Dark matter in galaxy clusters from X-ray & SZ effect

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Clusters of Galaxies

• The largest gravitationally-bound structures in the universe

"dunkle Materie" (Zwicky 1933)
 ~80% of total mass (~15% hot gas; few % stars)

Properties of the DM



Cosmology from the **internal structures** of Galaxy Clusters

- Mass distribution
 → (SI)DM / MOND (Ettori+19; Eckert+22)
 - Concentration/sparsity $\rightarrow \{\Omega_m; \sigma_8\}$ (Corasaniti+21, 22)
 - Triaxial shape → consistency with ΛCDM (Sereno+18)
 - X/SZ pressure profiles \rightarrow H₀ (*Kozmanyan+19;* Ettori+20)
 - Gas mass fraction $\rightarrow \{\Omega_m; \Lambda, W\}$ (Ettori+10; *Mantz+21*)

→ Reliable & robust reconstruction of the (total & baryonic) mass distribution



 $M_{tot} \sim R \ T \sim \Delta \ R^3 \sim T^{3/2} \sim M_{gas} \sim L^{3/4} \sim Y^{3/5}$

X-COP: *XMM* +*Planck* (Eckert+17)











277.00 276.80 276.60 276.40 276.20 Right ascension 276.00 275.80





207.60

207.80





207.40 207.20 207.00 Right ascension

205.80

205.60



124.60 124.40 124.40 Right ascension

124.40 124.20

124.00 123.80

125.00 124.80



139.60 139.40 Right accession 139.80





X-COP: "universal" profiles (& scatter; Ghirardini+19)



$$M_{
m tot}(< r) = -rac{r P_{
m gas}}{\mu m_{
m u} G n_{
m gas}} rac{d \log P_{
m gas}}{d \log r}$$



 ✓ Use of analytic mass models (e.g. NFW, ISO) by fitting T_{XMM} / P_{Planck} with values obtained from inversion of HE

$$\begin{split} \log \mathcal{L} &= -0.5 \left[(P - P_{model}) \Sigma_{tot}^{-1} (P - P_{model})^T + n \log \left(\det \left(\Sigma_{tot} \right) \right) | \right] \\ &- 0.5 \sum_{i=1}^n \left[\frac{(T_i - T_{model,i})^2}{\sigma_{T,i}^2 + [\sinh(\sigma_{int}) \cdot T_{model,i}]^2} - \log \left(\frac{1}{\sigma_{T,i}^2 + [\sinh(\sigma_{int}) \cdot T_{model,i}]^2} \right) \right] \\ &- 0.5 \left[\sum_{i=1}^n \frac{(\epsilon - \epsilon_{model,i})^2}{\sigma_{\epsilon,i}^2} \right] \end{split}$$



(Eckert, Ettori, et al. 2022a)



Mass reconstruction in A1795

(i) n_e profile reconstructed with the multi-scale method;

(ii) non parametric reconstruction of the 3D temperature profile compared to the spectroscopic X-ray measurements and the 3D temperature profile obtained by dividing the SZ pressure by the X-ray density (projected, spec-w, PSF convolved T) (iii) mass profiles obtained with different reconstructions (NFW, Einasto, Forward, and NP) -> https://github.com/domeckert/hydromass

X-COP: mass profiles (Eckert, Ettori, et al. 2022a)



(Eckert, Ettori, et al. 2022a)







- NFW profile provides an excellent description: deviations of less than 10% over a wide radial range; but more diversity in individual shape
- The average NFW concentration and its scatter agree very well with the prediction of the ΛCDM framework

(Eckert, Ettori, et al. 2022a)



 $M_{tot}(r) = M_{DM}(r) + M_{gas}(r) + M_{BCG}(r) + M_{sat}(r)$ stellar mass distributions from CFHT r-band imaging (Loubser+20)



				/					
Cluster	$f_{\mathrm{gas},2500}$	$f_{\star,2500}$	$f_{\rm bar,2500}$	$f_{gas,500}$	$f_{\star,500}$	$f_{ m bar,500}$	$f_{gas,200}$	$f_{\star,200}$	$f_{ m bar,200}$
A644	7.7 ± 0.1	1.2 ± 0.4	8.9 ± 0.5	12.8 ± 0.6	1.3 ± 0.5	14.1 ± 1.1	16.9 ± 1.2	1.5 ± 0.6	18.4 ± 1.7
A1795	9.6 ± 0.1	1.7 ± 0.6	11.3 ± 0.6	13.4 ± 0.3	1.3 ± 0.5	14.7 ± 0.7	15.8 ± 0.5	1.3 ± 0.4	17.1 ± 1.0
A2029	11.1 ± 0.1	2.8 ± 0.9	13.8 ± 1.1	14.4 ± 0.3	2.1 ± 0.7	16.5 ± 1.0	17.1 ± 0.7	2.0 ± 0.7	19.1 ± 1.4
A2142	12.0 ± 0.1	2.3 ± 0.8	14.3 ± 0.9	14.1 ± 0.2	1.7 ± 0.6	15.8 ± 0.8	14.7 ± 0.5	1.5 ± 0.5	16.2 ± 1.0
A2319	9.2 ± 0.1	2.0 ± 0.7	11.3 ± 0.8	17.0 ± 0.2	1.5 ± 0.5	18.5 ± 0.7	24.9 ± 0.5	1.5 ± 0.5	26.4 ± 1.0



Eckert+22a; Ettori+19 & +17 on RAR/MOND/EG

X-COP: SIDM

(Eckert, Ettori, et al. 2022b)

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$$\rho_{\text{Einasto}}(r) = \rho_s \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha} - 1\right)\right]$$

Table 1. Normal priors on the Einasto fit parameters. Here P_m and dP_m denote the outermost SZ pressure value and its error.

Parameter	Mean	σ	Min	Max
r _s [kpc]	700	300	100	3000
С	1.8	1.5	0	10
μ	5	3	0.2	20
\dot{P}_0	P_m	dP_m	$P_m - 2dP_m$	$P_m + 2dP_m$







X-COP: SIDM

(Eckert, Ettori, et al. 2022b)





 $\alpha_{\text{Einasto}} = \alpha_0 + \alpha_1 \left(\frac{\sigma/m}{1 \text{ cm}^2/\text{g}}\right)^{\gamma}$

 $\sigma/m < 0.19 \text{ cm}^2/g (95\% \text{ c.l.})$ at collision velocity $v_{DM-DM} \sim 1000 \text{ km/s}$

An XMM-Newton Multi-Year Heritage Program *Witnessing the culmination of structure formation in the Universe* URL: xmm-heritage.oas.inaf.it

CHEX-MATE (the Cluster HEritage project with XMM-Newton: Mass Assembly and Thermodynamics at the Endpoint of structure formation): **3 Msec** over the period 2018-21 to survey *homogenously* **118 Planck-SZ selected objects** comprising an unbiased census of:

- the population of clusters at the most recent time (z < 0.2)
- the most massive objects to have formed thus far in the history of the Universe



CHEX-MATE gallery 2021, A&A, 650, 104

P522G000.13+78.04	PSZ2G004.45-19.55	P5Z2G006.49+50.56	PSZ2G008.31-54.74	P522G006.94/88.22	P522G021.10+33.24	PSZ26028-63+50:13 2:90992	P5Z2G028.89+60.13	P5Z2G031.93+78.71	P522G033.81+77.18
PSZ2G040.03+74.95	PSZ2G040.58+77:12	P5220041.45+29.10	PS22G042.81+56.61	P5226044.20+48.66	P522G044.77-51.30	PSZ2G046.10+27.18	7522G04F,884-56-48	220078	P5Z2G049.22+30.87
P\$22G049.32+44.37	PS22(050:40+31.17	P\$22G053.53+59.52 z=0.113	P\$22G055.59+31.85	PSZ2G056.77+36.32	P522G050/93-55.08	PSZ2G057.25-45.34	PSZ2G057:61+34.93	P522G057/76+52.32	PSZ2G057:92+27.64
PS22G062,46-21,35	P5Z2G066.41+27.03	P\$226066.68+68.44	PS22G067,17+67.46	PS22G067:52+34.75	P522G068.22+15.18	P5Z2G071.63+29,78	PSZ2G072.62+41.46	P522G073.97-27.82	P522G075.71+13.51
P5Z2G077,39-26.63	r95226080.16+57.69	PSZ20080.37+14.64	95226680.41.33.23	PSZ2G083.29-31.03	P522G083.86+85.09,	PSZ26085.98+26.69	PSZ2G087.03-57.37	P522G092.71+73.46	PSZ2G094,69+26.36
P5220099.48+55.60	PS22G105.55+77.21	P5Z2G106.87-83.23	PSZ2G107.10+65.32	PSZ2G111.61-45.71	P5Z2Q111,75+70.37	P522G113.29-29.69	P5Z2G113.91-37.01	P5220114.79-33.71	P5Z2G124,20-36.48
P5Z26143.26+65.24	PSZ2G149,39-36.84	P5Z2G155.27-68.42	P522G159.91-73.50	P5220172.74+65.30	P522G172,98-53.55 z=0.373	PSZ2G179.09+60.12	PSZ2G186.37+37.26	P5220187.53+21.92	P5Z2G192.18+56.12 2000 2=0.124

CHEX-MATE multi-λ 2021, A&A, 650, 104



SZ data (including Planck) are public

62 objects with published WL analysis (*see LC² catalog, Sereno 15*); 26+ objects will have dedicated proposals (*HSC/Subaru PI: Sayers; Megacam/CFHT, PI: Gavazzi/Umetsu; OmegaCam/VST PI: Sereno*)

Goals of CHEX-MATE

 Selection for the 3 Msec program:

 SNR>6.5;
 $z \in [0.05, 0.6];$ $M_{Tier-2} > 7.25e14$

- Assess the relative importance of gravitational and non-gravitational processes in shaping cluster properties
- Probe the dynamical collapse of the gas on different scales
- Construct a consistent picture of cluster mass estimates
- Provide a unique reference for evolution studies and numerical modelling
- Legacy for Next Generation missions