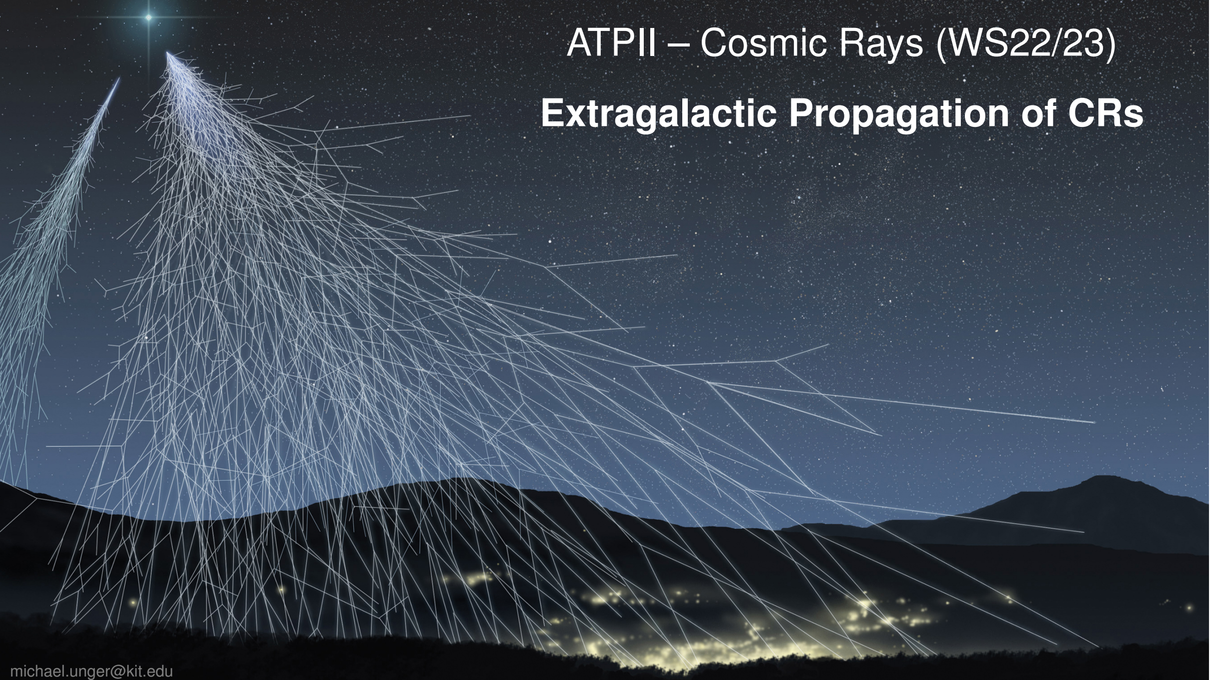
ATPII – Cosmic Rays (WS22/23)

Extragalactic Propagation of CRs



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Energy Spectrum of Ultrahigh-Energy Cosmic Rays

- gyro-radius in galactic magnetic field: (lecture 3)

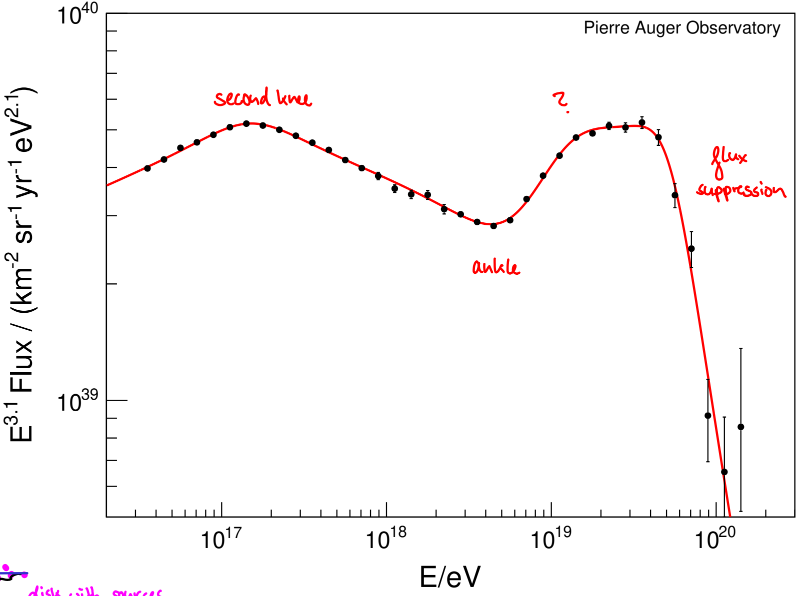
$$r_L = 1.1\ \text{kpc}\ \frac{R/\text{EV}}{B/\mu\text{G}}$$

rigidity R, magnetic field B

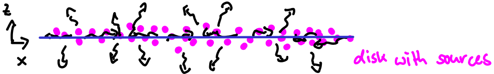
⇒ quasiballistic at UHE

- no strong UHE anisotropy

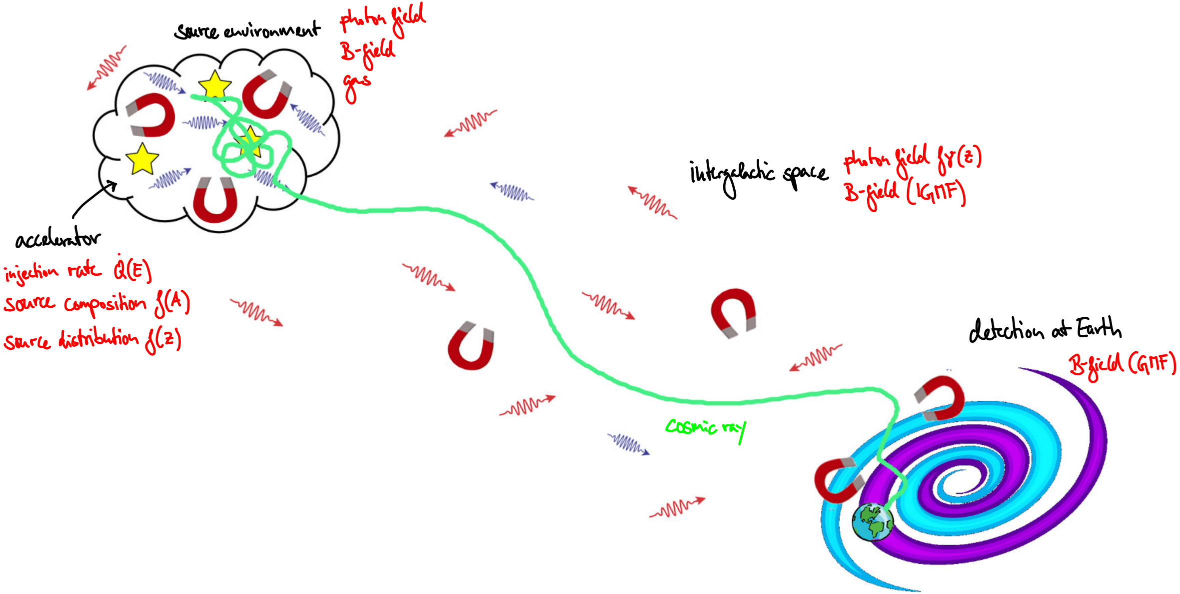
⇒ extragalactic origin?



$J_x > J_z$ ↔ not observed!



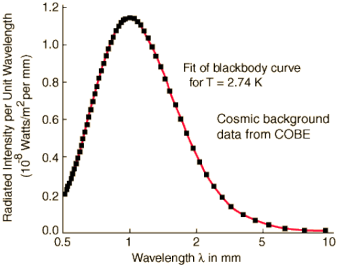
Extragalactic Cosmic-Ray Propagation



Greisen, Zatsepin, Kuzmin Cutoff (GZK)

$p + \gamma_{CMB} \rightarrow p + \pi^0$ or $n + \pi^+$

Penzias & Wilson 1965 (Nobel 1978)



VOLUME 16, NUMBER 17 PHYSICAL REVIEW LETTERS 25 APRIL 1966

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York

(Received 1 April 1966)

UPPER LIMIT OF THE SPECTRUM OF COSMIC RAYS

G. T. Zatsepin and V. A. Kuz'min

P. N. Lebedev Physics Institute, USSR Academy of Sciences

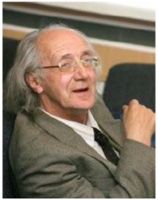
Submitted 26 May 1966

ZhETF Pis'ma 4, No. 3, 114-117, 1 August 1966

at peak:

$E_\gamma = h \cdot \nu_{max}$

$\approx 10^{-3}$ eV



Greisen, Zatsepin, Kuzmin Cutoff (GZK)

$$p_{CR} + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \quad \mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

$$\Delta^+ \rightarrow p + \pi^0, \quad \pi^0 \rightarrow \gamma\gamma$$

Cosmogenic photons and neutrinos !!

→ see summer semester

Reminder:

- 4-vectors: $\hat{p} = (E, \vec{p})$ $(c=1)$
- invariant mass: $\hat{p}^2 = m^2$
- scalar product: $\hat{p}_1 \cdot \hat{p}_2 = E_1 E_2 - \vec{p}_1 \vec{p}_2$

4-momentum conservation:

$$(\hat{p}_p + \hat{p}_\gamma)^2 = (p_n + p_\pi)^2 \overset{\text{at rest}}{=} (m_p + m_\pi)^2$$

$$= \hat{p}_p^2 + 2\hat{p}_p \hat{p}_\gamma + \hat{p}_\gamma^2 = m_p^2 + 2(E_p, \vec{p}_p)(E_\gamma, \vec{p}_\gamma) + 0$$

$$= m_p^2 + 4 E_p E_\gamma$$

using $|\vec{p}_p| = \sqrt{E_p^2 - m_p^2} \approx E_p$, $|\vec{p}_\gamma| = E_\gamma$

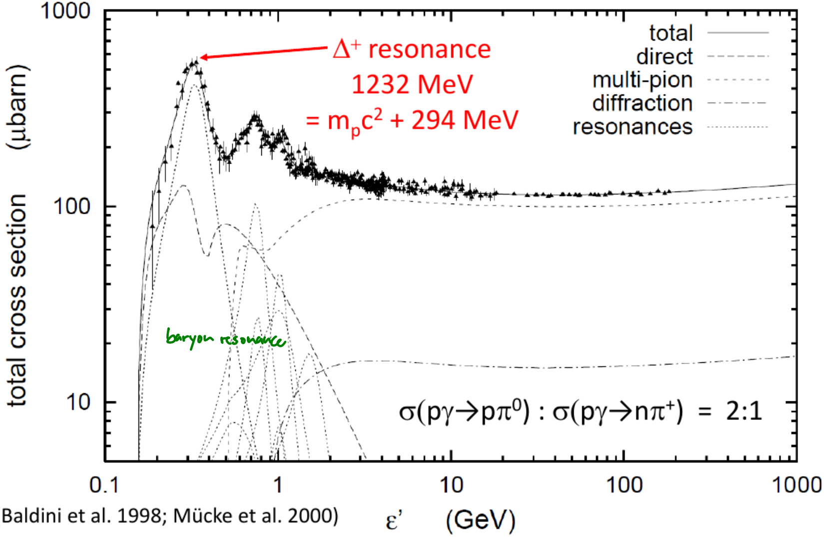
head-on collision

$$E_{GZK} = \frac{(m_n + m_\pi)^2 - m_p^2}{4E_\gamma} = 7 \cdot 10^{19}\, eV$$

⇔ flux suppression ?!?

Photo-Pion Production

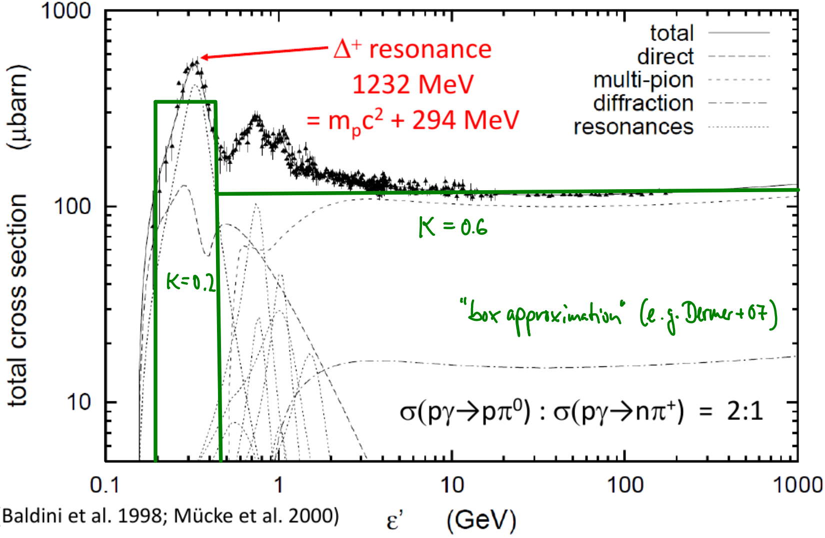
proton at rest



(Baldini et al. 1998; Mücke et al. 2000)

Photo-Pion Production

proton at rest



(Baldini et al. 1998; Mücke et al. 2000)

Photo-Pion Production

- interaction length:

  $\lambda = (\sigma \cdot n)^{-1}$ (σ: cross section, n: number density) → see lecture 4

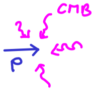
  e.g. $n_{CMB} = 400/cm^3$, $\sigma_{photopion} \approx 0.35\, mb$ → $\lambda \approx 2\, Mpc$

- inelasticity: relative energy loss per interaction: $\kappa \approx m_\pi / (m_p + m_\pi) = 0.125$

- energy loss length: $\chi = -c \left(\frac{1}{E} \frac{dE}{dx} \right)^{-1} = \frac{\lambda}{\kappa} \approx 20\, Mpc$ $\left(\frac{1}{E}\frac{\Delta E}{\Delta x} = \frac{1}{E} \frac{\kappa \cdot E}{\lambda} \right)$

  ⇒ GZK sphere: high energy particles must be produced "nearby"

- full calculation: integrate $\sigma(\varepsilon')$ over photon energy spectrum $n(\varepsilon)$ and isotropic photon directions



Lorentz-trafo to p rest frame:

$\varepsilon' = \Gamma \varepsilon (1 - \beta_p \cos\theta)$

using box approximation $\chi \approx \frac{13.7\, Mpc}{e^{-y}(1+y)}$ $y = 4 \cdot 10^{20}\, eV/E$

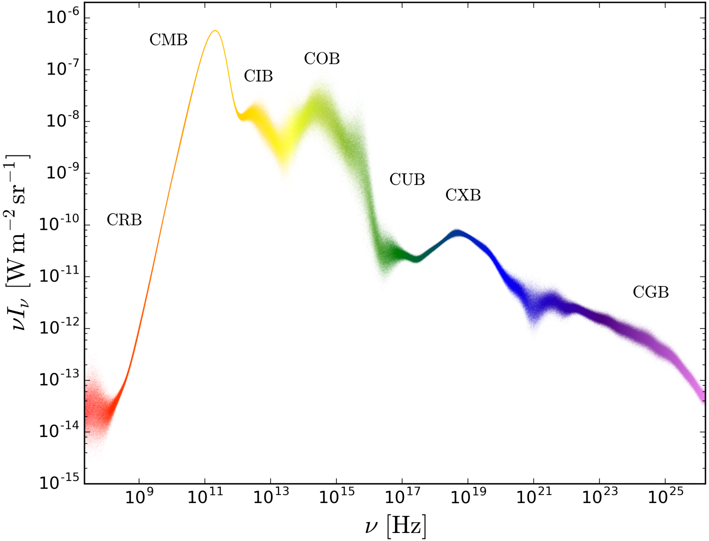
Extragalactic Photon Fields

spectral energy distribution $\nu I_\nu \equiv \nu \frac{dI}{d\nu} \sim E^2 \frac{dn}{dE}$

- extragalactic background light "EBL"
  starformation + AGN (redshifted)

- $\nu_{EBL}^{peak} \approx 10^2\, \nu_{CMB}^{peak}$

$\Rightarrow$ threshold $\sim 10^{-2} E_{GZK} \approx 10^{18}$ eV



arXiv:1802.03694

Pair Production and Adiabatic Loss

- $p + \gamma \rightarrow p + e^+ + e^-$
- inelasticity: $K_{e^+e^-} = \frac{2m_e}{m_p + 2m_e} \approx 10^{-3}$
- $\frac{K_\pi \sigma_\pi}{K_{e^+e^-} \sigma_{e^+e^-}} = 100 \Rightarrow \chi_{e^+e^-} = 100\, \chi_\pi$

$$E_{e^+e^-} = \frac{(m_n + 2m_e)^2 - m_p^2}{4E_\gamma} = 5 \cdot 10^{17}\, eV$$

(replace m_π with $2m_e$ in GZK equation)

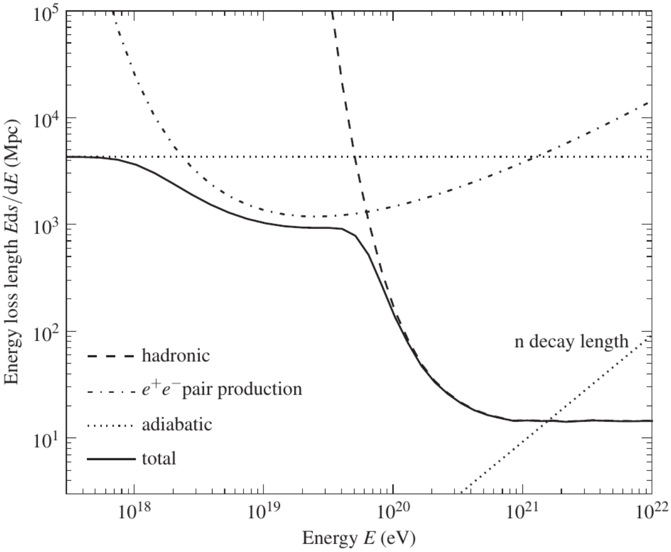
$$z = \frac{\lambda_{obs} - \lambda_0}{\lambda_0}$$

- expansion of universe: (z: redshift)

$$z = \frac{H_0 \cdot D}{c} \qquad H_0 \approx \frac{70\, km/s}{Mpc}$$

$$E_{earth} = E_{source} / (1 + z_{source}) \quad \underset{z=0}{\leftrightarrow} \quad \frac{1}{E}\frac{dE}{dt} = -H_0 \quad \leftrightarrow \quad \chi = c/H_0 \approx 4\, Gpc$$

Energy Loss of Protons (z=0)



Gaisser, Engel & Resconi, “Cosmic Rays & Particle Physics”

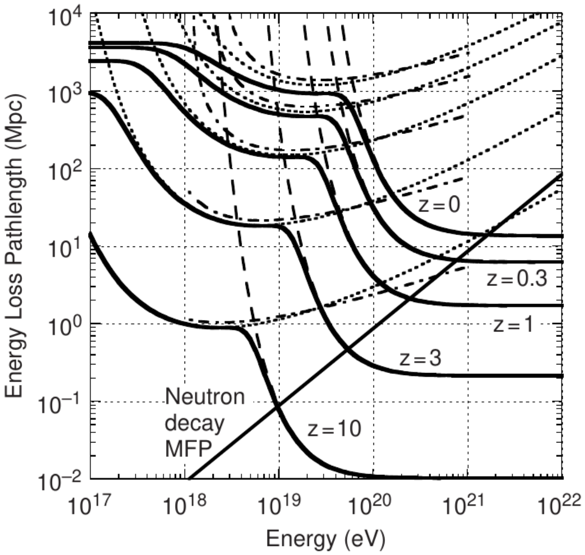
Energy Loss of Protons

cosmological distances:

CMB temperature: $T(z) = T_0\,(1+z)$

CMB density: $n(z) = n_0\,(1+z)^3$

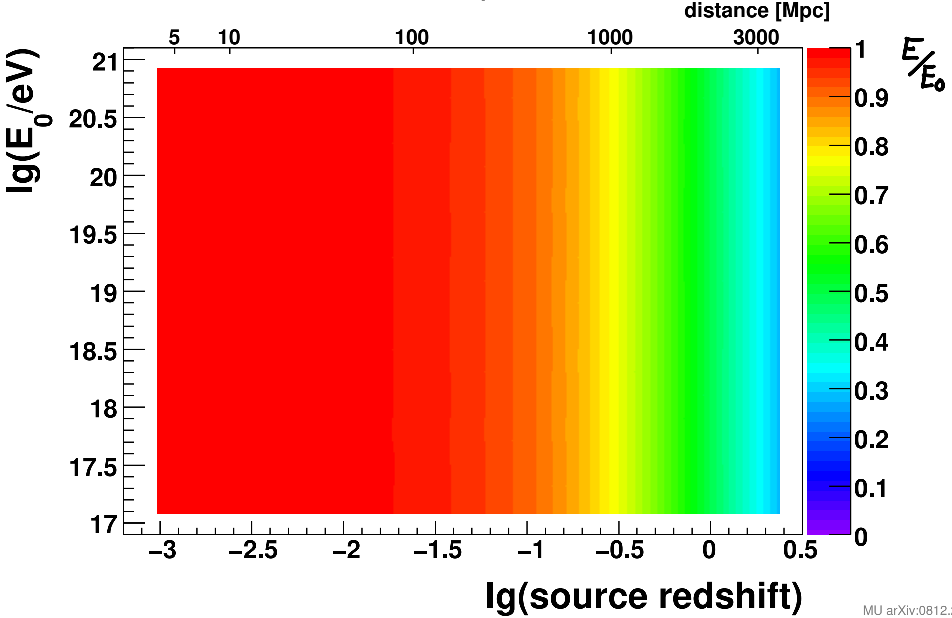
$$\Rightarrow \quad \chi(E,z) = (1+z)^{-3}\,\chi((1+z)\cdot E,\,0)$$



Dermer & Menon, "High Energy Radiation from Black Holes"

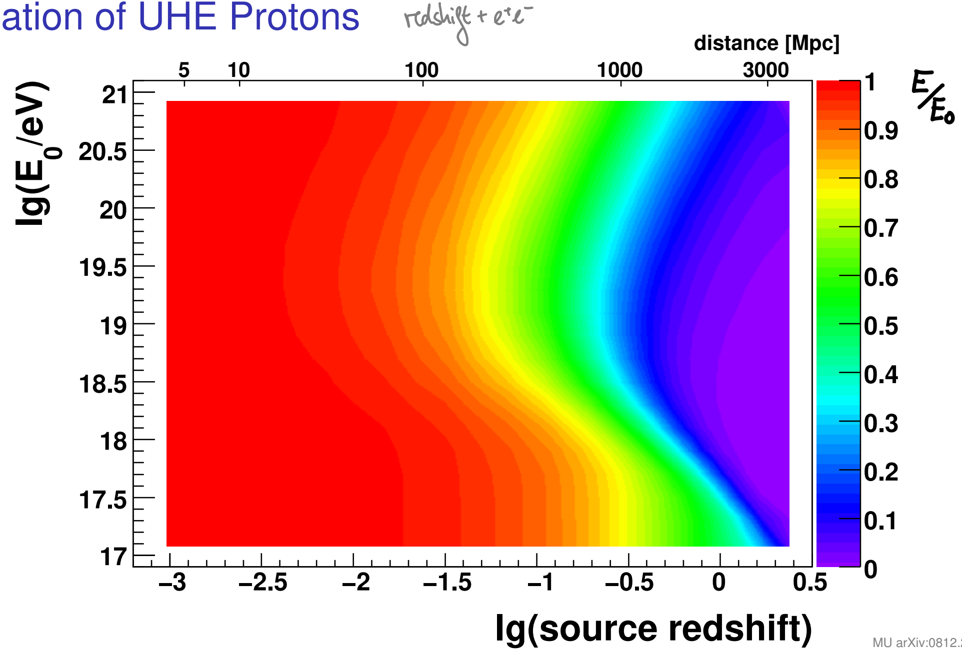
Propagation of UHE Protons

only redshift



MU arXiv:0812.2763

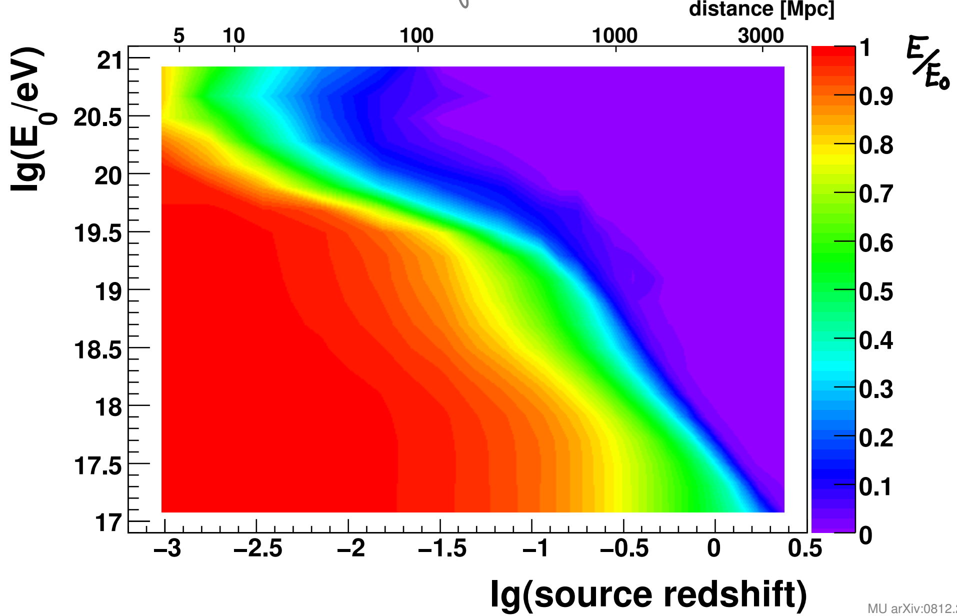
Propagation of UHE Protons



MU arXiv:0812.2763

Propagation of UHE Protons

redshift + e⁺e⁻ + photo-pion



MU arXiv:0812.2763

Propagation of UHE Nuclei

$(A,Z)+\gamma \rightarrow (A',Z') + (Z-Z')p + (A-A'-(Z-Z'))n$

(d, t, He, ... emission also possible)

- giant dipole resonance (GDR)

  collective oscillation of all p vs. all n

  mostly $A+\gamma \rightarrow (A-1) + n/p$

- quasi deuteron scattering (QD)

  scattering with n+p pair → p+n emission

- baryon resonances (BR)

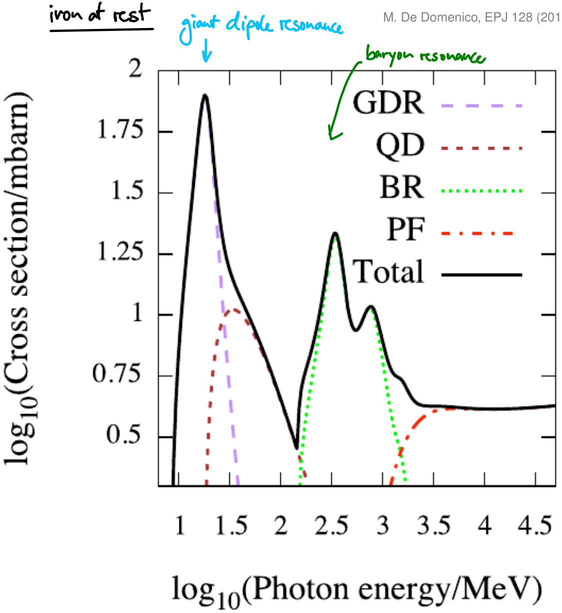
  photo-pion with nucleon $\langle N_{n/p} \rangle \approx 6$ (+π-production!)

- photo fragmentation (PF)

  nucleus breakup

iron at rest

M. De Domenico, EPJ 128 (2013) 99



Propagation of UHE Nuclei

D.Allard APP 39 (2012) 33

- Inelasticity of GDR:

  $A + \gamma \to (A-1) + n/p$

  $\Rightarrow$ energy loss per interaction: $K \sim \frac{1}{A}$

  $\Rightarrow K(He) = 0.25\,,\; K(Fe) = 0.018$

- cross section:

  $\sigma_{GDR} \sim A \;\Rightarrow\; K \cdot \sigma \approx \text{const}\,!$ same for all A!

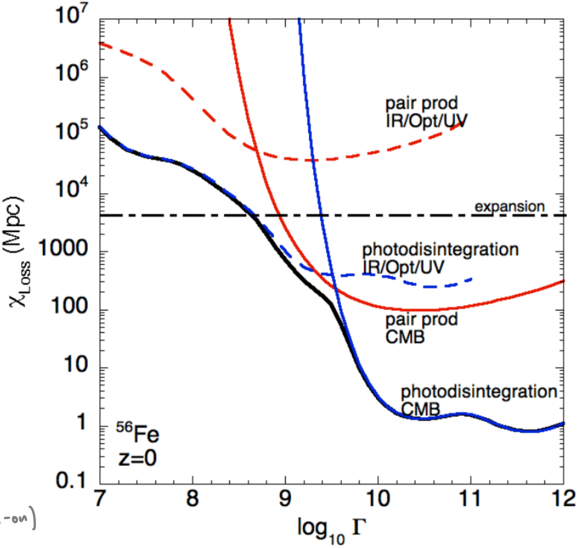
- $\sigma_{Fe} \approx 30\,\text{mb} \;\Rightarrow\; \frac{\chi_{Fe}}{\chi_p} \approx \frac{(\sigma_\pi K_\pi)_p}{(\sigma_{GDR} \cdot K_{GDR})_{Fe}} \approx 0.1$

- $\varepsilon'_{GDR} \approx 20\,\text{MeV}$ in nucleus rest frame. same for all A!

  $\Rightarrow$ same Lorentz-boost needed for all nuclei

  $\Gamma_{GDR} = \frac{E}{A \cdot m_p} = \frac{\varepsilon'_{GDR}}{2\,\varepsilon} \approx \frac{20\,\text{MeV}}{2 \cdot 10^{-3}\,\text{eV}} = 10^{10}$ (head-on)

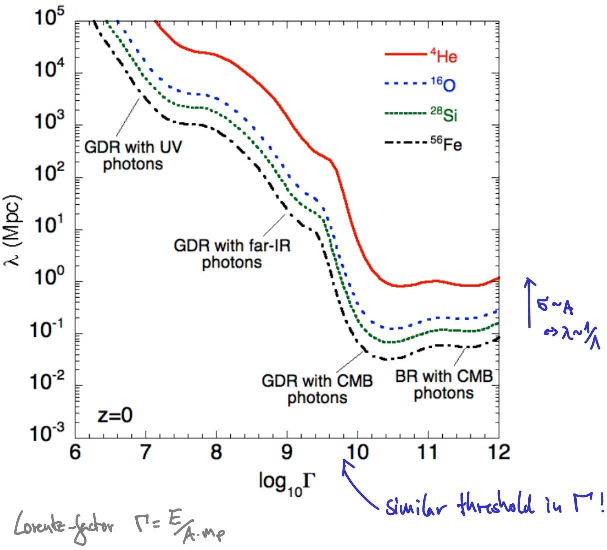
  $\Rightarrow$ cosmic coincidence $E^{p}_{photo\text{-}\pi} \approx E^{Fe}_{GDR}$ (threshold energies in full calculation $\Rightarrow$ see next page)

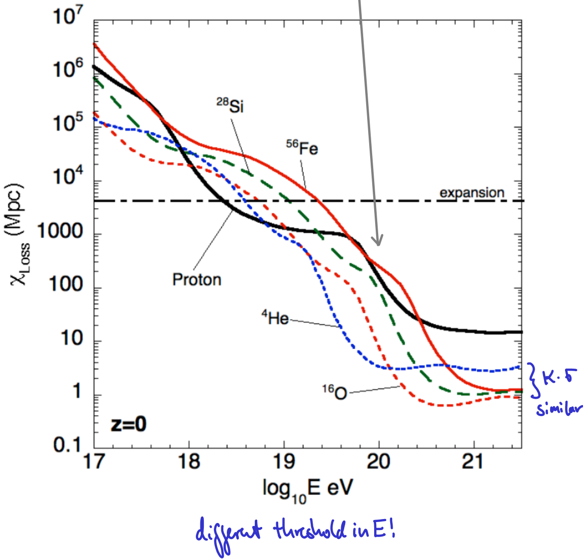


Propagation of UHE Nuclei

similar loss length p/Fe at UHE

D.Allard APP 39 (2012) 33

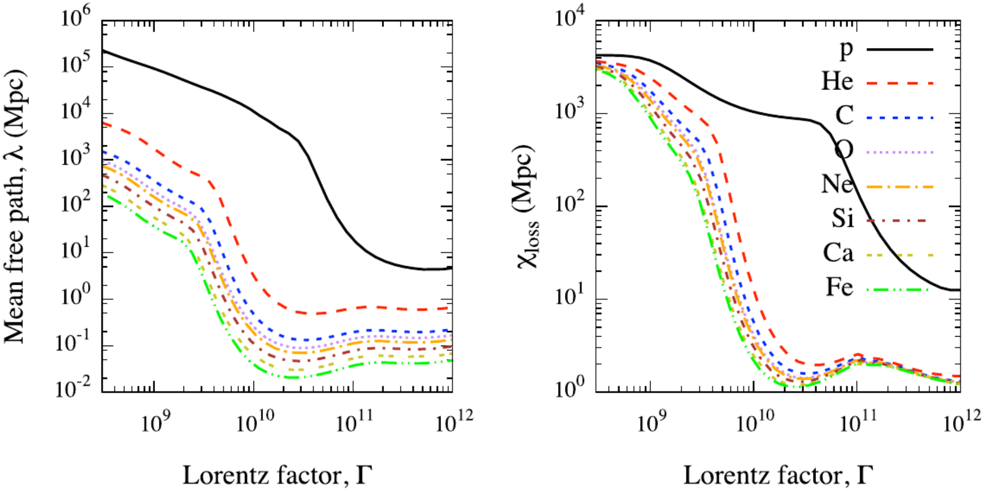




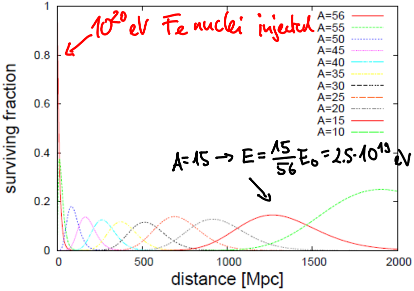
Propagation of UHE Nuclei

(variation of previous slide)

M. De Domenico, EPJ 128 (2013) 99



Propagation of UHE Nuclei



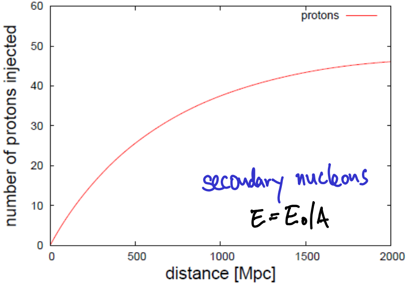
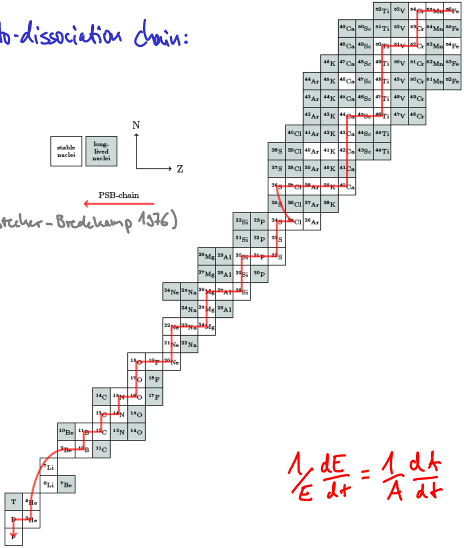


photo-dissociation chain:

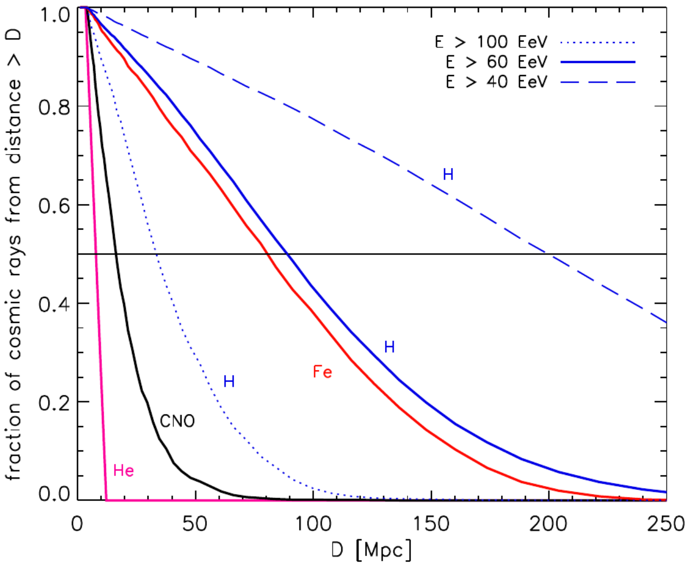


$$\frac{1}{E}\frac{dE}{dt}=\frac{1}{A}\frac{dA}{dt}$$

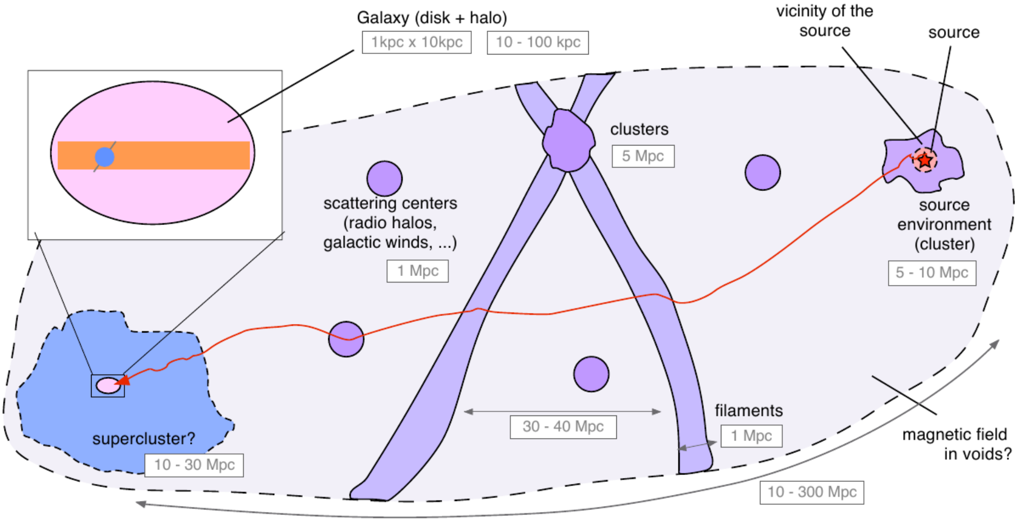
A. Taylor et al., Phys.Rev. **D77** (2008) 103007 and **D82** (2010) 123005

“GZK Sphere”

K. Kotera & A.V. Olinto ARAA 49 (2011) 119

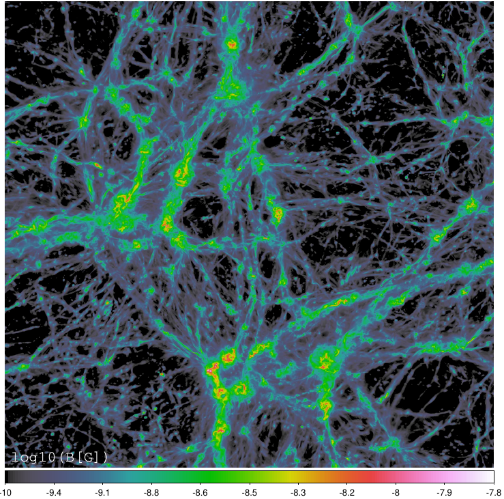


Extra- and Intergalactic Magnetic Fields



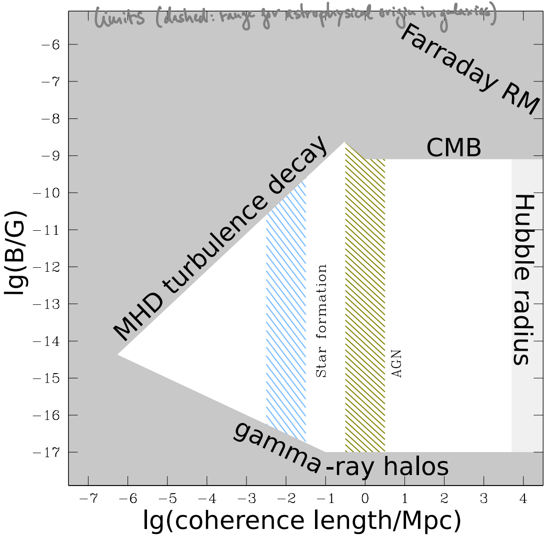
K. Kotera & A.V. Olinto ARAA 49 (2011) 119

50Mpc



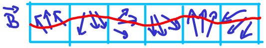
Projected (density weighted) magnetic field intensity for our 2400^3 simulation of a $(50\ \mathrm{Mpc})^3$ volume at $z = 0$.

Vazza et al. MNRAS 445 (2014) 3706



Durrer&Neronov, AAR **21** (2013) 62

Propagation Through the IGMF



$R_L > \lambda_c$

random walk in angle

- small-angle scattering for $r_L > \lambda_c$ (coherence length λ_c) ⇒ see lecture 4

- standard deviation of deflection $\theta_{rms} = \sqrt{\langle \Delta\theta^2 \rangle}$

$$\theta_{rms} \approx 3.5^\circ \left(\frac{B}{nG}\right) \left(\frac{10^{20}\,V}{R}\right) \left(\frac{d}{100\,Mpc}\right)^{1/2} \left(\frac{\lambda_c}{1\,Mpc}\right)^{1/2}$$

⇒ proton astronomy at UHE !

(maybe even carbon-astronomy if $B = 10^{-10}$ G)

- corresponding average time delay wrt ballistic @ $v = c$

$$\langle t \rangle = 3 \cdot 10^5\,yr \left(\frac{B}{nG}\right)^2 \left(\frac{10^{20}\,V}{R}\right)^2 \left(\frac{d}{100\,Mpc}\right)^2 \left(\frac{\lambda_c}{1\,Mpc}\right)$$

⇒ coincident detection of CR, γ, ν needs steady sources $> \langle t \rangle$

- magnetic horizon: $t < 1/H_0$ (Hubble time 14 Gyr)

$$R \lesssim \left(\frac{B}{nG}\right) \left(\frac{\lambda_c}{1\,Mpc}\right)^{1/2} \left(\frac{d}{70\,Mpc}\right) 10^{18}\,V$$

⇒ low-rigidity horizon