Open questions on the physics of radio halos and relics in galaxy clusters

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in collaboration with

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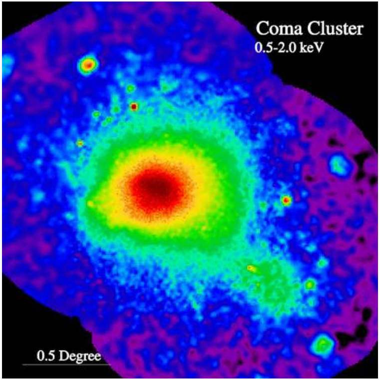
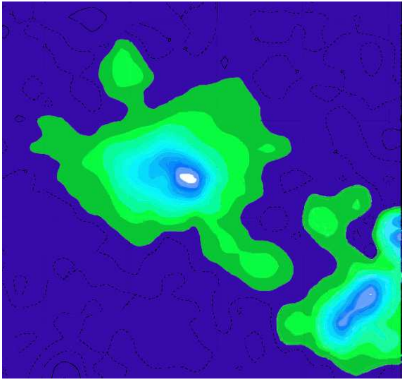
Aug 23 2012 / IAU Beijing

Giant radio halo and relic in the Coma cluster



thermal X-ray emission

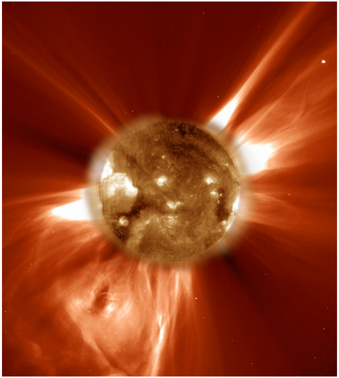
(Snowden/MPE/ROSAT)

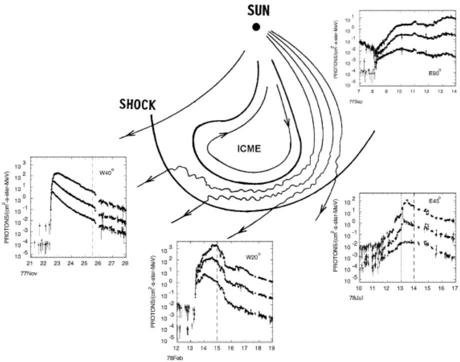


radio synchrotron emission

(Deiss/Effelsberg)

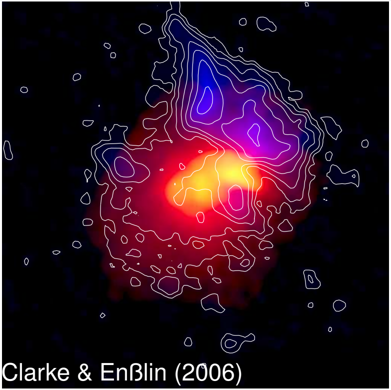
The problem

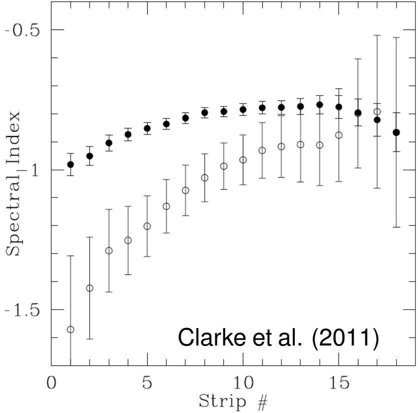




→ weak shocks ($\mathcal{M} \lesssim 4$) are inefficient in accelerating electrons!

Radio relic in A2256

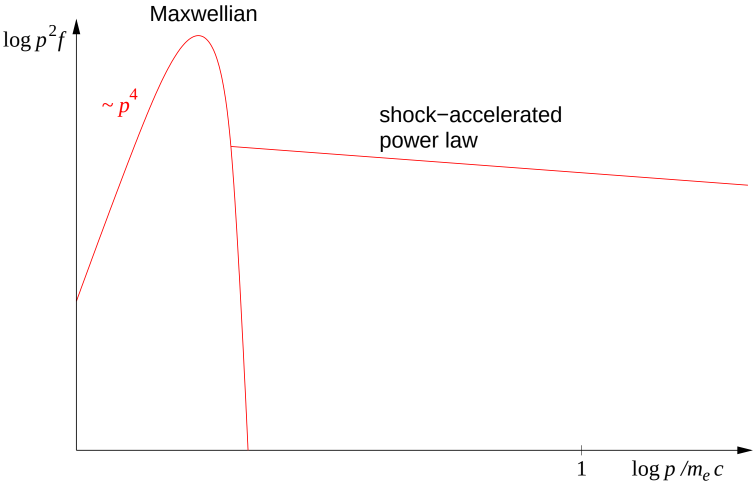




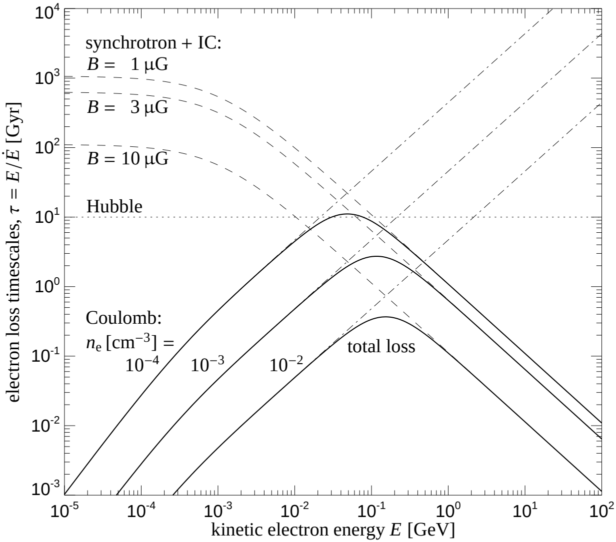
left: thermal X-ray emission (red/yellow), 1.4 GHz radio (blue/contours)
right: spectral index α_ν across the radio relic (south-east to the northwest)
$\alpha_\nu = 0.85 \quad \rightarrow \quad \mathcal{M} = 2.6$:
→ but how are the electrons accelerated if weak shocks are inefficient?

Build-up of the fossil electron distribution

Strong structure formation shocks during the era of cluster formation



Electron cooling times



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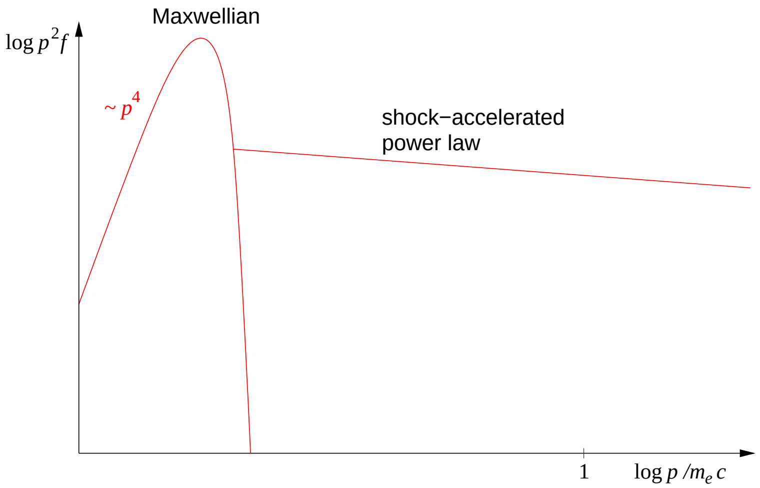

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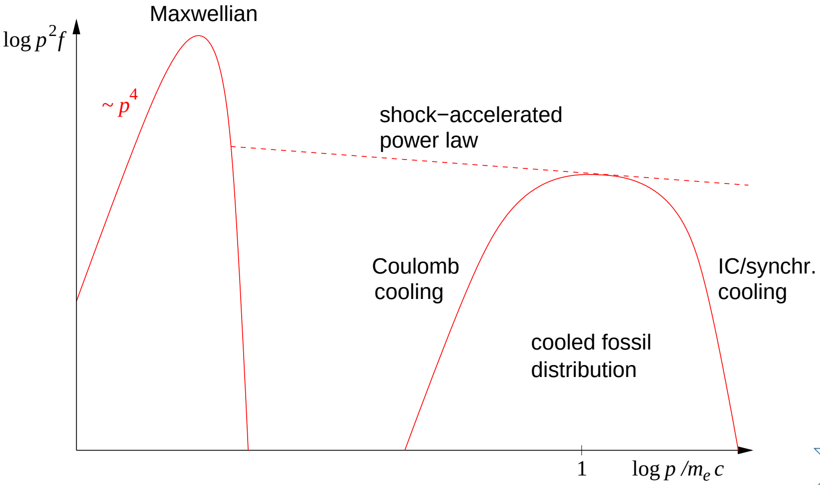

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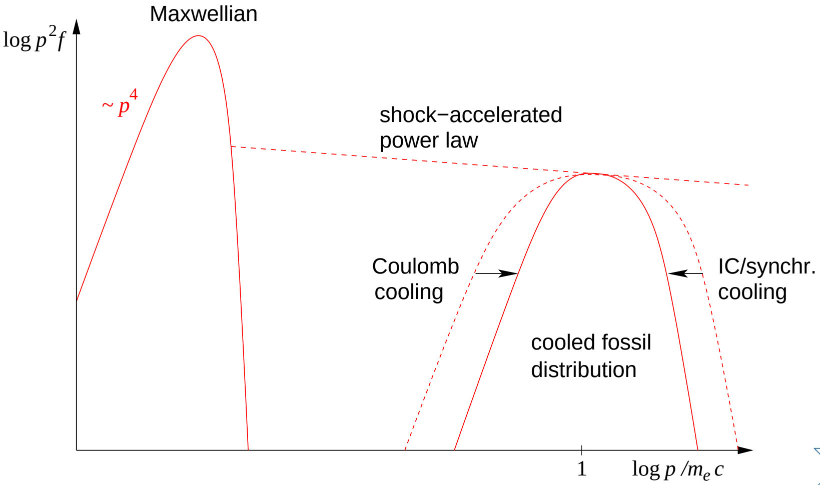
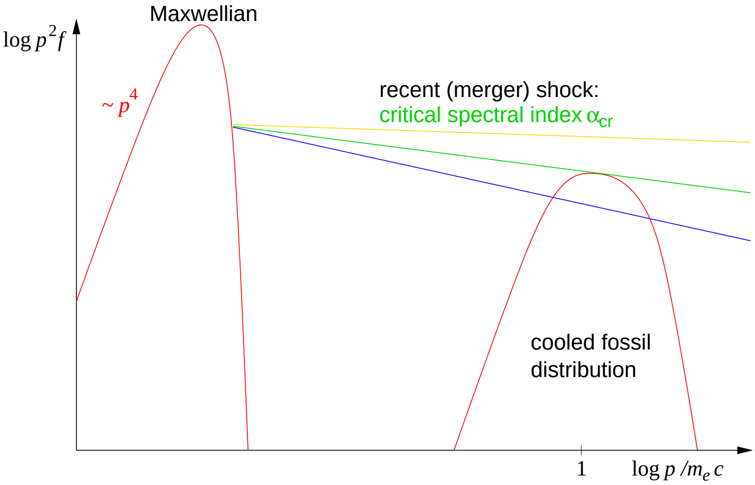


Illuminating radio relics

Re-acceleration of fossil electrons vs. primary acceleration



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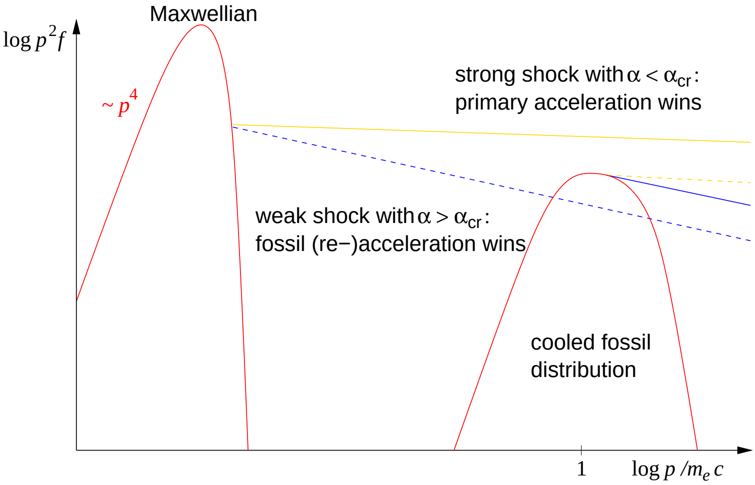

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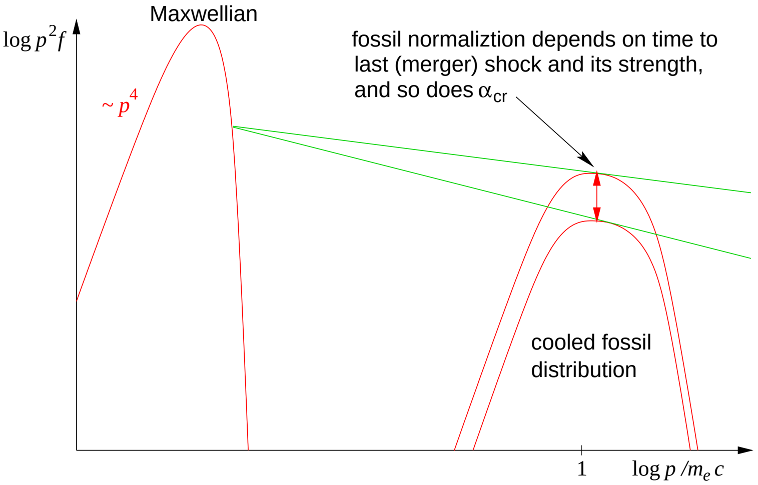
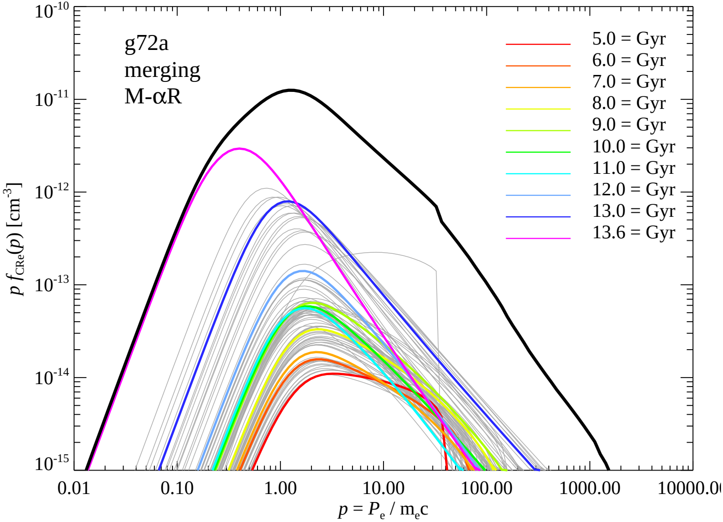
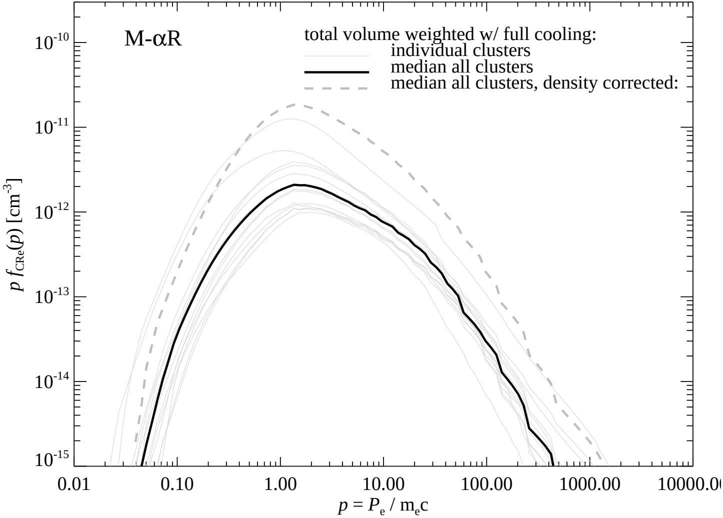


Time evolution of the fossil electron distribution



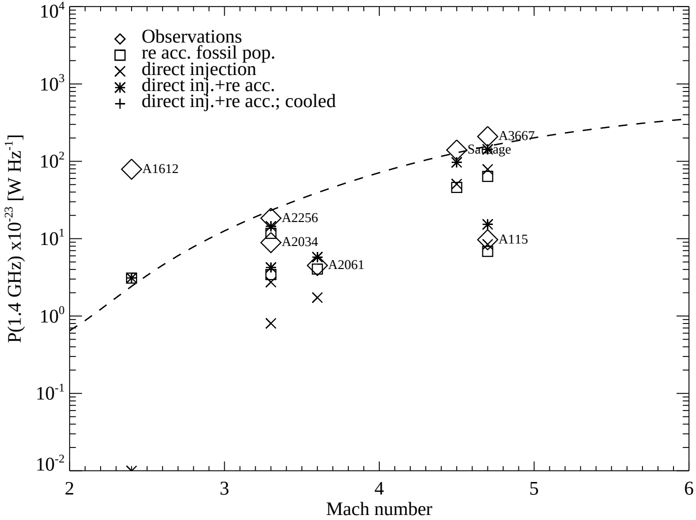
Pinzke, Oh, C.P. (2012)

Shape of the fossil electron distribution



Pinzke, Oh, C.P. (2012)

Relic luminosities



Pinzke, Oh, C.P. (2012)

New paradigm for radio relics

- distribution function of fossil electrons in cluster outskirts for the time after a merger $\tau_{\text{merger}} > 100$ Myrs has an approximate self-similar shape (electron cooling physics)
- normalization of fossil electrons depends on τ_{merger} and the shock Mach number $\mathcal{M}$
- radio relics at high-$\mathcal{M}$ shocks $\rightarrow$ primary electrons
  radio relics at low-$\mathcal{M}$ shocks $\rightarrow$ re-accelerated fossil electrons (Fermi 1)

$\rightarrow$ **hybrid Fermi 1 (re-)acceleration model can successfully explain radio relic luminosities**

Radio halo theory – (i) hadronic model

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

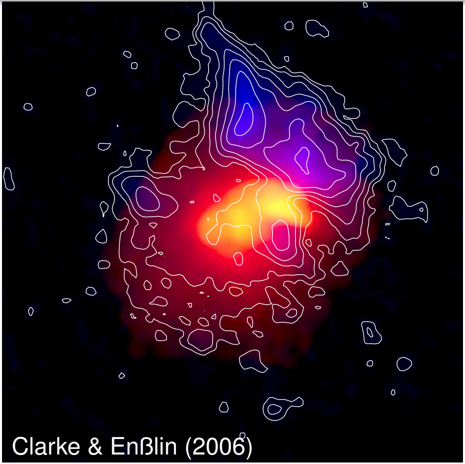
strength:

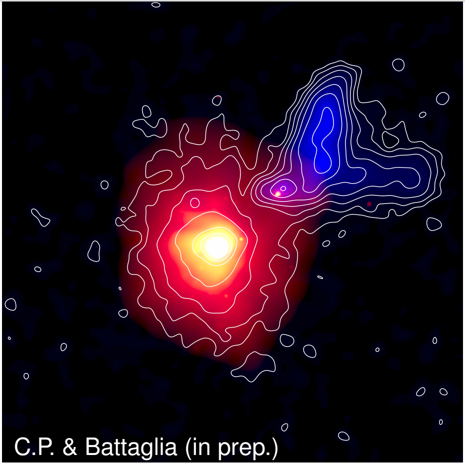
- all required ingredients available:
  shocks to inject CRp, gas protons as targets, magnetic fields
- predicted luminosities and morphologies as observed without tuning
- power-law spectra as observed

weakness:

- halo profiles are too extended so that $P_{\rm CR}/P_{\rm th}$ has to rise with r
- all clusters should have radio halos
- does not explain all reported spectral features

Observation – simulation 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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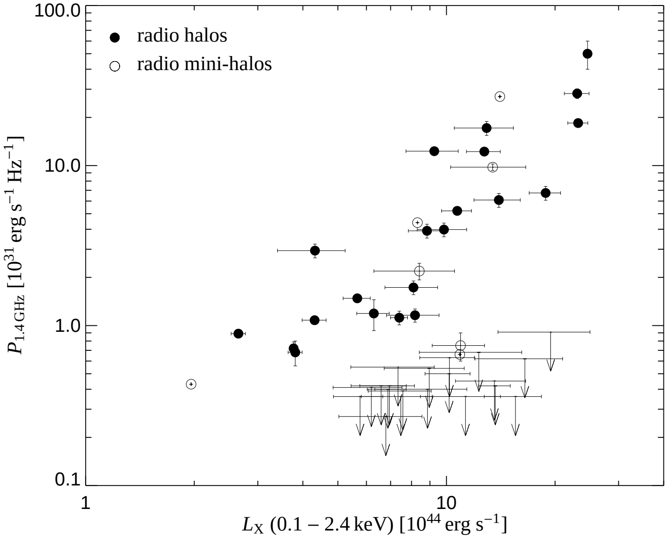
Radio luminosity - X-ray luminosity



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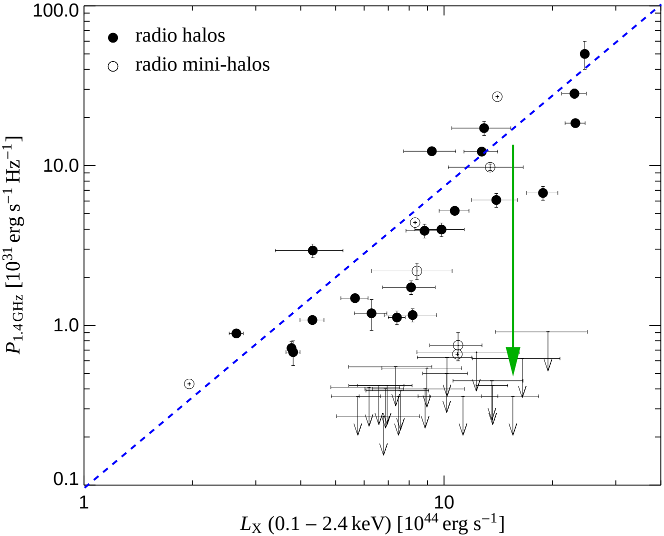

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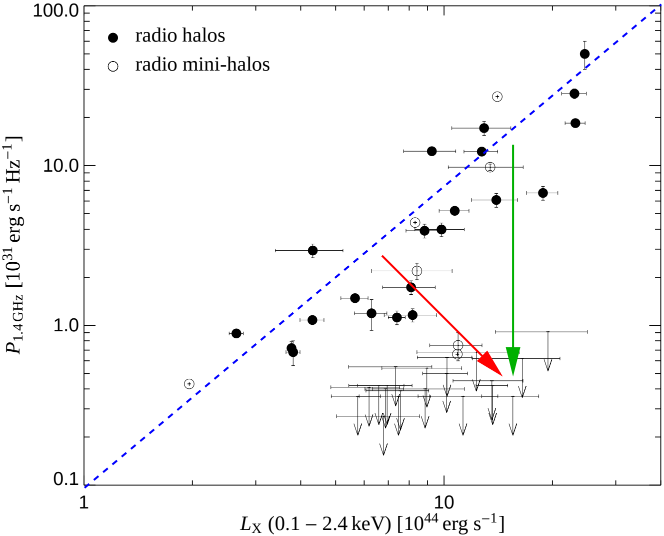
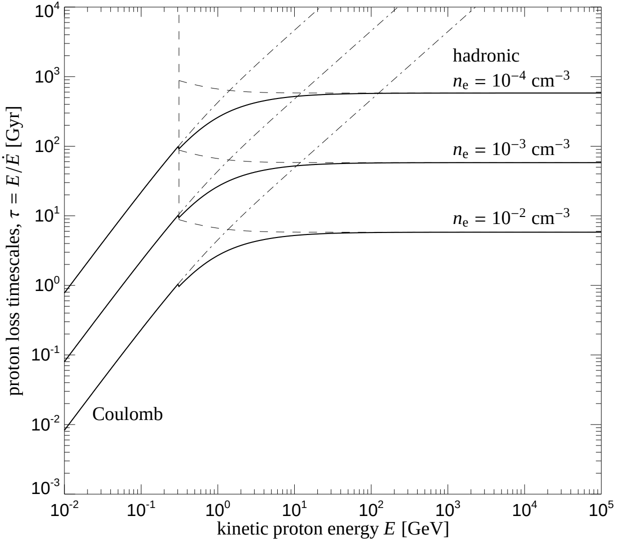


Proton cooling times



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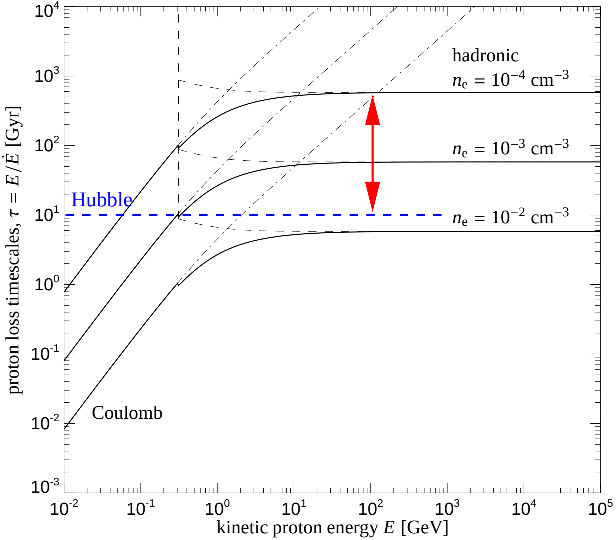
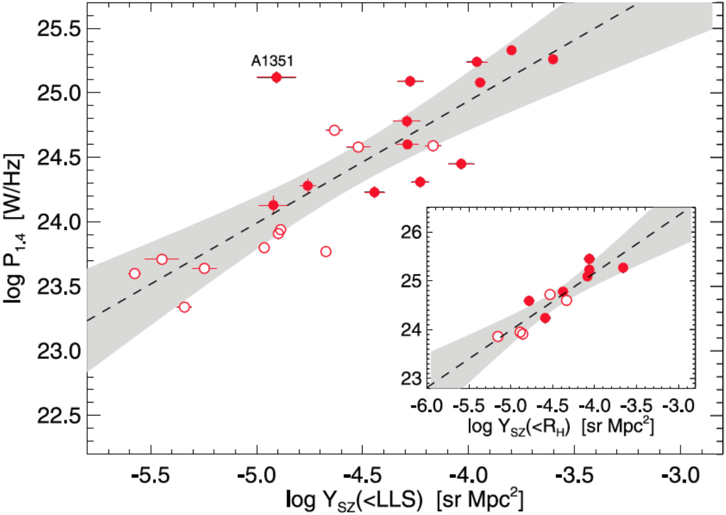


HITS

Radio luminosity - Sunyaev-Zel'dovich flux $Y(R_{\mathrm{LLS}})$



Basu (2012)

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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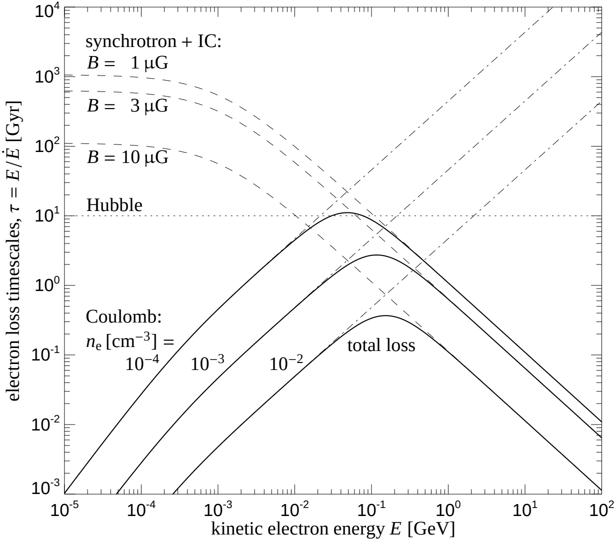
Electron cooling times



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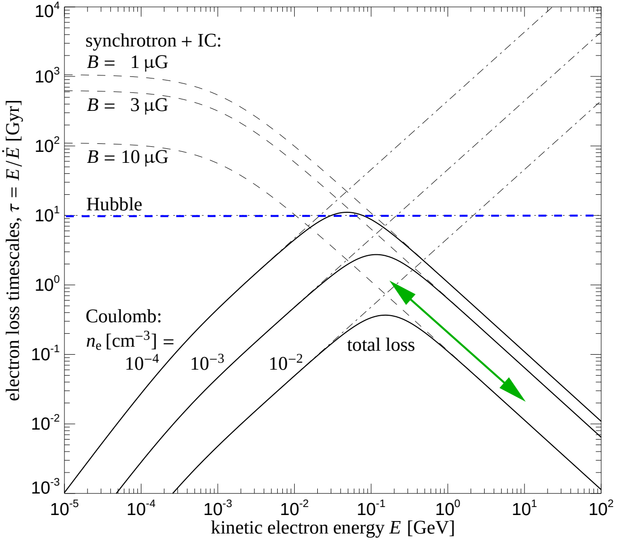

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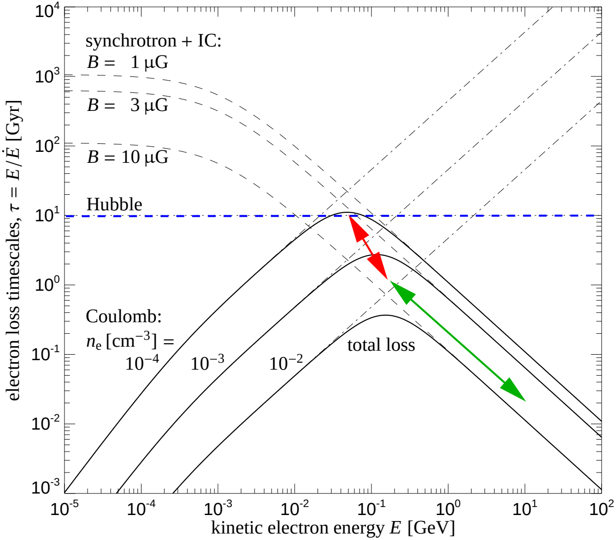
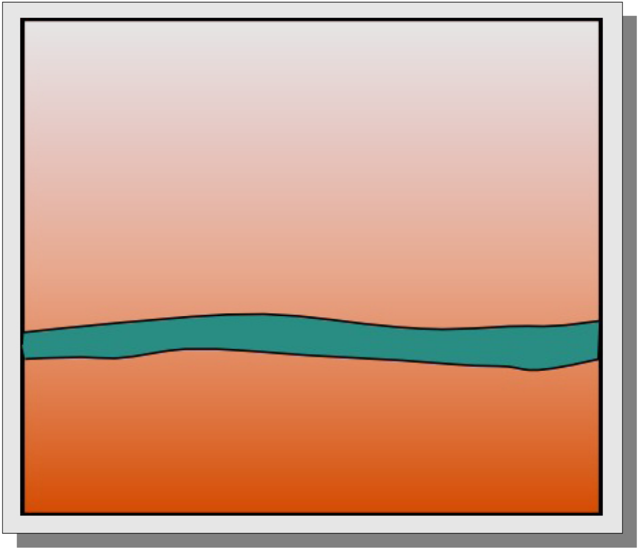
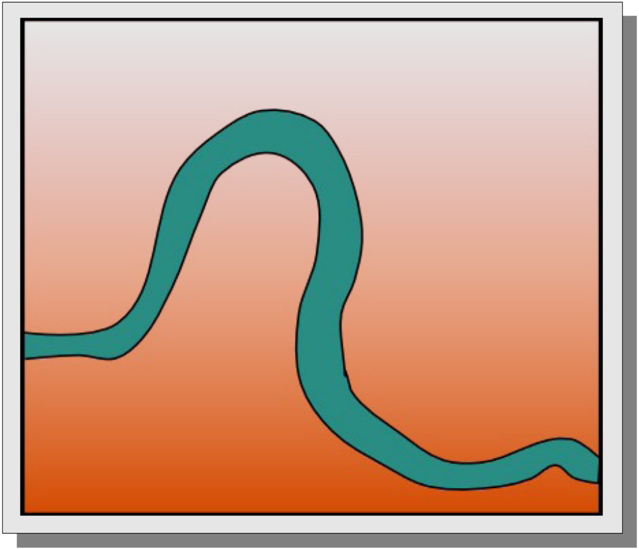


Cosmic ray transport – magnetic flux tube with CRs

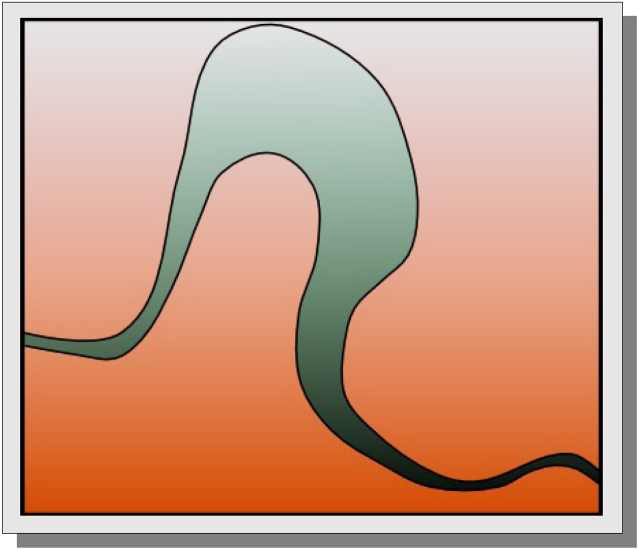


HITS

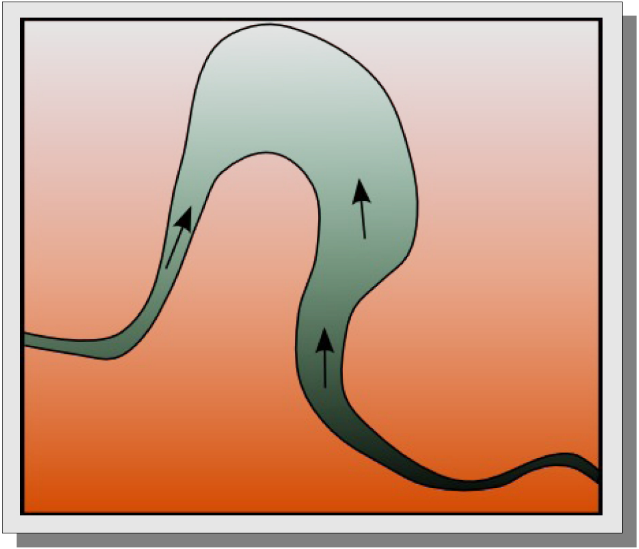
Cosmic ray advection



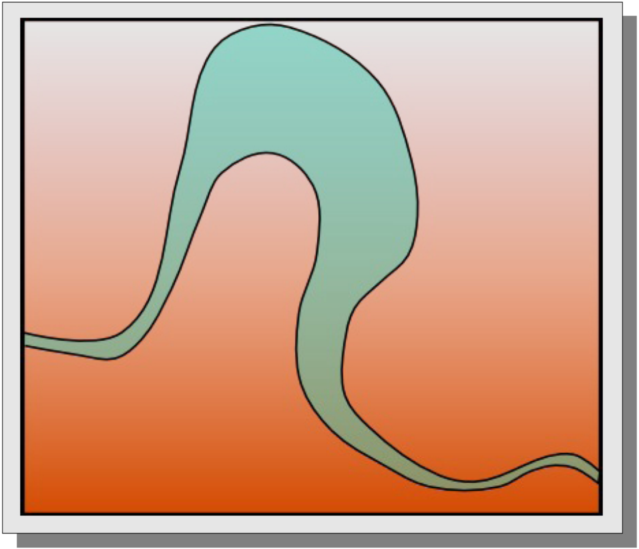
Adiabatic expansion and compression



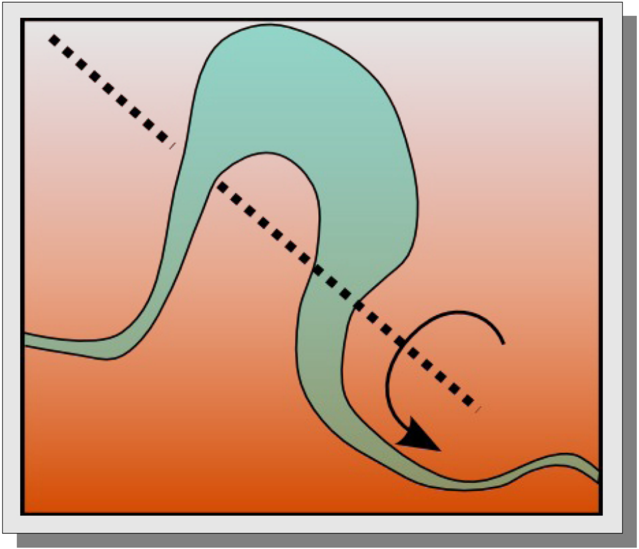
Cosmic ray streaming



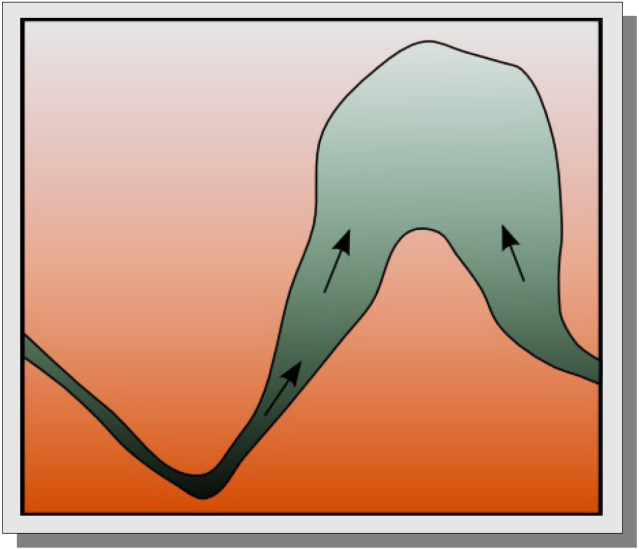
Expanded CRs



Turbulent pumping

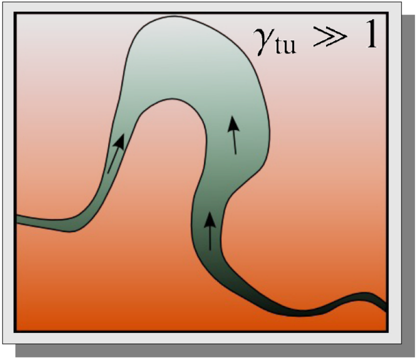


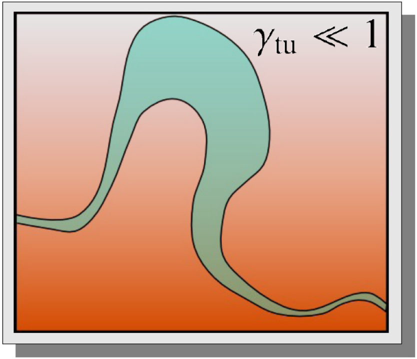
Turbulent pumping



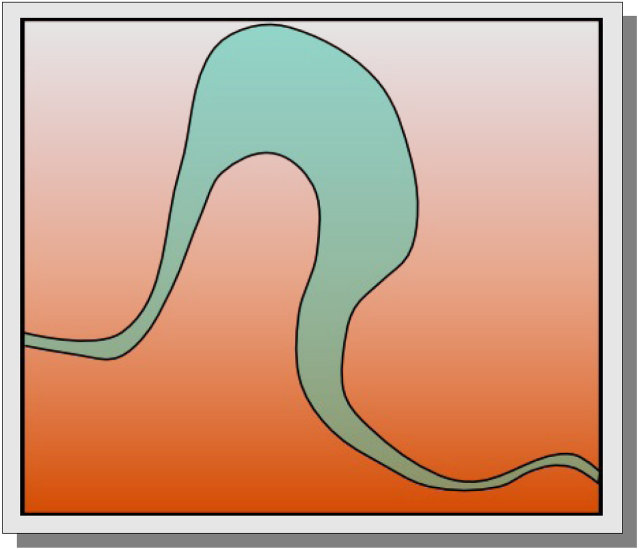
Turbulent-to-streaming ratio

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

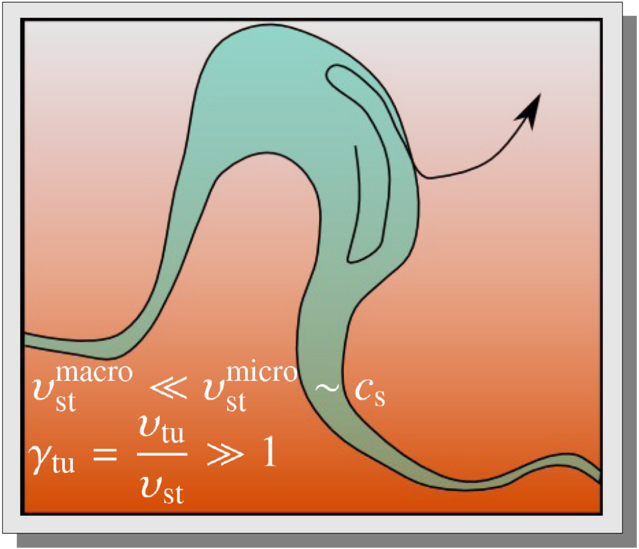




Are CRs confined to magnetic flux tubes?



Escape via diffusion: energy dependence



CR transport theory

CR continuity equation in the absence of sources and sinks:

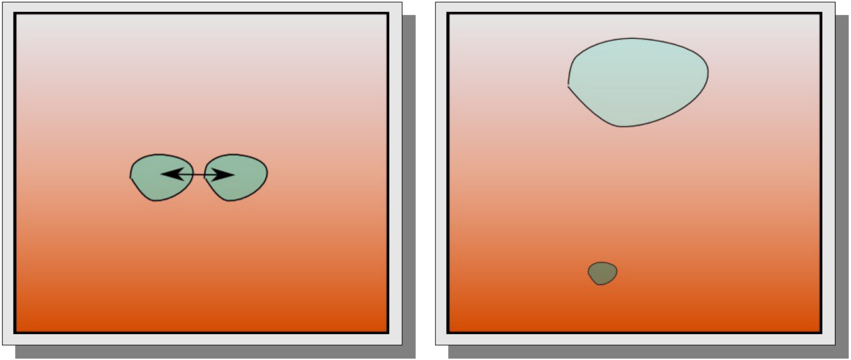
$$\frac{\partial \varrho}{\partial t} + \vec{\nabla} \cdot (\boldsymbol{\upsilon}\, \varrho) = 0 \qquad \boldsymbol{\upsilon} = \boldsymbol{\upsilon}_{\rm ad} + \boldsymbol{\upsilon}_{\rm di} + \boldsymbol{\upsilon}_{\rm st}$$

$$\begin{aligned}
\boldsymbol{\upsilon}_{\rm st} &= -\upsilon_{\rm st} \frac{\vec{\nabla}\,\varrho}{|\vec{\nabla}\,\varrho|} \\
\boldsymbol{\upsilon}_{\rm di} &= -\kappa_{\rm di} \frac{1}{\varrho} \vec{\nabla} \varrho \\
\boldsymbol{\upsilon}_{\rm ad} &= -\kappa_{\rm tu} \frac{\eta}{\varrho} \vec{\nabla} \frac{\varrho}{\eta}
\end{aligned} \qquad \kappa_{\rm tu} = \frac{L_{\rm tu}\, \upsilon_{\rm tu}}{3}$$

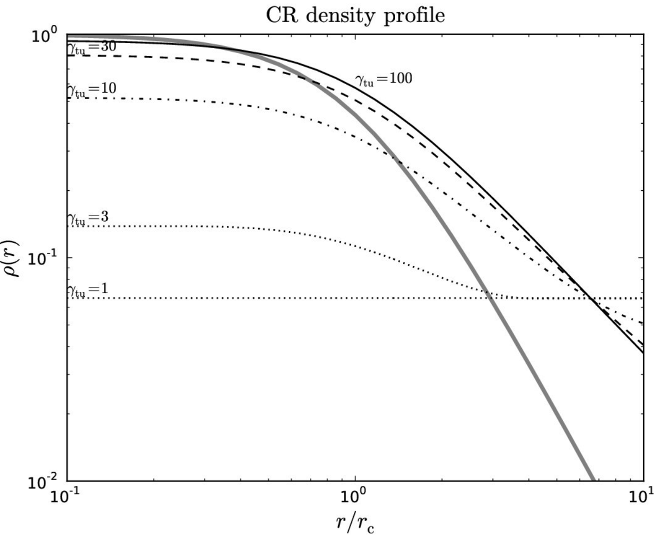
Enßlin, C.P., Miniati, Subramanian, 2011, A&A, 527, 99

CR profile due to advection

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



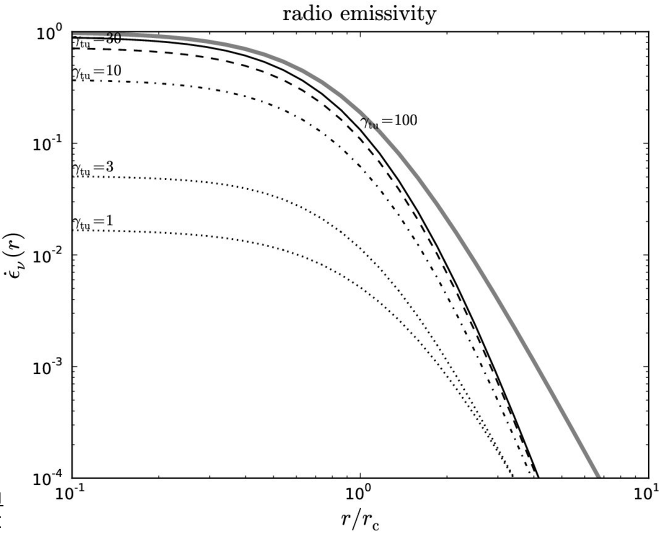
CR density profile



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

Radio emission profile

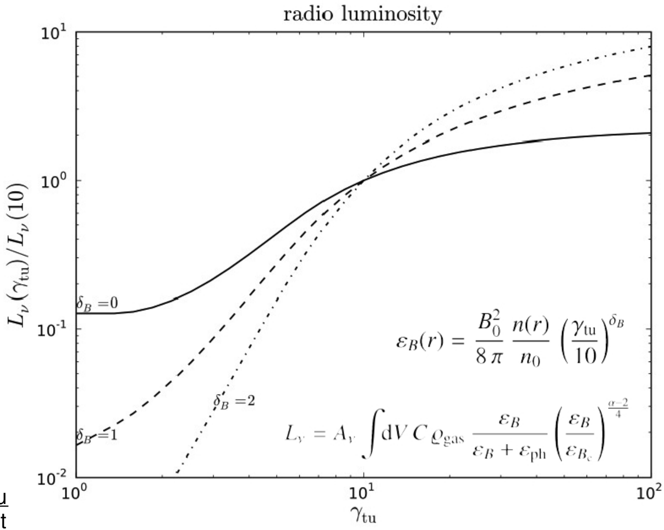
$p_{\mathrm{CR}} + p \rightarrow \pi^{\pm} \rightarrow e^{\pm} \rightarrow$ radio



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

Radio luminosity

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



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

Modeling radio halos (hadronic scenario)

phenomenological model setup:

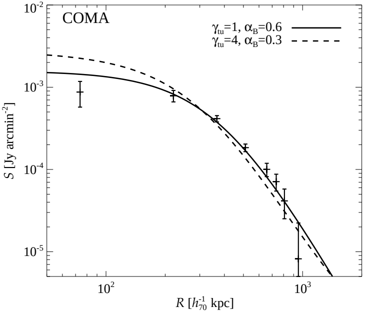
- cluster halos from large DM simulation (MultiDark)
- phenomenological gas model for cool core/non-cool core clusters (CC/NCC, calibrated to REXCESS X-ray observations)
- universal CR model from cosmological hydrodynamical simulations (Pinzke & C.P. 2010)
- parametrize magnetic field $B = B_0(n_{\text{th}}/n_{\text{th},0})^{\alpha_B}$
- parametrize CR transport by $\gamma_{\text{tu}} = \upsilon_{\text{tu}}/\upsilon_{\text{st}}$

$\rightarrow$ radio "quiet/loud" cluster populations for CC/NCC, respectively!

Zandanel, C.P., Prada, arXiv:1207.6410

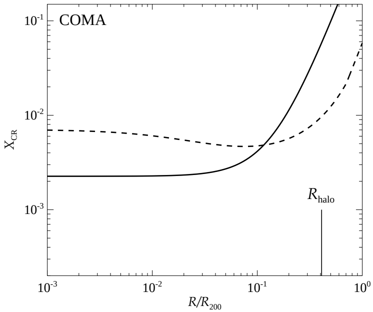
Giant radio halo in Coma

radio surface brightness:

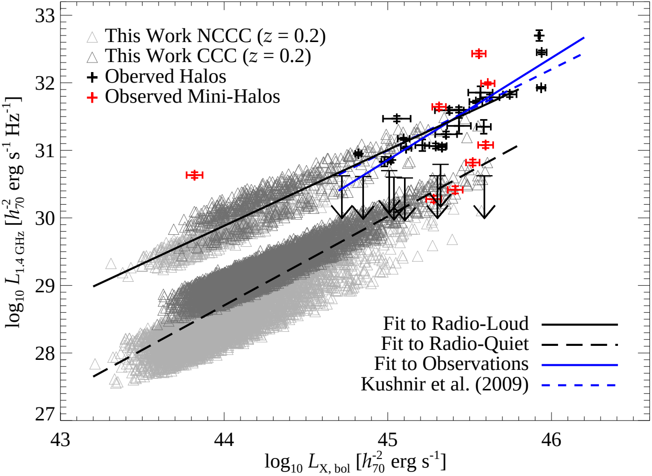


Zandanel, C.P., Prada (2012)

radial profile of $X_{\rm CR} = P_{\rm CR}/P_{\rm th}$:

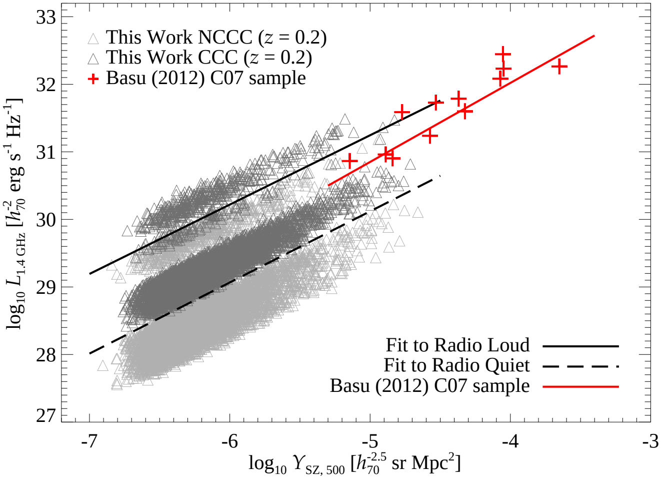


Radio luminosity - X-ray luminosity



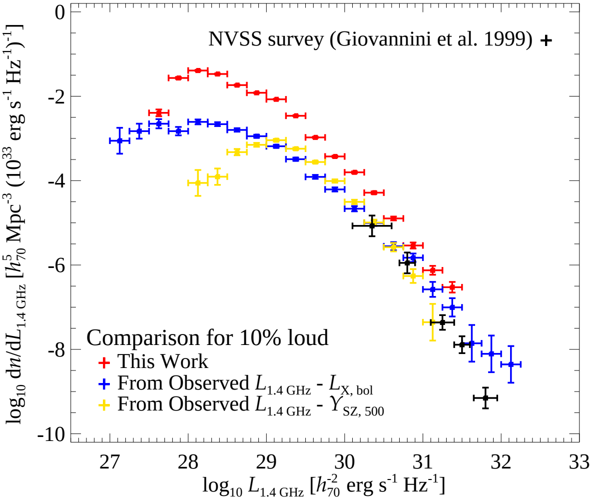
Zandanel, C.P., Prada (2012)

Radio luminosity - Sunyaev-Zel'dovich flux $Y(R_{\mathrm{LLS}})$



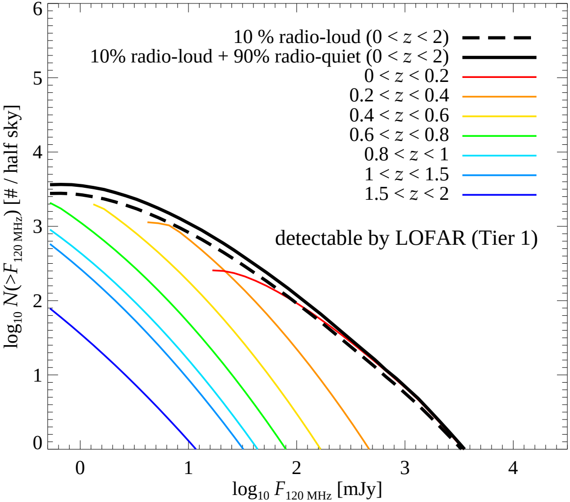
Zandanel, C.P., Prada (2012)

Radio halo luminosity function



Zandanel, C.P., Prada (2012)

Radio halo flux function for LOFAR (120 MHz)



Zandanel, C.P., Prada (2012)

Conclusions on radio halos

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

$\rightarrow$ bimodality of cluster radio halos at fixed L_{X}

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
- Zandanel, Pfrommer, Prada, submitted, arXiv:arXiv:1207.6410,
  On the physics of radio halos in galaxy clusters: scaling relations and luminosity functions
- Pinzke, Oh, Pfrommer, in prep.,
  Giant radio relics in galaxy clusters: re-acceleration of fossil relativistic electrons?

Modeling degeneracies for $\gamma_{\rm tu}$

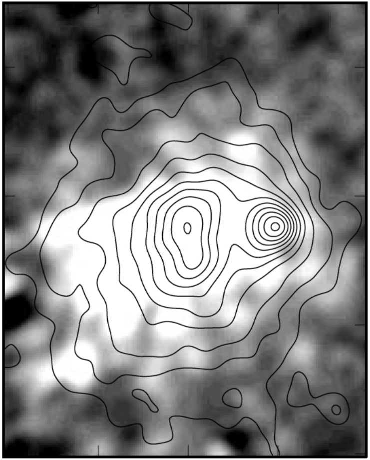
CR profiles are peaked when turbulent advection dominates CR transport ($\gamma_{\rm tu} = \upsilon_{\rm tu}/\upsilon_{\rm st} \gg 1$), but halo profiles can be flattened by the following processes (which biases the inferred $\gamma_{\rm tu}$ values low):

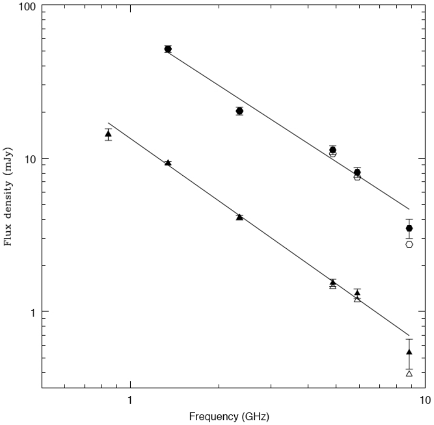
- contributions by (primary) relic emission or unresolved point sources in cluster outskirts
- non-sphericity in combination with a non-thermal clumping factor, $C_{\rm non-th}$, that is larger than its thermal analogue, $C_{\rm th}$:

$$C_{\rm non-th} = \left\langle \rho_{\rm gas}\rho_{\rm CR}\right\rangle / \left\langle \sqrt{\rho_{\rm gas}\rho_{\rm CR}}\right\rangle^2 ,$$
$$C_{\rm th} = \left\langle \rho_{\rm gas}^2\right\rangle / \left\langle \rho_{\rm gas}\right\rangle^2$$

- variations of spectral index caused by CR streaming
- CR profiles (for advection-dominated case) derive from radiative simulations that suffer from overcooling and may be too peaked

Radio halo and spectrum in the Bullet cluster





Liang et al. (2000): SZ-corrected