# Illuminating cosmological formation shocks

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in collaboration with

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# Outline

1. Cosmological structure formation shocks
   - Cosmological galaxy cluster simulations
   - Mach numbers and shock acceleration
   - Cosmic ray transport and distribution
2. Non-thermal processes in clusters
   - General picture
   - Shock related emission
   - Hadronically induced emission
3. Plasma and particle astrophysics
   - The magnetized cosmic web
   - High-energy $\gamma$-ray emission
   - Conclusions

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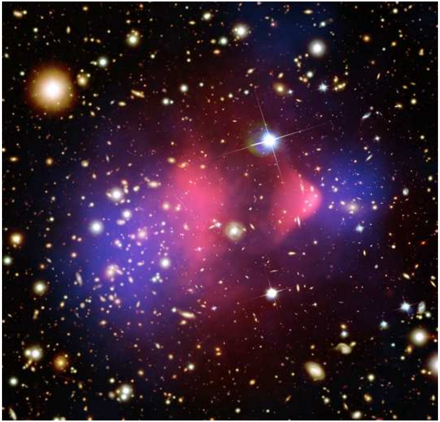
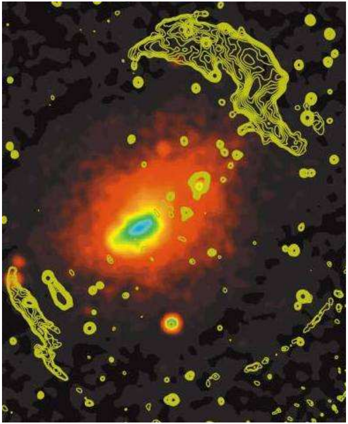
# Shocks in galaxy clusters



## 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, $\gamma$-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 $\gamma$-rays
- gold sample of cluster for precision cosmology: gauging non-thermal observables
- fundamental plasma physics:
  - diffusive shock acceleration for high-$\beta$ plasmas
  - origin and evolution of large scale magnetic fields
  - nature of turbulent models

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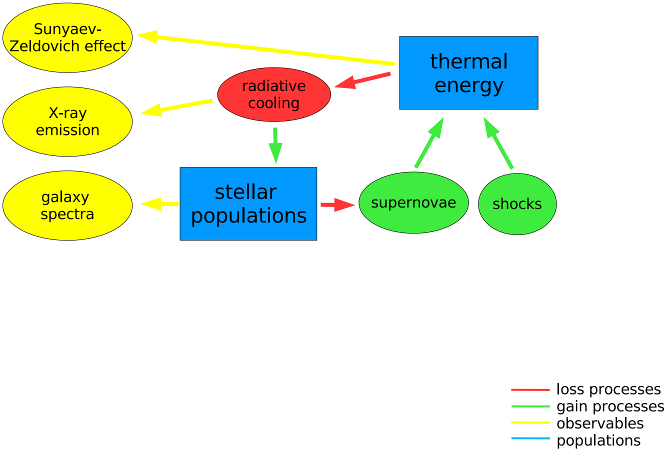
# Radiative simulations – flowchart

Cluster observables: Physical processes in clusters:

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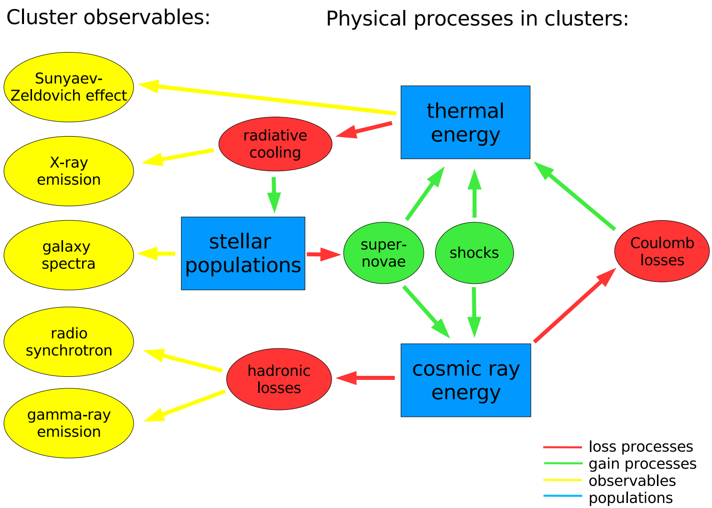
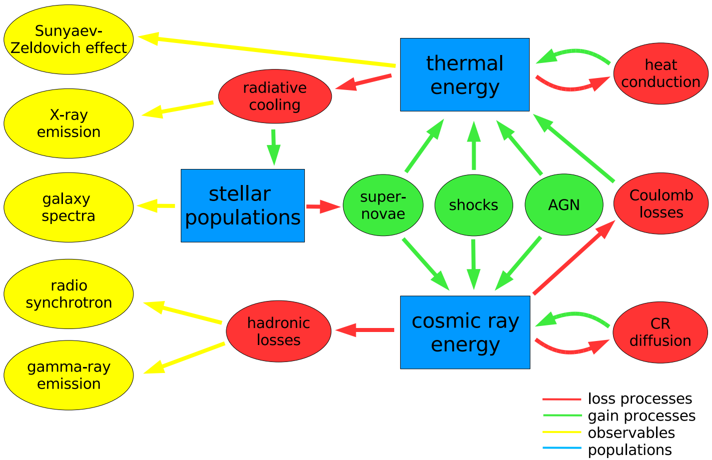
# Radiative simulations with cosmic ray (CR) physics



# Radiative simulations with extended CR physics

Cluster observables:

Physical processes in clusters:

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# 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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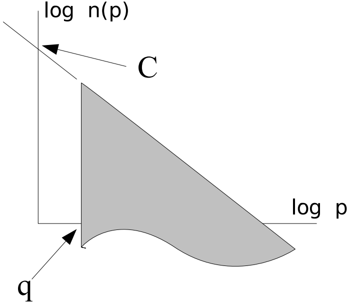
# CR spectral description




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

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

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

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

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

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

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

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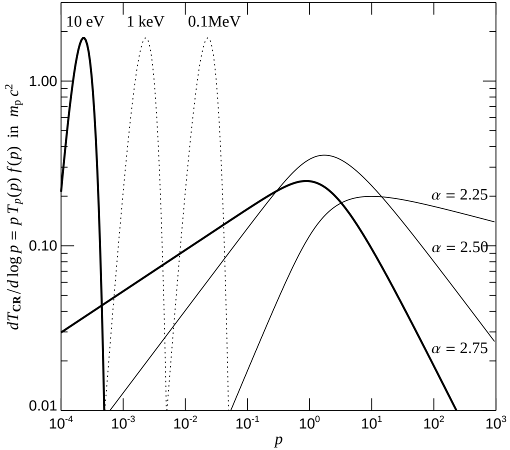
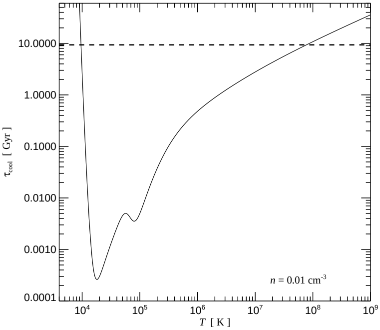
# Thermal & CR energy spectra

Kinetic energy per logarithmic momentum interval:

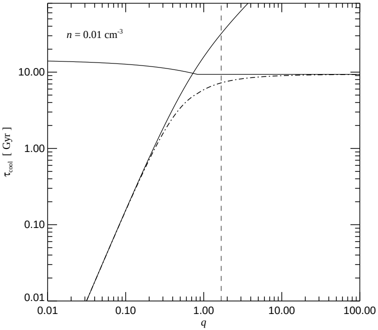


# Cooling time scales of CR protons

## Cooling of primordial gas:




## Cooling of cosmic rays:

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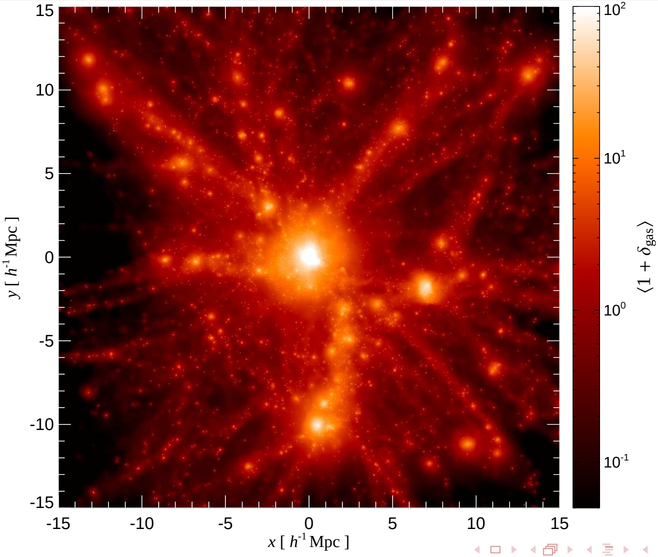
# Radiative cool core cluster simulation: gas density

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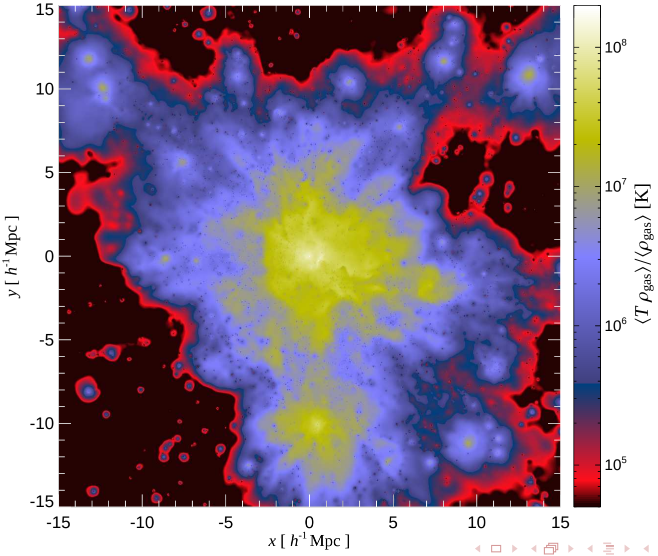
# Mass weighted temperature

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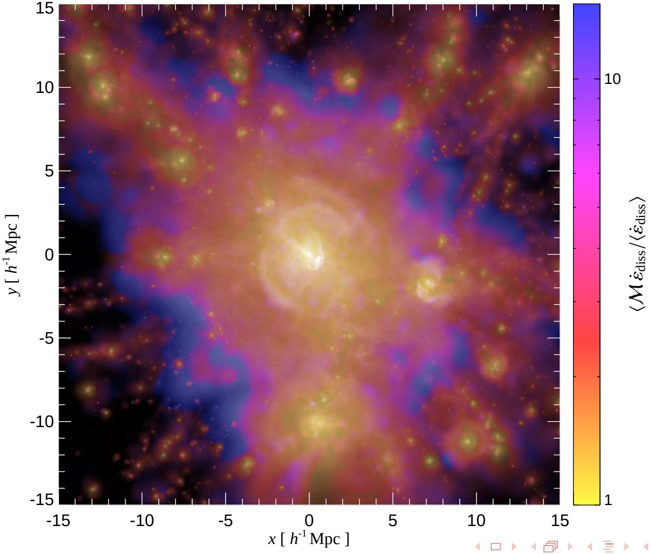
# Mach number distribution weighted by $\varepsilon_{\mathrm{diss}}$

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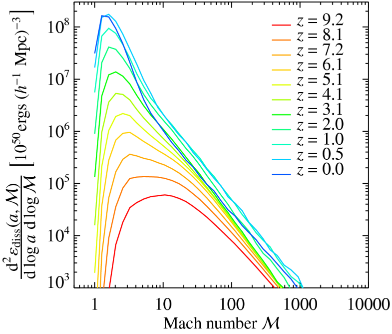
# Previous numerical work on Mach number statistics

- 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.)
- Vazza et al. 2008: Eulerian approach, coarse resolution, Mach number statistics (post-proc.)

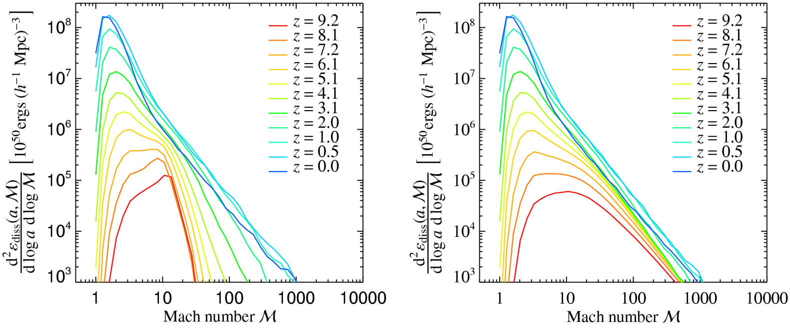
$\rightarrow$ increasing number of papers recently, with more expected to come that focus on the non-thermal emission from clusters and topics related to UHECRs (as we enter a new era of multi-frequency experiments).

# Cosmological shock statistics



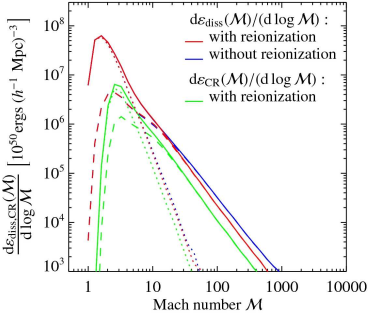

- more energy is dissipated at later times
- mean Mach number decreases with time

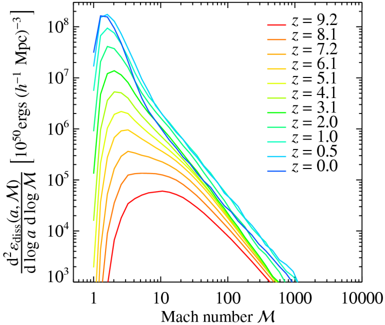
# Cosmological shock statistics: influence of reionization




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

# 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)

conditions:

- a collisionless shock wave
- magnetic fields to confine energetic particles
- plasma waves to scatter energetic particles → particle diffusion
- supra-thermal particles

mechanism:

- supra-thermal particles diffuse upstream across shock wave
- each shock crossing energizes particles through momentum transfer from recoil-free scattering off the macroscopic scattering agents
- momentum increases exponential with number of shock crossings
- number of particles decreases exponential with number of crossings

→ power-law CR distribution

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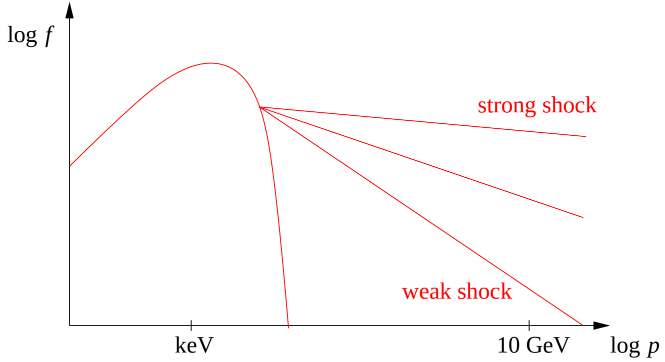
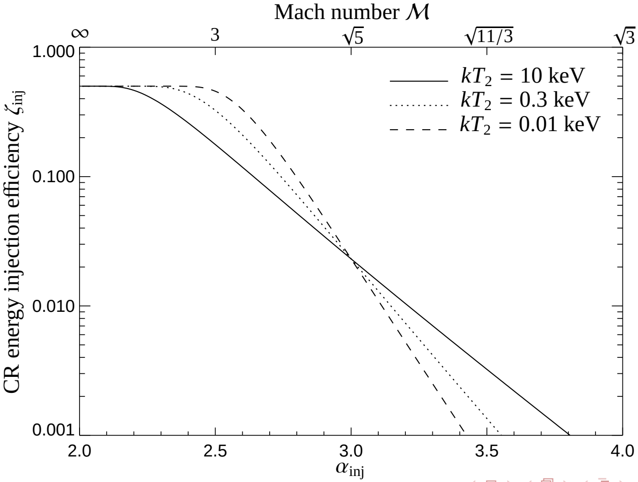
# Diffusive shock acceleration – Fermi 1 mechanism (2)

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

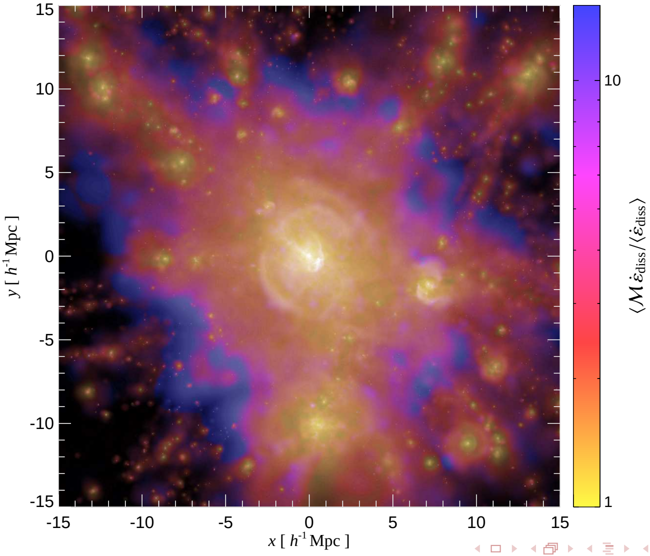


# Diffusive shock acceleration – efficiency (3)

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



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

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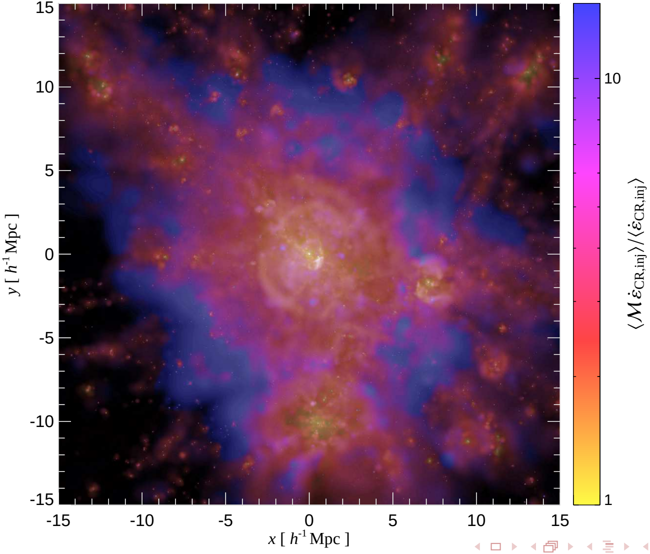
# Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$

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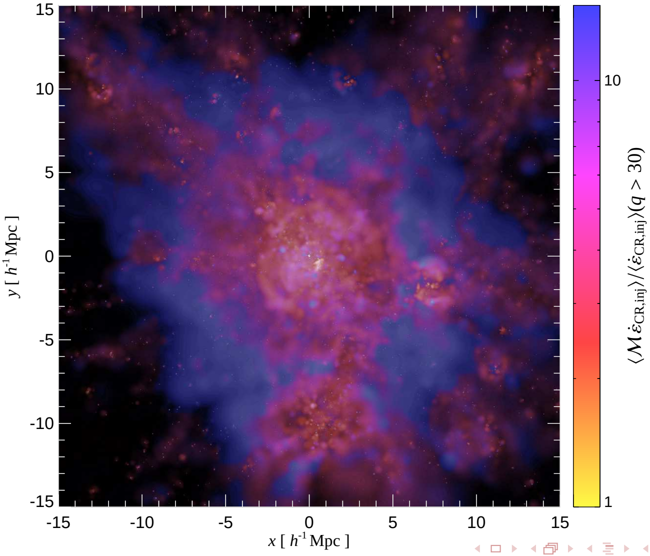
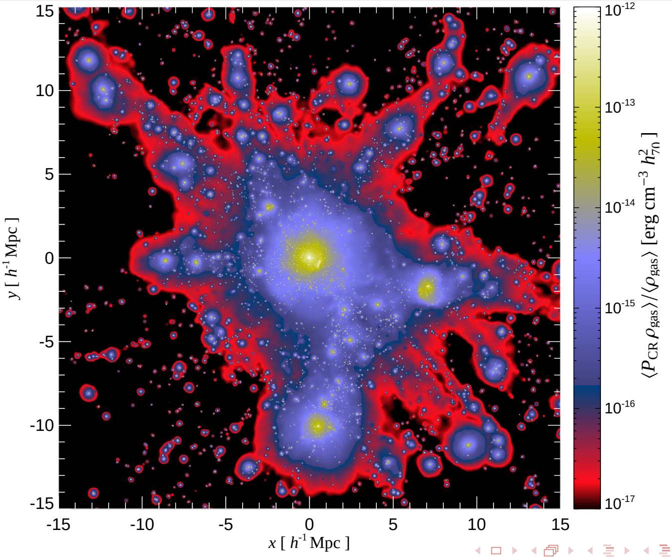
# Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}(q > 30)$



# CR pressure $P_{CR}$

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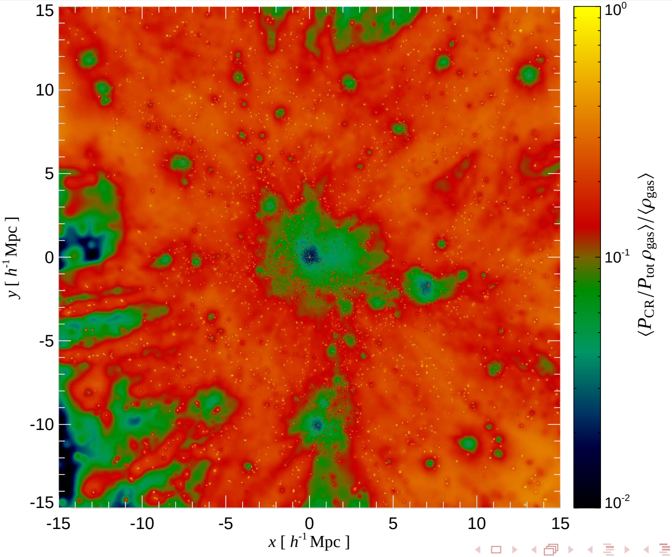
# Relative CR pressure $P_{\rm CR}/P_{\rm total}$



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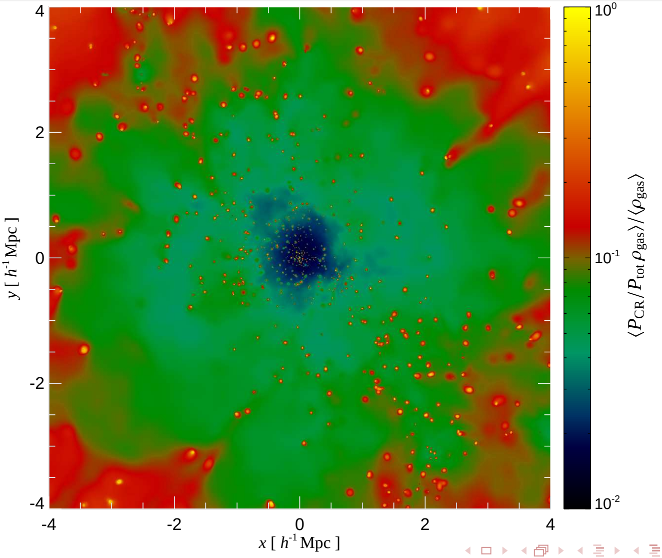


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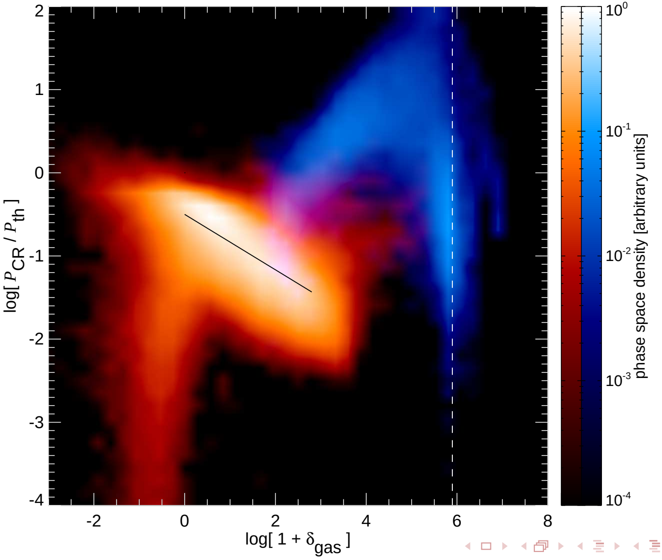
# CR phase-space diagram: final distribution @ $z = 0$

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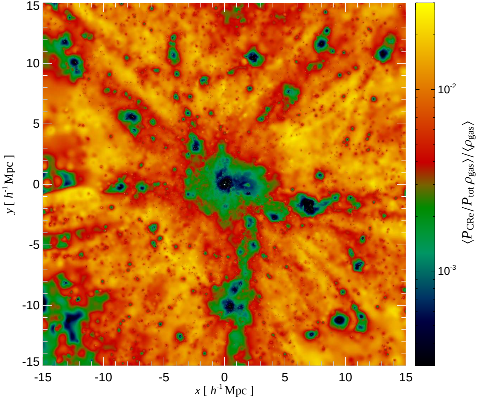
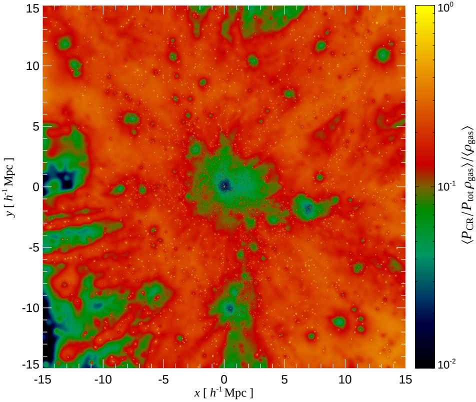
# CR electron versus CR proton pressure




Relative pressure of primary CR electrons.




Relative pressure of CR protons.

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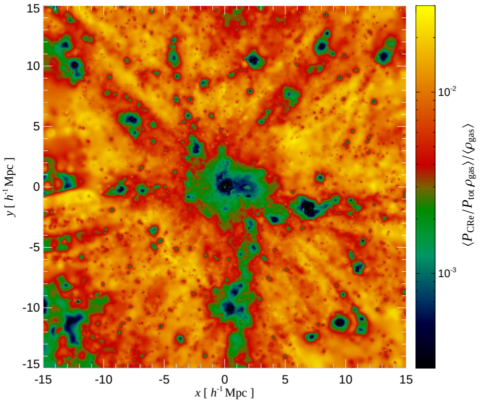
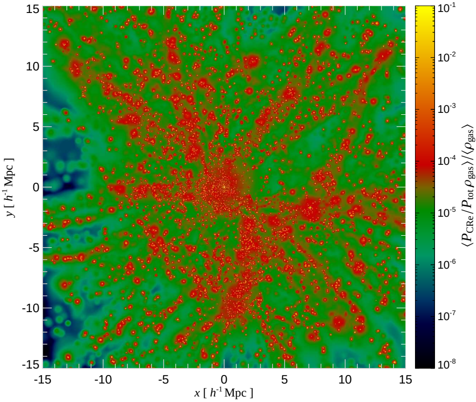
# Primary versus secondary CR electrons




Relative pressure of *primary* CR electrons.




Rel. pressure of *secondary* CR electrons.

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# Outline



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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.:

- 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 $\gamma$-ray space mission ($E \simeq (0.1 - 300)$ GeV)
- Imaging air Čerenkov telescopes ($E \simeq (0.1 - 100)$ TeV)

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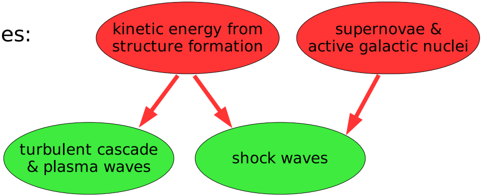
# Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:

Energy sources:

Plasma processes:



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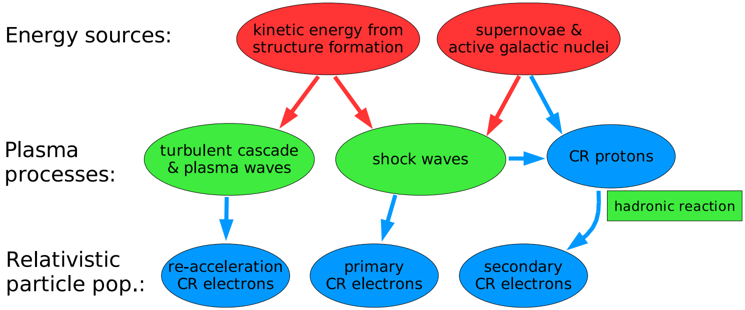

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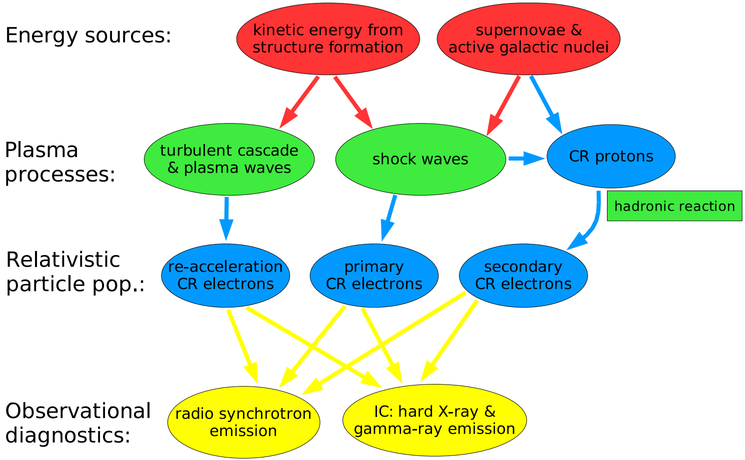

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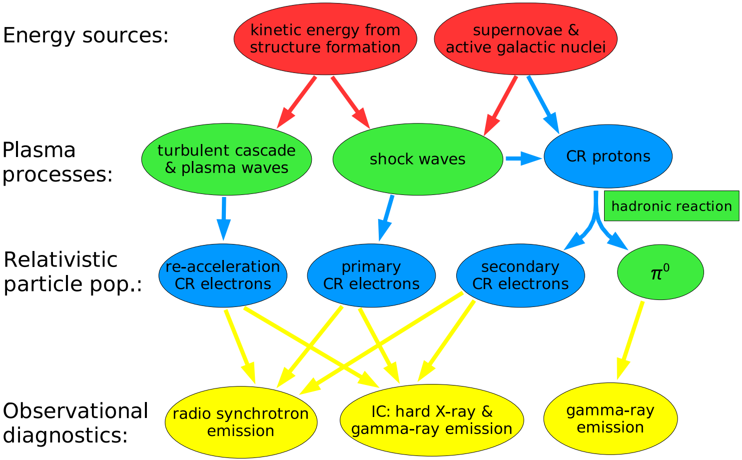


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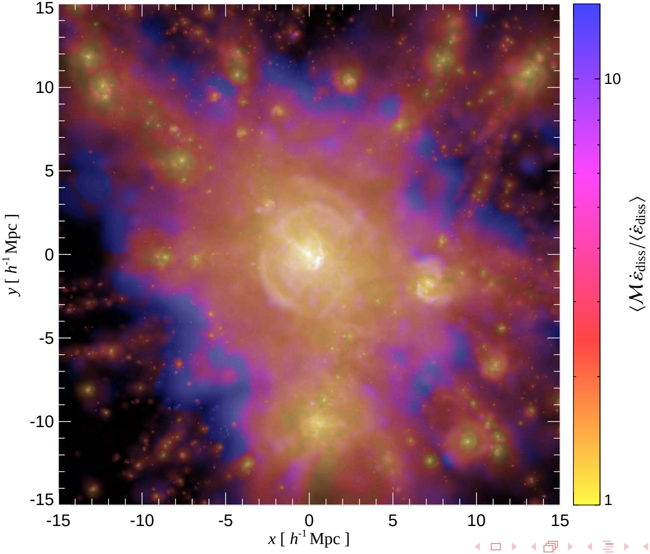
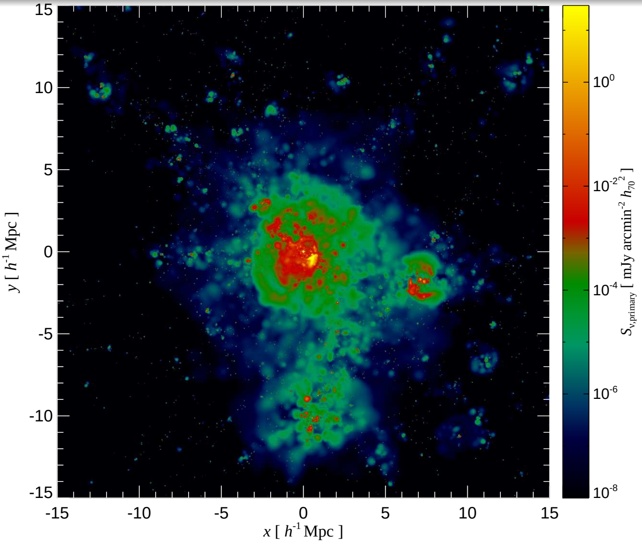
# Cosmic web: Mach number



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

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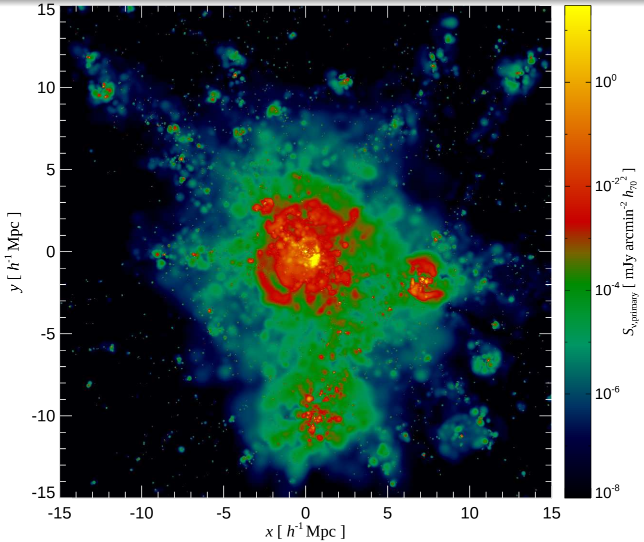
# Radio gischt: primary CRe (150 MHz)

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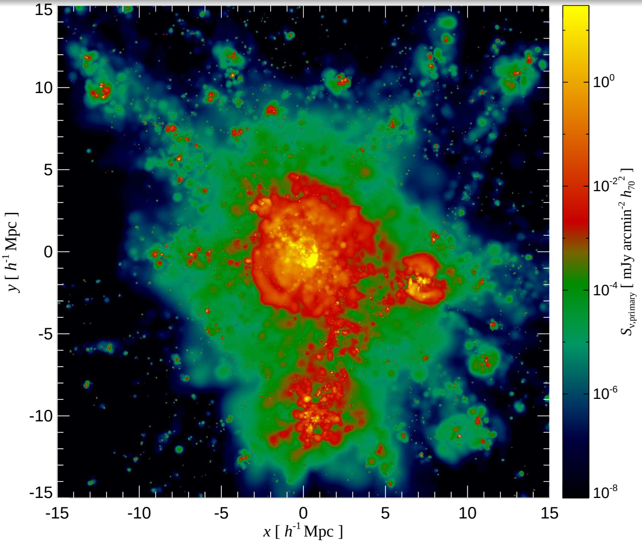
# Radio gischt: primary CRe (15 MHz)

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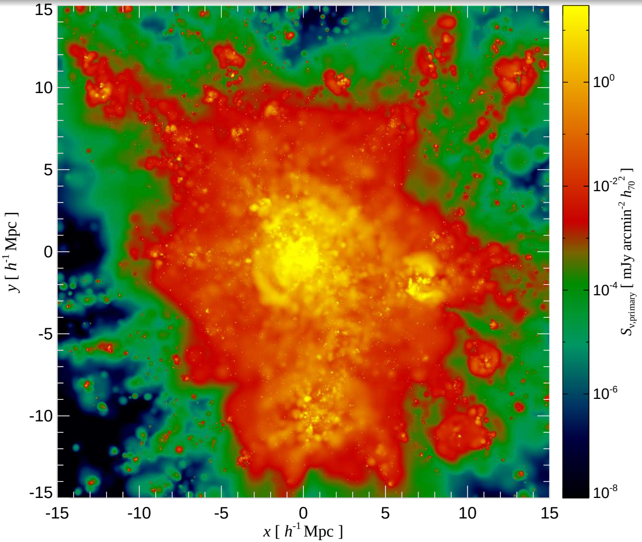
# Radio gischt: primary CRe (15 MHz), slower magnetic decline



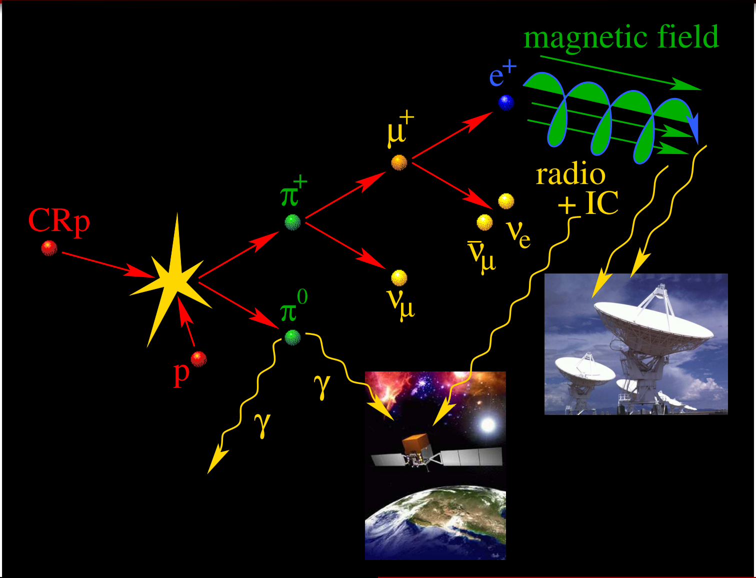
# Particle reactions

relativistic proton populations can often be expected, since

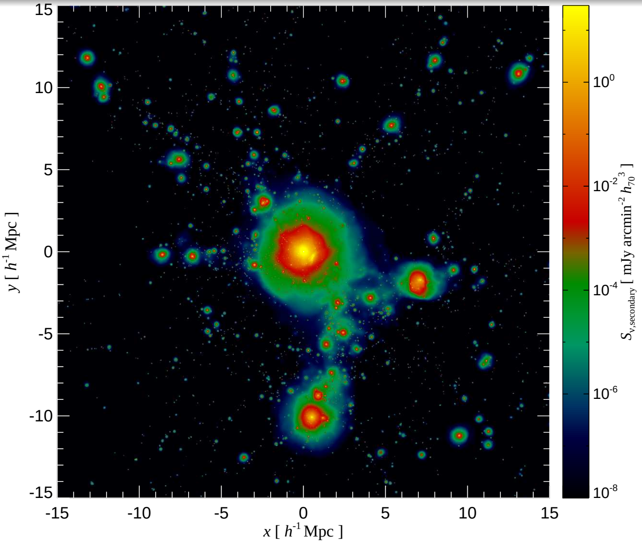
- acceleration mechanisms work for protons . . .
  - . . . as efficient as for electrons (adiabatic compression) or
  - . . . more efficient than for electrons (DSA, stochastic acc.)
- galactic CR protons are observed to have 100 times higher energy density than electrons
- CR protons are very inert against radiative losses and therefore long-lived ($\sim$ Hubble time in galaxy clusters, longer outside)

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

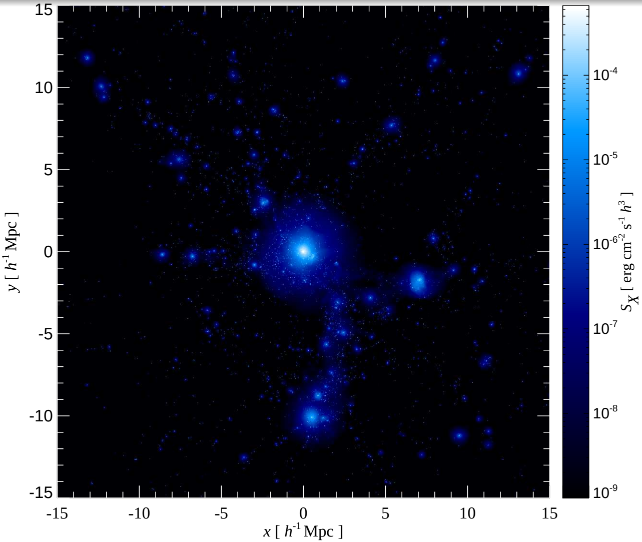
# Hadronic cosmic ray proton interaction



# Cluster radio emission by hadronically produced CRe



# Thermal X-ray emission

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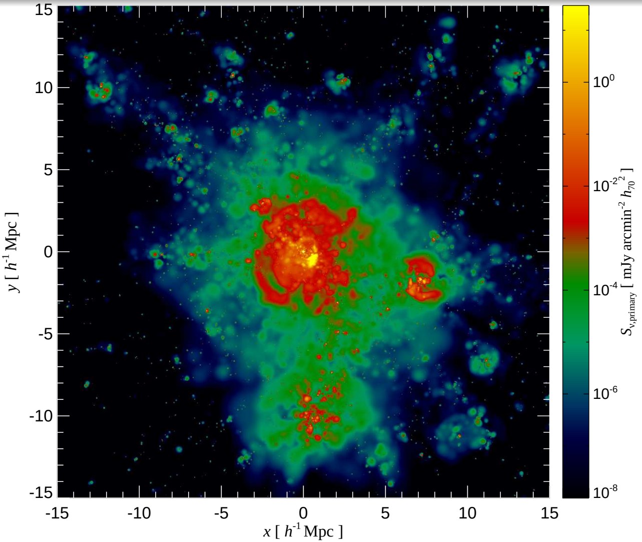


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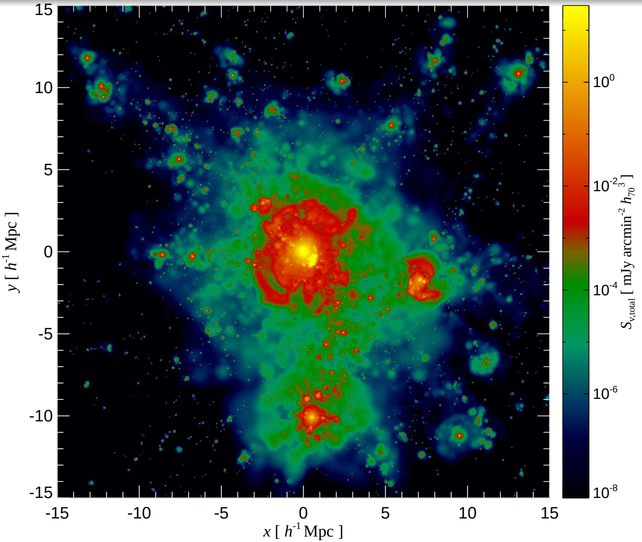
# Radio gischt + central hadronic halo = giant radio halo

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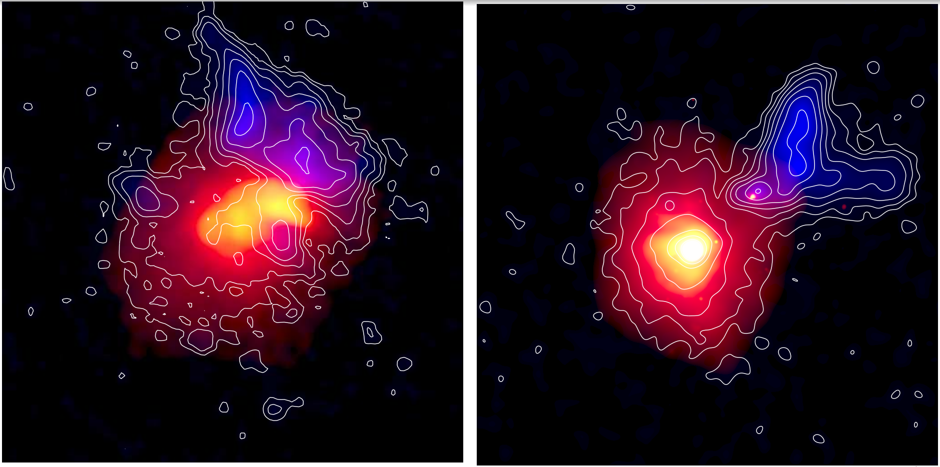
# Which one is the simulation/observation of A2256?



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

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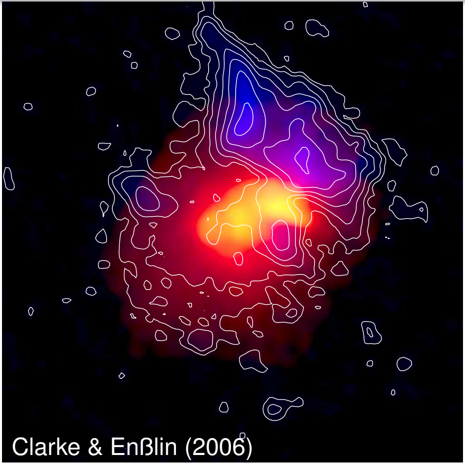
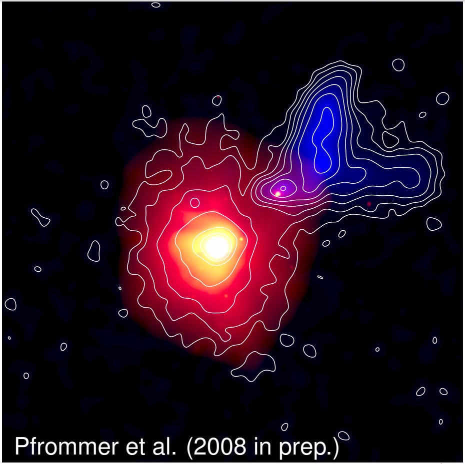
# Observation – simulation of A2256

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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

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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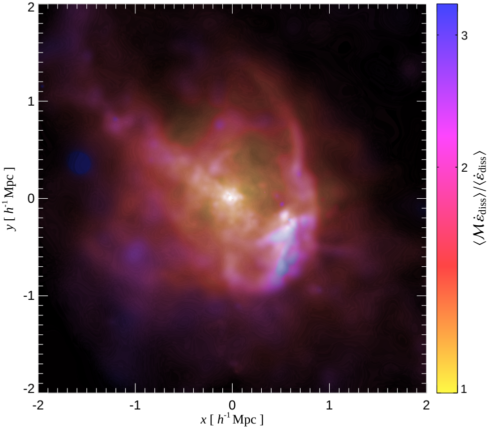
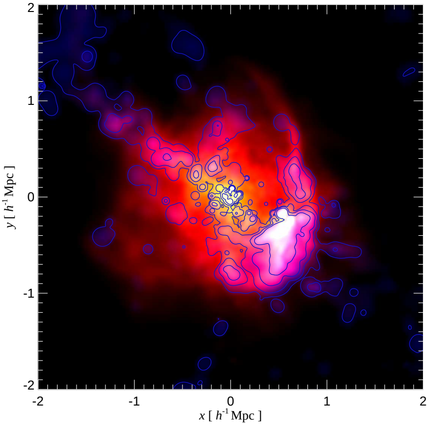
# Outline

1. Cosmological structure formation shocks
   - Cosmological galaxy cluster simulations
   - Mach numbers and shock acceleration
   - Cosmic ray transport and distribution
2. Non-thermal processes in clusters
   - General picture
   - Shock related emission
   - Hadronically induced emission
3. Plasma and particle astrophysics
   - The magnetized cosmic web
   - High-energy $\gamma$-ray emission
   - Conclusions

# 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 polarized low frequency radio emission* from galaxy clusters, we can probe

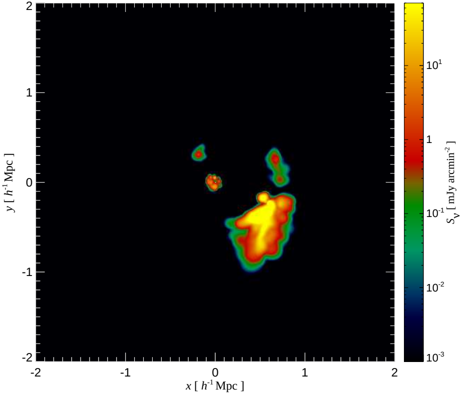
- the strength and coherence scale of magnetic fields on scales of galaxy clusters,
- the process of diffusive shock acceleration of electrons,
- the existence and properties of the WHIM,
- the observables beyond the thermal cluster emission which are sensitive to the dynamical state of the cluster.

* future radio interferometers @ $\nu \sim 150$ MHz: GMRT, LOFAR, MWA, LWA

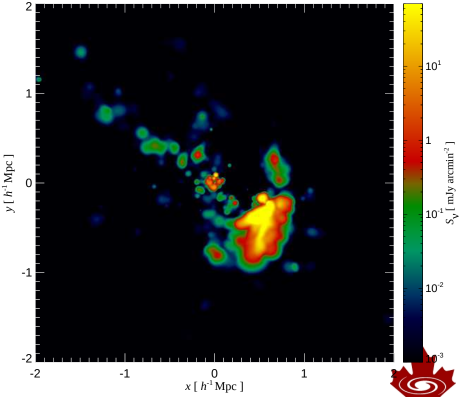
# Population of faint radio relics in merging clusters

## Probing the large scale magnetic fields

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




radio map with GMRT emissivity threshold




"theoretical" threshold (towards SKA)

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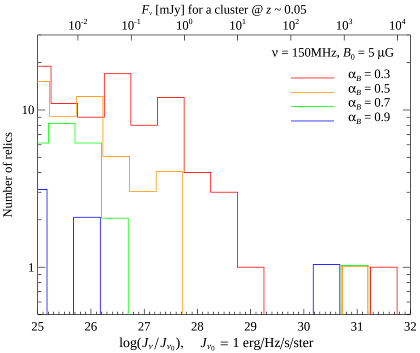
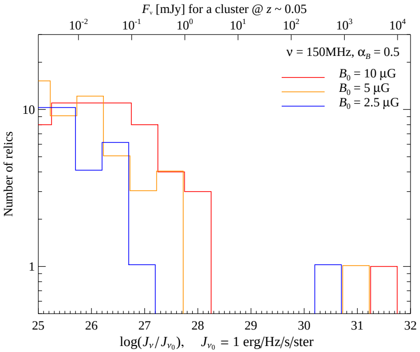
# Relic luminosity function – theory

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

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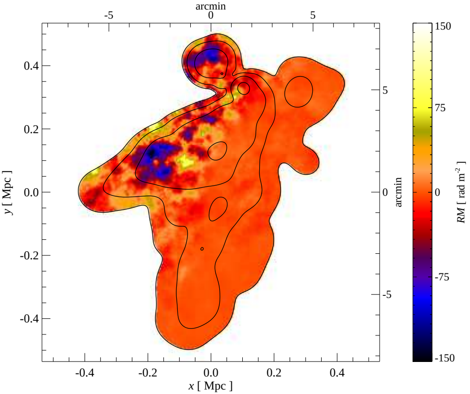
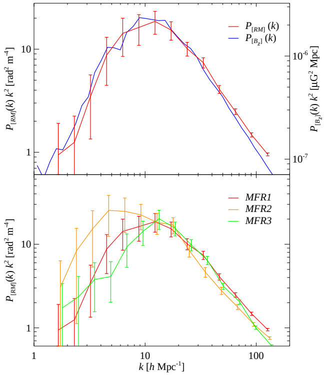
# Rotation measure (RM)

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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# The quest for high-energy $\gamma$-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 $\gamma$-rays
   - spectral and morphological $\gamma$-ray signatures $\rightarrow$ DM properties
3. probes plasma astrophysics:
   - macroscopic parameters for diffusive shock acceleration
   - combination of inverse Compton and radio emission sensitive to magnetic fields

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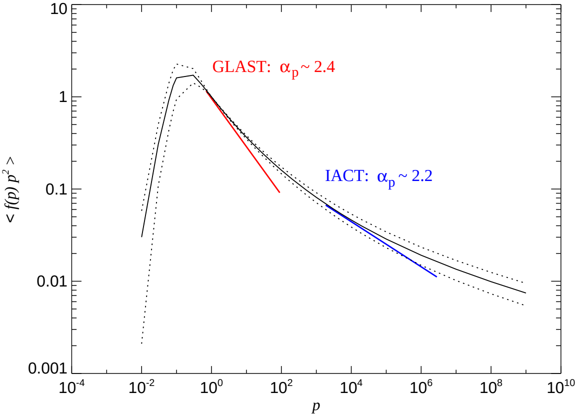
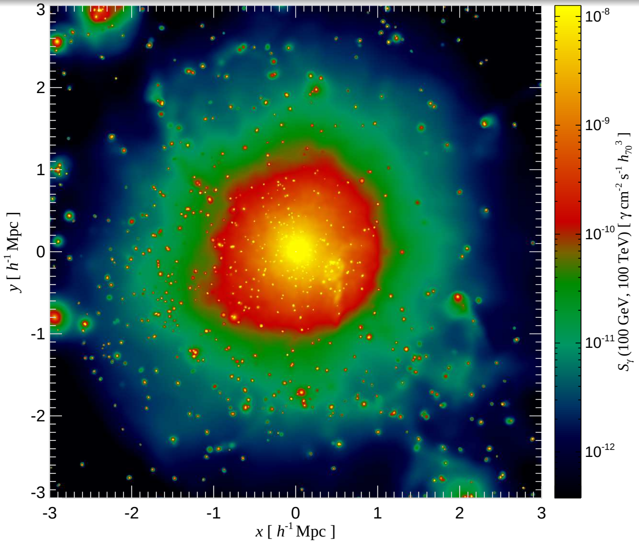
# Universal CR spectrum in clusters




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

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

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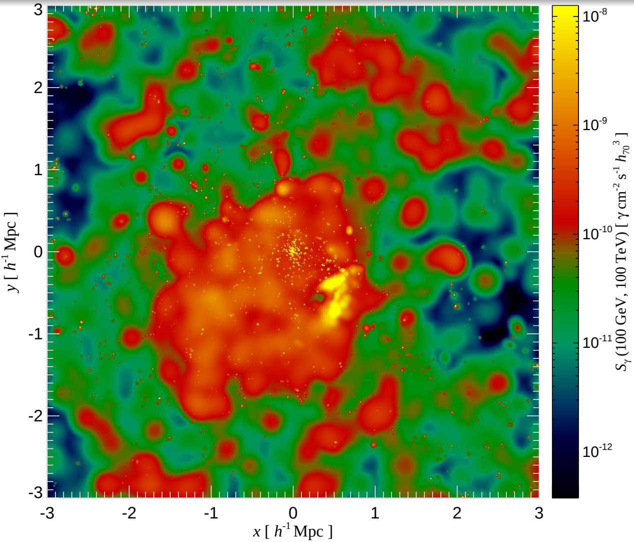
# Inverse Compton emission, $E_{\rm IC} > 100$ GeV

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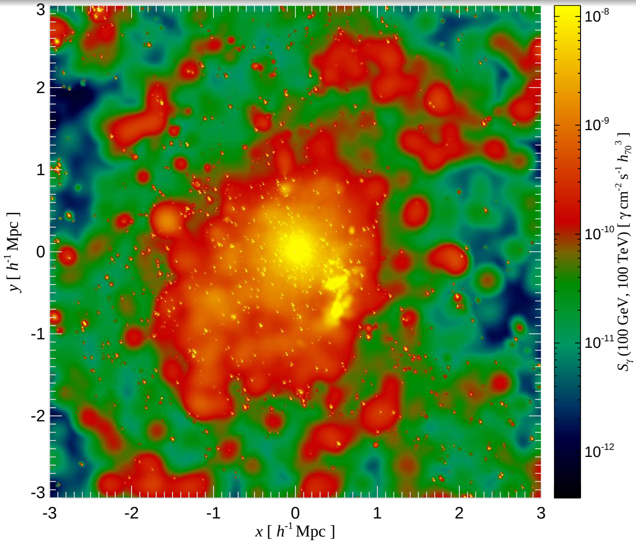
# Total $\gamma$-ray emission, $E_\gamma > 100$ GeV

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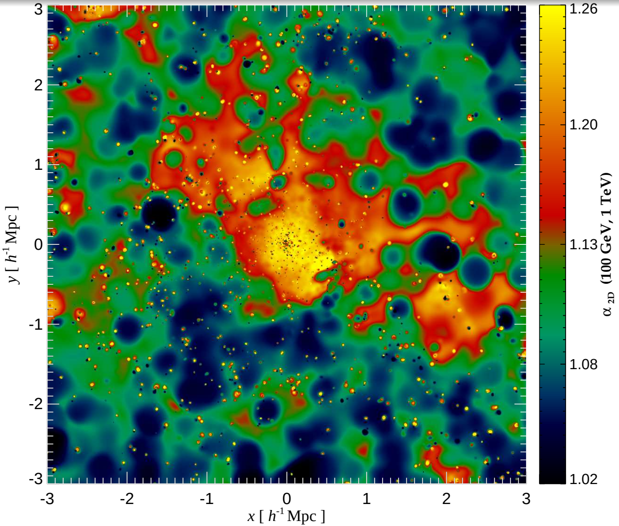
# Photon index $\Gamma^{1\ \mathrm{TeV}}_{100\ \mathrm{GeV}}$

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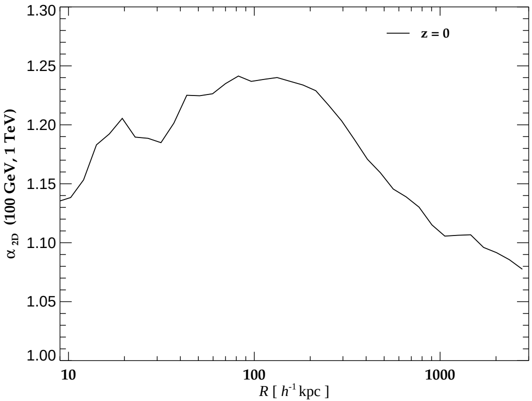
# Profile of photon index $\Gamma^{1\ \mathrm{TeV}}_{100\ \mathrm{GeV}}$




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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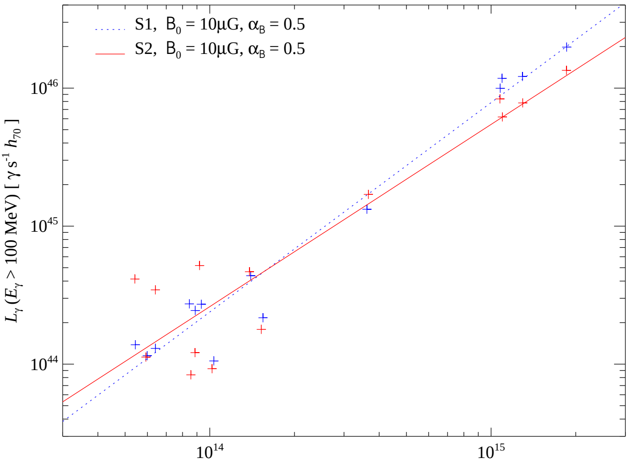
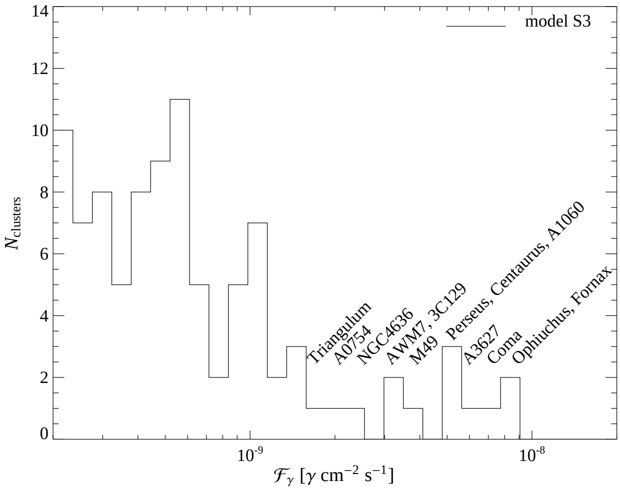
# Gamma-ray scaling relations




Scaling relation + complete sample of the brightest X-ray clusters (HIFLUCGS) $\rightarrow$ predictions for GLAST

# Predicted cluster sample for GLAST

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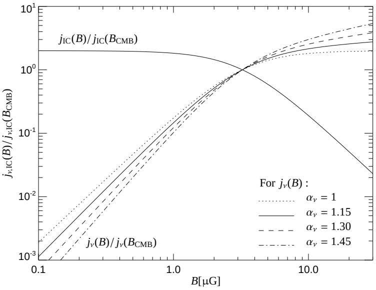
# Minimum $\gamma$-ray flux in the hadronic model (1)




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

Synchrotron luminosity:

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

$\gamma$-ray luminosity:

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

$\rightarrow$ minimum $\gamma$-ray flux:

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

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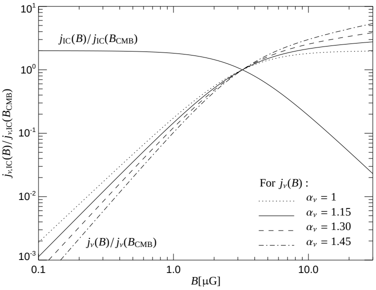
# Minimum $\gamma$-ray flux in the hadronic model (1)

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

$\gamma$-ray luminosity:

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

$\rightarrow$ minimum $\gamma$-ray flux:

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

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# Minimum $\gamma$-ray flux in the hadronic model (2)

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

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

- These limits can be made even tighter when considering energy constraints, $P_B < P_{\rm gas}/20$ and $B$-fields derived from Faraday rotation studies, $B_0 = 3\,\mu$G: $\mathcal{F}_{\gamma,\rm COMA} \gtrsim 2 \times 10^{-9}\gamma\ cm^{-2}s^{-1} = \mathcal{F}_{\rm GLAST,\ 2yr}$
- Non-detection by GLAST seriously challenges the hadronic model.
- Potential of measuring the CR acceleration efficiency for diffusive shock acceleration.

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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 $\gamma$-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, 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*
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