Galaxy Clusters – Cosmological Laboratories for High-Energy Astrophysics

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in collaboration with

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Outline

1. Physical cosmology
   - Structure formation in the Universe
   - Concept of shock waves
   - Particle acceleration
2. High-energy phenomena
   - Observations and simulations
   - Cosmic ray physics and cosmology
   - Non-thermal cluster emission
3. Dark matter searches
   - Theory and observations
   - Gamma-ray signatures
   - Implications for cosmological structure formation

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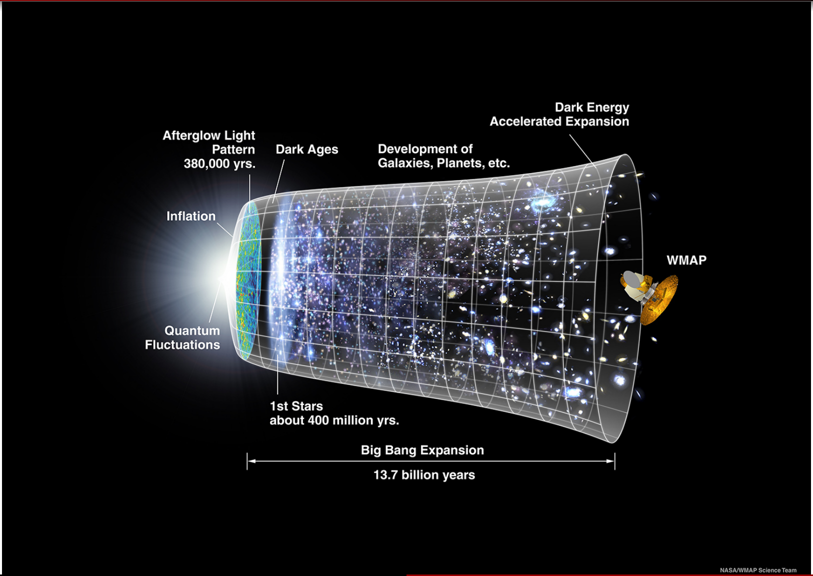
Timeline of our Universe



Origin of the cosmic microwave background

- In the early Universe, according to the theory of inflation, quantum fluctuations were inflated to macroscopic size.
- These fluctuations were then present in the density fields of dark matter, the ionized gas, and the photon field.
- Once these fluctuations entered the sound horizon, the gravitational attraction in overdensity regions was balanced by the radiation pressure of photons $\rightarrow$ acoustic oscillations.
- The Universe continued to expand and to cool adiabatically; at the characteristic temperature of $T \simeq 3 \times 10^3$ K hydrogen recombined $\rightarrow$ the Universe became transparent to photons.
- The oscillations ended since the radiation pressure ceased to act as restoring force; the line-of-sight velocity of the photons caused a Doppler boost $\rightarrow$ fluctuations in the microwave background with a characteristic amplitude of $\delta T / T \sim 10^{-5}$ $\rightarrow$ WMAP

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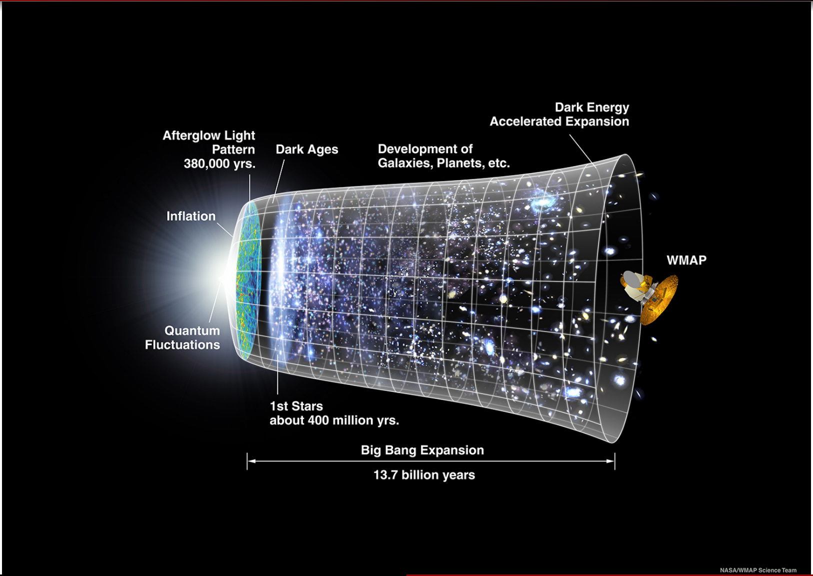

Hierarchical structure formation

- Since dark matter (DM) does not interact with photons, it had time to form tiny potential wells through gravitational interactions before recombination. Once set free from oscillations, the almost neutral primordial gas streams into those wells.
- The fluctuations continued to grow and accumulated more mass until they became non-linear.
- The originating very small dark matter halos decoupled from the general Hubble expansion of the Universe.
- When the continuously infalling gas impacted the dense halo gas, shock waves formed which heated the cold accreted gas to the virial temperature.
- These halos merged with other halos to form larger and larger objects which came into virial equilibrium, $E_{\text{pot}} + 2E_{\text{kin}} = 0$.

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The origin of galaxies and galaxy clusters

- Once the halos reached the size of a dwarf galaxy, gravitational attraction becomes stronger that the gas pressure → the gas collapsed, became denser and cooled by means of radiation processes in order to form a rotating gas disk in the halo center. Stars started to form – the birth of a spiral galaxy.
- In the course of structure formation, galaxy halos merged to form the largest virialized objects in the Universe: galaxy clusters.
- The forming shock waves are sourced by the gravitational energy of galaxy clusters: cluster mergers are the most energetic events in the Universe (after the Big Bang) and heat the gas to temperatures of $T \sim 10^8$K:
$$GM^2/R \sim 10^{64}\ \mathrm{erg} \sim 10^8\ \mathrm{K} \times 10^{15}\ M_\odot/m_\mathrm{p}$$
- The accelerated expansion of the Universe, caused by dark energy, delays and eventually stops structure formation → galaxy clusters will remain forever the largest objects in our Universe and the first to be disrupted again!

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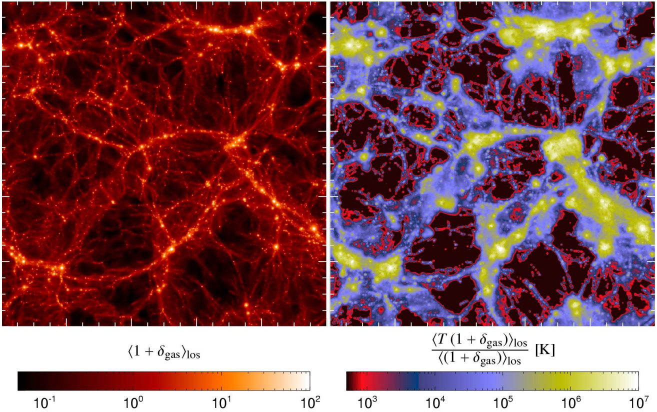
The structure of our Universe



The "cosmic web" today. *Left:* the projected gas density in a cosmological simulation. *Right:* gravitationally heated intracluster medium through cosmological shock waves (C.P. et al. 2006).

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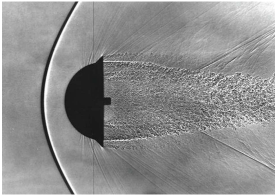
Shock waves

shock waves: sudden change in density, temperature, and pressure that decelerates supersonic flow.

thickness$\sim$ mean free path $\lambda_{\rm mfp}$

in air, $\lambda_{\rm mfp} \sim \mu$m,
on Earth, most shocks are mediated by collisions.



Mean free path to Coulomb collisions is huge:
$\lambda_{\rm mfp} \sim 100$ pc (SNR), $\lambda_{\rm mfp} \sim 100$ kpc (clusters)

Mean free path $\gg$ scales of interest!

$\rightarrow$ shocks must be mediated without collisions, but through interactions with collective fields
$\rightarrow$ collisionless shocks

(slide concept Spitkovsky)

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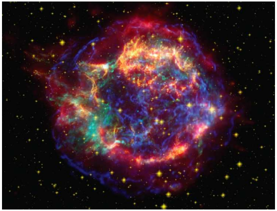

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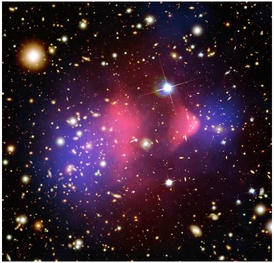

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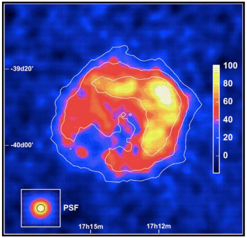
Collisionless shocks in supernova remnants

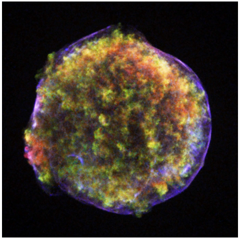
Astrophysical collisionless shocks can:

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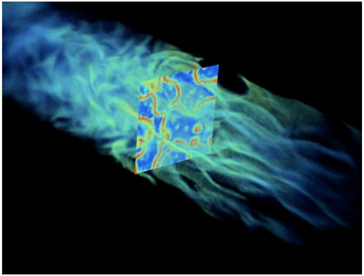
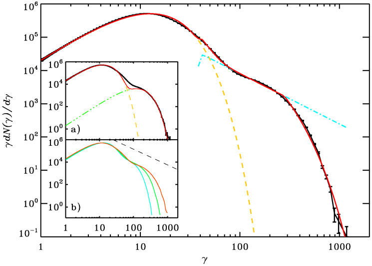
Particle-in-cell simulations of unmagnetized, relativistic pair shocks that are mediated by the Weibel instability (Spitkovsky 2008)



magnetic energy density (Spitkovsky 2008)



post-shock Maxwellian and accelerated CR power-law

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 scattering off magnetic fields (analogy: ping-pong ball in between approaching walls)
- momentum increases exponentially with number of shock crossings
- particle number decreases exponentially with number of crossings

→ power-law cosmic ray (CR) distribution

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Diffusive shock acceleration – Fermi 1 mechanism (1)

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- plasma waves to scatter energetic particles $\longrightarrow$ particle diffusion
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$\longrightarrow$ power-law cosmic ray (CR) distribution

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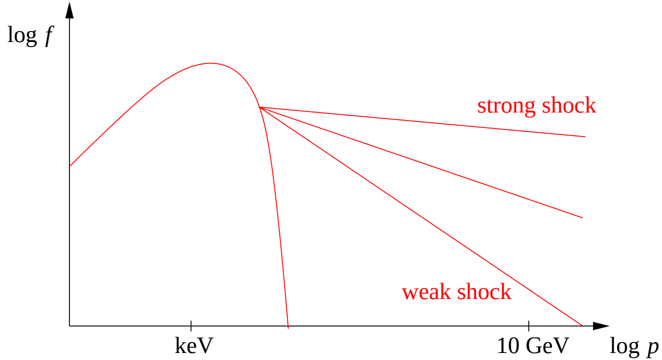
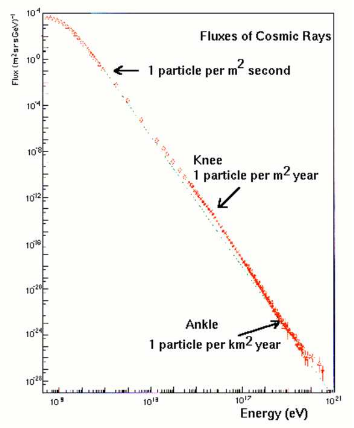
Diffusive shock acceleration – Fermi 1 mechanism (2)

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



Galactic cosmic ray spectrum



data compiled by Swordy

Galactic CR all particle spectrum:

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

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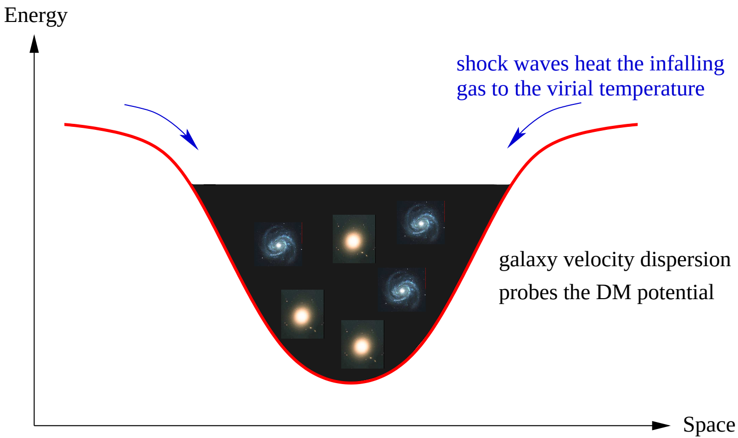
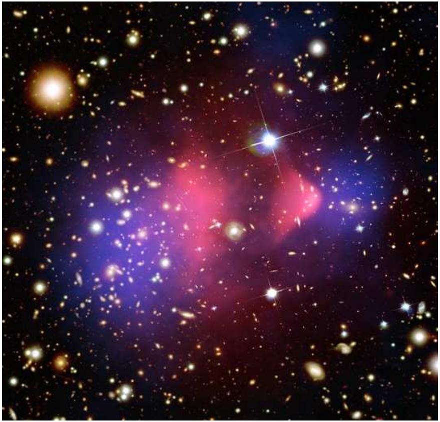
A theorist's perspective of a galaxy cluster . . .

Galaxy clusters are dynamically evolving dark matter potential wells:

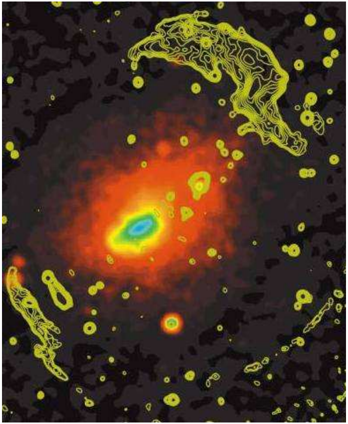


. . . and how the observer's Universe looks like



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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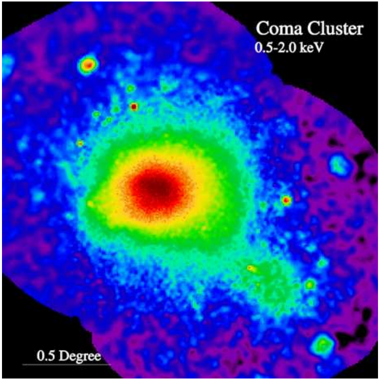
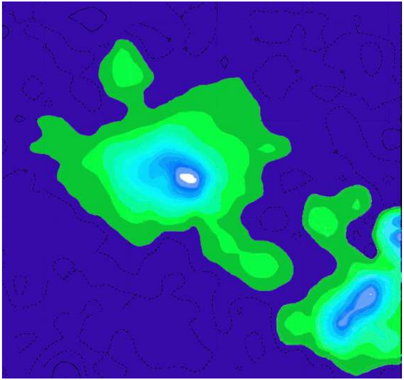
Giant radio halo in the Coma cluster



thermal X-ray emission

(Snowden/MPE/ROSAT)



radio synchrotron emission

(Deiss/Effelsberg)

High-energy astrophysics in galaxy clusters

- consistent picture of non-thermal processes in galaxy clusters (radio, soft/hard X-ray, γ-ray emission)
  $\rightarrow$ illuminating the process of structure formation
  $\rightarrow$ history of individual clusters: cluster archeology
- understanding the non-thermal pressure distribution to address biases of thermal cluster observables
- gold sample of clusters for precision cosmology: using non-thermal observables to gauge hidden parameters
- nature of dark matter: annihilation signal vs. cosmic ray (CR) induced γ-rays
- fundamental plasma physics:
  - diffusive shock acceleration
  - origin and evolution of large scale magnetic fields
  - nature of turbulent models

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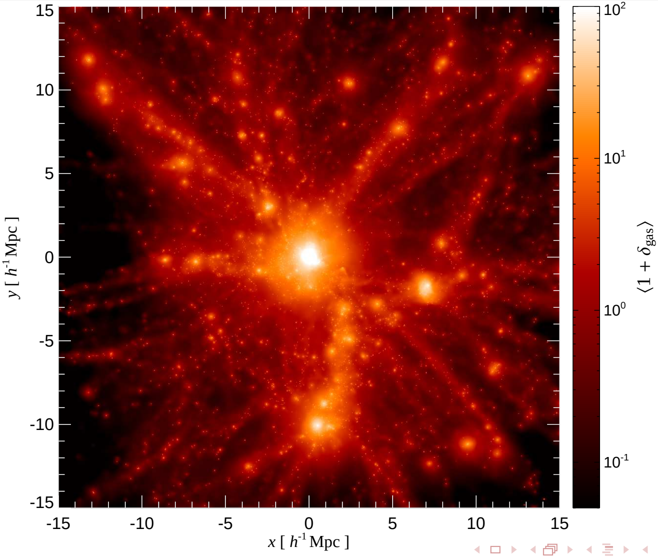
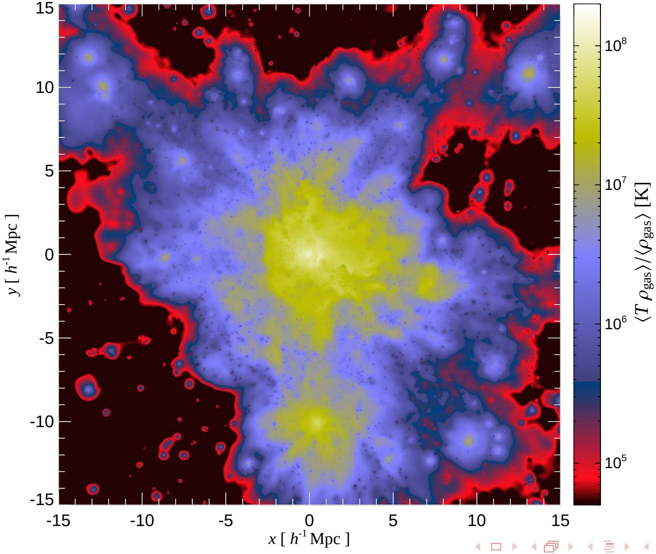
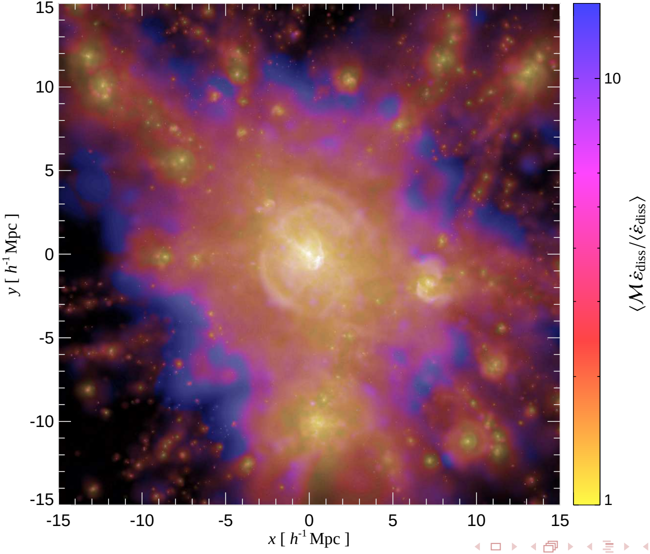
Radiative cool core cluster simulation: gas density



Mass weighted temperature



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



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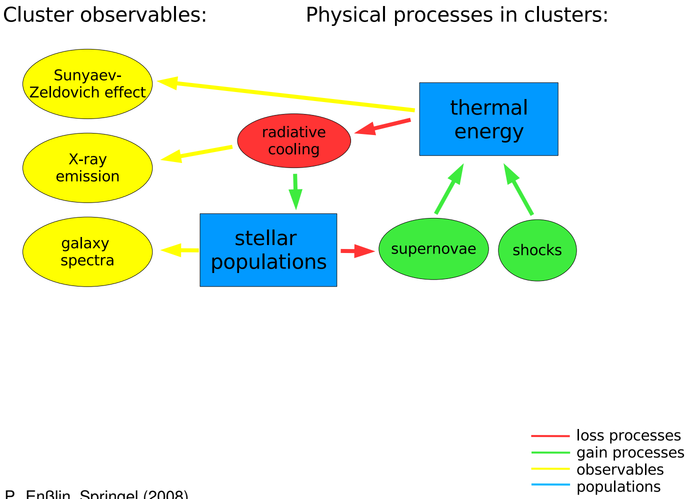
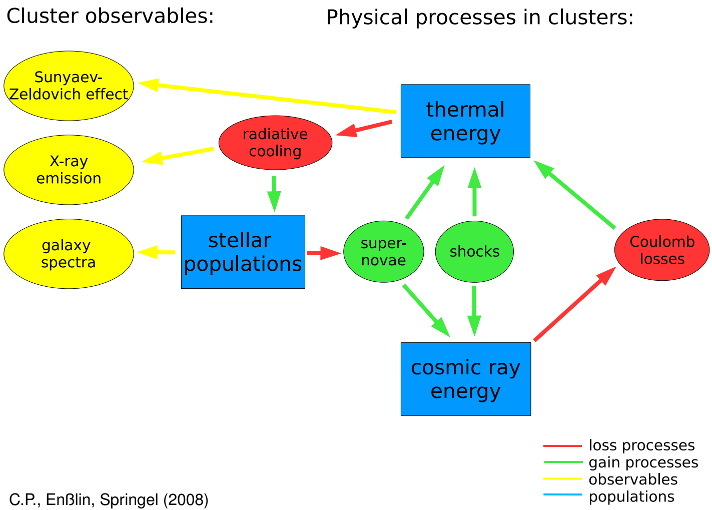
Radiative simulations – flowchart



C.P., Enßlin, Springel (2008)

Radiative simulations with CR physics



C.P., 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.

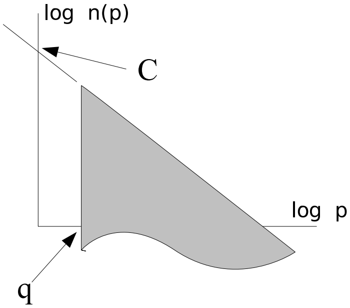
We seek a compromise between

- 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, C.P., 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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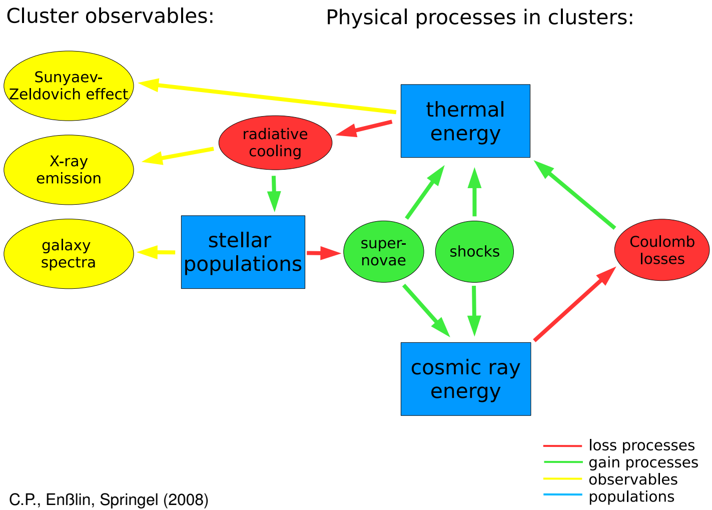
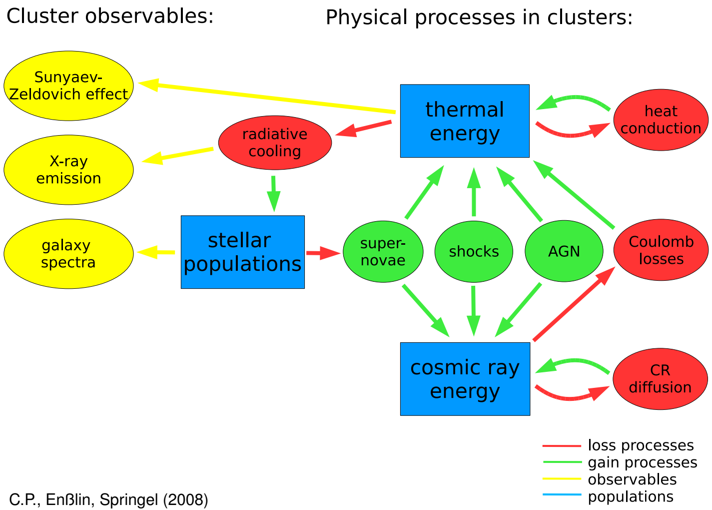
Radiative simulations with CR physics



C.P., Enßlin, Springel (2008)

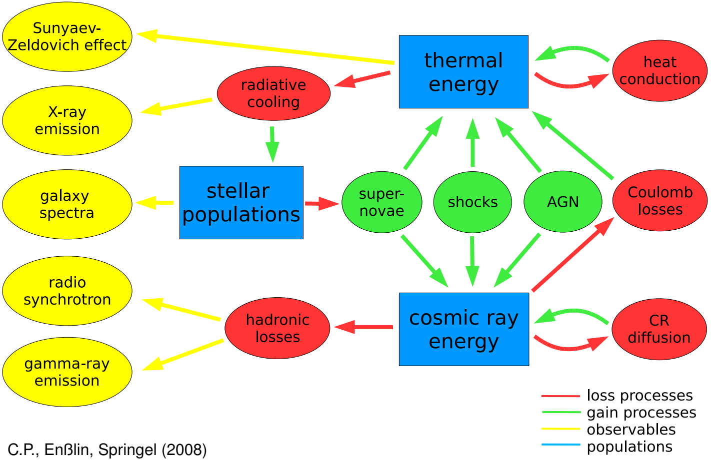
Radiative simulations with extended CR physics



C.P., Enßlin, Springel (2008)

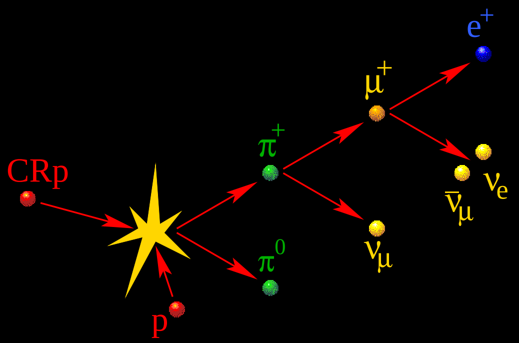
Radiative simulations with extended CR physics

Cluster observables: Physical processes in clusters:



C.P., Enßlin, Springel (2008)

Hadronic cosmic ray proton interaction



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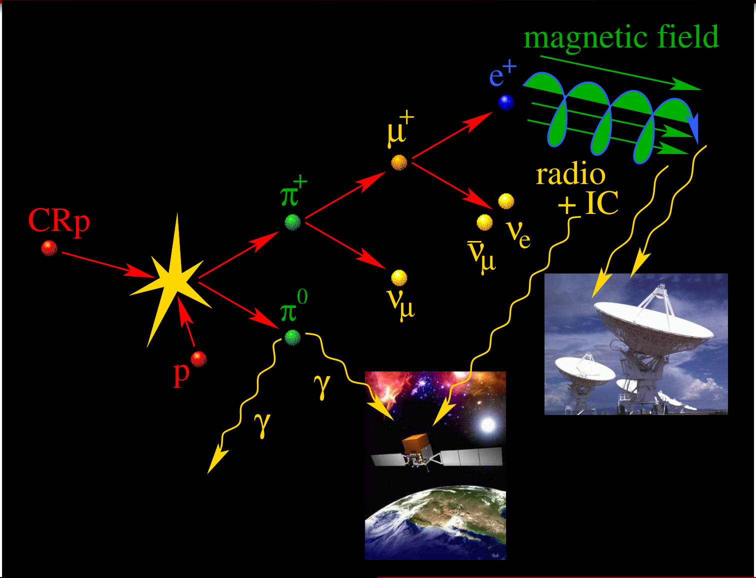
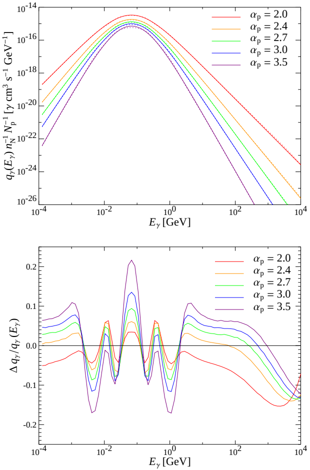


γ-ray source function in hadronic CRp-p interactions

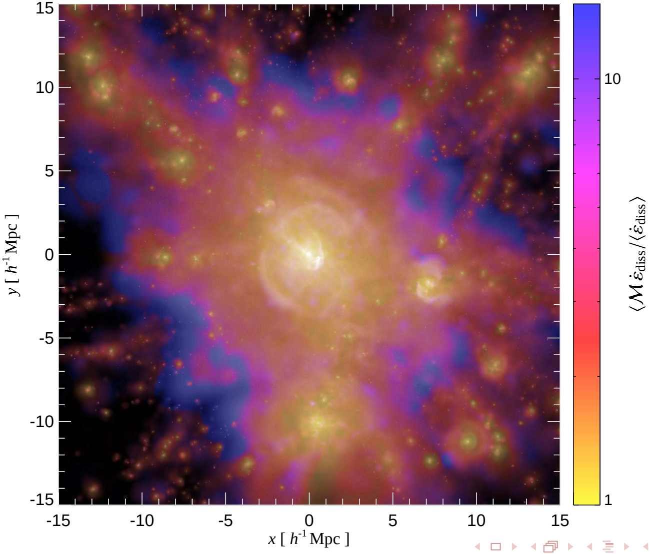


- compute the π^0-decay induced γ-ray source function q_γ analytically (with simplified assumptions)
- introducing complex physics *e.g.*, at the threshold of particle production phenomenologically
- for a CRp distribution, $f_{\rm CRp} \propto p^{-\alpha}$, the γ-ray source function is given by (C.P. & Enßlin 2004)

$$q_\gamma \propto \left[\left(\frac{2\,E_\gamma}{m_{\pi^0}c^2}\right)^{\delta} + \left(\frac{2\,E_\gamma}{m_{\pi^0}c^2}\right)^{-\delta}\right]^{-\alpha/\delta}$$

- *below:* relative deviation of our semi-analytic approach to numerically obtained γ-ray spectra

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



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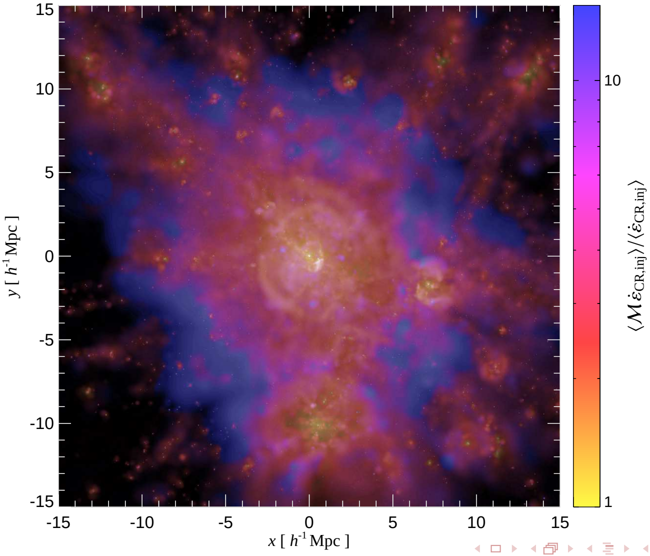
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$



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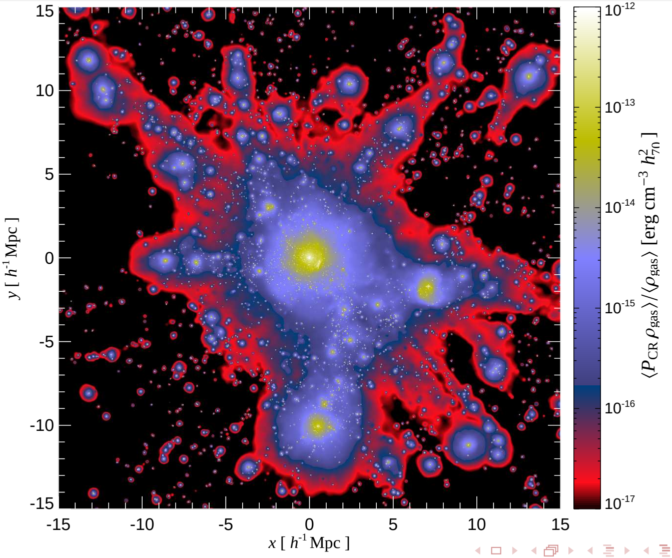
CR pressure P_{CR}



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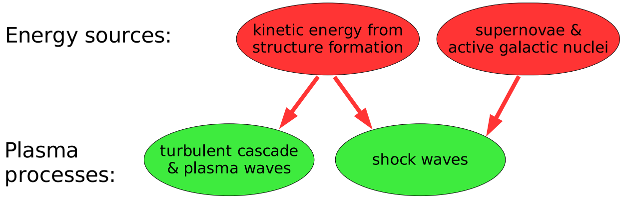
Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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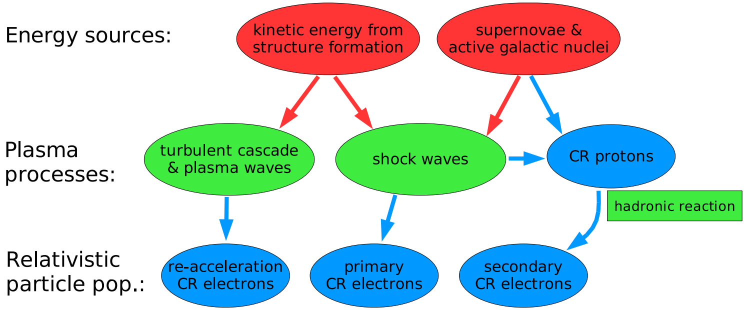

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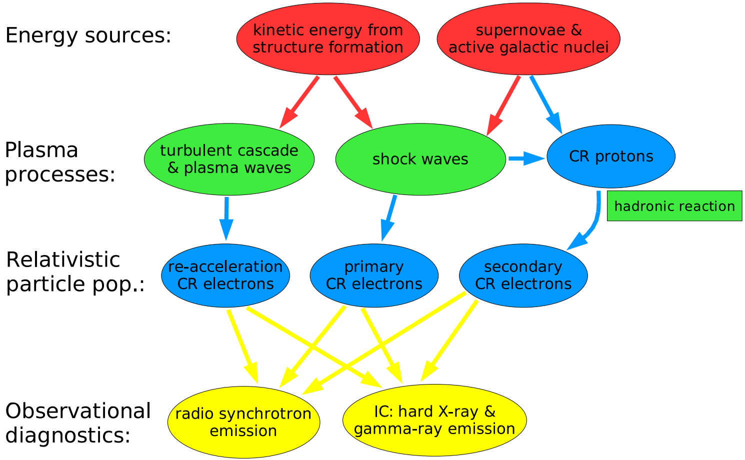

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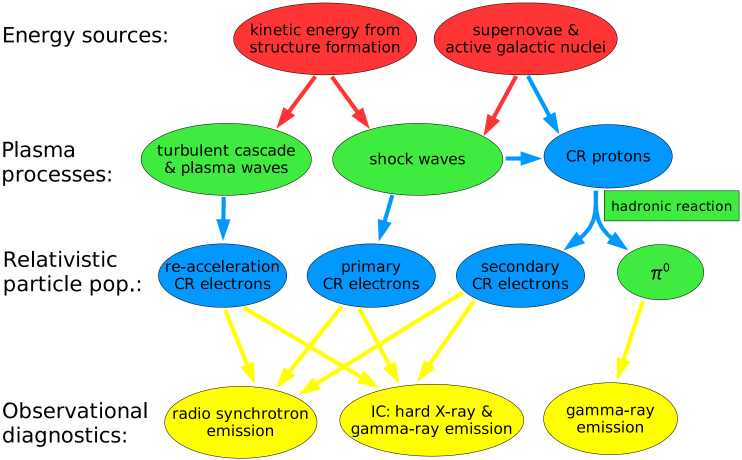
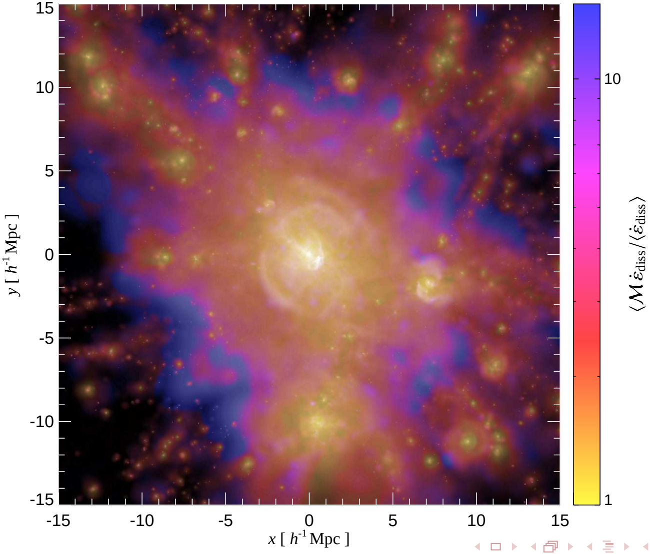
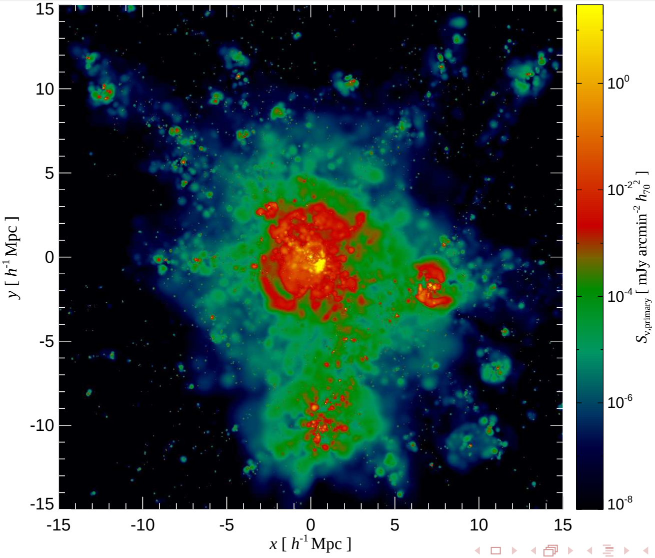


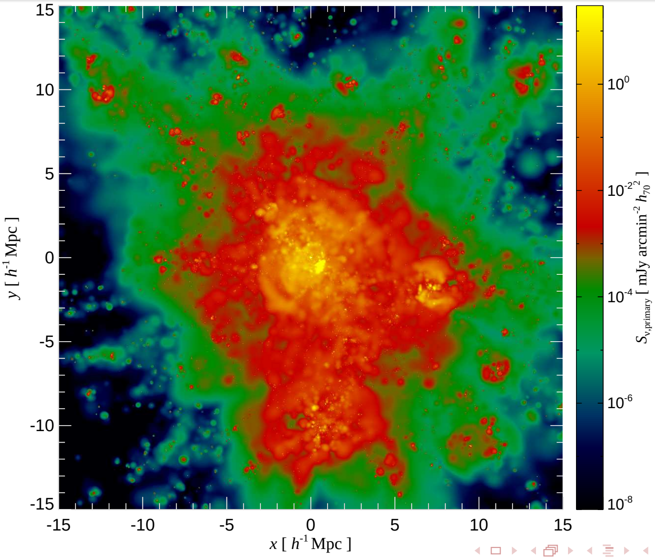
Cosmic web: Mach number



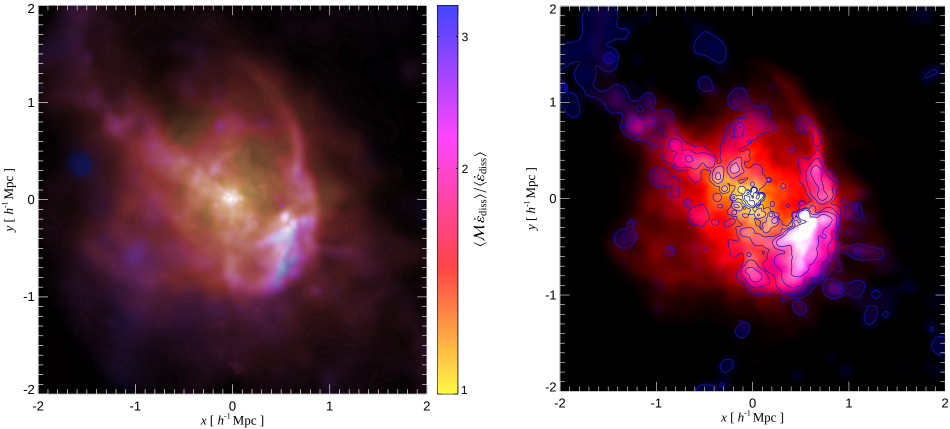
Radio gischt: primary CRe (150 MHz)



Radio gischt: primary CRe (150 MHz), slower magn. decline



Radio gischt illuminates cosmic magnetic fields



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

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

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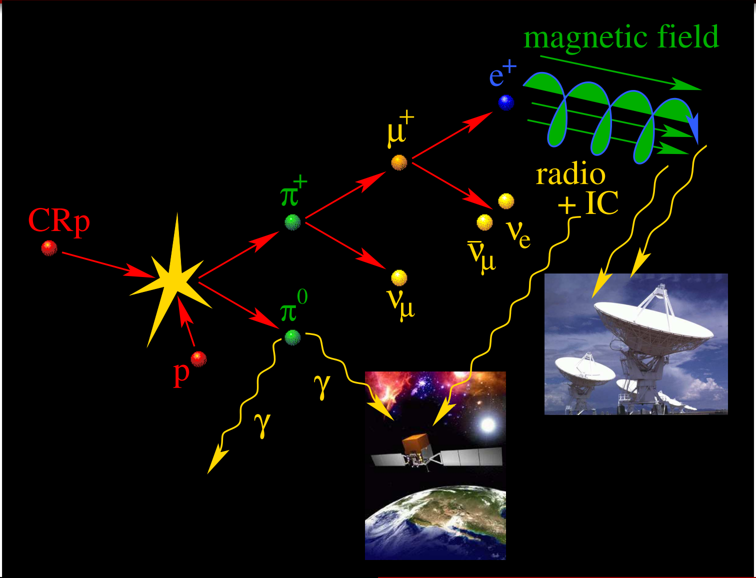
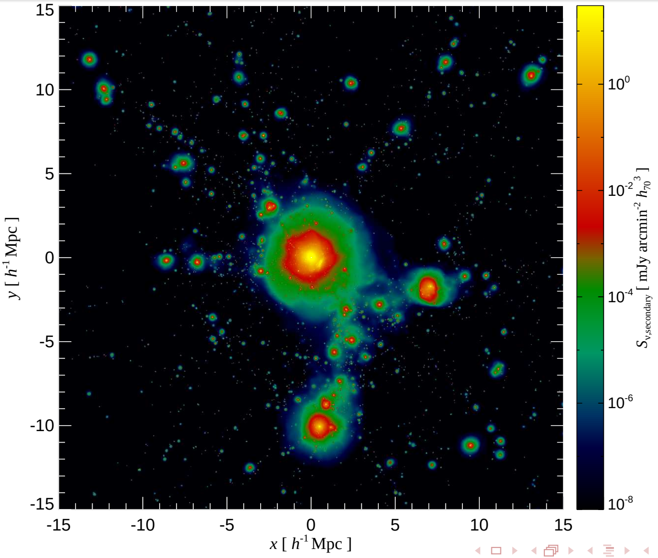
Hadronic cosmic ray proton interaction



Cluster radio emission by hadronically produced CRe



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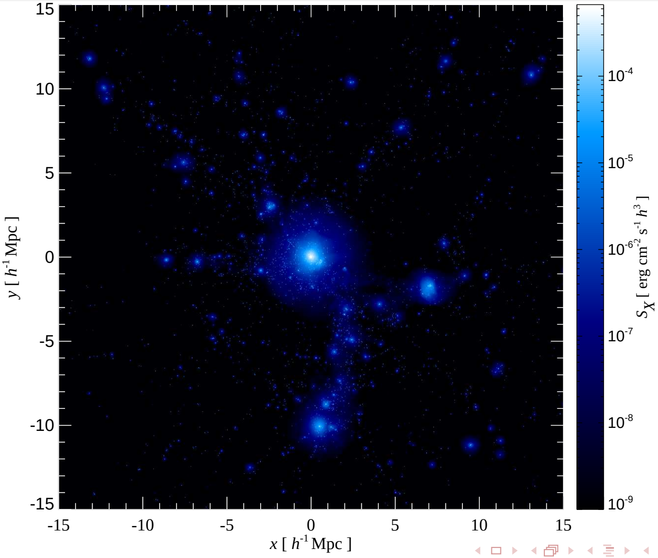
Thermal X-ray emission



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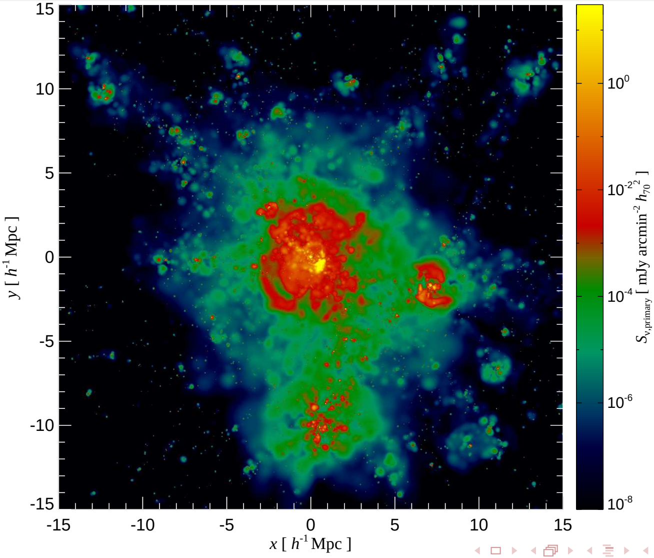
Radio gischt: primary CRe (150 MHz)



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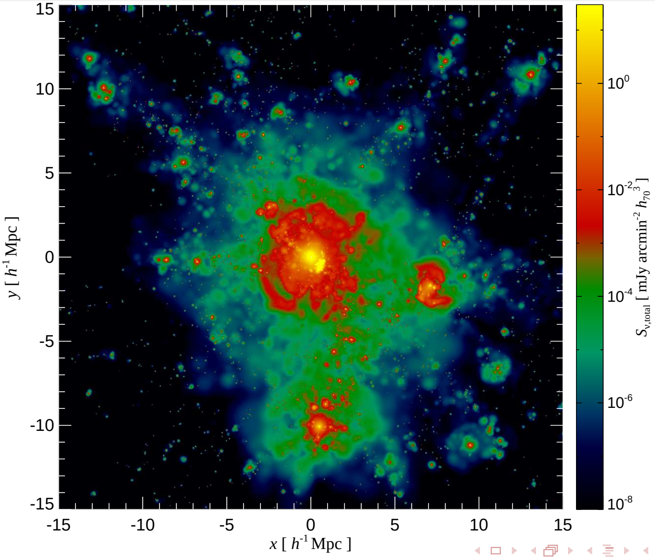
Radio gischt + central hadronic halo = giant radio halo



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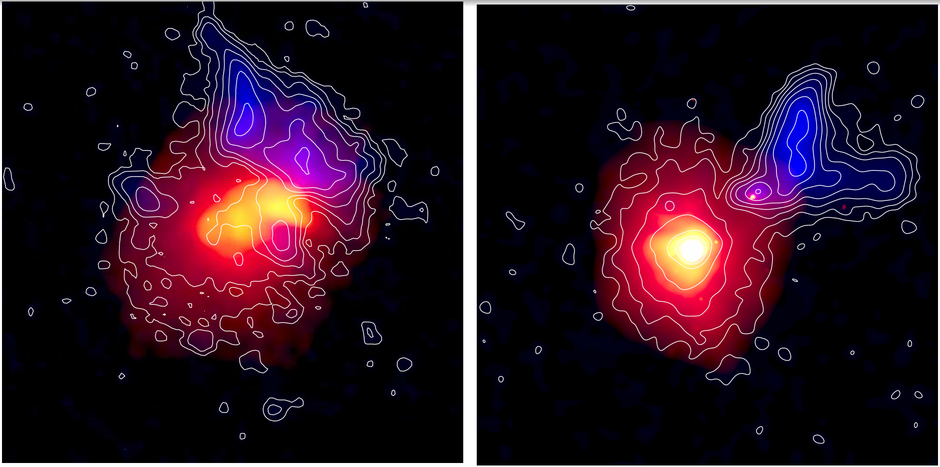
Which one is the simulation/observation of A2256?



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

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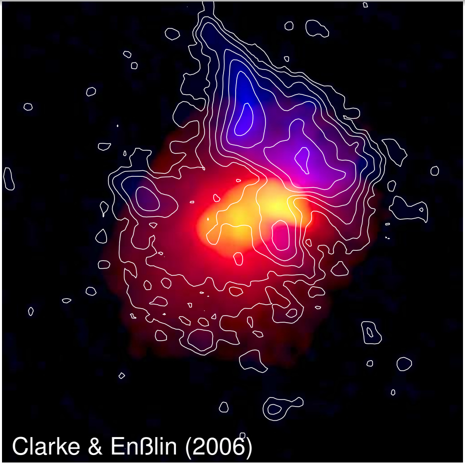
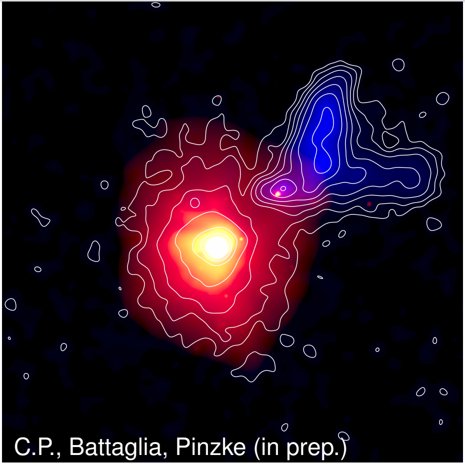
Observation – simulation of A2256





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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.:

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

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Outline

1. Physical cosmology
   - Structure formation in the Universe
   - Concept of shock waves
   - Particle acceleration
2. High-energy phenomena
   - Observations and simulations
   - Cosmic ray physics and cosmology
   - Non-thermal cluster emission
3. Dark matter searches
   - Theory and observations
   - Gamma-ray signatures
   - Implications for cosmological structure formation

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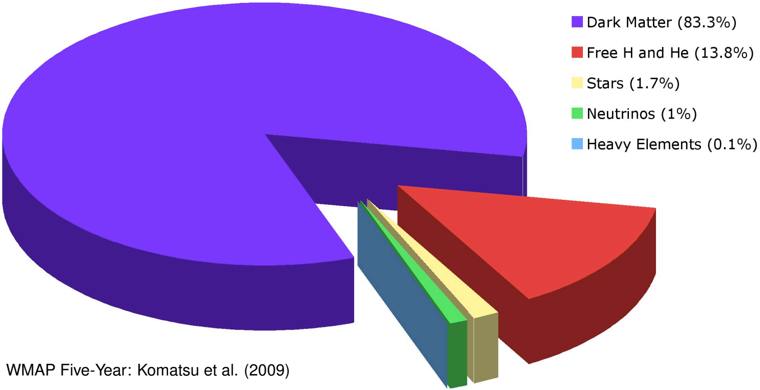
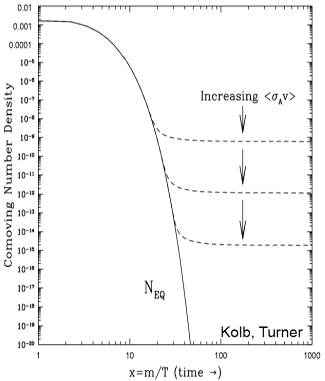
The matter content of the Universe – 2009



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

The WIMP miracle



- Fermi introduced a new mass scale of $m_{\text{weak}} \sim 100$ 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

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

-

$$\left.\begin{aligned} m_x &\sim m_{\text{weak}} \sim 100\text{ GeV} \\ g_x &\sim g_{\text{weak}} \sim 0.6 \end{aligned}\right\} \Omega_X \sim 0.1$$

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

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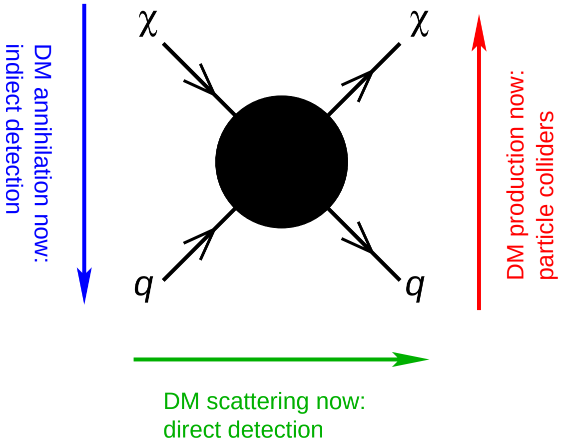
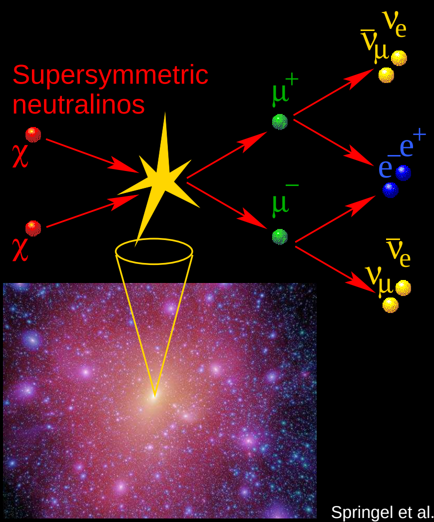
WIMP detection

Correct relic density → DM annihilation in the Early Universe

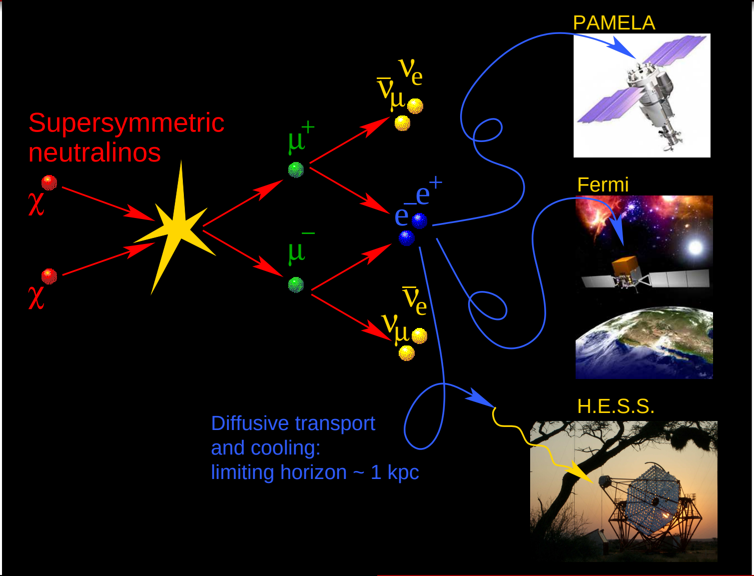


Indirect detection of dark matter

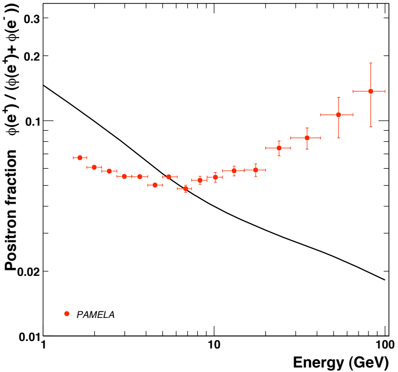


Springel et al. 2008

Indirect detection of dark matter

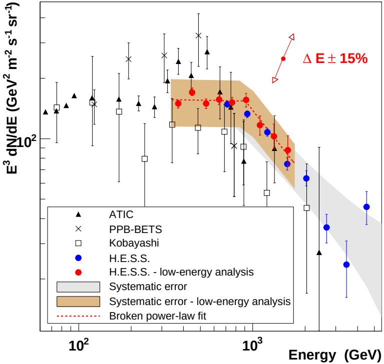


PAMELA and HESS data on electrons and positrons



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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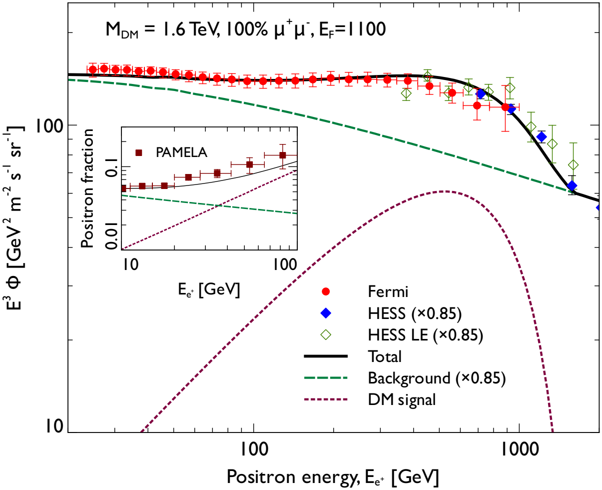
Combining recent electron and positron data

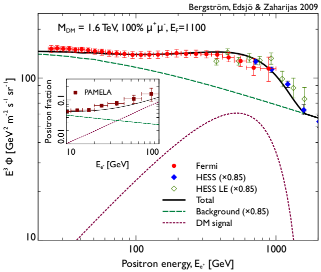
Fermi: excess number of leptons compared to background model (Abdo et al. 2009)

Bergström, Edsjö & Zaharijas 2009



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)

→ 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, C.P., Bergström, 2009, Phys. Rev. Lett., 103, 181302

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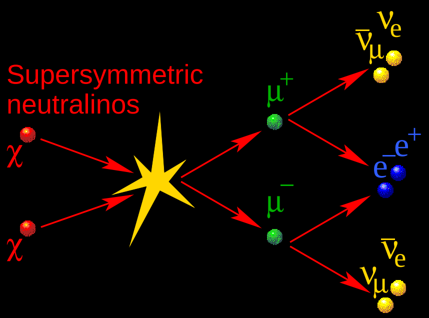
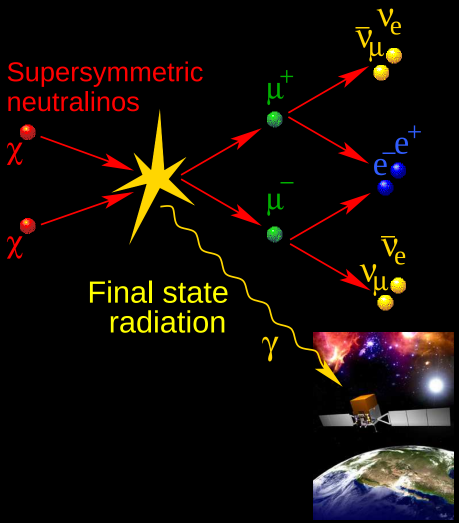
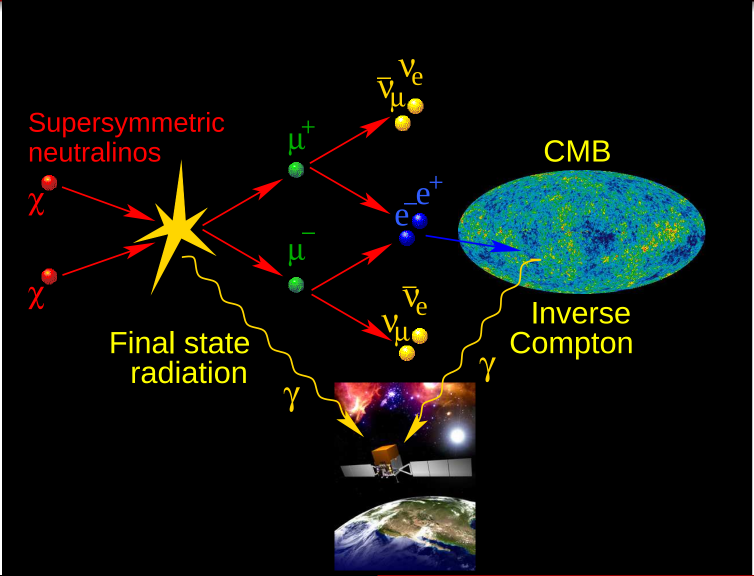
Indirect detection of DM through gamma-rays



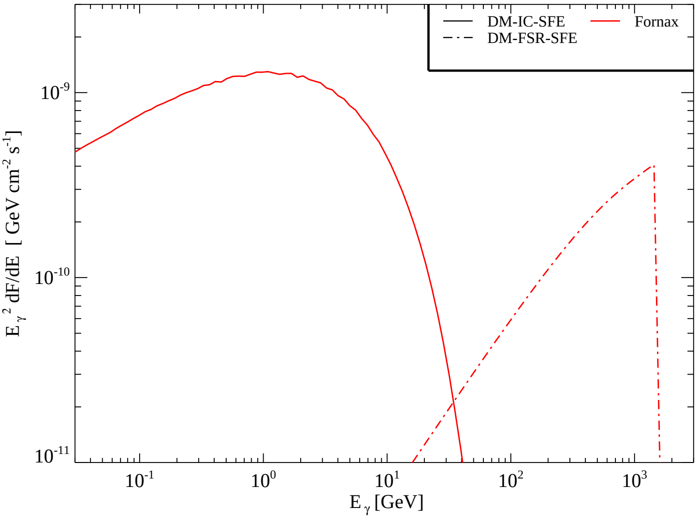
Indirect detection of DM through gamma-rays



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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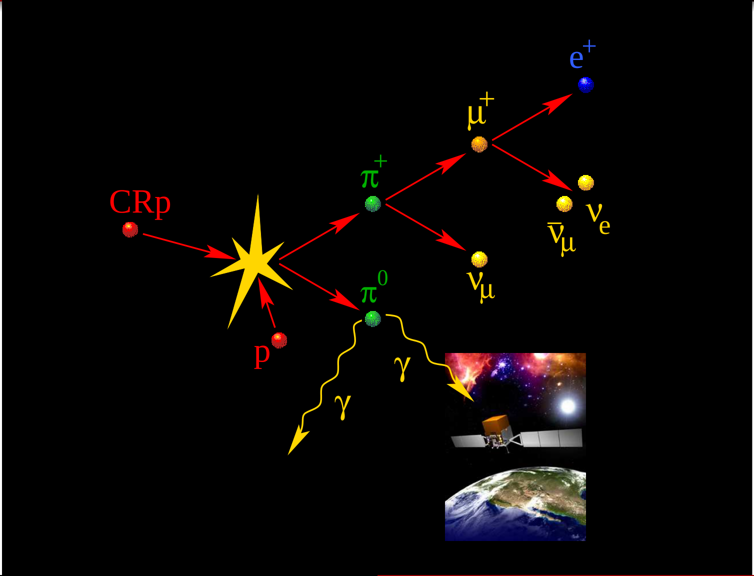
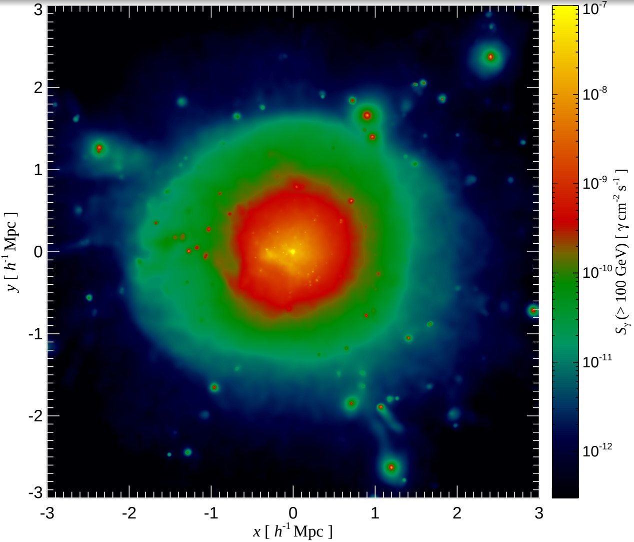
Hadronic cosmic ray proton interaction



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



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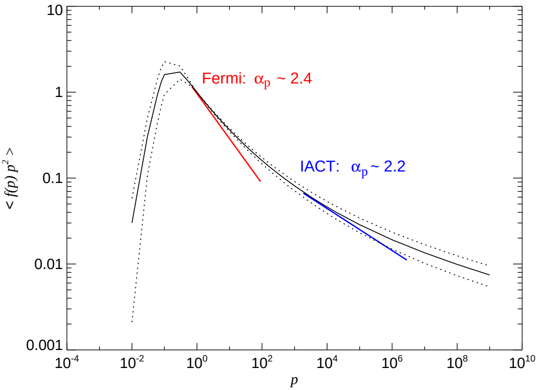
Universal CR spectrum in clusters



Normalized CR spectrum shows universal concave shape → governed mainly by hierarchical structure formation and adiabatic CR transport processes. (Pinzke & C.P. 2010)

→ very promising for disentangling the dark matter annihilation signal!

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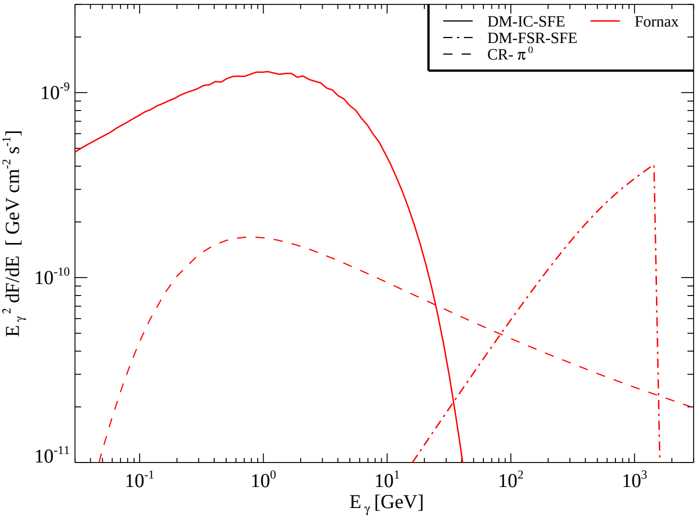
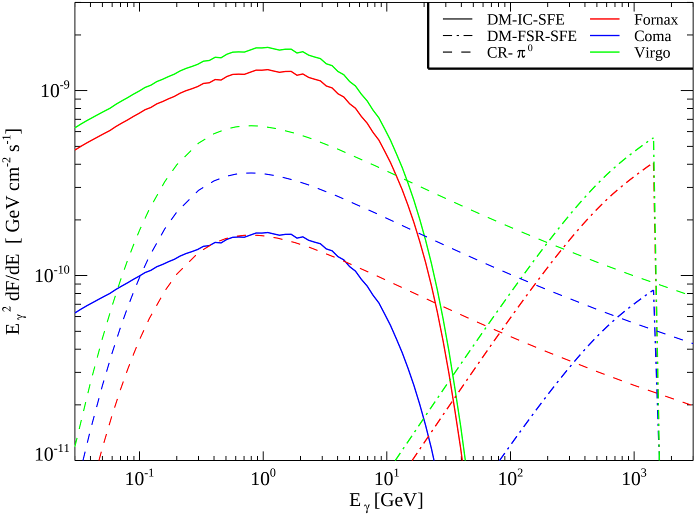
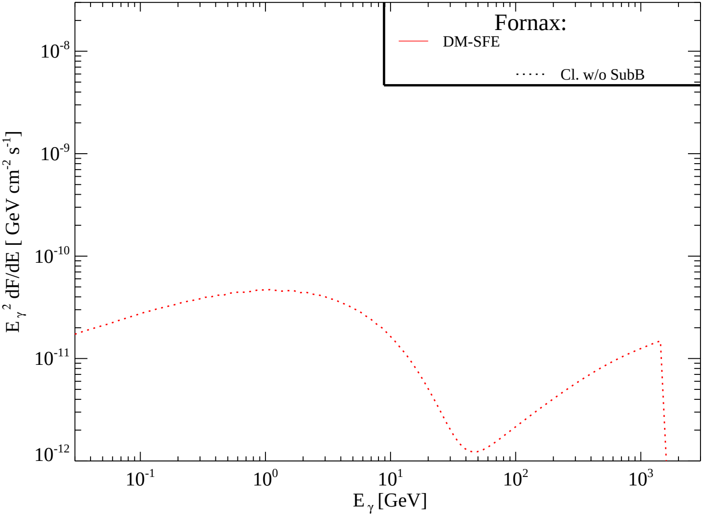
Gamma-ray spectrum from DM vs. CR interactions



Gamma-ray spectrum for various galaxy clusters



DM gamma-rays: without substructure



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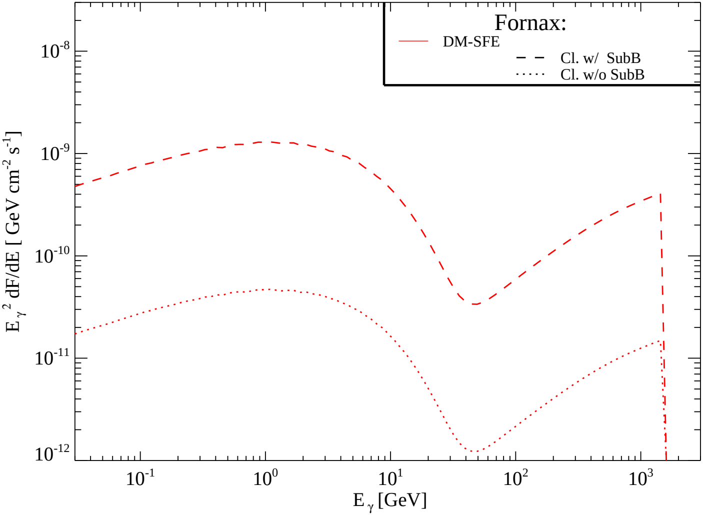
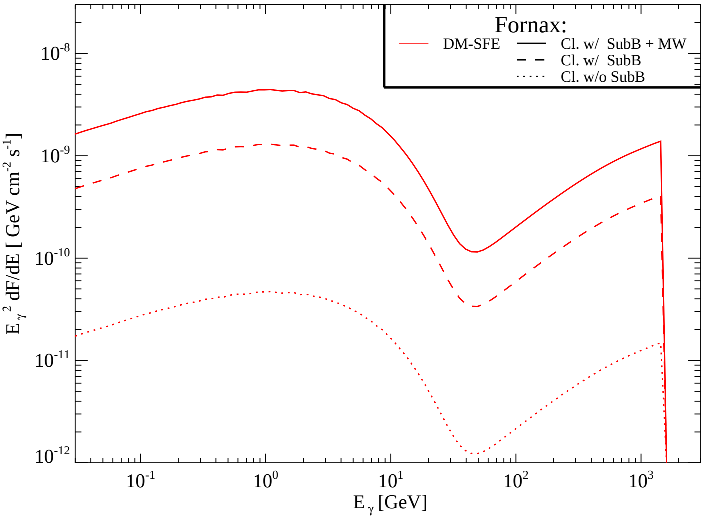
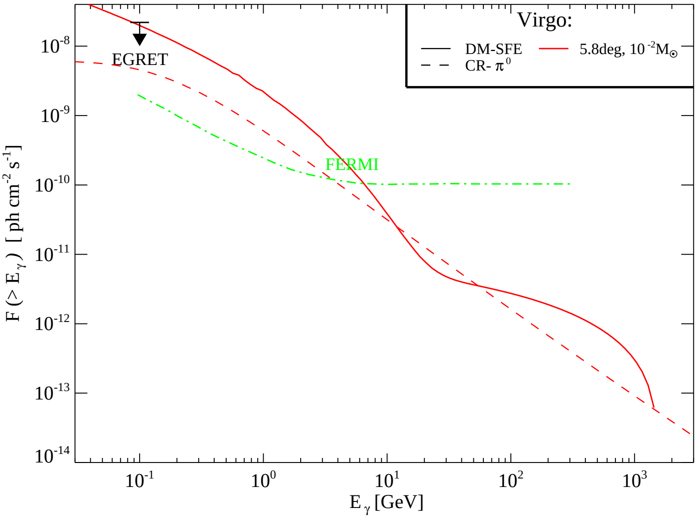
DM gamma-rays: with substructure



DM gamma-rays: with substructure and Milky Way

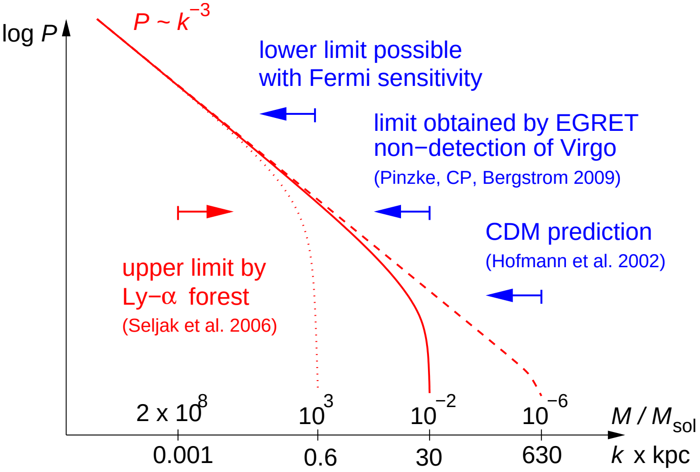


Probing small scales with gamma-rays



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.

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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, 2009, Phys. Rev. Lett., 103, 181302, *Gamma-rays from dark matter annihilations strongly constrain the substructure in halos*
- Battaglia, Pfrommer, Sievers, Bond, Enßlin, 2009, MNRAS, 393, 1073, *Exploring the magnetized cosmic web through low frequency radio emission*
- Pfrommer, 2008, MNRAS, 385, 1242 *Simulating cosmic rays in clusters of galaxies – III. Non-thermal scaling relations and comparison to observations*
- Pfrommer, Enßlin, Springel, 2008, MNRAS, 385, 1211, *Simulating cosmic rays in clusters of galaxies – II. A unified scheme for radio halos and relics with predictions of the γ-ray emission*
- Pfrommer, Enßlin, Springel, Jubelgas, Dolag, 2007, MNRAS, 378, 385, *Simulating cosmic rays in clusters of galaxies – I. Effects on the Sunyaev-Zel'dovich effect and the X-ray emission*
- Pfrommer, Springel, Enßlin, Jubelgas, 2006, MNRAS, 367, 113, *Detecting shock waves in cosmological smoothed particle hydrodynamics simulations*
- Enßlin, Pfrommer, Springel, Jubelgas, 2007, A&A, 473, 41, *Cosmic ray physics in calculations of cosmological structure formation*

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