Measuring the Mass of Missing Baryons in the Halo of Andromeda Galaxy with Gamma-Ray Observation

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Missing Baryon Problem

Where is the rest?
- Warm-Hot Intergalactic Medium (WHIM) (filamentary gas)
- Within virial radius?
  Gas in circumgalactic medium (CGM)
Measure Baryon Mass in CGM

Methods:

- X-ray
  (Miller & Bregman 2015, Li et al. 2018…)
  - hot gas (>10^6 K)
  - within 50-70 kpc

- UV absorption lines
  (Prochaska et al. 2017, Lehner et al. 2020…)
  - cool/warm gas (10^4-10^5.5 K)
  - less dominated

- Thermal SZ effect
  (Planck Collaboration 2013, Lim et al. 2018…)
  - massive galaxy

+ Uncertainty of Metallicity M(Z) → M(H)
Gas Density Profile ~ Gamma-Ray Observation

Key: radial distribution of gas

Gas density profile: \( n = n_0 / (1 + (r/r_c)^2)^{-3\beta/2} \)

\( \beta \sim 0.5 \) <50kpc

Is there flattening of the gas density profile outside 50 kpc?

Gamma-ray ~ mass of baryonic matter

\( \Rightarrow \) Gas mass in Milky Way halo < 3 \times 10^{10} M_{\odot}

(Liu et al. 2019, Feldmann et al. 2013)

Advantages:

- Gas in all phases, hot+warm+cool
- Not rely on the metallicity
- Gamma-ray halo beyond 100 kpc (M31)
M31 Gamma-ray Halo

- Extended gamma-ray halo, about 200 kpc
- May be produced by dark matter
- CR-origin gamma-ray should not overshoot the observed upper limit

Karwin et al. 2019

**Spherical halo**

*FM31 Observed γ-ray Intensity*

*Tangent Radius [kpc]*

**Spherical Halo Flux**

*fit with a power law per energy band*

*fit with a power law with exponential cutoff*
Our Model

CR transport equation:

\[
\frac{\partial n}{\partial t} = D(E)\nabla_n^2 n - v_w \nabla_r n + \frac{\partial [b(r, E, t)]}{\partial E} + Q(E, t)\delta^3(r-r_s)
\]

\[
Q_0(E) = N_0(E/1 \text{ GeV})^{-s}
\]

\[
L_{CR,0} = \frac{L_{CR, MW, SFR_{ML}}} {SFR_{MW}}
\]

\(D_0 (E/350 \text{ GeV})^{1/3}\)

\(D_0 \sim \text{main uncertainty}\)

\(D_0 = 5e29-1e31 \text{ cm}^2/\text{s}\)

(Yan & Lazarian 2008, Hopkins et al. 2021)

\(v_w = 0\)

bubble-like structure

height = 6-7.5 kpc

(Pshirkov et al. 2016, Hopkins et al. 2020)
Our Model

By modeling the ram-pressure on the leading edge of the LMC gas disk
(Salem et al. 2015)

\[ n_p(R = 48.2 \pm 5 \text{ kpc}) = 1.1^{+0.44}_{-0.45} \times 10^{-4} \text{ cm}^{-3} \]

By stacking X-ray emitting halo of galaxies
(Anderson et al. 2013, Bregman et al. 2018)

<50 kpc, \( \beta \sim 0.5 \), \( M \sim 5 \times 10^9 \) \( M_{\odot} \)

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

Adjust \( \beta_{\text{out}} \) to find the flattest allowed gas density profile
Result

- Conservative spectral model independent upper limits
- $35 \text{ GeV}, 1.5 \times 10^{-5} \text{ MeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}$
- $D_0 < 4 \times 10^{30} \text{ cm}^2/\text{s}, M_{\text{gas}} < 6 \times 10^{10} \text{ M}_\odot$

- Uncertainty:
  - $D_0$
  - CR spectral index
  - Star formation history
  - $M(<50\text{kpc})$
Result

- model dependent upper limit
- $35 \text{ GeV}, 3 \times 10^{-6} \text{ MeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$
- $D_0 < 1 \times 10^{31} \text{ cm}^2/\text{s}, M_{\text{gas}} < 5 \times 10^{10} \text{ M}_\odot$

- $M_{250 \text{kpc}} = (0.6-2.4) \times 10^{12} \text{ M}_\odot$
- $M_{\text{star}} = (1-1.5) \times 10^{11} \text{ M}_\odot$
What We Can Learn

- Observation of extended gamma-ray halo can metallicity independently constrain the baryon mass in CGM.

- Combining with X-ray and UV observations, we can get a more complete picture of radial distribution of gas in CGM.

- This method will become more constraining provided better understandings on CR diffusion in CGM and more sensitive gamma-ray telescopes in the future.

\[
M_{\text{cool, warm, 230kpc}} = 7.2 \times 10^9 \frac{Z}{Z_{\text{sun}}}^{-1} M_{\text{sun}} \quad \text{(Lehner et al. 2020)}
\]

\[
Z = 0.2 Z_{\text{sun}} \rightarrow 3.6 \times 10^{10} M_{\text{sun}} \quad Z = 0.3 Z_{\text{sun}} \rightarrow 2.4 \times 10^{10} M_{\text{sun}}
\]

\[
M_{\text{hot, 250kpc}} = 3-4 \times 10^{10} M_{\text{sun}} \quad \text{(MW value, 0.3Z_{\text{sun}})} \quad \text{(Bregman et al. 2018)}
\]
### Backup slides

| $D_0$ (cm$^2$/s) | $M_{<50 \text{kpc}} = 5 \times 10^9 M_\odot$ | $M_{<50 \text{kpc}} = 2 \times 10^9 M_\odot$ |
|------------------|---------------------------------|---------------------------------|
|                  | $\beta_{\text{out}}$         | $M_{<250 \text{kpc}} (M_\odot)$ | $\beta_{\text{out}}$         | $M_{<250 \text{kpc}} (M_\odot)$ |
| Case 1           | $2 \times 10^{30}$            | $\infty$                        | $< 2 \times 10^9$            | $\infty$                        | $< 2 \times 10^9$            |
|                  | $3 \times 10^{20}$            | $\infty$                        | $2.5 \times 10^9$            | $2$                             | $2.8 \times 10^9$            |
|                  | $6 \times 10^{30}$            | $2$                             | $6.9 \times 10^9$            | $0.6$                           | $1.4 \times 10^{10}$         |
|                  | $10^{31}$                      | $0.8$                           | $2.1 \times 10^{10}$         | $0.27$                          | $3.9 \times 10^{10}$         |
| Case 2           | $1 \times 10^{30}$            | $\infty$                        | $< 2 \times 10^9$            | $1.7$                           | $3 \times 10^9$              |
|                  | $2 \times 10^{30}$            | $1.7$                           | $7.8 \times 10^9$            | $0.53$                          | $1.7 \times 10^{10}$         |
|                  | $3 \times 10^{30}$            | $0.83$                          | $1.95 \times 10^{10}$        | $0.27$                          | $3.9 \times 10^{10}$         |
|                  | $4 \times 10^{30}$            | $0.53$                          | $4.06 \times 10^{10}$        | $0.13$                          | $6.3 \times 10^{10}$         |
