Cosmic rays in clusters of galaxies – Tuning in to the non-thermal Universe

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in collaboration with

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Outline

1. Cosmic rays in galaxy clusters
   - Introduction and motivation
   - Cluster simulations and cosmic ray physics
   - Cosmic ray pressure feedback

2. Particle acceleration processes
   - Diffusive shock acceleration
   - Stochastic acceleration
   - Particle reactions

3. Non-thermal cluster emission
   - Radiative processes
   - Unified model of radio halos and relics
   - High-energy gamma-ray emission
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Galaxy clusters are dynamically evolving dark matter potential wells:

- Shock waves heat the infalling gas to the virial temperature.
- Galaxy velocity dispersion probes the DM potential.

Energy

Space
Cosmic rays in galaxy clusters
Particle acceleration processes
Non-thermal cluster emission
Introduction and motivation
Cluster simulations and cosmic ray physics
Cosmic ray pressure feedback

... and how the observer's Universe looks like

1E 0657-56 ("Bullet cluster")
(X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)

Abell 3667
(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)
Why should we care about cosmic rays in clusters?
It allows us to explore complementary windows to cluster cosmology

1. Is high-precision cosmology possible using clusters?
   - Non-equilibrium processes such as cosmic ray pressure and turbulence possibly modify thermal X-ray emission and Sunyaev-Zel’dovich effect.
   - Non-thermal cluster emission will enable constructing a ‘gold sample’ for cosmology using orthogonal information on the dynamical cluster activity.

2. What can we learn from non-thermal cluster emission?
   - Understanding mechanism of diffuse radio and non-thermal X-ray emission of clusters.
   - Estimating the cosmic ray pressure contribution.
   - Fundamental physics: diffusive shock acceleration, large scale magnetic fields, and turbulence.
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Cosmic rays in galaxy clusters
Particle acceleration processes
Non-thermal cluster emission

Introduction and motivation
Cluster simulations and cosmic ray physics
Cosmic ray pressure feedback

Literature for the talk

- Enßlin, Pfrommer, Springel, and Jubelgas, in press, astro-ph/0603484, *Cosmic ray physics in calculations of cosmological structure formation*
- Jubelgas, Springel, Enßlin, and Pfrommer, astro-ph/0603485, *Cosmic ray feedback in hydrodynamical simulations of galaxy formation*
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Radiative simulations – flowchart

Cluster observables:
- Sunyaev-Zeldovich effect
- X-ray emission
- galaxy spectra

Physical processes in clusters:
- thermal energy
- radiative cooling
- stellar populations
- supernovae
- shocks

Legend:
- red: loss processes
- green: gain processes
- yellow: observables
- blue: populations
Radiative simulations with cosmic ray (CR) physics

Cluster observables:
- Sunyaev-Zeldovich effect
- X-ray emission
- Galaxy spectra
- Radio synchrotron
- Gamma-ray emission

Physical processes in clusters:
- Radiative cooling
- Stellar populations
- supernovae
- Shocks
- Coulomb losses
- Cosmic ray energy
- Hadronic losses

Loss processes:
- Gain processes:
- Observables:
- Populations:
Cluster observables:
- Sunyaev-Zeldovich effect
- X-ray emission
- galaxy spectra
- radio synchrotron
- gamma-ray emission

Physical processes in clusters:
- radiative cooling
- supernovae
- shocks
- AGN
- Coulomb losses
- hadronic losses
- cosmic ray energy

- heat conduction
- CR diffusion
- CR losses

Processes:
- loss processes
- gain processes
- observables
- populations
Previous numerical work on cosmic rays in clusters

COSMOCR: A numerical code for cosmic ray studies in computational cosmology (Miniati, 2001):

- advantages: good resolution in momentum space
- drawbacks: CR pressure not accounted for in EoM, insufficient spatial resolution (grid code), non-radiative gas physics

Figure: Hard X-rays, thermal X-rays, $\gamma$-rays, adopted from Miniati (2003)
An accurate description of CRs should follow the evolution of the spectral energy distribution of CRs as a function of time and space, and keep track of their dynamical, non-linear coupling with the hydrodynamics.

We seek a compromise between

- capturing as many physical properties as possible
- requiring as little computational resources as necessary

Assumptions:

- protons dominate the CR population
- a momentum power-law is a typical spectrum
- CR energy & particle number conservation
Our philosophy and description

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CR spectral description

\[ f(p) = \frac{dN}{dp dV} = C p^{-\alpha} \theta(p - q) \]

\[ q(\rho) = \left( \frac{\rho}{\rho_0} \right)^{\frac{1}{3}} q_0 \]

\[ C(\rho) = \left( \frac{\rho}{\rho_0} \right)^{\frac{\alpha+2}{3}} C_0 \]

\[ n_{\text{CR}} = \int_0^\infty dp f(p) = \frac{C q^{1-\alpha}}{\alpha-1} \]

\[ P_{\text{CR}} = \frac{m_p c^2}{3} \int_0^\infty dp f(p) \beta(p) p \]

\[ = \frac{C m_p c^2}{6} \beta \frac{1}{1+q^2} \left( \frac{\alpha-2}{2}, \frac{3-\alpha}{2} \right) \]
Kinetic energy per logarithmic momentum interval:

\[
\frac{dT_{\text{CR}}}{d \log p} = p T(p) f(p) \text{ in } m_p c^2
\]

For different values of \( \alpha \):
- \( \alpha = 2.25 \)
- \( \alpha = 2.50 \)
- \( \alpha = 2.75 \)
Cooling time scales of CR protons

Cooling of primordial gas:

Cooling of cosmic rays:

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Simulating Galaxy Clusters
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Radiative simulations with CR physics

Cluster observables:
- Sunyaev-Zeldovich effect
- X-ray emission
- Galaxy spectra
- Radio synchrotron
- Gamma-ray emission

Physical processes in clusters:
- Radiative cooling
- Stellar populations
- Supernovae
- Shocks
- Coulomb losses
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- Loss processes
- Gain processes
- Observables
- Populations

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Simulating Galaxy Clusters
Radiative cool core cluster simulation: gas density

\[ \langle 1 + \delta_{\text{gas}} \rangle \]
Mass weighted temperature

\[ \frac{\langle T \rho_{\text{gas}} \rangle}{\langle \rho_{\text{gas}} \rangle} \text{[K]} \]

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Mach number distribution weighted by $\varepsilon_{\text{diss}}$
Mach number distribution weighted by $\epsilon_{CR, inj}$
Mach number distribution weighted by $\varepsilon_{\text{CR, inj}}(q > 30)$
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CR pressure $P_{CR}$

$\langle P_{CR} \rho_{\text{gas}} \rangle / \langle \rho_{\text{gas}} \rangle [\text{erg cm}^{-3} h_{70}^{2}]$

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Relative CR pressure $P_{\text{CR}}/P_{\text{total}}$
Relative CR pressure $P_{CR}/P_{\text{total}}$
Phase-space diagram of radiative cluster simulation

\[
\log\left(1 + \delta_{\text{gas}}\right)
\quad \quad \log\left(\frac{P_{\text{CR}}}{P_{\text{th}}}\right)
\]

Phase space density [arbitrary units]

-4, -3, -2, -1, 0, 1, 2

-4, -3, -2, -1, 0, 1, 2

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Radiative simulations: pressure profile

Cool core cluster sample.
- red: only structure formation shock CRs,
- blue: structure formation & SNe CRs.

Merging cluster sample.
Radiative simulations: relative CR pressure profile

Cool core cluster sample.
- red: only structure formation shock CRs,
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Merging cluster sample.
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Radiative simulations: adiabatic index profile

Cool core cluster sample.
red: only structure formation shock CRs,
blue: structure formation & SNe CRs.

Merging cluster sample.
Thermal X-ray emission

- large merging cluster, $M_{\text{vir}} \simeq 10^{15} \, M_\odot / h$
- small cool core cluster, $M_{\text{vir}} \simeq 10^{14} \, M_\odot / h$
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**Difference map of $S_X$: $S_{X,CR} - S_{X,th}$**

![Diagram showing the difference map of $S_X$ with color bars indicating the range from $-10^{-2}$ to $10^2$.]

- **Large merging cluster**, $M_{\text{vir}} \approx 10^{15} M_\odot / h$
  - contributes to the scatter in the $M - L_X$ scaling relation

- **Cool core cluster**, $M_{\text{vir}} \approx 10^{14} M_\odot / h$
  - systematic increase of $L_X$ for small cool core clusters

- $\Delta L_X / L_X (r > 5 h^{-1} \text{ kpc }) = 9\%$

- $\Delta L_X / L_X (r > 5 h^{-1} \text{ kpc }) = 29\%$

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Compton $y$ parameter in radiative cluster simulation

large merging cluster, $M_{\text{vir}} \simeq 10^{15} M_\odot / h$

small cool core cluster, $M_{\text{vir}} \simeq 10^{14} M_\odot / h$
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**Compton $y$ difference map:** $y_{CR} - y_{th}$

large merging cluster, $M_{\text{vir}} \approx 10^{15} \, M_{\odot} / h$

small cool core cluster, $M_{\text{vir}} \approx 10^{14} \, M_{\odot} / h$

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Particle acceleration processes

particles are accelerated via:
- adiabatic compression
- diffusive shock acceleration (Fermi I)
- stochastic acceleration by plasma waves (Fermi II)
- particle reactions ($pp \rightarrow \pi \rightarrow \mu\nu \rightarrow e\nu\nu$)

particles are de-accelerated via:
- adiabatic expansion
- radiative cooling (synchrotron, inverse Compton, bremsstrahlung, hadronic interactions)
- non-radiative cooling (Coulomb interactions)
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Diffusive shock acceleration – Fermi 1 mechanism (1)

**conditions:**

- a collisionless shock wave
- magnetic fields to confine energetic particles
- plasma waves to scatter energetic particles → particle diffusion
- supra-thermal particles

**mechanism:**

- supra-thermal particles diffuse upstream across shock wave
- each shock crossing energizes particles through momentum transfer from recoil-free scattering off the macroscopic scattering agents
- momentum increases exponential with number of shock crossings
- number of particles decreases exponential with number of crossings

→ power-law CR distribution
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→ power-law CR distribution
Spectral index depends on the Mach number of the shock, 
\[ \mathcal{M} = \frac{v_{\text{shock}}}{c_s} \]
Diffusive shock acceleration – efficiency (3)

CR proton energy injection efficiency, $\zeta_{\text{inj}} = \varepsilon_{\text{CR}} / \varepsilon_{\text{diss}}$:

![Graph showing CR proton energy injection efficiency as a function of Mach number $M$ for different $kT_2$ values.](image)
Radiative cool core cluster simulation: gas density

\[ \langle 1 + \delta_{\text{gas}} \rangle \]
Cosmic web: Mach number

\[ \langle M \dot{\varepsilon}_{\text{diss}} \rangle / \langle \dot{\varepsilon}_{\text{diss}} \rangle \]
Radio web: primary CRe (1.4 GHz)
Radio web: primary CRe (150 MHz)
Radio web: primary CRe (15 MHz)
Radio web: primary CRe (15 MHz), slower magnetic decline
Abell 2256: giant radio relic & small halo

X-ray (red) & radio (blue, contours)  fractional polarization in color

Clarke & Enßlin (2006)
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Stochastic acceleration: recipe (1)

conditions:

- super-thermal or better relativistic particles
- magnetic fields to confine them
- high level of plasma waves to scatter them via gyro-resonances

mechanism:

- head on wave-particle collision energises particle
- tail on wave-particle collision de-energises particle
- statistically more head-on than tail-on collisions

→ net energy gain due to diffusion in momentum space

advantage: plasma waves are everywhere!
Stochastic acceleration: recipe (1)

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Stochastic acceleration: cartoon (2)

- Thermal energy
- Turbulent cascade
- Plasma waves

Wave-particle interaction

Thermal particles

Cosmic rays
Stochastic acceleration: cartoon (2)

- **thermal energy** → **turbulent cascade** → **plasma waves**

  - **shock waves**
  - **wave-particle interaction**

- **thermal particles** → **cosmic rays**
Stochastic acceleration: problems (3)

problems:

- low efficiency (2nd order in ratio of wave to particle velocity)
- waves like to cascade to small scales
- small-scale waves dissipate into the thermal pool
- wave energy budget is usually tight
- at locations with high wave density (e.g. shocks), more efficient acceleration mechanism may be in operation (e.g. DSA)

nevertheless: cluster radio halos may be due to stochastic re-acceleration of 0.2 MeV electrons (e.g. Brunetti et al.)
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relativistic proton populations can often be expected, since

- acceleration mechanisms work for protons . . . 
  - . . . as efficient as for electrons (adiabatic compression) or 
  - . . . more efficient than for electrons (DSA, stochastic acc.)
- galactic CR protons are observed to have 100 times higher energy density than electrons
- CR protons are very inert against radiative losses and therefore long-lived (\(\sim\) Hubble time in galaxy clusters, longer outside)

\(\rightarrow\) an energetic CR proton population should exist in clusters
Cluster radio emission by hadronically produced CRe

\[ S_{\nu,\text{secondary}} \left[ \text{mJy arcmin}^{-2} h_{70}^{3/2} \right] \]

\[ x \left[ h^{-1} \text{Mpc} \right] \]

\[ y \left[ h^{-1} \text{Mpc} \right] \]
Thermal X-ray emission

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The thermal plasma lost most information on how cosmic structure formation proceeded due to the dissipative processes. The thermal observables, X-ray emission and the Sunyaev-Zel’dovich effect, tell us only very indirectly (if at all) about the cosmic history. In contrast, non-thermal processes retain their cosmic memory since their particle population is not in equilibrium → cluster archaeology.

How can we read out this information about non-thermal populations? → new era of multi-frequency experiments, e.g.:

- **LOFAR, GMRT, MWA**: interferometric array of radio telescopes at low frequencies ($\nu \simeq (15 - 240) \text{ MHz}$)
- **Simbol-X**: future hard X-ray satellite ($E \simeq (0.5 - 70) \text{ keV}$)
- **GLAST**: high-energy $\gamma$-ray space mission ($E \simeq (0.1 - 300) \text{ GeV}$)
- Imaging air Čerenkov telescopes (TeV photon energies)
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Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:

Energy sources:
- kinetic energy from structure formation
- supernovae & active galactic nuclei

Plasma processes:
- turbulent cascade & plasma waves
- shock waves
Cosmic rays in galaxy clusters
Particle acceleration processes
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Radiative processes
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Relativistic particle pop.:
- re-acceleration CR electrons
- primary CR electrons
- secondary CR electrons

hadronic reaction
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Observational diagnostics:
- radio synchrotron emission
- IC: hard X-ray & gamma-ray emission

hadronic reaction
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Radio halos show a smooth unpolarized radio emission at Mpc-scales. How are they generated?

- **Primary accelerated CR electrons**: synchrotron/IC cooling times too short to account for extended diffuse emission.

- **Continuous in-situ acceleration** of pre-existing CR electrons either via interactions with magneto-hydrodynamic waves, or through turbulent spectra (Jaffe 1977, Schlickeiser 1987, Brunetti 2001, Brunetti & Lazarian 2007).


All of these models face theoretical short-comings when comparing to observations.
Unified model of radio halos and relics

Cluster radio emission varies with dynamical stage of a cluster:

- Cluster relaxes and develops cool core: radio mini-halo develops due to hadronically produced CR electrons, magnetic fields are adiabatically compressed (cooling gas triggers radio mode feedback of AGN that outshines mini-halo → selection effect).

- Cluster experiences major merger: two leading shock waves are produced that become stronger as they break at the shallow peripheral cluster potential → shock-acceleration of primary electrons and development of radio relics.

- Generation of morphologically complex network of virializing shock waves. Lower sound speed in the cluster outskirts lead to strong shocks → irregular distribution of primary electrons, MHD turbulence amplifies magnetic fields.

- Giant radio halo develops due to (1) boost of the hadronically generated radio emission in the center (2) irregular radio ‘gischt’ emission in the cluster outskirts.
Cluster radio emission varies with dynamical stage of a cluster:

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Radio gischt: primary CRe (150 MHz)
Radio gischt + central hadronic halo = giant radio halo
Giant radio halo profile

\[ S_{1.4 \text{GHz}} \, [\text{mJy arcmin}^{-2} h_{70}^{-3}] \]

- merger, \(10^{15} M_\odot/h\)
- combined radio
- primary radio
- secondary radio

\[ x = R / R_{\text{vir}} \]
Giant radio halo vs. mini-halo

\[ S_{1.4 \text{ GHz}} \text{ [mJy arcmin}^{-2} \text{]} \]

\[ x = \frac{R}{R_{\text{vir}}} \]

- merger, \(10^{15} M_\odot/h\)
- CC, \(10^{15} M_\odot/h\)
Radio relics + halos: spectral index

\[ \alpha \nu \]

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Low-frequency radio emission from clusters
Window into current and past structure formation

Our unified model accounts for . . .

- **correlation between merging clusters and giant halos**, occurrence of mini-halos in cool core clusters
- **observed luminosities of halos/relics** for magnetic fields derived from Faraday rotation measurements
- **observed morphologies, variations, spectral and polarization properties** in radio halos/relics

How we can make use of this information:

- **Radio relics**: produced by primary accelerated CR electrons at formation shocks → probes **current dynamical, non-equilibrium activity** of forming structures (shocks and magnetic fields)
- **Central radio halos**: produced by secondary CR electrons in hadronic CR proton interactions → tracing **time-integrated non-equilibrium activity**, modulated by recent dynamical activities
Low-frequency radio emission from clusters
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Correlation between X-ray and synchrotron emission

Correlation with secondary ‘halo’ emission, merging cluster, $M_{\text{vir}} \sim 10^{15} M_\odot / h$

Correlation with primary ‘relic’ emission, merging cluster, $M_{\text{vir}} \sim 10^{15} M_\odot / h$
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   - Unified model of radio halos and relics
   - High-energy gamma-ray emission
Thermal X-ray emission

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Simulating Galaxy Clusters
Hadronic $\gamma$-ray emission, $E_\gamma > 100$ MeV
Inverse Compton emission, $E_{IC} > 100$ MeV
Gamma-ray scaling relations

Scaling relation + complete sample of the brightest X-ray clusters (HIFLUCGS) \(\rightarrow\) predictions for GLAST
Predicted cluster sample for GLAST

- Triangulum A0754
- NGC4636
- AWM7, 3C129
- Perseus, Centaurus, A1060
- A3627
- Coma
- Ophiuchus, Fornax

$N_{\text{clusters}}$ vs. $F_\gamma \, [\gamma \text{ cm}^{-2} \text{ s}^{-1}]$
**Minimum \(\gamma\)-ray flux in the hadronic model (1)**

Synchrotron emissivity of high-energy, steady state electron distribution is independent of the magnetic field for \(B \gg B_{\text{CMB}}\)!

\[ j_{\nu}(B) = \begin{cases} \alpha_{\nu} = 1 & \nu = 1.15 \\ \alpha_{\nu} = 1.30 & \nu = 1.45 \end{cases} \]

**Synchrotron luminosity:**

\[ L_{\nu} = A_{\nu} \int dV n_{\text{CR}} n_{\text{gas}} \left( \frac{\varepsilon_B}{\varepsilon_{\text{CMB}} + \varepsilon_B} \right)^{(\alpha_{\nu} + 1)/2} \]

\[ \rightarrow A_{\nu} \int dV n_{\text{CR}} n_{\text{gas}} \left( \varepsilon_B \gg \varepsilon_{\text{CMB}} \right) \]

**\(\gamma\)-ray luminosity:**

\[ L_{\gamma} = A_{\gamma} \int dV n_{\text{CR}} n_{\text{gas}} \]

\[ \rightarrow \text{minimum } \gamma\text{-ray flux:} \]

\[ F_{\gamma,\text{min}} = \frac{A_{\gamma}}{A_{\nu}} \frac{L_{\nu}}{4\pi D^2} \]
Synchrotron emissivity of high-energy, steady state electron distribution is independent of the magnetic field for $B \gg B_{\text{CMB}}$!

Synchrotron luminosity:

$$L_\nu = A_\nu \int dV n_{\text{CR}} n_{\text{gas}} \frac{\epsilon_B}{\epsilon_{\text{CMB}} + \epsilon_B}$$

$$\rightarrow A_\nu \int dV n_{\text{CR}} n_{\text{gas}} \quad (\epsilon_B \gg \epsilon_{\text{CMB}})$$

$\gamma$-ray luminosity:

$$L_\gamma = A_\gamma \int dV n_{\text{CR}} n_{\text{gas}}$$

$\rightarrow$ minimum $\gamma$-ray flux:

$$F_{\gamma, \text{min}} = \frac{A_\gamma}{A_\nu} \frac{L_\nu}{4\pi D^2}$$
Minimum $\gamma$-ray flux in the hadronic model (2)

Minimum $\gamma$-ray flux ($E_\gamma > 100$ MeV) for the Coma cluster:

<table>
<thead>
<tr>
<th>CR spectral index</th>
<th>2.0</th>
<th>2.3</th>
<th>2.6</th>
<th>2.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_\gamma \left[10^{-10} \gamma \text{cm}^{-2} \text{s}^{-1}\right]$</td>
<td>0.8</td>
<td>1.6</td>
<td>3.4</td>
<td>7.1</td>
</tr>
</tbody>
</table>

- These limits can be made even tighter when considering energy constraints, $P_B < P_{\text{gas}}/20$ and $B$-fields derived from Faraday rotation studies, $B_0 = 3 \mu\text{G}$:
  \[ F_{\gamma,\text{COMA}} \gtrsim 2 \times 10^{-9} \gamma \text{cm}^{-2} \text{s}^{-1} = F_{\text{GLAST}, 2yr} \]

- Non-detection by GLAST seriously challenges the hadronic model.

- Potential of measuring the CR acceleration efficiency for diffusive shock acceleration.
Summary – 1. CR pressure feedback

1. Characteristics of the CRs in clusters:
   - CR proton pressure: time integrated non-equilibrium activities of clusters, modulated by recent mergers.
   - Primary CR electron pressure: resembles current accretion and merging shocks in the virial regions.

2. CR pressure modifies the ICM in merging clusters and cooling core regions:
   - Galaxy cluster X-ray emission is enhanced up to 35%, systematic effect in low-mass cooling core clusters.
   - Integrated Sunyaev-Zel’dovich effect remains largely unchanged while the Compton-y profile is more peaked.
   - GLAST should see hadronic γ-ray emission from clusters: measurement of CR protons and origin of radio halos.
Unified model for the generation of giant radio halos, radio mini-halos, and relics:

- Giant radio halos are dominated in the center by secondary synchrotron emission.
- Transition to the radio emission from primary electrons in the cluster periphery.

LOFAR/GMRT are expected to see the radio web emission: origin of cosmic magnetic fields.

We predict GLAST to detect $\sim$ ten $\gamma$-ray clusters: test of the presented scenario

→ exciting experiments allow a complementary view on structure formation as well as fundamental physics!
Thermal cluster observables (1)

Thermal bremsstrahlung emission, merging cluster, $M_{\text{vir}} \sim 10^{15} M_\odot / h$

Sunyaev-Zel'dovich effect, merging cluster, $M_{\text{vir}} \sim 10^{15} M_\odot / h$
Optical and radio synchrotron cluster observables (1)

Stellar mass density ("cluster galaxies"), merging cluster, $M_{\text{vir}} \simeq 10^{15} M_{\odot}/h$

Radio halo and relic emission, merging cluster, $M_{\text{vir}} \simeq 10^{15} M_{\odot}/h$
Thermal cluster observables (2)

Thermal bremsstrahlung emission, cool core cluster, $M_{\text{vir}} \sim 10^{14} M_\odot / h$

Sunyaev-Zel'dovich effect, cool core cluster, $M_{\text{vir}} \sim 10^{14} M_\odot / h$
Stellar mass density (“cluster galaxies”),
cool core cluster, $M_{\text{vir}} \sim 10^{14} M_\odot / h$

Radio halo and relic emission,
cool core cluster, $M_{\text{vir}} \sim 10^{14} M_\odot / h$