Cosmic ray transport in galaxy clusters – Implications for radio halos and gamma-rays

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in collaboration with

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Outline

1. Cosmological simulations
   - Introduction
   - Simulated physics
   - Cosmic rays in galaxy clusters
2. Non-thermal emission
   - Overview
   - Radio emission
   - Gamma-ray emission
3. Cosmic ray transport
   - Observations and models
   - CR pumping and streaming
   - Radio and gamma-ray bimodality

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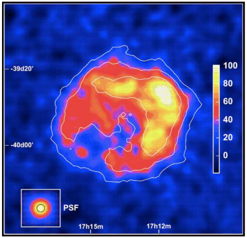
Collisionless shocks in supernova remnants

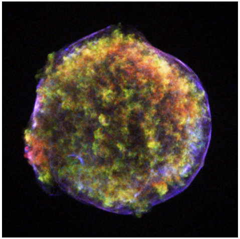
Astrophysical collisionless shocks can:

- 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)

Collisionless shocks

Astrophysical collisionless shocks can:

- accelerate particles (electrons and ions)
- amplify magnetic fields (or generate them from scratch)
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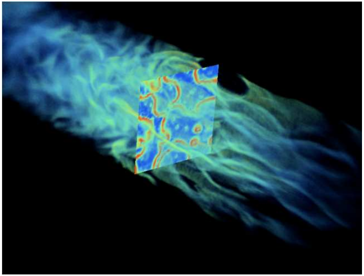
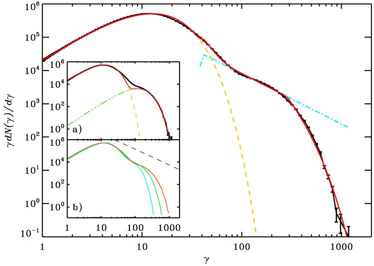
Particle-in-cell simulations of unmagnetized, relativistic pair shocks that are mediated by the Weibel instability (Spitkovsky 2008)

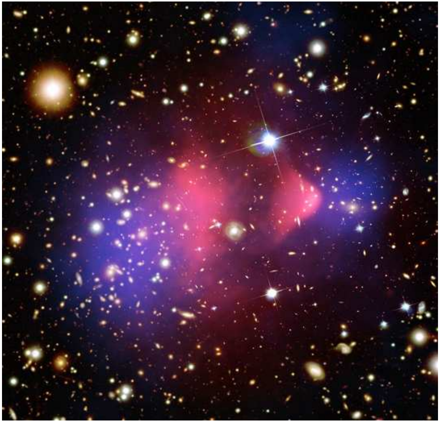


magnetic energy density (Spitkovsky 2008)



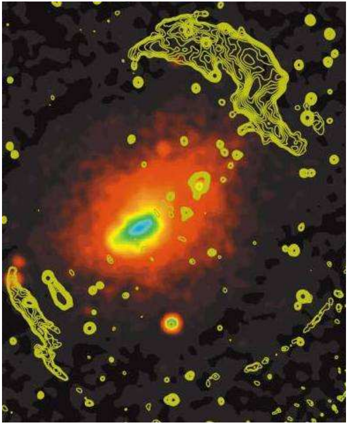
post-shock Maxwellian and accelerated CR power-law

Shocks in galaxy clusters



1E 0657-56 (“Bullet cluster”)

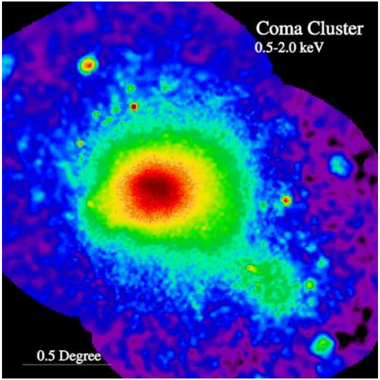
(X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)



Abell 3667

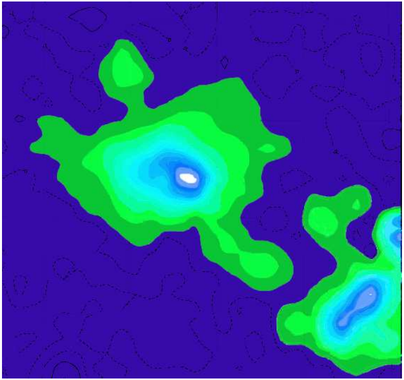
(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)

Giant radio halo in the Coma cluster



thermal X-ray emission

(Snowden/MPE/ROSAT)



radio synchrotron emission

(Deiss/Effelsberg)

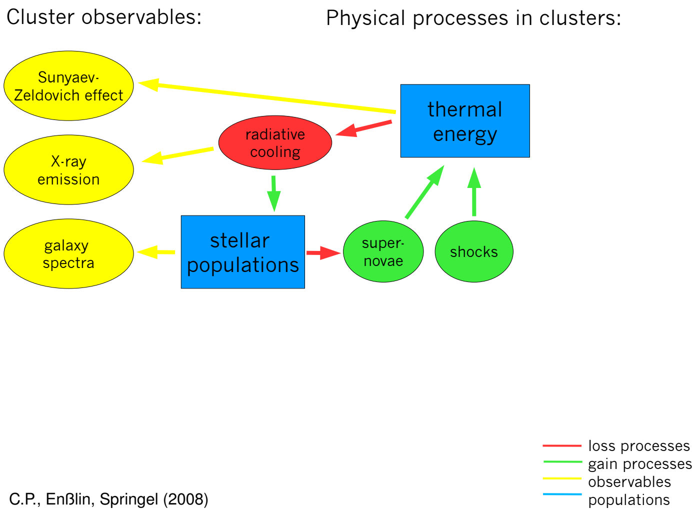
How universal is diffusive shock acceleration?

What can galaxy clusters teach us about shock acceleration and beyond?

Cosmological structure formation shock physics complementary to interplanetary and SNR shocks:

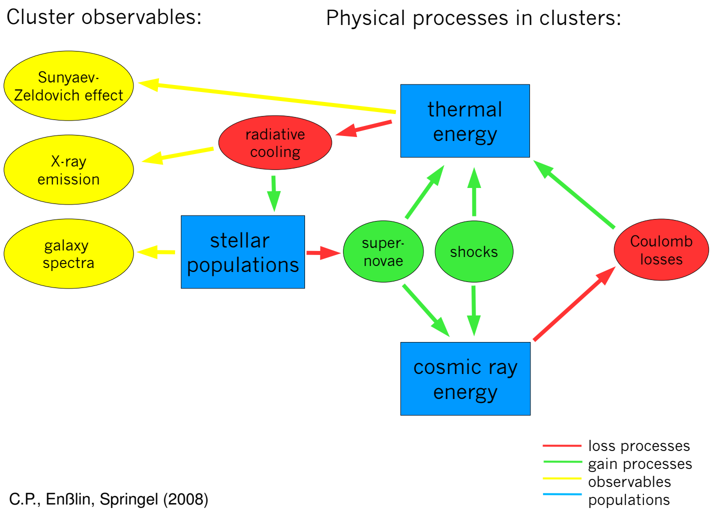
- probing unique regions of shock acceleration parameter space:
  $\rightarrow$ Mach numbers $\mathcal{M} \sim 2 \ldots 10$ with 'infinitely' extended (Mpc) and lasting (Gyr) shocks (observationally accessible @ $z = 0$)
  $\rightarrow$ plasma-β factors of $\beta \sim 10^2 \ldots 10^5$
- consistent picture 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
  $\rightarrow$ calibrating thermal cluster obervables: cluster cosmology

Radiative simulations – flowchart



C.P., Enßlin, Springel (2008)

Radiative simulations with CR physics



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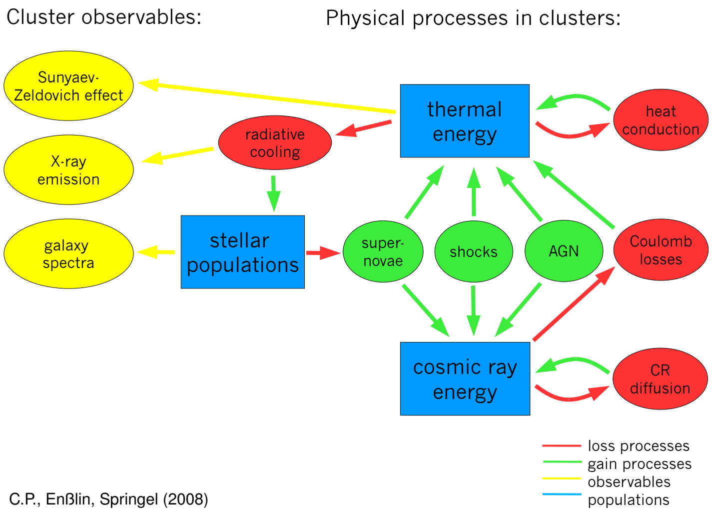
Radiative simulations with extended CR physics



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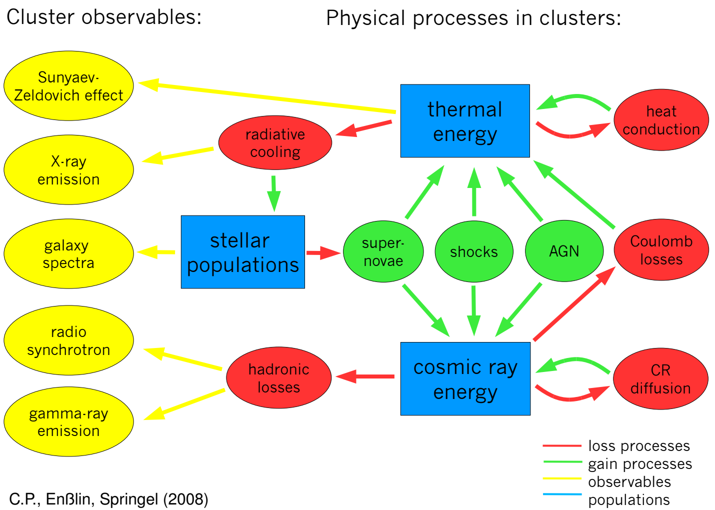

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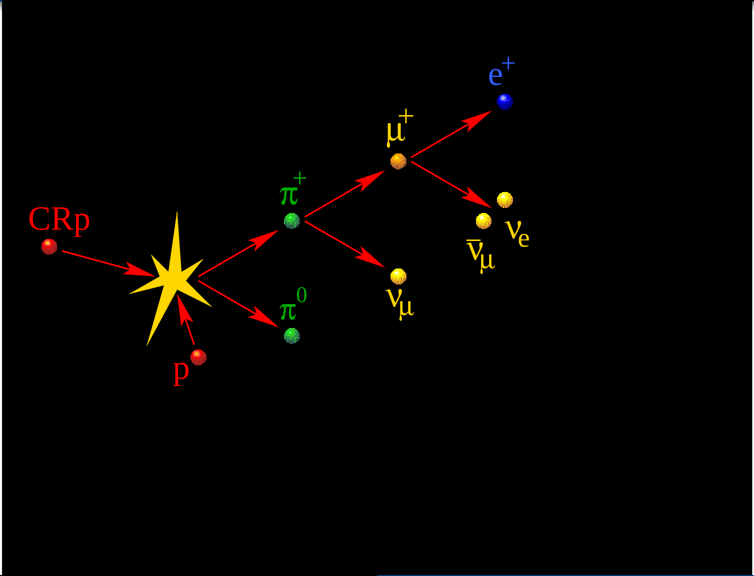
Hadronic cosmic ray proton interaction



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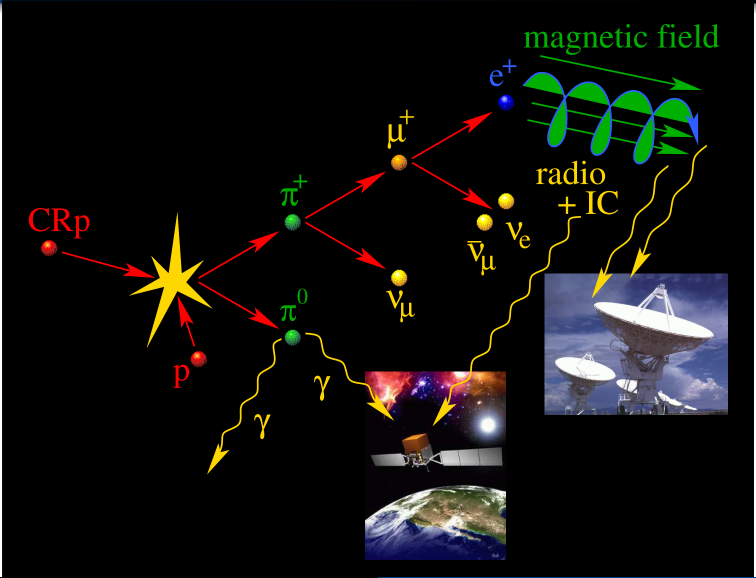


Our philosophy and description

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

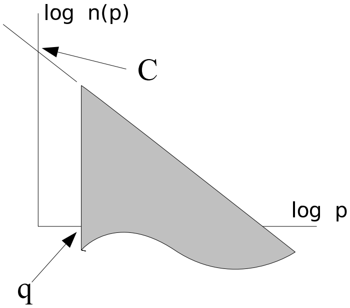
We seek a compromise between

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

Assumptions:

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

CR spectral description



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

Enßlin, C.P., Springel, Jubelgas (2007)

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

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

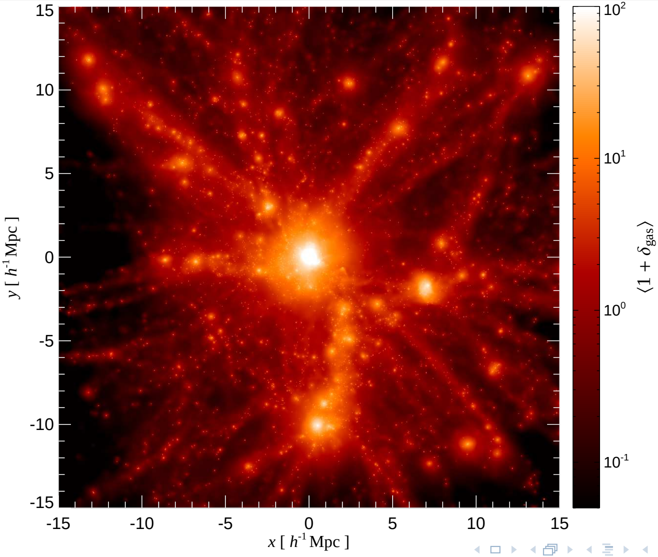
$$C(\rho) = \left(\frac{\rho}{\rho_0}\right)^{\frac{\alpha+2}{3}} C_0$$

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

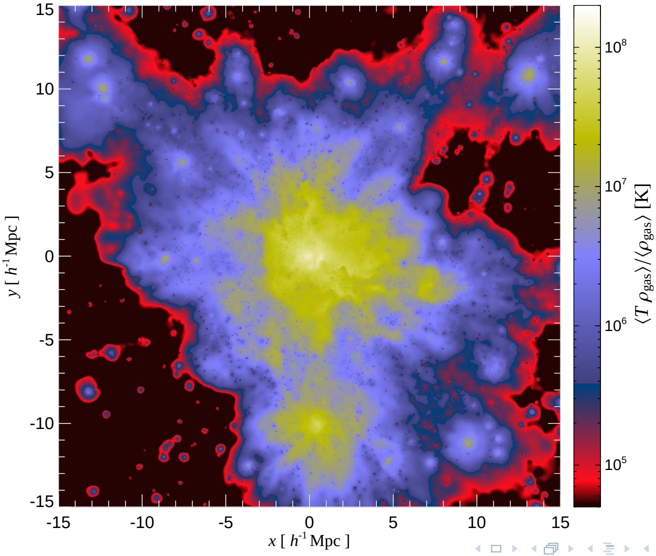
$$P_\mathrm{CR} = \frac{m_\mathrm{p} c^2}{3} \int_0^\infty \mathrm{d}p\, f(p)\, \beta(p)\, p$$

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

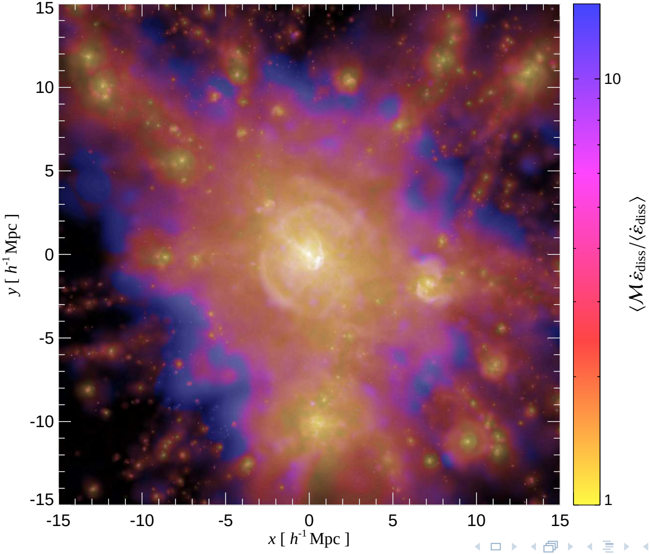
Cosmological cluster simulation: gas density



Mass weighted temperature

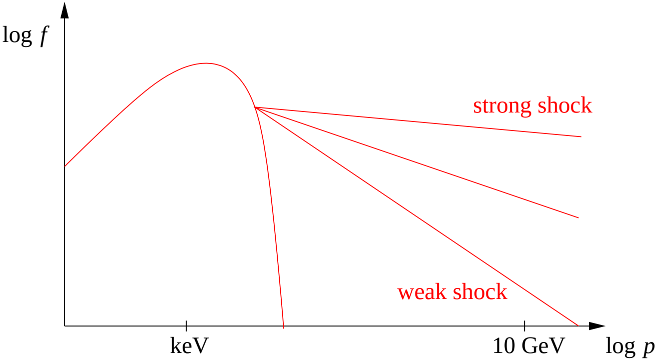


Mach number distribution weighted by $\varepsilon_{\rm diss}$



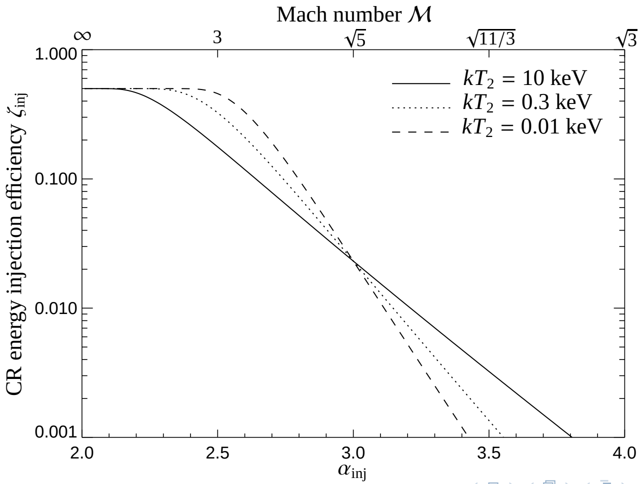
Diffusive shock acceleration – Fermi 1 mechanism (1)

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

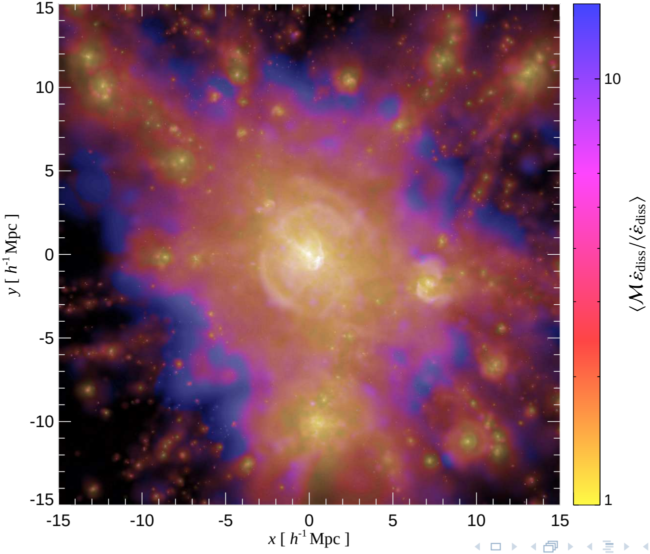


Diffusive shock acceleration – Efficiency (2)

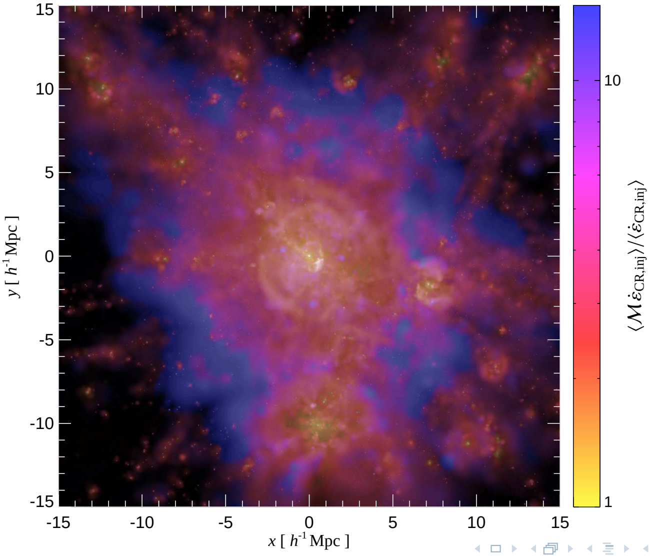
CR proton energy injection efficiency, $\zeta_{\text{inj}} = \varepsilon_{\text{CR}}/\varepsilon_{\text{diss}}$:



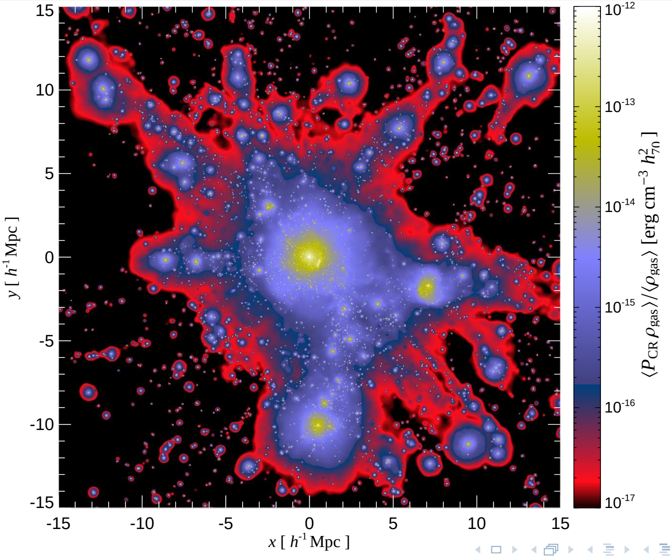
Mach number distribution weighted by $\varepsilon_{\rm diss}$



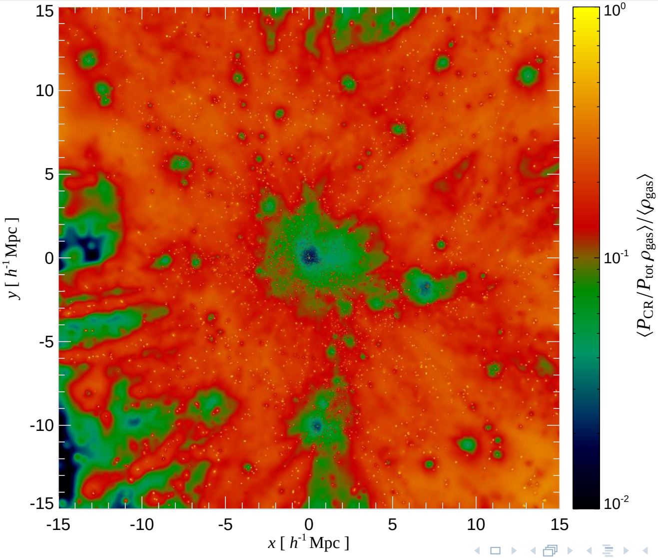
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$



CR pressure P_{CR}



Relative CR pressure P_{CR}/P_{total}



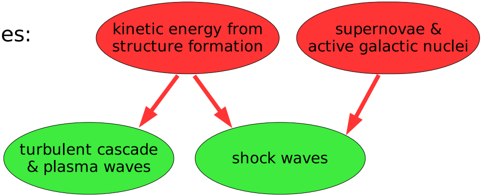
Outline

Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:

Energy sources:

Plasma processes:



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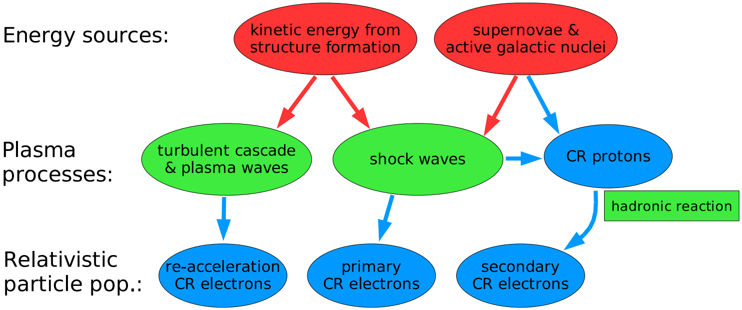

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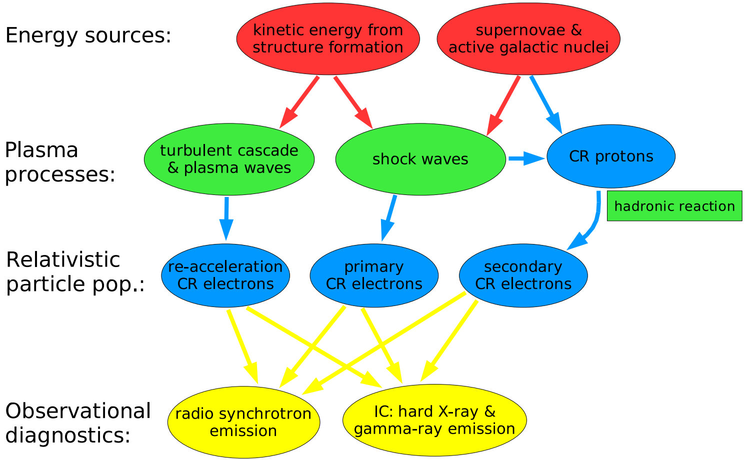

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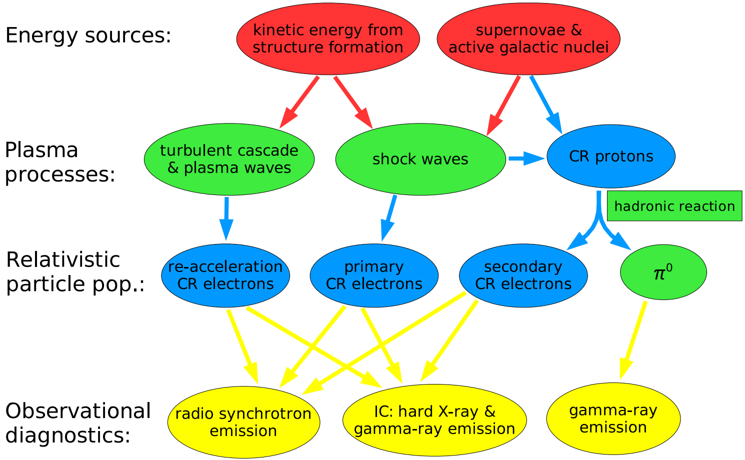
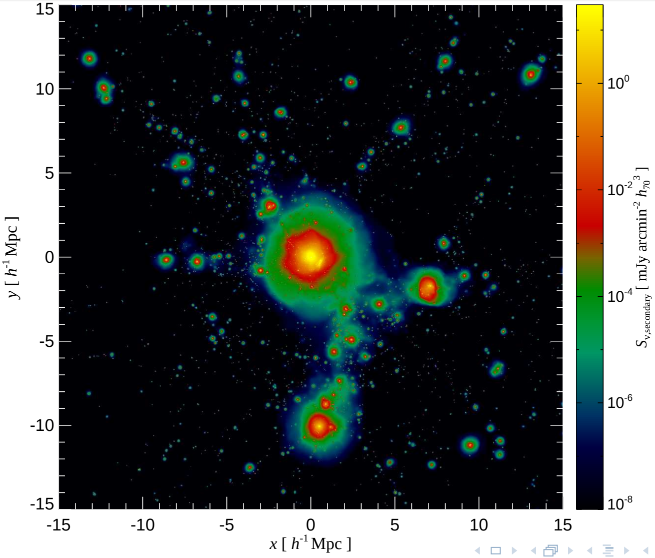
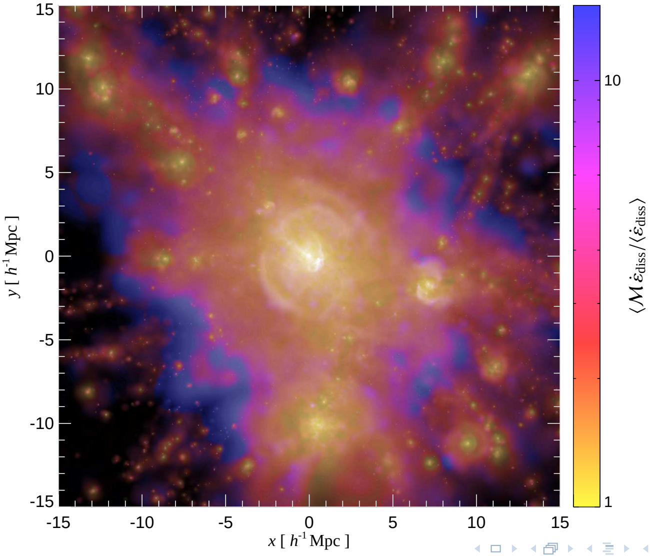


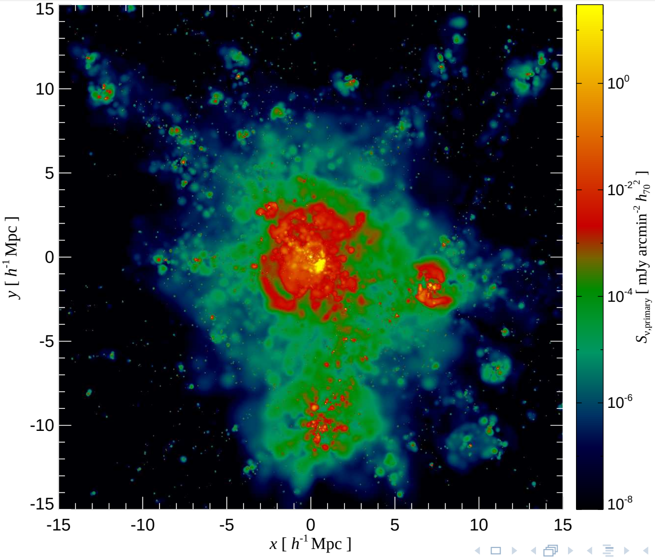
Cluster radio emission by hadronically produced CRe



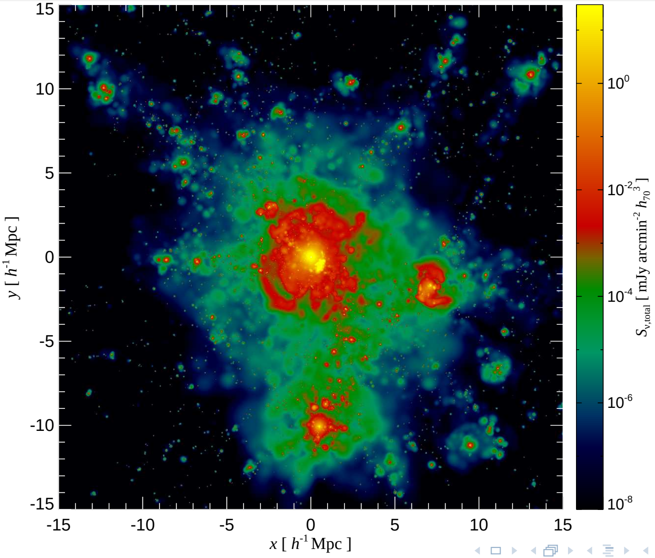
Cosmic web: Mach number



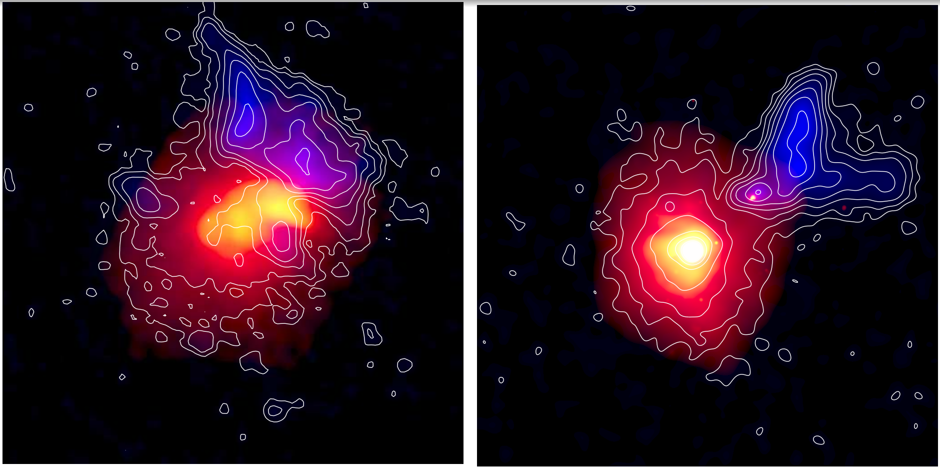
Radio gischt: primary CRe (150 MHz)



Radio gischt + central hadronic halo = giant radio halo

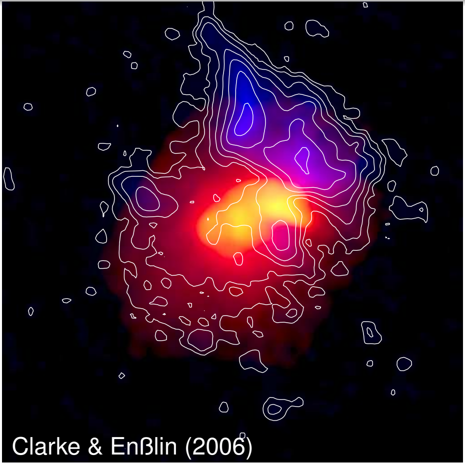


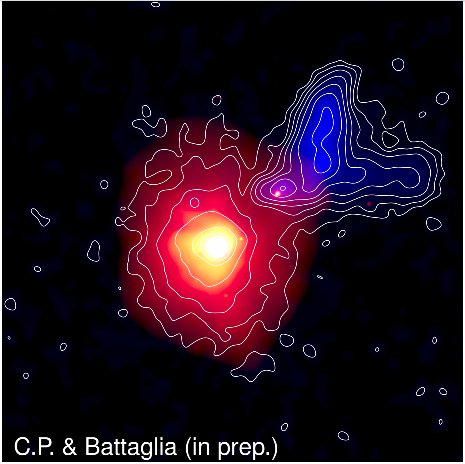
Which one is the simulation/observation of A2256?



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

Observation – simulation of A2256





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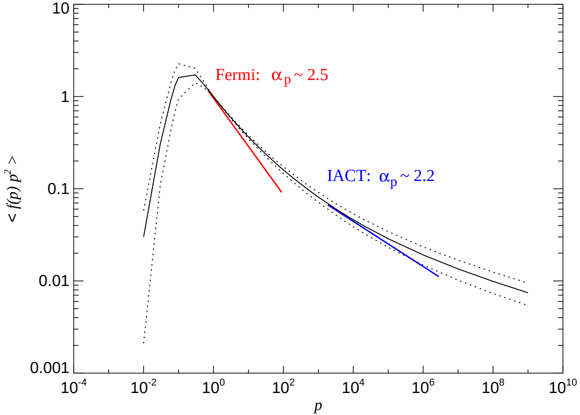
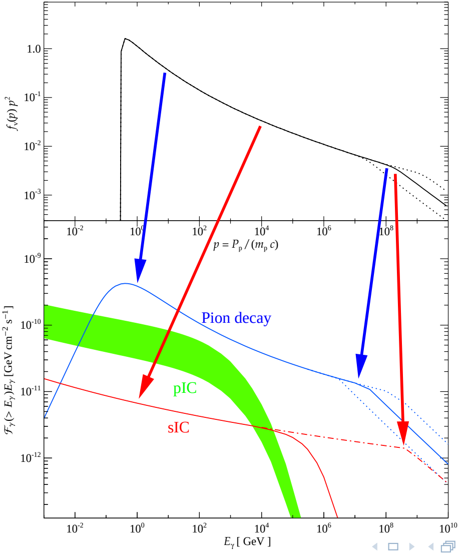
Universal CR spectrum in clusters (Pinzke & C.P. 2010)

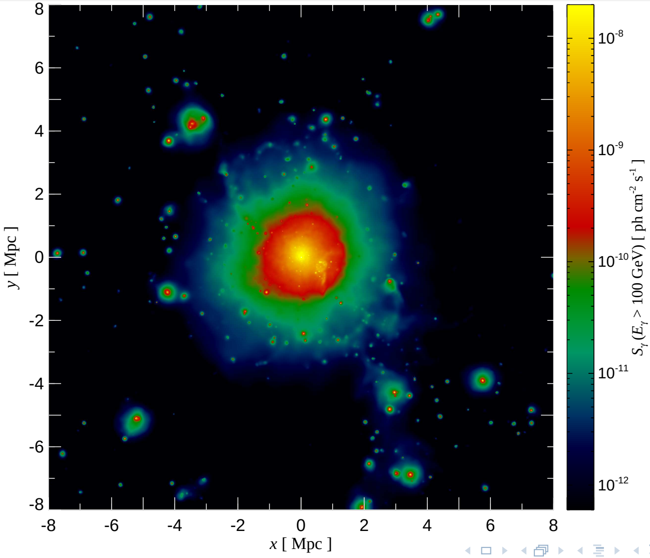


Normalized CR spectrum shows universal concave shape → governed by hierarchical structure formation and the implied distribution of Mach numbers that a fluid element had to pass through in cosmic history.

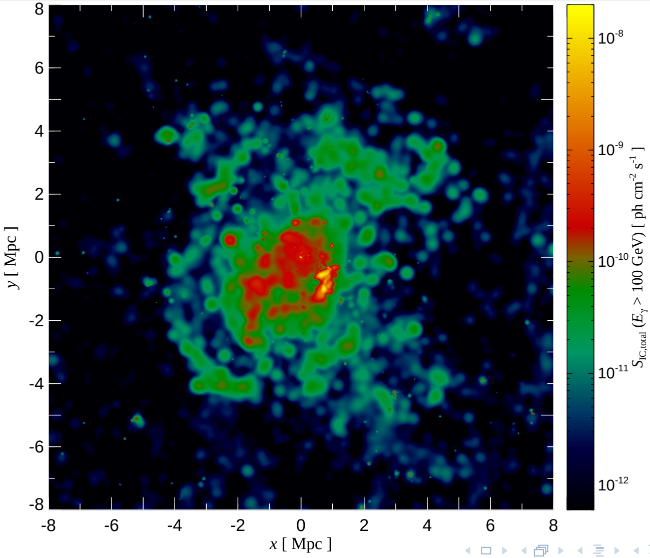
CR proton and γ-ray spectrum (Pinzke & C.P. 2010)



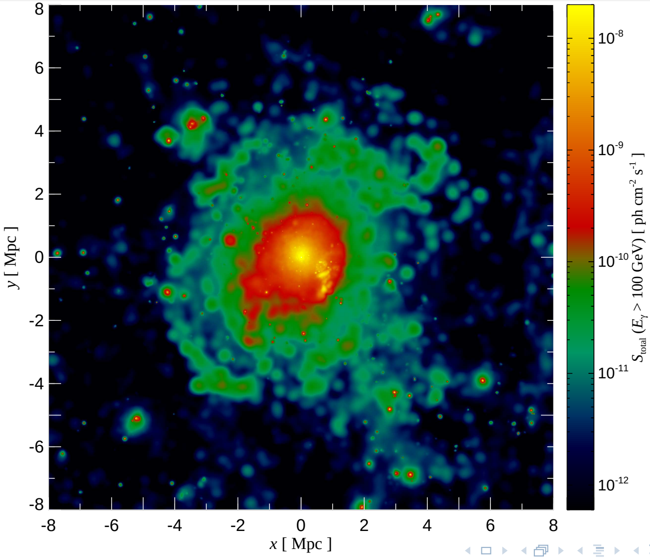
Hadronic γ-ray emission, $E_\gamma > 100$ GeV



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

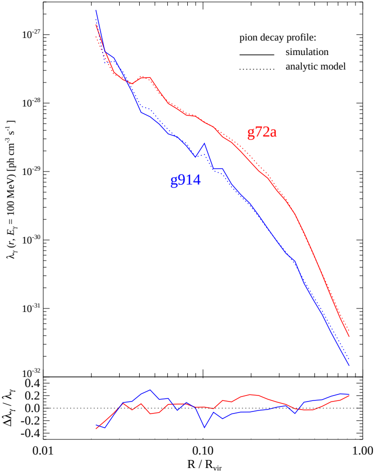


Total γ-ray emission, $E_\gamma > 100$ GeV

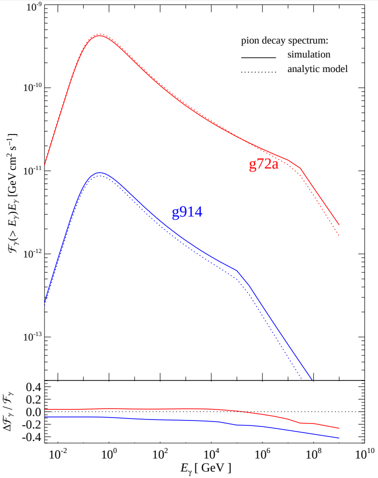


An analytic model for the cluster γ-ray emission

Comparison: simulation vs. analytic model, $M_{\rm vir} \simeq (10^{14}, 10^{15})\, M_\odot$

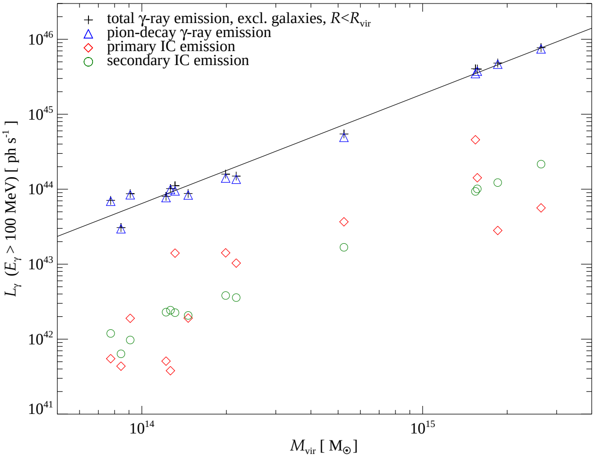


Spatial γ-ray emission profile



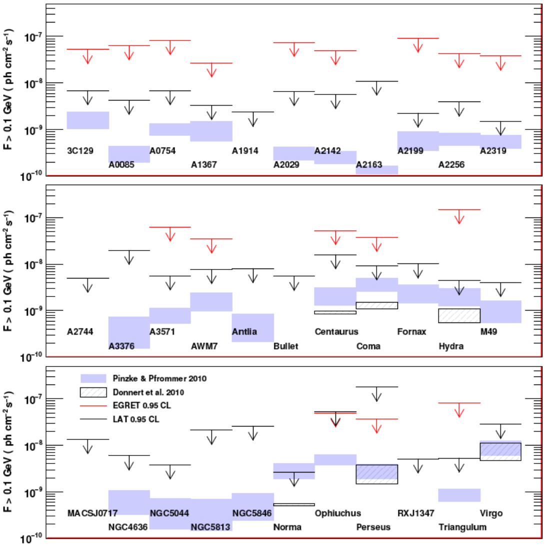
Pion decay spectrum

Gamma-ray scaling relations

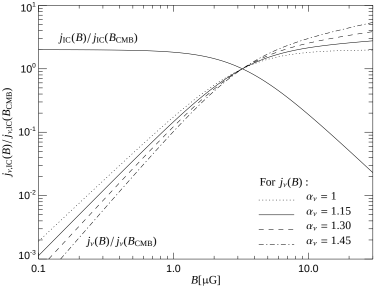


Scaling relation + complete sample of the brightest X-ray clusters (HIFLUGCS) → predictions for *Fermi* and *IACT's*

γ-ray limits and hadronic predictions (Ackermann et al. 2010)



Minimum γ-ray flux in the hadronic model



Synchrotron emissivity of steady state CRes 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:

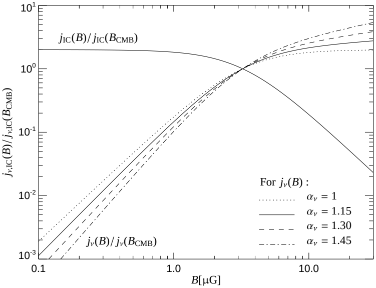
$$L_\gamma = A_\gamma \int \mathrm{d}V\, n_{\rm CR} n_{\rm gas}$$

$\rightarrow$ minimum γ-ray flux:

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

HITS

Minimum γ-ray flux in the hadronic model



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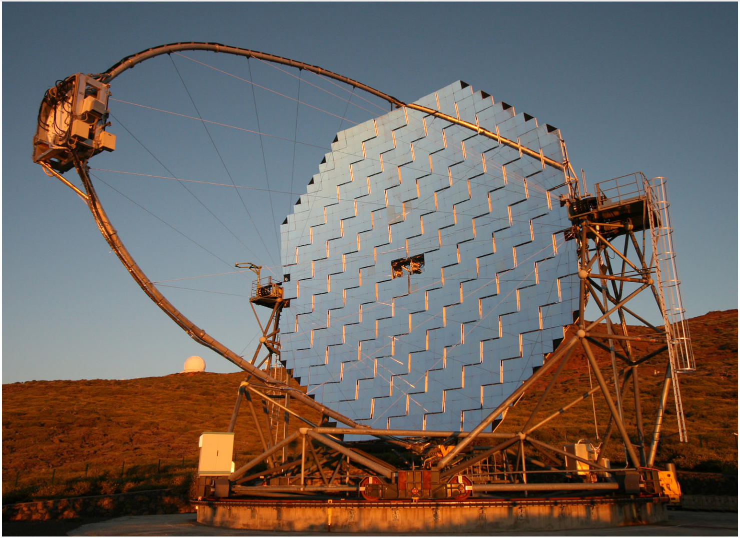
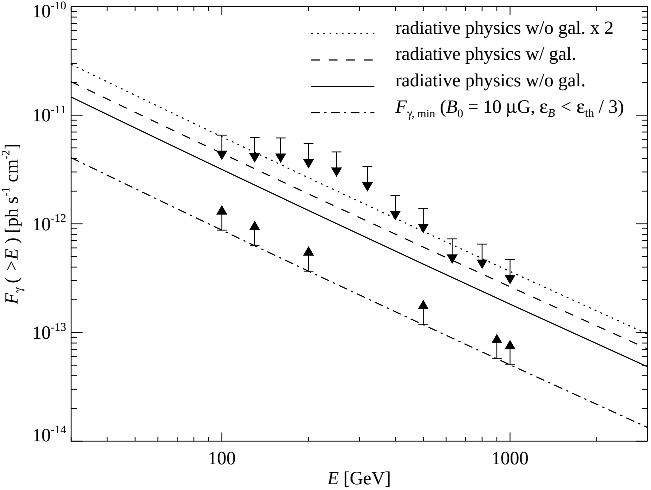
MAGIC observations of Perseus



Upper limit on the TeV γ-ray emission from Perseus



The MAGIC Collaboration: Aleksic et al. 2010

Results from the Perseus observation by *MAGIC*

- assuming $f \propto p^{-\alpha}$ with $\alpha = 2.1$, $P_{\mathrm{CR}} \propto P_{\mathrm{th}}$:
  $\langle P_{\mathrm{CR}} \rangle < 0.02 \langle P_{\mathrm{th}} \rangle$ → most stringent constraint on CR pressure!
- upper limits consistent with cosmological simulations:
  $F_{\text{upper limits}}(100\ \text{GeV}) = 2\, F_{\text{sim}}$ (optimistic model)
- simulation modeling of pressure constraint yields
  $\langle P_{\mathrm{CR}} \rangle / \langle P_{\mathrm{th}} \rangle < 0.04\ (0.08)$ for the core (entire cluster)
- resolving the apparent discrepancy:
  - concave curvature 'hides' CR pressure at GeV energies
  - relative CR pressure increases towards the outer parts (adiabatic compression and softer equation of state of CRs)

HITS

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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 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)

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.:

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Outline

1. Cosmological simulations
   - Introduction
   - Simulated physics
   - Cosmic rays in galaxy clusters
2. Non-thermal emission
   - Overview
   - Radio emission
   - Gamma-ray emission
3. Cosmic ray transport
   - Observations and models
   - CR pumping and streaming
   - Radio and gamma-ray bimodality

Radio halo theory – (i) hadronic model

$$p_{\rm CR} + p \rightarrow \pi^{\pm} \rightarrow e^{\pm}$$

strength:

- all required ingredients available:
  shocks to inject CRp, gas protons as targets, magnetic fields
- predicted luminosities and morphologies as observed without tuning
- power-law spectra as observed

weakness:

- all clusters should have radio halos
- does not explain all reported spectral features
- ...

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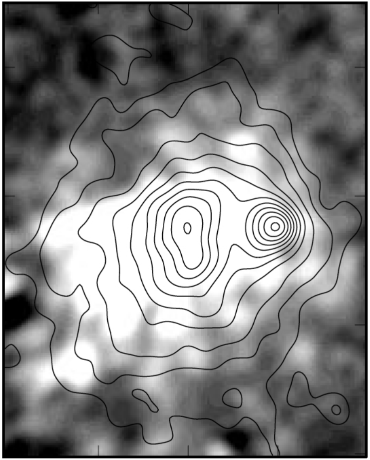
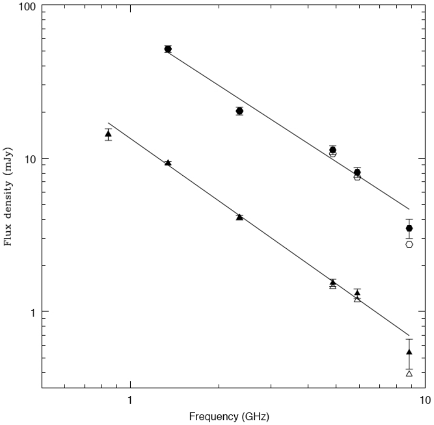
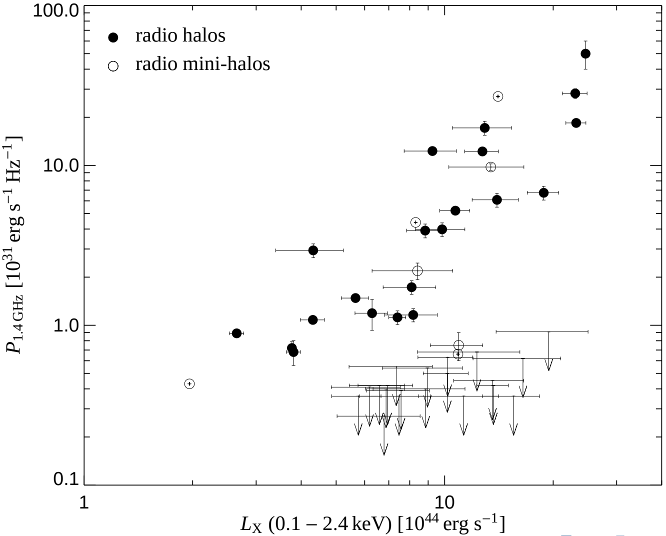
Radio halo and spectrum in the Bullet cluster





Liang et al. (2000): SZ-corrected

Radio luminosity - X-ray luminosity



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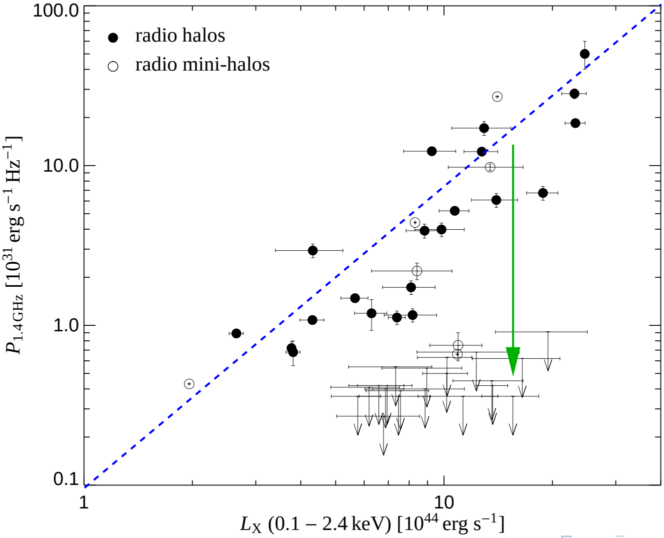

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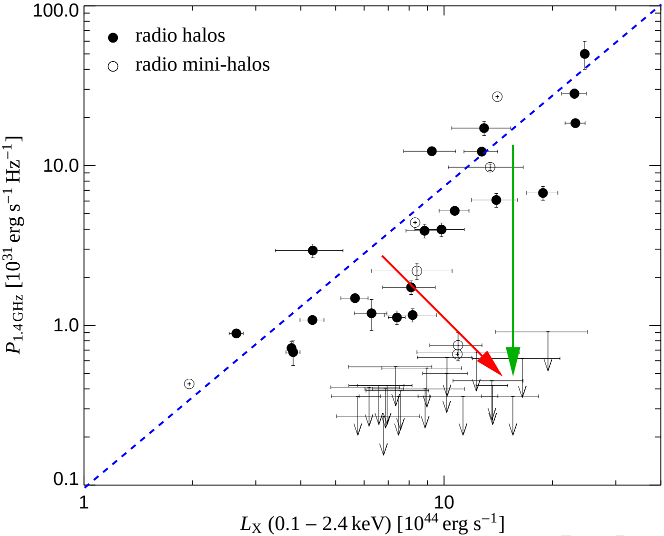
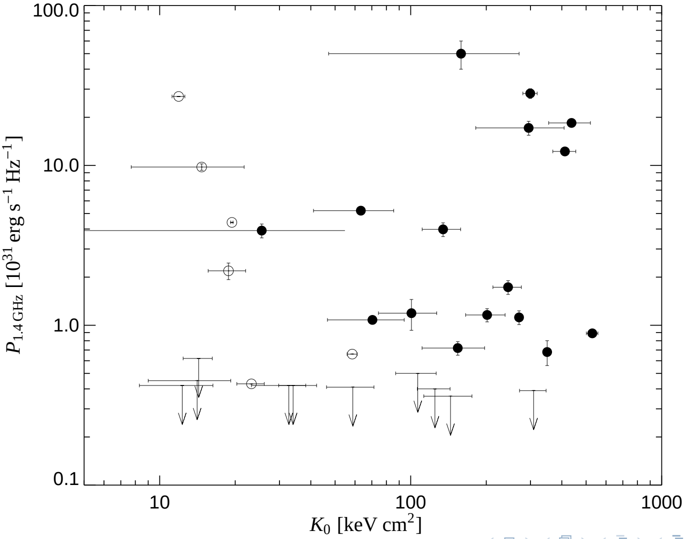


Radio luminosity - central entropy



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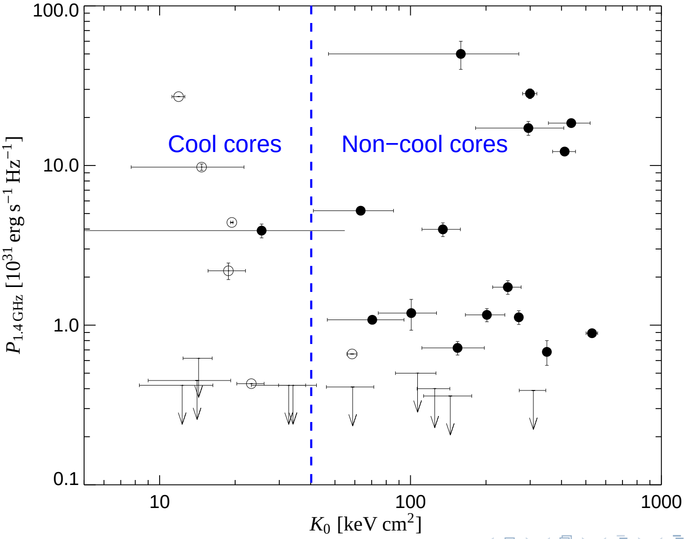

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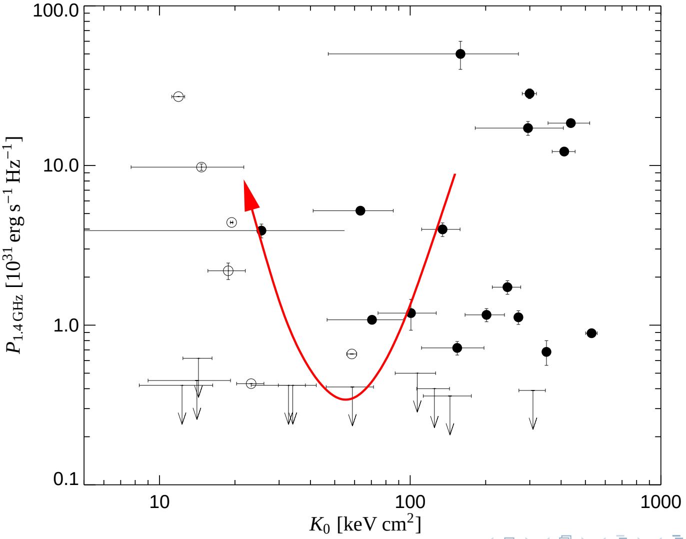

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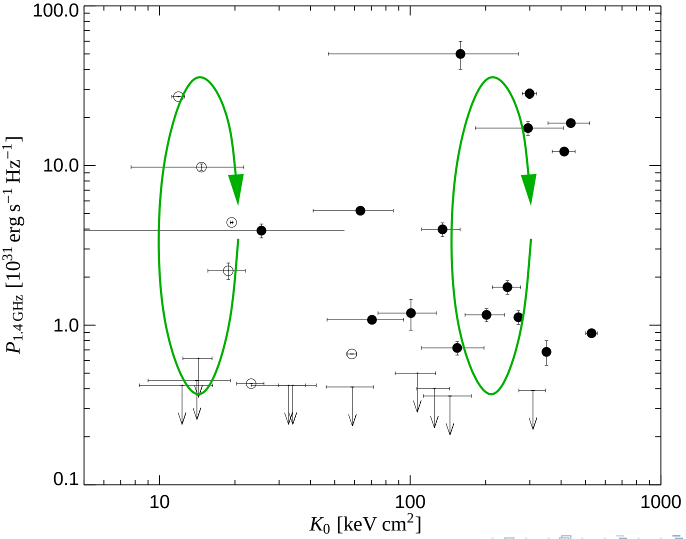
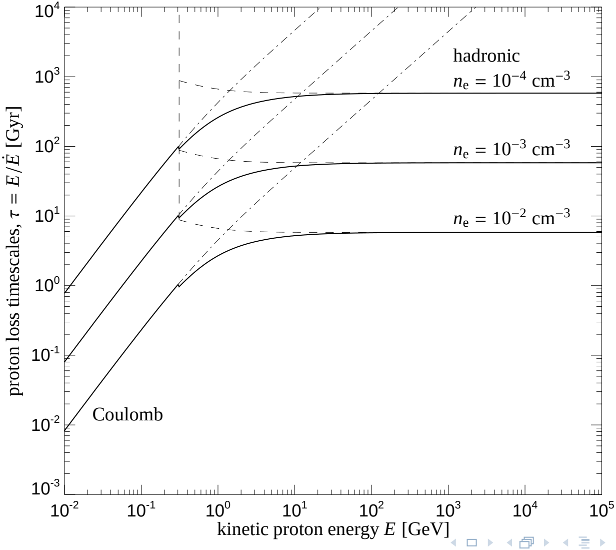


Proton cooling times



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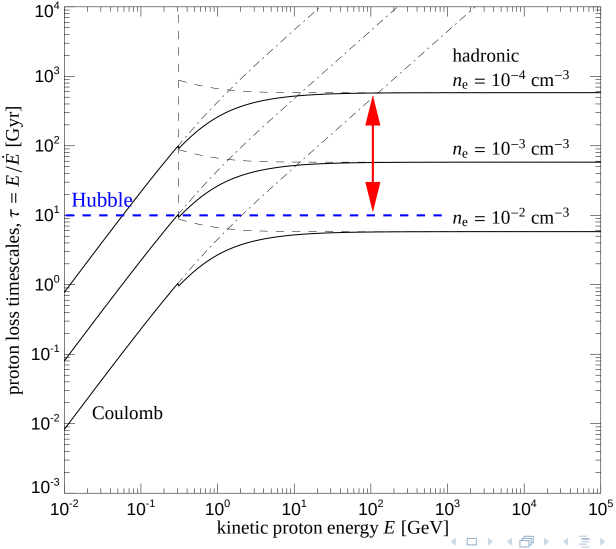

Radio halo theory – (ii) re-acceleration model

strength:

- all required ingredients available:
  radio galaxies & relics to inject CRe, plasma waves to re-accelerate, ...
- reported complex radio spectra emerge naturally
- clusters without halos $\leftarrow$ less turbulent

weakness:

- Fermi II acceleration is inefficient – CRe cool rapidly
- observed power-law spectra require fine tuning
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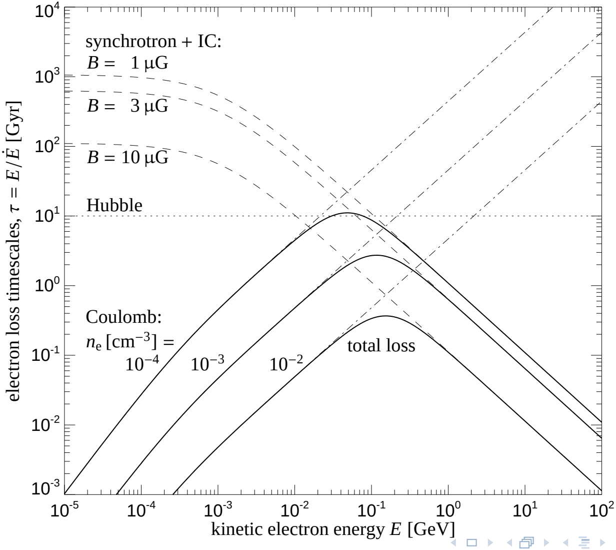
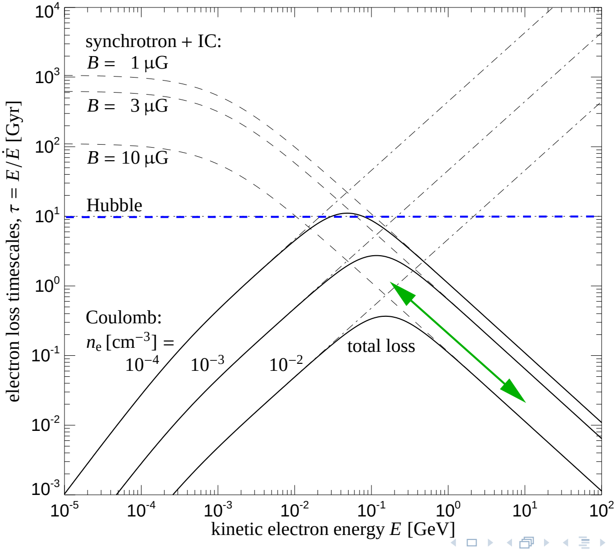
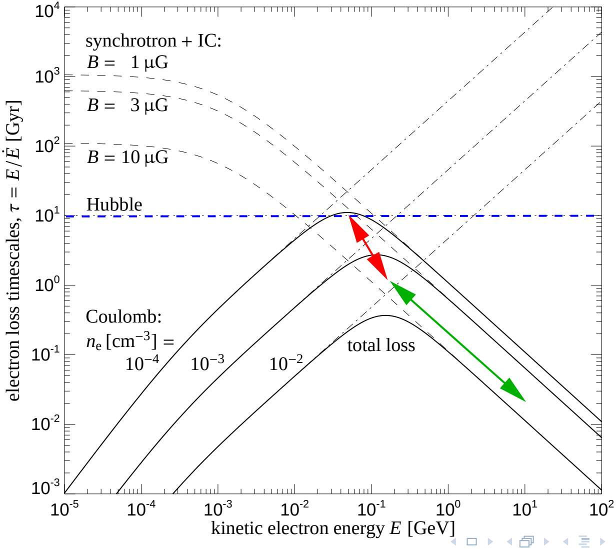
Electron cooling times



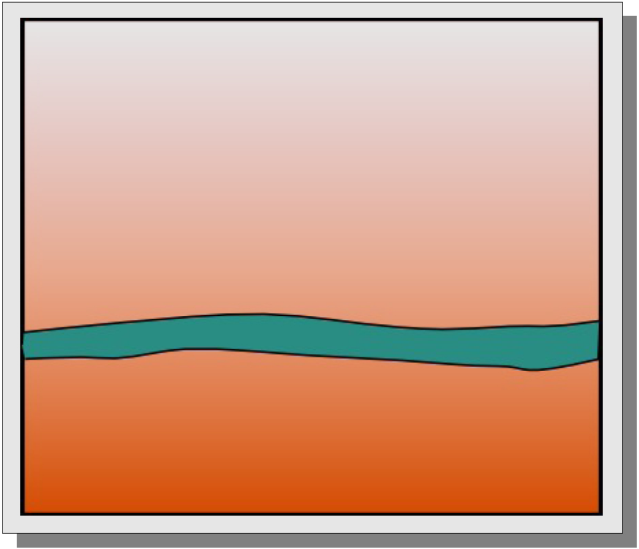
Electron cooling times



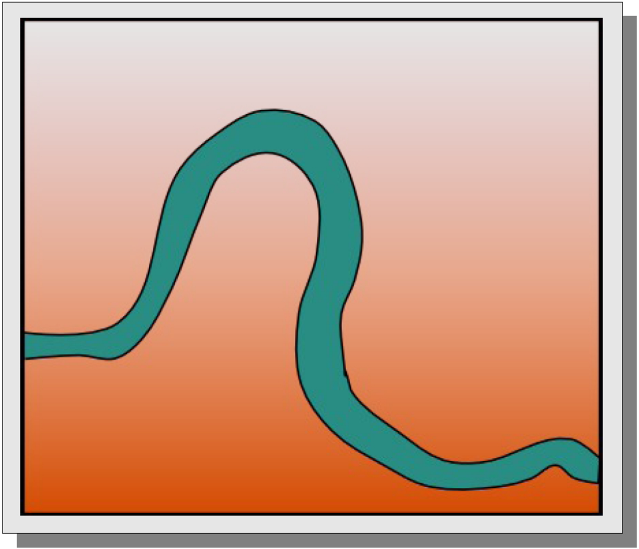
Electron cooling times



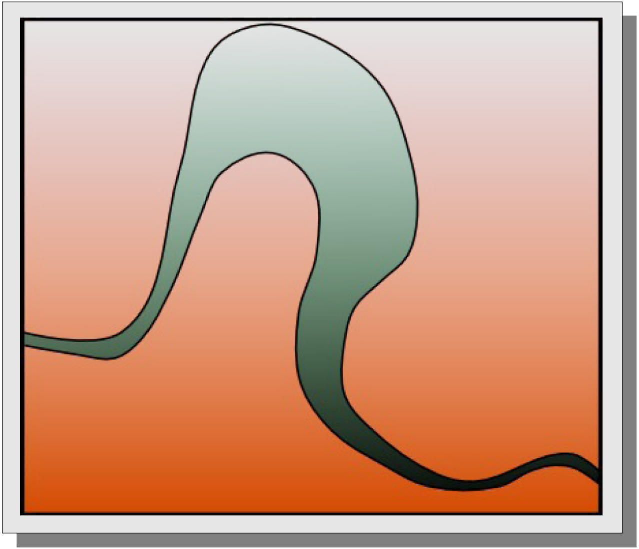
Cosmic ray transport – magnetic flux tube with CRs



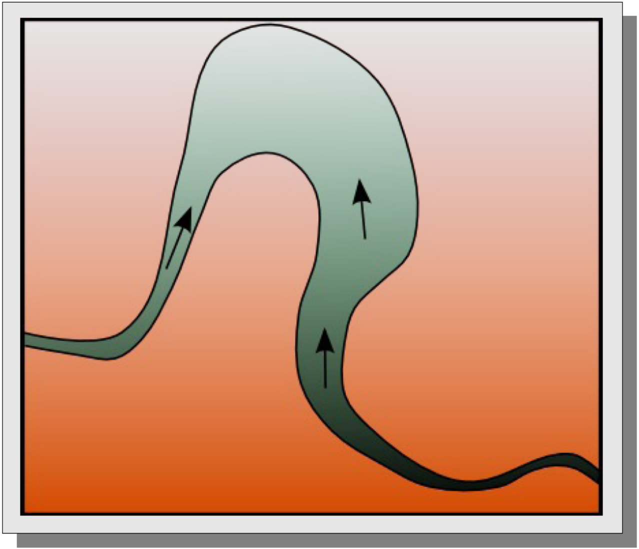
Cosmic ray advection



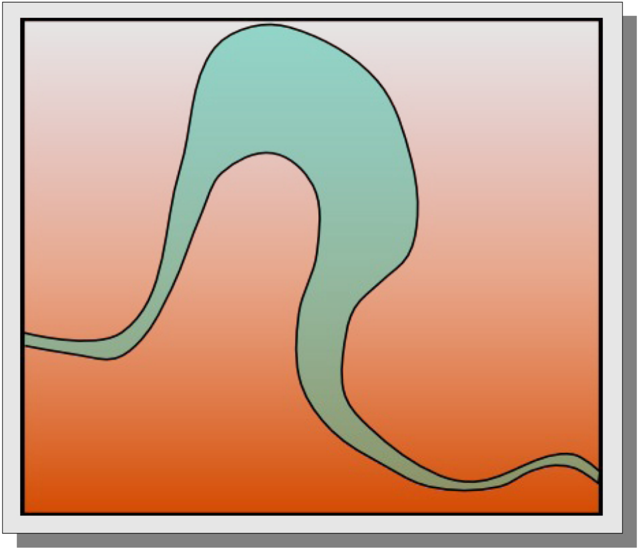
Adiabatic expansion and compression



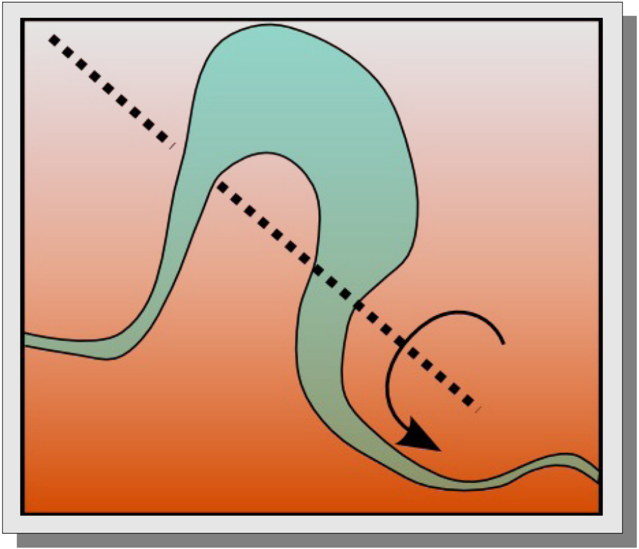
Cosmic ray streaming



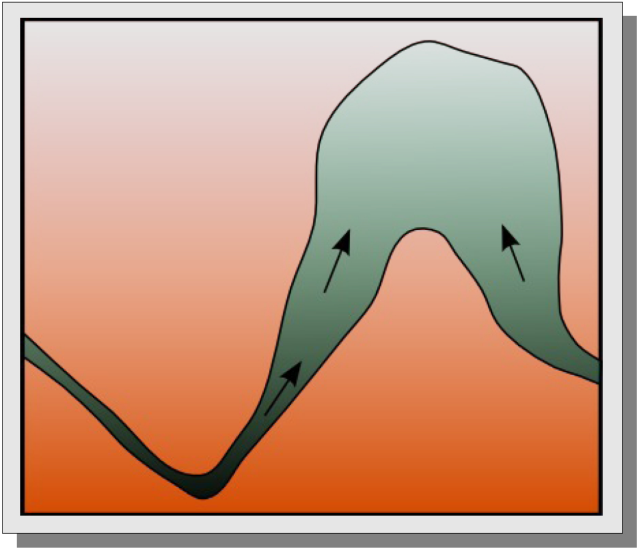
Expanded CRs



Turbulent pumping

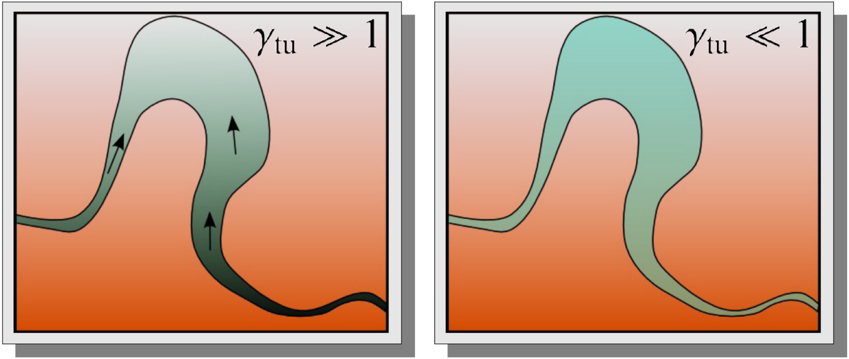


Turbulent pumping

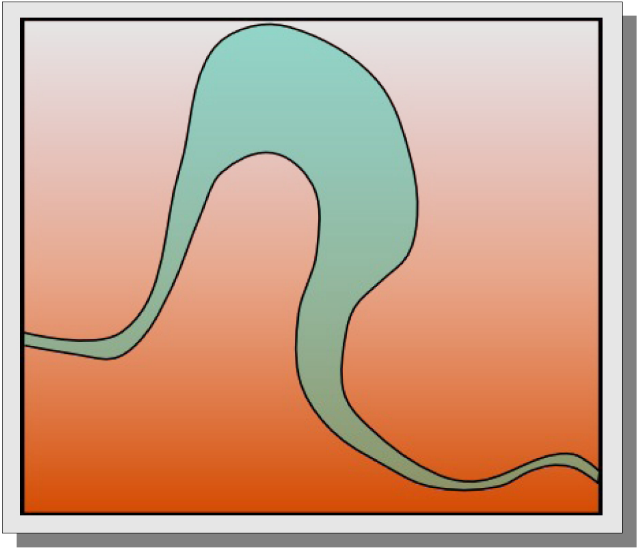


Turbulent-to-streaming ratio

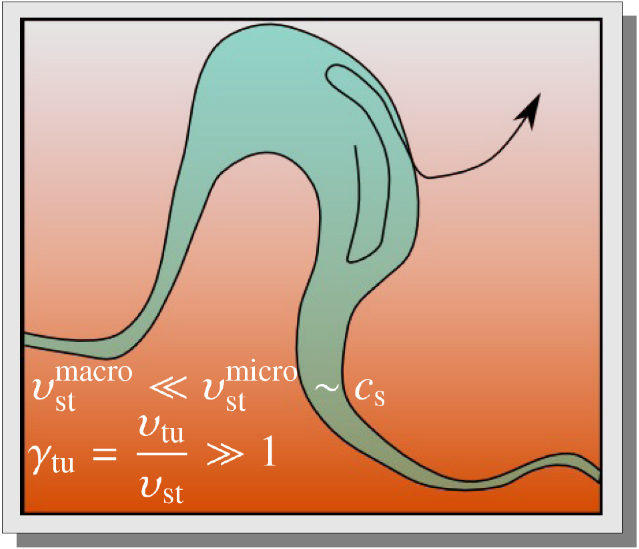
$$\gamma_{\rm tu} = \frac{\upsilon_{\rm tu}}{\upsilon_{\rm st}}$$



Are CRs confined to magnetic flux tubes?



Escape via diffusion: energy dependence



CR transport theory

CR continuity equation in the absence of sources and sinks:

$$\frac{\partial \varrho}{\partial t} + \vec{\nabla} \cdot (\boldsymbol{\upsilon}\, \varrho) = 0$$

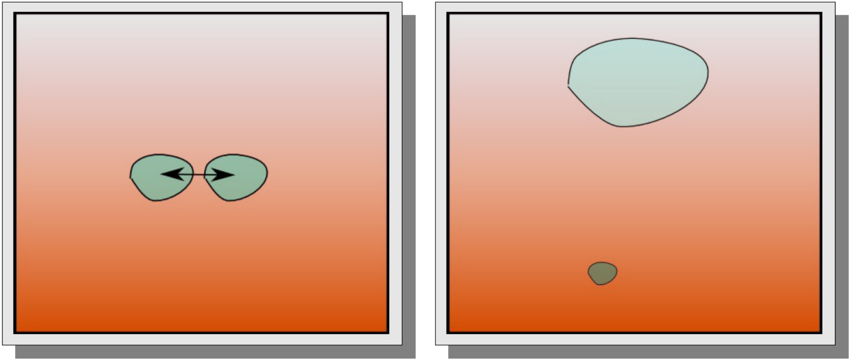
$$\boldsymbol{\upsilon} = \boldsymbol{\upsilon}_{\rm ad} + \boldsymbol{\upsilon}_{\rm di} + \boldsymbol{\upsilon}_{\rm st}$$

$$\begin{aligned} \boldsymbol{\upsilon}_{\rm st} &= -\upsilon_{\rm st} \frac{\vec{\nabla}\, \varrho}{|\vec{\nabla}\, \varrho|} \\ \boldsymbol{\upsilon}_{\rm di} &= -\kappa_{\rm di} \frac{1}{\varrho} \vec{\nabla} \varrho \\ \boldsymbol{\upsilon}_{\rm ad} &= -\kappa_{\rm tu} \frac{\eta}{\varrho} \vec{\nabla} \frac{\varrho}{\eta} \end{aligned}$$

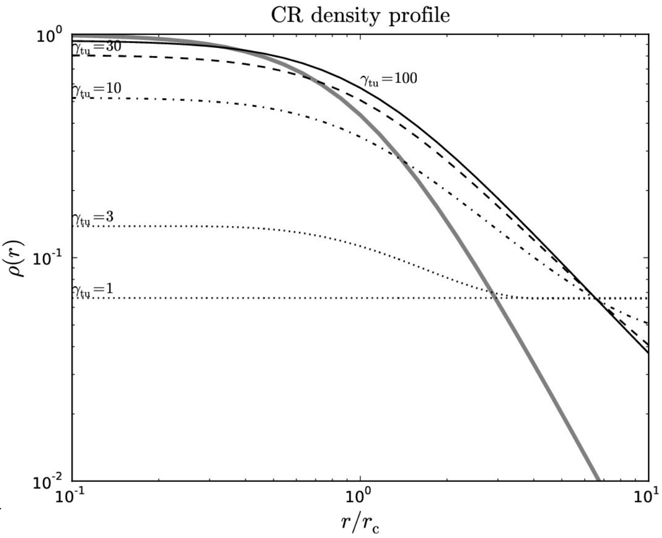
$$\kappa_{\rm tu} = \frac{L_{\rm tu}\, \upsilon_{\rm tu}}{3}$$

CR profile due to advection

$$\eta(r) = \left(\frac{P(r)}{P_0}\right)^{\frac{3}{5}}$$

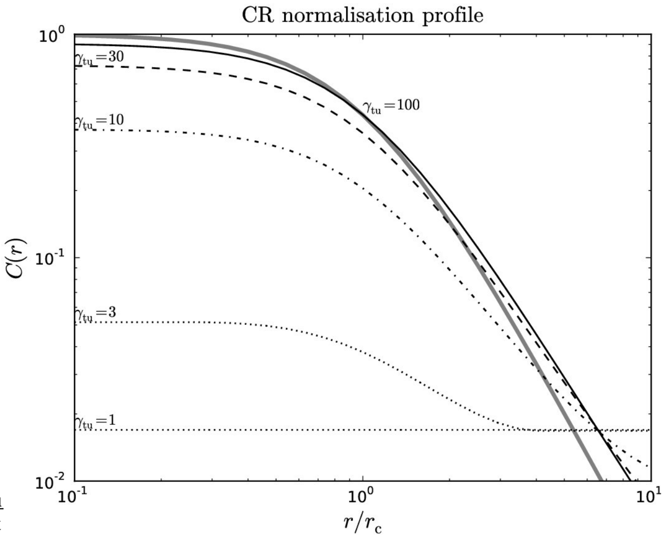


CR density profile



$$\gamma_{tu} = \frac{\upsilon_{tu}}{\upsilon_{st}}$$

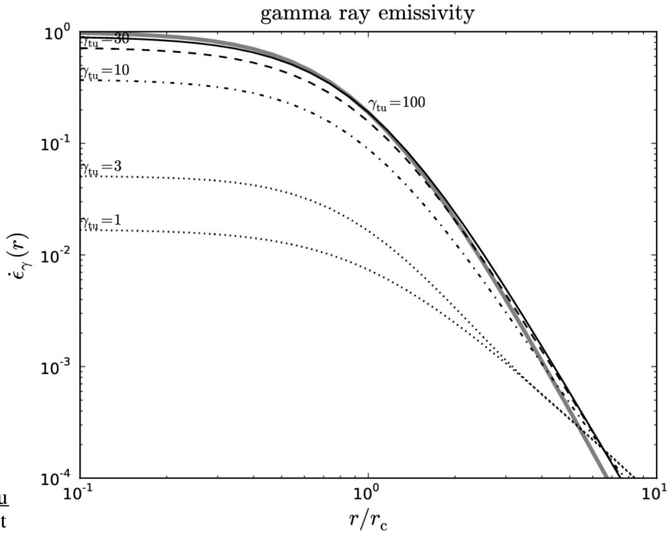
CR density at fixed particle energy



$$\gamma_{tu} = \frac{\upsilon_{tu}}{\upsilon_{st}}$$

Gamma-ray emission profile

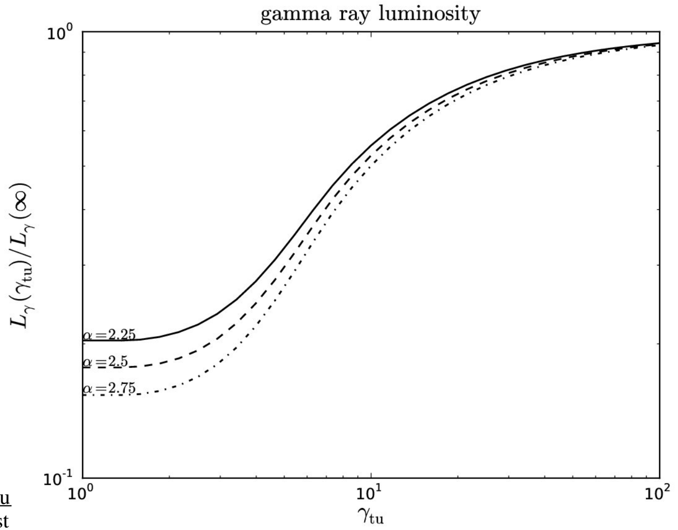
$p_{\rm CR} + p \rightarrow \pi^0 \rightarrow 2\gamma$



$$\gamma_{\rm tu} = \frac{\upsilon_{\rm tu}}{\upsilon_{\rm st}}$$

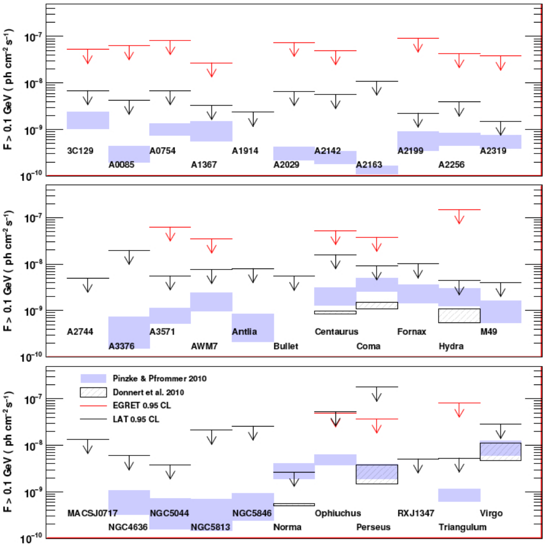
Gamma-ray luminosity

$p_{\mathrm{CR}} + p \rightarrow \pi^0 \rightarrow 2\gamma$



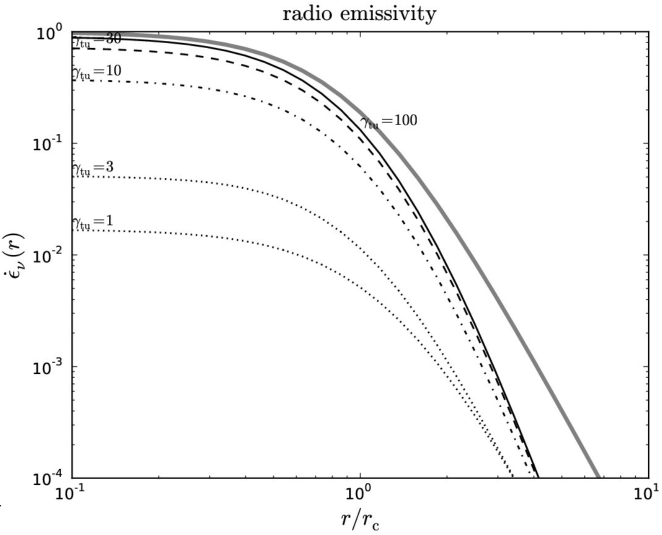
$$\gamma_{\mathrm{tu}} = \frac{\upsilon_{\mathrm{tu}}}{\upsilon_{\mathrm{st}}}$$

γ-ray limits and hadronic predictions (Ackermann et al. 2010)



Radio emission profile

$p_{CR} + p \rightarrow \pi^{\pm} \rightarrow e^{\pm} \rightarrow$ radio



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Radio luminosity

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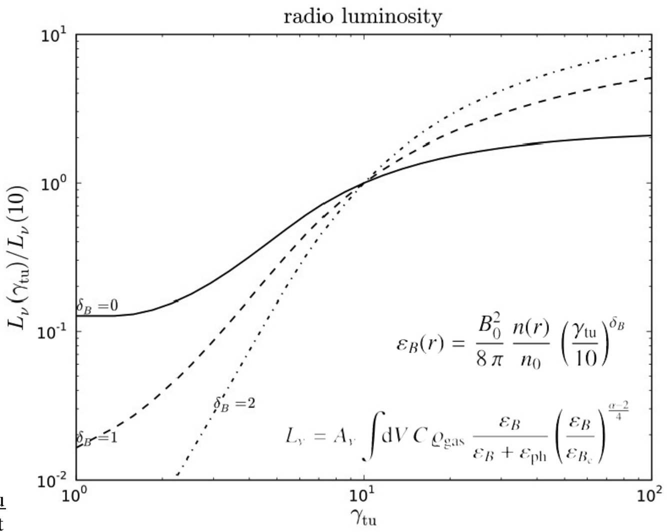

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Conclusions

- cosmological simulations predict universal CR spectrum and distribution (ignoring active CR transport)
  $\rightarrow$ Fermi limits consistent with simulations that use most optimistic assumptions of CR acceleration and transport
- streaming & diffusion produce spatially flat CR profiles
  advection produces centrally enhanced CR profiles
  $\rightarrow$ profile depends on advection-to-streaming-velocity ratio
- turbulent velocity $\sim$ sound speed $\leftarrow$ cluster merger
  CR streaming velocity $\sim$ sound speed $\leftarrow$ plasma physics
  $\rightarrow$ peaked/flat CR profiles in merging/relaxed clusters
- energy dependence of $v_{\rm st}^{\rm macro}$ $\rightarrow$ CR & radio spectral variations
  $\rightarrow$ outstreaming CR: dying halo $\leftarrow$ decaying turbulence

$\rightarrow$ bimodality of cluster radio halos & gamma-ray emission!

HITS

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Literature for the talk

- Enßlin, Pfrommer, Miniati, Subramanian, 2011, A&A, 527, 99, *Cosmic ray transport in galaxy clusters: implications for radio halos, gamma-ray signatures, and cool core heating*
- Pinzke & Pfrommer, 2010, MNRAS, 409, 449, *Simulating the gamma-ray emission from galaxy clusters: a universal cosmic ray spectrum and spatial distribution*
- 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*