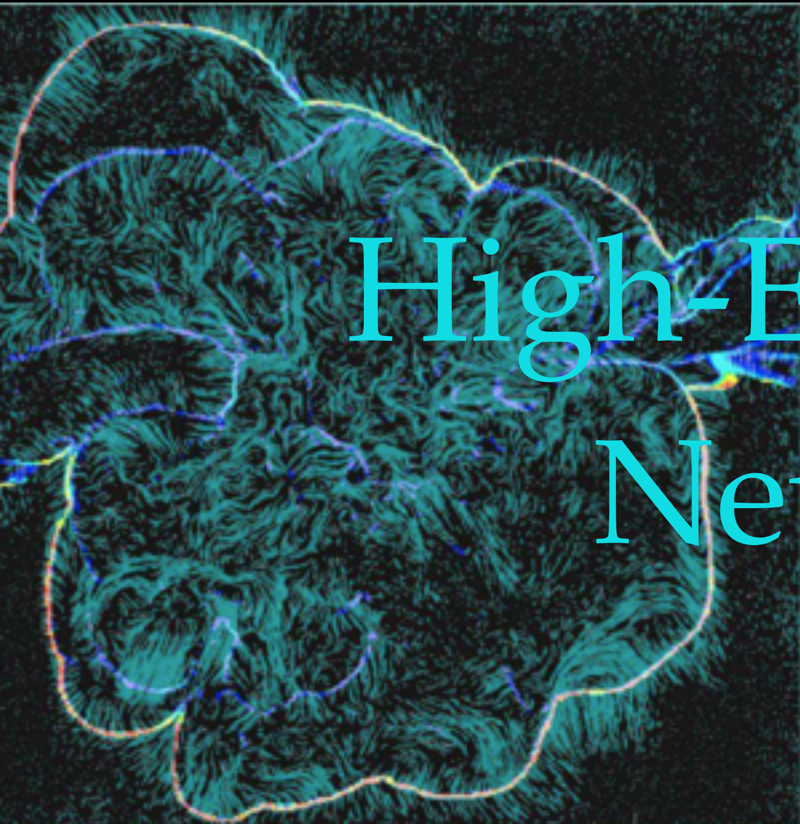


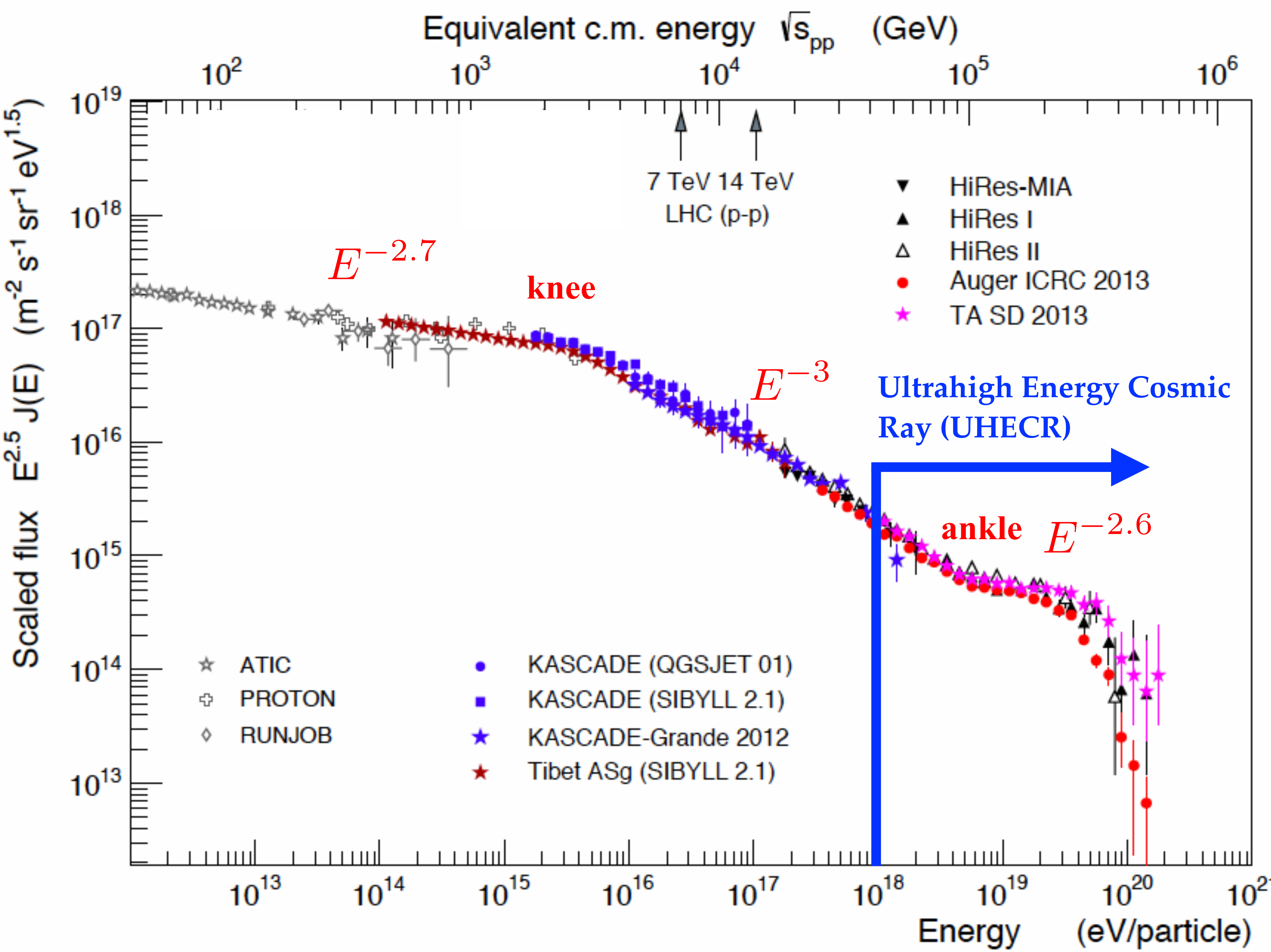
High-Energy Cosmic Rays and Neutrinos from Cluster Accretion Shocks

Ke Fang
JSI fellow @ University of Maryland &
NASA Goddard Space Fight Center

Sep 27, 2015 KIAA Workshop

103th Anniversary in 2015

Victor Hess ballon flights 1912 establishes the cosmic nature of ionizing radiation



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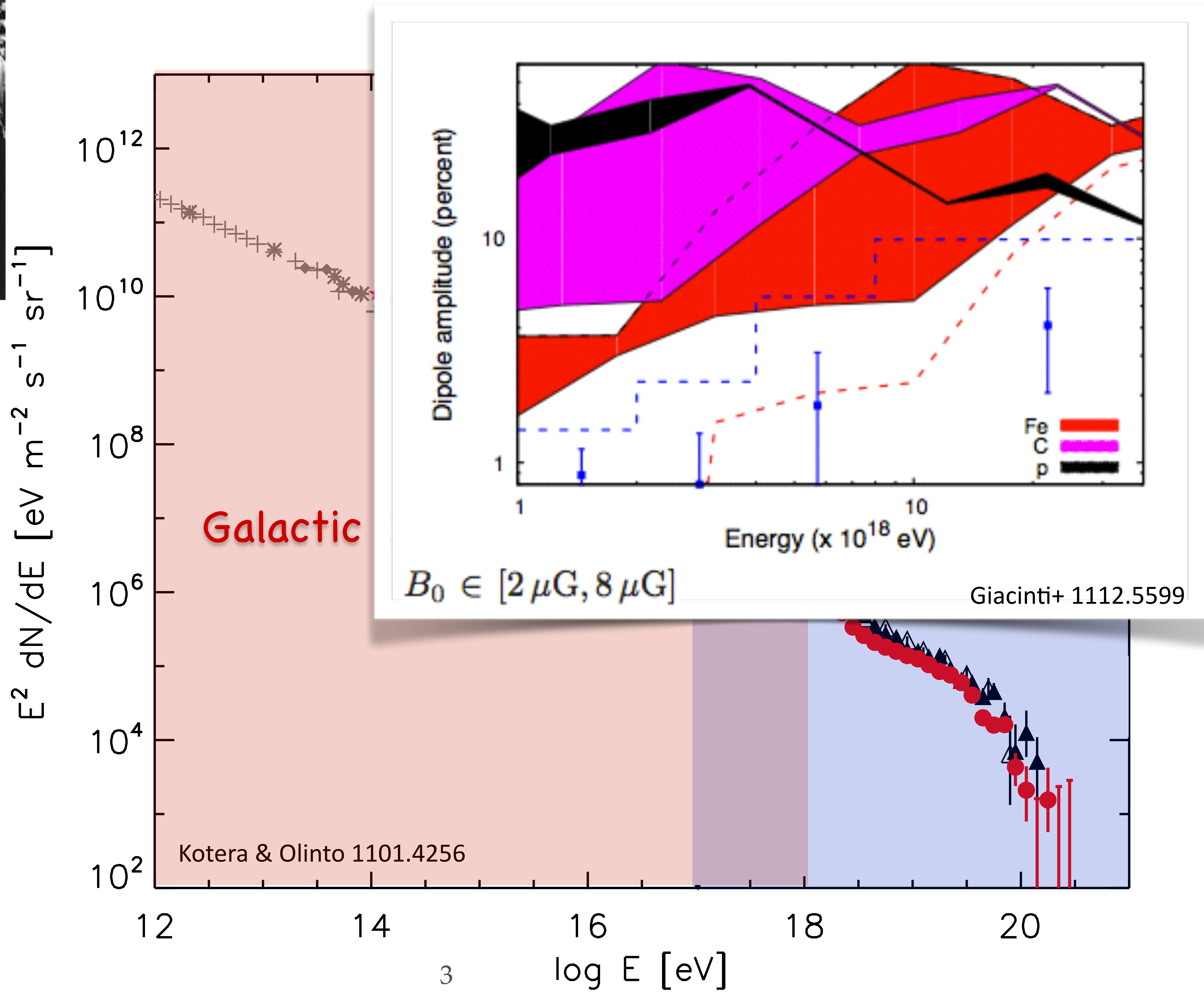
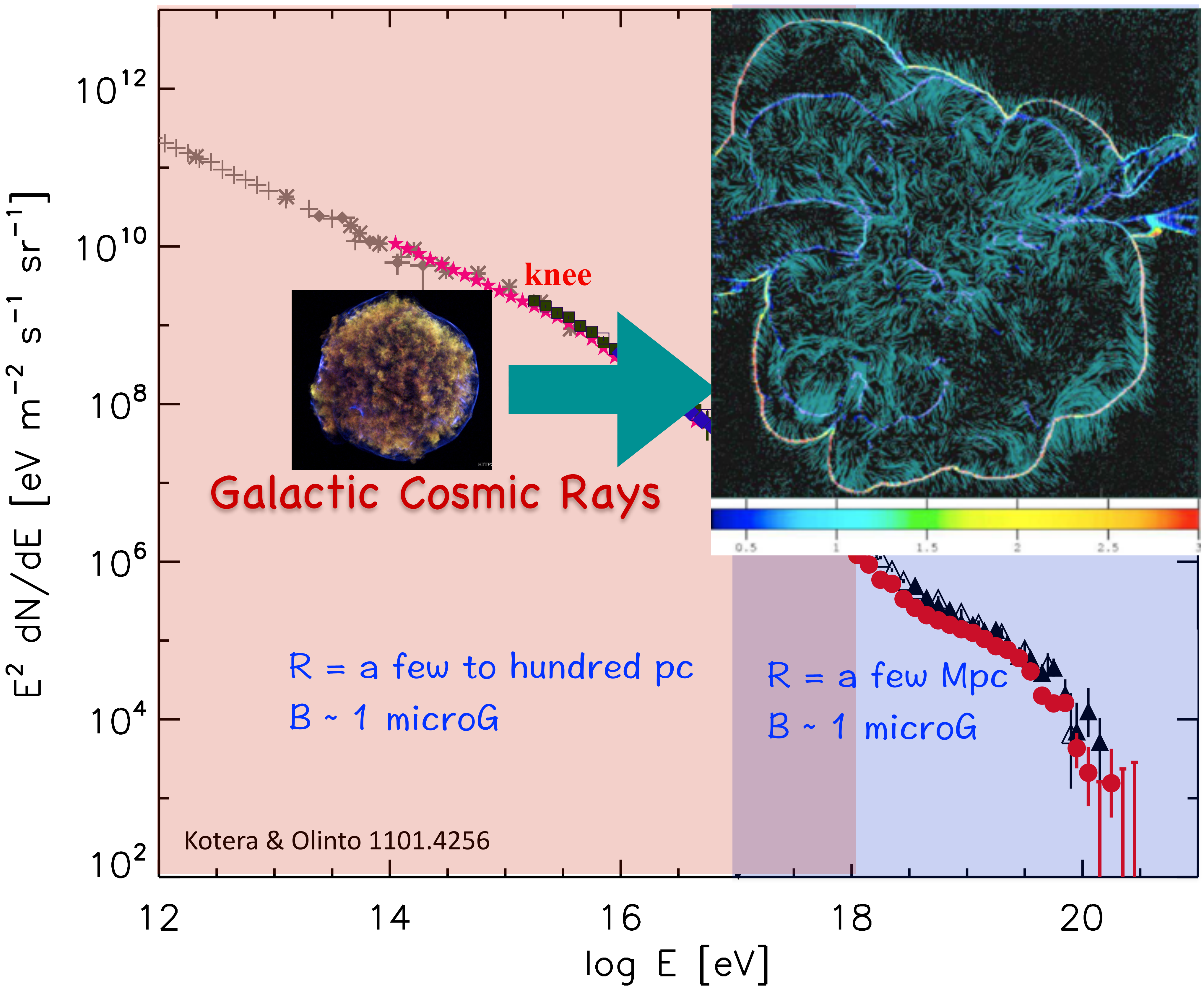
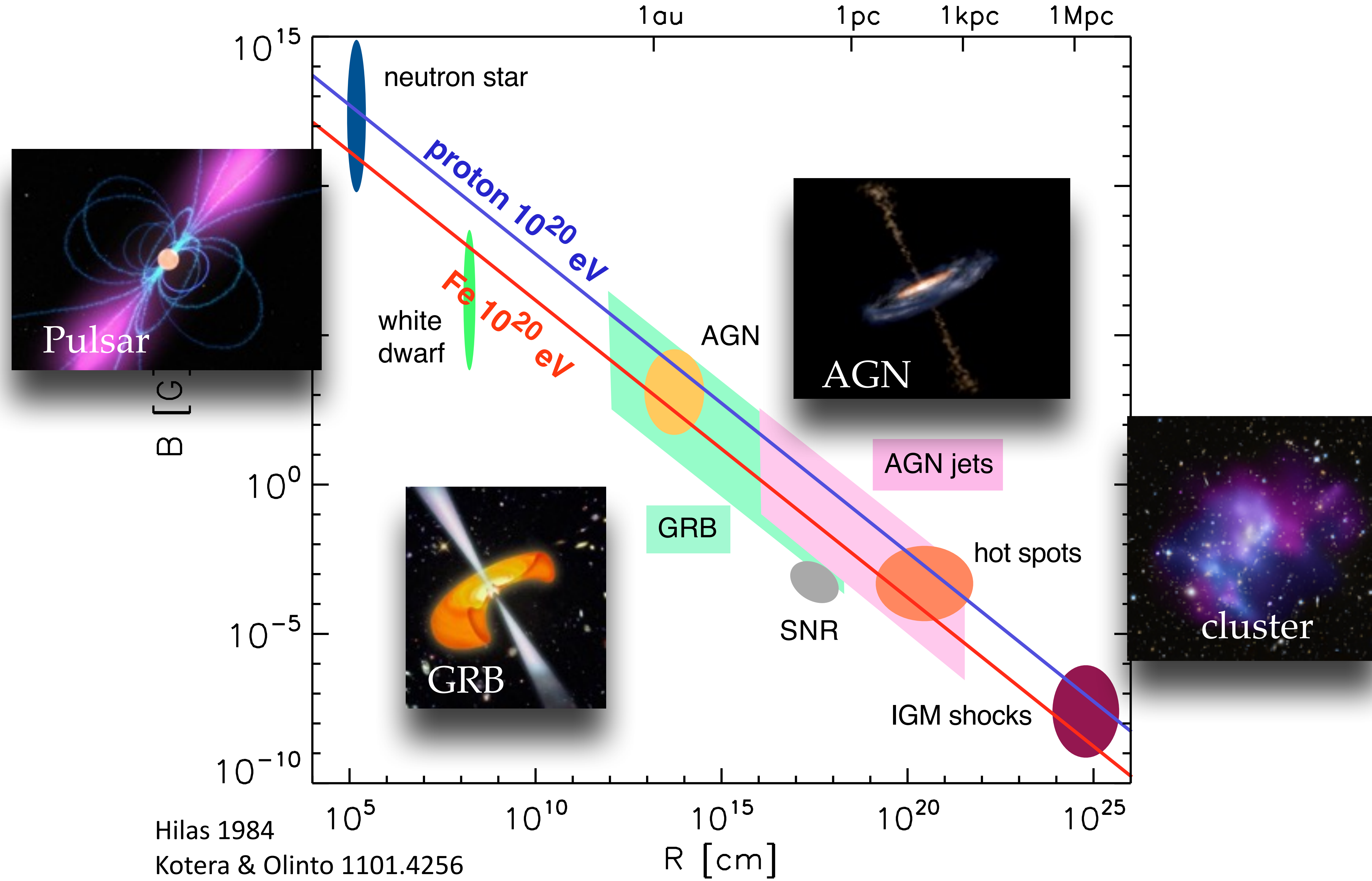


A Simple Scale-Up?



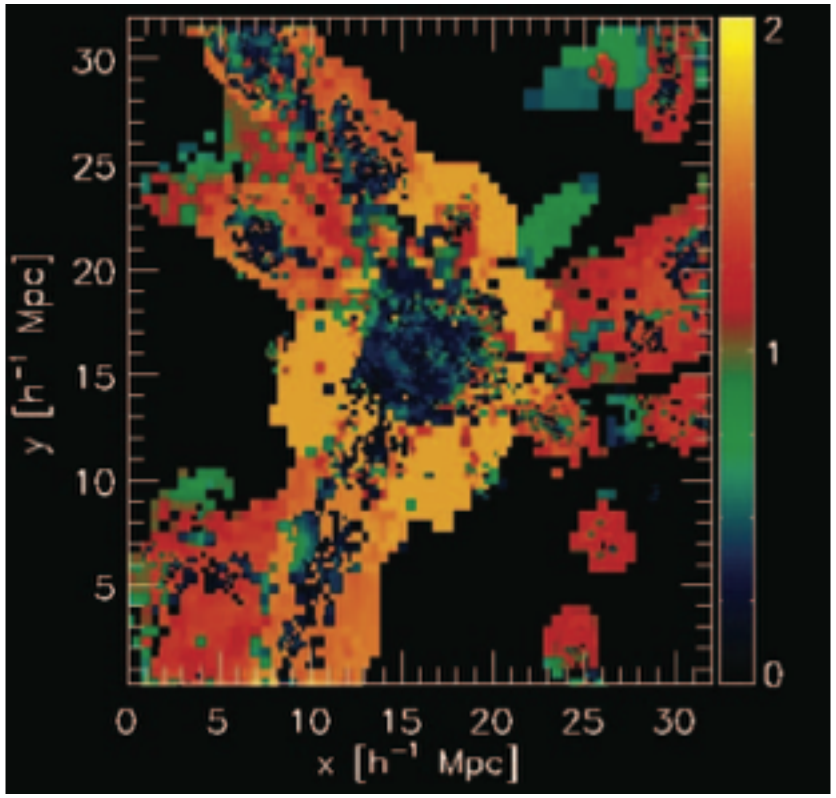
Clusters as Sources of UHECRs



Hilas 1984
Kotera & Olinto 1101.4256

Cosmic Ray Acceleration

Keshet, Waxman, Loeb+ 2003
Inoue & Aharonian 2005
Murase, Inoue & Nagataki 2008
Kotera, Allard, Murase+ 2009



Diffusive Shock Acceleration

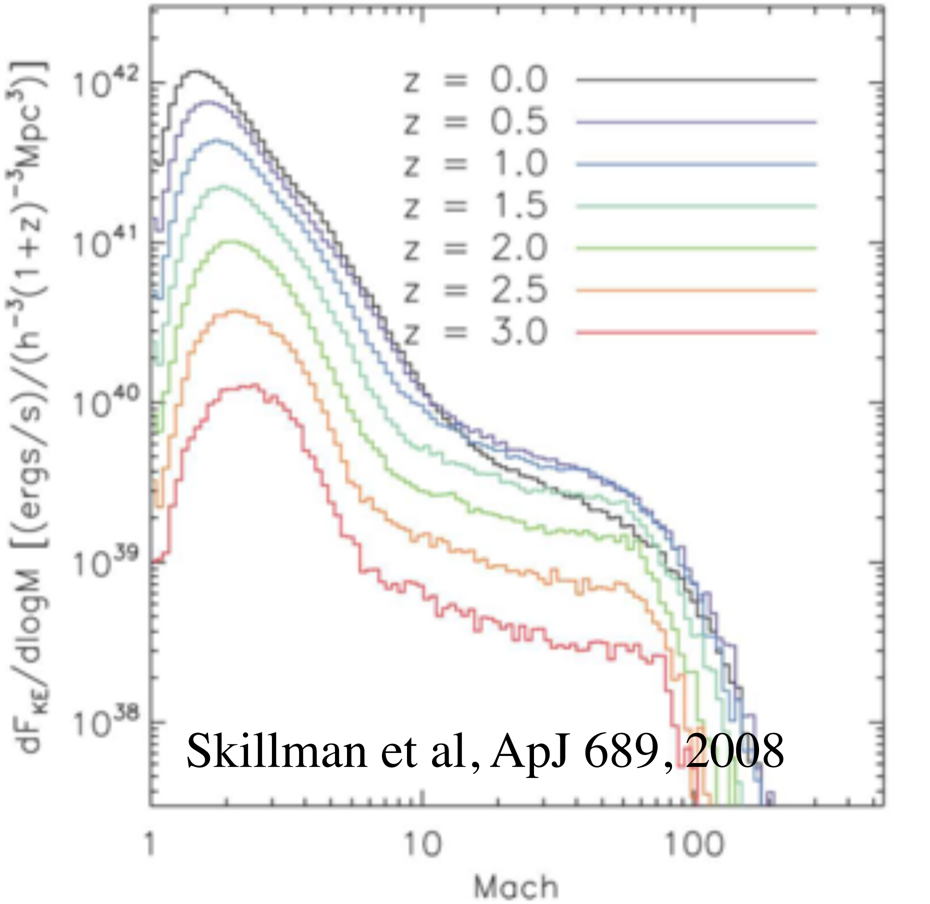
$$r_{\rm sh} \sim r_{\rm vir} = 3{\rm Mpc}\left(\frac{M}{10^{15}M_\odot}\right)^{1/3}$$ ← Cluster mass

$$v_{\rm sh} = \sqrt{\frac{GM}{r_{\rm sh}}} = 1300\,M_{15}^{1/3}\,{\rm km\,s^{-1}}$$

Magnetic Field ↓

$$t_{\rm acc} \sim 20 D_{\rm sh}/v_{\rm sh}^2 = 1.3\,E_{18}\,M_{15}^{-2/3}\,B_{-6}^{-1}Z^{-1}\,{\rm Gyr}$$

$$E_{\rm max} = 3\times 10^{18}\,M_{15}^{2/3}\,Z\,B_{-6}\,{\rm eV}$$



Energy Budget

$$\langle \dot{M}\rangle = 42 M_{12}^{1.127}(1+1.17z)E(z)\,M_\odot\,{\rm yr}^{-1}$$

$$L_{\rm CR} = f_b\,f_{\rm CR}\frac{GM\dot{M}}{r_{\rm sh}} = 2\times 10^{45}M_{15}^{2.05}f_{{\rm CR},-1}\,{\rm erg\,s^{-1}}$$

↑ channel fraction

Cosmic ray injection spectrum

$$\frac{dN_{\rm CR}}{dE} \propto E^{-\alpha} \qquad \alpha \sim 2-2.5$$

Cosmic Ray Diffusion in Cluster B Fields

Particle Larmor Radius

$$r_L = 1\, E_{18}\, B_{-6}^{-1}\, Z^{-1}\,\mathrm{kpc}$$

Coherence Length of B fields in massive cluster

$$l_0 \sim 0.1\,\mathrm{Mpc}$$

Diffusion regime

$$D_{\rm cl} = \frac{1}{3}\frac{\delta B}{B} c l_0 \left(\frac{r_L}{l_0}\right)^{2-w}$$

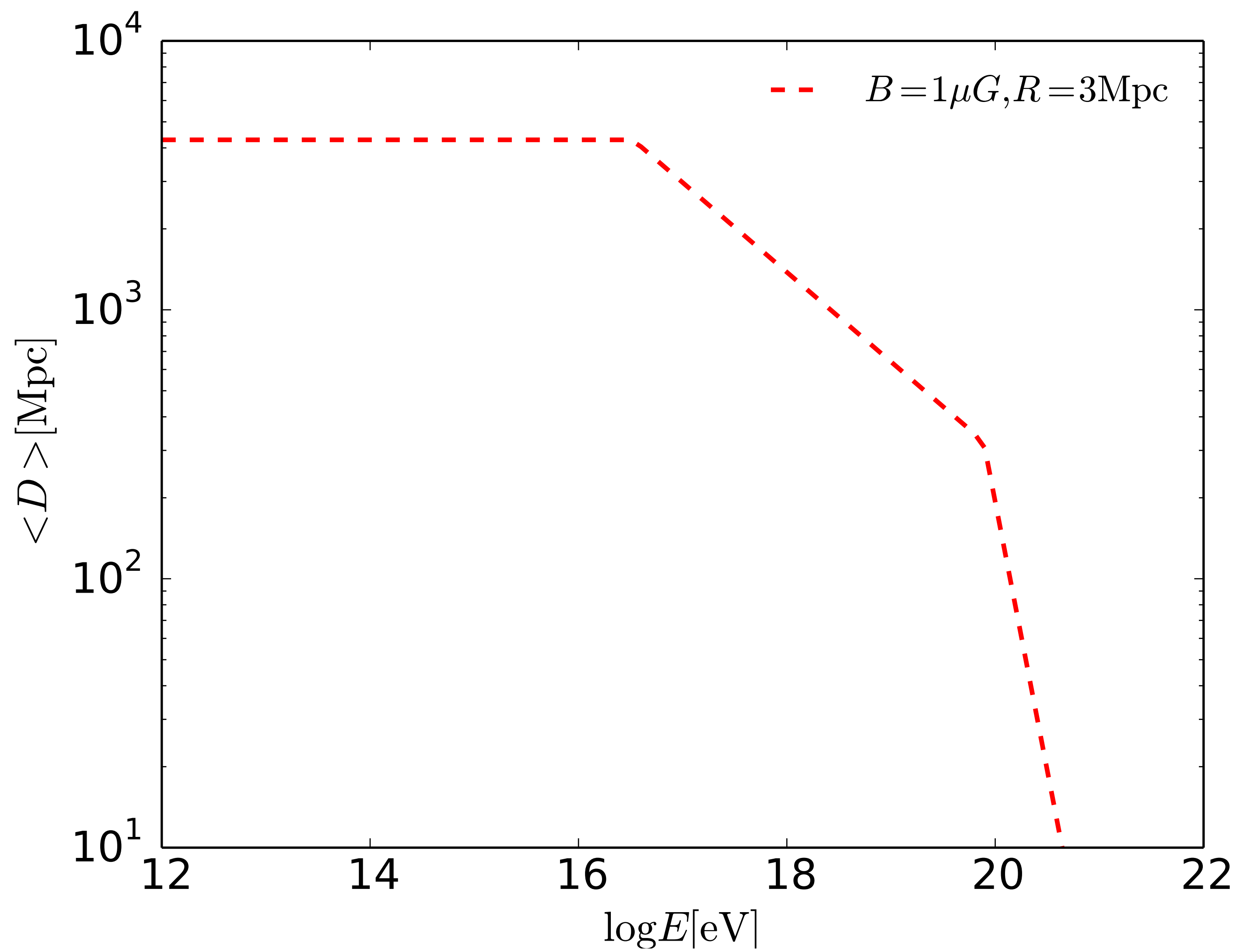
$$= 6.7 \times 10^{29} \left(\frac{E/Z}{1\,\mathrm{GV}}\right)^{1/3}$$

$$t_{\rm diff} = 3\, E_{18}^{-1/3}\,\mathrm{Gyr}$$

$$E_{\rm cr,min} = 2.8 \times 10^{16}\,\mathrm{eV}$$

Deflection regime

$$D_{\rm cl} \propto r_L^2\, l_c^{-1}$$



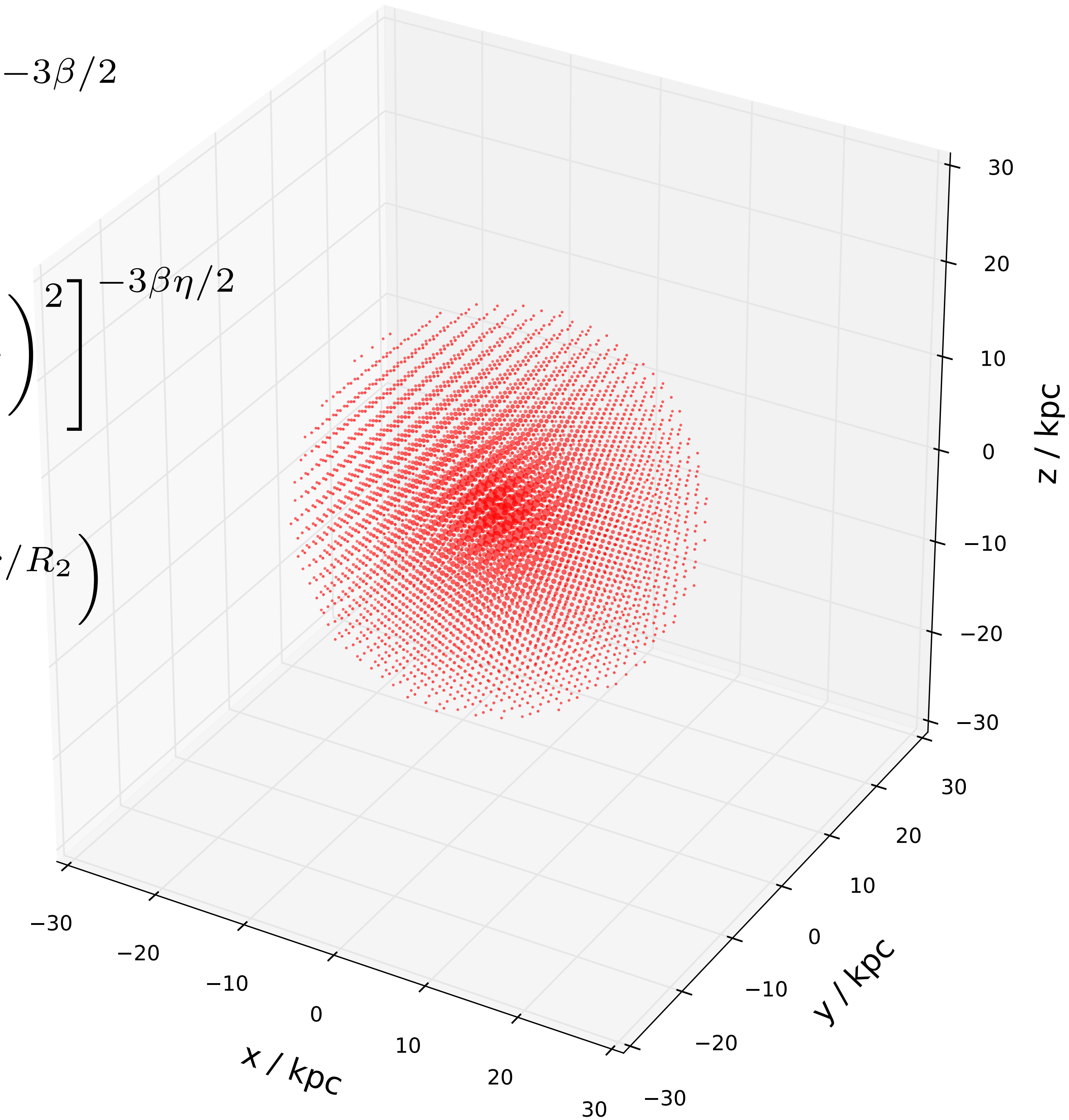
Turbulent Magnetic Field in Massive Clusters

Cavaliere & Fusco-Femiano, A&A 49, 137 (1976)

$$n_{\mathrm{ICM}}(r) = n_{\mathrm{ICM},0} \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-3\beta/2}$$

$$B(M,r) = B_0 \left(\frac{M}{M_0}\right)^{\lambda} \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-3\beta\eta/2}$$

$$B(r) = \max\left(B_1\, e^{-r/R_1}, B_2\, e^{-r/R_2}\right)$$



Interaction with ICM Baryons

$$p + p \to p + \pi^{\pm} + \ldots$$

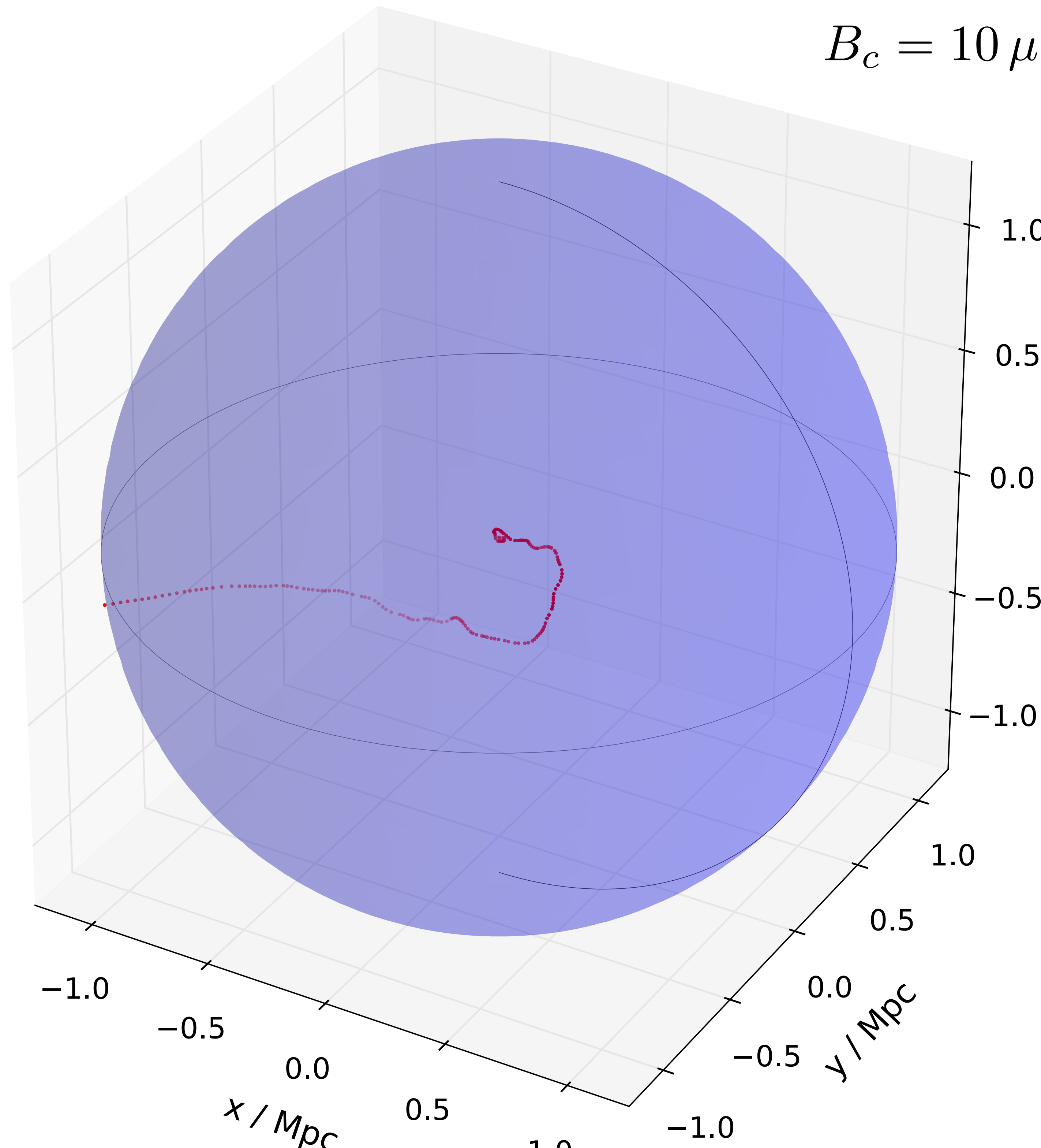
$$\pi^{\pm} \to e^{\pm} + \nu_\mu + \bar{\nu}_\mu + \nu_e(\bar{\nu}_e)$$

$$\tau = n_{\rm ICM}\sigma_{\rm pp}\kappa_{\rm pp}\frac{c\,t_{\rm diff}}{R} = 10^{-3}\,\frac{n_{\rm ICM}}{10^{-3}\,{\rm cm}^{-3}}\,\frac{R}{3\,{\rm Mpc}}\,\frac{c\,t_{\rm diff}}{R}$$

ICM density profile, turbulent IGMF structure ===> Simulation

Particle Trajectory - 100 EeV

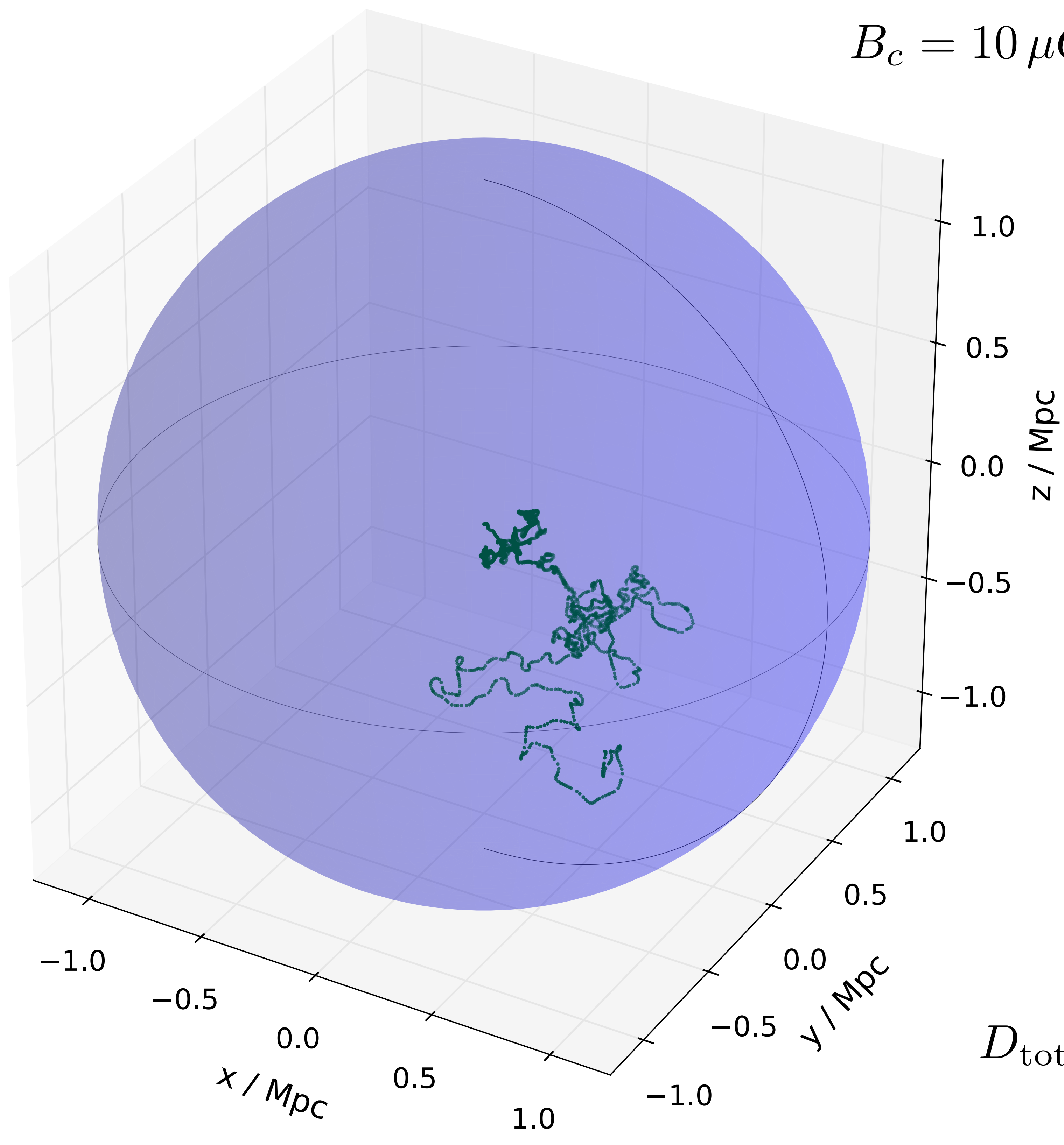
$B_c = 10\,\mu G, M = 10^{14}\,M_{\odot}$



$D_{\text{total}} = 2.6\,\text{Mpc}$

Particle Trajectory - 10 EeV

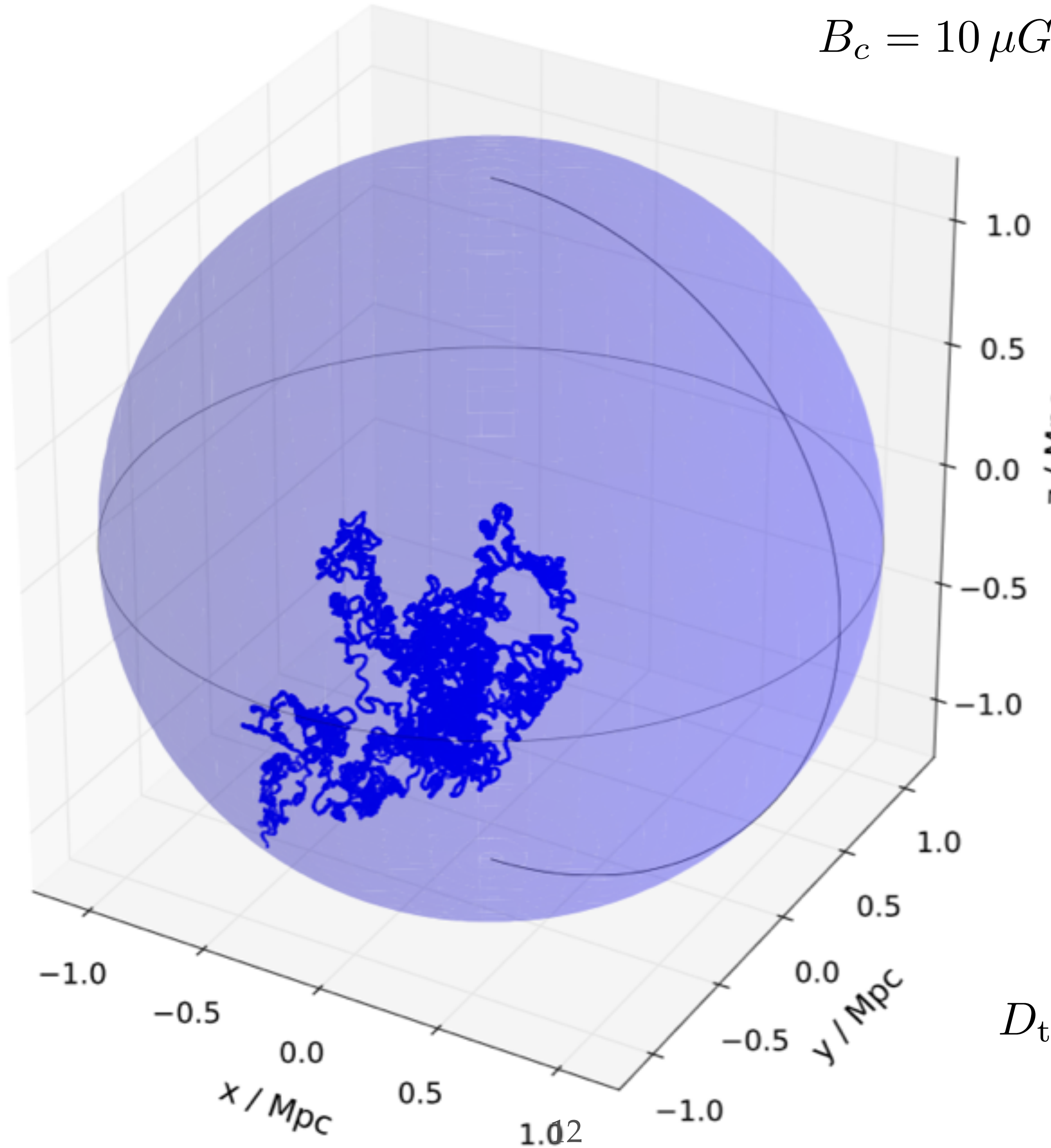
$B_c = 10\,\mu G, M = 10^{14}\,M_\odot$



$D_{\rm total} = 19.8\,{\rm Mpc}$

Particle Trajectory - 1 EeV

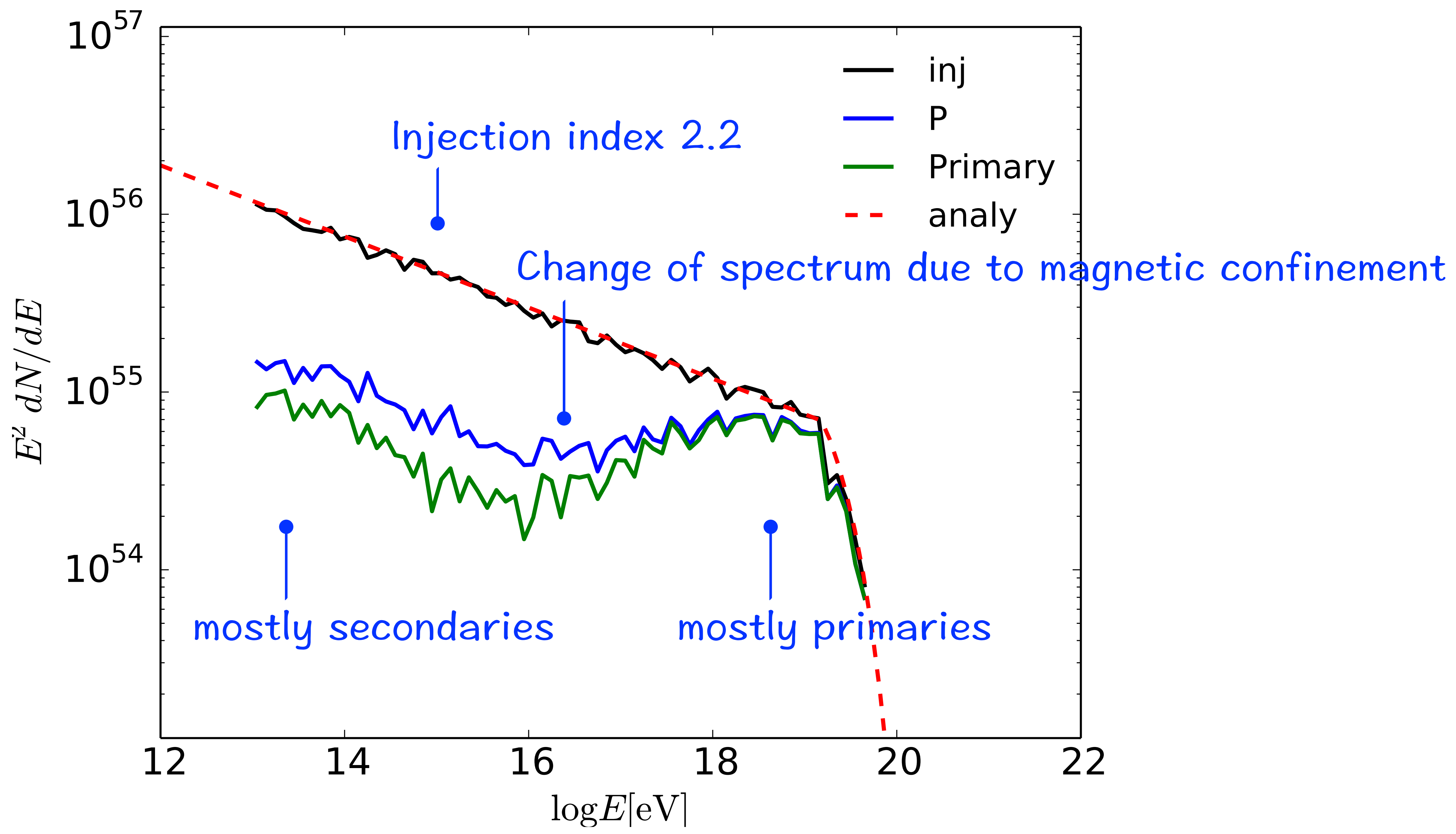
$B_c = 10\,\mu G, M = 10^{14}\,M_{\odot}$



$D_{\mathrm{total}} = 186.3\,\mathrm{Mpc}$

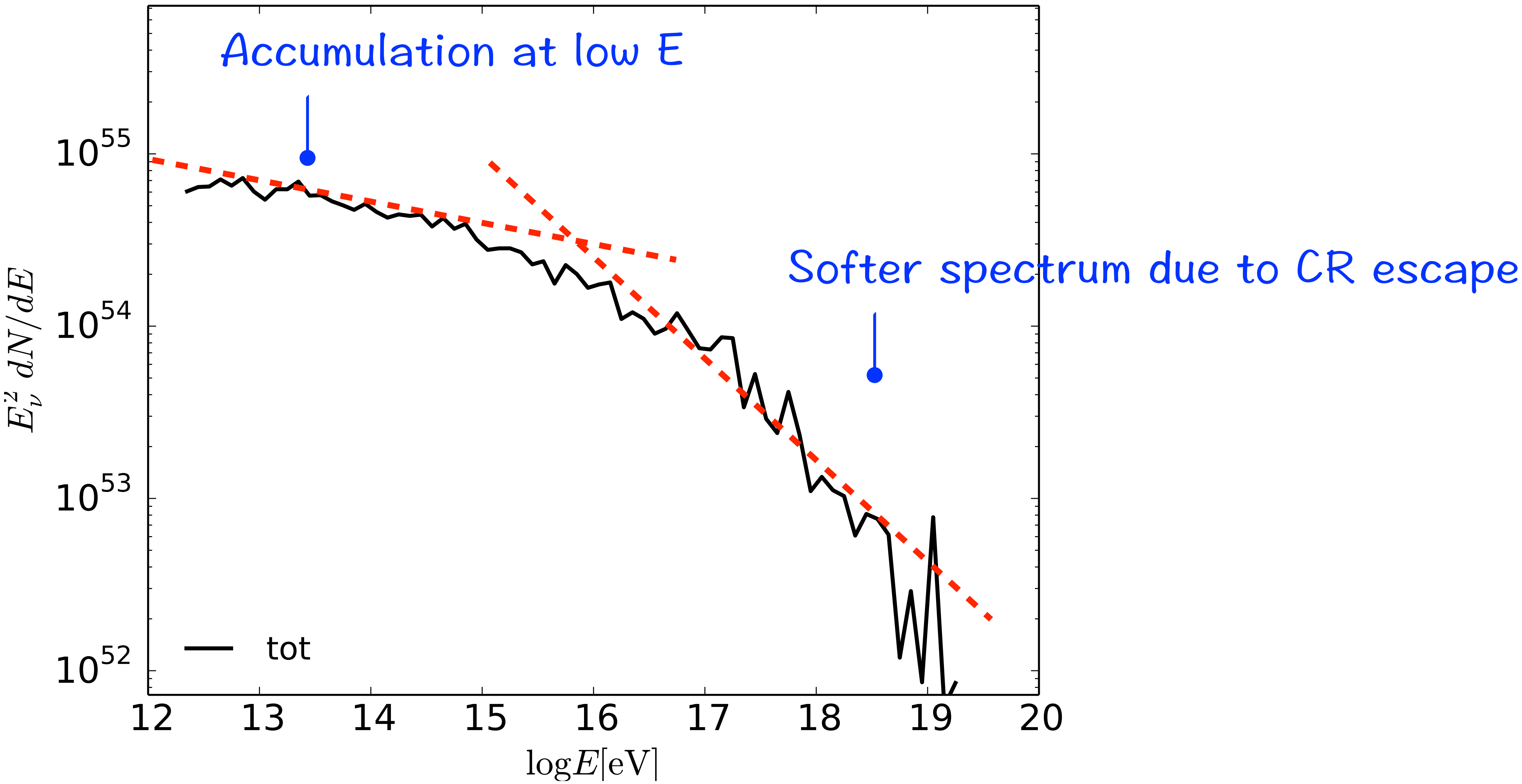
Cosmic Ray Flux from Single Cluster

$B_c = 40\,\mu G, M = 10^{15}\,M_\odot$



Neutrino Flux from Single Cluster

$B_c = 40\,\mu G, M = 10^{15}\,M_\odot$

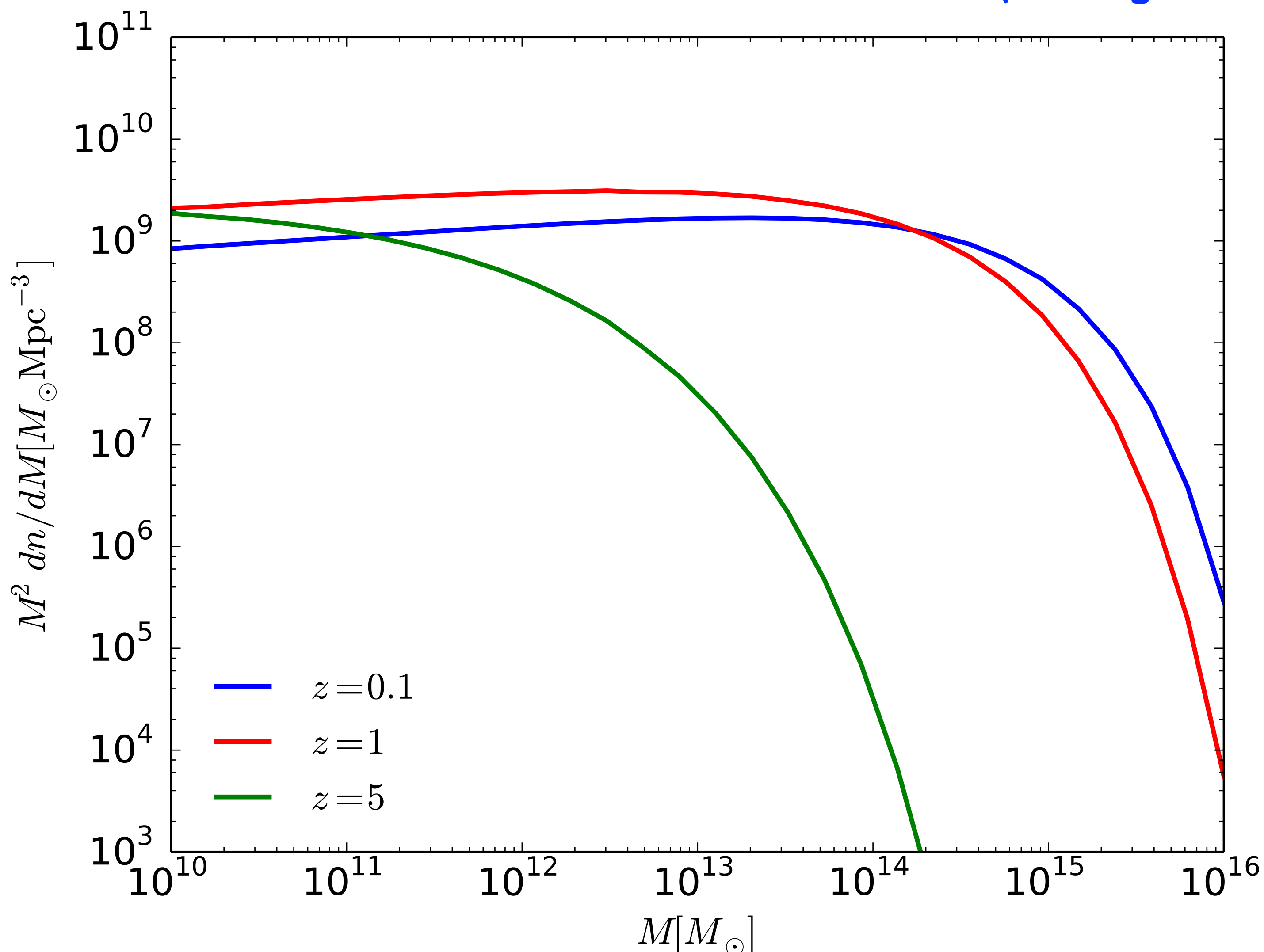


Cluster Mass Function

$$\frac{dn}{dM} = f(\sigma)\frac{\rho_m}{M}\frac{d\ln\ \sigma^{-1}}{dM}$$

rms variance of linear density field

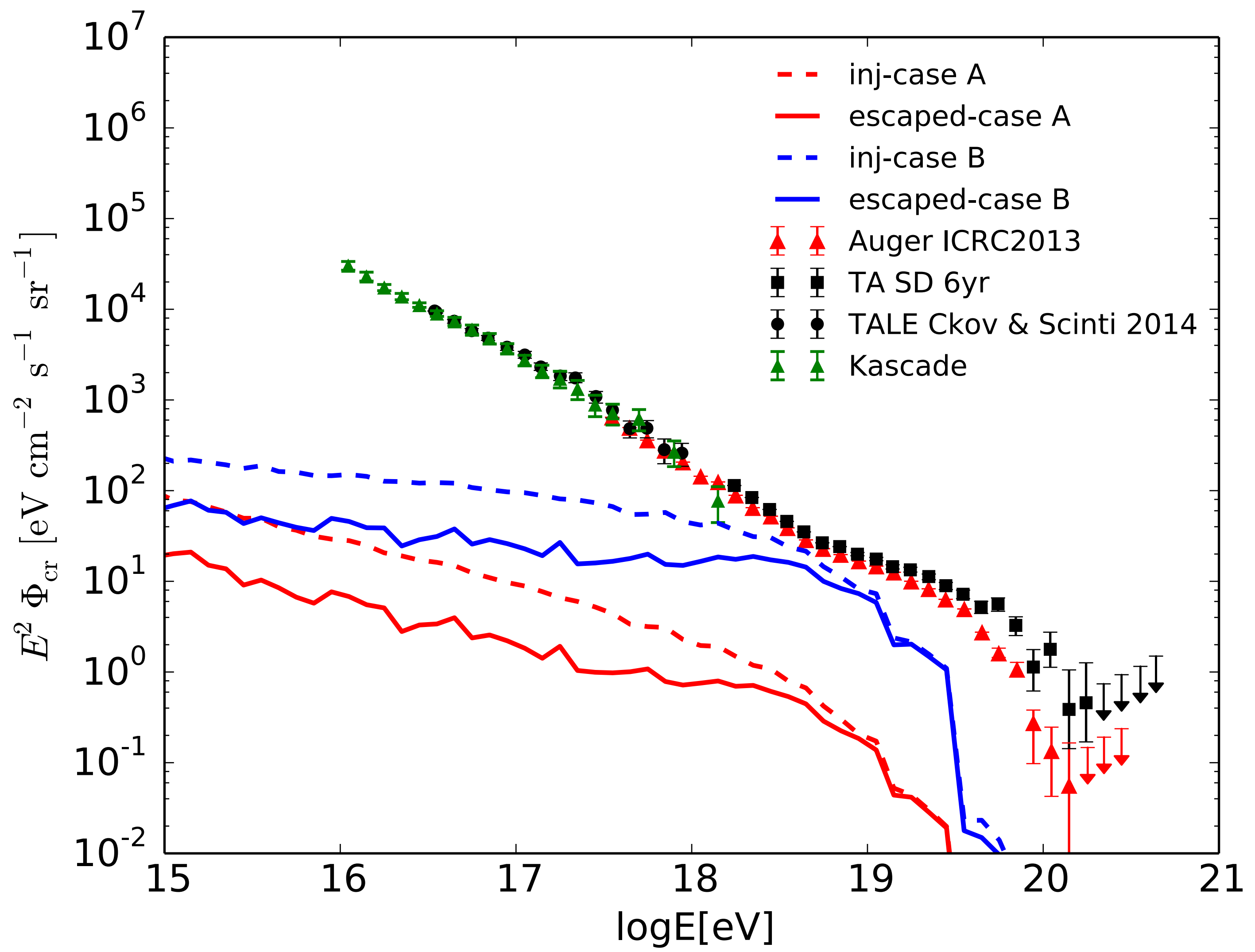
mass function multiplicity



Sheth & Tormen (1999)

Tinker et al 2008

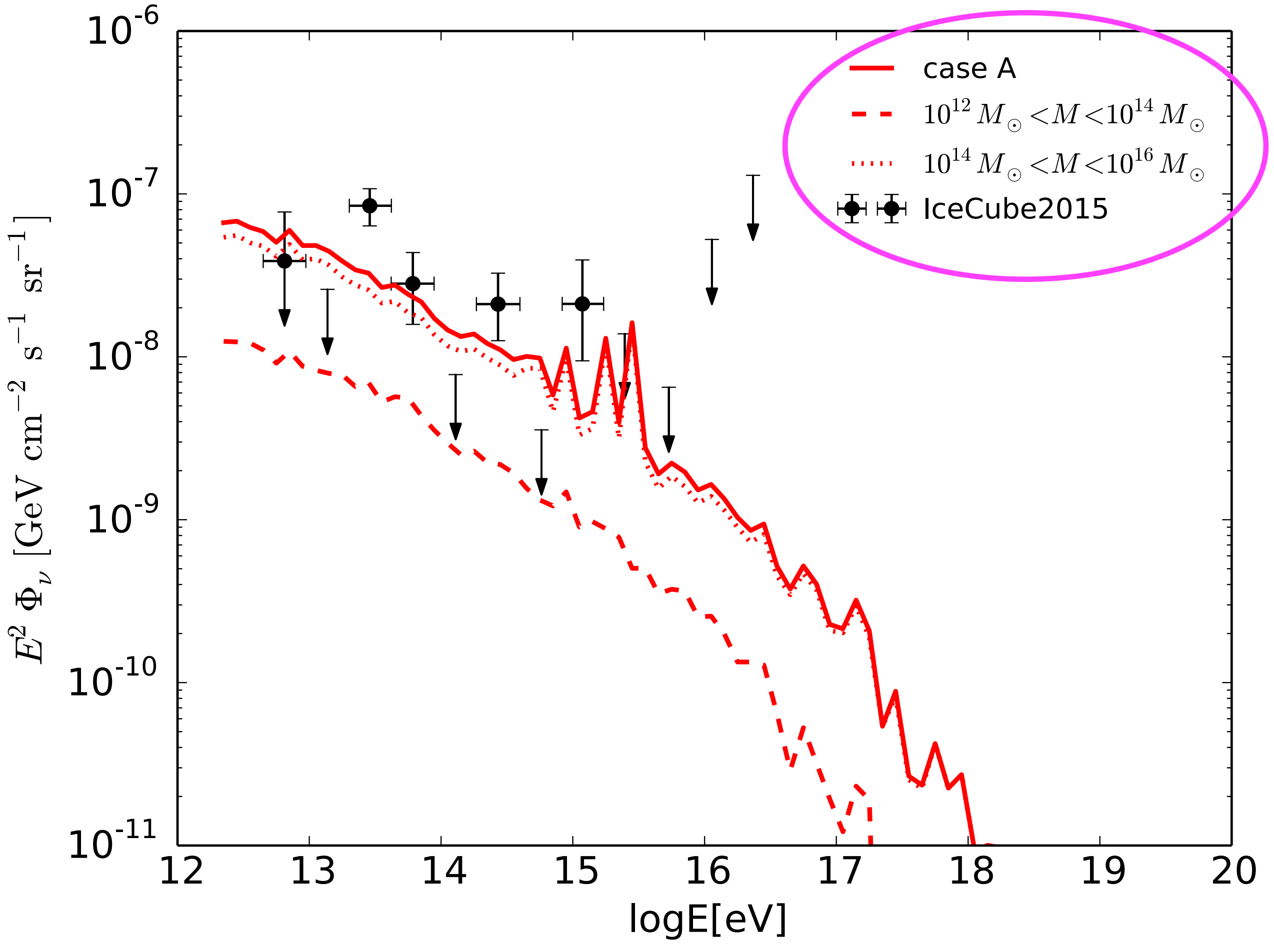
The Integrated Cosmic Ray Flux from Clusters

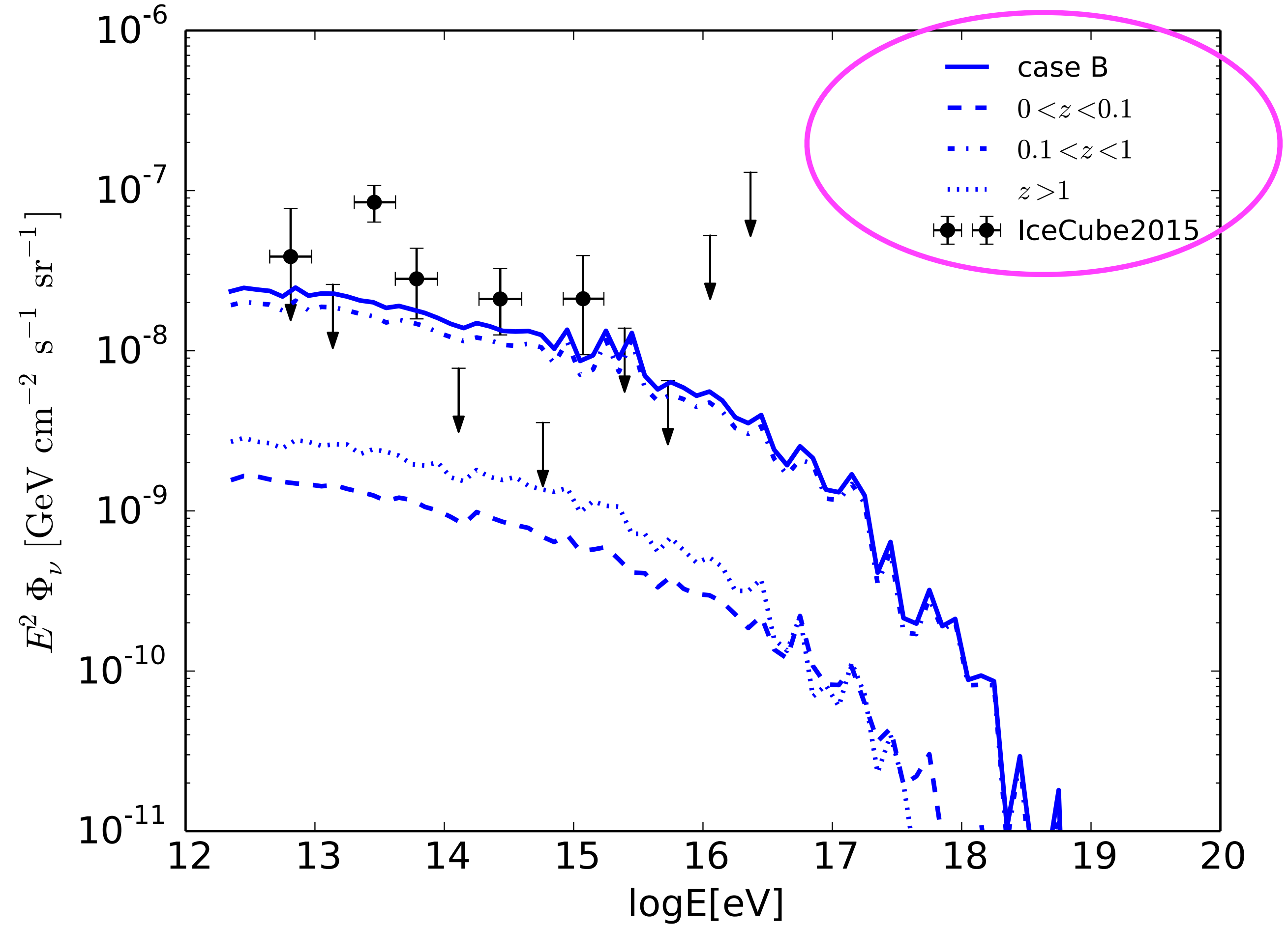


Case A - s = 2.5, frac = 0.1

Case B - s = 2.2, frac = 0.05

The Integrated Neutrino Flux from Clusters

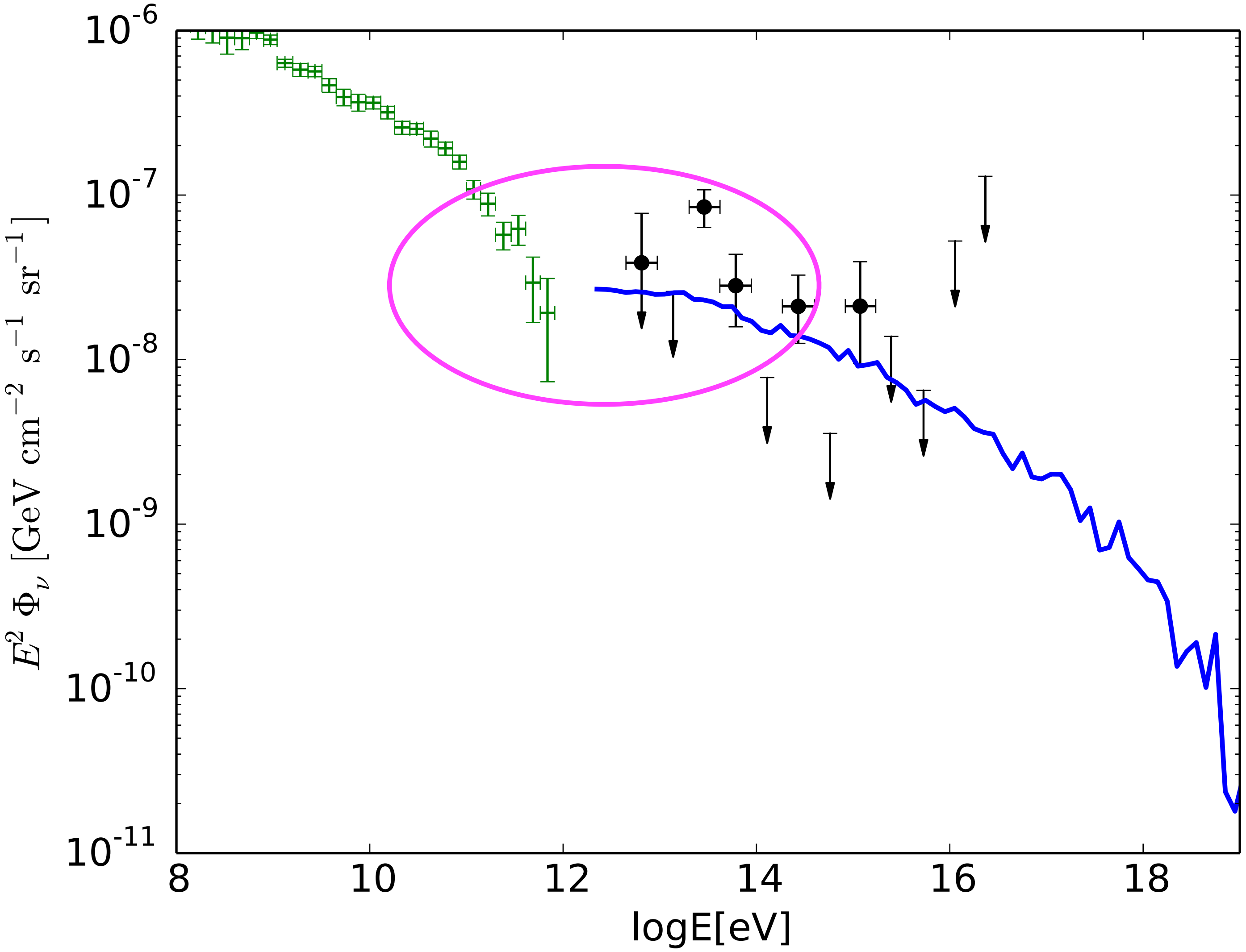


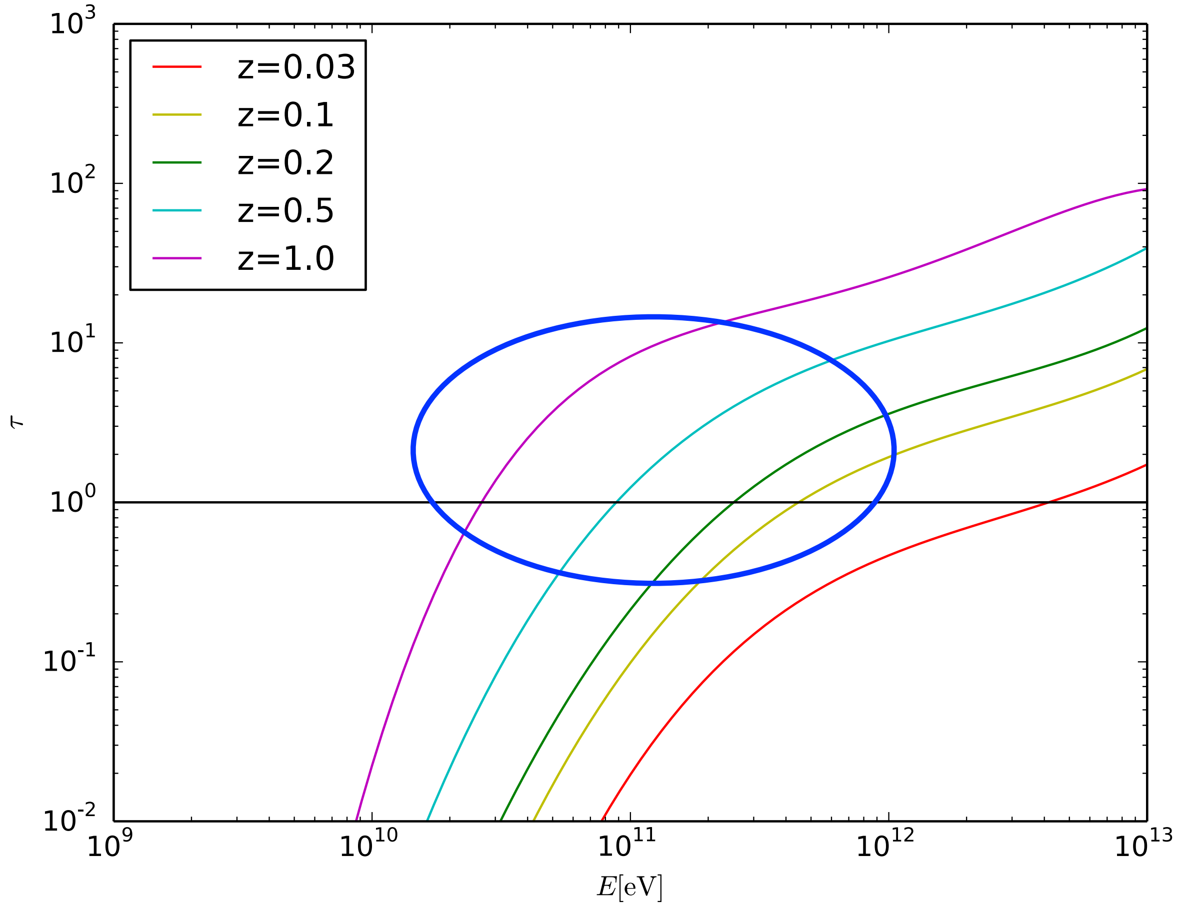


Case A - s = 2.5, frac = 0.1

Case B - s = 2.2, frac = 0.05

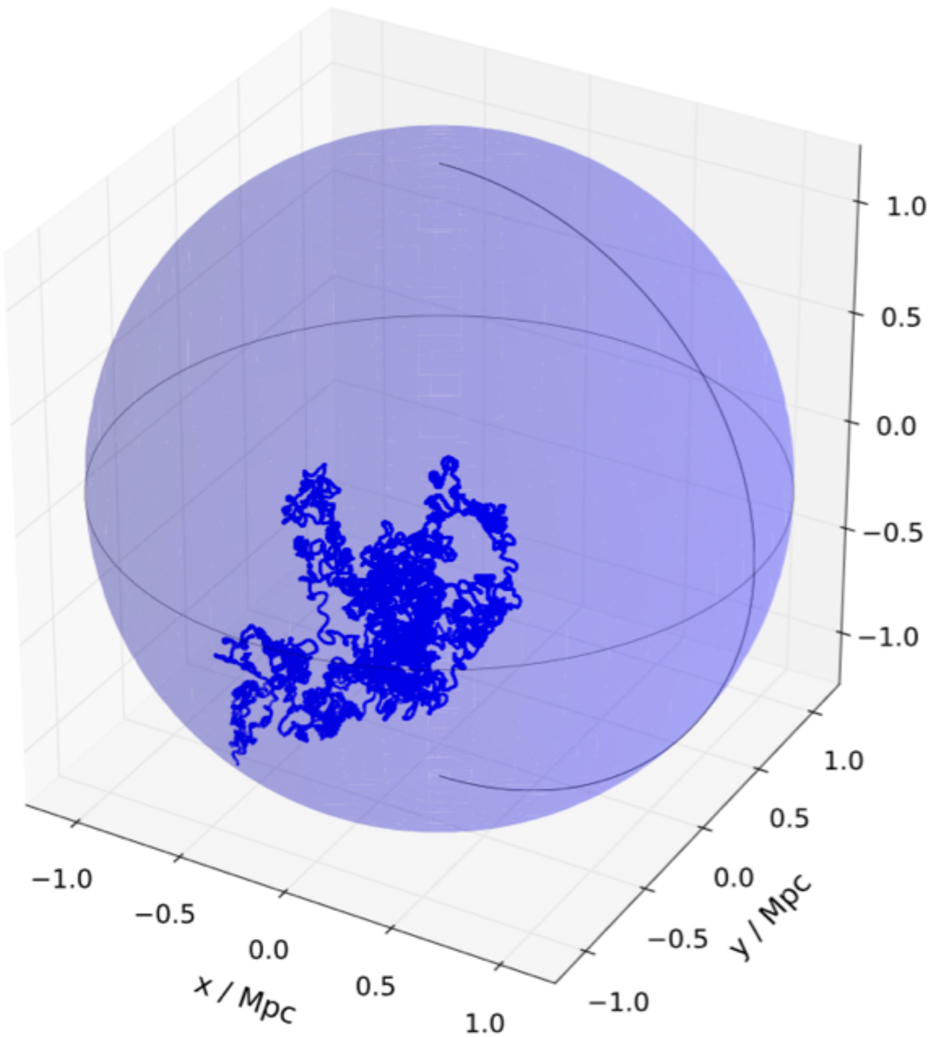
Consistency with Gamma-ray Limits

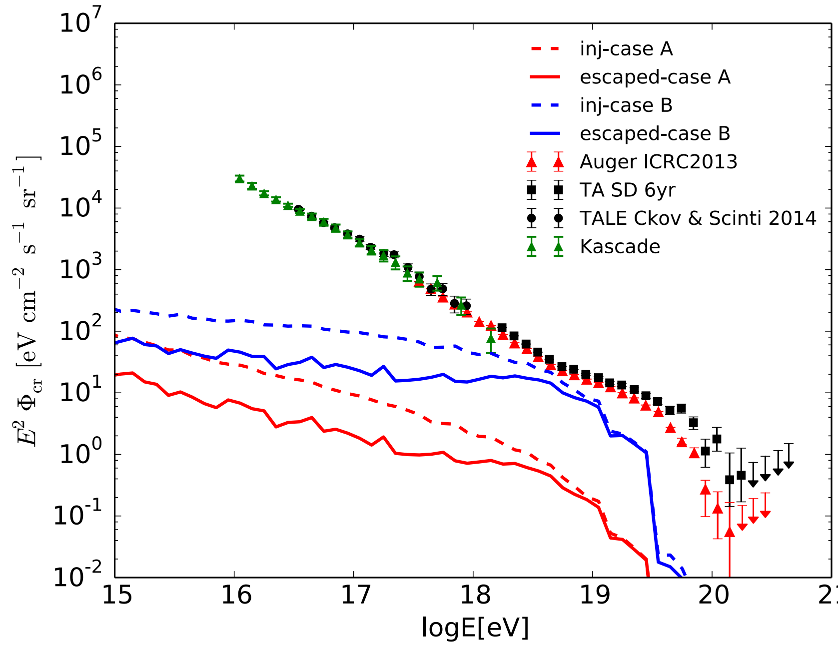


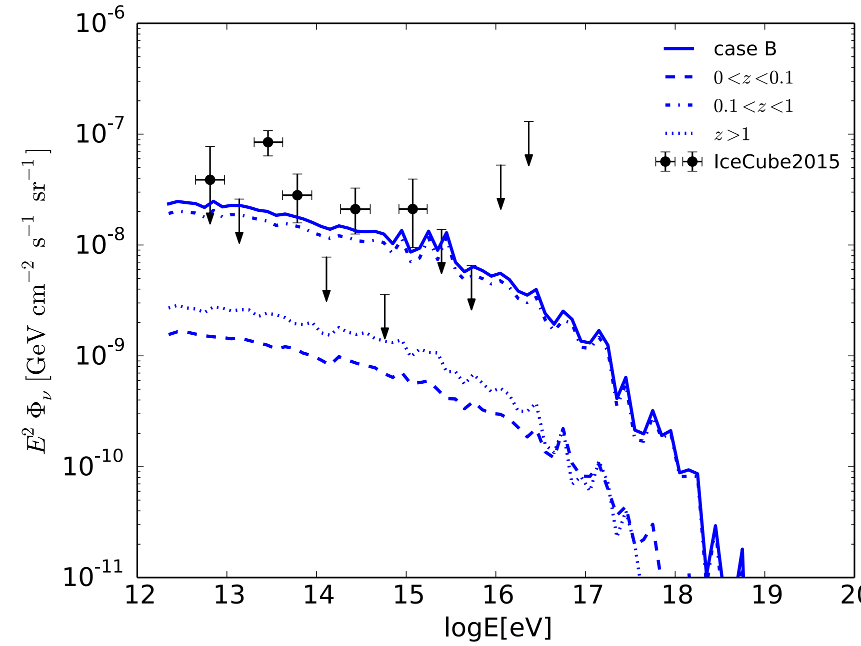


EBL attenuation will limit the gamma-ray production!

Conclusions





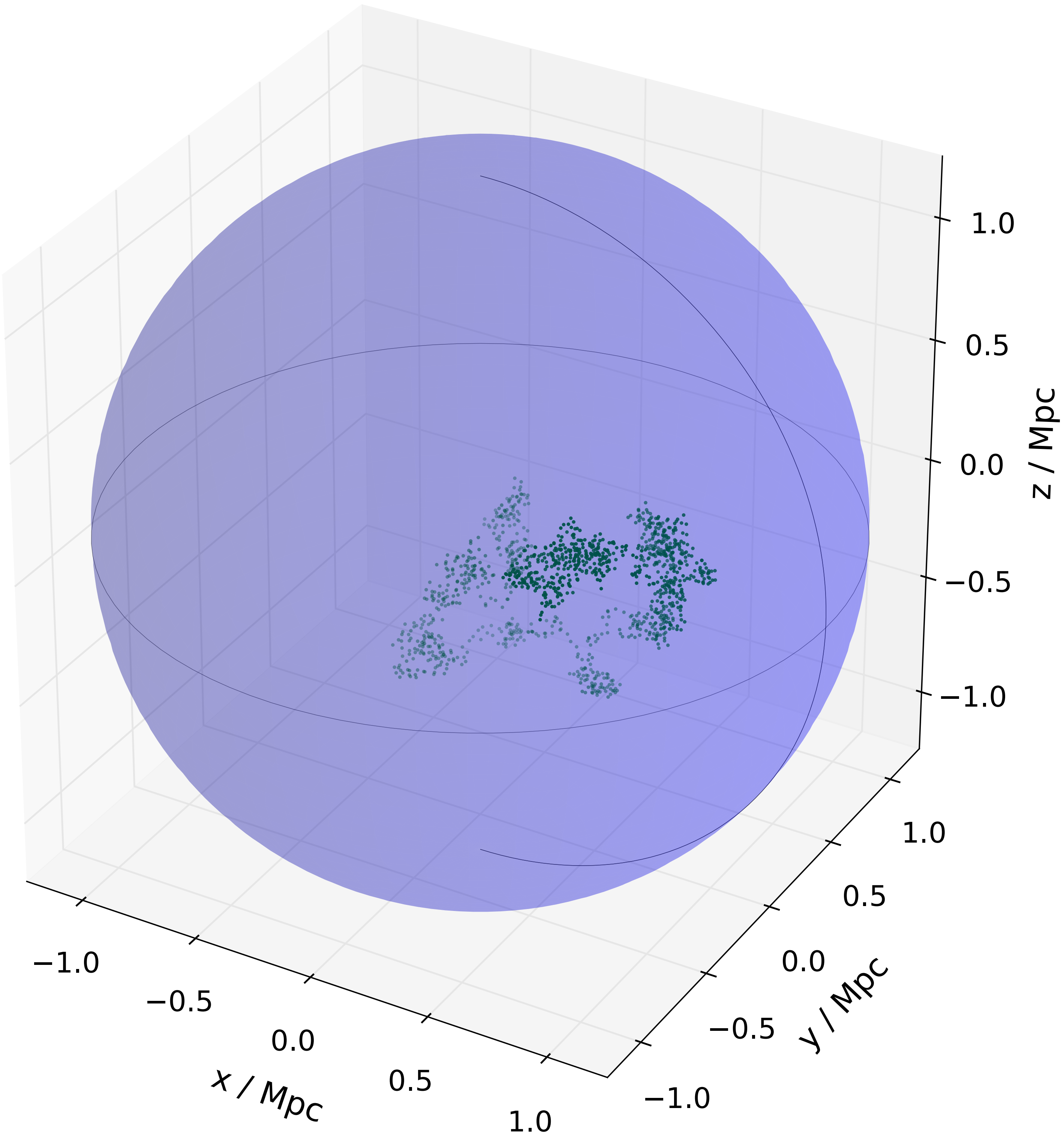


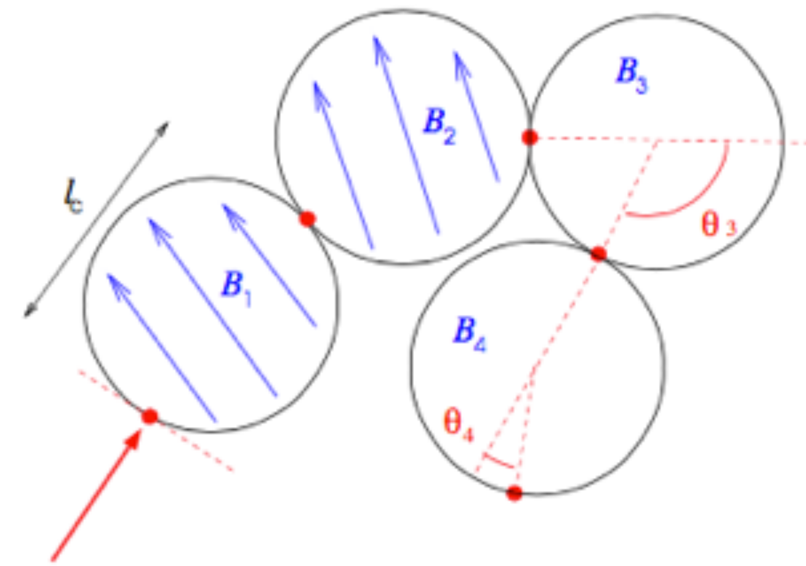
Cluster accretion shocks could significantly contribution to both high-energy cosmic rays around the ankle and TeV-PeV neutrinos detected by the IceCube Observatory.

Backup Slides

Particle Trajectory - 1 PeV

$$B_c = 10\,\mu G, M = 10^{14}\,M_\odot$$





Approximation for diffusion computation

Kotera & Lemoine 0706.1891