X-ray and SZ constraints on the properties of the CGM

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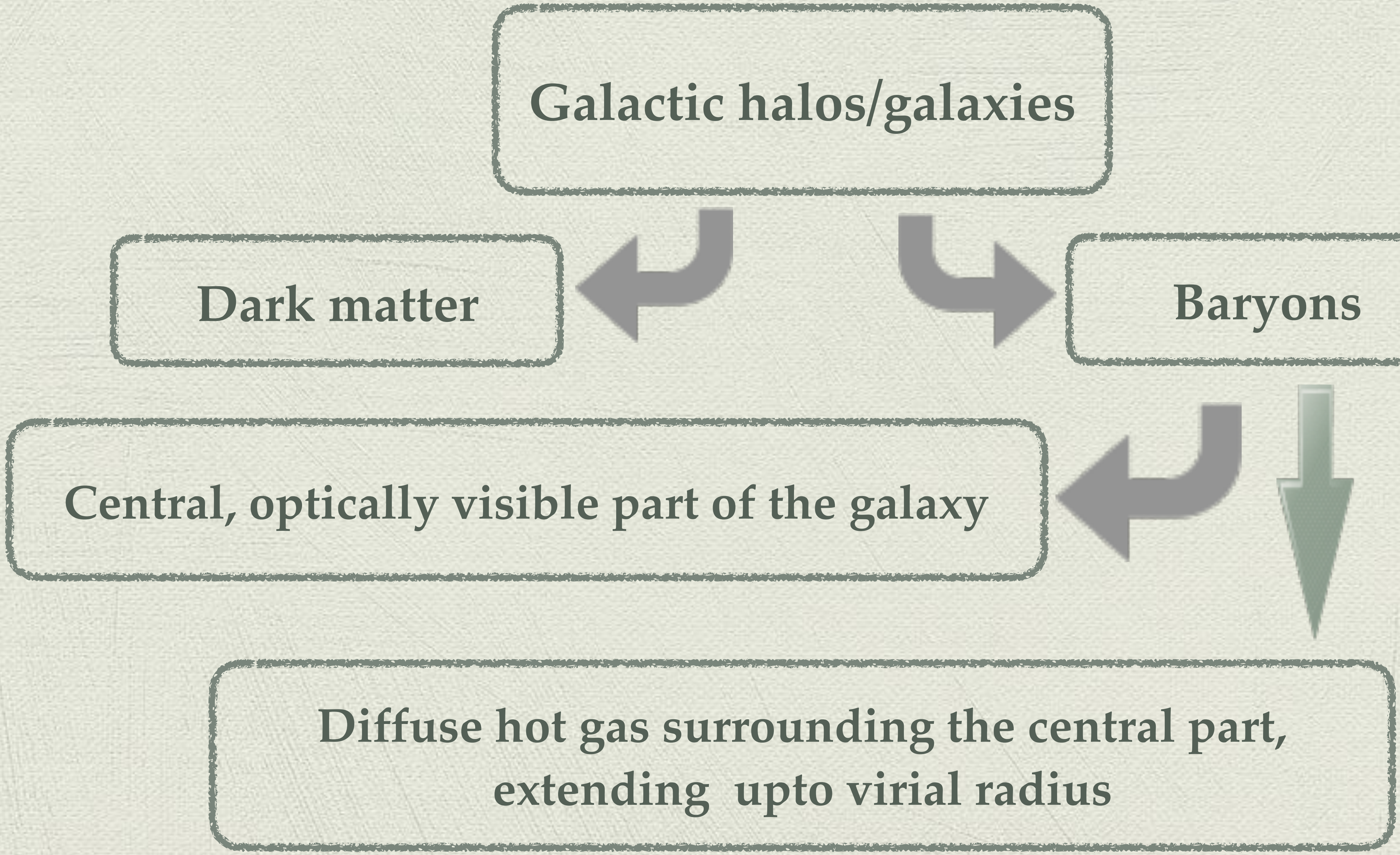
Singh et al 2018, MNRAS, 478, 2909

What is Circumgalactic medium?

When someone went for the US Visa interview…..

Circumgalactic medium



Different phases of CGM

- Cold CGM => $T < 10^4$ K
- Cool CGM => $10^4 < T < 10^5$ K
- Warm CGM => $10^5 < T < 10^6$ K
- Hot CGM => $T > 10^6$ K

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Motivation

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Lamdba-CDM predicts that baryons hold ~ 16% of the total galactic mass

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Approximately half of these baryons observationally missing!

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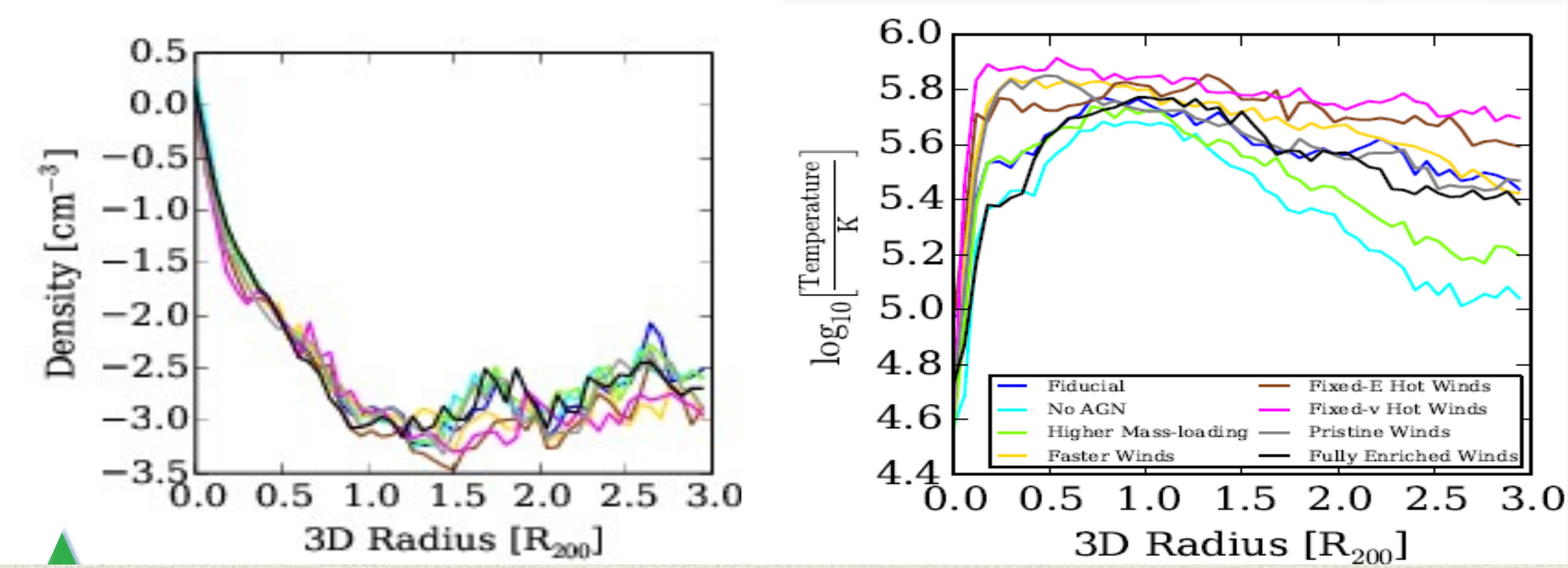
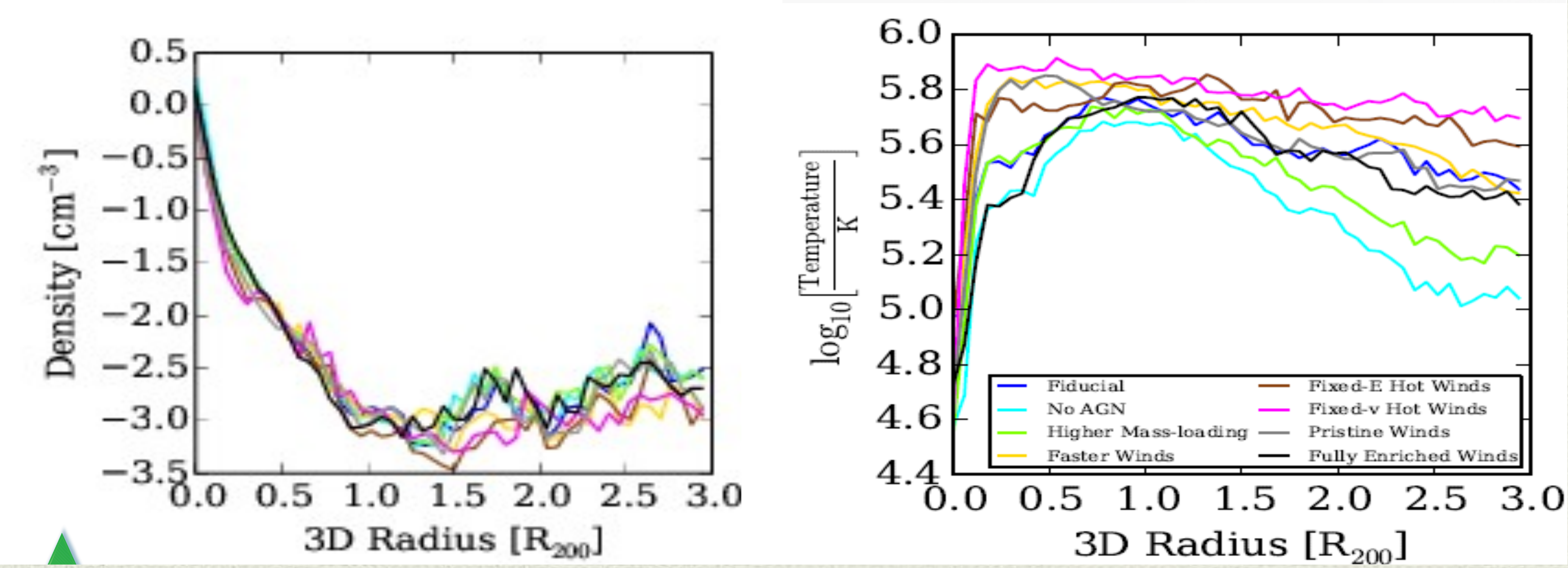
- The connection between feedback and CGM.

Feedback and CGM



Suresh et al 2015

Feedback and CGM



Suresh et al 2015

Constraining CGM properties provides an additional probe of feedback

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Amount of CGM, its density and temperature.

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Tools => Sunyaev-Zel'dovich (SZ) effect and X-ray emission.

SZ effect

- Inverse Compton scattering of low energy CMB photons by high energy intervening medium.

- Thermal SZ (tSZ): High energy of scattering medium due to its high temperature.

$$y = (k_b T_e n_e \sigma_T L)/m_e c^2$$

- Kinetic SZ (kSZ): Due to bulk motion.

$$y = (v_{los} n_e \sigma_T L)/m_e c^2$$

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- SZ effect can trace gas out large distances whereas X-ray is sensitive to the inner parts.
- Both SZ effect and X-ray emission have been extensively used to study galaxy clusters.
- Difficult to detect these signals in individual galaxies => **Stacking**.

SZ and X-ray datasets

- SZ: Planck collaboration et al. 2013 (P13)
  Planck + SDSS

- X-ray: Anderson et al. 2015 (A15)
  ROSAT + SDSS

SZ and X-ray datasets

$\log M_*$ $M_\odot$	$\log M_{500}(M_\odot)$ P13(A15)	$\tilde{Y}_{500} \pm \sigma\tilde{Y}_{500}$ 10^{-6}arcmin^2	$\log L_X^{\rm CGM} \pm \sigma L_X^{\rm CGM}$ log ergs/s	$\bar{z}$	Number of LBGs stacked P13(A15)
11.15	12.97 (13.09)	1.7 ± 1.0	40.99 ± 0.11	0.135	22085 (18430)
11.05	12.71 (12.91)	1.27 ± 0.78	40.55 ± 0.53	0.127	26026 (21583)
10.95	12.62 (12.75)	1.54 ± 0.60	40.28 ± 0.48	0.113	28325 (22689)
10.85	12.40 (12.60)	-	39.28 ± 0.93	0.105	27866 (22490)

Stacked SZ signal

Stacked SZ signal: Compton y-parameter integrated over a sphere of radius R_{500}.

$$Y_{500} = \frac{\sigma_T}{m_e c^2 D_A^2(z)} \int_0^{R_{500}} P_e dV,$$

$$\tilde{Y}_{500} \equiv Y_{500} E^{-2/3}(z) (D_A(z)/500\mathrm{Mpc})^2$$

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$$Y_{\mathrm{cyl}} = \frac{\sigma_T}{m_e c^2 D_A^2(z)} \int_0^{5R_{500}} 2\pi r dr \int_r^{5R_{500}} \frac{2P_e(r')r'dr'}{\sqrt{r'^2 - r^2}}$$

Stacked X-ray signal

Stacked X-ray luminosity in 0.5-2 keV band, radial range ~ $0.15R_{500}$ to R_{500}.

$$L_X^{\rm CGM} = \int_{0.15R_{500}}^{R_{500}} 2\pi r dr \int_r^{R_{500}} \frac{2\, n_e n_i \Lambda(Z, T_e) r' dr'}{\sqrt{r'^2 - r^2}}$$

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Model for CGM density & temp
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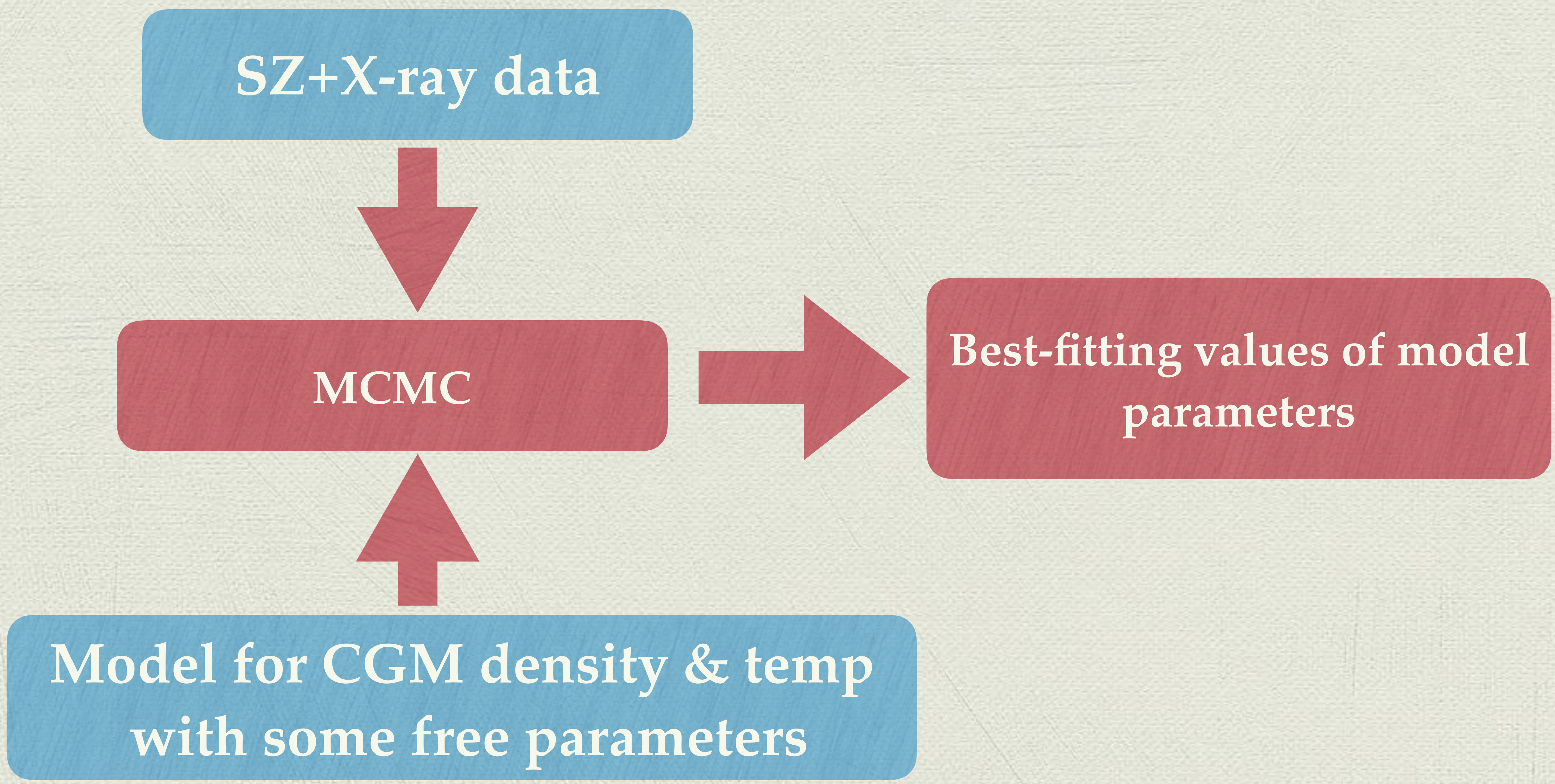
SZ+X-ray data
MCMC
Best-fitting values of model parameters
Model for CGM density & temp with some free parameters

CGM density and temperature

- **Power law model**

$$n_e(r) \propto r^{-3\beta}$$

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CGM density and temperature

- **Hydrostatic equilibrium**

$$n_e(r) \propto \exp\Big[-\Big(\frac{\mu m_p G M_v}{k_b T_{\rm gas} R_s}\Big)\frac{1-\log(1+r/R_s)/(r/R_s)}{\log(1+C_v)-C_v/(1+C_v)}\Big]$$

- $T_{gas} = f_T$ x virial temperature

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Results

Model	α_{fg} (Mean $\pm$ 68% CL)	α_{T} (Mean $\pm$ 68% CL)	f_{gas} ($10^{12} M_\odot$)	f_{gas} ($10^{13} M_\odot$)
$\beta = 0.4$	0.24 ± 0.061	$-0.59^{+0.071}_{-0.12}$	$3.2^{+1.7}_{-1.1}$ %	$5.5^{+1.8}_{-1.4}$ %
Hydro	$0.48^{+0.027}_{-0.051}$	$-0.33^{+0.052}_{-0.023}$	$0.6^{+0.3}_{-0.1}$ %	$1.8^{+0.5}_{-0.2}$ %

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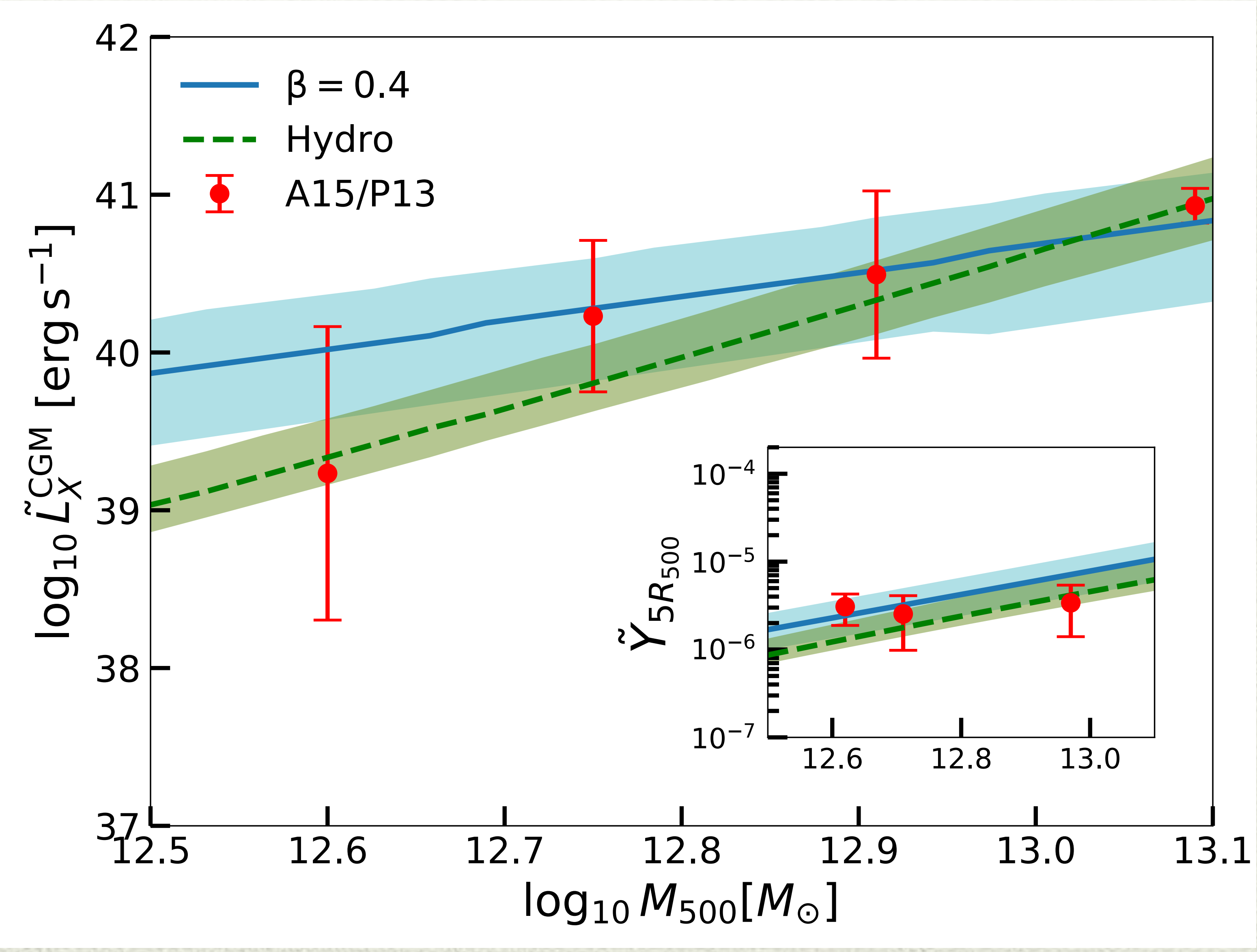
- f_{gas} => 20-30% of the baryon budget in massive galaxies in hot CGM for power law model.
- Hydro model ~ 4-11% of the baryon budget.
- T_{gas} ~ 0.21±0.05 keV at M_v ~ 10^{13} $M_\odot$ for power law model.
- T_{gas} ~ 0.38(+0.05/-0.02) keV at M_v ~ 10^{13} $M_\odot$ for hydro model.

Results



β = 0.4
Hydro
A15/P13
42
41
40
39
38
37
12.5
12.6
12.7
12.8
12.9
13.0
13.1
$\log_{10} \tilde{L}_X^{\rm CGM}\,[\rm erg\,s^{-1}]$
$\log_{10} M_{500} [M_\odot]$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$\tilde{Y}_{5R_{500}}$
12.6
12.8
13.0

Comparison with MilkyWay

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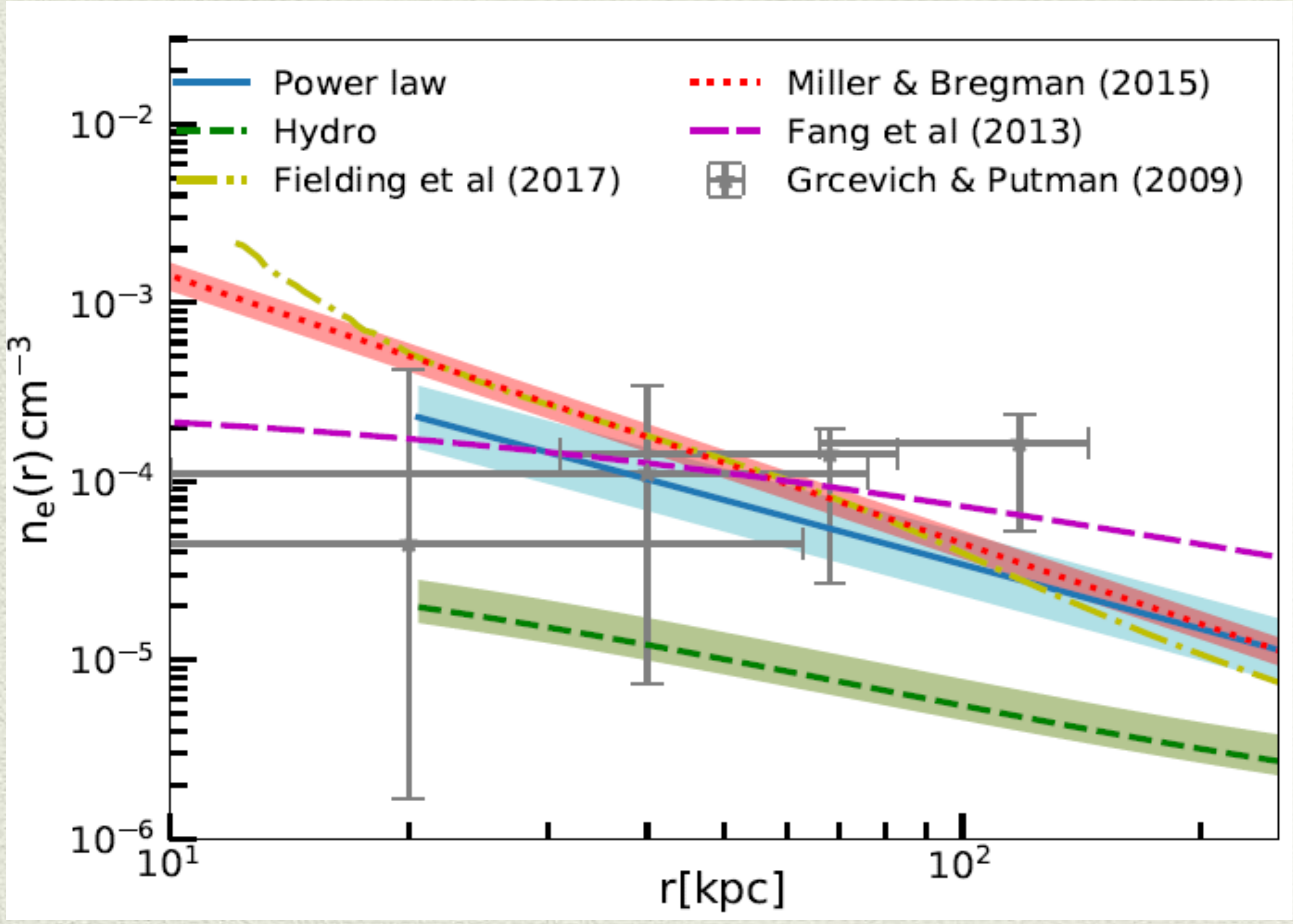

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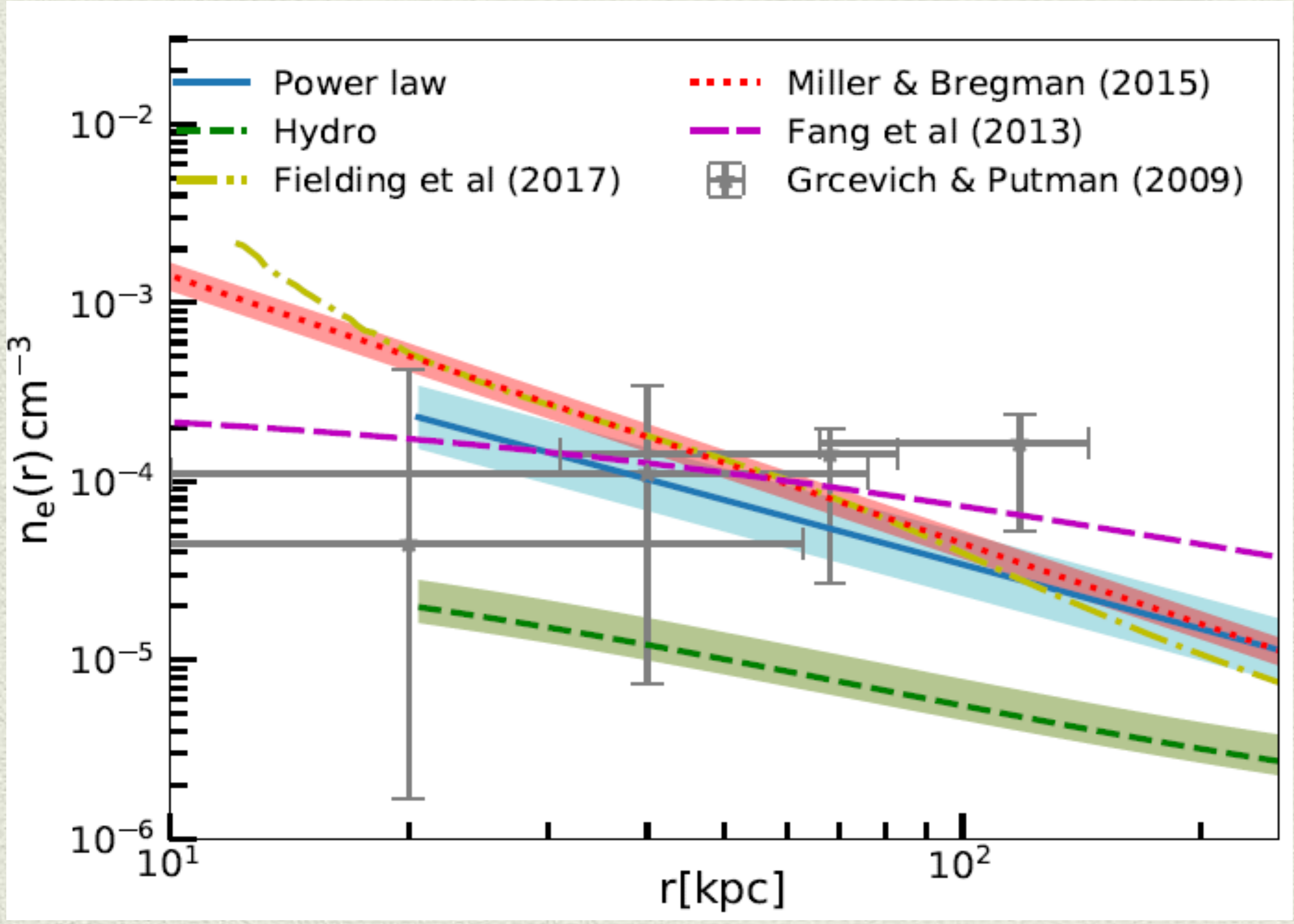

Power law model is broadly consistent with a number of observations whereas the hydro model under-predicts CGM density.

Comparison with other CGM phases

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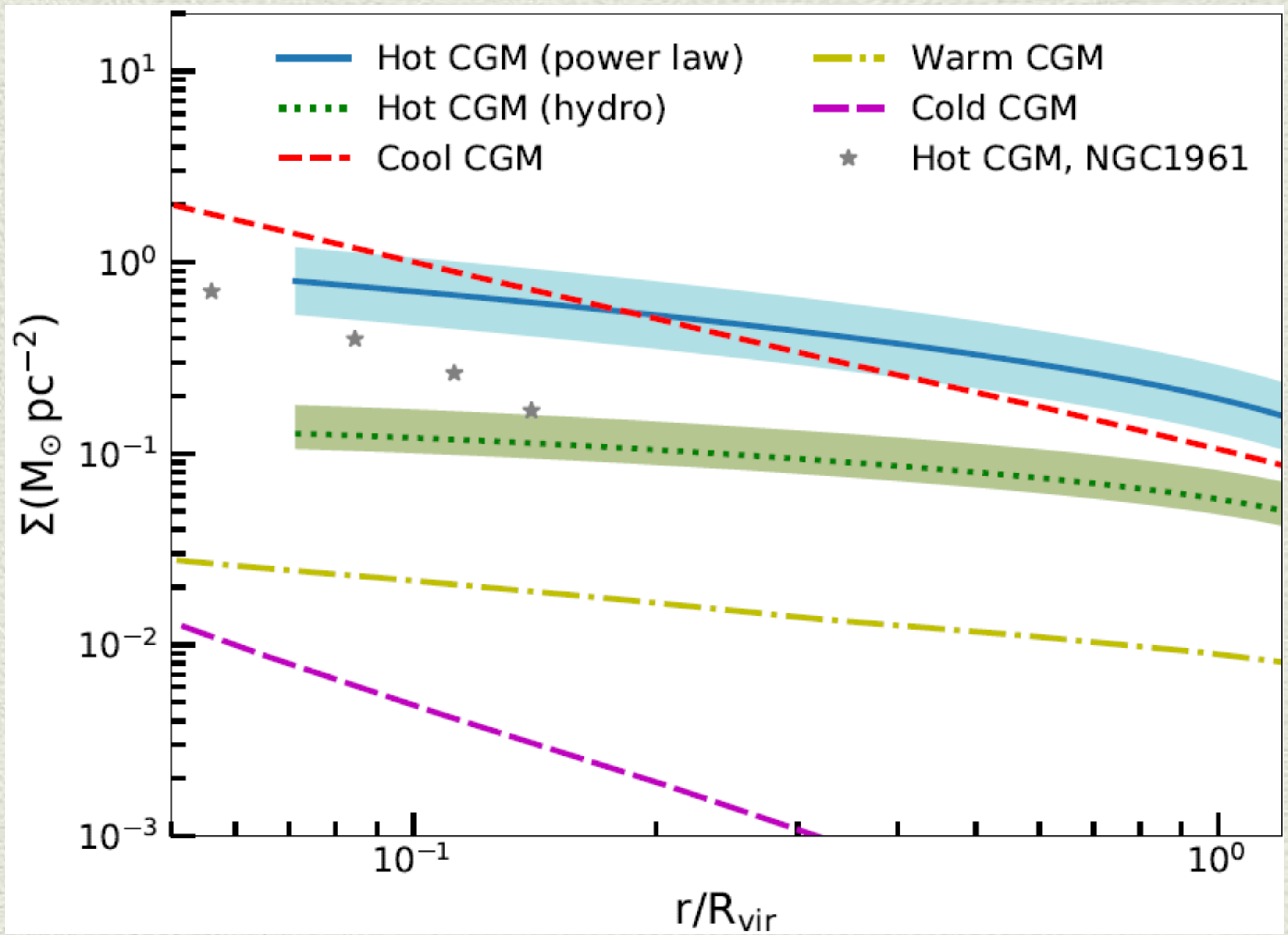

*Tumlinson, Peeples & Werk (2017)

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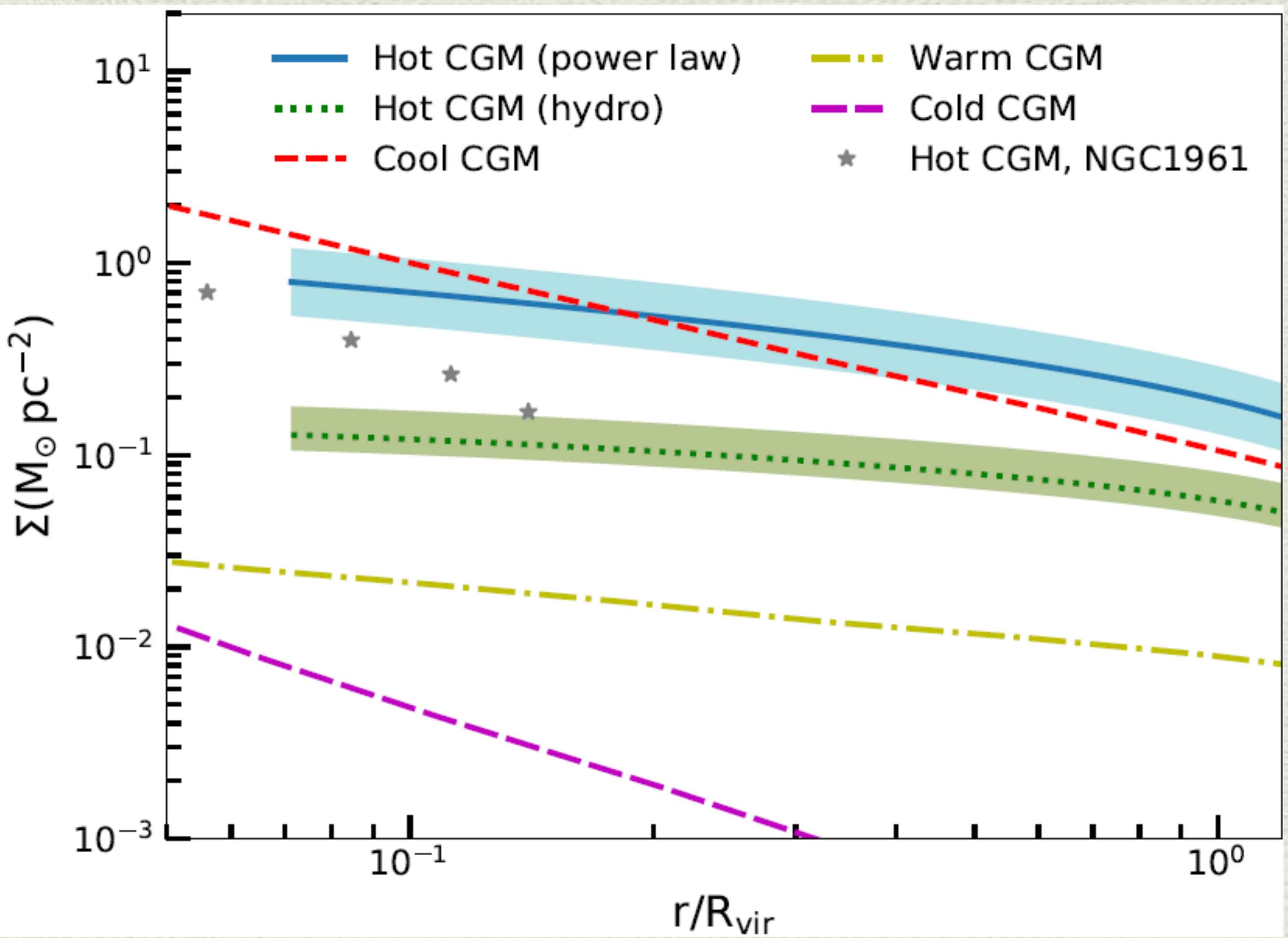

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Hot CGM can be the most dominant phase of the CGM.

Impact of uncertainties

- $T_{12} \sim 2 \times 10^6$ K and $Z_{CGM} = 0.2\ Z_\odot$

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- $T_{12} \sim 2\mathrm{x}10^6$ K and $Z_{CGM} = 0.2\ Z_\odot$
- $T_{12} \sim 10^6 - 4\mathrm{x}10^6$ K

Impact of uncertainties

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- $T_{12} \sim 10^6 - 4 \times 10^6$ K
- $Z_{CGM} = 0.4$

Impact of uncertainties

- $T_{12} \sim 2 \times 10^6$ K and $Z_{CGM} = 0.2\, Z_\odot$
- $T_{12} \sim 10^6 - 4 \times 10^6$ K
- $Z_{CGM} = 0.4$
- Variations in gas fraction and temperature are smaller than their uncertainties.

Summary

- Stacked SZ and X-ray measurements to constrain the properties of the CGM.
- Power law model gives f_{gas} ~ 3.2-5.5% (a baryon budget ~ 20-30%) at halo masses 10^{12} - 10^{13}.
- Hydro model gives f_{gas} ~ 0.6-1.8% (a baryon budget ~ 4-11%) at halo masses 10^{12} - 10^{13}.
- Power law model is consistent with the observations of MilkyWay.
- Hot CGM comparable to or larger than other cooler phases.
- Relaxing the assumptions about gas temperature and mettalicity doesn't affect the best-fitting values significantly.

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Thanks!

…….. after explaining all that!!