Astrophysics of galaxy clusters – Cosmic rays and magnetic fields

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in collaboration with

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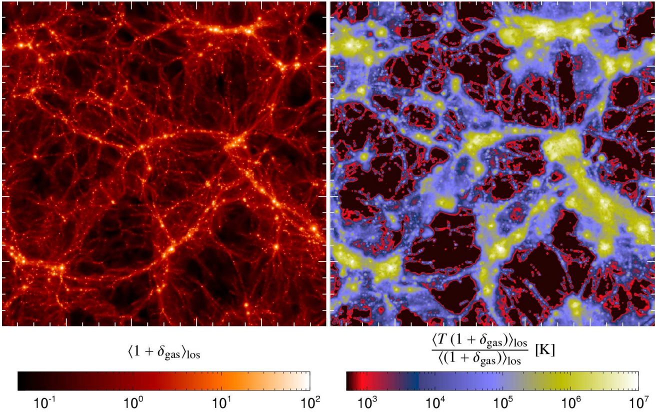
Outline

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

Outline

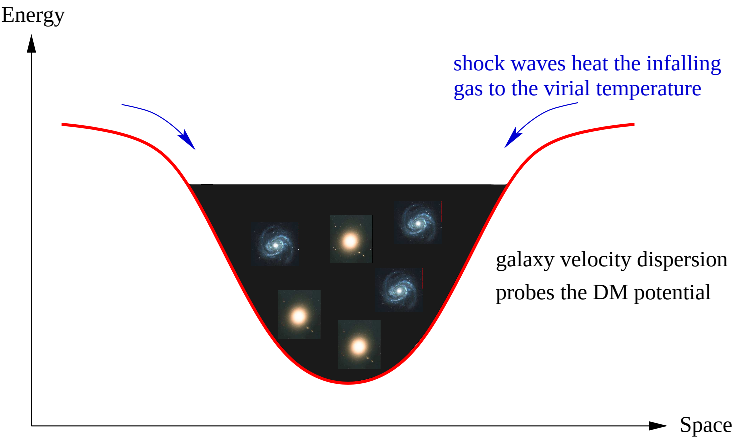
The structure of our Universe



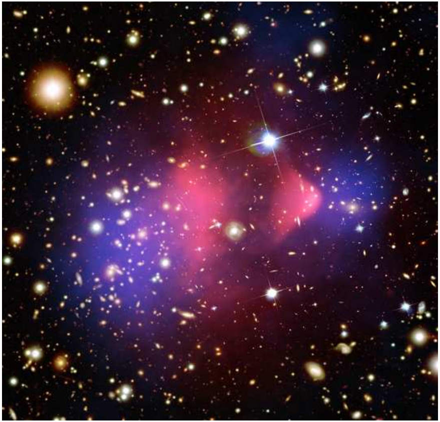
The "cosmic web" today. *Left:* the projected gas density in a cosmological simulation. *Right:* gravitationally heated intracluster medium through cosmological shock waves (C.P. et al. 2006).

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

Galaxy clusters are dynamically evolving dark matter potential wells:

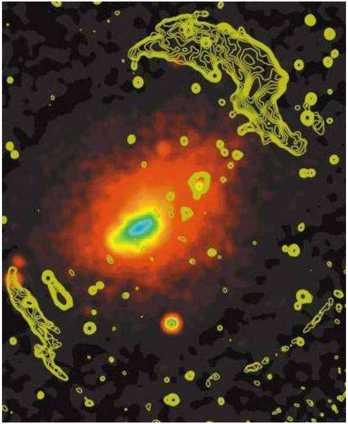


. . . and how the observer's Universe looks like



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.)

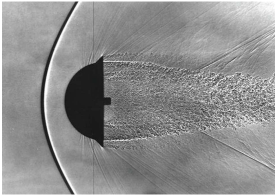


Abell 3667

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

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:

$\lambda_{\rm mfp} \sim L_{\rm cluster}/10, \qquad \lambda_{\rm mfp} \sim L_{\rm SNR}$

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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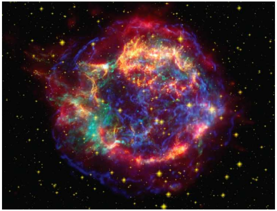

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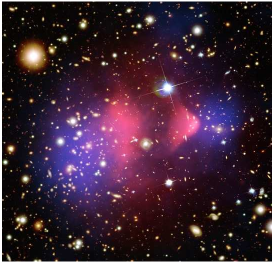

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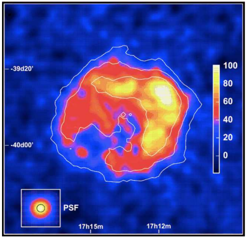
(slide concept Spitkovsky)

Shocks in supernova remnants

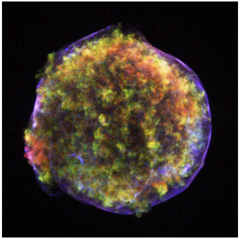
Astrophysical collisionless shocks can:

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

SN 1006 X-rays (CXC/Hughes)



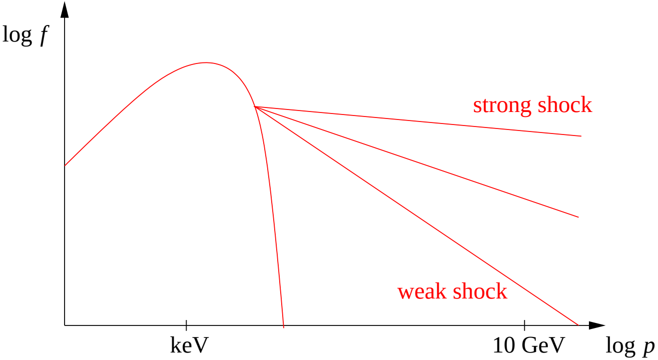
G347.3 HESS TeV (Aharonian et al. 2006)



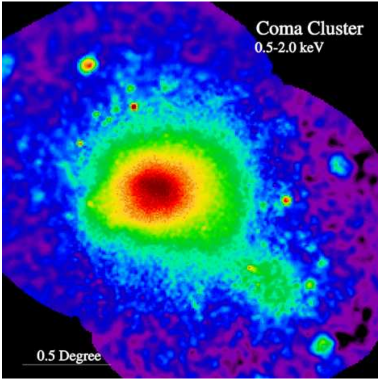
Tycho X-rays (CXC)

Shock acceleration

Spectral index of CRs depends on the shock strength:

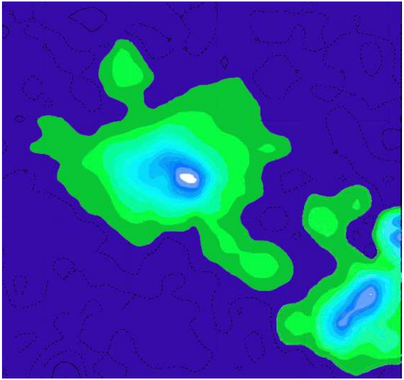


Giant radio halo in the Coma cluster



thermal X-ray emission

(Snowden/MPE/ROSAT)



radio synchrotron emission

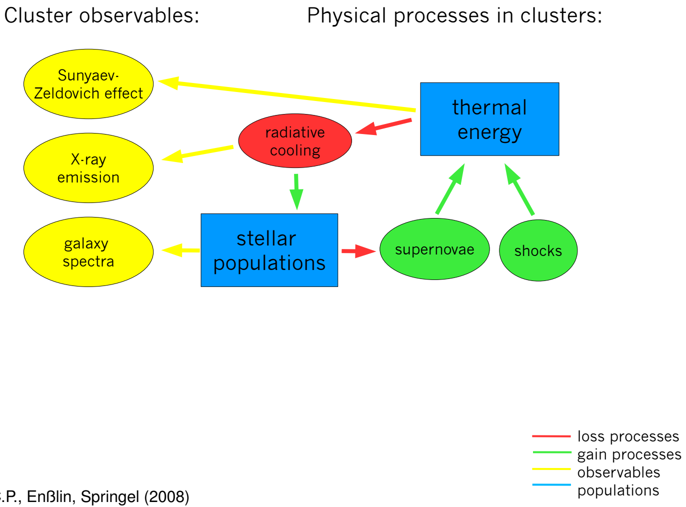
(Deiss/Effelsberg)

High-Energy Astrophysics in Galaxy Clusters

Understanding non-thermal emission (from radio to γ-rays)

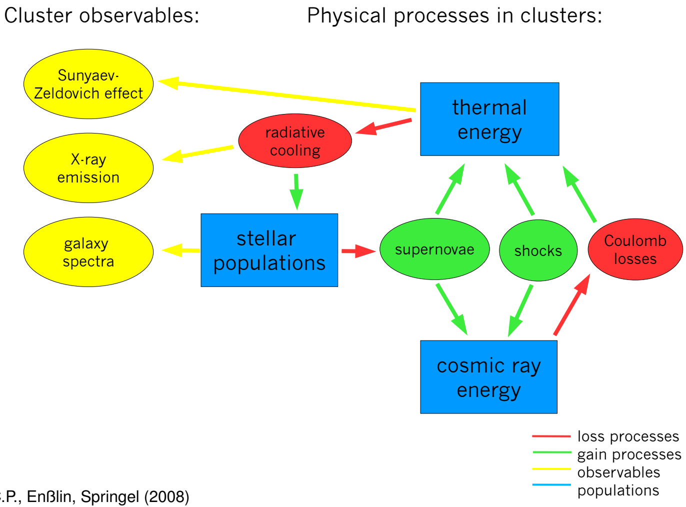
- plasma astrophysics:
  $\rightarrow$ shock and particle acceleration
  $\rightarrow$ large-scale magnetic fields
  $\rightarrow$ turbulence
- structure formation and galaxy cluster cosmology:
  $\rightarrow$ illuminating the process of structure formation
  $\rightarrow$ history of individual clusters: cluster archeology
  $\rightarrow$ calibrating thermal cluster observables: cluster cosmology
- indirect detection of dark matter:
  $\rightarrow$ cosmic ray vs. DM annihilation γ-rays

Cosmological simulations – flowchart



C.P., Enßlin, Springel (2008)

Cosmological simulations with cosmic ray physics



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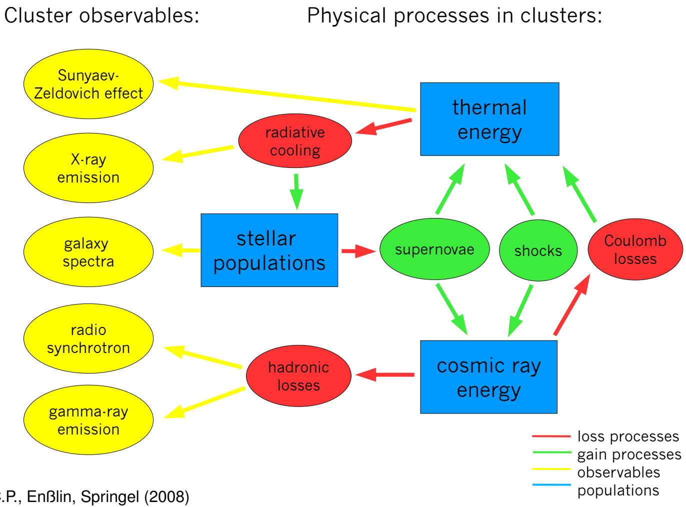

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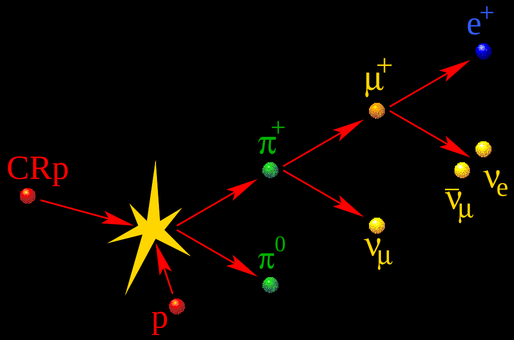
Hadronic cosmic ray proton interaction



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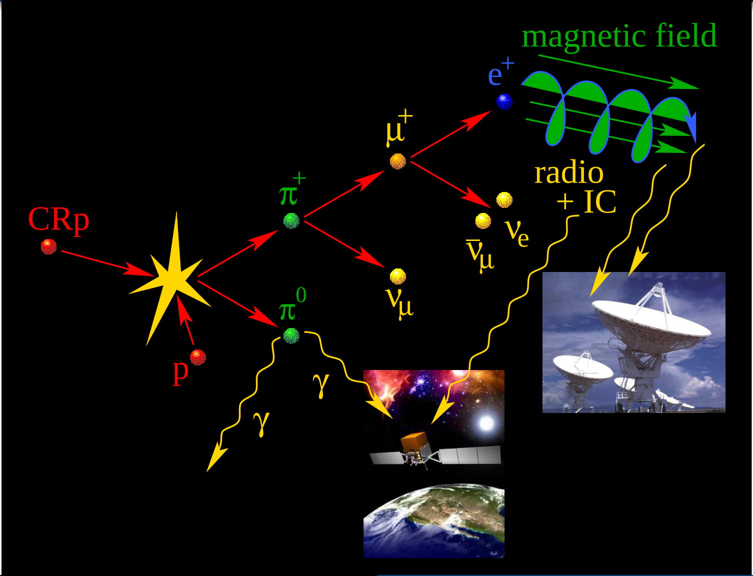
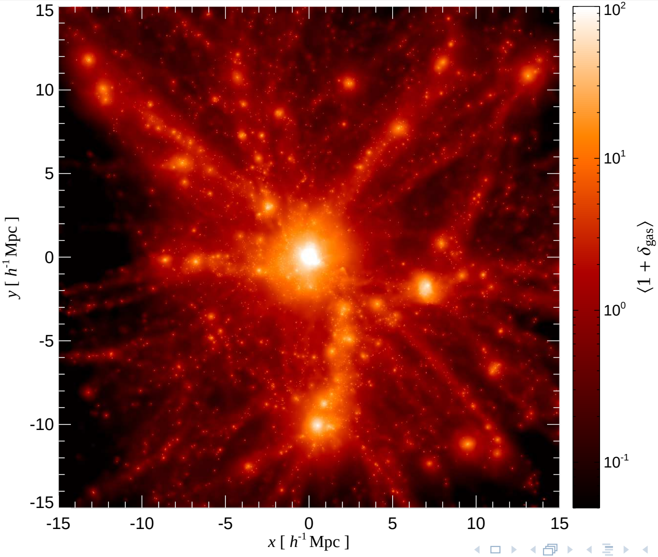
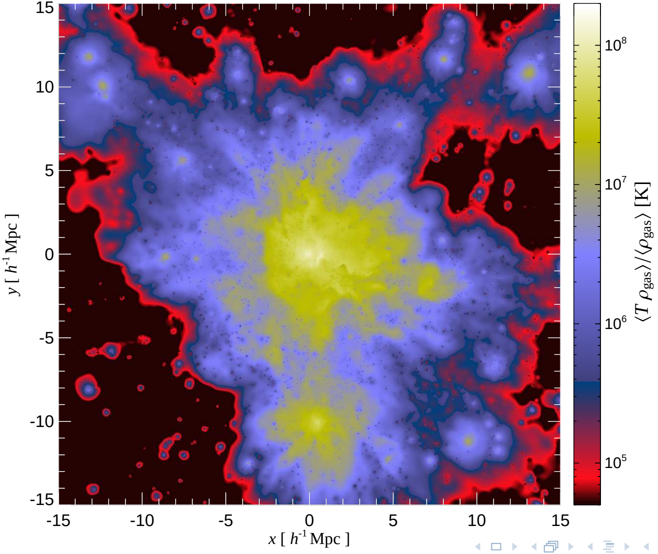


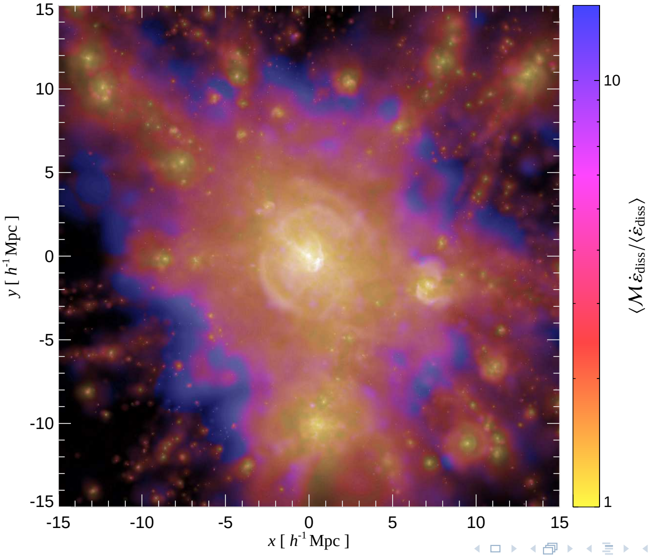
Cosmological cluster simulation: gas density



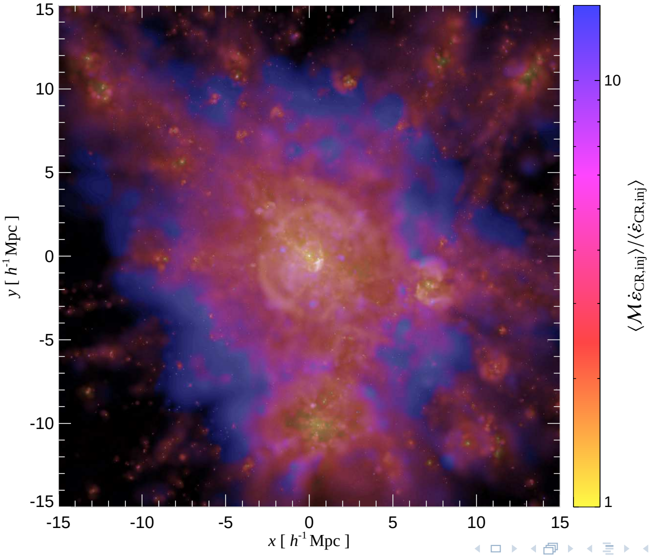
Mass weighted temperature



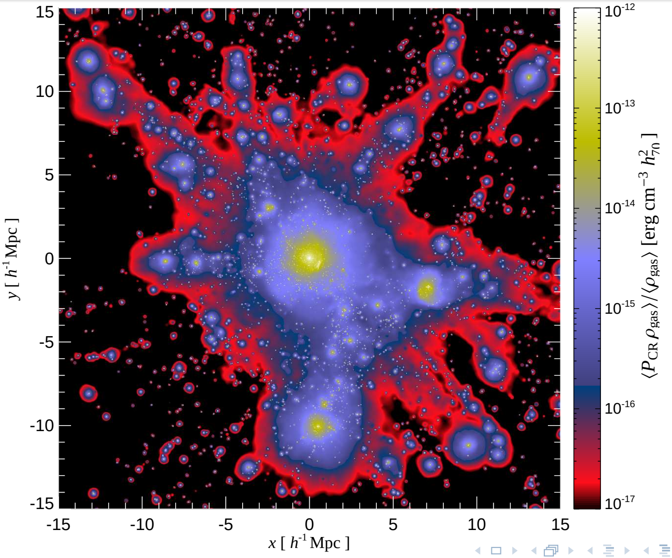
Shock strengths weighted by dissipated energy



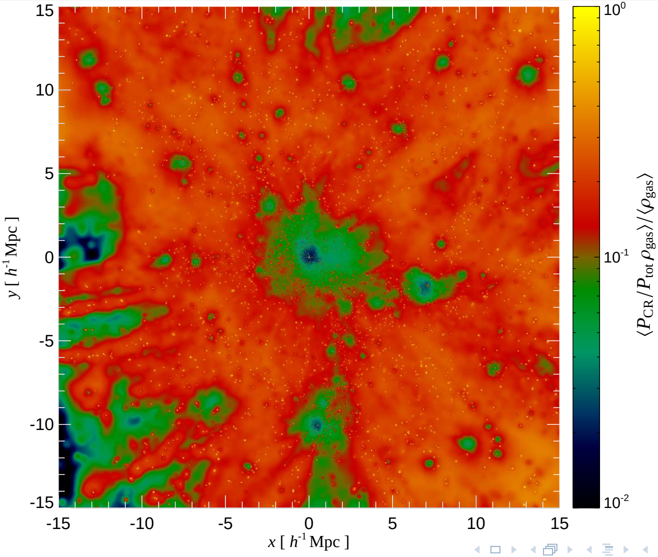
Shock strengths weighted by injected CR energy



Evolved CR pressure



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

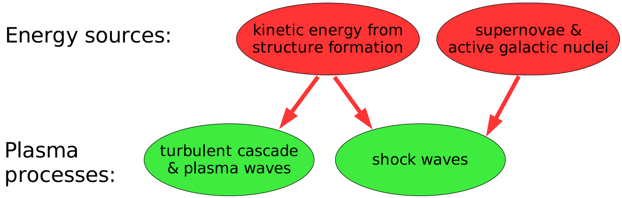


Outline

HITS

Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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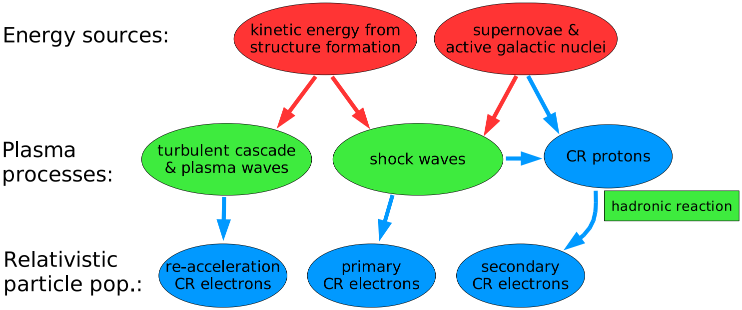

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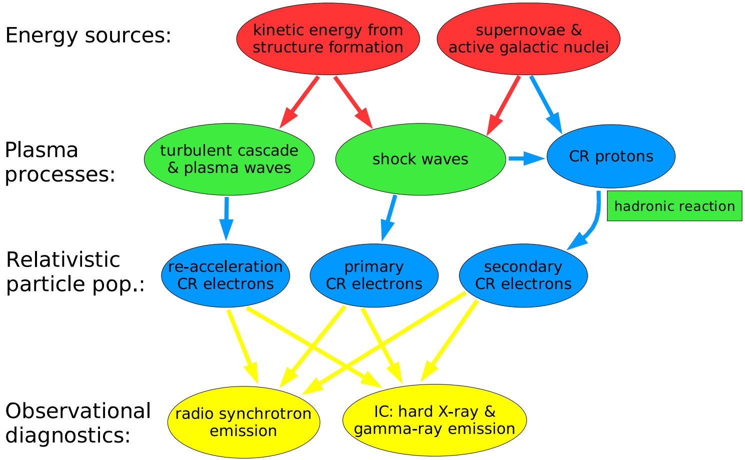

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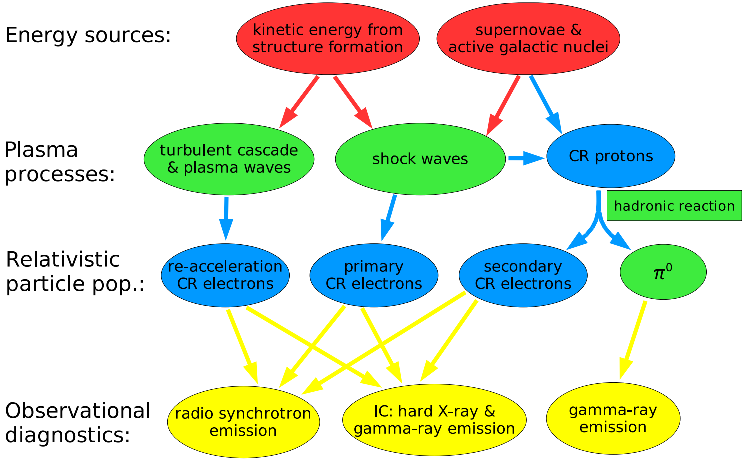
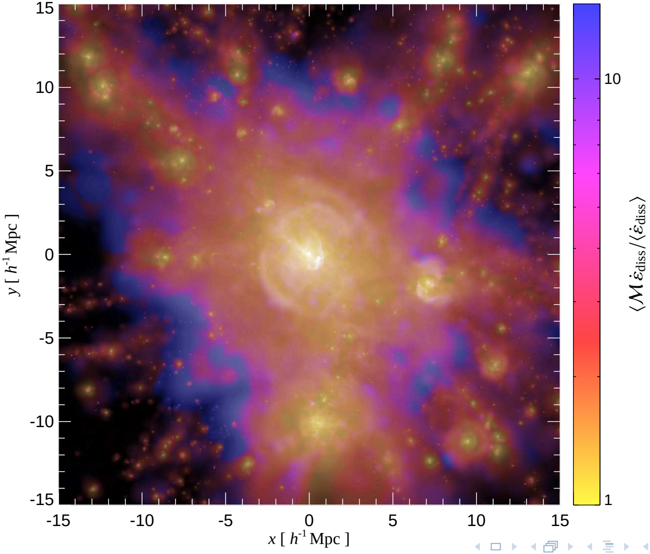
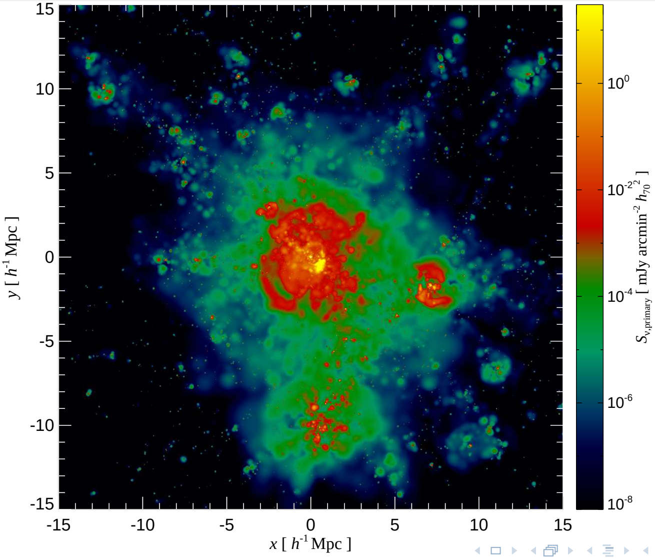


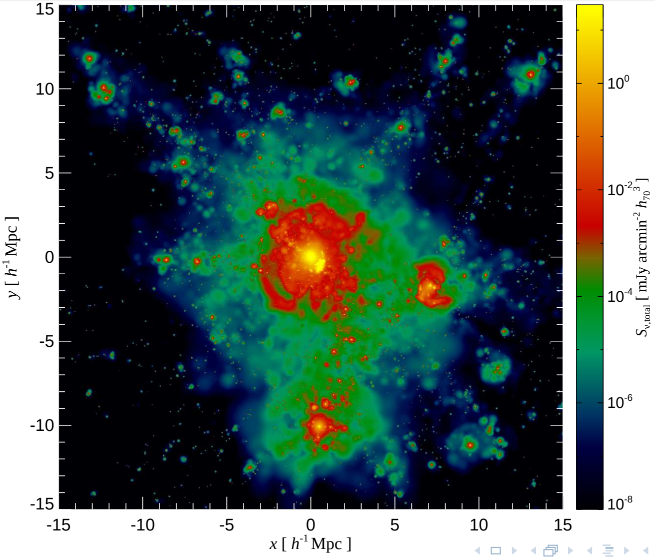
Structure formation shocks



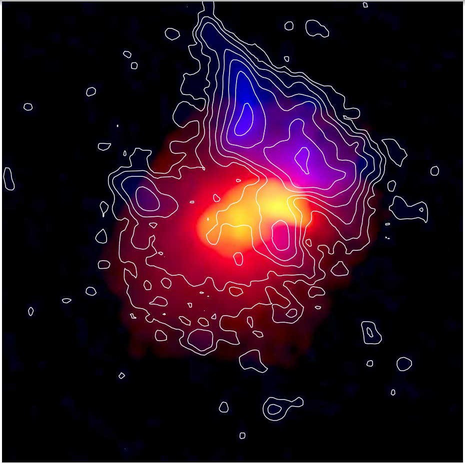
Radio gischt: shock-accelerated CRe

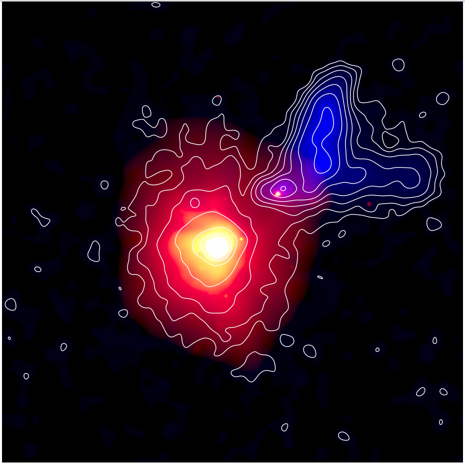


Radio gischt + central hadronic halo = giant radio halo



Which one is the simulation/observation of A2256?

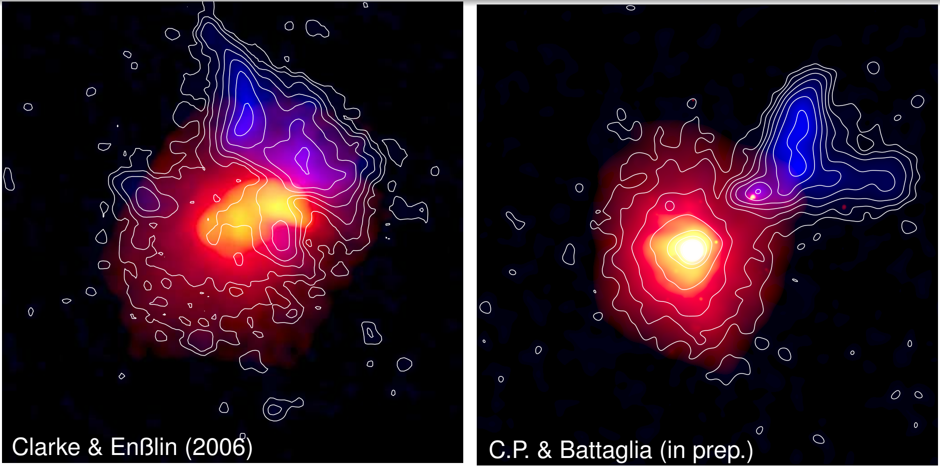




red/yellow: thermal X-ray emission,
blue/contours: 1.4 GHz radio emission with giant radio halo and relic

HITS

Observation – simulation of A2256



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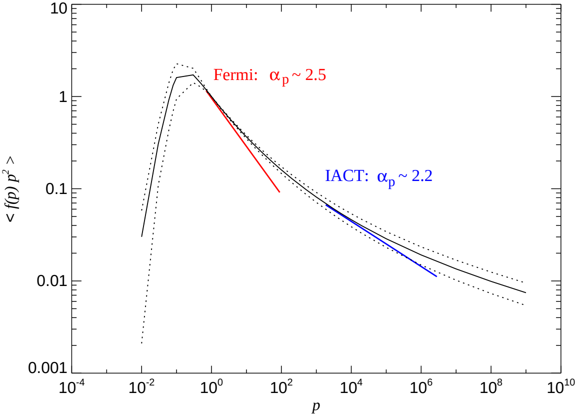
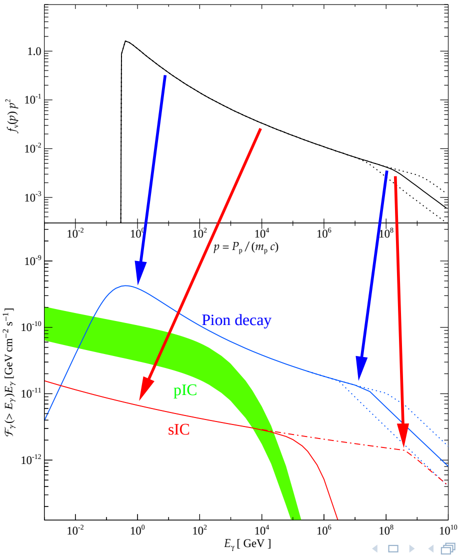
Universal CR spectrum in clusters (Pinzke & C.P. 2010)

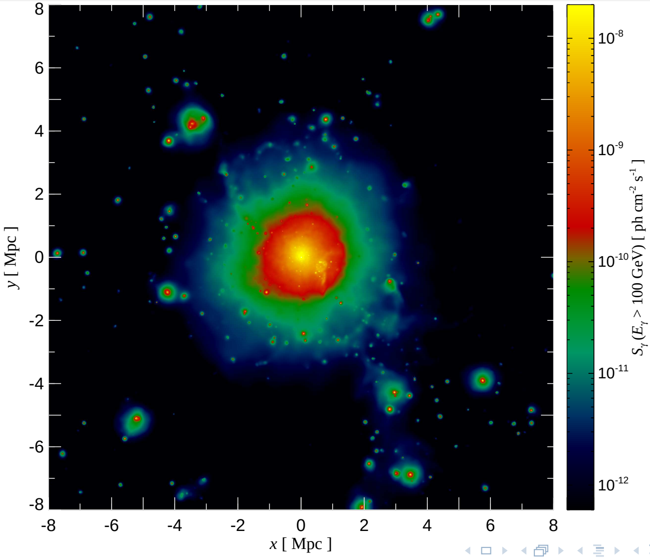


Normalized CR spectrum shows universal concave shape → governed by hierarchical structure formation and the implied distribution of Mach numbers that a fluid element had to pass through in cosmic history.

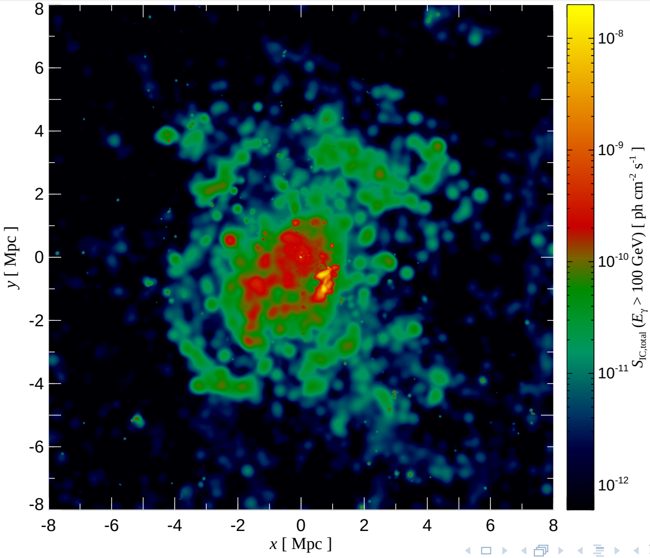
CR proton and γ-ray spectrum (Pinzke & C.P. 2010)



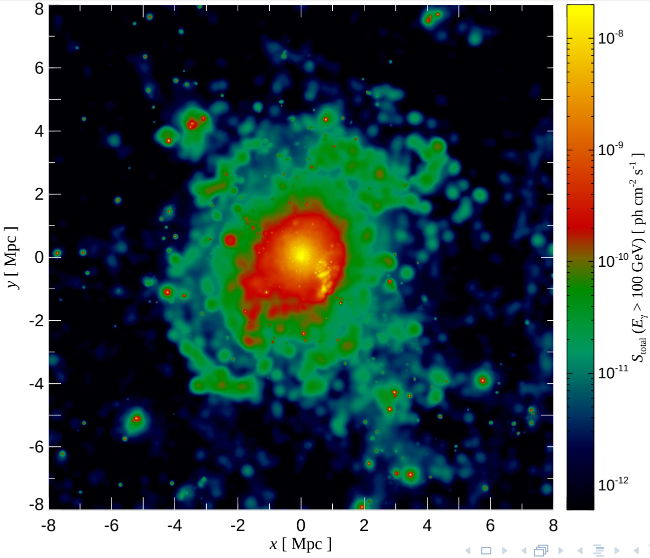
Hadronic γ-ray emission, $E_\gamma > 100$ GeV



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

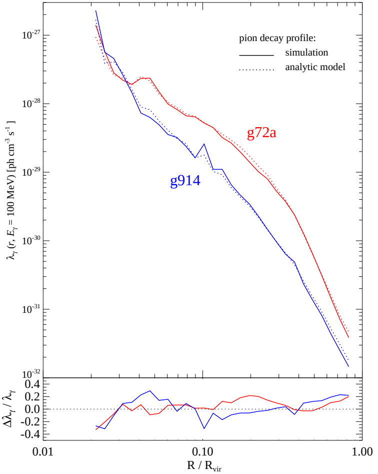


Total γ-ray emission, $E_\gamma > 100$ GeV

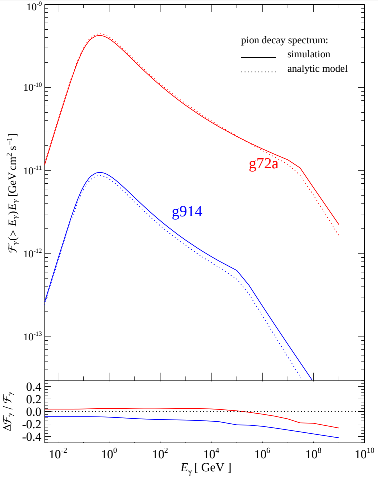


An analytic model for the cluster γ-ray emission

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

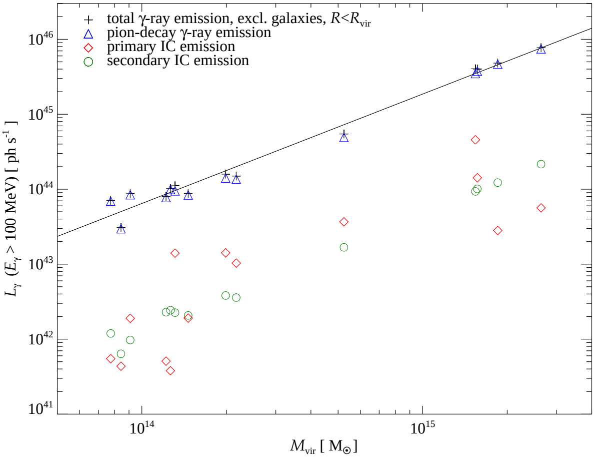


Spatial γ-ray emission profile



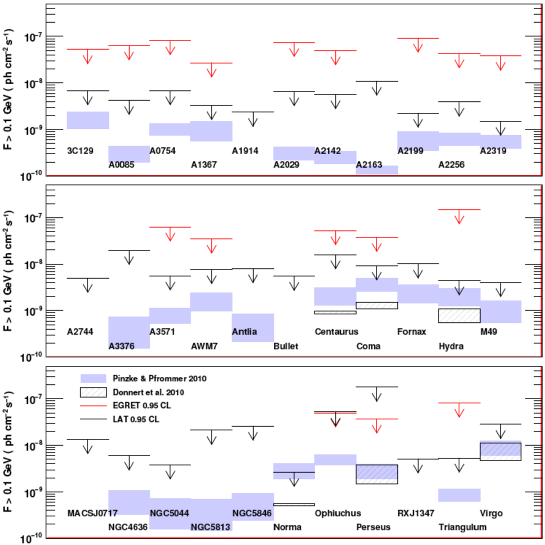
Pion decay spectrum

Gamma-ray scaling relations

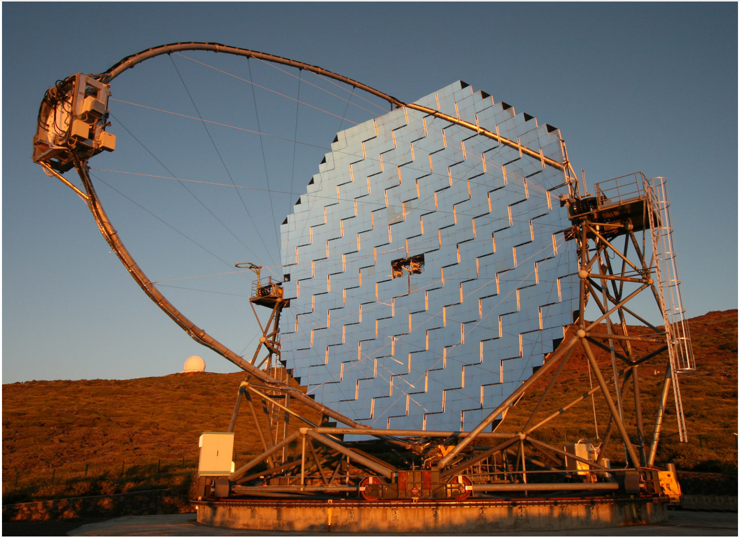


Scaling relation + complete sample of the brightest X-ray clusters (HIFLUGCS) → predictions for *Fermi* and *IACT's*

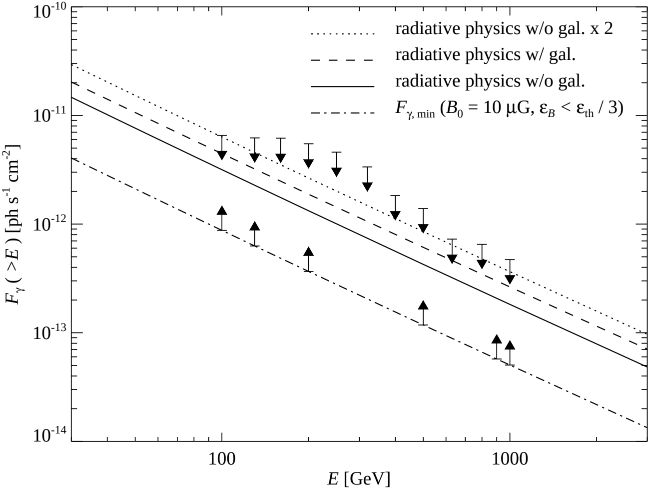
γ-ray limits and hadronic predictions (Ackermann et al. 2010)



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 $\alpha = 2.1$, $P_{\rm CR} \propto P_{\rm th}$:
  $\langle P_{\rm CR} \rangle < 0.02 \langle P_{\rm th} \rangle$ → most stringent constraint on CR pressure!
- upper limits consistent with cosmological simulations:
  $F_{\rm upper\ limits}(100\ {\rm GeV}) = 2\, F_{\rm sim}$ (optimistic model)
- simulation modeling of pressure constraint yields
  $\langle P_{\rm CR} \rangle / \langle P_{\rm th} \rangle < 0.04\ (0.08)$ for the core (entire cluster)
- resolving the apparent discrepancy:
  - concave curvature ‘hides’ CR pressure at GeV energies
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Conclusions on high-energy astrophysics in 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

→ Multi-messenger approach from the radio to γ-ray regime

Conclusions on high-energy astrophysics in clusters

New generation of observatories

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

- 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)
- MAGIC, H.E.S.S., Veritas, CTA: imaging air Čerenkov telescopes ($E \simeq (0.1-100)$ TeV)

Outline

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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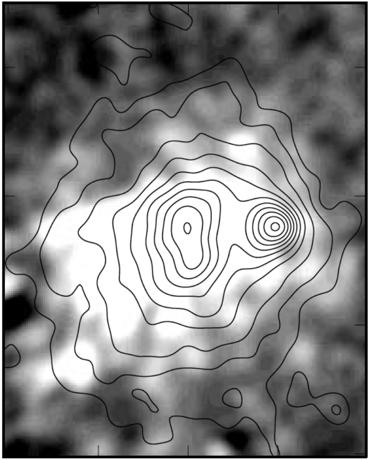
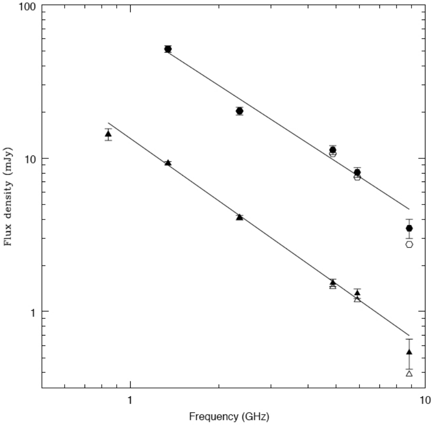
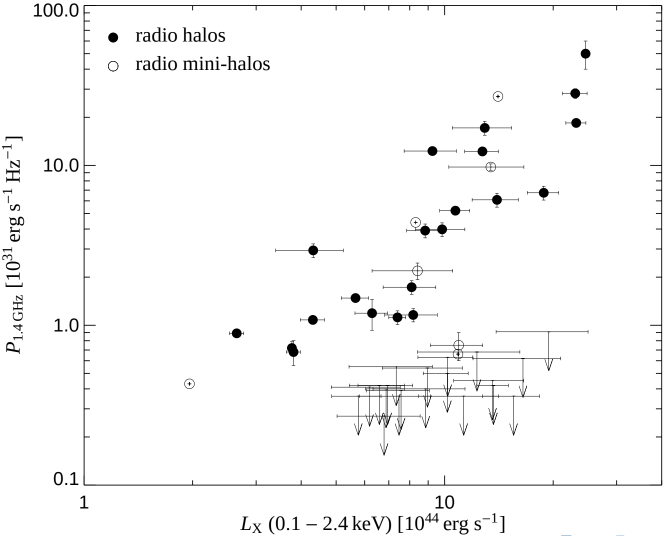
Radio halo and spectrum in the Bullet cluster





Liang et al. (2000): SZ-corrected

Radio luminosity - X-ray luminosity



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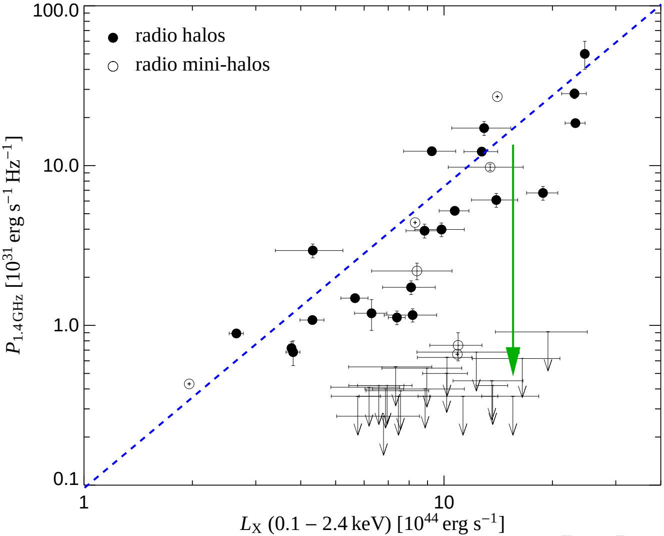

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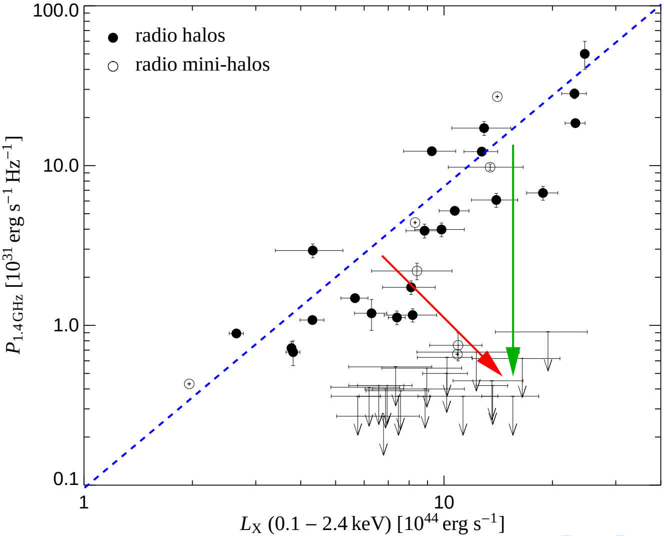
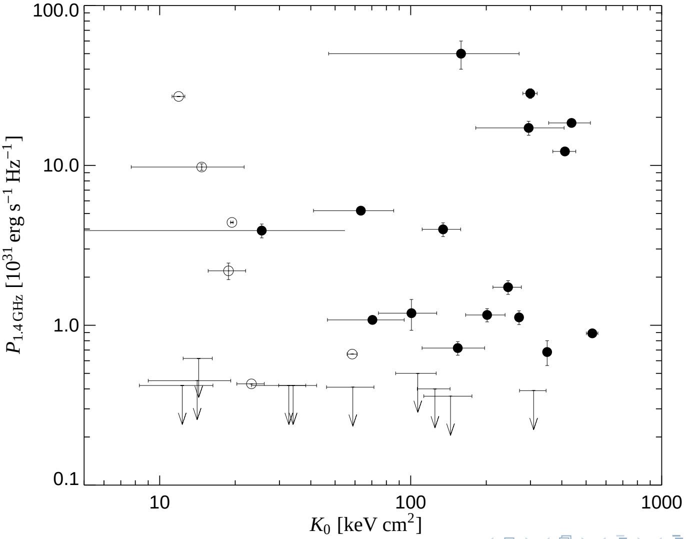


Radio luminosity - central entropy



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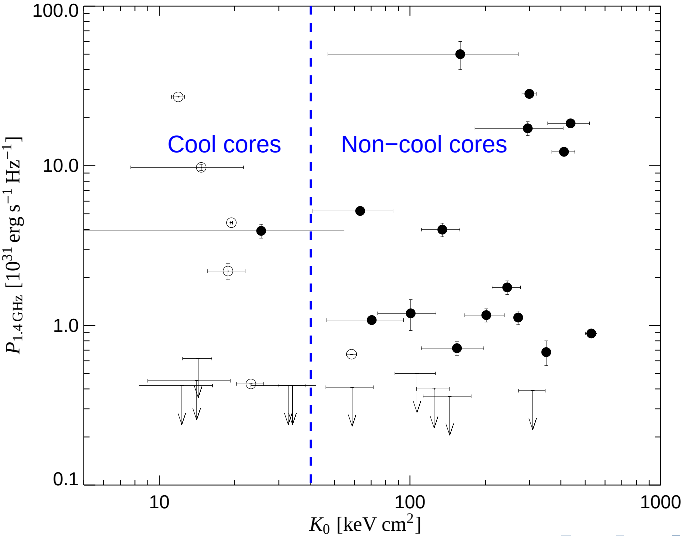

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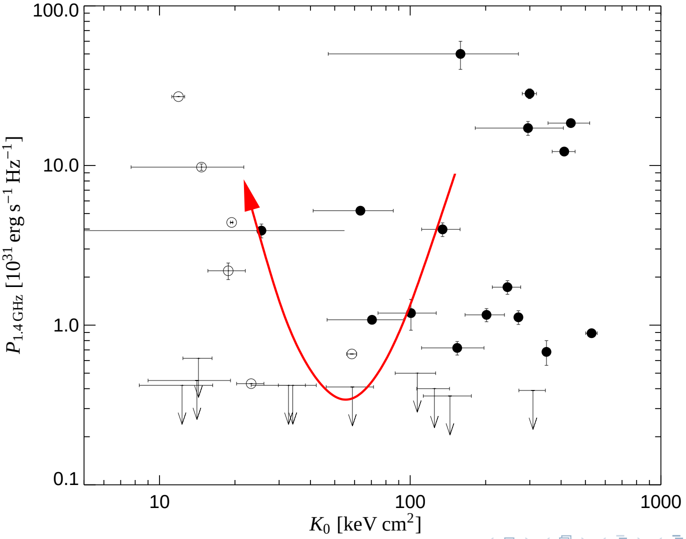
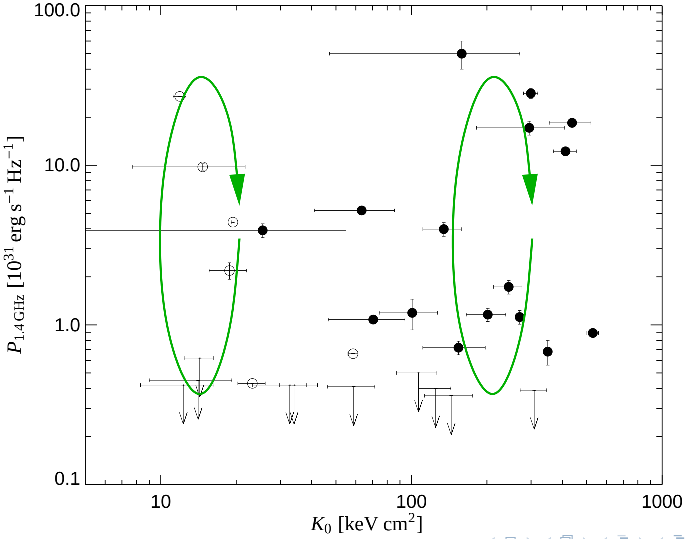
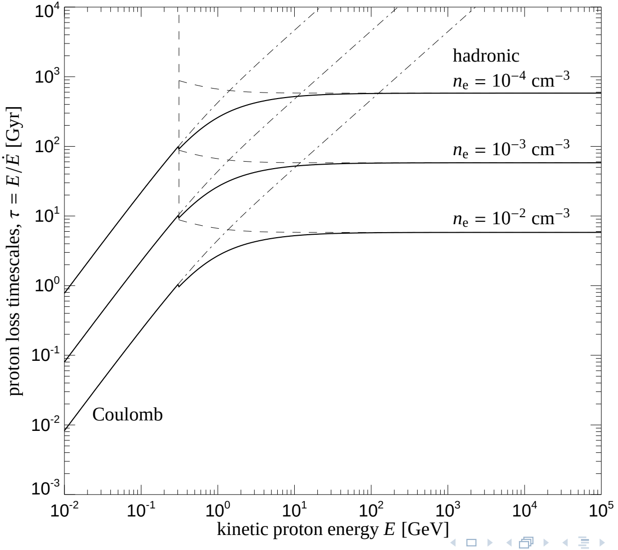


Radio luminosity - central entropy



Proton cooling times



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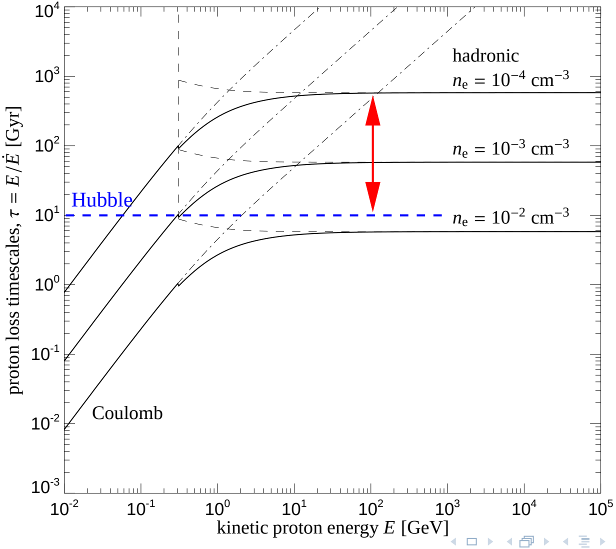

Radio halo theory – (ii) re-acceleration model

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 ← less turbulent

weakness:

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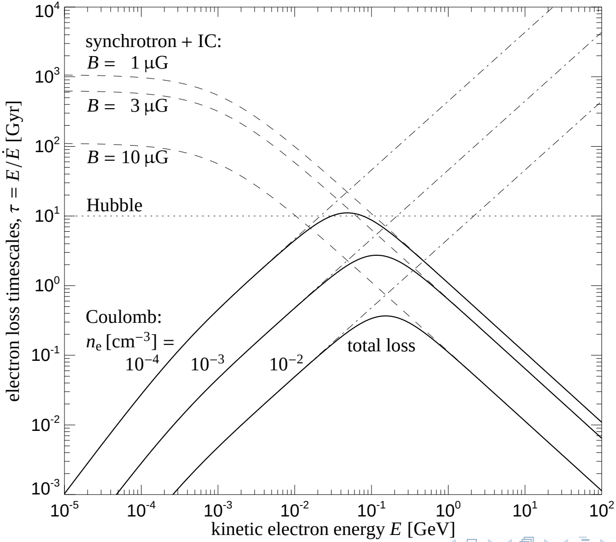
Electron cooling times



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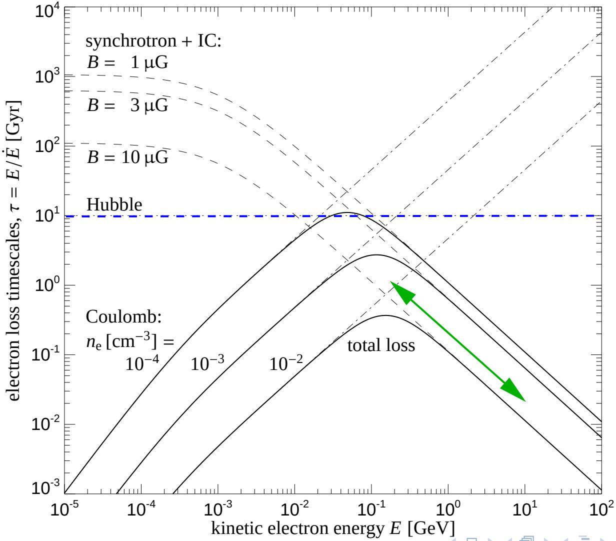
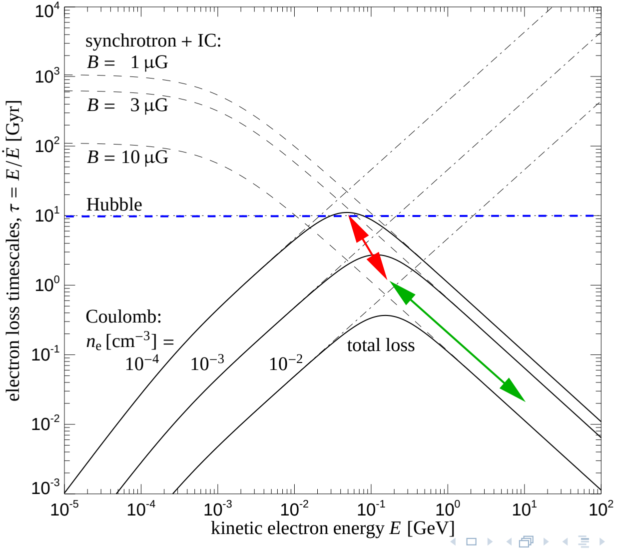
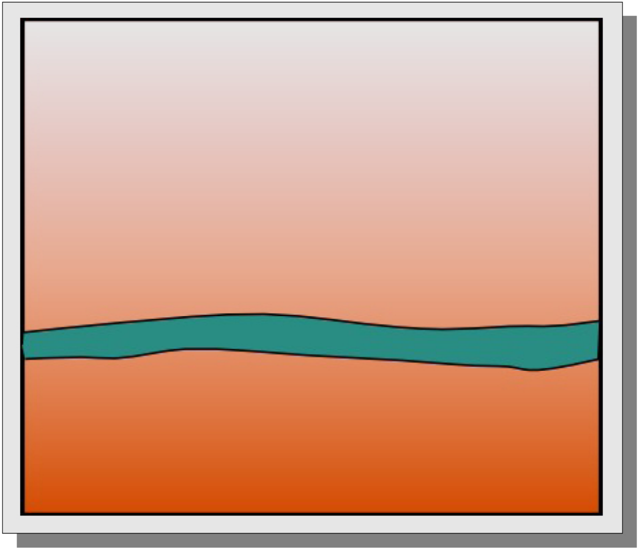


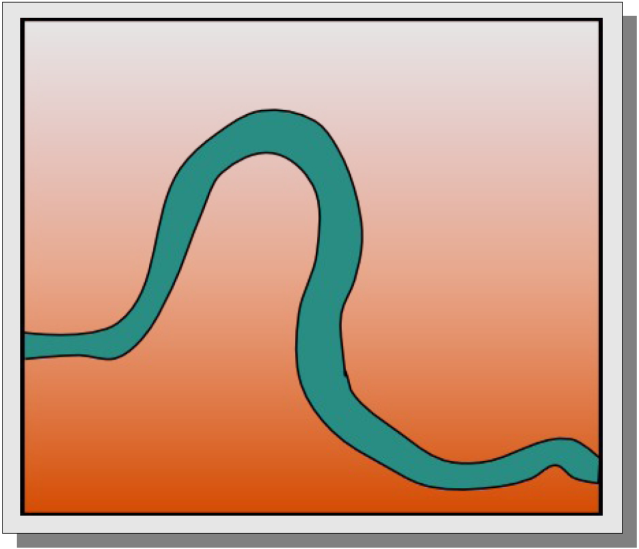
Electron cooling times



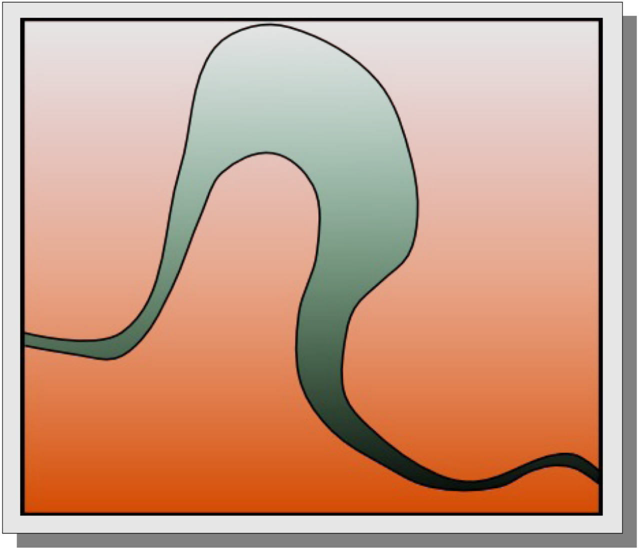
Cosmic ray transport – magnetic flux tube with CRs



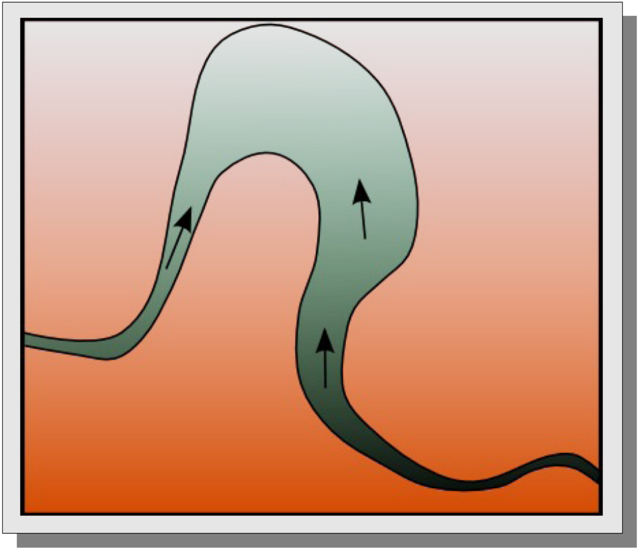
Cosmic ray advection



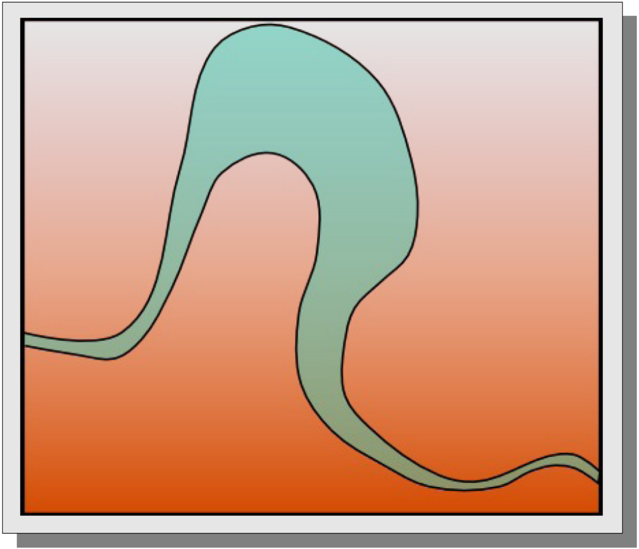
Adiabatic expansion and compression



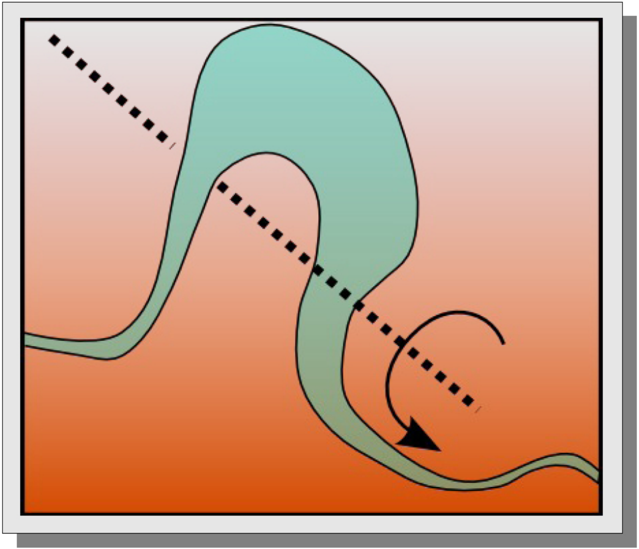
Cosmic ray streaming



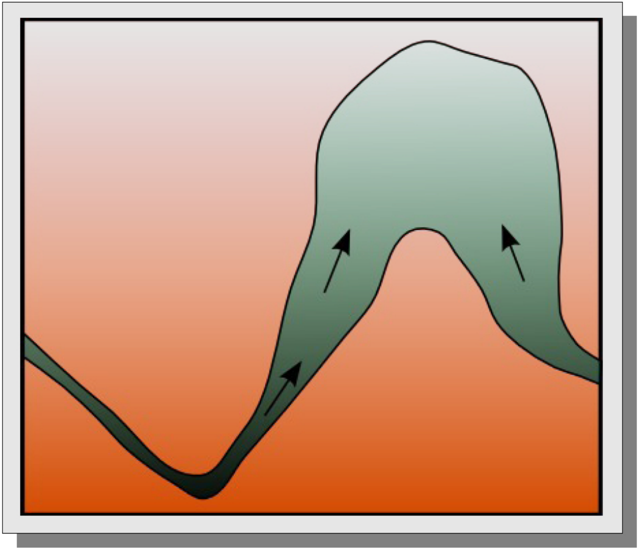
Expanded CRs



Turbulent pumping

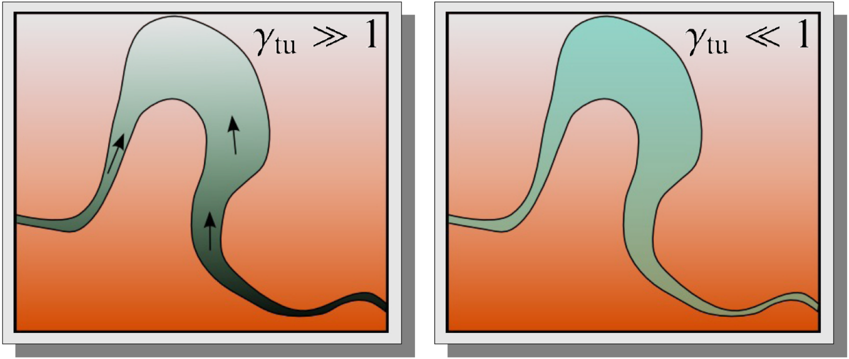


Turbulent pumping

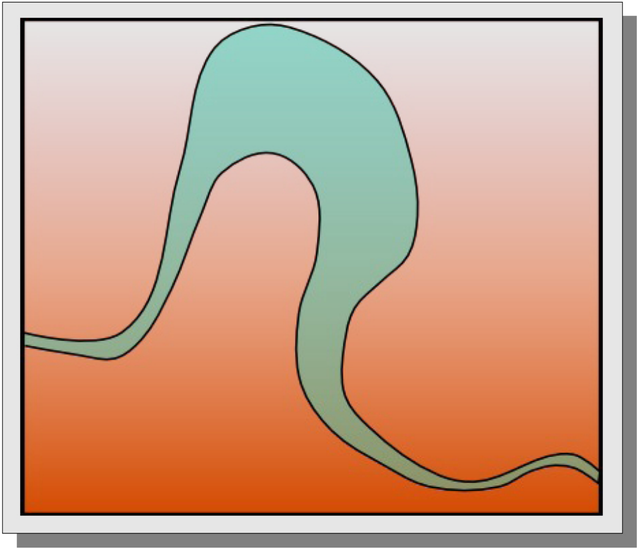


Turbulent-to-streaming ratio

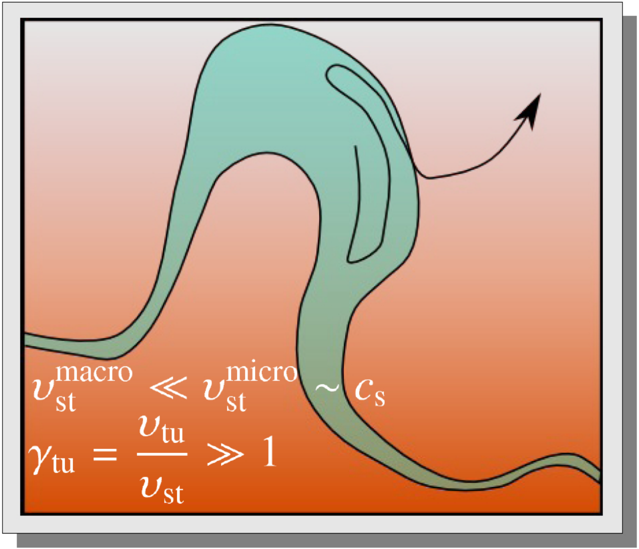
$$\gamma_{\rm tu} = \frac{\upsilon_{\rm tu}}{\upsilon_{\rm st}}$$



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:

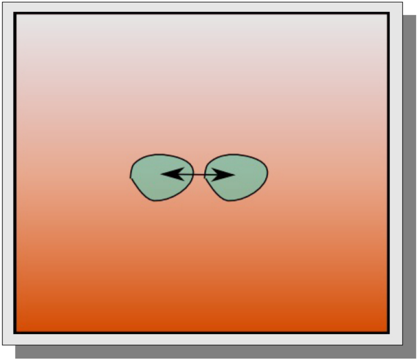
$$\frac{\partial \varrho}{\partial t} + \vec{\nabla} \cdot (\boldsymbol{\upsilon}\, \varrho) = 0 \qquad \boldsymbol{\upsilon} = \boldsymbol{\upsilon}_{\rm ad} + \boldsymbol{\upsilon}_{\rm di} + \boldsymbol{\upsilon}_{\rm st}$$

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

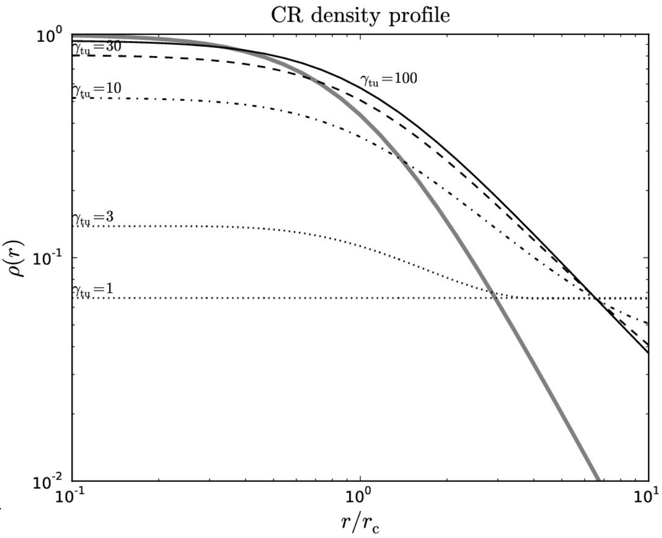
$$\kappa_{\rm tu} = \frac{L_{\rm tu}\, \upsilon_{\rm tu}}{3}$$

CR profile due to advection

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

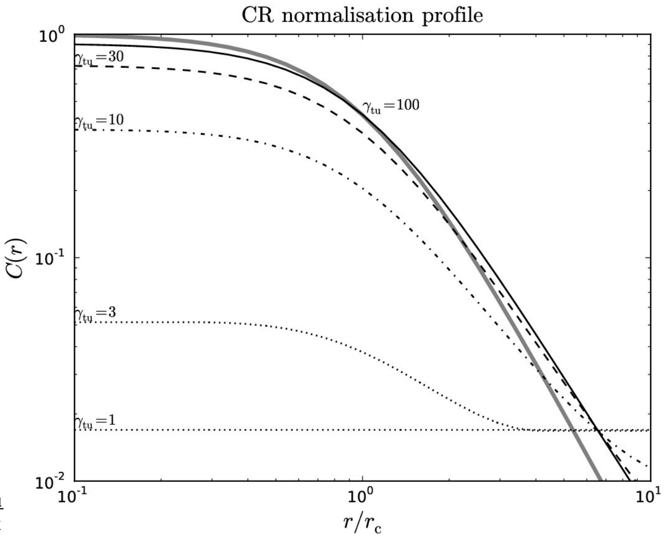


CR density profile



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

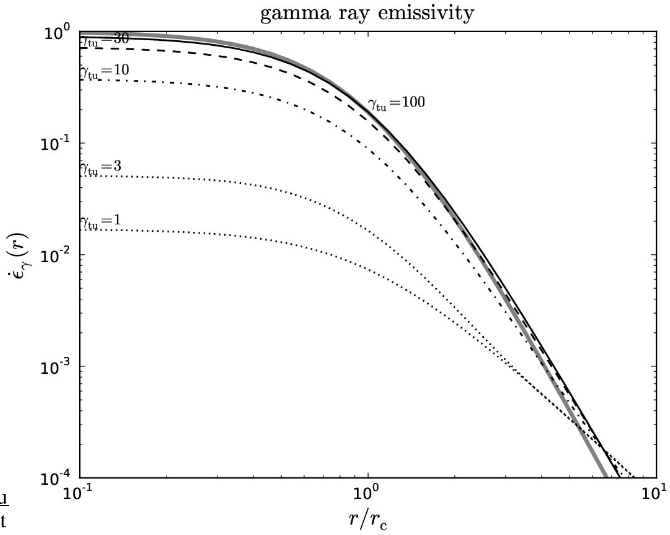
CR density at fixed particle energy



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

Gamma-ray emission profile

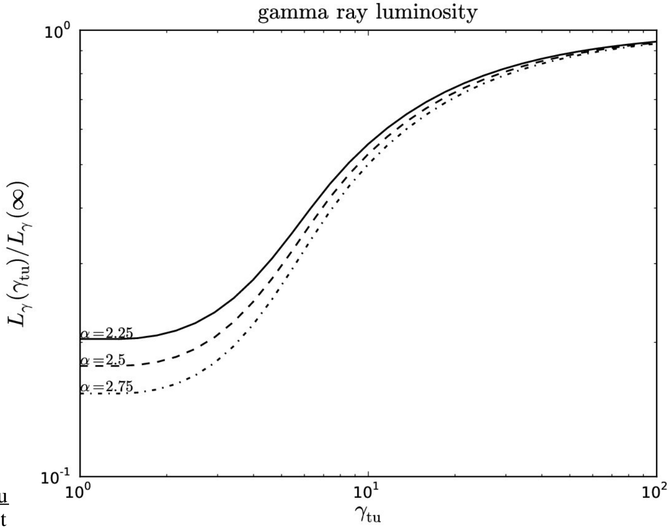
$p_{CR} + p \rightarrow \pi^0 \rightarrow 2\gamma$



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

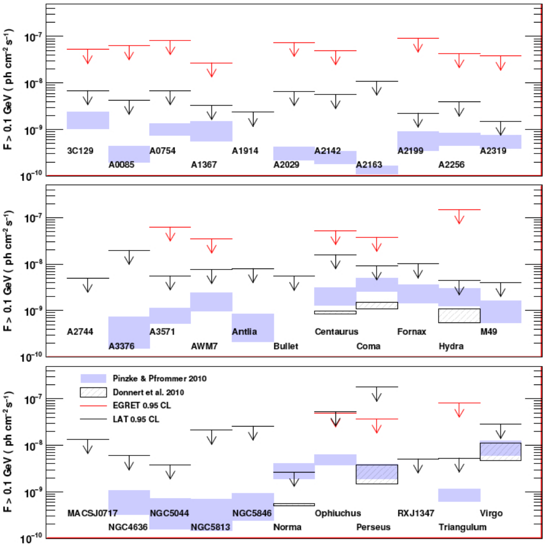
Gamma-ray luminosity

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



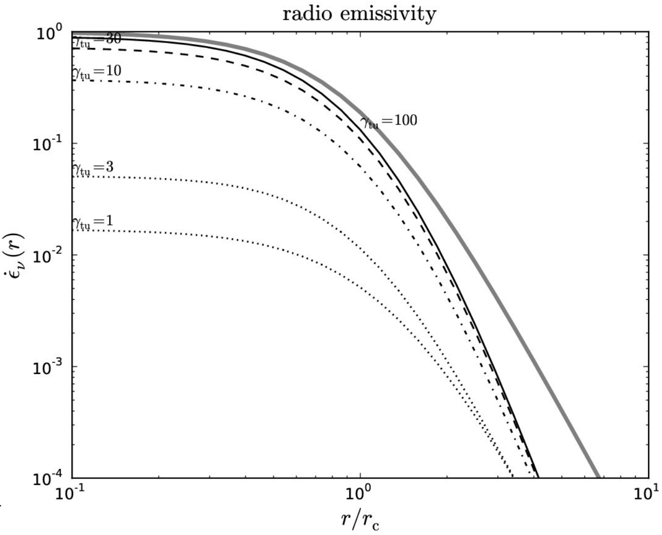
$$\gamma_{\mathrm{tu}} = \frac{\upsilon_{\mathrm{tu}}}{\upsilon_{\mathrm{st}}}$$

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



Radio emission profile

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



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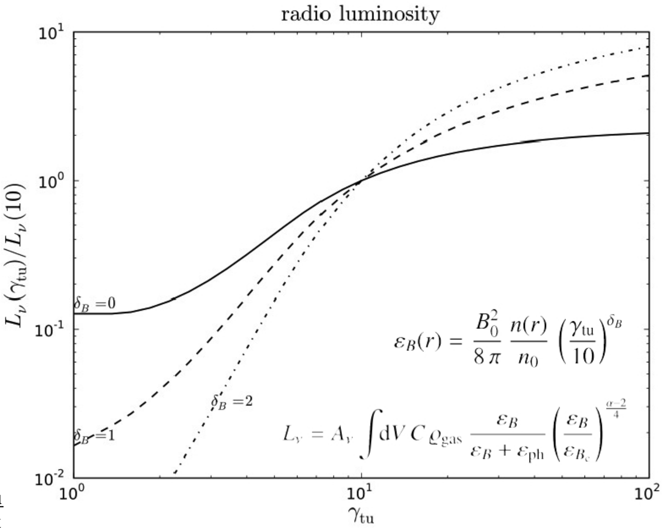
Radio luminosity

$p_{\mathrm{CR}} + p \to \pi^{\pm} \to e^{\pm} \to \text{radio}$



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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 $\upsilon_{\rm st}^{\rm macro}$ $\rightarrow$ CR & radio spectral variations
  $\rightarrow$ outstreaming CR: dying halo $\leftarrow$ decaying turbulence

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

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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*

HITS