

Fossil AGN as ultra high energy particle accelerators

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*Work done in collaboration with **Gregory Benford***

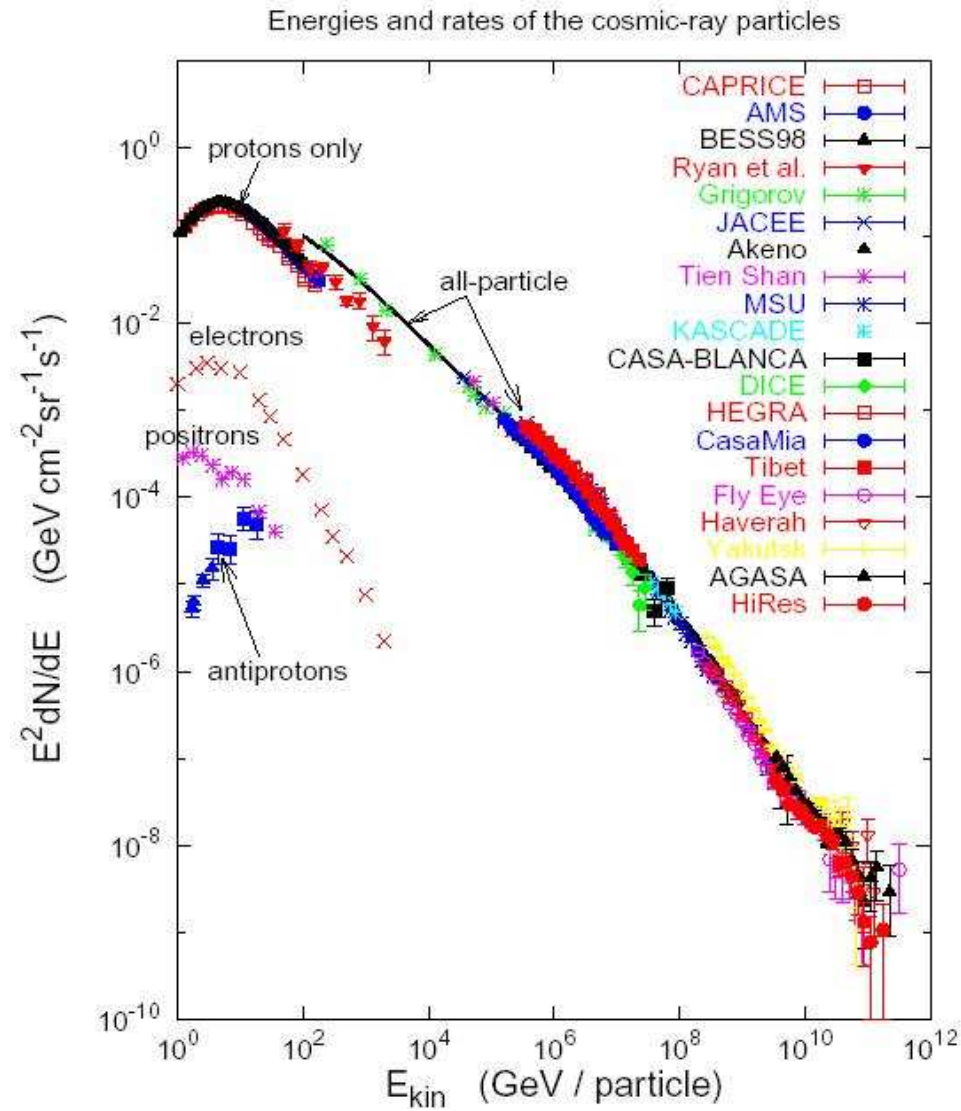
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Contents

1	Cosmic Rays	3
1.1	Extragalactic cosmic rays at Ultra High Energy (UHE)	4
1.2	Possible sites of cosmic ray acceleration	5
2	COLOSSAL MAGNETIC STRUCTURES BUILT BY A.G.N.	6

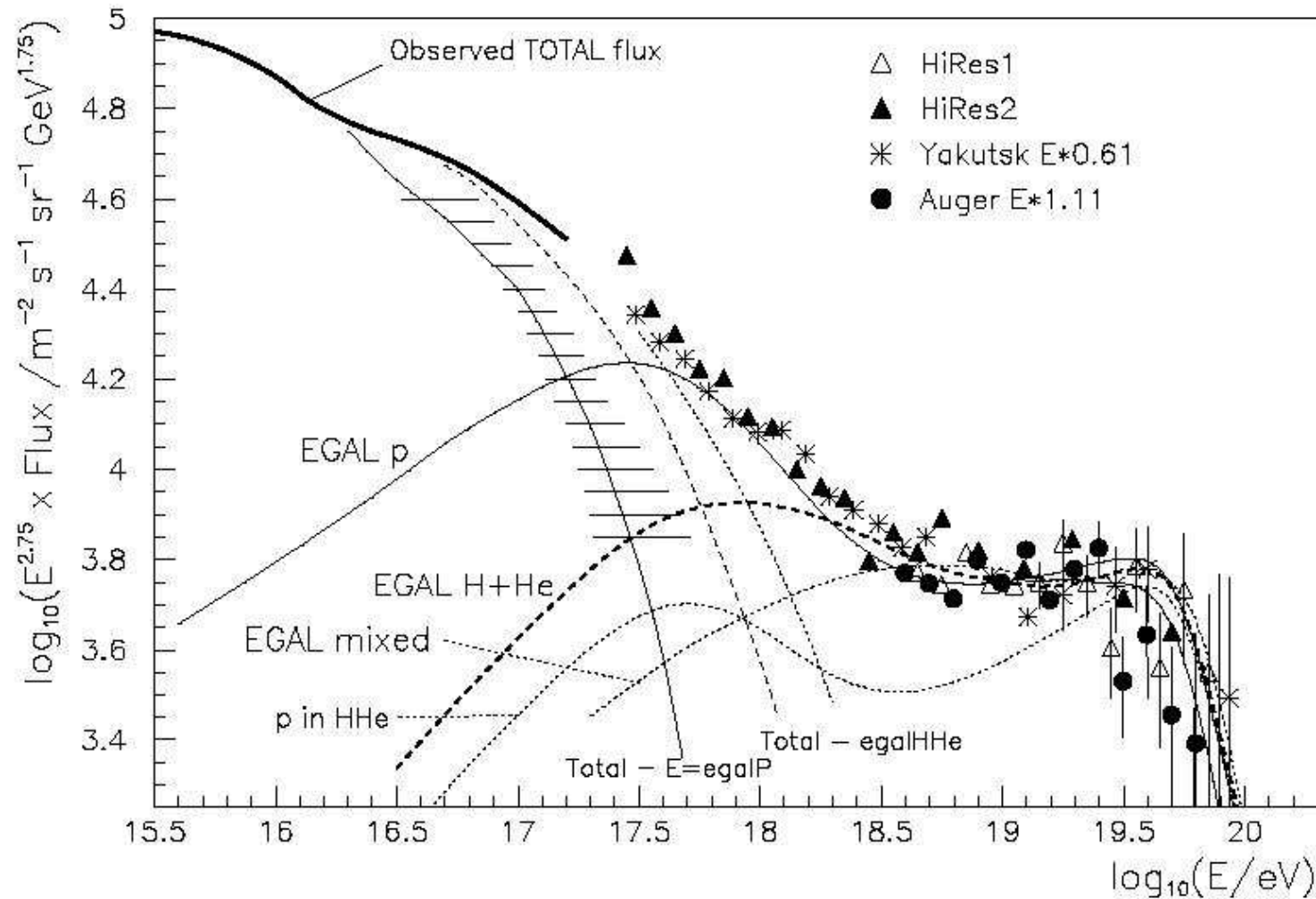
3	COSMIC RAY ACCELERATION BY FOSSIL A.G.N. JETS	11
3.1	Energetics	18
4	REMAINING QUESTIONS AND FUTURE WORK	20
5	CONCLUSIONS	21

1 Cosmic Rays



From the review by Hillas (2006).

1.1 Extragalactic cosmic rays at Ultra High Energy (UHE)

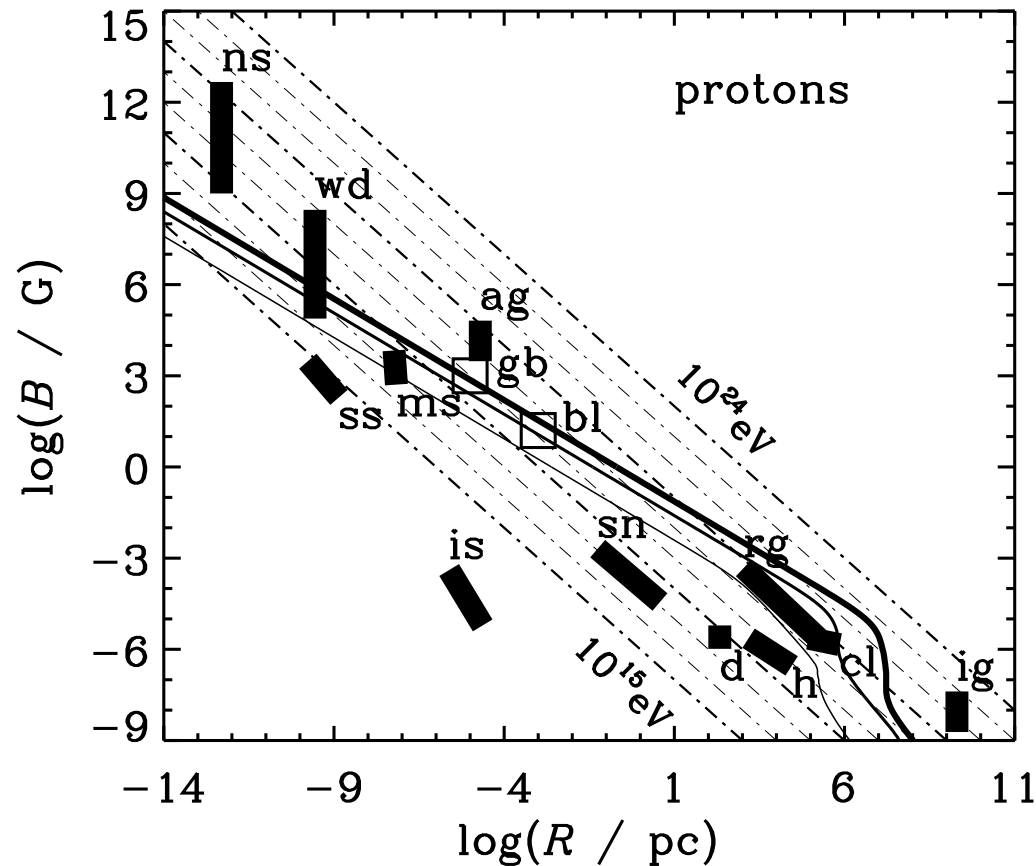


From the review by Hillas (2006).

1.2 Possible sites of cosmic ray acceleration

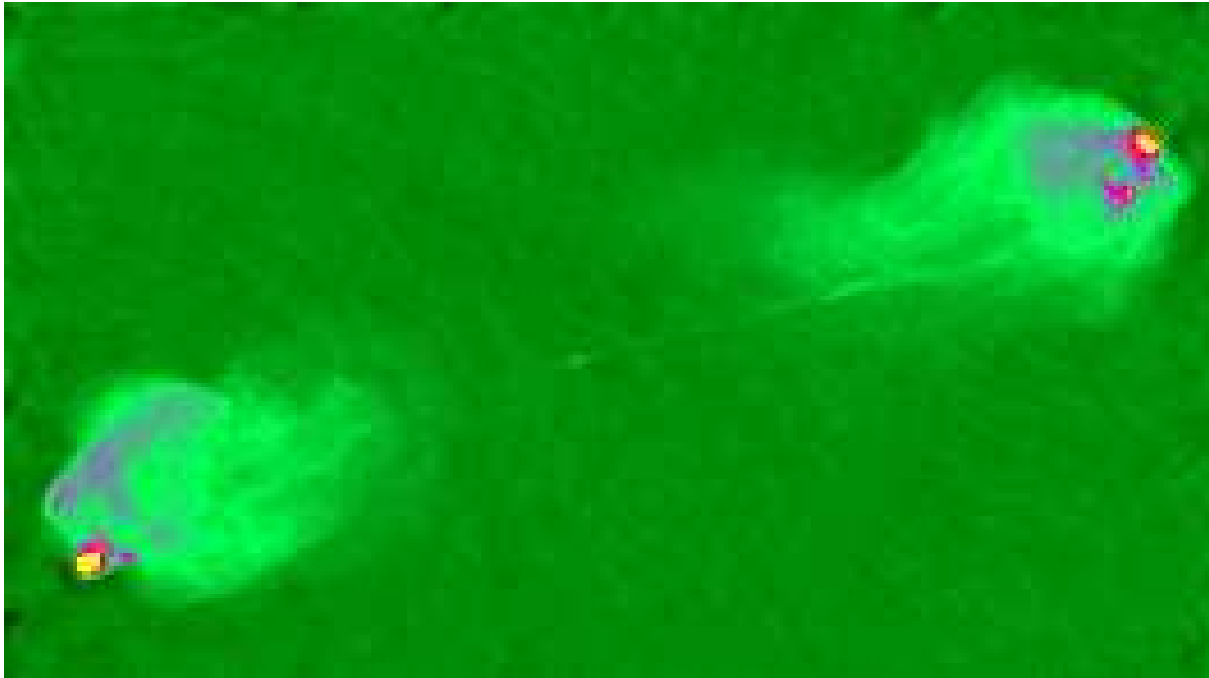
“Hillas plot” showing B and size of sources, and B vs. r_{gyro} (chain curves).

Origin of Extragalactic UHE CR remains uncertain.

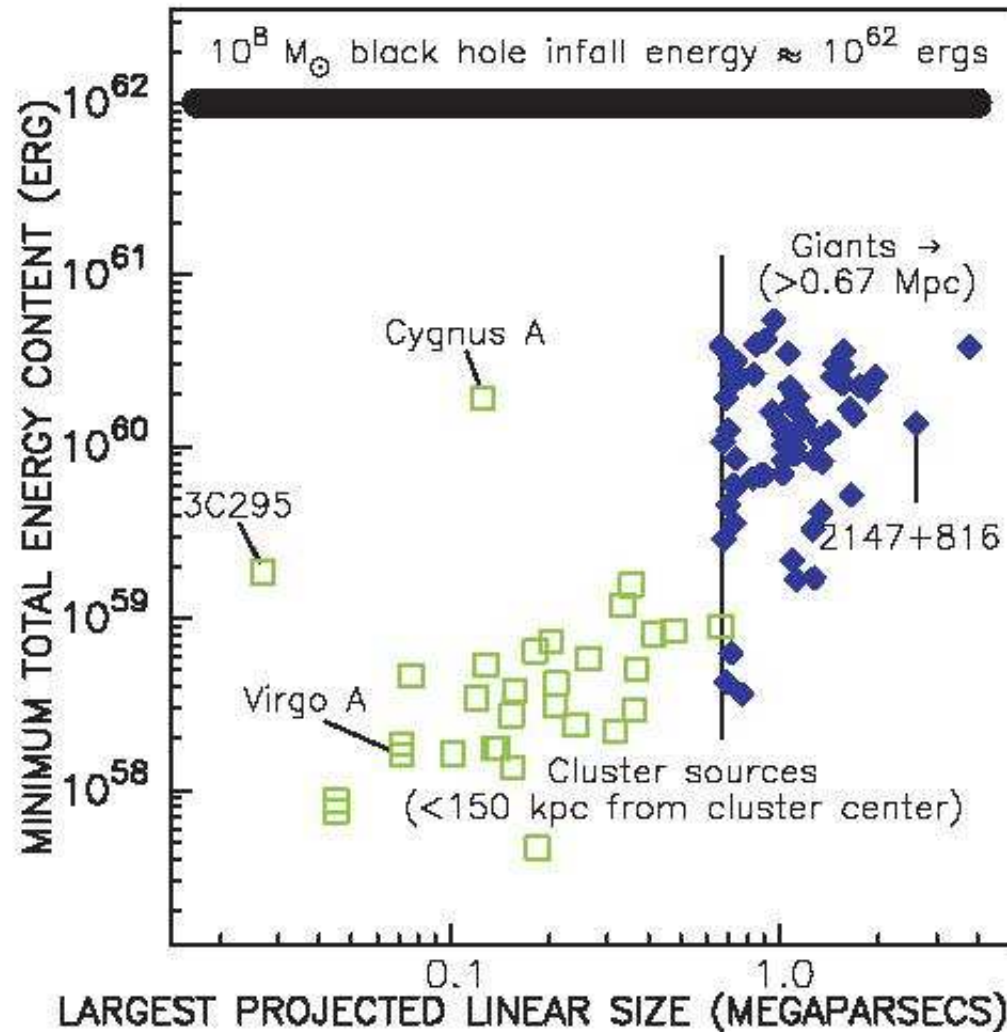


Neutron stars (ns), white dwarfs (wd), sunspots (ss), magnetic stars (ms), AGN (ag), ISM (is), SNR (sn), RG lobes (rg), galactic disk (d) and halo (h), clusters of galaxies (cl) IGM (ig), jet-frame synch. proton blazar (bl), jet-frame GRB models (gb).

2 COLOSSAL MAGNETIC STRUCTURES BUILT BY A.G.N.

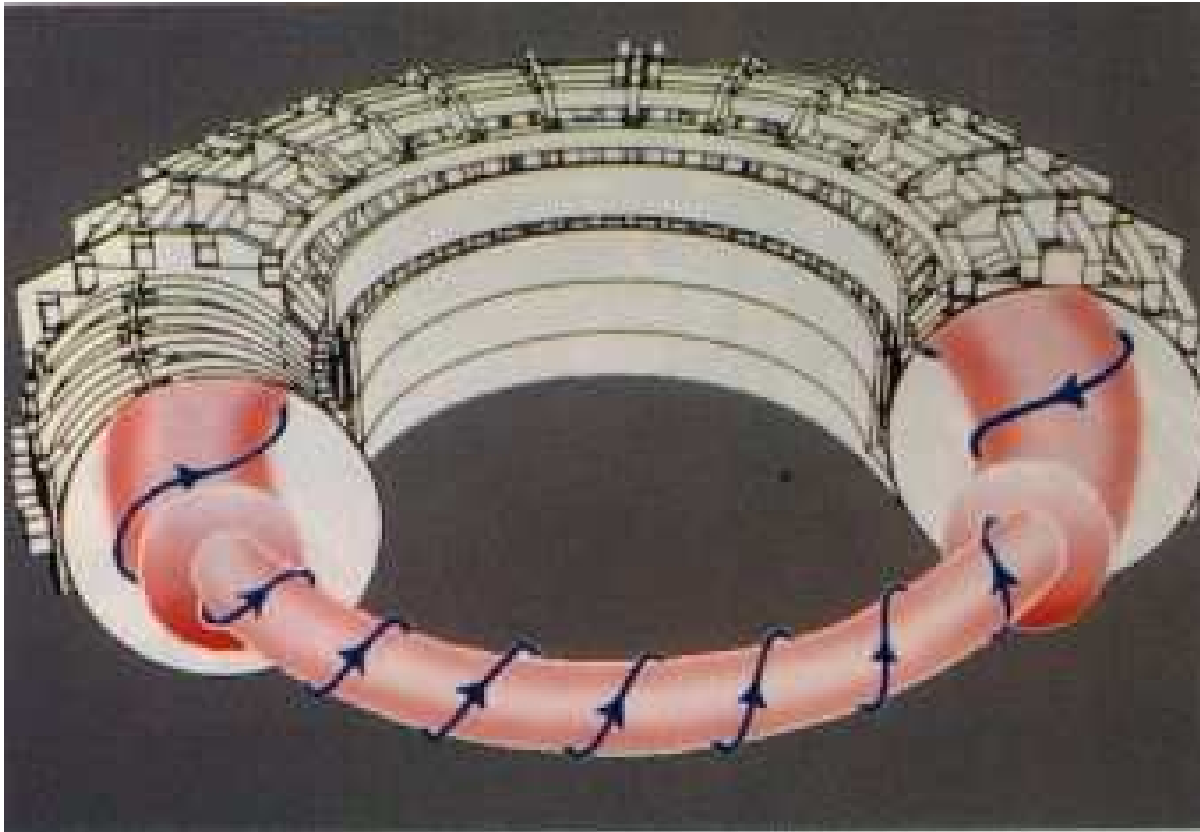


- Remnants of jets and their surrounding cocoons will remain long after AGN cease being active.
- These "fossil jets" are colossal MHD structures and may have total energies $\sim 10^{60}$ erg.
- **Could Fossil AGN explain the origin of the UHE CR?**



- Cosmic ray energy (traced by synchrotron emission) of radio galaxies vs. their sizes of estimated by Kronberg et al. (2001) — magnetic energy is probably higher.

- After a jet switches off, the fossil jet will organize itself into a stable configuration, such as the so-called reverse-field pinch (RFP) encountered in laboratory MHD experiments.



- In the lab the RFP is toroidal and is surrounded by a conducting wall for stability.

- AGN jets fossil are likely to settle down to a RFP with cylindrical geometry

D. B. Melrose, J. Nicholls and N. G. Broderick

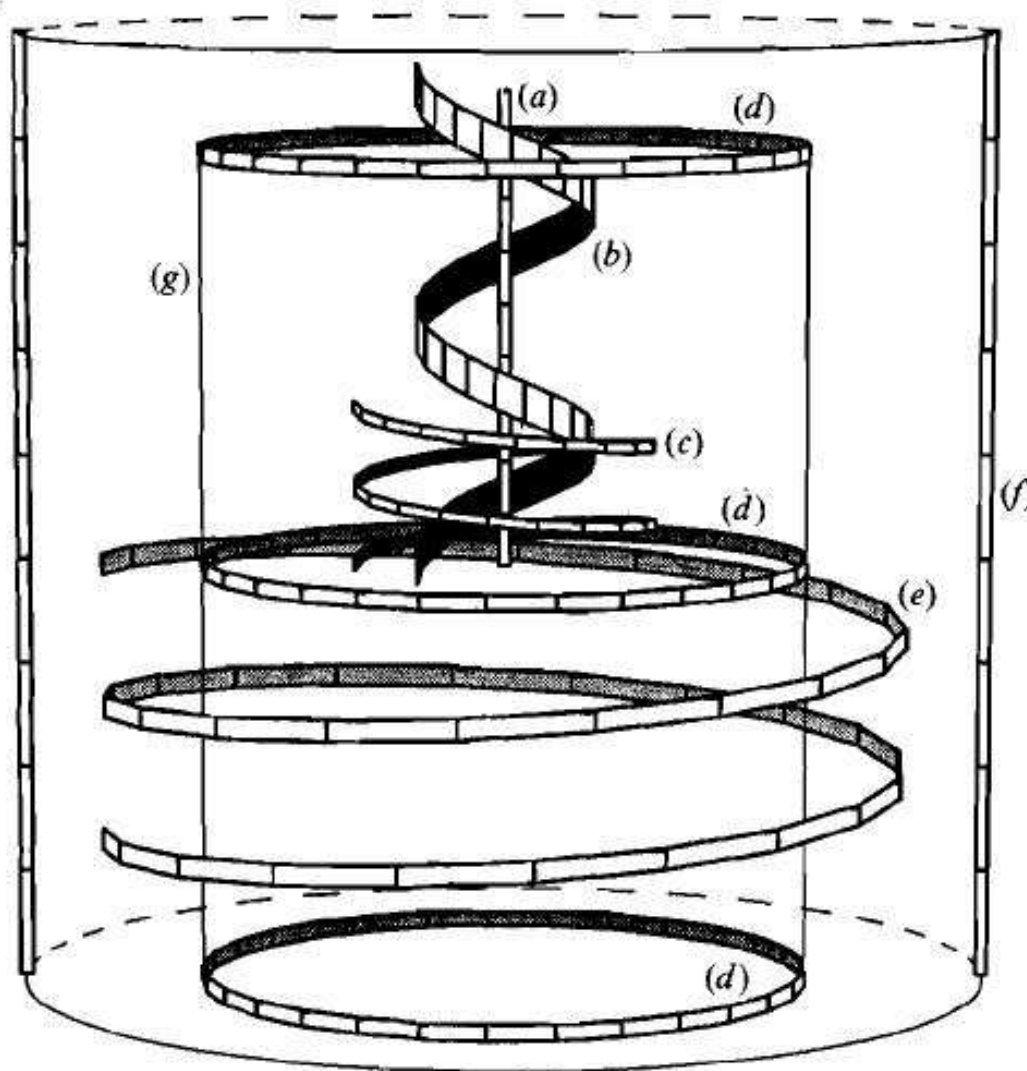
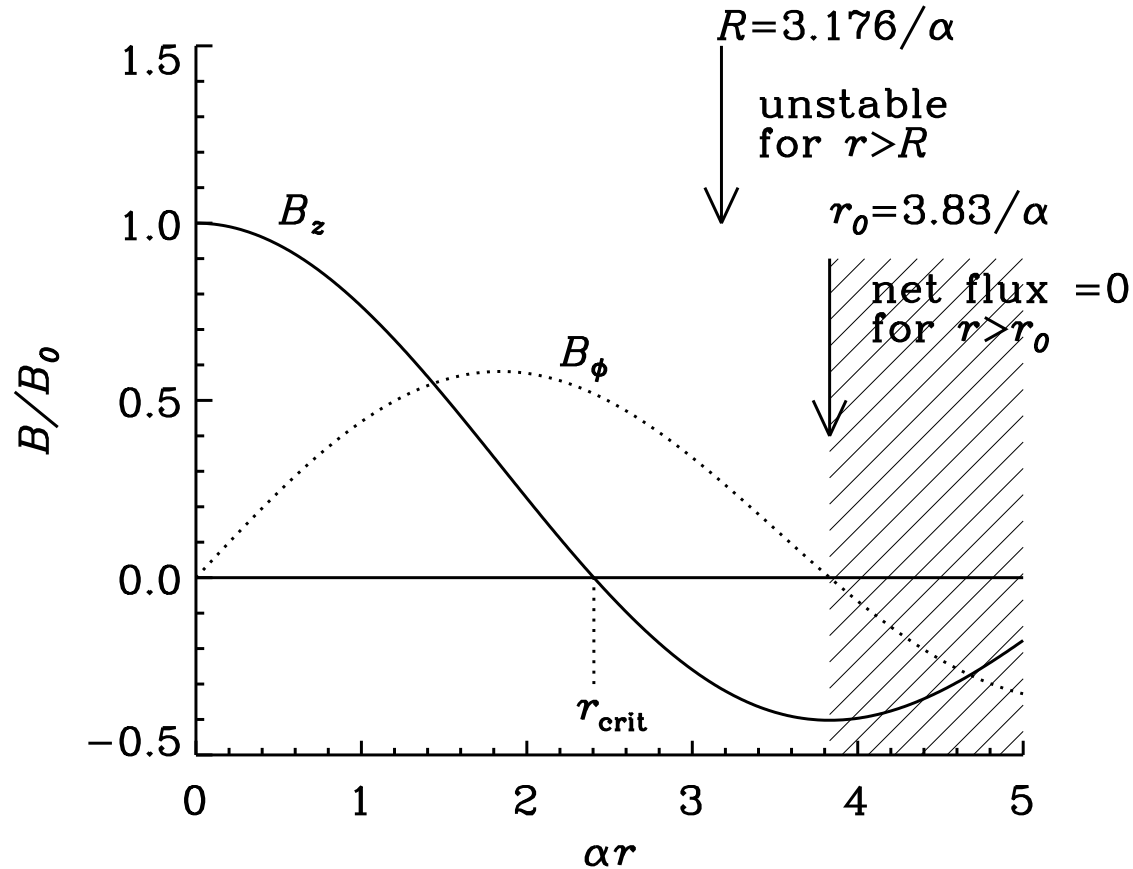


FIGURE 6. As in figure 5, but for a reverse-field pinch

- The RFP is force free



$$B_r = 0, \quad B_\phi(r) = B_0 J_1(\alpha r), \quad B_z(r) = B_0 J_0(\alpha r),$$

$$\vec{j}(r, \phi, z) = \frac{\vec{B}(r)\alpha}{\mu_0} \quad (\text{A m}^{-2}), \quad \vec{A}(r, \phi, z) = \frac{1}{\alpha} \vec{B}(r, \phi, z) \quad (\text{T m})$$

3 COSMIC RAY ACCELERATION BY FOSSIL A.G.N. JETS

- Reconnection leads to decay of magnetic structure on time scale t_{dec} inducing large-scale electric fields

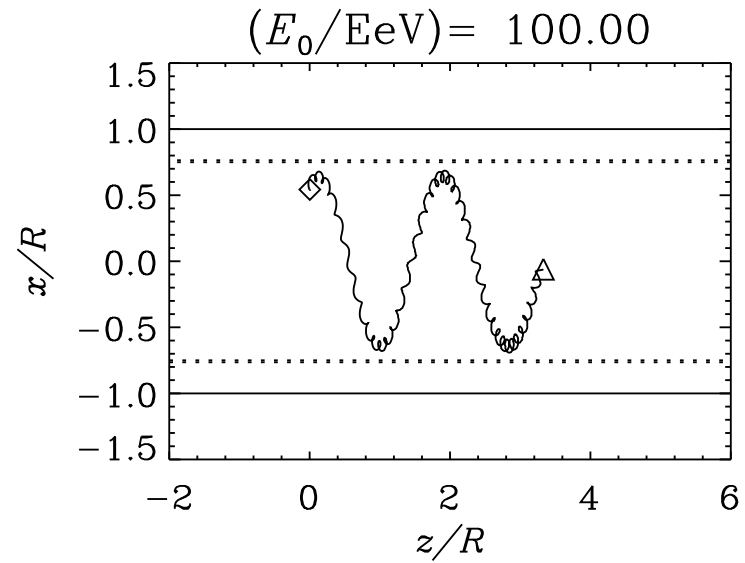
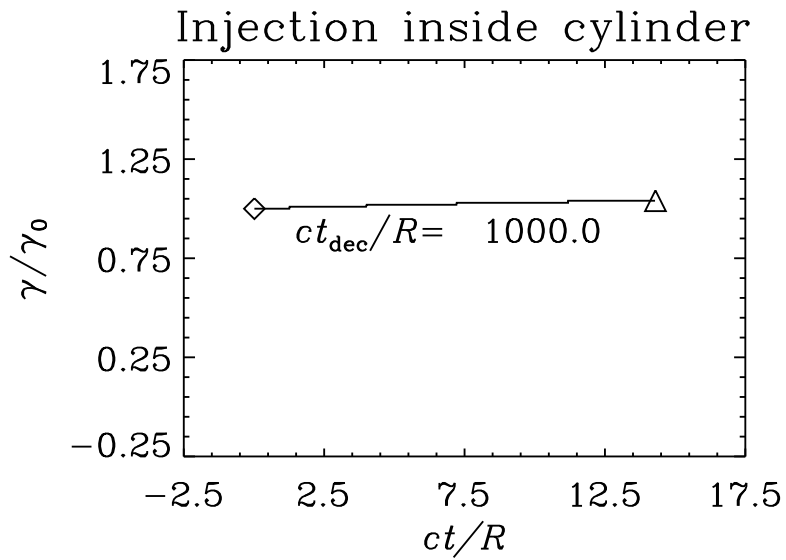
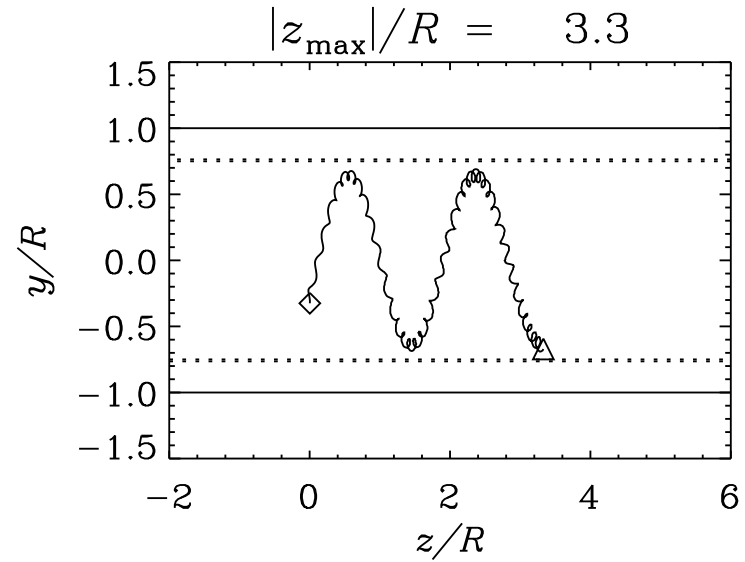
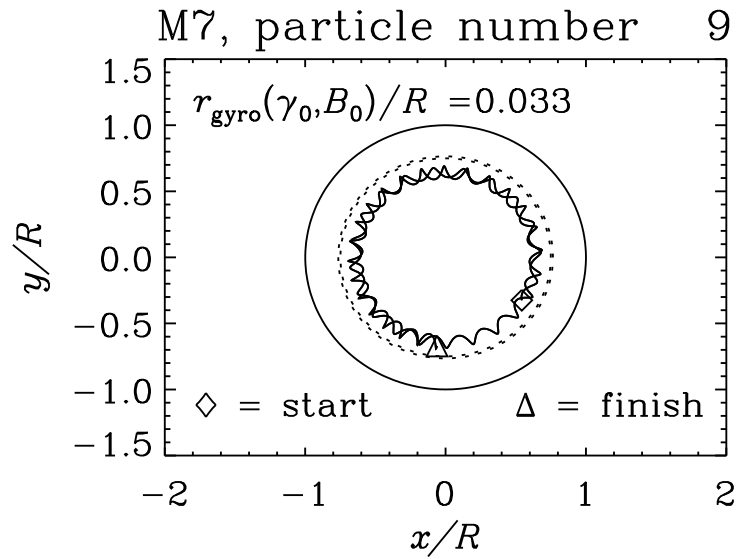
$$\vec{\mathcal{E}} = -\frac{\partial \vec{A}}{\partial t} = \frac{\vec{B}}{t_{\text{dec}}\alpha}.$$

- In practical units we have

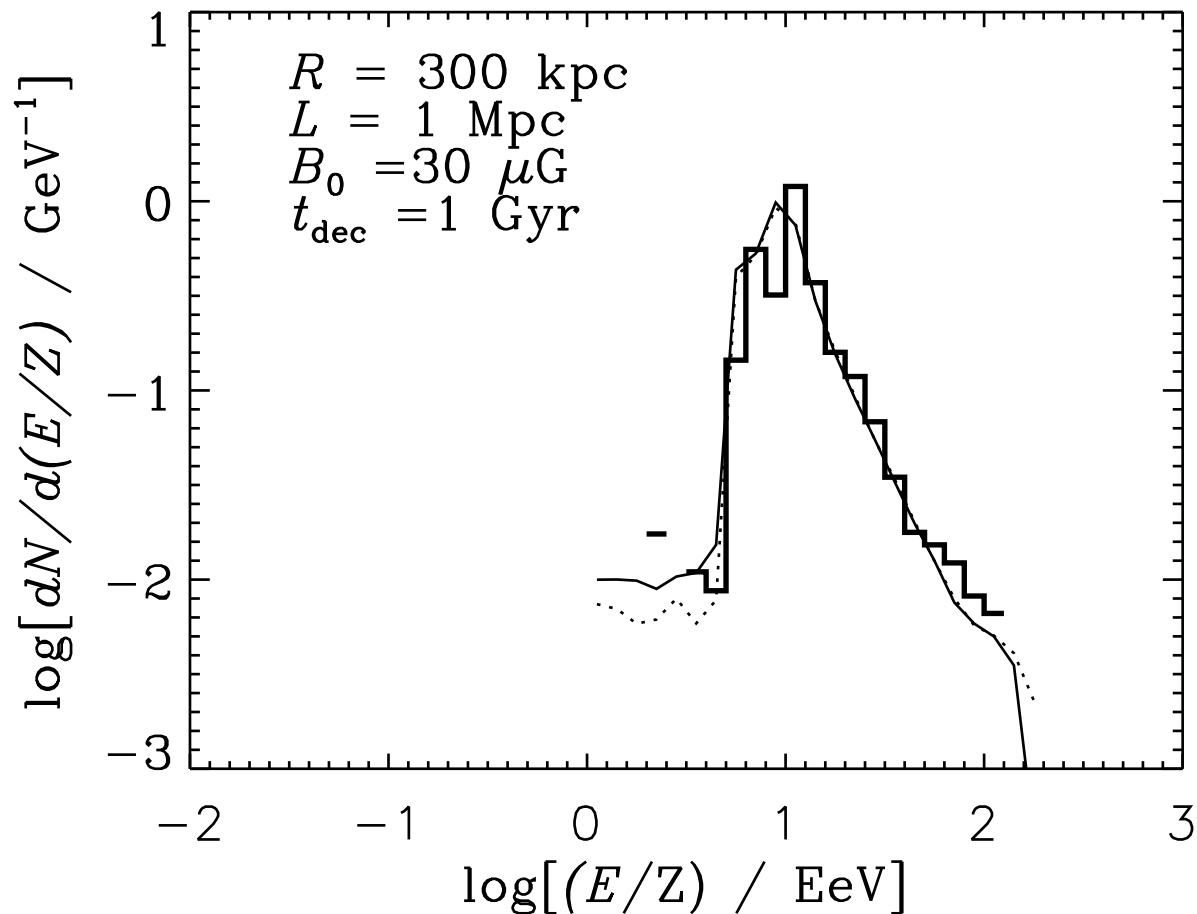
$$\mathcal{E}_\phi = 3.18 \times 10^{-5} J_1(\alpha r) \left(\frac{B_0}{10 \mu\text{G}} \right) \left(\frac{R}{100 \text{ kpc}} \right) \left(\frac{t_{\text{dec}}}{\text{Gyr}} \right)^{-1} \quad (\text{V/m}),$$

$$\mathcal{E}_z = 3.18 \times 10^{-5} J_0(\alpha r) \left(\frac{B_0}{10 \mu\text{G}} \right) \left(\frac{R}{100 \text{ kpc}} \right) \left(\frac{t_{\text{dec}}}{\text{Gyr}} \right)^{-1} \quad (\text{V/m}).$$

- This electric field can accelerate an existing seed population of cosmic rays, such as those accelerated in galaxies by SNR shocks, to ultra high energies.
- Particle trajectory simulations have been performed to demonstrate this.



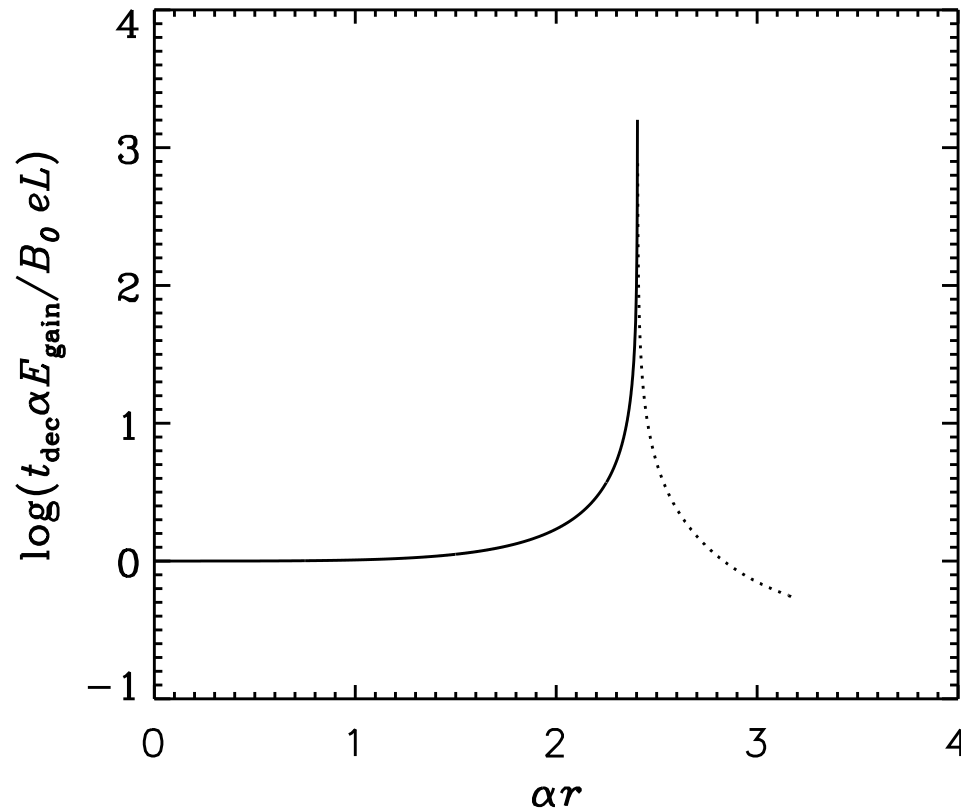
- Inject low energy cosmic rays uniformly and isotropically at both ends of the cylinder of length L .
- Spectrum depends on RLB_0/t_{decay} , but is independent of E_{inj}/Z .



$$E_{\text{inj}}/Z = 1 \text{ EeV} \equiv 10^{18} \text{ eV}$$

- Energy gain of charge Ze depends on length of (helical) field line

$$E_{\text{gain}} \approx 10^{18} Z \left(\frac{B_0}{10 \mu\text{G}} \right) \left(\frac{\ell}{\text{Mpc}} \right) \left(\frac{R}{100 \text{ kpc}} \right) \left(\frac{t_{\text{dec}}}{\text{Gyr}} \right)^{-1} \frac{J_0(\alpha r)^2 + J_1(\alpha r)^2}{J_0(\alpha r)} \text{ eV}$$



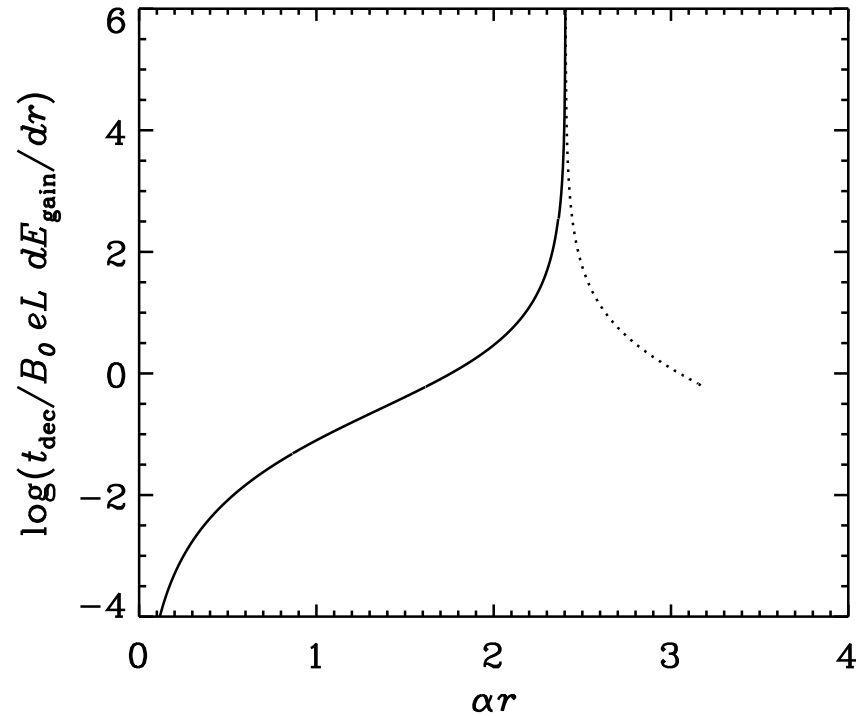
- Energy spectrum is

$$\frac{dN}{dE} \equiv \frac{dN}{dE_{\text{gain}}} = \frac{dN}{dr} \left[\frac{dE_{\text{gain}}}{dr} \right]^{-1}$$

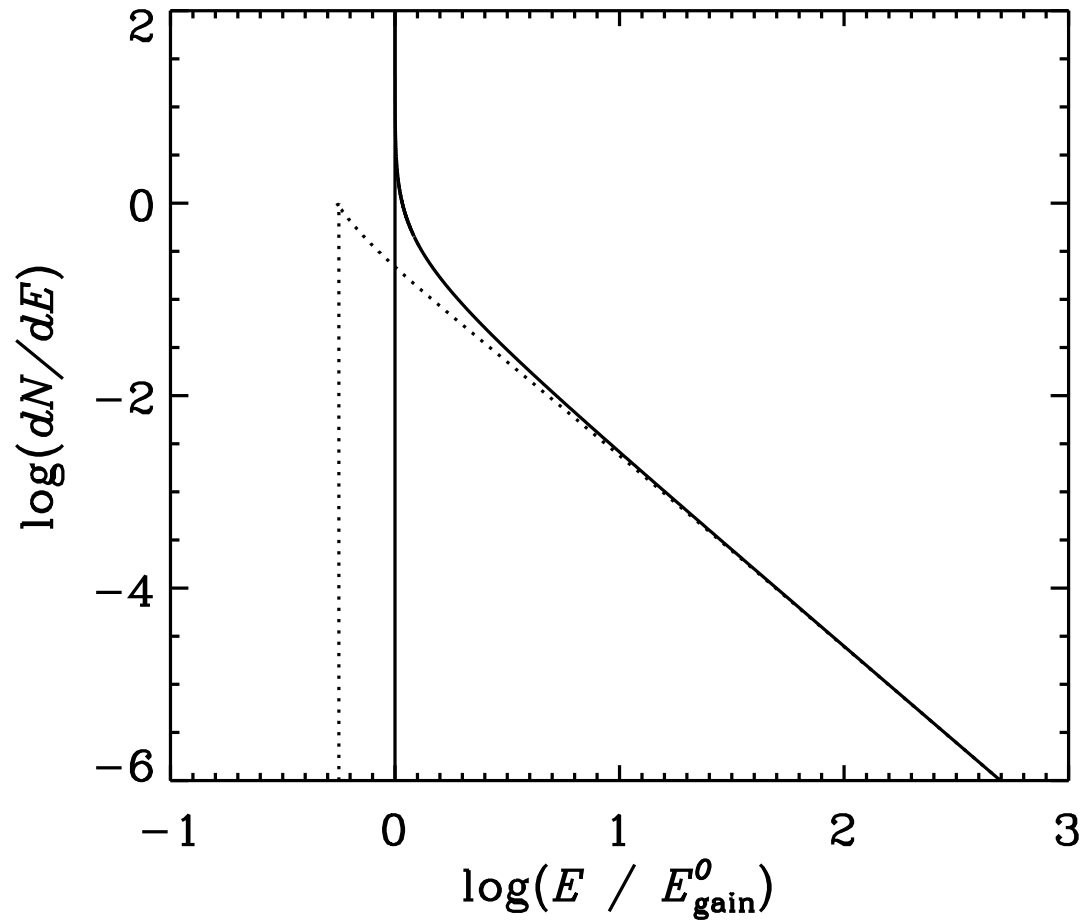
- dN/dr is the distribution in radius of the injection points.

$$\frac{dN}{dr} = \frac{2r}{R^2} \quad (0 < r < R).$$

- dE_{gain}/dr is

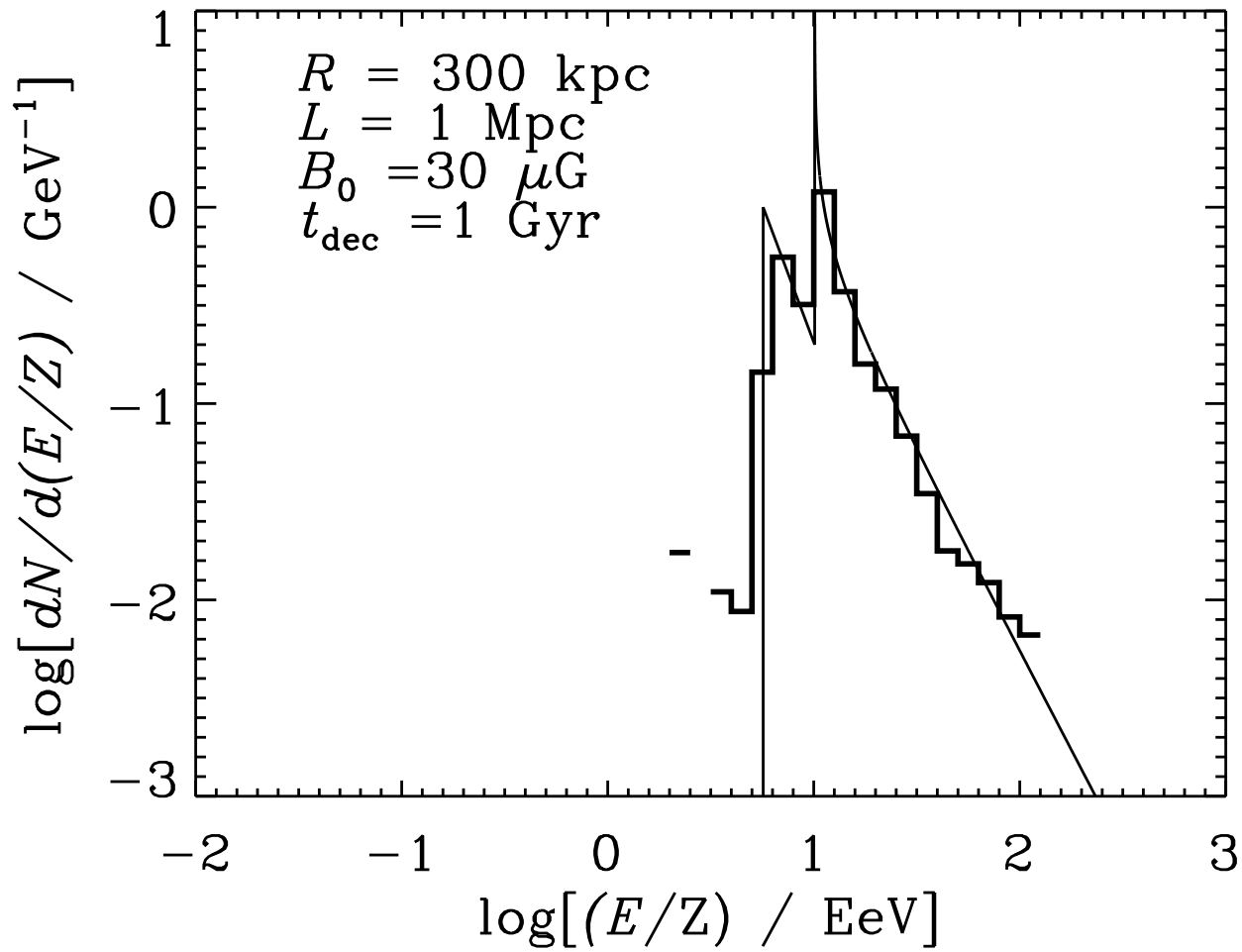


- Resulting energy spectrum has E^{-2} tail.



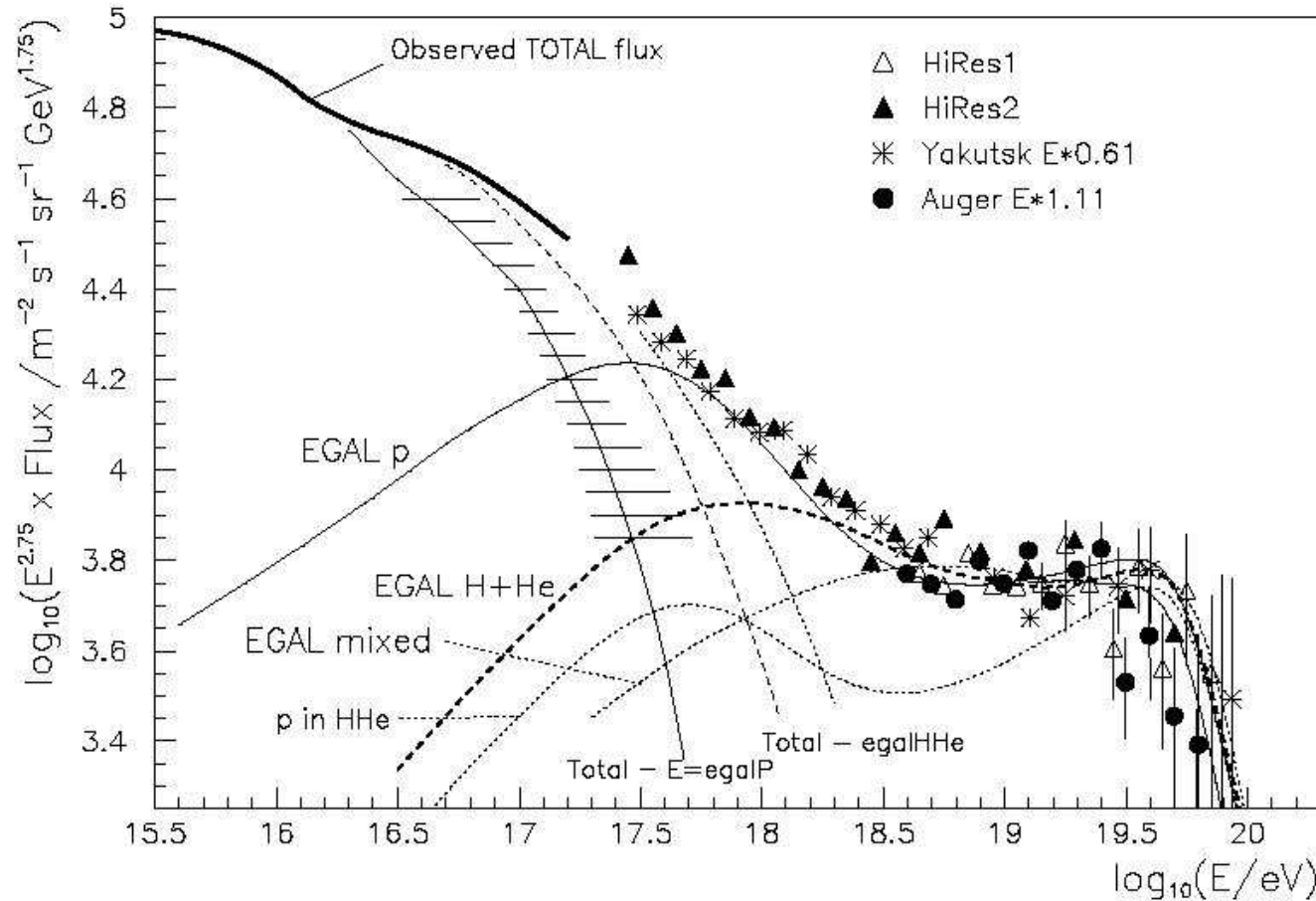
$$E_{\text{gain}}^0 = 10^{18} Z \left(\frac{B_0}{10 \mu\text{G}} \right) \left(\frac{\ell}{\text{Mpc}} \right) \left(\frac{R}{100 \text{ kpc}} \right) \text{ eV}$$

- Agrees with particle trajectory simulations



3.1 Energetics

- Do the energetics work? Can we explain the UHE CR above 10 EeV?



From the review by Hillas (2006).

- If an extragalactic source distribution locally produces an E^{-2} spectrum of protons above 10 EeV, the local power requirement is $\sim 10^{59}$ erg Gpc $^{-3}$ y $^{-1}$.
- “Local” here means within a few interaction lengths of UHECR for protons undergoing pion photoproduction on the CMBR, i.e. ~ 100 Mpc.

- Decaying magnetic fields with local filling factor η_B lose energy at a rate

$$\dot{U}_B = 10^{62} \eta_B \left(\frac{B_0}{10 \mu\text{G}} \right)^2 \left(\frac{t_{\text{dec}}}{\text{Gyr}} \right)^{-1} \text{ erg Gpc}^{-3} \text{ y}^{-1}$$

- Magnetic fields from QSOs can fill up to 5–20% of the IGM (Furlanetto & Loeb 2001) – probably higher locally since we are in a “Wall”.
- These crude energetics arguments show fossil AGN structure decay could be responsible for the observed UHE CR.

4 REMAINING QUESTIONS AND FUTURE WORK

- Future work will include exploring observational consequences of this model at radio, X-ray and gamma-ray energies.
- What cuts off the E^{-2} spectrum? Finite thickness of reconnection zone, or gyro-radius becoming too big?
- Will electron acceleration (in opposite direction to protons) be killed by streaming instability, or by other processes?
- If so, this will heat the plasma. Could this be seen in X-rays?
- If not, radio synchrotron and gamma-ray signals could be generated. Could these be detectable?
- How much of the energy of a fossil AGN goes into cosmic rays?

5 CONCLUSIONS

- Remnants of jets and their surrounding cocoons may still be present around or close to galaxies which contain AGN which are now no longer active.
- These "fossil jets" are colossal MHD structures and may have total energies $\sim 10^{60}$ erg.
- After a jet switches off, the fossil jet will organize itself into a stable configuration, such as the so-called reverse-field pinch (RFP) encountered in laboratory MHD experiments.
- In an RFP the longitudinal magnetic field changes direction at a critical distance from the axis, leading to re-connection there, and to slow decay of the large-scale RFP field.
- We show that this field decay induces large-scale electric fields which accelerate cosmic rays an E^{-2} power-law up to ultra-high energies.
- Energetics arguments do not rule out this mechanism for the origin of the UHE CR.