Deciphering an enigma – Non-thermal emission from galaxy clusters

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in collaboration with

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Outline

1. Plasma processes in galaxy clusters
   - Cosmological galaxy cluster simulations
   - Shocks and particle acceleration
   - Cosmic ray transport and pressure distribution
2. Non-thermal emission from clusters
   - Radio emission by shocks and turbulence
   - Hadronically induced radio emission
   - High-energy γ-ray emission
3. Future perspectives and directions
   - Overview
   - Defining the questions
   - Conclusions

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Outline

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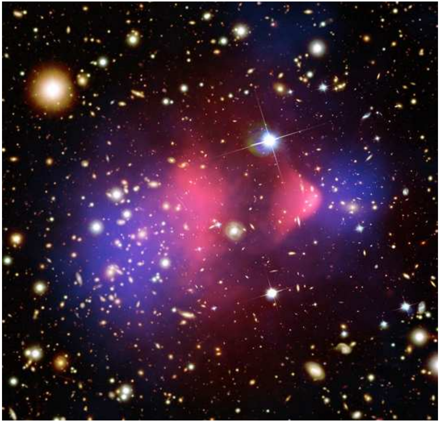
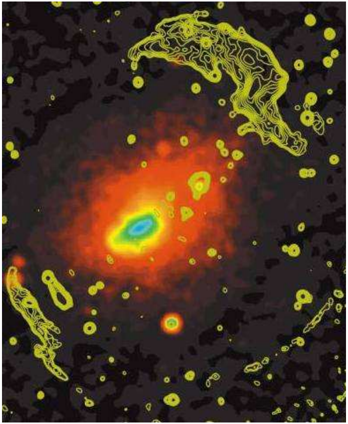
Shocks in galaxy clusters



1E 0657-56 ("Bullet cluster")

(X-ray: NASA/CXC/CfA/Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/Clowe et al.)



Abell 3667

(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)

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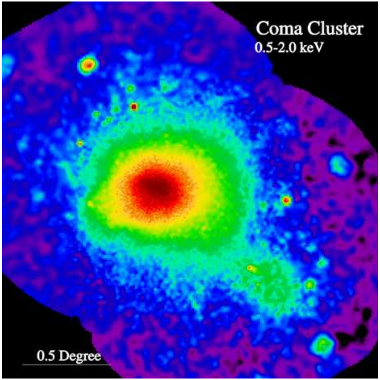
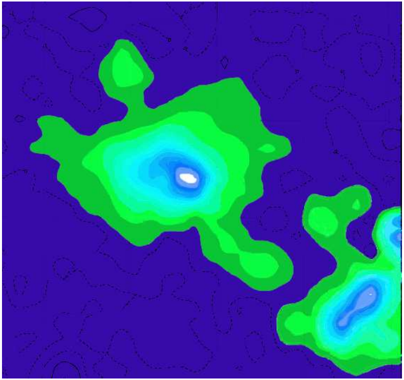
Giant radio halo in the Coma cluster



thermal X-ray emission

(Snowden/MPE/ROSAT)



radio synchrotron emission

(Deiss/Effelsberg)

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High-energy astrophysics in galaxy clusters

- 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
- understanding the non-thermal pressure distribution to address biases of thermal cluster observables
- gold sample of clusters for precision cosmology: using non-thermal observables to gauge hidden parameters
- nature of dark matter: annihilation signal vs. cosmic ray (CR) induced γ-rays
- 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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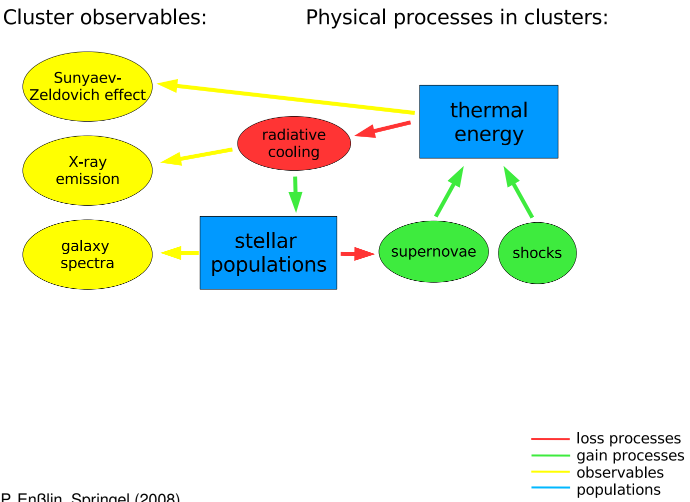
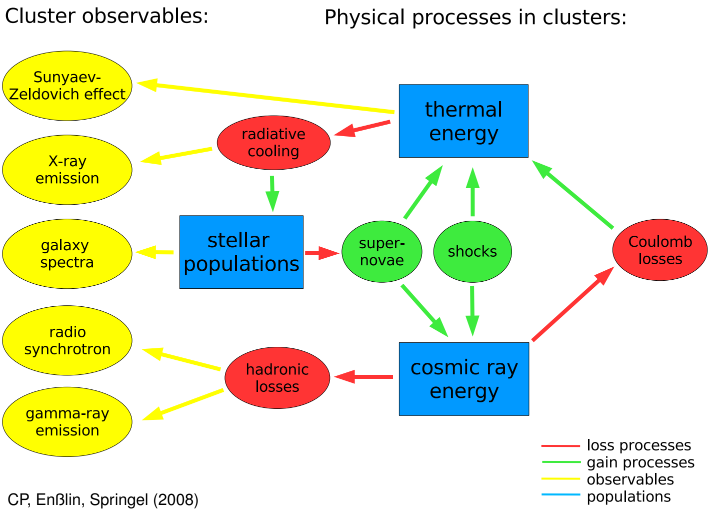
Radiative simulations – flowchart



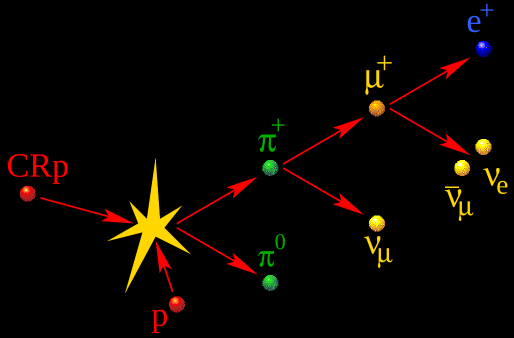
CP, Enßlin, Springel (2008)

Radiative simulations with cosmic ray (CR) physics



CP, Enßlin, Springel (2008)

Hadronic cosmic ray proton interaction



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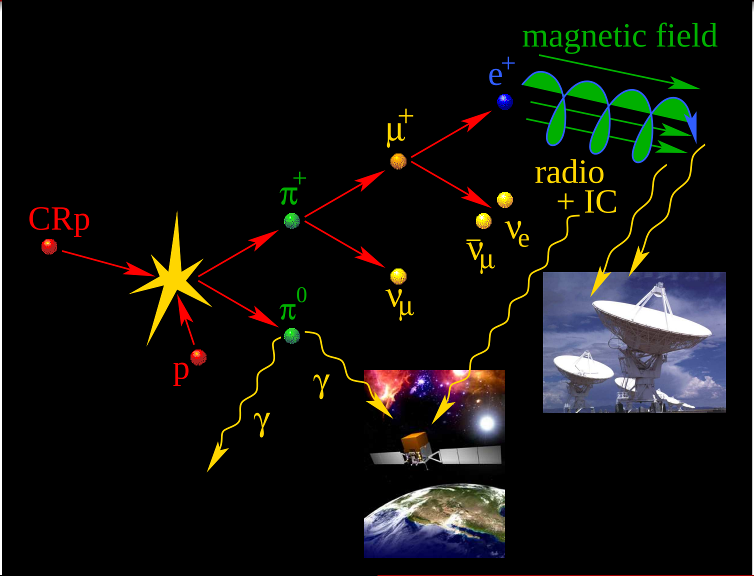

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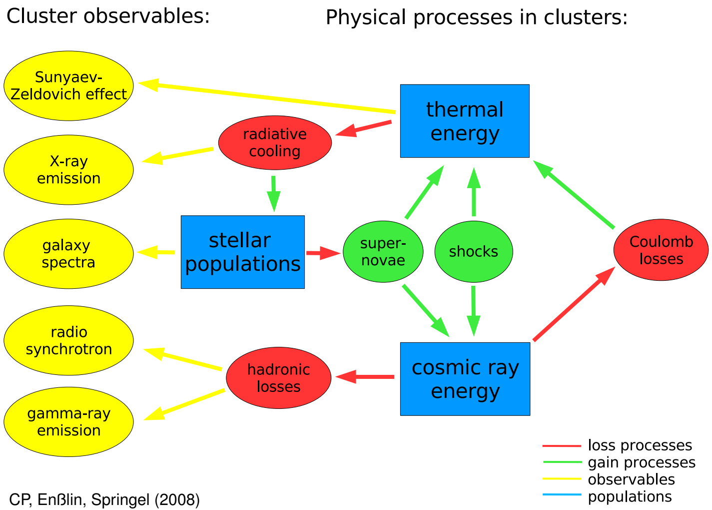
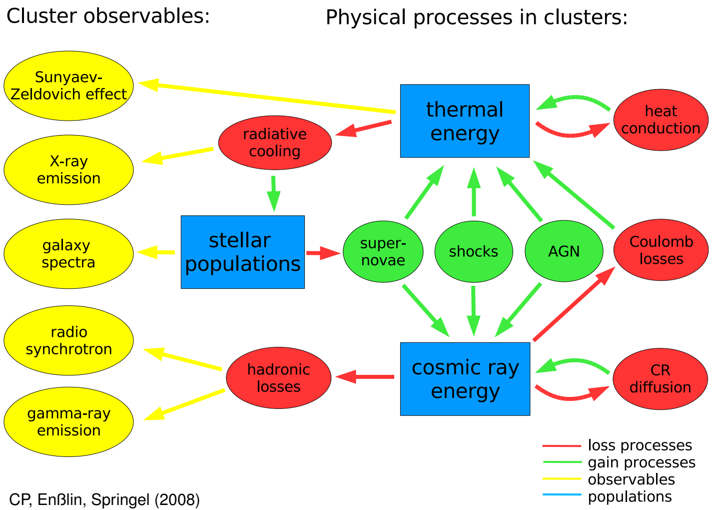


CP, Enßlin, Springel (2008)

Radiative simulations with extended CR physics



CP, Enßlin, Springel (2008)

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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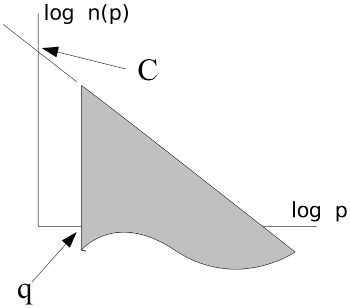
CR spectral description



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

Enßlin, CP, Springel, Jubelgas (2007)

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

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

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

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

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

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

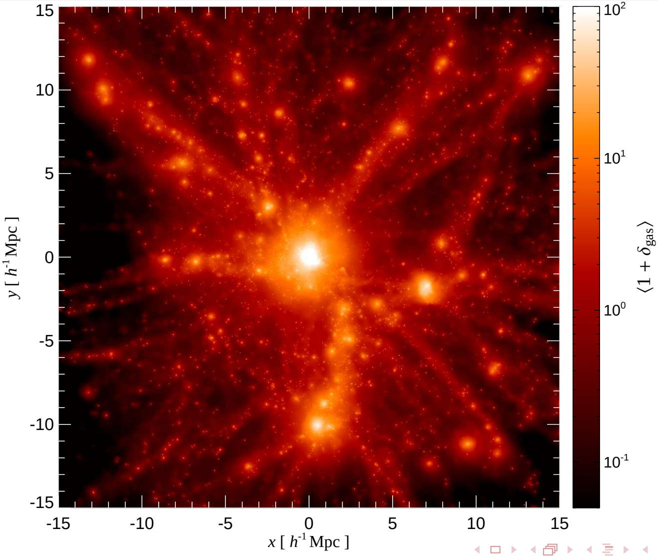
CR protons in clusters

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)

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

Radiative cool core cluster simulation: gas density



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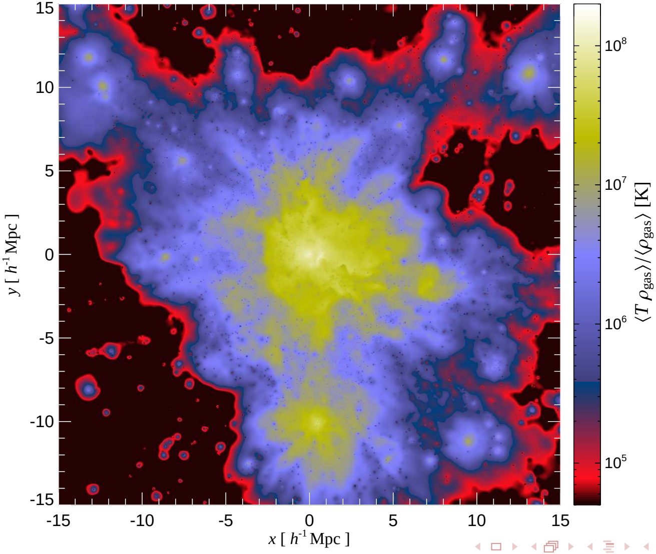
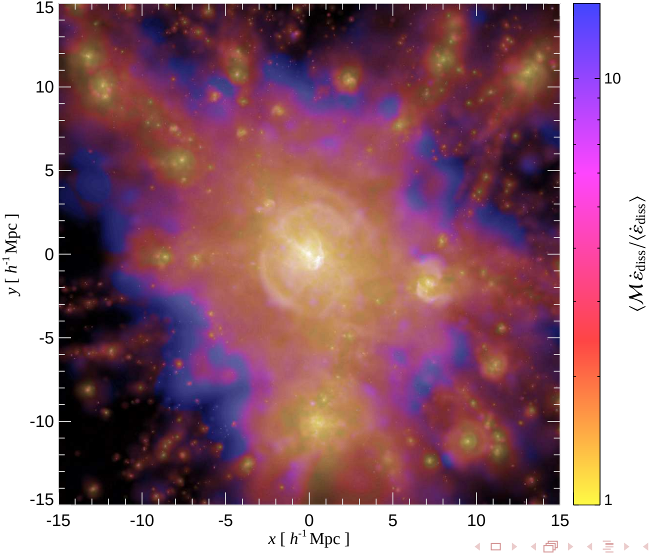
Mass weighted temperature



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 $\rightarrow$ 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

$\rightarrow$ power-law CR distribution

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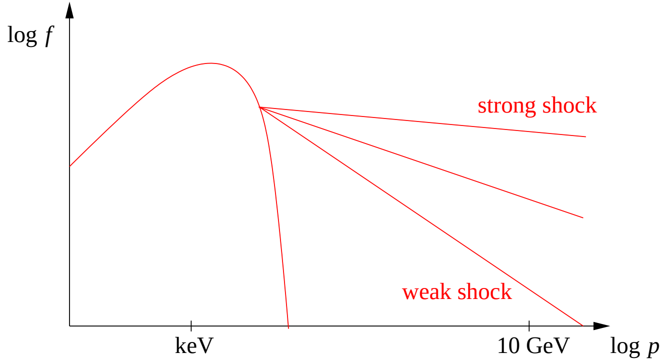
$\longrightarrow$ power-law CR distribution

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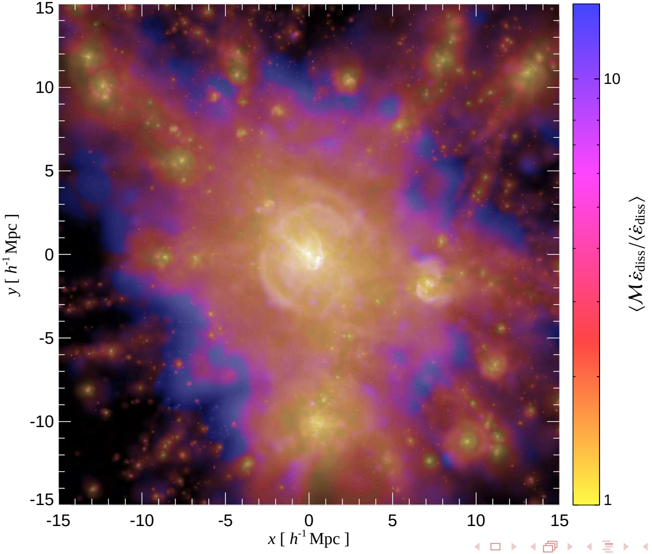
Mach number distribution weighted by $\varepsilon_{\rm diss}$



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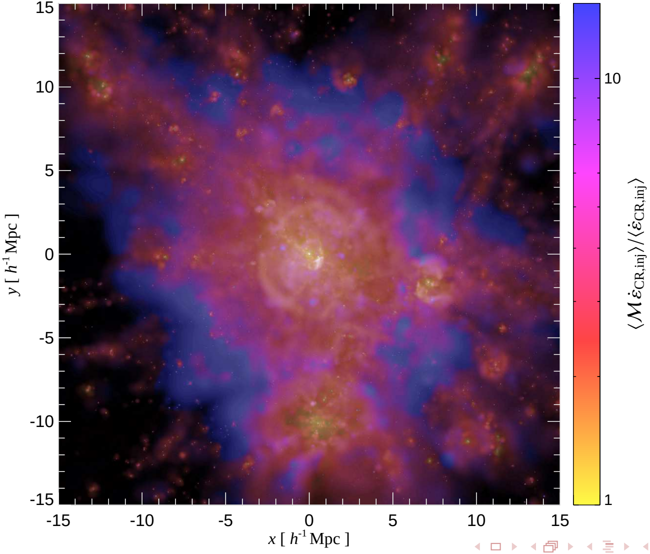
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$



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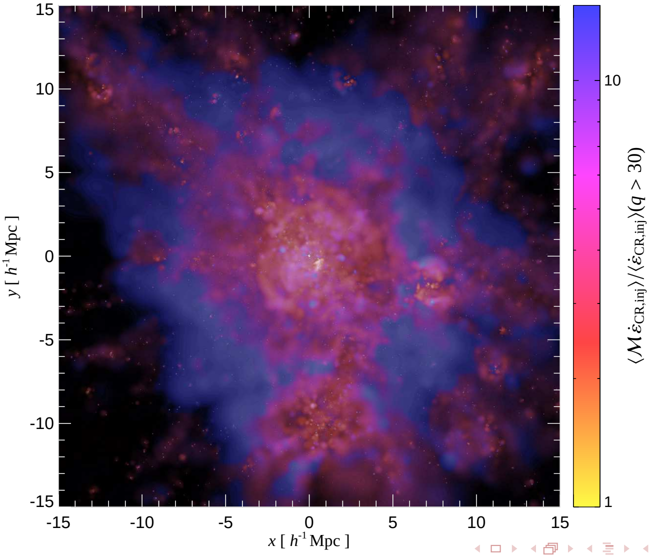
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}(q > 30)$



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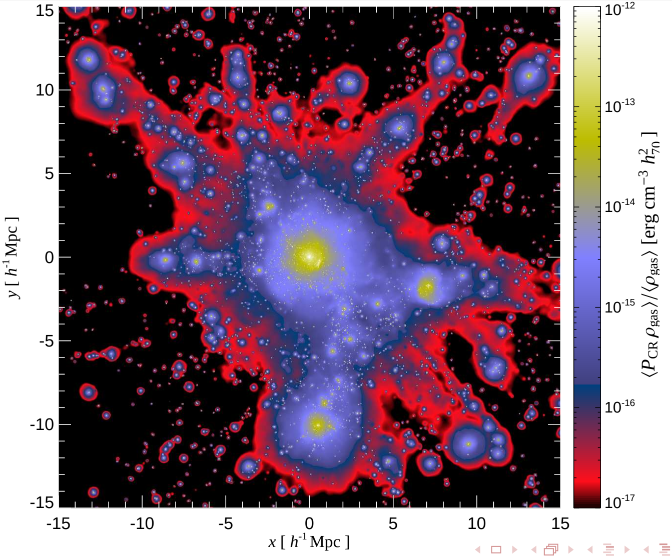
CR pressure P_{CR}



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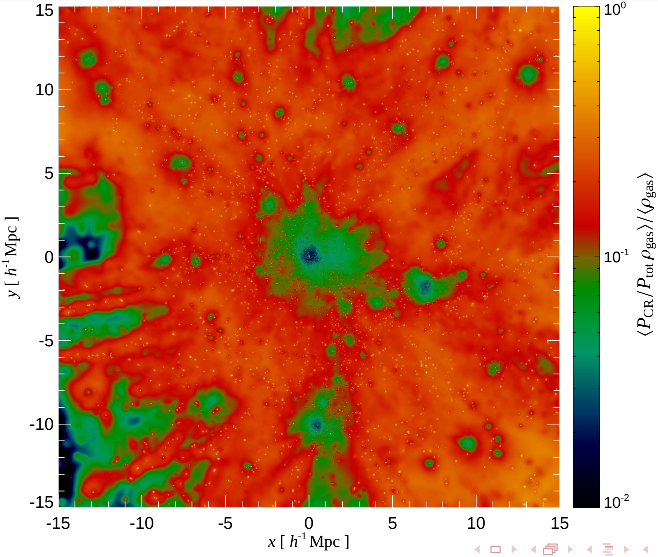
Relative CR pressure $P_{\rm CR}/P_{\rm total}$



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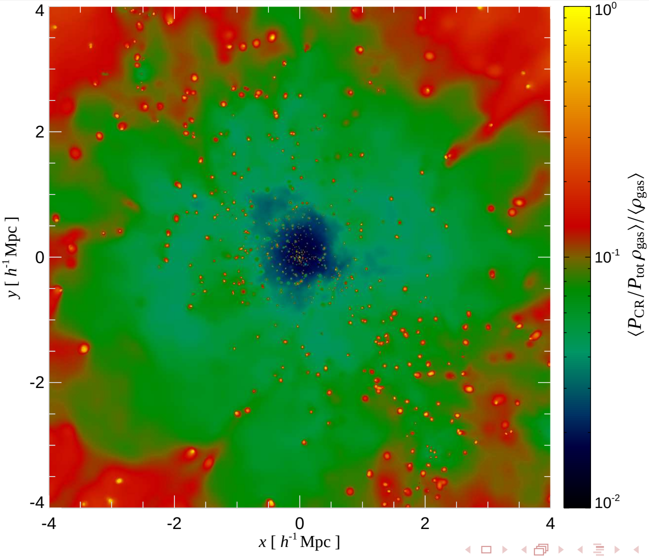
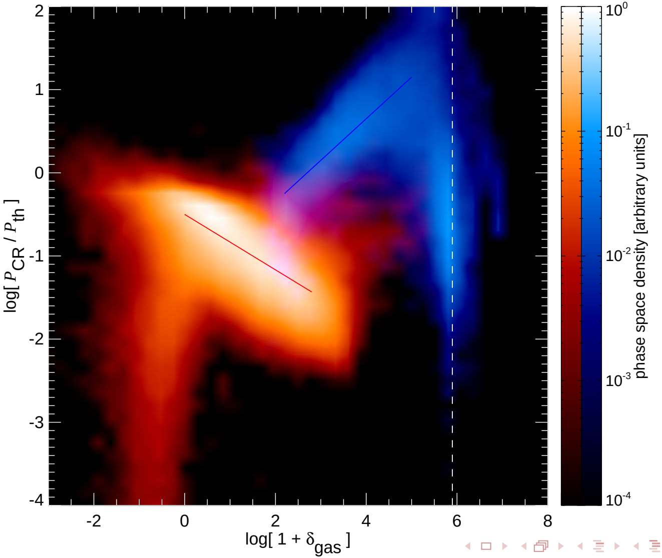


CR phase-space diagram: final distribution @ $z = 0$



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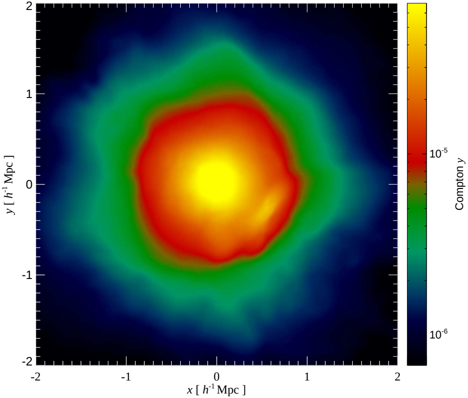
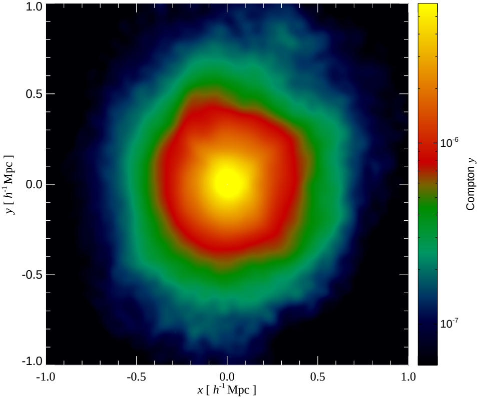
CR impact on SZ effect: Compton y parameter



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



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

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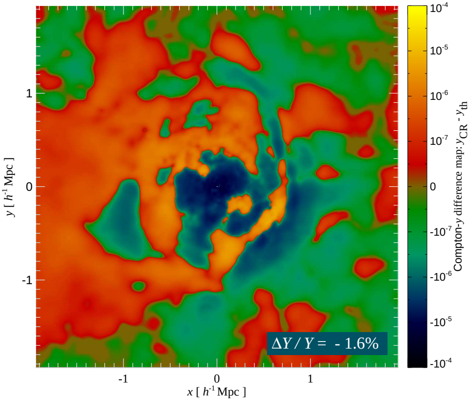
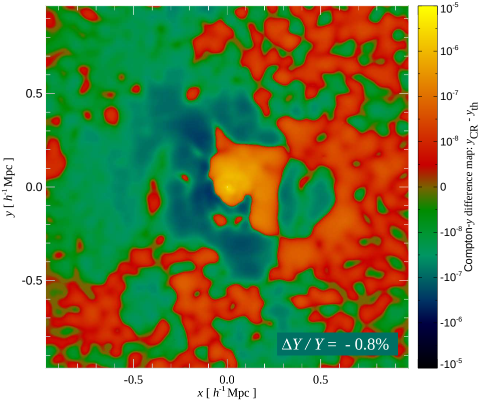
Compton y difference map: $y_{\rm CR} - y_{\rm th}$





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

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Outline

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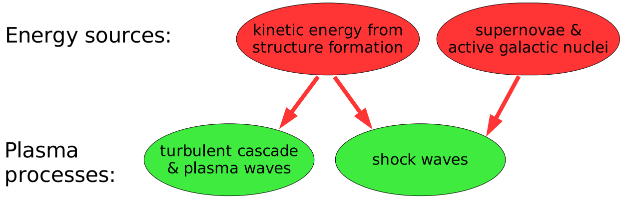
Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



Multi messenger approach for non-thermal processes

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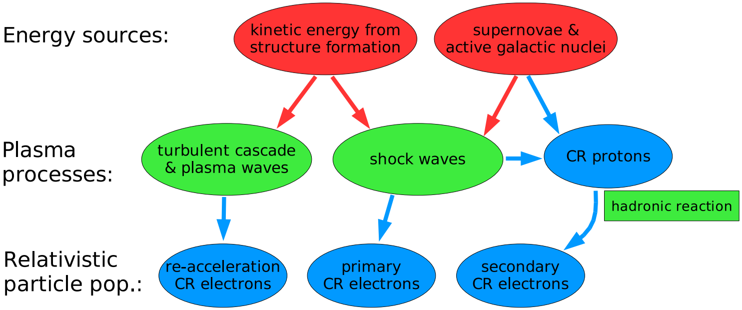

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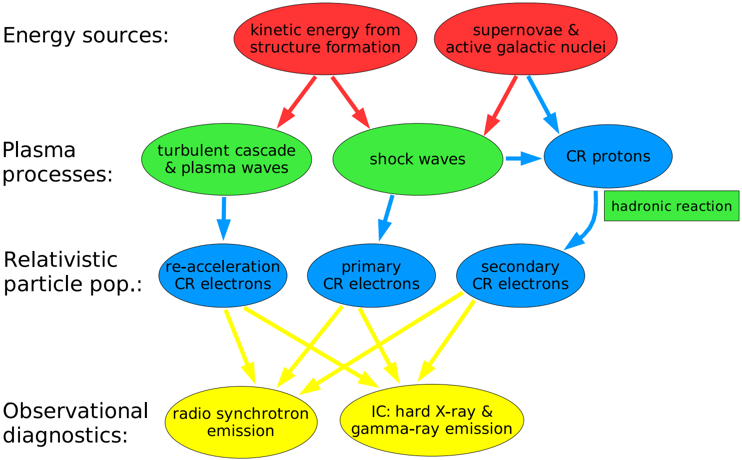

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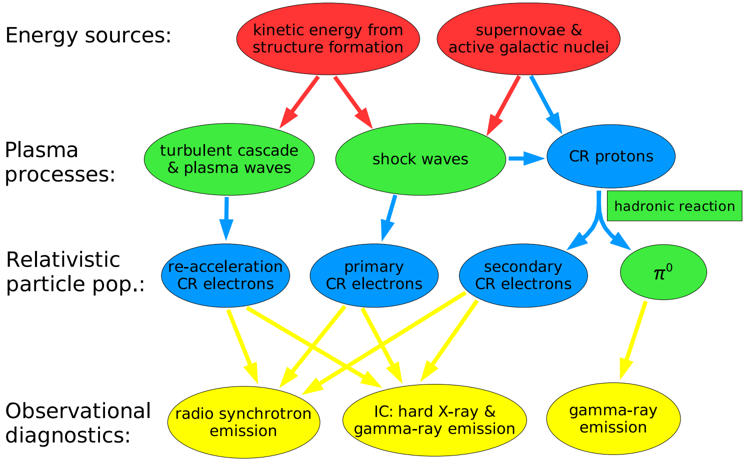
Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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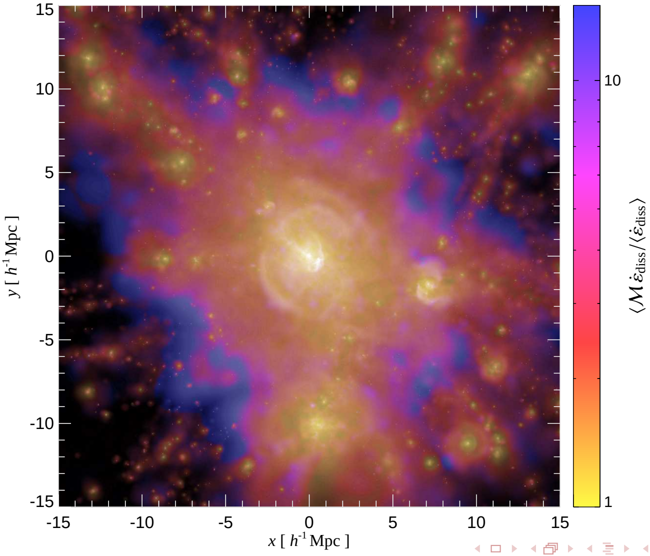
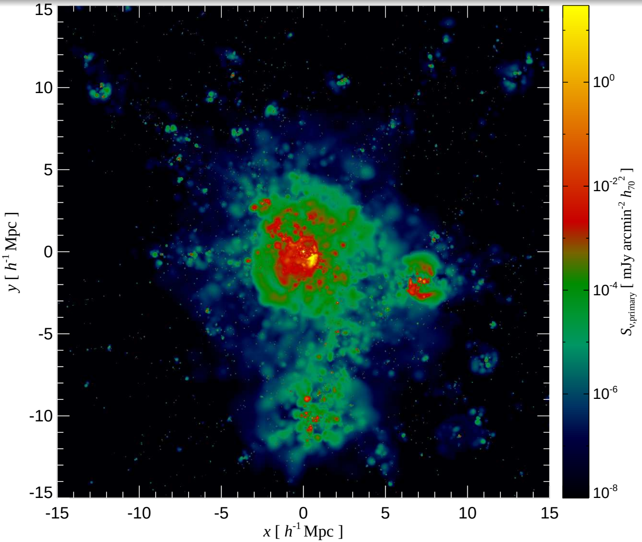
Cosmic web: Mach number



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



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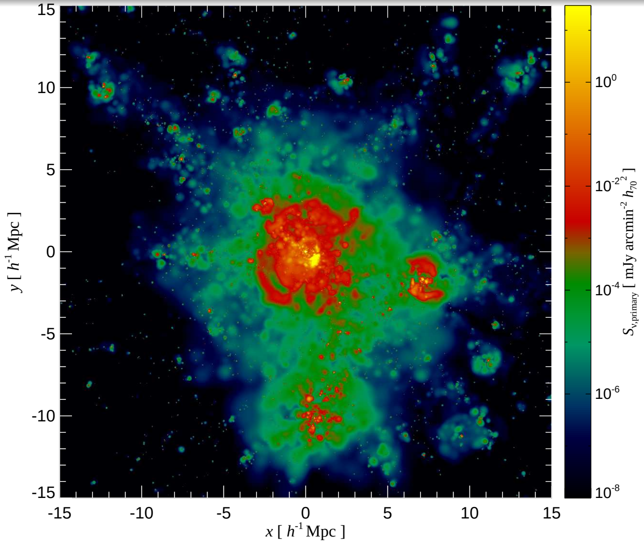
Radio gischt: primary CRe (150 MHz)



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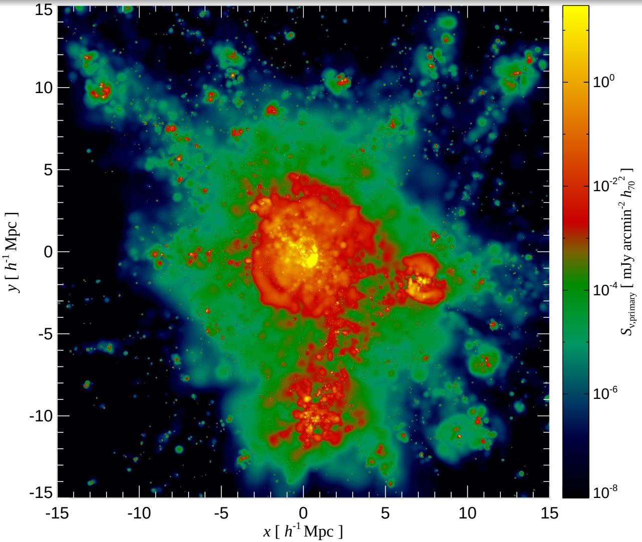
Radio gischt: primary CRe (15 MHz)



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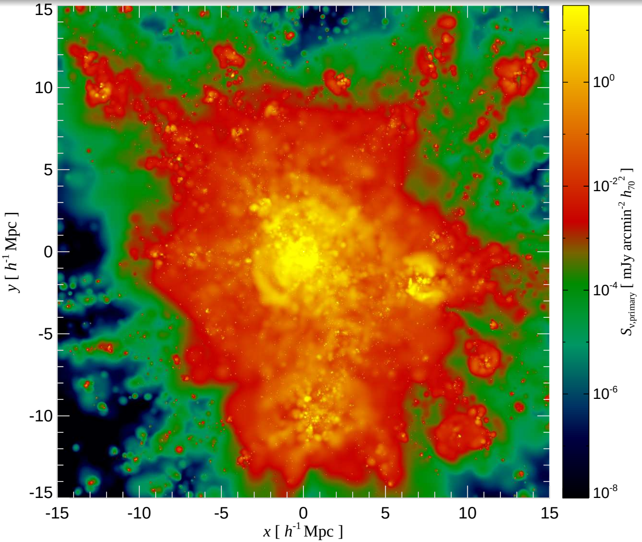
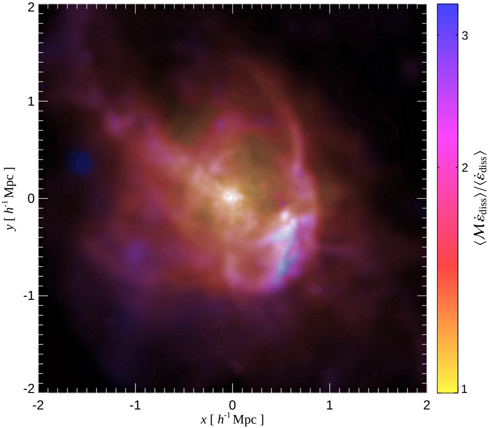
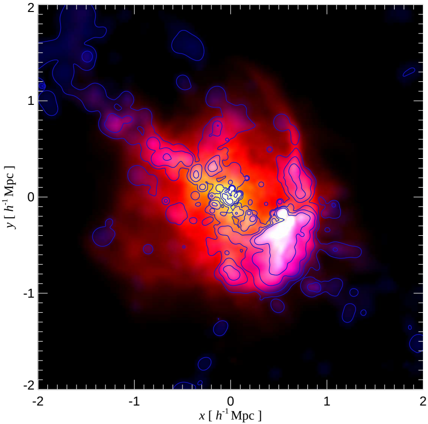
Radio gischt: primary CRe (15 MHz), slower magnetic decline



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

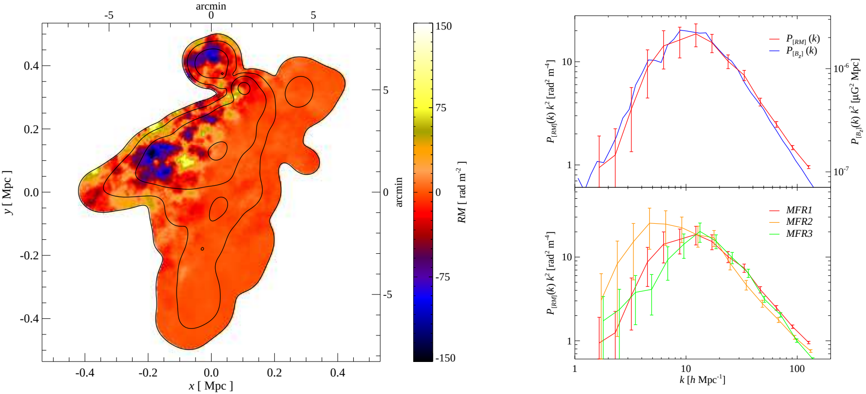
Battaglia, CP, Sievers, Bond, Enßlin (2008):

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.

Rotation measure (RM)

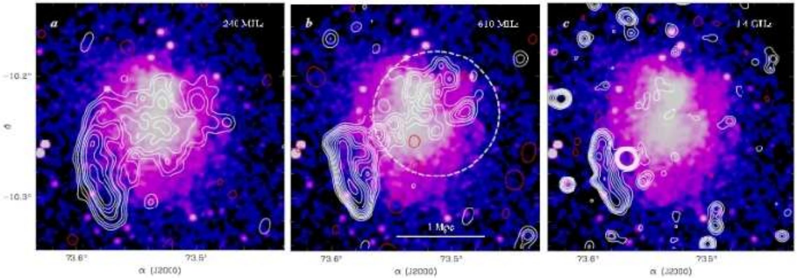
RM maps and power spectra have the potential to infer the magnetic pressure support and discriminate the nature of MHD turbulence in clusters:



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

Particle acceleration by turbulence or shocks?

Diffuse low-frequency radio emission in Abell 521 (Brunetti et al. 2008)

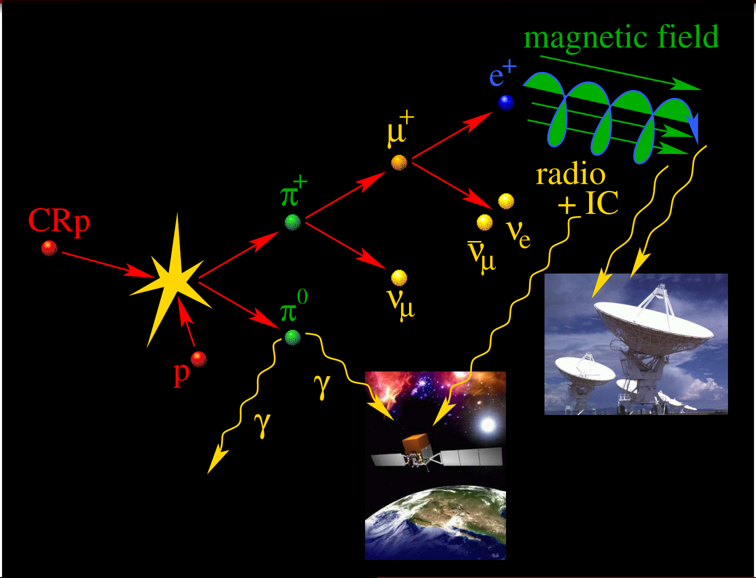


colors: thermal X-ray emission; contours: diffuse radio emission.

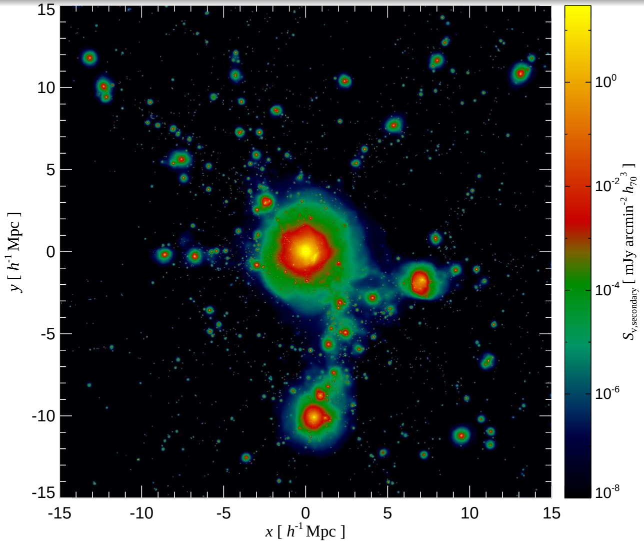
- "radio relic" interpretations with aged population of shock-accelerated electrons or shock-compressed radio ghosts (aged radio lobes),
- "radio halo" interpretation with re-acceleration of relativistic electrons through interactions with MHD turbulence.

→ synchrotron polarization is key to differentiate!

Hadronic cosmic ray proton interaction



Cluster radio emission by hadronically produced CRe



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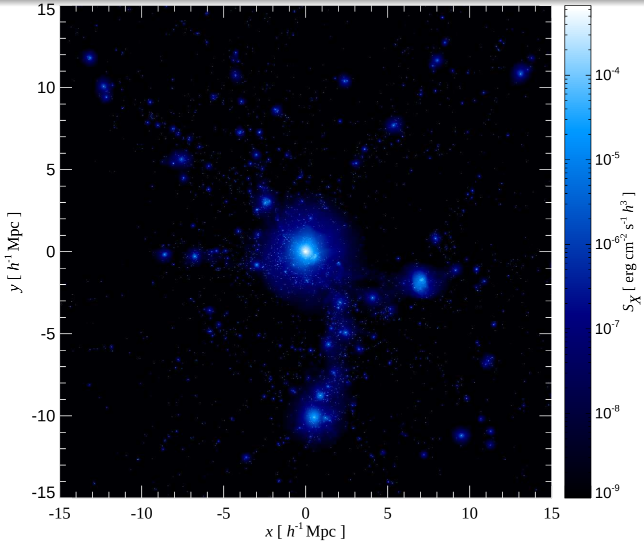
Thermal X-ray emission



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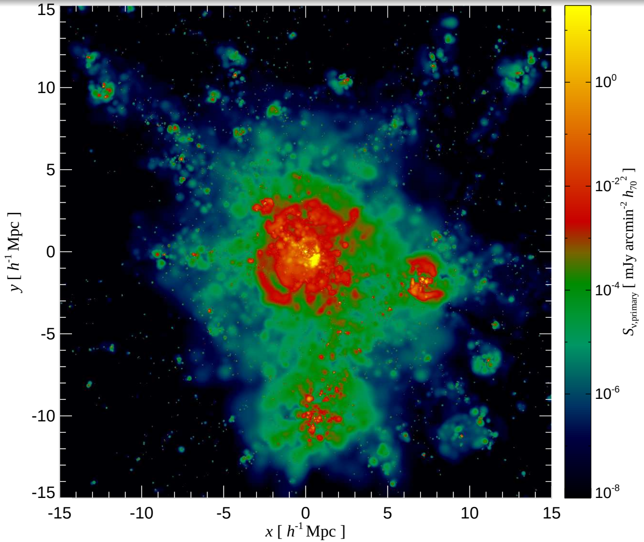
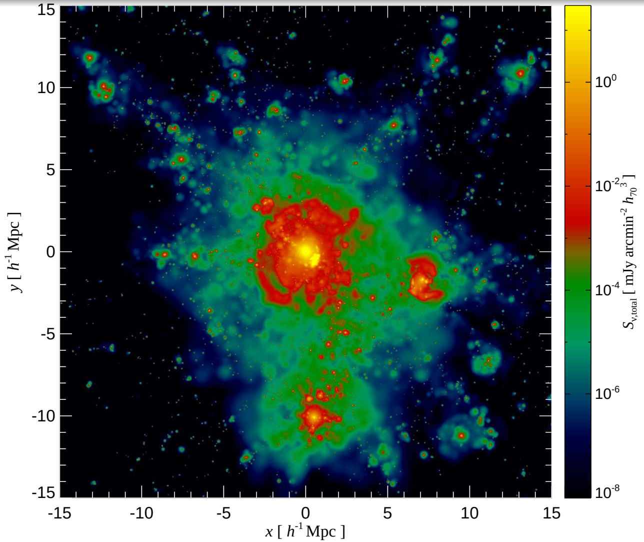
Radio gischt: primary CRe (150 MHz)



Radio gischt + central hadronic halo = giant radio halo



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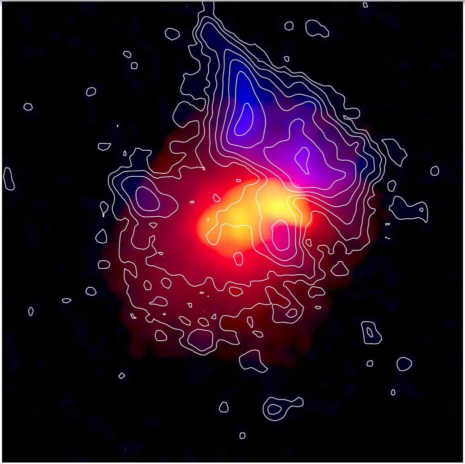
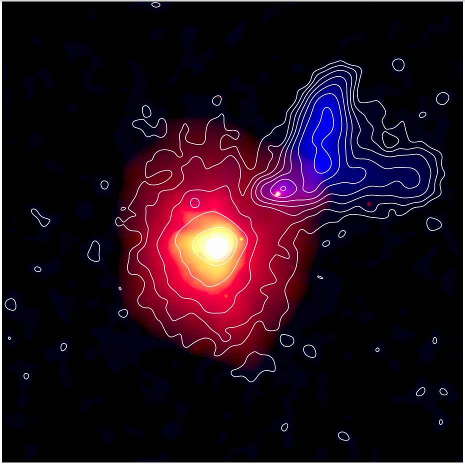
Which one is the simulation/observation of A2256?





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

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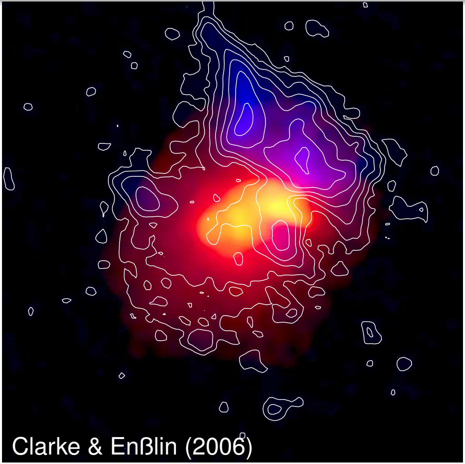
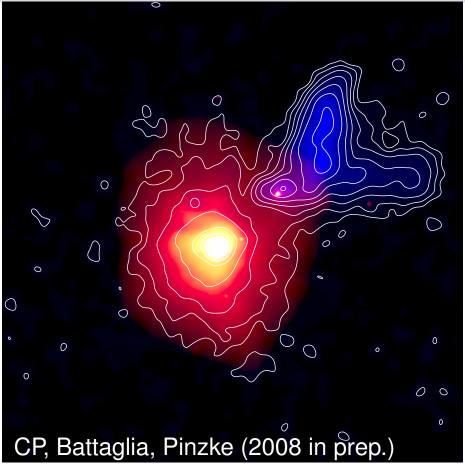
Observation – simulation of A2256





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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.

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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 $\rightarrow$ selection effect).
- Cluster experiences major merger: two leading shock waves are produced that become stronger as they break at the shallow peripheral cluster potential $\rightarrow$ 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 $\rightarrow$ 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?
$\rightarrow$ 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)

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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 $\rightarrow$ DM properties
3. probes plasma astrophysics such as macroscopic parameters for diffusive shock acceleration

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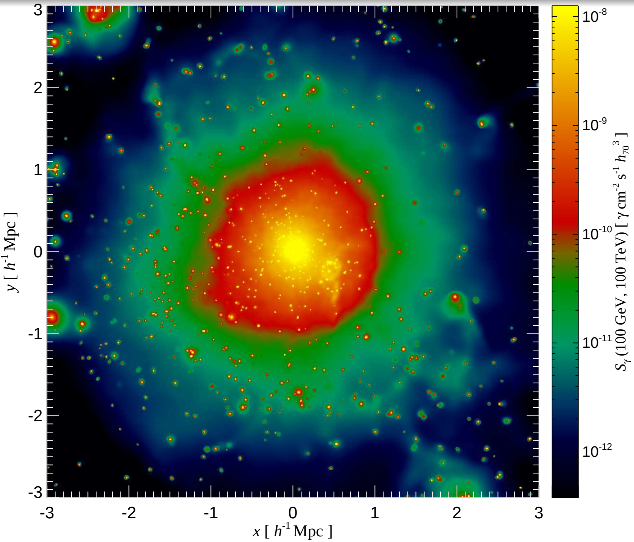
Hadronic γ-ray emission, $E_\gamma > 100$ GeV



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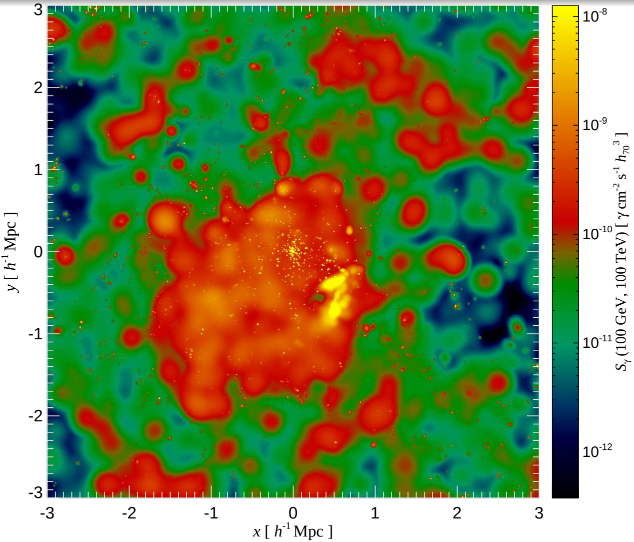
Inverse Compton emission, $E_{\rm IC} > 100$ GeV



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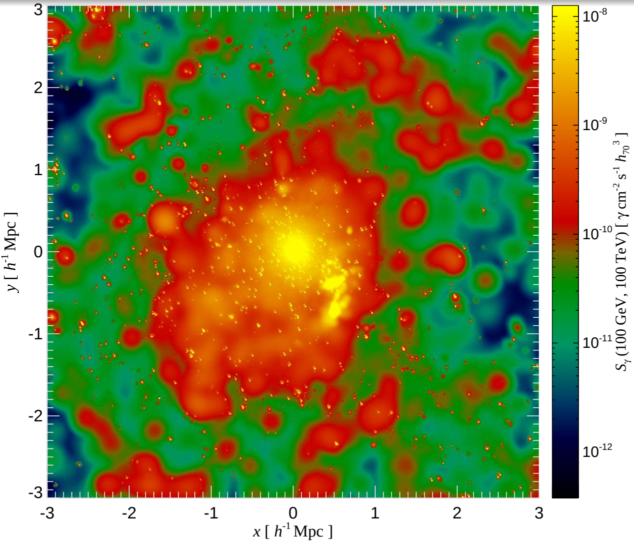
Total γ-ray emission, $E_\gamma > 100$ GeV



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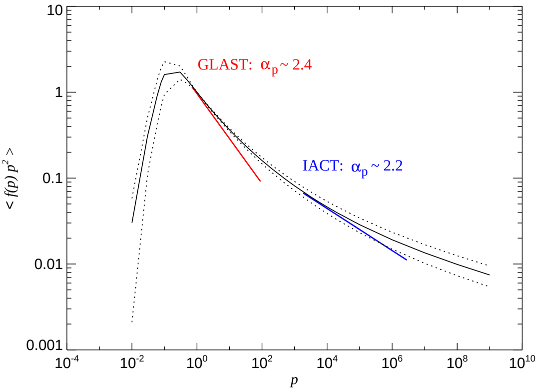
Universal CR spectrum in clusters



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

→ very promising for disentangling the dark matter annihilation signal!

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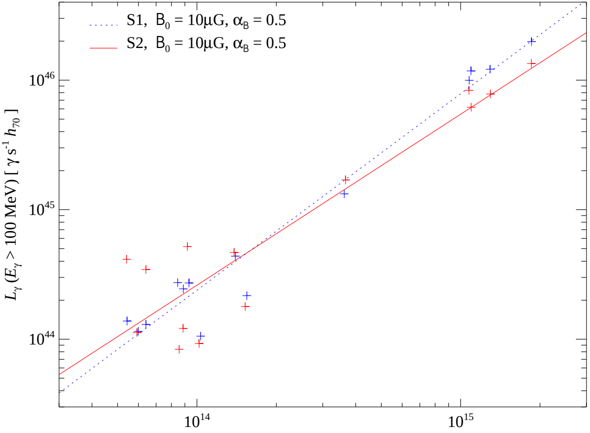
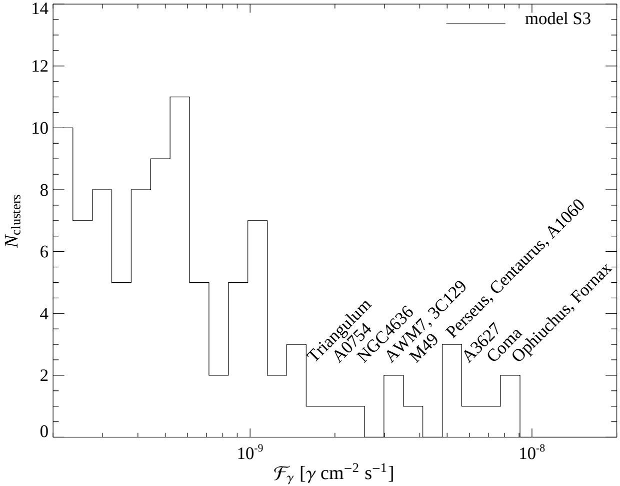
Gamma-ray scaling relations



Scaling relation + complete sample of the brightest X-ray clusters (extended HIFLUCGS) → predictions for *Fermi* (CP 2008)

Predicted cluster sample for *Fermi*



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Outline

1. Plasma processes in galaxy clusters
   - Cosmological galaxy cluster simulations
   - Shocks and particle acceleration
   - Cosmic ray transport and pressure distribution
2. Non-thermal emission from clusters
   - Radio emission by shocks and turbulence
   - Hadronically induced radio emission
   - High-energy γ-ray emission
3. Future perspectives and directions
   - Overview
   - Defining the questions
   - Conclusions

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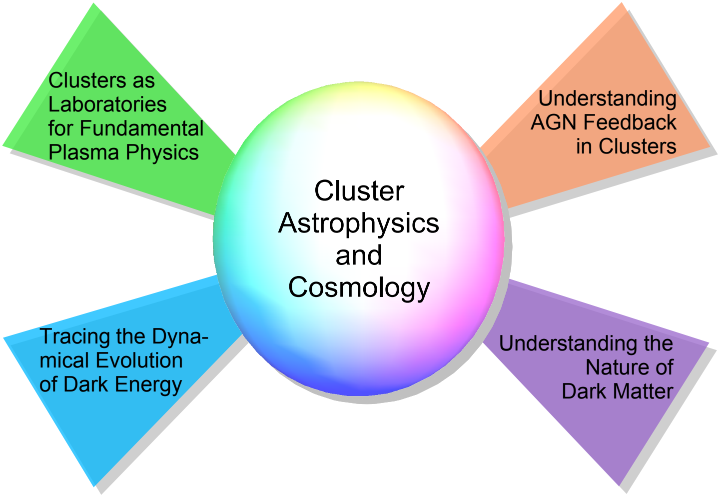
Future perspectives and directions



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Clusters as laboratories for plasma physics

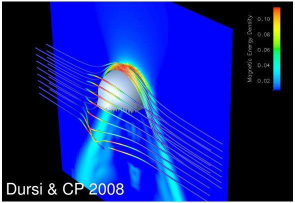
Opening up the radio and γ-ray window for the “non-thermal Universe”

- plasma processes (acceleration, turbulence, instabilities, anisotropic transport)
- cosmic rays (including ultra-high energy CRs)
- magnetic fields – origin, growth
- feedback processes (AGN, galaxies)

goal: connecting multi-frequency observables (LOFAR, Fermi) to high-resolution simulations → fundamental plasma astrophysics

large scales: cluster “cluster archeology”, cosmological surveys

small scales: solving riddles (cold fonts, bubble stability) → new effects (magnetic draping)



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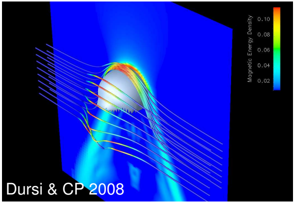
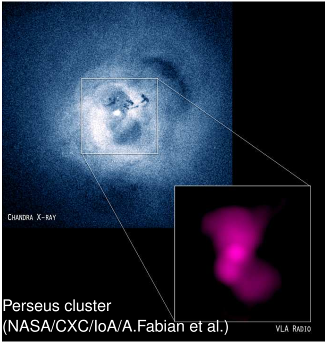


Understanding AGN feedback in clusters

The intertwined lives of supermassive black holes and cluster cores

1. AGN accretion, jet launch, bubble formation: magnetic fields, cosmic rays, and turbulence play crucial role
2. heating mechanism: cavity heating through releasing potential energy, weak shocks, sound damping, . . .
   (McNamara & Nulsen 2007)
3. cosmological impact: role in galaxy and cluster evolution



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

→ understanding both the detailed plasma physics and the statistical properties of the AGN feedback in the cosmological context

→ high-performance simulations of the involved physics and new observational strategies will elucidate the properties of the interaction

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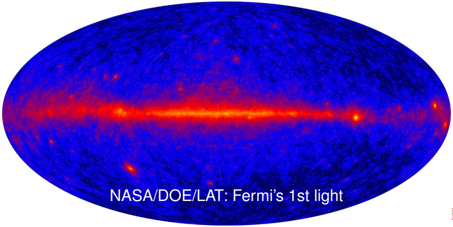
Understanding the nature of dark matter

Unveiling dark matter annihilation in the presence of astrophysical foregrounds

- disentangling the γ-ray emission resulting from dark matter annihilation from the cosmic ray induced signal
- electrons/positrons from dark matter annihilations vs. CR interactions: modified synchrotron emission characteristic; different particle spectra observed on Earth

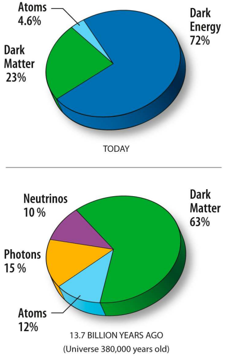
$\rightarrow$ self-consistent cosmic ray simulations (galaxy clusters, the Galaxy) and modeling of spectral and spatial emission characteristics necessary to discover the properties of dark matter


NASA/DOE/LAT: Fermi's 1st light

Tracing the dynamical evolution of dark energy

Joint analysis of simulated cluster surveys

- accelerated expansion of the Universe caused by either a cosmological fluid (scalar field, vacuum energy) or by modification of General Relativity for small curvature
- this causes modified evolution of the signal from cosmological standard candles (SNe) / yard sticks (baryon acoustic oscillations) or a different growth of structure (weak lensing, cluster surveys) → complementary probes of precision cosmology



(NASA/WMAP Science Team)

→ study of the influence of different physical processes on hydrodynamical cluster structure and survey observables (X-ray, Sunyaev-Zel'dovich, lensing, radio) in large cosmological simulations

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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!

1. Cosmological hydrodynamical simulations are indispensable for understanding non-thermal processes in galaxy clusters $\rightarrow$ illuminating the process of structure formation
2. Multi-messenger approach including radio synchrotron, hard X-ray IC, and HE γ-ray emission:
   - fundamental plasma physics: diffusive shock acceleration, large scale magnetic fields, and turbulence
   - nature of dark matter
   - gold sample of clusters for precision cosmology

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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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