# Cosmological structure formation shocks and cosmic rays in hydrodynamical simulations

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**Summary.** Cosmological shock waves during structure formation not only play a decisive role for the thermalization of gas in virializing structures but also for the acceleration of relativistic cosmic rays (CRs) through diffusive shock acceleration. We discuss a novel numerical treatment of the physics of cosmic rays in combination with a formalism for identifying and measuring the shock strength on-the-fly during a smoothed particle hydrodynamics simulation. In our methodology, the non-thermal CR population is treated self-consistently in order to assess its dynamical impact on the thermal gas as well as other implications on cosmological observables. Using this formalism, we study the history of the thermalization process in high-resolution hydrodynamic simulations of the Lambda cold dark matter model. Collapsed cosmological structures are surrounded by shocks with high Mach numbers up to 1000, but they play only a minor role in the energy balance of thermalization. However, this finding has important consequences for our understanding of the spatial distribution of CRs in the large-scale structure. In high resolution simulations of galaxy clusters, we find a low contribution of the averaged CR pressure, due to the small acceleration efficiency of lower Mach numbers of flow shocks inside halos and the softer adiabatic index of CRs. These effects disfavours CRs when a composite of thermal gas and CRs is adiabatically compressed. However, within cool core regions, the CR pressure reaches equipartition with the thermal pressure leading there to a lower effective adiabatic index and thus to an enhanced compressibility of the central intracluster medium. This effect increases the central density and pressure of the cluster and thus the resulting X-ray emission and the central Sunyaev-Zel'dovich flux decrement. The integrated Sunyaev-Zel'dovich effect, however, is only slightly changed.

## 1 Motivation

Cosmological shock waves form abundantly in the course of structure formation, both due to infalling cosmic plasma which accretes onto filaments, sheets and halos, as well as due to supersonic flows associated with merging substructures. Additionally, shock waves in the interstellar and intracluster media can be powered by non-gravitational energy sources, e.g. as a result of supernova explosions. Cosmologically, shocks are important in several respects for the thermal gas as well as for CR populations. (1) Shock waves dissipate gravitational energy associated with hierarchical clustering into thermal energy of the gas contained in dark matter halos, thus supplying the intra-halo medium with entropy and thermal pressure support: where and when is the gas heated to its present temperatures, and which shocks are mainly responsible for it? (2) Shocks also occur around moderately overdense filaments, heating the intragalactic medium. Sheets and filaments are predicted to host a warm-hot intergalactic medium with temperatures in the range $10^5\,\mathrm{K} < T < 10^7\,\mathrm{K}$ whose evolution is primarily driven by shock heating from gravitational perturbations developing into mildly nonlinear, non-equilibrium structures. Thus, the shock-dissipated energy traces the large scale structure and contains information about its dynamical history. (3) Besides thermalization, collisionless shocks are also able to accelerate ions through diffusive shock acceleration. These energetic ions are reflected at magnetic irregularities through magnetic resonances between the gyro-motion and waves in the magnetized plasma and are able to gain energy in moving back and forth through the shock front: what are the cosmological implications of such a CR component, and does this influence the cosmic thermal history? (4) Simulating realistic CR distributions within galaxy clusters will provide detailed predictions for the expected radio synchrotron and $\gamma$-ray emission. What are the observational signatures of this radiation that is predicted to be observed with the upcoming new generation of $\gamma$-ray instruments and radio telescopes?

To date it is unknown how much pressure support is provided by CRs to the thermal plasma of clusters of galaxies. A substantial CR pressure contribution might have a major impact on the properties of the intracluster medium (ICM) and potentially modify thermal cluster observables such as the X-ray emission and the Sunyaev-Zel'dovich (SZ) effect. In contrast, CR protons play a decisive role within the interstellar medium our own Galaxy. CRs and magnetic fields each contribute roughly as much energy and pressure to the galactic ISM as the thermal gas does. CRs trace past energetic events such as supernovae, and they reveal the underlying structure of the baryonic matter distribution through their interactions. CRs behave quite differently compared to the thermal gas. Their equation of state is softer, they are able to propagate over macroscopic distances, and their energy loss time-scales are typically larger than the thermal ones. Therefore, CR populations provide an important reservoir for the energy from supernova explosions or structure formation shock waves, and thereby help to maintain dynamical feedback for periods longer than thermal gas physics alone would permit.

## 2 Structure formation shock waves and cosmic rays

We have developed a formalism that is able to measure the shock strength instantaneously during an smoothed particle hydrodynamics (SPH) simulation [1]. The method is applicable both to non-relativistic gas, and to plasmas composed of CRs and thermal gas. We apply our methods to study the properties of structure formation shocks in high-resolution hydrodynamic simulations of the Lambda cold dark matter ($\Lambda$CDM) model using an extended version of the distributed-memory parallel TreeSPH code GADGET-2 [2] which includes self-consistent CR physics ([3], [4]). Fig. 1 shows the spatial distribution of structure formation shocks in compari-

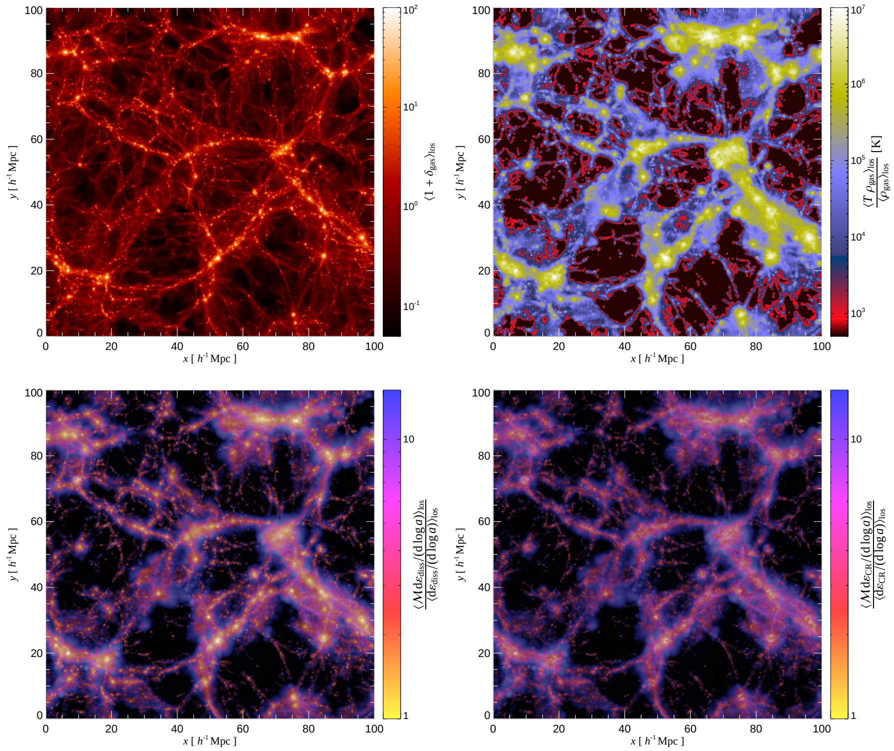


**Fig. 1.** Visualization of a non-radiative cosmological simulation at redshift $z = 0$ where the cosmic ray (CR) energy injection was only computed while the effect of the CR pressure on the dynamical evolution was not taken into account. The *top panels* show the overdensity of the gas and the mass weighted temperature of the simulation. The *bottom panels* show a visualization of the strength of structure formation shocks. The colour hue of the map on the left-hand side encodes the spatial Mach number distribution weighted by the rate of energy dissipation at the shocks. The map on the right-hand side shows the Mach number distribution weighted by the rate of CR energy injection above the momentum threshold of hadronic CR p-p interactions. The brightness of each pixel is determined by the respective weights, i.e. by the energy production density. Most of the energy is dissipated in weak shocks which are situated in the internal regions of groups or clusters, while collapsed cosmological structures are surrounded by strong external shocks (shown in blue). Since strong shocks are more efficient in accelerating CRs, the CR injection rate is more extended than the dissipation rate of thermal energy.

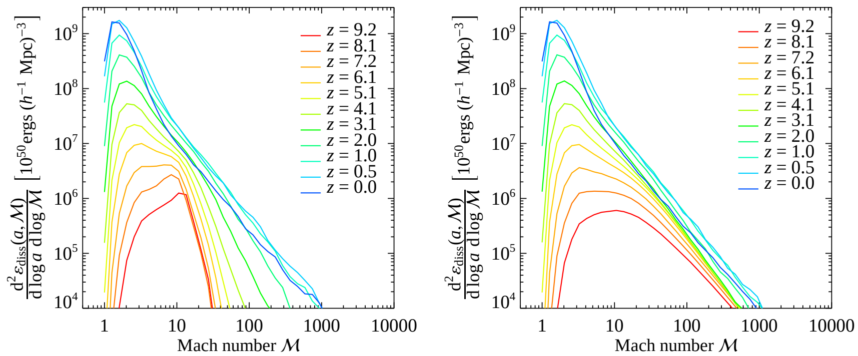


**Fig. 2.** Influence of reionisation (at redshift $z = 10$) on the Mach number statistics of non-radiative cosmological simulations. The figure on the *left-hand side* shows the differential Mach number distribution $d^2\varepsilon_{\rm diss}(a, \mathcal{M})/(d \log a \, d \log \mathcal{M})$ for our simulation with reionisation while the figure on the *right-hand side* shows this distribution for the simulation without reionisation. Strong shocks are effectively suppressed due to an increase of the sound velocity after reionisation.

son to the density and temperature distribution while Fig. 2 shows the cosmological Mach number distribution at different redshifts.[3]

The main results are as follows. (1) Most of the energy is dissipated in weak shocks internal to collapsed structures while collapsed cosmological structures are surrounded by external shocks with much higher Mach numbers, up to $\mathcal{M} \sim 1000$. Although these external shocks play a major role locally, they contribute only a small fraction to the global energy balance of thermalization. (2) More energy per logarithmic scale factor and volume is dissipated at later times while the mean Mach number decreases with time. This is because of the higher pre-shock gas densities within non-linear structures, and the significant increase of the mean shock speed as the characteristic halo mass grows with cosmic time. (3) A reionisation epoch at $z_{\rm reion} = 10$ suppresses efficiently strong shocks at $z < z_{\rm reion}$ due to the associated increase of the sound speed after reionisation. (4) Strong accretion shocks efficiently inject CRs at the cluster boundary. This implies that the dynamical importance of shock-injected CRs is comparatively large in the low-density, peripheral halo regions, but is less important for the weaker flow shocks occurring in central high-density regions of halos.

## 3 Cosmic rays in hydrodynamic cluster simulations

To study the impact of CRs on cluster scales, we performed cosmological high-resolution hydrodynamic simulations of a sample of galaxy clusters spanning a large range in mass and dynamical states, with and without CR physics. These clusters have originally been selected from a low-resolution dark-matter-only simulation of

[3]Note, that we corrected a missing factor 10 in the normalization of Fig.6 in [1].

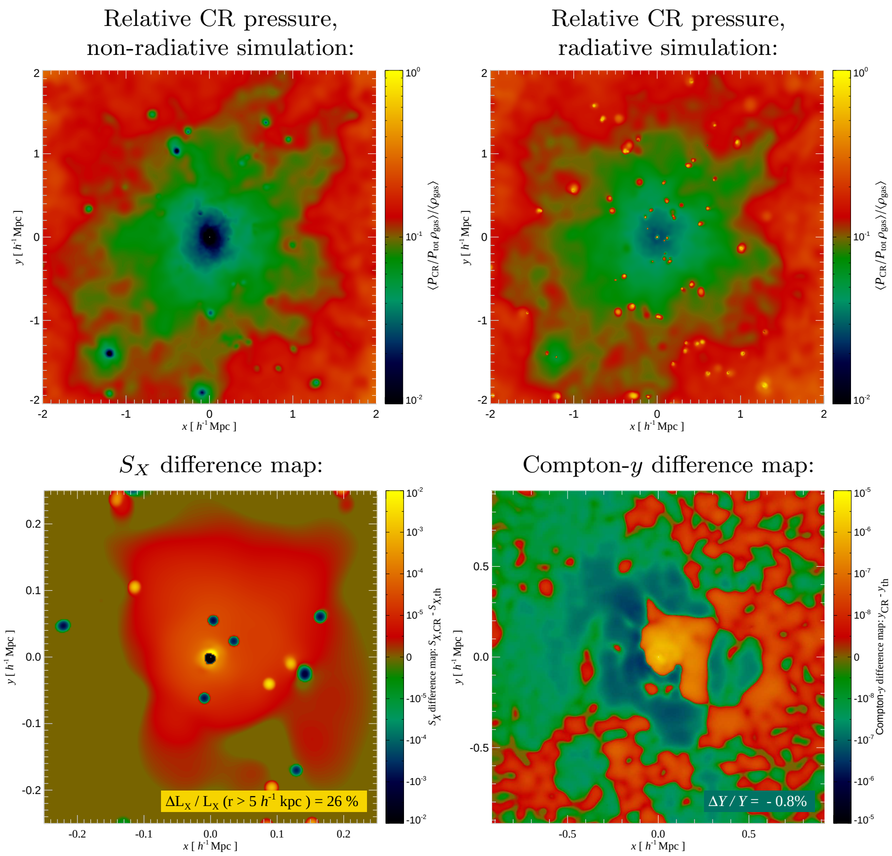


**Fig. 3.** The top panels show a visualization of the pressure contained in CRs relative to the total pressure $X_{\rm CR} = P_{\rm CR}/(P_{\rm CR} + P_{\rm th})$ in a zoomed simulation of an individual galaxy cluster with mass $M = 10^{14} h^{-1} M_\odot$. The map on the *left-hand side* shows a non-radiative simulation with CRs accelerated at structure formation shock waves while the map on the *right-hand side* is from a simulation with dissipative gas physics including cooling, star formation, supernova feedback, and structure formation CRs. The lower panels show the CR-induced difference of the X-ray surface brightness $S_X$ (*left-hand side*) and the Compton-$y$ parameter (*right-hand side*) in a radiative simulation with structure formation CRs compared to the corresponding reference simulation without CRs. The relative difference of the integrated X-ray surface brightness/Compton-$y$ parameter is given in the inlay. Within cool core regions, the CR pressure reaches equipartition with the thermal pressure, an effect that increases the compressibility of the central intracluster medium and thus the central density and pressure of the gas. This boosts the X-ray luminosity of the cluster and the central Sunyaev-Zel'dovich decrement while the integrated Sunyaev-Zel'dovich effect remains largely unaffected.

a flat $\Lambda$CDM model and then re-simulated using the 'zoomed initial conditions' technique. We account for CR acceleration at structure formation shocks and consider CR loss processes such as their thermalization by Coulomb interactions and catastrophic losses by hadronic interactions with ambient gas protons (see [5] for details). Within clusters, the relative CR pressure $X_{\mathrm{CR}} = P_{\mathrm{CR}}/(P_{\mathrm{CR}} + P_{\mathrm{th}})$ declines towards a low central value of $X_{\mathrm{CR}} \simeq 10^{-4}$ in non-radiative simulations due to a combination of the following effects: CR acceleration is more efficient at the peripheral strong accretion shocks compared to weak central flow shocks, adiabatic compression of a composite of CRs and thermal gas disfavours the CR pressure relative to the thermal pressure due to the softer equation of state of CRs, and CR loss processes are more important at the dense centres. Interestingly, $X_{\mathrm{CR}}$ reaches high values at the centre of the parent halo and each galactic substructure in our radiative simulation due to the fast thermal cooling of gas which diminishes thermal pressure support relative to that in CRs. This additional CR pressure support has important consequences for the thermal gas distribution at cluster centres and alters the resulting X-ray emission and the SZ effect significantly (cf. Fig. 3).

## 4 Conclusions

We studied the properties of cosmological shock waves using a technique that allows us to identify and measure the shock strength on-the-fly during an SPH simulation. Invoking a model for CR acceleration in shock waves, we have carried out the first hydrodynamical simulations that follows the CR physics self-consistently. These simulations show that it is crucial to consider the dynamical back-reaction of a non-thermal cosmic ray (CR) component in order to describe the intracluster medium reliably. The X-ray luminosity from galaxy clusters is boosted predominantly in low-mass cool core clusters due to the large CR pressure contribution in the centre that leads to a higher compressibility. The integrated Sunyaev-Zel'dovich effect is only slightly changed while the central SZ flux decrement is also increased. These CR-induced modifications can imprint themselves in changes of cluster scaling relations or modify their intrinsic scatter and thus change the effective mass threshold of X-ray or SZ surveys. Neglecting such a CR component in reference simulations can introduce biases in the determination of cosmological parameters.

## References

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