Non-thermal processes in galaxy clusters

cosmic rays, dark matter, turbulence, magnetic fields, ...

Bullet Cluster

Abell 2163

Anders Pinzke
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Cosmic rays in clusters of galaxies

Relativistic populations and radiative processes in clusters:

Energy sources:

- kinetic energy from structure formation
- supernovae & active galactic nuclei

Plasma processes:

Relativistic particle pop.:

Observational diagnostics:

Pfrommer et al. 2008
Cosmic rays in clusters of galaxies

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- shock waves

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- primary CR electrons

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- IC: hard X-ray & gamma-ray emission

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- secondary CR electrons

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- $\pi^0$

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- gamma-ray emission

Pfrommer et al. 2008
Galaxy cluster simulations

- **Gadget3**
  - *parallel TreeSPH code*
  - *updated cosmic ray physics (spatial and spectral information)*
  - *radiative hydrodynamics*

- **Simulate 14 high-resolution galaxy clusters**
  - *full cosmological environment*
  - *variety of dynamical stages*
  - *mass range of almost two orders of magnitudes*
CR proton/gamma-ray spectra

\[ R < R_{\text{vir}} \]
proton spectrum

\[ \text{CRp + p} \rightarrow \pi^0 \rightarrow 2\gamma \]

\[ p = P_p / (m_p c) \]

Pinzke, Pfrommer 2010

\[ \pi^0 \text{- decay} \]
plC
sIC

emission components

Energy [GeV]

normalized CR spectrum
energy weighted flux [GeV cm\(^{-2}\) s\(^{-1}\)]
Gamma-ray observations of clusters

**MAGIC IACT**

**Perseus**

- radiative physics w/o gal. x 2
- radiative physics w/ gal.
- $F_{\gamma} \min \left( B_0 = 10 \, \mu\text{G}, \varepsilon_\text{p} < \varepsilon_\text{h} / 3 \right)$

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![Graph showing gamma-ray flux vs energy for various clusters.](image)

**Fermi – 100 MeV**

- Pinke & Pfommer 2010
- Donnert et al. 2010
- EGRET 0.95 CL
- LAT 0.95 CL

**Clusters:**
- 3C129
- A0085
- A0754
- A1367
- A1914
- A2029
- A2142
- A2199
- A2256
- A2319
- A2744
- A3376
- A3571
- AWM7
- Antlia
- Bullet
- Centaurus
- Coma
- Fornax
- Hydra
- M49
- MACS J0717
- NGC 5044
- NGC 5846
- Ophiuchus
- Perseus
- RXJ1347
- Virgo
- NGC 4636
- NGC 5813
- Norma

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**Aleksic et al. 2009**

**Ackermann et al. 2010**
Annihilating dark matter - substructures

Large luminosity contribution from substructures.

The cold dark matter scenario predicts a smallest size for halos of $M_{\text{min}} \sim 10^{-6} M_{\odot}$.

*Hofmann, Schwarz and Stöcker, 2008*
*Green, Hofmann and Schwarz, 2005*

Extrapolating simulations to these scales:

$\rightarrow$ luminosity boosted by $200$

*Springel et al., 2008*
Constraining the DM halos size

- Gamma-ray upper limit from EGRET $\rightarrow M_{\text{min}} > 10^{-2} M_\odot$ (lower limit on substructure mass)
- Fluxes well above Fermi limits, however there are non trivial resolution effects and a more detailed analysis of extended sources would be needed.

Pinzke, Pfrommer and Bergström, 2009
Annihilating DM vs. CR interactions

Different BM models, Fornax

Bright prospects for detecting DM:
CR induced signal does not swamp the DM annihilation signal

→ Fornax is a prime candidate for annihilating dark matter
Ongoing/Future

Experiments:
- Fermi - stacked cluster analysis
  Limited by AGNs?
- Major Cherenkov telescope observations
  Observation time and target selection
- More sensitive radio observations; statistics, polarization, lower luminosities
- Better Faraday Rotation measurements; remove degeneracy for non-thermal emission

Theories/simulations:
- Detailed model for CR proton transport – diffusion, streaming,...
- MHD simulations; impact of B fields on relativistic populations
- Simulations that can resolve smaller substructures
  -> improve estimates of the substructure boost;
  key ingredient for cosmological DM searches
Extra Slides
Signs of non-thermal activity in galaxy clusters

**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.

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*Radio:* Feretti at al, 2004
Radio halos - origin

Radio observations alone can not distinguish the emission from re-accelerated electrons from the secondary electrons.

Re-acceleration models predict:
Low X-ray luminous clusters should not exhibit radio halos.

Hadronic models predict:
The radio halo emission should always be accompanied by some level of gamma-ray flux, emerging from the hadronic production of neutral pions that decay into gamma-rays.
Most clusters are best fitted with a rather flat radio power-law spectrum. However, some clusters show a much steeper spectrum.

Potential bias in radio observations:
Interpretation: relics?
Measurements: point source bias, reduced sensitivity at large frequencies
Origin of radio halos – observations II

Radio vs. X-ray luminosity

Bimodality of extended radio halo emission
Origin of radio halos – re-acc. model

Strength:
• all required ingredients available: radio galaxies and relics inject CRes, turbulence and plasma waves,...
• reported complex radio spectra emerge naturally
• less turbulence → clusters without a radio halo

Weakness:
• Fermi II acceleration is inefficient and CRes cool rapidly
• observed radio power-law spectra require fine tuning
• ...

Hardest prediction:
Low X-ray luminous clusters should not exhibit radio halos
Cassano et al. 2006, 2008

Should become testable with upcoming sensitive radio telescope arrays
Origin of radio halos – hadronic model

**Strength:**
- all required ingredients available: *shocks inject CRps, gas protons as targets, magnetic fields,*...
- predicted luminosities and morphologies agree with observations without any tuning
- Power-law spectra as observed

**Weakness:**
- simple CRp models predict that all clusters have a radio halo
- does not explain all reported spectral features
- ...

**Hardest prediction:**
The radio halo emission should always be accompanied by some level of gamma-ray flux, emerging from the hadronic production of neutral pions that decay into gamma-rays.
Hard X-ray measurements

Several observational claims of an excess to the thermal spectrum in the energy range 20 keV to 300 keV
Kaastra et al. 2008, for a complete review

Although, the presence and origin still remains controversial

Swift, Chandra and XMM-Newton
“...in most cases the clusters’ emission in the 0.3–200 keV band can be explained by a multi-temperature thermal model”
Ajello et al., 2010

Suzaku
Do not confirm previous claims of HXR excesses in several clusters
Wik et al., 2009; Nakazawa et al., 2009

Implications: primary electrons, secondary, re-accelerated?
Signs of non-thermal activity in galaxy clusters

Most concrete evidence comes from observations of extended radio halos

About 1/3 of clusters seen in X-rays have an extended radio halo

The origin is still disputed!

Ensllin at al, 2011, ...

A 2163 @ 327 MHz

Feretti at al, 2004
Annihilating dark matter - substructures

Constant offset in the luminosity from substructures between different mass resolutions in the simulation ($M_{\text{res}}$).

\[ \text{Norm} \propto \left( \frac{M_{\text{min}}}{M_{\text{res}}} \right)^{0.2^{2.6}} \]

Extrapolate to the minimal mass of dark matter halos ($M_{\text{min}}$) that can form. The cold dark matter scenario suggest $M_{\text{min}} \sim 10^{-6} M_\odot$.

\[ \text{Hofmann, Schwarz and Stöcker, 2008} \]
\[ \text{Green, Hofmann and Schwarz, 2005} \]
DM without Sommerfeld vs. CR interactions

The gamma-rays from dark matter extends out to the virial radius, while the CR induced emission is cutoff at about 10% of the virial radius.

Note the flat surface brightness profile of the DM which is induced by the boost from substructures.
Surface brightness for $E > 100$ GeV

- Pion decay gamma-rays dominate inside virial radius
- The strong magnetic field in the center suppress inverse Compton due to CRs cooling through synchrotron radiation
- Primary inverse Compton contribute substantially in the cluster periphery

Pinzke, Pfrommer 2010
Spatial CR distribution

CR spectra for different radial bins

Similar spectral shape inside $R_{\text{vir}}$

Approximate spatial universal shape!

Pinzke, Pfrommer 2010
Spatial CR distribution

\[ \tilde{C}_M \times 10^{-6} \]

\[ R / R \]

- Simulation
- Fit
- Large clusters
- Small clusters
Semi-analytic model

CRs approximately spatially and spectrally universal in galaxy clusters

Separate radial and spectral parts in a semi-analytic model

\[ f_v(p, R) = \tilde{C}_M(R) \frac{\rho(R)}{m_p} g(\zeta_{p,\text{max}}) D_p(p, p_{\text{break}}, q) \sum_i \Delta_i p^{-q_i} \]

Combining our semi-analytic CR model with gas density profiles inferred from X-ray measurements

**Hadronic model**  
*Pfrommer and Ensslin 2004*

- Neutrino flux, Secondary radio
- Gamma-ray flux, Surface brightness
Gamma-ray emission – DM versus CRs

MASS-TO-GAMMA-RAY SCALING RELATIONS

CR induced emission dominate in all clusters, however the spread in the scaling relations could potentially increase the ratio for several clusters.
CR cooling timescales