High-Energy Phenomena and Dark Matter Searches in Galaxy Clusters

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in collaboration with

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June 10, 2009 / Ludwig-Maximilians-Universität München

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Outline

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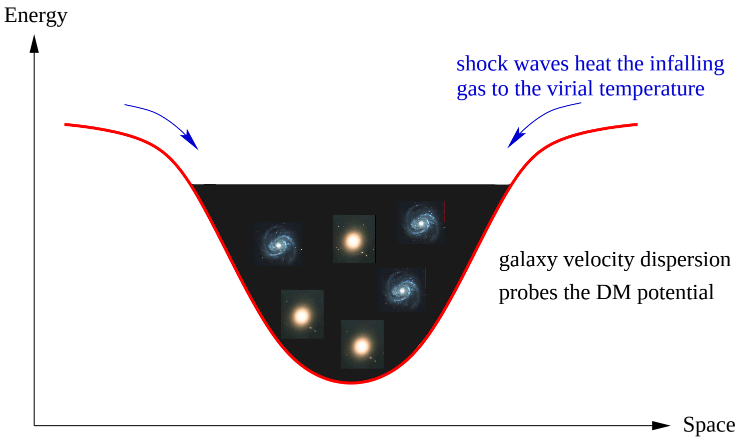
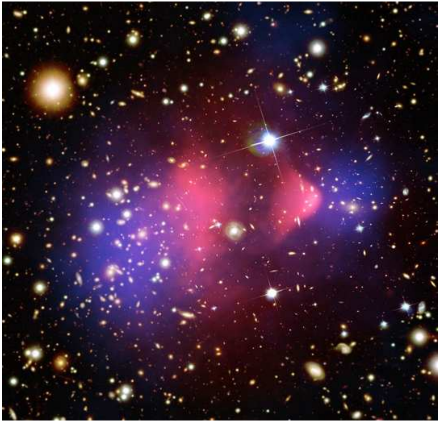
A theorist's perspective of a galaxy cluster . . .

Galaxy clusters are dynamically evolving dark matter potential wells:

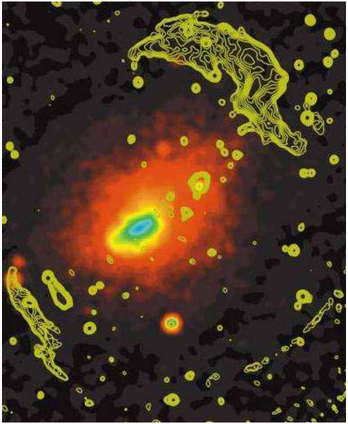


. . . and how the observer's Universe looks like



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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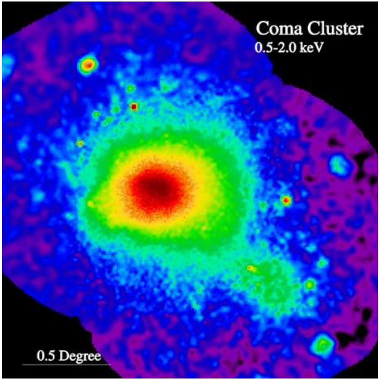
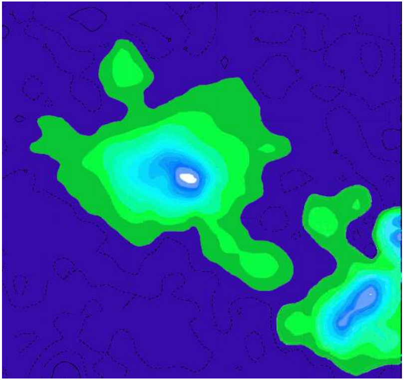
Giant radio halo in the Coma cluster



thermal X-ray emission

(Snowden/MPE/ROSAT)



radio synchrotron emission

(Deiss/Effelsberg)

The talk in a nutshell

Combining non-thermal observables (radio to γ-ray regime) with cosmological simulations provides a novel tool in studying fundamental high-energy/plasma astrophysics, cosmological structure formation, and dark matter:

- radio halos trace cosmic ray protons that are accelerated over cosmic history while the magnetic fields are amplified by a recent merger:
  $\rightarrow$ illuminating the process of structure formation
  $\rightarrow$ origin and evolution of cosmic magnetic fields, diffusive shock acceleration, and turbulence
- Gamma-ray observations might be the most sensitive probes of the smallest cosmological structures:
  $\rightarrow$ if the dark matter interpretation of recent Fermi/Pamela/HESS data is correct, then we live in a warm dark matter Universe

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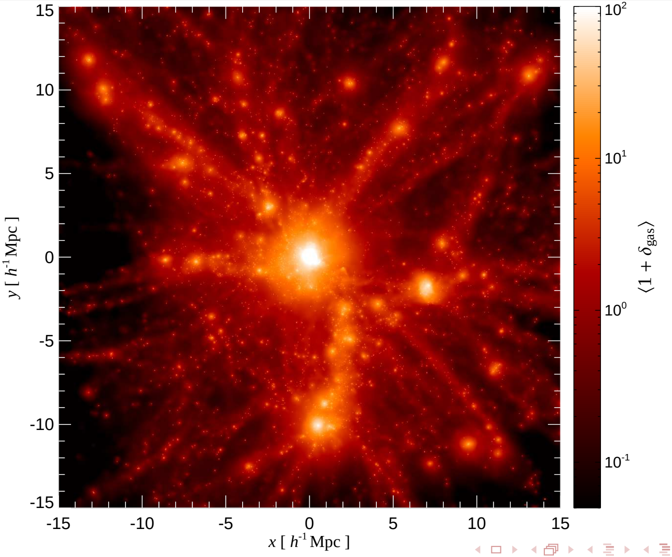
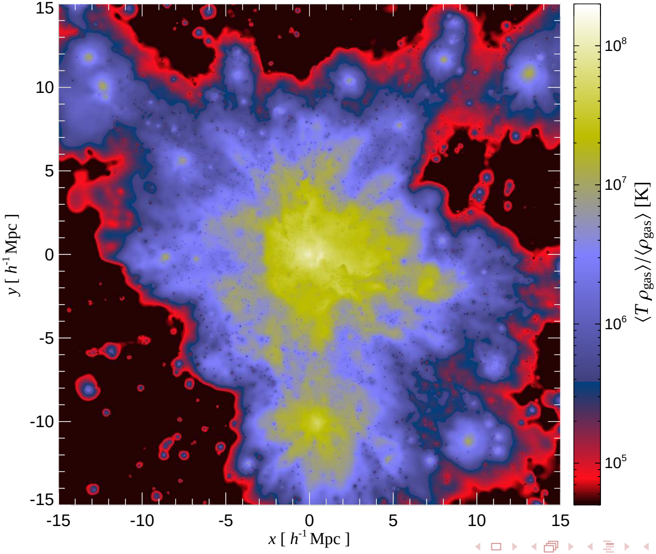
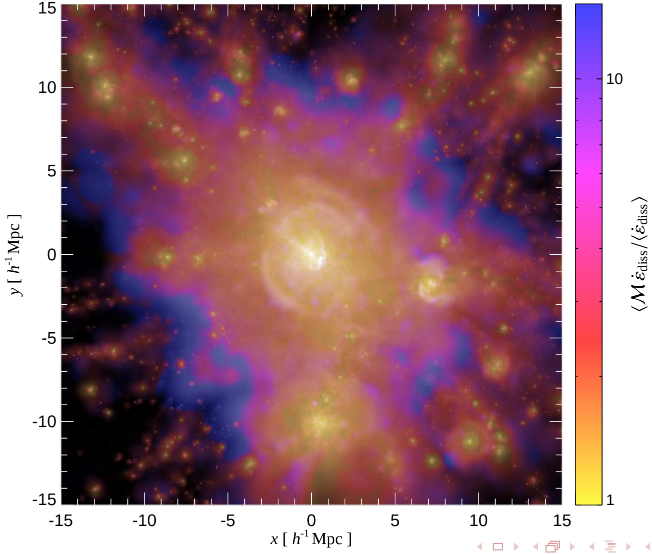
Radiative cool core cluster simulation: gas density



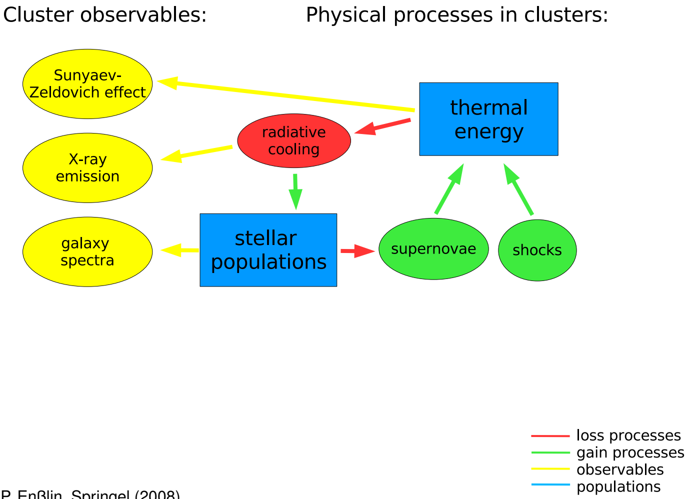
Mass weighted temperature



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



Radiative simulations – flowchart



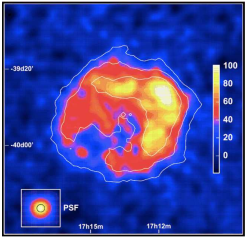
CP, Enßlin, Springel (2008)

Collisionless shocks at supernova remnants

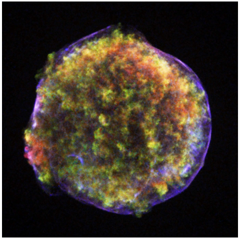
Astrophysical collisionless shocks can:

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

SN 1006 X-rays (CXC/Hughes)



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



Tycho X-rays (CXC)

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Diffusive shock acceleration – Fermi 1 mechanism (1)

conditions:

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

mechanism:

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

$\rightarrow$ power-law CR distribution

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$\longrightarrow$ power-law CR distribution

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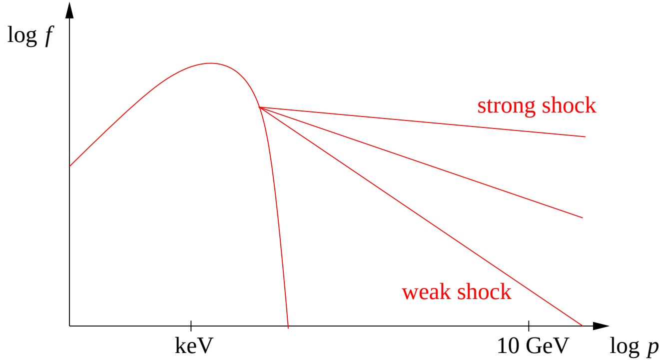
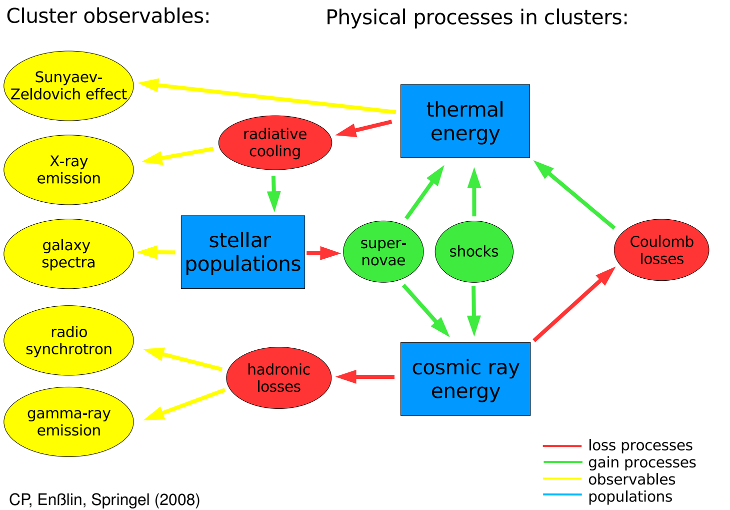
Diffusive shock acceleration – Fermi 1 mechanism (2)

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

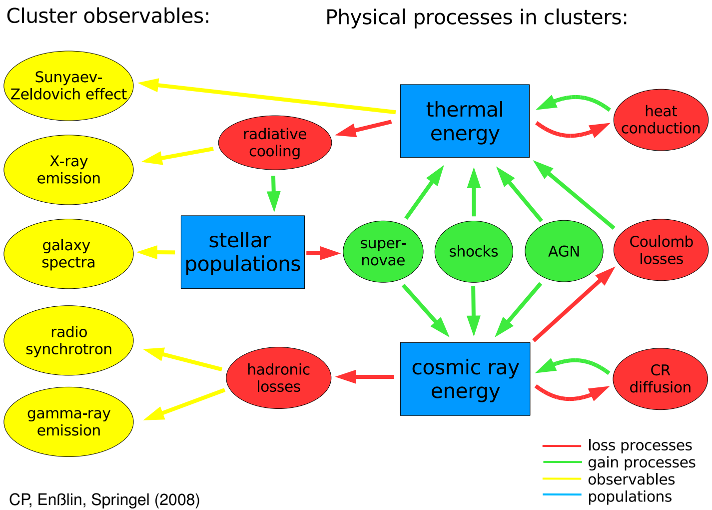


Radiative simulations with cosmic ray (CR) physics



CP, Enßlin, Springel (2008)

Radiative simulations with extended CR physics



CP, Enßlin, Springel (2008)

Our philosophy and description

An accurate description of CRs should follow the evolution of the spectral energy distribution of CRs as a function of time and space, and keep track of their dynamical, non-linear coupling with the hydrodynamics.

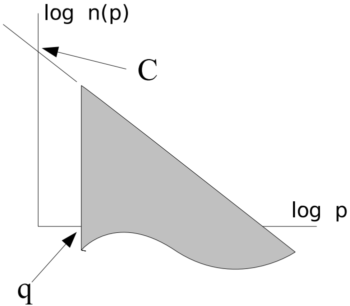
We seek a compromise between

- capturing as many physical properties as possible
- requiring as little computational resources as necessary

Assumptions:

- protons dominate the CR population
- a momentum power-law is a typical spectrum
- CR energy & particle number conservation

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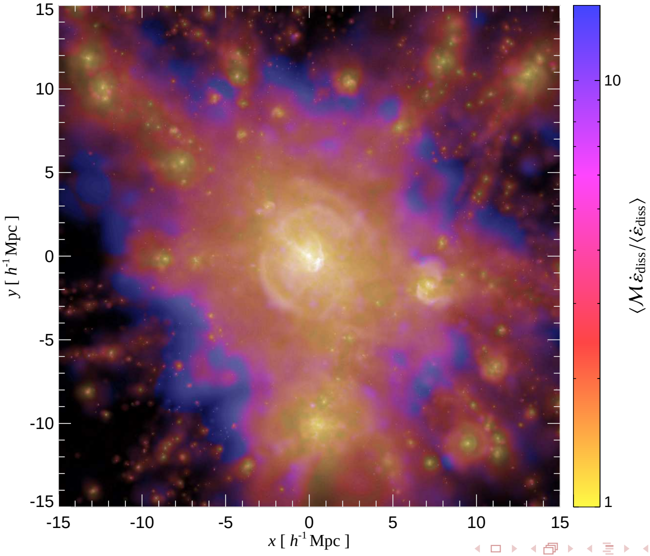
Mach number distribution weighted by $\varepsilon_{\rm diss}$



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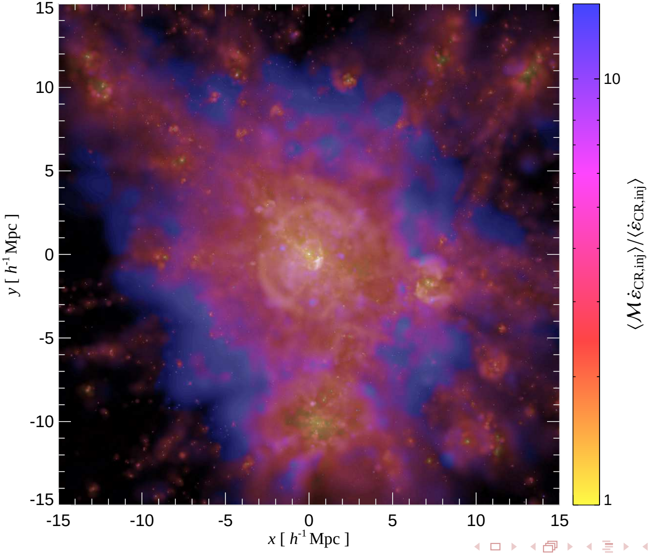
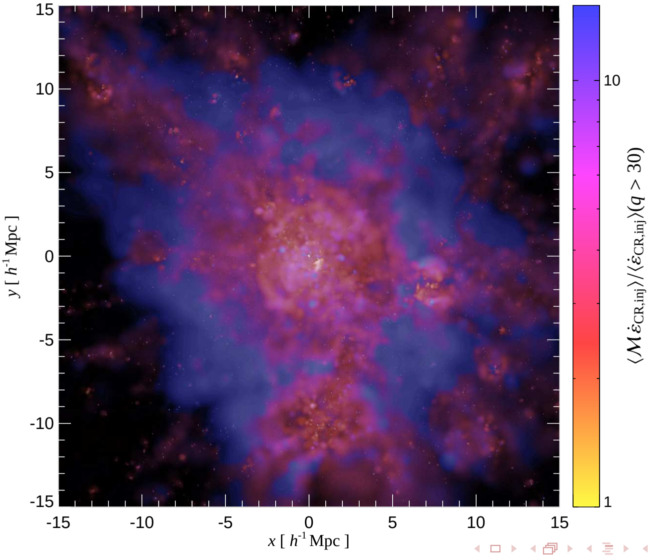
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$



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



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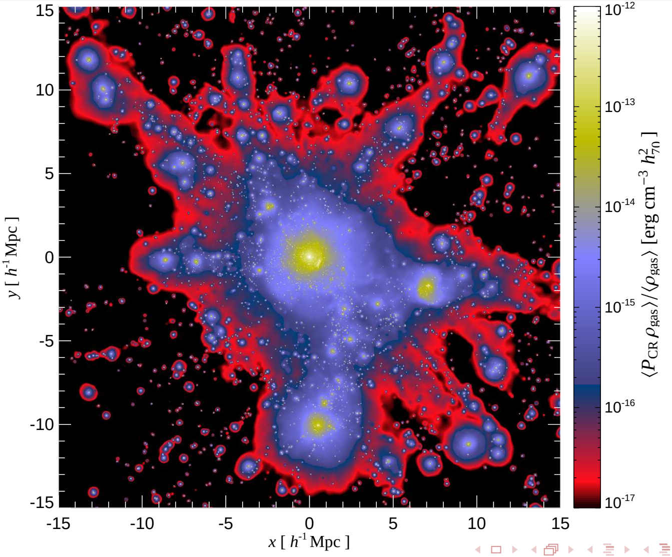
CR pressure P_{CR}



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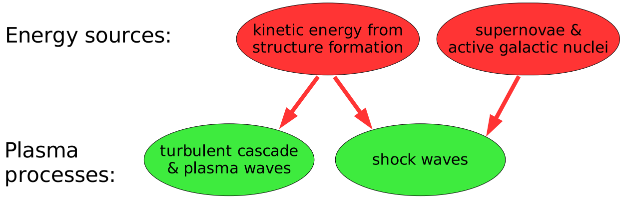
Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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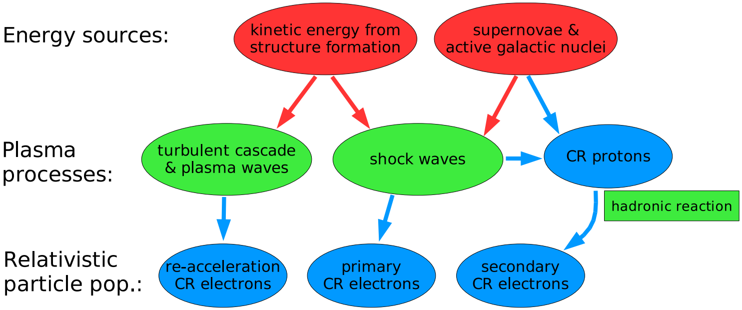

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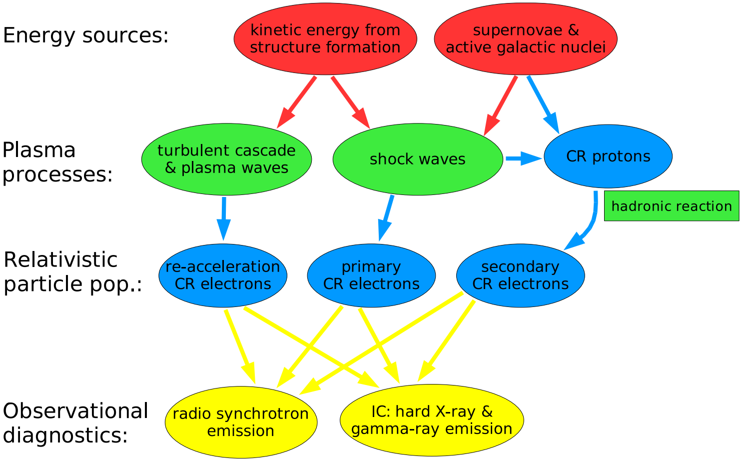

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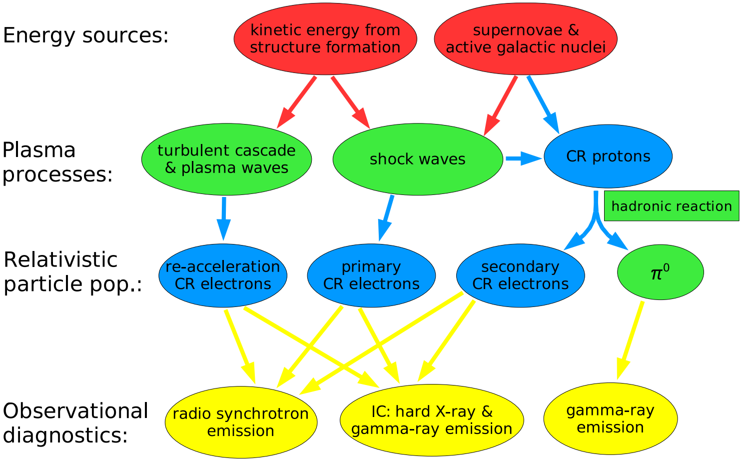
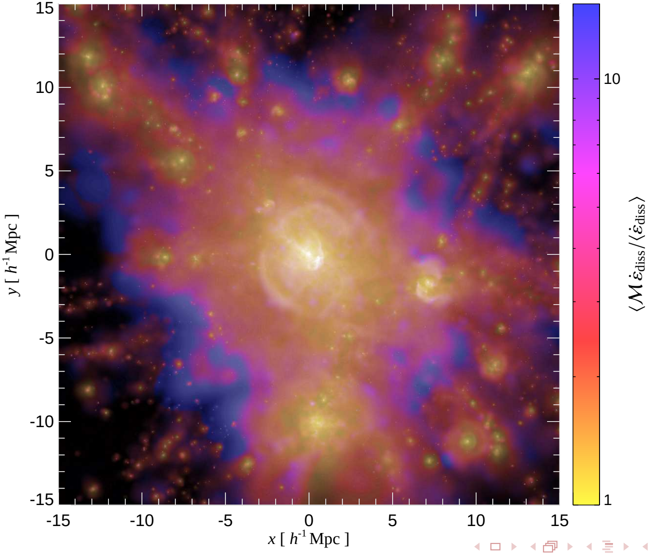


Cosmic web: Mach number



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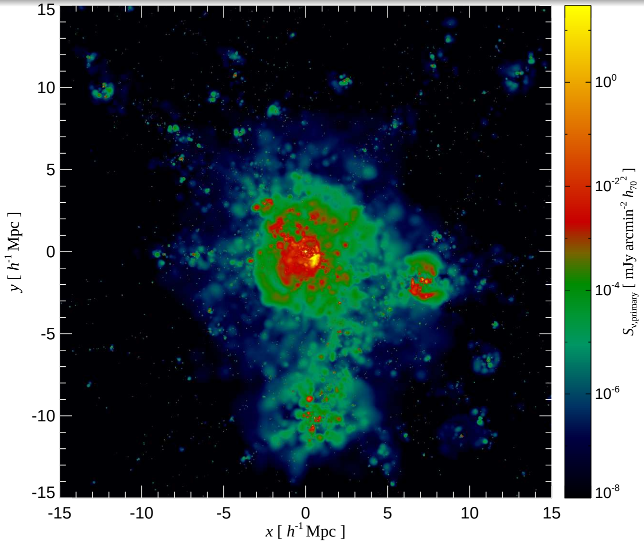
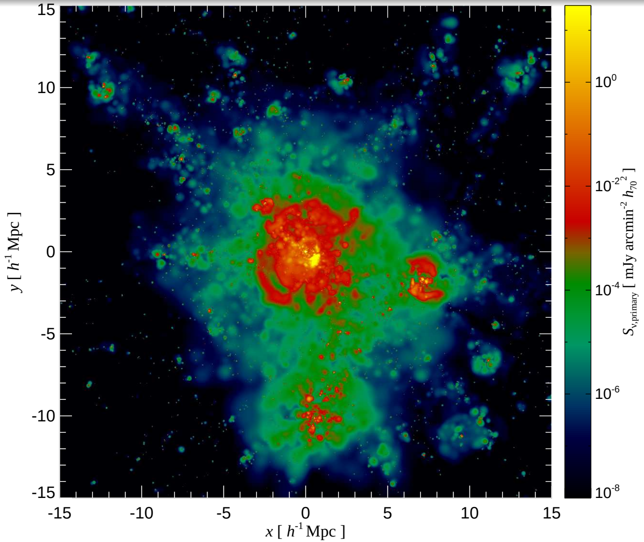
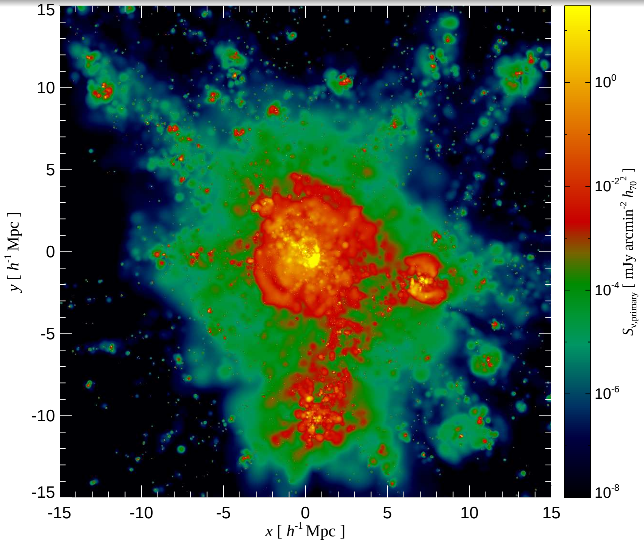
Radio gischt (relics): primary CRe (1.4 GHz)



Radio gischt: primary CRe (150 MHz)



Radio gischt: primary CRe (15 MHz)



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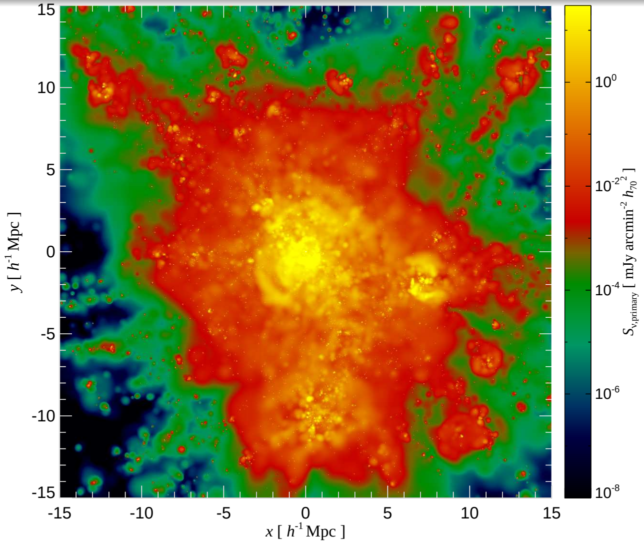
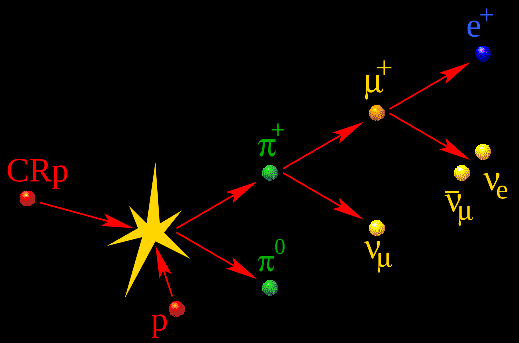
Radio gischt: primary CRe (15 MHz), slower magnetic decline



Hadronic cosmic ray proton interaction



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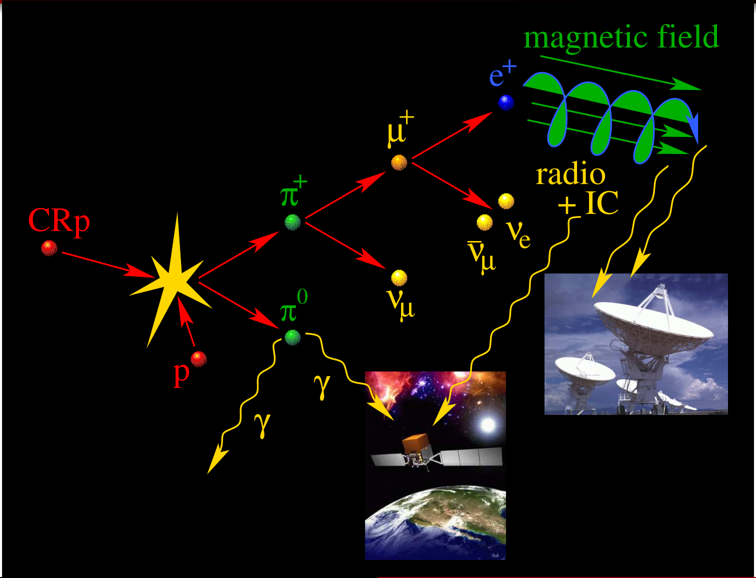
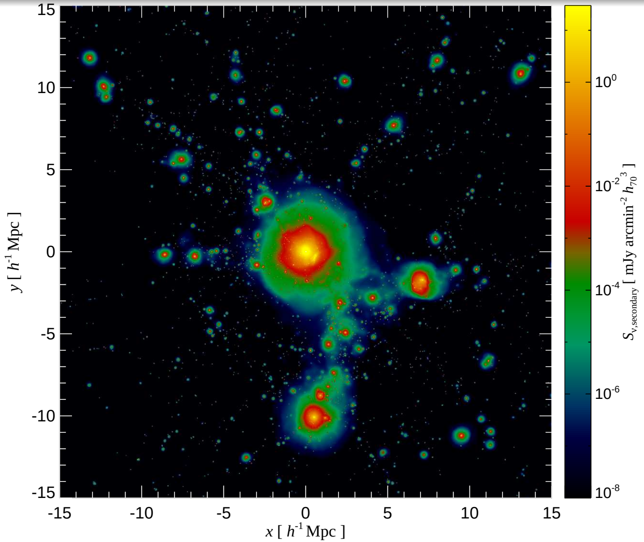


Cluster radio emission by hadronically produced CRe



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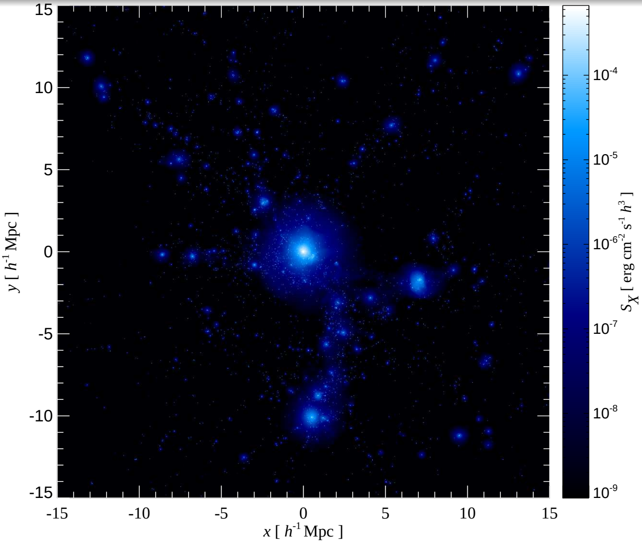
Thermal X-ray emission



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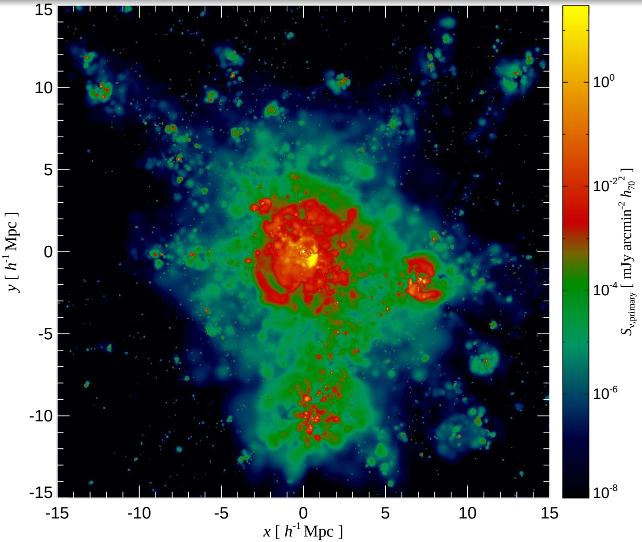
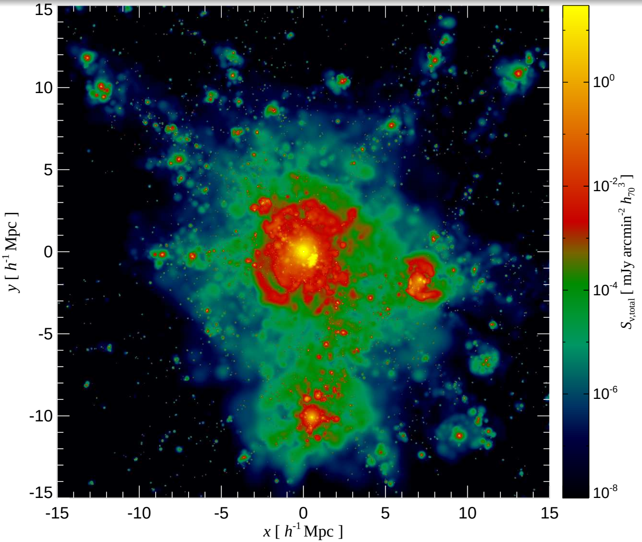
Radio gischt: primary CRe (150 MHz)



Radio gischt + central hadronic halo = giant radio halo



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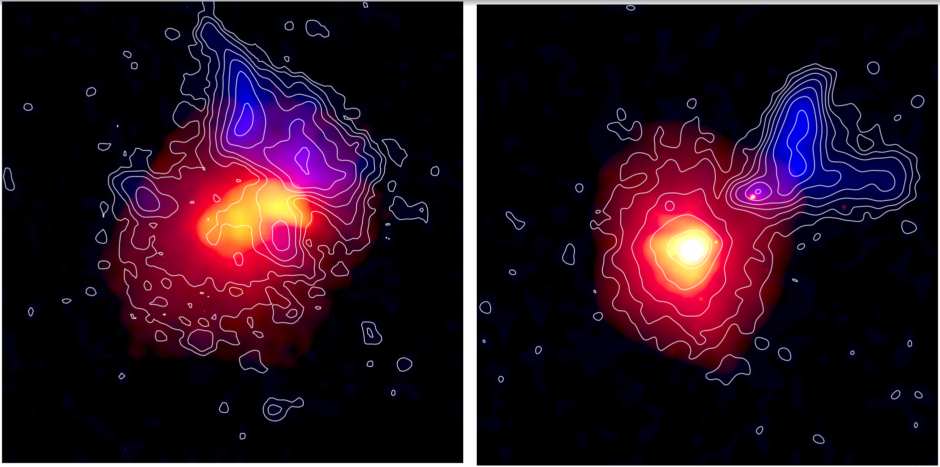
Which one is the simulation/observation of A2256?



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

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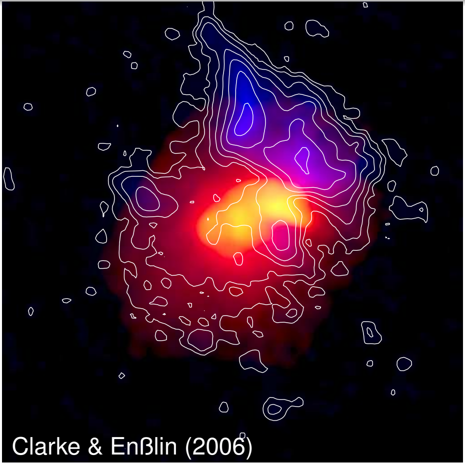
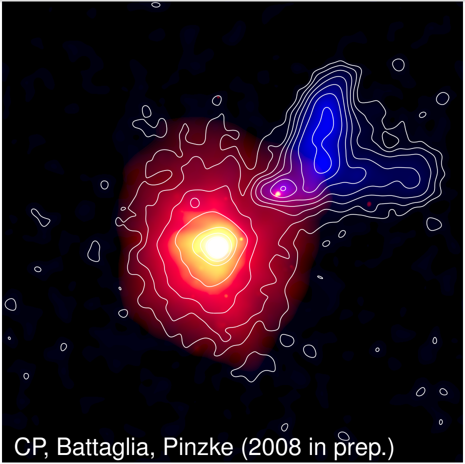
Observation – simulation of A2256


Clarke & Enßlin (2006)


CP, Battaglia, Pinzke (2008 in prep.)

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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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Conclusions on non-thermal emission from clusters

Exploring the memory of structure formation

- primary, shock-accelerated CR electrons resemble current accretion and merging shock waves
- CR protons/hadronically produced CR electrons trace the time integrated non-equilibrium activities of clusters that is modulated by the recent dynamical activities

How can we read out this information about non-thermal populations?
$\rightarrow$ new era of multi-frequency experiments, e.g.:

- GMRT, LOFAR, MWA, LWA, SKA: interferometric array of radio telescopes at low frequencies ($\nu \simeq (15 - 240)$ MHz)
- Simbol-X/NuSTAR: future hard X-ray satellites ($E \simeq (1 - 100)$ keV)
- Fermi γ-ray space telescope ($E \simeq (0.1 - 300)$ GeV)
- Imaging air Čerenkov telescopes ($E \simeq (0.1 - 100)$ TeV)

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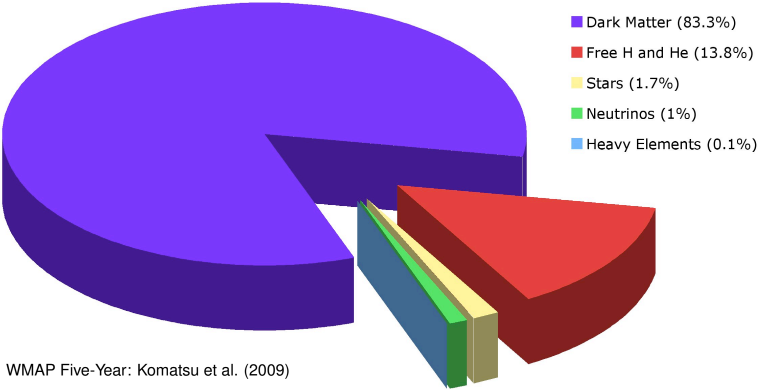
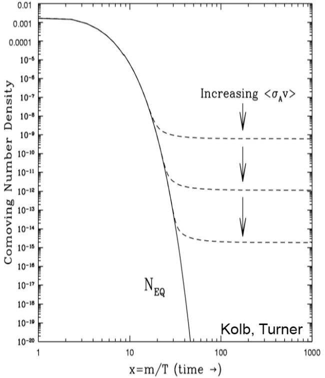
The matter content of the Universe – 2009



WMAP Five-Year: Komatsu et al. (2009)

The WIMP miracle



- Fermi introduced a new mass scale of $m_{\rm weak} \sim 100$ GeV to describe the beta decay: $n \to p\, e^-\, \bar{\nu}$
- assuming a new (heavy) particle X, initially in thermal equilibrium, with a relic density

$$\Omega_X \sim \frac{1}{m_{\rm Pl}\, T_0\, \langle \sigma v \rangle} \sim \frac{m_X^2}{m_{\rm Pl}\, T_0\, g_X^4}$$

-

$$\left.\begin{array}{l} m_x \sim m_{\rm weak} \sim 100\ \mathrm{GeV} \\ g_x \sim g_{\rm weak} \sim 0.6 \end{array}\right\} \Omega_X \sim 0.1$$

- Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter

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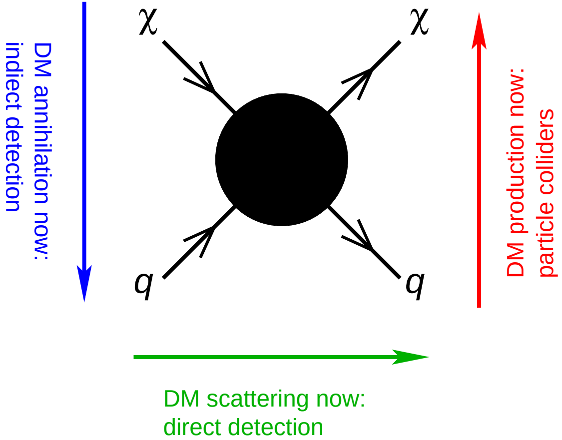
WIMP detection

Correct relic density $\rightarrow$ DM annihilation in the Early Universe



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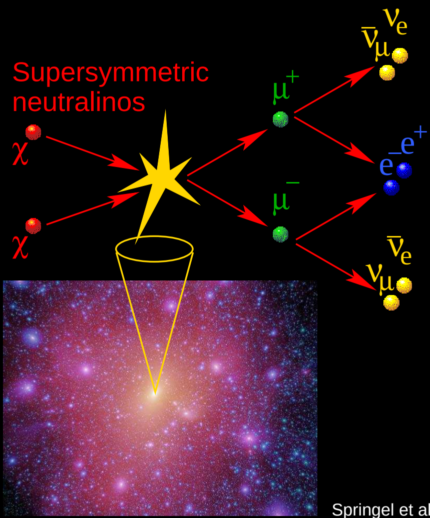
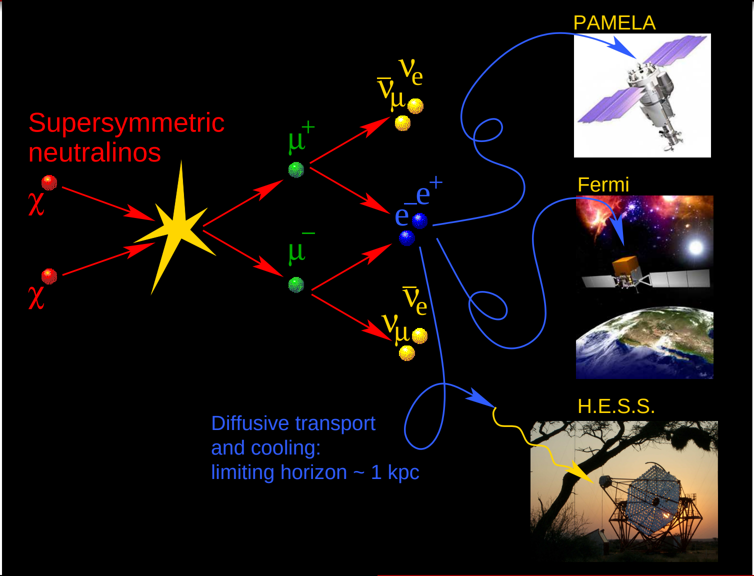
Indirect detection of dark matter

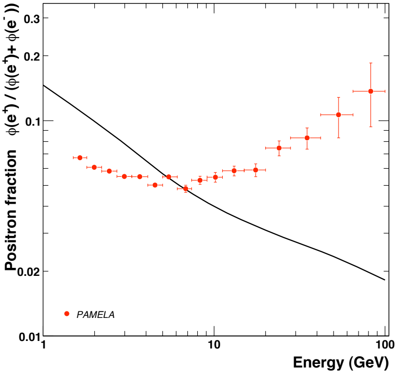


Springel et al. 2008

Indirect detection of dark matter

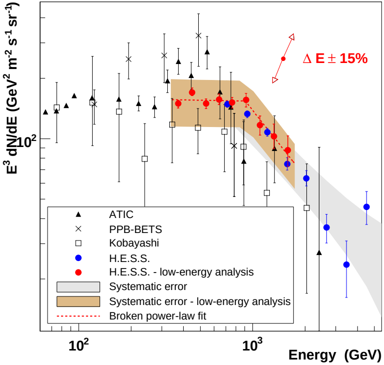


PAMELA and HESS data on electrons and positrons



PAMELA: (Adriani et al. 2009)

rising positron fraction with energy
→ e^- / e^+ pair acceleration source



HESS: (Aharonian et al. 2009)

break in the e^- / e^+ spectrum
→ maximum voltage of accelerator or DM particle mass

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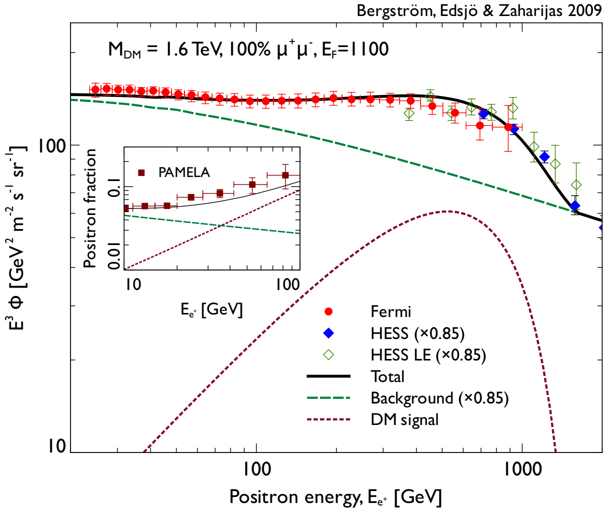
Combining recent electron and positron data

Fermi: excess number of leptons compared to background model (Abdo et al. 2009)



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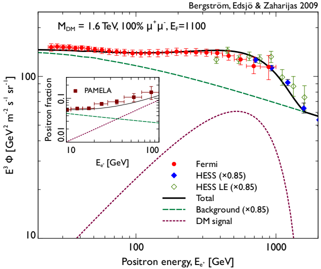
Interpretations of recent electron and positron data

- excess number of leptons compared to background (Fermi/HESS)
- break in the e^-/e^+ spectrum indicates special energy scale (HESS)
- rising positron fraction with energy (PAMELA)



1.) nearby pulsars:
energetics convincing but smoothness of Fermi data remains difficult to model (Harding & Ramaty 1987, Aharonian et al 1995, Malyshev et al. 2009)

2.) DM annihilations:
excellent fit to data but enhancement of cross-section over standard value and muon decay channel necessary (Bergström et al. 2009)

$\rightarrow$ Sommerfeld enhancement: $\langle \sigma v \rangle \sim c/v$ (Arkani-Hamed et al. 2009)

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The key questions

- How can we test this scenario?
- Which are the most promising objects to target?
- What are the cosmological implications of such an effective dark matter annihilation?

I will argue in favor of gamma-ray observations of galaxy clusters being able to scrutinize the DM interpretation of Fermi/HESS/PAMELA data and will end with a surprising cosmological result.

Pinzke, CP, Bergström, Phys. Rev. Lett., subm., arXiv:0905.1948 [astro-ph]

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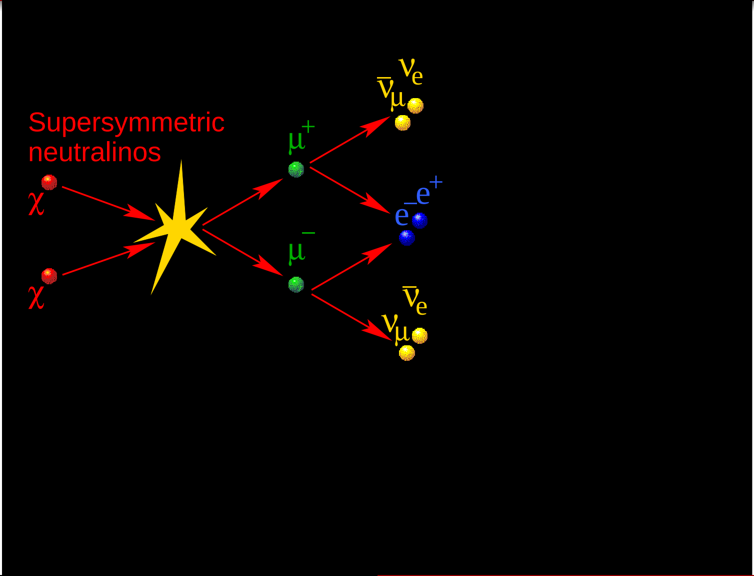
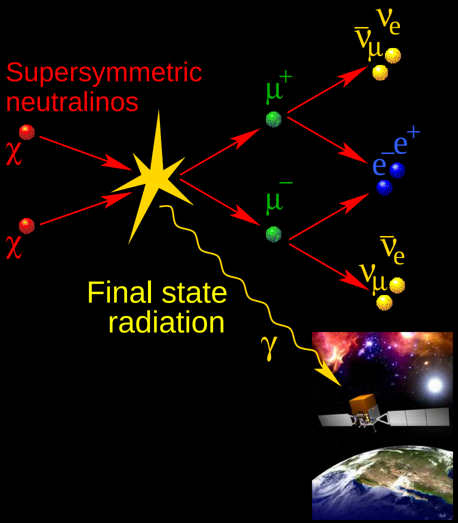
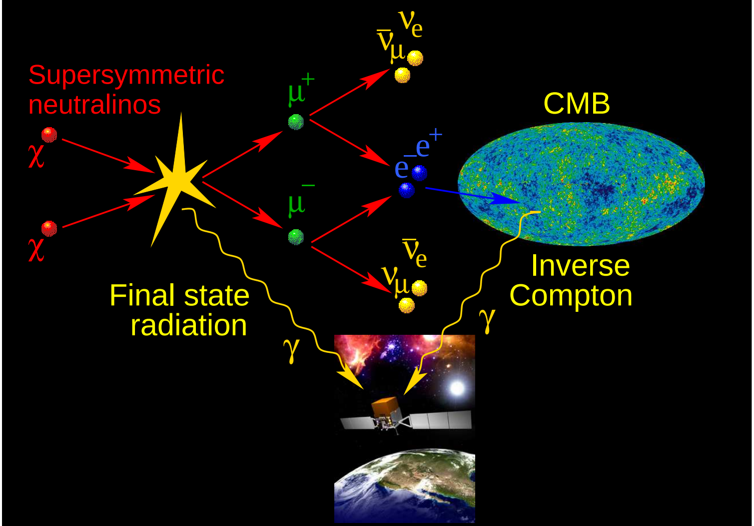
Indirect detection of DM through gamma-rays



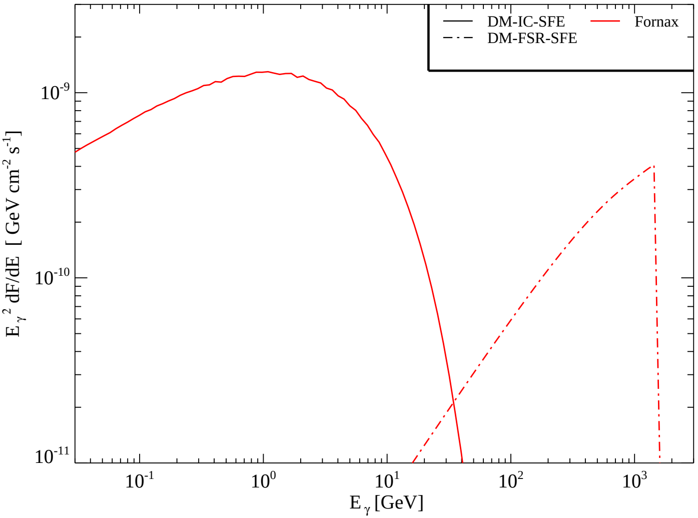
Indirect detection of DM through gamma-rays



Indirect detection of DM through gamma-rays



Gamma-ray spectrum from DM annihilations



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Galaxy clusters vs. dwarf galaxies

1. The DM annihilation flux of the smooth halo component scales as $F \sim \int \mathrm{d}V \rho^2 / D^2 \sim M / D^2$ assuming a universal density scaling[1]: the smooth component of dwarfs and galaxy clusters are equally bright!
2. Substructure in dark matter halos is less concentrated compared to the smooth halo component (dynamical friction, tidal heating and disruption): the DM luminosity is dominated by substructure at the virial radius, IF present!
   $\rightarrow$ these regions are tidally stripped in dwarf galaxies
   $\rightarrow$ galaxy clusters are dynamically 'young' and their subhalo population can boost the DM luminosity by up to 200 (Springel et al. 2008).

[1] A more refined argument that takes into account the different halo formation epochs breaking scale invariance yields the same result.

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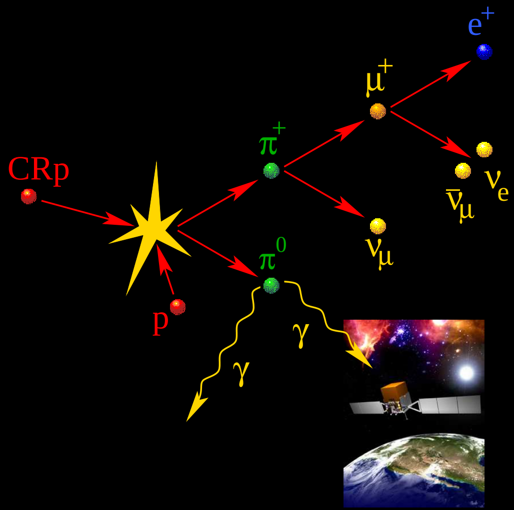
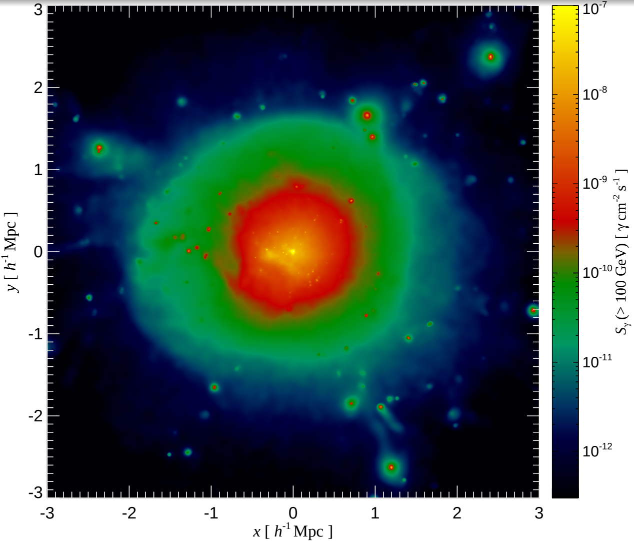
Hadronic cosmic ray proton interaction



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



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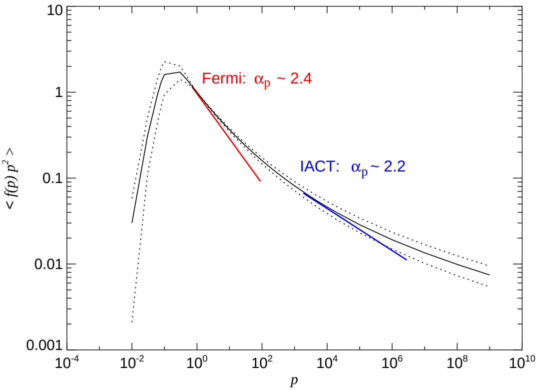
Universal CR spectrum in clusters



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

→ very promising for disentangling the dark matter annihilation signal!

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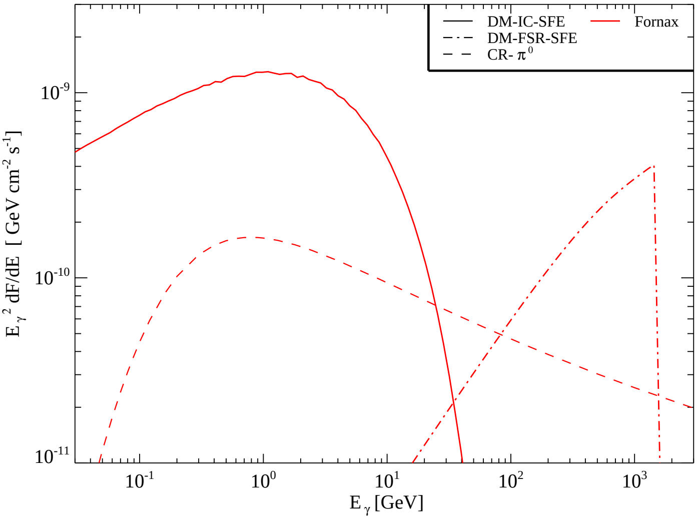
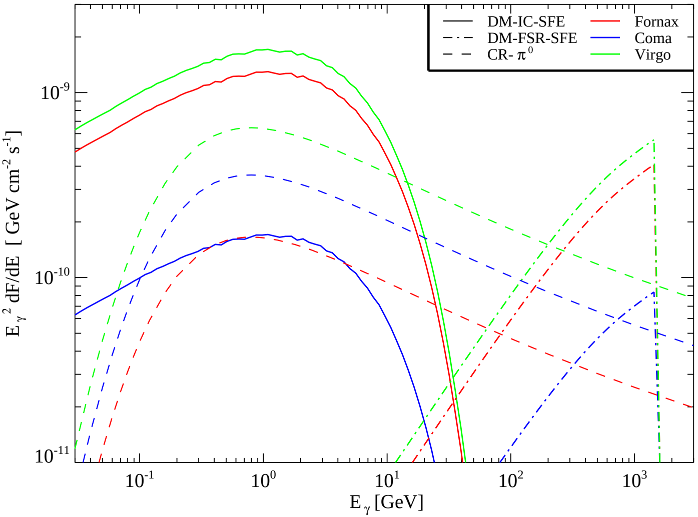
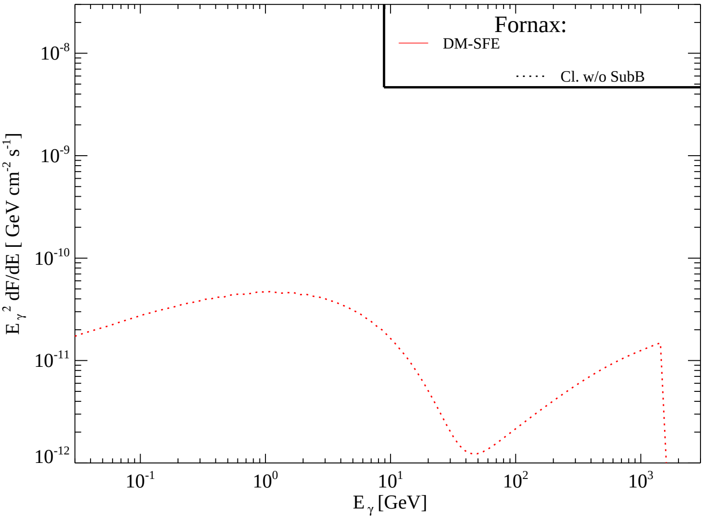
Gamma-ray spectrum from DM vs. CR interactions



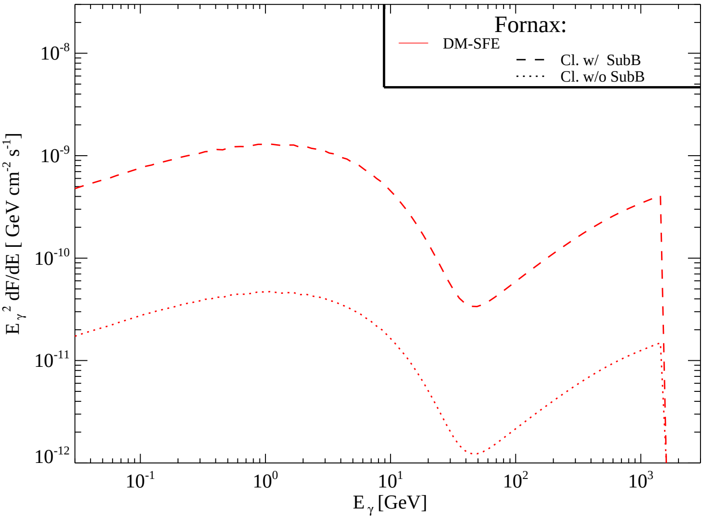
Gamma-ray spectrum for various galaxy clusters



DM gamma-rays: without substructure



DM gamma-rays: with substructure



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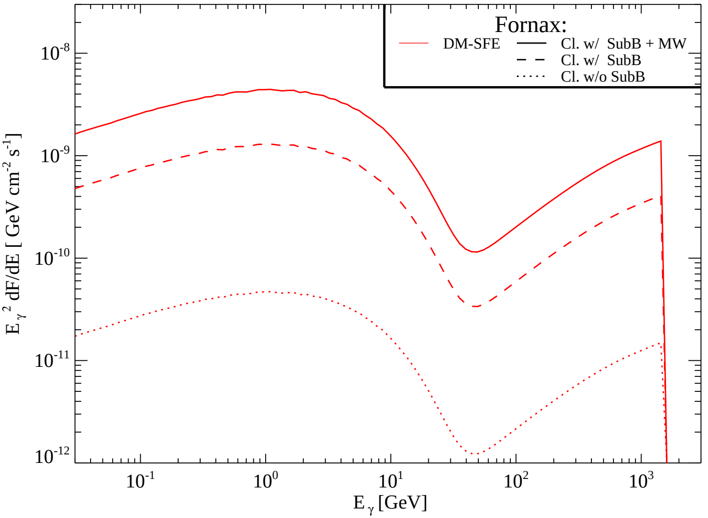
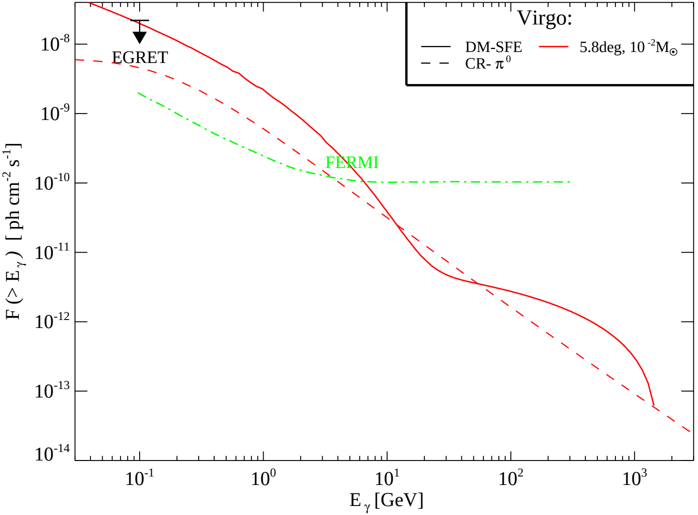
DM gamma-rays: with substructure and Milky Way



Probing small scales with gamma-rays



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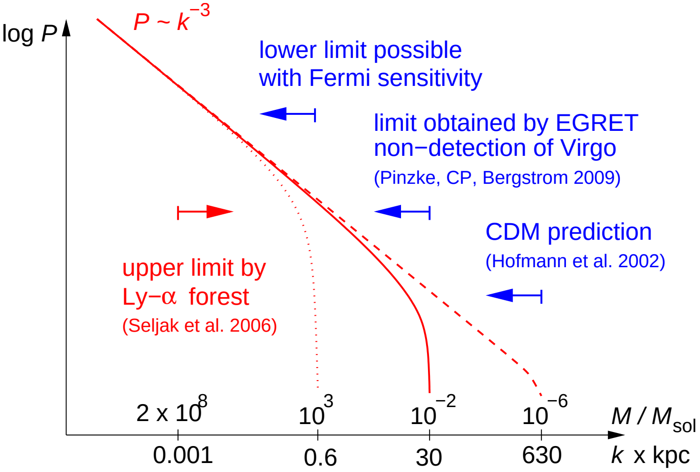
Implications for cosmological structure formation

Probing the linear power spectrum on the smallest scales



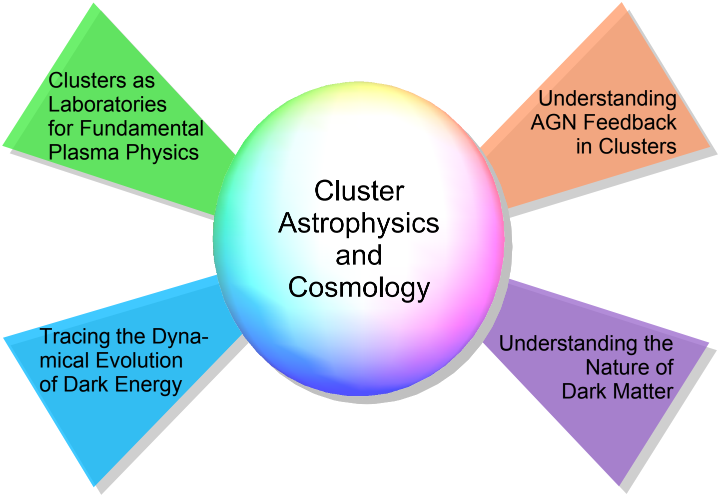
Conclusions on dark matter searches

- Gamma-ray observations of galaxy clusters by Fermi will test the DM interpretation of the Fermi/HESS/PAMELA data in the next years.
- If the DM interpretation is correct, then we either live in a warm dark matter Universe or there is a new dynamical effect during non-linear structure formation that wipes out the smallest structures.
- Gamma-ray observations might be the most sensitive probes of the smallest cosmological structures.

Outline

1. High-energy phenomena
   - Introduction and motivation
   - Shocks and particle acceleration
   - Non-thermal emission from clusters
2. Dark matter searches
   - Theory and observations
   - Gamma-ray signatures
   - Implications for cosmological structure formation
3. Future perspectives
   - Overview
   - Defining the questions
   - Conclusions

Future perspectives and directions



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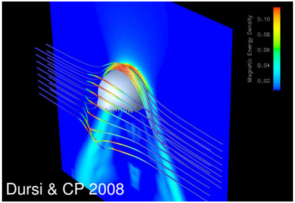
Clusters as laboratories for plasma physics

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

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

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

large scales: cluster “cluster archeology”, cosmological surveys (eROSITA, DES)
small scales: solving riddles (cold fonts, bubble stability) → new effects (magnetic draping)



Dursi & CP 2008

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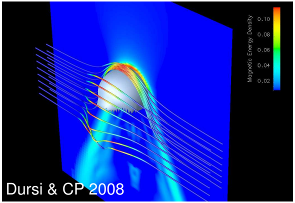

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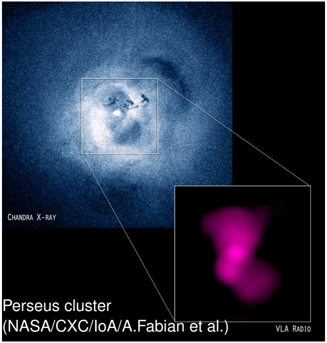
Understanding AGN feedback in clusters

The intertwined lives of supermassive black holes and cluster cores

1. AGN accretion, jet launch, bubble formation: magnetic fields, cosmic rays, and turbulence play crucial role
2. heating mechanism: cavity heating through releasing potential energy, weak shocks, sound damping, . . .

   (McNamara & Nulsen 2007)
3. cosmological impact: role in galaxy and cluster evolution



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

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

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

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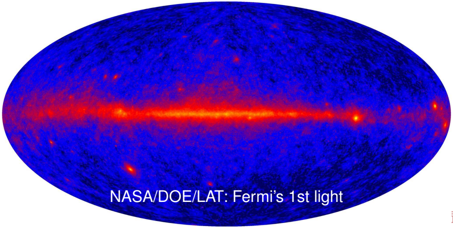
Understanding the nature of dark matter

Unveiling dark matter annihilation in the presence of astrophysical foregrounds

- disentangling the γ-ray emission resulting from dark matter (DM) annihilation from the cosmic ray induced signal
- electrons/positrons from DM annihilations vs. CR interactions: modified synchrotron emission and local particle spectra

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

$\rightarrow$ collaborative opportunities with J. Weller/S. Hofmann/A. Burkert



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

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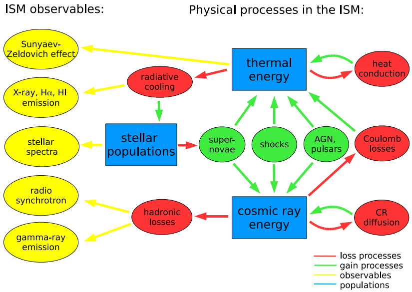
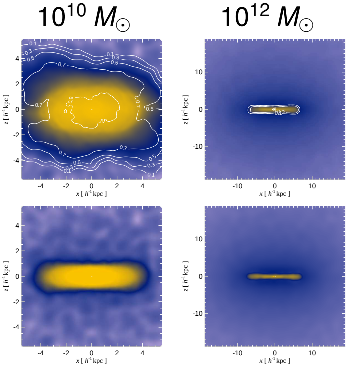
Modelling non-thermal processes in the ISM





Jubelgas, Springel, Enßlin, CP (2008)

interesting astrophysics associated with dynamically modeling non-thermal processes in the ISM

→ collaborative opportunities with A. Burkert/H. Lesch and timely projects of γ-ray (MAGIC, Fermi) and radio emission (LOFAR)

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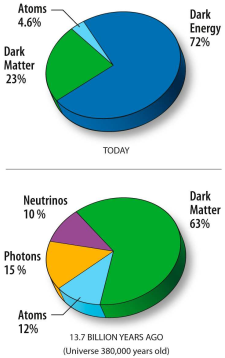
Tracing the dynamical evolution of dark energy

Joint analysis of simulated cluster surveys

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



(NASA/WMAP Science Team)

→ study of the influence of different physical processes on cluster mock catalogues in the X-rays (eROSITA) and the Sunyaev-Zel'dovich effect (Planck, SPT, ACT) → collaborative opportunities with J. Weller

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Conclusions

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

1. Cosmological hydrodynamical simulations are indispensable for understanding non-thermal processes in galaxy clusters
$\rightarrow$ illuminating the process of structure formation

2. Multi-messenger approach including radio synchrotron, hard X-ray IC, and HE γ-ray emission:
   - fundamental plasma physics: diffusive shock acceleration, large scale magnetic fields, and turbulence
   - nature of dark matter
   - gold sample of clusters for precision cosmology

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Literature for the talk

- Pinzke, Pfrommer, Bergström, Phys. Rev. Lett., submitted, arXiv:0905.1948, *Gamma-rays from dark matter annihilations strongly constrain the substructure in halos*
- Pfrommer, 2008, MNRAS, 385, 1242 *Simulating cosmic rays in clusters of galaxies – III. Non-thermal scaling relations and comparison to observations*
- Pfrommer, Enßlin, Springel, 2008, MNRAS, 385, 1211, *Simulating cosmic rays in clusters of galaxies – II. A unified scheme for radio halos and relics with predictions of the γ-ray emission*
- Pfrommer, Enßlin, Springel, Jubelgas, Dolag, 2007, MNRAS, 378, 385, *Simulating cosmic rays in clusters of galaxies – I. Effects on the Sunyaev-Zel'dovich effect and the X-ray emission*
- Pfrommer, Springel, Enßlin, Jubelgas, 2006, MNRAS, 367, 113, *Detecting shock waves in cosmological smoothed particle hydrodynamics simulations*
- Enßlin, Pfrommer, Springel, Jubelgas, 2007, A&A, 473, 41, *Cosmic ray physics in calculations of cosmological structure formation*
- Jubelgas, Springel, Enßlin, Pfrommer, A&A, , 481, 33, *Cosmic ray feedback in hydrodynamical simulations of galaxy formation*

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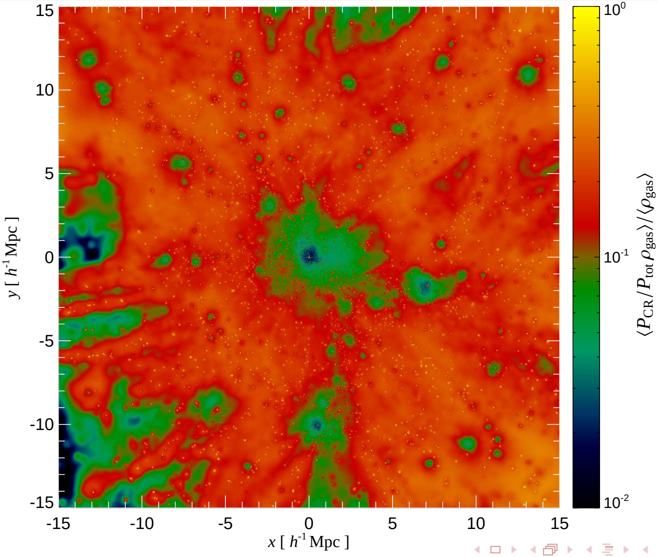
Relative CR pressure $P_{\rm CR}/P_{\rm total}$



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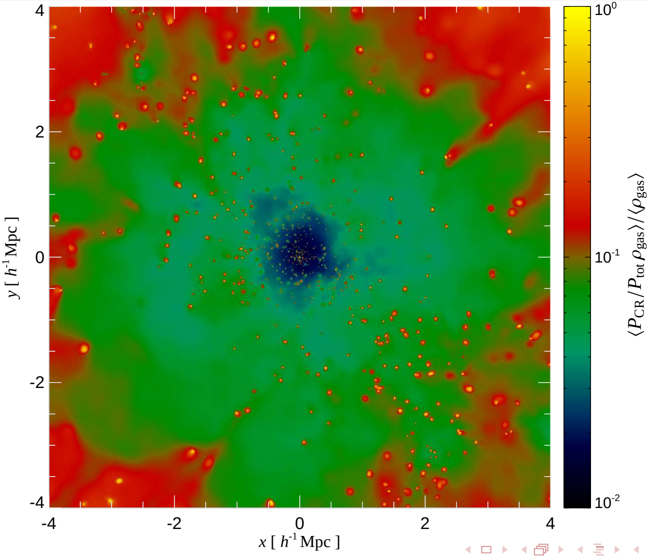

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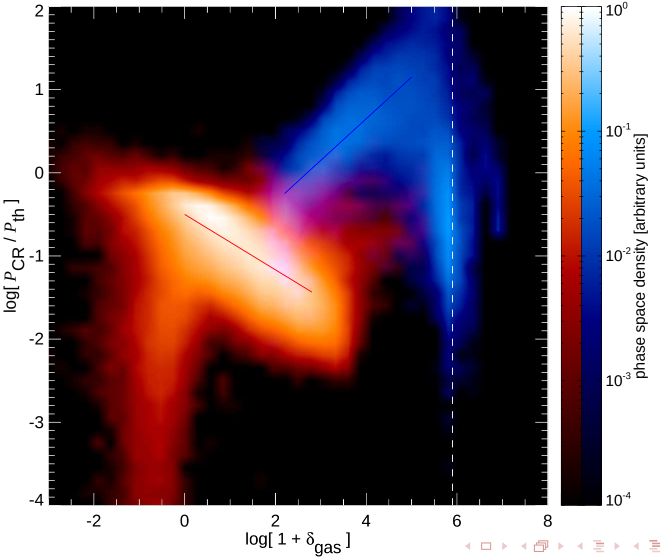
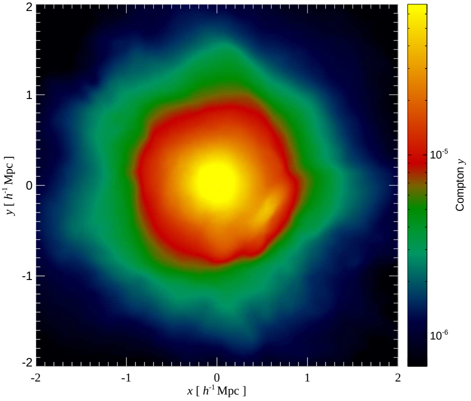
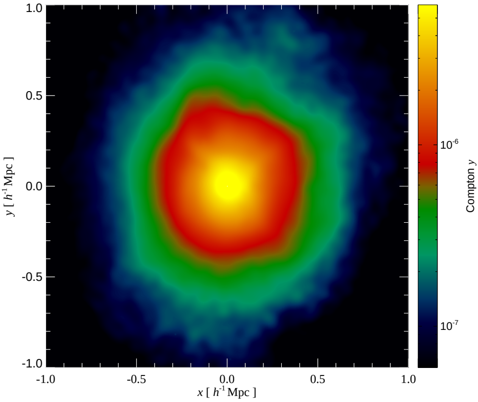
CR phase-space diagram: final distribution @ $z = 0$



CR impact on SZ effect: Compton y parameter



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



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

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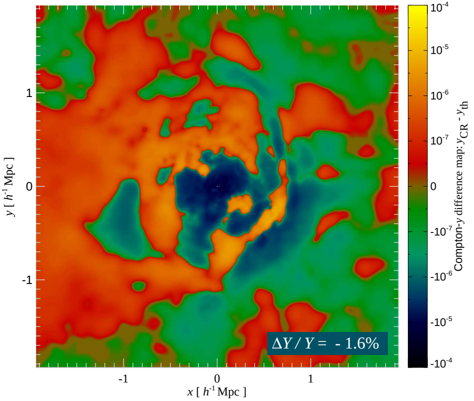
Compton y difference map: $y_{\rm CR} - y_{\rm th}$



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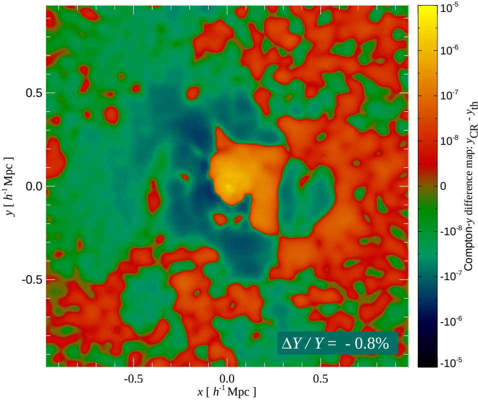

small cool core cluster, $M_{\rm vir} \simeq 10^{14} M_\odot / h$

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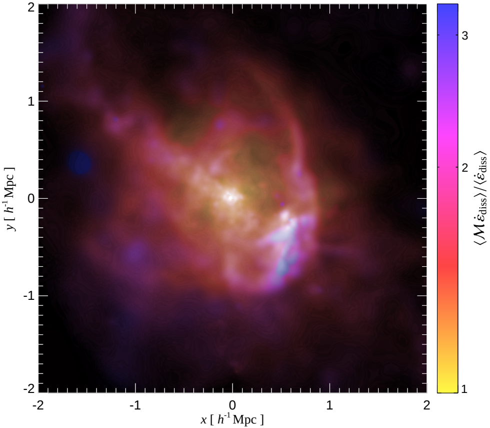
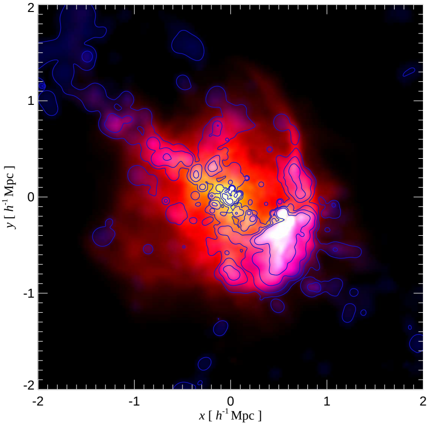
Radio gischt illuminates cosmic magnetic fields



Structure formation shocks triggered by a recent merger of a large galaxy cluster (Battaglia, CP, et al. 2008).



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.

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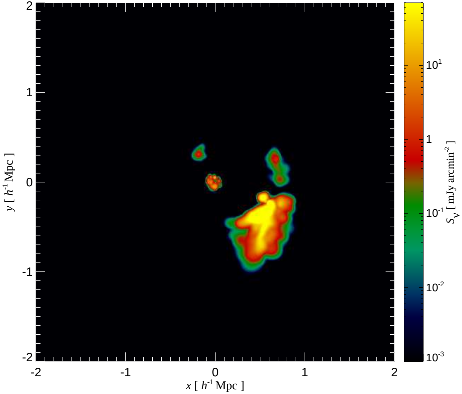
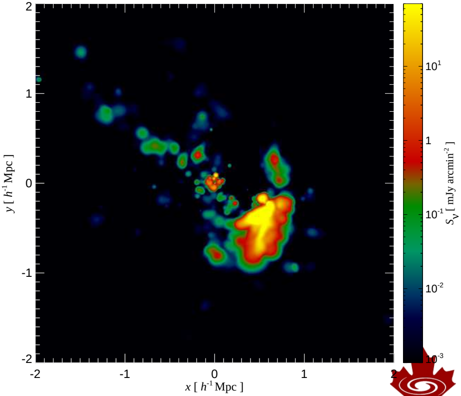
Population of faint radio relics in merging clusters

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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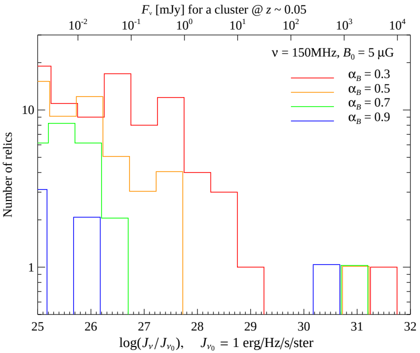
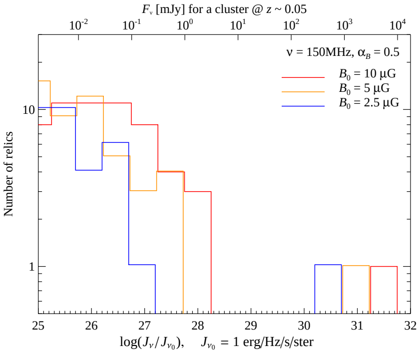
Relic luminosity function – theory

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

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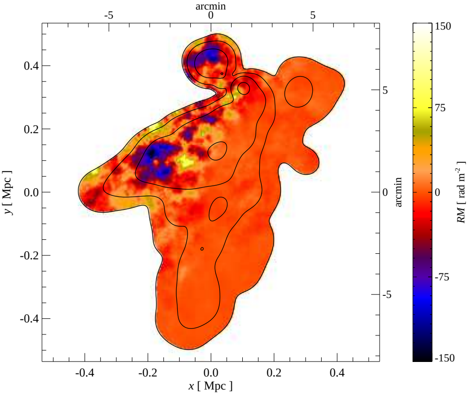
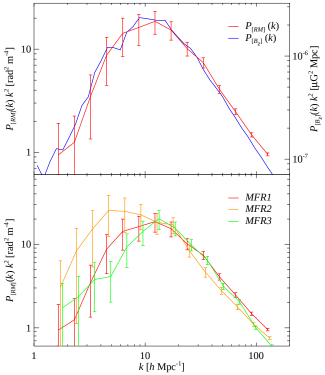
Rotation measure (RM)

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

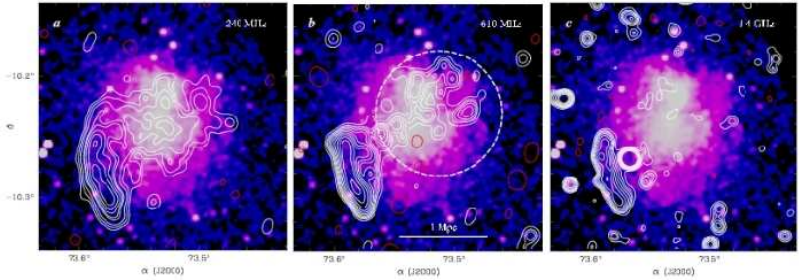




Left: RM map of the largest relic, right: Magnetic and RM power spectrum comparing Kolmogorow and Burgers turbulence models.

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!