The quest for high-energy gamma-ray emission from galaxy clusters

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in collaboration with

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Outline

1. Cosmic rays in galaxy clusters
   - Introduction and motivation
   - Cosmological galaxy cluster simulations
   - Shocks, particle acceleration, and transport
2. Diffuse radio emission in clusters
   - Non-thermal processes in clusters
   - Radio emission by shocks and turbulence
   - Hadronically induced radio emission
3. High-energy γ-ray emission
   - Morphology and spectra
   - Predictions for Fermi and MAGIC
   - Conclusions

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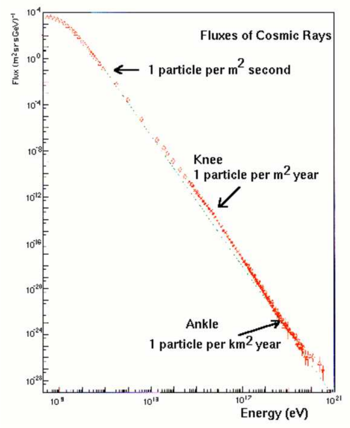
Galactic cosmic ray spectrum



data compiled by Swordy

Galactic CR all particle spectrum:

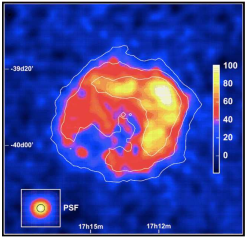
- spans $\sim$ 40 decades in flux when accounting for solar modulation that blocks low energy CRs
- ranges 12 decades in energy
- “knee” indicates characteristic maximum energy of galactic accelerators
- CRs beyond the “ankle” have extra-galactic origin

Supernova remnants

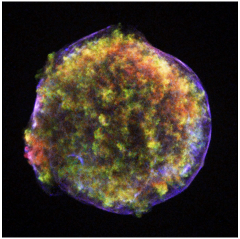
Properties of supernova remnants:

- Non-relativistic collisionless shocks ($\sim 10^3$ km/s)
- Class of young SNRs emitting synchrotron X-rays: direct evidence of electron acceleration to 50-100 TeV (Slane et al. 1999, 2001; Vink et al. 2006)
- 100 GeV-TeV emission (HESS sources): hadronic or IC leptonic?
- Cosmic ray protons modify shock dynamics – SNRs probably accelerate CRs; B field amplification (e.g. Vink & Laming 2003, Uchiyama et al. 2007)

SN 1006 X-rays (CXC/Hughes)



G347.3 HESS TeV
(Aharonian et al. 2006)



Tycho X-rays (CXC)

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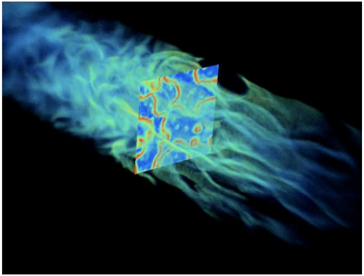
Collisionless shocks

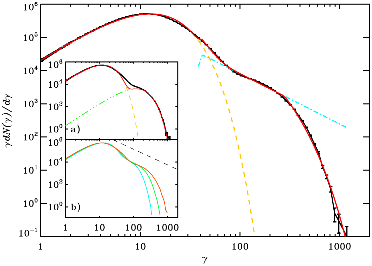
Astrophysical collisionless shocks can:

- accelerate particles
- amplify magnetic fields (or generate them from scratch)
- exchange energy between electrons and ions

Particle-in-cell simulations of unmagnetized, relativistic pair shocks that are mediated by the Weibel instability (Spitkovsky 2008)



magnetic energy density (Spitkovsky 2008)



post-shock Maxwellian and accelerated CR power-law

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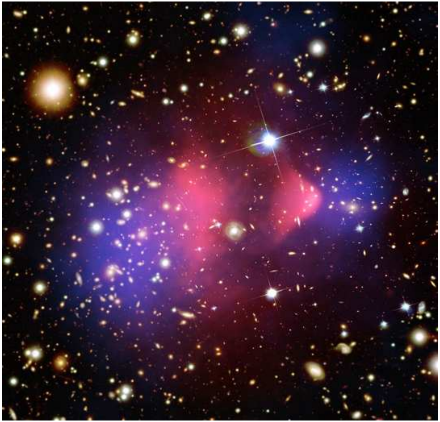
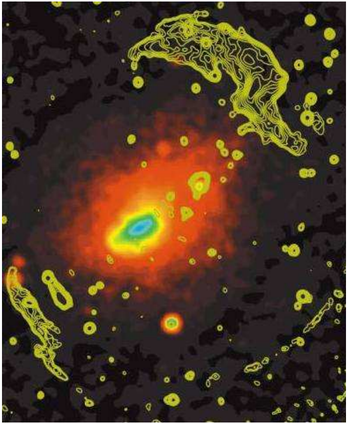
Shocks in galaxy clusters



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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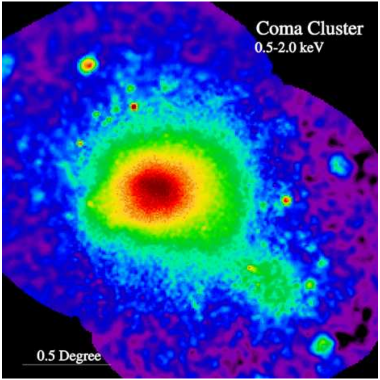
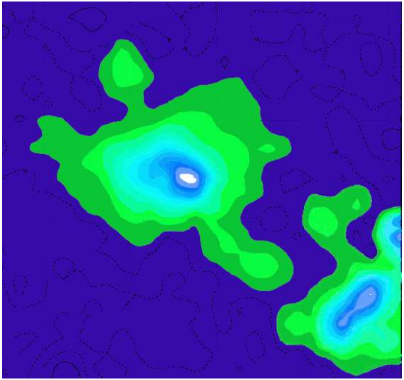
Giant radio halo in the Coma cluster



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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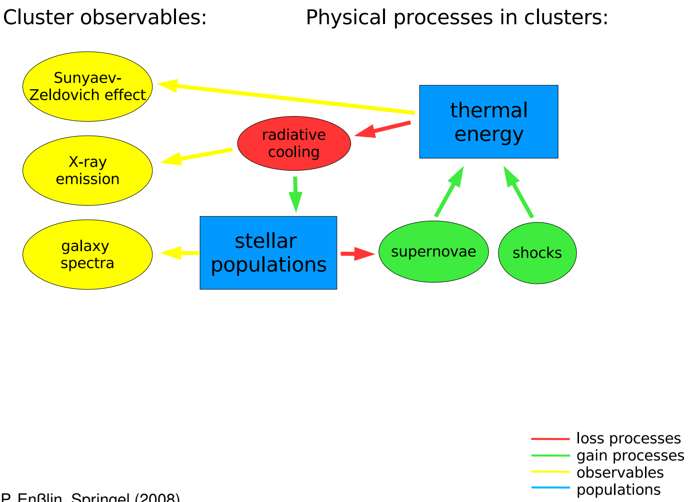
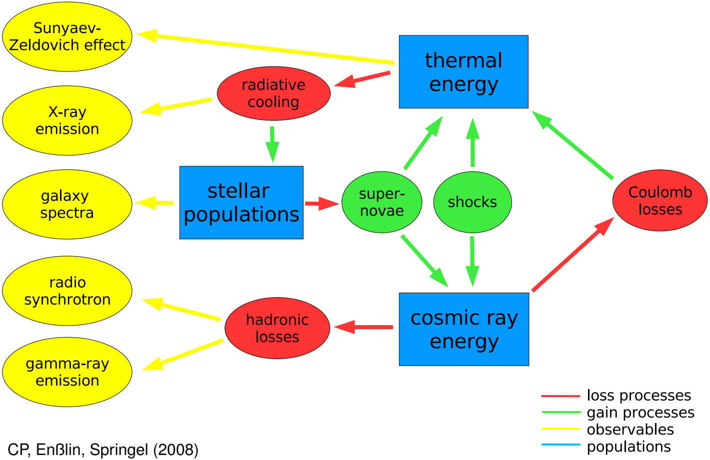
Radiative simulations – flowchart



CP, Enßlin, Springel (2008)

Radiative simulations with cosmic ray (CR) physics

Cluster observables: Physical processes in clusters:



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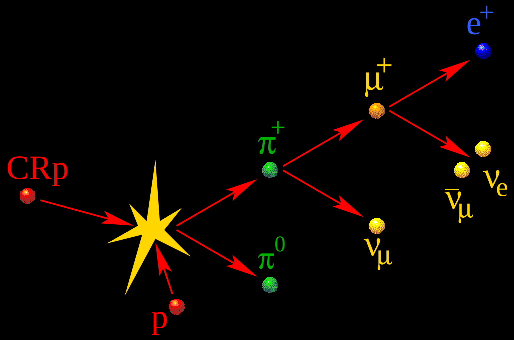
Hadronic cosmic ray proton interaction



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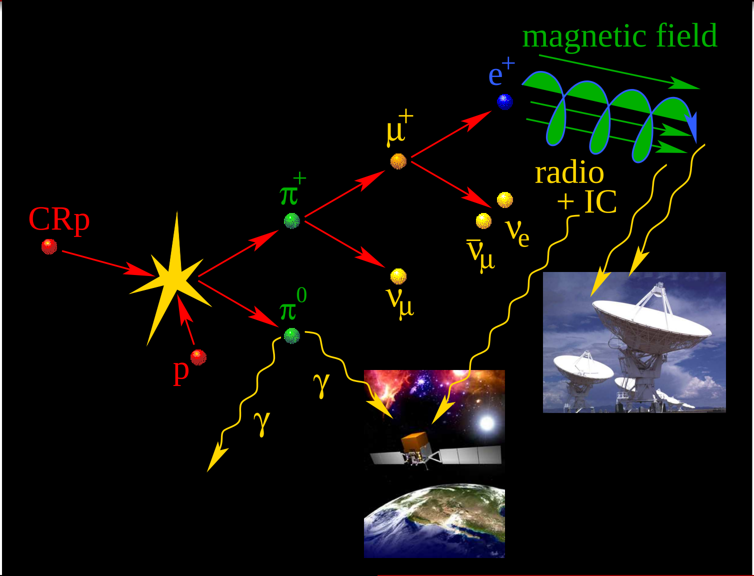

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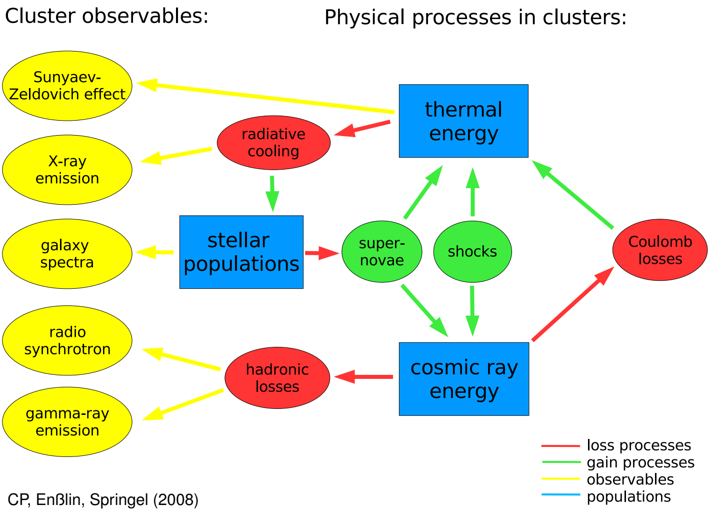
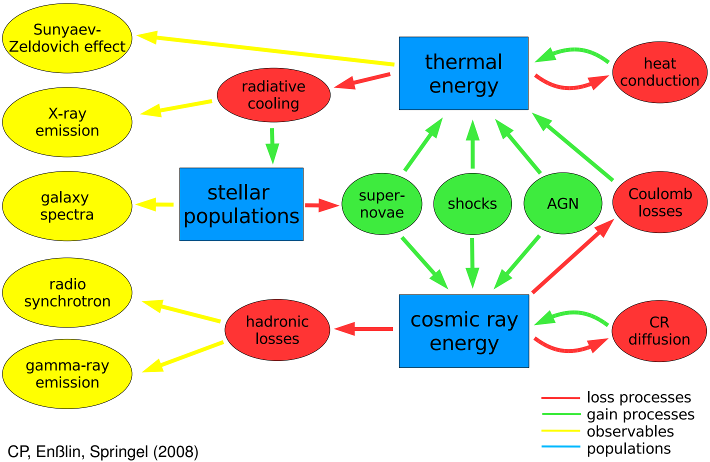


CP, Enßlin, Springel (2008)

Radiative simulations with extended CR physics

Cluster observables: Physical processes in clusters:



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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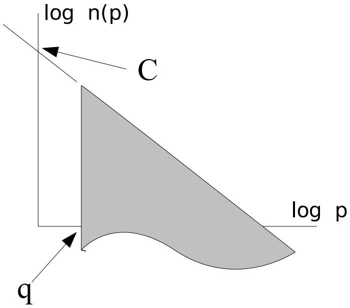
CR spectral description



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

Enßlin, CP, Springel, Jubelgas (2007)

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

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

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

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

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

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

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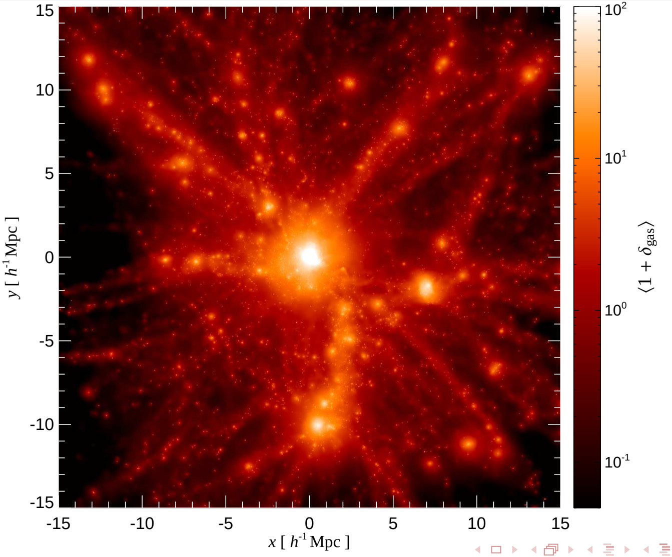
CR protons in clusters

relativistic proton populations can often be expected, since

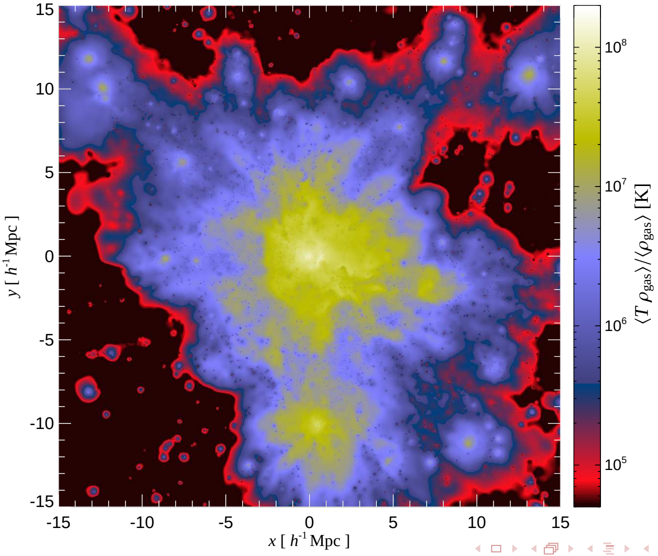
- acceleration mechanisms work for protons ...
  - ...as efficient as for electrons (adiabatic compression) or
  - ...more efficient than for electrons (DSA, stochastic acc.)
- galactic CR protons are observed to have 100 times higher energy density than electrons
- CR protons are very inert against 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



Mass weighted temperature



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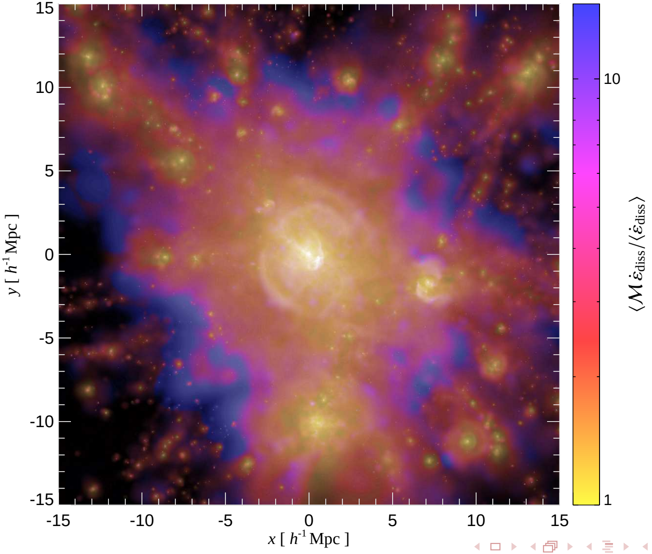
Mach number distribution weighted by $\varepsilon_{\rm diss}$



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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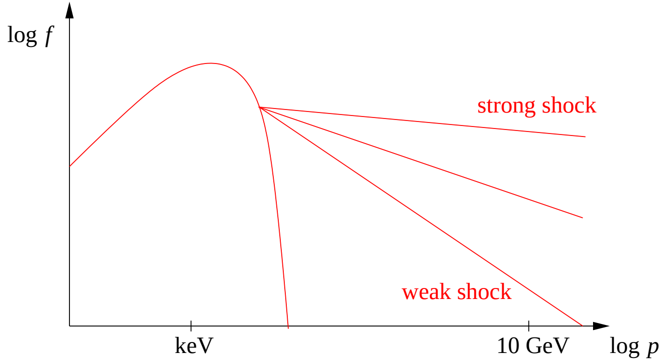
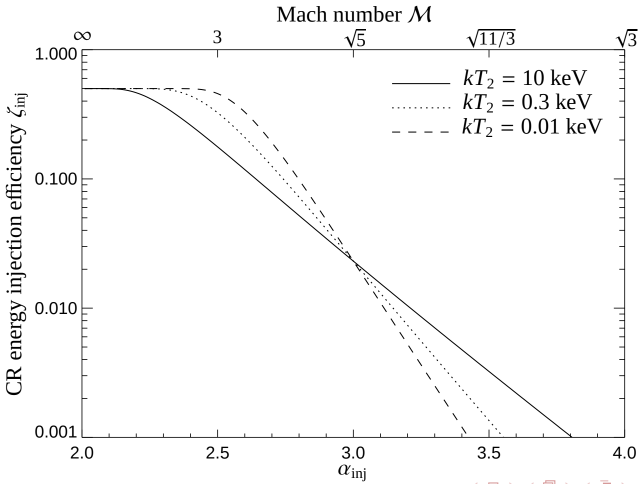
Diffusive shock acceleration – Fermi 1 mechanism (2)

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

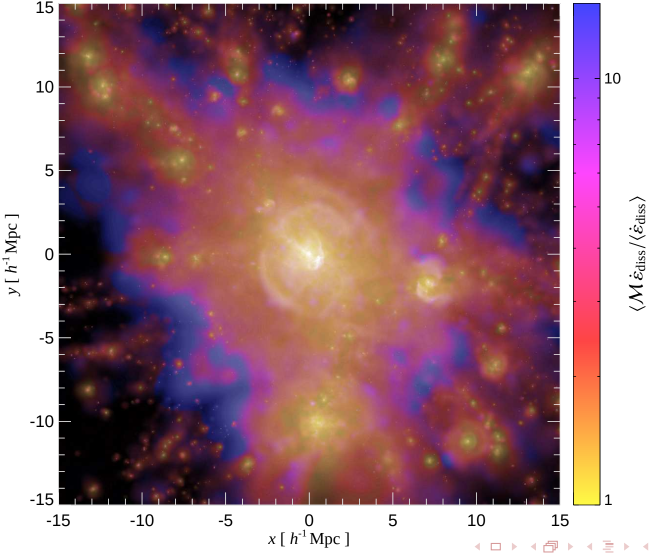


Diffusive shock acceleration – efficiency (3)

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



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



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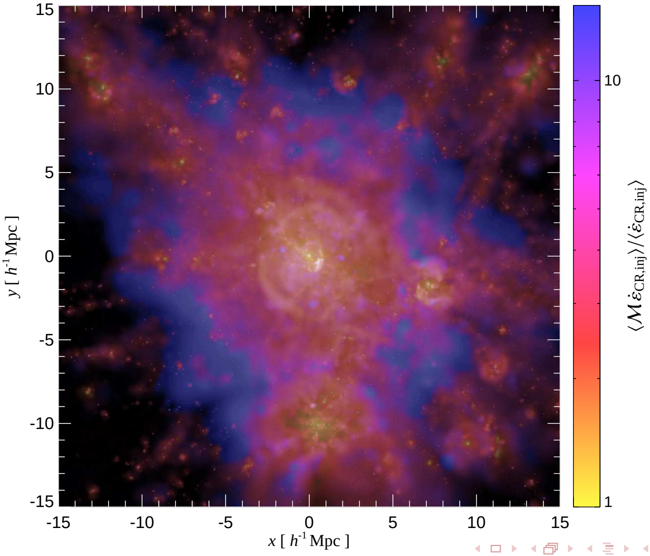
Mach number distribution weighted by $\varepsilon_{\rm CR,inj}$



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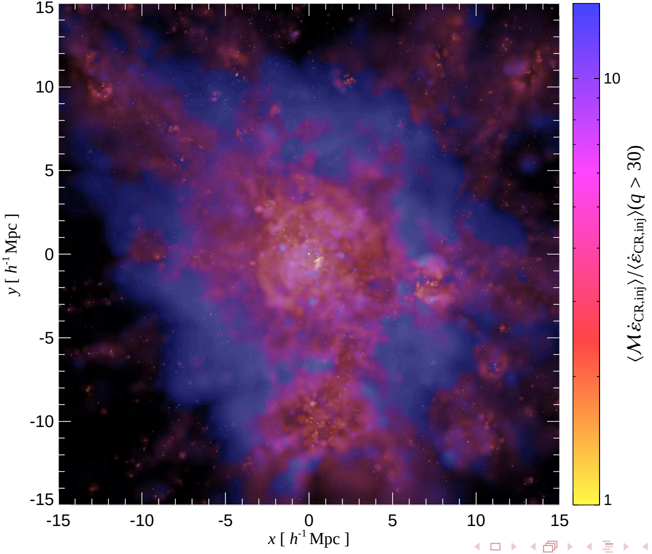
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}(q > 30)$



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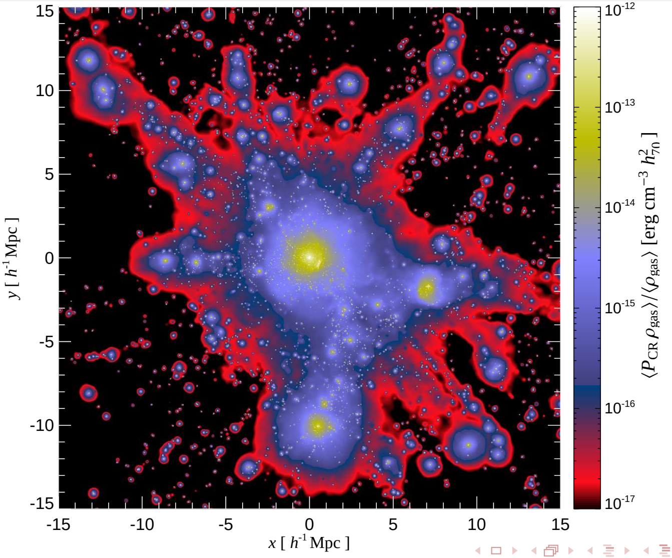
CR pressure P_{CR}



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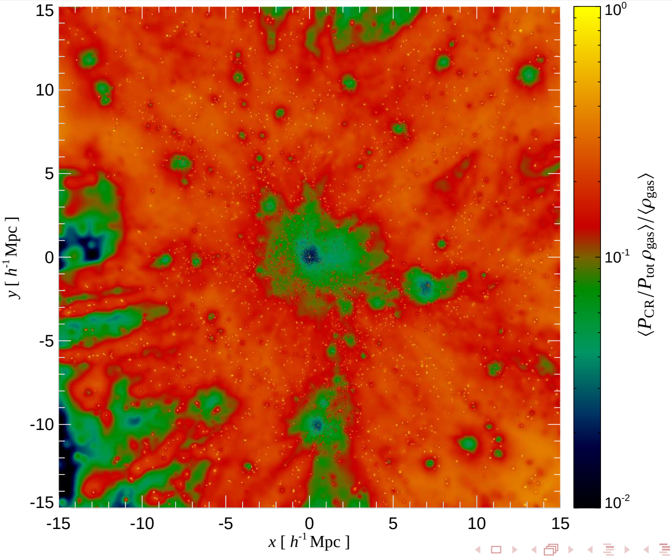
Relative CR pressure P_{CR}/P_{total}



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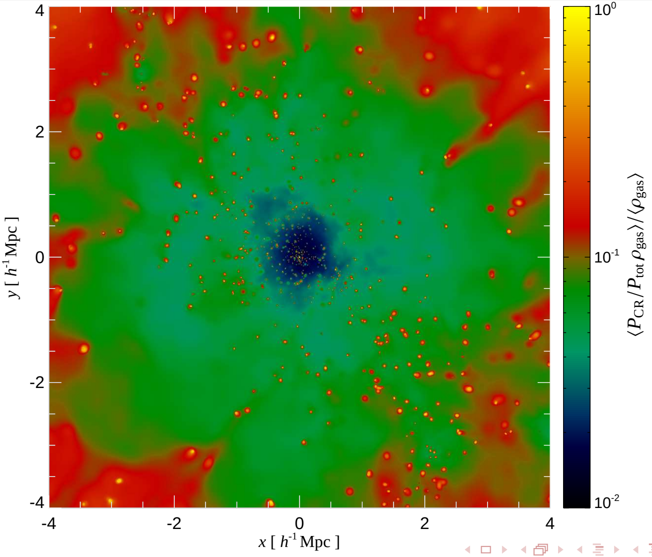
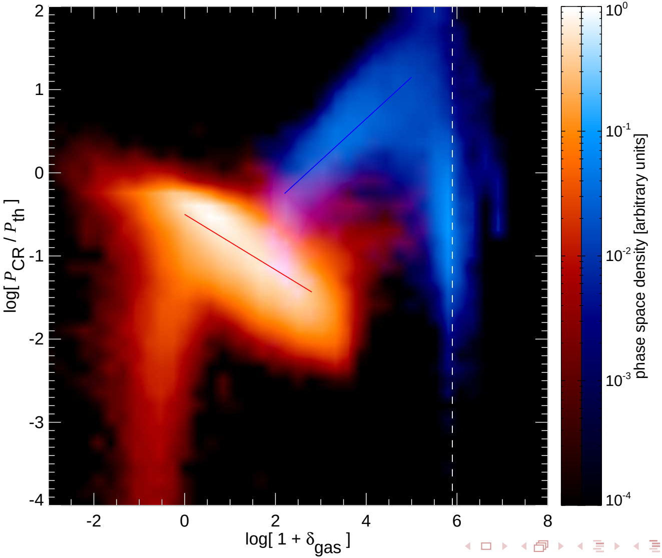


CR phase-space diagram: final distribution @ $z = 0$



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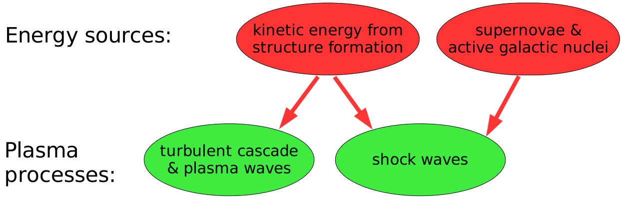
Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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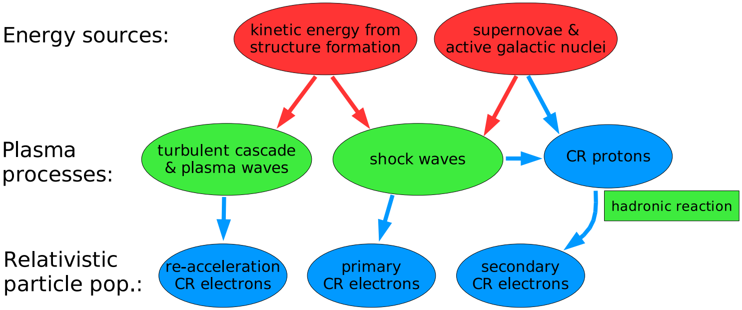

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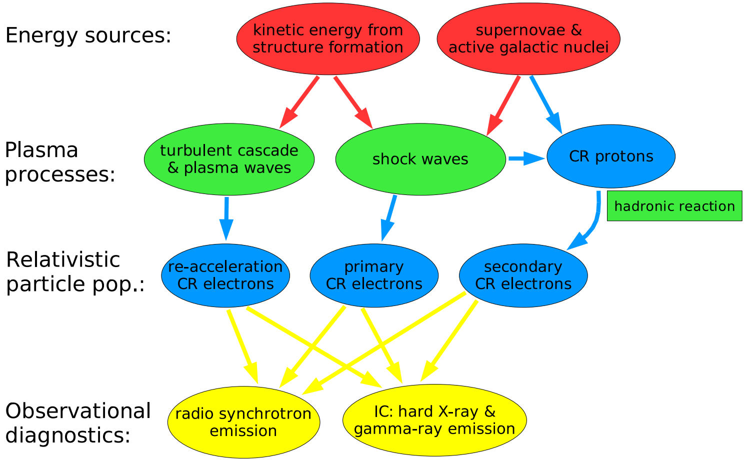

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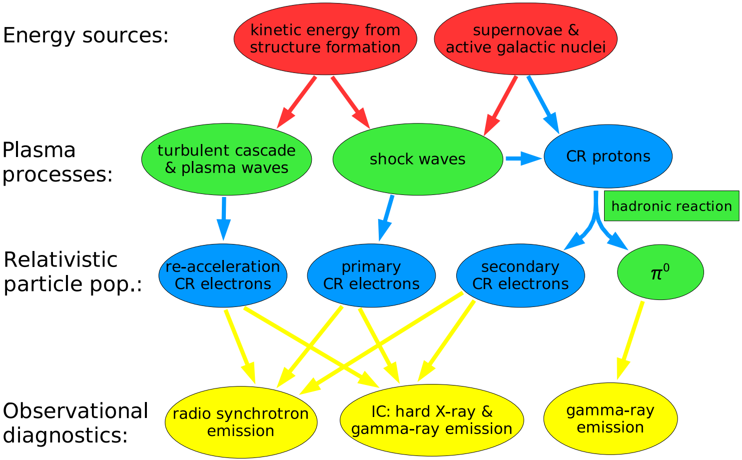
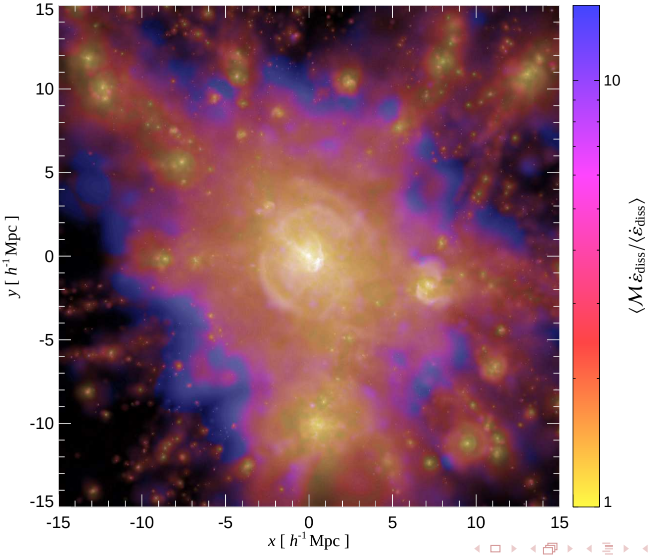


Cosmic web: Mach number



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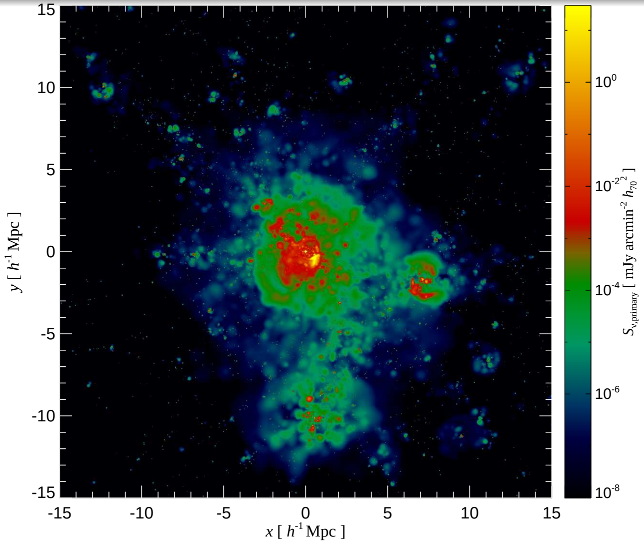
Radio gischt (relics): primary CRe (1.4 GHz)



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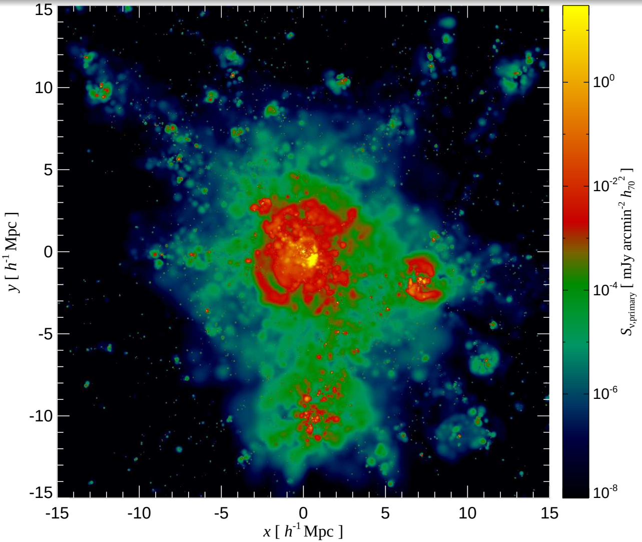
Radio gischt: primary CRe (150 MHz)



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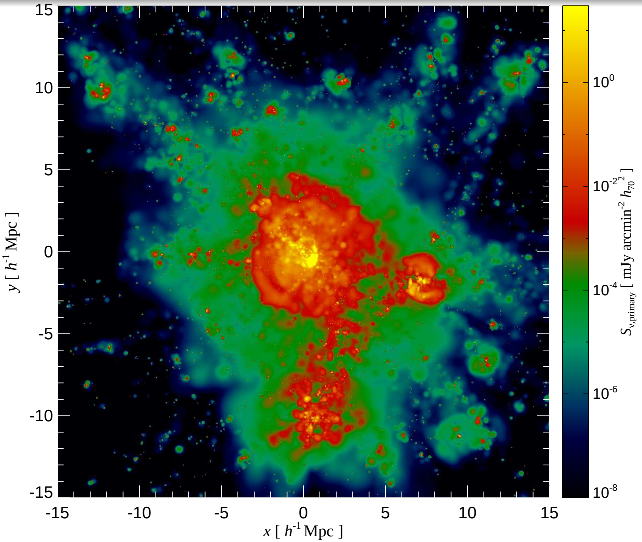
Radio gischt: primary CRe (15 MHz)



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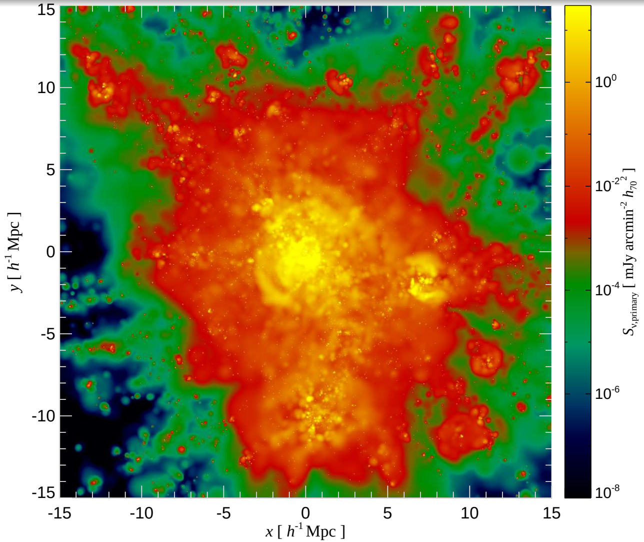
Radio gischt: primary CRe (15 MHz), slower magnetic decline



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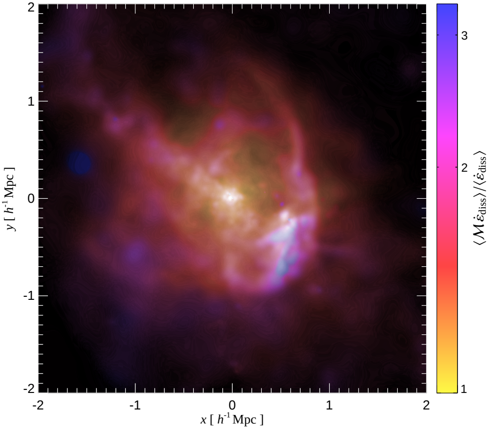
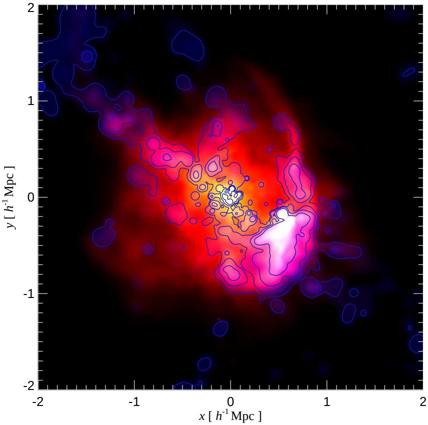
Radio gischt illuminates cosmic magnetic fields





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

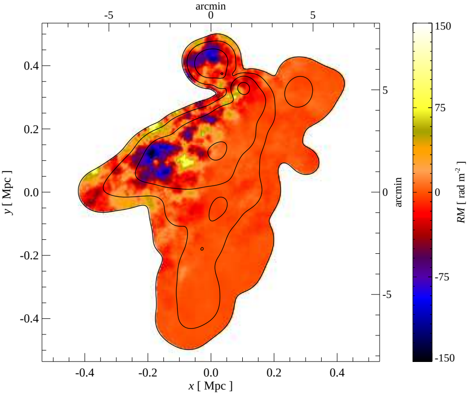
Battaglia, CP, Sievers, Bond, Enßlin (2008):

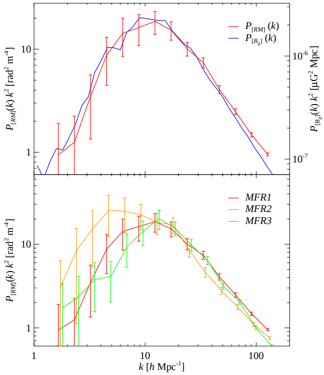
By suitably combining the observables associated with diffuse polarized radio emission at low frequencies ($\nu \sim$ 150 MHz, GMRT/LOFAR/MWA/LWA), we can probe

- 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.

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:

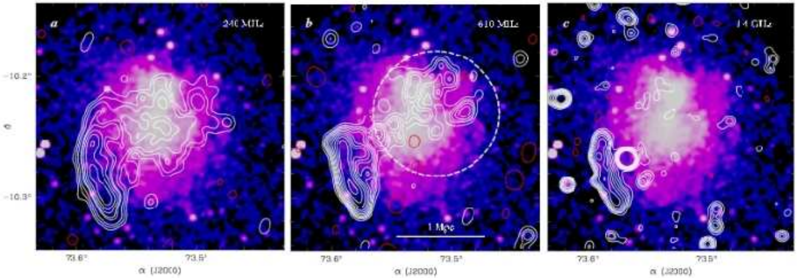




Left: RM map of the largest relic, right: Magnetic and RM power spectrum comparing Kolmogorow and Burgers turbulence models.

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!

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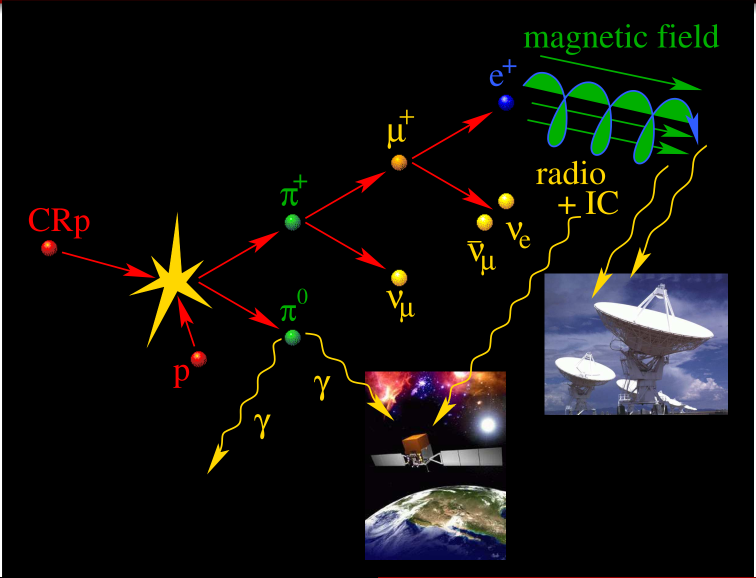
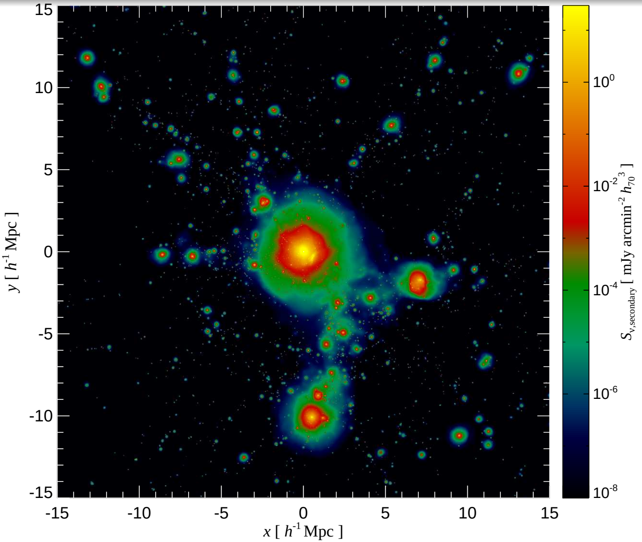
Hadronic cosmic ray proton interaction



Cluster radio emission by hadronically produced CRe



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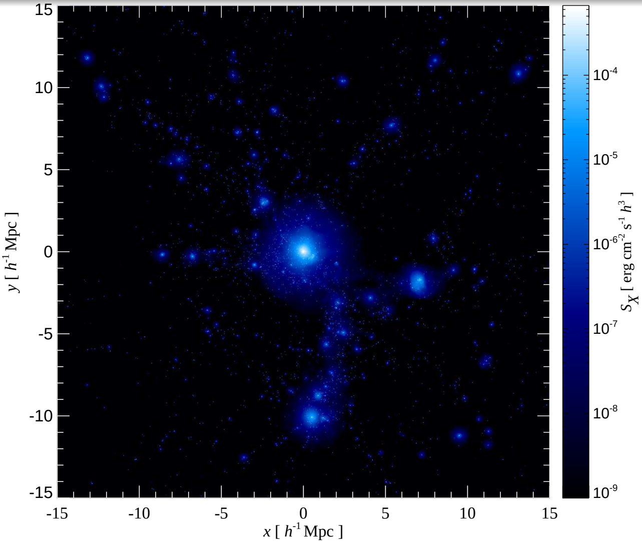
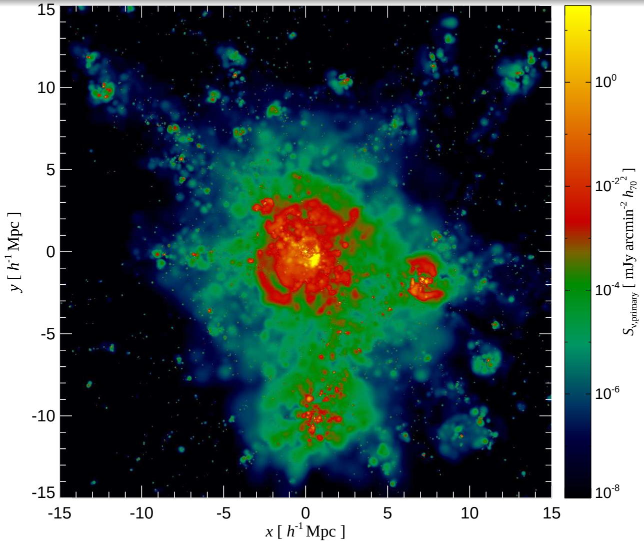
Thermal X-ray emission



Radio gischt: primary CRe (150 MHz)



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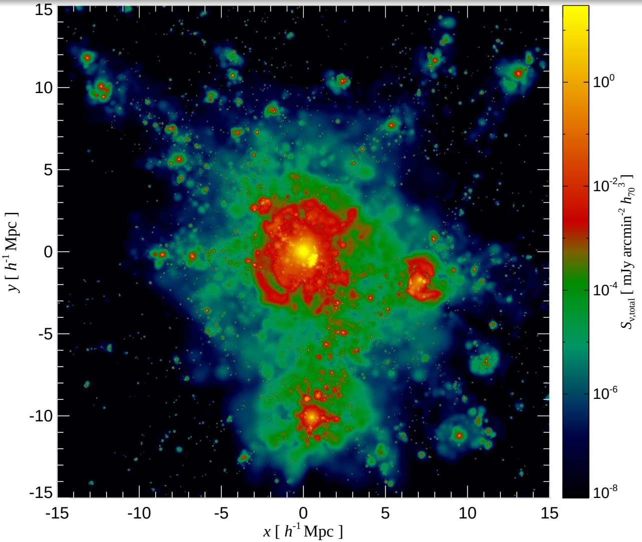
Radio gischt + central hadronic halo = giant radio halo



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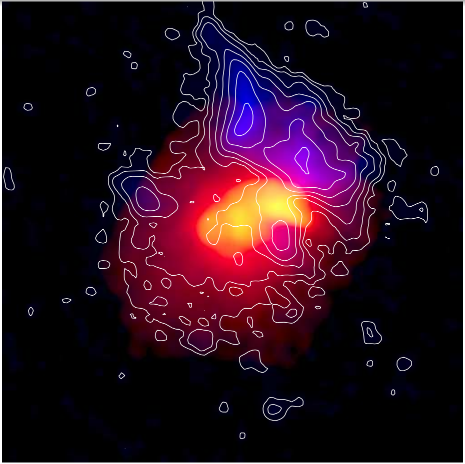
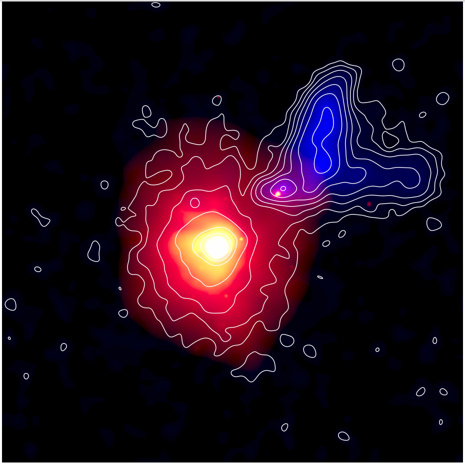
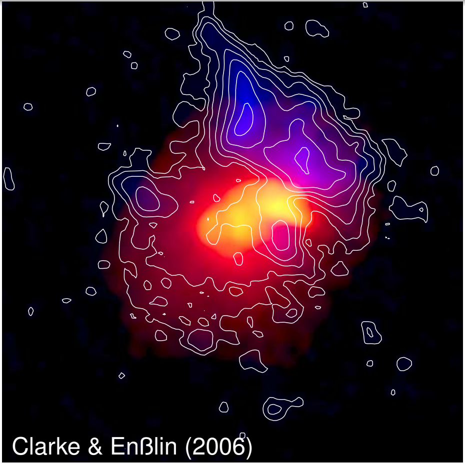
Which one is the simulation/observation of A2256?

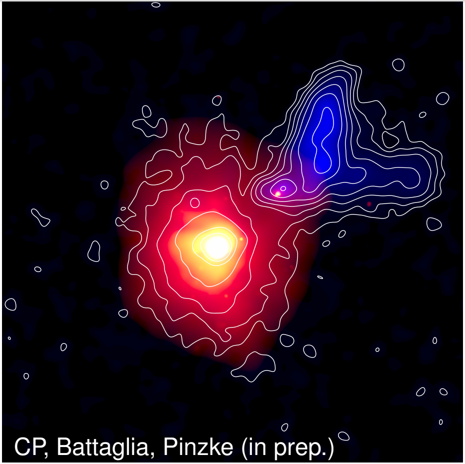




red/yellow: thermal X-ray emission,
blue/contours: 1.4 GHz radio emission with giant radio halo and relic

Observation – simulation of A2256





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blue/contours: 1.4 GHz radio emission with giant radio halo and relic

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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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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)
- Čerenkov telescopes: MAGIC, HESS, VERITAS ($E \simeq (0.1 - 100)$ TeV)

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Outline

1. Cosmic rays in galaxy clusters
   - Introduction and motivation
   - Cosmological galaxy cluster simulations
   - Shocks, particle acceleration, and transport
2. Diffuse radio emission in clusters
   - Non-thermal processes in clusters
   - Radio emission by shocks and turbulence
   - Hadronically induced radio emission
3. High-energy γ-ray emission
   - Morphology and spectra
   - Predictions for Fermi and MAGIC
   - Conclusions

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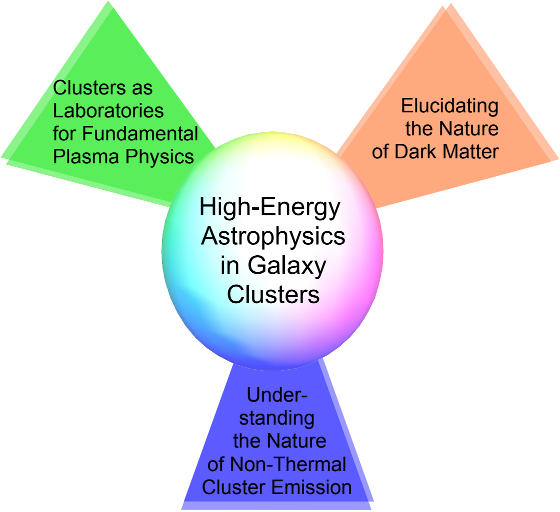
High-energy astrophysics in galaxy clusters

Why would you look for clusters in γ-rays?



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The quest for high-energy γ-ray emission from clusters
Multi-messenger approach towards fundamental astrophysics

1. understanding the nature of non-thermal cluster emission:
   - complements current non-thermal observations of galaxy clusters in radio and hard X-rays
   - unveiling the contribution of cosmic ray protons $\rightarrow$ gauging radio observables to obtain a cluster "gold" sample for cosmology
2. clusters as laboratories for fundamental plasma astrophysics:
   - macroscopic parameters for diffusive shock acceleration
   - origin and evolution of magnetic fields
3. elucidating the nature of dark matter:
   - disentangling annihilation signal vs. CR induced γ-rays
   - spectral and morphological γ-ray signatures $\rightarrow$ DM properties

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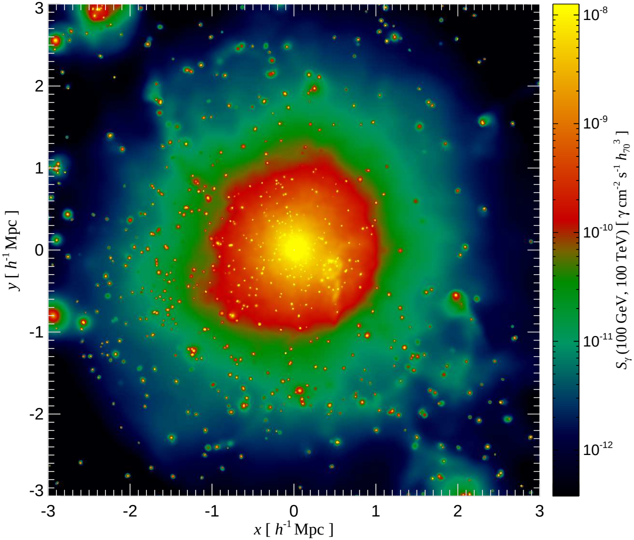
Hadronic γ-ray emission, $E_\gamma > 100$ GeV (Pinzke & CP, in prep.)



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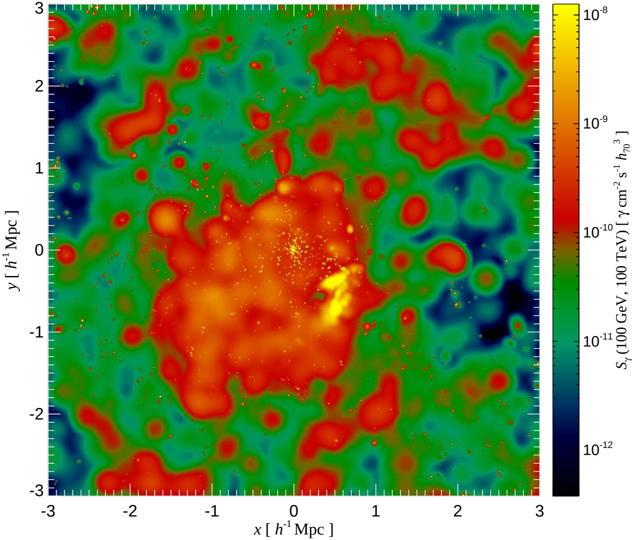
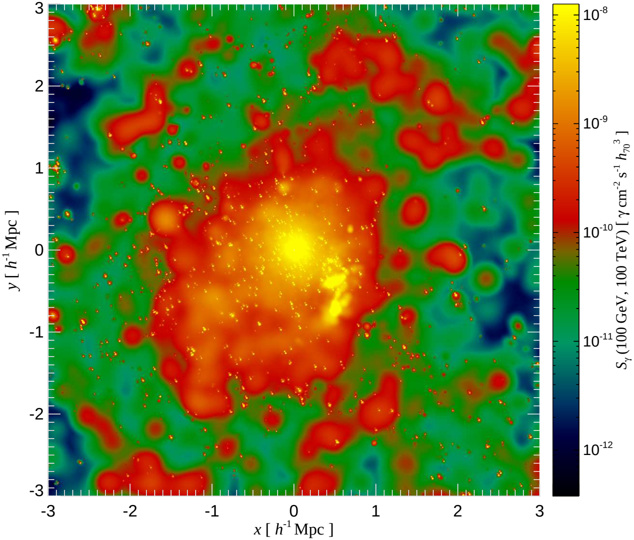
Inverse Compton emission, $E_{\mathrm{IC}} > 100$ GeV (Pinzke & CP, in prep.)



Total γ-ray emission, $E_\gamma > 100$ GeV (Pinzke & CP, in prep.)



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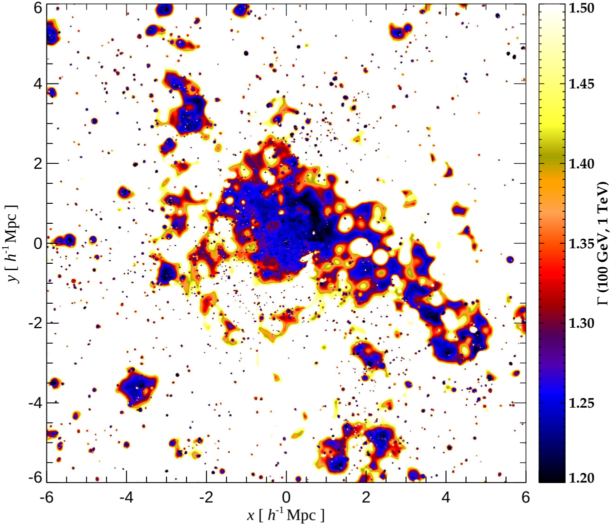
Photon index between 100 GeV and 1 TeV (Pinzke & CP, in prep.)



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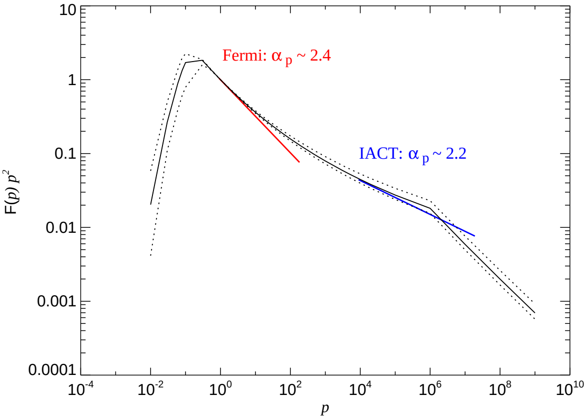
Universal CR spectrum in clusters (Pinzke & CP, in prep.)



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

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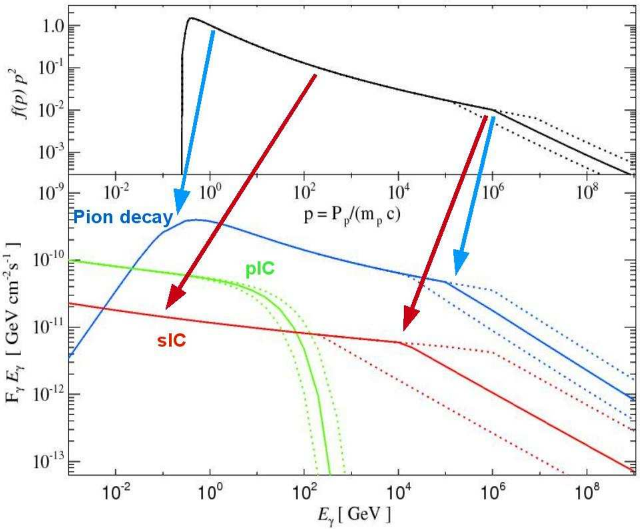
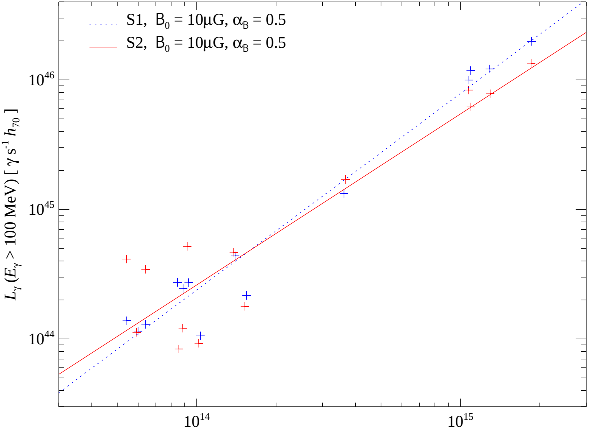
Cosmic ray and γ-ray spectrum in clusters (Pinzke & CP, in prep.)



Gamma-ray scaling relations



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

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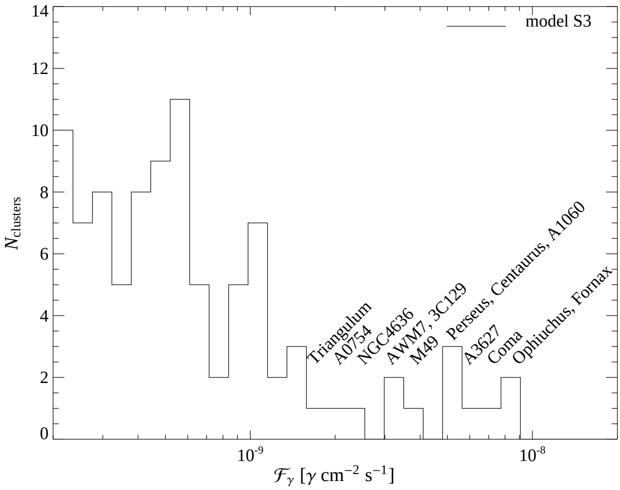
Predicted cluster sample for Fermi



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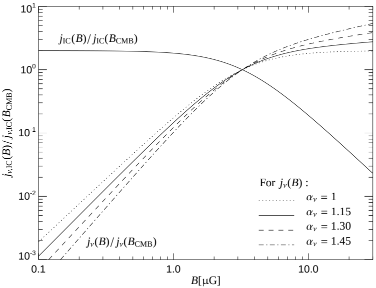
Minimum γ-ray flux in the hadronic model



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

Synchrotron luminosity:

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

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

γ-ray luminosity:

$$L_\gamma = A_\gamma \int dV\, n_{\rm CR} n_{\rm gas}$$

$\rightarrow$ minimum γ-ray flux:

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

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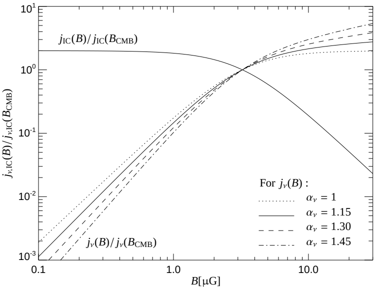
Minimum γ-ray flux in the hadronic model



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γ-ray luminosity:

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$\to$ minimum γ-ray flux:

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

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Minimum γ-ray flux in the hadronic model: Fermi

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

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

- These limits can be made even tighter when considering energy constraints, $P_B < P_{\rm gas}/30$ and B-fields derived from Faraday rotation studies, $B_0 = 3\,\mu$G:
  $\mathcal{F}_{\gamma,\rm COMA} \gtrsim (1.1\ldots1.5)\times10^{-9}\gamma\,cm^{-2}s^{-1} \lesssim \mathcal{F}_{\rm Fermi,\ 2yr}$
- Non-detection by Fermi seriously challenges the hadronic model.
- Potential of measuring the CR acceleration efficiency for diffusive shock acceleration.

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Minimum γ-ray flux in the hadronic model: MAGIC

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

CR spectral index	2.0	2.3	2.6	2.9
$\mathcal{F}_\gamma$ [$10^{-14}\, ph\, cm^{-2} s^{-1}$]	20.2	7.6	2.9	1.1

- These limits can be made even tighter when considering energy constraints, $P_B < P_\mathrm{gas}/30$, FRM B-fields with $B_0 = 3\,\mu$G, and $\alpha_\mathrm{p} < 2.3$ (caution: this assumes a power-law scaling): $\mathcal{F}_{\gamma,\mathrm{COMA}} \gtrsim (5.3 \ldots 7.6) \times 10^{-13} \gamma\, cm^{-2} s^{-1}$
- Potential of measuring the CR spectrum, the effective acceleration efficiency for diffusive shock acceleration, and relate this to the history of structure formation shock waves (Mach number distribution).

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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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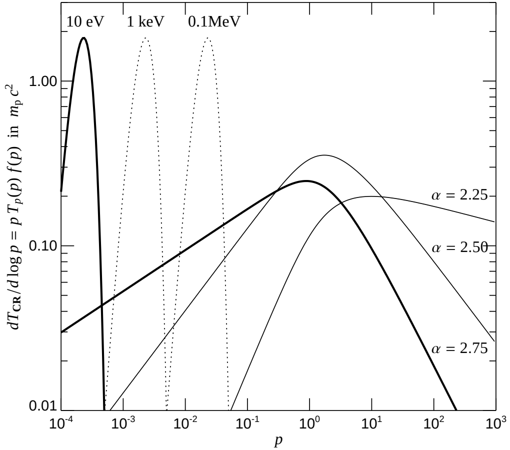
Thermal & CR energy spectra

Kinetic energy per logarithmic momentum interval:



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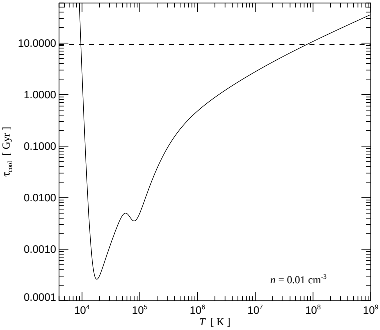
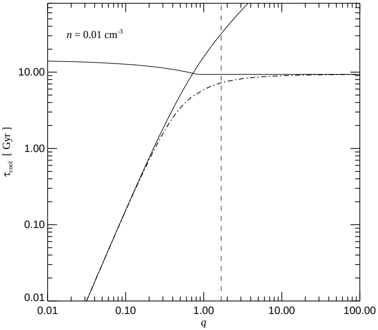
Cooling time scales of CR protons

Cooling of primordial gas:



Cooling of cosmic rays:



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*