Cosmological constraints from eFEDS spectral data

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24.05.2024

Introduction

- Matter distribution is very sensitive to a variety of cosmological parameters
- Galaxy clusters are powerful cosmological probes
- We can't measure the masses of clusters directly, so we have to rely on other observables

Introduction

- N. Clerc et al. 2012[1] proposed a way of cosmological analysis that utilizes X-ray count-rate - hardness ratio diagram
- The idea is that even in shallow surveys, substantial information on cluster temperature is present in the raw X-ray data
- The goal of this study is to adapt CR-HR method to eFEDS data and compare the obtained cosmological constraints with [2]

[1] N. Clerc et al. 2012, MNRAS 423, 3545–3560
[2] Chiu, I. N., et al. 2023, MNRAS, 522, 1601

Observables

- CR — count rate in $0.2 - 2.3\,\mathrm{keV}$ energy band
- $\ln \mathrm{HR} = \ln\left(\frac{\mathrm{CR}_{[1-2]}}{\mathrm{CR}_{[0.5-1]}}\right)$ - ln of hardness ratio
- z - photometric redshift

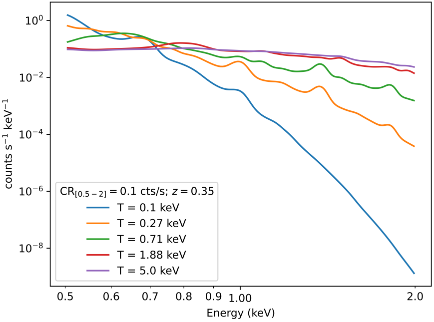
Data set

- This work uses a sample of clusters in *eROSITA* Final Equatorial Depth Survey (eFEDS) [3]
- This work utilizes spectroscopic measurements of $\mathrm{CR}_{[1-2]}$, $\mathrm{CR}_{[0.5-1]}$ [4]
- A cut in cluster redshift is applied: $0.1 < z < 1.2$
- f_{cont} cut reduces contamination due to point sources: $f_{cont} < 0.3$
- clusters with $\sigma_{\ln HR} = \sqrt{\left(\frac{\sigma_{\mathrm{CR}_{[1-2]}}}{\mathrm{CR}_{[1-2]}}\right)^2 + \left(\frac{\sigma_{\mathrm{CR}_{[0.5-1]}}}{\mathrm{CR}_{[0.5-1]}}\right)^2} > 1$ are excluded
- Final cluster sample contains 448 sources

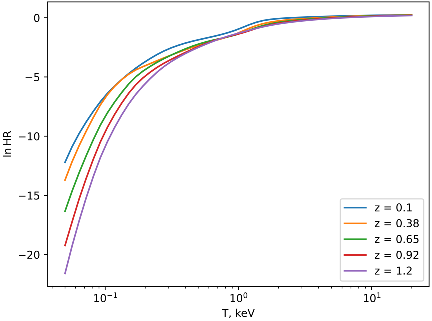
[3] A. Liu, et al. A&A 661, A2 (2022)
[4] T. Liu et al. A&A 661, A5 (2022)

$\ln \mathrm{HR}$ modelling

- The spectra are modelled with XSPEC and convolved with eROSITA response matrices
- ICM emission is modelled with thermal plasma model apec having metal abundance of $0.3 Z_\odot$
- The Galactic hydrogen absorption is modeled using `tbabs` with column density of $n_H = 3.5 \times 10^{20} \mathrm{cm}^{-2}$

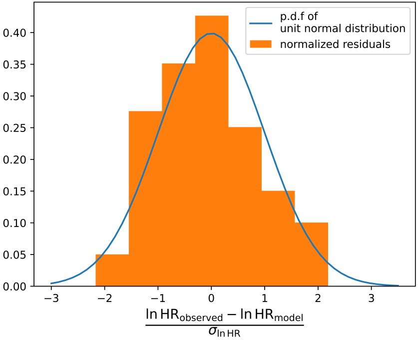


Synthetic spectra



$\ln \mathrm{HR}$ as a function of T

$\ln \mathrm{HR}$ modelling



Normalized residuals histogram

The accuracy of the model is tested on a subsample of 64 clusters with reliable T measurements

$\chi^2/64 = 0.953$

T - M scaling relation

$$\frac{T}{\mathrm{keV}} = A_T \left(\frac{M_{500}}{2.4 \cdot 10^{14} h^{-1} M_\odot} \right)^{B_T + \delta_T \ln\left(\frac{1+z}{1.35}\right)} \left(\frac{E(z)}{E(0.35)} \right)^{\frac{2}{3}} \left(\frac{1+z}{1.35} \right)^{\gamma_T}$$

- $E(z) = H(z)/H_0$
- σ_T - log-normal intrinsic scatter
- M_{500}, is defined by a sphere where the interior mass density is 500 times the cosmic critical density $\rho_c(z)$ at the cluster redshift z

CR - M scaling relation

$$\frac{\mathrm{CR}}{\mathrm{cts/s}} = A_{\mathrm{CR}} \left(\frac{M_{\mathbf{500}}}{1.4 \cdot 10^{\mathbf{14}} h^{-\mathbf{1}} M_{\odot}} \right)^{B_{\mathrm{CR}} + \delta_{\mathrm{CR}} \ln\left(\frac{\mathbf{1}+z}{\mathbf{1.35}}\right)} \left(\frac{E(z)}{E(0.35)} \right)^{\mathbf{2}} \left(\frac{1+z}{1.35} \right)^{\gamma_{\mathrm{CR}}} \left(\frac{D_L(0.35)}{D_L(z)} \right)^{\mathbf{2}} b(M_{\mathbf{500}}, z)$$

- $D_L(z)$ - luminosity distance
- σ_{CR} - intrinsic scatter
- $b(M_{500}, z)$ - count-rate bias

CR - M scaling relation

$$\ln(b(M_{500}, z)) = A_b + \left(B_b - \delta_b \ln\left(\frac{z}{0.35}\right)\right) \ln\left(\frac{M_{500}}{1.4 \cdot 10^{14} h^{-1} M_\odot}\right) + \gamma_b \ln\left(\frac{z}{0.35}\right)$$

A_b, B_b, δ_b, γ_b were calibrated by simulations [5]:

$A_b = 0.18 \pm 0.02$
$B_b = -0.16 \pm 0.03$
$\delta_b = -0.015 \pm 0.05$
$\gamma_b = 0.42 \pm 0.03$

[5] Chiu et al. 2022, A&A 661, A11

Cluster distribution

- $\frac{\mathrm{d}n}{\mathrm{d}M}$ - halo mass function [6]

$$\frac{\mathrm{d}^3 N}{\mathrm{d}z\,\mathrm{dCR}\,\mathrm{d}\ln\mathrm{HR}} = \int \mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M}\,\frac{\mathrm{d}^2 V}{\mathrm{d}z\mathrm{d}\Omega}\,\Delta\Omega\; P(\mathrm{CR}, \ln\mathrm{HR} | M, z, \vec{p})$$

- $\frac{\mathrm{d}^2 V}{\mathrm{d}z\mathrm{d}\Omega}$ - comoving volume
- $\Delta\Omega$ - survey solid angle
- $\vec{p}$ - model parameters

[6] Bocquet S., Saro A., Dolag K., Mohr J., 2016, MNRAS, 456, 2361

Cluster distribution

$$P(\mathrm{CR}, \ln \mathrm{HR} | M, z, \vec{p}) =$$
$$\int \mathrm{d}\widehat{\mathrm{CR}}\, \mathrm{d}T\; P(\mathrm{CR}|\widehat{\mathrm{CR}}, z)\; P(\ln \mathrm{HR}|\mathrm{CR}, T, z)\; P(\widehat{\mathrm{CR}}, T|M, z, \vec{p})$$

- $P(\mathrm{CR}|\widehat{\mathrm{CR}}, z)\; P(\ln \mathrm{HR}|\mathrm{CR}, T, z)$ - scatter of CR and $\ln \mathrm{HR}$ due to the measurement error
- $P(\widehat{\mathrm{CR}}, T|M, z, \vec{p})$ - describes the intrinsic scatter of T and CR

Cluster distribution

$P(\mathrm{CR}|\widehat{\mathrm{CR}}, z)$ - normal distribution with $\mu = \widehat{\mathrm{CR}}$ and $\sigma = \delta_{\mathrm{CR}}(\mathrm{CR}, z)$

$P(\ln \mathrm{HR}|\mathrm{CR}, T, z)$ - normal distribution with $\mu = \ln \mathrm{HR}(z, T)$ and $\sigma = \delta_{\ln \mathrm{HR}}(\mathrm{CR}, z)$

$$\delta_{\mathrm{CR}}(\mathrm{CR}, z) = 0.0154 \left(\frac{\mathrm{CR}}{0.1\mathrm{cts/s}}\right)^{0.576} \left(\frac{z}{0.35}\right)^{-0.079}$$

$$\delta_{\ln \mathrm{HR}}(\mathrm{CR}, z) = 0.35 \left(\frac{\mathrm{CR}}{0.1\mathrm{cts/s}}\right)^{-0.6}$$

Cluster distribution

$P(\widehat{\mathrm{CR}}, T|M, z, \vec{p})$ - bivariate log-normal distribution with covariance matrix:

$$\begin{pmatrix} \sigma_{\mathrm{CR}}^2 & \rho\sigma_{\mathrm{CR}}\sigma_T \\ \rho\sigma_{\mathrm{CR}}\sigma_T & \sigma_T^2 \end{pmatrix}$$

Completeness function

$$C(\mathrm{CR}, z) = \frac{1}{2}\left(1 + \mathrm{erf}\,\frac{\ln \mathrm{CR} - \ln \mathrm{CR}_{50,z}}{s_{\mathrm{CR}}}\right)$$

$$\mathrm{CR}_{50,z} = \mathrm{CR}_{50}\left(\frac{D_A(z)}{D_A(0.35)}\right)^{\gamma_z}$$

- $D_A(z)$ - angular diameter distance
- CR_{50}, s_{CR} - were measured in: Chiu, I. N., et al. 2023

  $\mathrm{CR}_{50} = 0.0624 \pm 0.0057$
  $s_{\mathrm{CR}} = 0.6514 \pm 0.1687$
- Differential number count is modified:

$$\frac{\mathrm{d}^3 N}{\mathrm{d}z\,\mathrm{d}\mathrm{CR}\,\mathrm{d}\ln \mathrm{HR}} \to C(\mathrm{CR}, z) \times \frac{\mathrm{d}^3 N}{\mathrm{d}z\,\mathrm{d}\mathrm{CR}\,\mathrm{d}\ln \mathrm{HR}}$$

Likelihood

Probability of observing N_i clusters in bin i: $P_i = \frac{n_i^{N_i}}{N_i!} e^{-n_i}$

where $n_i = \iiint_i \frac{\mathrm{d}^3 N}{\mathrm{d}z\,\mathrm{dCR}\,\mathrm{d}\ln\mathrm{HR}} \mathrm{d}z\,\mathrm{dCR}\,\mathrm{d}\ln\mathrm{HR}$

$$\ln L = \sum_i (N_i \ln n_i - n_i)$$

Fine binning limit ($N_i = \{0;1\}$):

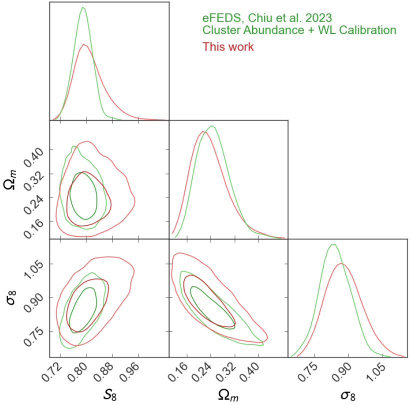
$$\ln L = \sum_i \ln \frac{\mathrm{d}^3 N}{\mathrm{d}z\mathrm{d}\ln CR\mathrm{d}\ln HR} - \int_{0.1}^{1.2} \mathrm{d}z \int_0^{+\infty} \mathrm{dCR} \int_{-\infty}^{+\infty} \mathrm{d}\ln\mathrm{HR} \frac{\mathrm{d}^3 N}{\mathrm{d}z\,\mathrm{dCR}\,\mathrm{d}\ln\mathrm{HR}}$$

Priors

Cosmology	
Parameter	Prior
Ω_m	$\mathcal{U}[0.1, 0.5]$
σ_8	$\mathcal{U}[0.6, 1.2]$
Ω_b	$\mathcal{U}[0.042, 0.049]$
H_0	$\mathcal{U}[50, 90]$
n_s	$\mathcal{U}[0.92, 1]$
T - M scaling relation	
A_T	$\mathcal{U}[0.525]$
B_T	$\mathcal{U}[0, 5]$
γ_T	$\mathcal{U}[-3, 3]$
δ_T	$\mathcal{U}[-3, 3]$
σ_T	$\mathcal{U}[0.05, 0.8]$
Correlated scatter	
ρ	$\mathcal{U}(-0.9, 0.9)$

CR - M scaling relation	
Parameter	Prior
A_{CR}	$\mathcal{N}(0.13, 0.03^2)$
B_{CR}	$\mathcal{N}(1.65, 0.2^2)$
γ_{CR}	$\mathcal{N}(0, 1.5^2)$
δ_{CR}	$\mathcal{N}(0, 1.5^2)$
σ_{CR}	$\mathcal{N}(0.3, 0.08^2)$
Count-rate bias	
A_b	$\mathcal{N}(0.18, 0.02^2)$
B_b	$\mathcal{N}(-0.16, 0.03^2)$
γ_b	$\mathcal{N}(0.42, 0.03^2)$
δ_b	$\mathcal{N}(-0.015, 0.05^2)$
Completeness function	
CR_{50}	$\mathcal{N}(0.062, 0.0057^2)$
s_{CR}	$\mathcal{N}(0.651, 0.168^2)$
γ_z	$\mathcal{U}[-3, 3]$

Results



$$\Omega_m = 0.230^{+0.066}_{-0.051}$$

$$\sigma_8 = 0.877^{+0.085}_{-0.076}$$

$$S_8 = \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.3} = 0.804^{+0.052}_{-0.037}$$

eFEDS, Chiu et al. 2023

	Cluster Abundance	Cluster Abundance + WL Calibration
Ω_m	$0.230^{+0.063}_{-0.069}$	$0.245^{+0.048}_{-0.058}$
σ_8	$0.867^{+0.073}_{-0.082}$	$0.833^{+0.075}_{-0.063}$
S_8	$0.792^{+0.049}_{-0.036}$	$0.791^{+0.028}_{-0.031}$

The goodness of fit

- Each observable dimension is binned in 10 bins
- Since the numbers of counts per bin is low, χ^2 cannot be used
- Modified Cash-statistic (Kaastra J. S., 2017, A&A, 605, A51):

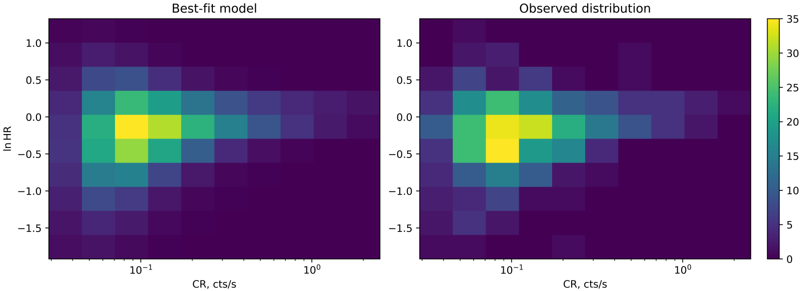
$$C = 2\sum_{i=1}^{n} s_i - N_i + N_i \ln(N_i/s_i)$$

- N_i - observed number of clusters in i-th bin, s_i - predicted number of clusters

$$\langle C \rangle = \sum_{i=1}^{n} 2 \sum_{k=0}^{\infty} P_k(s_i)(s_i - k + k \ln(k/s_i))$$

- $P_k(s_i)$ - Poisson distribution

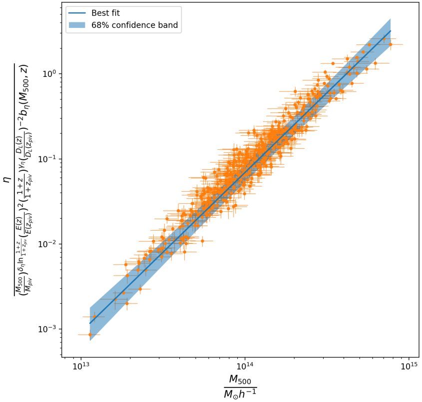
The goodness of fit



$$C_{observed} = 401$$

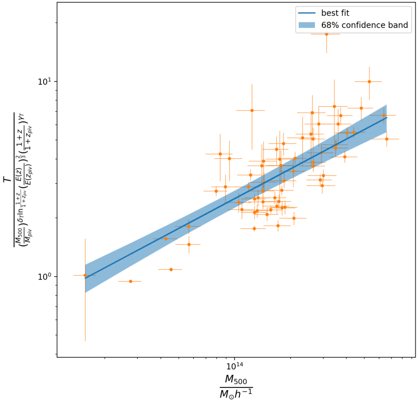
$$\langle C \rangle = 392 \qquad \Delta C^2 = 25^2$$

CR - M scaling relation



	This work	eFEDS, Chiu et al. 2023
A_{CR}	$0.130^{+0.029}_{-0.03}$	$0.133^{+0.026}_{-0.020}$
B_{CR}	$1.871^{+0.163}_{-0.155}$	$1.86^{+0.20}_{-0.15}$
γ_{CR}	$-1.14^{+0.498}_{-0.526}$	$-0.83^{+0.44}_{-0.50}$
δ_{CR}	$-0.629^{+0.421}_{-0.434}$	$-0.58^{+0.43}_{-0.50}$
σ_{CR}	$0.272^{+0.078}_{-0.076}$	$0.291^{+0.133}_{-0.078}$

T - M scaling relation



	This work	eFEDS, Chiu et al. 2022
A_T	$3.946^{+0.504}_{-0.439}$	$3.27^{+0.26}_{-0.31}$
B_T	$0.503^{+0.074}_{-0.066}$	0.65 ± 0.11
γ_T	$-0.595^{+0.458}_{-0.444}$	$-1.03^{+0.54}_{-0.75}$
δ_T	$-0.321^{+0.315}_{-0.281}$	$-0.02^{+0.66}_{-0.70}$
σ_T	0.339 ± 0.05	$0.069^{+0.061}_{-0.014}$

Conclusions

- This study presents a cosmological analysis of the eFEDS clusters sample using the CR-HR diagram method
- Cosmological constraints are consistent with previous analysis of the eFEDS data
- Constraints on CR-M scaling relation parameters are in a good agreement with those of Chiu et al. 2023
- T-M scaling relation constraints are in tension with the results from other cluster studies
- Possible source of error - large measurement uncertainties of HR
- Mean exposure time of the eRASS is higher than that of the eFEDS. This will make it possible to measure the spectral characteristics of clusters with greater accuracy

Thank you for your attention!