Cosmic ray transport in galaxy clusters: implications for radio halos

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in collaboration with

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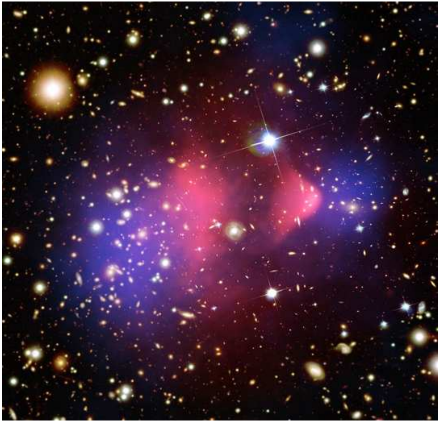
Nov 17, 2010 / Non-thermal phenomena in clusters, Nice

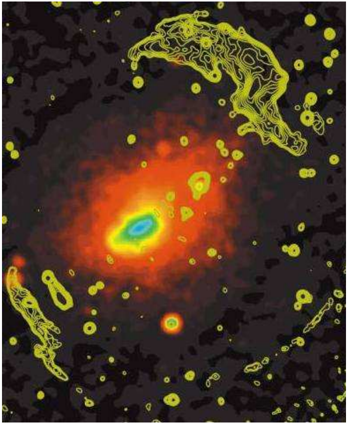
Outline

Shocks in galaxy clusters



1E 0657-56 (“Bullet cluster”)

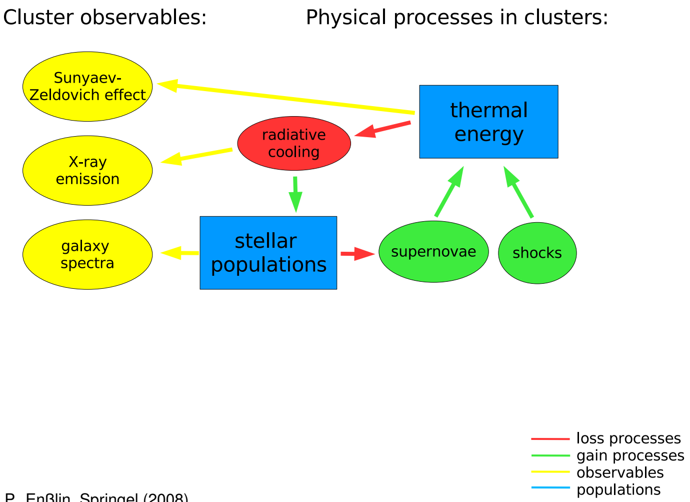
(X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)



Abell 3667

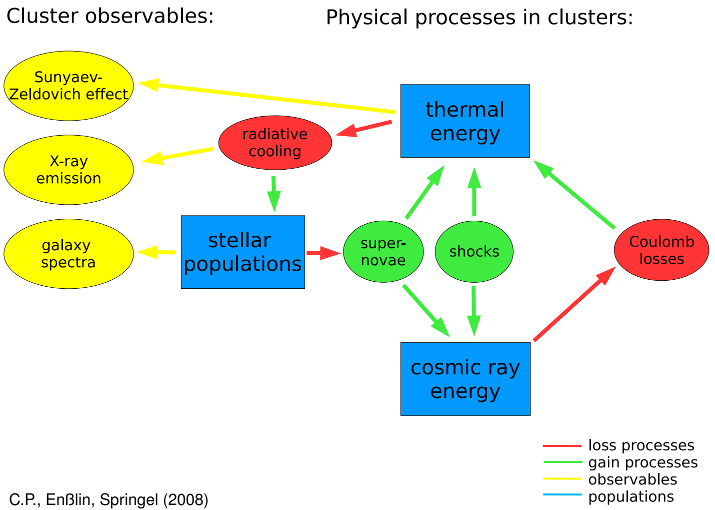
(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)

Radiative simulations – flowchart



C.P., Enßlin, Springel (2008)

Radiative simulations with CR physics



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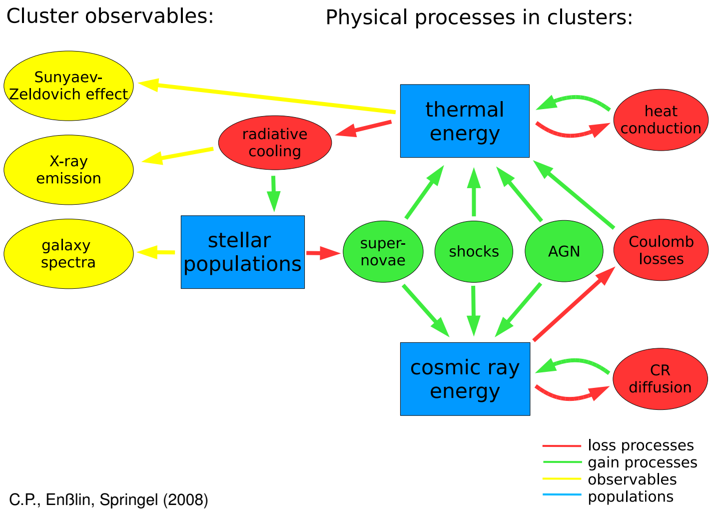
Radiative simulations with extended CR physics



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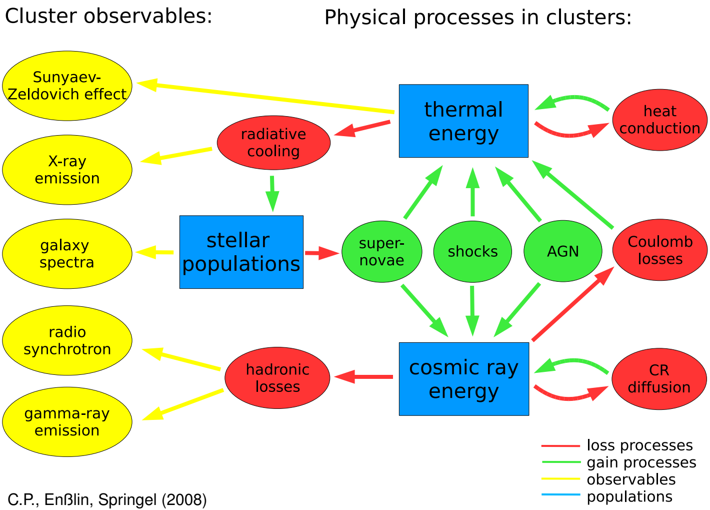
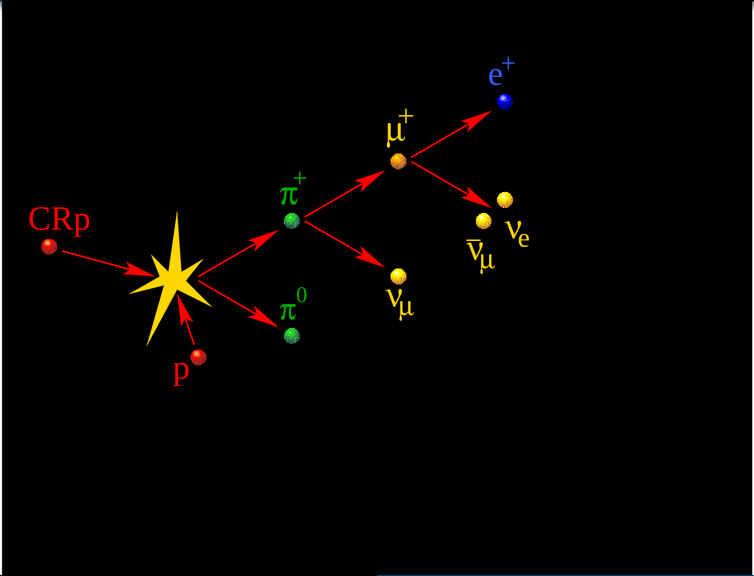


C.P., Enßlin, Springel (2008)

Hadronic cosmic ray proton interaction



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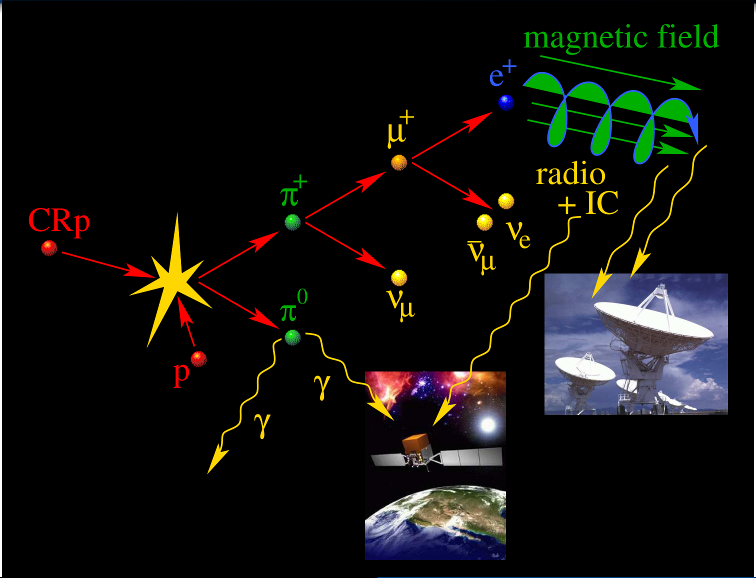
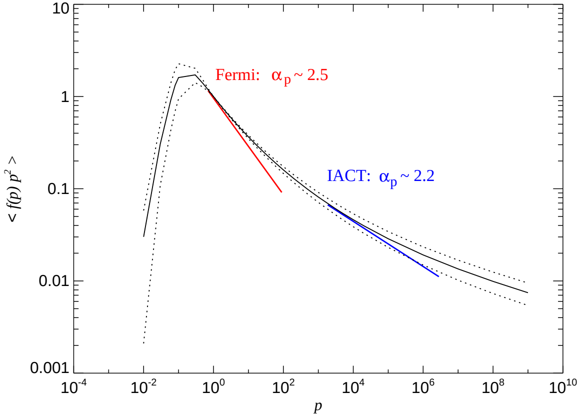
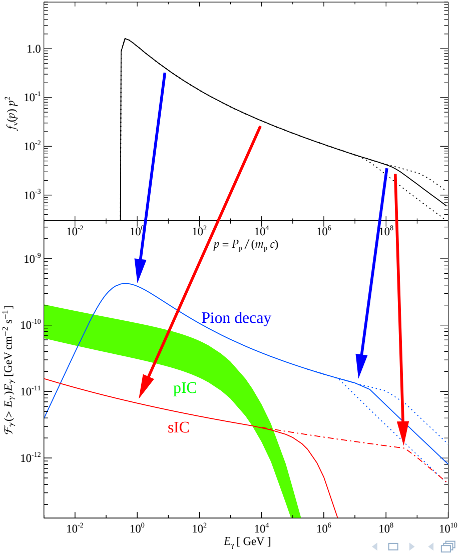


Universal CR spectrum in clusters (Pinzke & CP 2010)

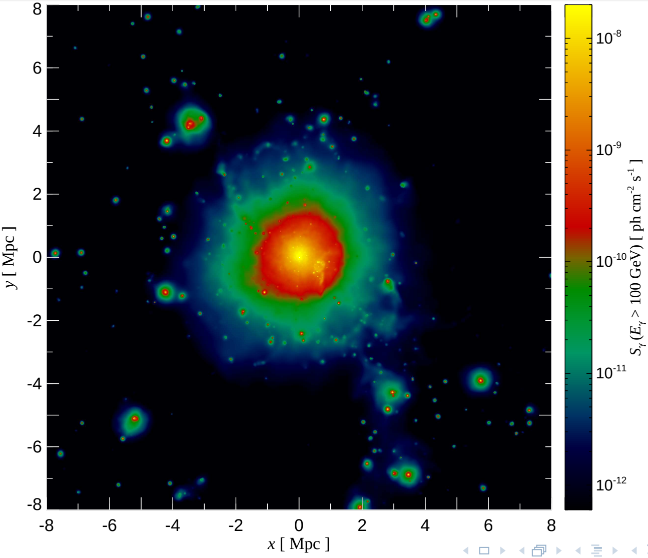


Normalized CR spectrum shows universal concave shape → governed by hierarchical structure formation and the implied distribution of Mach numbers that a fluid element had to pass through in cosmic history.

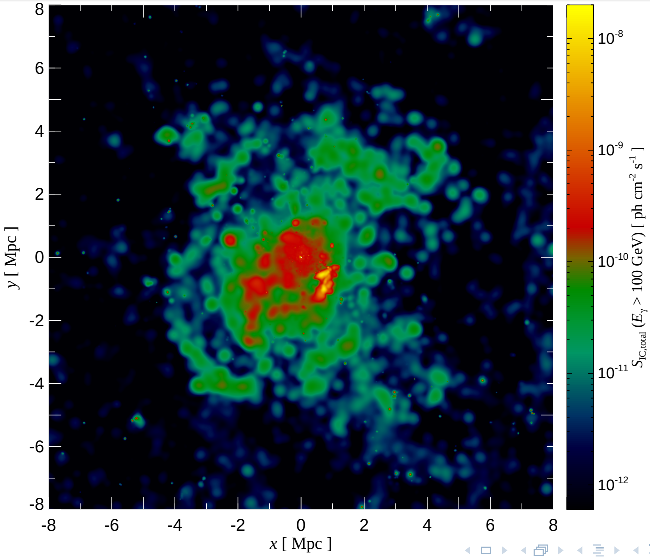
CR proton and γ-ray spectrum (Pinzke & CP 2010)



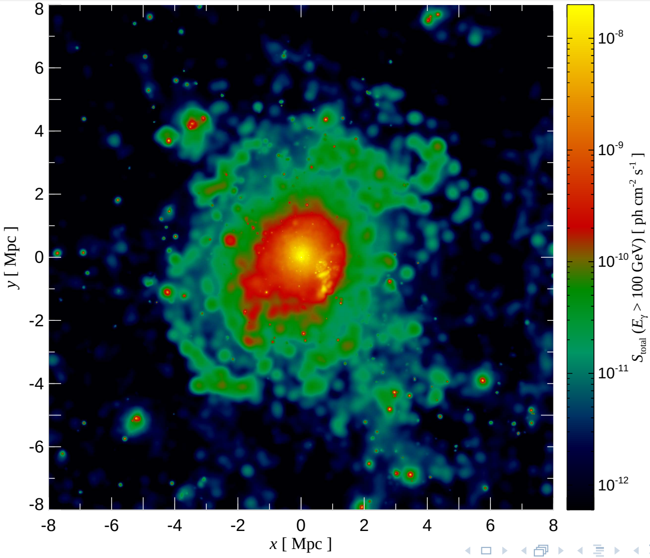
Hadronic γ-ray emission, $E_\gamma > 100$ GeV



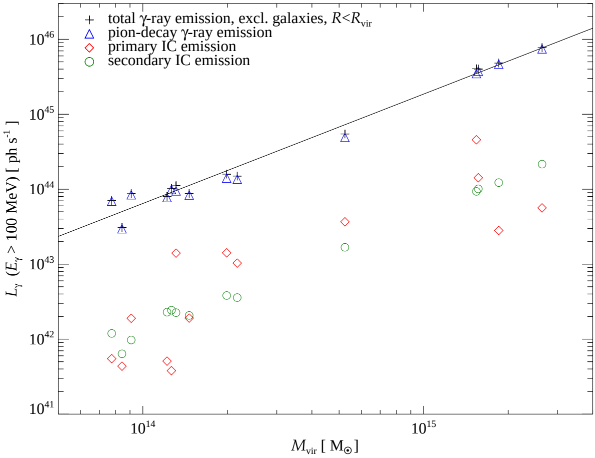
Inverse Compton emission, $E_{\mathrm{IC}} > 100$ GeV



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

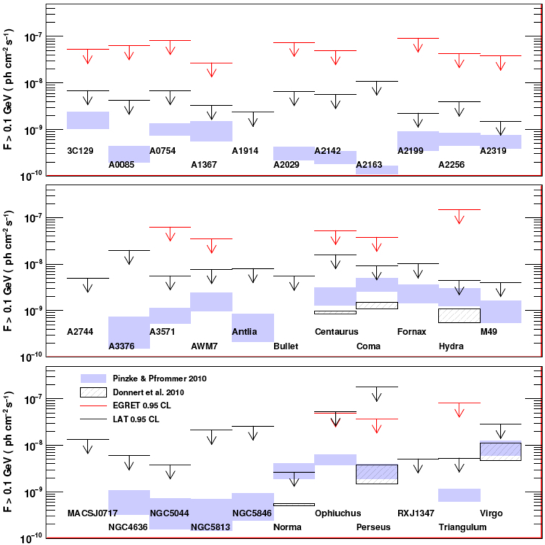


Gamma-ray scaling relations

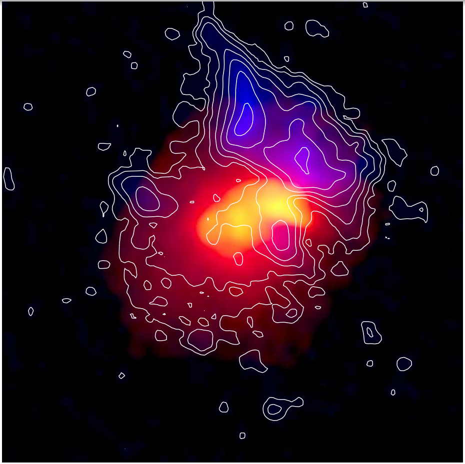


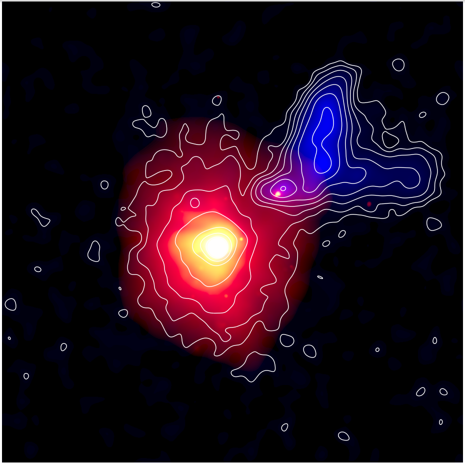
Scaling relation + complete sample of the brightest X-ray clusters (HIFLUGCS) → predictions for *Fermi* and *IACT's*

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



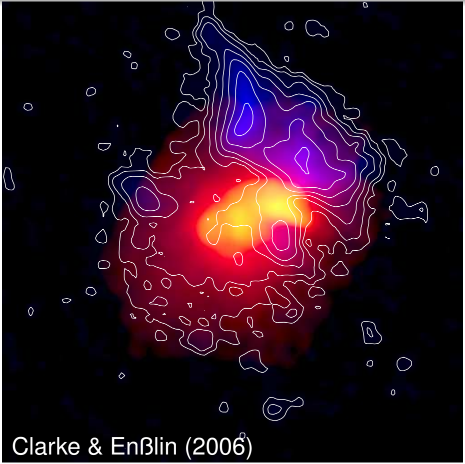
Which one is the simulation/observation of A2256?

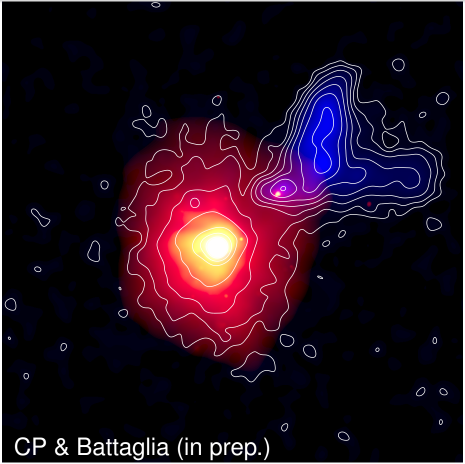




red/yellow: thermal X-ray emission,
blue/contours: 1.4 GHz radio emission with giant radio halo and relic

Observation – simulation of A2256





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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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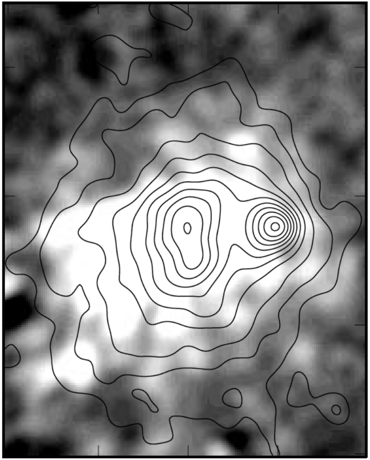
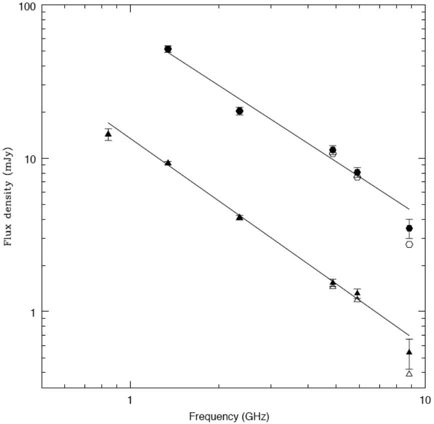
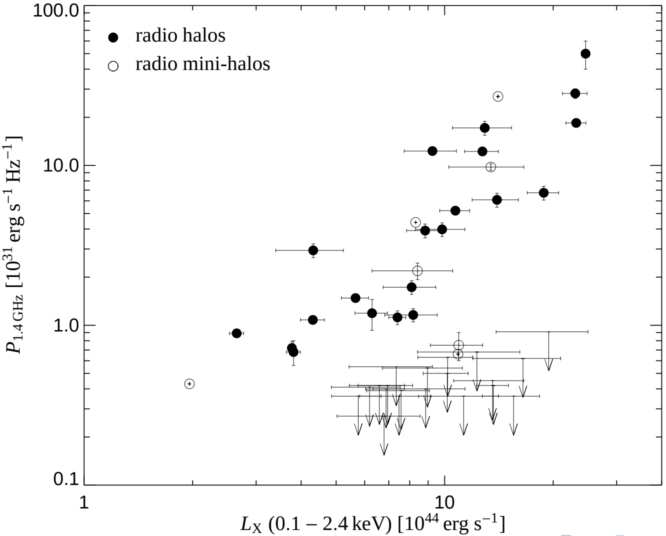
Radio halo and spectrum in the Bullet cluster





Liang et al. (2000): SZ-corrected

Radio luminosity - X-ray luminosity



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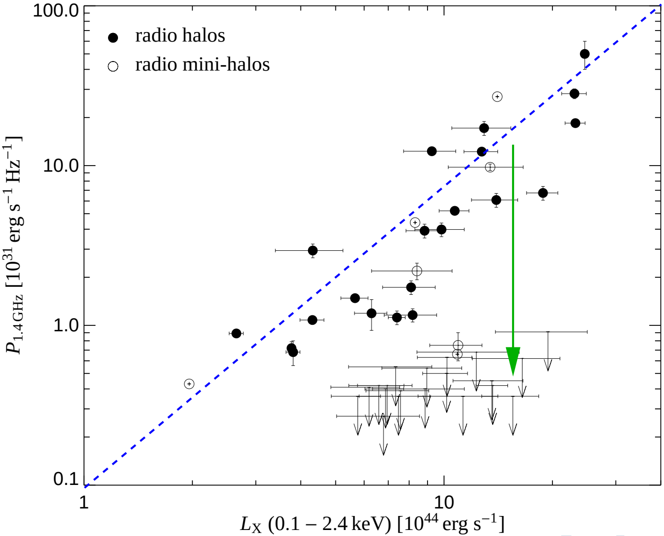

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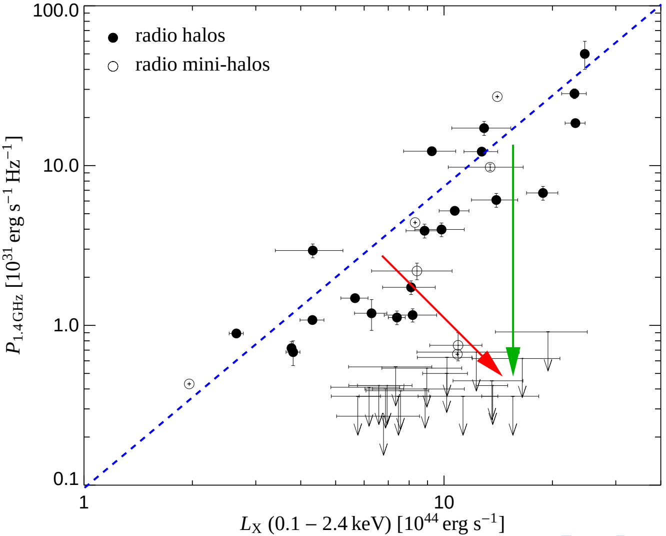
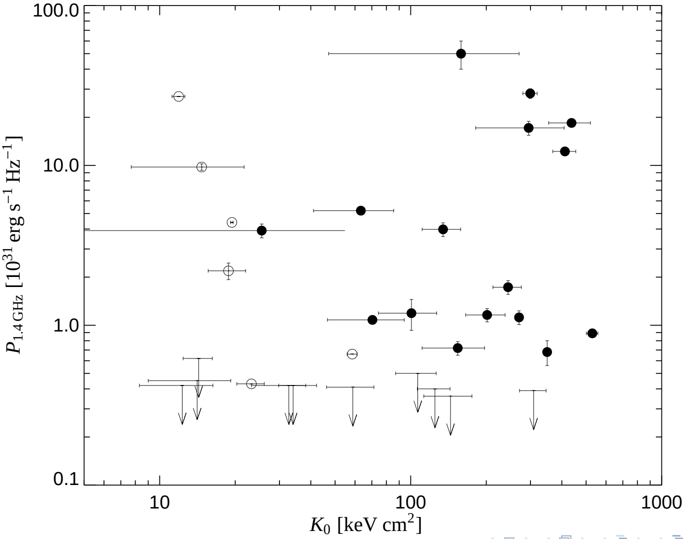


Radio luminosity - central entropy



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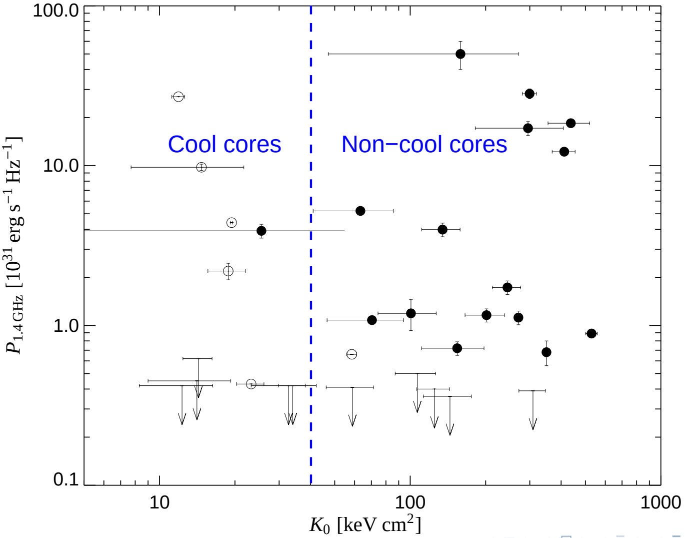

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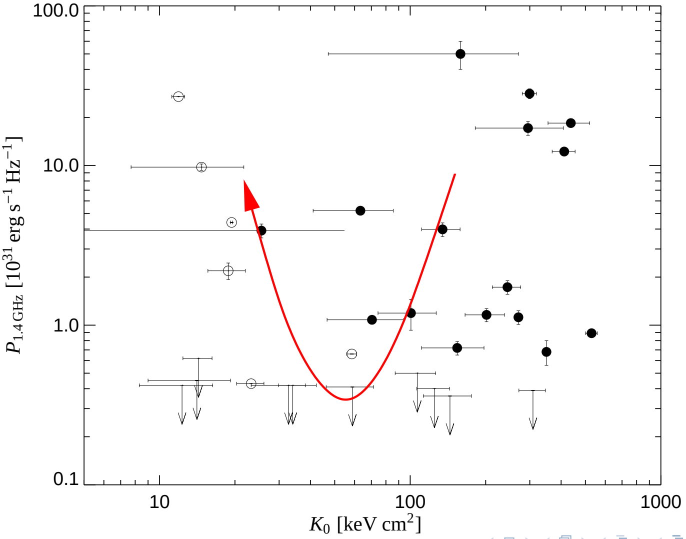

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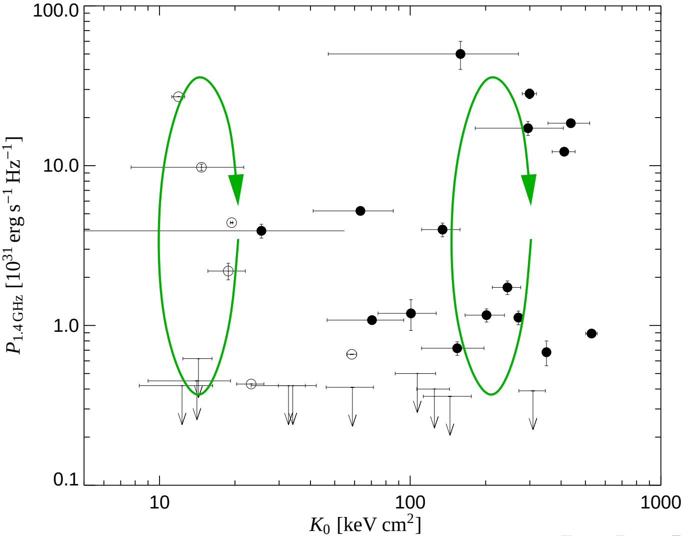
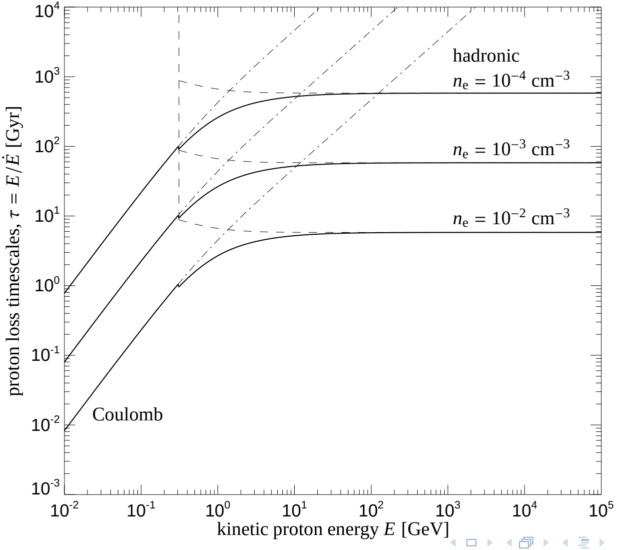


Proton cooling times



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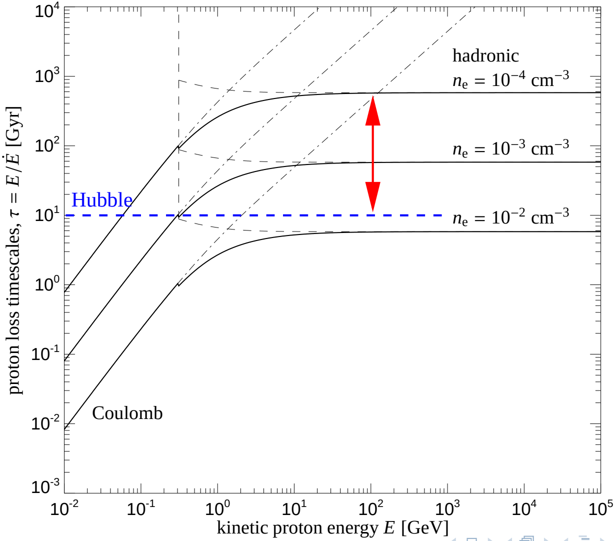

Radio halo theory – (ii) re-acceleration model

strength:

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  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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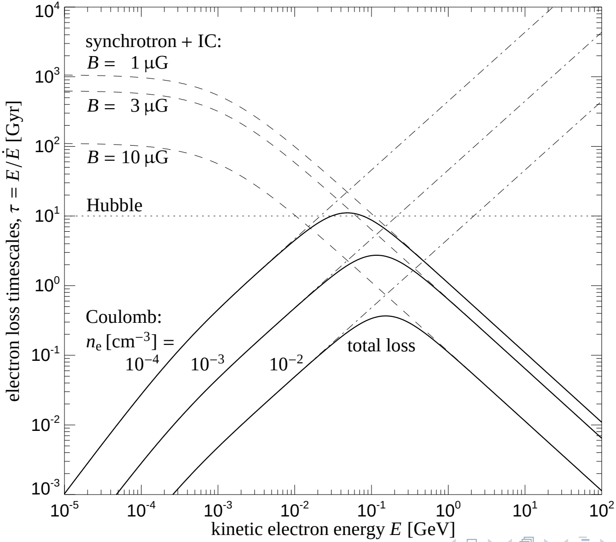
Electron cooling times



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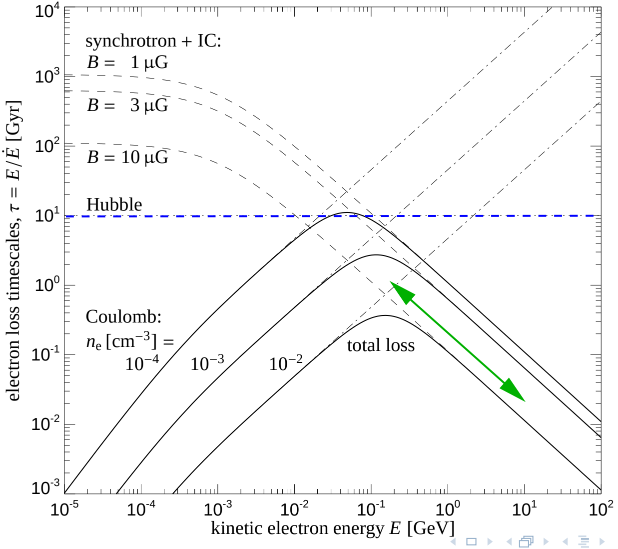

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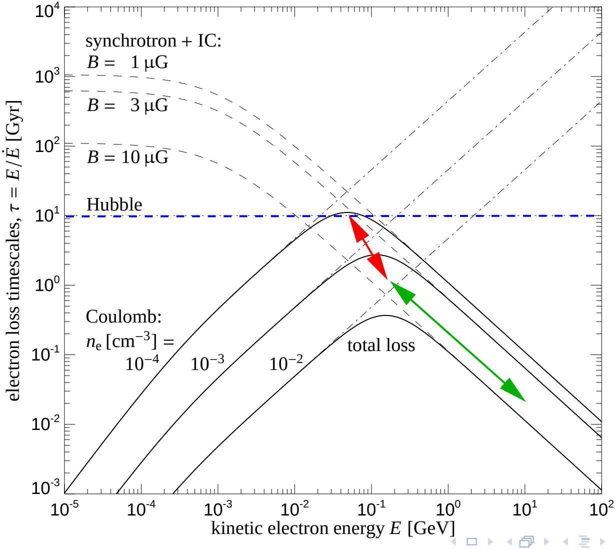

Fermi II acceleration is inefficient

- diffusion equation for wave energy $\mathcal{W}_k$ (Brunetti & Lazarian 2007)

$$\frac{\partial \mathcal{W}_k}{\partial t} = \frac{\partial}{\partial k}\left[k^2 D_{kk} \frac{\partial}{\partial k}\left(\frac{\mathcal{W}_k}{k^2}\right)\right] - \sum_i \Gamma_i(k)\mathcal{W}_k + I(k)$$

- stationary turbulent spectrum (inertial range: $\Gamma_i \sim 0$):

$\mathcal{W}_k\big|_{\text{closed box}} \propto k^{-3/2} \rightarrow$ re-acceleration of CRs $\rightarrow$ radio halo

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- stationary turbulent spectrum (inertial range: $\Gamma_i \sim 0$):

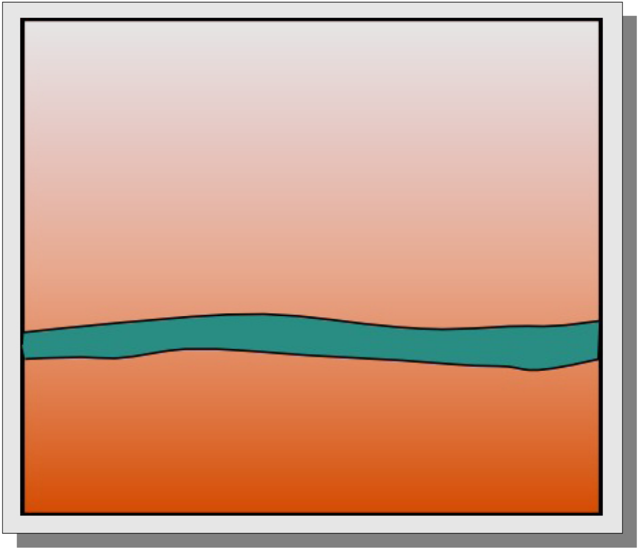
$$\mathcal{W}_k\big|_{\text{closed box}} \propto k^{-3/2} \rightarrow \text{re-acceleration of CRs} \rightarrow \text{radio halo}$$

- radio luminosity dominated by core & cores are leaky boxes:

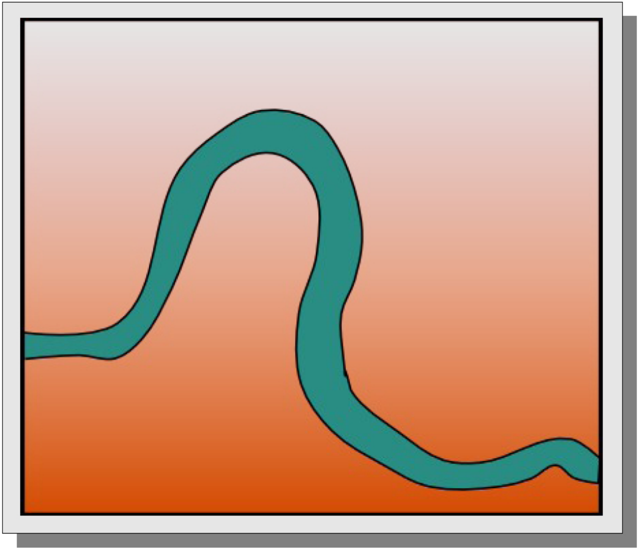
  $\rightarrow$ sound waves carry energy to cluster periphery, steepen to shocks and dissipate

  $\rightarrow$ much less energy available for re-acceleration!

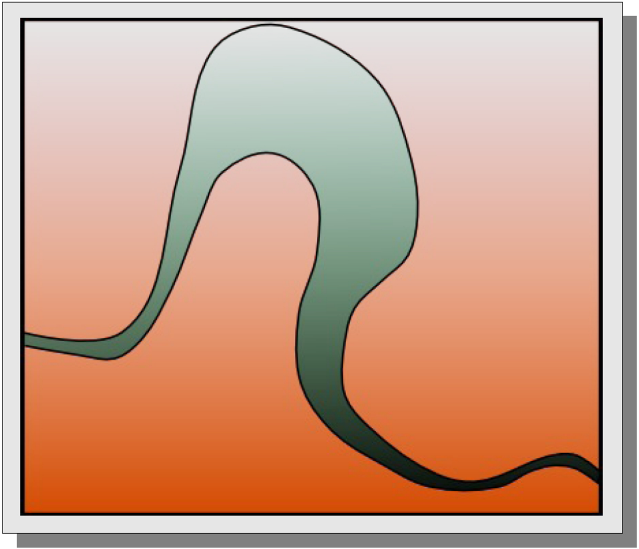
Cosmic ray transport – magnetic flux tube with CRs



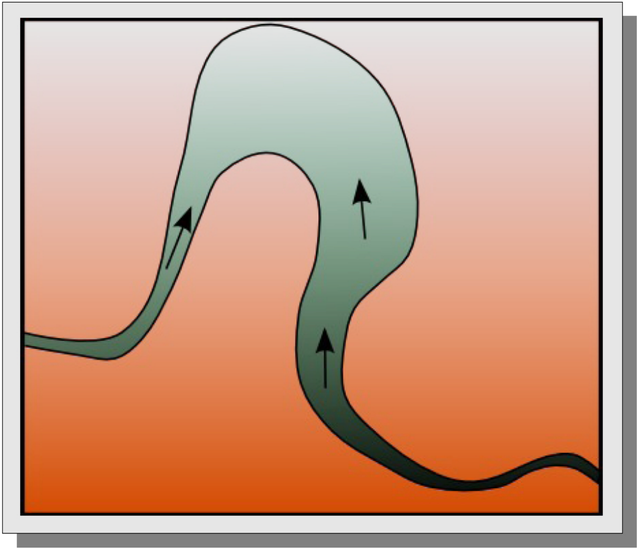
Cosmic ray advection



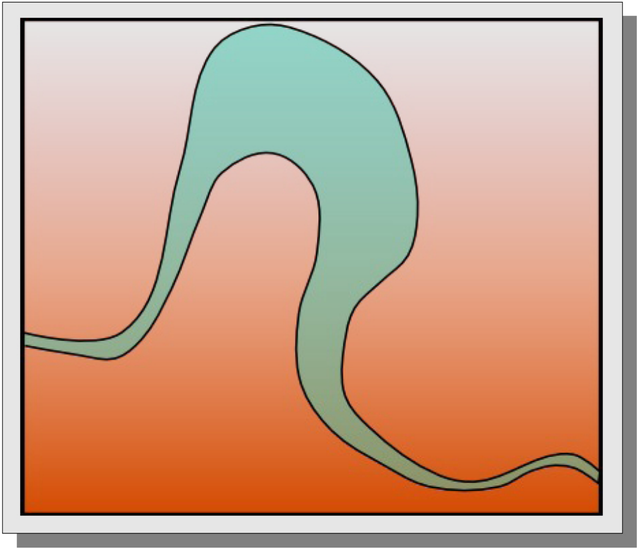
Adiabatic expansion and compression



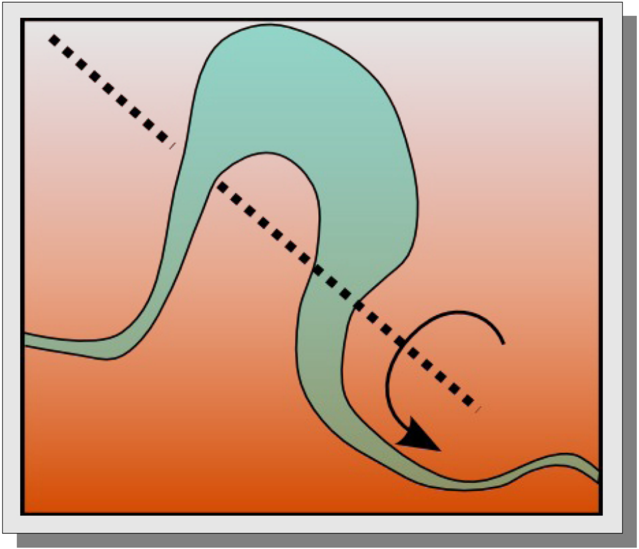
Cosmic ray streaming



Expanded CRs



Turbulent pumping



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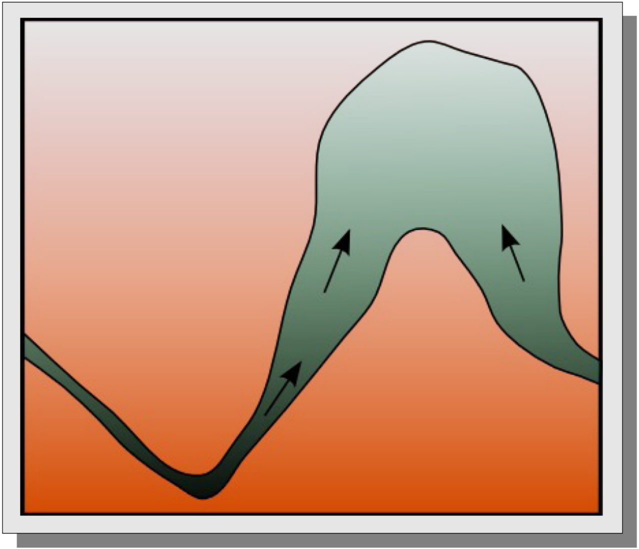
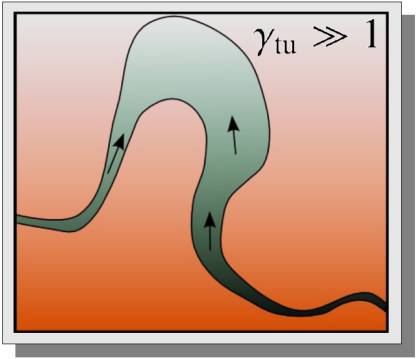
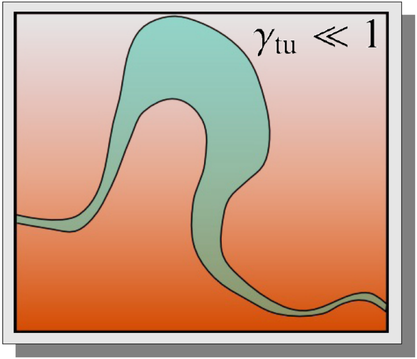


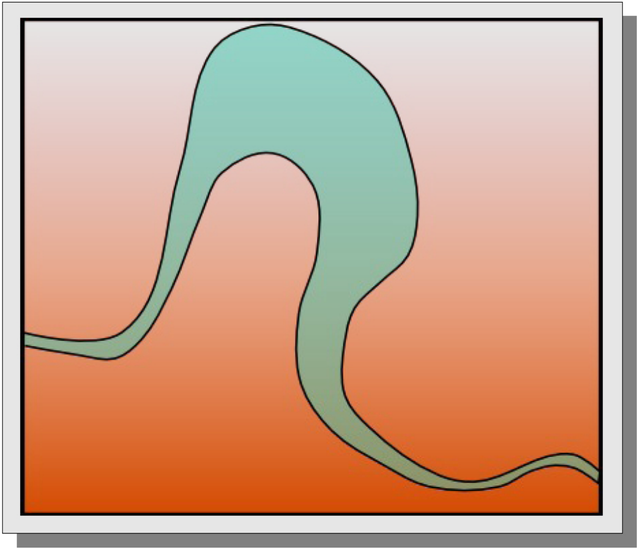
Turbulent-to-streaming ratio

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

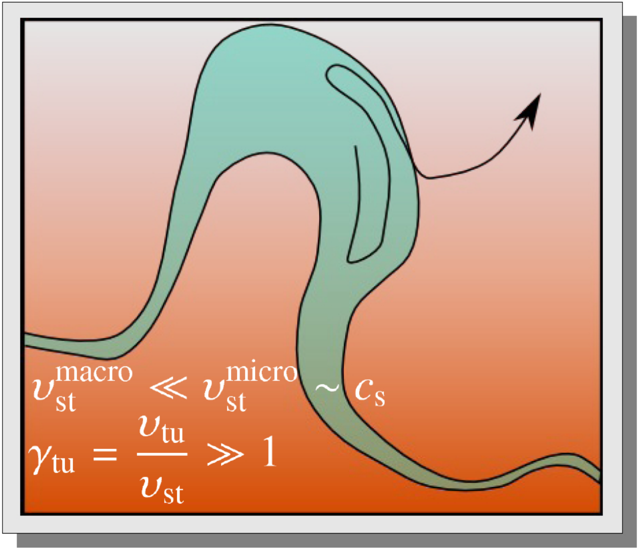




Are CRs confined to magnetic flux tubes?



Escape via diffusion: energy dependence



CR transport theory

CR continuity equation in the absence of sources and sinks:

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

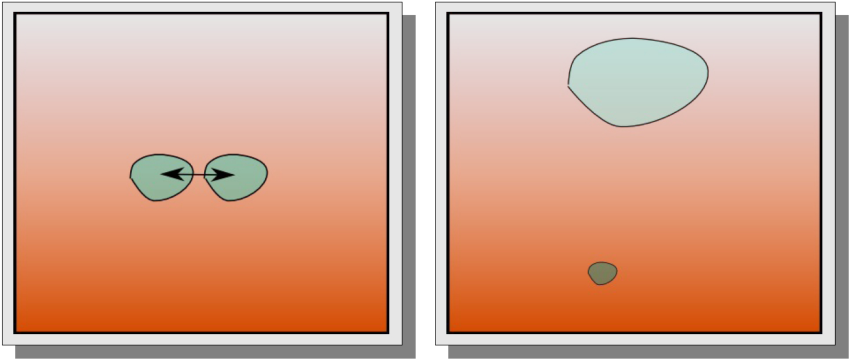
$$\boldsymbol{\upsilon} = \boldsymbol{\upsilon}_{\rm ad} + \boldsymbol{\upsilon}_{\rm di} + \boldsymbol{\upsilon}_{\rm st}$$

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

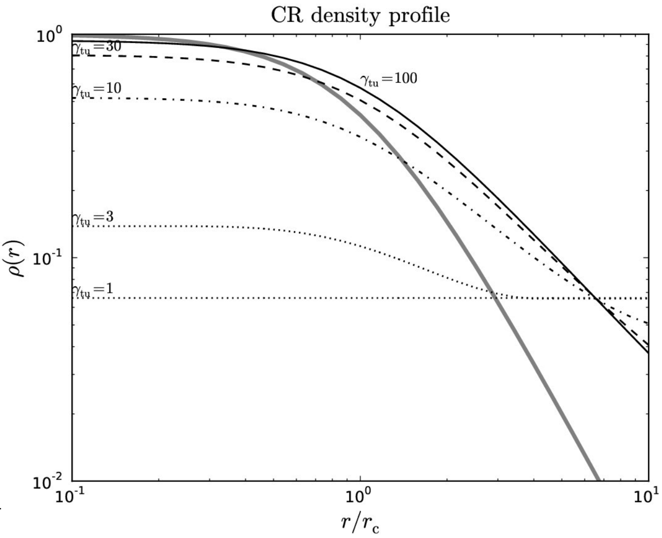
$$\kappa_{\rm tu} = \frac{L_{\rm tu}\, \upsilon_{\rm tu}}{3}$$

CR profile due to advection

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

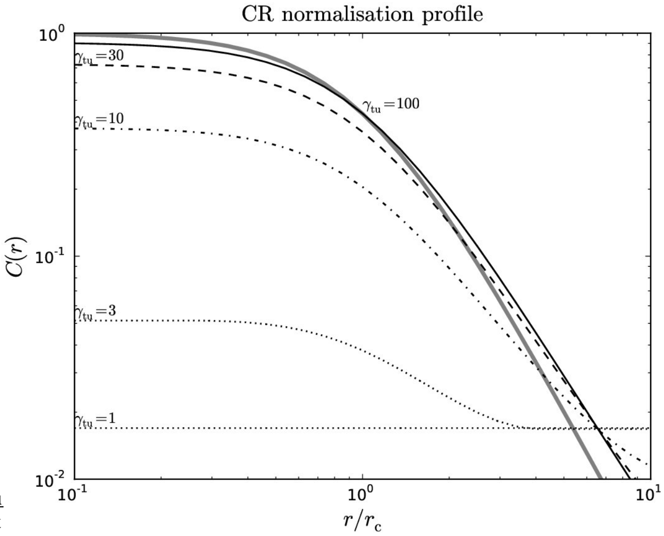


CR density profile



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

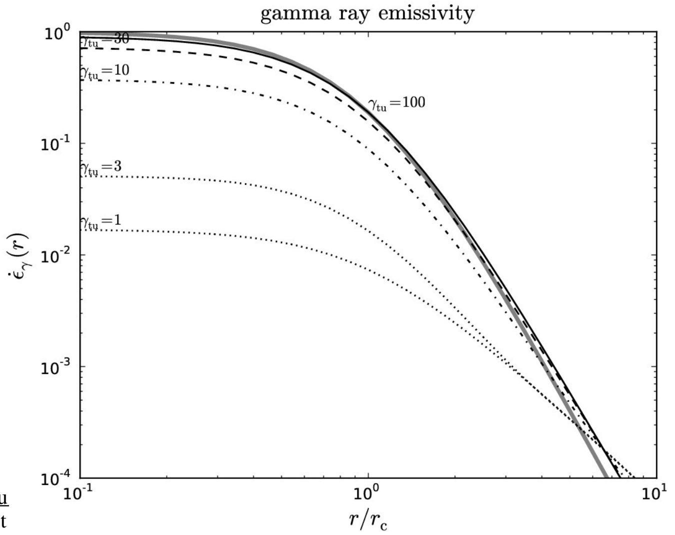
CR density at fixed particle energy



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

Gamma-ray emission profile

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



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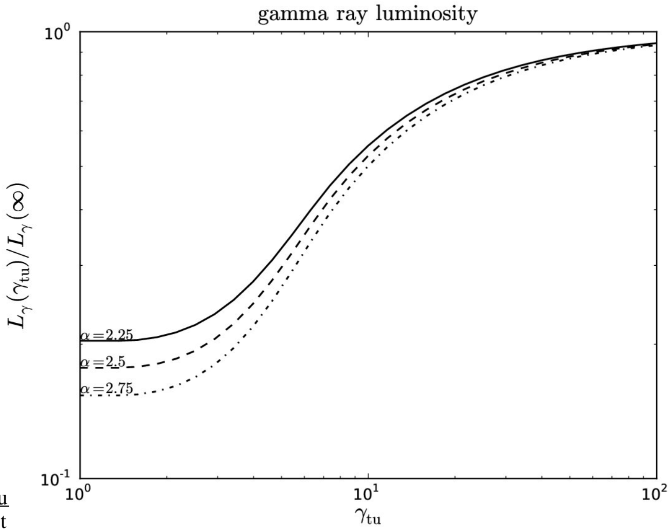
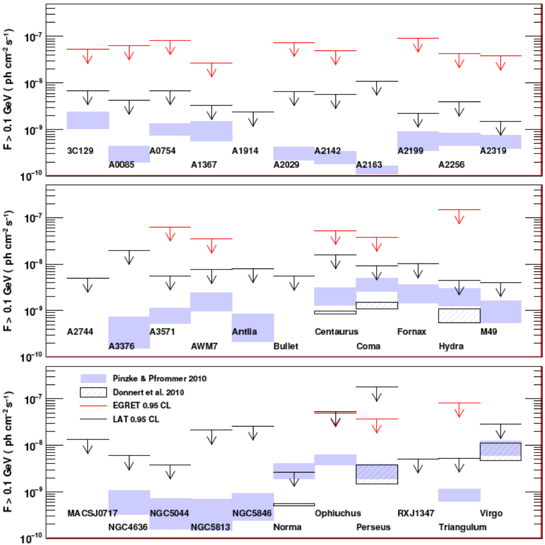
Gamma-ray luminosity

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



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

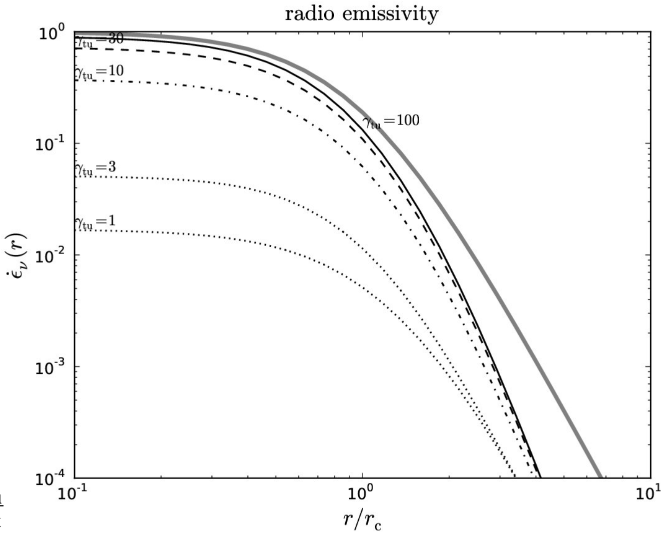
γ-ray limits and hadronic predictions (Ackermann et al. 2010)



HITS

Radio emission profile

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



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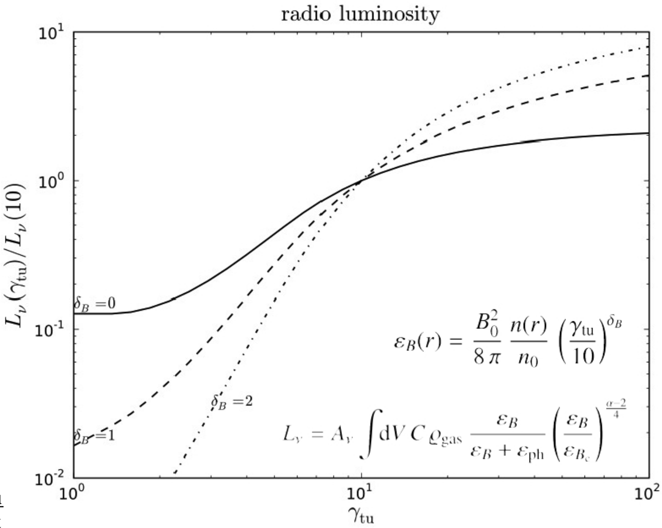
Radio luminosity

$p_{\rm CR} + p \rightarrow \pi^{\pm} \rightarrow e^{\pm} \rightarrow$ 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 $v_{\mathrm{st}}^{\mathrm{macro}}$ $\rightarrow$ 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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  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 $v_{\mathrm{st}}^{\mathrm{macro}}$ $\rightarrow$ CR & radio spectral variations
  $\rightarrow$ outstreaming CR: dying halo $\leftarrow$ decaying turbulence

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

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
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