Illuminating cosmological formation shocks – a critical review

Christoph Pfrommer

Canadian Institute for Theoretical Astrophysics, Canada

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Outline

1. Cosmological structure formation shocks
   - Introduction and motivation
   - Cosmological galaxy cluster simulations
   - Mach number distributions and CR acceleration
2. Non-thermal processes in clusters
   - General picture
   - Shock related emission
   - Hadronically induced emission
3. Plasma and particle physics
   - The magnetized cosmic web
   - Dark matter annihilation vs. CR induced emission
   - Conclusions

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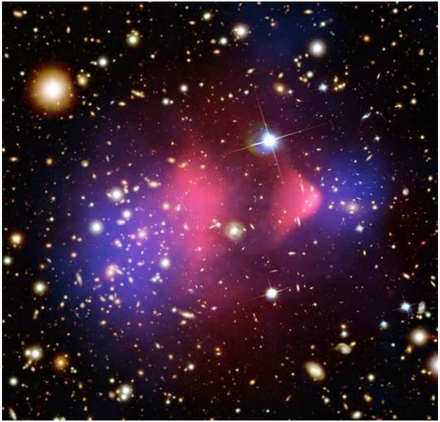
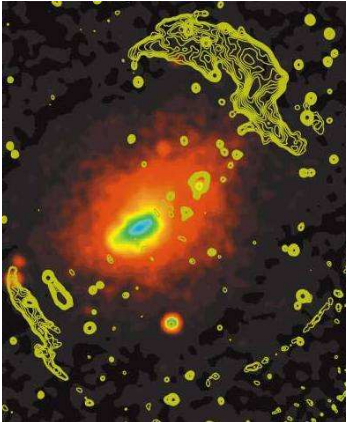
Shocks in galaxy clusters



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)
  $\rightarrow$ illuminating the process of structure formation
  $\rightarrow$ 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 low-β plasmas
  - origin and evolution of large scale magnetic fields
  - nature of MHD turbulence

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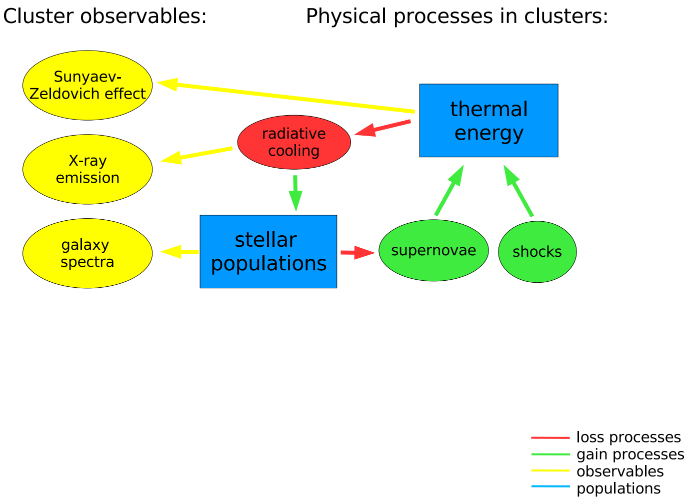
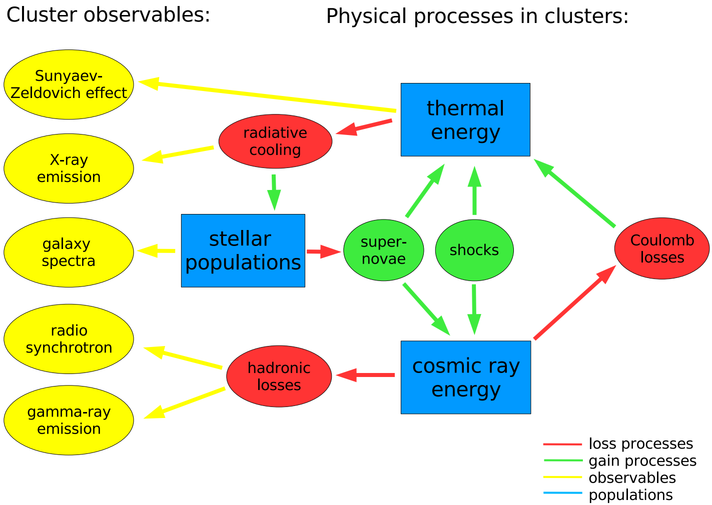
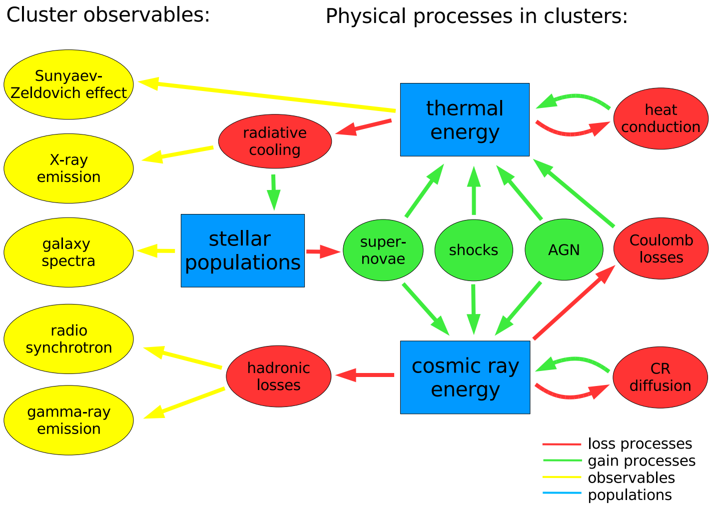
Radiative simulations – flowchart



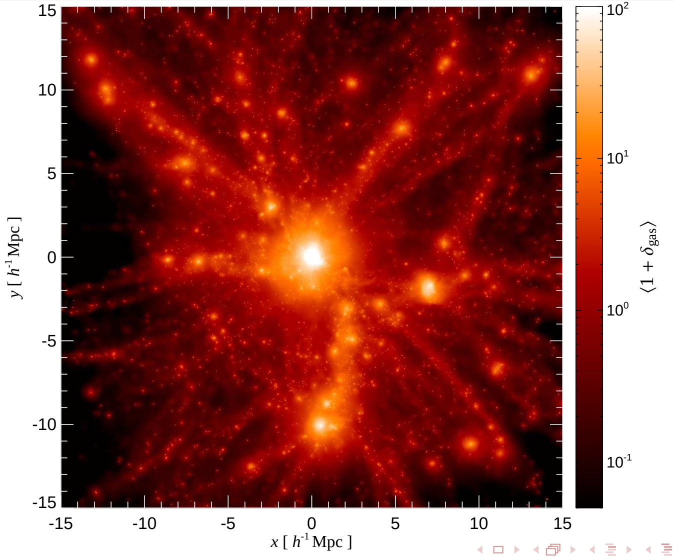
Radiative simulations with cosmic ray (CR) physics



Radiative simulations with extended CR physics



Radiative cool core cluster simulation: gas density



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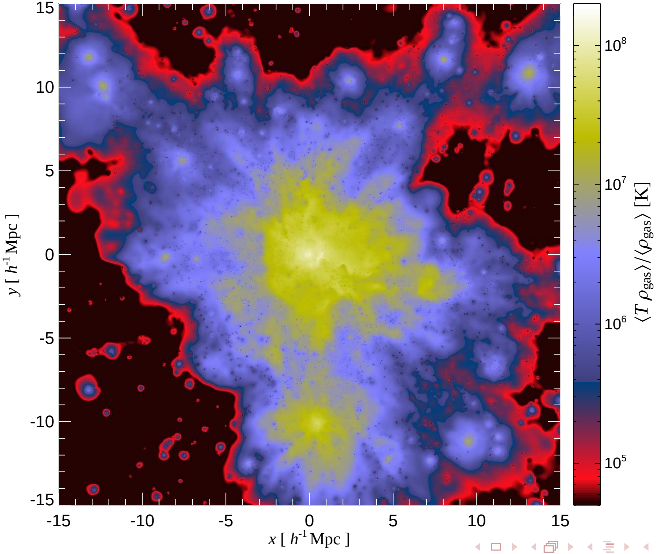
Mass weighted temperature



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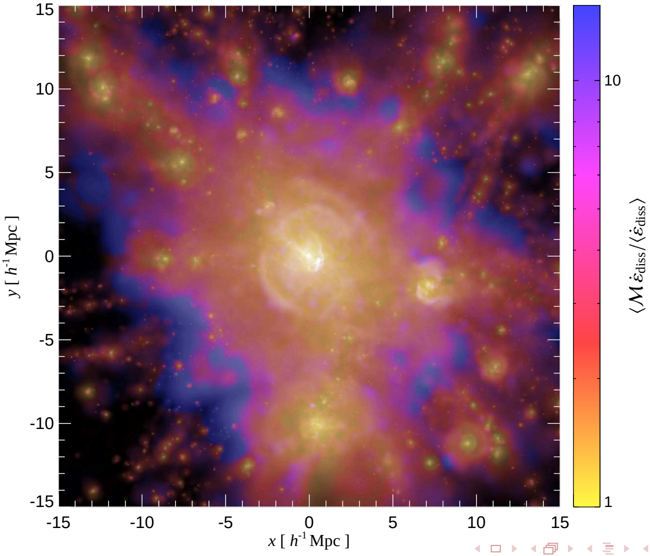
Mach number distribution weighted by $\varepsilon_{\mathrm{diss}}$



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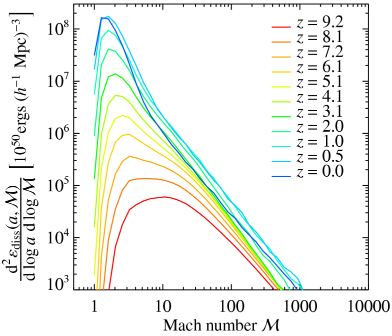
Previous numerical work on Mach number statistics

- Miniati et al. (2000, 01, 02, 03): Eulerian approach, coarse resolution, passive CR evolution, NT cluster emission
- Ryu et al. (2003, 07, 08), Kang et al. 2005: Eulerian Mach number statistics (post-proc.), vorticity and magnetic field generation
- Pfrommer et al. (2006, 07, 08): Lagrangian approach, Mach number statistics (on the fly), self-consistent CR evolution, NT cluster emission
- Skillman et al. 2008: Eulerian AMR, Mach number statistics (post-proc.)
- Hoeft et al. 2008: Lagrangian approach, Mach number statistics (post-proc.)

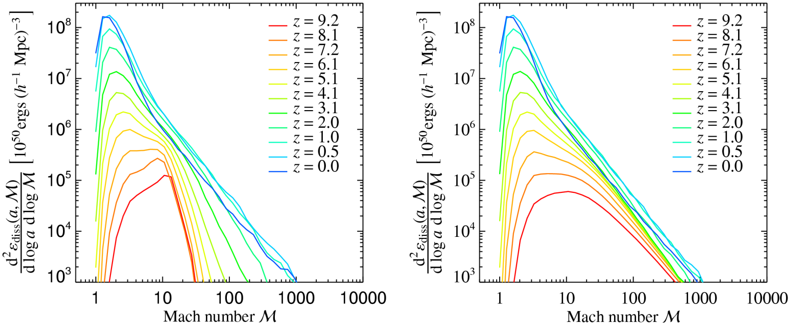
→ increasing number of papers recently, with more expected to come that focus on the non-thermal emission from clusters and topics related to UHECRs (as we enter a new era of multi-frequency experiments).

Cosmological shock statistics



- more energy is dissipated at later times
- mean Mach number decreases with time

Cosmological shock statistics: influence of reionization



- reionization epoch at $z_{reion} = 10$ suppresses efficiently strong shocks at $z < z_{reion}$ due to jump in sound velocity
- cosmological constant causes structure formation to cease

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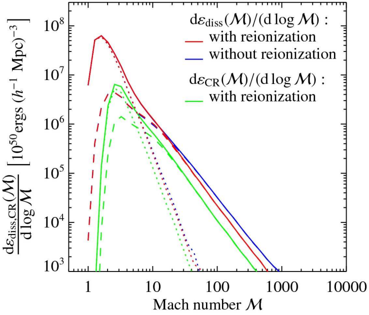
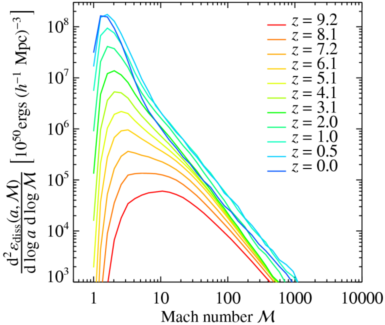
Cosmological shock statistics: CR injection





- Mach number dependent injection efficiency of CRs favors medium Mach number shocks ($\mathcal{M} \gtrsim 3$) for the injection, and even stronger shocks when accounting for Coulomb interactions
- more energy is dissipated in weak shocks internal to collapsed structures than in external strong shocks

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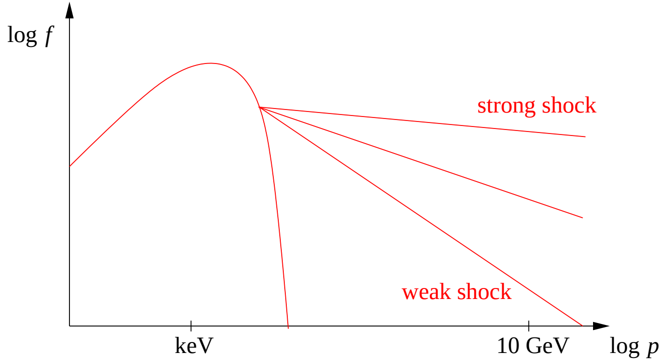
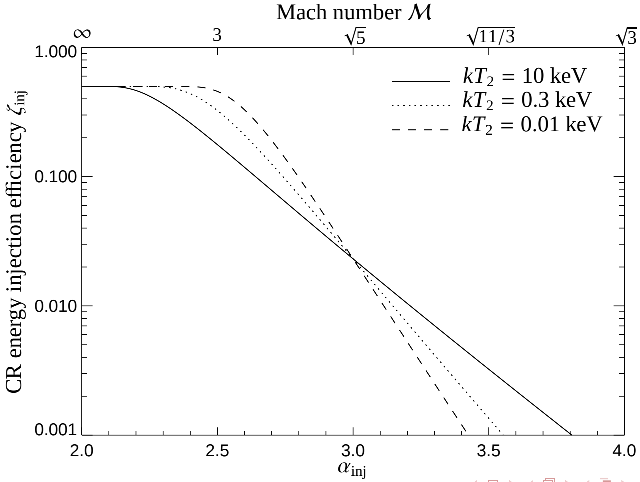
Diffusive shock acceleration – Fermi 1 mechanism (1)

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

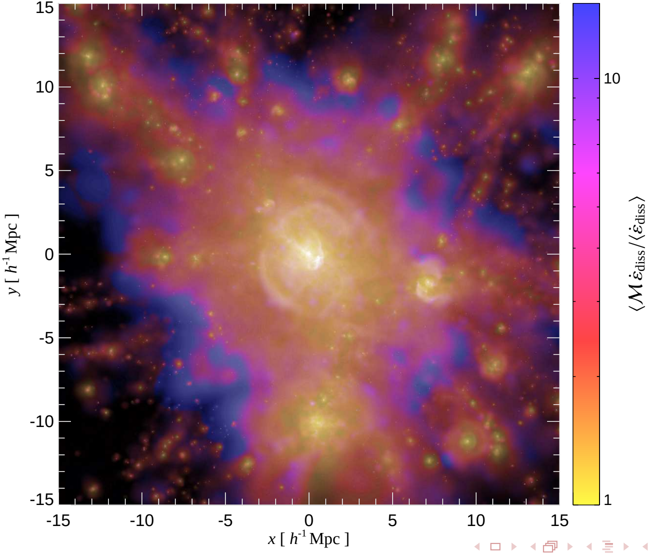


Diffusive shock acceleration – efficiency (2)

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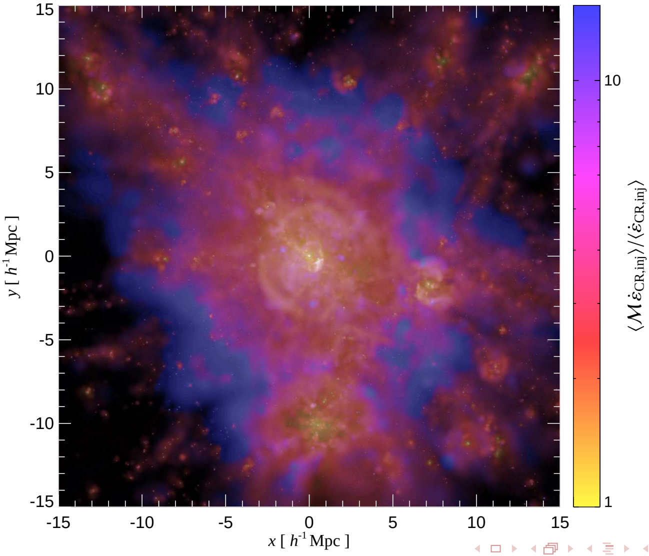
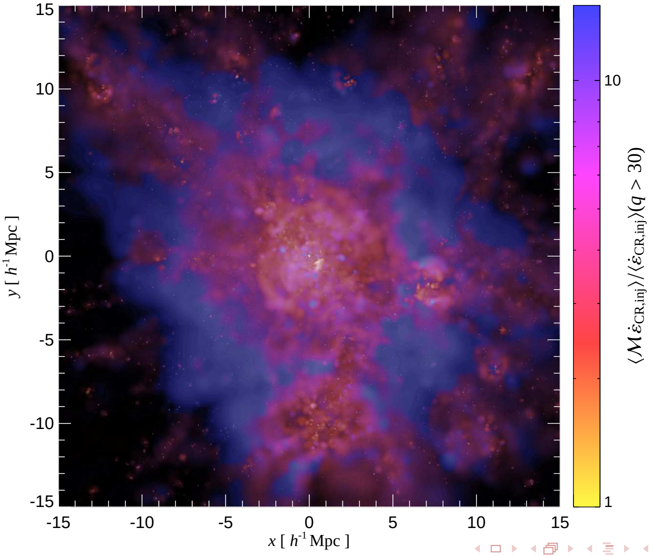
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$



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



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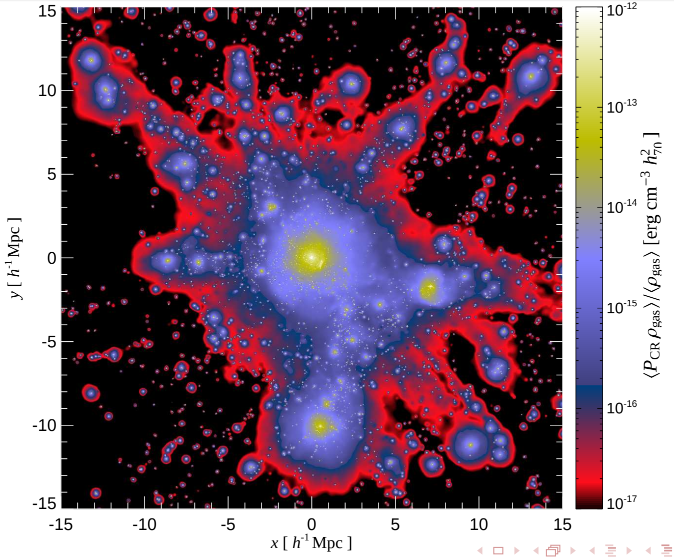
CR pressure P_{CR}



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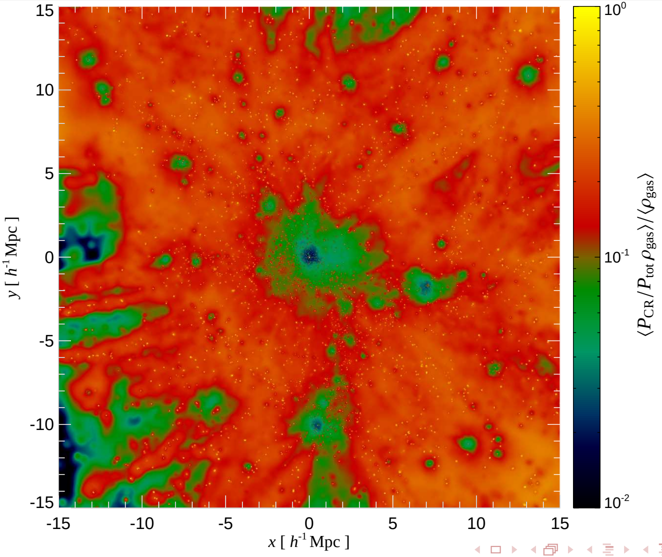
Relative CR pressure $P_{\mathrm{CR}}/P_{\mathrm{total}}$



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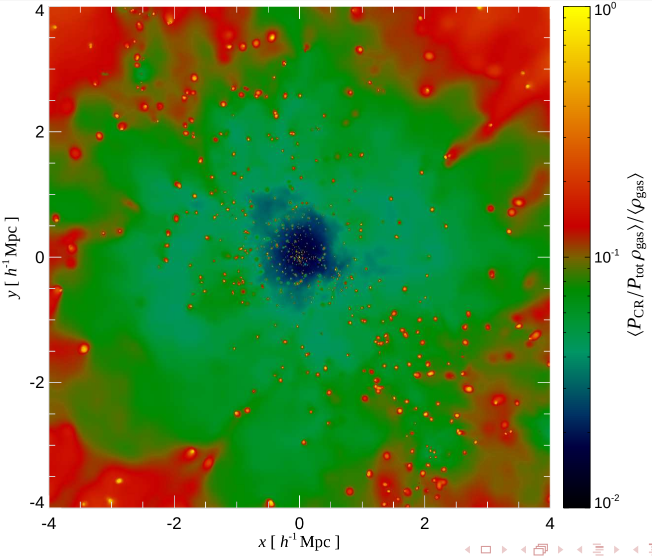

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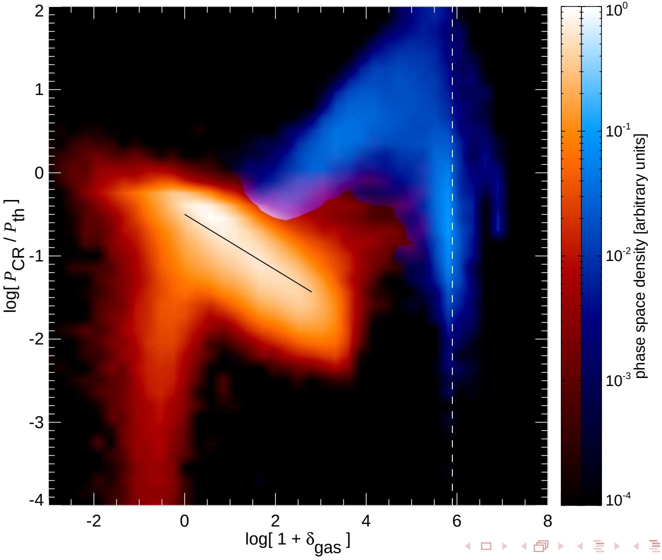
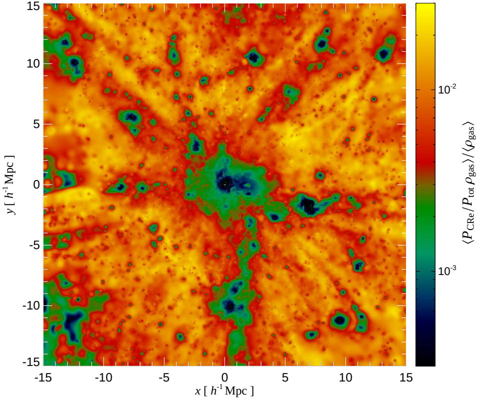
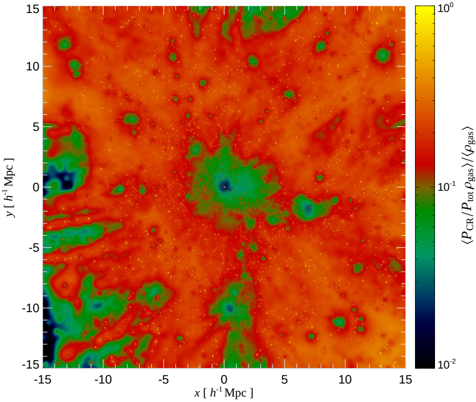
CR phase-space diagram: final distribution @ $z = 0$



CR electron versus CR proton pressure





Relative pressure of primary CR electrons.

Relative pressure of CR protons.

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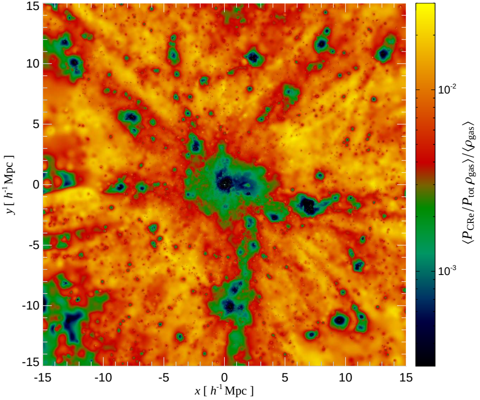
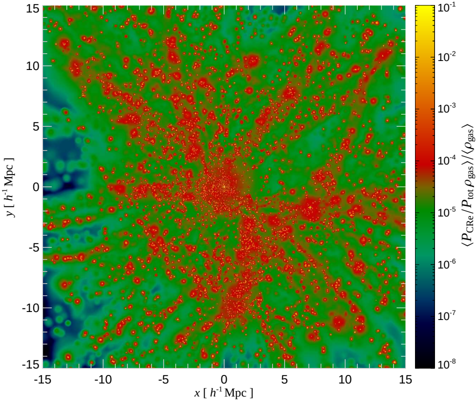
Primary versus secondary CR electrons



Relative pressure of *primary* CR electrons.



Rel. pressure of *secondary* CR electrons.

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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)
- Glast: high-energy γ-ray space mission ($E \simeq (0.1 - 300)$ GeV)
- Imaging air Čerenkov telescopes ($E \simeq (0.1 - 100)$ TeV)

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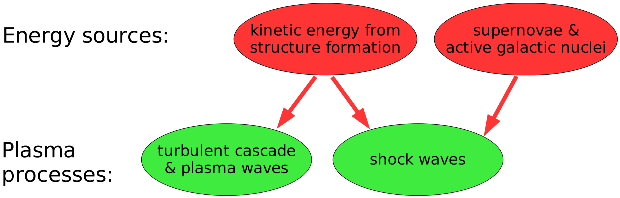
Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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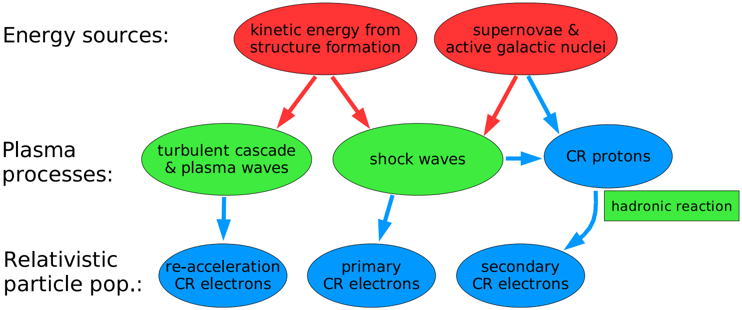

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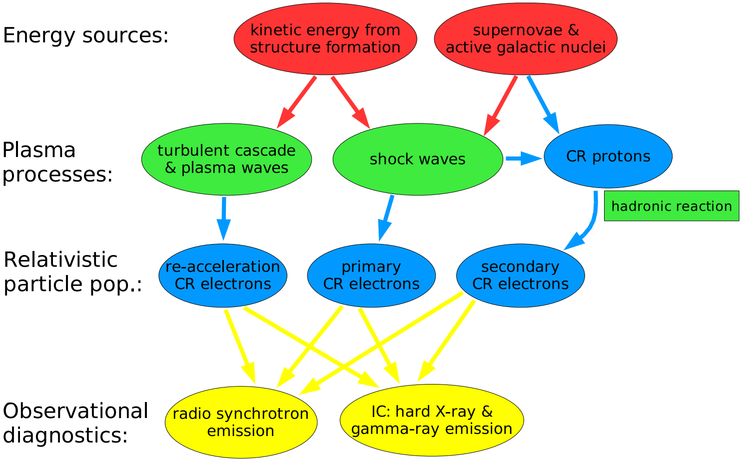

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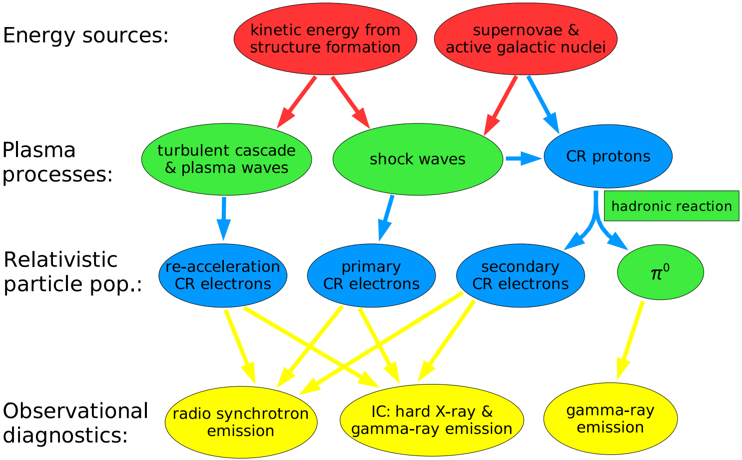

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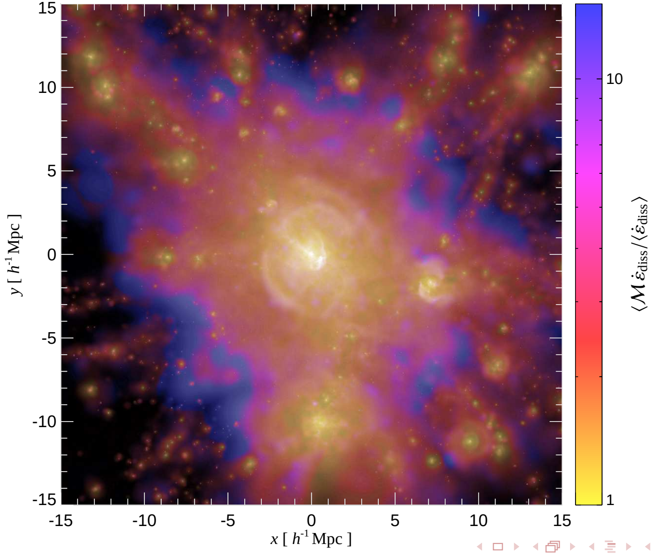
Cosmic web: Mach number



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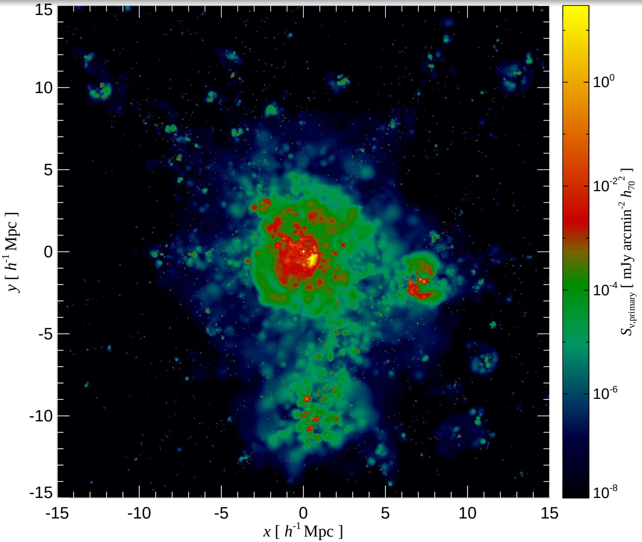
Radio gischt (relics): primary CRe (1.4 GHz)



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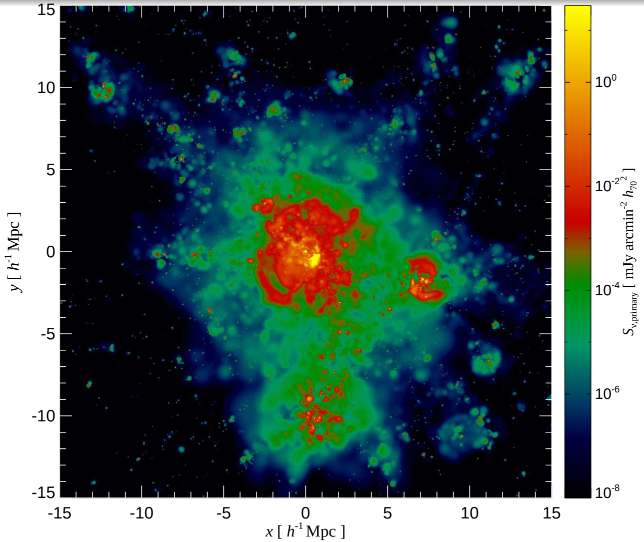
Radio gischt: primary CRe (150 MHz)



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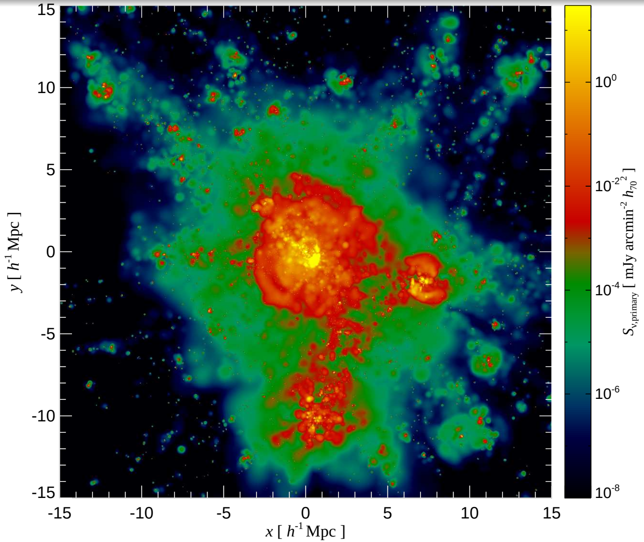
Radio gischt: primary CRe (15 MHz)



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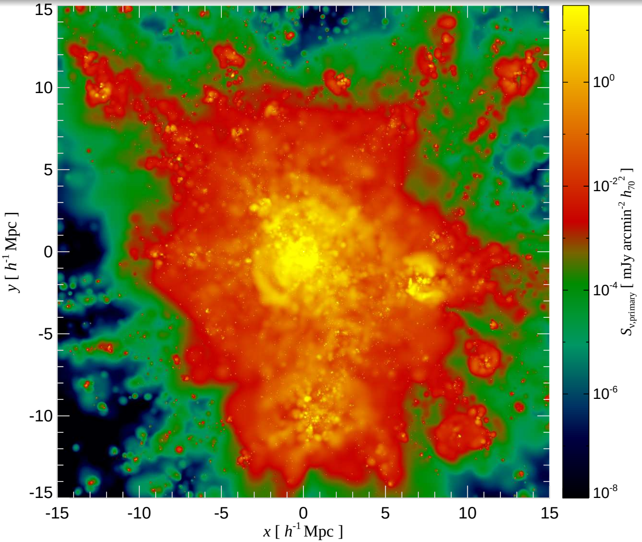
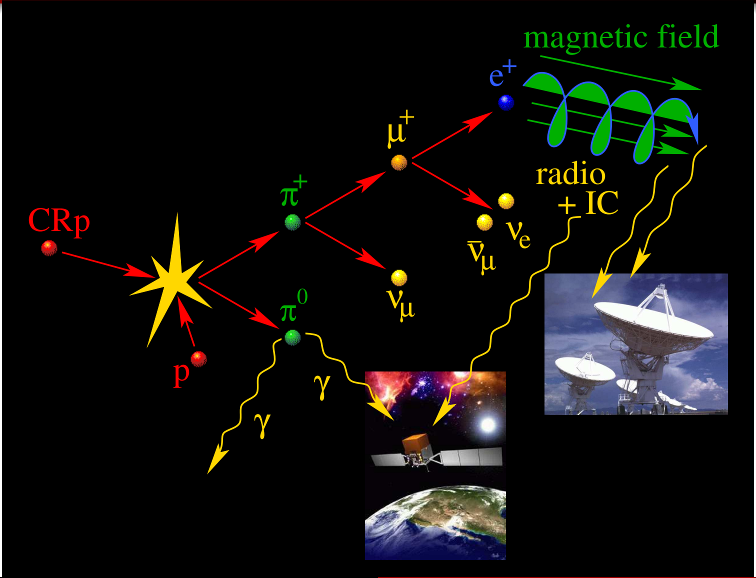
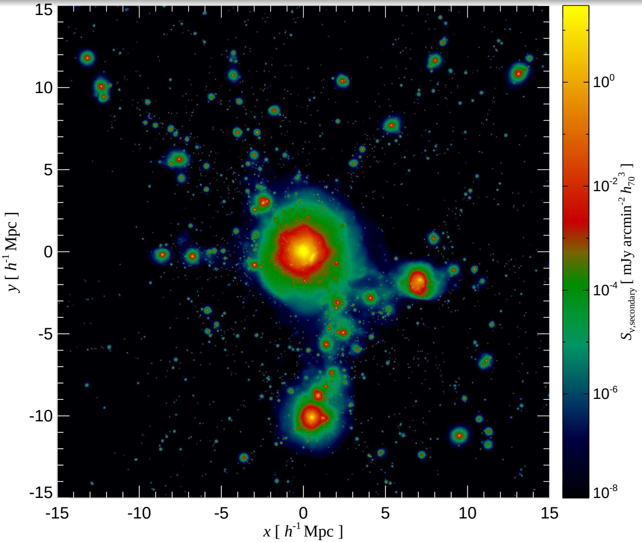
Radio gischt: primary CRe (15 MHz), slower magnetic decline



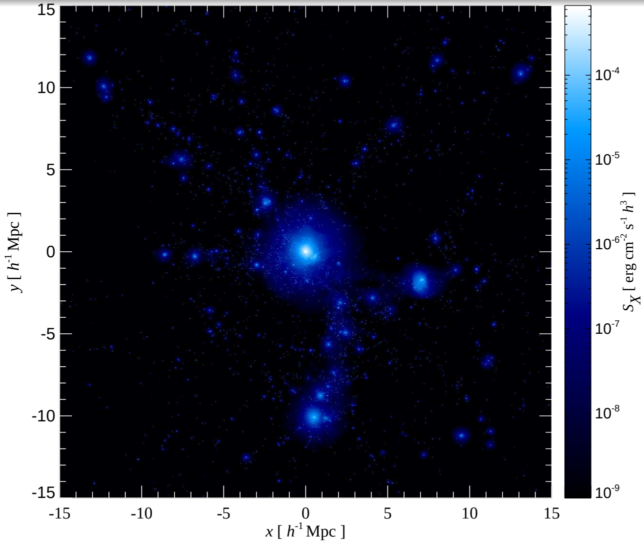
Hadronic cosmic ray proton interaction



Cluster radio emission by hadronically produced CRe



Thermal X-ray emission



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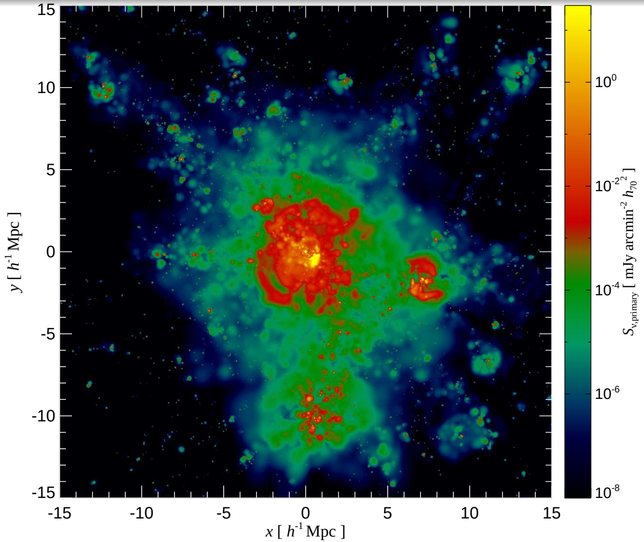
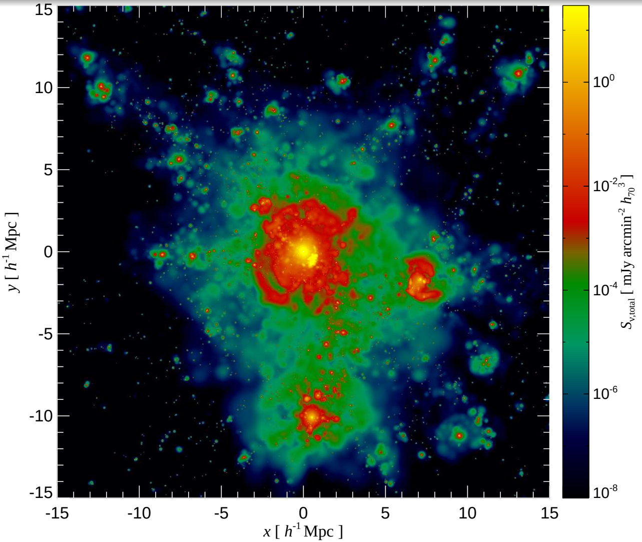
Radio gischt: primary CRe (150 MHz)



Radio gischt + central hadronic halo = giant radio halo



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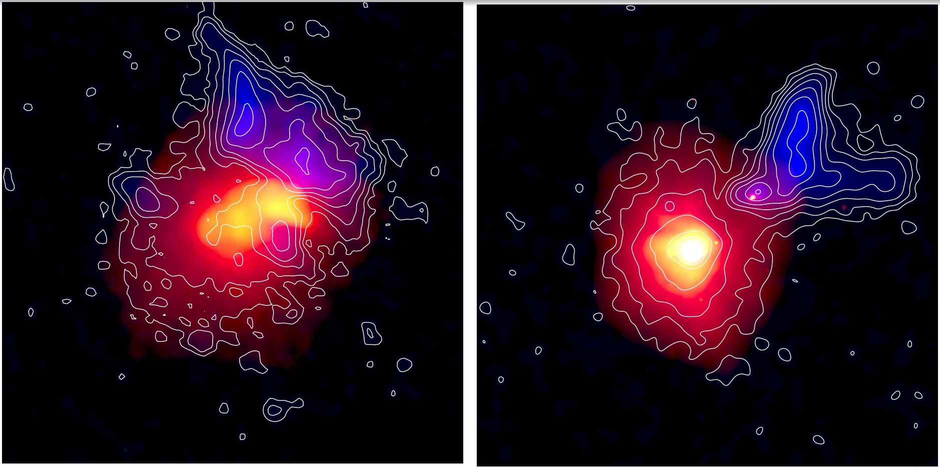
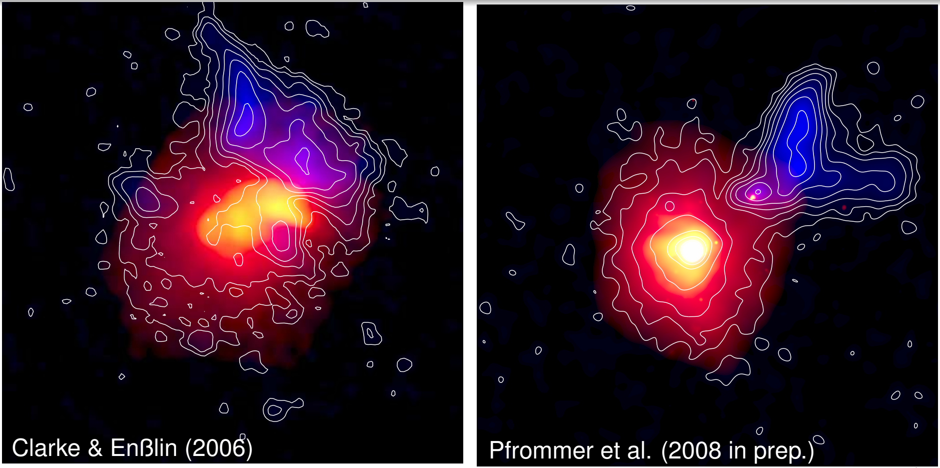
Which one is the simulation/observation of A2256?



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

Observation – simulation 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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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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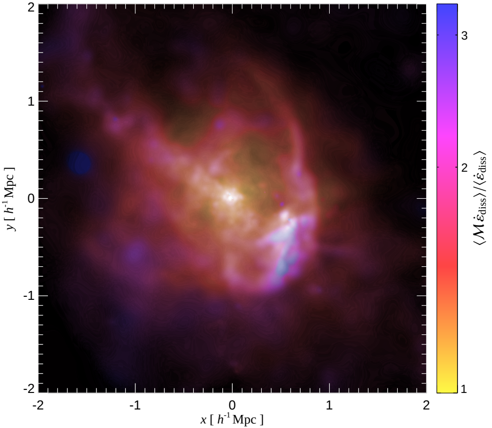
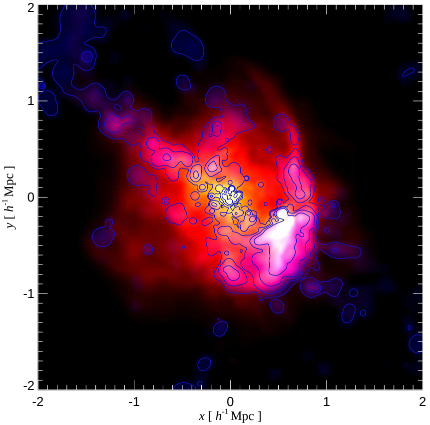
Radio gischt illuminates cosmic magnetic fields





Structure formation shocks triggered by a recent merger of a large galaxy cluster.

red/yellow: shock-dissipated energy, blue/contours: 150 MHz radio gischt emission from shock-accelerated CRe

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Diffuse cluster radio emission – an inverse problem

Exploring the magnetized cosmic web

Battaglia, Pfrommer, Sievers, Bond, Enßlin (2008):
By suitably combining the observables associated with diffuse polarized radio emission at low frequencies ($\nu \sim$ 150 MHz, GMRT/LOFAR/MWA/LWA), we can probe

- the strength and coherence scale of magnetic fields on scales of galaxy clusters,
- the process of diffusive shock acceleration of electrons,
- the existence and properties of the WHIM,
- the exploration of observables beyond the thermal cluster emission which are sensitive to the dynamical state of the cluster.

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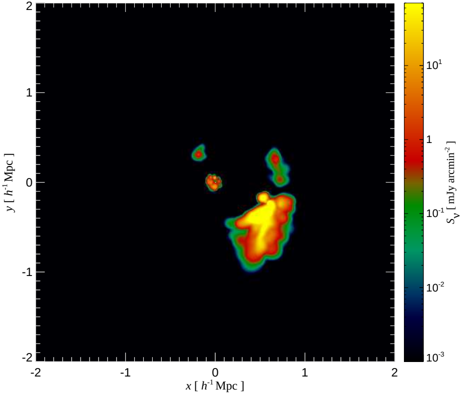
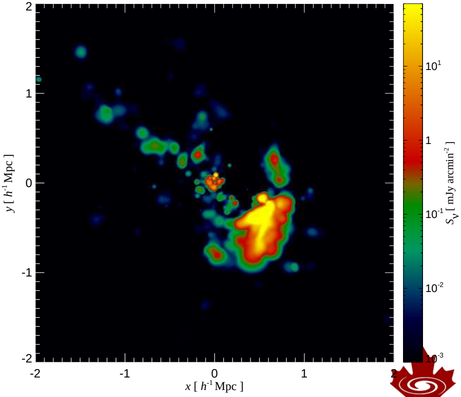
Population of faint radio relics in merging clusters

Probing the large scale magnetic fields

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



radio map with GMRT emissivity threshold



“theoretical” threshold (towards SKA)

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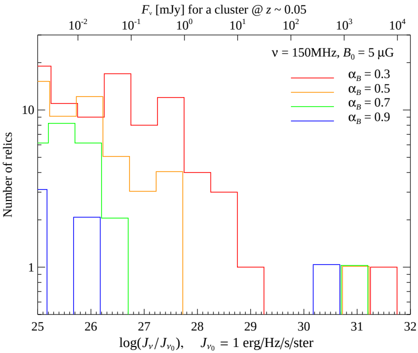
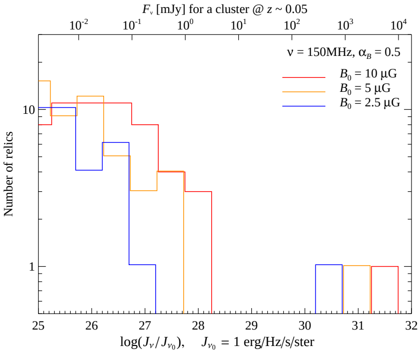
Relic luminosity function – theory

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



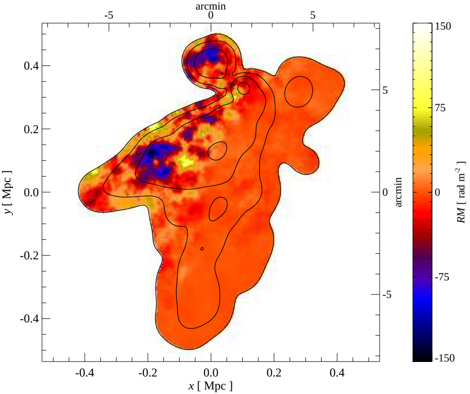
varying magnetic decline with radius

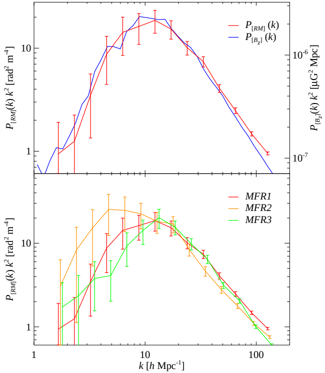


varying overall normalization of the magnetic field

Rotation measure (RM)

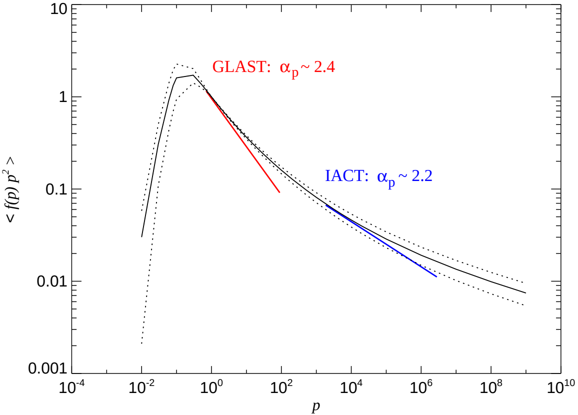
RM maps and power spectra have the potential to infer the magnetic pressure support and discriminate the nature of MHD turbulence in clusters:





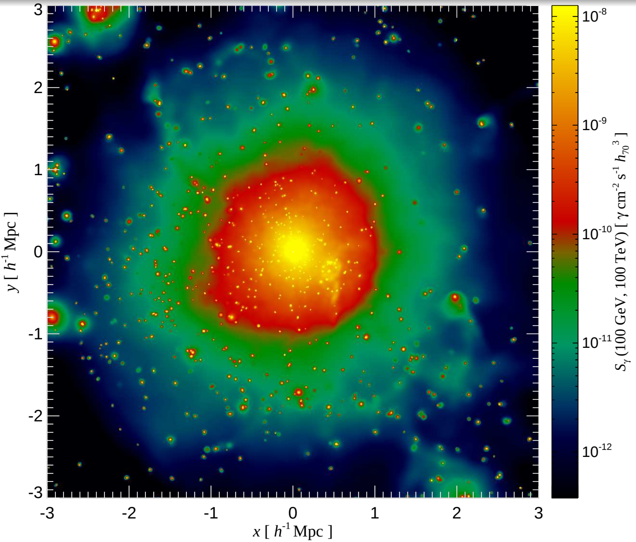
Left: RM map of the largest relic, right: Magnetic and RM power spectrum comparing Kolmogorow and Burgers turbulence models.

Universal CR spectrum in clusters



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

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



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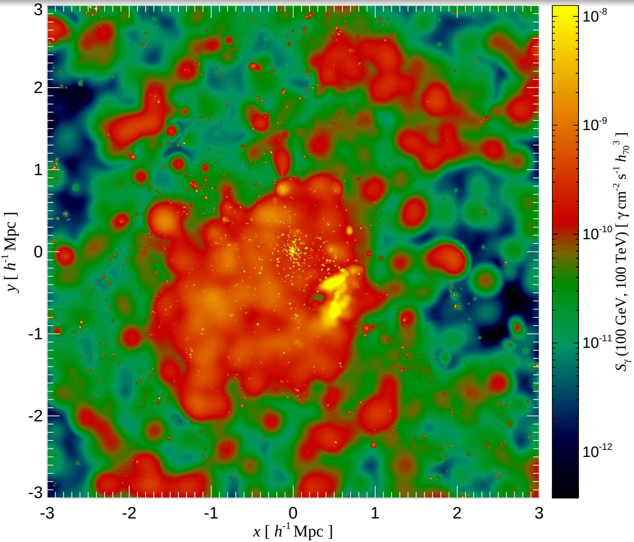
Inverse Compton emission, $E_{\mathrm{IC}} > 100$ GeV



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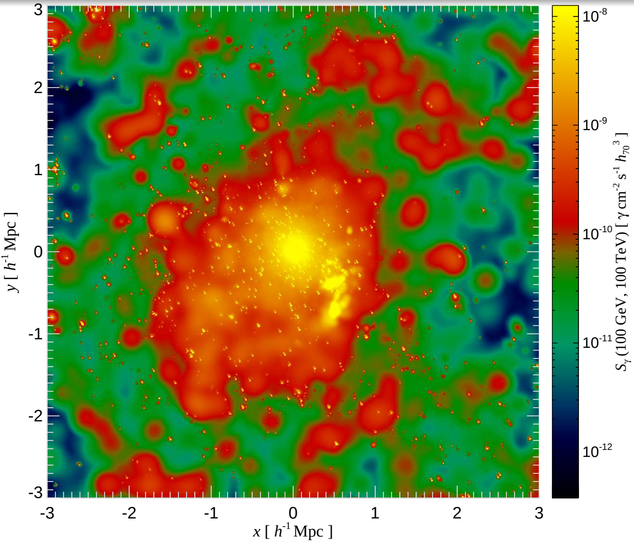
Total γ-ray emission, $E_\gamma > 100$ GeV



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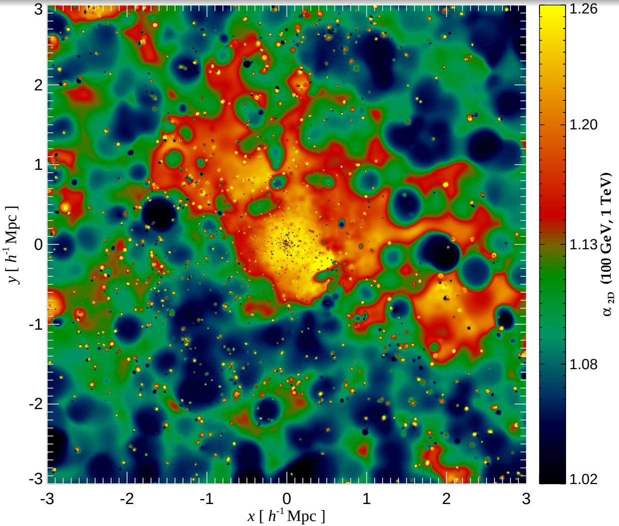
Photon index $\Gamma_{100\ \mathrm{GeV}}^{1\ \mathrm{TeV}}$



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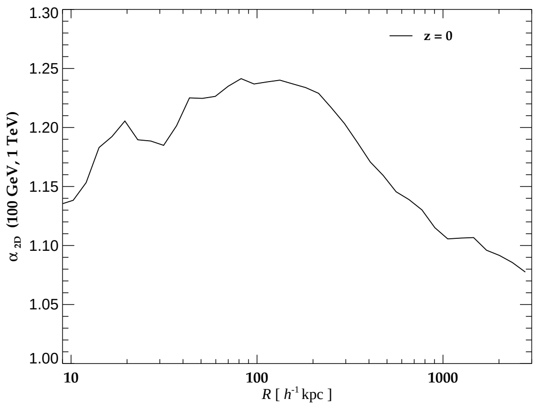
Profile of photon index $\Gamma_{100\ \mathrm{GeV}}^{1\ \mathrm{TeV}}$



Smooth variation of Γ: inner parts dominated by pion decay, transition to primary IC from formation shocks at cluster periphery and WHIM

→ bright prospects for DM annihilation! (Pinzke & Pfrommer, in prep.)

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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 cluster for precision cosmology

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Literature for the talk

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- 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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