Non-thermal processes in galaxy clusters – How reliable is the Sunyaev-Zel’dovich effect?

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in collaboration with

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Mar 7, 2009 / CIfAR meeting, Mont-Tremblant
Outline

1. Introduction and motivation
   - Observations
   - The big questions
   - Cosmological simulations

2. Galaxy cluster thermodynamics
   - Cosmological galaxy cluster simulations
   - Cosmic ray acceleration and transport
   - Effect on the Sunyaev-Zel’dovitch effect

3. Non-thermal emission from clusters
   - General picture
   - Cluster radio halos
   - High-energy $\gamma$-ray emission
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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.)
High-energy astrophysics in galaxy clusters

- understanding the **non-thermal pressure distribution** from cosmic rays, turbulence: what is the bias on the SZ effect?
- consistent picture of non-thermal processes in galaxy clusters (radio, soft/hard X-ray, $\gamma$-ray emission)
  → illuminating the **process of structure formation**
  → history of individual clusters: **cluster archeology**
- **nature of dark matter**: annihilation signal vs. cosmic ray (CR) induced $\gamma$-rays
- **fundamental plasma physics**:
  - diffusive shock acceleration in high-$\beta$ 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:
- Stellar populations
- Radiative cooling
- Thermal energy
- Supernovae
- Shocks

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

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

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

Loss processes
Gain processes
Observables
Populations

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

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Introduction and motivation
Galaxy cluster thermodynamics
Non-thermal emission from clusters

Observations
The big questions
Cosmological simulations

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:
- thermal energy
- 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:
- Radiative cooling
- Stellar populations
- Supernovae
- Shocks
- AGN
- Coulomb losses
- Cosmic ray energy
- Hadronic losses
- CR diffusion
- Heat conduction

Loss processes (red)
Gain processes (green)
Observables (yellow)
Populations (blue)

CP, Enßlin, Springel (2008)
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Mass weighted temperature

\[ \langle T \rho_{\text{gas}} \rangle / \langle \rho_{\text{gas}} \rangle \,[K] \]
Mach number distribution weighted by $\varepsilon_{\text{diss}}$
Mach number distribution weighted by $\varepsilon_{CR, inj}$
Mach number distribution weighted by $\epsilon_{\text{CR, inj}}(q > 30)$
Non-thermal processes in galaxy clusters

CR pressure $P_{CR}$
Relative CR pressure $P_{\text{CR}}/P_{\text{total}}$
Relative CR pressure $P_{CR}/P_{total}$

![Graph showing the relative CR pressure $P_{CR}/P_{total}$ in a galaxy cluster. The graph plots the relative CR pressure against the gas density, with a color scale ranging from $10^{-4}$ to $10^{2}$.](image)
CR phase-space diagram: final distribution @ $z = 0$
Influence of CR pressure and turbulence on $M_{\text{hydrostatic}}$

$\rho_{\text{gas}}^{-1} \frac{dP_{\text{tot}}}{dr} = -\frac{GM(<r)}{r^2}$, where $P_{\text{tot}} = P_{\text{th}} + P_{\text{nth}}$, CP in prep.
Influence of cooling, star formation and CRs on $P(r)$

\[ y \propto \int \frac{dV}{P_{e,th}} \]

CP et al. 2007; Battaglia, Bond, CP, Sievers in prep.

cosmological galaxy cluster simulations
non-radiative simulations
radiative simulations
Influence of AGN feedback on the SZ effect

→ AGN feedback lowers the central Compton-$y$ parameter and pushes the gas beyond $R_{\text{vir}}$ (importance at high-$z$!)

Sijacki, CP, Springel, Enßlin 2008
Take home messages (1)

1. Non-radiative simulations overestimate central pressure by a factor of $\sim 10$ and the total Compton-$y$ parameter by $\sim 33\%$
   - Transforming baryons into stars
   - Radiative cooling removes low-entropy ($S \sim T/\rho^{2/3}$) gas which is replaced by high-$S$ gas that has a lower initial pressure $P \sim S \rho^{5/3}$

2. Feedback by CRs, galactic winds modify the SZ effect only on the per cent level

3. Total Compton-$y$ dominated by the exterior parts (uncertainties in cores less severe, apart from integral effect on overall gas fraction), but turbulence effects on the order of $\sim 10 – 20\%$

→ Huge effort to investigate these problems and its influence on the $C_\ell$’s systematically using large cosmological box simulations.
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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

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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

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Multi messenger approach for non-thermal processes

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Non-thermal processes in galaxy clusters
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 processes in galaxy clusters
Observation – simulation of A2256

Clarke & Enßlin (2006)

CP, Battaglia, Pinzke (2008 in prep.)

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 ($\nu \approx (15 - 240) \text{ MHz}$)
- **Simbol-X/NuSTAR**: future hard X-ray satellites ($E \approx (1 - 100) \text{ keV}$)
- **Fermi $\gamma$-ray space telescope** ($E \approx (0.1 - 300) \text{ GeV}$)
- **Imaging air Čerenkov telescopes** ($E \approx (0.1 - 100) \text{ TeV}$)
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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
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Hadronic $\gamma$-ray emission, $E_\gamma > 100$ GeV

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Non-thermal processes in galaxy clusters
Inverse Compton emission, $E_{IC} > 100$ GeV

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Total $\gamma$-ray emission, $E_\gamma > 100$ GeV

$S_{\gamma}(100 \text{ GeV}, 100 \text{ TeV}) \left[ \frac{\gamma}{\text{cm}^2 \cdot \text{s}^{-1} \cdot h_{70}^{-3}} \right]$
Universal CR spectrum in clusters

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)
Predicted cluster sample for *Fermi*

![Graph showing predicted cluster sample for Fermi with various clusters and their corresponding gamma-ray flux densities.](image)
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


