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 M_{tot} (~15% hot gas; few % stars)
- **Cosmology from N(M), clustering** & *internal structure:* Uno itinere non potest perveniri ad tam grande secretum
- Mass distribution \Rightarrow (SI)DM / MOND (Ettori+19; Eckert+22) Concentration/sparsity \Rightarrow { Ω_m ; σ_8 } (Corasaniti+21, 22) Triaxial shape \Rightarrow consistency with Λ CDM (Sereno+18) X/SZ pressure profiles \Rightarrow H₀ (Kozmanyan+19; Ettori+20) Gas mass fraction \Rightarrow { Ω_m ; Λ , w} (Ettori+10; Mantz+22) Bulleticity \Rightarrow (SI)DM / MOND γ -ray signal from DM in clusters (\Rightarrow INAF-CTA AdR @OAS-Bologna)

Reliable & robust reconstruction of the (total & baryonic) M distribution



Bullet cluster

Dark

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MACSJ0025

Hydrostatic Mass, velocities & non-thermal pressure



Hydrostatic bias: $(1-b) = M_X/M_{500}$



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Planck ESZ sample (120 obj; *Lovisari, Ettori+20*)

Gianfagna+21

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











68.60 68.40 68.20 68.00 67.80 67.60 67.40 67.20 67.00 Right ascension











139.80 139.60 139.40 Dight acconcion







207.80 207.60 207.40 207.20 207.00 Right ascension 206.80 124.80 124.60 124.40 124.20 124.00 123.80 **Right ascension**

125.00



X-COP: thermodynamic profiles (Ghirardini+19; *M_{HE}*: Ettori+19; *P_{NT}*: Eckert+19)



X-COP: non-thermal P

(Eckert+ 19 arXiv:1805.00034)







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; *PI Ettori & Pratt +~80 collaborators*): **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	PSZ2G006.49+50.56	PSZ2G008.31-54.74	P522G006,94+81,22	PS22G021.10+33.24	PSZ2G028-63+50.15 2=0.092	P5Z2G028.89+60.13	P5Z2G031-93+78,71	P522G033.81+77.18
PSZ2G040.03+74.95	P5Z2G040.5B+77.12	P5220041,45+29.10	PS22G042.81+56.61	PSZ2G044.20+48.66	PSZ2G044.77-51.30	P5Z2G046.10+27.18	7522G046,88+56.48	2222604810+57.16	P5Z2G049.22+30.87
P5Z2G049.32+44.37 z=0.097	P522G050.40+31.17	PSZ2G053.53+59.52 z=0.113	P\$226055.59+31.85	PSZ2G056.77+36.32	PSZ2G056/93-55.08	PSZ2G057.25-45.34	PS22G057:61+34.93	PS22G057/78(52.32	PSZ2G057:92+27.64
P522G062.46-21.35	PSZ2G066.41+27.03	P522G066.68+68.44	PSZ2G067,17+67.46 z=0.171	PSZ2G067.52+34.75	P5Z2G068.22+15.18	PSZ2G071.63+29,78	PSZ2G072.62+41.46	P5Z2G073.97-27.82	PSZ2G075.71+13.51
P522G077.90-26.63	PSZ2C080.16+57.65	P522G080.37+14.64	95226080.41-33.24	P522G083.29-31.03	PSZ26083.86+85.09.	P5226085.98+26.69	PSZ2G087.03-57.37	P5Z2G092.71+73.46	PSZ2G094.69+26.36
PS22C099.48+65.60	P5220105.55+77.21	P5Z2G106.87-83.23	PSZ2G107.10+65.32	PSZ2G111.61-45.71	P5220111.75+70.37 2=0183	P5226118.79-29.69	P5Z2G113.91-37.01	P522C[14,79-33,0]	P5/20124/20-36.48
PSZ26143.26+65.24	PSZ2G149.39/36.84	PSZ2G155.27-68.42	PSZ2G159.91-73.50	P522(1172,74+65.30) 2=0.079	PSZ2G172.98-53.55	PSZ2G179.09+60.12	PSZ20186.37+37.26	P5Z2G187.53+21.92	P5Z2G192.18+56.12 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*)

Temperature structure in the ICM (Lovisari, Ettori et al. arXiv:2311.02176)

Velocities in the ICM



Gaspari+13-14, Zhuravleva+14: Iow M flow → δK High M → δP

Schuecker+04: Coma

Heinrich+24: ICM density fluctuations in ~80 nearby (z<1) GCs

Temperature structure in the ICM (Lovisari, Ettori et al. arXiv:2311.02176)



 $\Rightarrow M = v/c_s \sim \sigma_T/T$ $\Rightarrow E_{turb} / E_{therm} = 0.5 \gamma (\gamma - 1) (3 M_{1D}^2) = 0.5 \gamma (\gamma - 1) M^2$

Temperature structure in the ICM (Lovisari, Ettori et al. arXiv:2311.02176)



 $b = 1 - M_{HE}/M_{tot} = (E_{th}/E_{turb} + 1)^{-1}$ ~0.06 [0.03-0.13] / after integration: 0.11 [0.04-0.22]

S_X fluctuations in the ICM (Dupourqué, Clerc et al. arXiv:2403.03064)



6 September 2023, 23:42 UTC XRISM/SLIM successful launch



Velocities in the ICM

Compilation of v_{ICM} (mostly 1 σ upper limits) (Sanders arXiv:2301.12791)





Hitomi collaboration, Nature 2016

Velocities in the ICM: XRISM

PV: Perseus (5 pointings), Coma (2), M87 (4), Centaurus, A3667, **A2029 (3)**, (A2319 as a test)

AO1 (~30% of t_{exp}; ESA: 8%, 7x more time requested): Phoenix, The toothbrush, Ophiuchus, A85, A496, A754, A1060/Hydra-A, A1413, *A1689*, A1914, A2034, A2052, *A2142*, A2163, A2199, A3395, A3571, MKW4, more on Perseus, Coma, Centaurus, A3667, ...



Take-home messages on P_{NT}

Analytic model (Ettori & Eckert 22) of P_{NT} \rightarrow b_{HE,} σ_{turb} i(cm)z (Ettori+20, 23): a semi-analytic model based on
 P_{univ} + cMz; reproduce spatially-resolved & integrated
 quantities \rightarrow forecasting b_{HE} (vel_{bapec})

✓ in relaxed objects (X-COP): b₅₀~0.1 (<0.2)
 ✓ (CHEX-MATE; M_{Planck}): b₅₀~0.1 (<0.3)
 ✓ Required: b_{Planck} = 0.38 ± 0.03

Hydrodynamic simulations (from e.g. Magneticum, the300, ENZO) convolved with SIXTE-like tools are needed to infer correlation between intrinsic and observed properties (turbulence, bulk motions, structure functions, true b_{HE})



