High-Energy Phenomena and Dark Matter Searches in Galaxy Clusters

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in collaboration with

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Outline

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Properties of dark matter

What have galaxy clusters taught us about dark matter?

Dark matter exists and is . . .

- . . . gravitationally interacting: most of the matter in the Universe is dark (galaxy clusters, galactic rotation curves, gravitational lensing, CMB, . . .)

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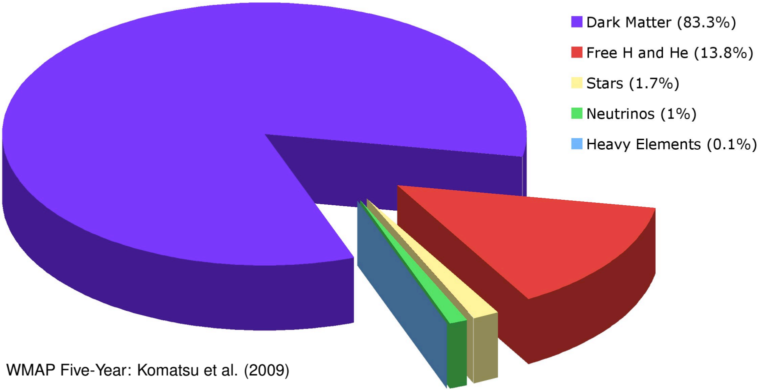
The matter content of the Universe – 2009



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

Zwicky: first evidence for dark matter

- Zwicky (1933) applied the virial theorem to the Coma cluster of galaxies:

  $$E_{\mathrm{grav}} + 2E_{\mathrm{kin}} = 0$$

- E_{kin}: energy based on galaxies motions, E_{grav}: estimated gravitational energy
- Zwicky found about 400 times more estimated mass than visually observable

- “missing mass problem”: the gravity of the visible galaxies in the cluster would be far too small for such fast orbits:

  $\rightarrow$ there must be some non-visible form of matter that provides enough of the mass and gravity to hold the cluster together

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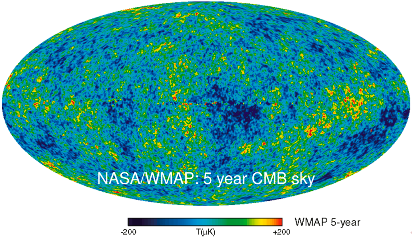
- . . . non-baryonic: it does not interact electro-magnetically with ordinary matter (CMB + structure formation)

Evidence for non-baryonic dark matter

- temperature fluctuations the epoch of recombination ($z \simeq 1100$) have an amplitude $\delta T/T \simeq 10^{-5}$
- linear regime of structure formation: $\delta(z) \propto 1/(1+z)$
- if dark matter were baryonic, we would only have time to grow fluctuations of size $\delta \simeq 10^{-2}$
- since we observe galaxies with $\delta \gtrsim 10^{2}$, dark matter fluctuations must have started to grow before recombination which is only possible if dark matter does not interact electro-magnetically with matter



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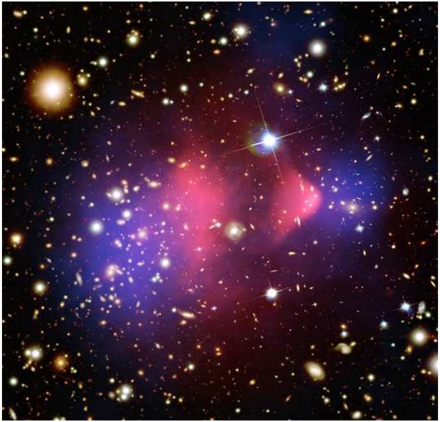
Evidence for collisionless dark matter



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.)

- red: X-ray emitting cluster plasma
- blue: weak lensing (dark matter) map
- yellow: galaxies

the (collisionless) galaxies follow the dark matter distribution, the bulk of the plasma lags behind

→ dark matter is collisionless

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→ dark matter is a weakly interacting massive particle (WIMP), but what is it really (SUSY, extra dimensions, . . .)?

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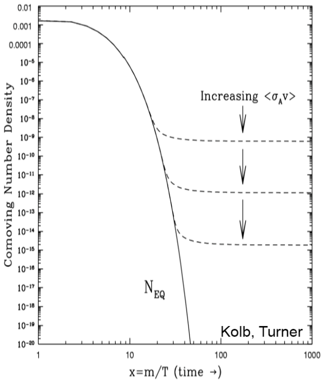
The WIMP miracle



- Fermi introduced a new mass scale of $m_{\rm weak} \sim 100$ GeV to describe the beta decay: $n \rightarrow p\, e^- \, \bar{\nu}$
- 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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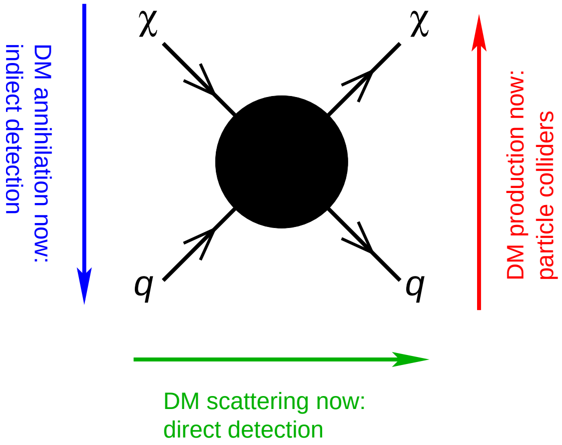
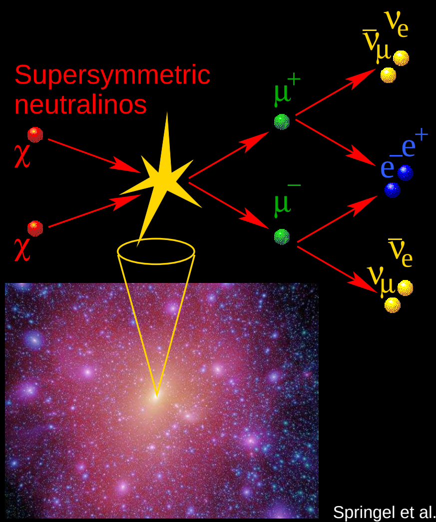
WIMP detection

Correct relic density → DM annihilation in the Early Universe

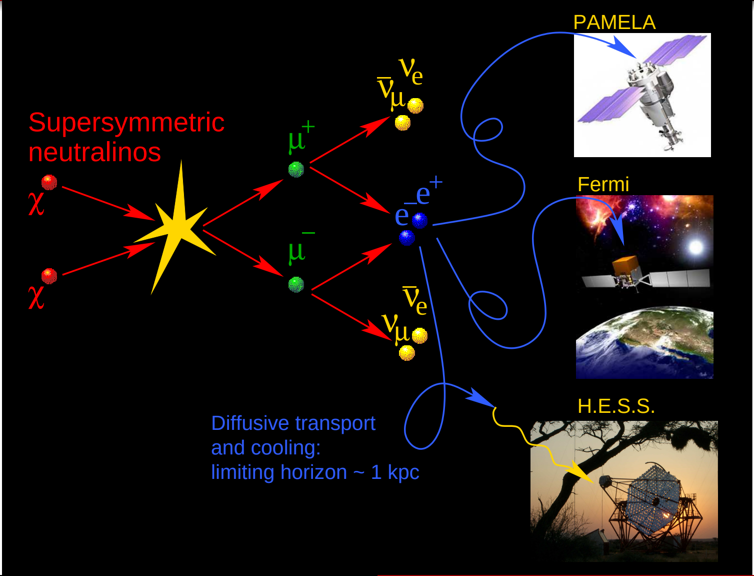


Indirect detection of dark matter

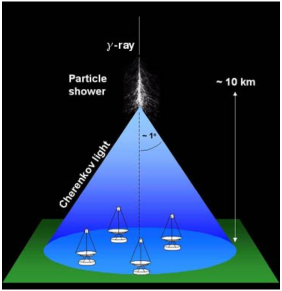


Springel et al. 2008

Indirect detection of dark matter



Imaging air Čerenkov telescopes – the technique (1)



- high-energy γ-ray impacts the Earth's atmosphere and sets off an electro-magnetic cascade in the vicinity of a nucleus
- e^+/e^- travel faster than the speed of light in the atmosphere $\rightarrow$ emission of a cone of blue Čerenkov light

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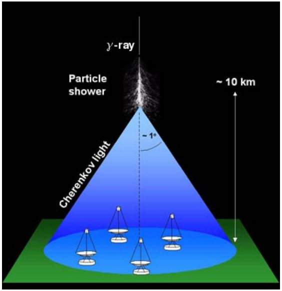
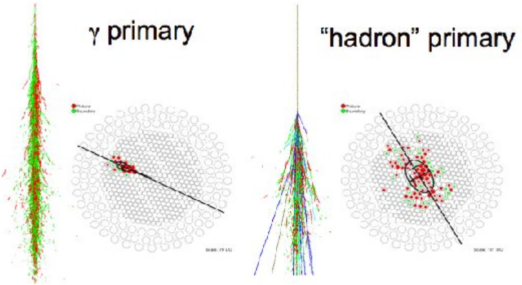
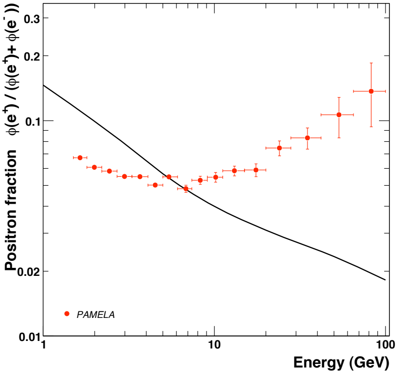
Imaging air Čerenkov telescopes – the technique (2)





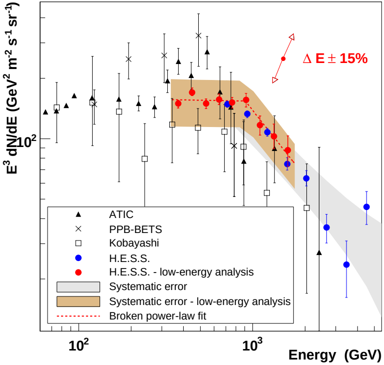
- primary γ-rays and hadrons cause different shower characteristics $\rightarrow$ separation of γ-rays from 'background' events
- opening angle and shower location in the shower image allows reconstructing the initial energy and direction of the γ-ray

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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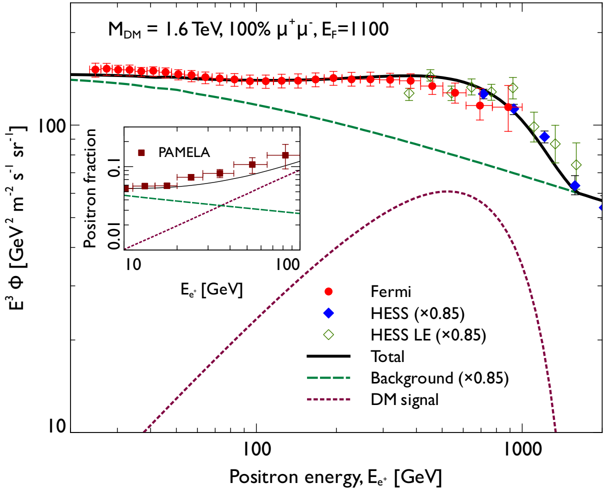
Combining recent electron and positron data

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

Bergström, Edsjö & Zaharijas 2009



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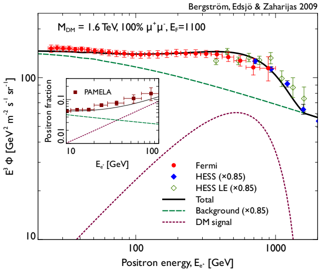
Interpretations of recent electron and positron data

- 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 was claimed to be 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, CP, Bergström, Phys. Rev. Lett., 2009, 103, 181302

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Dissecting the dark matter flux

$$N_\gamma = \left[\int_{\mathrm{LOS}} \rho_\chi^2 \, \mathrm{d}l_\chi\right] \frac{\langle\sigma v\rangle}{2M_\chi^2} \left[\int_{E_{\mathrm{th}}}^{M_\chi} \left(\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}\right)_{\mathrm{SUSY}} A_{\mathrm{eff}}(E)\,\mathrm{d}E\right] \frac{\Delta\Omega}{4\pi}\,\tau_{\mathrm{exp}}$$

- astrophysics: contains the uncertainty about the DM profile with its central behavior and the substructure distribution
- particle physics: assuming DM is supersymmetric, there is the uncertainty about the cross section, neutralino mass, and decay channels
- detector properties: energy dependent effective area, detector response, scanning strategy, . . .

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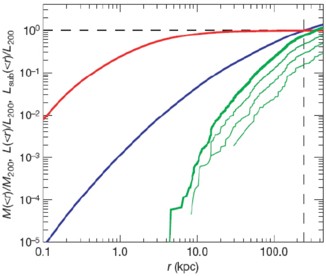
Boost factors

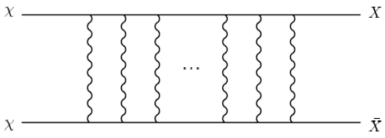
Substructures:



$$N = (M_{\rm min}/M_{\rm lim})^{0.226}$$

Springel *et al.*, Nature **456N7218** 73 (2008)

Sommerfeld:



$$\langle\sigma v\rangle \approx \langle\sigma v\rangle_0 \times (c/v)$$

$$v = 960\ \mathrm{km/s} \times (M_{200}/10^{15}\ M_\odot)^{1/3}$$

Galaxy clusters vs. dwarf galaxies

Why look for clusters in the γ-ray band?

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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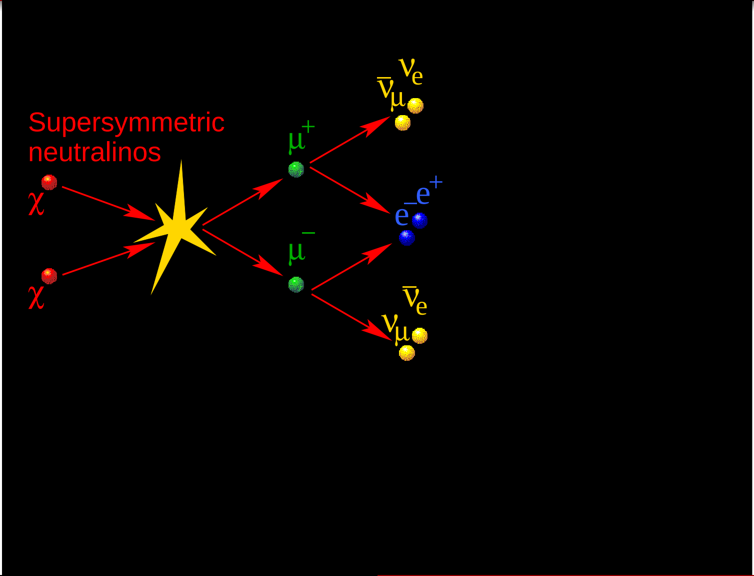
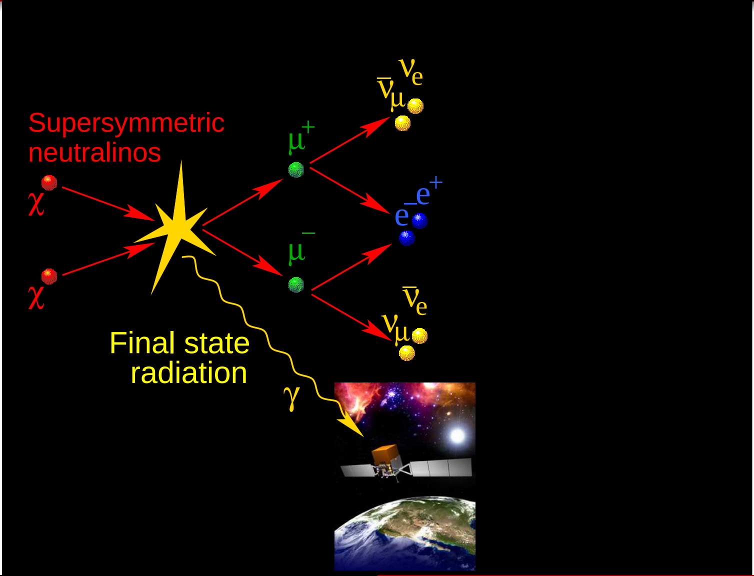
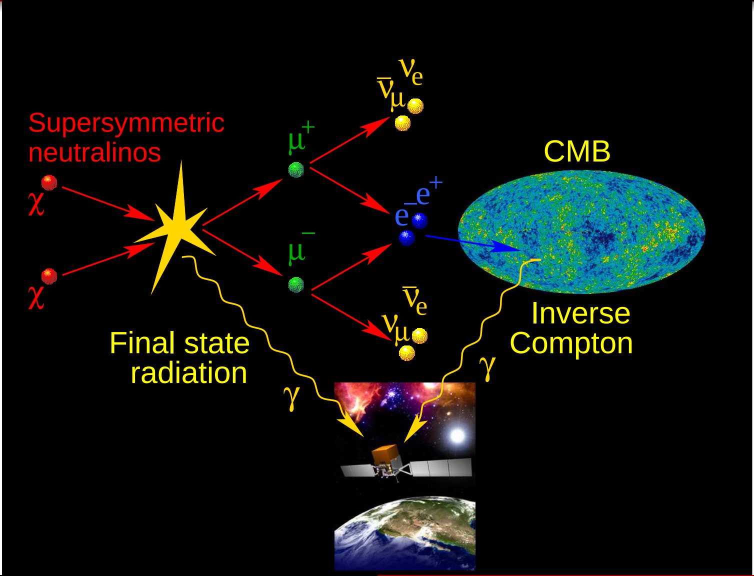
Indirect detection of DM through gamma-rays



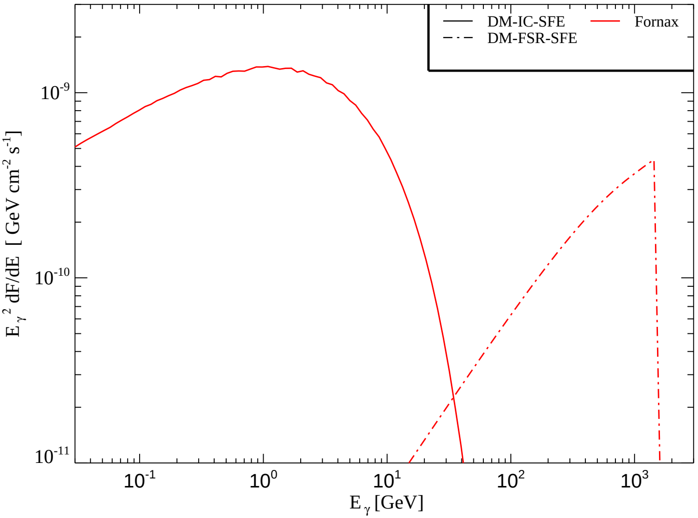
Indirect detection of DM through gamma-rays



Indirect detection of DM through gamma-rays



Gamma-ray spectrum from DM annihilations



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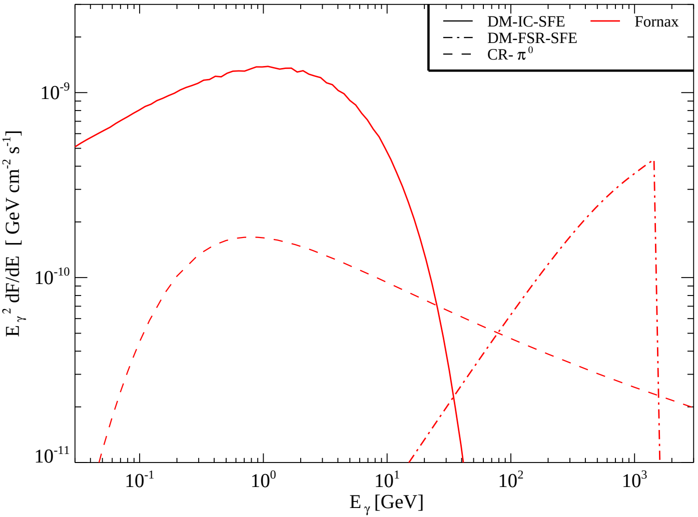
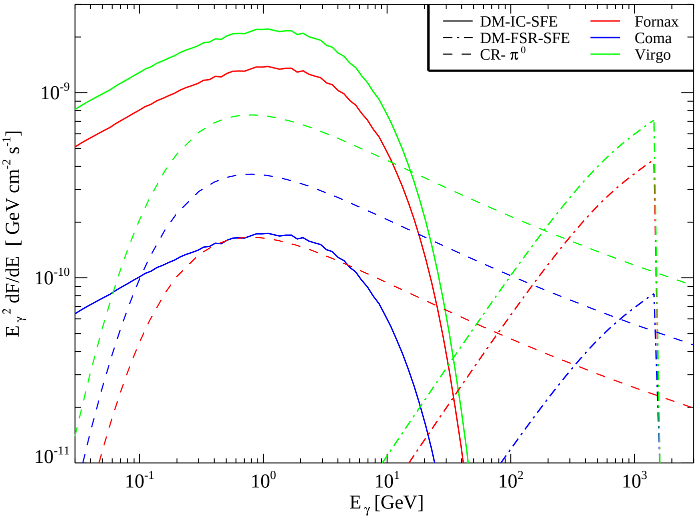
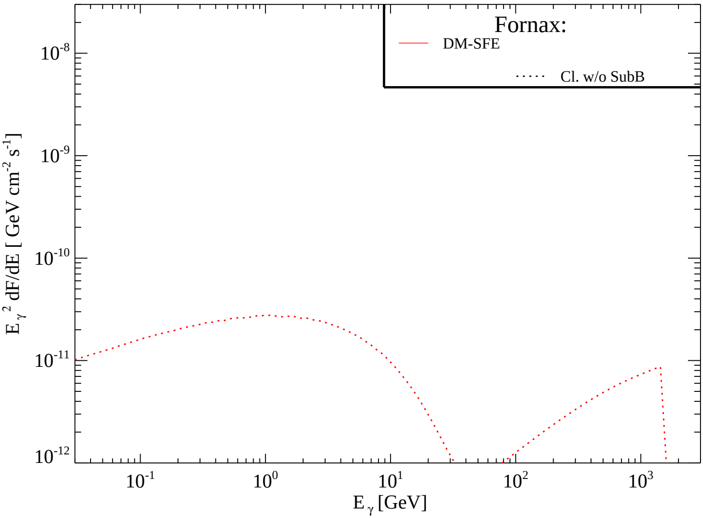
Gamma-ray spectrum from DM vs. CR interactions



Gamma-ray spectrum for various galaxy clusters



DM gamma-rays: without substructure



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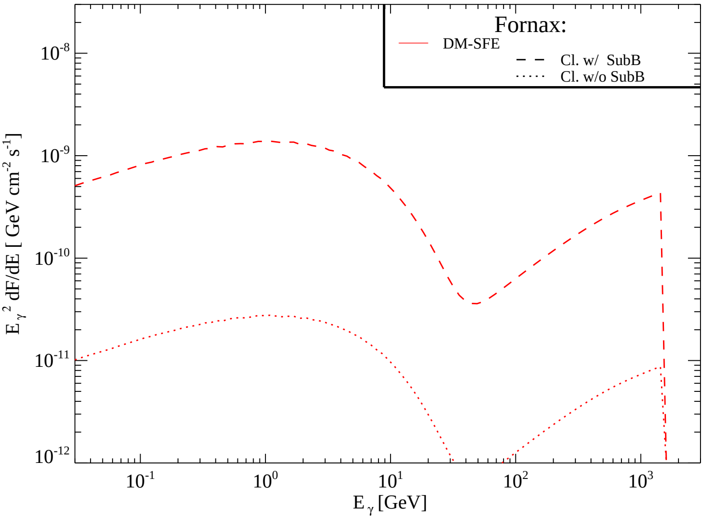

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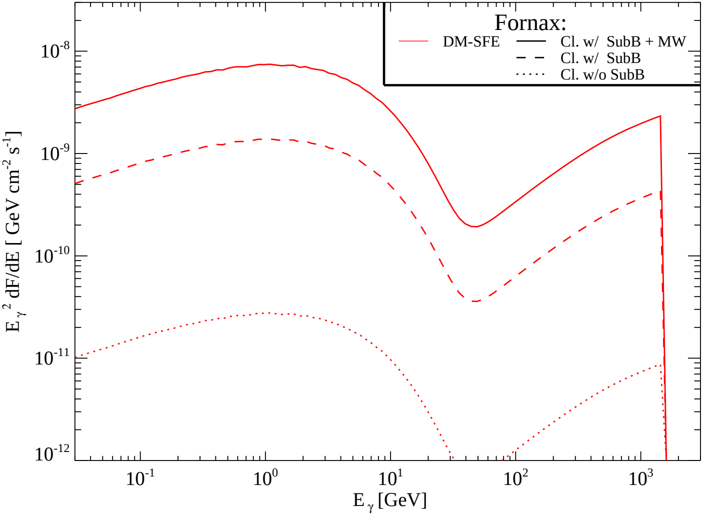
DM gamma-rays: with substructure and Milky Way



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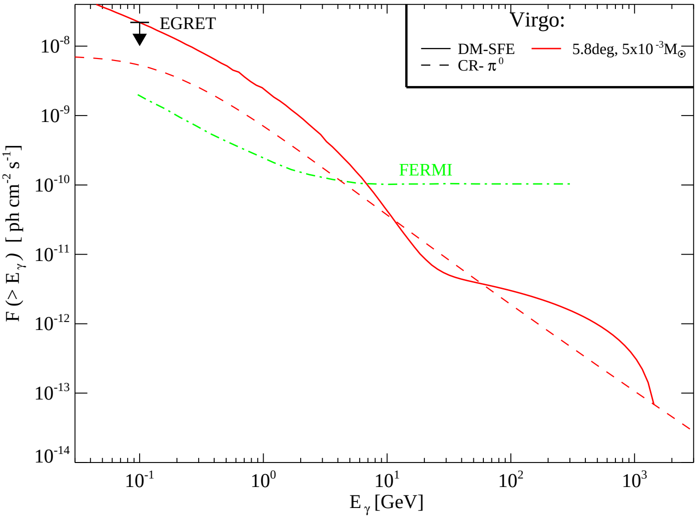
Probing small scales with gamma-rays



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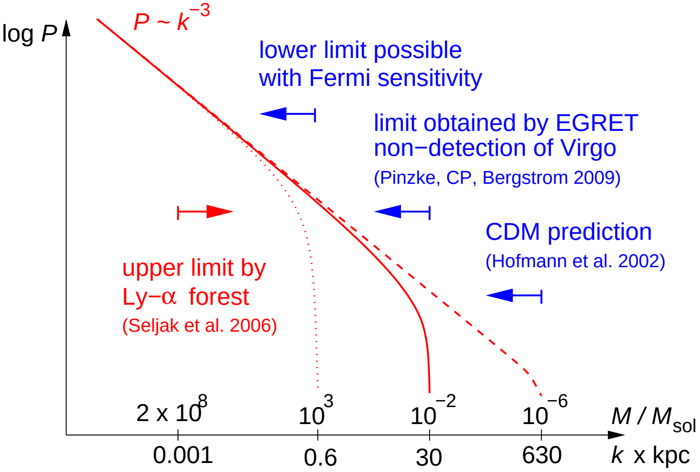
Implications for cosmological structure formation

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.

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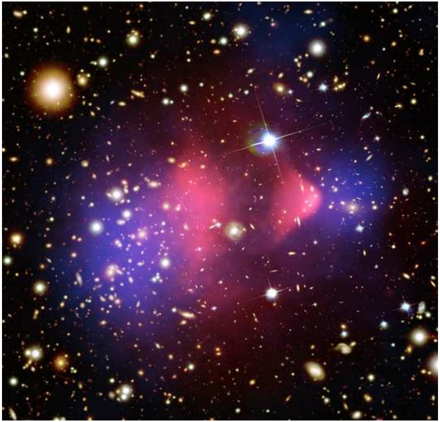
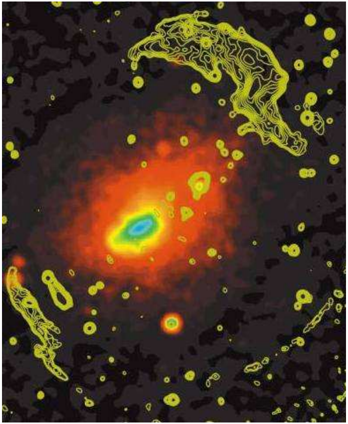
Shocks in galaxy clusters



1E 0657-56 (“Bullet cluster”)

(X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)



Abell 3667

(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)

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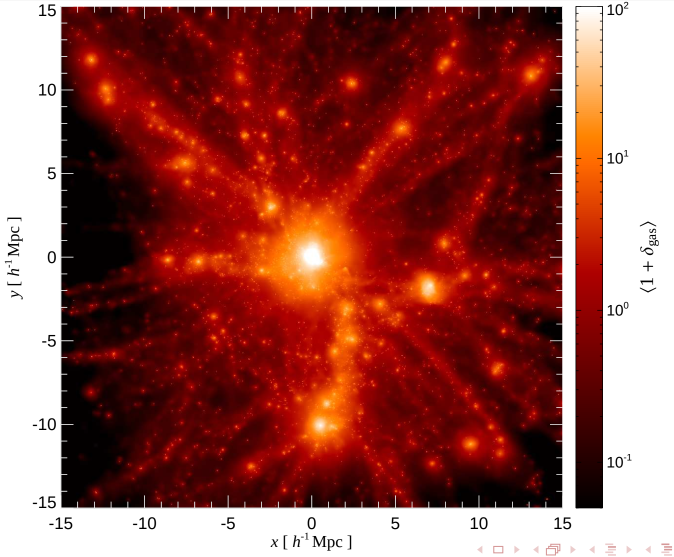
Radiative cool core cluster simulation: gas density



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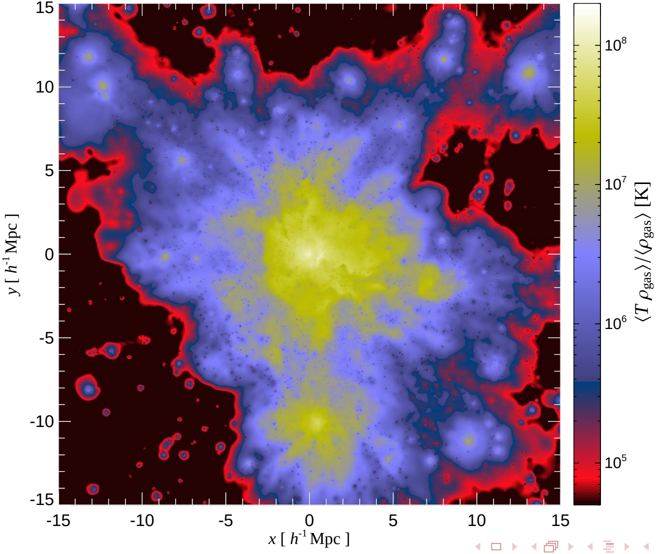
Mass weighted temperature



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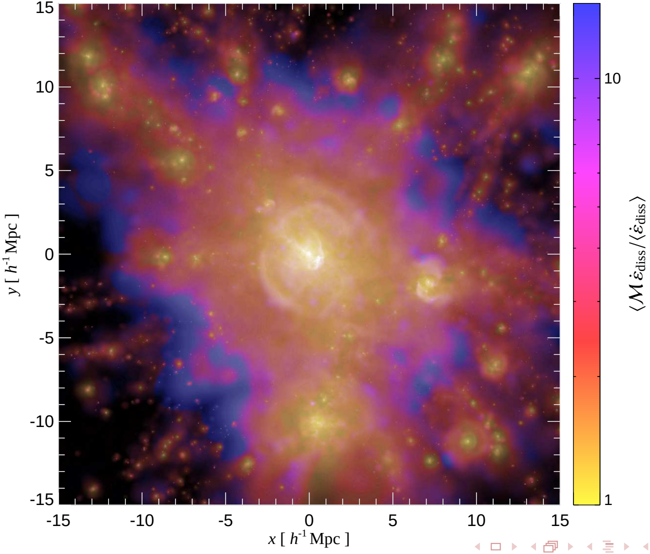
Mach number distribution weighted by $\varepsilon_{\rm diss}$



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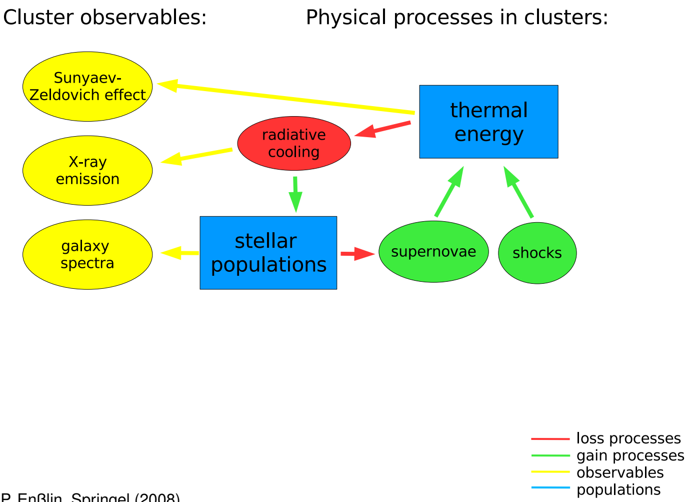
Radiative simulations – flowchart



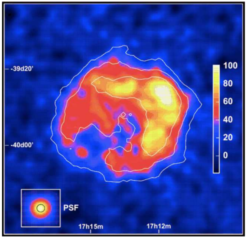
CP, Enßlin, Springel (2008)

Collisionless shocks at supernova remnants

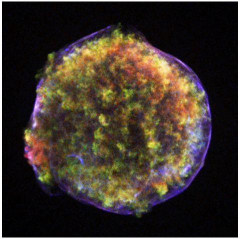
Astrophysical collisionless shocks can:

- 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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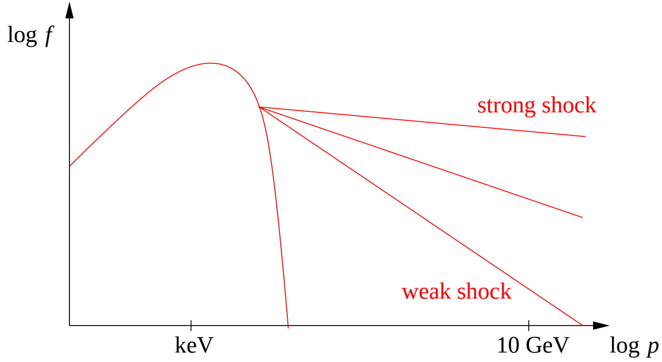
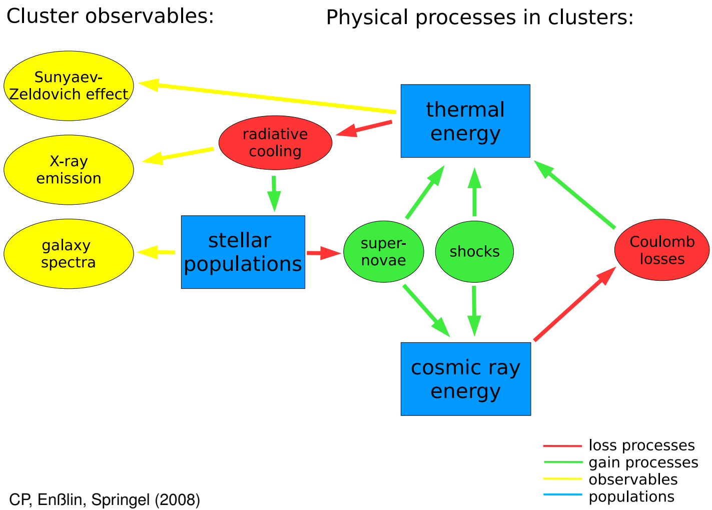
Diffusive shock acceleration – Fermi 1 mechanism

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

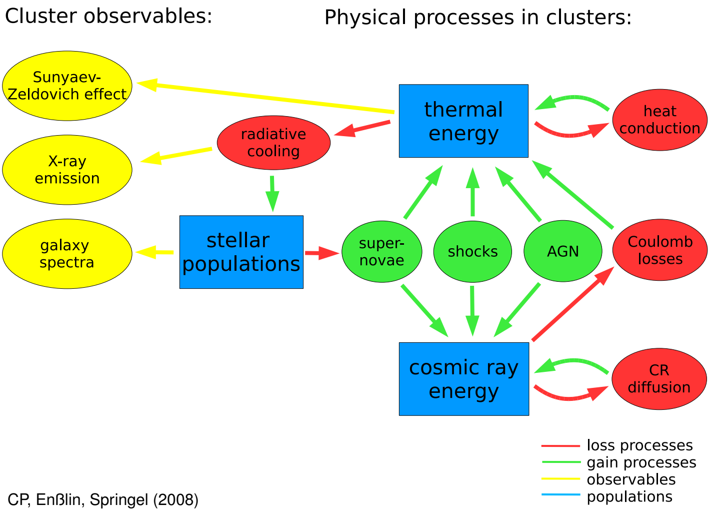


Radiative simulations with cosmic ray (CR) physics



CP, Enßlin, Springel (2008)

Radiative simulations with extended CR physics



CP, Enßlin, Springel (2008)

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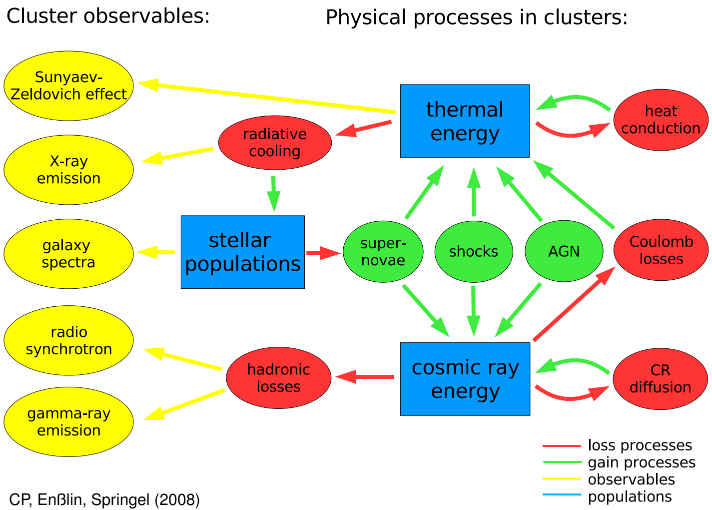
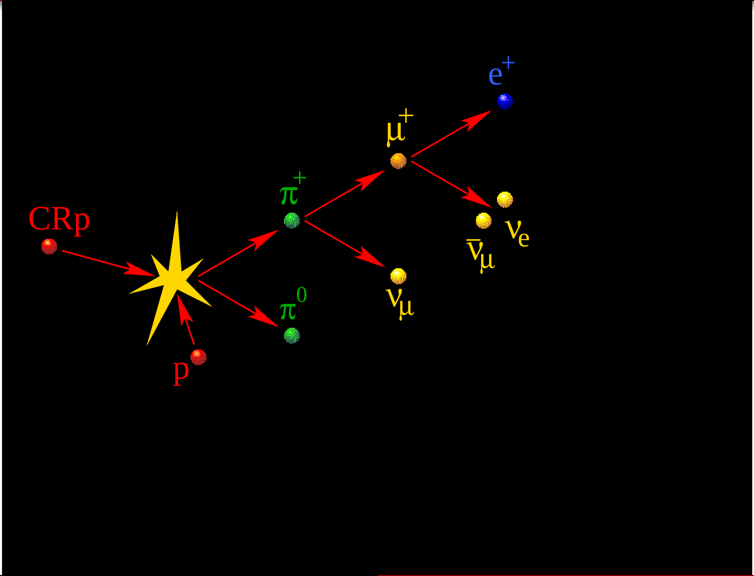


CP, Enßlin, Springel (2008)

Hadronic cosmic ray proton interaction



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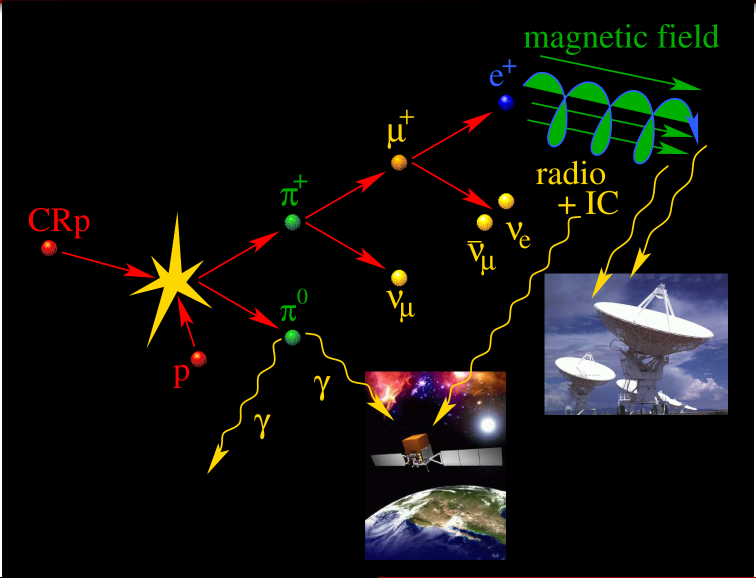
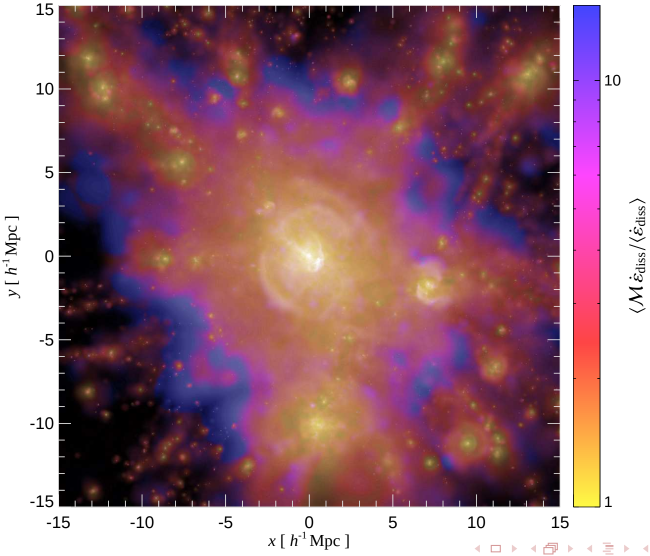


Mach number distribution weighted by $\varepsilon_{\rm diss}$



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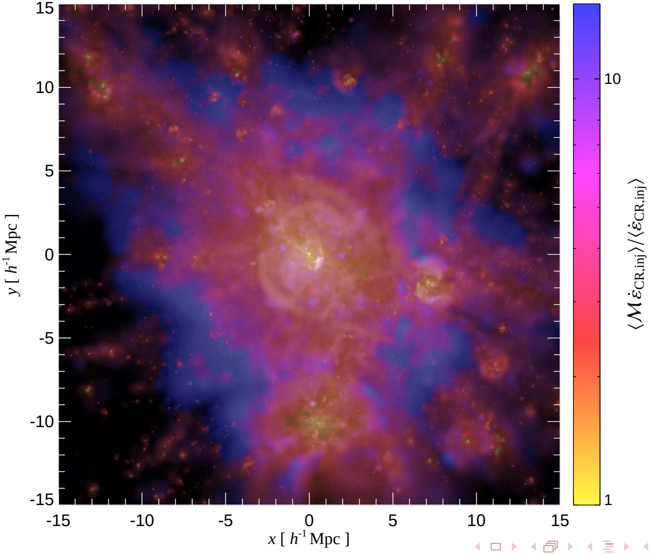
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$



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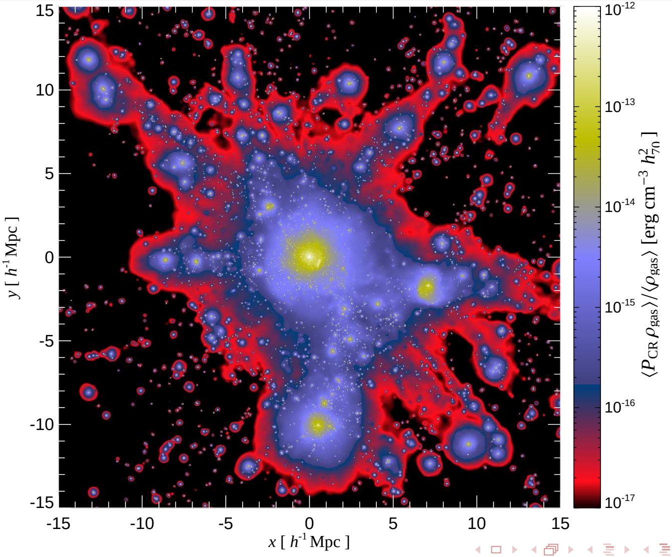
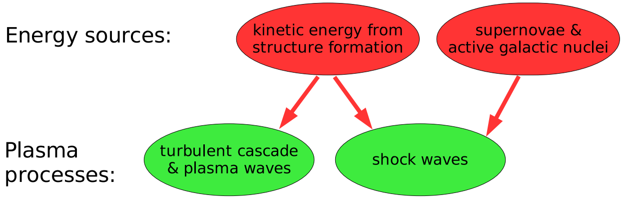
CR pressure P_{CR}



Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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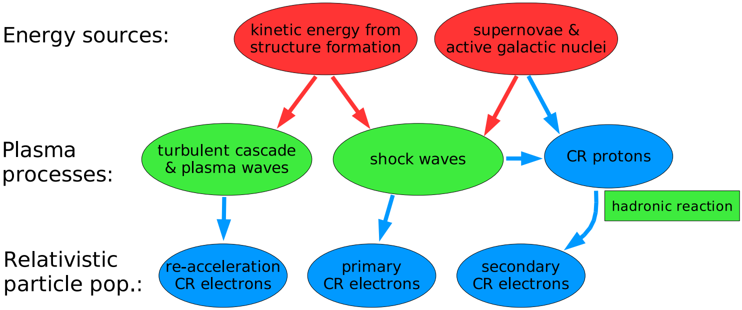

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Multi messenger approach for non-thermal processes

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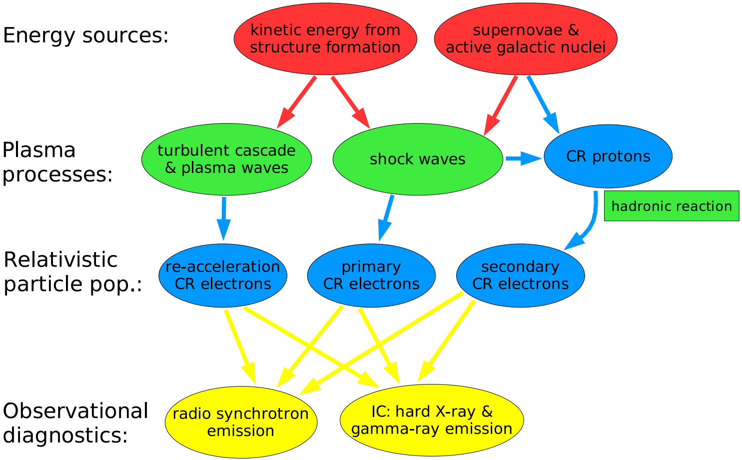

Multi messenger approach for non-thermal processes

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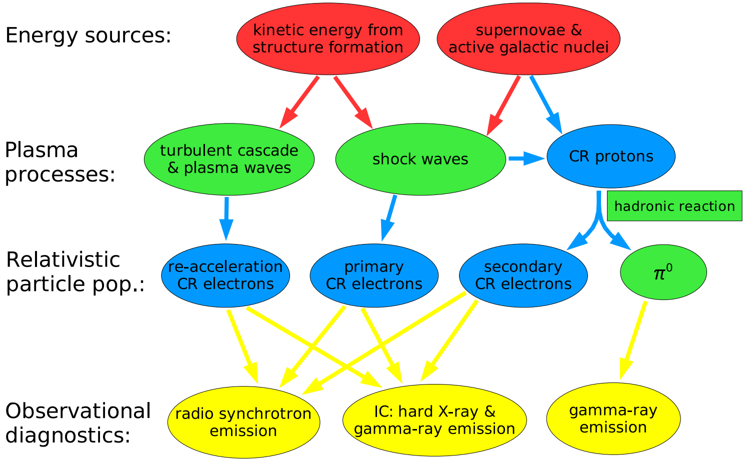
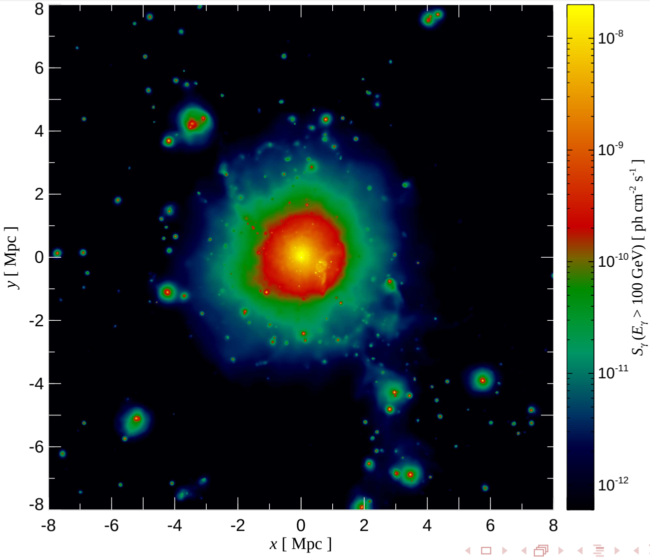


Hadronic γ-ray emission, $E_\gamma > 100$ GeV



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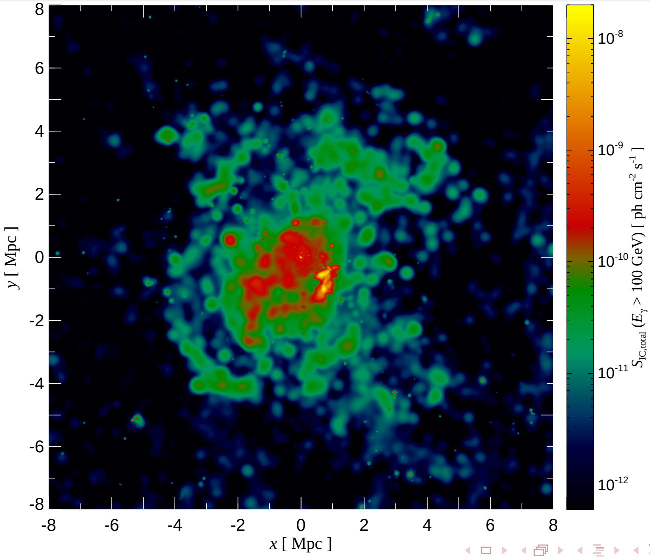
Inverse Compton emission, $E_{\rm IC} > 100$ GeV



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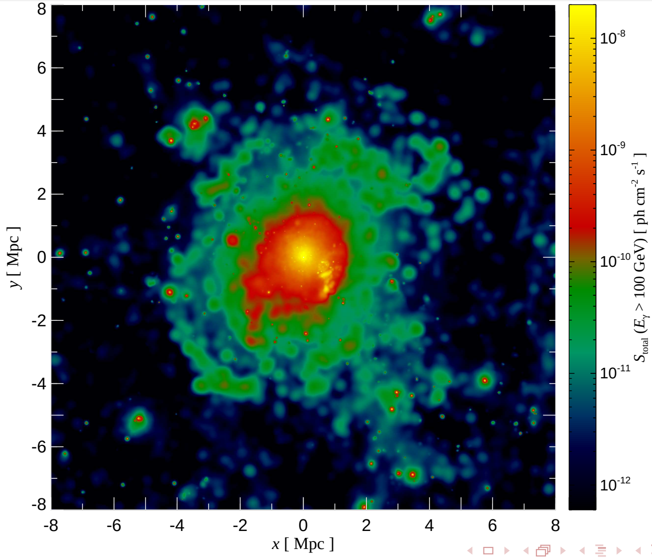
Total γ-ray emission, $E_\gamma > 100$ GeV



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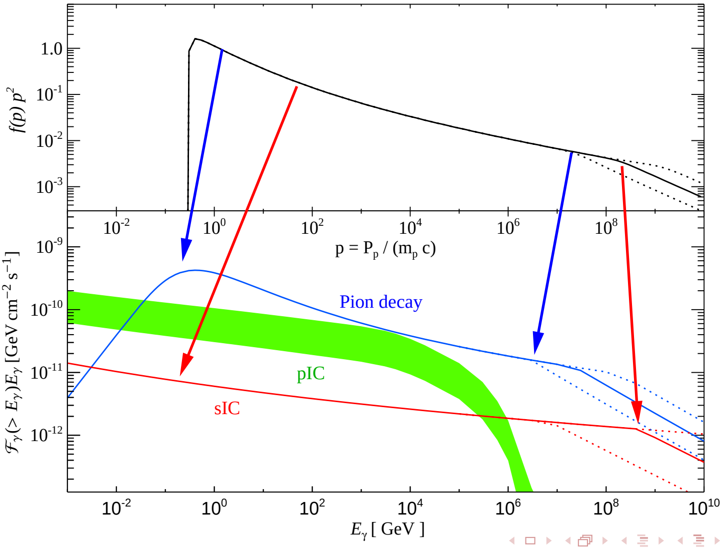
CR proton and γ-ray spectrum (Pinzke & CP 2009)



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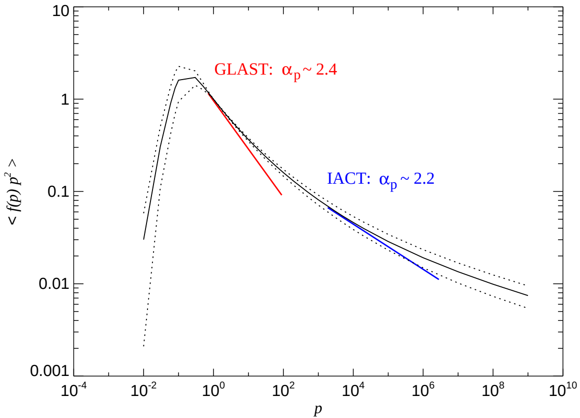
Universal CR spectrum in clusters



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

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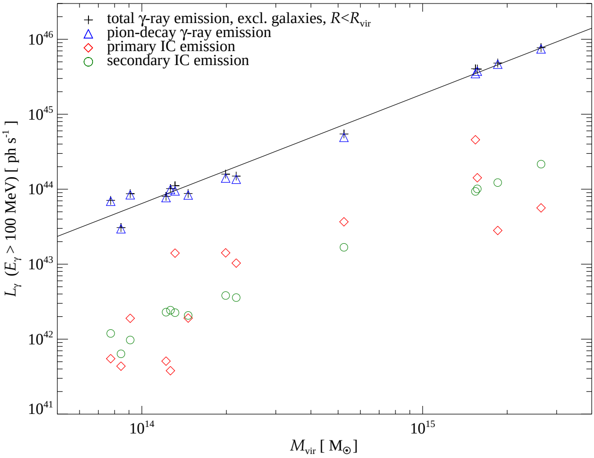
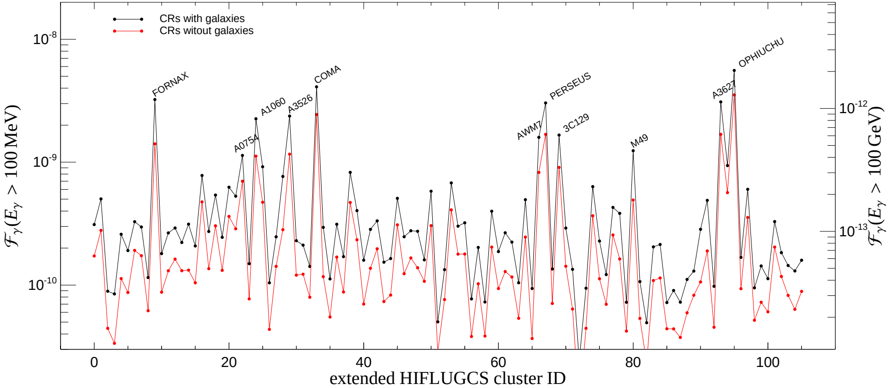
Gamma-ray scaling relations



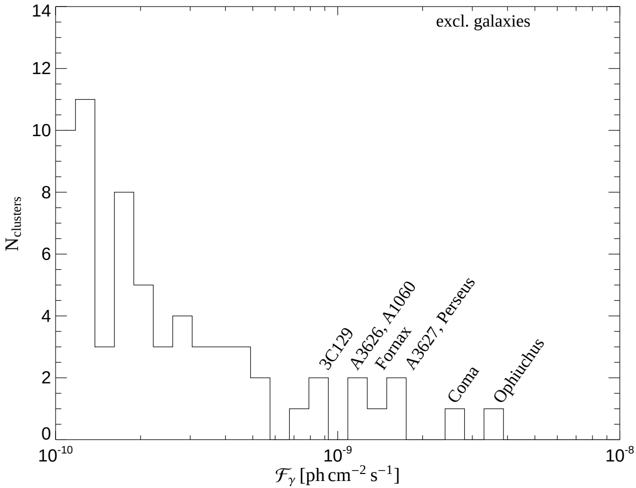
Scaling relation + complete sample of the brightest X-ray clusters (HIFLUGCS) → predictions for *Fermi* and *IACT's*

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



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

Predicted cluster sample for *Fermi* – brightest objects



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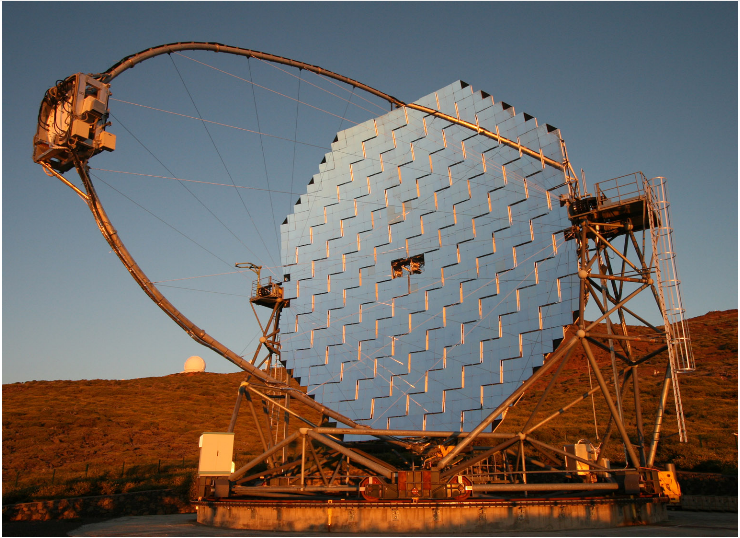
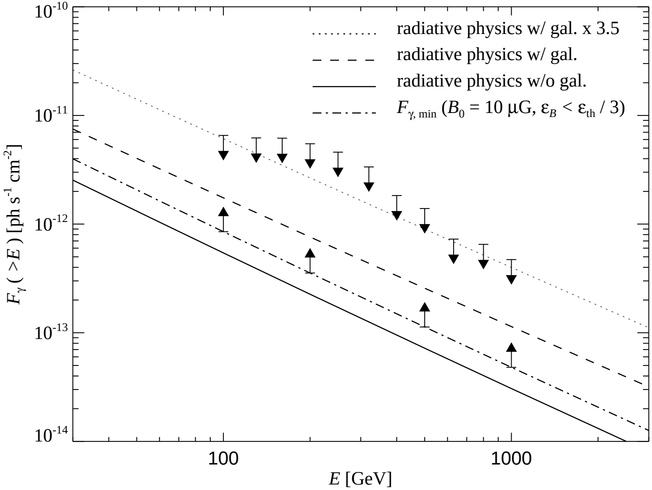
MAGIC observations of Perseus



Upper limit on the TeV γ-ray emission from Perseus



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

Results from the Perseus observation by *MAGIC*

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

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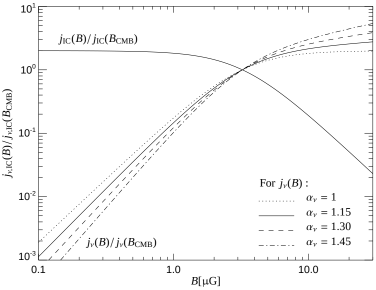
Minimum γ-ray flux in the hadronic model



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

Synchrotron luminosity:

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

γ-ray luminosity:

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

$\rightarrow$ minimum γ-ray flux:

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

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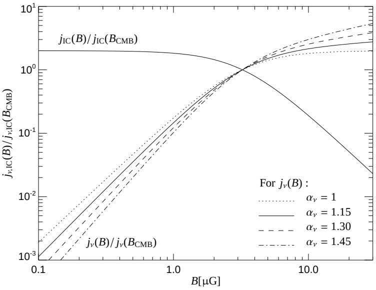
Minimum γ-ray flux in the hadronic model



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$\to$ minimum γ-ray flux:

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

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Minimum γ-ray flux in the hadronic model: *Fermi*

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

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

- These limits can be made even tighter when considering energy constraints, $P_B < P_{\rm gas}/30$ and B-fields derived from Faraday rotation studies, $B_0 = 3\,\mu$G:
  $\mathcal{F}_{\gamma,\rm COMA} \gtrsim (1.1\ldots1.5)\times10^{-9}\gamma\, cm^{-2}s^{-1} \lesssim \mathcal{F}_{\rm Fermi,\ 2yr}$
- Non-detection by Fermi seriously challenges the hadronic model.
- Potential of measuring the CR acceleration efficiency for diffusive shock acceleration.

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Conclusions on high-energy phenomena

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

Literature for the talk

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- Pfrommer, 2008, MNRAS, 385, 1242 *Simulating cosmic rays in clusters of galaxies – III. Non-thermal scaling relations and comparison to observations*
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- 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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