Cosmic Rays in Galaxy Clusters – Simulations and Reality

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in collaboration with

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Outline

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1. Cosmological structure formation shocks
   - Observations
   - Cosmological galaxy cluster simulations
   - Mach number distribution
2. Simulating cosmic rays
   - Formalism
   - Cosmic ray pressure
   - Cosmological implications
3. Diffuse radio emission in clusters
   - Non-thermal processes in clusters
   - Shock related emission
   - Hadronically induced emission

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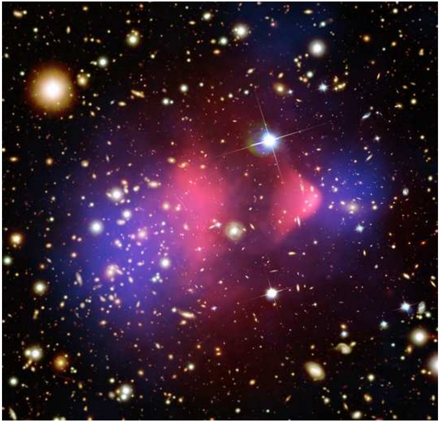
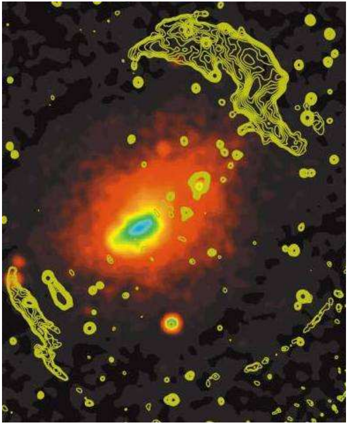
Shocks in galaxy clusters



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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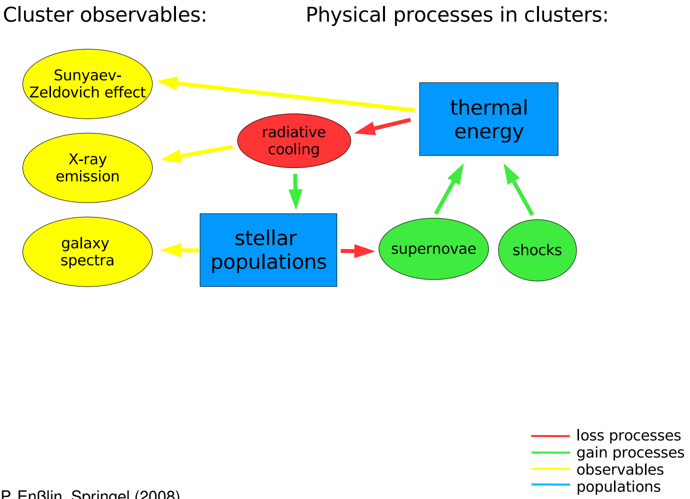
Topics of interest

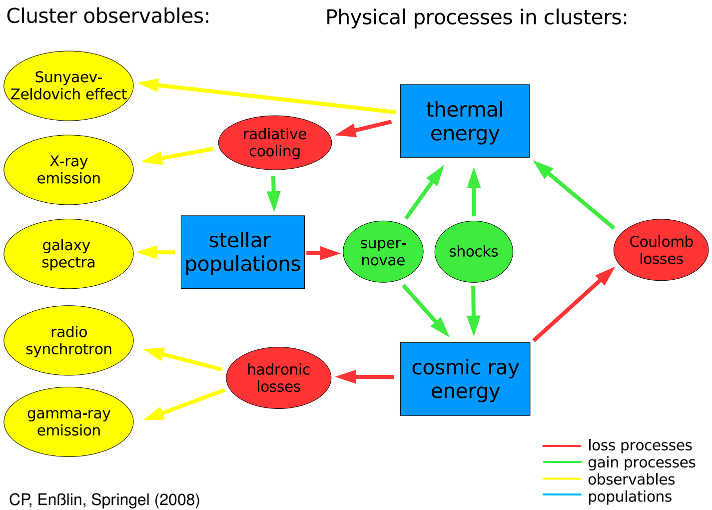
- consistent picture of non-thermal processes in galaxy clusters (radio, soft/hard X-ray, γ-ray emission)
  $\rightarrow$ illuminating the process of structure formation
  $\rightarrow$ history of individual clusters: cluster archeology
- fundamental plasma physics complementary to SNRs:
  - diffusive shock acceleration for intermediate Mach numbers
  - origin and evolution of large scale magnetic fields
  - nature of turbulent models
- understanding the non-thermal pressure distribution to address biases of thermal cluster observables (gold sample of clusters for precision cosmology)
- nature of dark matter: annihilation signal vs. cosmic ray (CR) induced γ-rays

Radiative simulations with GADGET – flowchart



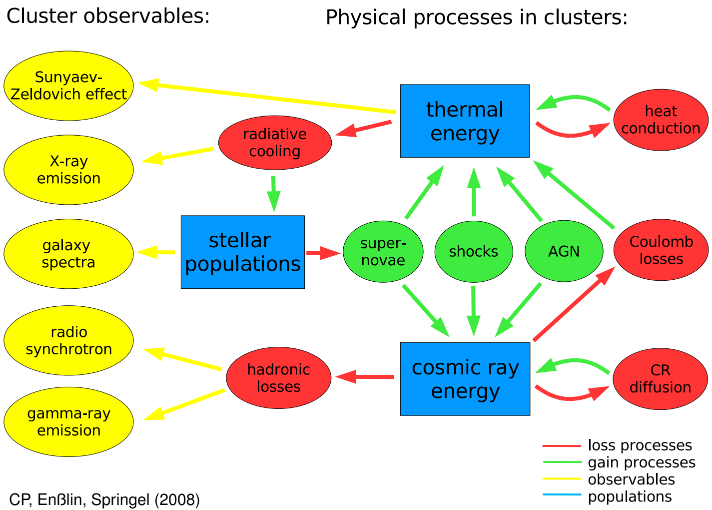
CP, Enßlin, Springel (2008)

Radiative simulations with cosmic ray (CR) physics



CP, Enßlin, Springel (2008)

Radiative simulations with extended CR physics



CP, Enßlin, Springel (2008)

Previous numerical work on Mach number statistics

- Miniati et al. (2000, 01, 02, 03): Eulerian approach, coarse resolution, passive CR evolution, NT cluster emission
- Ryu et al. (2003, 07, 08), Kang et al. 2005: Eulerian Mach number statistics (post-proc.), vorticity and magnetic field generation
- Pfrommer et al. (2006, 07, 08): Lagrangian approach, Mach number statistics (on the fly), self-consistent CR evolution, NT cluster emission
- Skillman et al. 2008: Eulerian AMR, Mach number statistics (post-proc.)
- Hoeft et al. 2008: Lagrangian approach, Mach number statistics (post-proc.)

$\rightarrow$ increasing number of papers recently, with more expected to come that focus on the non-thermal emission from clusters and topics related to cosmic magnetic fields (as we enter a new era of multi-frequency experiments).

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Detecting shock waves in SPH – Idea

Using the entropy conserving formalism with the entropic function $A(s) = P\rho^{-\gamma}$ (Springel & Hernquist 2002):

$$\frac{A_2}{A_1} = \frac{A_1 + \mathrm{d}A_1}{A_1} = 1 + \frac{f_h h}{\mathcal{M}_1 c_1 A_1} \frac{\mathrm{d}A_1}{\mathrm{d}t} = \frac{P_2}{P_1}\left(\frac{\rho_1}{\rho_2}\right)^{\gamma}$$

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma+1)\mathcal{M}_1^2}{(\gamma-1)\mathcal{M}_1^2 + 2}$$

$$\frac{P_2}{P_1} = \frac{2\gamma\mathcal{M}_1^2 - (\gamma-1)}{\gamma+1}$$

- SPH shock is broadened to a scale of the order of the smoothing length h, i.e. $f_h h$, and $f_h \sim 2$
- approximate instantaneous particle velocity by pre-shock velocity (denoted by $v_1 = \mathcal{M}_1 c_1$)

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Detecting shock waves in SPH – Details

1. Broad Mach number distributions $f(\mathcal{M}) = \dfrac{\mathrm{d}^2 u_\mathrm{th}}{\mathrm{d}t\,\mathrm{d}\log\mathcal{M}}$ because particle quantities within the (broadened) shock front do not correspond to those of the pre-shock regime.
   Solution: introduce decay time $\Delta t_\mathrm{dec} = f_h h/(\mathcal{M}_1 c)$, meanwhile the Mach number is set to the maximum (only allowing for its rise in the presence of multiple shocks).
2. Weak shocks imply large values of Δt_dec:
   Solution: $\Delta t_\mathrm{dec} = \min[f_h h/(\mathcal{M}_1 c), \Delta t_\mathrm{max}]$
3. Strong shocks with $\mathcal{M} > 5$ are slightly underestimated because there is no universal shock length.
   Solution: recalibrate strong shocks!

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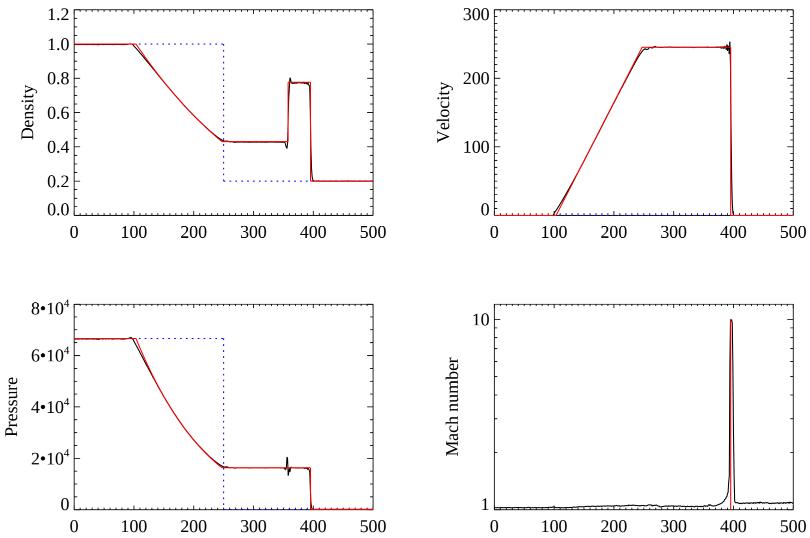
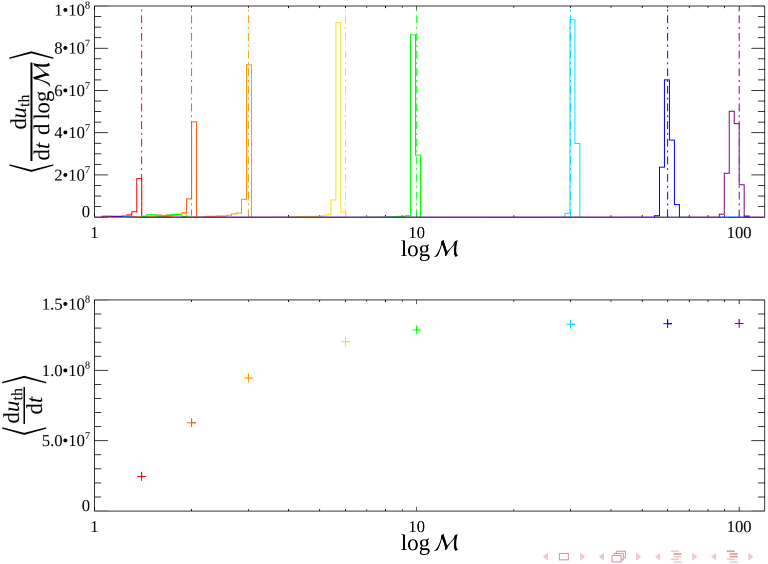
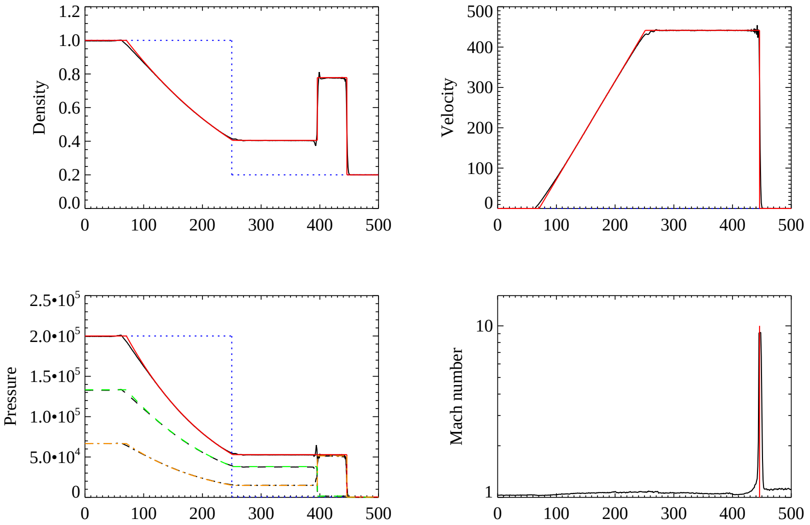
Shock tube: thermodynamics



Shock tube: Mach number statistics



Shock tube (CRs & gas)



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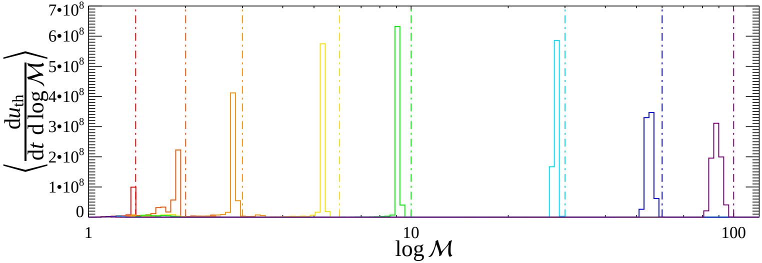
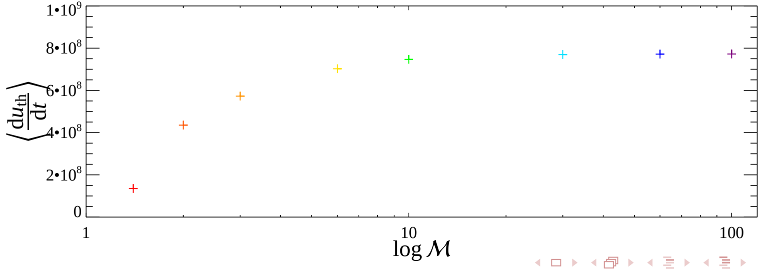
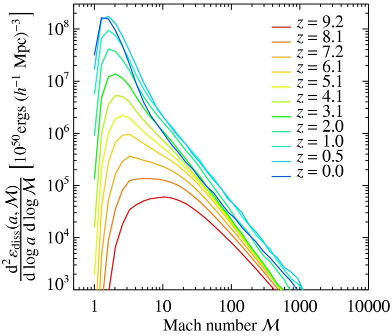




Cosmological shock statistics



- more energy is dissipated at later times
- mean Mach number decreases with time

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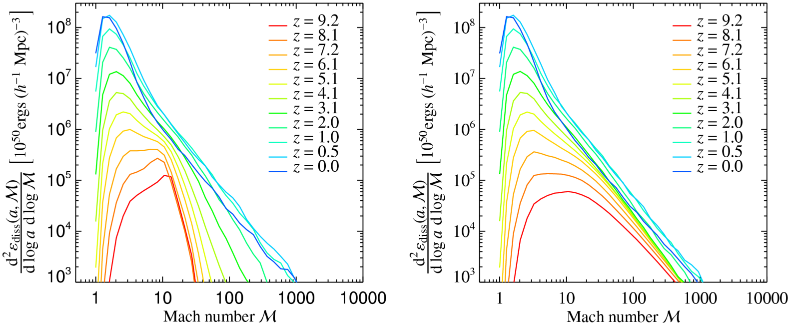
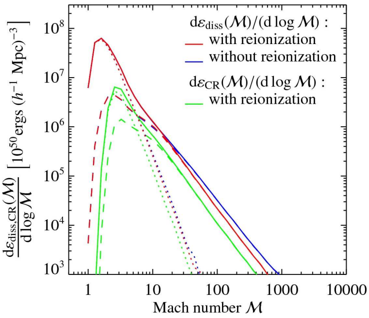
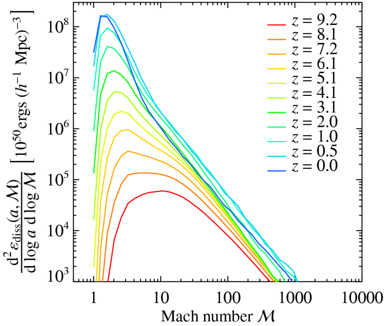
Cosmological shock statistics: influence of reionization



- reionization epoch at $z_{\rm reion} = 10$ suppresses efficiently strong shocks at $z < z_{\rm reion}$ due to jump in sound velocity
- cosmological constant causes structure formation to cease

Cosmological shock statistics: CR injection





- Mach number dependent injection efficiency of CRs favors medium Mach number shocks ($\mathcal{M} \gtrsim 3$) for the injection, and even stronger shocks when accounting for Coulomb interactions
- more energy is dissipated in weak shocks internal to collapsed structures than in external strong shocks

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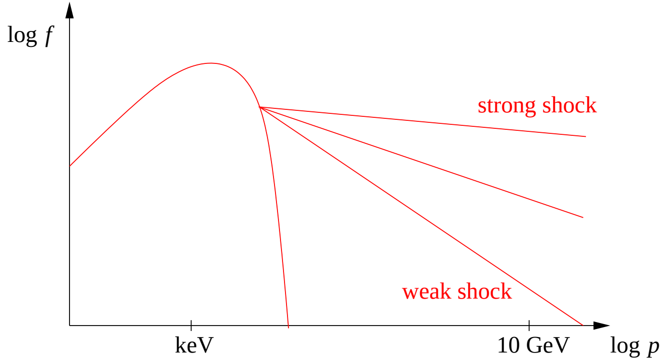
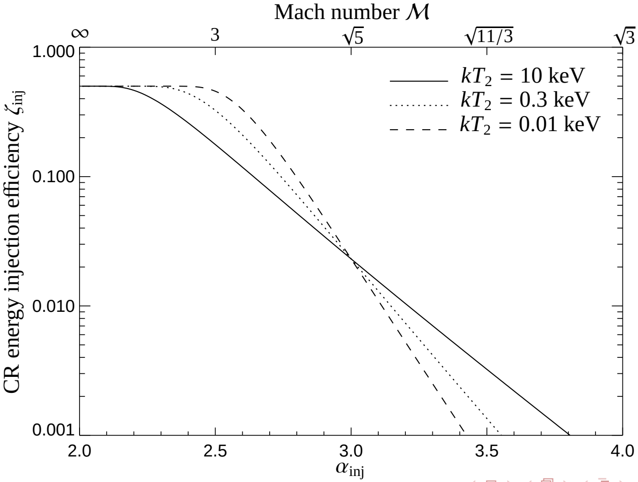
Diffusive shock acceleration – Fermi 1 mechanism (1)

Spectral index depends on the Mach number of the shock, $\mathcal{M} = \upsilon_{\mathsf{shock}}/c_{\mathsf{s}}$:

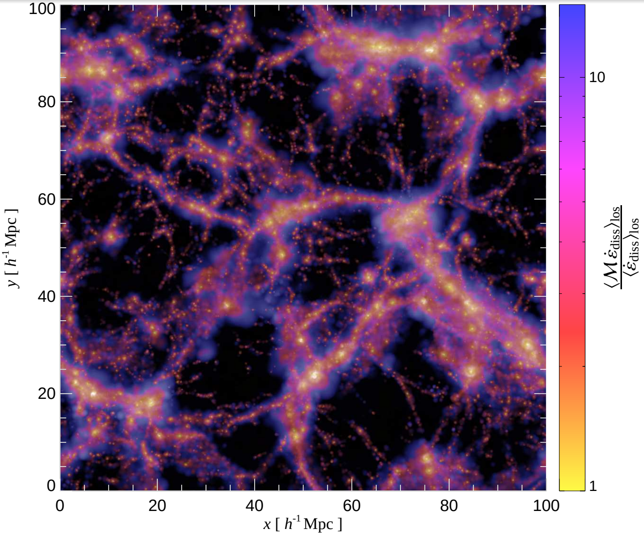


Diffusive shock acceleration – efficiency (2)

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



Cosmological Mach numbers: weighted by $\varepsilon_{\rm diss}$



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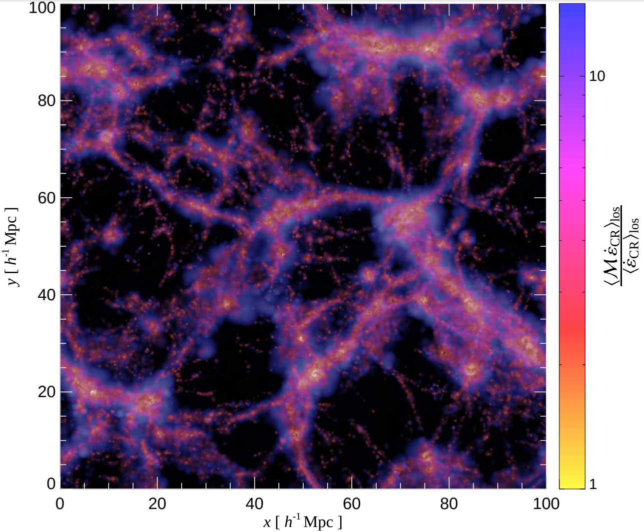

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Our philosophy and description

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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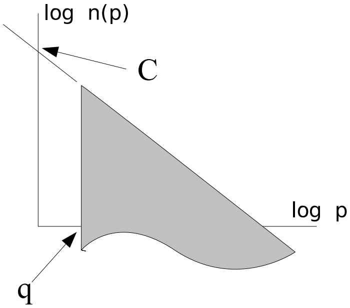
CR spectral description



$$p = P_\mathrm{p} / m_\mathrm{p}\, c$$

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

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

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

$$n_\mathrm{CR} = \int_0^\infty \mathrm{d}p\, f(p) = \frac{C\, q^{1-\alpha}}{\alpha - 1}$$

$$P_\mathrm{CR} = \frac{m_\mathrm{p} c^2}{3} \int_0^\infty \mathrm{d}p\, f(p)\, \beta(p)\, p$$

$$= \frac{C\, m_\mathrm{p} c^2}{6} \mathcal{B}_{\frac{1}{1+q^2}} \left(\frac{\alpha-2}{2}, \frac{3-\alpha}{2}\right)$$

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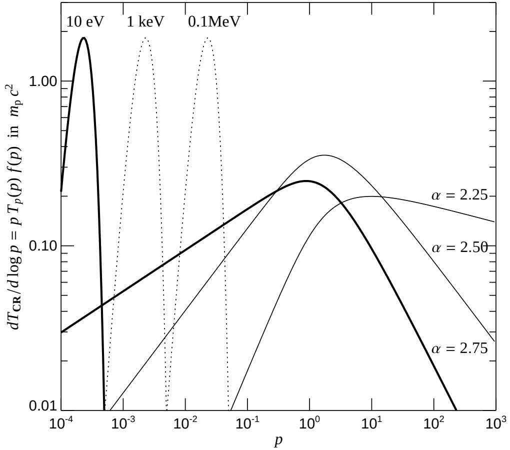
Thermal & CR energy spectra

Kinetic energy per logarithmic momentum interval:



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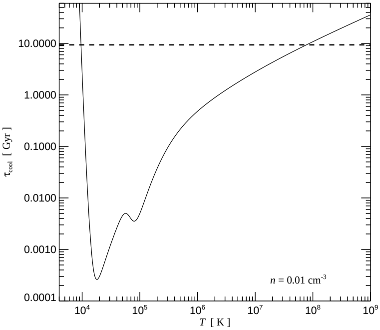
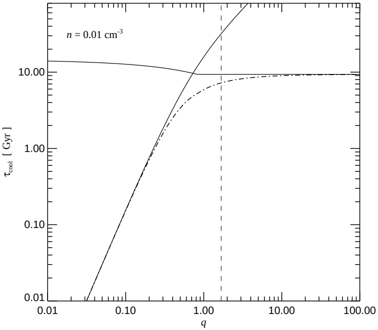
Cooling time scales of CR protons

Cooling of primordial gas:



Cooling of cosmic rays:



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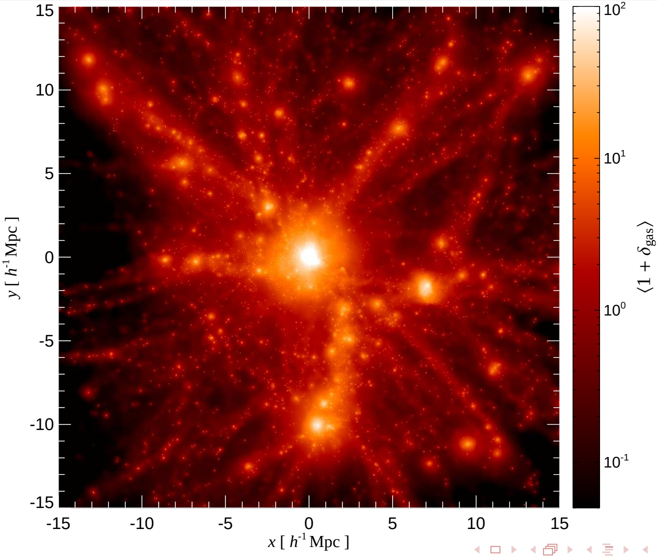
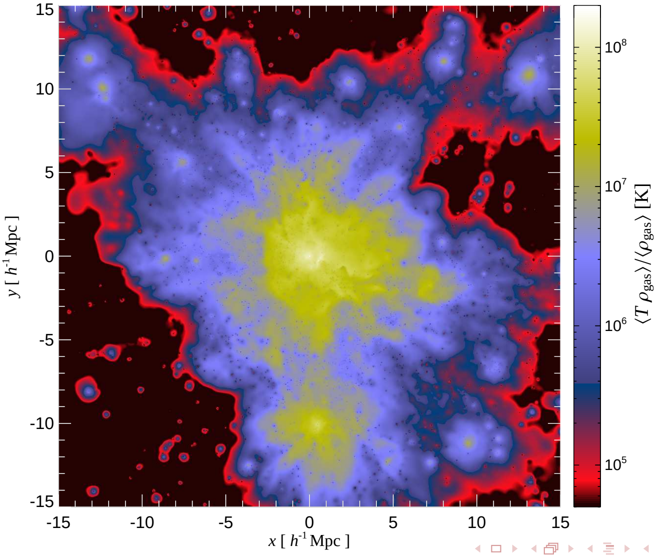
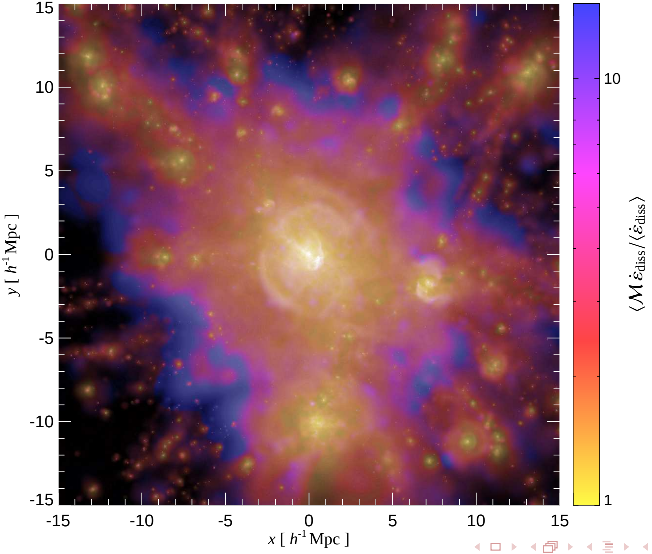
Radiative cool core cluster simulation: gas density



Mass weighted temperature



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



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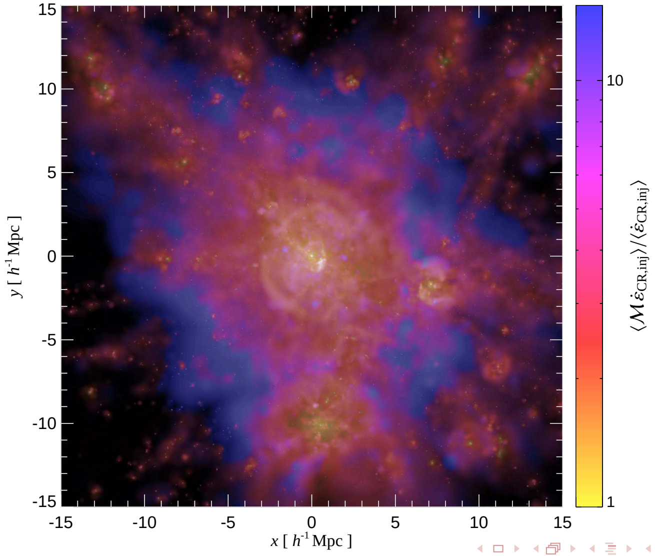
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$



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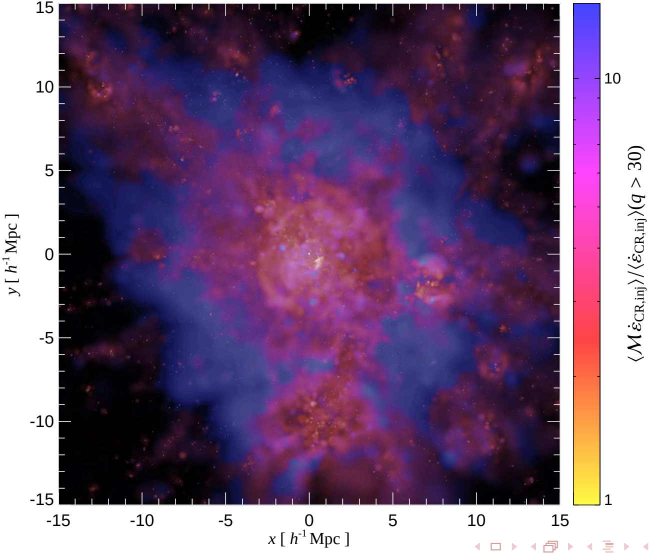
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}(q > 30)$



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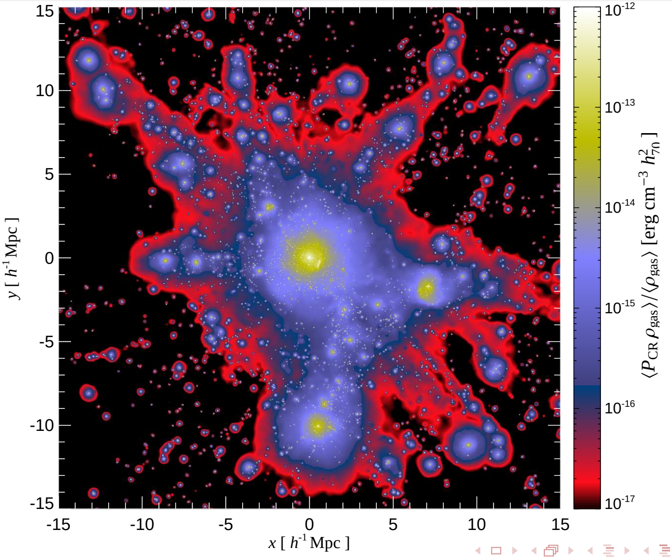
CR pressure P_{CR}



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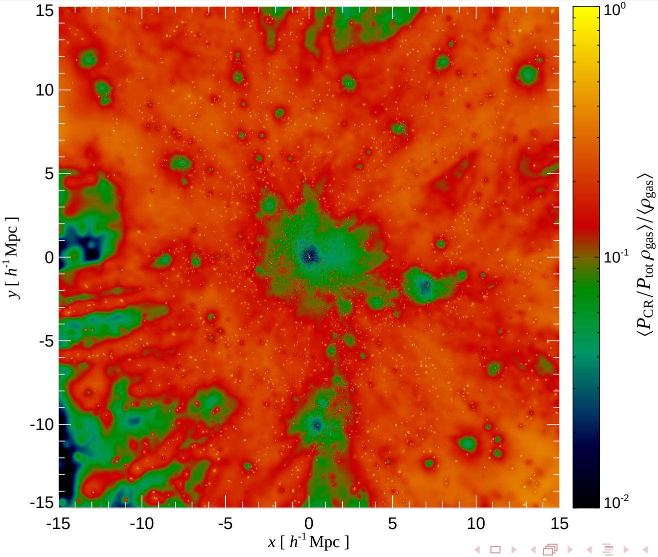
Relative CR pressure $P_{\mathrm{CR}}/P_{\mathrm{total}}$



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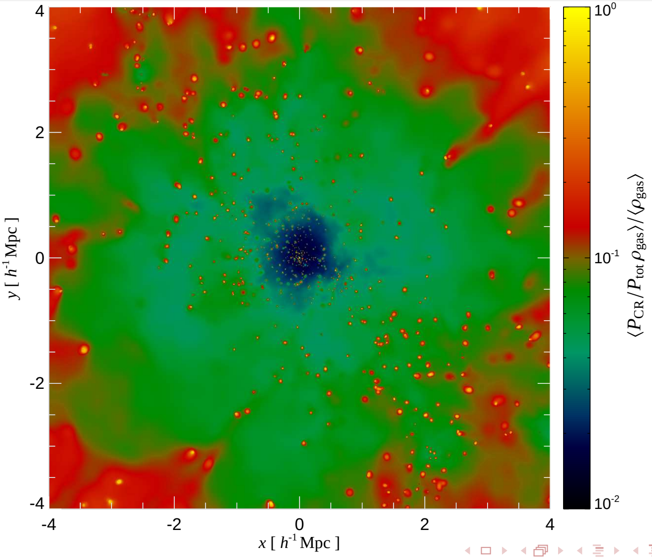

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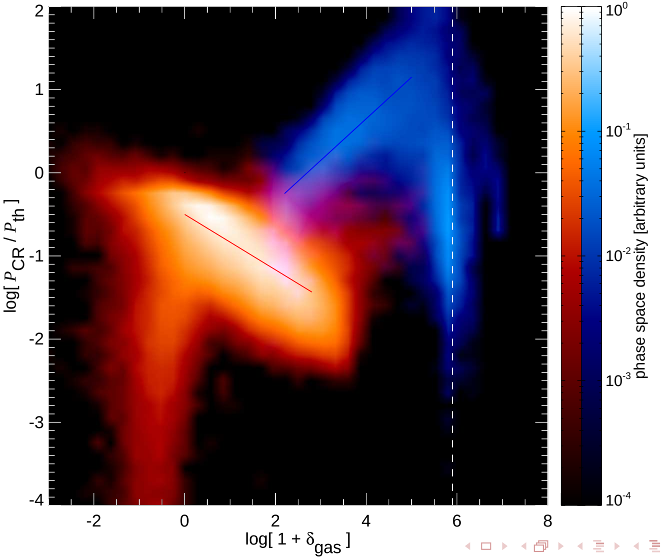
CR phase-space diagram: final distribution @ $z = 0$



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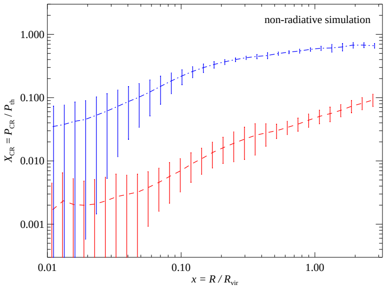
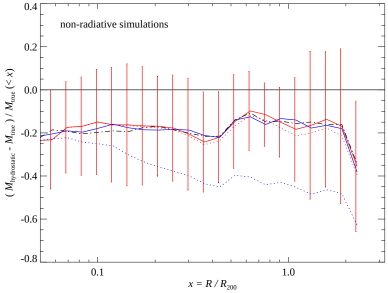
CR pressure and hydrostatic masses

Non-radiative simulations: mean and σ over cluster sample

CR pressure profile:



Difference in hydrostatic masses:



- $\rho_{gas}^{-1} \frac{\mathrm{d}P_{tot}}{\mathrm{d}r} = -\frac{G\,M(<r)}{r^2}$, where $P_{tot} = P_{th} + P_{nth}$ (CP & Majumdar in prep.)
- “turbulence” dominates ΔM-bias, CR pressure only secondary effect on ΔM

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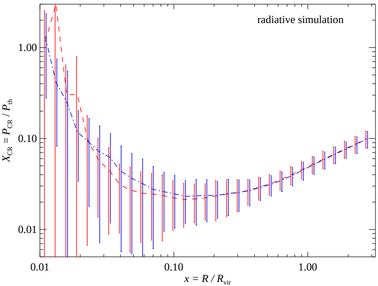
CR pressure and hydrostatic masses

Radiative simulations with star formation: mean and σ over cluster sample

CR pressure profile:



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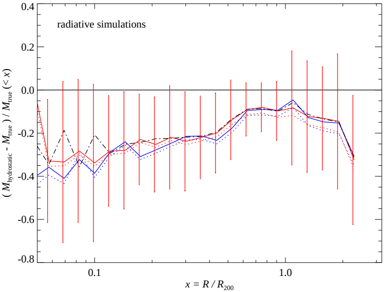

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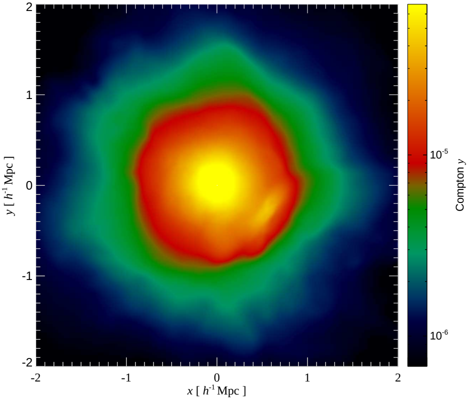
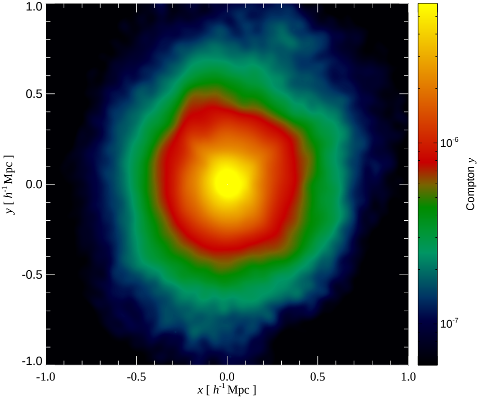
CR impact on SZ effect: Compton y parameter



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



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

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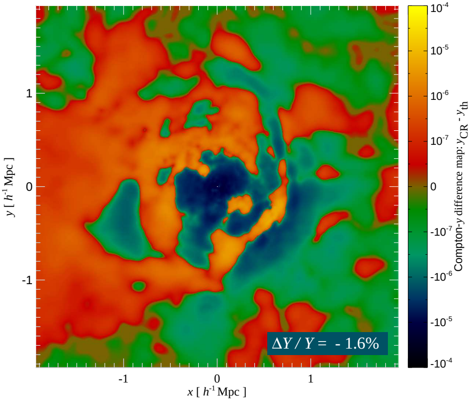
Compton y difference map: $y_{\rm CR} - y_{\rm th}$



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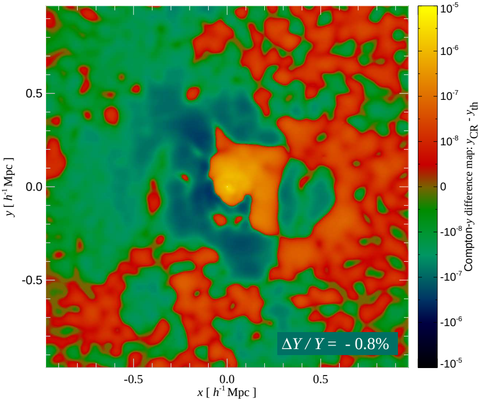

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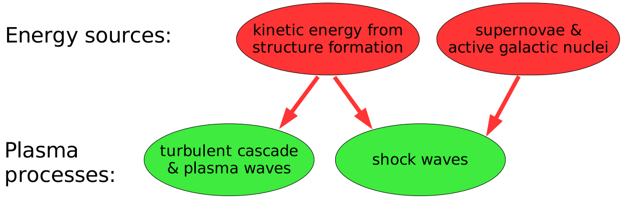
Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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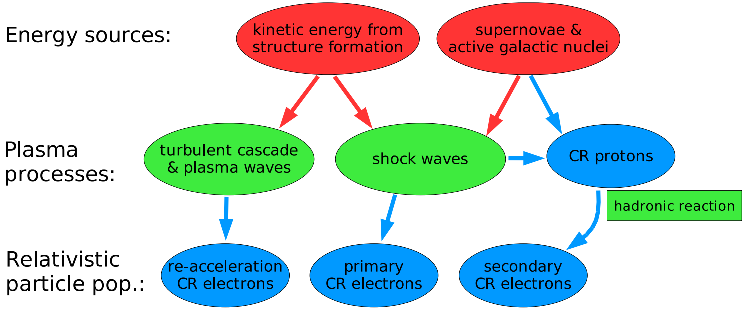

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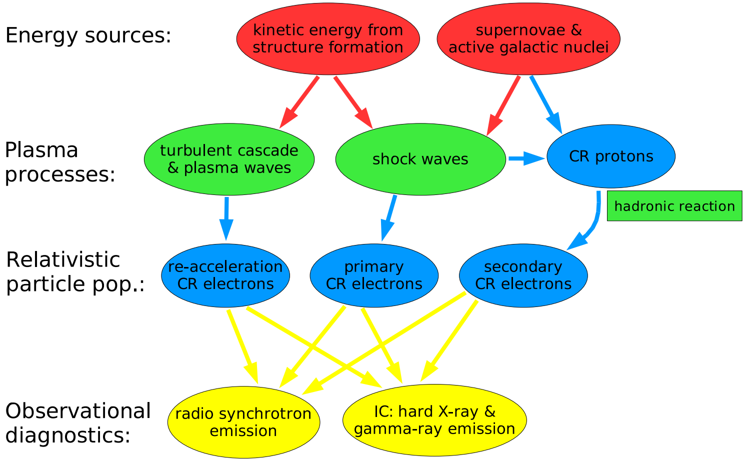

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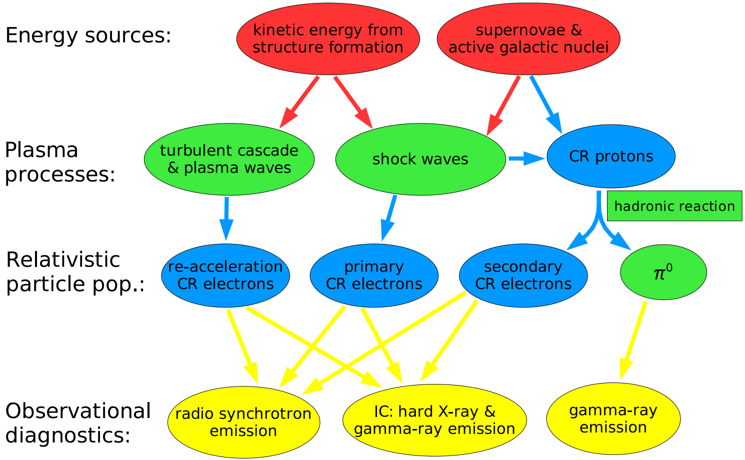

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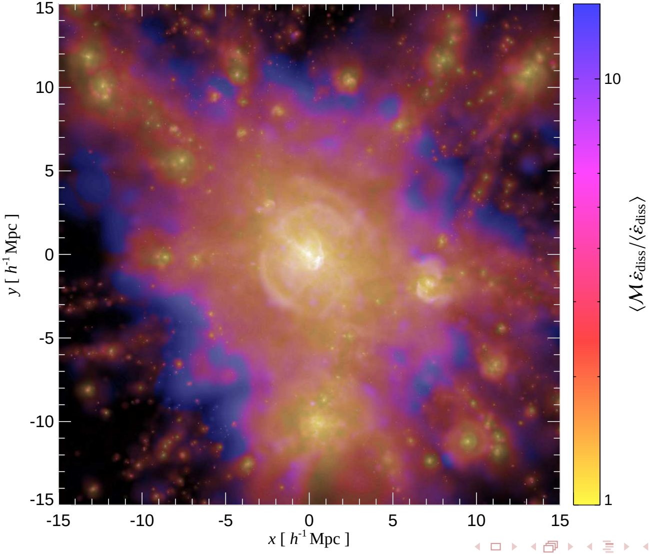
Cosmic web: Mach number



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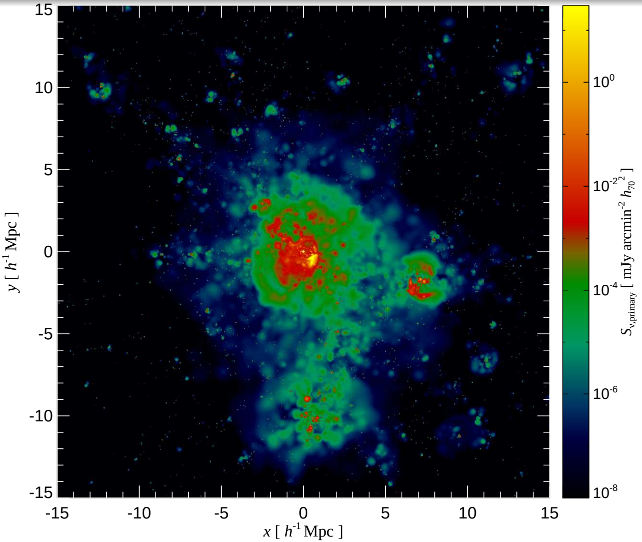
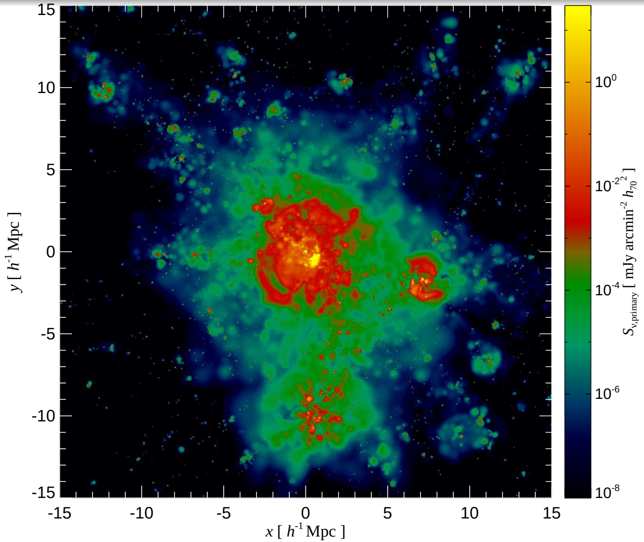
Radio gischt (relics): primary CRe (1.4 GHz)



Radio gischt: primary CRe (150 MHz)



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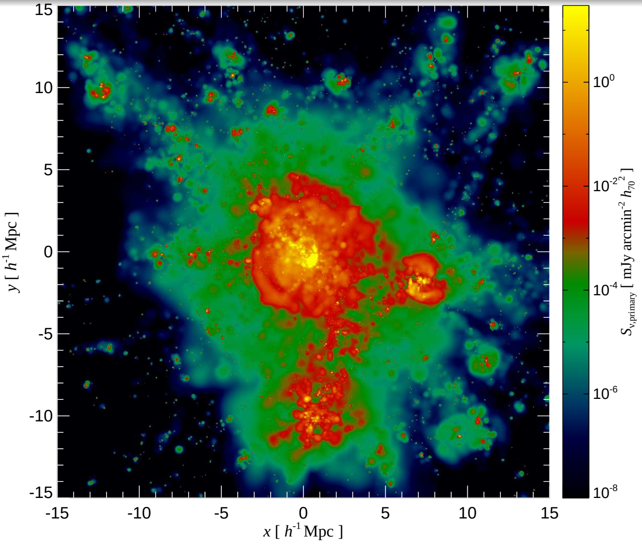
Radio gischt: primary CRe (15 MHz)



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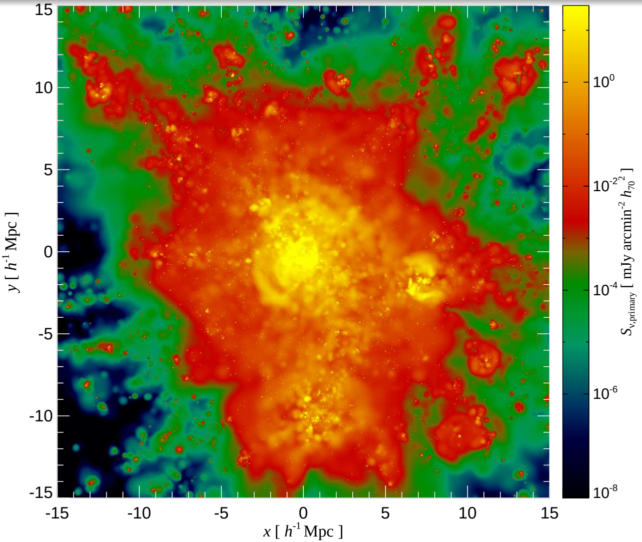
Radio gischt: primary CRe (15 MHz), slower magnetic decline



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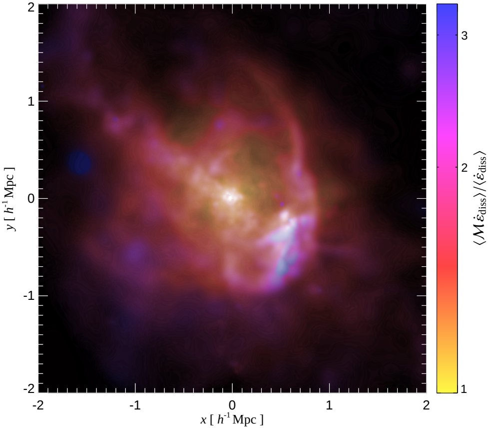
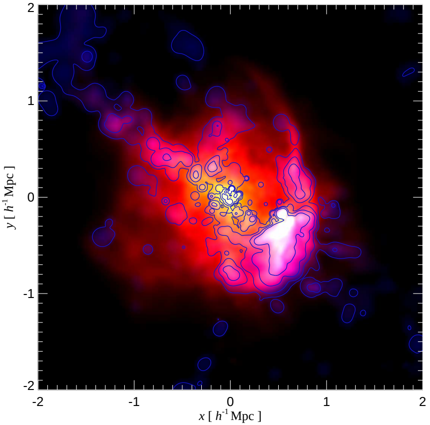
Radio gischt illuminates cosmic magnetic fields





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

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Diffuse cluster radio emission – an inverse problem

Exploring the magnetized cosmic web

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.

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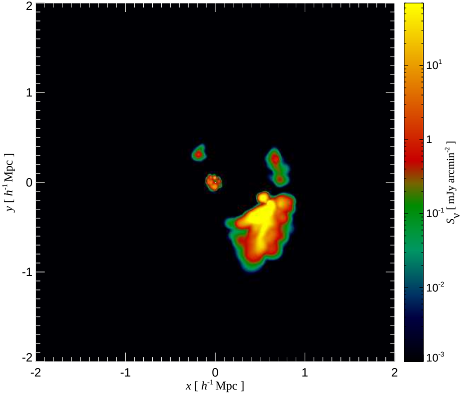
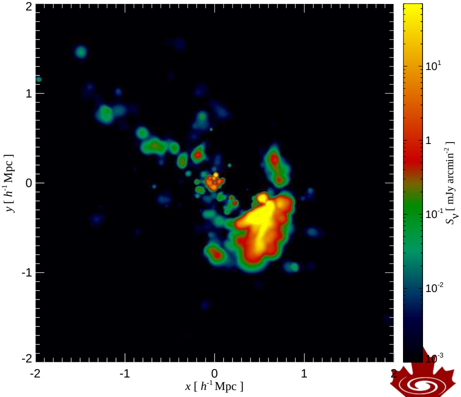
Population of faint radio relics in merging clusters

Probing the large scale magnetic fields

Finding radio relics in 3D cluster simulations using a friends-of-friends finder with an emission threshold → relic luminosity function



radio map with GMRT emissivity threshold



“theoretical” threshold (towards SKA)

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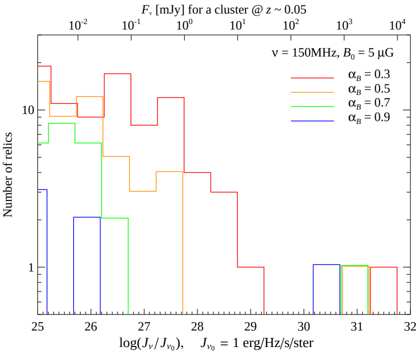
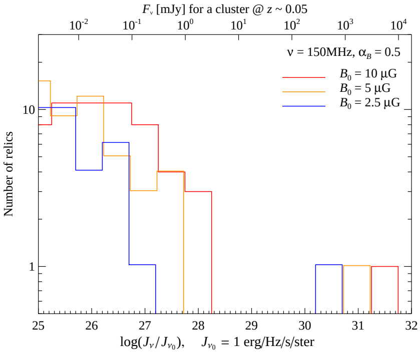
Relic luminosity function – theory

Relic luminosity function is very sensitive to large scale behavior of the magnetic field and dynamical state of cluster:



varying magnetic decline with radius



varying overall normalization of the magnetic field

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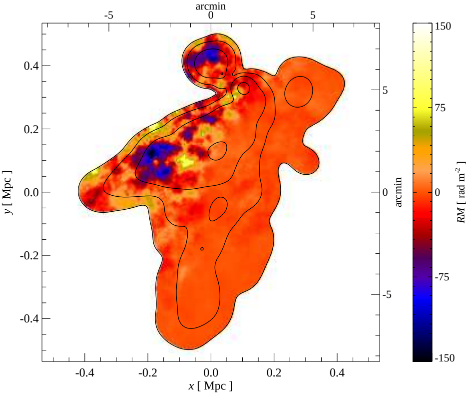
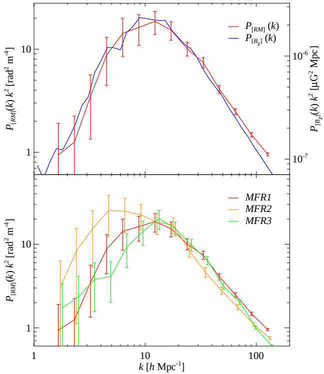
Rotation measure (RM)

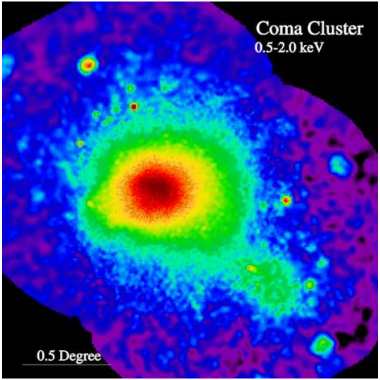
RM maps and power spectra have the potential to infer the magnetic pressure support and discriminate the nature of MHD turbulence in clusters:





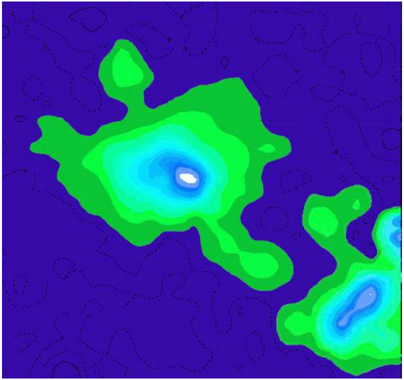
Left: RM map of the largest relic, right: Magnetic and RM power spectrum comparing Kolmogorow and Burgers turbulence models.

Giant radio halo in the Coma cluster



thermal X-ray emission

(Snowden/MPE/ROSAT)



radio synchrotron emission

(Deiss/Effelsberg)

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Previous models for giant radio halos in clusters

Radio halos show a smooth unpolarized radio emission at Mpc-scales. How are they generated?

- Primary accelerated CR electrons: synchrotron/IC cooling times too short to account for extended diffuse emission.
- Continuous in-situ acceleration of pre-existing CR electrons either via interactions with magneto-hydrodynamic waves, or through turbulent spectra (Jaffe 77, Schlickeiser 87, Brunetti et al. 01, 04, Brunetti & Blasi 05, Brunetti & Lazarian 07, . . .).
- Hadronically produced CR electrons in inelastic collisions of CR protons with the ambient gas (Dennison 80, Vestrad 82, Blasi & Colafrancesco 99, Miniati 01, Pfrommer et al. 04, 08, . . .).

All of these models face either theoretical short-comings when comparing to observations or their success has not been demonstrated in a cosmological framework.

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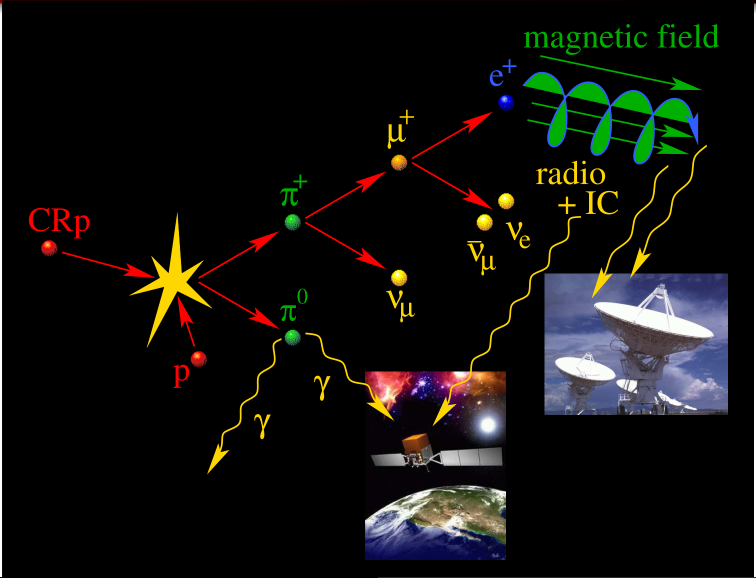
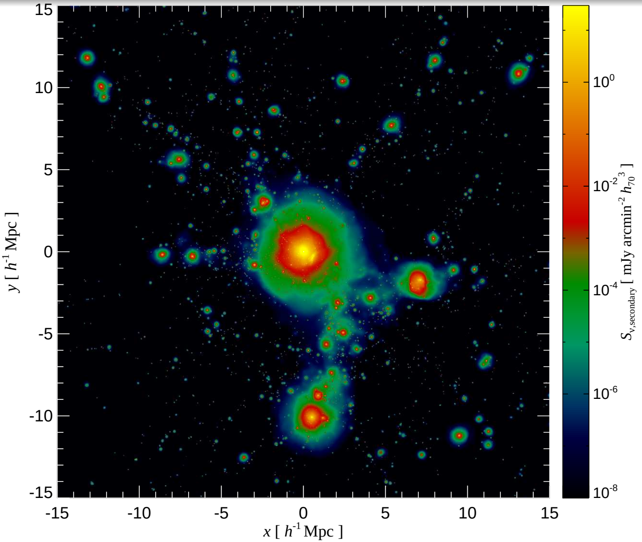
Hadronic cosmic ray proton interaction



Cluster radio emission by hadronically produced CRe



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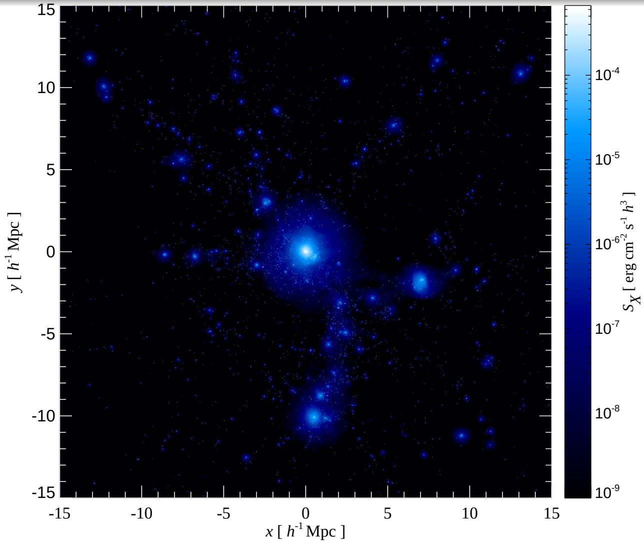
Thermal X-ray emission



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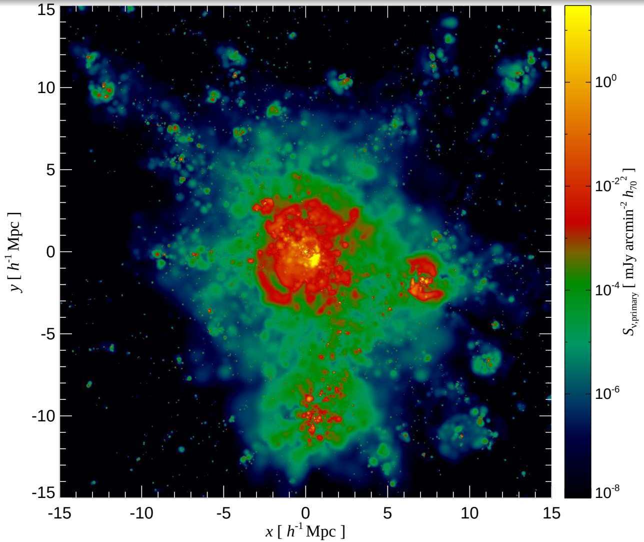
Radio gischt: primary CRe (150 MHz)



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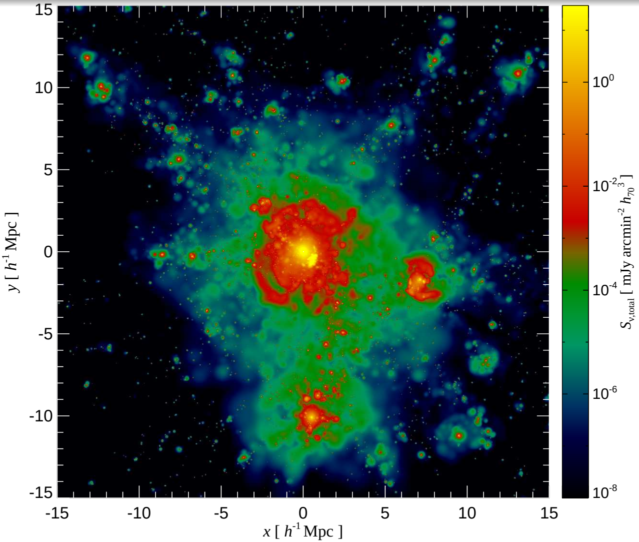
Radio gischt + central hadronic halo = giant radio halo



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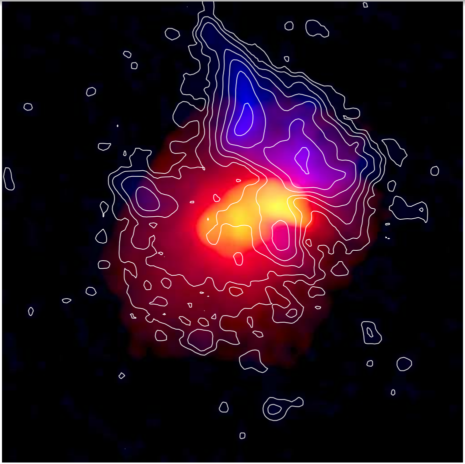
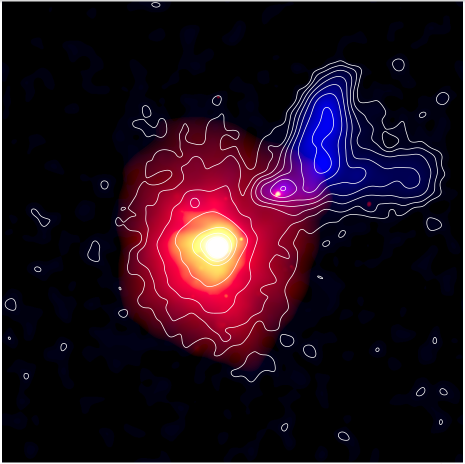
Which one is the simulation/observation of A2256?





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

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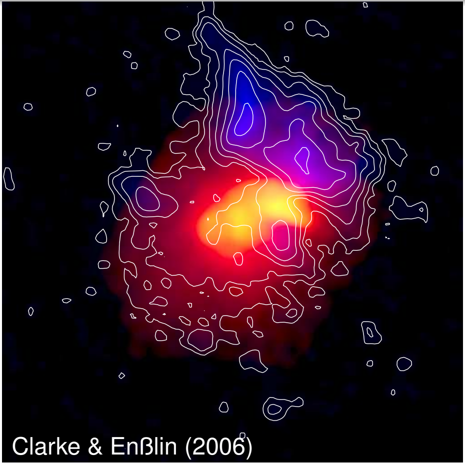
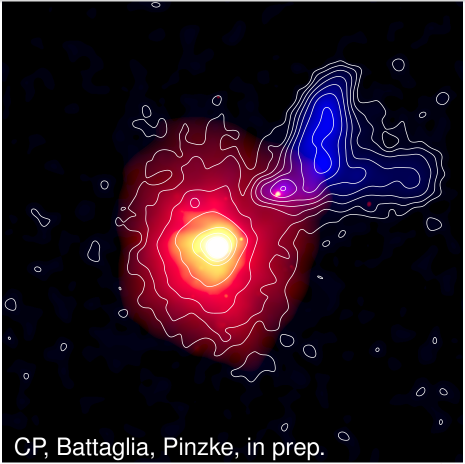
Observation – simulation of A2256





red/yellow: thermal X-ray emission,
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Unified model of radio halos and relics (CP, Enßlin, Springel 2008)

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.

CITA–ICAT

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?
$\rightarrow$ new era of multi-frequency experiments, e.g.:

- GMRT, LOFAR, MWA, LWA, SKA: interferometric array of radio telescopes at low frequencies ($\nu \simeq (15 - 240)$ MHz)
- Simbol-X/NuSTAR: future hard X-ray satellites ($E \simeq (1 - 100)$ keV)
- Fermi γ-ray space telescope ($E \simeq (0.1 - 300)$ GeV)
- Imaging air Čerenkov telescopes ($E \simeq (0.1 - 100)$ TeV)

CITA–ICAT

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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 and fundamental plasma astrophysics!

1. Cosmological hydrodynamical simulations are indispensable for understanding non-thermal processes in galaxy clusters $\rightarrow$ illuminating the process of structure formation
2. Adiabatic compression disfavors the thermal pressure relative to the CR pressure: only small bias of hydrostatic masses and Sunyaev-Zel'dovich effect
3. Unified model for the generation of giant radio halos, radio mini-halos, and relics: interplay of primary and secondary synchrotron emission.

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Literature for the talk

- Battaglia, Pfrommer, Sievers, Bond, Enßlin, 2008, MNRAS, in print, arXiv:0806.3272, *Exploring the magnetized cosmic web through low frequency radio emission*
- Pfrommer, 2008, MNRAS, 385, 1242 *Simulating cosmic rays in clusters of galaxies – III. Non-thermal scaling relations and comparison to observations*
- Pfrommer, Enßlin, Springel, 2008, MNRAS, 385, 1211, *Simulating cosmic rays in clusters of galaxies – II. A unified scheme for radio halos and relics with predictions of the γ-ray emission*
- Pfrommer, Enßlin, Springel, Jubelgas, Dolag, 2007, MNRAS, 378, 385, *Simulating cosmic rays in clusters of galaxies – I. Effects on the Sunyaev-Zel'dovich effect and the X-ray emission*
- Pfrommer, Springel, Enßlin, Jubelgas, 2006, MNRAS, 367, 113, *Detecting shock waves in cosmological smoothed particle hydrodynamics simulations*
- Enßlin, Pfrommer, Springel, Jubelgas, 2007, A&A, 473, 41, *Cosmic ray physics in calculations of cosmological structure formation*
- Jubelgas, Springel, Enßlin, Pfrommer, A&A, , 481, 33, *Cosmic ray feedback in hydrodynamical simulations of galaxy formation*

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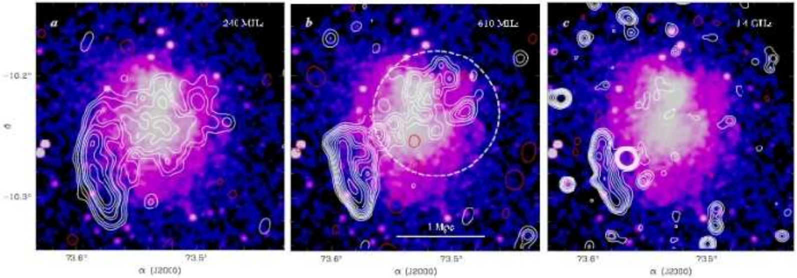
Diffuse low-frequency radio emission in Abell 521

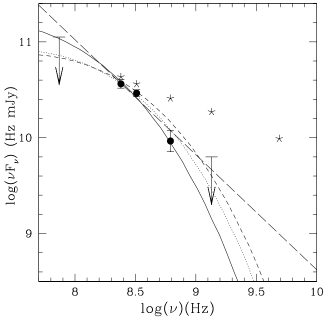
Brunetti et al. 2008, Nature, 455, 944:



colors: thermal X-ray emission, contours: diffuse radio emission,
→ presence of radio structure at 610 MHz and their absence at three times higher/lower frequency is incompatible with synchrotron theory!

Radio spectrum of “radio halo” in Abell 521

Brunetti et al. 2008, Nature, 455, 944:



- asterisks denote spectrum of the radio relic with $\alpha_\nu \sim 1.5$
- filled circles that of “radio halo” with $\alpha_\nu \sim 2.1$

“radio halo” interpretation:

- re-acceleration of relativistic electrons (Brunetti et al.)
- hadronic model inconsistent with spectra and morphology

“radio relic” interpretations:

- aged population of shock-accelerated electrons
- populations of several shock-compressed radio ghosts (aged radio lobes)

→ polarization is key to differentiate