Cosmological Simulations of Galaxy Clusters

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in collaboration with

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Outline

1. Galaxy cluster simulations
   - Observations and simulations
   - Shocks and cosmic rays
   - Non-thermal emission

2. AGN feedback in clusters
   - Observations
   - Isolated clusters
   - Cosmological simulations

3. Cluster cosmology
   - Sunyaev-Zel’dovich power spectrum
   - Scaling relations and number counts
   - Future challenges
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A theorist’s perspective of a galaxy cluster . . .

Galaxy clusters are dynamically evolving dark matter potential wells:

- **Energy**
  - Shock waves heat the infalling gas to the virial temperature

- **Space**
  - Galaxy velocity dispersion probes the DM potential
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.)

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Cosmological Simulations of Galaxy Clusters
Galaxy clusters at the crossroads of astrophysics and cosmology
Metal enrichment as tracer of feedback processes

- clusters form at the intersection of the filamentary cosmic web: groups and (proto-)clusters harbour the most energetic cosmic beacons, which feedback to the surrounding IGM by galactic winds/AGN
- highly inhomogeneous enrichment of the primordial gas by metals, magnetic fields, cosmic rays; high-density peaks (proto-clusters) enrich earlier than low-density regions
- advective/turbulent transport adds complexity to the low-redshift metallicity observables
- understanding the map from initial to final distribution unveils formation, evolution, and astrophysics of galaxy clusters
  - supermassive black holes
  - turbulence and plasma instabilities
  - magnetic fields and (ultra high-energy) cosmic rays
Radiative cool core cluster simulation: gas density
Mass weighted temperature

\[ \frac{\langle T \rho_{\text{gas}} \rangle}{\langle \rho_{\text{gas}} \rangle} [\text{K}] \]
Mach number distribution weighted by $\varepsilon_{\text{diss}}$
Radiative simulations – flowchart

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

Physical processes in clusters:
- radiative cooling
- supernovae
- shocks

C.P., Enßlin, Springel (2008)
Radiative simulations with CR physics

Cluster observables:
- Sunyaev-Zeldovich effect
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Physical processes in clusters:
- Stellar populations
- Thermal energy
- Radiative cooling
- Supernovae
- Shocks
- Cosmic ray energy
- Coulomb losses

C.P., Enßlin, Springel (2008)
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Physical processes in clusters:
- Thermal energy
- Radiative cooling
- Stellar populations
- Supernovae
- Shocks
- AGN
- Coulomb losses
- Cosmic ray energy
- CR diffusion
- Heat conduction

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

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

C.P., Enßlin, Springel (2008)
Hadronic cosmic ray proton interaction

\[ p + \text{CRp} \rightarrow \pi^0, \pi^+, \mu^+, e^+, \nu\mu, \nu_e \]
Hadronic cosmic ray proton interaction
Mach number distribution weighted by $\dot{\varepsilon}_{\text{diss}}$
Mach number distribution weighted by $\epsilon_{\text{CR},\text{inj}}$
CR pressure $P_{\text{CR}}$

\[ \frac{\langle P_{\text{CR}} \rho_{\text{gas}} \rangle}{\langle \rho_{\text{gas}} \rangle} \left[ \text{erg cm}^{-3} h_{270}^{-2} \right] \]

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Galaxy cluster simulations
AGN feedback in clusters
Cluster cosmology
Observations and simulations
Shocks and cosmic rays
Non-thermal emission

CR proton and $\gamma$-ray spectrum (Pinzke & CP 2009)

- normalized CR spectrum shows universal concave shape $\rightarrow$ governed mainly by hierarchical structure formation and adiabatic CR transport processes
- concave shape imprinted on dominating pion-decay $\gamma$-ray spectrum (blue)
- primary IC emission from shock-accelerated electrons (green) and secondary IC emission (red) subdominant
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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Plasma processes:
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Relativistic particle pop.:
- re-acceleration CR electrons
- primary CR electrons
- secondary CR electrons

CR protons

hadronic reaction
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
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Observational diagnostics:
- radio synchrotron emission
- IC: hard X-ray & gamma-ray emission
Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:

**Energy sources:**
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**Relativistic particle pop.:**
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- $\pi^0$

**Observational diagnostics:**
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- Gamma-ray emission

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Cosmological Simulations of Galaxy Clusters
Cosmic web: Mach number
Radio gischt: primary CRe (150 MHz)
Radio gischt: primary CRe (150 MHz), slower magn. decline
Hadronic cosmic ray proton interaction
Cluster radio emission by hadronically produced CRe
Thermal X-ray emission
Radio gischt: primary CRe (150 MHz)
Radio gischt + central hadronic halo = giant radio halo
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
Observation – simulation of A2256

- **Clarke & Enßlin (2006)**
  - **red/yellow**: thermal X-ray emission,
  - **blue/contours**: 1.4 GHz radio emission with giant radio halo and relic

- **C.P., Battaglia, Pinzke (in prep.)**

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**Observations and simulations**

- Galaxy cluster simulations
- AGN feedback in clusters
- Cluster cosmology
- Shocks and cosmic rays
- Non-thermal emission

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**Cosmological Simulations of Galaxy Clusters**
Conclusions on 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.:

- **LOFAR, GMRT, MWA, LWA, SKA**: interferometric array of radio telescopes at low frequencies \((\nu \sim (15 – 240) \text{ MHz})\)
- **NuSTAR, Xenia**: future 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** \((E \sim (0.1 – 100) \text{ TeV})\)
Conclusions on non-thermal emission from clusters
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Plasma bubbles (1)

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

Abell 2052
(Blanton et al., 2001)

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Cosmological Simulations of Galaxy Clusters
Plasma bubbles (2)

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

MS 0735 cluster
CR feedback by AGN: isolated galaxy cluster

Isolated, non-cosmological cluster simulations: $t = 0.07 t_H$

$\langle T \rangle_M$: without CRs

$\langle T \rangle_M$: with CRs

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

CR feedback by AGN: isolated galaxy cluster

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

$\langle T \rangle_M$: without CRs

$\langle T \rangle_M$: with CRs

$1 + \frac{P_{CR}}{P_{th}}$

CR feedback by AGN: isolated galaxy cluster

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

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

$\langle T \rangle_M$: without CRs

$\langle T \rangle_M$: with CRs

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

→ 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
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

$\Delta S_X$: observation vs. simulation

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

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

CR feedback by AGN: profiles of $\rho$ and $T$

AGN feedback reduces the amount of formed stars to reconcile the observations! (Sijacki, C.P., Springel, Enßlin 2008)
galaxy clusters are exponentially sensitive to new physics beyond the standard model:
- testing Einstein’s gravity on large scales
- dark energy or $\Lambda$
- non-Gaussianity

Sunyaev-Zel’dovich power spectrum depends on cosmology and cluster physics:

$$C_\ell = g^2 \int_{0}^{z_{\text{max}}} dz \frac{dV}{dz} \int dM \frac{dn(z, M)}{dM} |\tilde{y}_\ell(M, z)|^2$$

amplitude of the SZ power spectrum $C_\ell \propto A_{\text{SZ}} \propto \sigma^7_8$
Baryon and stellar mass fraction

\[ f_{\text{star}}(< r) = \frac{M_{\text{star}}(< r)}{M_{\text{tot}}(< r)} \]

is reduced by AGN feedback to observed values.
Stacked pressure profile

\[ P(r)r^3 \propto \frac{dE}{d\log r} \] peaks around virial radius with large convergence region
Stacked pressure profile
Analytic models and simulations without AGN feedback are in conflict with X-ray data

SZ power spectrum with AGN feedback

Cosmological parameters: low-\(\ell\) part, cluster astrophysics at \(z \gtrsim 0.8\): high-\(\ell\) part

SZ power spectrum with AGN feedback

Importance of hydrodynamic simulations: effect of unvirialized motions/turbulence

Cosmological constraints
SPT data with WMAP $\sigma_8 = 0.8$ consistent with our AGN models

\[ \ell(\ell + 1)C_\ell/(2\pi) \text{ at } 150\text{GHz} \ [\mu\text{K}] \]

- tSZ AGN feedback
- kSZ contribution
- $tSZ + 0.46 \ kSZ$
- $A_{SZ} \ SPT_{DSFG} \ AGN \ feedback$
- Primary CMB

Cosmological constraints
SPT data with WMAP \( \sigma_8 = 0.8 \) inconsistent with simple non-radiative models

\[ \ell(\ell + 1)C_\ell/(2\pi) \text{ at } 150\text{GHz } [\mu\text{K}] \]

Cosmological constraints

SPT data with WMAP $\sigma_8 = 0.8$ inconsistent with (semi-)analytic models

$\ell(\ell + 1)C_\ell / (2\pi)$ at 150GHz [$\mu$K]

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.
How cluster physics changes scaling relations (2)

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

bottom: relative diff. due to CR feedback \(\rightarrow\) system. negative (positive) bias for $Y(L_X)$

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Cosmological Simulations of Galaxy Clusters
$L_X - T$ scaling relation: impact of AGN feedback

Puchwein, Sijacki, Springel (2008)
Degeneracies of the cluster redshift distribution (1)

- 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 \textit{rms} fluctuations of overdensity within spheres of $8 \, h^{-1}$ 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)

\[ \sigma_8 \text{ - Mass Limit degeneracy} \]

- \( N_{\text{clusters}} \approx 25000 \)
- \( \sigma_8 = 0.77, M_{\text{lim}} = 2 \times 10^{14} \text{ Msun} \)
- \( \sigma_8 = 0.83, M_{\text{lim}} = 2 \times 10^{14} \text{ Msun} \)
- \( \sigma_8 = 0.77, M_{\text{lim}} = 1.65 \times 10^{14} \text{ Msun} \)
- \( \sigma_8 = 0.77, M_{\text{lim}} = 1.62 \times 10^{14} \text{ Msun} \)
Conclusions on cluster cosmology

- crucial to *separate effects* of cluster physics from cosmology or physics beyond the standard model
- inhomogeneous, localized and self-regulated feedback by AGN . . .
  - solves over-cooling and recovers observed stellar mass fractions
  - brings simulated X-ray profiles/scaling relations in agreement with observations
  - brings simulated SZ power spectra in agreement with observations (for $\sigma_8$ from primordial CMB fluctuations)
Future perspectives and directions

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

Cluster Astrophysics and Cosmology
Literature for the talk