The Physics of Galaxy Clusters
15th Lecture

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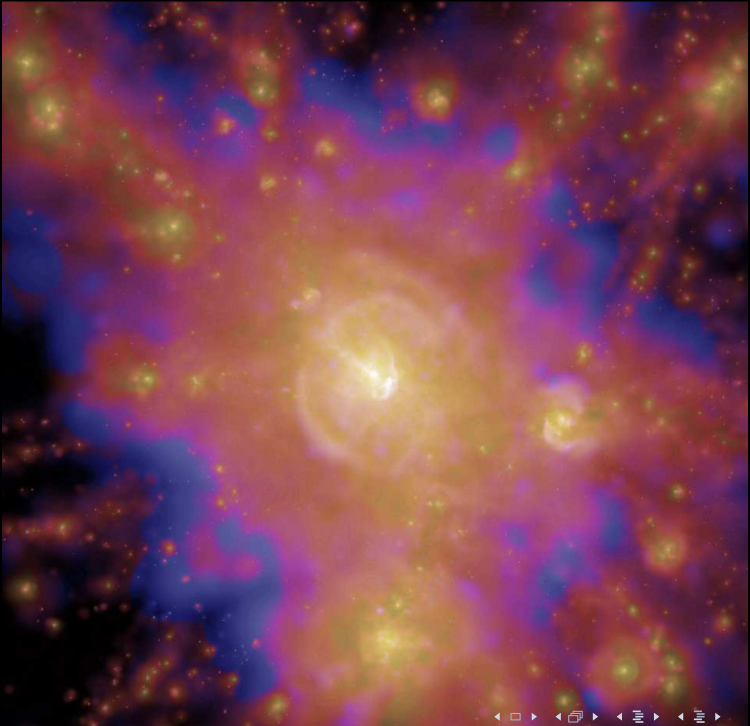
Lectures in the International Astrophysics Masters Program at Potsdam University

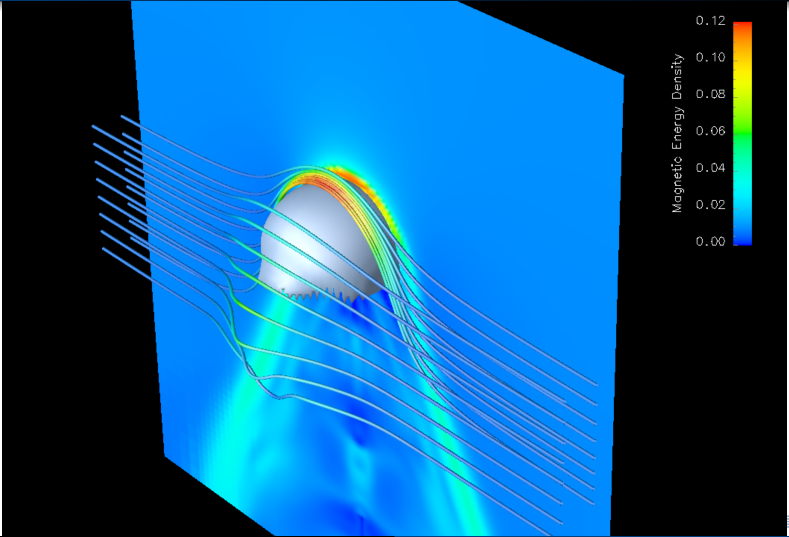


Outline

1. Magnetic draping
   - Physics
   - Analytics
   - Simulations
2. Cluster radio emission
   - Shocks and radiative processes
   - Radio relic phenomena
   - Radio halos
3. Galaxy cluster cosmology

What is magnetic draping?

Interaction of an obstacle (Earth, star, galaxy, . . .) with a magnetized plasma



What is magnetic draping?

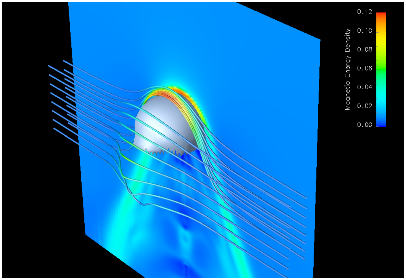
Interaction of a moving object (star, galaxy, . . .) with a magnetized plasma

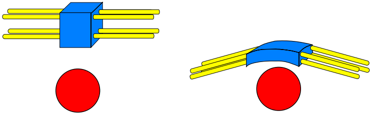
Consider the rest frame of the object:

- magnetic flux is frozen into the plasma that is advected onto the object
- competition between "plowing up" and slipping around of field lines set field strength in draping layer:

$$\frac{B^2}{8\pi} = \alpha \rho_0 v^2$$

- magnetic pressure pushes field lines around the object
- magnetic tension and inertia of the flux-frozen magnetic field that is anchored and advected with the ambient plasma slow down object





Thickness of the draping sheath - analytics

Energy density of magnetic draping sheath balances ram pressure:

$$\begin{aligned}
B &= \frac{B_0}{\sqrt{1-\frac{R^3}{(R+s)^3}}} \approx \sqrt{\frac{R}{3s}}B_0 + \mathcal{O}\left(\sqrt{\frac{s}{R}}\right)\\
P_B &= \frac{B^2}{8\pi} = P_{B_0}\frac{R}{3s} = \alpha\rho_0 v^2\\
\mathcal{M}_\mathrm{A}^2 &= \frac{v^2}{v_A^2} = \frac{\rho_0 v^2}{2P_{B_0}} = \frac{1}{2}\beta\gamma\mathcal{M}^2\\
l_\mathrm{drape} &\equiv s = \frac{R}{6\alpha\mathcal{M}_\mathrm{A}^2} = \frac{R}{3\alpha\beta\gamma\mathcal{M}^2} \sim 100\,\mathrm{pc},
\end{aligned}$$

for $R \simeq 30$ kpc, $\beta = P_\mathrm{th}/P_B \simeq 50$, and a trans-sonic flow, $\mathcal{M}^2 \simeq 1/\gamma$.

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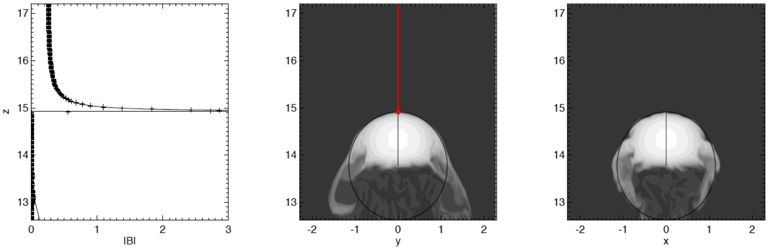
Thickness of the draping sheath – simulations



amplified draping field $B = \frac{1}{\sqrt{1-\frac{R^3}{r^3}}} B_0, \quad l_{\rm drape} \simeq \frac{R}{6\alpha\mathcal{M}_{\rm A}^2}$ with $\alpha \simeq 2$;

left: fitting peak position and a fall-off radius of the theory prediction; *right:* density cut-planes; circle shows radius and position given by the fit to the magnetic field structure, left;

$\rightarrow$ astonishing agreement of curvature radius at the working surface with potential flow predictions!

Magnetic energy of the draping layer

- in the draping layer, $\varepsilon_B \simeq \alpha\rho v^2$, is solely given by the ram pressure and *completely* independent of $\varepsilon_{\rm icm}$
- assume sphere with radius R and volume $V_{\rm sph}$, constant thickness of the drape $l_{\rm drape}$ over an area $A = 2\pi R^2$:

$$\begin{aligned} E_{B,\,\rm drape} &= \frac{B_{\rm drape}^2}{8\pi} A\, l_{\rm drape} = \frac{B_{\rm drape}^2}{8\pi} \frac{A\, R}{6\alpha\, \mathcal{M}_A^2} \\ &= \alpha\rho v_{\rm gal}^2 \frac{A\, R}{6\alpha} \frac{B_{\rm icm}^2}{4\pi\, \rho v_{\rm gal}^2} = \frac{1}{2}\, \varepsilon_{B,\,\rm icm}\, V_{\rm sph} = \frac{1}{2}\, E_{B,\,\rm icm} \end{aligned}$$

$\rightarrow$ “Archimedes principle of magnetic draping”

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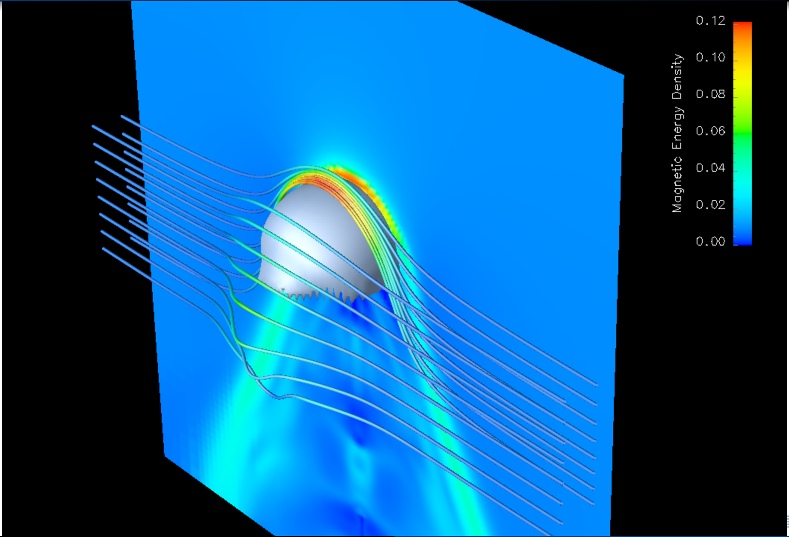

Energetics of cluster mergers

- ***Galaxy cluster mergers*** dissipate a gravitational binding energy of

$$E_{\mathrm{pot}} \simeq \frac{3}{5}\,\frac{GM_{\mathrm{cl}}^2}{r_{\mathrm{cl}}} \simeq 2.6 \times 10^{64}\,\mathrm{erg}\left(\frac{M_{\mathrm{cl}}}{10^{15}\,\mathrm{M}_\odot}\right)^2\left(\frac{r_{\mathrm{cl}}}{2\,\mathrm{Mpc}}\right)^{-1}$$

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$$E_{\text{pot}} \simeq \frac{3}{5}\,\frac{GM_\star^2}{r_\star} \simeq 2.4\times10^{53}\ \text{erg}\left(\frac{M_\star}{1.5\,\text{M}_\odot}\right)^2\left(\frac{r_\star}{15\ \text{km}}\right)^{-1}$$

of which most is radiated in neutrinos and only $\sim 10^{51}$ erg is available as kinetic energy to drive the shock into the ISM

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  $\Rightarrow$ ***cluster mergers are the most energetic events*** (after the Big Bang)

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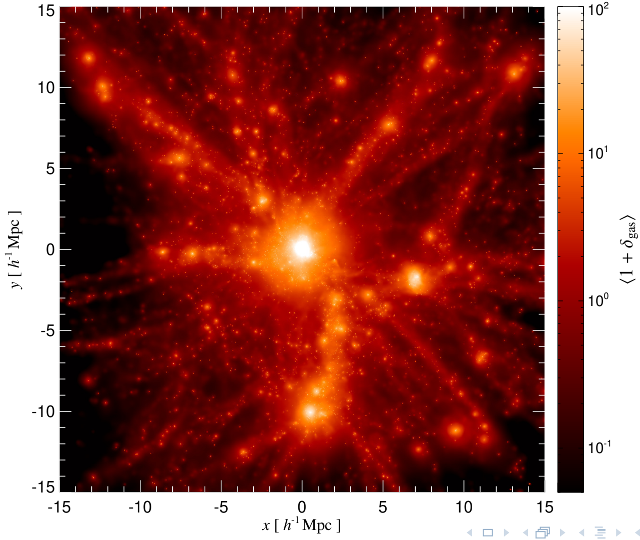
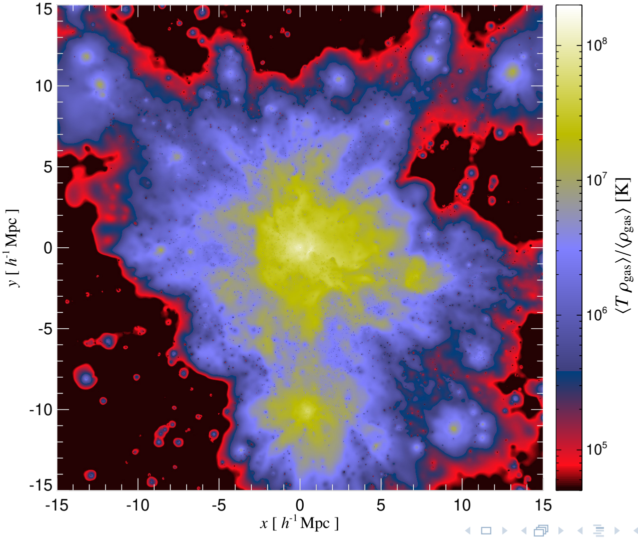
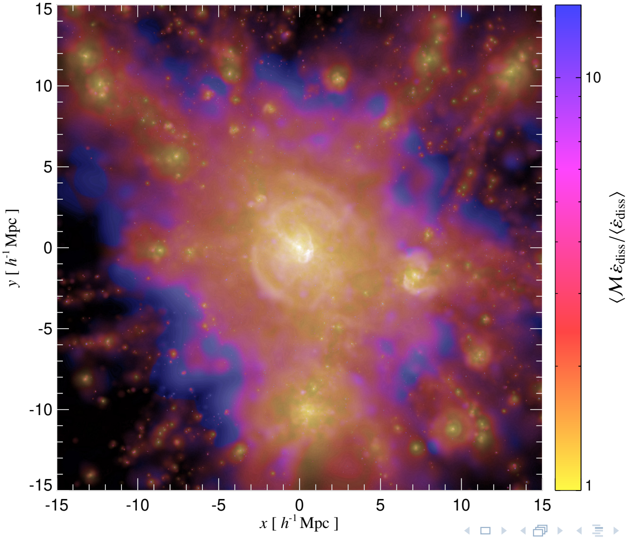
Cosmological cluster simulation: gas density



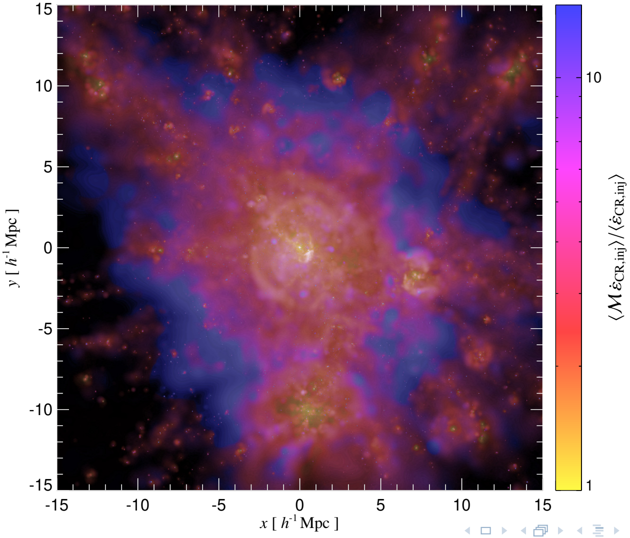
Mass weighted temperature



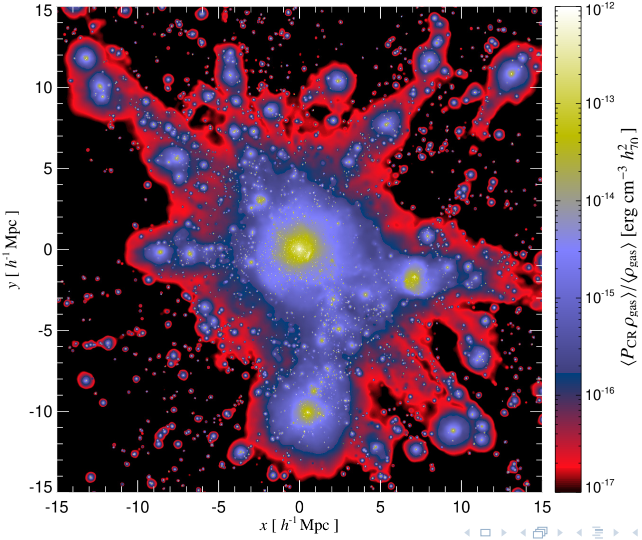
Shock strengths weighted by dissipated energy



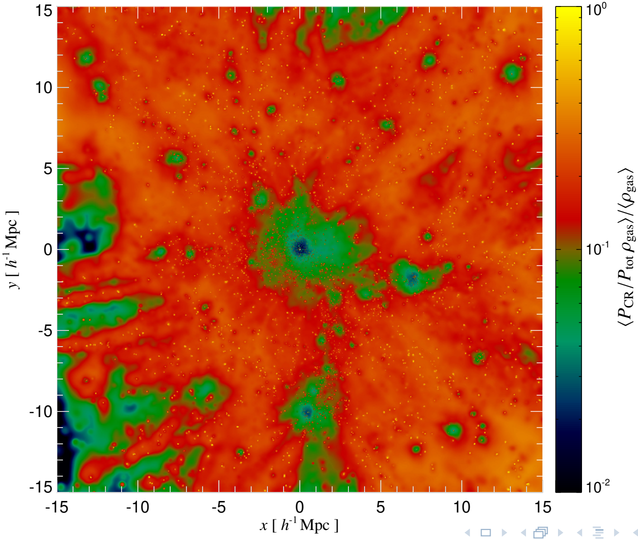
Shock strengths weighted by injected CR energy



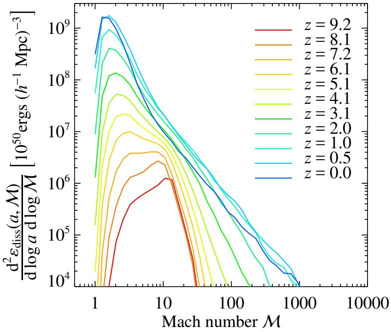
Evolved CR pressure



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

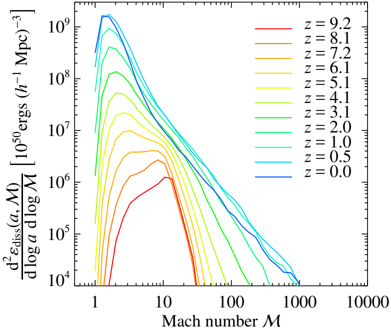


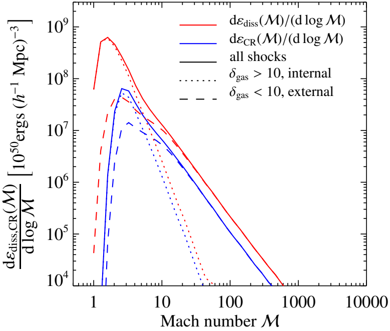
Cosmological shock statistics



- more energy is dissipated at later times
- mean Mach number decreases with time

Cosmological shock statistics: CR acceleration

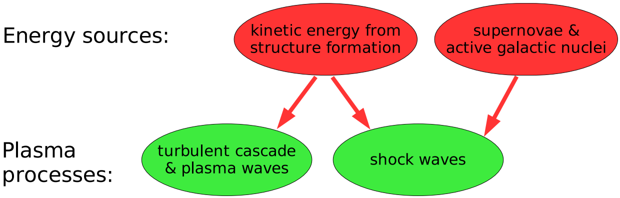




- more energy is dissipated in weak shocks internal to collapsed structures than in external strong shocks
- injected CR energy within clusters only makes up a small fraction of the total dissipated energy

Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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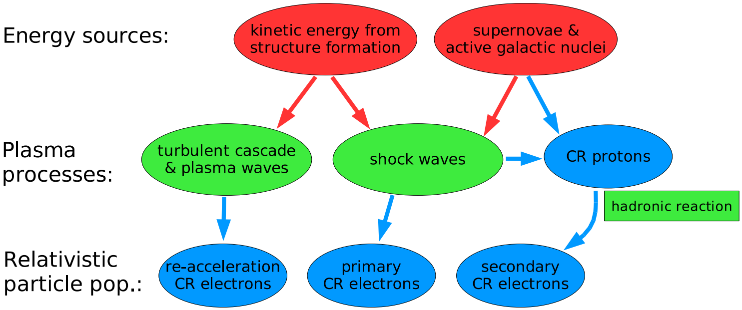
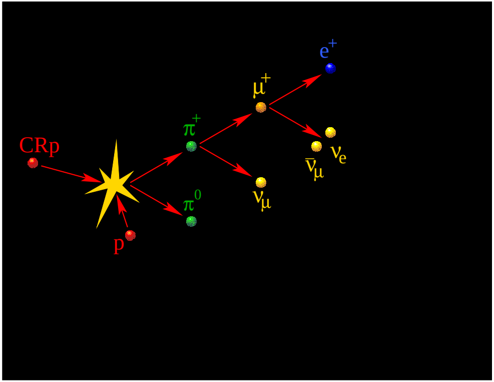


Hadronic cosmic ray proton interaction



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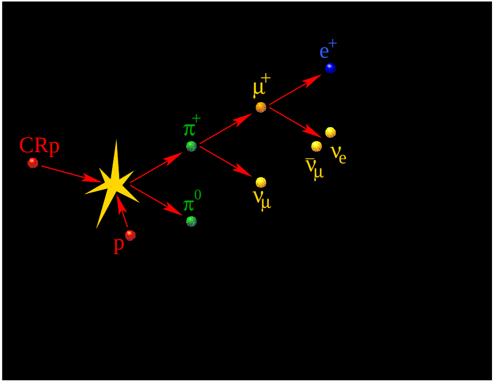

- ***decay kinematics*** ⇒ mean energy of gamma ray and secondary electrons:

$$\langle E_\gamma \rangle = \frac{1}{2} \langle E_{\pi^0} \rangle \simeq \frac{1}{8} E_\mathrm{p} \quad \text{and} \quad \langle E_{\mathrm{e}^\pm} \rangle = \frac{1}{4} \langle E_{\pi^\pm} \rangle \simeq \frac{1}{16} E_\mathrm{p},$$

where inverse multiplicity $\frac{1}{2}$ × inelasticity $\frac{1}{2} = \frac{1}{4}$

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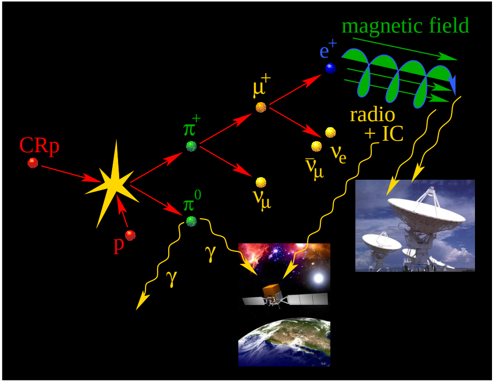

- ***decay kinematics*** $\Rightarrow$ mean energy of gamma ray and secondary electrons:

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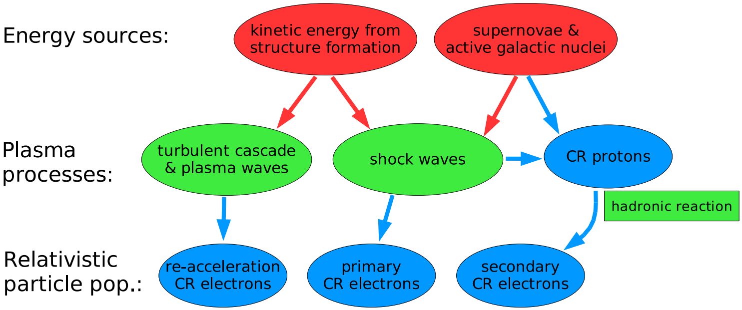

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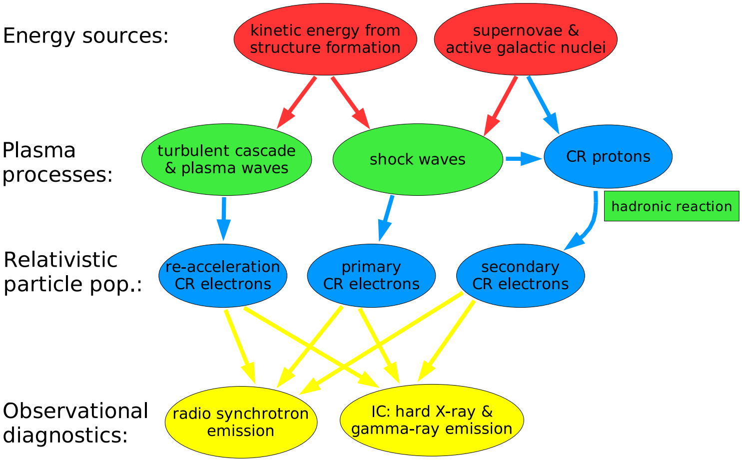

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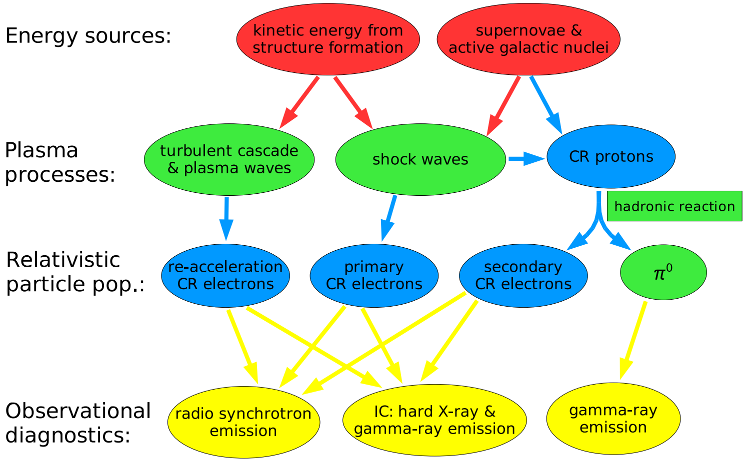

Hadronic and Coulomb cooling of ions

- ***hadronic cooling time:***

$$t_{\mathrm{pp}} = \frac{1}{0.5\sigma_{\mathrm{pp}}\, n_{\mathrm{n}}\, c}$$

where $\sigma_{\mathrm{pp}} = 32$ mbarn is the inelastic proton cross section with an inelasticity 0.5 and $n_{\mathrm{n}} = \rho/m_{\mathrm{p}}$ is the number density of target nucleons

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- ***Coulomb cooling timescale:***

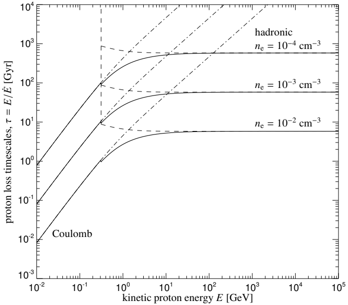
$$t_{\mathrm{Coul,i}} = \frac{E}{|\dot{E}|}\bigg|_{\mathrm{Coul,i}} \approx t_{\mathrm{d}}^{\mathrm{ei}}\,\frac{m_{\mathrm{i}}}{m_{\mathrm{e}}} = \frac{m_{\mathrm{i}}}{m_{\mathrm{e}} n_{\mathrm{e}} v_{\mathrm{i}} \sigma_{\mathrm{ei}}} = \frac{m_{\mathrm{i}}}{m_{\mathrm{e}} n_{\mathrm{e}} v_{\mathrm{i}} 2\pi b_0^2 \ln\Lambda} = \frac{m_{\mathrm{i}} v_{\mathrm{i}}^3}{8\pi m_{\mathrm{e}} n_{\mathrm{e}} r_0^2 c^4 \ln\Lambda},$$

where $t_{\mathrm{d}}^{\mathrm{ei}}$ and v_{i} are the deflection time and relative velocity of a CR ion and thermal electron, n_{e} is the electron number density, $r_0 = Ze^2/(m_{\mathrm{e}} c^2)$ is the classical electron radius, $\ln\Lambda \sim 35$–40 is the Coulomb logarithm, and

$$b_0 = \frac{2Ze^2}{m_{\mathrm{e}} v_{\mathrm{i}}^2} = \frac{2 r_0 c^2}{v_{\mathrm{i}}^2}$$

is the critical impact parameter for a (rare) large-angle scattering event

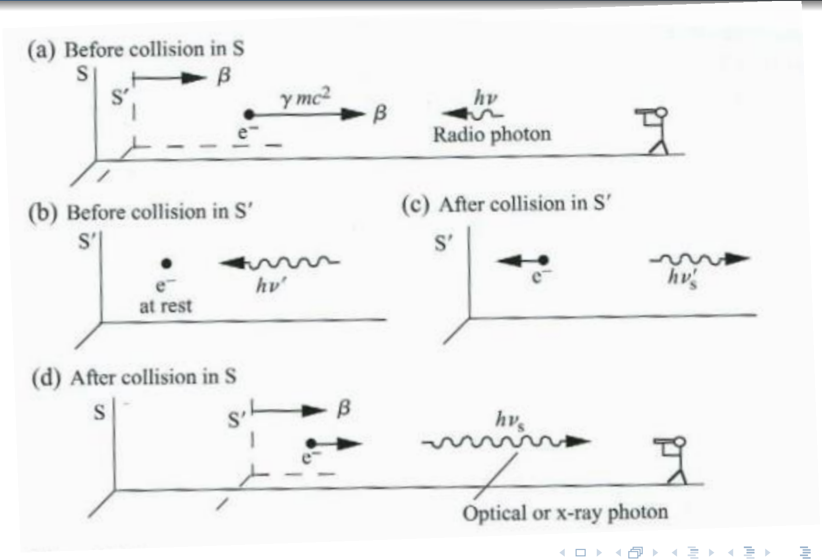
Cooling times of protons



Enßlin+ (2011)

- ***CR protons*** thermalize their low-energy particles via Coulomb/ionization interactions, but retain their (pressure carrying) population above GeV energies because of small hadronic losses

Inverse Compton interaction – 1



Inverse Compton interaction – 2

- energy exchange between CR electron of energy $E_\mathrm{e} = \gamma_\mathrm{e} m_\mathrm{e} c^2$ and a low-energy photon of energy E:

  * Lorentz boosting into the electron rest frame: $E' = \gamma_\mathrm{e} E (1 - \beta_\mathrm{e} \cos\theta)$
  * elastic scattering in the electron rest frame: $E_1' = E'$
  * Lorentz de-boosting into the lab frame: $E_1 = \gamma_\mathrm{e} E_1' (1 + \beta_\mathrm{e} \cos\theta_1')$

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- the net photon energy gain = CR electron loss is (for all but very small angles):

$$E_1 \sim \gamma_\mathrm{e}^2 E \quad \Rightarrow \quad \langle E_1 \rangle = \frac{4}{3} \gamma_\mathrm{e}^2 \langle E \rangle$$

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- the inverse Compton energy loss rate of a CR electron

$$\dot{E}_\mathrm{e} = -\sigma_\mathrm{T} c n_\mathrm{ph} \langle E_1 \rangle = -\frac{4}{3} \sigma_\mathrm{T} c \varepsilon_\mathrm{ph} \gamma_\mathrm{e}^2 = -\frac{\sigma_\mathrm{T} c}{6\pi} B_\mathrm{ph}^2 \gamma_\mathrm{e}^2,$$

where $\varepsilon_\mathrm{ph} = \langle E \rangle n_\mathrm{ph} = B_\mathrm{ph}^2/(8\pi)$ and σ_T is the Thomson cross section

Inverse Compton and synchrotron cooling

The energy loss rate of a relativistic electron of energy $E_\mathrm{e} = \gamma_\mathrm{e} m_\mathrm{e} c^2$ is given by

$$\dot{E}_\mathrm{e} = -\frac{\sigma_\mathrm{T} c}{6\pi} (B_\mathrm{cmb}^2 + B^2)\gamma_\mathrm{e}^2 \quad \Rightarrow \quad t_\mathrm{cool} = \frac{E_\mathrm{e}}{|\dot{E}_\mathrm{e}|} = \frac{6\pi m_\mathrm{e} c}{\sigma_\mathrm{T} \left(B_\mathrm{cmb}^2 + B^2\right) \gamma_\mathrm{e}}$$

where B is the magnetic field strength and $B_\mathrm{cmb} \simeq 3.2\mu\mathrm{G}$ is the equivalent field of the cosmic microwave background (cmb) energy density today:

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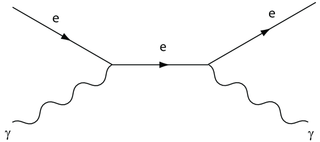
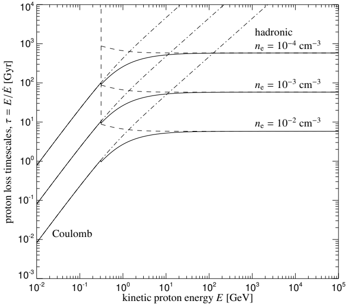
- the first term $\propto B_\mathrm{cmb}^2$ describes energy loss due to inverse Compton (IC) scattering off of CMB photons, while the second term $\propto B^2$ describes energy loss due to synchrotron emission
- the structural similarity of the formulae is not a coincidence but caused by the same Feynman diagram of the scattering process: while IC emission evokes real photons, synchrotron emission borrows a virtual photon from the magnetic field



Cooling times of protons



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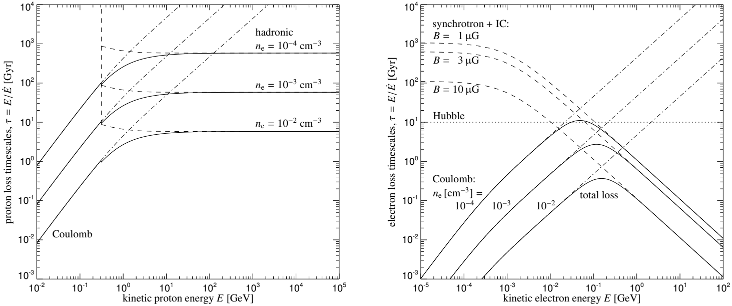
Cooling times of protons and electrons



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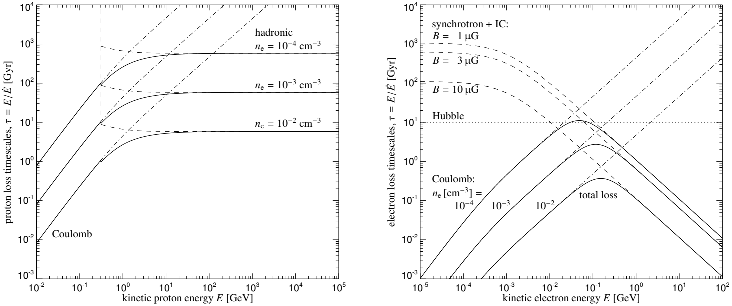

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  $\Rightarrow$ ***bottleneck at*** $\gamma_e \sim 100$ ***causes accumulation of fossil CR electrons***

Electron cooling and synchrotron emission

- the cooling time $t_\mathrm{cool} = E_\mathrm{e}/|\dot{E}_\mathrm{e}|$ of a relativistic electron is given by

$$t_\mathrm{cool} = \frac{E_\mathrm{e}}{|\dot{E}_\mathrm{e}|} = \frac{6\pi m_\mathrm{e} c}{\sigma_\mathrm{T} \left(B_\mathrm{cmb}^2 + B^2\right) \gamma_\mathrm{e}} \approx 200\,\mathrm{Myr},$$

for $B = 1\ \mu\mathrm{G}$ and $\gamma_\mathrm{e} = 10^4$

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$$\nu_\text{syn} = \frac{3eB}{2\pi\, m_\text{e} c}\, \gamma_\text{e}^2 \simeq 1\ \text{GHz}\, \frac{B}{\mu\text{G}} \left(\frac{\gamma_\text{e}}{10^4}\right)^2$$

AIP

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- combining both equations by eliminating the Lorentz factor $\gamma_{\rm e}$ yields the cooling time of electrons that emit at frequency $\nu_{\rm syn}$,

$$t_{\rm cool} = \frac{\sqrt{54\pi m_{\rm e} c\, eB\nu_{\rm syn}^{-1}}}{\sigma_{\rm T}\,(B_{\rm cmb}^2 + B^2)} \lesssim 190\,\left(\frac{\nu_{\rm syn}}{1.4\,\mathrm{GHz}}\right)^{-1/2}\ \mathrm{Myr}$$

  $\Rightarrow$ the cooling time $t_{\rm cool}$ is then bound from above and attains its maximum cooling time at $B = B_{\rm cmb,0}/\sqrt{3} \simeq 1.8\,\mu$G, independent of the magnetic field

Equilibrium distribution of CR electrons

- CR electron acceleration: in galaxies, CR electrons are either directly accelerated at supernova remnant shocks or in hadronic CR proton interactions $\rightarrow$ source function $s_\mathrm{e} = C E_\mathrm{e}^{-\alpha_\mathrm{e}}$, with $\alpha_\mathrm{e} \simeq 2 - 2.4$

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- solution: for $\dot{E}_\mathrm{e}(E_\mathrm{e}) < 0$, this equation is solved by

$$f_\mathrm{e}(E_\mathrm{e}) = \frac{1}{|\dot{E}_\mathrm{e}(E_\mathrm{e})|}\int_{E_\mathrm{e}}^{\infty} \mathrm{d}E_\mathrm{e}' s_\mathrm{e}(E_\mathrm{e}') = \frac{C}{(\alpha_\mathrm{e}-1)\,|\dot{E}_\mathrm{e}(E_\mathrm{e})|}\,E_\mathrm{e}^{1-\alpha_\mathrm{e}} \propto E_\mathrm{e}^{-\alpha_\mathrm{e}-1}$$

where we assumed synchrotron/IC loss processes in the last step

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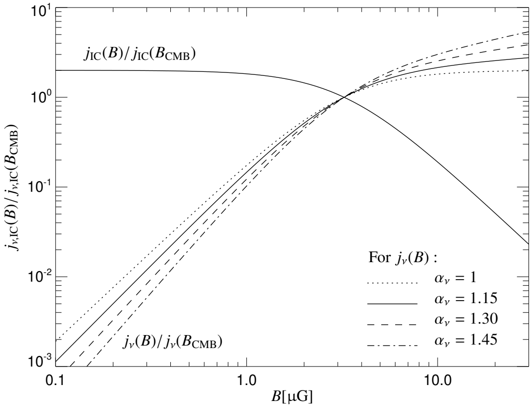
Synchrotron vs. inverse Compton emissivity

In steady state, the emissivity in the IC/synchrotron regime is nearly independent of B



inverse Compton cooling regime: $B < B_{\mathrm{CMB}} \simeq 3.2\,(1+z)^2\,\mu\mathrm{G}$,

synchrotron cooling regime: $B > B_{\mathrm{CMB}}$.

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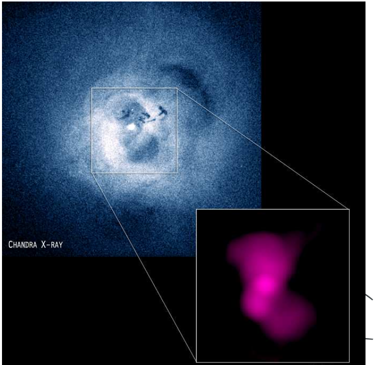
AGN bubbles and relic relativistic plasma

Paradigm: super-massive black holes with $M_\bullet \sim (10^9 - 10^{10})\,\mathrm{M}_\odot$ co-evolve with their hosting cD galaxies at the centers of galaxy clusters. They launch relativistic jets that potentially provide energetic feedback to balance cooling as in the active galactic nucleus (AGN) in NGC 1275, the cD galaxy in the Perseus cluster.



Perseus cluster (NRAO/VLA/G. Taylor)

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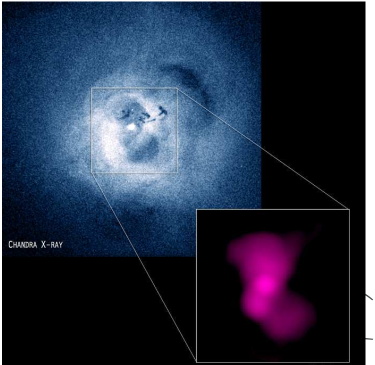
- AGN jets inflate radio lobes upon interacting with the ambient ICM
- jet/lobes provide $p\mathrm{d}V$ work that push the X-ray emitting gas away
- light bubbles are filled with non-thermal components and rise buoyantly, relativistic electrons cool via synchrotron emission
- when relativistic electrons have cooled sufficiently, lobes become invisible in the radio band: X-ray cavities with "ghost bubbles" south and north-west to NGC 1275



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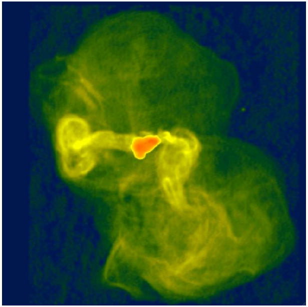
Messier 87 at radio wavelengths



$\nu = 1.4$ GHz (Owen+ 2000)

- high-ν: freshly accelerated CR electrons
  low-ν: fossil CR electrons $\rightarrow$ time-integrated AGN feedback!

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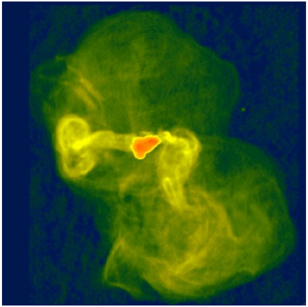

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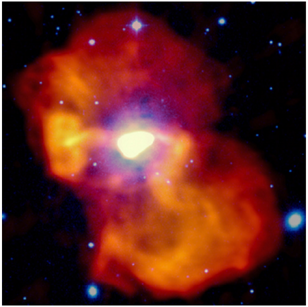
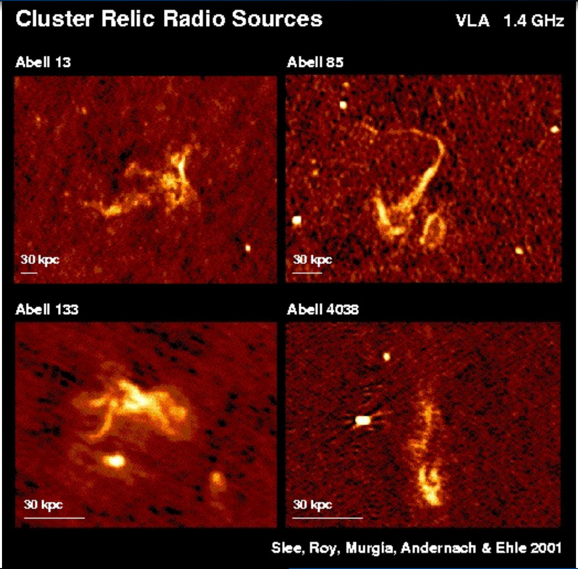


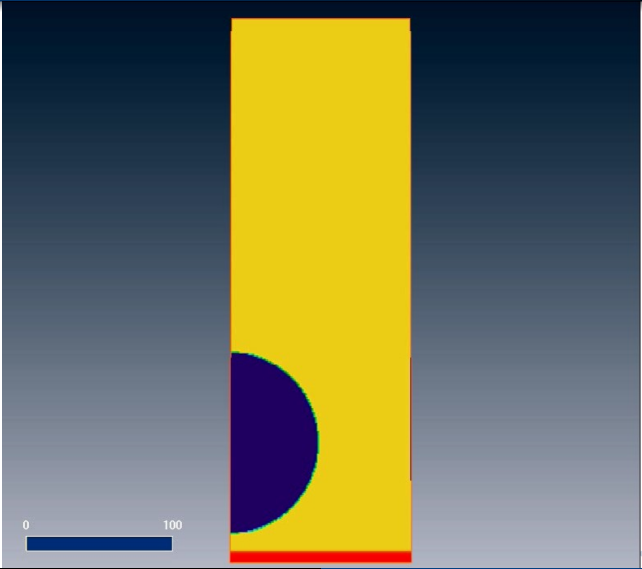
$\nu = 140$ MHz (LOFAR/de Gasperin+ 2012)

- high-ν: freshly accelerated CR electrons
  low-ν: fossil CR electrons $\rightarrow$ time-integrated AGN feedback!
- LOFAR: halo confined to same region at all frequencies and no low-ν spectral steepening $\rightarrow$ puzzle of "missing fossil electrons"
- solution: electrons are fully mixed with the dense cluster gas and cooled through Coulomb interactions

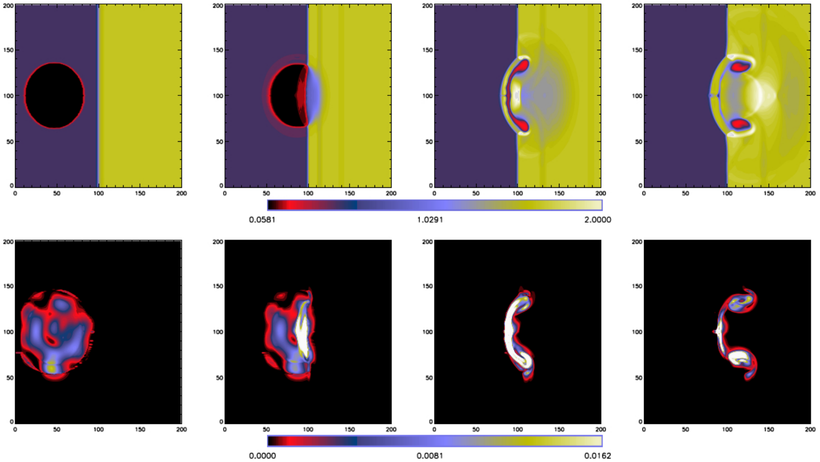
Radio phoenix



Shock overruns an aged radio bubble (Pfrommer & Jones 2011)



Bubble transformation to vortex ring



Enßlin & Brüggen (2002): gas density *(top)* and magnetic energy density *(bottom)*

Radio phoenix rising from the ashes of ghost bubbles

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- this boosts the radio emission, which scales as

$$j_\nu \propto P_\mathrm{CRe} P_B \propto C^{8/3} \sim 100 \ldots 460$$

  for a compression factor $C = 6 \ldots 10$ and weak magnetic fields, $B \lesssim B_\mathrm{cmb}$

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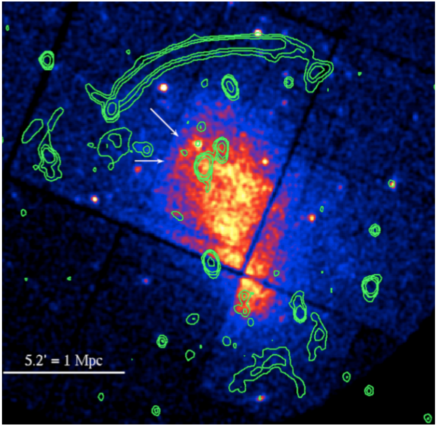
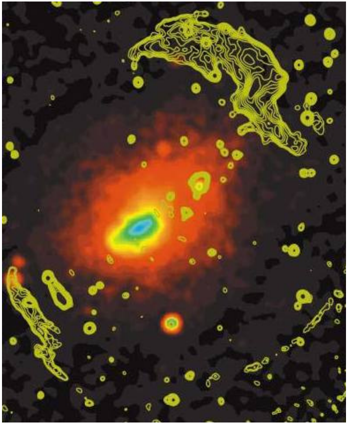
Radio gischt: double relic sources



CIZA J2242.8+5301 ("sausage relic")

X-ray: XMM, radio: WSRT/Ogrean+



Abell 3667

radio: Johnston-Hollitt, X-ray: ROSAT/PSPC

Overview of diffuse radio phenomenon

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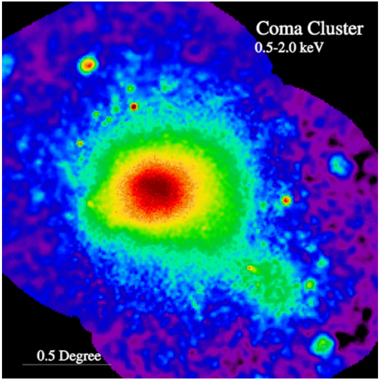
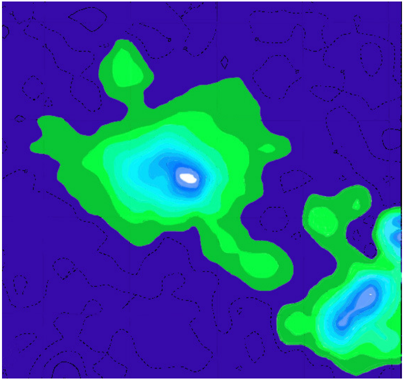
  - radio mini halos: occur in cool core clusters, few times 100 kpc in size, emission extends over cool core

Giant radio halo in the Coma cluster



thermal X-ray emission

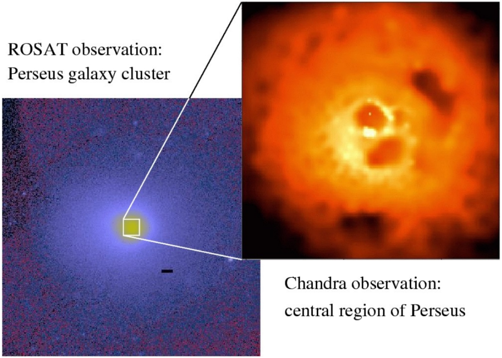
Snowden/MPE/ROSAT



radio synchrotron emission

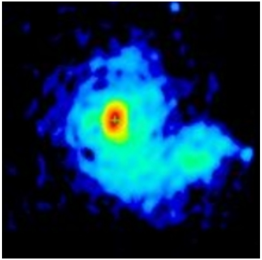
Deiss/Effelsberg

Radio mini halo in the Perseus cluster



thermal X-ray emission

ROSAT, NASA/IoA/Fabian+



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Pedlar/VLA

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Giant radio relics

- recall the cooling time of electrons that emit at frequency ν_{syn},

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$$v_2 = \frac{\rho_1}{\rho_2} v_1 = \frac{(\gamma-1)\mathcal{M}_1^2 + 2}{(\gamma+1)\mathcal{M}_1^2} v_1 = 400 \left(\frac{v_1}{1200\,\mathrm{km\,s}^{-1}}\right) \mathrm{km\,s}^{-1}$$

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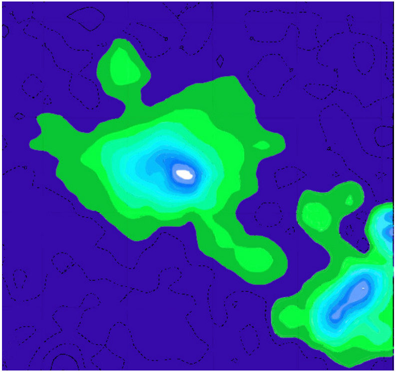
- this implies a maximum cooling length $L_{\rm cool,\,max} = v_2 t_{\rm cool,\,max} = 80$ kpc, which decreases for larger magnetic field strengths to take on a value for 5 μG of

$$L_{\rm cool} = v_2 t_{\rm cool} = \frac{v_2\sqrt{54\pi m_e c\, eB\nu_{\rm syn}^{-1}}}{\sigma_{\rm T}\,(B_{\rm cmb}^2 + B^2)} \approx 30 \left(\frac{\nu_{\rm syn}}{1.4\,\rm GHz}\right)^{-1/2} \rm kpc$$

typical radial extents of radio shocks are of that size ⇒ use the relic geometry to estimate magnetic field strengths (projection effects!)

Giant radio halos

- the maximum cooling length is $L_{\text{cool, max}} = v_2 t_{\text{cool, max}} = 80$ kpc at 1.4 GHz
- the spatial extend of giant radio halos is ~ 2 Mpc and the emission is not polarized



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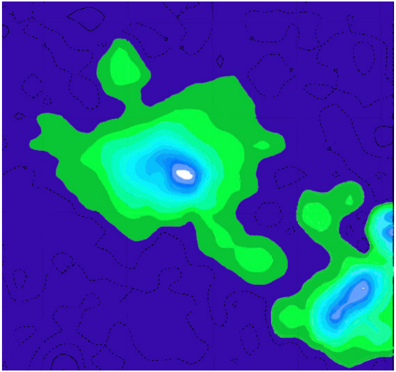

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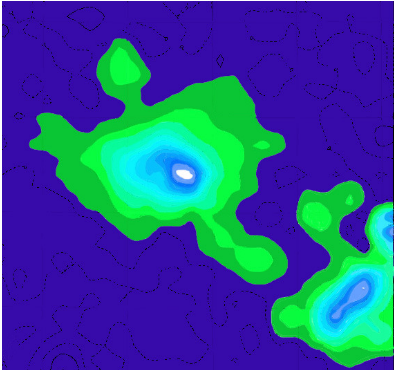

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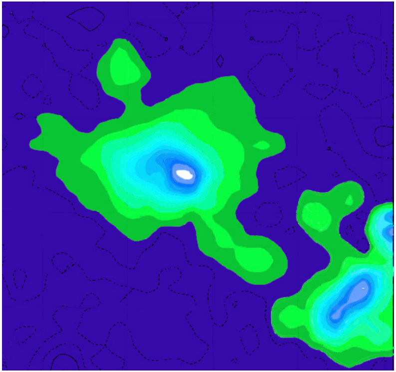

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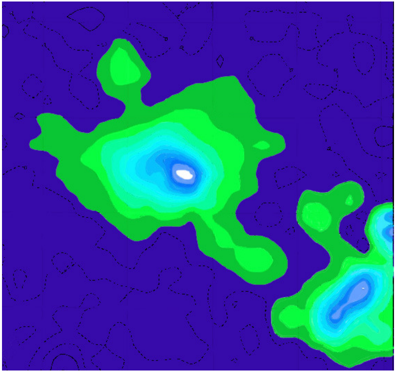

radio synchrotron emission (Deiss/Effelsberg)

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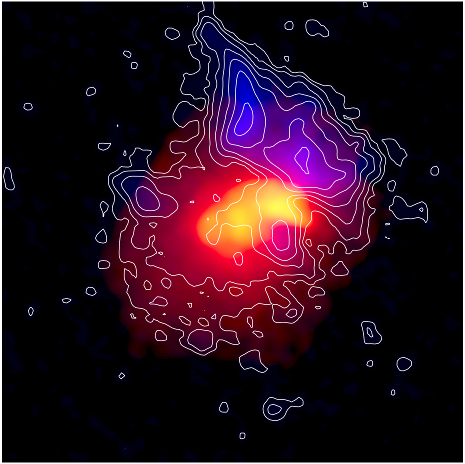
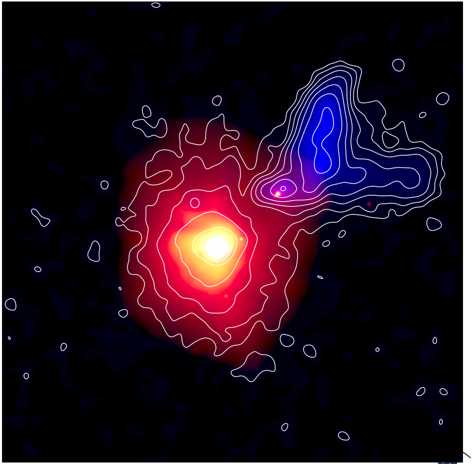
- reacceleration model: fossil or secondary electrons interact with turbulent magneto-hydrodynamic waves and experience Fermi-II acceleration that makes them visible at radio wave lengths

AIP

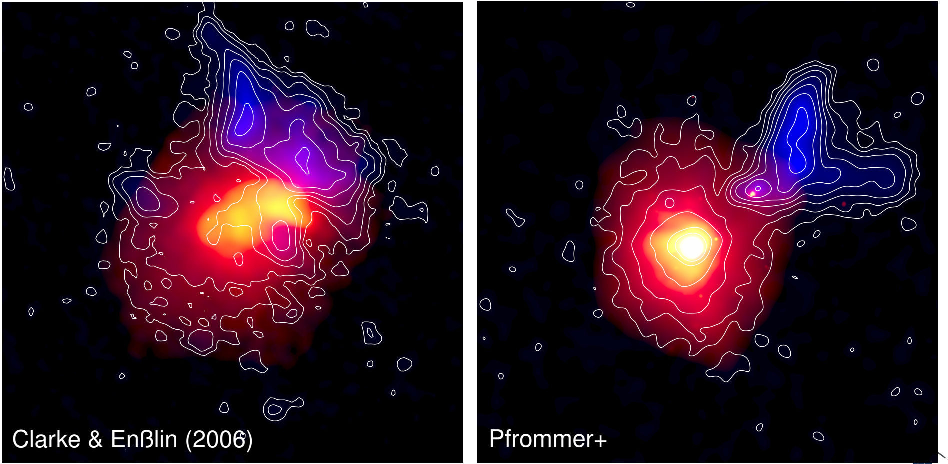
Which one is the simulation/observation of A2256?





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

Observation – simulation of A2256



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

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
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AIP

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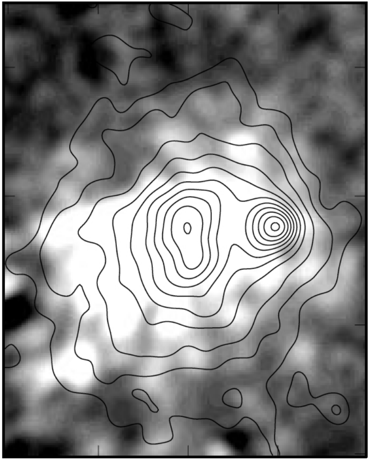
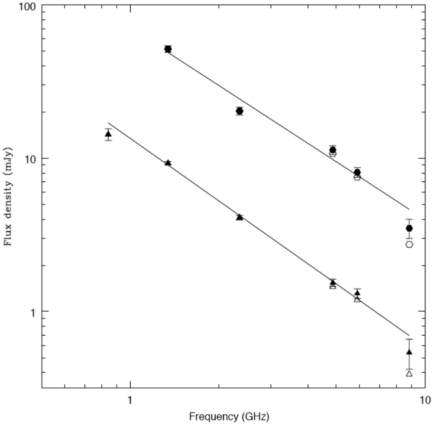
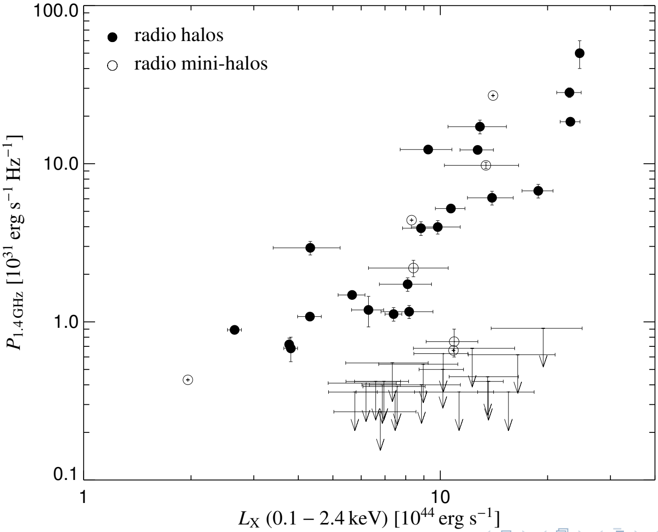
Radio halo and spectrum in the Bullet cluster





Liang et al. (2000): SZ-corrected

Radio luminosity - X-ray luminosity



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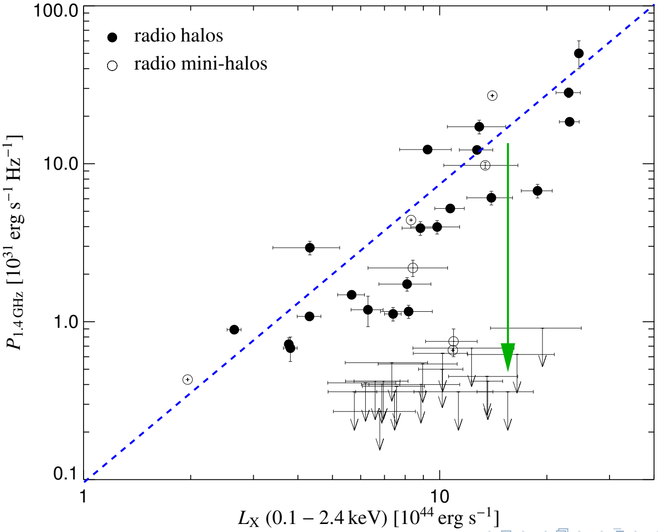

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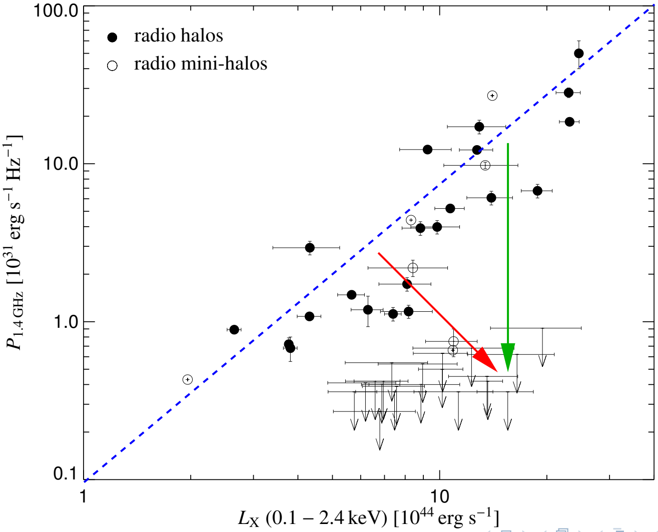
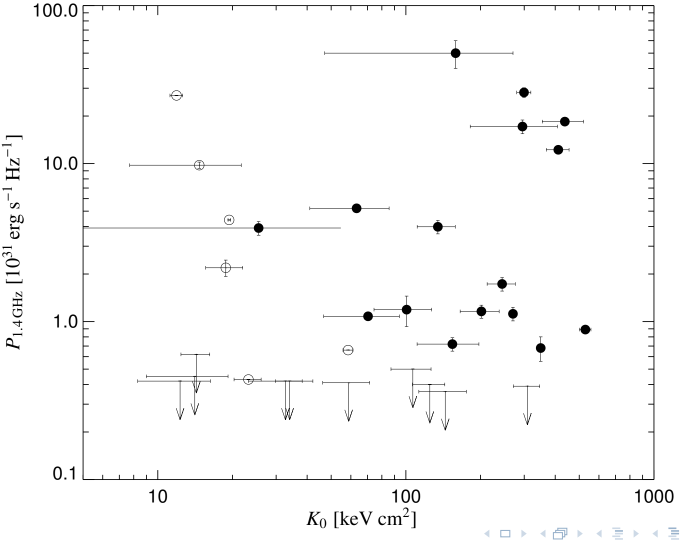


Radio luminosity - central entropy



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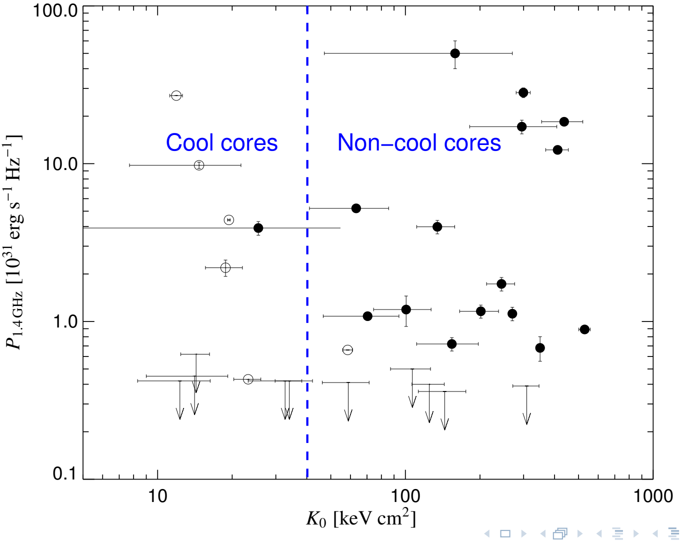

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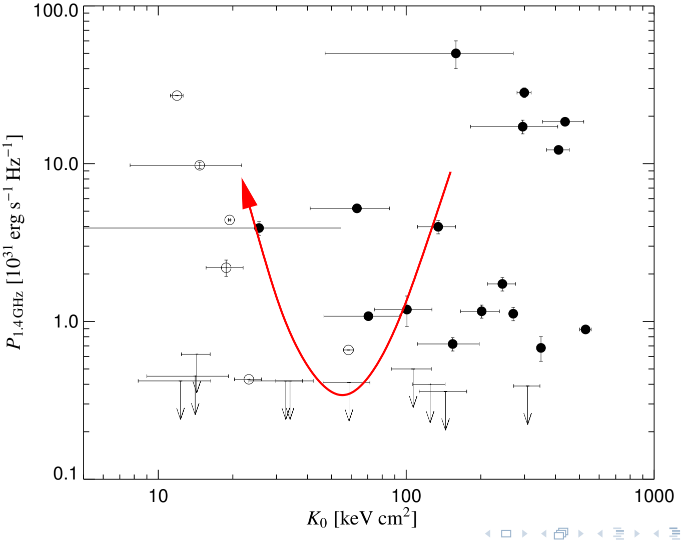

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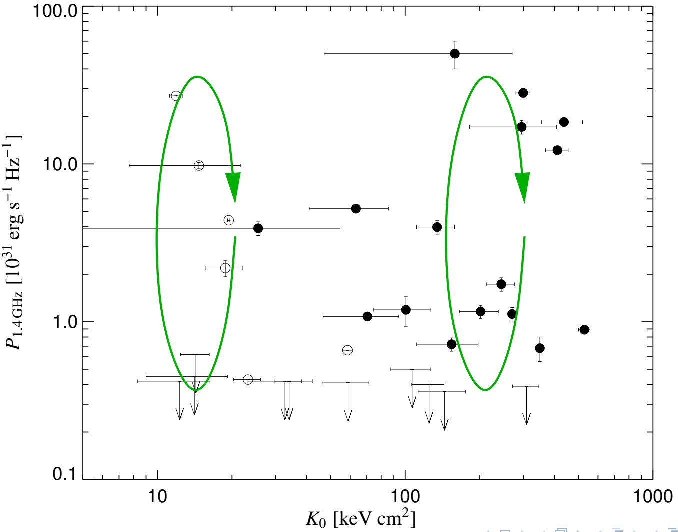
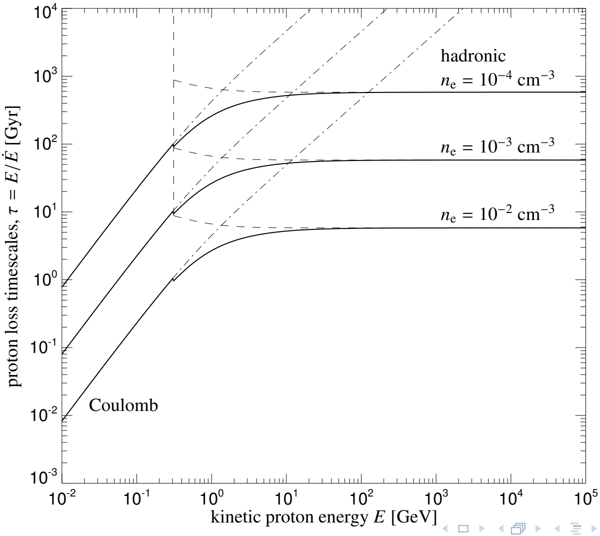


Proton cooling times



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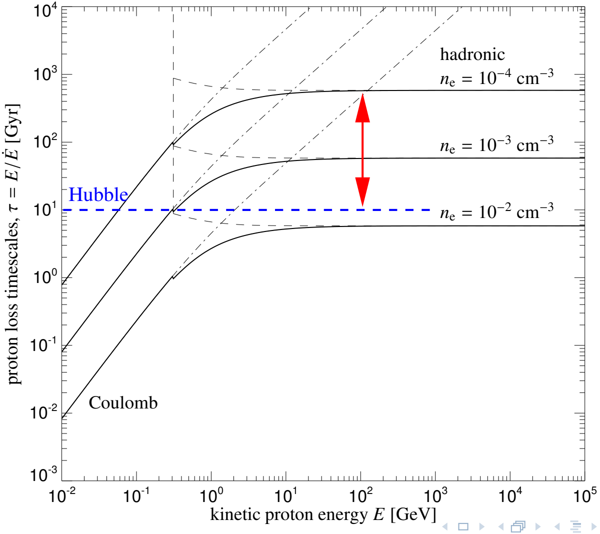

Radio halo theory – (ii) re-acceleration model

strength:

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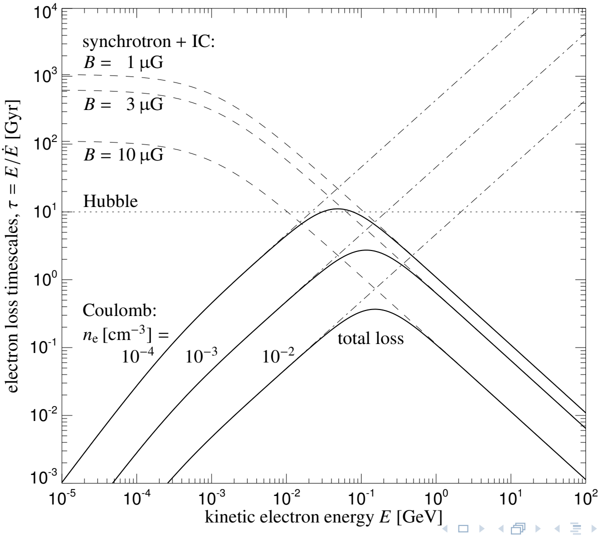
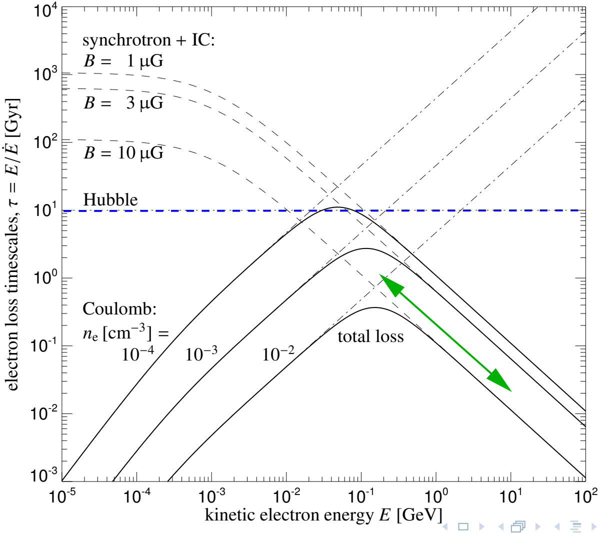
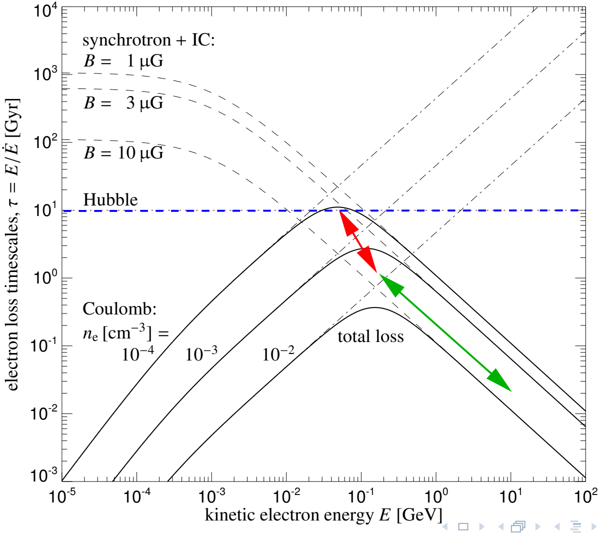
Electron cooling times



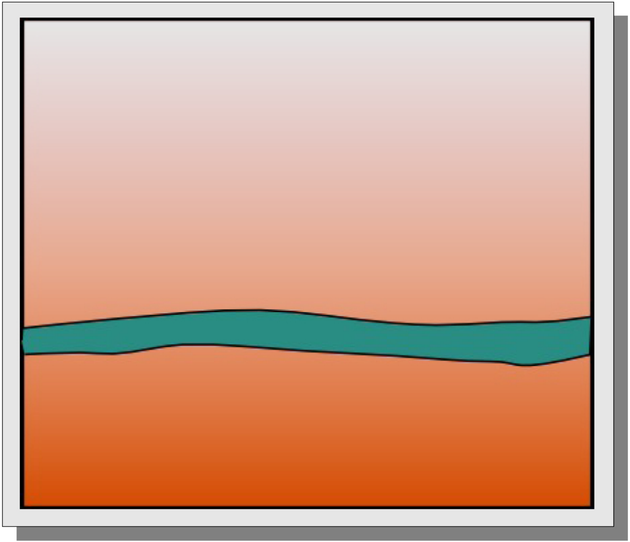
Electron cooling times



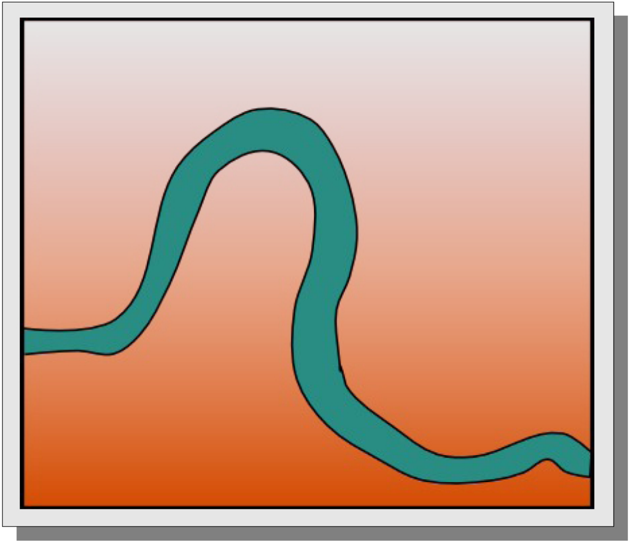
Electron cooling times



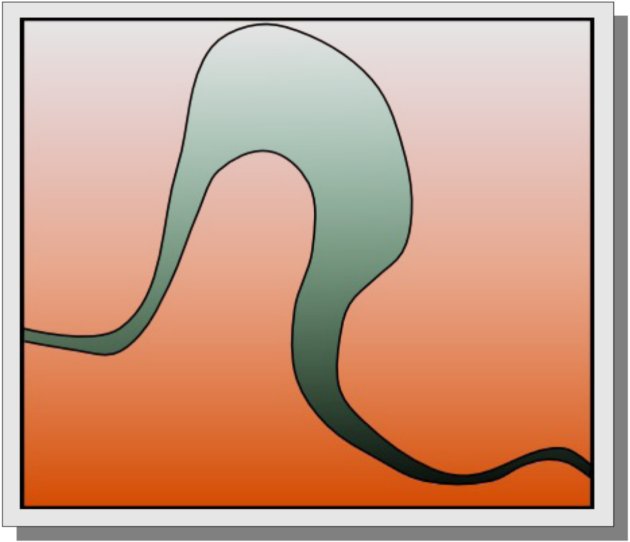
Cosmic ray transport – magnetic flux tube with CRs



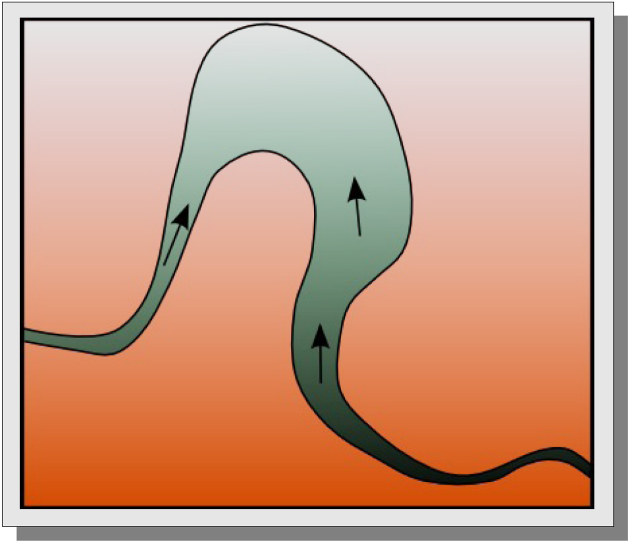
Cosmic ray advection



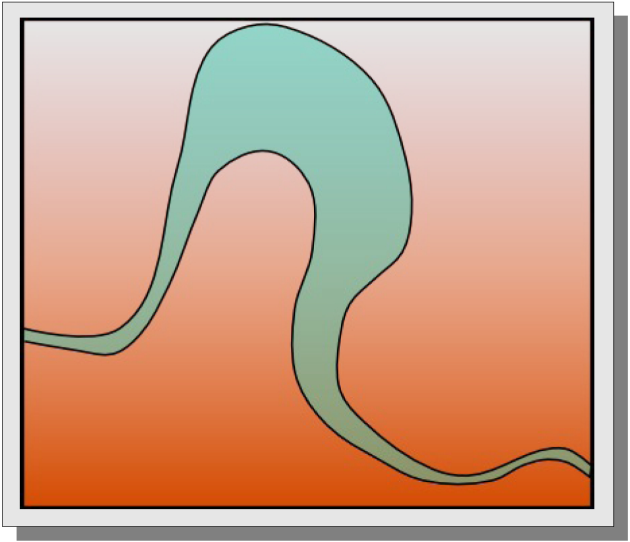
Adiabatic expansion and compression



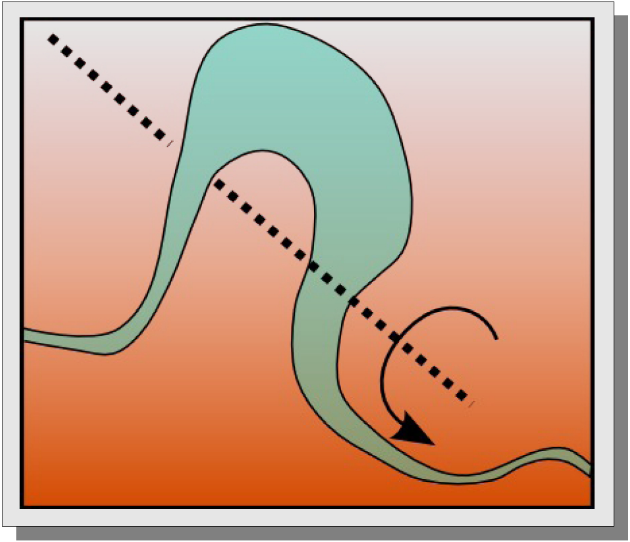
Cosmic ray streaming



Expanded CRs



Turbulent pumping



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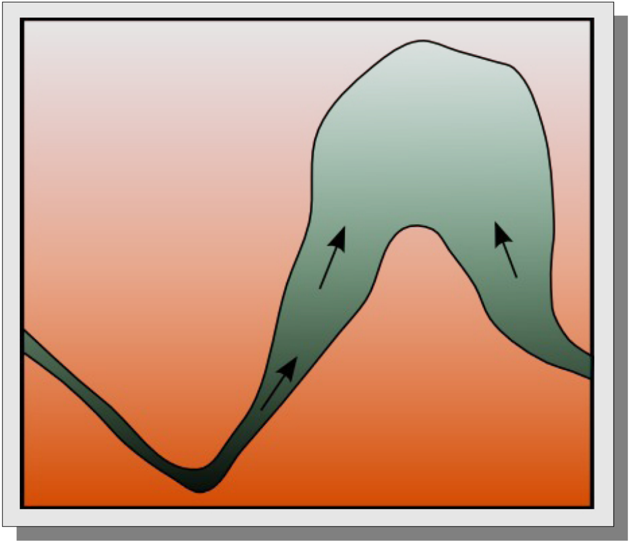
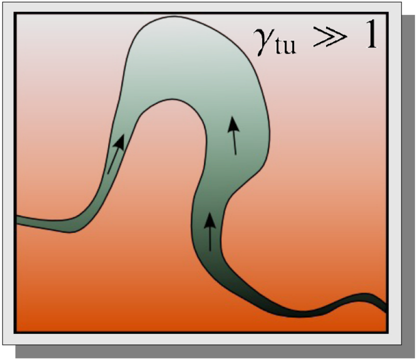
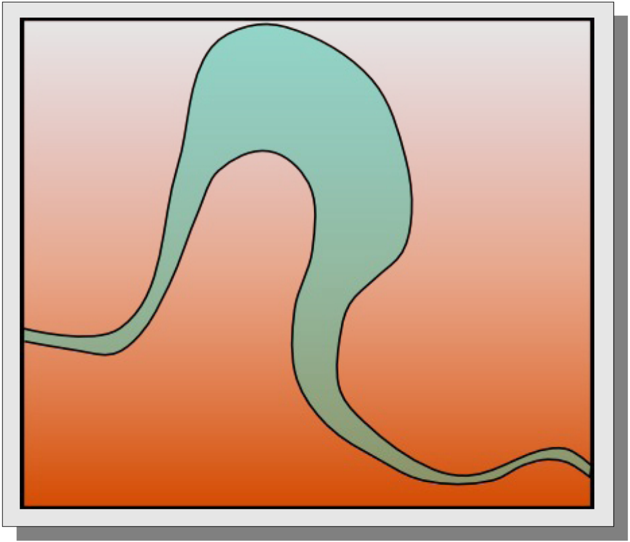


Turbulent-to-streaming ratio

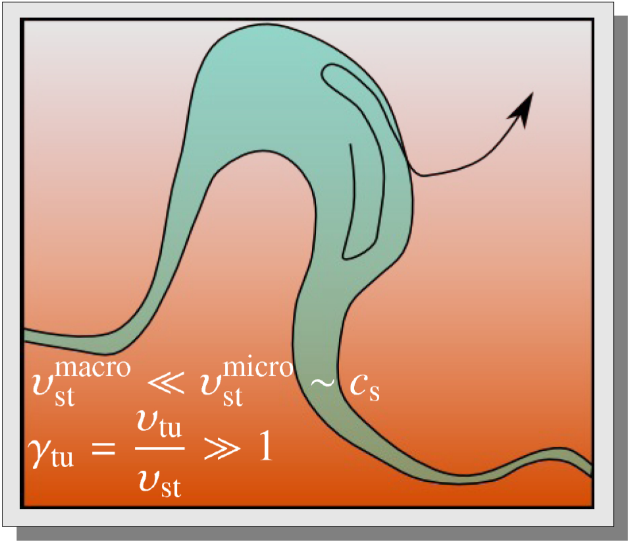
$$\gamma_{\rm tu} = \frac{\upsilon_{\rm tu}}{\upsilon_{\rm st}}$$



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:

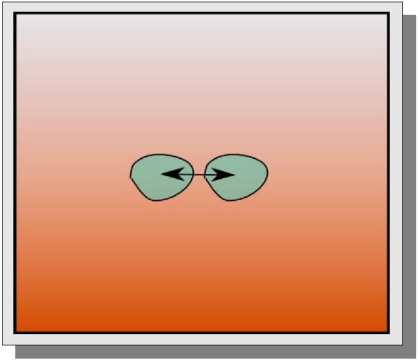
$$\frac{\partial \varrho}{\partial t} + \boldsymbol{\nabla} \cdot (\boldsymbol{\upsilon}\, \varrho) = 0 \qquad \boldsymbol{\upsilon} = \boldsymbol{\upsilon}_{\mathrm{ad}} + \boldsymbol{\upsilon}_{\mathrm{di}} + \boldsymbol{\upsilon}_{\mathrm{st}}$$

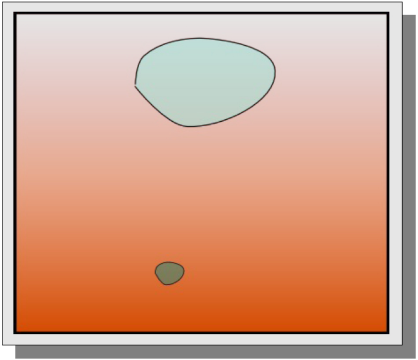
$$\begin{aligned} \boldsymbol{\upsilon}_{\mathrm{st}} &= -\upsilon_{\mathrm{st}} \frac{\boldsymbol{\nabla}\, \varrho}{|\boldsymbol{\nabla}\, \varrho|} \\ \boldsymbol{\upsilon}_{\mathrm{di}} &= -\kappa_{\mathrm{di}}\, \frac{1}{\varrho} \boldsymbol{\nabla} \varrho \\ \boldsymbol{\upsilon}_{\mathrm{ad}}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

Enßlin, Pfrommer, Miniati, Subramanian, 2011, A&A, 527, 99

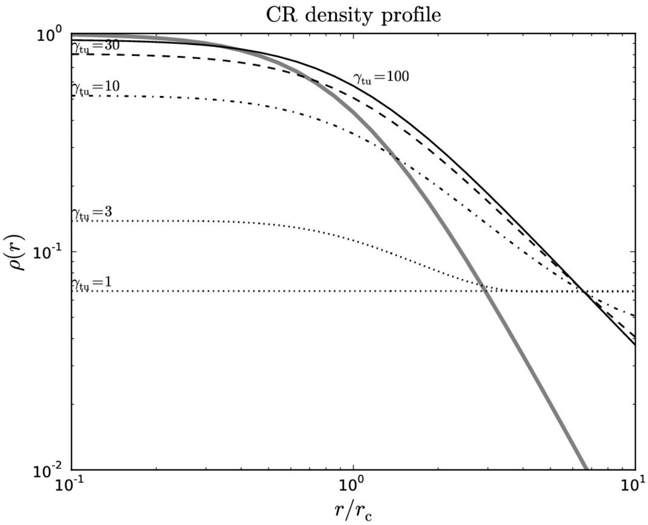
CR profile due to advection

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





CR density profile



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

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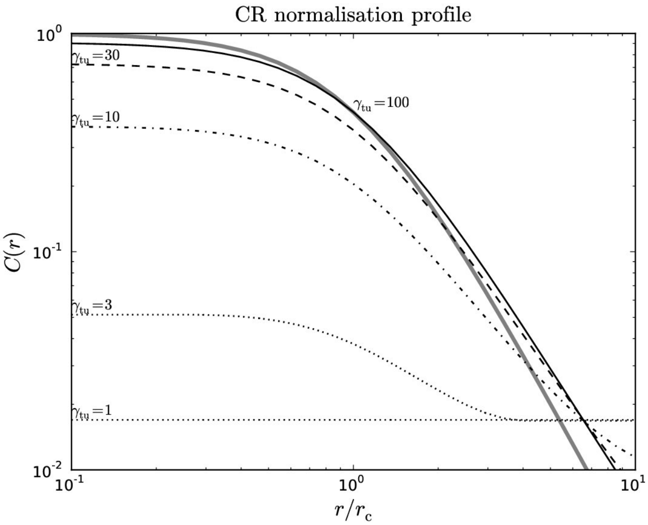
CR density at fixed particle energy



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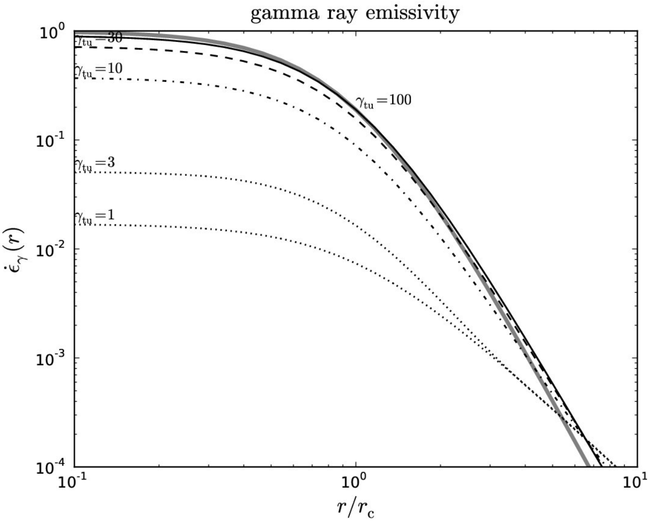
Gamma-ray emission profile

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



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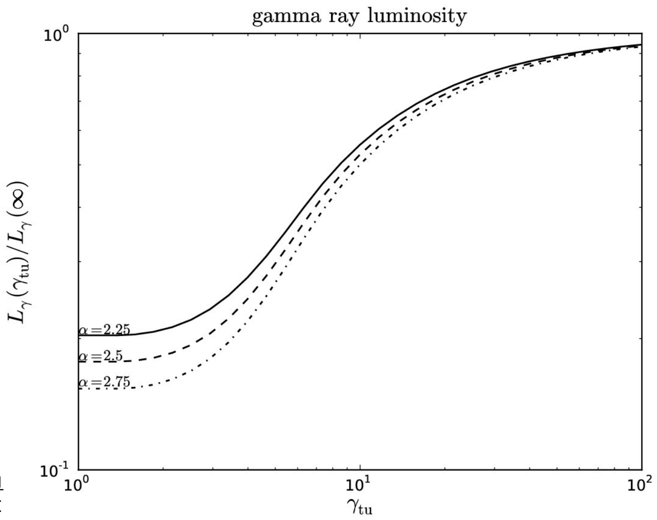
Gamma-ray luminosity

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



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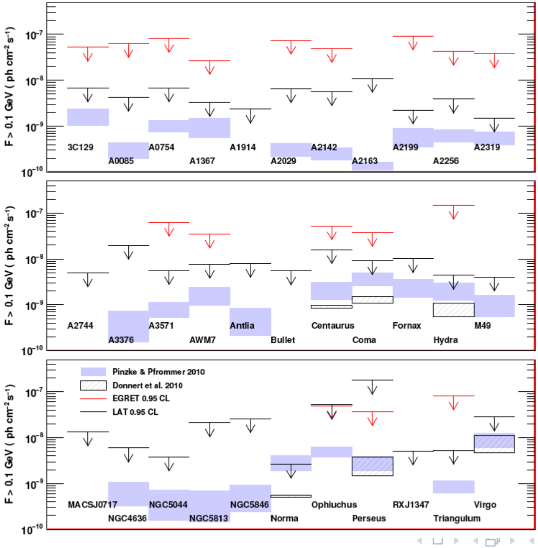
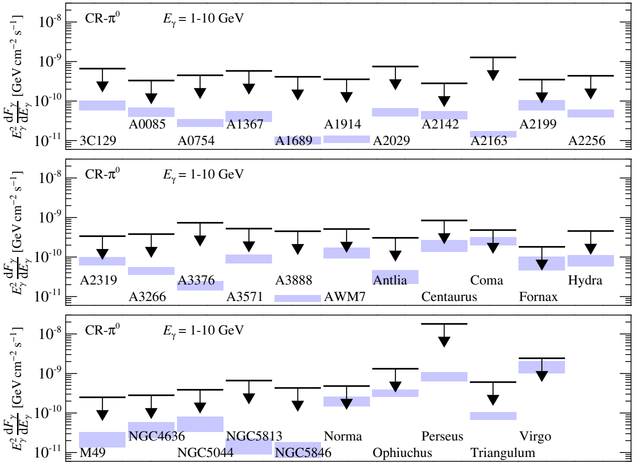
γ-ray limits and hadronic predictions (Ackermann et al. 2010)

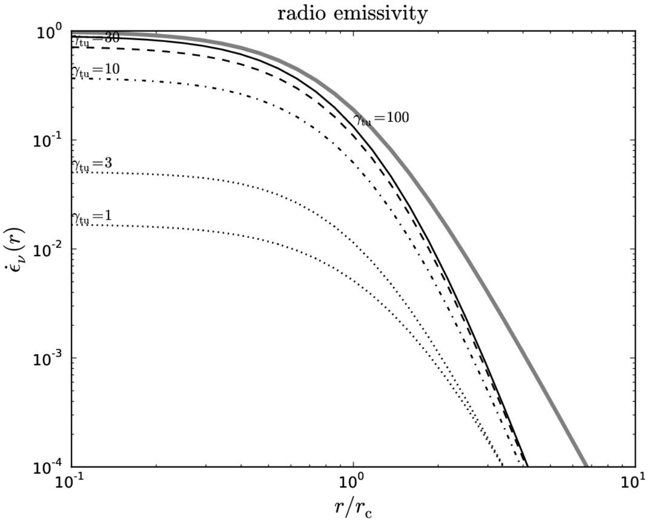


γ-ray limits and hadronic predictions (Pinzke et al. 2011)



Radio emission profile

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



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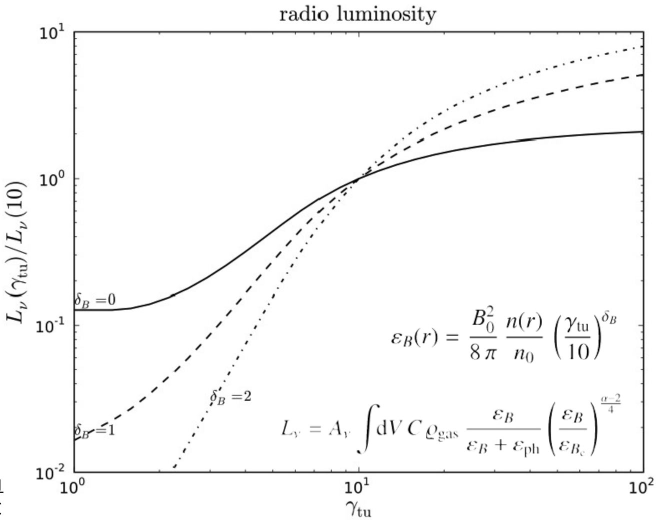
Radio luminosity

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



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Conclusions on radio halos and CR transport

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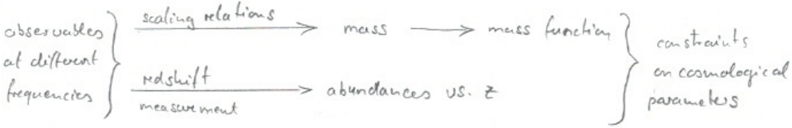
- turbulent velocity $\sim$ sound speed $\leftarrow$ cluster merger
  CR streaming velocity $\sim$ Alfvén speed $\leftarrow$ plasma physics
  $\rightarrow$ peaked/flat CR profiles in merging/relaxed clusters
- energy dependence of $\upsilon_{\text{st}}^{\text{macro}}$ $\rightarrow$ CR & radio spectral variations
  $\rightarrow$ outstreaming CR: dying halo $\leftarrow$ decaying turbulence

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

Cluster cosmology: general picture



- Cluster abundance to measure the fluctuation amplitude σ_8
- Cluster abundance evolution to measure $\Omega_\mathrm{m} = \Omega_\mathrm{c} + \Omega_\mathrm{b}$
- Cluster baryon fraction to estimate $\Omega_\mathrm{b}/\Omega_\mathrm{m}$
- Cluster distribution to estimate power spectrum and baryon acoustic oscillations in the large-scale structure
- Cluster thermal SZ power spectrum to measure fluctuation amplitude σ_8
- Cluster core structure as a test of the nature of dark matter

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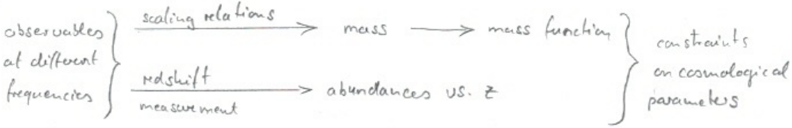
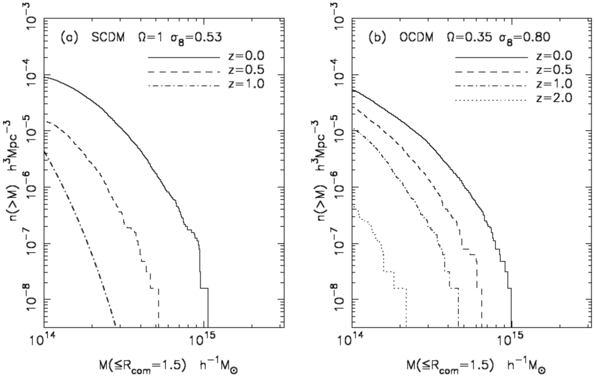


- Cluster abundance to measure the fluctuation amplitude σ_8
  problem: converting cluster observables (L, T, ...) to mass
- Cluster abundance evolution to measure $\Omega_\mathrm{m} = \Omega_\mathrm{c} + \Omega_\mathrm{b}$
  problem: possible evolution of the L–M or T–M relations
- Cluster baryon fraction to estimate $\Omega_\mathrm{b}/\Omega_\mathrm{m}$
  problems: X-rays sensitive to clumping, extrapolation to R_{200}
- Cluster distribution to estimate power spectrum and baryon acoustic oscillations in the large-scale structure
  problem: sparse sampling
- Cluster thermal SZ power spectrum to measure fluctuation amplitude σ_8
  problem: cluster physics (AGN feedback) affects Compton-y
- Cluster core structure as a test of the nature of dark matter
  problem: how does cD assembly affect DM profile?

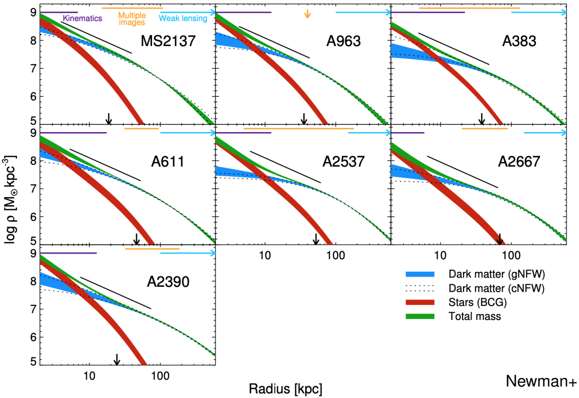
Cluster abundance



Bahcall+ (1997)

- cluster abundances at a given redshift z are given by a combination of the parameters σ_8 and Ω_m
- cluster evolution sets σ_8 and Ω_m separately so that a measurement of cluster abundances as a function of z breaks degeneracy and constrains σ_8 and Ω_m

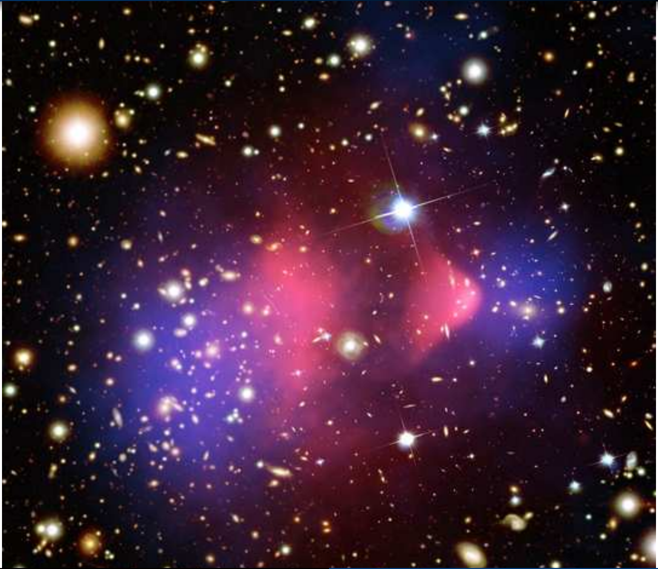
Clusters probe the nature of dark matter – 1



Newman+ (2013)

- radial density profiles for dark matter halo, stars in the BCG, and their total
- black line segment has slope $\rho \propto r^{-1.13}$ (from DM-only simulations)
  $\Rightarrow$ tension with cold DM or cluster physics modifies density slopes?

Clusters probe the nature of dark matter – 2



Conclusions

- the non-thermal universe uncovered by high-energy radiation provides new probes of fundamental physics and cosmology
- optical and X-ray astronomy have provided impressive discoveries of new phenomena; now the age of low-frequency and high-sensitivity radio astronomy has begun and cosmic ray physics is about to open up
- this enables new insights into the most energetic phenomena in the universe and to study plasma physics and non-equilibrium processes such as shock acceleration and turbulence
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→ non-thermal multi-messenger analyses:

"The only true voyage of discovery would be not to visit new landscapes but to possess other eyes and to behold the universe through the eyes of another, of a hundred others."

Marcel Proust