The Milky Way Mass Constrained by Its Hot Gaseous Halo

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The Milky Way (MW) mass \(M_{\text{vir}}\) is a fundamental quantity in astronomy. Although it has been measured extensively, it is still uncertain to more than a factor of two due to limited number or spatial coverage of kinematic tracers\(^1,2\). Here we use a novel method to constrain \(M_{\text{vir}}\) based on the properties of the MW corona. We build a hydrostatic corona model with non-thermal pressure support and a physically-motivated density profile, and derive the temperature distribution, which depends on \(M_{\text{vir}}\). While the temperature profile decreases substantially with radius, the X-ray-emission-weighted average temperature \(T_{\text{em}}\) is quite uniform toward different sight lines, consistent with X-ray observations\(^3,4\). Using available measurements of \(T_{\text{em}}\), we find that \(M_{\text{vir}} = 1.60^{+1.35}_{-0.41} \times 10^{12} M_{\odot}\) assuming an Navarro-Frenk-White (NFW) total matter distribution. This estimate is independent of the uncertain total corona mass and the gas temperature at very large radii, and is on the high mass side of current measurements. Adopting a \(\beta\) model for the corona density distribution or a total matter distribution contributed by an NFW dark matter distribution and a central cold baryonic matter distribution leads to similar estimates of \(M_{\text{vir}}\). Non-thermal pressure support, which likely exists in the corona, leads to higher values of \(M_{\text{vir}}\).

During cosmic structure formation, dark matter and baryonic particles fall into existing gravitational potential wells. Within the virial radius (\(r_{\text{vir}}\)) of a gravitating halo, it is often assumed that particles are virialized and lose memory of initial conditions, reaching a dynamical equilibrium. Under this approximation, the halo matter distribution can be measured through the Jeans equation for collisionless particles\(^5\), such as dark matter, stars, globular clusters and satellite galaxies, and through the hydrostatic equilibrium (HSE) equation for collisional particles such as hot gas\(^6,7\). The former method has been used extensively, including to measure the MW mass \(M_{\text{vir}}\)\(^1,2\), while the latter has been used to measure the mass profiles of massive elliptical galaxies and galaxy clusters\(^6,7\).

X-ray observations of galaxy clusters often measure the radial temperature and density profiles of the hot halo gas up to about \(0.5r_{\text{vir}}\)\(^8\) and recently even up to \(r_{\text{vir}}\) in some systems\(^9\). Assuming spherical symmetry, hydrostatic masses \(M(< r)\) within a radius \(r\) can be determined from thermal pressure gradients via \(\rho^{-1}dP/dr = -GM(< r)/r^2\) (see Methods for the meanings of the

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symbols, and have been further used to constrain cosmological parameters. Hydrodynamic simulations suggest that non-thermal pressure support from radial and rotating bulk motions, turbulent motions, cosmic rays, and magnetic fields typically causes an underestimate of the real cluster mass by about 10 – 20%, but recent X-ray observations imply a substantially lower non-thermal pressure fraction \( f_{\text{nt}} \sim 6 – 10\% \), suggesting the potential importance of subtle microphysical processes such as physical and turbulent viscosity in dissipation and angular momentum transport.

Mounting multi-wavelength observations indicate that there exists a hot corona surrounding our MW, possibly extending to its virial radius and accounting for a substantial fraction of the missing baryons of the MW. However, X-ray observations of the MW corona have not yet been used to measure \( M_{\text{vir}} \), partly due to the low corona density and surface brightness. Furthermore, our special location near the center of the MW halo makes it very difficult, if possible, to measure the density and temperature gradients of the corona gas. Here we show that the available corona measurements, mainly the corona temperature, can already put reasonably good constraints on \( M_{\text{vir}} \). Throughout this paper, \( M_{\text{vir}} \) refers to the total mass enclosed within \( r_{\text{vir}} \), which is defined as the radius within which the mean matter density equals 200 times the critical density of the universe.

The virial theorem provides a very crude estimate of the corona temperature at \( r_{\text{vir}} \): \( T_{\text{vir}} \sim 5 \times 10^5 (M_{\text{vir}}/10^{12} M_\odot)^{2/3} \) K. At \( r < r_{\text{vir}} \), \( T \) further rises due to adiabatic compression and heatings by turbulence, shocks, stellar feedback and active galactic nucleus (AGN) feedback. However, if the gas temperature is too high, the MW gravity could not hold the gas for a given density distribution, leading to the corona expansion and a decrease in temperature. This argument is manifested in a generalized HSE equation \( dP/dr = -(1-f_{\text{nt}})G\rho M(<r)/r^2 \), where \( f_{\text{nt}} \) represents the impact of non-thermal pressure support, which may also be written as

\[
\frac{d \ln T}{d \ln r} - \frac{d \ln \rho}{d \ln r} = (1-f_{\text{nt}}) \frac{\mu m_\mu}{k_B T} \frac{G M(<r)}{r}.
\]

Following any disturbance on scale \( L \), the corona will return back to the HSE quickly after a sound crossing time \( t_s \equiv L/c_s \sim 4.6(L/1 \text{kpc})(T/2 \times 10^6 \text{ K})^{-0.5} \) Myr. We adopt the NFW profile for the MW total matter distribution and a physically-motivated density profile for the corona (see Methods). The radial temperature profile of the corona can thus be solved from the HSE equation.

We first consider models with the frequently-adopted MW mass \( M_{\text{vir}} = 10^{12} M_\odot \), corresponding to \( r_{\text{vir}} = 207 \) kpc, a concentration \( c = 6.36 \) according to Equation (8), and a scale radius \( r_s \equiv r_{\text{vir}}/c = 32.5 \) kpc (see Methods). The left panel of Fig. 1 shows radial profiles of thermal electron number density and temperature in five representative HSE models with varying values of \( r_2 \) from 100 to 300 kpc and \( f_{\text{nt}} \) from 0 to 0.2. Here \( r_2 \) is a key parameter in our corona density distribution (Methods). As \( r_2 \) increases, the hot gas is distributed more extendedly and its slope drops. According to Equation (1), the temperature slope increases, leading to an increase in the gas temperature in the inner region. Similarly, an increase in \( f_{\text{nt}} \) leads to a decrease in the gas
temperature in the inner region. Remarkably, in all these five models, the gas temperatures in the halo are typically less than the observed value of $T_{\text{obs}} \sim 2.2 \times 10^6$ K.

**Figure 1** Radial distributions of thermal electron number density (top) and temperature (bottom) in our models. **Left:** Five characteristic equilibrium models with $M_{\text{vir}} = 10^{12} M_\odot$. The dotted, short-dashed, and long-dashed lines refer to the hydrostatic models with $f_{\text{nt}} = 0$ and $r_2 = 100, 200,$ and $300$ kpc (see Methods for our physically-motivated corona density model), respectively. For typical values of $r_2$ between 100 and 300 kpc, the central gas temperature increases slightly with it. The solid line shows a model with a constant non-thermal pressure fraction $f_{\text{nt}} = 0.2$, which results in substantially lower gas temperatures compared to the corresponding hydrostatic model with $f_{\text{nt}} = 0$ and the same density profile. The dot-dashed line refers to an equilibrium model with $f_{\text{nt}} = 0.2$ at $r \leq 50$ kpc and 0 at larger radii, which has similar gas temperatures in the inner region as the model with a radially constant value of $f_{\text{nt}} = 0.2$. Note that the value of $f_{\text{nt}}$ does not affect our corona density model. The solid square and circle data points correspond to recent density estimates $^{18,19}$. **Right:** Five hydrostatic MW corona models with $f_{\text{nt}} = 0$, $r_2 = 200$ kpc, and $M_{\text{vir}} = 10^{12} M_\odot$ (solid), $1.25 \times 10^{12} M_\odot$ (dotted), $1.5 \times 10^{12} M_\odot$ (short-dashed), $1.75 \times 10^{12} M_\odot$ (long-dashed), and $2 \times 10^{12} M_\odot$ (dot-dashed) are presented. As $M_{\text{vir}}$ increases from $10^{12} M_\odot$ to $2 \times 10^{12} M_\odot$, the central gas temperature increases significantly from about $2 \times 10^6$ K to $3 \times 10^6$ K.

We explored the parameter space of our model and found that the gas temperature distribution is strongly affected by $M_{\text{vir}}$, as illustrated in the right panel of Fig. 1. As implied in Equation (1), $M_{\text{vir}}$ determines the gravitational potential well of the halo and thus significantly affects the
equilibrium gas temperature distribution, while its impact on our model density profile (Eq. 11) is negligible. As $M_{\text{vir}}$ increases from $10^{12} M_\odot$ to $2 \times 10^{12} M_\odot$, the central gas temperature roughly increases from $2 \times 10^6$ keV to $3 \times 10^6$ K. The radial density distribution of the corona, characterized by the model parameter $r_2$, plays a minor role in determining the derived equilibrium temperature distribution, as seen in the left panel of Fig. 1. Although the total corona mass has not yet been well constrained by observations, it has no impact on the derived temperature profile, as the HSE equation (Eq. 1) is scale free with respect to density.

Figure 2  Line-of-sight averaged gas temperature distribution $T_{\text{em}}$ in Galactic coordinates. **Left:** $T_{\text{em}}$ in a representative model with $M_{\text{vir}} = 1.60 \times 10^{12} M_\odot$, $f_{\text{nt}} = 0$, and $r_2 = 200$ kpc. $T_{\text{em}}(l, b)$ is weighed by 0.5–2.0 keV X-ray emission, and averaged along individual sight lines from the Earth to a distance of 240 kpc. The presented model results in a characteristic value of $T_{\text{em}}$ along $l = 90^\circ$ equal to the median temperature $2.22 \times 10^6$ K observed in ref. 4. The temperature is quite uniform along different sight lines, varying roughly within $T_{\text{em}} \approx 2.1 - 2.5 \times 10^6$ K and increasing slightly toward the Galactic Centre (GC). In reality, the gas temperature along the sight lines toward the GC region is expected to be significantly affected by Galactic feedback processes, such as the Fermi bubbles.

**Right:** Dependence of $T_{\text{em}}$ on $M_{\text{vir}}$. Here $T_{\text{em}}$ is shown as a function of Galactic longitude at three Galactic latitudes $b = 30^\circ$ (solid), $60^\circ$ (dotted), and $80^\circ$ (dashed). The top green, middle cyan, and bottom black lines refer to models with varying virial masses of the MW: $M_{\text{vir}} = 2 \times 10^{12} M_\odot$, $1.5 \times 10^{12} M_\odot$, $10^{12} M_\odot$, respectively. Default values of $f_{\text{nt}} = 0$ and $r_2 = 200$ kpc are adopted in all these models.

A comparison between the predicted halo gas temperature with the observed value can thus be used to constrain the MW mass $M_{\text{vir}}$. To this end, we adopt the Astrophysical Plasma Emission Code (APEC) to calculate the average gas temperatures $T_{\text{em}}$ along individual sight lines weighted by the 0.5 – 2.0 keV X-ray emission. We assume that the hot gas is optically thin and under collisional ionization equilibrium, and the gas metallicity is $Z = 0.3 Z_\odot$. The line-of-sight averaged gas temperature can be calculated as follows:

$$T_{\text{em}}(l, b) = \frac{\int_{\text{los}} n_e n_H T_e(T, Z) dR}{\int_{\text{los}} n_e n_H \epsilon(T, Z) dR},$$

(2)
where $\epsilon(T, Z)$ is the $0.5 - 2.0$ keV X-ray emissivity of the hot gas, and $l$ and $b$ refer to the Galactic longitude and latitude, respectively. The distance $R$ of each gas element to the Earth is related to its Galactocentric distance $r$ via $r^2 = R^2 + R^2_\odot - 2R_\odot R \cos l \cos b$, where $R_\odot = 8.5$ kpc is the distance between the Earth and the GC. Along each line of sight, the integration in Equation (2) is done to a distance of 240 kpc from the Earth.

Although the gas temperature $T(r)$ drops substantially along the radial direction in our models (see Fig. 1), the line-of-sight averaged temperature $T_{em}$ varies very little across different sight lines (typically $< 10\%$ at $|b| > 30^\circ$), as clearly illustrated in Fig. 2. This is merely due to the fact that $T(r)$ is spherically-symmetric and $R_\odot$ is very small compared to the halo size, and this is also consistent with the observed fairly uniform gas temperature $T_{obs} \sim 0.2$ keV in both Suzaku$^3$ and XMM-Newton observation$^4$. The right panel of Fig. 2 shows the variations of $T_{em}$ as a function of Galactic longitude and latitude for three models with different MW masses. It is clear that, while $T_{em}$ varies very little with Galactic latitude and longitude, it increases significantly with $M_{vir}$. Our calculations thus indicate that the observed fairly uniform gas temperature toward different sight lines does not preclude substantial radial variations in the corona temperature distribution.

To constrain the MW mass, we use the predicted value of $T_{em}$ along $l = 90^\circ$, which as illustrated in Fig. 2, is independent of the value of $b$ and is roughly the mean value of $T_{em}$ along all sightlines. We first consider models with $f_{nt} = 0$ and take $M_{vir}$ and $r_2$ as the two main model parameters. For any given value of $r_2$, we determine the value of $M_{vir}$ so that the resulted $T_{em}$ along $l = 90^\circ$ equals $T_{obs}$ derived in XMM-Newton observation$^4$, which typically varies between the lower-quartile temperature $2.01 \times 10^6$ K and upper-quartile temperature $2.64 \times 10^6$ K. We assume that Galactic feedback processes have a substantial impact on the halo gas distribution, resulting in $100 \lesssim r_2 \lesssim 300$ kpc (Methods). Such a gas density distribution is roughly consistent with the $\beta$ model ($\rho \propto r^{-1.5}$) suggested by observations$^{16,23}$ at Galactocentric distances of a few tens to $\sim 200$ kpc. As $r_2$ increases, the equilibrium gas temperature increases, resulting in a decrease in the derived value of $M_{vir}$, as clearly shown in Fig. 3. Considering a baseline model with $T_{obs} = 2.22 \times 10^6$ K$^4$ and $r_2 = 200$ kpc and the uncertainties in both $T_{obs}$ and $r_2$ described above, we derive $M_{vir} = 1.60^{+1.35}_{-0.41} \times 10^{12} M_\odot$. As shown in Fig. 3, non-thermal pressure support leads to even higher values of $M_{vir}$, and for the baseline model, $M_{vir}$ increases by $\sim 20\%$ and $47\%$ if $f_{nt} = 0.1$ and 0.2, respectively.
Figure 3  The MW mass constrained by the X-ray-measured corona gas temperature. Assuming that the $0.5 – 2.0$ keV X-ray emission weighted average temperature $T_{em}$ along $l = 90^\circ$ equals a given observed gas temperature $T_{obs}$, the MW virial mass is derived and shown as a function of $r_2$. The solid line represents the case with $T_{obs} = 2.22 \times 10^6$ K, the median temperature measured by $0.5 – 2.0$ keV XMM-Newton observations$^4$. The short-dashed and dotted lines refer to the upper-quartile and lower-quartile temperatures measured by ref.$^4$: $T_{obs} = 2.64 \times 10^6$ K, $2.01 \times 10^6$ K, respectively. The long-dashed and dot-dashed lines show the impact of non-thermal pressure support on the derived value of $M_{vir}$ with $f_{nt} = 0.1$ and 0.2, respectively.

For the baseline model, we have $M_{vir} = 1.60 \times 10^{12} M_\odot$, and subsequently, $r_{vir} = 242$ kpc, $c = 6.07$, $r_s = 39.8$ kpc, and a local dark matter density at the solar position of $0.22$ GeV cm$^{-3}$. The total hot gas mass within $r_{vir}$ is $M_{hot} = 3.8 \times 10^{10} M_\odot$. Taking the cold baryonic mass of the MW to be $M_{cold} \sim 6 \times 10^{10} M_\odot$,$^{126}$ the total baryonic mass within $r_{vir}$ is $M_{bary} \sim 9.8 \times 10^{10} M_\odot$. However, according to the cosmic baryon fraction $f_b = 0.15$,$^{27}$ the MW’s baryonic allotment should be $M_b = f_b M_{vir} = 2.51 \times 10^{11} M_\odot$. Therefore, the baryonic mass missing within $r_{vir}$ is $M_{mbary} \sim 1.53 \times 10^{11} M_\odot$ (about 61%), potentially residing beyond $r_{vir}$ or in a cool phase in the halo.

The derived MW mass is independent of the outer gas temperature $T_{out}$. In our model, the
The gas temperature is solved inwards according to Equation (1) starting from the outer boundary \( r_{\text{out}} = 300 \text{ kpc} \) with \( T = T_{\text{out}} \), which mainly affects the gas temperature in the outer region (see Extended Data Fig. 1). However, \( T_{\text{em}} \) is mainly determined by the inner region \( R_\odot < r < 50 \text{ kpc} \). For a representative sight line toward \( l = 90^\circ \) in our baseline model, \( \sim 95\% \) of the 0.5 – 2.0 keV X-ray surface brightness is contributed by this region. Within this region, Equation (4) leads to \( P(r) = P(r_{\text{out}}) + \int_r^{r_{\text{out}}} (1 - f_{\text{int}}) \rho \frac{d\phi}{dr} dr \approx \int_r^{r_{\text{out}}} (1 - f_{\text{int}}) \rho \frac{d\phi}{dr} dr \) as \( P(r_{\text{out}}) \) is typically lower than \( P(r) \) by two orders of magnitude due to the fast decreasing of the gas density at large radii. The adopted value of gas metallicity has nearly no impact on \( M_{\text{vir}} \) either. For the baseline model, higher values of \( Z = 0.5 Z_\odot \) and \( Z_\odot \) lead to a negligible increase in \( M_{\text{vir}} \) by 0.07% and 0.12%, respectively.

We also applied our calculations to the \( \beta \) model of the corona density distribution (Methods). At \( r \gtrsim 1 \text{ kpc} \), the \( \beta \) model with a core radius \( r_c = 0.1 \text{ kpc} \) is essentially the same as the power-law profile (\( \rho \propto r^{-1.5} \)) frequently used in X-ray observations.\(^{10,25}\) As illustrated in Extended Data Fig. 2, this model leads to an equilibrium temperature profile decreasing inwards in the inner region (\( r \lesssim 40 \text{ kpc} \)), indicating that the temperature profile in this model is not isothermal as assumed in many observations.\(^{16}\) Equation (1) shows that the temperature slope \(-d\ln T/dr \ln r \) is determined by \( M(<r) \), \( T \), and the gas density slope \(-d\ln \rho/dr \). When the density slope increases, the temperature slope decreases and even becomes negative, thus leading to inward-decreasing temperature profiles. To match the characteristic \( T_{\text{em}} \) along \( l = 90^\circ \) with \( T_{\text{obs}} = 2.22 \times 10^6 \text{ K} \), the derived MW mass in this model is \( M_{\text{vir}} = 7.30 \times 10^{12} M_\odot \), much higher than current measurements of \( M_{\text{vir}} \).\(^{12}\) If the core radius is larger (see Extended Data Fig. 2), \( M_{\text{vir}} \) typically decreases from \( M_{\text{vir}} = 2.08 \times 10^{12} M_\odot \) if \( r_c = 20 \text{ kpc} \) to \( M_{\text{vir}} = 1.41 \times 10^{12} M_\odot \) if \( r_c = 30 \text{ kpc} \), consistent with the results from our density model.

The total matter distribution in the MW affects the gas temperature and density distributions, and is assumed to be an NFW profile in our default models presented above. However, baryonic physics may play a complicated role in shaping the total matter distribution, potentially causing contraction or expansion of the dark matter halo.\(^{29,31}\) Here we consider a case where the total matter distribution is contributed by an NFW dark matter distribution with the virial mass \( M_{\text{vir, dm}} \) and a cold baryonic matter (stars and cold gas) distribution with \( M_{\text{cold}} = 6 \times 10^{10} M_\odot \) (Methods). This matter distribution is more centrally peaked than the NFW profile, potentially leading to a more centrally peaked corona density distribution with \( r_1 < 0.75 r_s \) (see Methods and Extended Data Fig. 3). As \( r_1 \) increases from 0 to 0.3 \( r_s \), the gas temperature in the inner region rises quickly. Despite possible feedback heating processes in the GC,\(^{30,32}\) X-ray observations toward many regions near the GC indicate that the hot gas temperature is around 0.3 keV.\(^{33,19}\) Considering this constraint, we consider models with \( 0 < r_1 < 0.3 r_s \) and \( r_2 = 200 \text{ kpc} \), and the dark matter virial mass required by \( T_{\text{em}} = 2.22 \times 10^6 \text{ K} \) along \( l = 90^\circ \) varies from \( M_{\text{vir, dm}} = 2.13 \times 10^{12} M_\odot \) if \( r_1 = 0 \) to \( 1.03 \times 10^{12} M_\odot \) if \( r_1 = 0.3 r_s \) (Extended Data Fig. 4), consistent with the results from our default models.

Our derived value of \( M_{\text{vir}} = 1.60^{+1.35}_{-0.41} \times 10^{12} M_\odot \) when \( f_{\text{int}} = 0 \) is consistent with the
estimates of $M_{\text{vir}} = 0.5-2 \times 10^{12} M_\odot$ in the literature but on the high mass side\cite{12,34,35}. If $f_{\text{nt}} = 0.1$, $M_{\text{vir}} = 1.92^{+1.66}_{-0.51} \times 10^{12} M_\odot$ is even higher. Our results imply that the Magellanic Clouds and the Leo I dwarf spheroidal are bound to the MW\cite{36,37}, a large fraction of the baryons are missing in the MW, and the “too-big-to-fail” problem still poses a serious challenge to the cold dark matter theory\cite{38}. The error bars in $M_{\text{vir}}$ here come from the uncertainties in $T_{\text{obs}}$ and the corona density profile. Zoom-in cosmological simulations of MW-like galaxies are expected to improve our understanding of the corona temperature and density distributions, potentially shrinking the error bars. The SRG/eROSITA telescope is currently taking a sensitive full-sky X-ray survey with X-ray spectra taken automatically along all the sightlines, which may statistically improve the measurement of $T_{\text{obs}}$ and its variations with Galactic latitude and longitude, increasing the accuracy of the X-ray constraint on $M_{\text{vir}}$. 
Methods

Hydrostatic equilibrium with non-thermal pressure support. We assume that the hot circum-galactic medium of our Galaxy is spherically symmetric with respect to the GC, and roughly in hydrostatic equilibrium extending from at least the solar position out to large radii near the virial radius. Including the potential impact of non-thermal pressure support, the gas in hydrostatic equilibrium satisfies

\[ \nabla P = -(1 - f_{\text{nt}}) \rho \nabla \Phi, \]  

where \( \rho \) and \( P \) are the gas density and thermal pressure respectively, \( f_{\text{nt}} \) is the non-thermal pressure fraction, and \( \Phi \) is the gravitational potential of our Galaxy. The gas pressure \( P \), temperature \( T \) and thermal electron number density \( n_e \) are related via the ideal gas law:

\[ P = \frac{\rho k_B T}{\mu m_\mu} = \frac{\mu_e n_e k_B T}{\mu}, \]

where \( k_B \) is Boltzmann’s constant, \( m_\mu \) is the atomic mass unit, and \( \mu = 0.61 \) and \( \mu_e = 1.17 \) are the mean molecular weight per particle and per electron, respectively.

The MW gravitational potential. In our default model, we assume that the total matter distribution in the Galactic halo follows an Navarro-Frenk-White (NFW) profile:

\[ \rho_{\text{tot}}(r) = \frac{M_0/2\pi}{r(r+r_s)^2}, \]

where \( r_s \) is a scale radius and \( M_0 \) is a characteristic mass. The values of \( r_s \) and \( M_0 \) can be derived from the virial mass \( M_{\text{vir}} \) and the concentration \( c \equiv r_{\text{vir}}/r_s \) of the matter distribution:

\[ r_s = \frac{1}{c} \left( \frac{3M_{\text{vir}}}{4\pi \rho_c \Delta} \right)^{1/3}, \]

\[ M_0 = \frac{M_{\text{vir}}}{2[\ln(1+c) - \frac{c}{1+c}]]. \]

Here the virial radius \( r_{\text{vir}} \) is defined as the radius (often denoted as \( r_{200} \)) within which the mean matter density equals \( \rho_c \Delta = 200 \rho_c \), where \( \rho_c = 3H_0^2/8\pi G \) is the critical density of the universe, \( G \) is the gravitational constant, \( H_0 = 100h \) km s\(^{-1}\) Mpc\(^{-1}\) is the Hubble constant, and \( h = 0.7 \). \( M_{\text{vir}} \), often denoted as \( M_{200} \), is thus the total mass enclosed within the virial radius \( r_{\text{vir}} \). For a given value of \( M_{\text{vir}} \), we determine the concentration \( c \) according to the correlation between \( c \) and \( M_{\text{vir}} \) derived from cosmological simulations:

\[ c = 5.74 \left( \frac{M_{\text{vir}}}{2 \times 10^{12} h^{-1} M_\odot} \right)^{-0.097}. \]
The gravitational potential contributed by the NFW matter distribution is
\[ \Phi(r) = -\frac{2GM_0 \ln(1 + r/r_s)}{r/r_s}. \] (9)

Baryonic physics is expected to affect the dark matter distribution, potentially causing contraction or expansion of the dark matter halo\(^{28-30}\). In addition to our default NFW total matter distribution described above, we also consider a model where the MW total matter is contributed by an NFW dark matter distribution with the virial mass \( M_{\text{vir, dm}} \) and a cold baryonic matter distribution with \( M_{\text{cold}} = 6 \times 10^{10} M_\odot \). For simplicity, we adopt a spherically-symmetric Hernquist profile\(^{42}\) to approximate the spatial density distribution of the cold baryonic matter, which corresponds to a gravitational potential
\[ \Phi_{\text{cold}} = -\frac{GM_{\text{cold}}}{r + a}. \] (10)

The parameter \( a \) is chosen to be \( a = 1.5 \) kpc so that the resulting gravitational acceleration \( g_{\text{cold}} \equiv d\Phi_{\text{cold}}/dr \) fits reasonably well with that in the more realistic cold baryonic matter model in ref\(^{26}\) (described in detail in ref\(^{22}\)) along the MW rotation axis at \( r \gtrsim 5 \) kpc (see Extended Data Fig. 5). The central cold baryonic matter in the axisymmetric two-dimensional (2D) model\(^{26}\) includes a thin stellar disk, a thick stellar disk, a stellar bulge, an atomic gaseous disk, and a molecular gaseous disk. As described in ref\(^{21}\), the gravitational acceleration within the central \( \sim 10 \) kpc is dominated by the cold baryonic matter in this model.

**Our physically-motivated model for the MW corona.** We assume that the hot corona gas in the MW halo follows an analytic density distribution\(^{43}\)
\[ \rho(r) = \frac{\rho_0}{(r + r_1)^\alpha(r + r_2)^{3-\alpha}}. \] (11)

where \( \rho_0 \) is a constant normalization, \( r_1 \) represents an inner core whose value is chosen to be \( r_1 = 3r_s/4 \) (unless stated otherwise) as suggested by cosmological simulations\(^{44}\), and \( r_2 \) represents the impact of Galactic feedback processes on the halo gas distribution\(^{44-45}\). In this paper, we mainly consider models with \( \alpha = 1 \). When \( \alpha = 1 \) and \( r_2 = r_s \), Equation (11) reduces to a cored NFW distribution, representing the case without any impact of feedback processes. AGN and stellar feedback processes in the Galaxy are expected to deposit energy and momentum into the gaseous halo, heating the gas and pushing the halo gas outward. Thus a realistic gas distribution in the halo is expected to have \( r_2 > r_s \). Our density distribution is relatively flat at \( r \ll r_1 \), and scales roughly as \( \rho \propto r^{-1} \) at \( r_1 \ll r \ll r_2 \). At sufficiently large radii \( r \gg r_2 \), the gas density distribution approaches to the reduced NFW distribution: \( \rho(r) \propto r^{-3} \), guaranteeing that distant regions are not substantially affected by feedback processes.

We determine the normalization of the gas density profile with the electron number density \( n_e = 9.3 \times 10^{-5} \) cm\(^{-3} \) at \( r = 59 \) kpc, which is the average density from two recent estimates based on the ram-pressure stripping models of Milky Way satellites: \( n_e = 6.8-18.8 \times 10^{-5} \) cm\(^{-3} \).
at $r = 70 \pm 20$ kpc from ref\cite{18} and $n_e = 3.4-8.0 \times 10^{-5} \text{ cm}^{-3}$ at $r = 48.2 \pm 2.5$ kpc from ref\cite{19}. We note that the density normalization has no impact on the derived gas temperature profile, as Equation (3) is scale free with respect to density when solving for $T$.

Using Equations (3), (4), (9), and (11), we solve the gas temperature profile starting from an outer boundary $r_{out} = 300$ kpc. The gas temperature at the outer boundary is assumed to be $T_{out} = 4 \times 10^5$ K, which has little impact on the derived temperature profile in the inner region $r \lesssim 50$ kpc (See Extended Data Fig. 1).

**The $\beta$ model.** For comparison, we also consider the $\beta$ model for the density profile of the halo gas

$$\rho(r) = \rho_0 (1 + (r/r_c)^2)^{-3\beta/2},$$

where $\rho_0$ is the core density, $r_c$ is the core radius, and $-3\beta$ is the slope of the profile at large radii. In this paper, we follow recent X-ray observations\cite{16, 25} and adopt $\beta = 0.5$. Similar to our density model (Equation (11)), the density normalization of the $\beta$ model is determined by assuming $n_e = 9.3 \times 10^{-5} \text{ cm}^{-3}$ at $r = 59$ kpc, and the gas temperature at $r_{out} = 300$ kpc is taken to be $T_{out} = 4 \times 10^5$ K. Several representative density and temperature profiles of the $\beta$ model are shown in Extended Data Fig. 2. Note that the model with $r_c = 0.1$ kpc is essentially the same as the power-law profile ($\rho \propto r^{-1.5}$) frequently used in X-ray studies of the MW corona\cite{16, 25} for the radial range shown in this figure.

**Data availability.** The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

**Code availability.** The code used to solve the HSE equation is available from the corresponding author upon reasonable request.

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Author contributions

F.G. designed the project, performed the calculations, drew most figures, and wrote up the manuscript. R.Z. worked on the APEC code and the model of the 2D cold baryonic matter distribution, and drew the left panel of Fig. 2. X.-E.F. performed a preliminary parameter study of our physically-motivated corona model.
Competing interests

The authors declare no competing interests.

Additional information

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Extended data

Extended Data Fig. 1. The impact of the outer gas temperature $T_{\text{out}}$ on the equilibrium temperature profile. The radial profile of gas temperature is shown in three models with $T_{\text{out}} = 10^5$ K (solid), $4 \times 10^5$ K (dotted), and $10^6$ K (dashed). In all these three models, $M_{\text{vir}} = 1.60 \times 10^{12} M_\odot$, $f_{\text{nt}} = 0$, and $r_2 = 200$ kpc. It is clear that the value of $T_{\text{out}}$ has negligible impact on the gas temperature at $r \lesssim 50$ kpc.
Extended Data Fig. 2. Radial distributions of thermal electron number density (top) and temperature (bottom) in the $\beta$ model. In all these four models, $M_{\text{vir}} = 10^{12} M_\odot$, $f_{\text{nt}} = 0$, $\beta = 0.5$, and $T_{\text{out}} = 4 \times 10^5$ K. Here $r_c$ refers to the core radius (see Methods). As $r_c$ increases, the gas density distribution becomes more spatially extended, and the equilibrium gas temperature in the inner region increases.
Extended Data Fig. 3. Impact of the MW mass profile on the halo gas distribution. Radial profiles of thermal electron number density (top) and temperature (bottom) are shown as a function of Galactocentric radius in three models where the total MW mass is contributed by an NFW dark matter profile with $M_{\text{vir, dm}} = 10^{12} M_\odot$ and a cold baryonic matter distribution with $M_{\text{cold}} = 6 \times 10^{10} M_\odot$ (see Methods). Due to the additional gravity from the central stars and cold gas, the hot gas density profiles in these three models (solid, dotted, and short-dashed lines) are expected to be more centrally peaked, with smaller values of $r_1$ than in our default model (long-dashed line), where the total matter distribution is assumed to be an NFW profile with $M_{\text{vir}} = 10^{12} M_\odot$ and $r_1 = 0.75 r_s$. In all the four models shown, $f_{\text{tot}} = 0$ and $r_2 = 200$ kpc. As $r_1$ increases, the gas density distribution becomes more spatially extended, and the equilibrium gas temperature in the inner region increases.
Extended Data Fig. 4. X-ray-constrained virial mass of the NFW dark matter halo of the MW. The MW total matter distribution is assumed here to be contributed by an NFW dark matter distribution with the virial mass $M_{\text{vir},\text{dm}}$ and a cold baryonic matter distribution with $M_{\text{cold}} = 6 \times 10^{10} M_\odot$ (see Methods). $M_{\text{vir},\text{dm}}$ is then derived by assuming that the $0.5 - 2.0$ keV X-ray emission weighted average temperature $T_{\text{em}}$ along $l = 90^\circ$ equals $T_{\text{obs}} = 2.22 \times 10^6$ K. The additional gravity from the stars and cold gas results in a more centrally peaked corona density distribution with $r_1 < 0.75 r_s$. The solid, dotted, and dashed lines correspond to the models with $r_1 = 0$, $0.1 r_s$, and $0.3 r_s$, respectively (see Extended Data Fig. 3). In the calculations here, we assume that $f_{\text{int}} = 0$. 

![Graph showing the relationship between virial mass and radius for different models with $r_1 = 0$, $0.1 r_s$, and $0.3 r_s$.](image-url)
Extended Data Fig. 5. The gravitational acceleration along the MW rotation axis contributed by the cold baryonic matter. For the density profile of the central cold baryonic matter, we use a spherically-symmetric 1D Hernquist model (dotted line) to approximate the axisymmetric 2D model described in ref. (solid line). The central cold baryonic matter in the 2D model includes a thin stellar disk, a thick stellar disk, a stellar bulge, an atomic gaseous disk, and a molecular gaseous disk. At $z \gtrsim 5$ kpc, our 1D model provides a reasonably good fit to the 2D model along the MW rotation axis.