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AstroParticle physics of LSS in HXRs

DM, CRs & BHs

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Abstract. We discuss the relevance of Hard X-ray observations of Large Scale Structures in the universe, and especially of galaxy clusters, to unveil several issues that are relevant for Cosmology and Astro-Particle Physics of cosmic structures: the nature of Dark Matter, the origin of cosmic rays, the role of magnetic fields and the impact of black holes.

Key words. galaxies: clusters: Cosmology: astro-particle physics

1. Introduction

The description of the Large Scale Structure (LSS) network in the universe and especially of its pillars – galaxies and galaxy clusters – is continuously enriching of physical details regarding their matter and field content.

Dark Matter (DM) is the dominant form of matter and creates the potential wells of LSS: if we consistently take into account the fundamental nature of DM particles,[1] we are inevitably bound to consider the effects of their annihilation (in the case of neutralino SUSY DM particles) or their decay (in the case of sterile neutrinos) on the structure and evolution of the atmospheres of cosmic structures.

Baryonic material collected in the DM potential wells of LSS is likely shocked and heated by large–scale shocks (see, e.g. (Ryu et al. 2003; Pfrommer et al. 2007)) which produce a complex distribution of shock waves in both the intergalactic and intracluster (IC) media. The presence of shock waves, with relatively high Mach numbers, naively suggests that Fermi-like acceleration might take place in LSS thereby accelerating **cosmic rays** (CRs) that can be efficiently confined especially in galaxy clusters (Colafrancesco & Blasi 1998).

Radio observations and magneto-hydro-dynamic (MHD) simulations also suggest that large scale **magnetic fields** (of both primordial origin and or post-recombination generation (see e.g. (Giovannini 2005) for a review) are associated to the distribution of baryonic material collected in LSS potential wells (see e.g. (Sigl et al. 2005; Dolag et al. 2005)). The seed magnetic field is likely amplified

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[1] Viable candidates for a cosmologically relevant DM are neutralinos (the lightest MSSM particles, see Jungman (1996)), sterile neutrinos (the lightest right-handed neutrino, see (Shaposhnikov 2007)), light DM particles (see (Boyanovsky et al. 2007)).

and made turbulent by the coupling of gravitational collapse and MHD processes during the collapse of groups and clusters of galaxies. Evidence for such wide-scale and turbulent intra-cluster magnetic field is indicated by the diffuse radio synchrotron emission found in many nearby clusters (with typical values $B \sim 0.1 - 2\ \mu$G), by radio relic features in dynamically active clusters (with typical values $B \sim 0.2 - 5\ \mu$G) and by Faraday Rotation measurements of background and embedded polarized radio sources (with typical values $B \sim 1 - 50\ \mu$G (Govoni & Feretti 2004).
Very massive DM clumps that collapse at high redshifts ($z \sim 6 - 7$) often contain the most massive galaxies and the most massive **Black Holes** (BHs) at their centers (see results from the Millennium simulation, (Springel et al. 2005)). The AGN descendants of these ancient supermassive BHs are found to be part of the massive galaxies located today at the centers of the most massive galaxy clusters (see, e.g., CenA, M87/Virgo, Perseus, A262, A4059) with their radio lobes penetrating the ICM for tens or hundreds of kpcs. It is often observed that the radio jets/lobes end up in approximately spherical **bubbles of relativistic plasma** that appear as cavities in the X-ray images of galaxy clusters, with dimensions ranging from a few kpcs (as in Perseus) up to $\sim$ 100 kpc (as in the case of the cluster MS0735-556, see (McNamara & Nulsen 2007)).
The cores of galaxy clusters which host such non-thermal phenomena (BHs, cavities, CRs, magnetic fields, DM) are systematically cooler than the outer regions of the clusters with their inner temperature setting at a value $\sim \frac{1}{3} - \frac{1}{2}$ of the outer temperature, usually consistent with the virial expectation. It seems that a heating agent of non-gravitational/non-thermal nature with a heating rate able to accomodate itself to the cooling rate of the IC plasma is active in the cluster's **cool core** so as to maintain it in a quasi-stationary, warm configuration (Colafrancesco et al. 2004; Colafrancesco & Marchegiani 2007).

The previous evidence indicates that galaxy clusters – the largest bound structures in the universe – are the largest storage rooms for cosmic material (galaxies, DM, hot thermal plasma, non-thermal and relativistic plasma, BHs, magnetic fields, CRs). In this respect, they can be considered as the largest laboratories for Astro Particle Physics in the universe.

2. The Hard X-Ray Way

The Hard X-Ray (HXR) energy band is crucial to unveil several, if not all, of the previous aspects of the AstroParticle physics description of galaxy clusters.
Dark Matter. Secondary $e^{\pm}$ produced by neutralino (χ) annihilation through $\chi\chi \to X + \pi^{\pm} \to X + e^{\pm}$ Compton up-scatter CMB (and other background) photons that redistribute on a wide frequency range up to gamma-ray frequencies (see Fig.1). Neutralino annihilation produces a HXR spectrum that can be detected in massive clusters by SimbolX in the most favourable scenarios. The detectability of signals produced by neutralino models with low neutralino masses M_χ (which are able to recover the radio-halo spectra in cluster) are favoured because they provide larger fluxes ($F \sim \langle\sigma v\rangle \cdot M_\chi^{-2}$). Increasing M_χ yields fainter HXR and γ-ray fluxes, which turn out to be undetectable by the next coming high-energy experiments and also even by GLAST. Increasing the annihilation cross-section $\langle\sigma v\rangle$ can provide high HXR signals but the relative $\pi^0 \to \gamma\gamma$ gamma-ray flux at $E > 100$ MeV could exceed the EGRET limit on clusters (see Fig.1 for the case of Coma). Lowering the magnetic fields down to values $\sim 0.15\mu$G can again increase the HXR flux but also in this case the $\pi^0 \to \gamma\gamma$ gamma-ray flux predicted by the same model at $E > 100$ MeV exceeds the EGRET limit on Coma.
Similar consideration hold for dark galaxies which are dominated by DM (Colafrancesco et al. 2007). Dwarf spheroidal galaxies in the local group are, in fact, among the cleanest candidates to detect neutralino DM signals at all frequencies being mostly devoid of diffuse gas and relativistic plasmas. In this context, the HXR emission from Draco as produced by ICS of CMB photons upscattered by secondary electrons produced in a neutralino DM model with $M_\chi = 100$ GeV

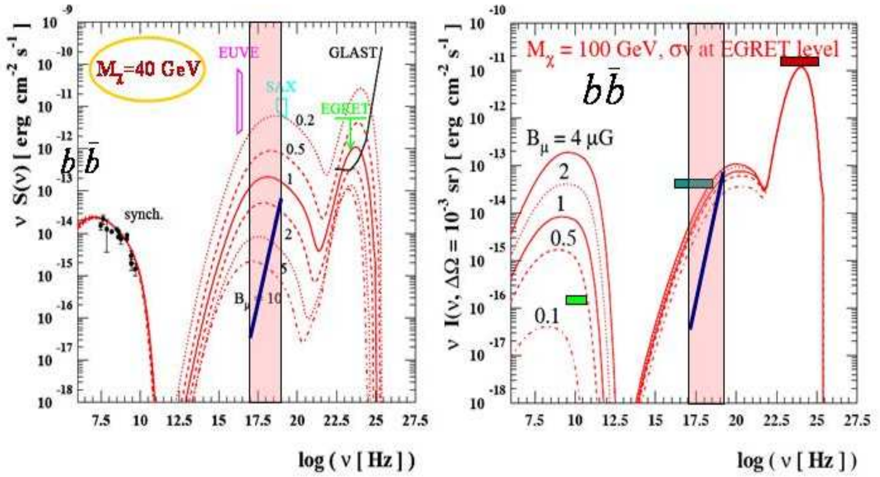

Fig. 1. The Spectral Energy Distribution (SED) produced by neutralino annihilation in the Coma cluster (left panel) and in the Draco dSph. galaxy (right panel) (Colafrancesco et al. 2006, 2007). The 20-80 keV energy band (shaded area) and the SimbolX nominal sensitivity (blue solid line) are shown.

whose annihilation cross-section is normalized to yield the EGRET upper limit at 1 GeV could be detectable by SimbolX (see Fig.1).

As for *sterile neutrinos*, their radiative decay ($\nu_s \rightarrow \nu_i + \gamma$, where ν_i indicate the standard low-mass neutrinos) in clusters produces a narrow line emission whose energy provides information on the sterile neutrino mass m_s. X-ray emission spectra from galaxy clusters are a powerful tool to set contraints on sterile neutrinos in the plane $m_s - sin^2(2\theta)$. The available constraints on sterile neutrinos from HXR spectra of clusters (Colafrancesco 2007), combined with those obtained from the CXB, Lyα limits and gamma-ray line limits from the MW are shown in Fig.2. Models with lower mixing angles θ and neutrino masses m_s up to a $\sim 10^2 - 10^3$ keV are still viable. In this case, next generation high-sensitivity HXR detectors like SimbolX or the next generation soft γ-ray experiments will be able to set relevant constraints on this DM model.

Cosmic ray origin. Observations of HXR excess in nearby clusters with radio halos have been proposed to confirm the existence of a diffuse population of CRs under the hypothesis that the HXR emission is predominantly due to Inverse Compton Scattering (ICS) of CMB photons off the intracluster CRs. A basic problem stands out with the origin of the CRs supposedly producing the radio halo features. Two general mechanisms have been explored so far: i) direct or stochastic acceleration and/or re-acceleration caused by merging shocks and/or IC turbulence (see Brunetti at this Meeting); ii) in-situ, (quasi-) station-

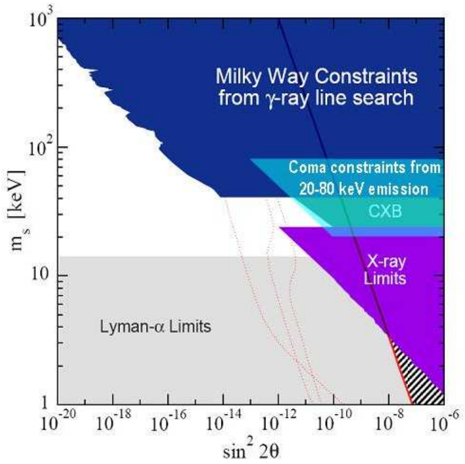

Fig. 2. The sterile neutrino mass m_s and mixing $sin^2(2\theta)$ parameter space, with shaded regions excluded. The strongest direct bounds are shown, labeled as Milky Way, CXB, and X-ray limits. The strongest indirect bounds are shown by the grey horizontal band. The excluded Dodelson-Widrow model is shown by the solid line; rightward, the DM density is too high (stripes). The dotted lines indicate example models, now truncated by the present constraints. The cyan shaded area indicates our constraints from the HXR (soft gamma-ray) limit on Coma ((Colafrancesco 2007)). Figure adapted from (Yuksel et al. 2007).

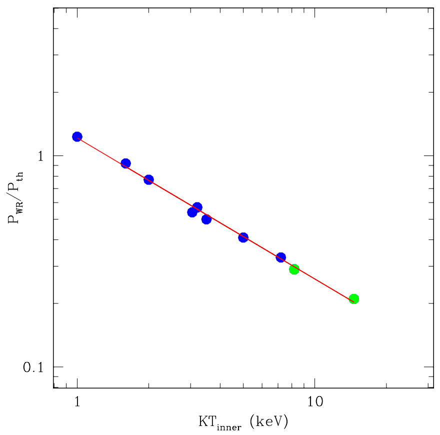

Fig. 3. The correlation of the central pressure ratio P_{WR}/P_{th} with the inner temperature T_{inner} for clusters with cool cores and radio halos. The fit $P_{WR}/P_{th} \propto (kT_{inner})^{-2/3}$ is shown as a solid line. Blue dots refer to cool-core clusters and green dots to non cool-core clusters.

ary production mechanisms like pp collisions (Colafrancesco & Blasi 1998) or the interaction of UHECR hadrons with CMB photons (Inoue et al. 2005).
Shock acceleration in cluster atmosphere is not efficient on time scales $\lesssim 2 \cdot 10^7$ yr because the energy gained by the particles is actually redistributed to the whole IC plasma on a timescale much shorter than that of the acceleration process itself (Wolfe & Melia 2006). Turbulent acceleration of particles out of the IC gas thermal pool can produce a quasi-stationary suprathermal region (Dogiel et al. 2007) where particles actually may gain energy, but they don't have sufficient time to produce a true power-law spectrum extending to relativistic energies, like that required to explain radio-halo emission.
In-situ production of secondary electrons by pp collisions rely on the possibility to accumulate and store CR hadrons in clusters for long time scales (see (Colafrancesco & Blasi 1998)) and can produce a radio halo spectrum whose shape is analogous to that of the parent CR protons and yet in agreement with the radio halo spectra, when no high or low frequency curvature is not very prominent ((Marchegiani et al. 2007)). In addition, this last model can easily be tested against the observations of gamma-ray emission from the same radio-halo clusters with the next coming SimbolX and GLAST experiments. The alternative model in which highly relativistic secondary electrons (with $E_e \sim 10^{15-16}$ eV) are produced by the interaction of UHECRs with CMB photons and fitted to recover the HXR emission spectrum of clusters by synchrotron radiation, predicts a ICS emission which extends up into the TeV range where Cherenkov array telescopes can test this hypothesis, but hardly fails to reproduce the radio-halo emission. This model largely relies on the possibility to have strong sources of CR hadrons

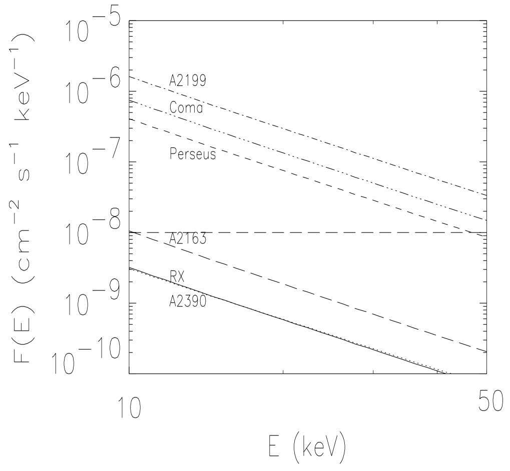

Fig. 4. ICS emission in the HXR band of the secondary electrons for the radio emitting clusters. RX stands for RX J1347.5-1145. The horizontal, long-dashed line represents the approximate sensivity of SimbolX in the 10 – 50 keV range. The HXR fluxes have been computed using a magnetic field compatible with the observed radio emission of each cluster.

(likely replicas of M87 in Virgo) located in the cluster environment, an assumption that could eventually tested with the next high-sensitivity gamma-ray telescopes operating in the GeV – TeV range.

BHs, cavities and AGNs in clusters. CRs can also be injected in the cluster atmosphere by the jets of the AGNs which are settling in the clusters' potential wells. BHs in the cluster's core generate jets and lobes filled with non-thermal, relativistic particles which are both directly injected into the ambient medium and confined in buoyant bubbles. The relativistic particles injected by BHs can both diffuse in the ambient medium and accumulate into the cluster environment, eventually reaching a quasi-stationary equilibrium condition with the cluster's material, or remain locked in non-thermal bubbles until they are released at a subsequent stage into the ambient medium.

The complex admixture of thermal atmosphere in which non-thermal bubbles are embedded can be studied using multi-frequency observations of clusters from radio to gamma-rays and quite efficiently by HXR observations. In fact, while the cluster's thermal atmosphere dominates the cluster emission at X-ray ($\sim 0.1 - 10$ keV) energies, the HXR band at $E \gtrsim 20$ keV will provide evidence for the emerging emission of both the central AGN and in particular of the associated relativistic plasma bubbles (if their electron spectra are flat enough). The next generation HXR spectro-imaging observations of clusters obtainable with SimbolX in the 20-80 keV band, will be able, in many cases, to separate spatially the different spectral components associated to the thermal plasma and to the non-thermal cavities.

The non-thermal activity triggered by the BHs at the cluster centers might produce a feedback onto the IC gas that could help in quenching the cooling of the IC gas. However, it is becoming clear that the non-thermal heating must be distributed in a way to adapt itself to the IC gas cooling, i.e. with a similar pressure distribution $P_{non-th} \sim P_{th}$ (Sanders & Fabian 2007), as in the case of the Perseus cluster.

Under the assumption that AGNs inject CRs which diffuse in clusters' cores, it has been shown (Colafrancesco & Marchegiani 2007) that there are specific correlations between the thermal and non-thermal properties of galaxy clusters with cool cores. The observed temperature distribution in clusters' cool cores can be reproduced by using an energy balance condition in which the X-ray energy emitted by clusters is supplied, in a quasi-steady state, by the hadronic cosmic rays, which act as "warming rays" (WRs). The temperature profile of the intracluster (IC) gas is strictly correlated with the pressure distribution of the WRs and, consequently, with the non-thermal emission (radio, hard X-ray and gamma-ray) induced by the interaction of the WRs with the IC gas. The WR model provides other observable features of galaxy clusters: a correlation of the pressure ratio (WRs to thermal IC gas) with the inner cluster temperature $(P_{WR}/P_{th}) \sim (kT_{inner})^{-2/3}$, a correlation of the HXR luminosity with the inner cluster temperature (see Fig.3), a substantial number of cool-core clusters observable with GLAST-LAT experiment, a surface brightness of radio halos in cool-core clusters that recovers the observed one, a hard X-ray ICS emission from cool-core clusters that is systematically lower than the observed limits and yet observable with the next generation high-sensitivity and spatial resolution HXR experiments like SimbolX (see Fig.4). Such features make it possible to prove or disprove this model as an explanation of the cooling-flow problems on the basis of multi-frequency observations of galaxy clusters.

3. The role of SimbolX

HXR observations of LSS (from galaxies to galaxy clusters) may unveil several issues that are relevant for a full understanding of the evolution of cosmic structures: the nature of Dark Matter, the origin of cosmic rays, the role of magnetic fields and the impact of black holes. In this context, high-sensitivity and good spatial resolution HXR instruments, like those planned for the SimbolX mission (Ferrando et al. 2005), will play a crucial role for unveiling a complete Astro-Particle Physics view of cosmic structure evolution.

References

Bagchi, J. et al. 2002, astro-ph/0204389
D. Boyanovsky, H. J. de Vega, N. Sanchez 2007, arXiv:0710.5180
Colafrancesco, S. & Blasi, P. 1998, APPhys., 9, 227
Colafrancesco, S., Dar, A. & DeRujula, A. 2004, A&A, 413, 441
Colafrancesco, S., Profumo, S. & Ullio, P. 2006, A&A, 455, 21
Colafrancesco, S., Profumo, S. & Ullio, P. 2007, PRD, 75, 3513
Colafrancesco, S. & Marchegiani, P. 2007, A&A submitted
Colafrancesco, S. 2007, ChJASS, in press
Dogiel, V. et al. 2007, A&A, 461, 433
Dolag, K. et al. 2004, astro-ph/0410419
Ferrando, P. et al. 2005, astro-ph/0508674
Giovannini, M. 2004, IJMPD, 13, 391-502
Govoni, F. & Feretti, L. 2004, IJMPD, 13, 1549
Jungman, et al. 1996, Phys. Rep., 267, 195
Inoue, S. et al. 2005, ApJ, 628, L9
Marchegiani, P., Perola, G.C. & Colafrancesco, S. 2007, A&A, 465, 41
McNamara, B.R. & Nulsen, P.E.J. 2007, arXiv:0709.2152
Pfrommer, C. et al. 2007, arXiv:0707.1707]
Ryu, D. et al. 2003. astro-ph/0305164
Sanders, J.C. & Fabian, A.C. 2007, [arXiv:0705.2712
Shaposhnikov, M. 2007, astro-ph/0703673
Sigl, G. et al. 2004, astro-ph/0409098
Springel, V. et al. 2005, astro-ph/0504097
Wolfe, B. & Melia, F. 2006, ApJ, 638, 125
Yuksel et al. 2007, arXiv:0706.4084v1