Inferring Halo Gas Fractions with Mock X-ray Observations of Cosmological Hydrodynamical Simulations

Why do we care about gas fraction?

One reason is: Missing Baryon Problem

In a flat Universe: $\Omega_{DM}+\Omega_{\Lambda}+\Omega_{baryon}=1$

26% 69.2% 4.8%

Then DM is ~85% of all matter , and baryons are ~ 15%

Total mass of the MW: $\sim 1 \cdot 10^{12}\,M_{\odot}$

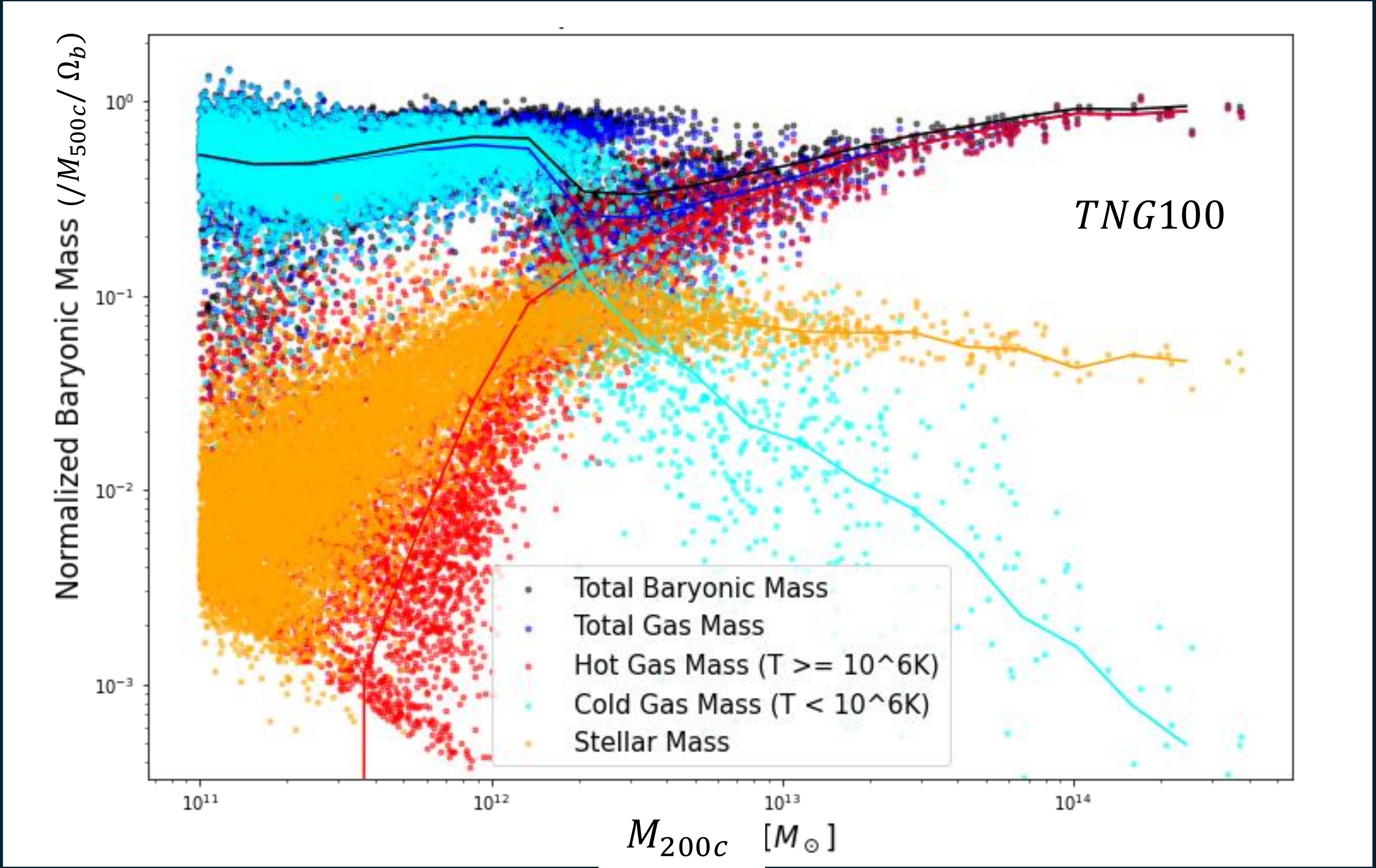
Total mass of stars and gas: $\sim 5 \cdot 10^{10}\,M_{\odot}$

Expected mass of stars and gas: $\sim 15 \cdot 10^{10}\,M_{\odot}$

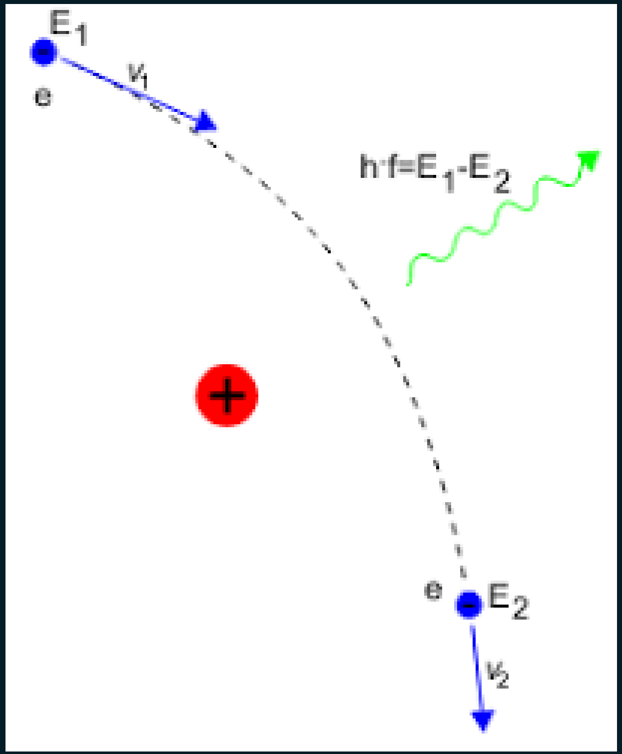
Fraction of collapsed baryons: 5% / 15% = 1/3.

2/3 of baryons outside of collapsed halos -> “Missing baryons”

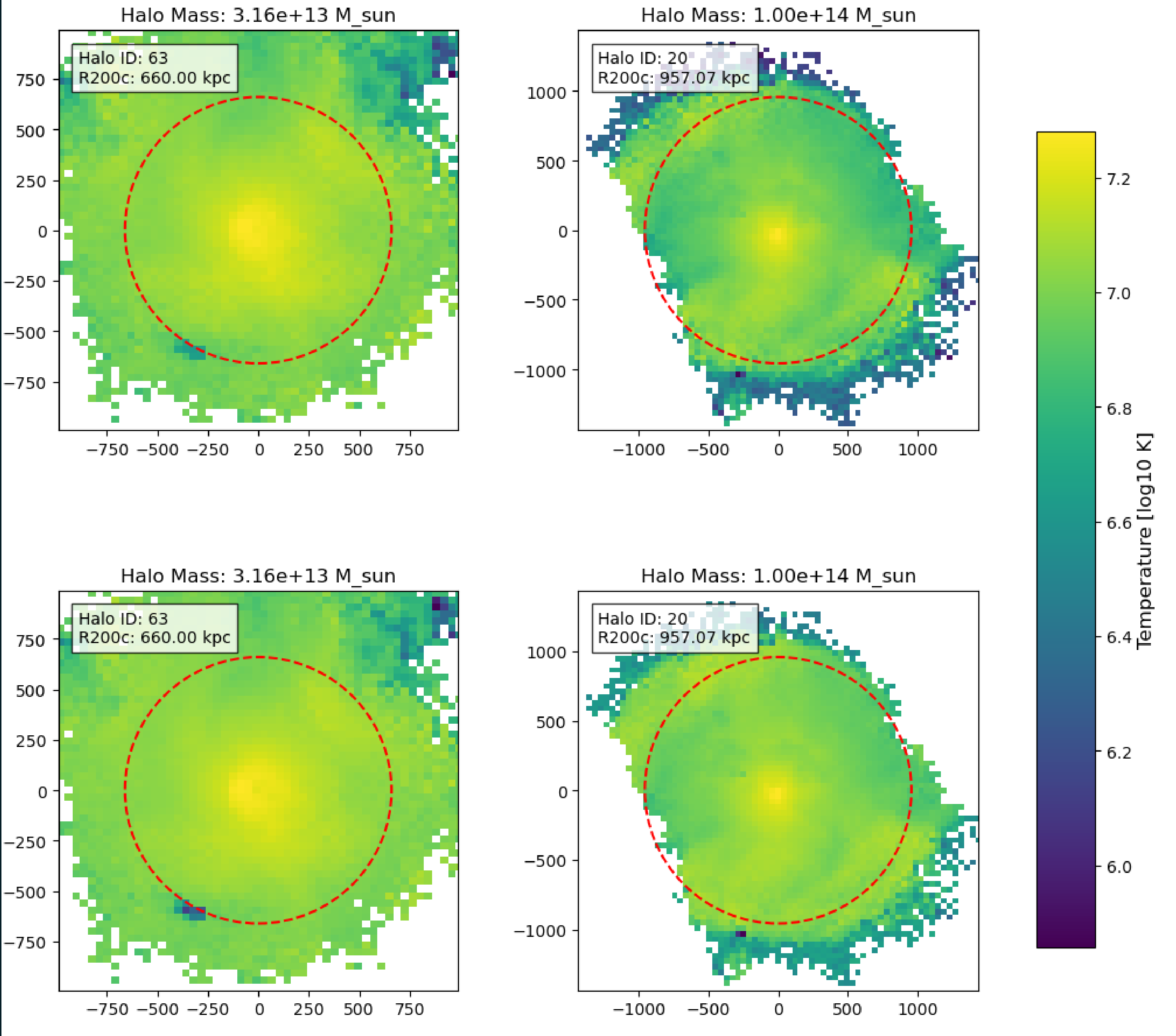
Stars, BHs, cold and hot gas?



Hot Gas; How to Detect?
X-ray; Bremstrehlung



Mass Weighted Temperature
X-Ray Luminosity Weighted Temperature



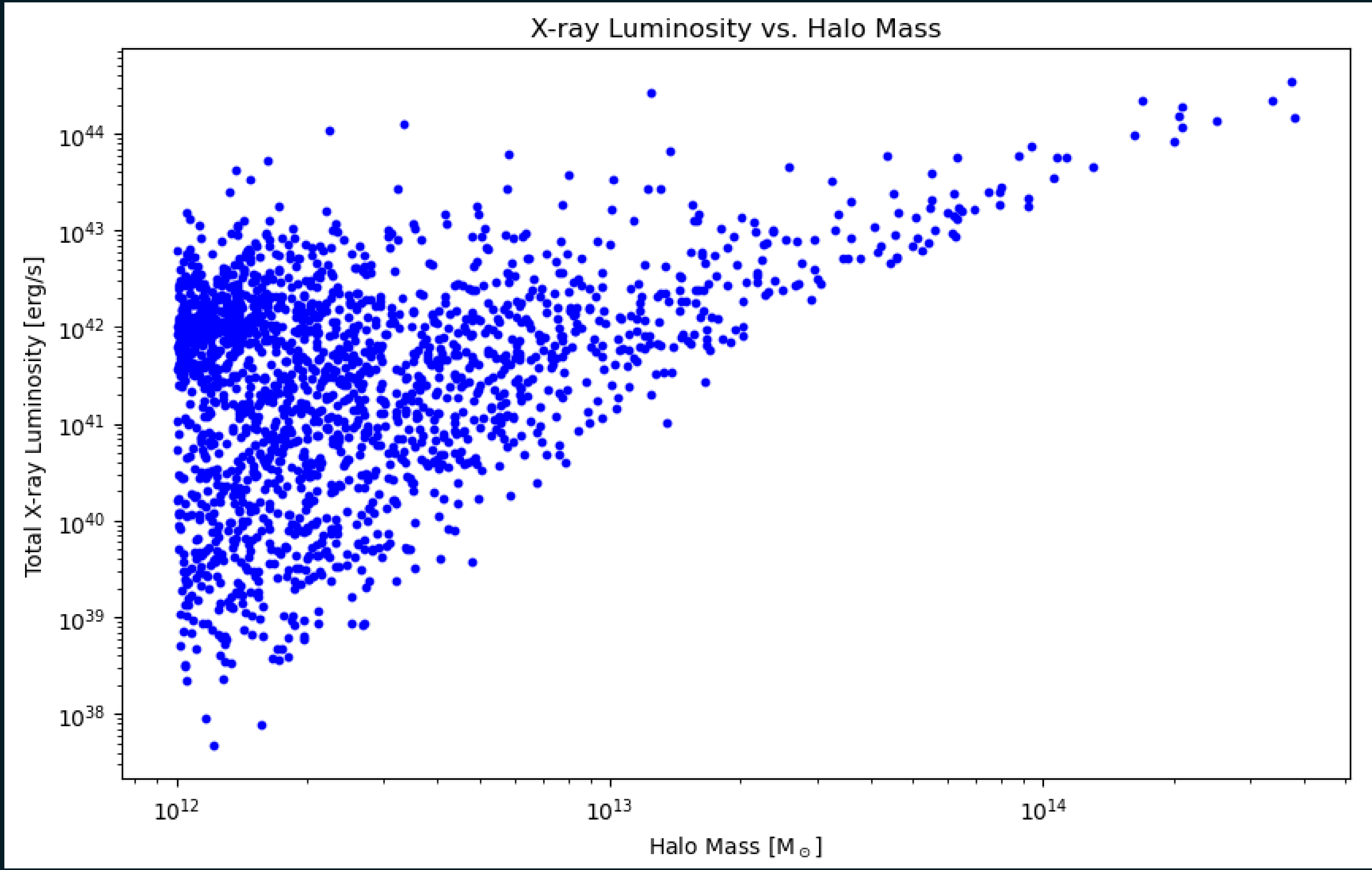
How to measure X-Ray Luminosity?
Navarro et al. (1995)

$$L_X = 1.2 \times 10^{-24} (\mu m_p)^{-2} m_g \sum_{i=1}^{N_{gas}} \rho_i T_i^{1/2} \text{ erg s}^{-1}$$

- $\mu = 0.6$ for a fully ionized gas
- m_g: Mass of a gas cell
- ρ_i, T_i: Density and temperature at the position of the i-th cell

Navarro et al. (1995)

$$L_X = 1.2 \times 10^{-24} (\mu m_p)^{-2} m_g \sum_{i=1}^{N_{gas}} \rho_i T_i^{1/2} \text{ erg s}^{-1}$$



Observational Paper:

Baryon content in a sample of 91 galaxy clusters selected by the South Pole Telescope at 0.2 < z < 1.25

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Cluster Sample:
- **SPT-SZ 2500 deg² survey** (Bleem et al. 2015)
- Includes **91 galaxy clusters** at 0.25<z<1.25 with SZE detection significance ξ>6.8
- Later followed by Chandra X-Ray observations

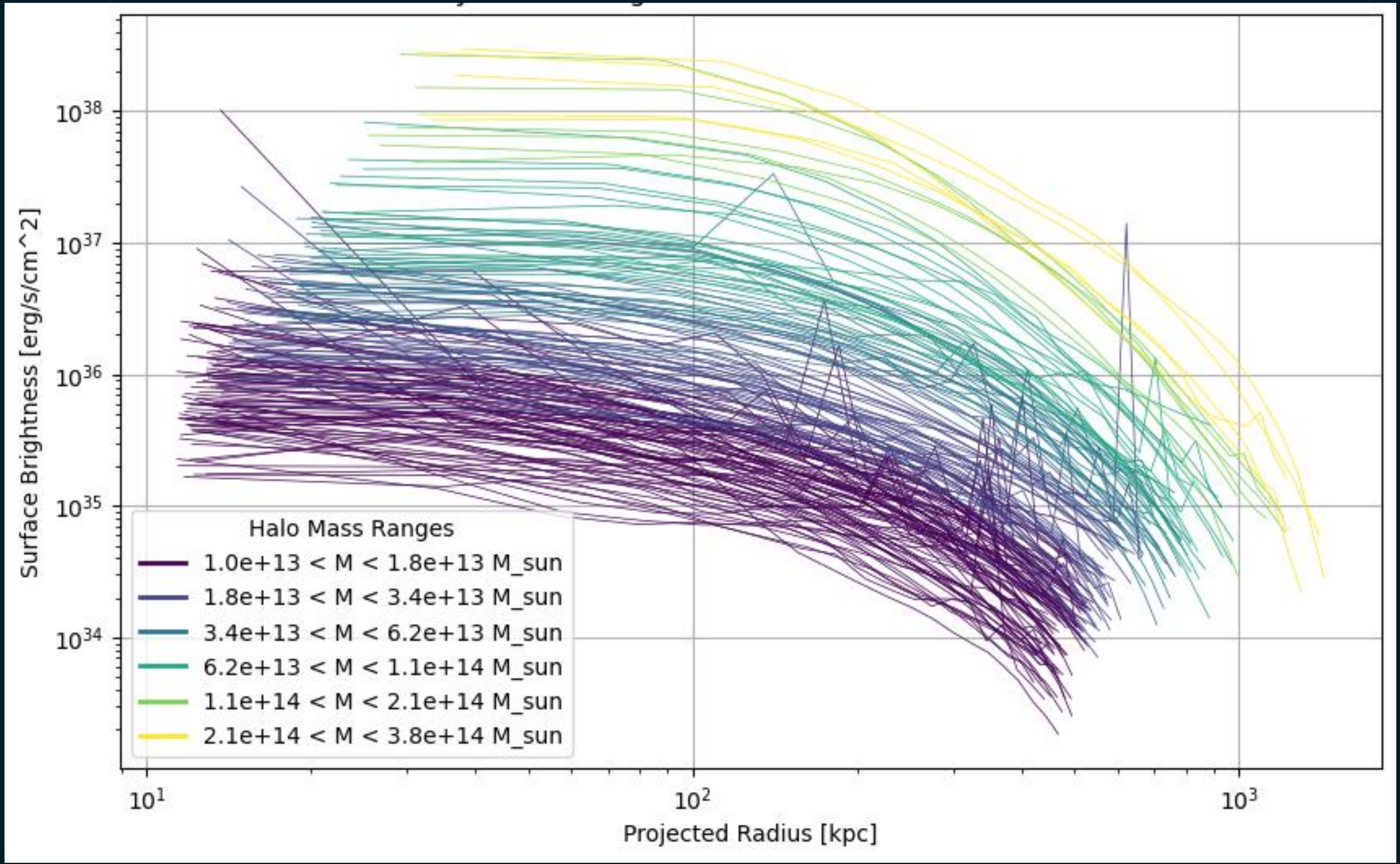
Halo Mass (M_{500}): SZE scaling relation from the SPT Collaboration

Mass of the ICM (M_{ICM}):
- Clusters imaged through the Chandra XVP program
- Surface Brightness profile extracted extending to 1.5 R_{500}
- Fitting surface brightness profile using projected β-model along the line of sight
- Integrating the Fitted profile to R_{500}
- R_{500} is based on the SZE Halo mass

Making a Mock (?)

1- Surface Brightness Profile

$$S(R) = \frac{L_X}{\pi\left[(R+\delta R)^2 - R^2\right]},$$



Making a Mock (?)

$$EM(r) = (1+z)^4 \frac{S(R)}{\Lambda(T,z)}.$$

2- Emissivity
(Kay & Pratt 2022)

3- Modified Beta Model
(McDonald et al. 2013)

$$n_e n_p = n_0^2 \frac{\left(\frac{r}{r_c}\right)^{-\alpha}}{\left(1+\frac{r^2}{r_c^2}\right)^{3\beta-\frac{\alpha}{2}} \left(1+\frac{r^3}{r_s^3}\right)^{-\frac{\epsilon}{3}}}$$

$$\int_0^{2r_{vir}} n_e^2 dl = \int_0^{2r_{vir}} n_0^2 \frac{\left(\frac{r}{r_c}\right)^{-\alpha}}{\left(1+\frac{r^2}{r_c^2}\right)^{3\beta-\frac{\alpha}{2}} \left(1+\frac{r^3}{r_s^3}\right)^{-\frac{\epsilon}{3}}} dl$$

$A = 1.397$ and $Z = 1.199$.

$$\rho_g = m_p n_e A/Z$$

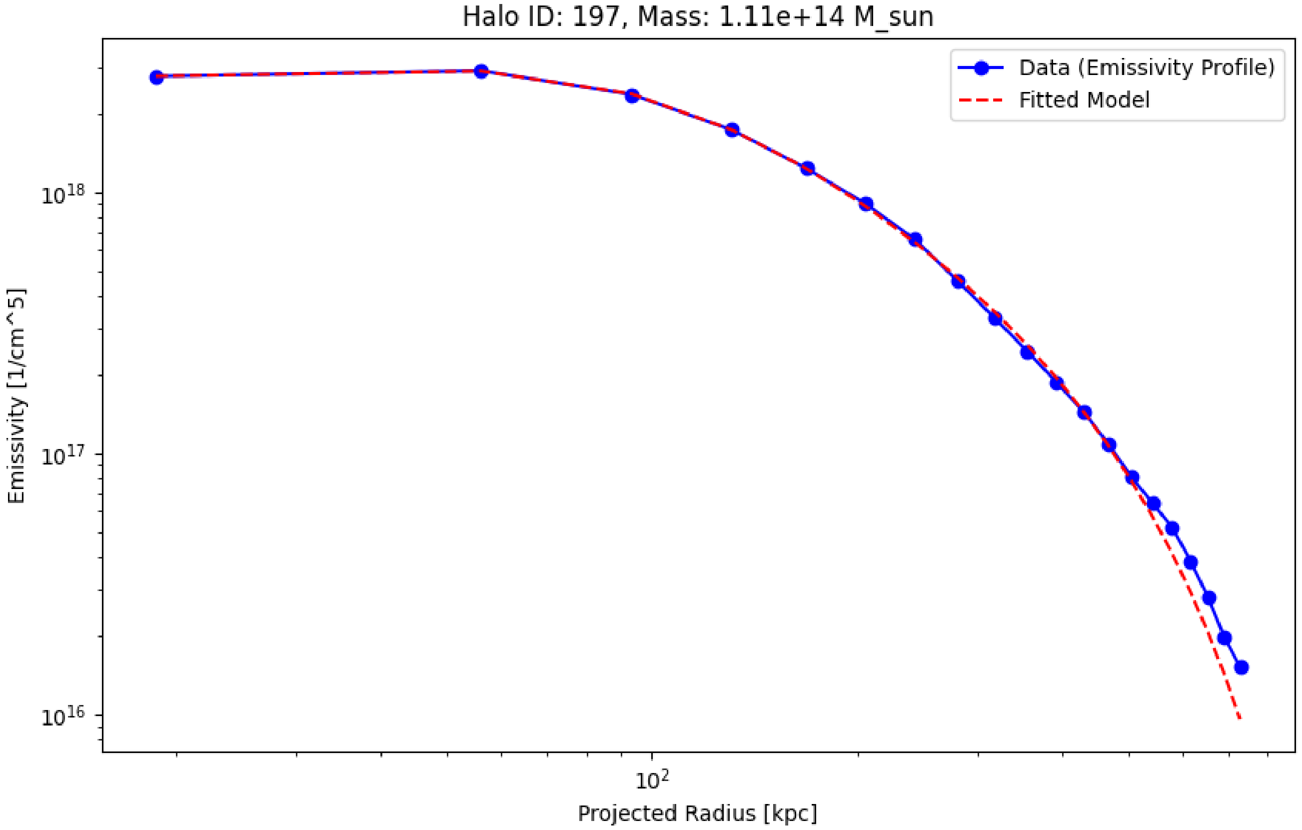
$$n_e = Z n_p$$

Making a Mock (?)

3- Modified Beta Model (McDonald et al. 2013)

$$EM(r) = (1+z)^4 \frac{S(R)}{\Lambda(T,z)}.$$

$$\int_0^{2r_{vir}} n_e^2 dl = \int_0^{2r_{vir}} n_0^2 \frac{\left(\frac{r}{r_c}\right)^{-\alpha}}{\left(1+\frac{r^2}{r_c^2}\right)^{3\beta-\frac{\alpha}{2}}\left(1+\frac{r^3}{r_s^3}\right)^{-\frac{\epsilon}{3}}} dl$$



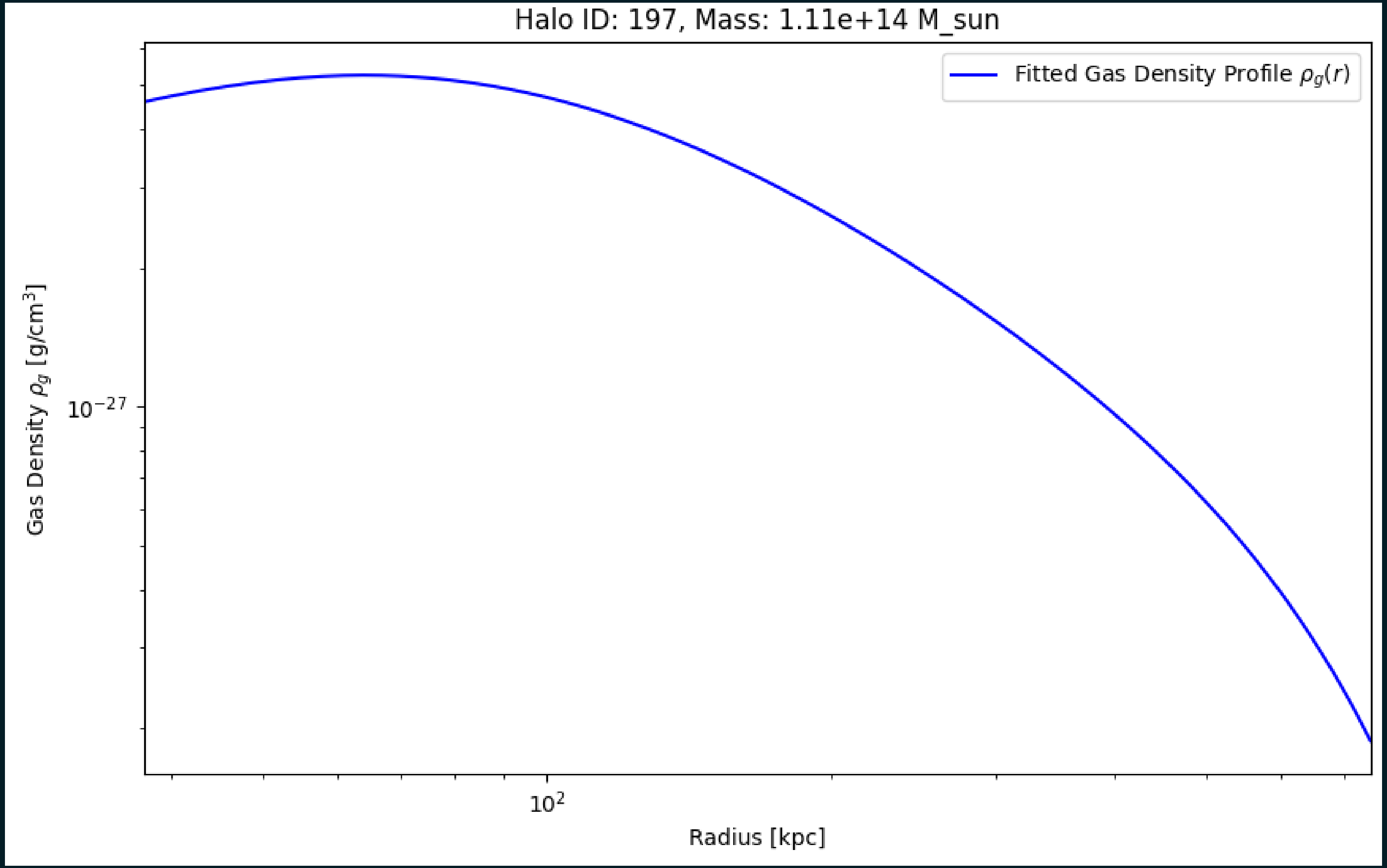
$$r = \sqrt{R^2 + l^2}$$

Making a Mock (?)

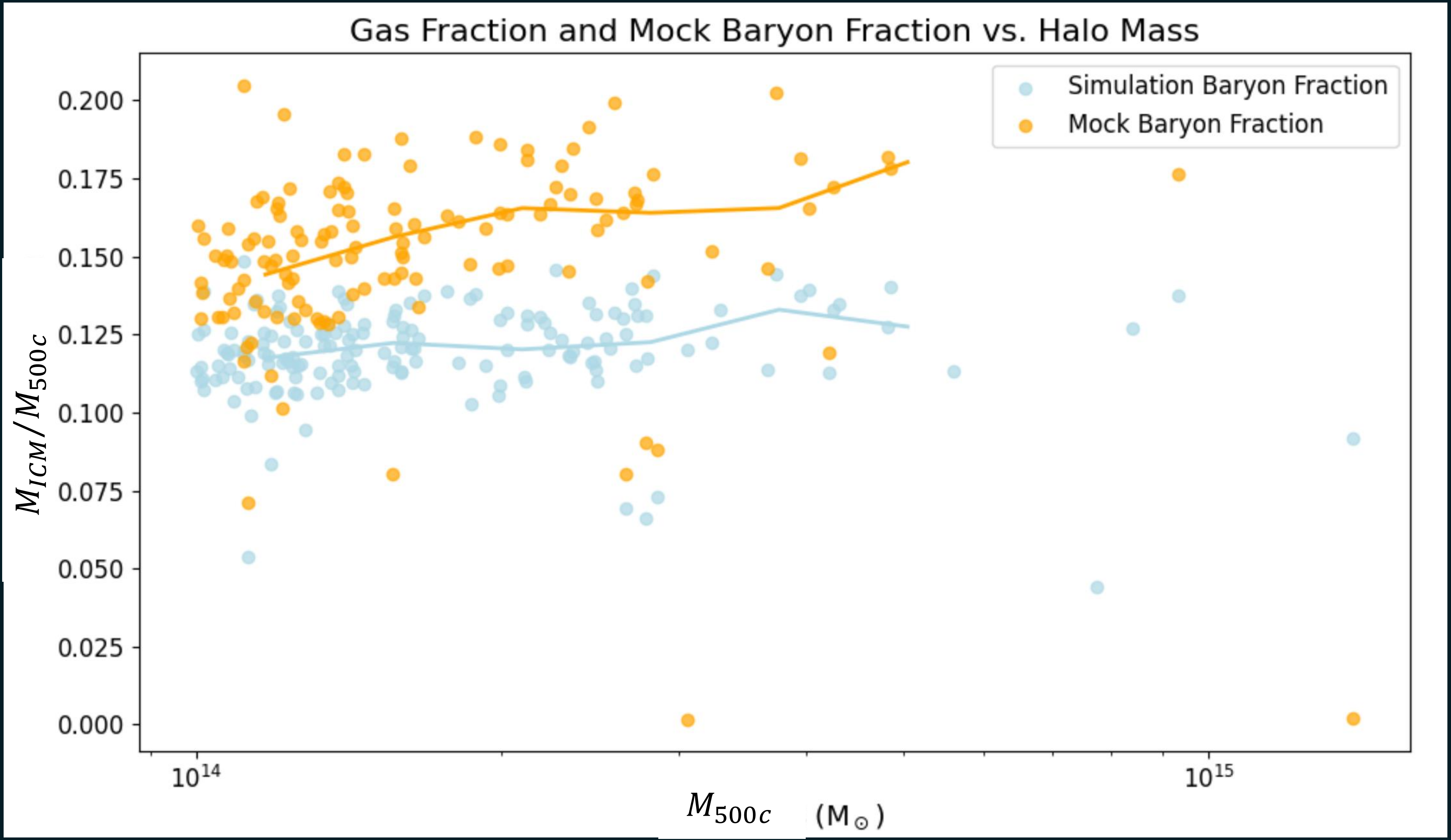
$$\rho_g^2(r) = \frac{n_0^2 A^2 m_p^2}{Z} \frac{\left(\frac{r}{r_c}\right)^{-\alpha}}{\left(1+\frac{r^2}{r_c^2}\right)^{3\beta-\frac{\alpha}{2}} \left(1+\frac{r^3}{r_s^3}\right)^{-\frac{\epsilon}{3}}};$$

4- Calculate Density with the Optimal parameters

5- Integrate the gas density profile over the radial range from 0 to R500 to get the mass of the ICM

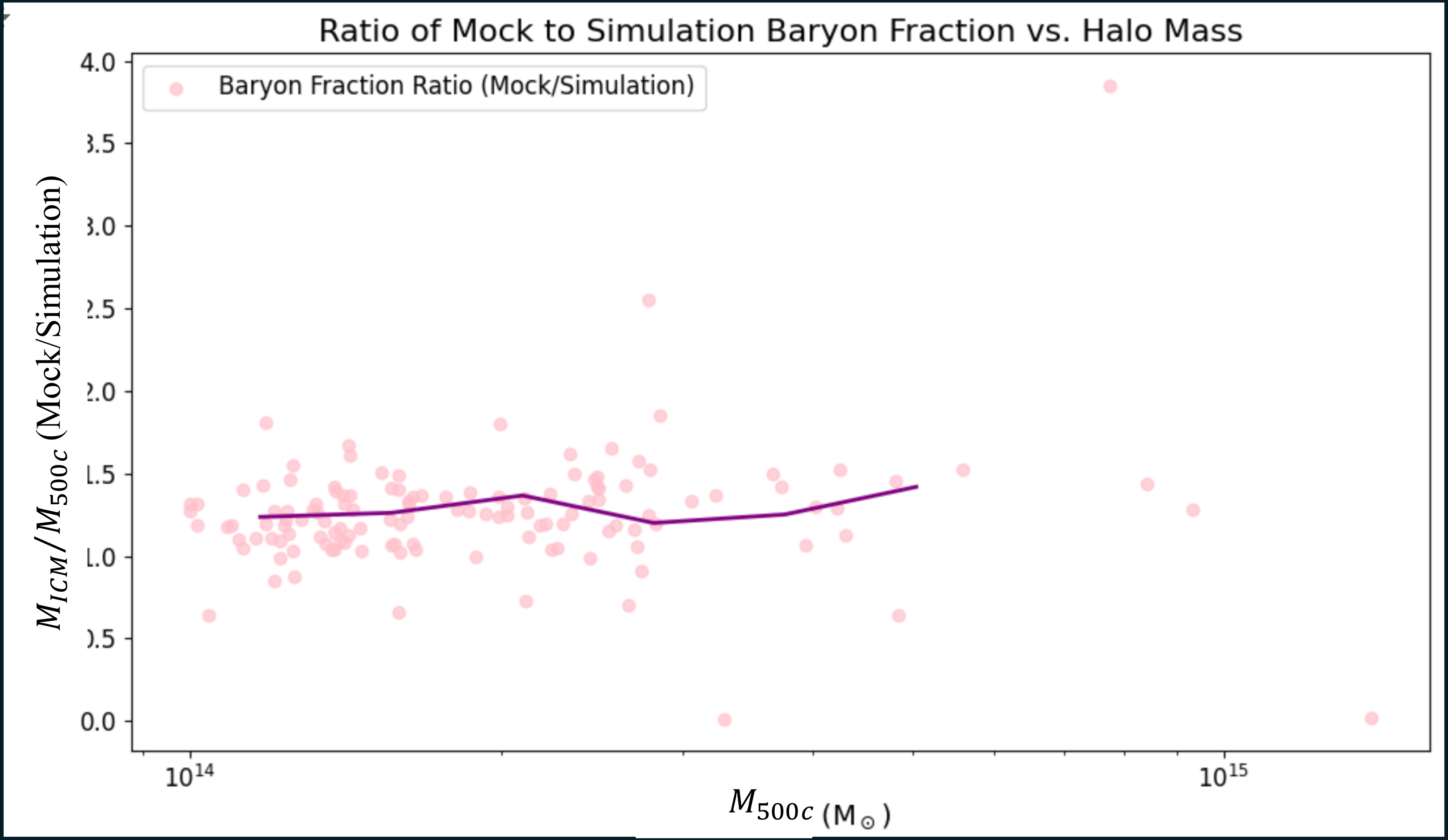


Results



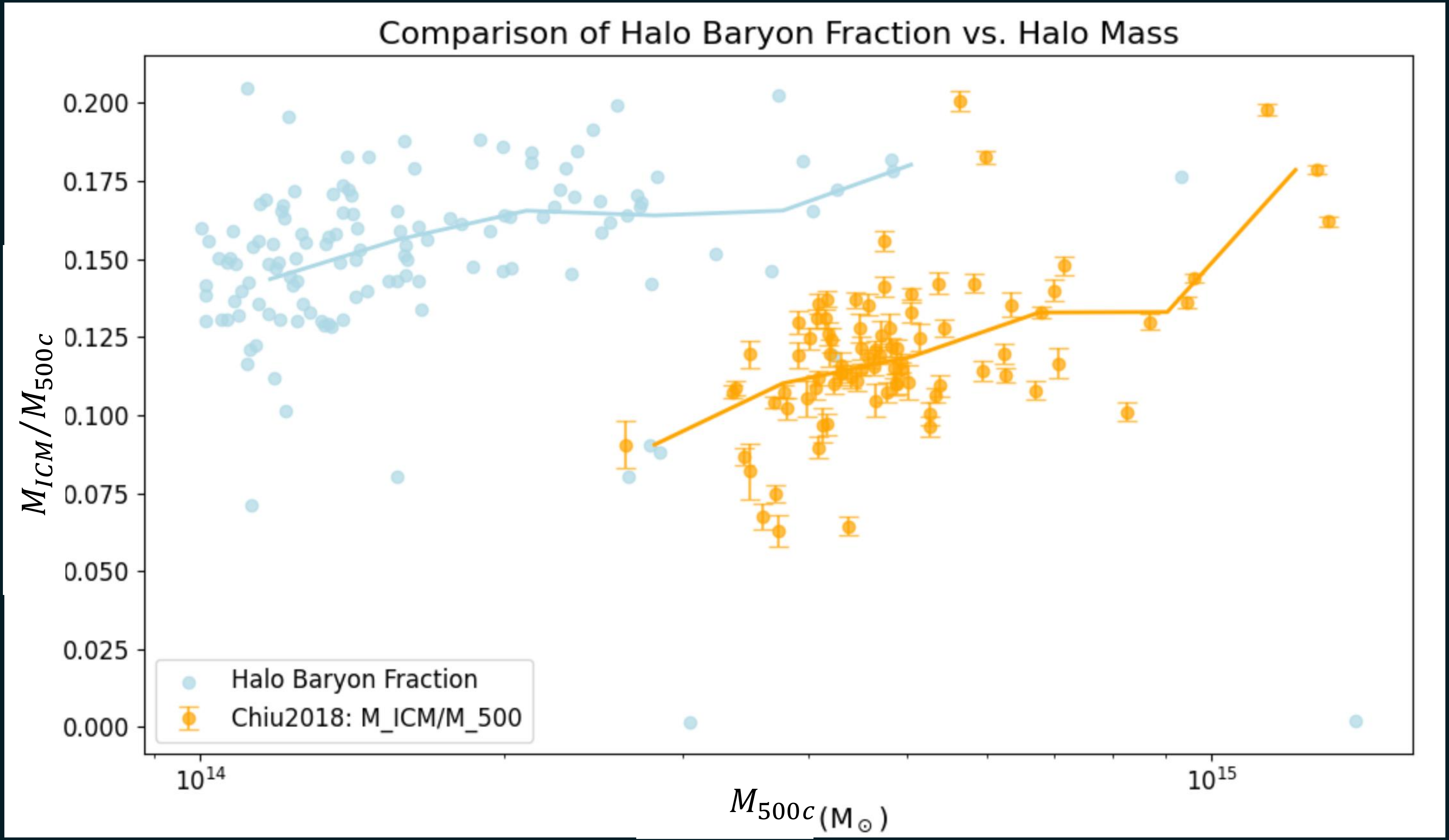
Gas Fraction and Mock Baryon Fraction vs. Halo Mass
Simulation Baryon Fraction
Mock Baryon Fraction
0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
M_{ICM}/M_{500c}
10^{14}
10^{15}
M_{500c} ($M_\odot$)

Results



Ratio of Mock to Simulation Baryon Fraction vs. Halo Mass
Baryon Fraction Ratio (Mock/Simulation)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
M_{ICM}/M_{500c} (Mock/Simulation)
10^{14}
10^{15}
M_{500c} ($M_\odot$)

Results



Comparison of Halo Baryon Fraction vs. Halo Mass
M_{ICM}/M_{500c}
0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
10^{14}
10^{15}
M_{500c} ($M_\odot$)
Halo Baryon Fraction
Chiu2018: M_ICM/M_500