# Particle acceleration processes in the cosmic large-scale structure

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**Abstract.** The energetic shock waves associated with the violent large-scale structure formation process are able to accelerate relativistic electrons and protons. The induced non-thermal emission, especially at long radio wavelength, provides a fascinating perspective into structure formation, the relativistic Universe, and cosmic magnetic fields.

**Keywords.** acceleration of particles, large-scale structure of universe

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The formation of the cosmic large-scale structure is accompanied by shock waves which permeate and enclose the denser regions of the universe (Fig. 1). These shock waves and the induced turbulence can lead to particle acceleration. Four particle acceleration processes may be relevant for the production of relativistic particle populations (cosmic rays, CRs) in the large-scale structure, namely adiabatic compression, diffusive shock acceleration, stochastic acceleration, and particle reactions. All these acceleration processes have to compete against energy losses due to adiabatic expansion, radiative cooling (synchrotron, inverse Compton, bremsstrahlung, hadronic interactions), and non-radiative cooling (Coulomb losses). Different processes will dominate in different cosmic environments, particle energy ranges and for different particle types (electrons/protons).

**Adiabatic compression** can revive the observable radio emission of old CR electrons in fossil radio plasma of a former radio galaxy (radio ghost). The electrons gain energy adiabatically, which in combination with the increasing magnetic field strength raises significantly the synchrotron frequency of the electrons at the high energy cooling cutoff. This may explain the small radio relics observed in several galaxy clusters, as argued by Enßlin & Gopal-Krishna (2001) and by Enßlin & Brüggen (2002).

**Diffusive shock acceleration** at shock waves can accelerate thermal particles, and thereby can become very efficient in generating CRs if the injection spectrum is sufficiently flat, which depends on the shock Mach number. Thus, the higher-Mach number shocks in the outskirts of clusters and the accretion shock waves have a higher CR injection efficiency compared to the shock in cluster centers, as can be seen in Fig. 1. The resulting radio emission probably explains the giant radio relics (radio tsunamis, Enßlin et al. (1998), see Fig. 2).

**Stochastic acceleration** of CRs by plasma waves can re-accelerate existing CR populations. This may explain the radio halos in galaxy clusters by the re-activation of longer-lived 0.3 GeV CR electrons to $\sim 10$ GeV (see contributions by C. Sarazin and G. Brunetti).

**Particle reactions** of a long-lived CR proton populations will induce secondary electrons from the hadronic chain $pp \rightarrow \pi^{\pm} \rightarrow \nu_{\mu}\, \mu^{\pm} \rightarrow \nu_{\mu}\, \nu_{e}\, e^{\pm}$ which may also be able to produce cluster radio halos (Dennison (1980), and see Fig. 2).

**Long wavelength radioastronomy** is expected to play the leading role in unraveling acceleration processes in the large-scale structure.

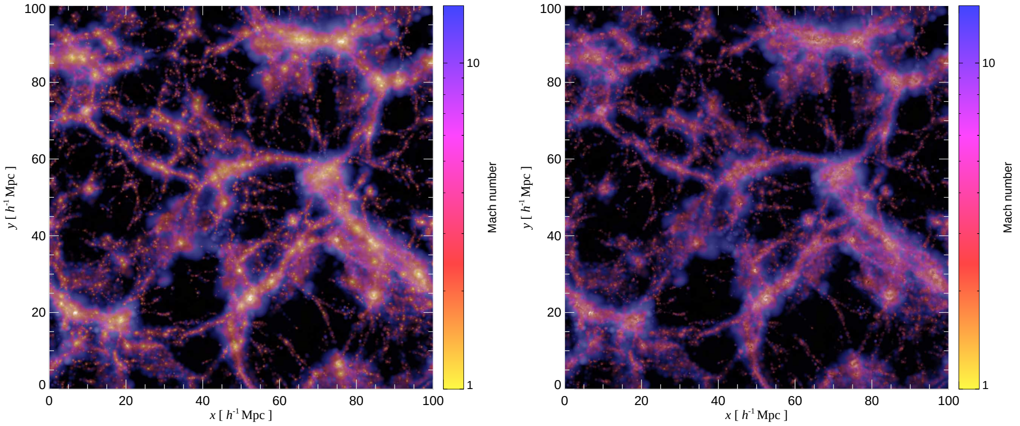

**Figure 1.** Energy dissipation by shock waves in a cosmological structure formation simulation by Pfrommer et al. (2006). The brightness displays the logarithm of the dissipation rate, the color indicates the (dissipation weighted) Mach numbers. Left: total dissipation. Right: dissipation into cosmic rays.

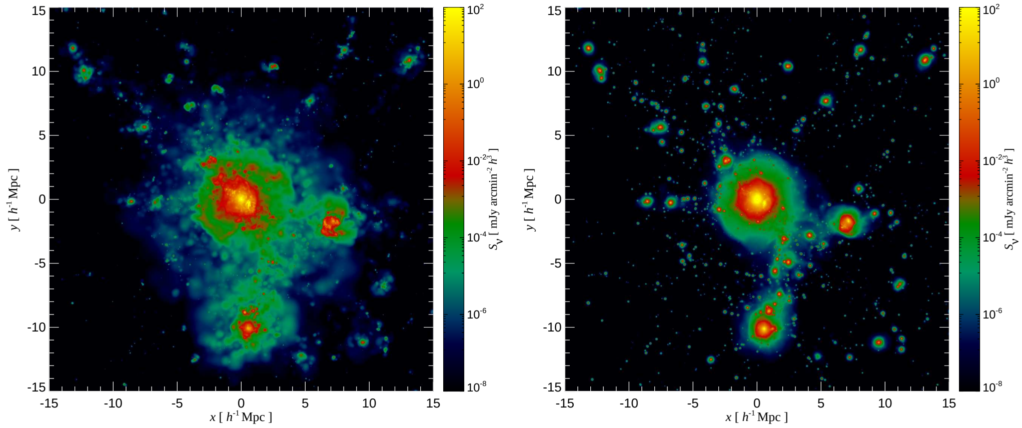

**Figure 2.** 150 MHz radio emission of a simulated galaxy cluster. Left: emission due to shock accelerated electrons (giant radio relics/radio tsunamis) Right: emission due to secondary electrons from hadronic interactions of formerly shock accelerated protons (hadronic radio halo).

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