Deciphering an enigma – Non-thermal emission from galaxy clusters

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in collaboration with

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Plasma processes in galaxy clusters

1. Cosmological galaxy cluster simulations
2. Shocks and particle acceleration
3. Cosmic ray transport and pressure distribution

Non-thermal emission from clusters

1. Radio emission by shocks and turbulence
2. Hadronically induced radio emission
3. High-energy $\gamma$-ray emission

Future perspectives and directions

1. Overview
2. Defining the questions
3. Conclusions
Outline

1. Plasma processes in galaxy clusters
   - Cosmological galaxy cluster simulations
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2. Non-thermal emission from clusters
   - Radio emission by shocks and turbulence
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Shocks in galaxy clusters

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

Abell 3667
(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)
Giant radio halo in the Coma cluster

thermal X-ray emission
(Snowden/MPE/ROSAT)

radio synchrotron emission
(Deiss/Effelsberg)
consistent picture of non-thermal processes in galaxy clusters (radio, soft/hard X-ray, γ-ray emission) → illuminating the process of structure formation → history of individual clusters: cluster archeology

understanding the non-thermal pressure distribution to address biases of thermal cluster observables

gold sample of clusters for precision cosmology: using non-thermal observables to gauge hidden parameters

nature of dark matter: annihilation signal vs. cosmic ray (CR) induced γ-rays

fundamental plasma physics:
  - diffusive shock acceleration in high-β plasmas
  - origin and evolution of large scale magnetic fields
  - nature of turbulent models
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

CP, Enßlin, Springel (2008)
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
- Cosmic ray energy
- Coulomb losses

Loss processes: red
Gain processes: green
Observables: yellow
Populations: blue

CP, Enßlin, Springel (2008)
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Hadronic cosmic ray proton interaction

\[
\begin{align*}
\text{CRp} & \rightarrow \pi^+ \rightarrow \mu^+ \rightarrow e^+ \\
p & \rightarrow \pi^0 \rightarrow \nu_\mu \\
\end{align*}
\]
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Radiative simulations with cosmic ray (CR) physics

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

CP, Enßlin, Springel (2008)
Radiative simulations with extended CR physics

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

Physical processes in clusters:
- thermal energy
- radiative cooling
- shocks
- supernovae
- AGN
- Coulomb losses
- CR diffusion
- hadronic losses
- cosmic ray energy
- heat conduction
- loss processes
- gain processes
- observables
- populations

CP, Enßlin, Springel (2008)
Our philosophy and description

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
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CR spectral description

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

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

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

\[ n_{CR} = \int_{0}^{\infty} dp \, f(p) = \frac{C q^{1 - \alpha}}{\alpha - 1} \]

\[ P_{CR} = \frac{m_p c^2}{3} \int_{0}^{\infty} dp \, f(p) \, \beta(p) \, p \]

\[ = \frac{C m_p c^2}{6} \beta^{\frac{1}{1+q^2}} \left( \frac{\alpha - 2}{2}, \frac{3 - \alpha}{2} \right) \]

Enßlin, CP, Springel, Jubelgas (2007)
CR protons in clusters

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 (∼ Hubble time in galaxy clusters, longer outside)

→ an energetic CR proton population should exist in clusters
Radiative cool core cluster simulation: gas density

\[ \langle 1 + \delta_{\text{gas}} \rangle \]
Mass weighted temperature
Plasma processes in galaxy clusters
Non-thermal emission from clusters
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Cosmological galaxy cluster simulations
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Cosmic ray transport and pressure distribution

Mach number distribution weighted by $\varepsilon_{\text{diss}}$

![Mach number distribution](image)

$\langle M \dot{\varepsilon}_{\text{diss}} / \langle \dot{\varepsilon}_{\text{diss}} \rangle \rangle$
**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 macroscopic scattering agents
- momentum increases exponentially with number of shock crossings
- particle number decreases exponentially with number of crossings

→ power-law CR distribution
Diffusive shock acceleration – Fermi 1 mechanism (1)

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→ power-law CR distribution
Diffusive shock acceleration – Fermi 1 mechanism (2)

Spectral index depends on the Mach number of the shock, $\mathcal{M} = n_{\text{shock}}/c_s$:

\[
\log f \quad \log p
\]

- strong shock
- weak shock

$10$ GeV

$\log p$

$\log f$

$\text{keV}$

$\text{weak shock}$

$\text{strong shock}$

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Non-thermal emission from galaxy clusters
Mach number distribution weighted by $\varepsilon_{\text{diss}}$
Mach number distribution weighted by $\varepsilon_{CR, inj}$

\[ \langle M \dot{\varepsilon}_{CR, inj} \rangle / \langle \dot{\varepsilon}_{CR, inj} \rangle \]
Mach number distribution weighted by $\varepsilon_{\text{CR, inj}}(q > 30)$
CR pressure $P_{CR}$

$\langle P_{CR} \rho_{gas} \rangle / \langle \rho_{gas} \rangle [\text{erg cm}^{-3} h_{270}^2]$
Relative CR pressure $P_{CR}/P_{\text{total}}$
Relative CR pressure $\frac{P_{\text{CR}}}{P_{\text{total}}}$
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CR phase-space diagram: final distribution @ \( z = 0 \)

\[
\log[\frac{P_{CR}}{P_{th}}] \quad \log[1 + \delta_{\text{gas}}] \quad \text{phase space density [arbitrary units]}
\]

\[
10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 10^{0}
\]

\[
10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 10^{0}
\]

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CR impact on SZ effect: Compton $y$ parameter

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

small cool core cluster, $M_{\text{vir}} \simeq 10^{14} M_\odot / h$
Compton $y$ difference map: $\Delta Y / Y = -1.6\%$

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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Multi messenger approach for non-thermal 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
Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:

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- CR protons

Relativistic particle pop.:
- re-acceleration CR electrons
- primary CR electrons
- secondary CR electrons

hadronic reaction
Multi messenger approach for non-thermal processes

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Observational diagnostics:
- radio synchrotron emission
- IC: hard X-ray & gamma-ray emission
Cosmic web: Mach number

\[ \langle M_{\dot{\varepsilon}_{\text{diss}}} / \dot{\varepsilon}_{\text{diss}} \rangle \]

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Radio gischt (relics): primary CRe (1.4 GHz)
Radio gischt: primary CRe (150 MHz)
Radio gischt: primary CRe (15 MHz)
Radio gischt: primary CRe (15 MHz), slower magnetic decline
Radio gischt illuminates cosmic magnetic fields

Structure formation shocks triggered by a recent merger of a large galaxy cluster.

red/yellow: shock-dissipated energy,
blue/contours: 150 MHz radio gischt emission from shock-accelerated CRe
Battaglia, CP, Sievers, Bond, Enßlin (2008):

By suitably combining the observables associated with diffuse polarized radio emission at low frequencies ($\nu \sim 150$ MHz, GMRT/LOFAR/MWA/LWA), we can probe

- the strength and coherence scale of magnetic fields on scales of galaxy clusters,
- the process of diffusive shock acceleration of electrons,
- the existence and properties of the WHIM,
- the exploration of observables beyond the thermal cluster emission which are sensitive to the dynamical state of the cluster.
Rotation measure (RM)

RM maps and power spectra have the potential to infer the magnetic pressure support and discriminate the nature of MHD turbulence in clusters:

Left: RM map of the largest relic, right: Magnetic and RM power spectrum comparing Kolmogorov and Burgers turbulence models.

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Particle acceleration by turbulence or shocks?

Diffuse low-frequency radio emission in Abell 521 (Brunetti et al. 2008)

(colors: thermal X-ray emission; contours: diffuse radio emission.

- “radio relic” interpretations with aged population of shock-accelerated electrons or shock-compressed radio ghosts (aged radio lobes),
- “radio halo” interpretation with re-acceleration of relativistic electrons through interactions with MHD turbulence.

→ synchrotron polarization is key to differentiate!)
Hadronic cosmic ray proton interaction

Plasma processes in galaxy clusters
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Radio emission by shocks and turbulence
Hadronically induced radio emission
High-energy $\gamma$-ray emission
Cluster radio emission by hadronically produced CRe

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Non-thermal emission from galaxy clusters
Plasma processes in galaxy clusters
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Radio emission by shocks and turbulence
Hadronically induced radio emission
High-energy $\gamma$-ray emission

Thermal X-ray emission

The image shows a plot of X-ray emission in galaxy clusters, with the intensity represented on a logarithmic scale. The x-axis corresponds to $x [h^{-1} \text{Mpc}]$ and the y-axis to $y [h^{-1} \text{Mpc}]$. The emission intensity is denoted as $S_X [\text{erg cm}^{-2} \text{s}^{-1} h^3]$, with values ranging from $10^{-15}$ to $10^{-9}$.

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Non-thermal emission from galaxy clusters
Radio gischt: primary CRe (150 MHz)
Radio gischt + central hadronic halo = giant radio halo

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Which one is the simulation/observation of A2256?

red/yellow: thermal X-ray emission,
blue/contours: 1.4 GHz radio emission with giant radio halo and relic

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Non-thermal emission from galaxy clusters
Observation – simulation of A2256

- red/yellow: thermal X-ray emission,
- blue/contours: 1.4 GHz radio emission with giant radio halo and relic
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.
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Non-thermal emission from clusters
Exploring the memory of structure formation

- primary, shock-accelerated CR electrons resemble current accretion and merging shock waves
- CR protons/hadronically produced CR electrons trace the time integrated non-equilibrium activities of clusters that is modulated by the recent dynamical activities

How can we read out this information about non-thermal populations?
→ new era of multi-frequency experiments, e.g.:
  - GMRT, LOFAR, MWA, LWA, SKA: interferometric array of radio telescopes at low frequencies ($\nu \sim (15 − 240) \text{ MHz}$)
  - Simbol-X/NuSTAR: future hard X-ray satellites ($E \sim (1 − 100) \text{ keV}$)
  - Fermi $\gamma$-ray space telescope ($E \sim (0.1 − 300) \text{ GeV}$)
  - Imaging air Čerenkov telescopes ($E \sim (0.1 − 100) \text{ TeV}$)

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Non-thermal emission from galaxy clusters
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  - **Imaging air Čerenkov telescopes**: \((E \approx (0.1 – 100) \text{ TeV})\)
The quest for high-energy $\gamma$-ray emission from clusters

Multi-messenger approach towards fundamental astrophysics

1. complements current non-thermal observations of galaxy clusters in radio and hard X-rays:
   - identifying the nature of emission processes
   - unveiling the contribution of cosmic ray protons

2. elucidates the nature of dark matter:
   - disentangling annihilation signal vs. CR induced $\gamma$-rays
   - spectral and morphological $\gamma$-ray signatures $\rightarrow$ DM properties

3. probes plasma astrophysics such as macroscopic parameters for diffusive shock acceleration
Hadronic $\gamma$-ray emission, $E_\gamma > 100$ GeV
Inverse Compton emission, $E_{IC} > 100$ GeV
Total $\gamma$-ray emission, $E_\gamma > 100$ GeV

\[ S_\gamma (100 \text{ GeV}, 100 \text{ TeV}) \left[ \gamma \text{ cm}^{-2} \text{s}^{-1} \text{ h}^{-1} \right] \]

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

\[ y \left[ h^{-1} \text{Mpc} \right] \]
Normalized CR spectrum shows universal concave shape → governed mainly by hierarchical structure formation and adiabatic CR transport processes. (Pinzke & CP, in prep.)

→ very promising for disentangling the dark matter annihilation signal!
Gamma-ray scaling relations

Scaling relation + complete sample of the brightest X-ray clusters (extended HIFLUCGS) → predictions for Fermi (CP 2008)
Radio emission by shocks and turbulence
Hadronically induced radio emission
High-energy $\gamma$-ray emission

Predicted cluster sample for *Fermi*

![Graph showing predicted cluster sample for Fermi](image)

- **N clusters**
- **$F_\gamma$ [\(\gamma \text{ cm}^{-2} \text{ s}^{-1}\)]**

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

Model S3
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Plasma processes in galaxy clusters
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Future perspectives and directions

Clusters as Laboratories for Fundamental Plasma Physics
Understanding AGN Feedback in Clusters
Understanding the Nature of Dark Matter
Tracing the Dynamical Evolution of Dark Energy

Cluster Astrophysics and Cosmology
Clusters as laboratories for plasma physics
Opening up the radio and $\gamma$-ray window for the "non-thermal Universe"

- plasma processes (acceleration, turbulence, instabilities, anisotropic transport)
- cosmic rays (including ultra-high energy CRs)
- magnetic fields – origin, growth
- feedback processes (AGN, galaxies)

**goal:** connecting multi-frequency observables (LOFAR, Fermi) to high-resolution simulations $\rightarrow$ fundamental plasma astrophysics

large scales: cluster "cluster archeology", cosmological surveys
small scales: solving riddles (cold fonts, bubble stability) $\rightarrow$ new effects (magnetic draping)
Clusters as laboratories for plasma physics
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Understanding AGN feedback in clusters
The intertwined lives of supermassive black holes and cluster cores

1. **AGN accretion, jet launch, bubble formation:** magnetic fields, cosmic rays, and turbulence play crucial role

2. **heating mechanism:** cavity heating through releasing potential energy, weak shocks, sound damping, . . .

   (McNamara & Nulsen 2007)

3. **cosmological impact:** role in galaxy and cluster evolution

→ understanding both the **detailed plasma physics and the statistical properties** of the AGN feedback in the cosmological context
→ **high-performance simulations** of the involved physics and **new observational strategies** will elucidate the properties of the interaction
Understanding the nature of dark matter
Unveiling dark matter annihilation in the presence of astrophysical foregrounds

- disentangling the $\gamma$-ray emission resulting from dark matter annihilation from the cosmic ray induced signal
- electrons/positrons from dark matter annihilations vs. CR interactions: modified synchrotron emission characteristic; different particle spectra observed on Earth

→ self-consistent cosmic ray simulations (galaxy clusters, the Galaxy) and modeling of spectral and spatial emission characteristics necessary to discover the properties of dark matter

NASA/DOE/LAT: Fermi's 1st light
Tracing the dynamical evolution of dark energy
Joint analysis of simulated cluster surveys

- accelerated expansion of the Universe caused by either a cosmological fluid (scalar field, vacuum energy) or by modification of General Relativity for small curvature

- this causes modified evolution of the signal from cosmological standard candles (SNe) / yard sticks (baryon acoustic oscillations) or a different growth of structure (weak lensing, cluster surveys) → complementary probes of precision cosmology

→ study of the influence of different physical processes on hydrodynamical cluster structure and survey observables (X-ray, Sunyaev-Zel’dovich, lensing, radio) in large cosmological simulations
Conclusions

In contrast to the thermal plasma, the non-equilibrium distributions of CRs preserve the information about their injection and transport processes and provide thus a unique window of current and past structure formation processes!

1. **Cosmological hydrodynamical simulations** are indispensable for understanding non-thermal processes in galaxy clusters → illuminating the process of structure formation

2. **Multi-messenger approach** including radio synchrotron, hard X-ray IC, and HE $\gamma$-ray emission:
   - **fundamental plasma physics**: diffusive shock acceleration, large scale magnetic fields, and turbulence
   - **nature of dark matter**
   - **gold sample** of clusters for precision cosmology
Literature for the talk


