^{10} M_\odot$ based on the gamma-ray observation of the extended halo of the galaxy. A flattening of the average CGM density profile beyond 50 kpc is allowed if a large diffusion coefficient in the halo $D_0 > 6 \times 10^{30} \text{ cm}^2/\text{s}$ (for 350 GeV cosmic rays) presents. The missing baryon fraction that can be accounted for by the CGM also depends on the total mass of the dark matter halo of Andromeda Galaxy and the total stellar mass in the galaxy, both of which are subject to uncertainties. Employing median values of these relevant quantities, we would get that the fraction is about 30% at most. But considering the uncertainties leads us to the conclusion that CGM may explain at most (6 – 100)% of the missing baryons related to the galaxy. To get a more accurate estimation of the missing baryon fraction in the CGM, we need a better understanding on the properties

of the turbulence in the extended galactic halo, a more accurate measurement on the total mass of the dark matter halo and stellar mass of Andromeda Galaxy. In addition, the next generation gamma-ray detectors may perform advanced observation on the diffuse gamma-ray flux or deeper upper limits of the halo of nearby galaxies, making gamma-ray emission a more accurate probe of the missing baryons of galaxies.

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