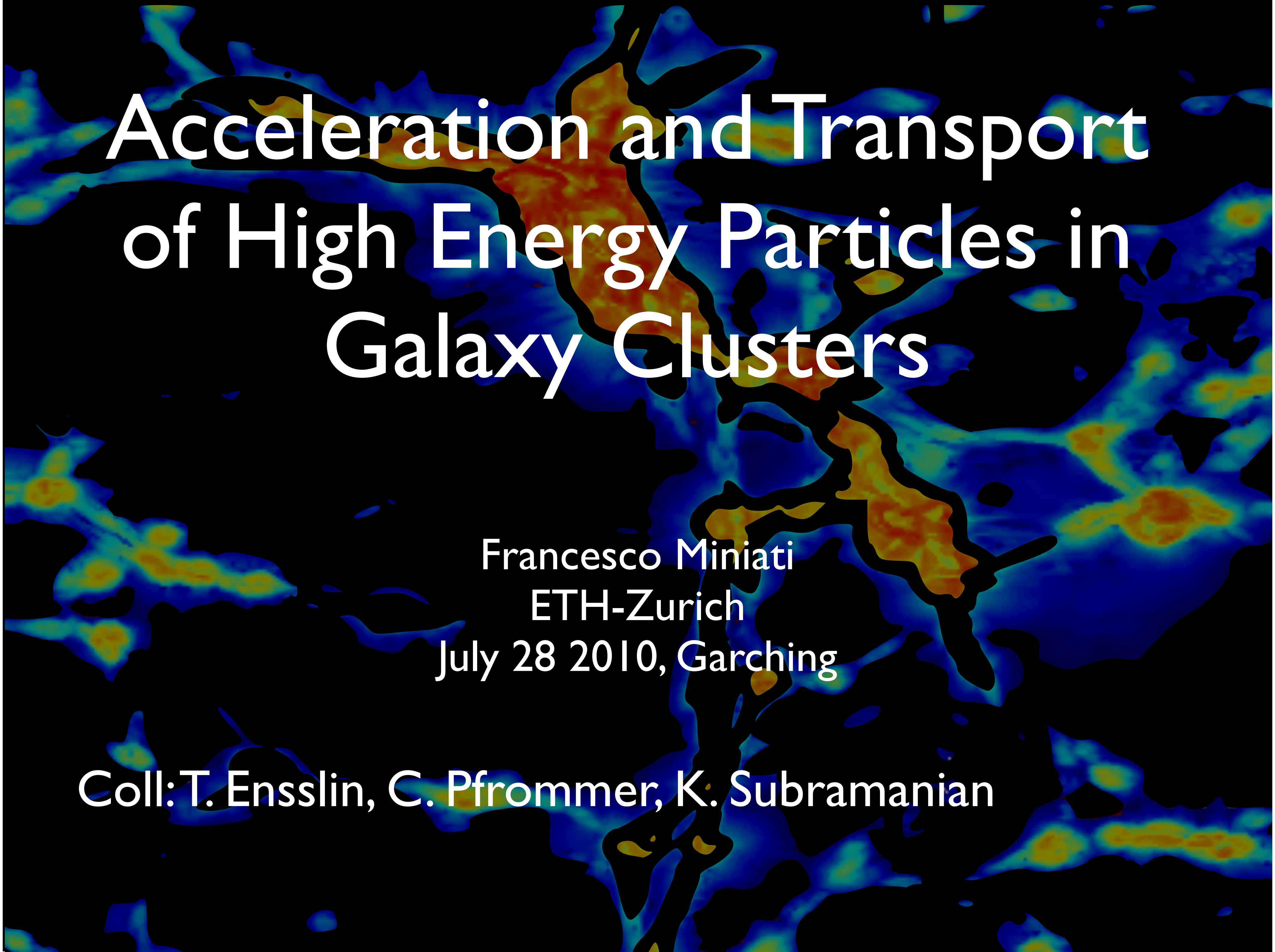


Acceleration and Transport of High Energy Particles in Galaxy Clusters

Francesco Miniati
ETH-Zurich
July 28 2010, Garching

Coll: T. Ensslin, C. Pfrommer, K. Subramanian

Focus of this talk

$$r_g(p) = \frac{pc}{eB} \simeq 3\times 10^{12}\left(\frac{pc}{\mathrm{GeV}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)\mathrm{cm}$$

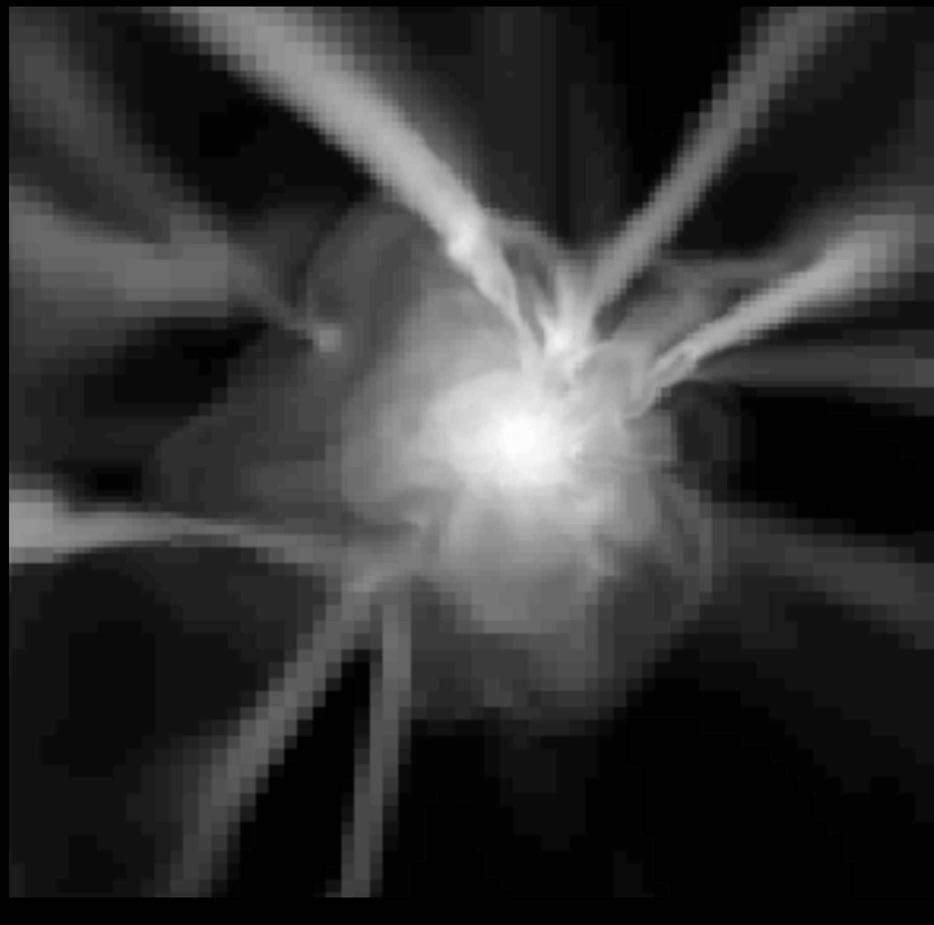
$$= 10^{-6}\ \mathrm{pc}$$

Microscale-Astrophysics of Galaxy Clusters

Cluster Shocks

Structure formation shocks have high Mach numbers (Miniati+ 2000, Ryu+ 2003, Pfrommer+ 2005, Skillman+ 2008)

Shocks classes :
Internal M~4-5
External M ≥ 10



Collisionless shocks dissipate into CRs (Krymsky 1977, Skadron+ 1977, Bell1978, Balndford & Ostriker 1978)

Non-thermal Emission

Straightforward Predictions:

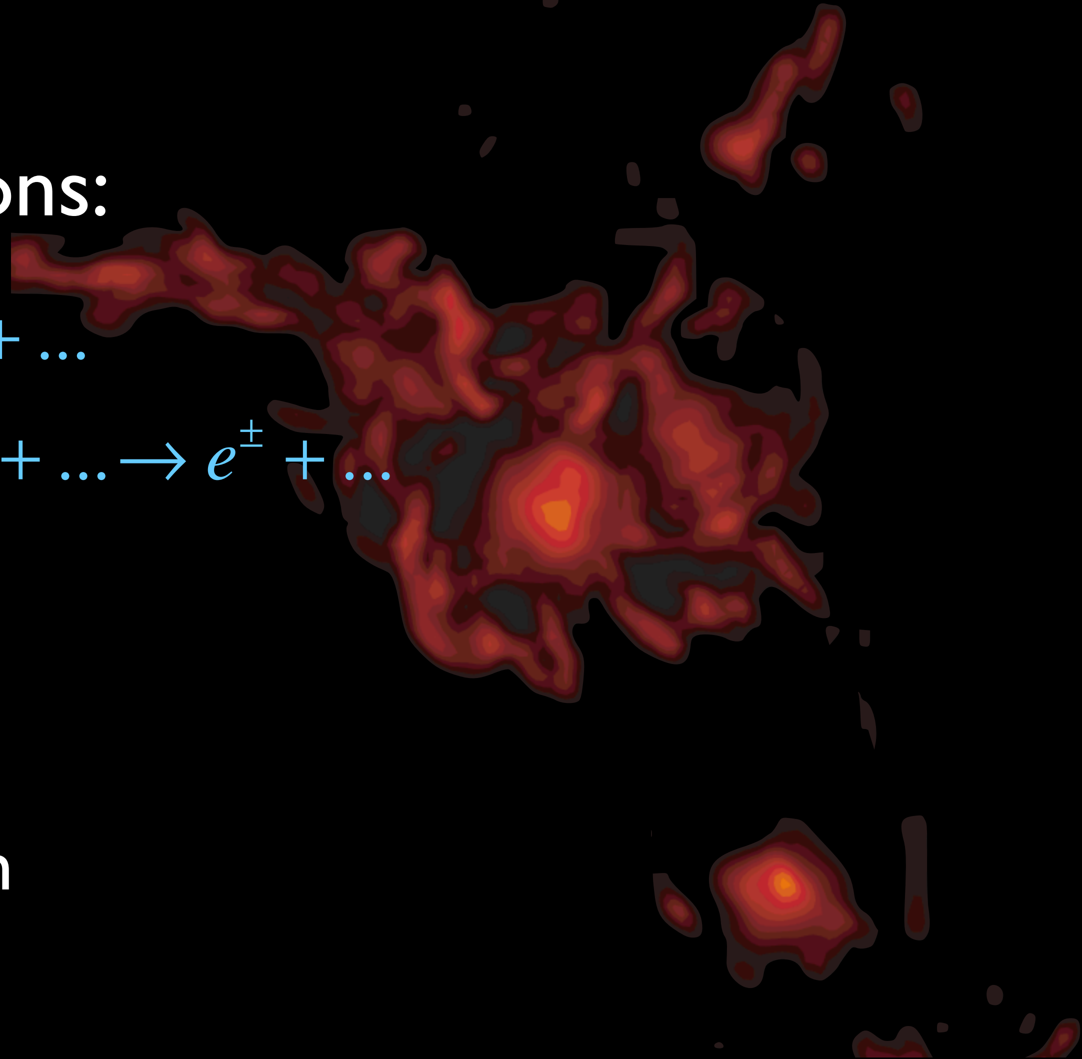
$$p_{CR}\, p_{ICM} \nearrow \pi^0 + \ldots \rightarrow \gamma\gamma + \ldots$$

$$p_{CR}\, p_{ICM} \searrow \pi^\pm + \ldots \rightarrow \mu^\pm + \ldots \rightarrow e^\pm + \ldots$$

i) gamma-ray emission

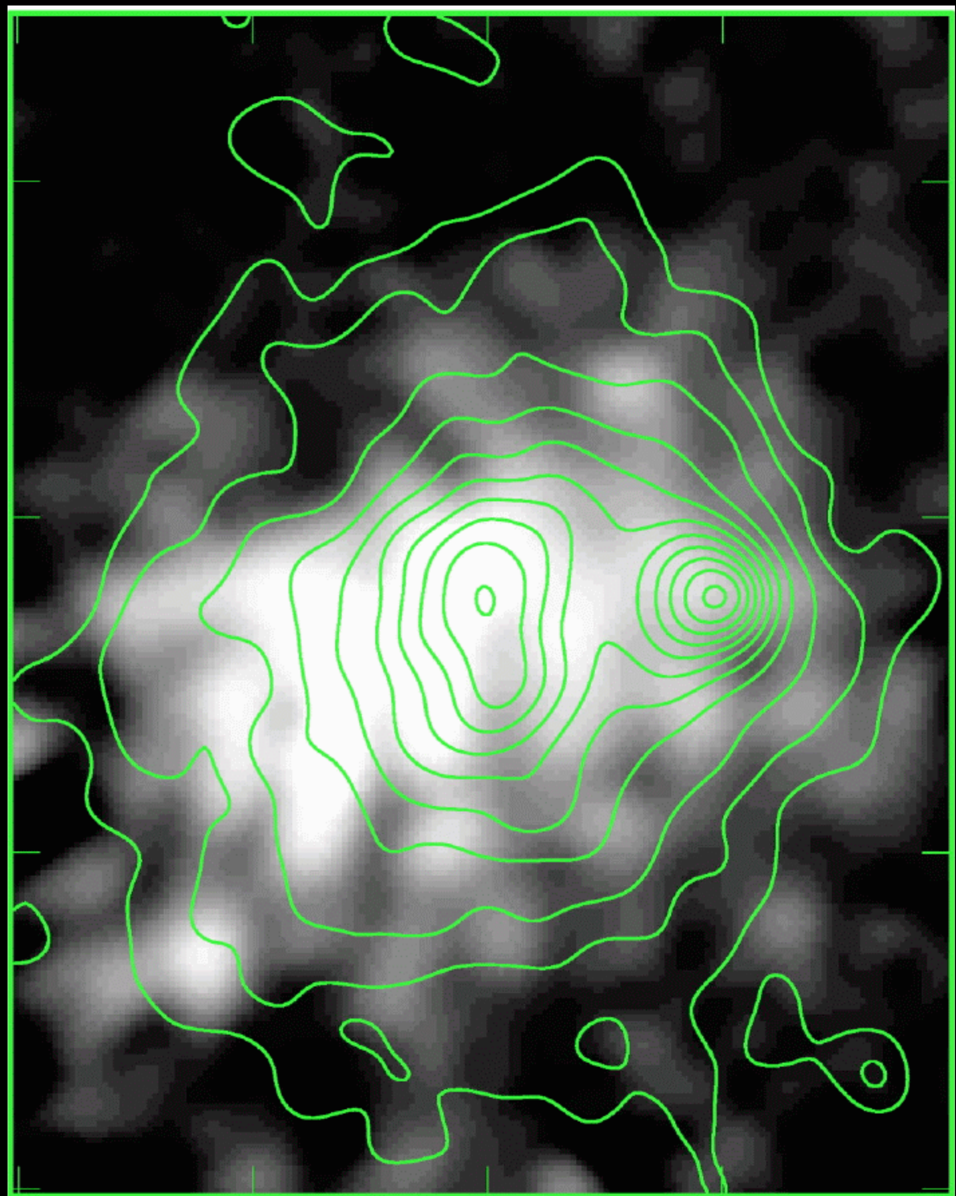
ii) radio emission

gamma-ray upper limits from
Fermi, H.E.S.S, MAGIC

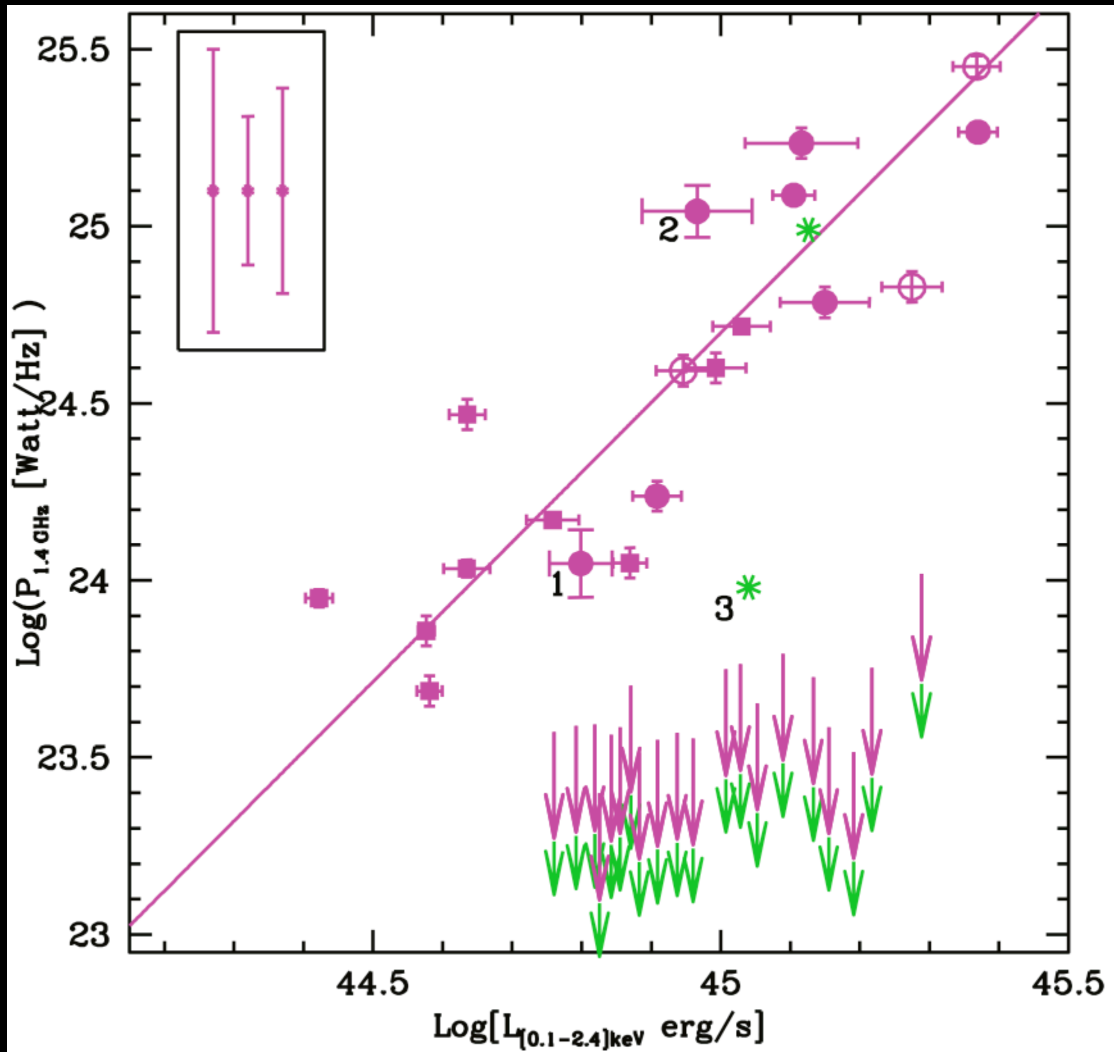


Miniati 2003

Bullet Cluster at Radio WL



Bimodality in Cluster Diffuse Radio Emission



Brunetti et al. (2007)

What’s wrong ?

Simulation results based on following simple assumptions:

A. Accretion shocks accelerate CR protons

B. Magnetic fields are seeded at high-z more or less uniformly

C. CRs diffusion negligible (CRs tied up to ICM by B)

What's wrong ?

Simulation results based on following simple assumptions:

A. Accretion shocks accelerate CR protons

B. Magnetic fields are seeded at high-z more or less uniformly

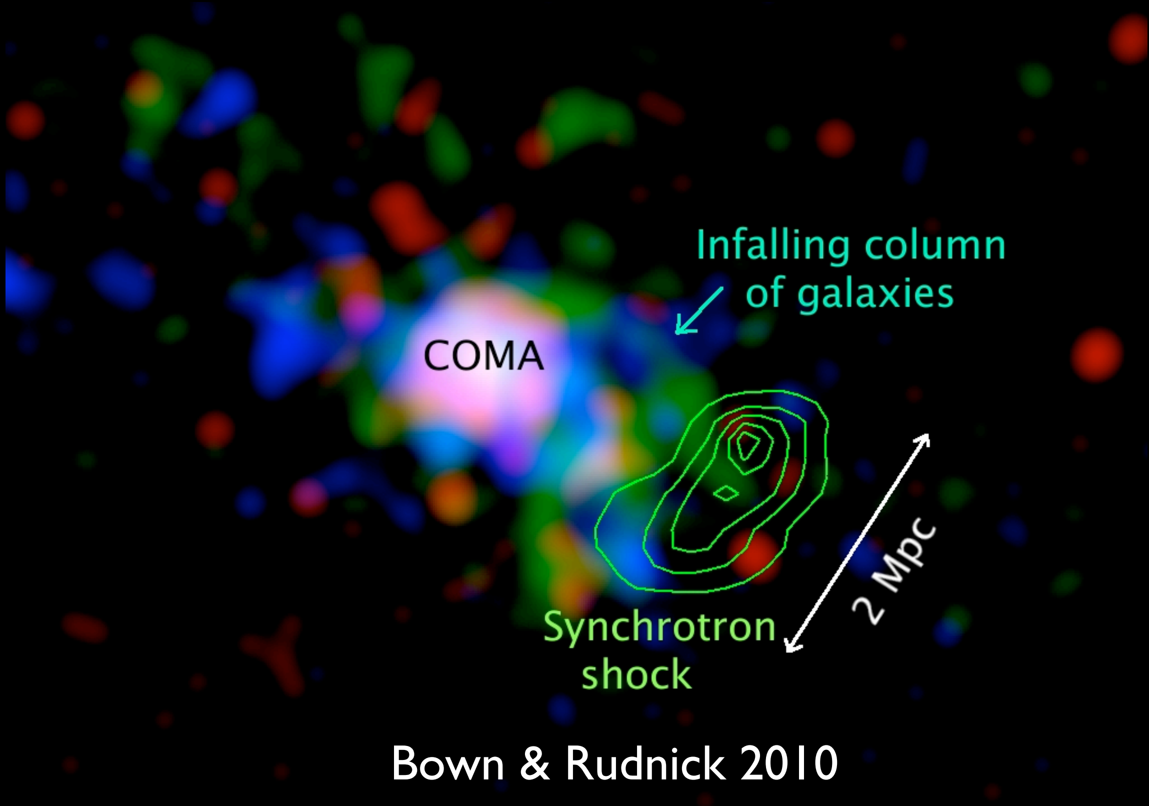
C. CRs diffusion negligible (CRs tied to ICM by B)

(A): Accretion shocks accelerate CR protons(?)

- SNRs
- radio relics show that e^- are accelerated at cosmic shocks
- Particle-in-Cell simulations indicate that at least relativistic collision-less shocks produce supra-thermal particles even if initially unmagnetized (e.g. Spitosky 2008)

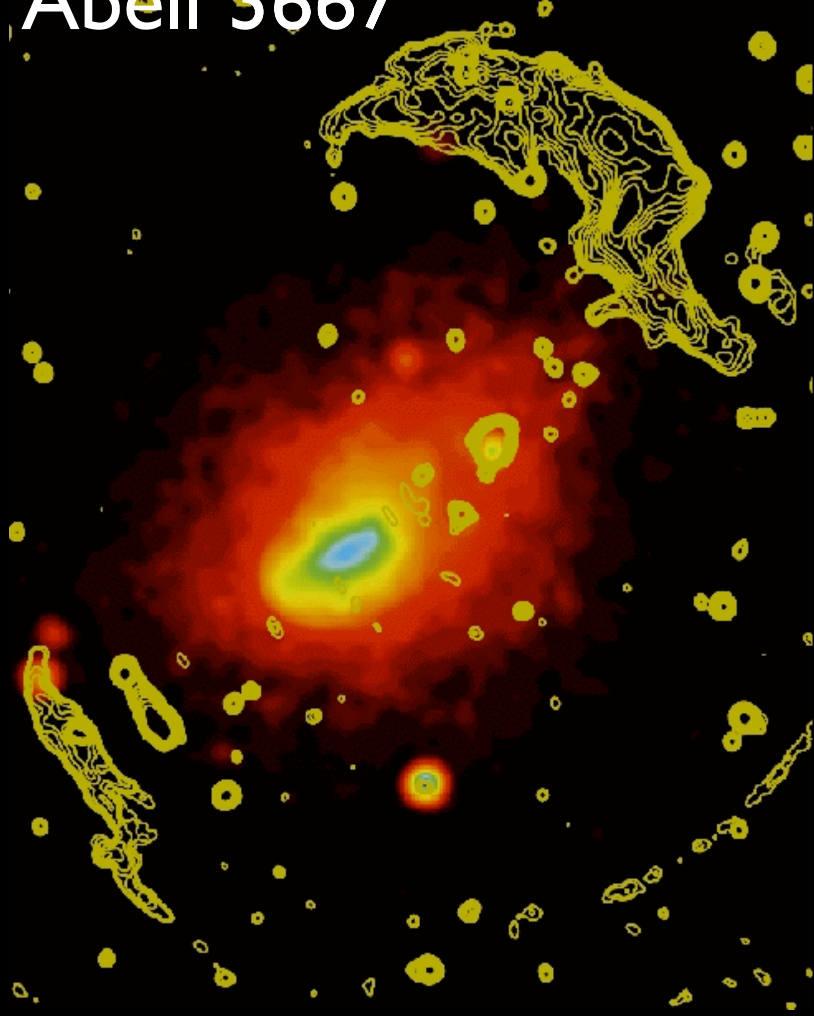
CR are accelerated at filament termination shocks

Relic Radio Emission



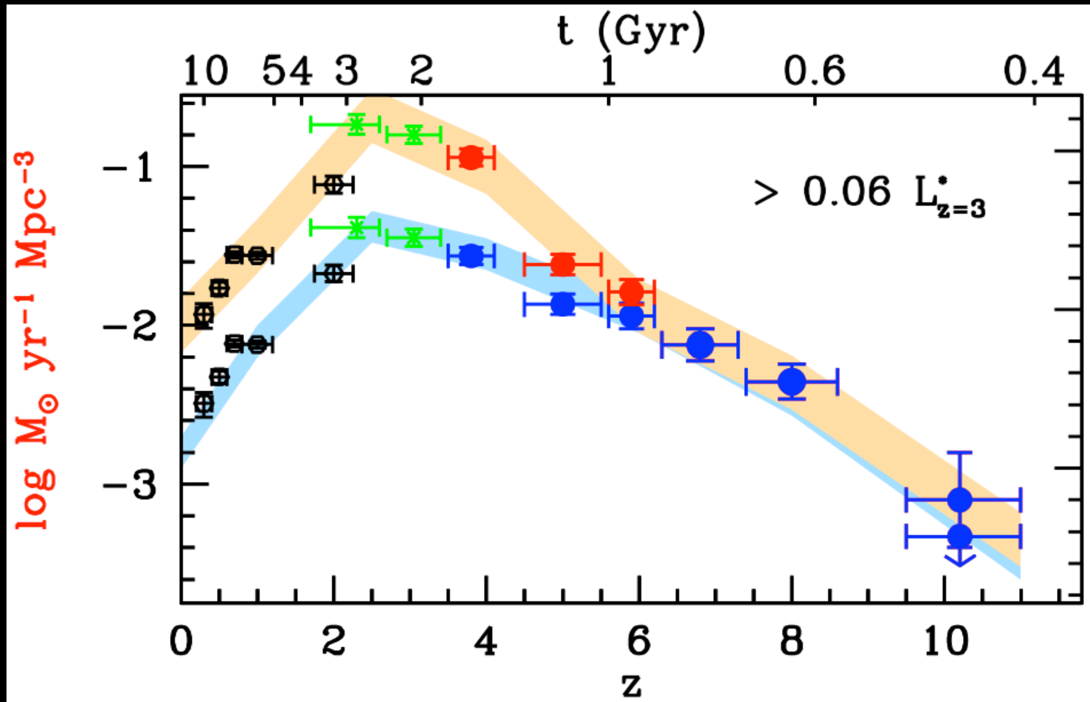
Bown & Rudnick 2010

Abell 3667



credits to M. Johnston-Hollitt

CRs from Galaxies



Bouwens et al 2010

For example, Voelk et al (1996) find P_{CR}/P_{th}~ 5-10%

What's wrong ?

Simulation results based on following simple assumptions:

A. Accretion shocks accelerate CR protons
B. Magnetic fields are seeded at high-z more or less uniformly
C. CRs diffusion negligible (CRs tied to ICM by B)

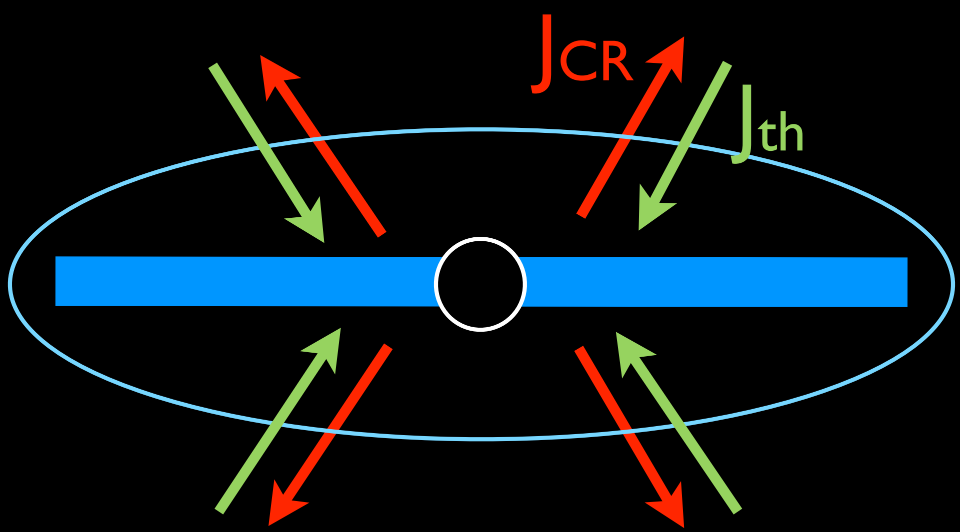
(B):Bimodality in B-field

$$j_{synch} \propto n_{CR}(E)\frac{B^2}{B^2 + B_{CMB}^2}$$

- non radio-halos GCs have μG magnetic fields (RM, from Clarke et al. 2001, 2004)
- magnetic seeds are probably generated uniformly in the proto-cluster regions (Miniati & Bell 2010, Kulsrud+ 1997, Gnedin + 2000, Vogt+2005, Donnert+2009)

Resistive Mechanism

Miniati & Bell 2010 (arXiv:1001.2011)



CR current, j_{cr}, drives a return current in the thermal plasma, j_{th}, that tends to cancel j_{cr} itself.

$$\vec{E}' = \frac{\vec{j}_{th}}{\sigma},$$

$$\sigma_{Spitzer} \simeq 10^7 \left(\frac{T}{K}\right)^{3/2} s^{-1}$$

$$\frac{\partial \vec{B}}{\partial t} = -c\vec{\nabla} \times \vec{E} \approx 10^{-16} \frac{\mathrm{G}}{\mathrm{Gyr}}$$

What's wrong ?

Simulation results based on following simple assumptions:

A. Accretion shocks accelerate CR protons

B. Magnetic fields are seeded at high-z more or less uniformly

C. CRs diffusion negligible (CRs tied to ICM by B)

(C:) CR diffusion negligibly small ?

Voelk et al (1996):

- fluctuations $\frac{\delta B}{B} \sim 1$ driven by galaxy motions
- fluctuations extend down to the gyration radius of CR particles, i.e.:

$$r_g(p) = \frac{pc}{eB} \simeq 3 \times 10^{12} \left(\frac{pc}{\mathrm{GeV}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)\mathrm{cm}$$

(C:) CR diffusion negligibly small ?

- However, this neglects damping of the waves by plasma effects, e.g. transit-time damping, cyclotron resonance, non-linear Landau damping...
- For example during a merger when the turbulent motions are high, Brunetti & Lazarian (2007) estimate a cutoff of the power spectrum of the magnetosonic waves:

$$\lambda_{cutoff} = \frac{1}{3}\mathrm{kpc} \gg r_g \sim 10^{-9}\,\mathrm{kpc}$$

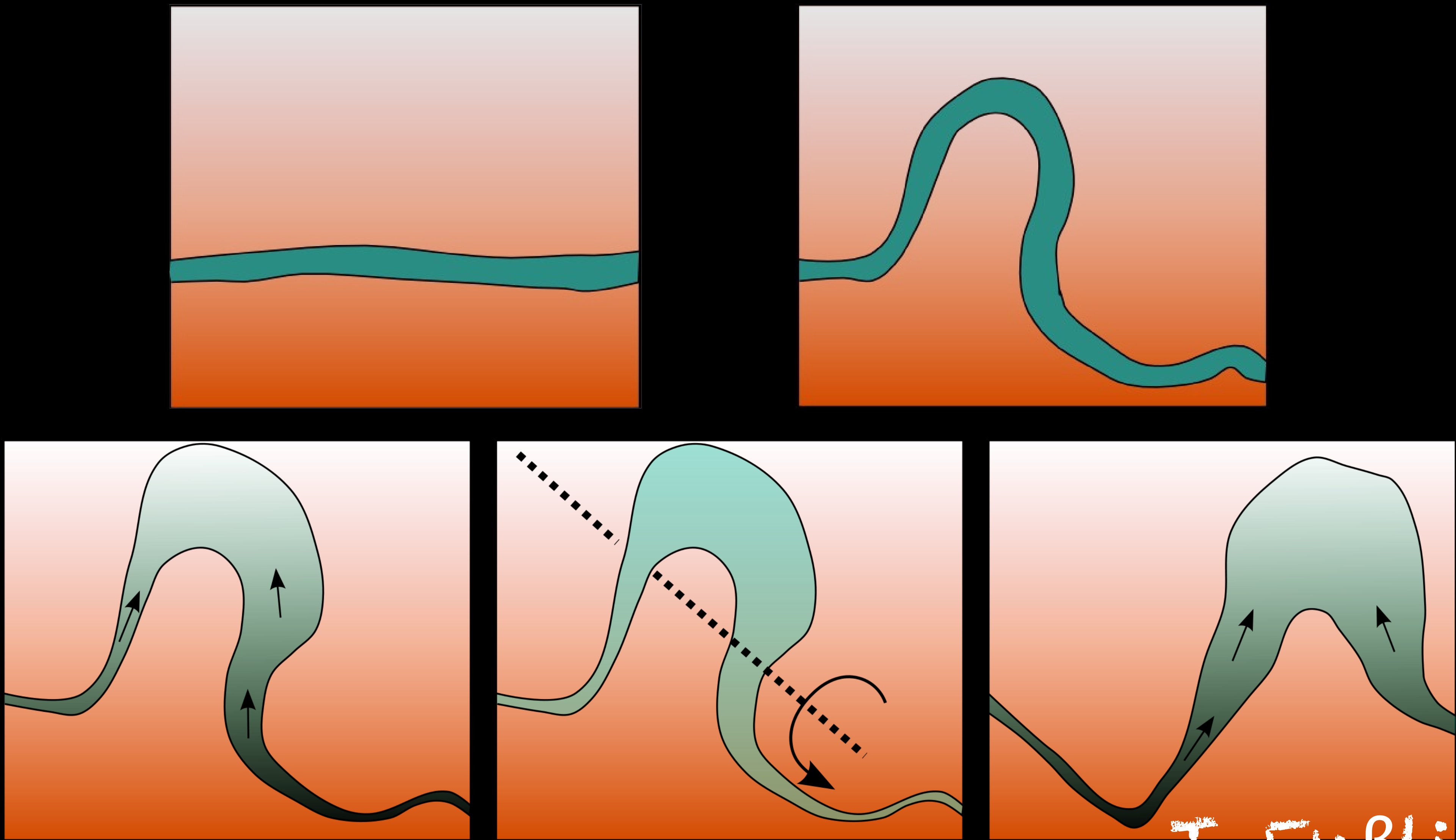
(C:) CR diffusion negligibly small ?

- After the merger has relaxed, the turbulence level decreases significantly and things get even worse, i.e. damping significant at even larger wavelengths.
- At this two effects are important:

i) streaming of CRs generates the necessary scattering (Achterberg 1981, Foote&Kulsrud 1979, Yan&Lazarian 2008)

ii) mirroring from bent magnetic fields lines

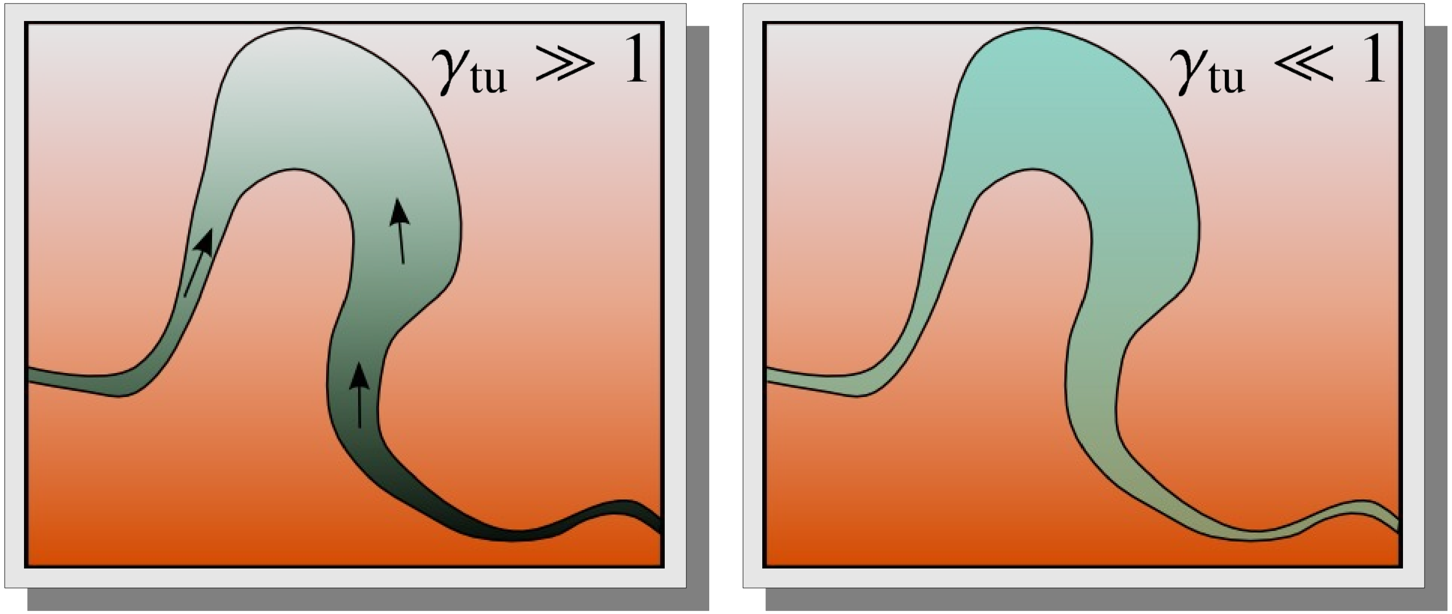
Rolling Flux-tubes



T. Enßlin

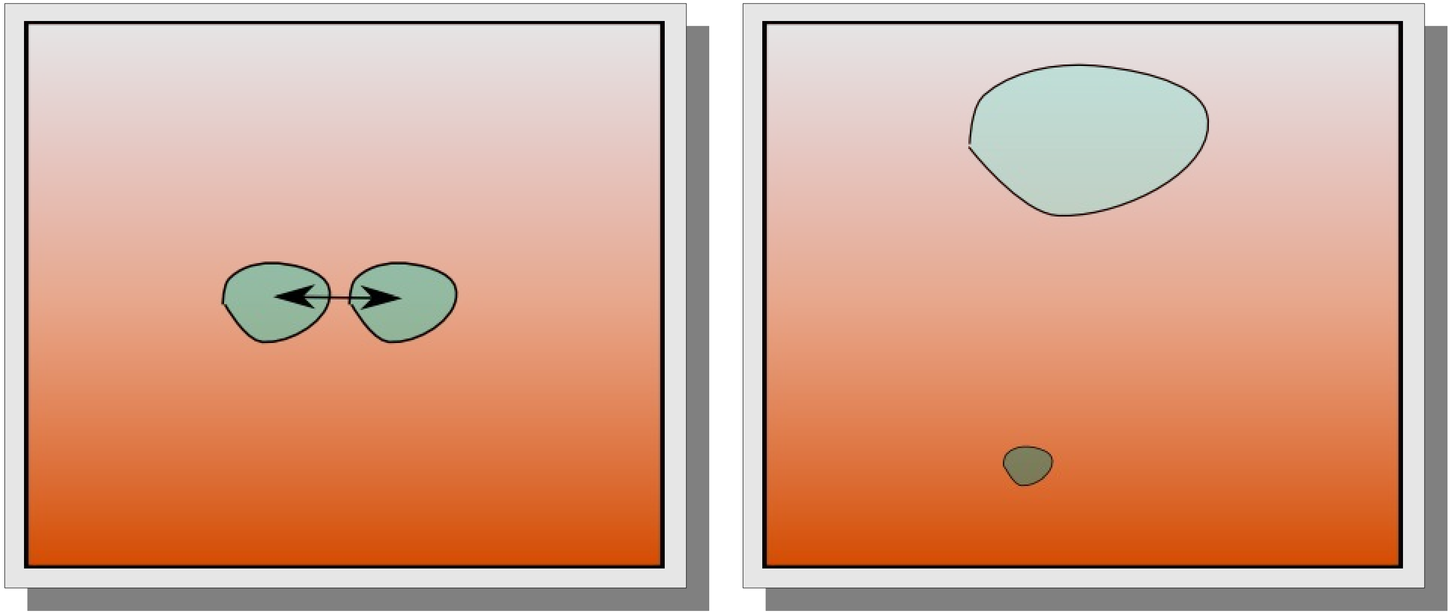
turbulent to streaming ratio

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



CR profile due to advection

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



CR profile

$$f_{CR} : x_1 \rightarrow x_2 \qquad \rho_{CR}(x_1) \rightarrow \rho_{CR}(x_2) = \rho_{CR}(x_1)\left(\frac{P_2}{P_1}\right)^{1/\gamma}$$

$$\frac{\rho_{CR}(x_2)}{\rho_{CR}(x_1)} = \left(\frac{P_2}{P_1}\right)^{1/\gamma}$$

CR transport model

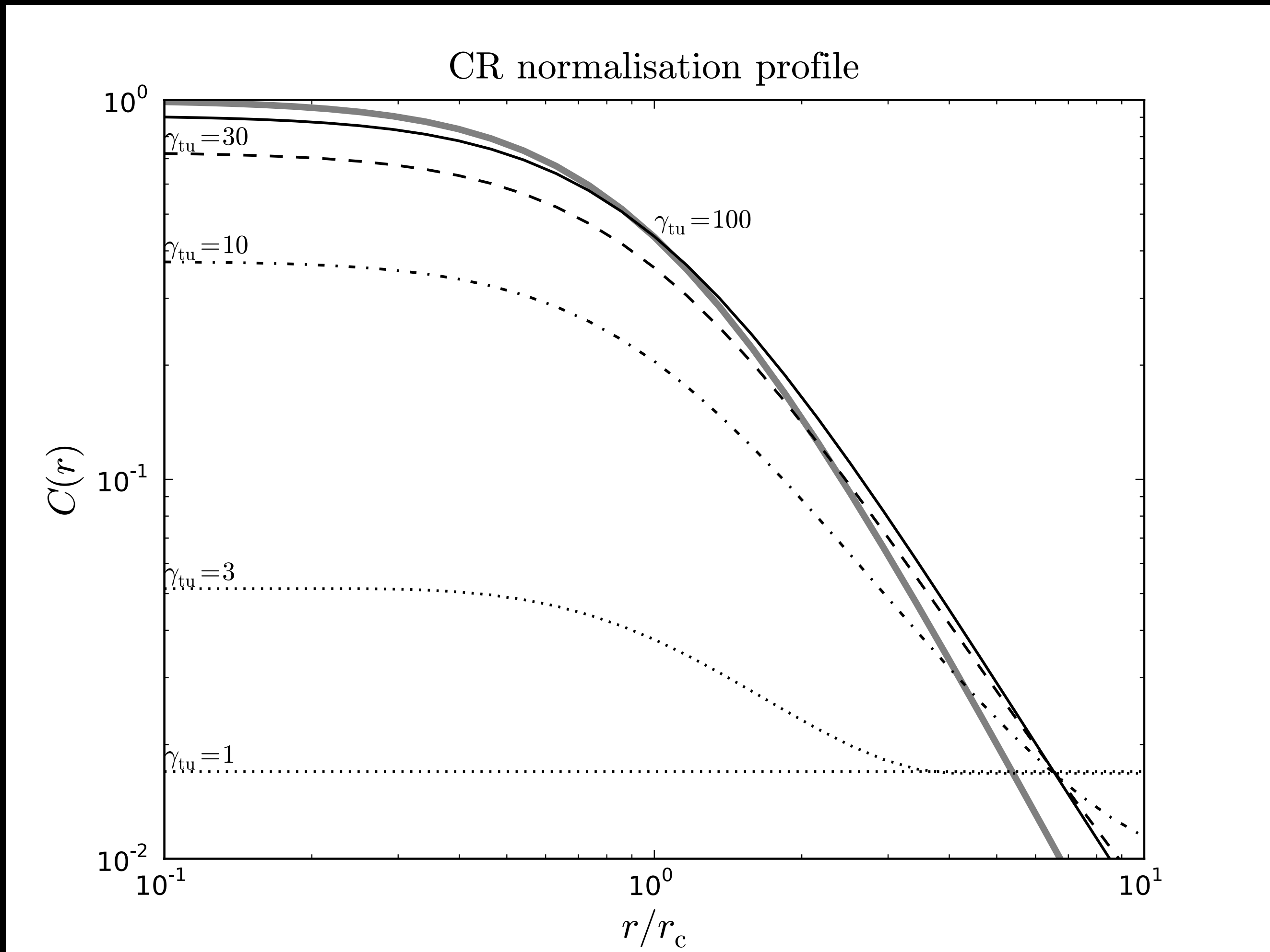
$$\frac{\partial \rho_{CR}}{\partial t} = \vec{\nabla} \cdot \left(\rho_{CR} \vec{u}_{CR} \right) \qquad \vec{u}_{CR} = \vec{u}_{st} + \vec{u}_{ad} + \vec{u}_{di}$$

$$\vec{u}_{st} = -u_{st} \frac{\vec{\nabla} \rho_{CR}}{\left| \vec{\nabla} \rho_{CR} \right|}$$

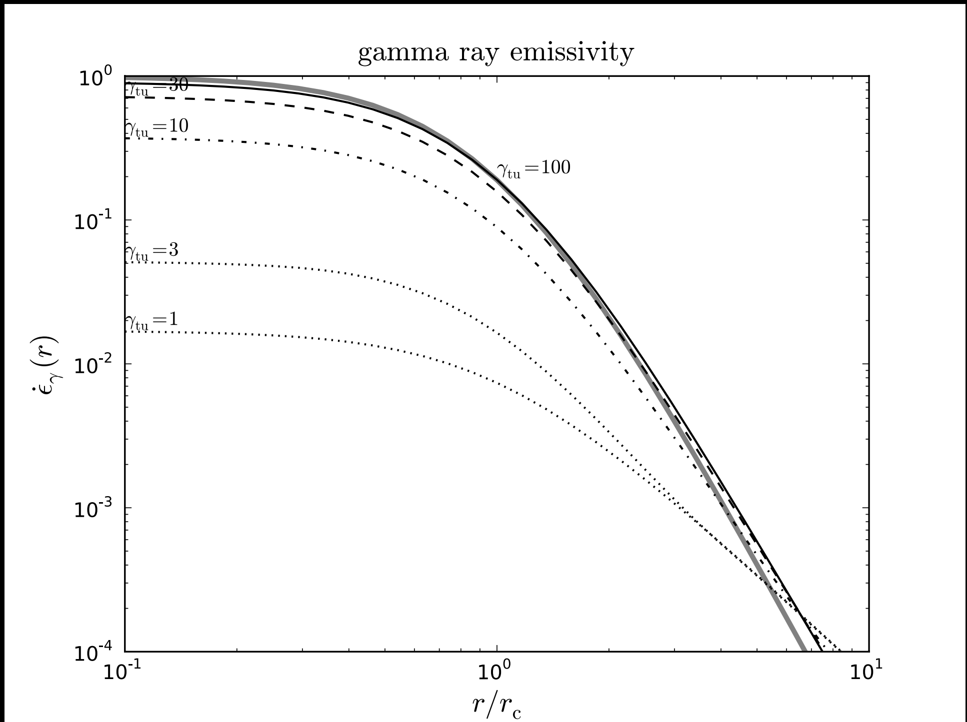
$$\vec{u}_{ad} = -\kappa_{tu} \vec{\nabla} \ln \frac{\rho_{CR}}{\eta} \qquad \kappa_{tu} = \frac{L_{tu} u_{tu}}{3}$$

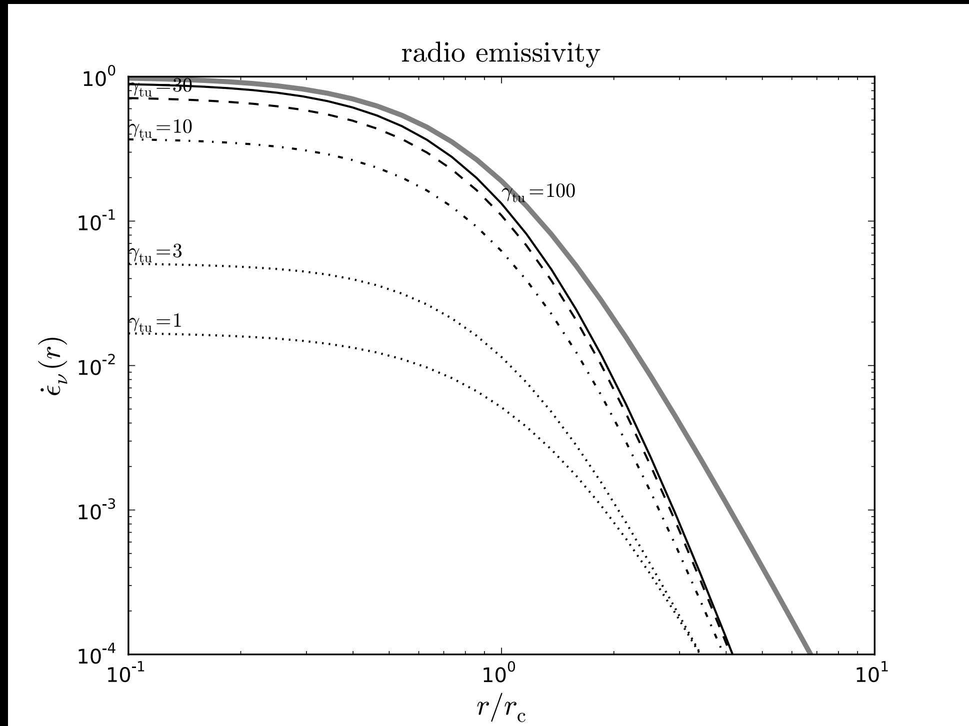
$$\vec{u}_{st} = -\kappa_{di} \vec{\nabla} \ln \rho_{CR}$$

CR Spatial Distribution



Gamma-ray, Synchrotron Emissivities





Summary

A. Not yet in a position to rule out acceleration of CR protons at structure formation shocks

B. no problem with seeding the magnetic field

C. Assumption that CR diffusion in GCs is negligibly small is most likely an oversimplification. CR transport in ICM needs important revision, with essential input from both theory and simulations.

D. Radio halo emission powered by hadronic interactions switch-off timescales depend on streaming of CRs and magnetic field lines topology after the merger has settled