The imprint of cluster physics on the SZ effect: from bubbles to cosmological parameters

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in collaboration with

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Outline

1. Galaxy cluster gastrophysics
   - Cosmological galaxy cluster simulations
   - Cosmic ray acceleration and transport
   - Imprint on the Sunyaev-Zel’doovich effect

2. Galaxy cluster cosmology
   - Scaling relations
   - Bias of cosmological parameters
   - Hydrostatic cluster masses and non-thermal processes

3. Sunyaev-Zel’doovich bubbles
   - Unveiling the bubbles’ composition
   - Cosmological simulations of AGN feedback
   - Conclusions
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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.)

The imprint of cluster physics on the SZ effect
How does cluster physics (cooling & star formation, turbulence, cosmic rays, AGN feedback) impact on the thermal pressure distribution?
→ how are SZ scaling relations and hydrostatic masses biased?
→ do we understand our numerical methods well enough to trust these answers?

How does this propagate into uncertainties of cosmological parameters ($\Omega_8, w$) and possibly bias their mean?

How can the SZ effect help in solving the cooling flow problem and shape our understanding of cluster evolution?
Radiative simulations – flowchart

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

Physical processes in clusters: thermal energy, radiative cooling, supernovae, shocks

C.P., 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:

- Thermal energy
- Radiative cooling
- Stellar populations
- Supernovae
- Shocks
- Cosmic ray energy
- Coulomb losses
- Hadronic losses

C.P., Enßlin, Springel (2008)

The imprint of cluster physics on the SZ effect
Hadronic cosmic ray proton interaction

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The imprint of cluster physics on the SZ effect
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
- Cosmic ray energy
- Coulomb losses
- Hadronic losses

C.P., 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
- Shock waves
- AGN
- Coulomb losses
- Cosmic ray energy
- Hadronic losses
- CR diffusion
- Heat conduction

Loss processes: Red
Gain processes: Green
Observables: Yellow
Populations: Blue

C.P., Enßlin, Springel (2008)
Radiative cool core cluster simulation: gas density

\[ \langle 1 + \delta_{gas} \rangle \]

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

\[ y \ [ h^{-1} \text{Mpc}] \]

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The imprint of cluster physics on the SZ effect
Galaxy cluster gasphysics
Galaxy cluster cosmology
Sunyaev-Zel'dovich bubbles

Cosmological galaxy cluster simulations
Cosmic ray acceleration and transport
Imprint on the Sunyaev-Zel'dovich effect

Mass weighted temperature

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

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The imprint of cluster physics on the SZ effect
Mach number distribution weighted by $\varepsilon_{\text{diss}}$
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
Spectral index depends on the Mach number of the shock,
\[ \mathcal{M} = \frac{v_{\text{shock}}}{c_s} : \]

\[ \log f \]
\[ \text{keV} \quad 10 \text{ GeV} \quad \log p \]

strong shock

weak shock

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Diffusive shock acceleration – efficiency (3)

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

\[
\begin{align*}
\text{Mach number } \mathcal{M} & \\
\text{CR energy injection efficiency } \zeta_{\text{inj}} & \\
\alpha_{\text{inj}} & \\
\end{align*}
\]

- $kT_2 = 10 \text{ keV}$
- $kT_2 = 0.3 \text{ keV}$
- $kT_2 = 0.01 \text{ keV}$

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The imprint of cluster physics on the SZ effect
Mach number distribution weighted by $\varepsilon_{\text{diss}}$

![Image of Mach number distribution weighted by $\varepsilon_{\text{diss}}$.](image)

$\langle M \dot{\varepsilon}_{\text{diss}} / \langle \dot{\varepsilon}_{\text{diss}} \rangle \rangle$

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

$\langle P_{\text{CR}} \rho_{\text{gas}} \rangle / \langle \rho_{\text{gas}} \rangle \left[ \text{erg cm}^{-3} h_{70}^{-2} \right]$
Relative CR pressure $\frac{P_{\text{CR}}}{P_{\text{total}}}$

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The imprint of cluster physics on the SZ effect
Relative CR pressure $P_{\text{CR}} / P_{\text{total}}$
CR phase-space diagram: final distribution @ $z = 0$

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CR impact on SZ effect: Compton $y$ parameter

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

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

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

small cool core cluster, $M_{\text{vir}} \sim 10^{14} M_\odot / h$
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How cluster physics changes scaling relations (1)

- Cooling and star formation depletes the gas reservoir, which decreases the SZ flux and increases the effective mass threshold for an SZ flux–limited cluster sample

\[ Y_{\text{min}} \]

\[ M_{\text{lim}} \]

\[ M_{\text{lim}} \]

non-rad. simulation

radiative simulation

}\[ Y \]

SZ flux

total cluster mass \( M \)
How cluster physics changes scaling relations (2)

top: scaling relations of non-radiative/radiative simulations, $Y(M_{200})$ vs. $y_0(M_{200})$

bottom: relative diff. due to CR feedback → system. negative (positive) bias for $Y (y_0)$!
Quantifying the CR pressure bias

Relative CR pressure $X_{\text{CR}} \sim 0.02 \ldots 0.04$ decreases for more massive clusters, is larger for radiative simulations due to the small thermal cooling time scale.

Relative difference due to CR feedback of $Y_{\text{general}} \propto \int dV (P_{\text{th}} + P_{\text{CR}})$, that accounts for the unobservable CR pressure contribution and explicitly shows the origin of the cluster mass dependent bias of $Y$. 

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The imprint of cluster physics on the SZ effect
The number density of massive clusters is exponentially sensitive to the amplitude of the initial Gaussian fluctuations, whose normalization we usually describe using $\sigma_8$, the *rms* fluctuations of overdensity within spheres of $8 \, h^{-1} \, \text{Mpc}$.

The cluster redshift distribution $dn/dz$ is increased by a lower effective mass threshold $M_{\text{lim}}$ in a survey or by increasing $\sigma_8$ respectively $\Omega_m \rightarrow$ degeneracies of cosmological parameters with respect to cluster physics.
Degeneracies of the cluster redshift distribution (2)

\( \sigma_8 \) – Mass Limit degeneracy

\[ dN / dz d\Omega \quad (10^4 \text{ deg}^2) \]

\( N_{\text{clusters}} \approx 25000 \)

\( \sigma_8 = 0.77, \; M_{\text{lim}} = 2 \times 10^{14} \text{ Msun} \)

\( \sigma_8 = 0.83, \; M_{\text{lim}} = 2 \times 10^{14} \text{ Msun} \)

\( \sigma_8 = 0.77, \; M_{\text{lim}} = 1.65 \times 10^{14} \text{ Msun} \)

\( \sigma_8 = 0.77, \; M_{\text{lim}} = 1.62 \times 10^{14} \text{ Msun} \)
Bias of cosmological parameters using SZ surveys (1)

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C.P. & Majumdar in prep:

- **self-calibration** around the (correct) radiative model with CR physics yields **unbiased parameters**, however at the expense of large uncertainties of $\Delta \Omega_m = 0.038$, $\Delta \sigma_8 = 0.057$, and $\Delta \omega = 0.37$.

- **wrong Bayesian** prior put on our non-radiative model with CR physics $\rightarrow$ biases on the $1\sigma$ level

- SPT-like survey ($F_{\text{lim}} = 5\,\text{mJy}, 4000\,\text{deg}^2$), assuming WMAP5: radiative model yields $1.5 \times 10^4$ clusters, the non-radiative $2.2 \times 10^4$
Influence of CR pressure and turbulence on $M_{\text{hydrostatic}}$

\[ \rho_{\text{gas}}^{-1} \frac{dP_{\text{tot}}}{dr} = -\frac{GM(<r)}{r^2}, \text{ where } P_{\text{tot}} = P_{\text{th}} + P_{\text{nth}}, \]

C.P. & Majumdar in prep.

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The imprint of cluster physics on the SZ effect
Difference in hydrostatic masses: AMR vs. SPH (1)

Origin of entropy cores in non-radiative simulations (Mitchell et al. 2009)
Difference in hydrostatic masses: AMR vs. SPH (2)
Exploring possible causes of the differences (Mitchell et al. 2009)

- difference in gravity solvers
- Galilean non-invariance of mesh codes
- ‘pre-shocking’ in the SPH runs due artificial viscosity
- difference in the amount of mixing in SPH and mesh codes

Mitchell et al. 2009: projected entropy maps during core collision suggests different treatment of vorticity in the simulations → mixing!

Ascasibar & Markewitch (2006) reproduce long-lived spiral X-ray structures with an SPH code; these features are absent in AMR calculations due to efficient mixing.
Difference in hydrostatic masses: AMR vs. SPH (3)
The final spatial distribution of particles: difference in mixing (Mitchell et al. 2009)
Shock-accelerated fluid interfaces
Validating models and codes with experiments (Benjamin 2004)

- LANL code validation program of an AMR code with single cylinder experiments: testing the onset of turbulence with the Richtmyer-Meshkov instability
- Collaborative, iterative approach in both calculations and experiments was needed
- Large-scale density and vorticity fields agree between experiment and simulation, significant differences at smaller spatial scales → crucial for understanding mixing!
Take home messages (1)

- SZ scaling relation \( Y = Y_0 M_{15}^{\text{slope}} \) is affected by
  - cooling & star formation: slope \( \sim 5/3 \) very weakly modified, amplitude \( Y_0 \) reduced by (up to) 30\%, the answer depends on our ability to accurately model metal cooling star formation, feedback . . .
  - cosmic rays from shocks: slope very weakly modified, amplitude \( Y_0 \) only slightly reduced by 2 . . . 4\%

- large scatter in \( y_0 \) but total Compton-y dominated by the exterior parts (uncertainties in cores less severe, apart from integral effect on overall gas fraction) \( \rightarrow \) lesson to go out to \( \sim R_{\text{vir}} \)

- hybrid self-calibration with weak simulation biases might be the way to go . . .
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Plasma bubbles (1)

Perseus cluster
(NASA/IoA/A.Fabian et al.)

Abell 2052
(Blanton et al., 2001)
Plasma bubbles (2)

Hydra A cluster
(X-ray: NASA/CXC/SAO; Radio: NRAO)

MS 0735 cluster
Understanding AGN feedback in clusters
The intertwined lives of supermassive black holes and cluster cores

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

   (McNamara & Nulsen 2007)

2. **Minimum energy arguments** of radio bubbles: $\varepsilon_{\text{CRe}} \simeq 0.1 \varepsilon_{\text{th}} \rightarrow$ where is the ‘missing’ pressure?

3. **AGN accretion and jets**: what is the composition of AGN jets – hadronic/leptonic scenario?

   $\rightarrow$ **new observational strategies** needed to elucidate the properties of the interaction $\rightarrow$ understanding of the detailed plasma physics!

Idea of SZ bubble observations

Disadvantages of bubble X-ray observations: \( L_X \propto n_e^2 \sqrt{kT_e} \)

- very hot, dilute gas barely contributes to X-ray luminosity
- projected foreground and background emission contaminates weak signal
- projected substructure in outer regions could mock signal

Advantages of bubble SZ observations:

\[ y \propto \int n_e kT_e \, dl = \int P_e \, dl \]

- SZ effect measures directly the ‘missing’ quantity pressure
- possibility of bubble detections in outer cluster regions
- relativistic SZ effect sensitive to (trans-)relativistic bubble fillings
Planckian distribution function of the CMB $I(x)$:

$$I(x) = i_0 i(x) = \frac{2(kT_{\text{CMB}})^3}{(hc)^2} \frac{x^3}{e^x - 1},$$

The relative change $\delta i(x)$ in flux density as a function of dimensionless frequency $x = h\nu/(kT_{\text{CMB}})$ for a line-of-sight through a galaxy cluster is given by

$$\delta i(x) = g(x) y_{\text{gas}} - h(x) w_{\text{gas}} + [j(x) - i(x)] \tau_{\text{rel}},$$

- thermal SZ effect
- relativistic SZ effect
- kinetic SZ effect
Spectral distortions

![Spectral distortion plot](image)

The imprint of cluster physics on the SZ effect

- $g(x)$
- $h(x)$
- $\tilde{g}_{UCRe}(x)$
- $\tilde{g}_{CRE}(x)$
- $\tilde{g}_{50\text{ keV}}(x)$
- $\tilde{g}_{20\text{ keV}}(x)$

$spectral\ distortion$

frequency $\nu$ [GHz]

dimensionless frequency $x = h\nu/kT_{CMB}$
Bubble model: visual

Pressure of the cooling core cluster is described by a multiple $\beta$-model, radio plasma bubbles are spheres cutting out the thermal pressure.
Unperturbed line-of-sight (not intersecting the bubble), the observed thermal Comptonization parameter reads

\[ y_{\text{cl}}(x_1, x_2) = \sum_{i=1}^{N} y_i \left( 1 + \frac{x_1^2 + x_2^2}{r_{y,i}^2} \right)^{-(3\beta y, i-1)/2} \]

where \( y_i = \sigma_T (m_e c^2)^{-1} P_i r_{y,i} \beta \left( \frac{3\beta y, i-1}{2}, \frac{1}{2} \right). \)

In the case of a line-of-sight intersecting the surface of the bubble, the area covered by the bubble reads

\[ y_b(x_1, x_2) = y_{\text{cl}}(x_1, x_2) - \sum_{i=1}^{N} y_i \left( 1 + \frac{x_1^2 + x_2^2}{r_{y,i}^2} \right)^{-(3\beta y, i-1)/2} \]

\[ \times \left[ \text{sgn}(z) \frac{2}{I_{qy,i}(z)} \left( \frac{1}{2}, \frac{3\beta y, i - 1}{2} \right) \right]^{z_+} \]

\[ \times \left[ \frac{2}{I_{qy,i}(z)} \left( \frac{1}{2}, \frac{3\beta y, i - 1}{2} \right) \right]^{z_-} \]
A2052: SZE versus thermal X-rays

Chandra: 76′′ × 76′′
(Blanton et al., 2001)

‘simulated’ GBT observation
ν = 90 GHz, size: 80′′ × 80′′
Perseus: SZE versus thermal X-rays

‘simulated’ ALMA observation
\[ \nu = 144 \text{ GHz, size: } 2.5' \times 2.5' \]

Chandra: 6' × 6'
(NASA/IoA/A.Fabian et al.)
Unveiling the composition of bubbles

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The imprint of cluster physics on the SZ effect
Spectral distortions – recap

→ detailed observations will reveal the **dynamically dominant composition** (relativistic electrons/protons, magnetic fields, hot thermal gas)
CR feedback by AGN: isolated galaxy cluster (1)

Isolated, non-cosmological cluster simulations: \(t = 0.07t_H\)

\[\langle T \rangle_M: \text{without CRs}\]

\[\langle T \rangle_M: \text{with CRs}\]

\[1 + \frac{P_{CR}}{P_{th}}\]

Isolated, non-cosmological cluster simulations: $t = 0.12t_H$

\[
\langle T \rangle_M: \text{without CRs} \quad \langle T \rangle_M: \text{with CRs} \quad 1 + \frac{P_{\text{CR}}}{P_{\text{th}}}
\]

CR feedback by AGN: isolated galaxy cluster (3)

Isolated, non-cosmological cluster simulations: $t = 0.24t_H$

$\langle T \rangle_M$: without CRs

$\langle T \rangle_M$: with CRs

$1 + P_{CR}/P_{th}$

CR feedback by AGN: isolated galaxy cluster (4)

Isolated, non-cosmological cluster simulations: $t = 0.24t_H$

$\langle T \rangle_M$: without CRs

$\langle T \rangle_M$: with CRs

$1 + P_{\text{CR}}/P_{\text{th}}$

$\rightarrow$ bubble dynamics, coherence and maximum cluster-centric distance reached are affected by the presence of a relativistic component filling the bubbles! (Sijacki, C.P., Springel, Enßlin 2008)
CR feedback by AGN: cosmological galaxy cluster (1)

Ripples/weak shocks driven by AGN bubbles

X-ray brightness $S_X$, Virgo-like cluster

unsharp masked image $\Delta S_X$

CR feedback by AGN: cosmological galaxy cluster (2)

$\Delta S_X$: observation vs. simulation

Perseus cluster (NASA/CXC/IoA/A.Fabian et al.)

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


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The imprint of cluster physics on the SZ effect
CR feedback by AGN: profiles of $\rho$ and $T$

\begin{align*}
\rho_{\text{SZ}}(r) \, [\text{M}_{\odot} \cdot \text{kpc}^{-3}] \\
T \, [\text{keV}]
\end{align*}

$z = 0.5$  $z = 0.2$  $z = 0.0$

$T \sim r^{0.3}$  $T \sim r^{0.3}$  $T \sim r^{0.3}$

CR feedback by AGN: gas and baryon fraction

AGN feedback reduces the amount of formed stars to reconcile the observations! (Sijacki, C.P., Springel, Enßlin 2008)
CR feedback by AGN: Influence on the SZ effect

thermal AGN feedback

AGN feedback with CR-filled bubbles

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

Sijacki, C.P., Springel, Enßlin 2008

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The imprint of cluster physics on the SZ effect
CR feedback by AGN is a promising solution to the over-cooling problem:

- for the first time, temperature profiles and gas fractions in cosmological simulations are in agreement with observation
- successful reproduction of observational features such as X-ray ripples and bubble morphologies

high-resolution SZ observations of bubbles with GBT/ALMA can elucidate the dynamical component of bubbles → important for solving the cooling flow problem

→ exciting first results: interplay of SZ observations and simulations provide great promises for understanding clusters and (to some degree) cosmology!
Literature for the talk


