Testing generalized scalar-tensor theories of gravity with the pressure profiles of galaxy clusters

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Outline

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DHOST modification

Perturbed gravitational forces on small scales:

$$\frac{\mathrm{d}\Phi}{\mathrm{d}r} = \frac{G_{\mathrm{N}}^{\mathrm{eff}}\mathcal{M}(r)}{r^2} + \Xi_1 G_{\mathrm{N}}^{\mathrm{eff}}\mathcal{M}''(r)\,, \tag{1}$$

$$\frac{\mathrm{d}\Psi}{\mathrm{d}r} = \frac{G_{\mathrm{N}}^{\mathrm{eff}}\mathcal{M}(r)}{r^2} + \Xi_2 \frac{G_{\mathrm{N}}^{\mathrm{eff}}\mathcal{M}'(r)}{r} + \Xi_3\, G_{\mathrm{N}}^{\mathrm{eff}}\mathcal{M}''(r)\,, \tag{2}$$

with the *modified* or *effective Newton's constant* $G_{\mathrm{N}}^{\mathrm{eff}} = \tilde{\gamma}_{\mathrm{N}} G_{\mathrm{N}}$

Essentially a screening (Vainshtein) mechanism [Crisostomi & Koyama, 2018]

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Hydrostatic Equilibrium

The Hydrostatic equilibrium,

$$\frac{1}{\rho_{\rm gas}(r)}\frac{{\rm d}P_{\rm gas}(r)}{{\rm d}r} = -\frac{{\rm d}\Phi}{{\rm d}r}\,,$$

Modified according to the DHOST theory as,

$$\frac{{\rm d}\Phi(r)}{{\rm d}r} = \frac{G_{\rm N}^{\rm eff} M_{\rm HSE}(r)}{r^2} + \Xi_1 G_{\rm N}^{\rm eff}\frac{d^2 M_{\rm HSE}(r)}{dr^2}$$

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Pressure profile is now,

$$P^{\rm th}(r) = P^{\rm th}(0) - 1.8\mu m_{\rm p}\int_0^r n_{\rm e}(\tilde{r})\left[\frac{G_{\rm N}^{\rm eff} M_{\rm HSE}(\tilde{r})}{\tilde{r}^2} + \Xi_1 G_{\rm N}^{\rm eff} M''_{\rm HSE}(\tilde{r})\right]{\rm d}\tilde{r}$$

Mass profile and Electron density

NFW mass profile [Navarro et al., 1996]:

$$M(< r) = M_{500} \frac{\ln\left(1 + c_{500}x\right) - c_{500}x/(1 + c_{500}x)}{\ln\left(1 + c_{500}\right) - c_{500}/(1 + c_{500})}\,,\; x = \frac{r}{R_{500}}$$

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Vikhlinin profile [Vikhlinin et al., 2006]:

$$\frac{n_e(r)}{n_0} = \frac{(r/r_c)^{-\alpha/2}[1+(r/r_s)^{\gamma}]^{-\varepsilon/(2\gamma)}}{[1+(r/r_c)^2]^{(3/2)\beta-\alpha/4}}$$

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Total number of parameters:

$$\begin{aligned}\Theta_{\rm DHOST} &\in \{\Xi_1, \tilde{\gamma}_{\rm N}\}\\ \Theta_{\rm ED} &\in \{n_0, \alpha, \beta, \varepsilon, r_{\rm c}, r_{\rm s}\}\\ \Theta_{\rm M} &\in \{M_{500}, c_{500}\}\end{aligned}$$

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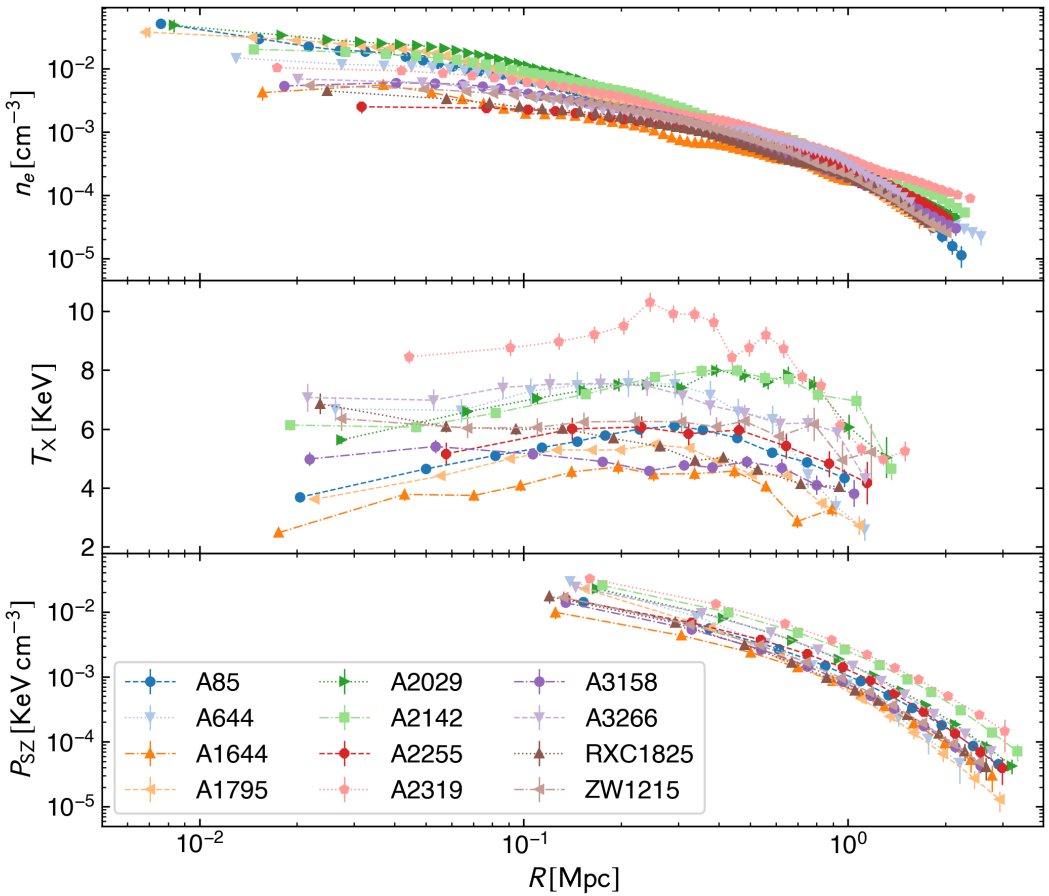
Data

Keeping it brief:

- A compilation of 12 clusters, namely X-COP [Ettori et al., 2019] (Hereafter E19) (See talks by Prof. Ettori tomorrow)



Likelihood

Joint likelihood for the observables:

$$
\begin{aligned}
-2\ln\mathcal{L} &= (\mathrm{P}_{\mathrm{SZ}}^{\mathrm{obs}} - \mathrm{P}_{\mathrm{SZ}}^{\mathrm{mod}})\Sigma_{\mathrm{TOT}}^{-1}(\mathrm{P}_{\mathrm{SZ}}^{\mathrm{obs}} - \mathrm{P}_{\mathrm{SZ}}^{\mathrm{mod}})^{T} + \ln \mid \Sigma_{\mathrm{TOT}} \mid \\
&+ \sum_{j=1}^{N_{P_{\mathrm{X}}}} \left[\frac{(P_{\mathrm{X},i}^{\mathrm{obs}} - P_{\mathrm{X},i}^{\mathrm{mod}})^2}{\sigma_{P_{\mathrm{X},i}}^2 + \sigma_{P,\mathrm{int}}^2} + \ln(\sigma_{P_{\mathrm{X},i}}^2 + \sigma_{P,\mathrm{int}}^2) \right] \\
&+ \sum_{i=1}^{N_{\mathrm{n_e}}} \left[\frac{(n_{e,i}^{\mathrm{obs}} - n_{e,i}^{\mathrm{mod}})^2}{\sigma_{n_{e,i}}^2} \right]
\end{aligned}
$$

Complete Bayesian analysis sampling over the parameters:

$$\Theta = \Theta_{\mathrm{ED}} \cup \Theta_{\mathrm{M}} \cup \Theta_{\mathrm{DHOST}}$$

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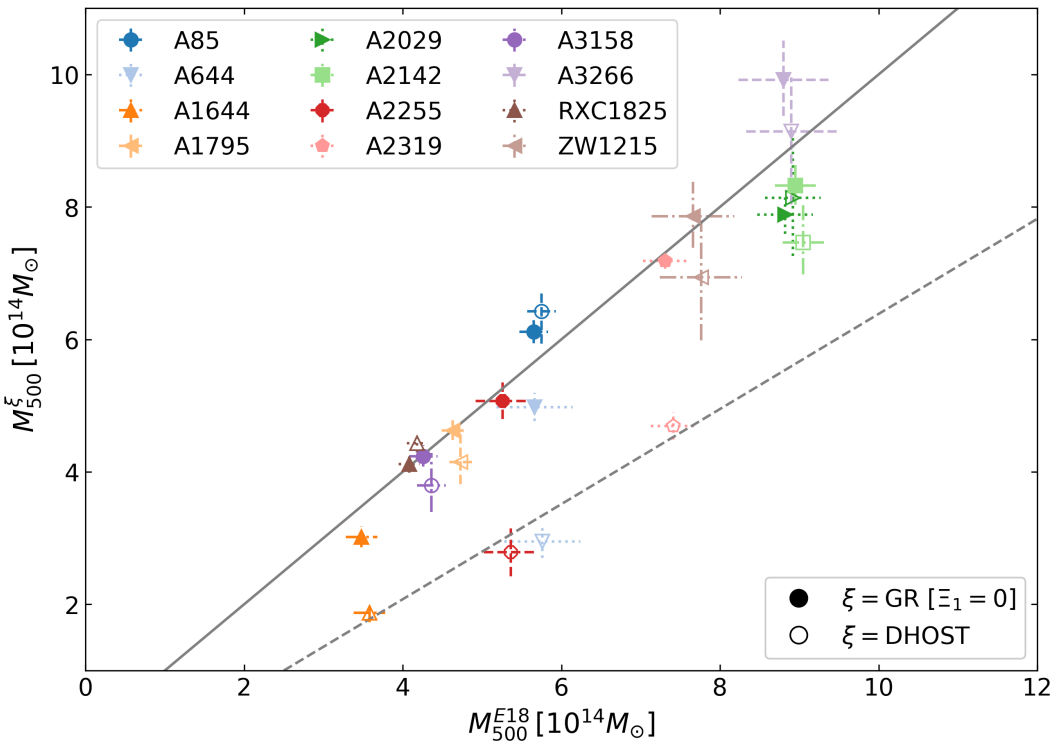
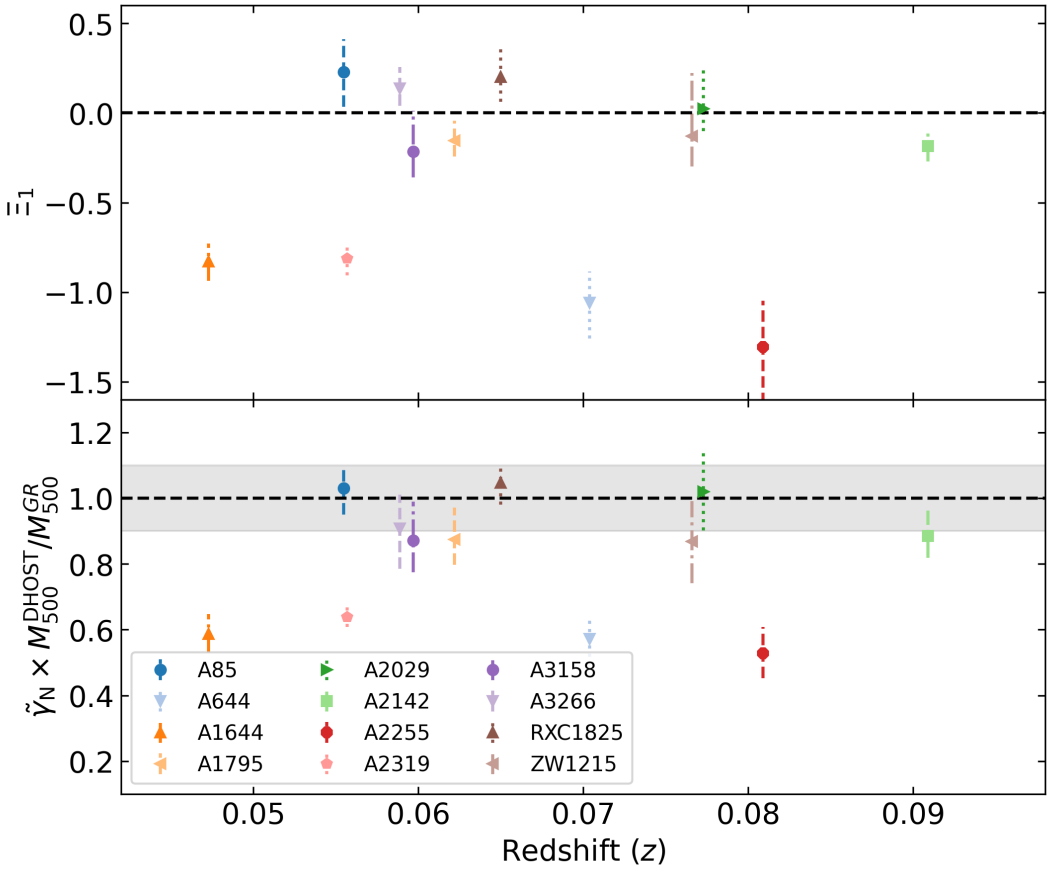
Mass comparisons and DHOST parameters

- Comparison of the mass estimates from the original analysis E19
- DHOST scenario masses in open markers



Mass comparisons and DHOST parameters

- Comparing DHOST parameters w.r.t GR case



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Primary observations

- 8 clusters show good agreement with mild deviations
- 4 clusters show extreme deviation from GR (non-NFW clusters):

A644, A1644, A2255 and A2319

NFW not the best fitting mass profile, as shown in E19

- Maybe such a large deviation is not so strange !!

Interesting aspect to investigate further

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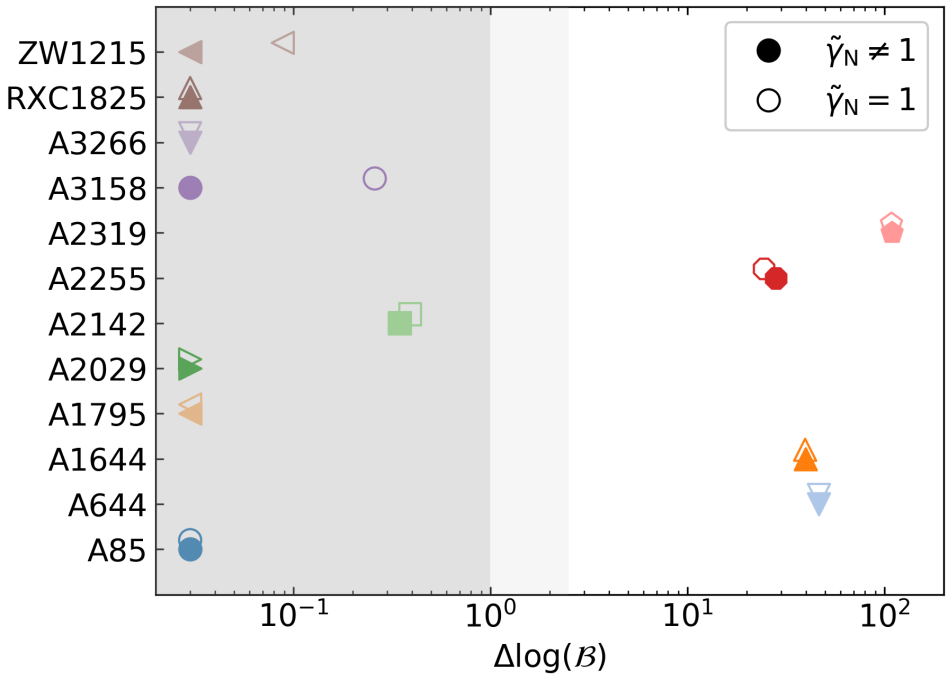
Model Selection - Bayesian evidence

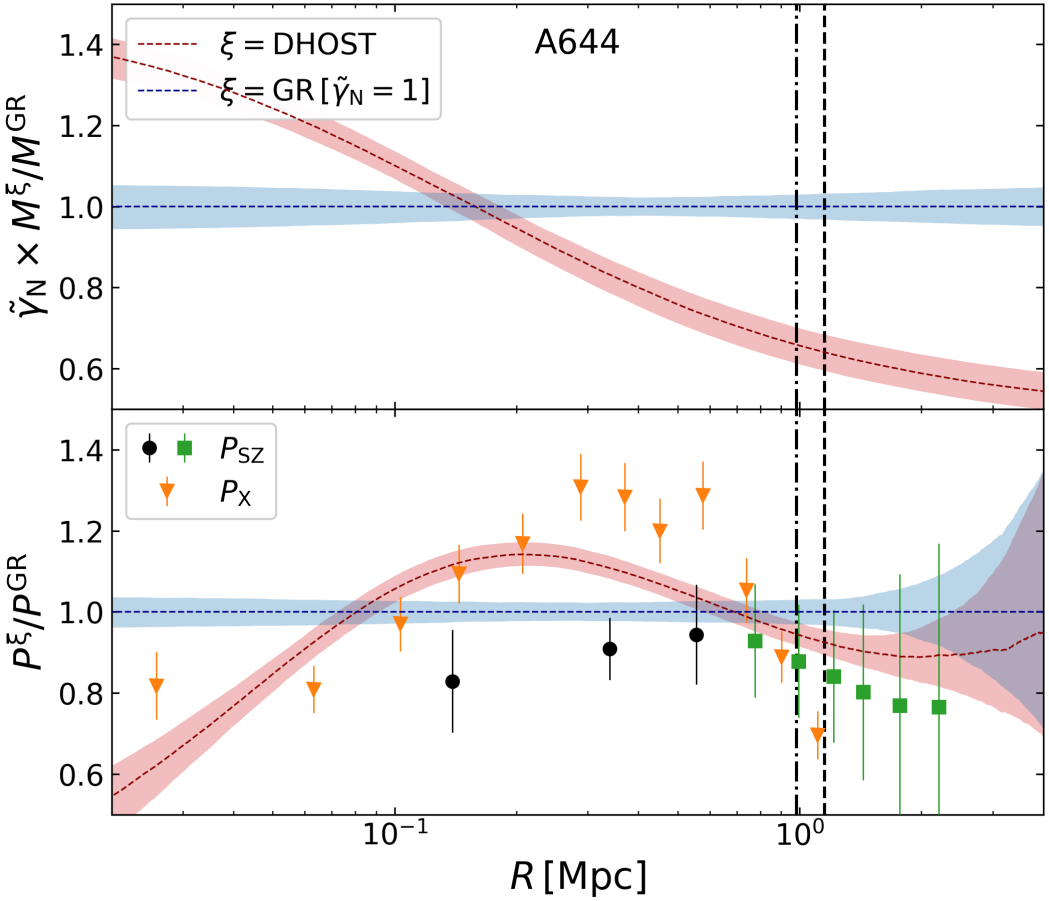
Both GR and DHOST have equivalent fit quality

Except for the 4 non-NFW clusters



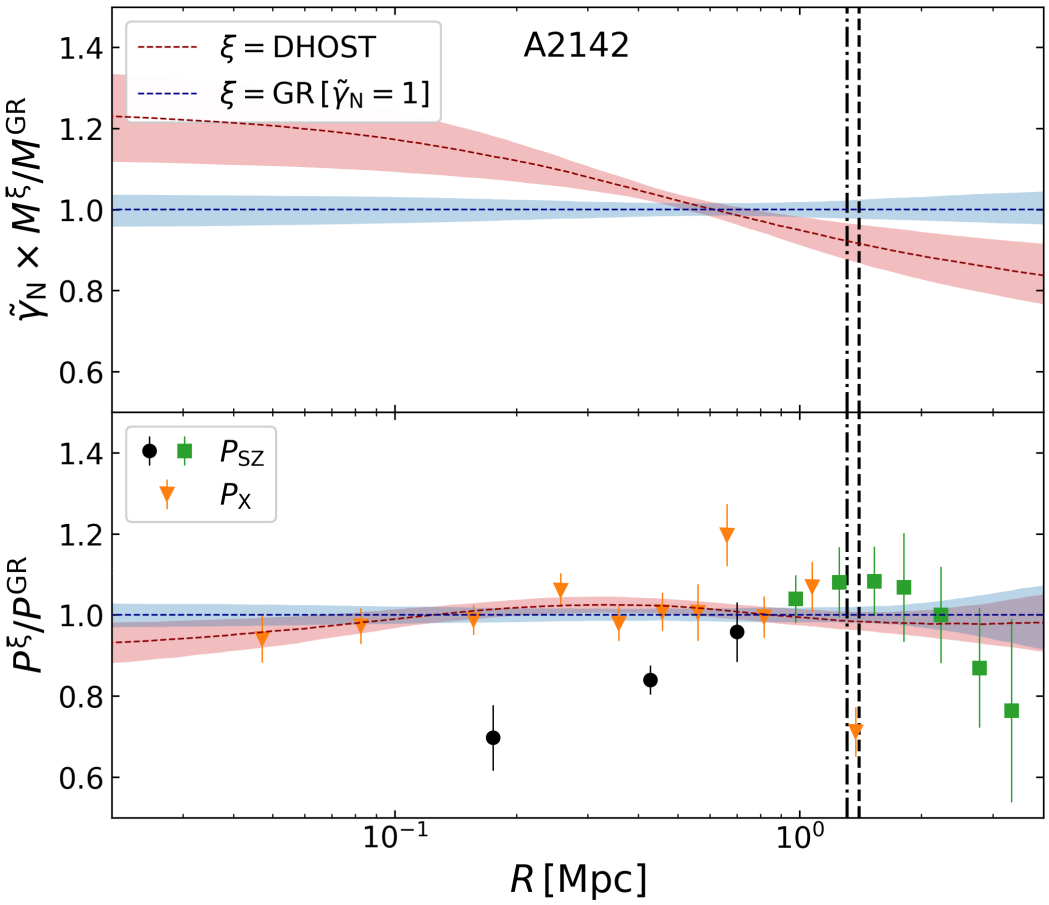
Example fit to non-NFW cluster – A644

Large deviation compensating for the fit to the P_{X} and P_{SZ} data



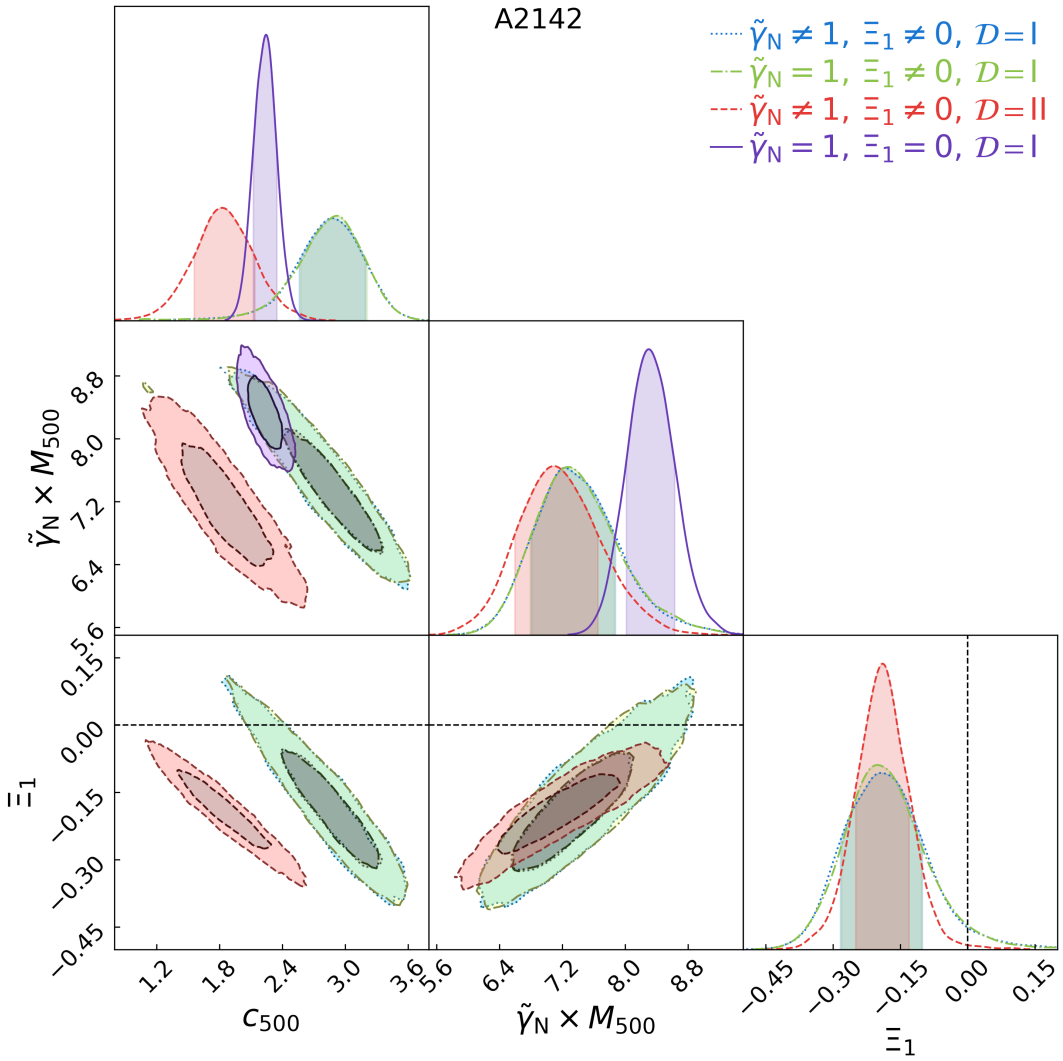
Example fit to NFW cluster – A2142

Mild deviation w.r.t the GR case



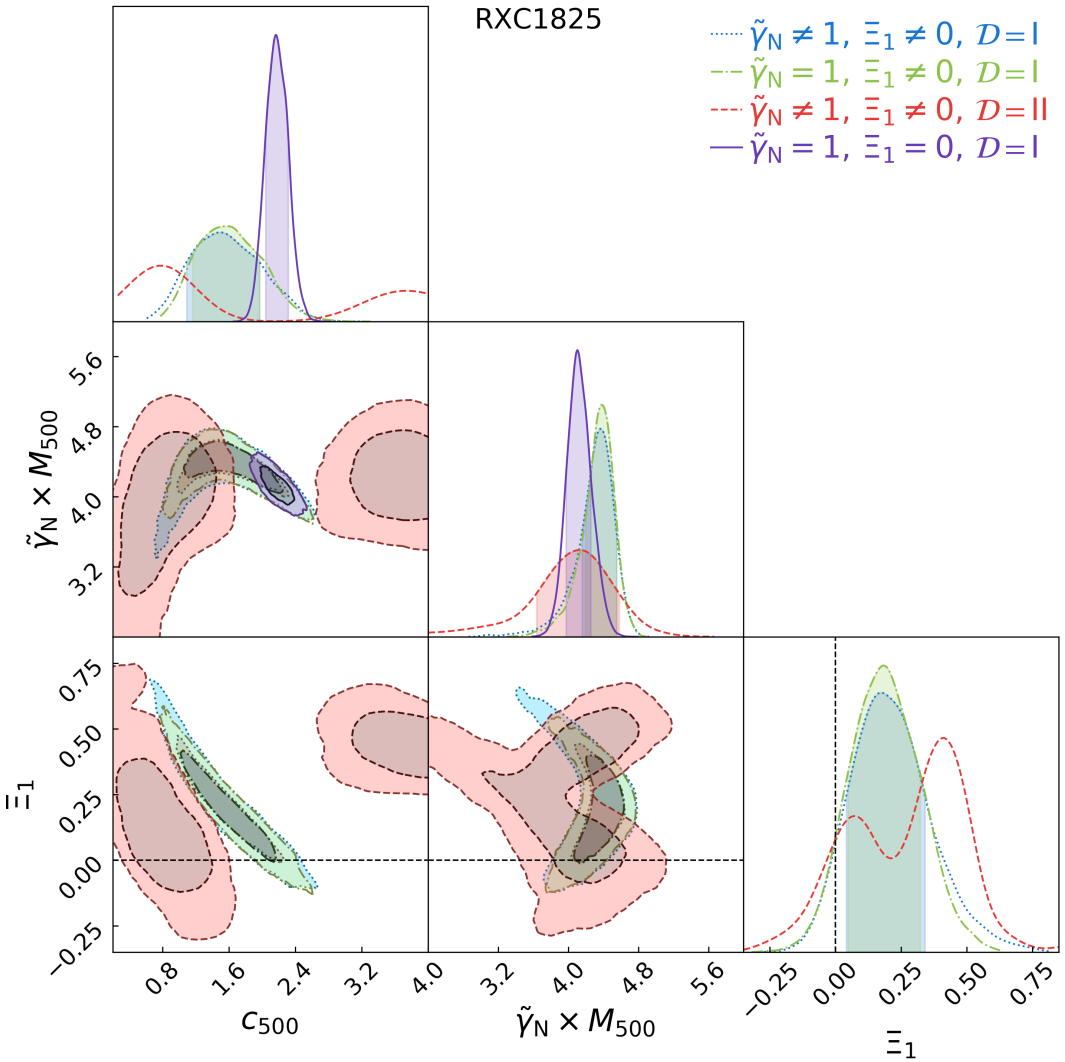
Example fit to NFW cluster – A2142

Posteriors from the MCMC analysis



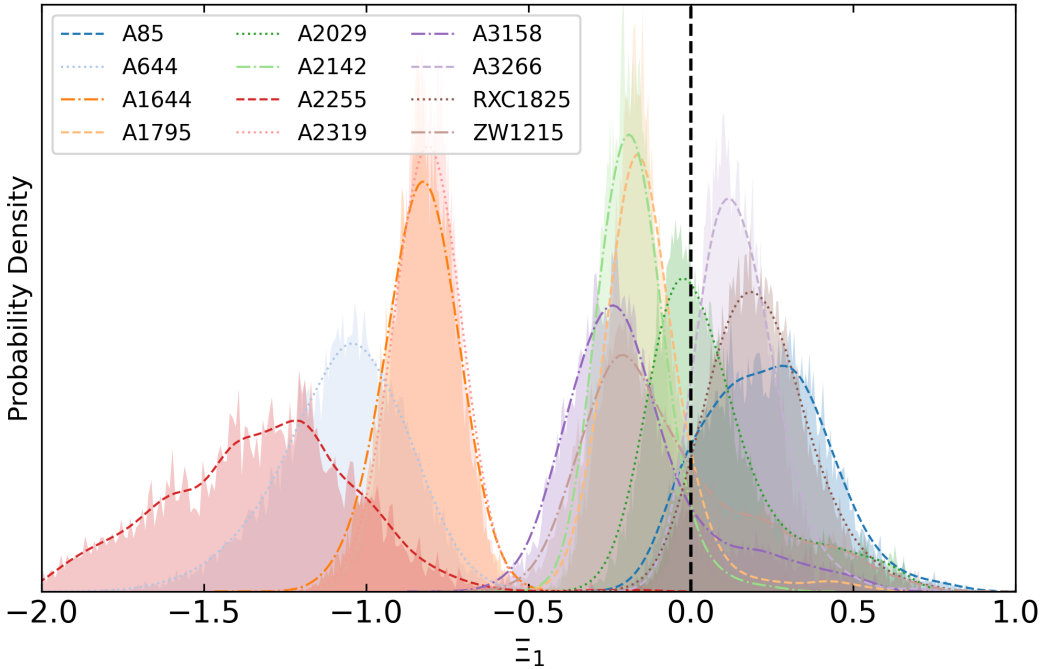
Example fit to NFW cluster – RXC1825

Posteriors from the MCMC analysis - In this case with enhanced correlations



Ξ_1 distributions and Joint constraint

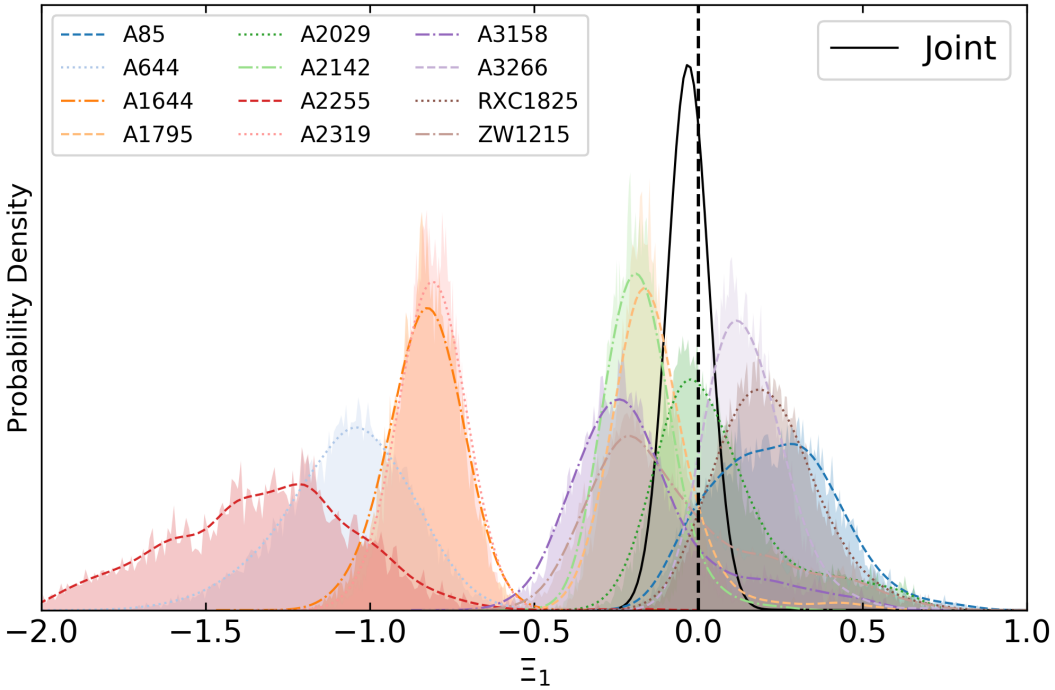
Posteriors of Ξ_1 obtained form the MCMC analysis



Ξ_1 distributions and Joint constraint

A proxy for joint constraint

- $\Xi_1 = -0.030 \pm 0.043$ [This work]
- $\Xi_1 = -0.028^{+0.23}_{-0.17}$ [Sakstein et al., 2016]



Contrasting with other limits

Existing limits for other observables:

- $\Xi_1 > -0.17$, requiring a stable static solution in non-relativistic stars [Saito et al., 2015]

- $\Xi_1 < 0.007$, consistency of the minimum mass for hydrogen burning in stars with the lowest mass red dwarf Sakstein [2015a,b]

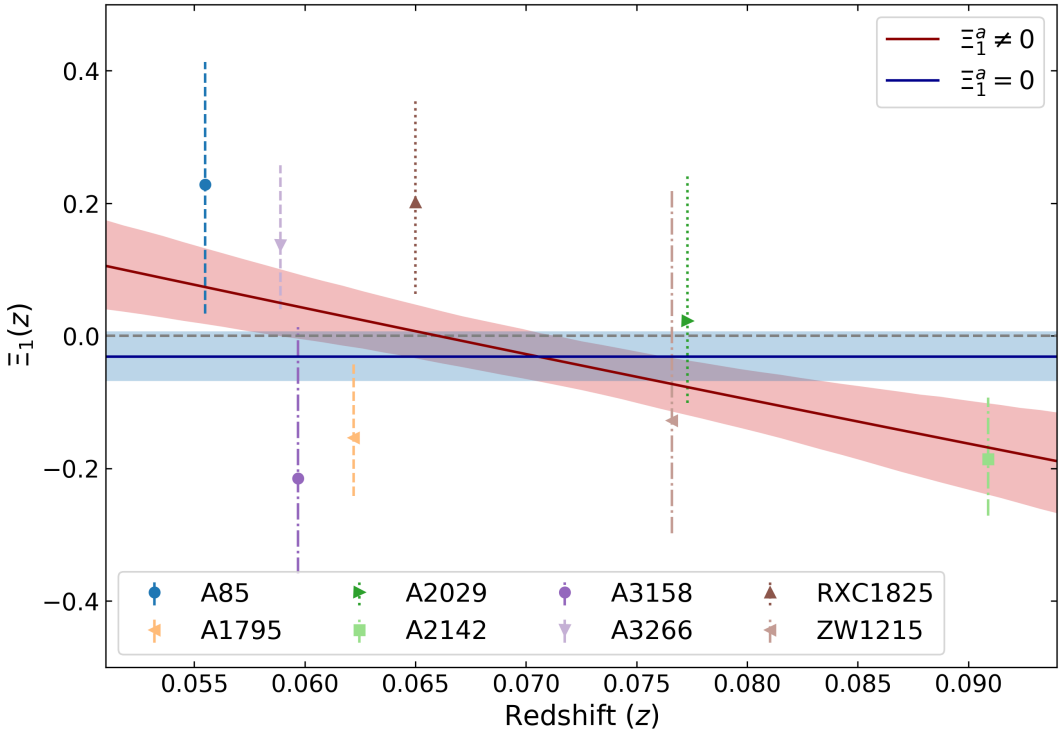
$$-0.17 < \Xi_1 < 0.007 \; [\mathrm{small-scale\,theoretical\,limits}]$$
$$-0.12 < \Xi_1 < 0.055 \; [\mathrm{cluster-scale\;95\%\,C.L.\,limits}] - \mathrm{This\,work}$$

Excellent agreement and improvement only with 8 clusters

Redshift evolution

Can also possibly indicate a redshift evolution

$$\Xi_1(z) = \Xi_1^0 + \frac{z}{1+z}\Xi_1^{\mathrm{a}}, \tag{3}$$



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Summary and outlook

Summary:

- Utilized the the well-compiled X-COP, to assess deviations from GR
- Need to assess large deviations in the 4 non-NFW clusters
- A well structured formalism to assess evolution in redshift
- Overall a very good agreement with other limits and improved constraints.

Future extensions:

- Inclusion of Weak lensing information to constrain Ξ_2 parameter
- Using larger redsfhit range of clusters, to assess cosmology
- Ease the MCMC analysis to extend for larger compilations
- Take advantage of future observations (such as NIKA2)

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Thank you !!

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References I

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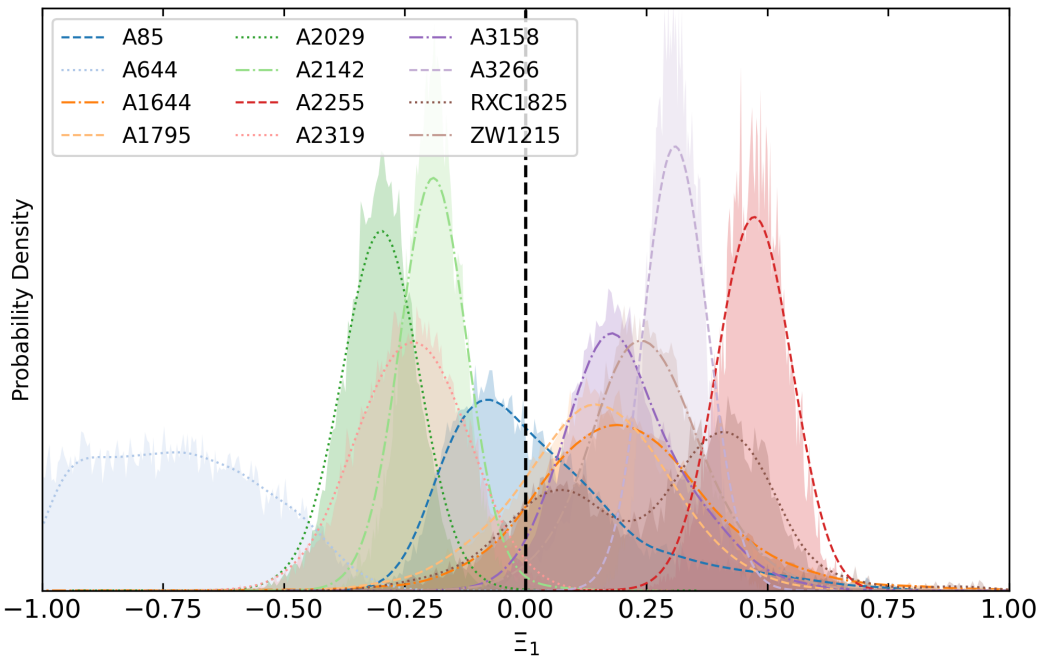
Extra ..

Analysis using the P_{SZ} data alone



Extra ..

Analysis of 12 simulated relaxed clusters [MUSIC]

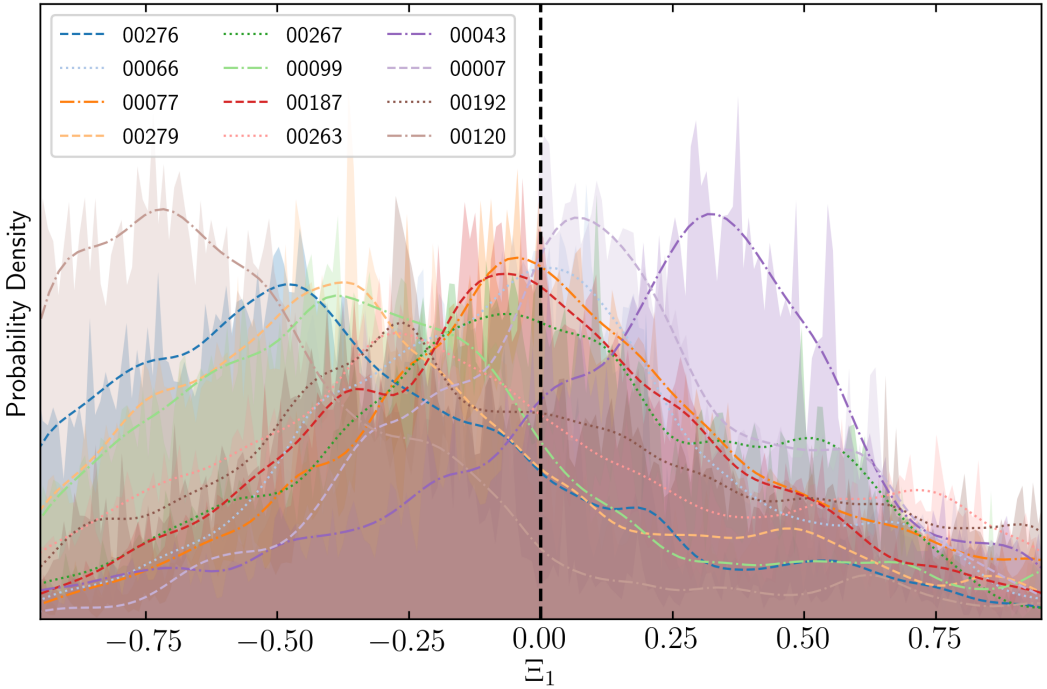


Table of all the constraints ..

Cluster	GR			DHOST					$\Delta \log(\mathcal{B})$
	c_{500}	M_{500} $[10^{14}\ M_\odot]$	R_{500} [Mpc]	c_{500}	M_{500} $[10^{14}\ M_\odot]$	R_{500} [Mpc]	Ξ_1	$\tilde{\gamma}_N \times M_{500}$ $[10^{14}\ M_\odot]$	
A85 (z=0.0555)	$2.048^{+0.088}_{-0.062}$	$6.14^{+0.14}_{-0.21}$	$1.270^{+0.010}_{-0.015}$	$1.16^{+0.57}_{-0.32}$	$4.10^{+3.43}_{-0.63}$	$1.292^{+0.017}_{-0.030}$	$0.30^{+0.11}_{-0.27}$	$6.46^{+0.26}_{-0.45}$	-3.7
A644† (z=0.0704)	$4.22^{+0.31}_{-0.17}$	$4.93^{+0.25}_{-0.18}$	$1.175^{+0.020}_{-0.015}$	$6.76^{+0.28}_{-0.33}$	$3.80^{+5.13}_{-0.71}$	$0.980^{+0.028}_{-0.030}$	$-1.04^{+0.18}_{-0.19}$	$2.85^{+0.24}_{-0.26}$	46.5
A1644† (z=0.0473)	$0.949^{+0.096}_{-0.103}$	$3.00^{+0.17}_{-0.15}$	$1.003^{+0.019}_{-0.017}$	$2.89^{+0.23}_{-0.20}$	$2.03^{+3.77}_{-0.67}$	$0.844^{+0.020}_{-0.027}$	$-0.837^{+0.119}_{-0.090}$	$1.78^{+0.13}_{-0.16}$	39.9
A1759 (z=0.0622)	$3.08^{+0.15}_{-0.10}$	$4.59^{+0.18}_{-0.12}$	$1.150^{+0.015}_{-0.010}$	$3.71^{+0.47}_{-0.35}$	$2.88^{+2.69}_{-0.81}$	$1.101^{+0.032}_{-0.035}$	$-0.169^{+0.111}_{-0.090}$	$4.03^{+0.34}_{-0.39}$	-2.9
A2029 (z=0.0773)	$3.14^{+0.12}_{-0.17}$	$7.84^{+0.33}_{-0.26}$	$1.369^{+0.019}_{-0.015}$	$3.31^{+0.49}_{-0.84}$	$6.0^{+4.9}_{-1.6}$	$1.352^{+0.089}_{-0.016}$	$-0.04^{+0.19}_{-0.12}$	$8.04^{+0.96,*}_{-0.88}$	-3.0
A2142 (z=0.0909)	$2.25^{+0.10}_{-0.12}$	$8.30^{+0.33}_{-0.28}$	$1.389^{+0.017}_{-0.017}$	$2.86^{+0.33}_{-0.29}$	$4.55^{+6.06}_{-0.92}$	$1.326^{+0.040}_{-0.024}$	$-0.203^{+0.101}_{-0.079}$	$7.21^{+0.65}_{-0.40}$	0.4
A2255† (z=0.0809)	$0.68^{+0.13}_{-0.10}$	$5.02^{+0.31}_{-0.26}$	$1.180^{+0.023}_{-0.021}$	$2.44^{+0.15}_{-0.21}$	$5.2^{+2.4}_{-2.1}$	$0.953^{+0.046}_{-0.043}$	$-1.1^{+0.26,*}_{-0.32}$	$2.66^{+0.38}_{-0.36}$	28.2
A2319†, ‡ (z=0.0557)	$3.400^{+0.129}_{-0.086}$	$7.15^{+0.16}_{-0.09}$	$1.336^{+0.010}_{-0.006}$	$5.14^{+0.13}_{-0.16}$	$8.83^{+3.63,*}_{-2.26}$	$1.151^{+0.020}_{-0.016}$	$-0.827^{+0.108}_{-0.076}$	$4.57^{+0.23}_{-0.19}$	109.6
A3158 (z=0.0597)	1.81 ± 0.12	$4.21^{+0.19}_{-0.14}$	$1.119^{+0.016}_{-0.012}$	$2.62^{+0.38}_{-0.56}$	$2.46^{+2.90}_{-0.62}$	$1.054^{+0.057}_{-0.029}$	$-0.23^{+0.15}_{-0.18}$	$3.51^{+0.57}_{-0.31}$	-0.4
A3266 (z=0.0589)	0.93 ± 0.10	$9.90^{+0.57}_{-0.59}$	$1.489^{+0.027}_{-0.030}$	$0.71^{+0.17}_{-0.20}$	$6.3^{+4.0}_{-1.8}$	$1.455^{+0.045}_{-0.055}$	$0.100^{+0.137}_{-0.079}$	$9.23^{+0.87}_{-0.99}$	-1.3
RXC1825 (z=0.0650)	$2.16^{+0.15}_{-0.12}$	$4.11^{+0.15}_{-0.13}$	$1.108^{+0.013}_{-0.012}$	$1.54^{+0.44}_{-0.43}$	$2.68^{+2.49}_{-0.46}$	$1.130^{+0.016}_{-0.018}$	$0.17^{+0.17}_{-0.13}$	$4.37^{+0.17}_{-0.22}$	-0.3
ZW1215 (z=0.0766)	$1.32^{+0.11}_{-0.14}$	$7.82^{+0.51}_{-0.50}$	$1.368^{+0.029}_{-0.029}$	$1.98^{+0.51}_{-0.84}$	$7.23^{+4.31,*}_{-2.85}$	$1.331^{+0.041}_{-0.076}$	$-0.21^{+0.27}_{-0.18}$	$7.14^{+0.65}_{-1.18}$	-4.5

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DHOST Lagrangian

Action of the viable Class Ia DHOST theory after GW170817 event ($c_g^2 = c^2$):

$$S = \int d^4x \sqrt{-g}\, \mathcal{L}\,, \tag{4}$$

where

$$\begin{aligned} L^{\mathrm{DHOST}}_{c_g^2=c^2} &= P + Q\,\Box\phi + F\,R + A_3\phi^\mu\phi^\nu\phi_{\mu\nu}\Box\phi \\ &+ \frac{1}{8F}\left(48{F_X}^2 - 8(F - XF_X)A_3 - X^2A_3^2\right)\phi^\mu\phi_{\mu\nu}\phi_\lambda\phi^{\lambda\nu} \\ &+ \frac{1}{2F}\left(4F_X + XA_3\right)A_3(\phi_\mu\phi^{\mu\nu}\phi_\nu)^2\,. \end{aligned} \tag{5}$$

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DHOST Lagrangian

Dimensionless coefficients:

$$
\begin{aligned}
\Xi_1 &= -\frac{(4F_X - XA_3)^2}{16FA_3}\,, \\
\Xi_2 &= -\frac{2XF_X}{F}\,, \\
\Xi_3 &= \frac{16{F_X}^2 - A_3^2X^2}{16A_3F}\,, \\
\Xi_0 &= -\frac{F_XX}{F} - \frac{3}{4}\frac{A_3X^2}{F}\,.
\end{aligned}
\tag{6}
$$

Bayesian Evidence

We utilize the Bayesian evidence criteria readily available in an MCMC analysis

$$p(\Theta|\mathcal{D},\mathcal{M}) = \frac{p(\mathcal{D}|\Theta,\mathcal{M})\pi(\Theta|\mathcal{M})}{p(\mathcal{D}|\mathcal{M})} \tag{7}$$

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