Turbulence and Particle Acceleration in Giant Radio Halos: the Origin of Seed Electrons

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About one third of X-ray-luminous clusters show smooth, unpolarized radio emission on \~\!Mpc scales, known as giant radio halos (RHs) \textsuperscript{1}. They appear only in disturbed, merging clusters and the RH luminosity correlates with the X-ray luminosity \textsuperscript{2,4} and the Compton $y$-parameter \textsuperscript{4}. The RHs show that CRs and magnetic fields permeate a large volume fraction of the intracluster medium (ICM). The dominant CR source, given the smoothness and enormous extent of RHs, is thought to be structure formation shocks \textsuperscript{1,2,3,4}. At the same time, plasma processes, the origin of magnetic fields and particle acceleration in a turbulent, high-$\beta$ plasma like the ICM are not well understood. Radio halos thus provide an incisive probe of non-thermal processes in the high-$\beta$ ICM.

One promising model for RHs is re-energetization of seed suprathermal electrons by Fermi II acceleration when ICM turbulence becomes transonic during mergers \textsuperscript{2,4,9}. Due to the short radiative cooling time of high-energy relativistic electrons, the cluster synchrotron emission quickly fades away after a merger, which naturally explains the observed bimodality of RHs.

However, there is a salient piece missing in the turbulent reacceleration model. It relies heavily on the assumption of an abundant, volume-filling population of seed suprathermal electrons; direct Fermi II acceleration from the thermal pool is precluded by strong Coulomb losses \textsuperscript{2,10}. These seeds are presumed to be either fossil CR electrons (CRes) accelerated by diffusive shock acceleration (DSA) during structure formation \textsuperscript{11}, or secondaries injected by hadronic interaction of CR protons (CRps) with thermal protons \textsuperscript{12}. While analytic estimates have been made, there has been no ab initio demonstration that structure formation can lead to the required abundance of seed electrons with the correct spatial and spectral characteristics. This is a non-trivial requirement: Coulomb cooling in dense cluster cores is severe, and DSA fossil electrons may not survive. On the other hand, for secondaries to constitute the seed population, the CRp population required in the best-studied case of the Coma cluster must have a very broad and flat (or even slightly inverted) spatial profile \textsuperscript{13}, in contrast with the thermal plasma whose energy density declines steeply with radius. In this Letter we show that such a distribution is not predicted by cosmological simulations (see lower right panel of Fig. \textsuperscript{1}) \textsuperscript{2,11,12,13}.

Indeed, arriving at a seed population with the required characteristics is highly constraining, and has the potential to teach us much about the origin of CRps/CRes in...
clusters. We consider 3 new possibilities: (i) Our model $M$-turbulence: a significantly flatter turbulent profile than what was adopted in [13], which allows seed CRps to follow the steep profile that is suggested by structure formation simulations. (ii) Our model $M$-streaming: streaming CRPs that produce flat distributions of CRs in the ICM [16, 17], which also flattens the secondary electron distribution. (iii) Our model $M$-primaries: if the acceleration efficiency of CRPs is below about 0.1\% in weak (perpendicular) shocks and the ratio of injected electrons-to-protons $K_{ep} \sim 0.1$, this yields a dominant primary population with a flat spatial distribution, since primaries have a weaker density dependence than secondaries. In this work we pursue these three possibilities further. We employ cosmological simulations of CRs in clusters, in tandem with new insights from our recent work on DSA generated fossil electrons [18], to generate the first quantitative calculation of primary and secondary seed electrons.

**Method.** The transport of relativistic electrons and protons in the ICM is a complex process that depends both on the details of the thermal component (gas density, temperature, and pressure) as well as non-thermal component (turbulence, magnetic fields, fossil CRs). We use high resolution galaxy cluster simulations to derive the thermal and fossil CR properties (shock accelerated primary CRes and CRPs, as well as secondary CRes produced in p-p collisions) [6, 14, 15, 19]. In this Letter we focus on our simulated cluster, g72a, which is a massive $1.6 \times 10^{15} M_\odot$ cluster that experienced a merger about 1-2 Gyrs ago. Since the cluster mass, density and temperature profiles are all similar to the well studied Coma cluster [14, 15], we will compare our calculations to radio and gamma-ray observations of Coma.

In our Galaxy, the CRe-to-CRp ratio at a few GeV is $K_{ep} \sim 10^{-2}$. Hence, we adopt this as a fiducial value for the CRe-to-CRp acceleration efficiency (see [15] for more discussion). However, as recent PIC simulations have shown, this is likely very different at weak shocks, with electrons efficiently accelerated at perpendicular shocks [21, 23] and ions efficiently accelerated at parallel shocks [22]. Thus, depending on magnetic geometry, $K_{ep}$ could be either larger or smaller. In this work we use a simple test-particle model for the CRp acceleration [15, 25]. The ratio of accelerated proton-to-dissipated energy in the downstream of strong shocks varies from 1-10\%, depending on the adopted model (for more details, see the Results section), and is a factor 10-100 lower for weak shocks. However, some observations of radio relics suggest higher values of $K_{ep}$, due to the absence of gamma-ray emission, which probes the CRp population [23]. This suggests primary CRes as a viable alternative scenario to secondary CRes as seeds for the giant RHs. In our $M$-primaries scenario, we adopt $K_{ep} = 0.1$ (viable for primarily perpendicular shocks) to test this possibility.

As previously noted, secondaries produced by shock accelerated CRp have the wrong spatial profile to explain RH observations; because they arise from a two body process, they are too centrally concentrated. They also produce $\gamma$-ray emission in excess of Fermi-LAT upper limits [13, 23, 26]. However, if CRPs stream in the ICM, then their spatial profile could potentially flatten sufficiently [16, 17]. This scenario is very attractive: it generates seed electrons with the right spatial footprint, and by removing CRPs from the core, obeys gamma-ray constraints. Turbulence plays two opposing roles: Alfvenic turbulence damps waves generated by the CR streaming instability [27, 28], thus reducing self-confinement; but compressible fast modes scatter CRs directly. Turbulent damping is still efficient for highly subsonic conditions [17], while we assume compressible fast modes only provide effective spatial confinement during the periods of transonic, highly super-Alfvénic ($M_A \sim 5$) turbulence associated with mergers. Thus, CRs can stream out when the cluster is kinematically quiescent. Furthermore, even Alfvenic streaming timescales are relatively short ($\sim 0.1 - 0.5$ Gyr; [17]) compared to the timescale on which the CRp population is built up. Based on these findings, we adopt a toy model for our $M$-streaming scenario in which CR streaming quickly produces flat CRp profiles. We assume that CRs cannot stream significantly past perpendicular $B$-fields at the accretion shock, so that the total number of CRs is conserved.

Given a seed population of CRs, we adopt essentially the same set of plasma physics assumptions as the reacceleration model for RHs [8, 12], leaving exploration of parameter space to future work. We solve the isotropic, gyro-phase averaged Fokker-Planck equation (via a Crank-Nicholson scheme) for the time evolution of the CRe distribution in the Lagrangian frame [8, 12]:

$$\frac{df_e(p,t)}{dt} = \frac{\partial}{\partial p} \left\{ f_e(p,t) \left[ \frac{dp}{dt} \right]_C + \frac{p}{3} (\vec{\nabla} \cdot \vec{v}) + \frac{dp}{dt} - \frac{1}{p^2} \frac{\partial}{\partial p} \left( p^2 D_{pp} \right) \right\} - (\vec{\nabla} \cdot \vec{v}) f_e(p,t) + \frac{\partial^2}{\partial p^2} \left[ D_{pp} f_e(p,t) \right] + Q_e [p,t; f_p(p,t)] .$$  (1)

Here $f_e$ is the one-dimensional distribution in position $x$ (suppressed for clarity), momentum $p$ and time $t$ (which is normalized such that the number density is given by $n_e(t) = \int dp f_e(p,t)$), $d/dt = \partial/\partial t + \vec{v} \cdot \vec{\nabla}$ is the Lagrangian derivative, $\vec{v}$ is the gas velocity, $|dp|/dt$ represents radiative (r) and Coulomb (C) losses, $D_{pp}$ is the momentum space diffusion coefficient, and $Q_e$ denotes the injection rate of primary and secondary electrons in the ICM. The $\vec{\nabla} \cdot \vec{v}$ terms represent adiabatic gains and losses. During post-processing of our Coma-like cluster simulation, we solve the Fokker-Planck equation over a redshift interval from $z = 5$ to 0. The simulated cluster undergoes a major merger over the last 1-2 Gyrs that injects large turbulent eddies. After about 1 Gyr those have decayed
down to the scale needed to reaccelerate particles. In all our calculations we assume that turbulent reacceleration is efficiently accelerating particles for 650 Myrs and that during this turbulent phase CR streaming and spatial diffusion can be neglected. In our M-streaming model, CR streaming and diffusion are incorporated separately during kinematically quiescent times that precede the merger. As a result, flat CRp profiles are produced on relatively short timescales (∼ 0.1 – 0.5 Gyr).

The time evolution of the spectral energy distribution of CRps, \( f_p(p,t) \), is similarly given by:

\[
\frac{df_p(p,t)}{dt} = \frac{\partial}{\partial p} \left\{ f_p(p,t) \left[ \frac{df_p}{dt} \right]_c + \frac{p}{3} \left( \vec{\nabla} \cdot \vec{v} \right) \right\} - \frac{1}{p^2} \frac{\partial}{\partial p} \left\{ p^2 D_{pp}(p,t) \right\} - \left( \vec{\nabla} \cdot \vec{v} \right) f_p(p,t) + \frac{\partial^2}{\partial p^2} \left[ D_{pp}(p,t) \right] - \frac{f_{pp}(p,t)}{\tau_{\text{had}}(p)} + Q_p(p,t),
\]

where \( Q_p(p,t) \) denotes the injection rate of shock accelerated CRps as a function of momentum \( p \) and time \( t \), and \( \tau_{\text{had}} \) is the timescale of hadronic losses that produce pions via CRp collisions with thermal protons of the ICM [e.g. 12]. We incorporate momentum diffusion for electrons and protons from transit-time-damping (TTD) resonance with compressible magneto-hydrodynamic (MHD) turbulence, to model Fermi-II reacceleration [8, 12]. The TTD resonance requires the wave frequency \( \omega = \kappa \parallel v_\parallel \), where \( \kappa || \) and \( v_\parallel \) are the parallel (projected along the magnetic field) wavenumber and particle velocity, respectively. This implies that the particle transit time across the confining wave region matches the wave period, \( \lambda || / v_\parallel = T \). The resonance changes the component of particle momentum parallel to seed magnetic fields, which over time leads to increasing anisotropy in the particle distribution that decreases the efficiency of reacceleration with time. As in ref. 12, we assume that there exists a mechanism—such as the firehose instability—that isotropizes the CR distribution function at the gyro-scale and on the reacceleration time scale, which ensures sustained efficient reacceleration with time. The particle pitch-angle averaged momentum-diffusion coefficient of isotropic particles that couple to fast magnetosonic modes via TTD resonance is \( 8 \) (Eqn. 47):

\[
D_{pp}(p,t) = \frac{\pi}{16c} \frac{p^2}{\rho} \left( \frac{\beta |B_k|^2}{16\pi W} \right) I_\theta \int_{k_{\text{cut}}} W(k)k \, dk,
\]

where \( \beta \) is the thermal-to-magnetic pressure ratio, and \( c \) is the speed of light. The energy density \( W \) of a mode in a magnetized plasma stems from both electromagnetic fields and resonant particles. For a high-\( \beta \) plasma, the pitch angle averaged ratio of beta-weighted magnetic-to-total energy density saturates to \( \langle |B_k|^2/2W \rangle \approx 10^{1.4} \) (see figure 2 in [8]). The pitch angle of the CR momentum with the magnetic field orientation is given by \( \theta \), and \( I_\theta \) is the phase velocity of the fast magnetosonic waves given approximately by the sound speed, \( V_{\text{ph}} \sim c_s \). For a sound speed typical for the ICM of 1000 km/s, \( I_\theta \approx 5 \). As in [8], we initially assume that the velocity of turbulent eddies is \( V_0 \approx 0.47c_s \) throughout the cluster. This gives a turbulent acceleration time scale, \( \tau_{\text{pp}} = p^2/4D_{pp} \), that is typically few 100 Myrs in the ICM.

We adopt a simplified isotropic Kraichnan MHD turbulent spectrum for the fast modes per elemental range \( dk \) of the form

\[
W(k) \approx \sqrt{I_0 \rho V_{\text{ph}}} k^{-3/2}, \tag{4}
\]

for \( k_0 < k < k_{\text{cut}} \), where we assume an injection scale for the turbulence, \( k_0 = 2\pi/(100 \text{ kpc}) \). The volumetric injection rate of turbulent energy, \( I_0 \), is fixed by requiring that the total turbulent energy density on the largest scales \( \epsilon_{\text{turb}} = \int W(k)dk \approx 0.2\epsilon_{\text{th}} \), where \( \epsilon_{\text{th}} \) is the thermal energy density [8, 12]. In this work we investigate different spatial models for injected turbulence. We assume that \( \epsilon_{\text{turb}} \propto \epsilon_{\text{th}}^{\alpha_{\text{t}}}, \) where \( \alpha_{\text{t}} = 0.69 \) for M-turbulence, \( \alpha_{\text{t}} = 0.84 \) for M-streaming, and \( \alpha_{\text{t}} = 0.91 \) for M-primaries (note that in previous work, \( \alpha_{\text{t}} = 1 \) was adopted [13]). Our flatter turbulent profiles are motivated by fits to cosmological simulations [29, 31] and the range indicates uncertainties of the turbulent profile in Coma. Future observations (by Astro-H) and simulations will help to clarify this issue. Provided dissipation of turbulence in the ICM is collisionless, turbulent cascades of compressible modes become suppressed when thermal and relativistic particles resonantly interact with magnetosonic waves via TTD on a timescale \( \Gamma^{-1} \) that is approaching the cascading timescale given by \( \tau_{kk} \approx k^2/D_{kk} \). Here the wave-wave diffusion coefficient of magnetosonic modes is given by

\[
D_{kk} \approx V_{\text{ph}} k^4 \left( \frac{W(k)}{\rho V_{\text{ph}}^2} \right), \tag{5}
\]

Thus, the cascade is suppressed for wave numbers above:

\[
k_{\text{cut}} \approx \frac{81}{14} \frac{I_0}{\rho V_{\text{ph}}} \left( \frac{\sum_i \Gamma_i(k, \theta)}{k} \right)^{-2}, \tag{6}
\]

where \( 2\pi/k_{\text{cut}} \approx 0.1 – 1 \text{ kpc} \) in the ICM. This constitutes an effective mean free path for CRs, unless plasma instabilities can mediate interactions between turbulence and particles on smaller scales [12]. In this work we only consider damping via TTD due to thermal electrons, and neglect subdominant damping with thermal protons and relativistic particles. The latter will be subdominant in the ICM for a CR to thermal energy density ratio \( \lesssim 10 \% \) [8], which is always satisfied. The azimuthally averaged turbulent damping rate from thermal electrons [8] in a high-\( \beta \)
plasma is \( \langle \Gamma_c \rangle \simeq \langle k \rangle V_{ph} \sqrt{3/20} \exp(-5x/3) \sin^2 \theta \approx 0.0435k V_{ph} \), where \( x = (m_e/m_p) \cos^2 \theta \). The magnetic field in the ICM is typically \( \sim \mu G \). To compute the synchrotron surface brightness profiles, we use the profile of the magnetic field strength derived from Faraday rotation observations of Coma [32] in combination with the density profile derived from X-ray measurements [33].

**Results and Discussion.** Let us first consider the two models which rely on secondary electrons. After turbulent reacceleration, the volume-weighted, relative CRp energy density and CRp number density inside the RH for \( M\)-turbulence (\( M\)-streaming), are found to be \( 3 \) (2) \% and \( 3.0 \times 10^{-8} \) (\( 4.5 \times 10^{-8} \)), respectively. As we will see later, these densities are just of the right order of magnitude to reproduce radio observations in the Coma cluster. In addition we predict the gamma-ray flux within the virial radius of the Coma cluster from CRPs that produce decaying neutral pions for \( M\)-turbulence (\( M\)-streaming) with \( F_{\gamma}(>500 \text{MeV}) = 1.6 \times 10^{-10} \times (2.3 \times 10^{-10}) \text{ph} \text{s}^{-1} \text{cm}^{-2} \). Both fluxes are well below current limits set by Fermi-LAT [26], and will be challenging to probe in the near future. The spectral index of the CRp distribution is relatively steep \( \alpha_p \sim 2.6 \) for the CRp energies \( E \gtrsim 10 \text{GeV} \) that are relevant for the injection of radio-emitting secondary CRs. The steep spectrum is ultimately a consequence of our test particle model for Fermi-I acceleration [15], where we steepen the spectral index to avoid acceleration efficiencies above \( \zeta_p = 15\% \).

In Fig. 1, we find that all three scenarios in which the seeds undergo Fermi-II reacceleration can reproduce the Coma RH profile at 352 MHz. In the panel of Brunetti et al. (2012) we show that without CR streaming or a flat turbulent profile, our simulations of reaccelerated CRs produce radio profiles that are too steep. Indeed, even using the assumptions of previous work – where complete freedom in the seed population was allowed – it is not possible to reproduce observations in both frequencies. This signals that this problem is generic and requires either additional modifications to the plasma physics of Fermi-II acceleration or a better understanding of potential observational systematics.

In principle, reacceleration via TTD leads to spectral steepening with particle energy due to the inefficiency of the acceleration process to counter the stronger cooling losses with increasing energy. Since synchrotron emission peaks at frequency \( \nu_{\text{syn}} \approx 1 B/\mu G(\gamma/10^4)^2 \text{GHz} \), this translates into a spectral steepening of the total radio spectrum (see Fig. 2). A given radio window samples higher energy electrons for a decreasing field strength in the cluster outskirts. Hence, the spectral steepening with energy should translate into a radial spectral steepening [13]. However, because of the weak dependence of the electron Lorentz factor on emission frequency (\( \gamma \propto \sqrt{\nu_{\text{syn}}} \)), this effect is only visible in our simulations for \( \nu_{\text{syn}} \gtrsim 5 \text{GHz} \). Most importantly, our simulated fluid elements at a given radius sample a broad distribution of shock history, density and temperature, which implies very similar synchrotron brightness profiles at \( \nu_{\text{syn}} = 352 \text{MHz} \) and 1.4 GHz. The discrepancy of the observed and simulated 1.4 GHz profiles could instead be due to systematic flux calibration error in single dish observations. Interestingly, we can match the 1.4 GHz data if we reduce the zero point by adding 10\% of the central flux to every data point; this flattens the outer profile [37]. Alternatively, this may point to weaknesses in the theoretical modeling of the particle acceleration process and may require a stronger cutoff in the particle energy spectrum.

In Fig. 2 we show that our three models that include Fermi-II reacceleration can individually reproduce the convexly curved total radio spectrum found in the Coma cluster. Seed CRs that do not experience turbulent reacceleration have a power-law spectrum in disagreement with observations. In order to match both the spatial and spectral profiles in Coma, we can constrain the acceleration efficiency for the strongest shocks in our three models: \( M\)-streaming, \( M\)-turbulence, and \( M\)-primaries to \( \zeta_p < 0.15 \), \( \zeta_p < 0.05 \), and \( \zeta_p < 0.004 \), respectively. Following the Mach number \( (M) \)-dependence of the acceleration efficiency suggested in [18], the efficiency in weak shocks \( (M \sim 2.5 - 3.5) \) that dominates the CR distribution function, has an acceleration efficiency for protons \( \zeta_p \approx 0.0001 - 0.01 \), and for electrons \( \zeta_e \approx 0.001 \).

**Conclusions.** The standard reacceleration model for RHs requires a population of seed electrons to undergo turbulent reacceleration. These seeds are generally thought to be secondary electrons from hadronic CRp interactions. In this work we use cosmological simulations to derive a population of seed CRps originating from structure formation shocks and merger shocks during the cluster build up. The resulting secondary population is inconsistent with RH observations. We propose 3 possible solutions that all produce gamma-ray emission below current upper limits and that reproduce both the spectrum and the surface brightness profiles of the Coma RH: (i) injected turbulence that is flatter than in previously adopted models, (ii) streaming CRs, (iii) shock accelerated CR electrons injected with \( K_{ep} \sim 0.1 \). We will pursue further implications and distinguishing characteristics of these competing models in future work.

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FIG. 1: Radio surface brightness profiles of Fermi-II reaccelerated CR electrons of a simulated post-merging cluster similar to Coma. We compare profiles at 352 MHz (blue lines and crosses) to those at 1.4 GHz (green lines and crosses). The red crosses show the reprocessed 1.4 GHz data, where a zero level of about 10% of the central value is adopted. The solid lines show predicted emission from a reaccelerated fossil population, while dotted lines show emission from a fossil population without reacceleration. The panels show the emission from CR protons and secondary electrons reaccelerated by a flat turbulent profile (upper left panel), secondary electrons generated by streaming CR protons (upper right panel), primary electrons (lower left panel), and simulated secondary electrons together with previous estimates for the Coma cluster (lower right panel).

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FIG. 2: Radio synchrotron flux as a function of frequency. Red lines are derived from simulations, while the black crosses are compiled from observations [36]. The lines show the emission from secondary electrons generated by streamed CR protons (solid line), CR protons and secondary electrons reaccelerated by a flat turbulent profile (dashed line), and primary electrons (dash-dotted line). We contrast the reaccelerated populations to a population of DSA accelerated CR protons that produce secondaries (dotted line).

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