Particle Acceleration and Radiation from Galaxy Clusters

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in collaboration with

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Outline

1. Cosmological simulations with cosmic rays
   - Motivation and observations
   - Cosmological galaxy cluster simulations
   - Non-thermal processes in clusters
2. Gamma-ray emission from clusters
   - Spectra and morphology
   - Predictions for Fermi and IACT's
   - MAGIC observations of Perseus
3. Diffuse radio emission in clusters
   - The cosmic magnetized web
   - Properties of cluster magnetic fields
   - Cluster turbulence

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Outline

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How universal is diffusive shock acceleration (DSA)?

What can galaxy clusters teach us about the process of shock acceleration?

Cosmological structure formation shock physics complementary to interplanetary and SNR shocks:

- probing unique regions of DSA parameter space:
  $\rightarrow$ Mach numbers $\mathcal{M} \sim 2 \ldots 10$ with 'infinitely' extended (Mpc) and lasting (Gyr) shocks (observationally accessible @ $z = 0$)
  $\rightarrow$ plasma-β factors of $\beta \sim 10^2 \ldots 10^5$
- origin and evolution of large scale magnetic fields and nature of turbulent models in a 'cleaner environment' (1-phase medium)
- 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

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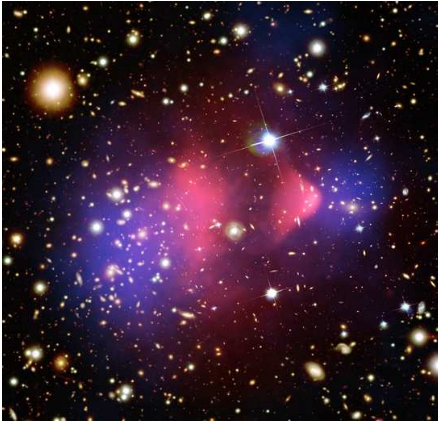
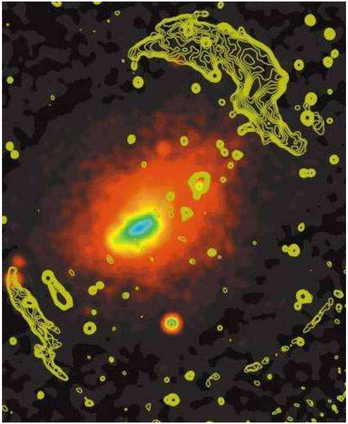
Shocks in galaxy clusters



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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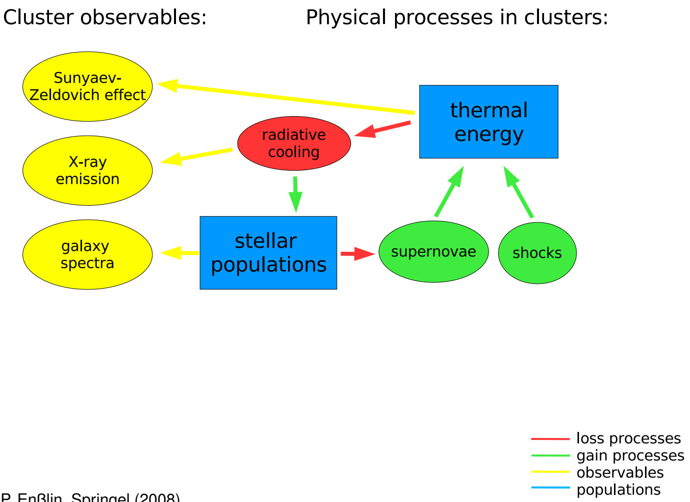
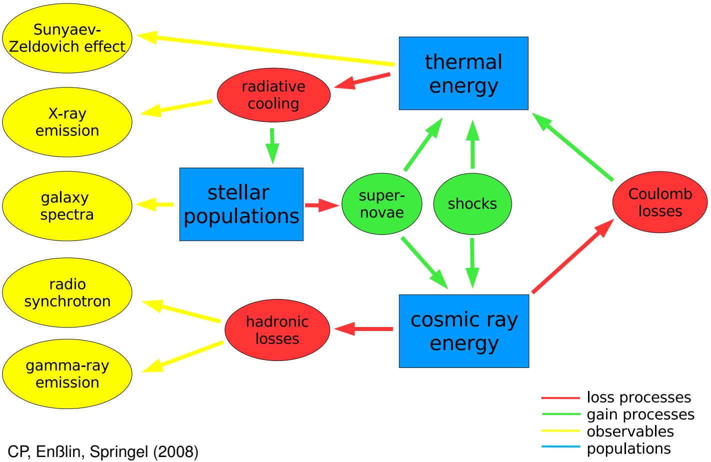
Radiative simulations with GADGET – flowchart



CP, Enßlin, Springel (2008)

Radiative simulations with cosmic ray (CR) physics

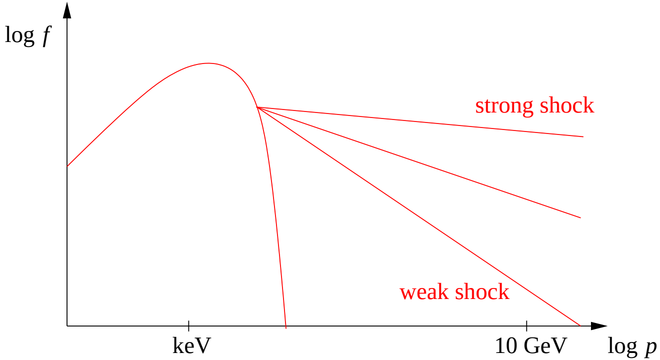
Cluster observables: Physical processes in clusters:



CP, Enßlin, Springel (2008)

Diffusive shock acceleration – Fermi 1 mechanism (1)

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



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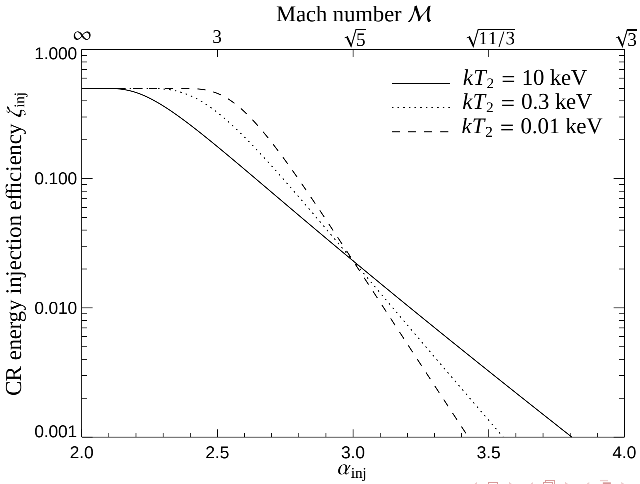
Diffusive shock acceleration – efficiency (2)

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



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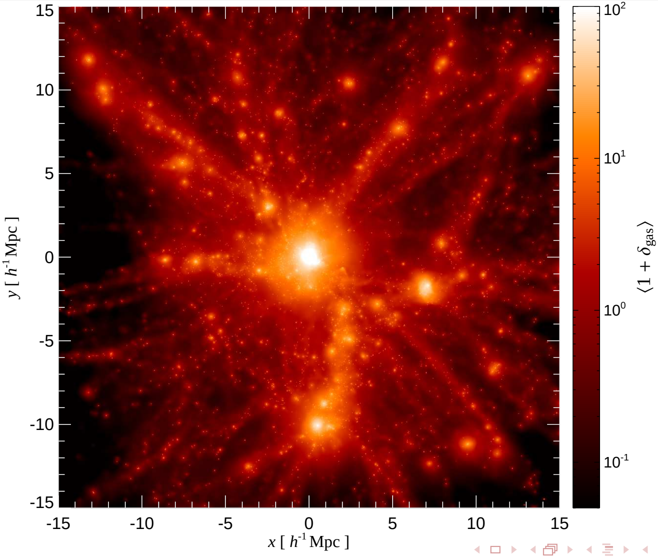
Radiative cool core cluster simulation: gas density



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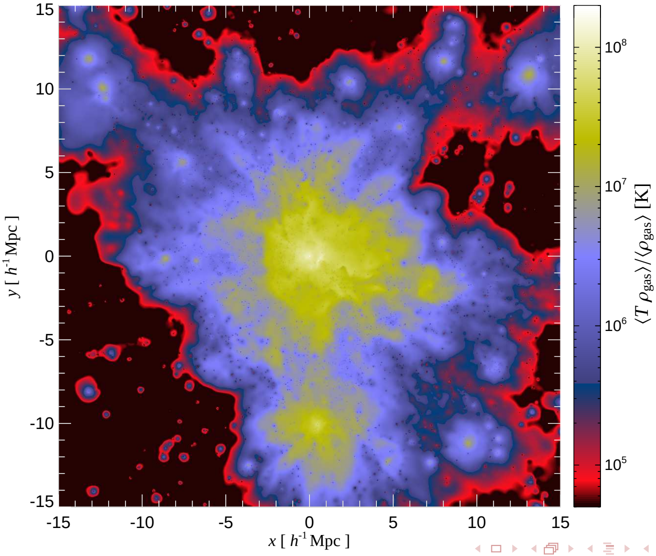
Mass weighted temperature



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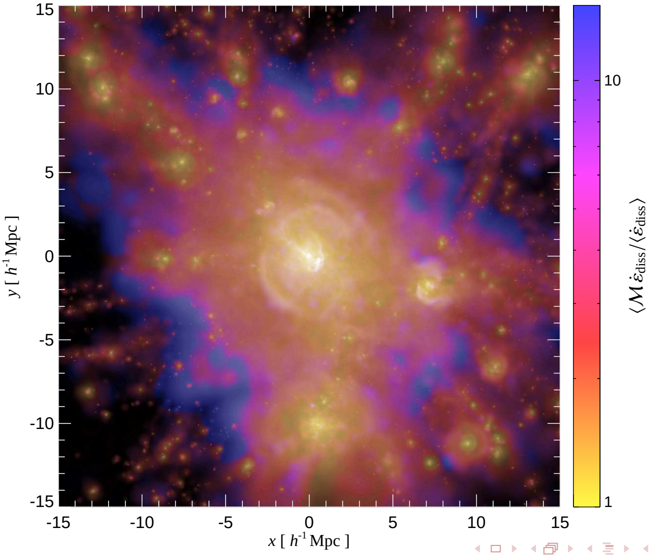
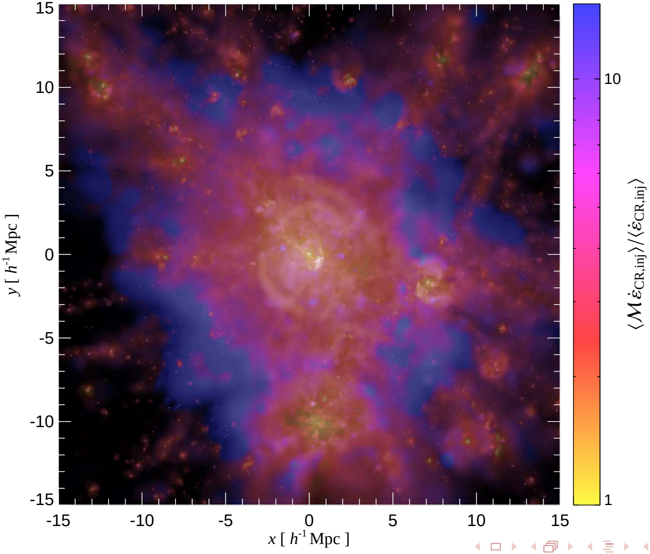
Mach number distribution weighted by $\varepsilon_{\rm diss}$



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



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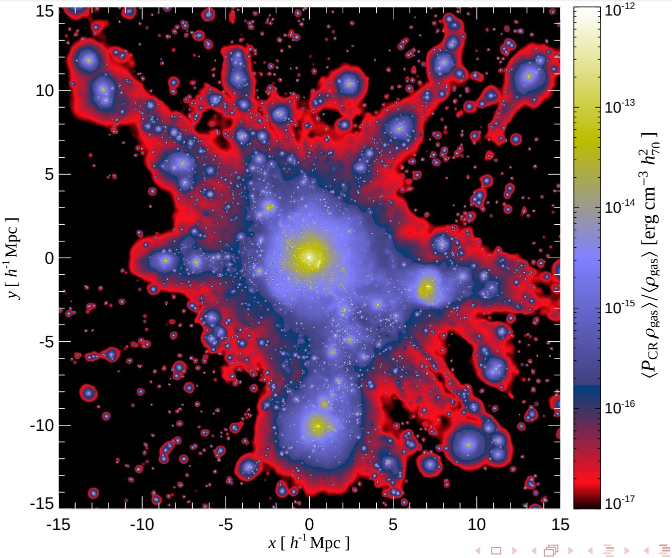
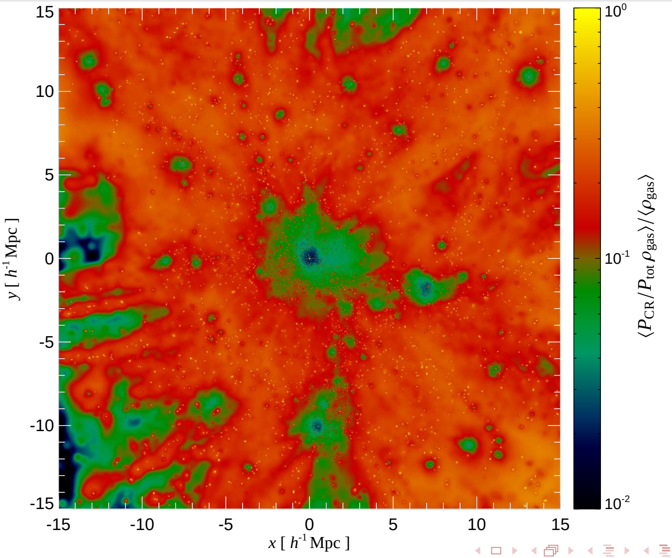
CR pressure P_{CR}



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



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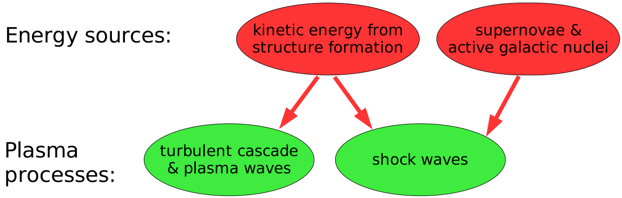
Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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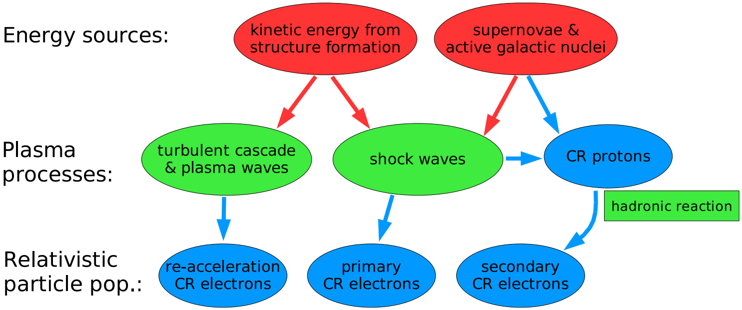

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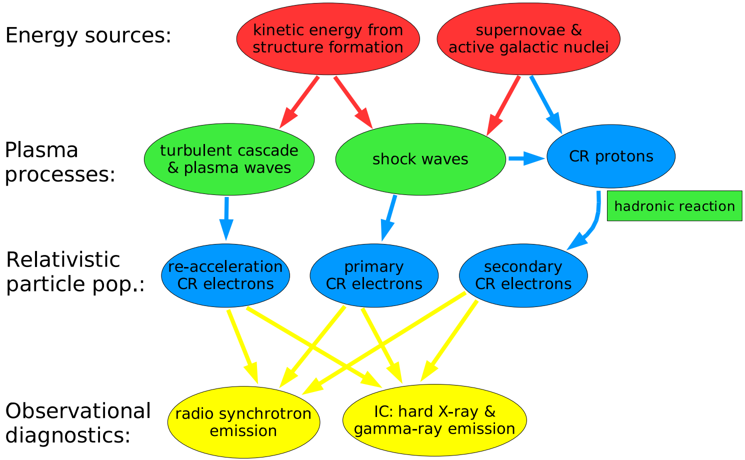

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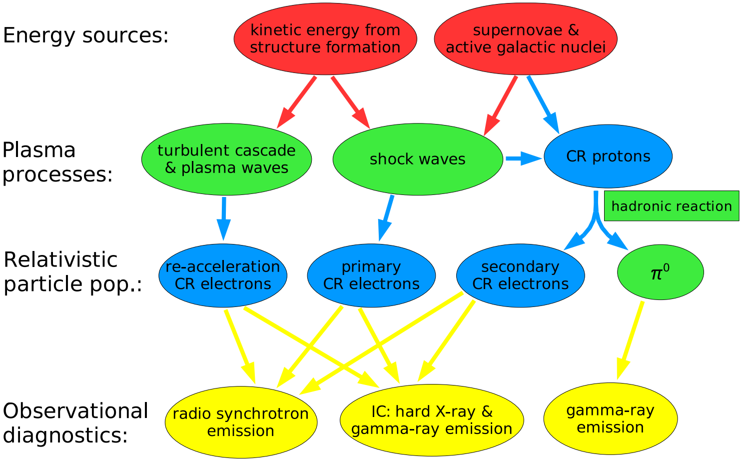

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Non-thermal emission from clusters

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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Outline

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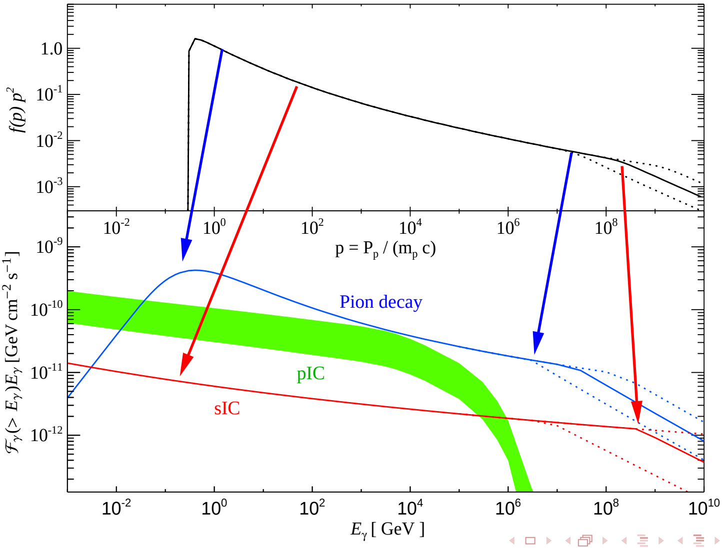
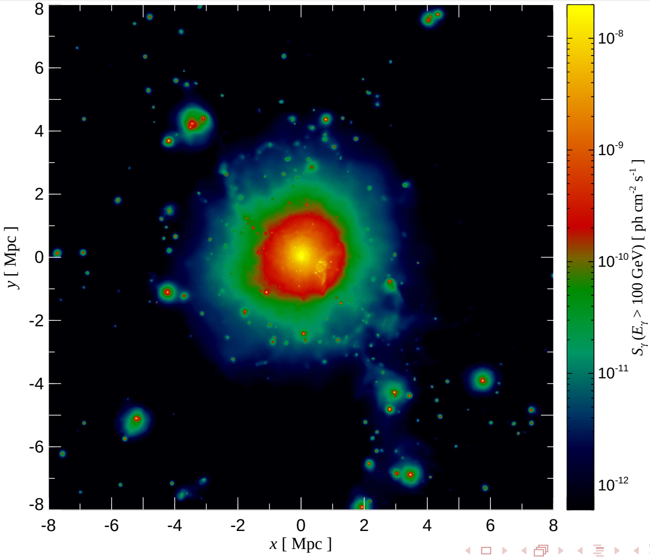
CR proton and γ-ray spectrum (Pinzke & CP 2009)



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



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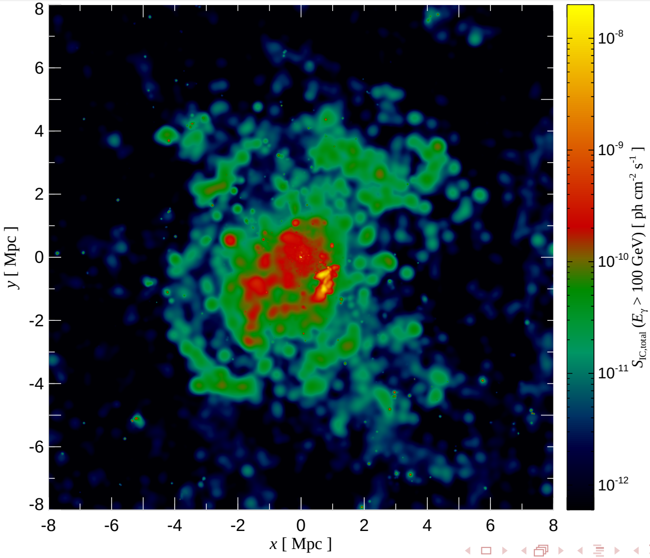
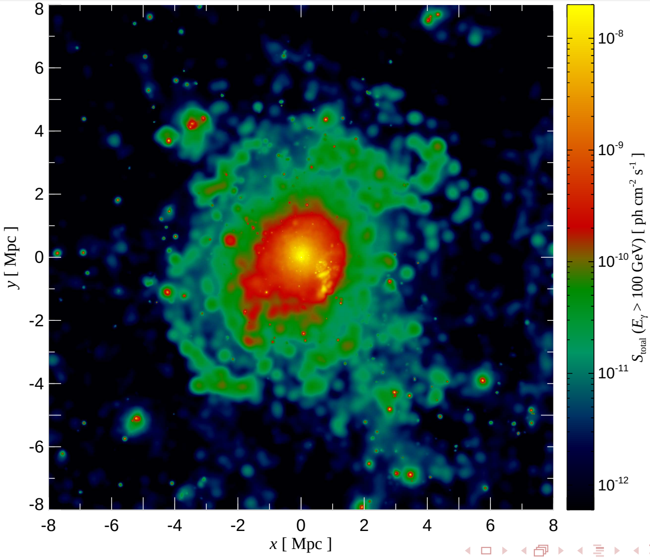
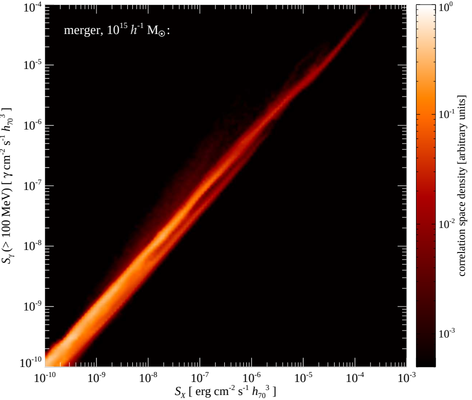
Inverse Compton emission, $E_{\mathrm{IC}} > 100$ GeV

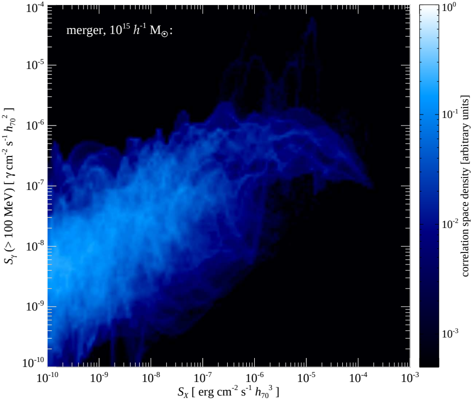


Total γ-ray emission, $E_\gamma > 100$ GeV



Correlation between thermal X-ray and γ-ray emission





Correlation with pion decay/sec. IC emission, X-ray and secondary emission $\propto n^2$ (CP, Enßlin, Springel 2008)

Correlation with primary IC emission, correlation space substructure
→ oblique curved shocks; *B*-generation!

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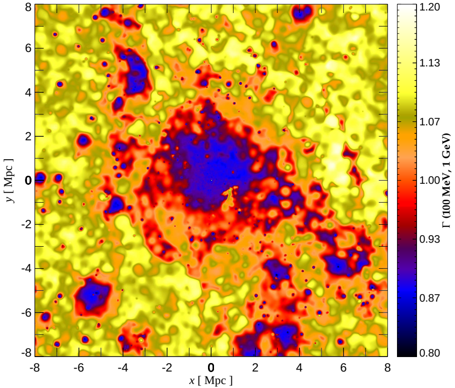
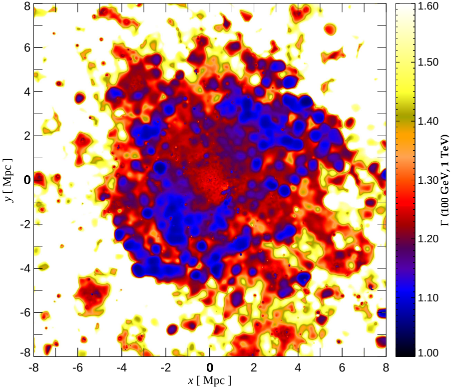
Photon index Γ - variations on large scales



$\Gamma_{100\,\mathrm{MeV}}^{1\,\mathrm{GeV}}$ (Fermi): pion bump (center)

transition to pIC (strong accretion shocks)



$\Gamma_{100\,\mathrm{GeV}}^{1\,\mathrm{TeV}}$ (IACT's): pion-decay (center)

pIC (accretion shocks, cutoff E_{max})

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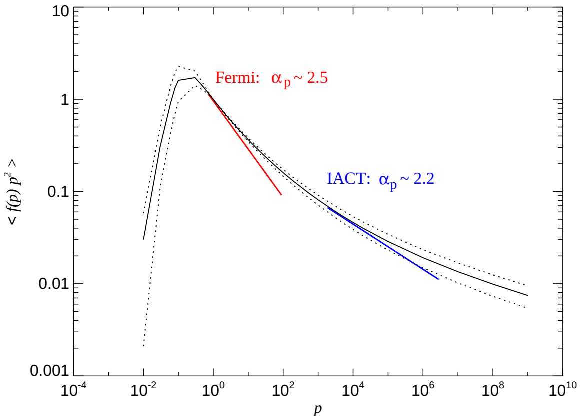
Universal CR spectrum in clusters



Normalized CR spectrum shows universal concave shape → governed by hierarchical structure formation and the implied distribution of Mach numbers that a fluid element had to pass through in cosmic history (Pinzke & CP 2009).

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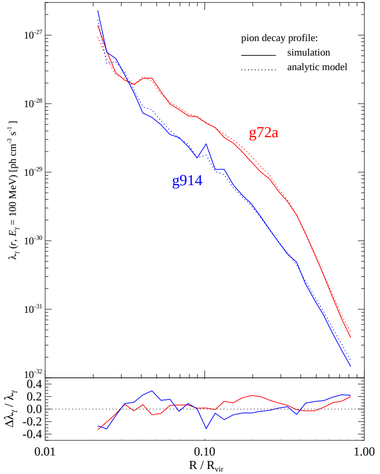
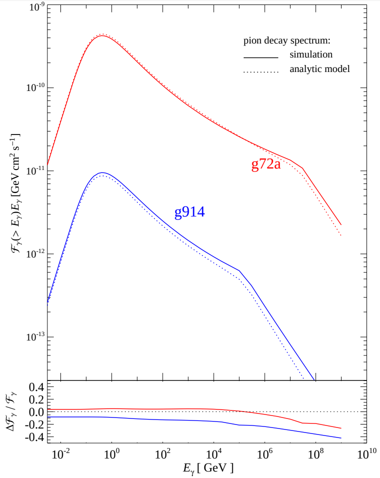
An analytic model for the cluster γ-ray emission

Comparison: simulation vs. analytic model, $M_{\mathrm{vir}} \simeq (10^{14}, 10^{15})\,\mathrm{M}_\odot$



Spatial γ-ray emission profile



Pion decay spectrum

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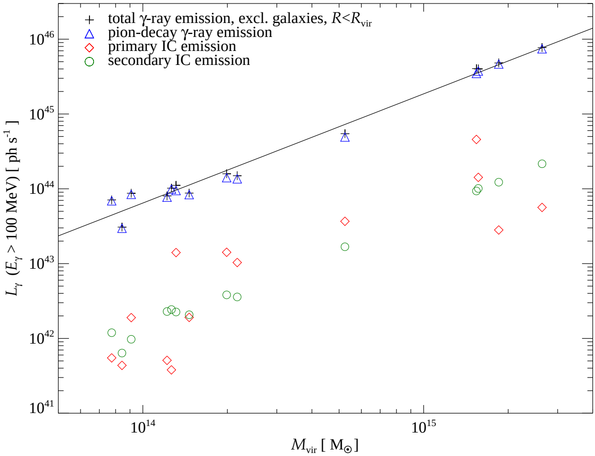
Gamma-ray scaling relations



Scaling relation + complete sample of the brightest X-ray clusters (HIFLUGCS) → predictions for *Fermi* and *IACT's*

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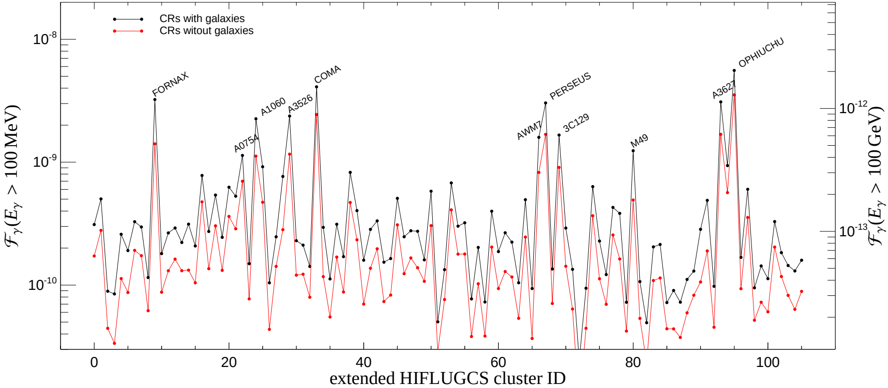
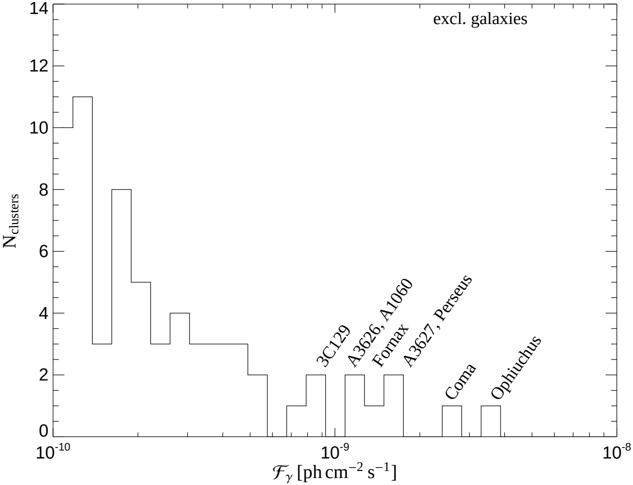
Predicted cluster sample for *Fermi* and *IACT's*



black: optimistic model, including galactic 'point sources' that bias γ-ray flux high; red: realistic model, excluding galactic 'point sources'

Predicted cluster sample for *Fermi* – brightest objects



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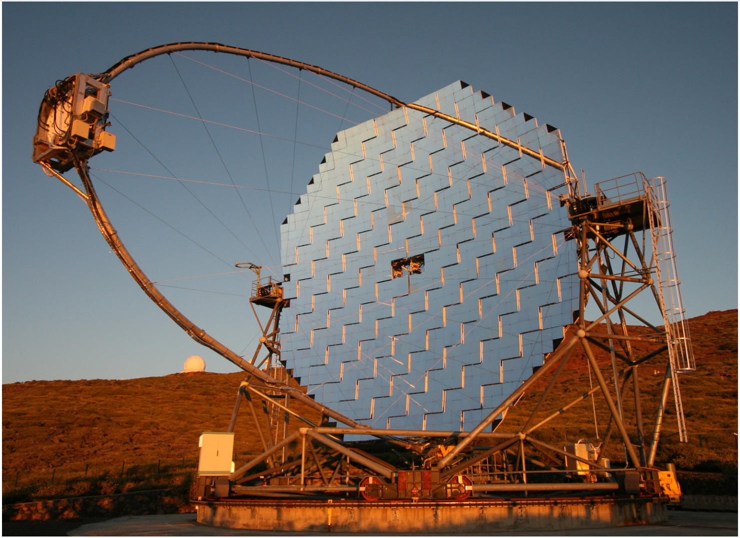
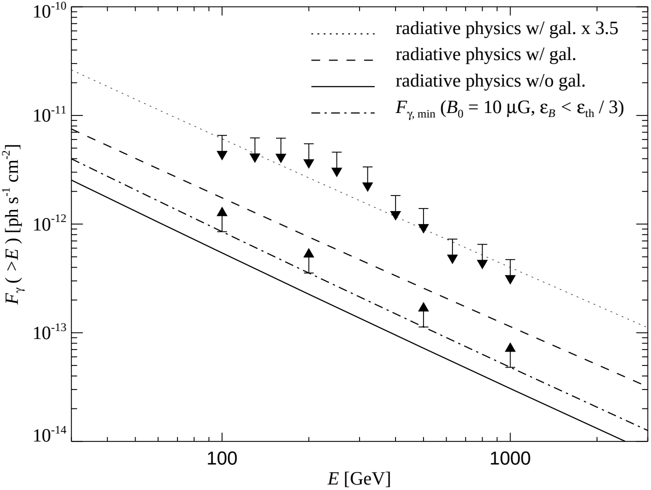
MAGIC observations of Perseus



Upper limit on the TeV γ-ray emission from Perseus



The MAGIC Collaboration: Aleksic et al. & CP et al. 2009

Results from the Perseus observation by *MAGIC*

- assuming $f \propto p^{-\alpha}$ with $\alpha = 2.1$, $P_{\rm CR} \propto P_{\rm th}$:
  $E_{\rm CR} < 0.017 E_{\rm th} \rightarrow$ most stringent constraint on CR pressure!
- upper limits consistent with cosmological simulations:
  $F_{\rm upper\ limits}(100\,GeV) = 3.5\,F_{\rm sim}$ (optimistic model)
- simulation modeling of pressure constraint yields
  $\langle P_{\rm CR}\rangle/\langle P_{\rm th}\rangle < 0.07\,(0.14)$ for the core (entire cluster)
- 3 physical effects that resolve the apparent discrepancy:
  - concave curvature 'hides' CR pressure at GeV energies
  - galactic 'point sources' bias γ-ray flux high and pressure limits low (partly physical)
  - relative CR pressure increases towards the outer parts (adiabatic compression and softer equation of state of CRs)

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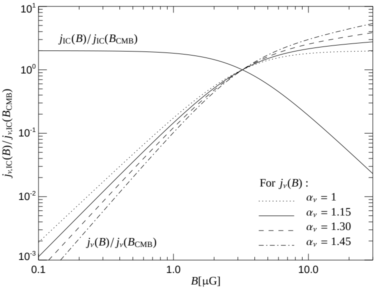
Minimum γ-ray flux in the hadronic model



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

Synchrotron luminosity:

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

γ-ray luminosity:

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

$\rightarrow$ minimum γ-ray flux:

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

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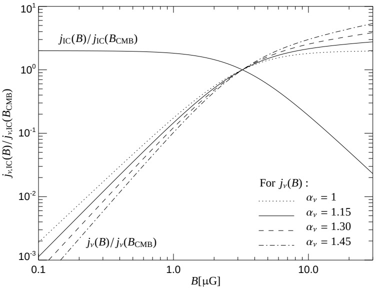
Minimum γ-ray flux in the hadronic model



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γ-ray luminosity:

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$\rightarrow$ 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: *Fermi*

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

CR spectral index	2.0	2.3	2.6	2.9
$\mathcal{F}_\gamma$ [$10^{-10}\,\mathrm{ph\,cm^{-2}s^{-1}}$]	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:
  $\mathcal{F}_{\gamma,\rm COMA} \gtrsim (1.1\dots1.5)\times10^{-9}\gamma\, cm^{-2}s^{-1} \lesssim \mathcal{F}_{\rm Fermi,\ 2yr}$
- 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: *IACT's*

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, $P_B < P_{\rm gas}/30$, FRM B-fields with $B_0 = 3\,\mu$G, and $\alpha_{\rm p} < 2.3$ (caution: this assumes a power-law scaling): $\mathcal{F}_{\gamma,\rm COMA} \gtrsim (5.3\ldots7.6)\times10^{-13}\gamma\, cm^{-2}s^{-1}$
- 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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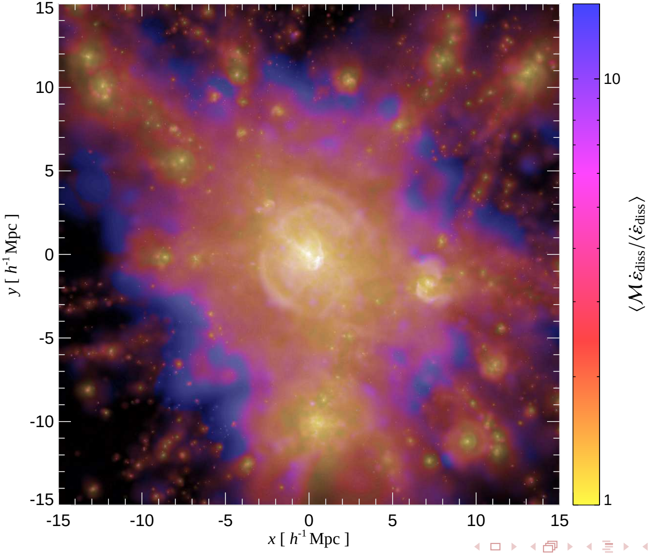
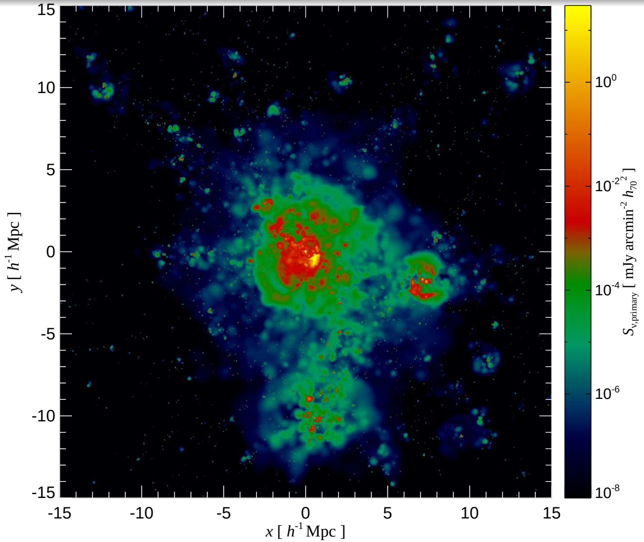
Outline

Cosmic web: Mach number



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



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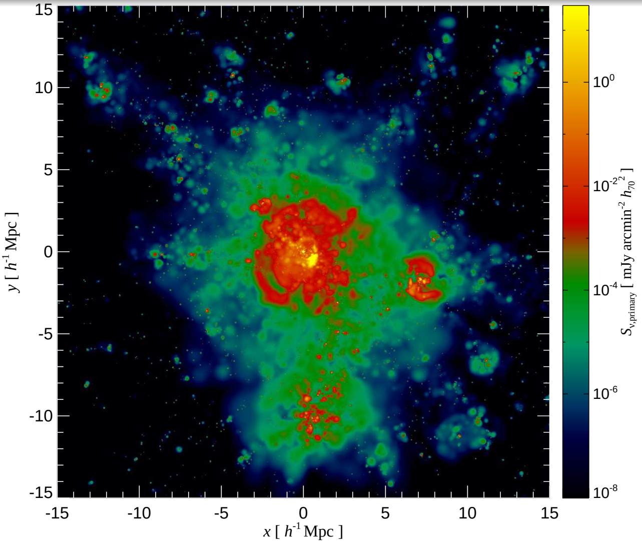
Radio gischt: primary CRe (150 MHz)



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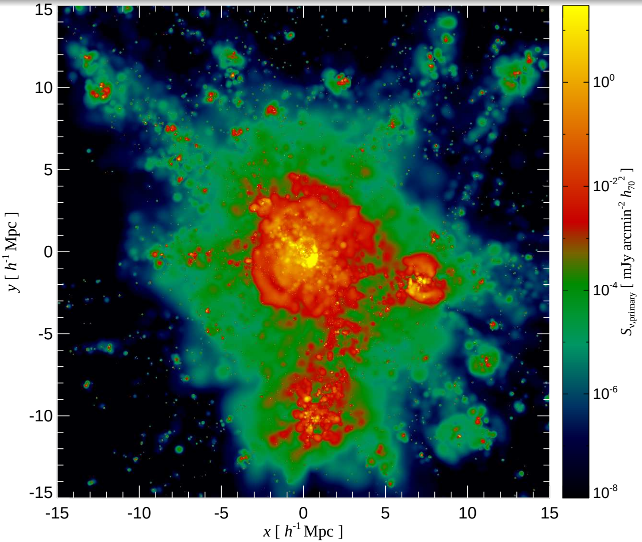
Radio gischt: primary CRe (15 MHz)



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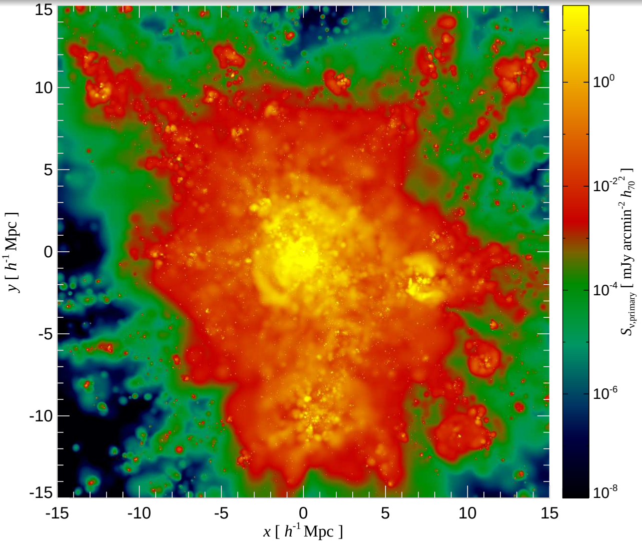
Radio gischt: primary CRe (15 MHz), slower magnetic decline



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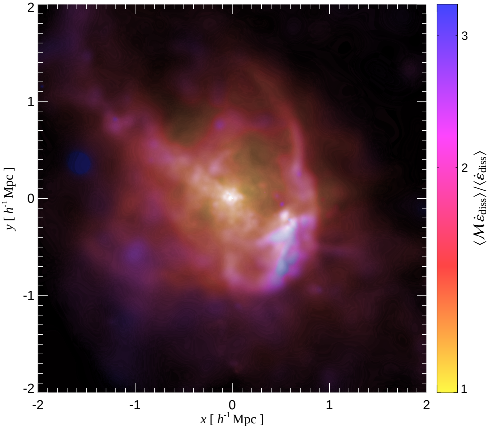
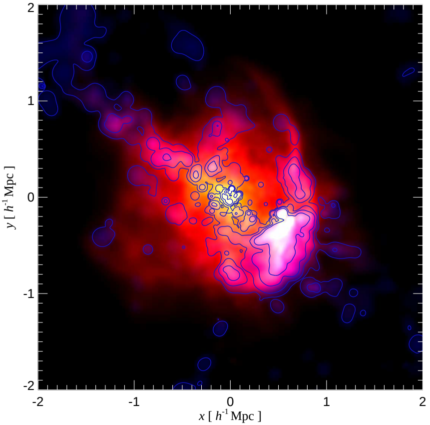
Radio gischt illuminates cosmic magnetic fields





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):

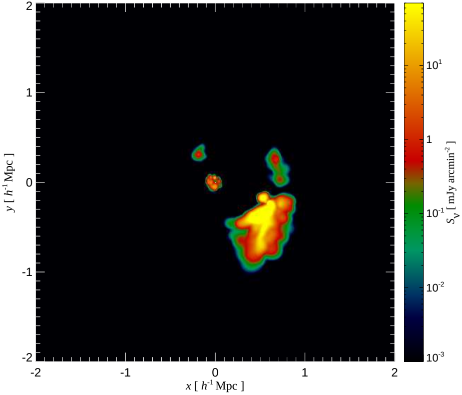
By suitably combining the observables associated with diffuse polarized radio emission at low frequencies ($\nu \sim$ 150 MHz, GMRT/LOFAR/MWA/LWA), we can probe

- 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.

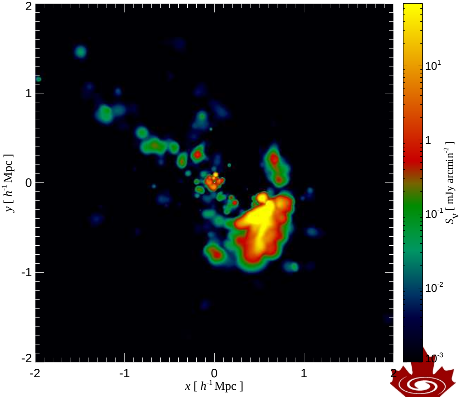
Population of faint radio relics in merging clusters

Probing the large scale magnetic fields

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



radio map with GMRT emissivity threshold



"theoretical" threshold (towards SKA)

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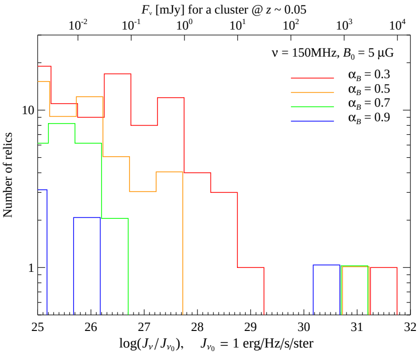
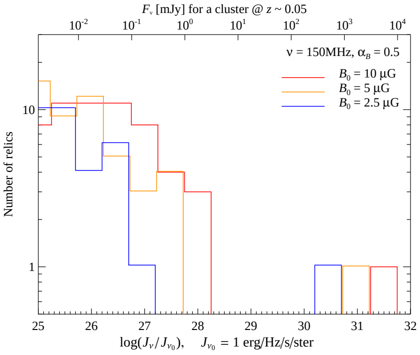
Relic luminosity function – theory

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



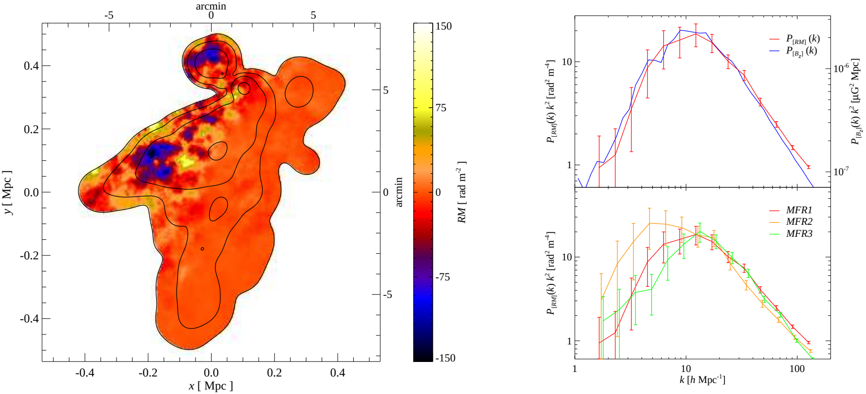
varying magnetic decline with radius



varying overall normalization of the magnetic field

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.

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Conclusions

In contrast to the thermal plasma, the non-equilibrium distributions of CRs preserve the information about their injection and transport processes and provide thus a unique window of current and past structure formation processes and diffusive shock acceleration!

1. Universal distribution of CR protons determined by maximum shock acceleration efficiency $\zeta_{\rm max}$ and adiabatic transport: mapping between the hadronic γ-ray emission and $\zeta_{\rm max}$
   $\rightarrow$ cosmological simulations are indispensable for exploring this (non-linear) map
   $\rightarrow$ spectral shape illuminates the process of structure formation
2. Primary radio (gischt) emission traces the magnetized cosmic web; sensitive to electron acceleration efficiency
   $\rightarrow$ Faraday rotation on polarized Mpc-sized relics allows determining the nature of the intra-cluster turbulence

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