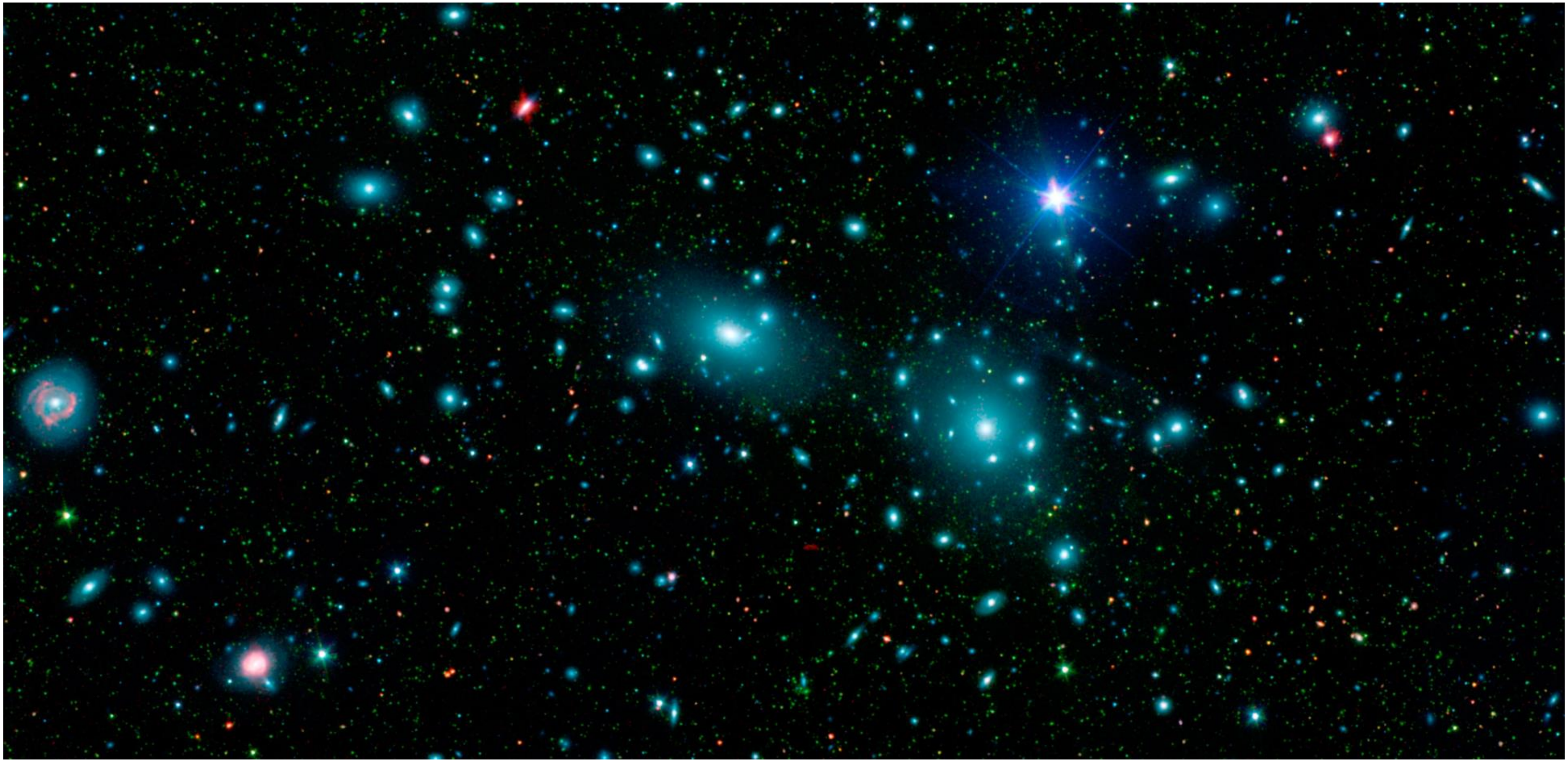
Cosmic Ray Streaming in Galaxy Clusters



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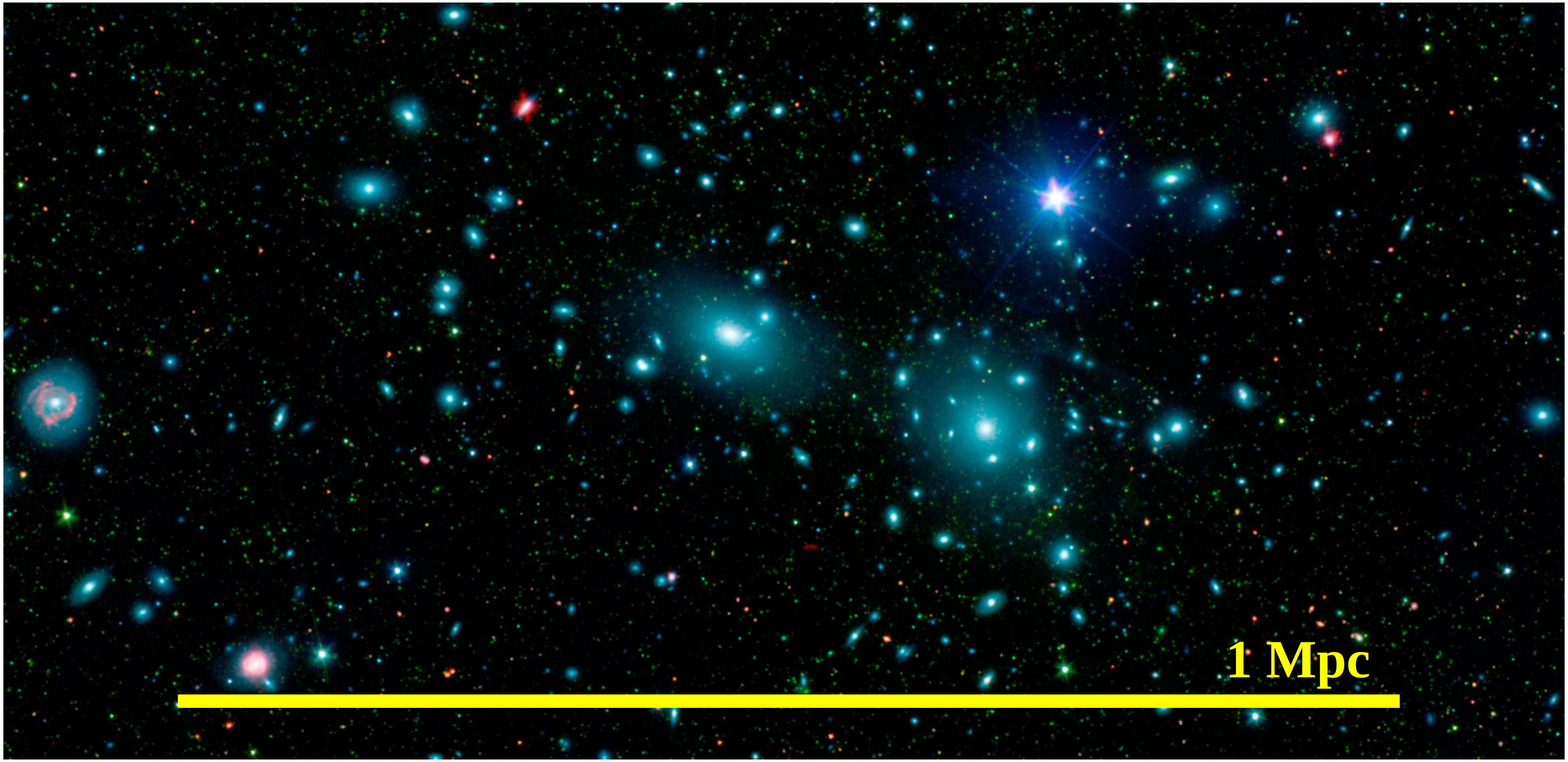
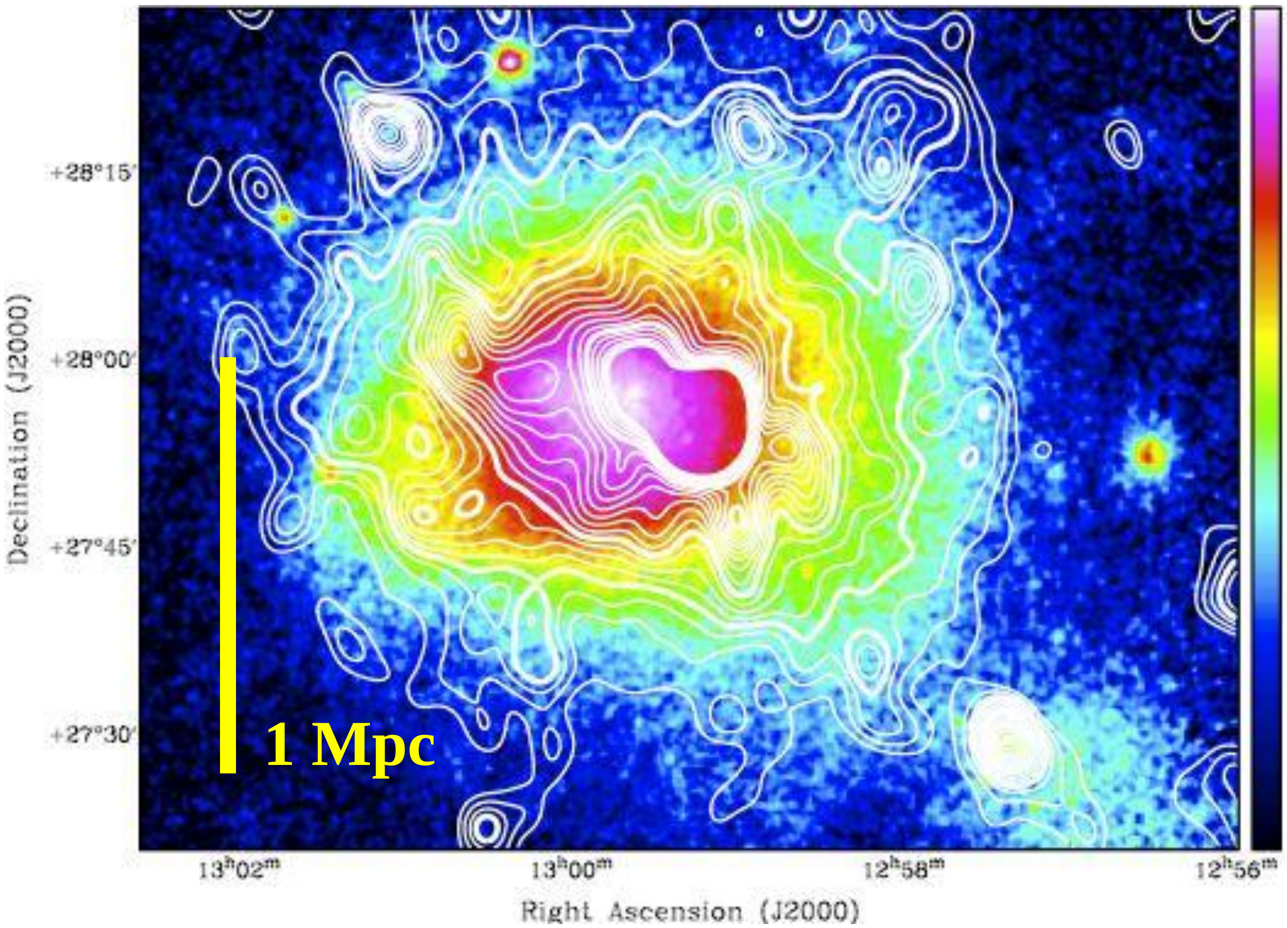
Galaxy Clusters

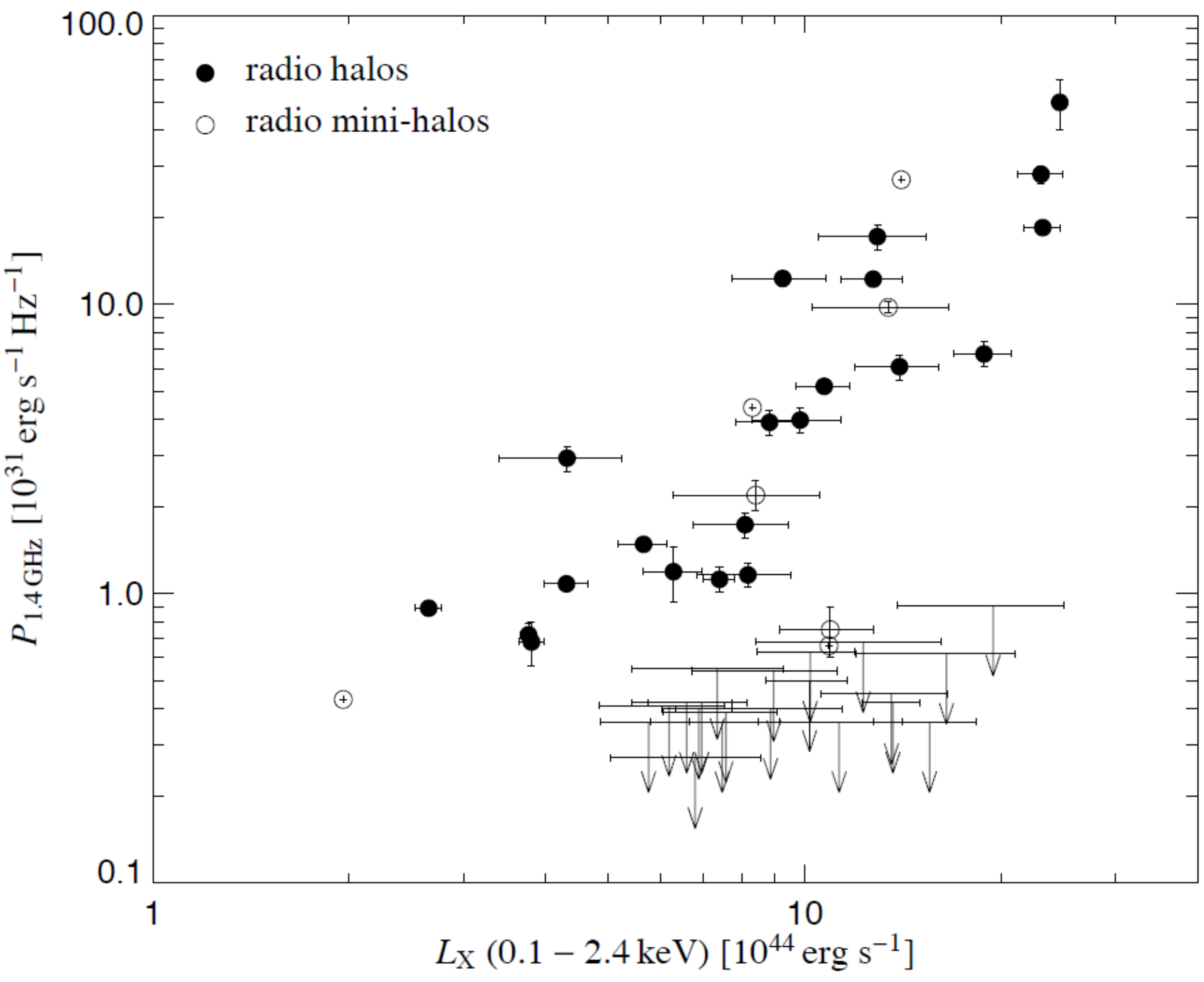


Radio Haloes



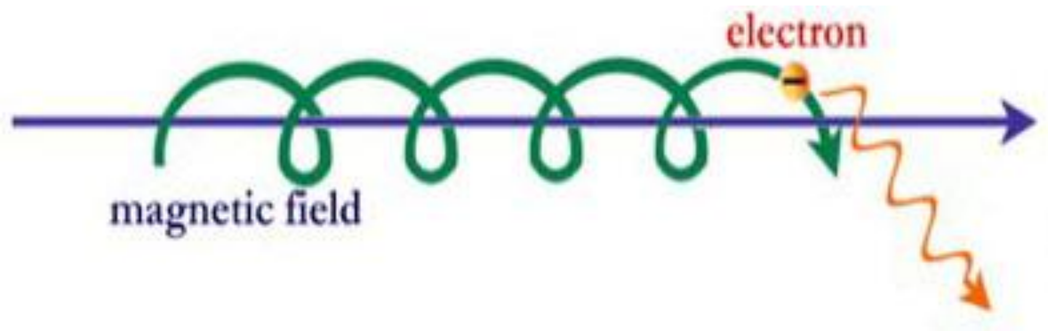
Brown and Rudnick 2011

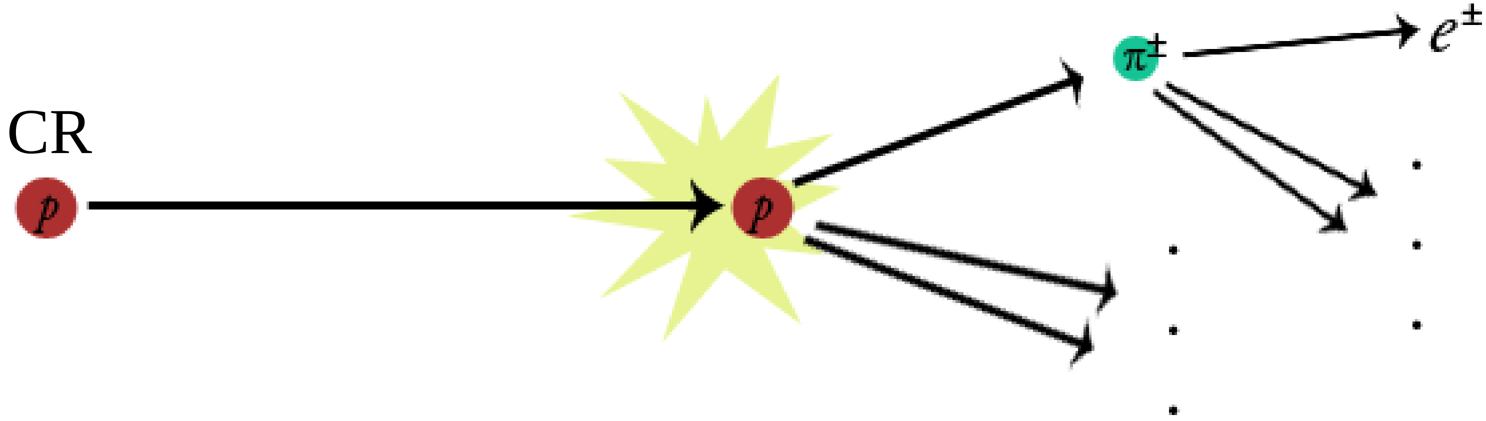
Radio Haloes



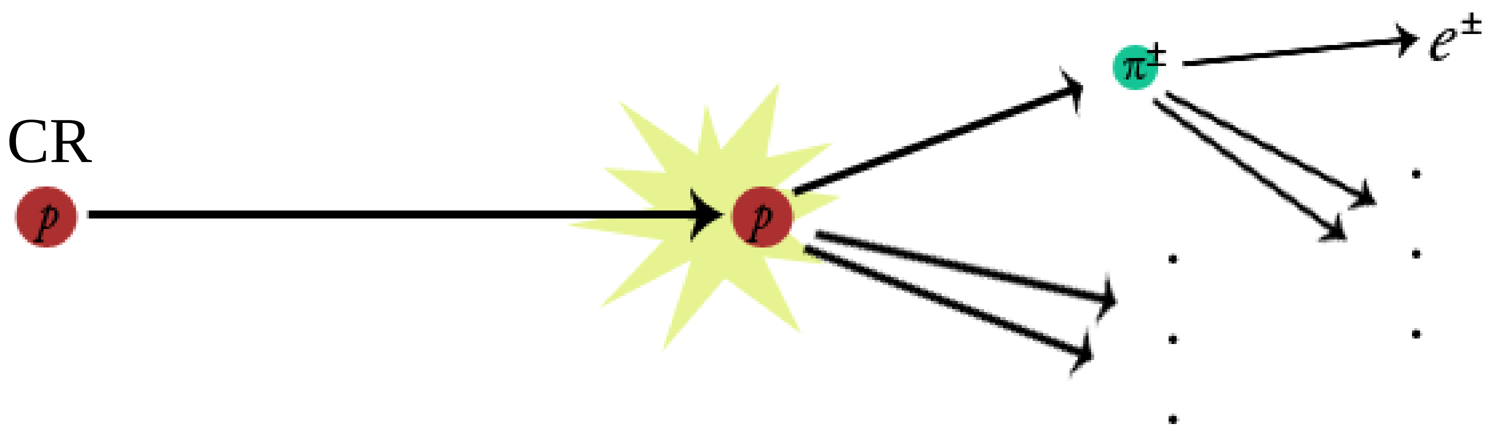
Ensslin et al 2012

Hadronic Model



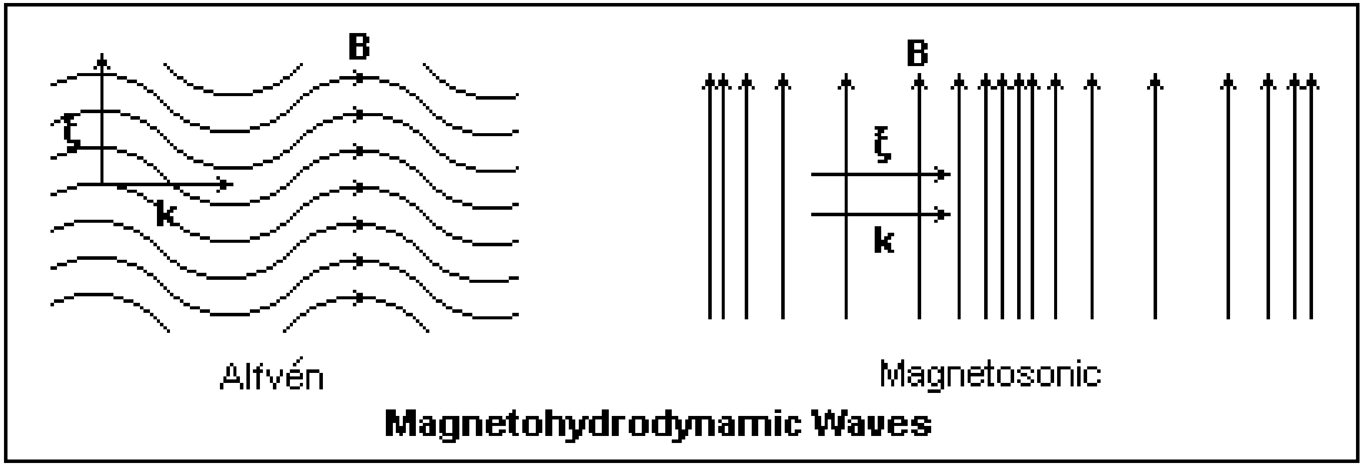


Hadronic Model



Possibly detectable in gamma rays and neutrinos

CR Transport - Alfvén Waves



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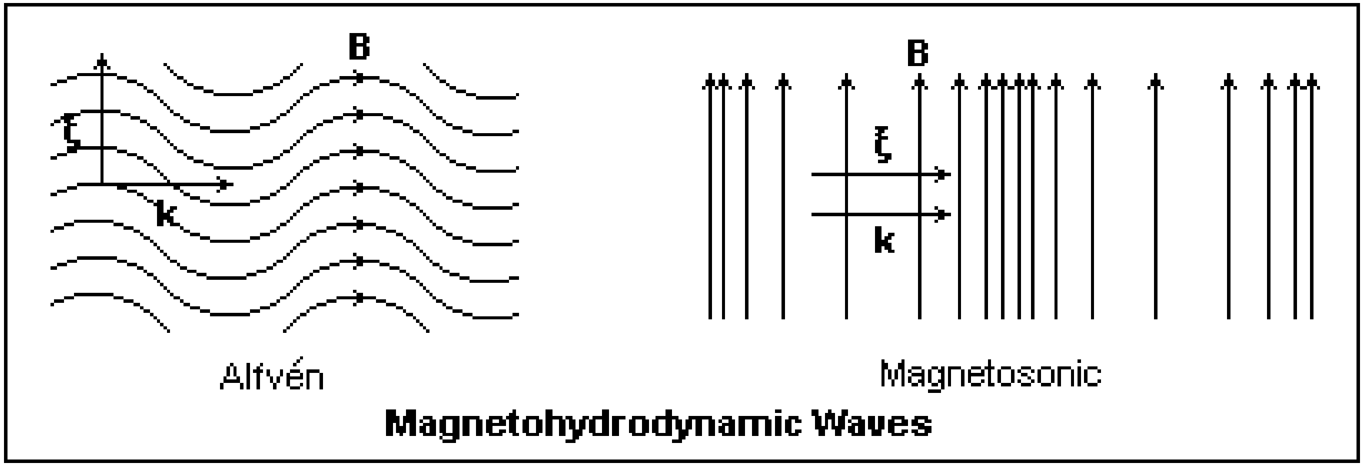

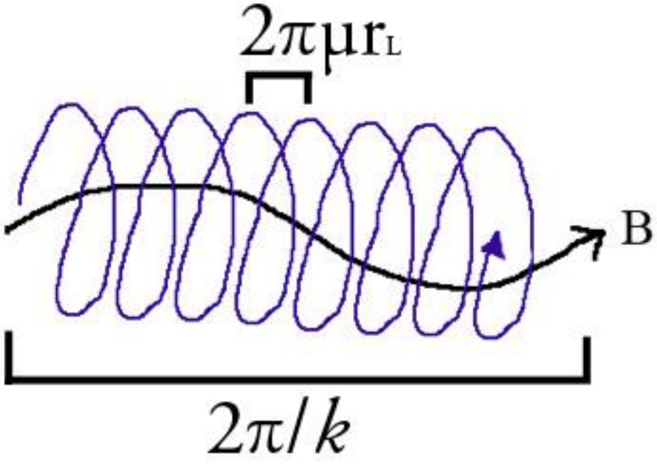

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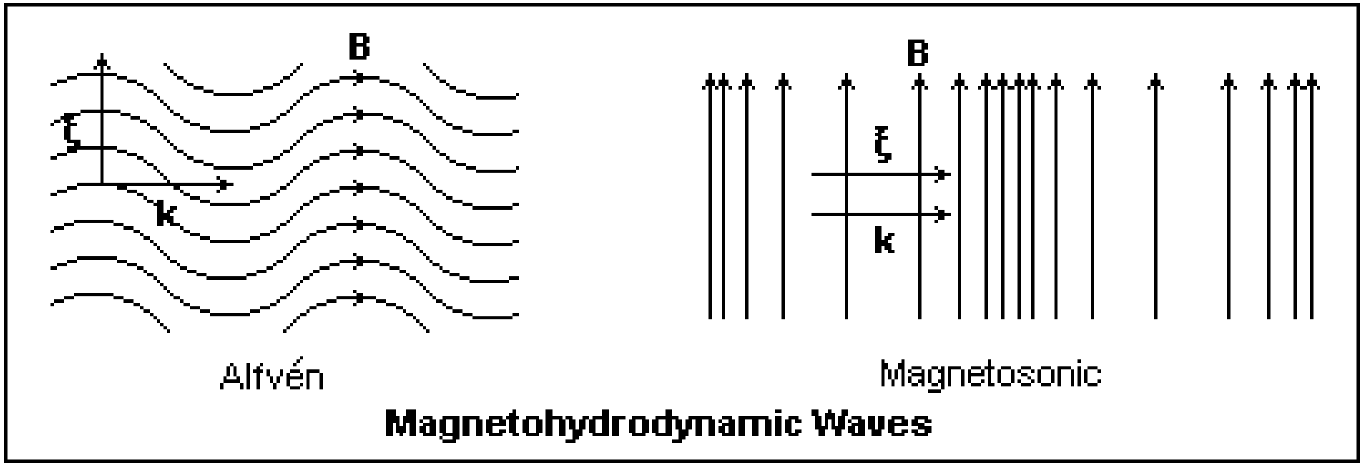
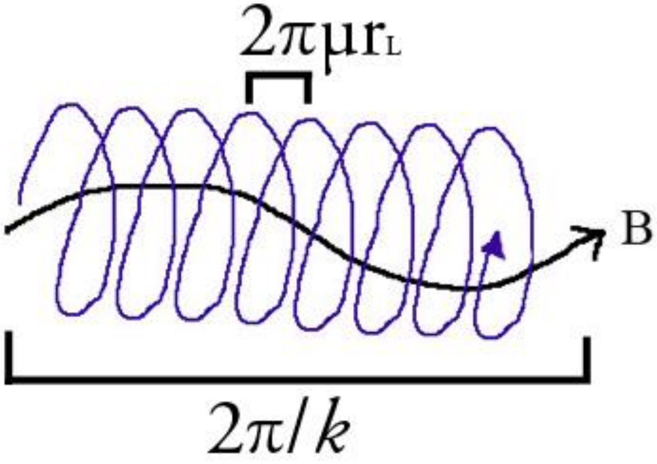
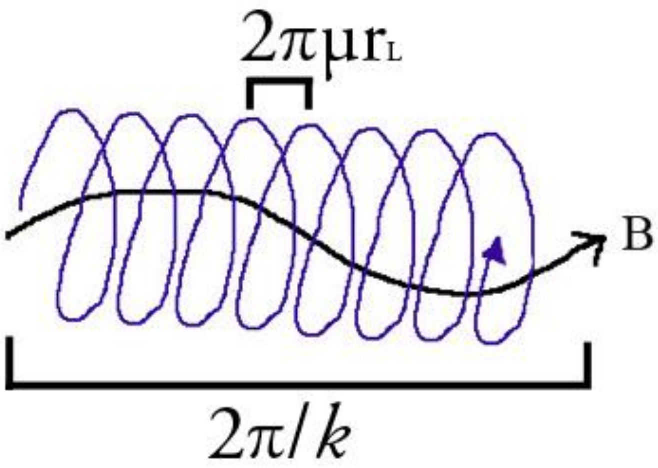




<u>Resonance condition</u>

$$k_{||} = \frac{1}{\mu r_L},\ r_L = \gamma r_0$$

Streaming Instability



Resonance condition

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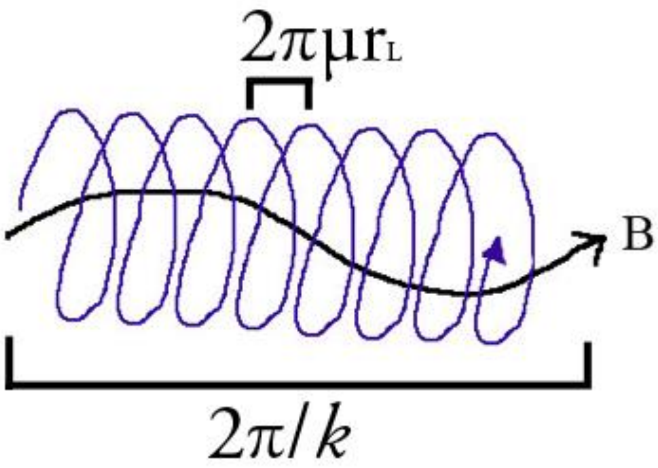

Resonance condition

$$k_{\|} = \frac{1}{\mu r_L}, \; r_L = \gamma r_0$$

Compare bulk CR drift speed $v_{\rm D}$ with Alfvén speed $v_{\rm A}$:

$$\vec{v_{\rm D}} P_{\rm c} \equiv \vec{F_{\rm c}}$$

$$v_A = \frac{B}{\sqrt{4\pi\rho}}$$

$v_{\rm D} > v_{\rm A}$ waves generated

$v_{\rm D} < v_{\rm A}$ waves damped

$v_{\rm D} = v_{\rm A}$ isotropy (no CR flux in wave frame)

Self Confinement

no waves, no scattering $\rightarrow$ $v_{\mathrm{D}} = c$

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but CRs generate waves via streaming instability, so

waves, scattering $\rightarrow$ $v_D = v_A$

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no waves, no scattering → $v_D = c$

but CRs generate waves via streaming instability, so

waves, scattering → $v_D = v_A$

More accurately, the bulk motion of CRs is determined by

$$\Gamma_{\rm growth}(v_{\rm D}) = \Gamma_{\rm damping}$$

Evolution Equations

Mass: $$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

Momentum: $$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) = -\nabla P_g - \nabla P_c - \rho \nabla \Phi$$

Energy: $$\frac{\partial E_g}{\partial t} + \nabla \cdot (E_g \mathbf{v}) = -P_g \nabla \cdot \mathbf{v} - \mathbf{v}_A \cdot \nabla P_c - n_e^2 \Lambda(T)$$

CR Energy: $$\frac{\partial E_c}{\partial t} + \nabla \cdot [E_c(\mathbf{v} + \mathbf{v_A})] = -P_c \nabla \cdot (\mathbf{v} + \mathbf{v_A}) + \mathbf{v}_A \cdot \nabla P_c + \nabla \cdot (\kappa \nabla P_c)$$

B Field: $$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

Evolution Equations

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B Field: $$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

Evolution Equation

$$\frac{\partial f_p}{\partial t} + (\mathbf{u} + \mathbf{v}_A) \cdot \nabla f_p =$$

$$\frac{1}{3} p \frac{\partial f_p}{\partial p} \nabla \cdot (\mathbf{u} + \mathbf{v}_A)$$

$$+ \frac{1}{p^3} \nabla \cdot \left(\frac{\Gamma_{\rm damp} B^2 \mathbf{n}}{4\pi^3 m_p \Omega_0 v_A} \frac{\mathbf{n} \cdot \nabla f_p}{|\mathbf{n} \cdot \nabla f_p|} \right)$$

$$- \nabla \cdot \left[\frac{v_A L_{\rm MHD}}{3} \rho^{1.5} \nabla \left(\frac{f_p}{\rho^{1.5}} \right) \right]$$

Evolution Equation

advection

$$\frac{\partial f_p}{\partial t} + (\mathbf{u} + \mathbf{v}_A) \cdot \nabla f_p =$$

compression/
expansion

$$\frac{1}{3} p \frac{\partial f_p}{\partial p} \nabla \cdot (\mathbf{u} + \mathbf{v}_A)$$

streaming

$$+ \frac{1}{p^3} \nabla \cdot \left(\frac{\Gamma_{\rm damp} B^2 \mathbf{n}}{4\pi^3 m_p \Omega_0 v_A} \frac{\mathbf{n} \cdot \nabla f_p}{|\mathbf{n} \cdot \nabla f_p|} \right)$$

turbulent
mixing

$$- \nabla \cdot \left[\frac{v_A L_{\rm MHD}}{3} \rho^{1.5} \nabla \left(\frac{f_p}{\rho^{1.5}} \right) \right]$$

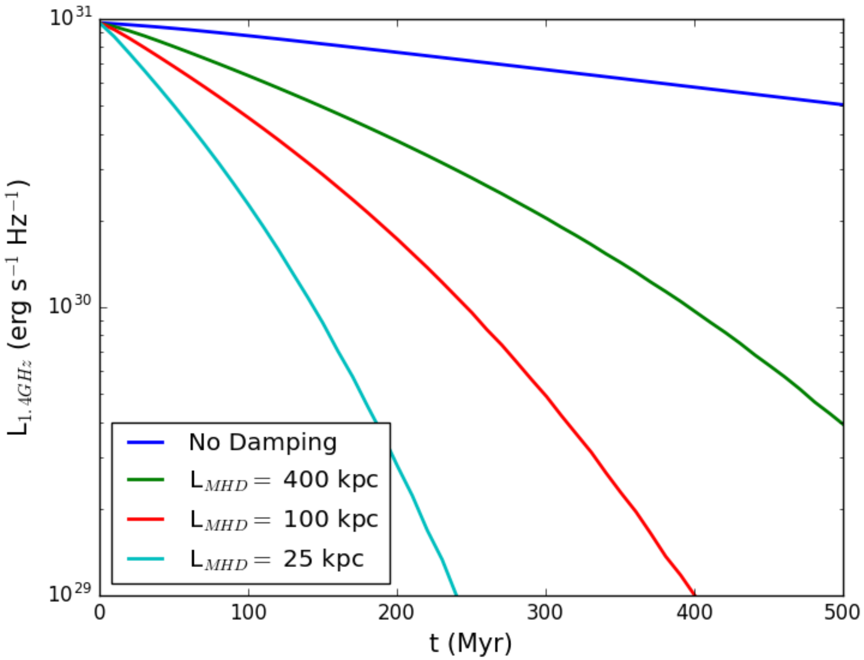
Goal:

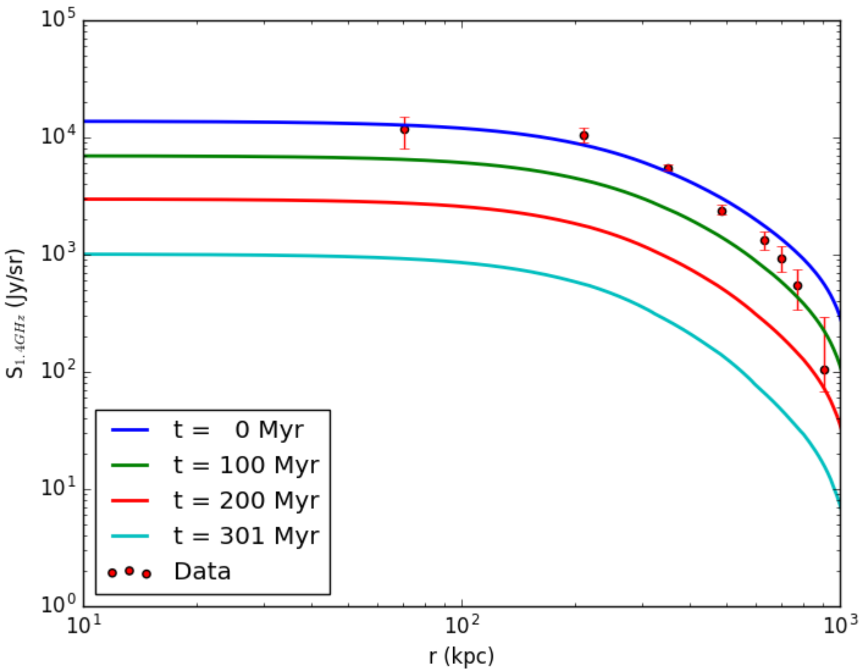
With the above simple physics, what happens to radio and gamma emission in galaxy clusters over time?

Method:

Spherically symmetric 1D simulations of CR streaming in individual galaxy clusters using ZEUS

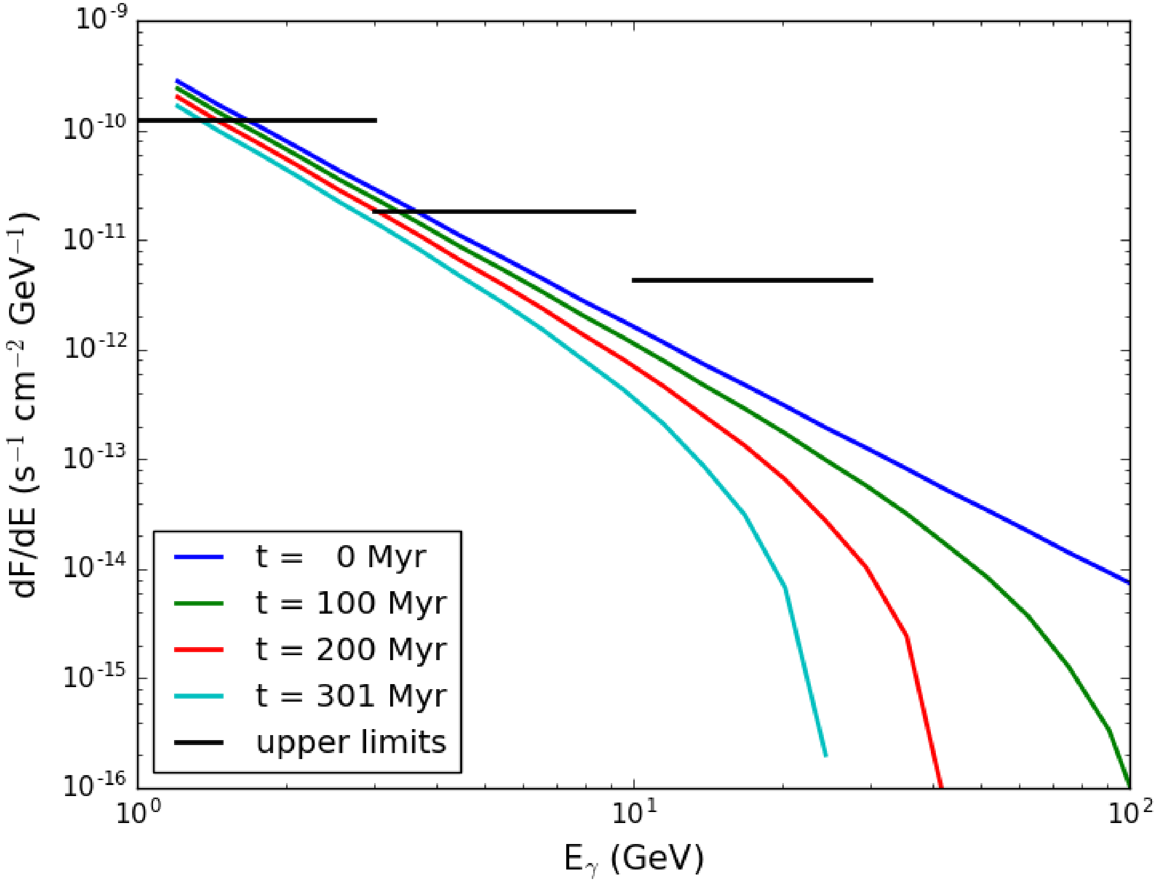
Coma Cluster Radio Emission





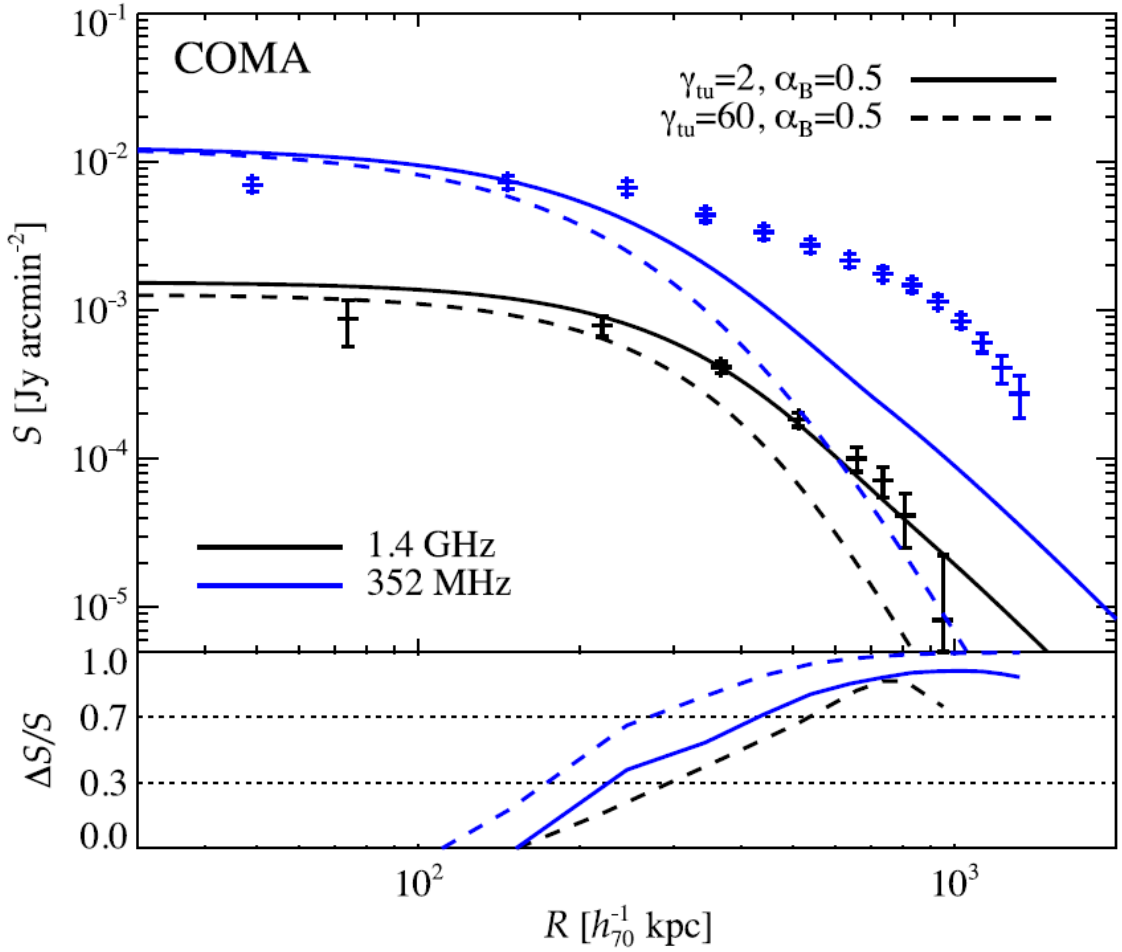
*Observations from Deiss et al 1997 (Effelsberg 100-m telescope)

Coma Cluster γ-ray Emission



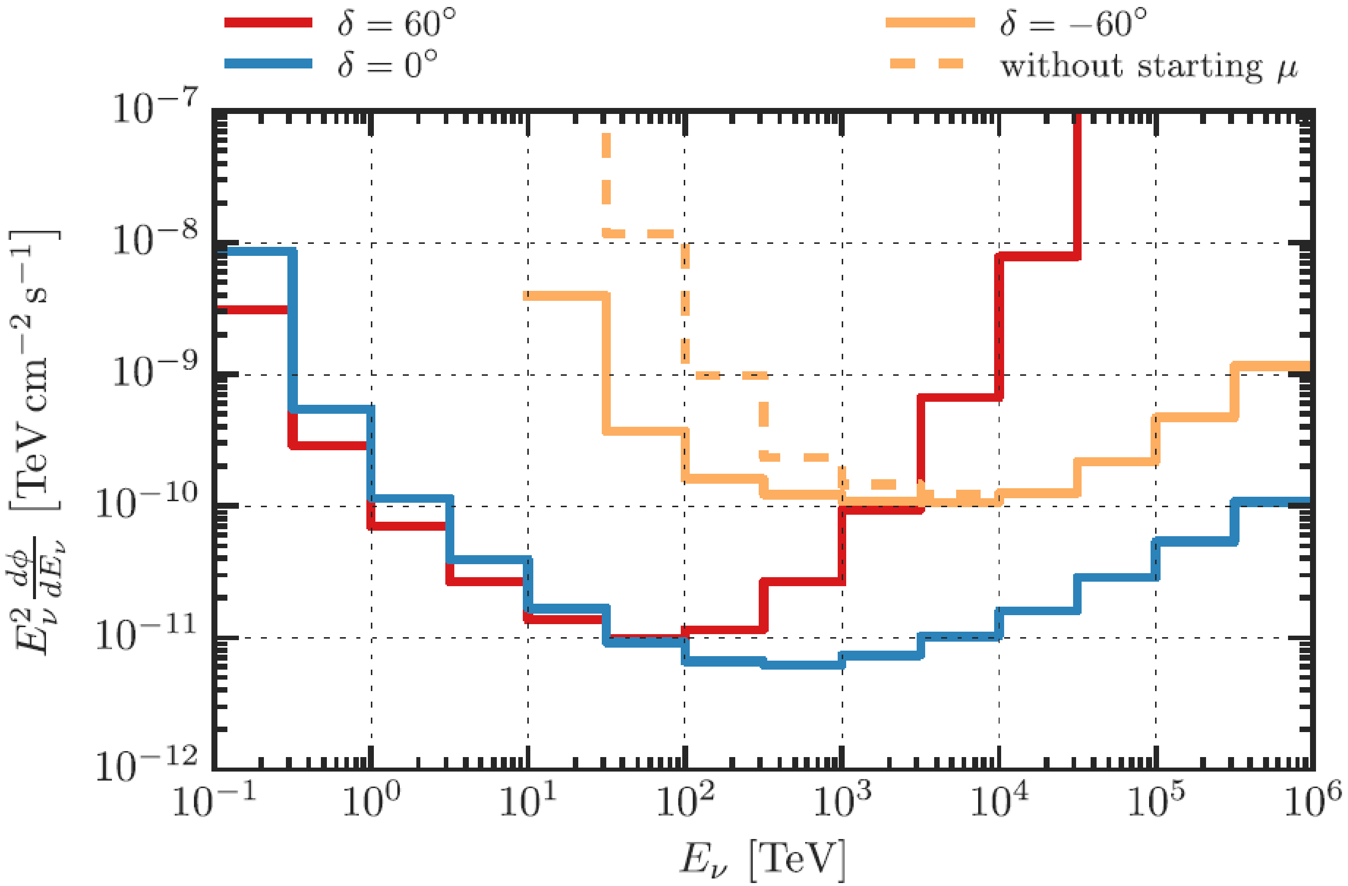
*Upper limits from Arlen et al 2012 (*Fermi* and VERITAS)

Problem: Lower Frequencies



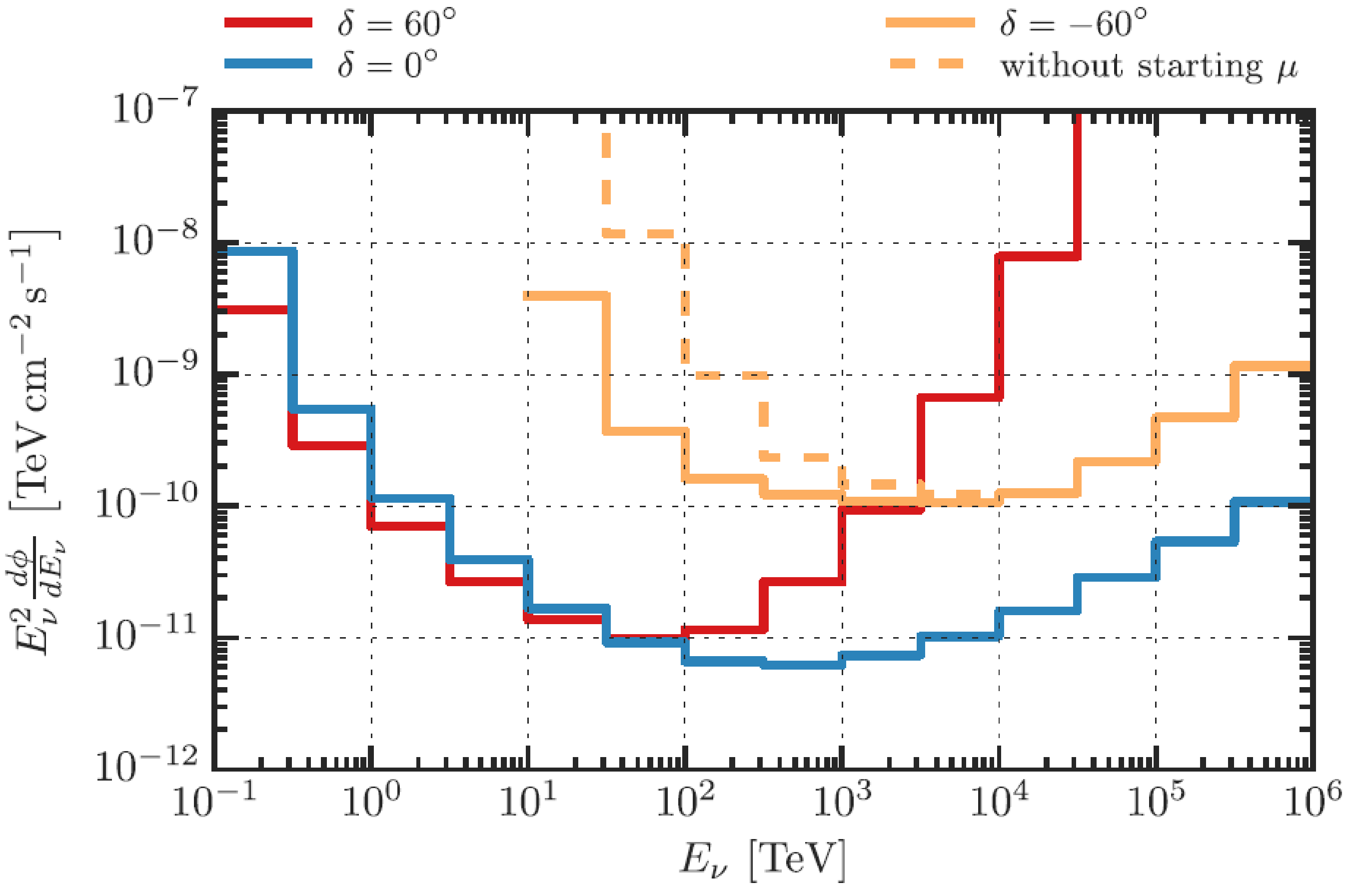
*352 MHz: Brown and Rudnick 2011 (WSRT)

Coma Cluster Neutrino Emission?



*Aartsen et al 2017

Coma Cluster Neutrino Emission?



*Aartsen et al 2017

Preliminary Coma prediction

Conclusions

1. CR distribution in Coma cluster is spatially very flat
2. Reasonable levels of wave damping can dim Coma's radio halo on time scales of 100s of Myr

Limitations

1. Assumptions made about *B*-field strength and topology affect results
2. Low frequency data cannot be explained
3. Gamma ray non-detections are getting more and more restrictive