Deciphering an enigma – Non-thermal emission from galaxy clusters

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in collaboration with

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Outline

1. Cosmological structure formation shocks
   - Cosmological galaxy cluster simulations
   - Mach numbers and shock acceleration
   - Cosmic ray transport and pressure distribution
2. Diffuse radio emission in clusters
   - General picture of non-thermal processes in clusters
   - Shock related emission
   - Hadronically induced emission
3. High-energy γ-ray emission
   - Morphology and spectra
   - Predictions for *Fermi*
   - Minimum γ-ray flux

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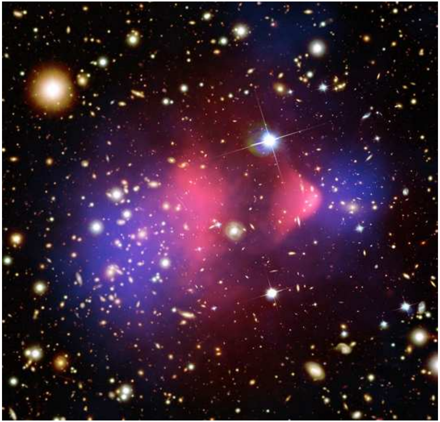
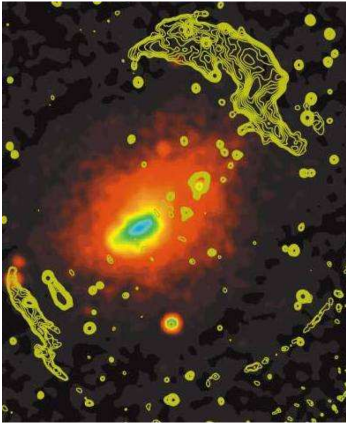
Shocks in galaxy clusters



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)
  → illuminating the process of structure formation
  → history of individual clusters: cluster archeology
- understanding the non-thermal pressure distribution to address biases of thermal cluster observables
- nature of dark matter: annihilation signal vs. cosmic ray (CR) induced γ-rays
- gold sample of clusters for precision cosmology: using non-thermal observables to gauge hidden parameters
- fundamental plasma physics:
  - diffusive shock acceleration in high-β plasmas
  - origin and evolution of large scale magnetic fields
  - nature of turbulent models

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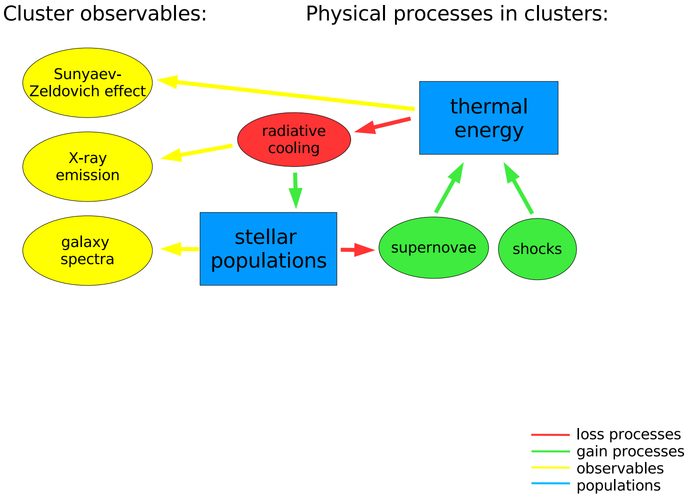
Radiative simulations – flowchart



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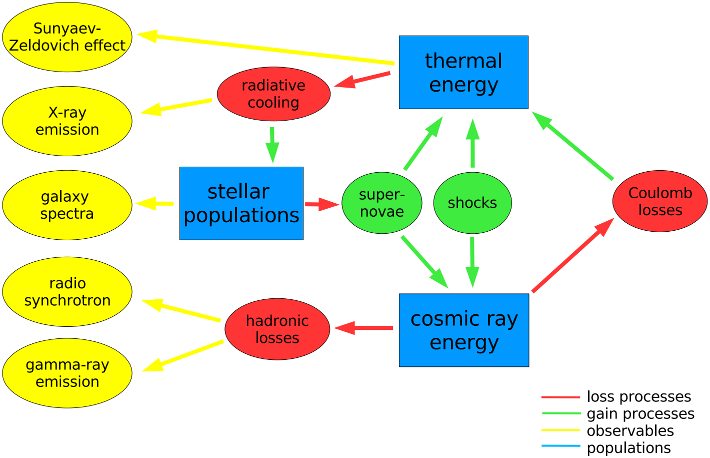
Radiative simulations with cosmic ray (CR) physics

Cluster observables:

Physical processes in clusters:



Sunyaev-Zeldovich effect

X-ray emission

galaxy spectra

radio synchrotron

gamma-ray emission

radiative cooling

stellar populations

hadronic losses

thermal energy

super-novae

shocks

cosmic ray energy

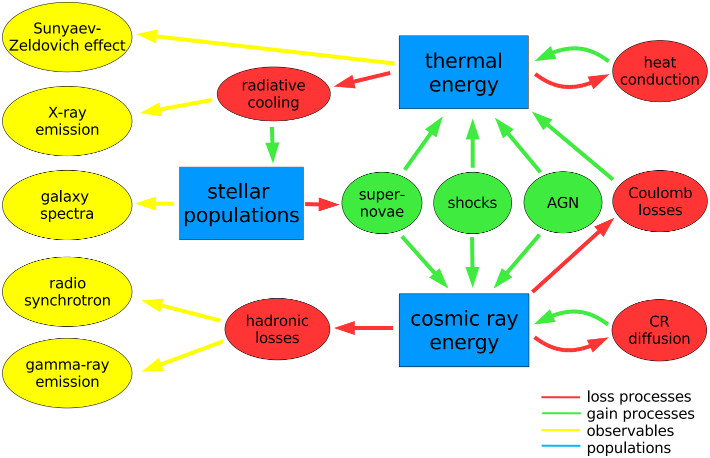
Coulomb losses

🟥 loss processes
🟩 gain processes
🟨 observables
🟦 populations

Radiative simulations with extended CR physics

Cluster observables:

Physical processes in clusters:



Previous numerical work on cosmic rays in clusters

COSMOCR: A numerical code for cosmic ray studies in computational cosmology (Miniati, 2001):

- advantages: good resolution in momentum space
- drawbacks: CR pressure not accounted for in EoM, insufficient spatial resolution (grid code), non-radiative gas physics

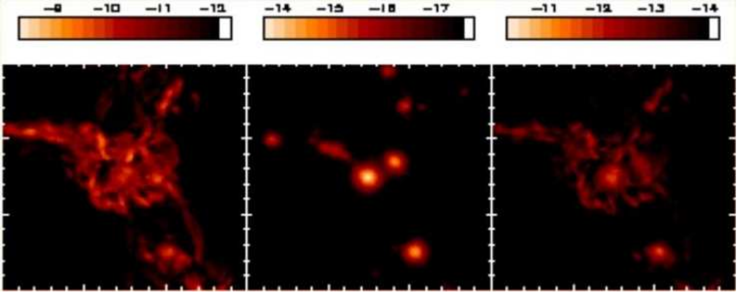


Figure: Hard X-rays, thermal X-rays, γ-rays, adopted from Miniati (2003)

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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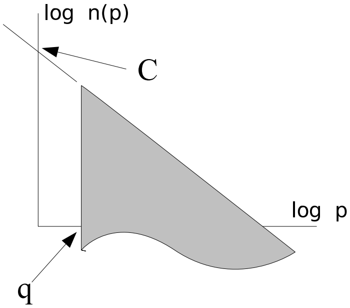
CR spectral description



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

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

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

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

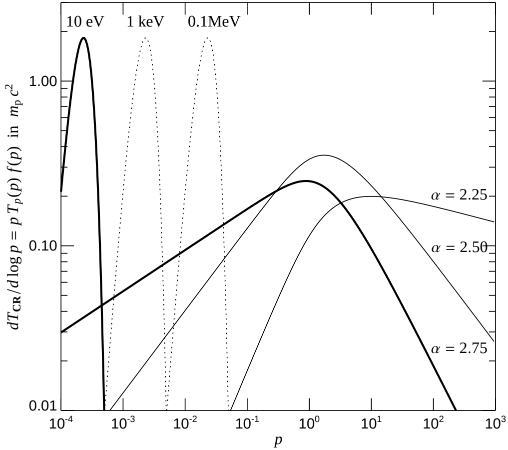
$$n_\mathrm{CR} = \int_0^\infty \mathrm{d}p\, f(p) = \frac{C\, q^{1-\alpha}}{\alpha - 1}$$

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

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

Thermal & CR energy spectra

Kinetic energy per logarithmic momentum interval:



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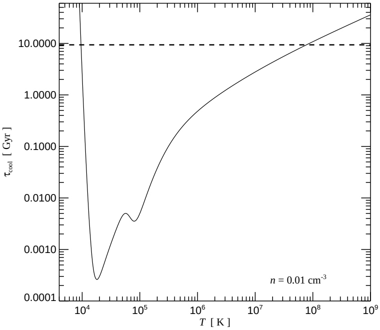
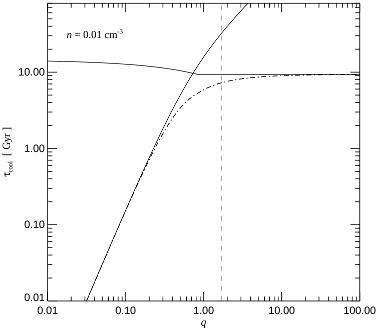
Cooling time scales of CR protons

Cooling of primordial gas:



Cooling of cosmic rays:



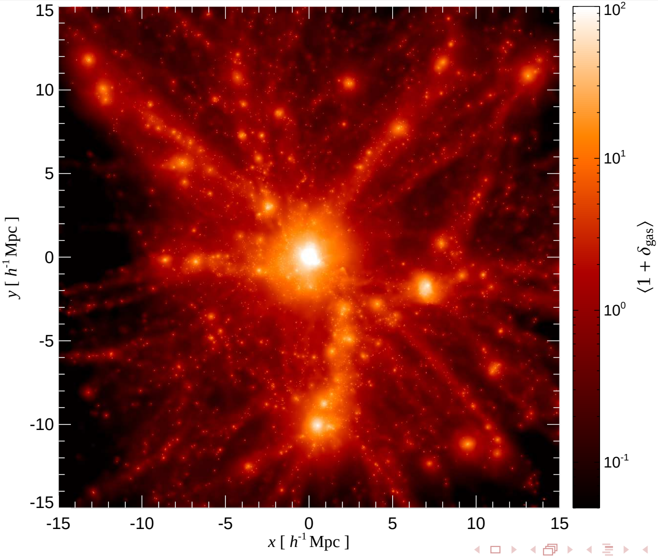
CR protons in clusters

relativistic proton populations can often be expected, since

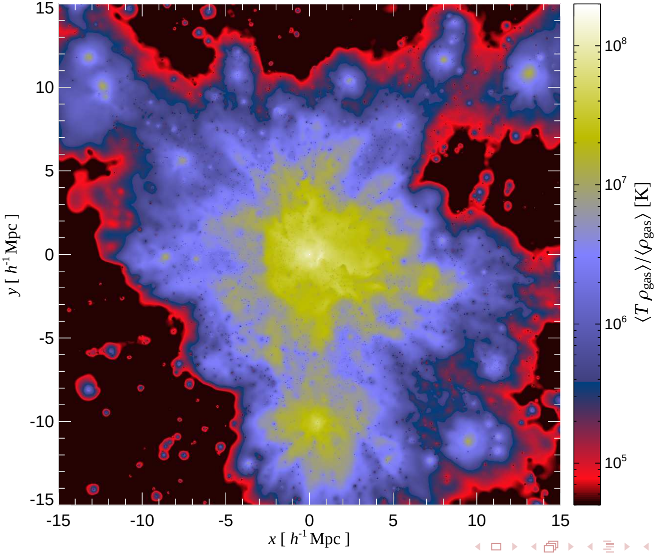
- acceleration mechanisms work for protons . . .
    - . . . as efficient as for electrons (adiabatic compression) or
    - . . . more efficient than for electrons (DSA, stochastic acc.)
- galactic CR protons are observed to have 100 times higher energy density than electrons
- CR protons are very inert against radiative losses and therefore long-lived ($\sim$ Hubble time in galaxy clusters, longer outside)

→ an energetic CR proton population should exist in clusters

Radiative cool core cluster simulation: gas density



Mass weighted temperature



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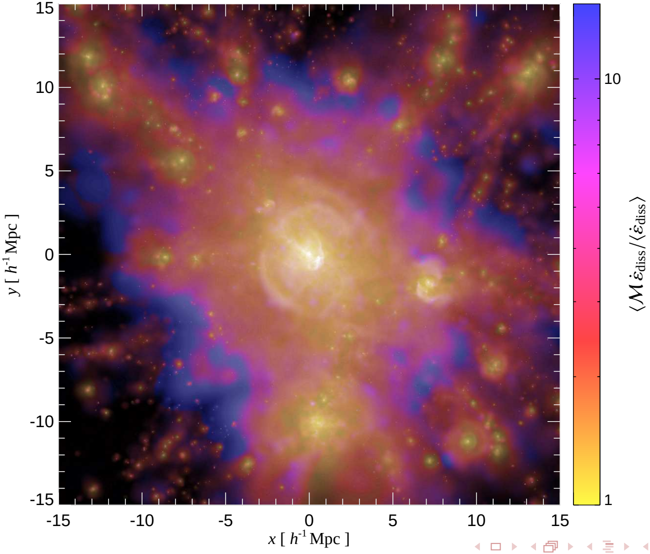
Mach number distribution weighted by $\varepsilon_{\text{diss}}$



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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

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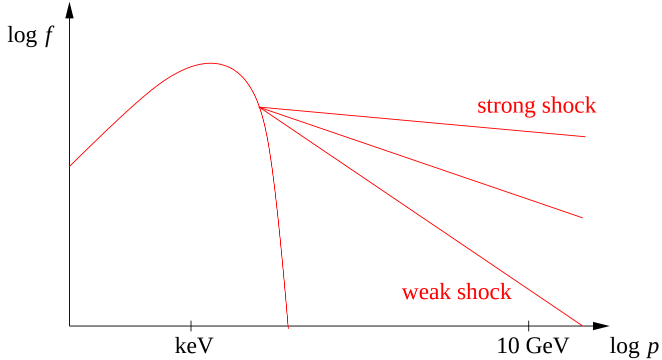
Diffusive shock acceleration – Fermi 1 mechanism (2)

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



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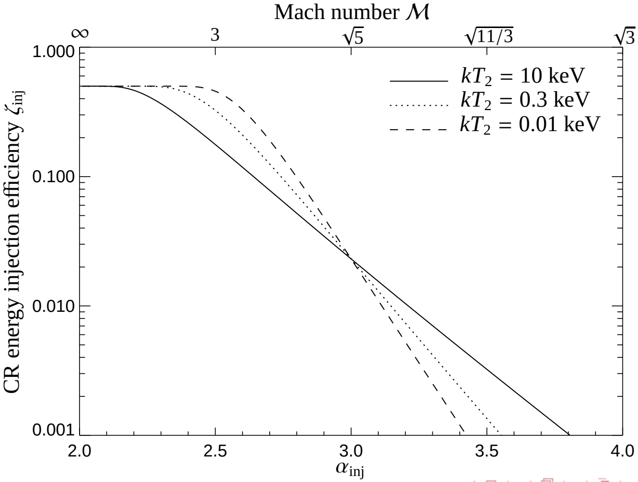
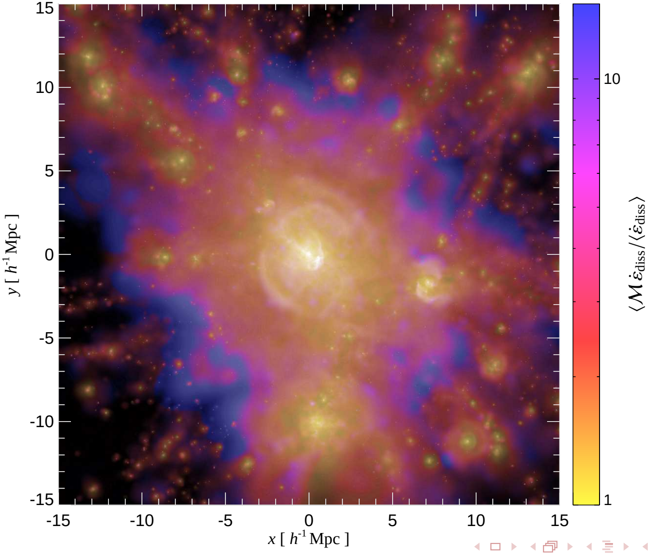
Diffusive shock acceleration – efficiency (3)

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



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



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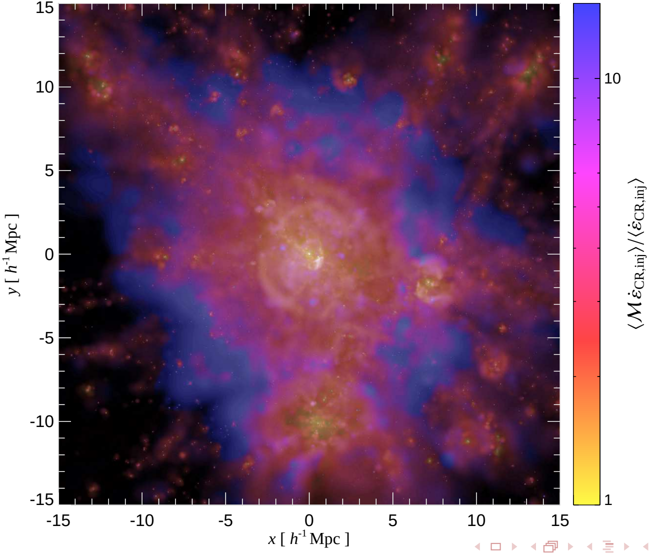
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$



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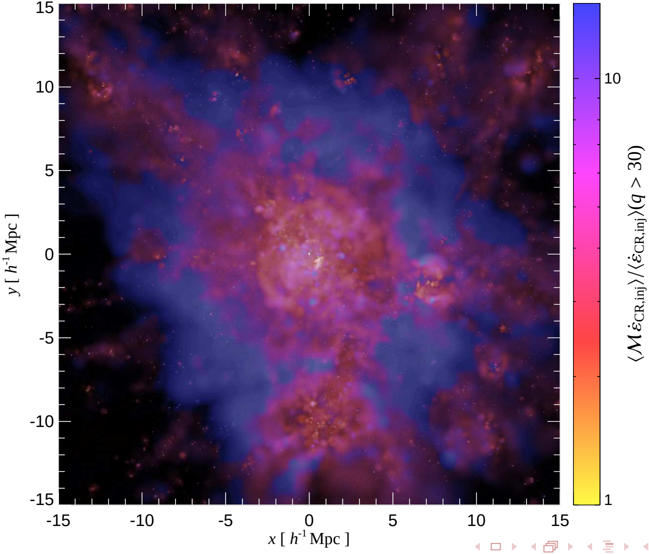
Mach number distribution weighted by $\varepsilon_{\text{CR,inj}}(q > 30)$



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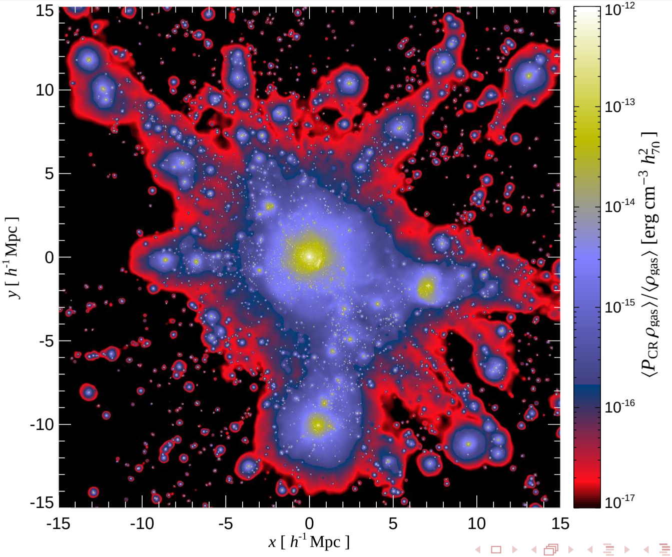
CR pressure P_{CR}



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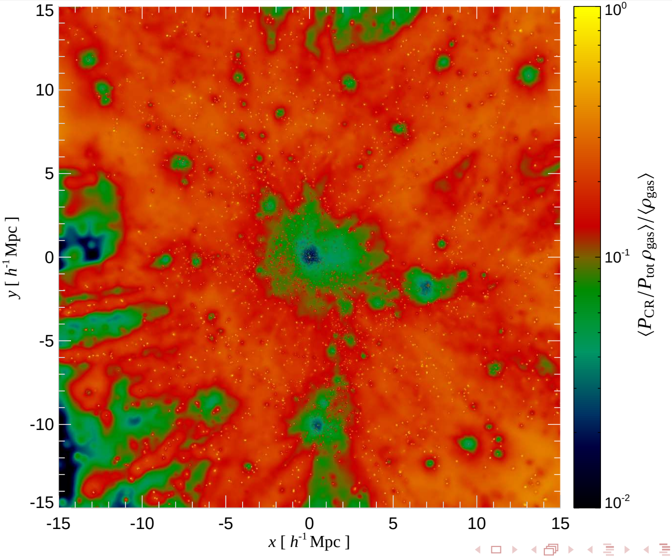
Relative CR pressure $P_{\mathrm{CR}}/P_{\mathrm{total}}$



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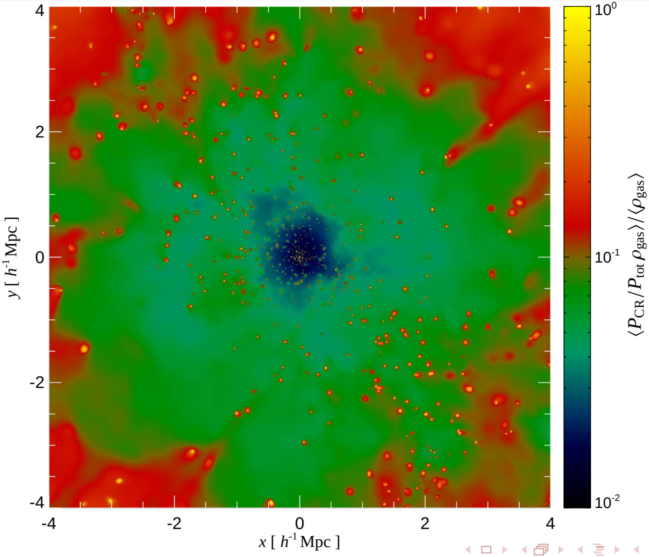

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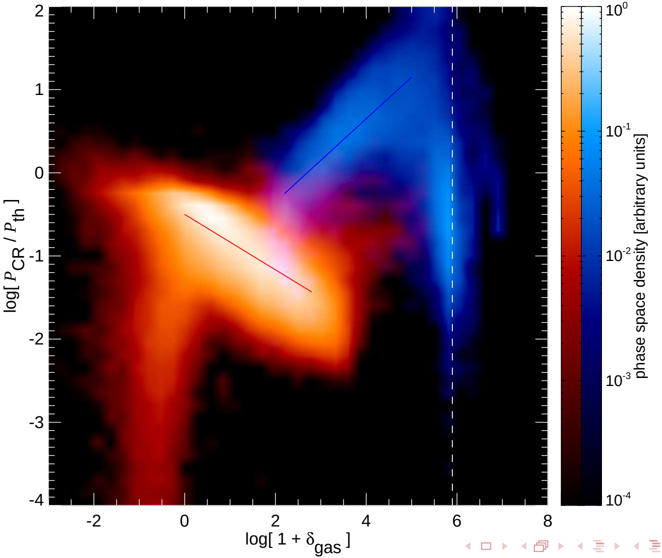
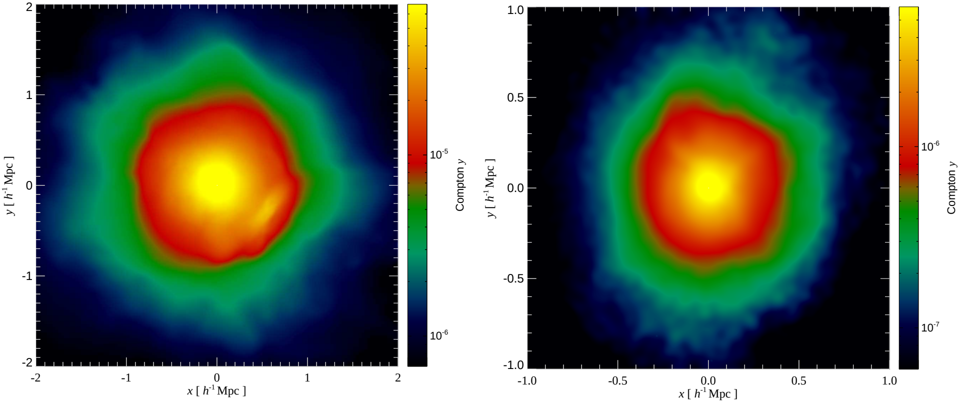
CR phase-space diagram: final distribution @ $z = 0$



CR impact on SZ effect: Compton *y* parameter



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

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

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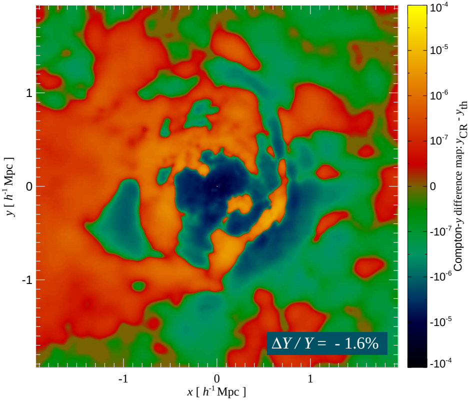
Compton y difference map: $y_{\mathrm{CR}} - y_{\mathrm{th}}$



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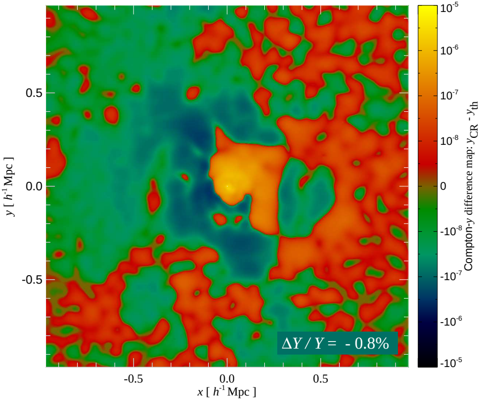

small cool core cluster, $M_{\mathrm{vir}} \simeq 10^{14} M_\odot / h$

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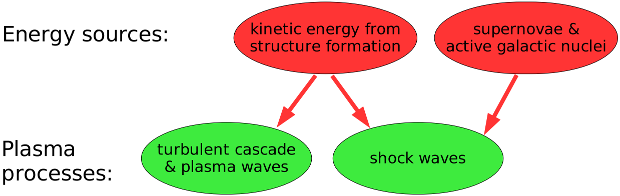
Multi messenger approach for non-thermal processes

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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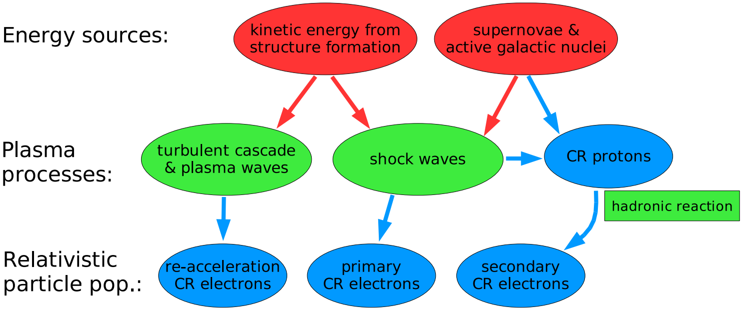

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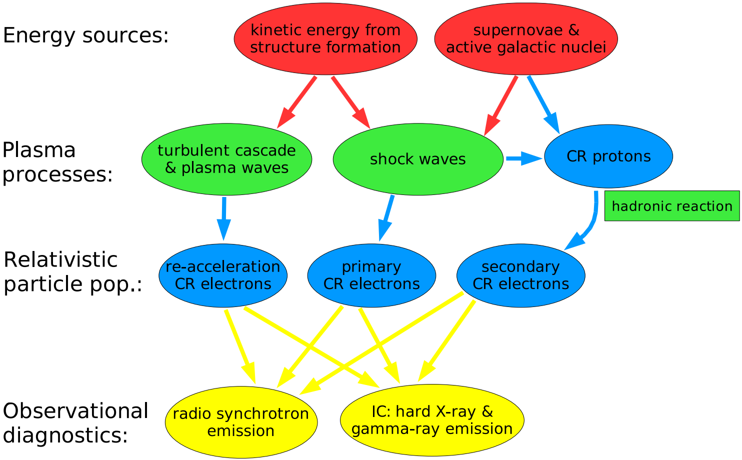

Energy sources:
- kinetic energy from structure formation
- supernovae & active galactic nuclei

Plasma processes:
- turbulent cascade & plasma waves
- shock waves
- CR protons

hadronic reaction

Relativistic particle pop.:
- re-acceleration CR electrons
- primary CR electrons
- secondary CR electrons

Observational diagnostics:
- radio synchrotron emission
- IC: hard X-ray & gamma-ray emission

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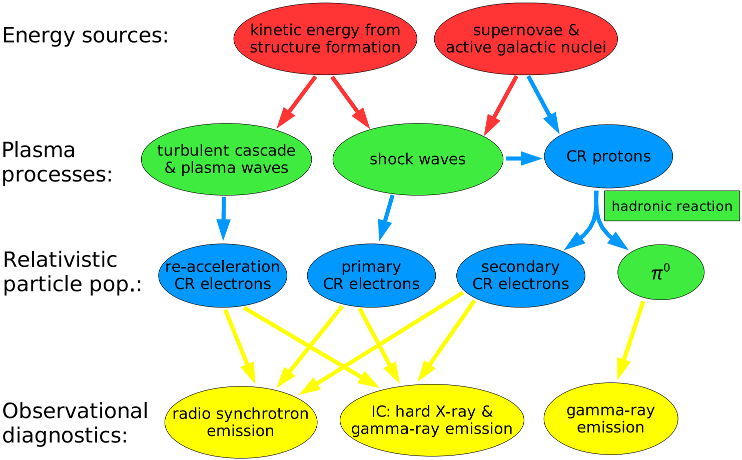
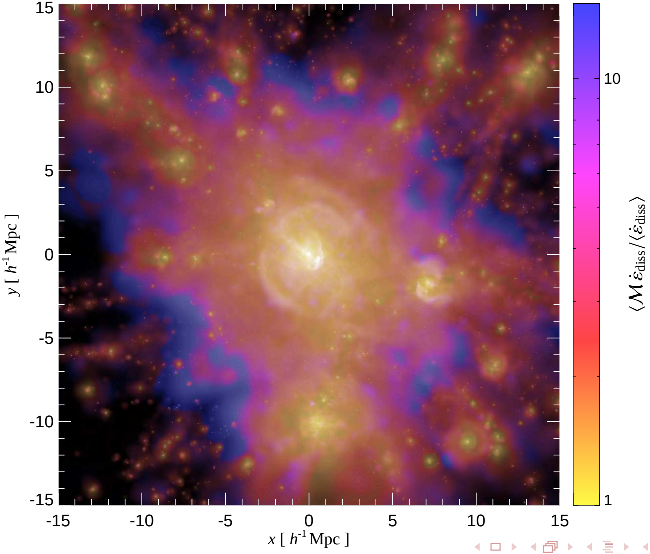


Cosmic web: Mach number



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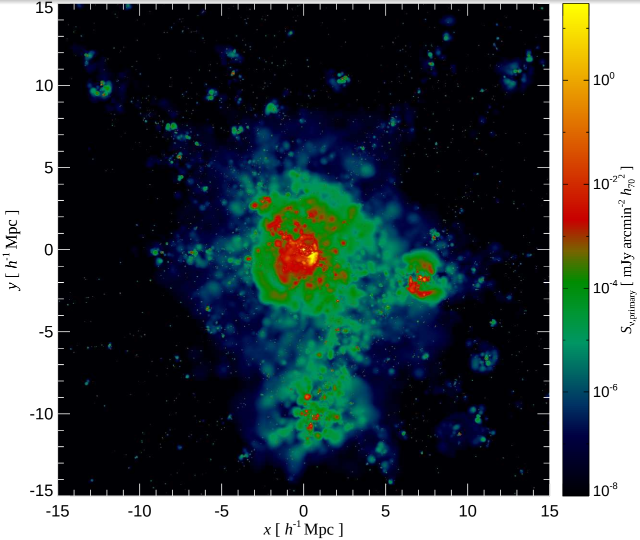
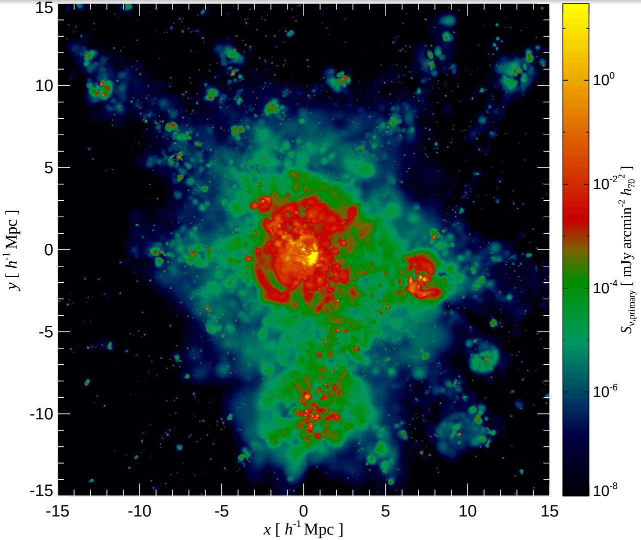
Radio gischt (relics): primary CRe (1.4 GHz)



Radio gischt: primary CRe (150 MHz)



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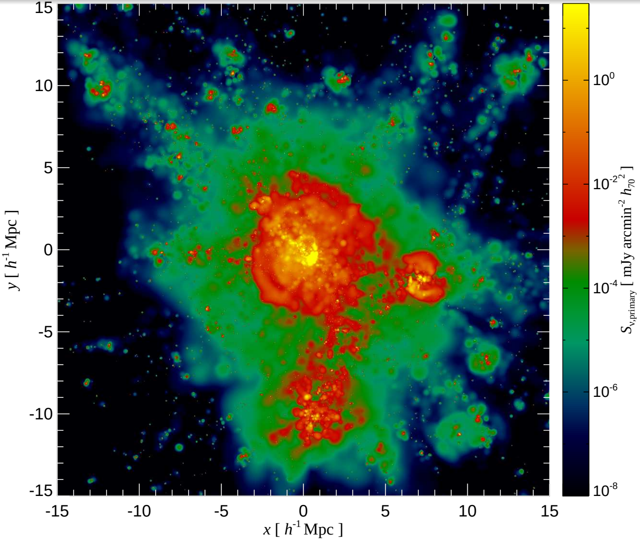
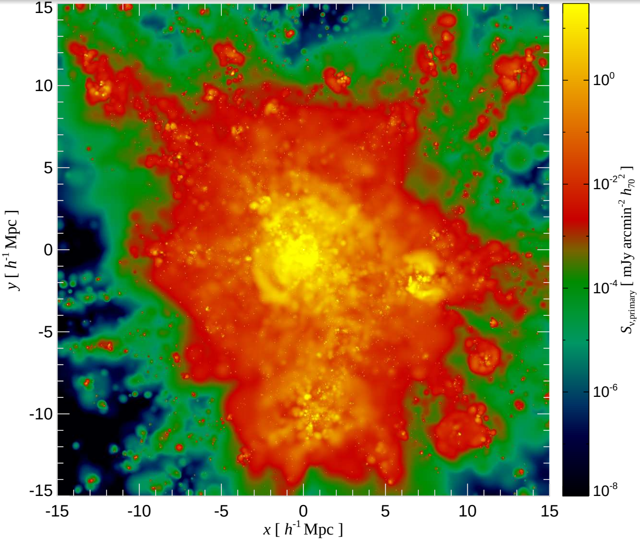
Radio gischt: primary CRe (15 MHz)



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



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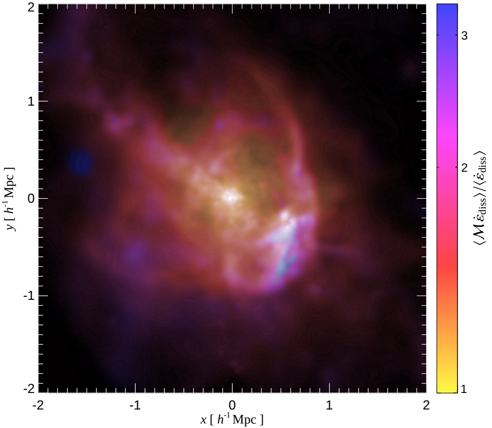
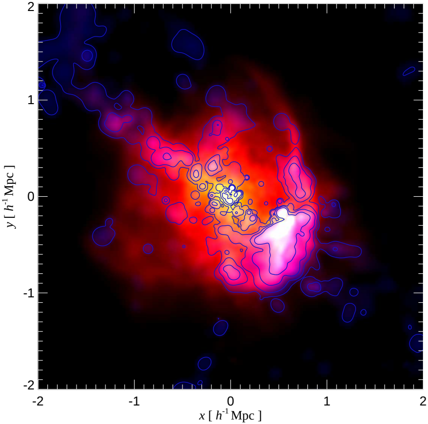
Radio gischt illuminates cosmic magnetic fields



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, Pfrommer, 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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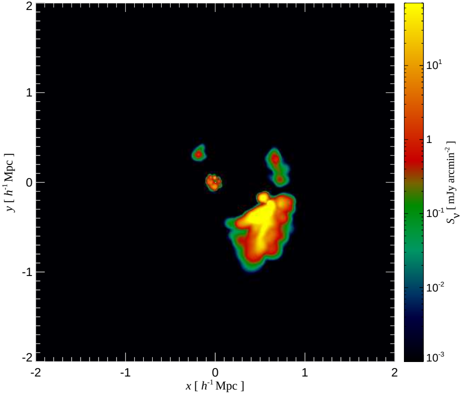
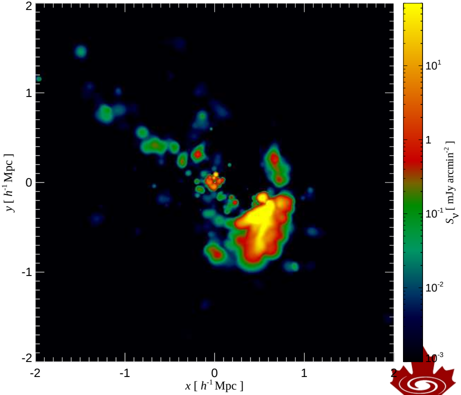
Population of faint radio relics in merging clusters

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



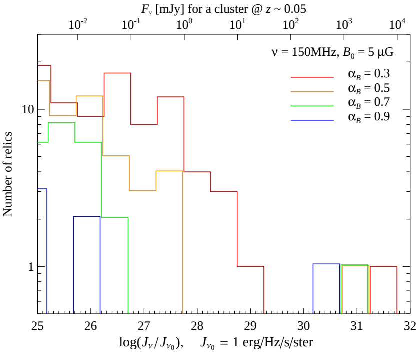
radio map with GMRT emissivity threshold



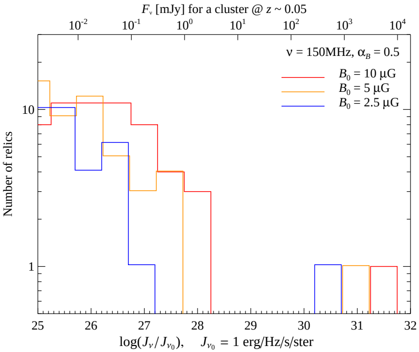
“theoretical” threshold (towards SKA)

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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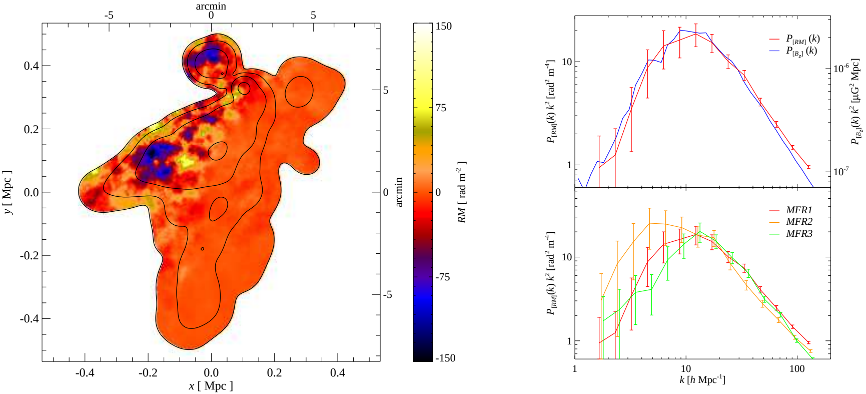
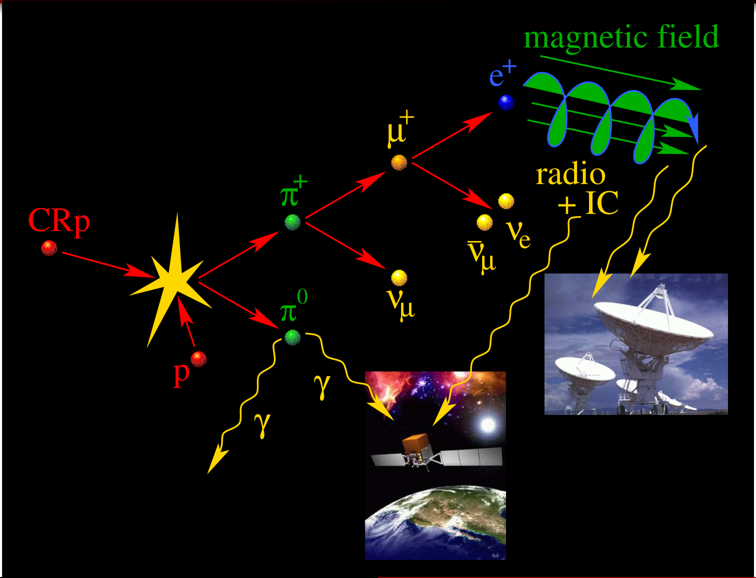
Rotation measure (RM)

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

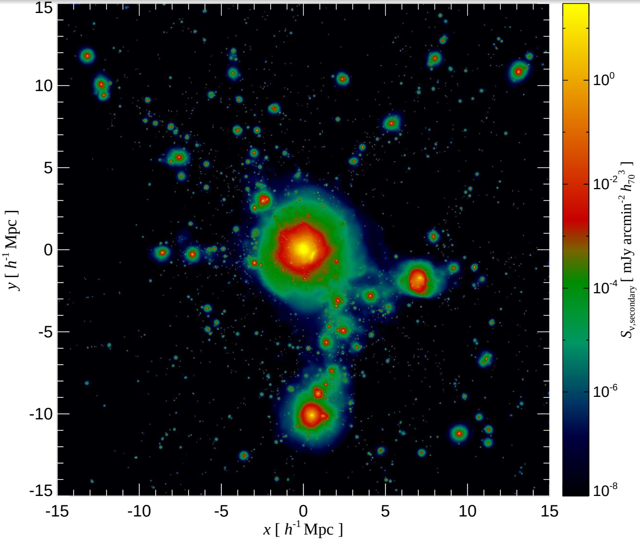


Left: RM map of the largest relic, right: Magnetic and RM power spectrum comparing Kolmogorow and Burgers turbulence models.

Hadronic cosmic ray proton interaction



Cluster radio emission by hadronically produced CRe



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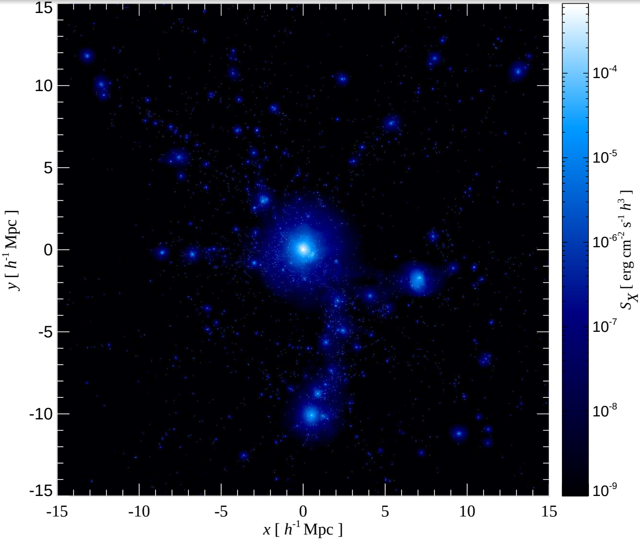
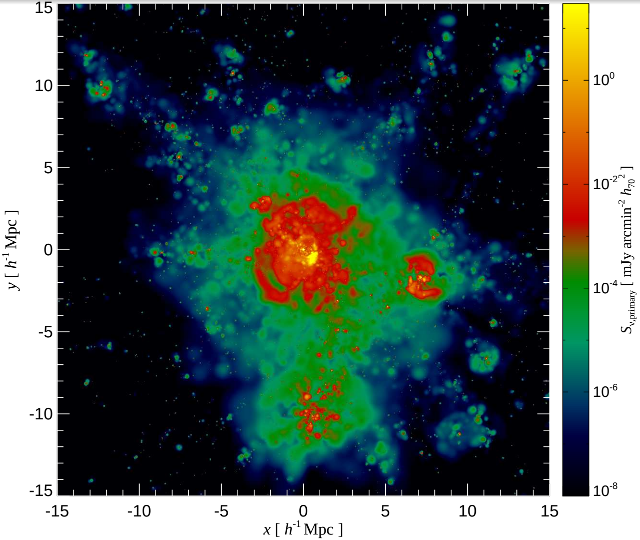
Thermal X-ray emission



Radio gischt: primary CRe (150 MHz)



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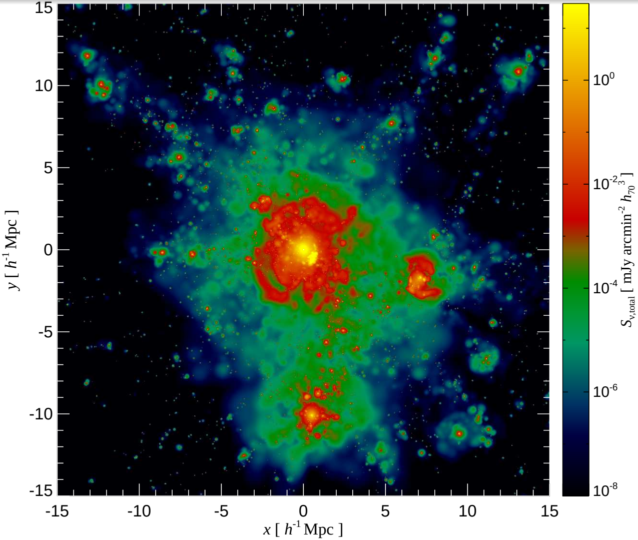
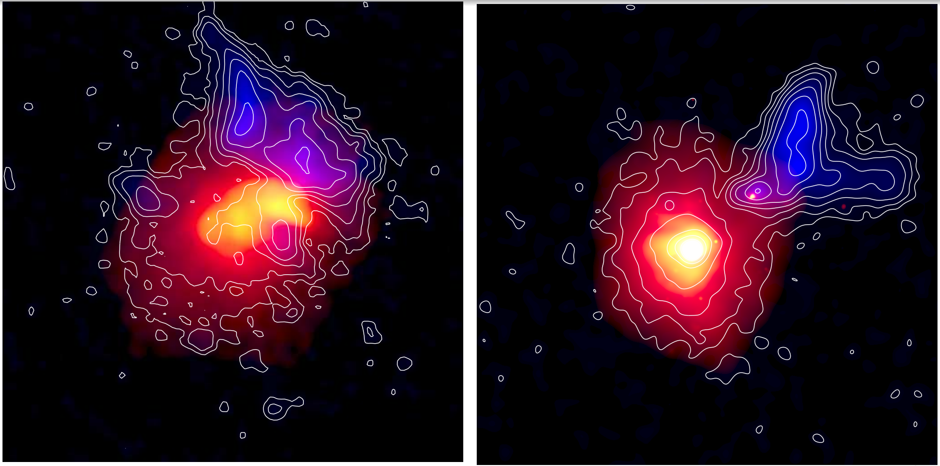
Radio gischt + central hadronic halo = giant radio halo

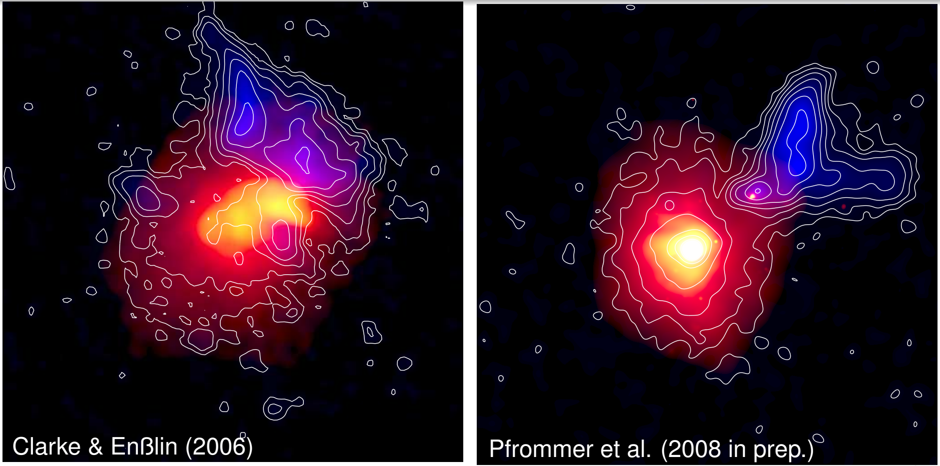


Which one is the simulation/observation of A2256?



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

Observation – simulation of A2256



red/yellow: thermal X-ray emission,
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Unified model of radio halos and relics

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 ($\nu \simeq (15 - 240)$ 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)

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Outline

1. Cosmological structure formation shocks
    - Cosmological galaxy cluster simulations
    - Mach numbers and shock acceleration
    - Cosmic ray transport and pressure distribution
2. Diffuse radio emission in clusters
    - General picture of non-thermal processes in clusters
    - Shock related emission
    - Hadronically induced emission
3. High-energy γ-ray emission
    - Morphology and spectra
    - Predictions for *Fermi*
    - Minimum γ-ray flux

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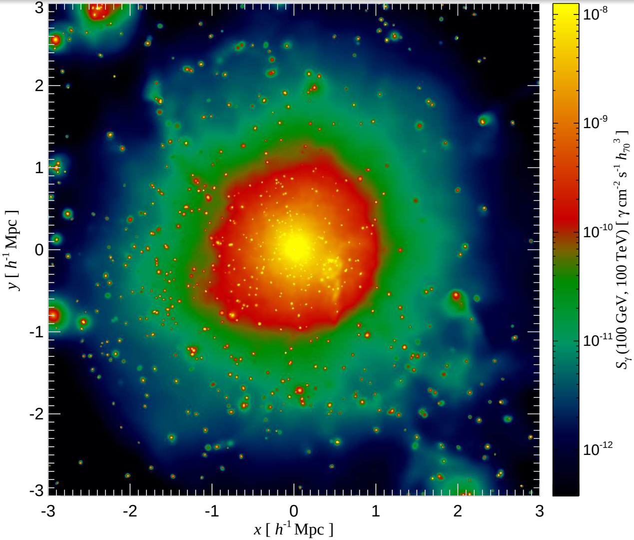
The quest for high-energy γ-ray emission from clusters

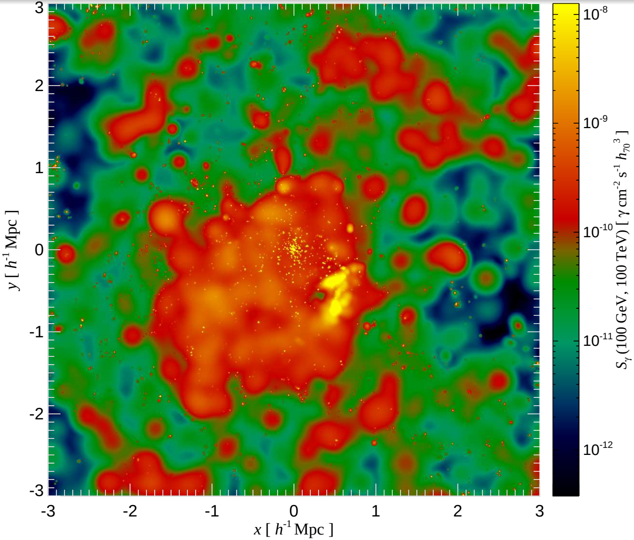
Multi-messenger approach towards fundamental astrophysics

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 γ-rays
    - spectral and morphological γ-ray signatures → DM properties
3. probes plasma astrophysics such as macroscopic parameters for diffusive shock acceleration

Hadronic γ-ray emission, $E_\gamma > 100$ GeV



Inverse Compton emission, $E_{\mathrm{IC}} > 100$ GeV



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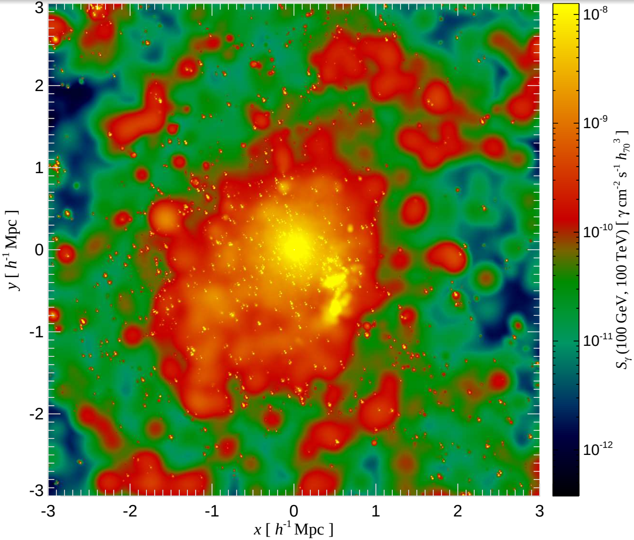
Total γ-ray emission, $E_\gamma > 100$ GeV



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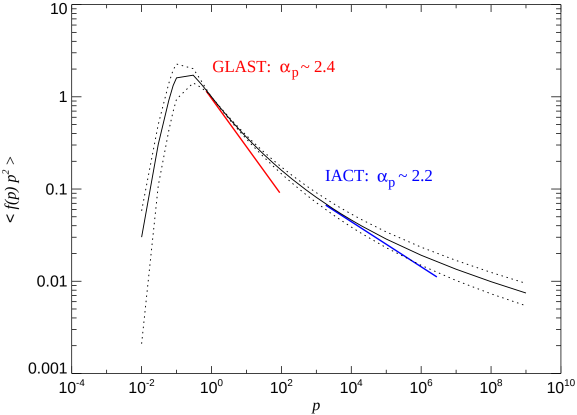
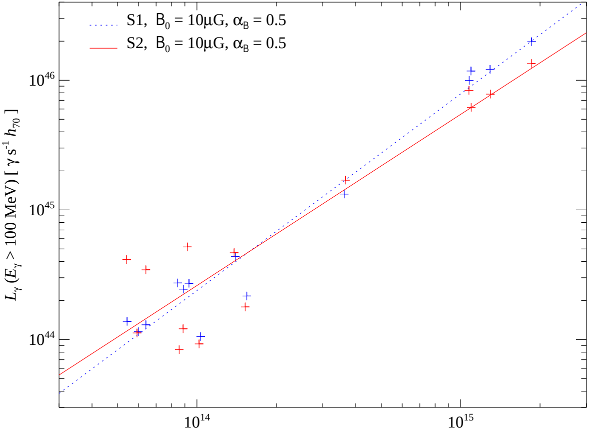
Universal CR spectrum in clusters



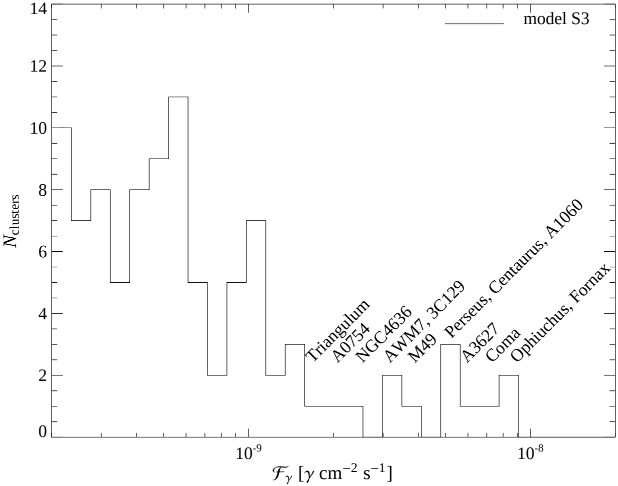
Normalized CR spectrum shows universal concave shape → governed mainly by hierarchical structure formation and adiabatic CR transport processes. (Pinzke & Pfrommer, in prep.)

Gamma-ray scaling relations

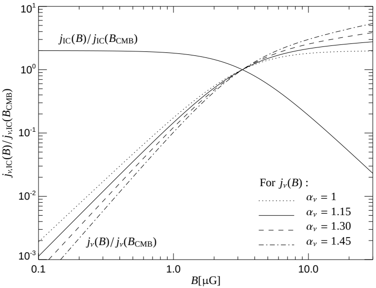


Scaling relation + complete sample of the brightest X-ray clusters (extended HIFLUCGS) → predictions for *Fermi*

Predicted cluster sample for *Fermi*



Minimum γ-ray flux in the hadronic model (1)



Synchrotron emissivity of high-energy, steady state electron distribution is independent of the magnetic field for $B \gg B_{\mathrm{CMB}}$!

Synchrotron luminosity:

$$L_\nu = A_\nu \int \mathrm{d}V\, n_{\mathrm{CR}} n_{\mathrm{gas}} \frac{\varepsilon_B^{(\alpha_\nu+1)/2}}{\varepsilon_{\mathrm{CMB}} + \varepsilon_B}$$

$$\rightarrow A_\nu \int \mathrm{d}V\, n_{\mathrm{CR}} n_{\mathrm{gas}} \quad (\varepsilon_B \gg \varepsilon_{\mathrm{CMB}})$$

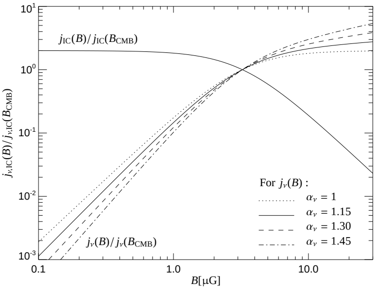
γ-ray luminosity:

$$L_\gamma = A_\gamma \int \mathrm{d}V\, n_{\mathrm{CR}} n_{\mathrm{gas}}$$

$\rightarrow$ minimum γ-ray flux:

$$\mathcal{F}_{\gamma,\mathrm{min}} = \frac{A_\gamma}{A_\nu} \frac{L_\nu}{4\pi D^2}$$

Minimum γ-ray flux in the hadronic model (1)



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$$L_\gamma = A_\gamma \int \mathrm{d}V\, n_\mathrm{CR} n_\mathrm{gas}$$

→ minimum γ-ray flux:

$$\mathcal{F}_{\gamma,\mathrm{min}} = \frac{A_\gamma}{A_\nu} \frac{L_\nu}{4\pi D^2}$$

Minimum γ-ray flux in the hadronic model (2)

Minimum γ-ray flux ($E_\gamma > 100$ MeV) for the Coma cluster:

CR spectral index	2.0	2.3	2.6	2.9
$\mathcal{F}_\gamma$ $[10^{-10}\gamma\, cm^{-2} s^{-1}]$	0.8	1.6	3.4	7.1

- These limits can be made even tighter when considering energy constraints, $P_B < P_{\rm gas}/20$ and B-fields derived from Faraday rotation studies, $B_0 = 3\,\mu$G: $\mathcal{F}_{\gamma,\rm COMA} \gtrsim 2 \times 10^{-9}\gamma\, cm^{-2} s^{-1} = \mathcal{F}_{\rm Fermi,\ 2yr}$
- Non-detection by *Fermi* seriously challenges the hadronic model.
- Potential of measuring the CR acceleration efficiency for diffusive shock acceleration.

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 → illuminating the process of structure formation
2. Unified model for the generation of giant radio halos, radio mini-halos, and relics: interplay of primary and secondary synchrotron emission.
3. We predict *Fermi* to detect $\sim$ ten γ-ray clusters: test of the presented scenario

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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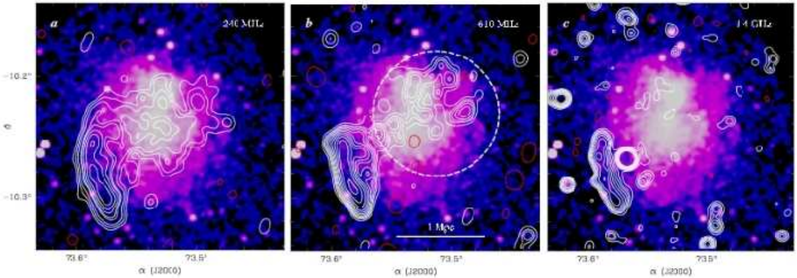
Diffuse low-frequency radio emission in Abell 521

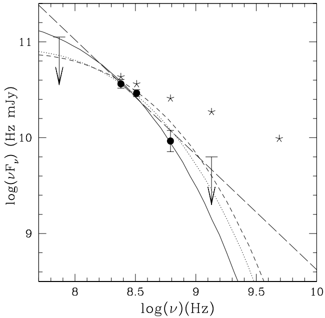
Brunetti et al. 2008, Nature, 455, 944:



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