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 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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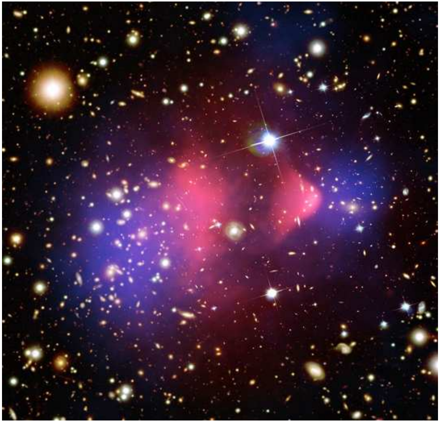
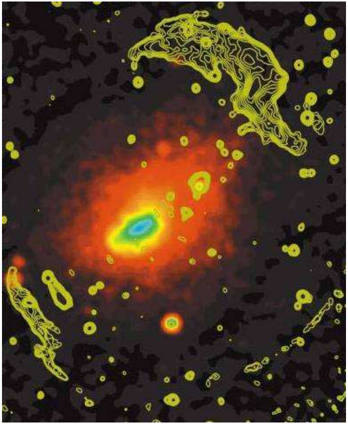
Shocks in galaxy clusters



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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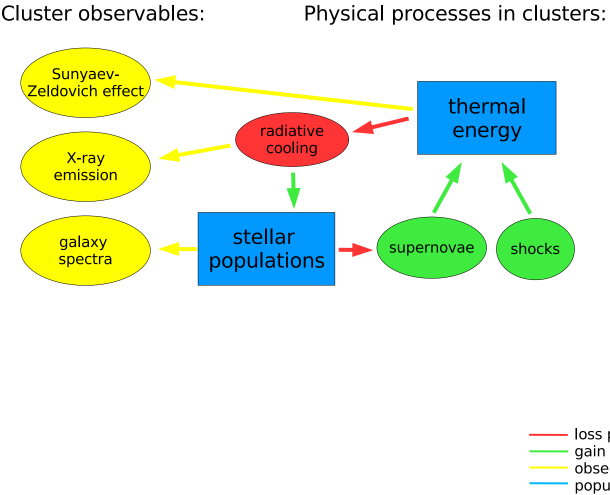
Topics of interest

Multi-messenger approach of galaxy clusters:

- 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
- nature of dark matter: annihilation signal vs. CR induced γ-rays
- gold sample of cluster for precision cosmology: gauging non-thermal observables
- fundamental plasma physics:
  - diffusive shock acceleration for high-β plasmas
  - origin and evolution of large scale magnetic fields
  - nature of turbulent models

Radiative simulations – flowchart



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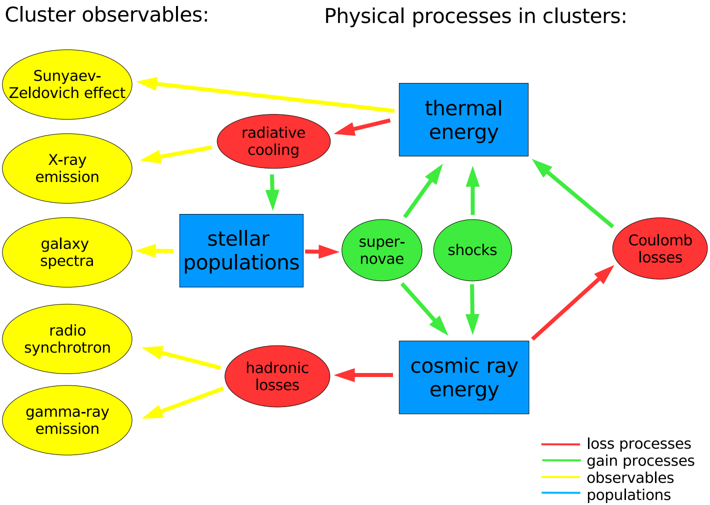
Radiative simulations with cosmic ray (CR) physics



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

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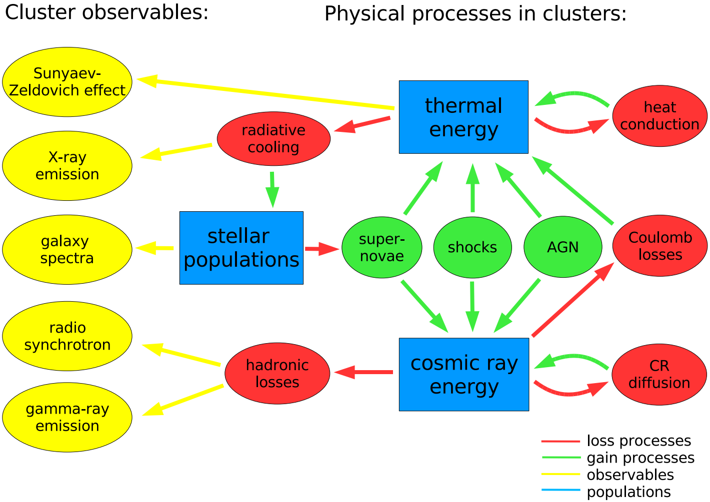
Radiative simulations with extended CR physics



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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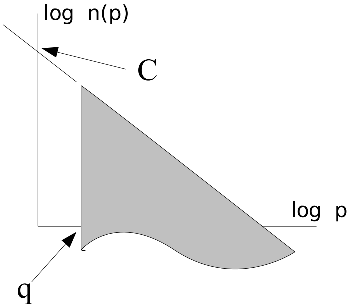
CR spectral description



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

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

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

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

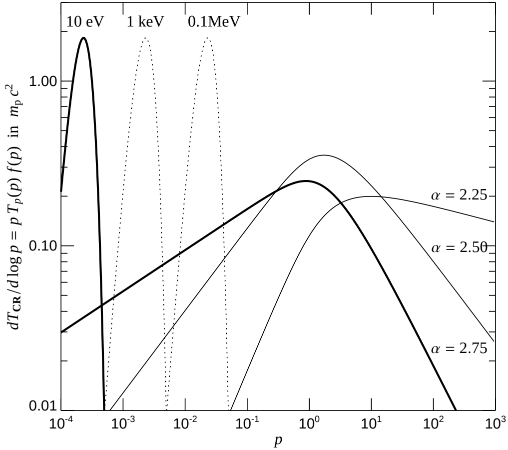
$$n_{\rm CR} = \int_0^\infty {\rm d}p\, f(p) = \frac{C\,q^{1-\alpha}}{\alpha-1}$$

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

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

Thermal & CR energy spectra

Kinetic energy per logarithmic momentum interval:



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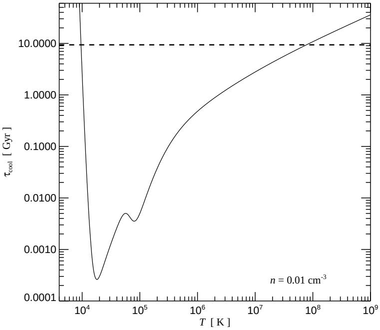
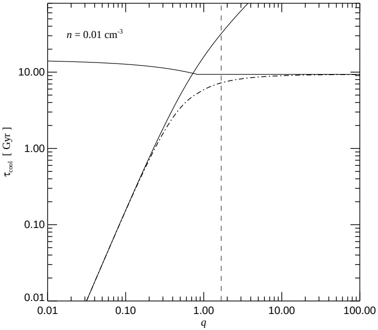
Cooling time scales of CR protons

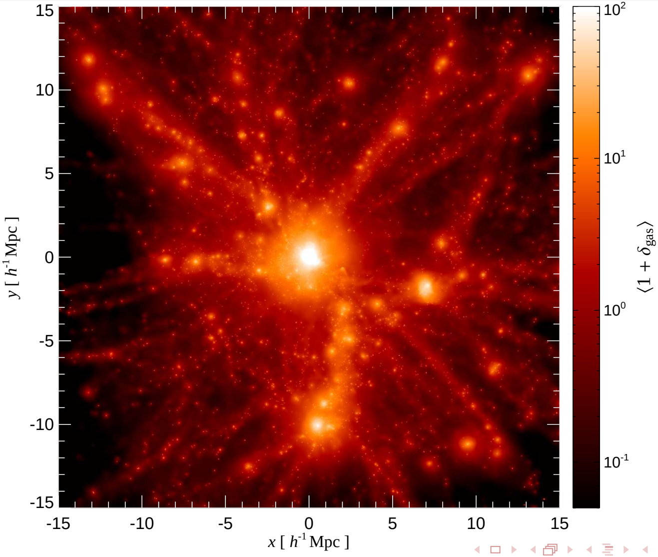
Cooling of primordial gas:



Cooling of cosmic rays:



Radiative cool core cluster simulation: gas density



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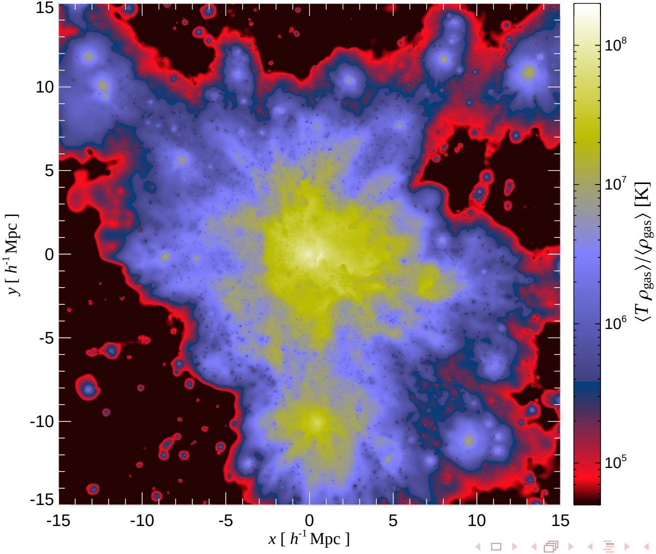
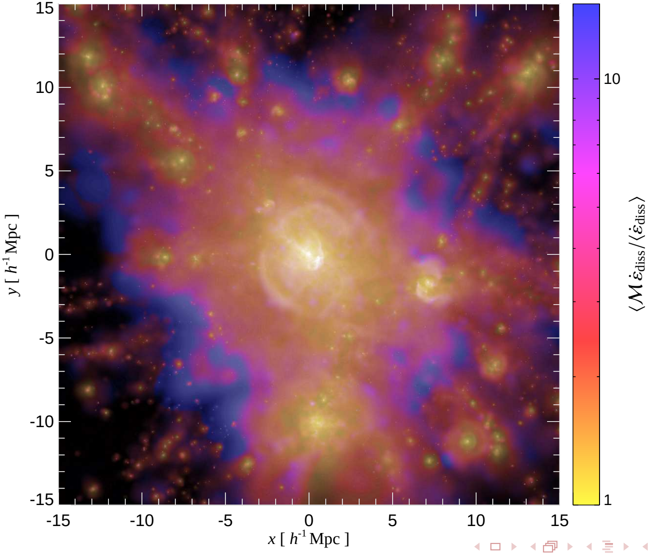
Mass weighted temperature



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



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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 the macroscopic scattering agents
- momentum increases exponential with number of shock crossings
- number of particles decreases exponential with number of crossings

→ power-law CR distribution

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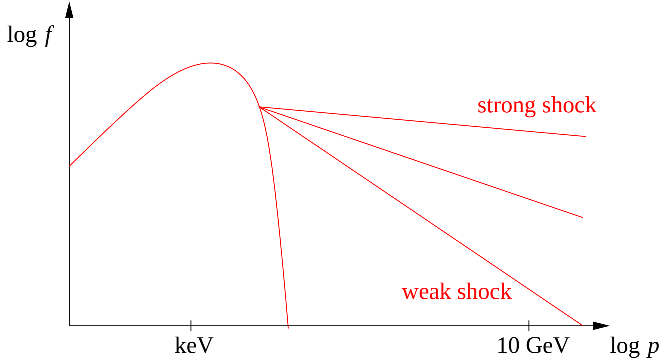
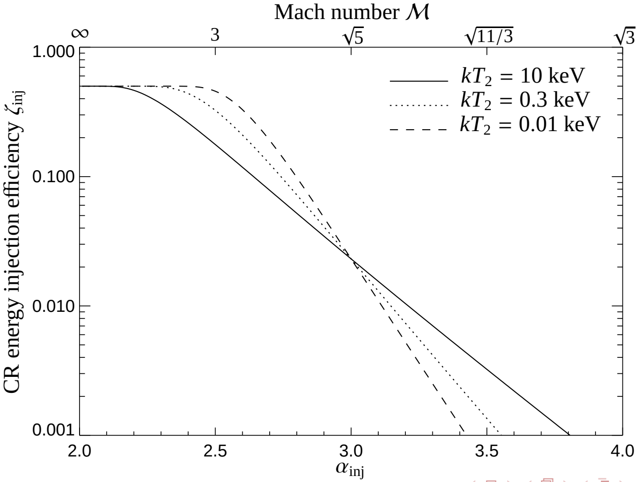
Diffusive shock acceleration – Fermi 1 mechanism (2)

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



Diffusive shock acceleration – efficiency (3)

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



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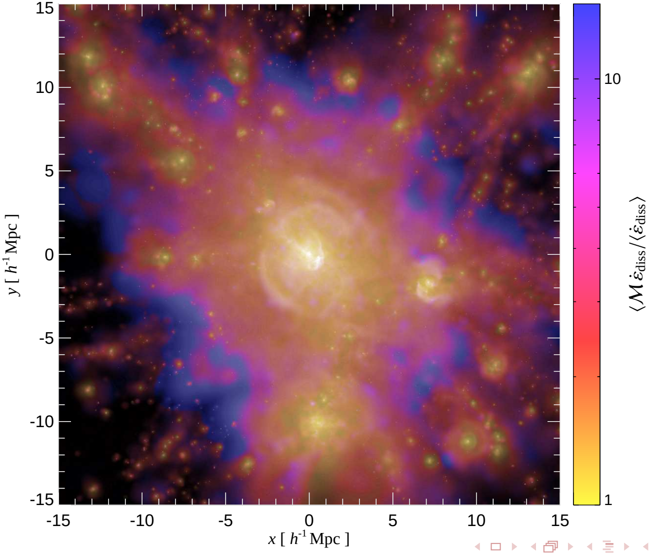
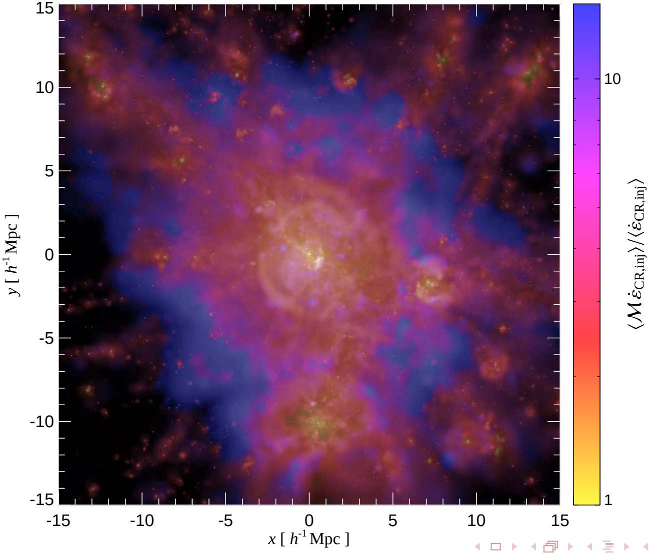
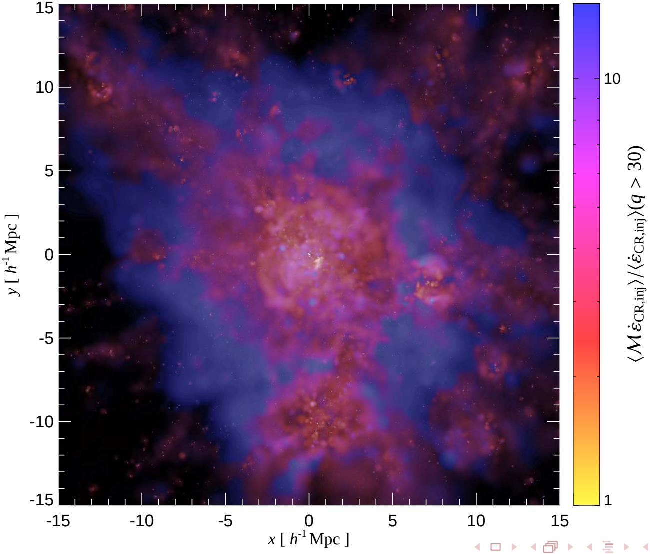
Mach number distribution weighted by $\varepsilon_{\text{diss}}$



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



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



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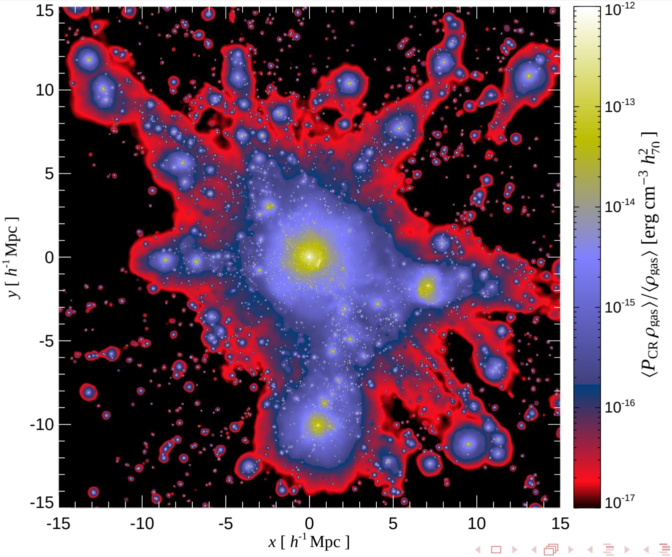
CR pressure P_{CR}



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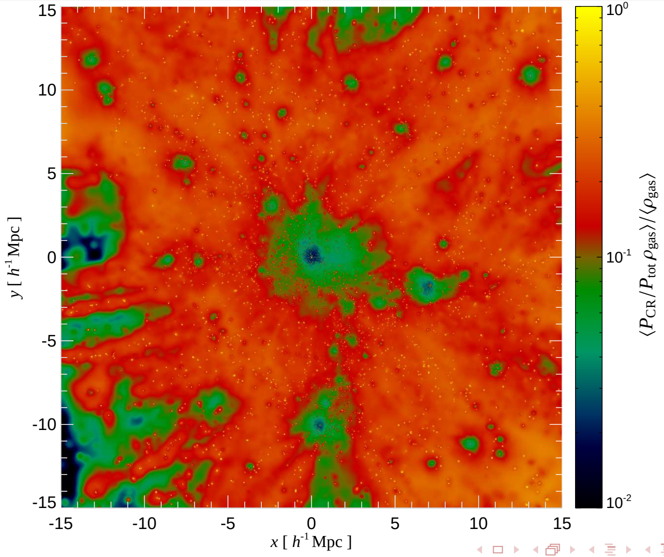
Relative CR pressure $P_{\mathrm{CR}}/P_{\mathrm{total}}$



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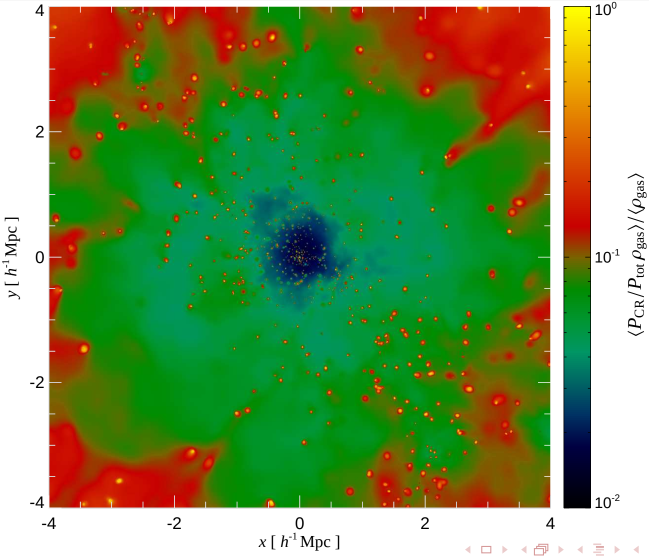

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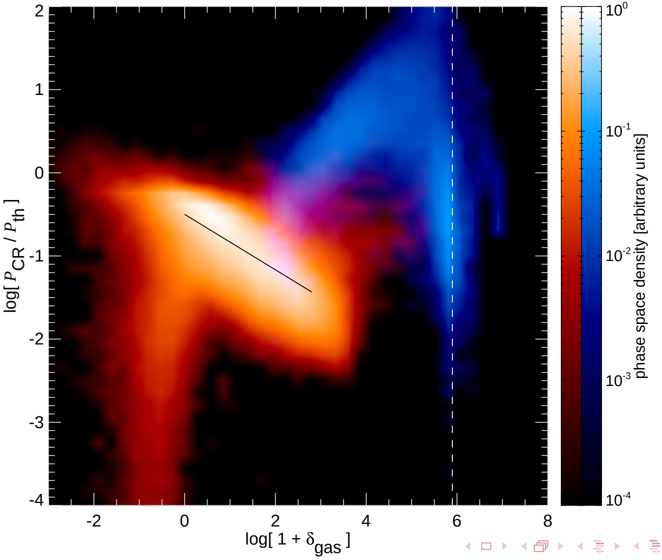
CR phase-space diagram: final distribution @ $z = 0$



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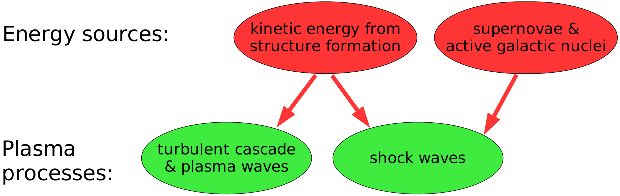
Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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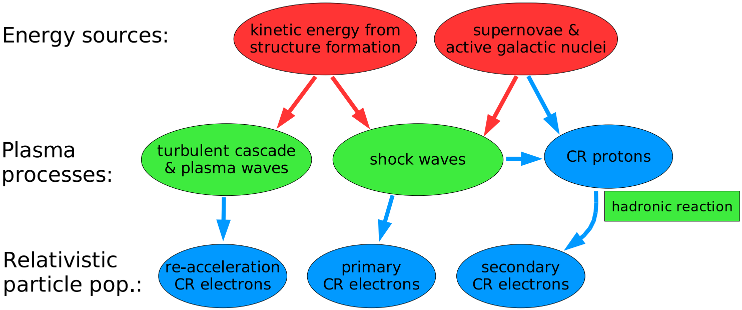

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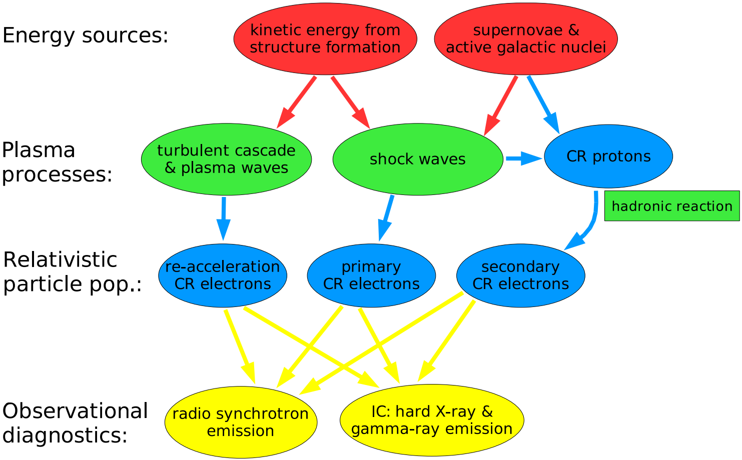

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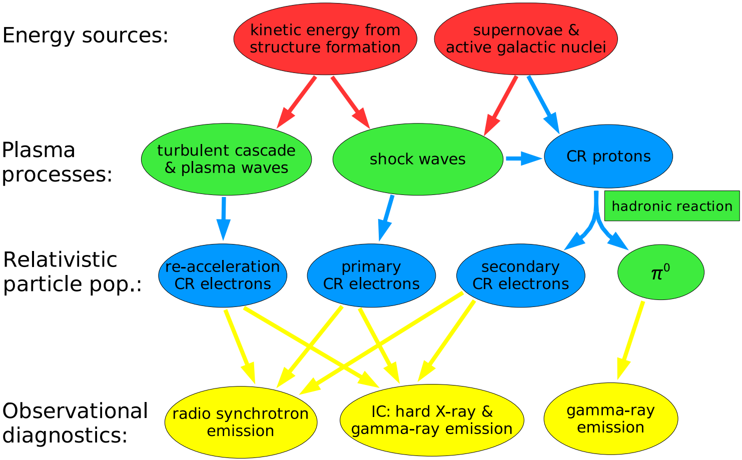
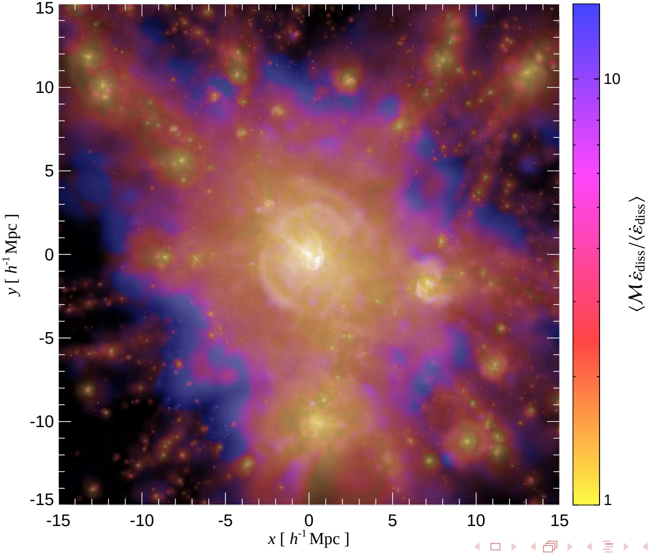


Cosmic web: Mach number



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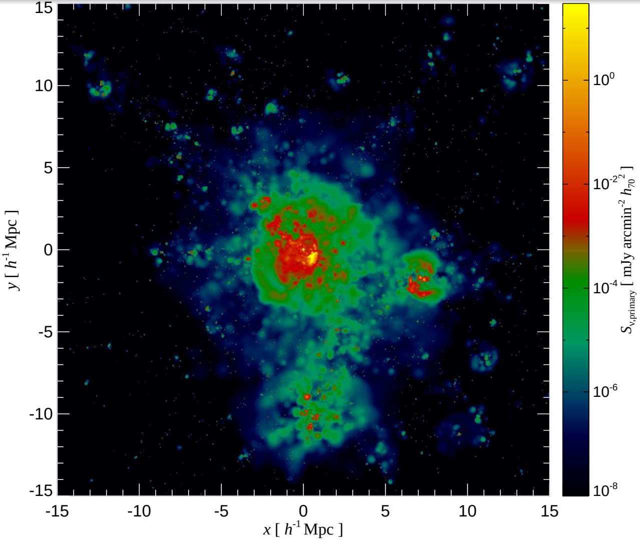
Radio gischt (relics): primary CRe (1.4 GHz)



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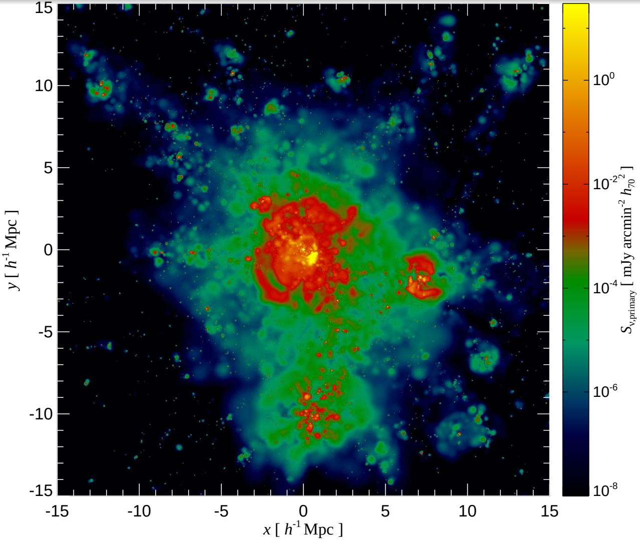
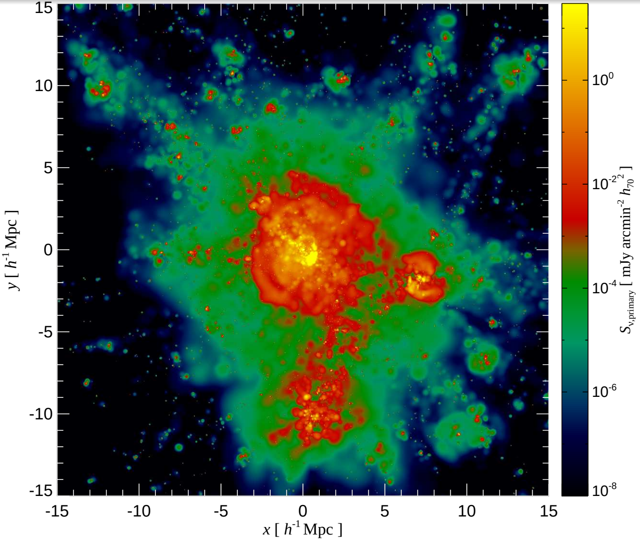
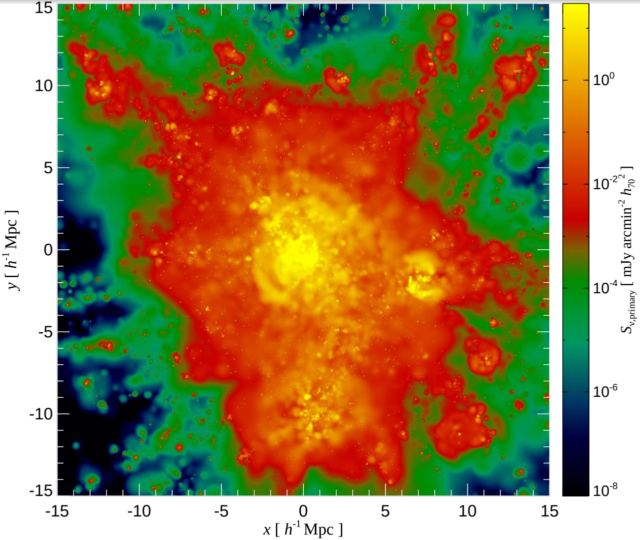
Radio gischt: primary CRe (150 MHz)



Radio gischt: primary CRe (15 MHz)



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



Particle reactions

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)

$\rightarrow$ an energetic CR proton population should exist in clusters

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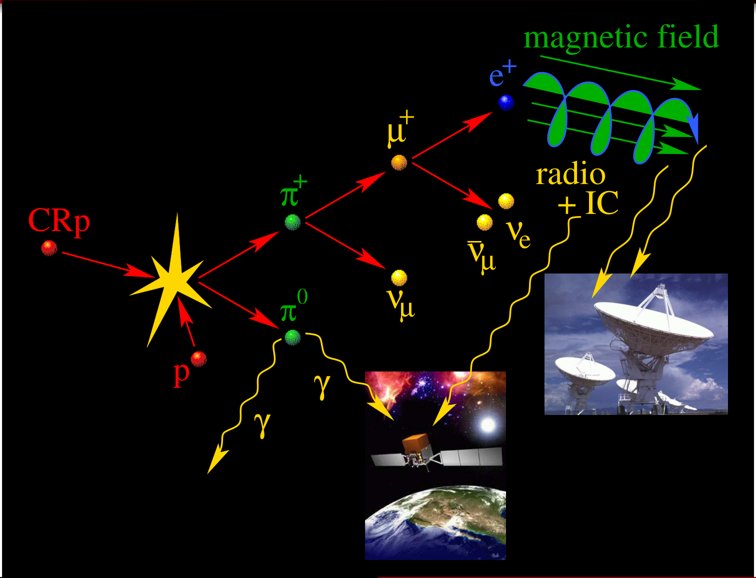
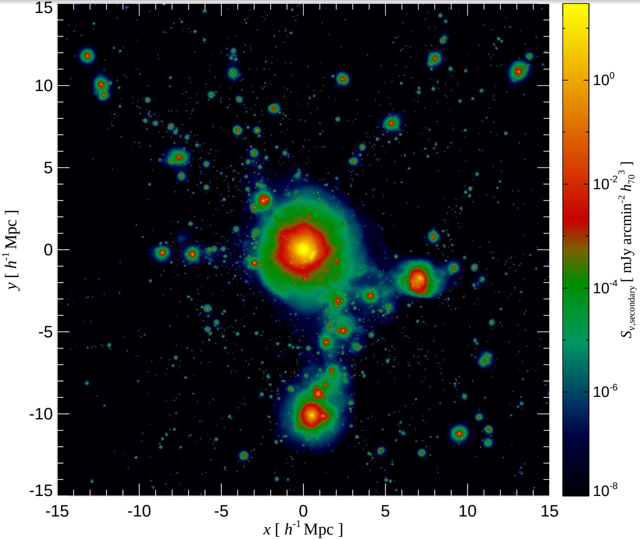
Hadronic cosmic ray proton interaction



Cluster radio emission by hadronically produced CRe



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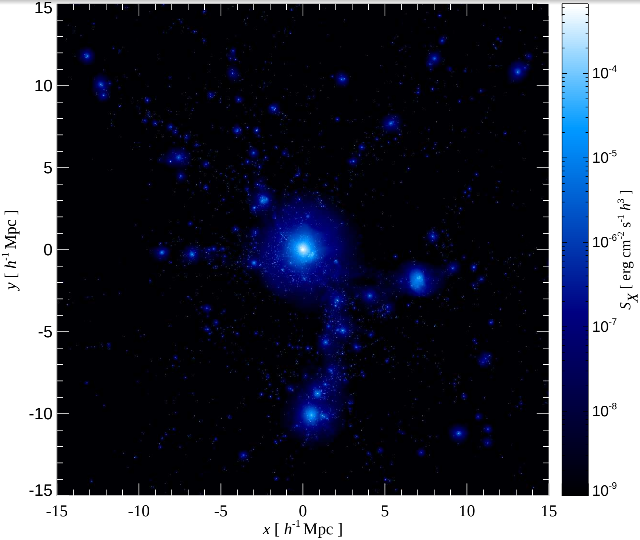
Thermal X-ray emission



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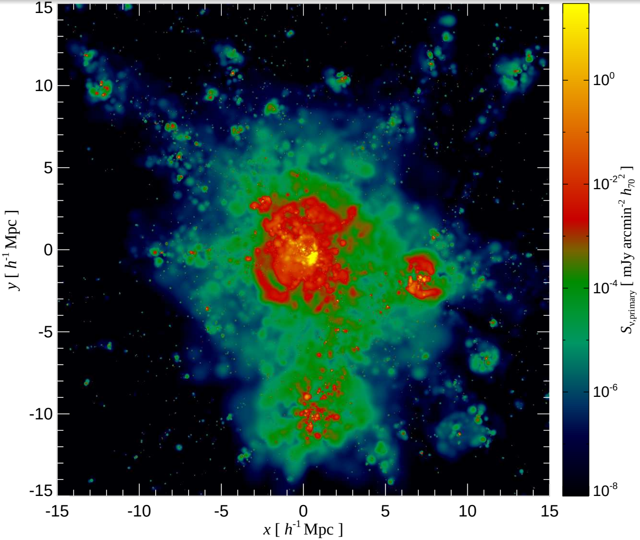
Radio gischt: primary CRe (150 MHz)



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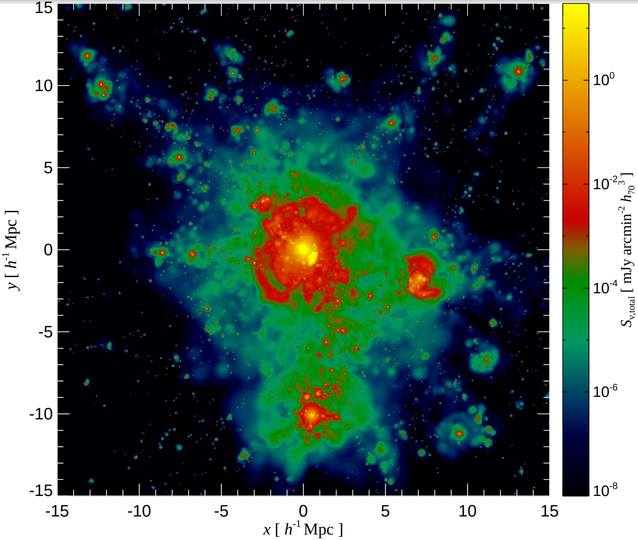
Radio gischt + central hadronic halo = giant radio halo



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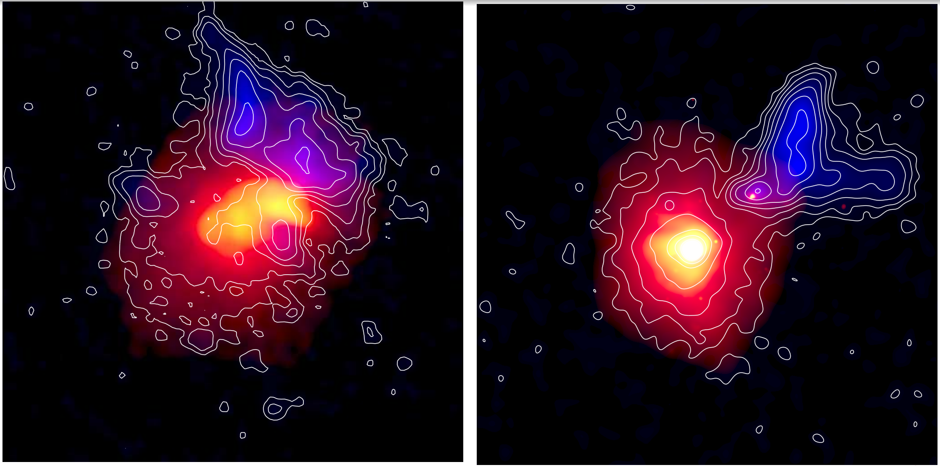
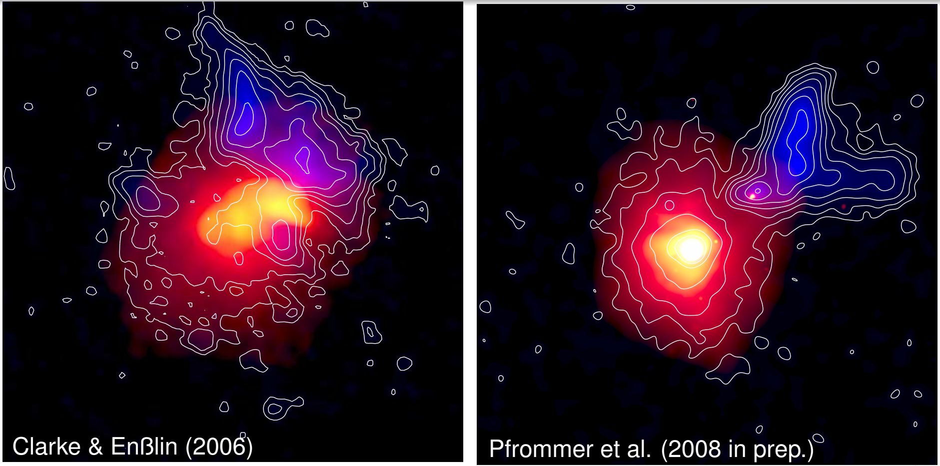
Which one is the simulation/observation of A2256?



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

Observation – simulation of A2256



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

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.:

- LOFAR, GMRT, MWA, LWA: 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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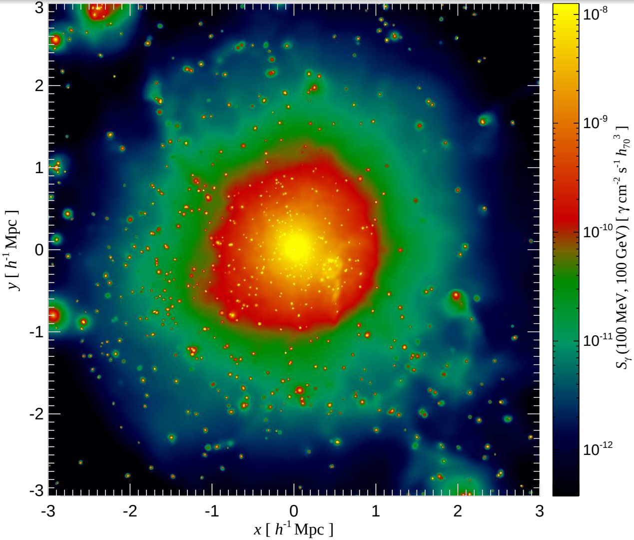
The quest for high-energy γ-ray emission from clusters

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, $E_\gamma > 100$ MeV



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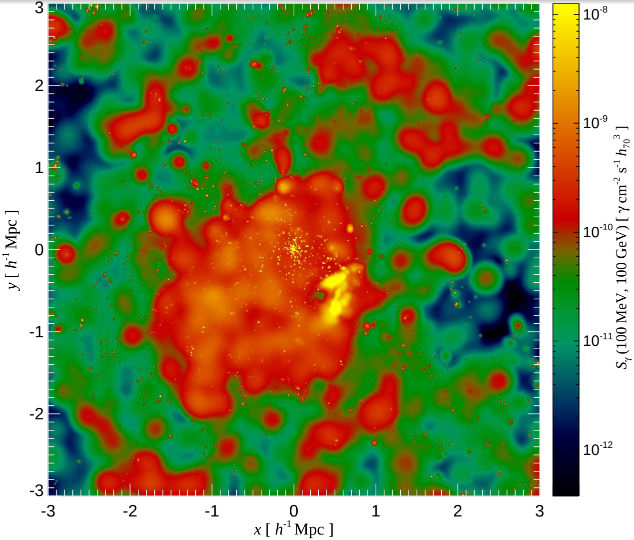
Inverse Compton emission, $E_{\mathrm{IC}} > 100$ MeV



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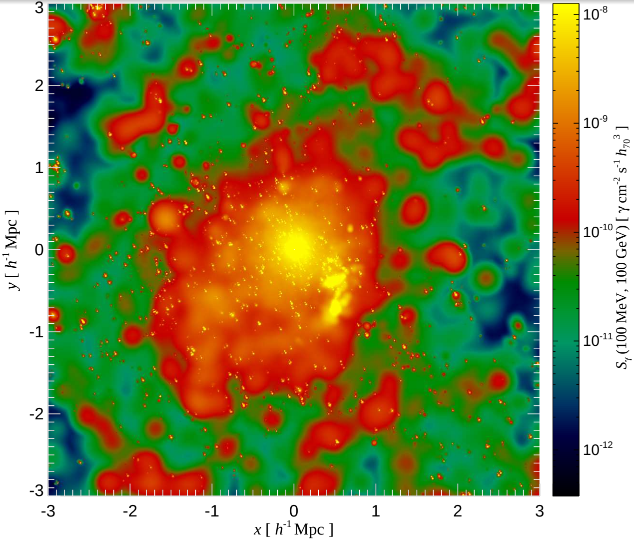
Total γ-ray emission, $E_\gamma > 100$ MeV



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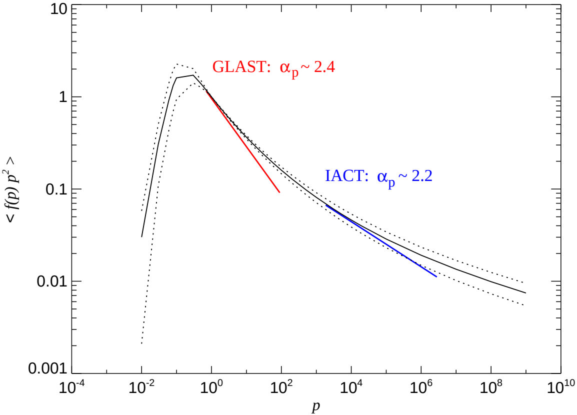
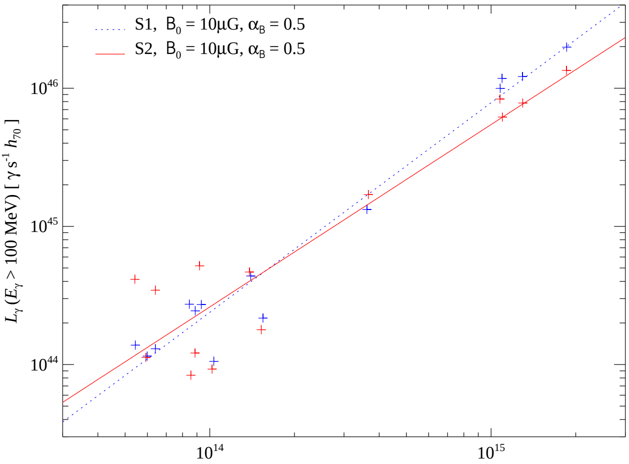
Universal CR spectrum in clusters



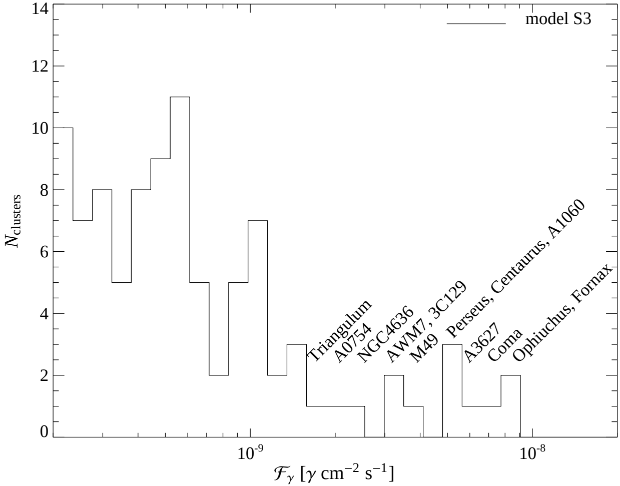
Normalized CR spectrum shows universal concave shape → governed mainly by hierarchical structure formation and adiabatic CR transport processes. (Pinzke & Pfrommer, in prep.)

Gamma-ray scaling relations

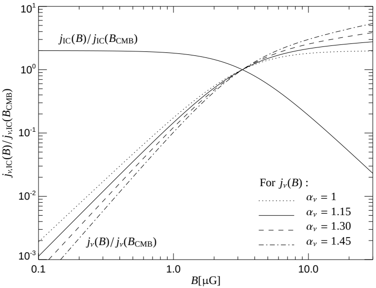


Scaling relation + complete sample of the brightest X-ray clusters (HIFLUCGS) → predictions for *Fermi*

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:

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

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

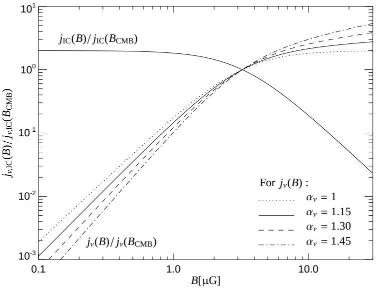
γ-ray luminosity:

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

→ 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)



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

Synchrotron luminosity:

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

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

γ-ray luminosity:

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

$\rightarrow$ minimum γ-ray flux:

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

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

- Pfrommer, 2008, MNRAS, 385, 1242 *Simulating cosmic rays in clusters of galaxies – III. Non-thermal scaling relations and comparison to observations*
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- 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, in print, astro-ph/0603485, *Cosmic ray feedback in hydrodynamical simulations of galaxy formation*

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