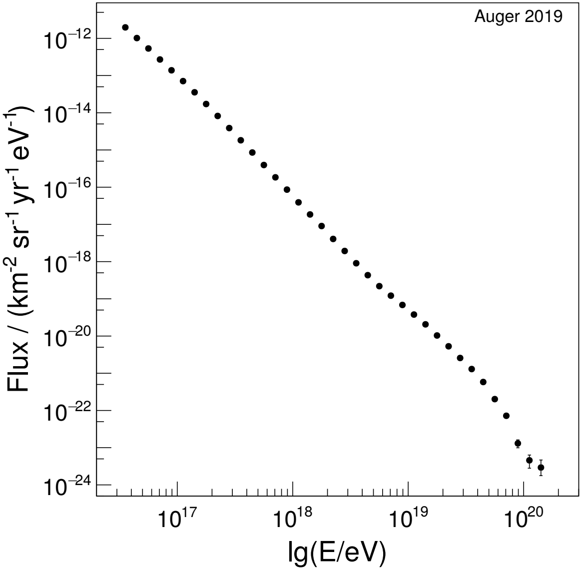
Source Models for Particles of Ultra-High Energy

HIRSAP Workshop 2019

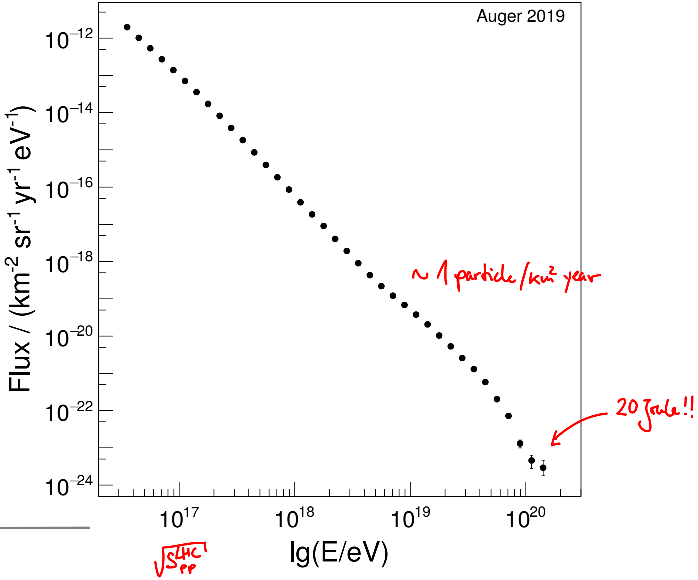
.

M. Unger (KIT)

Energy Spectrum of Ultrahigh-Energy Cosmic Rays

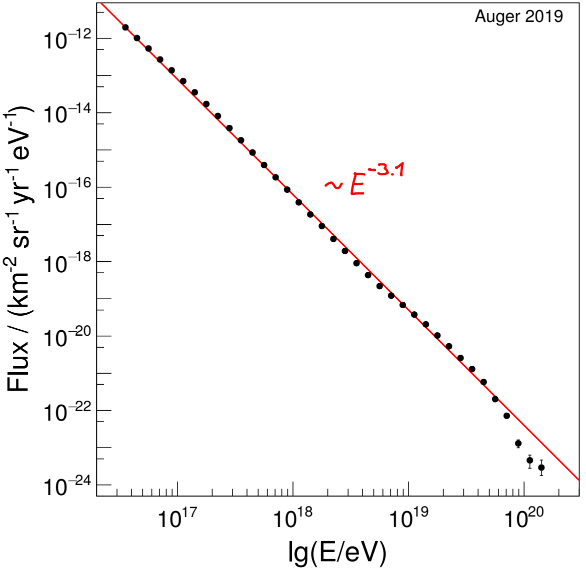


Energy Spectrum of Ultrahigh-Energy Cosmic Rays

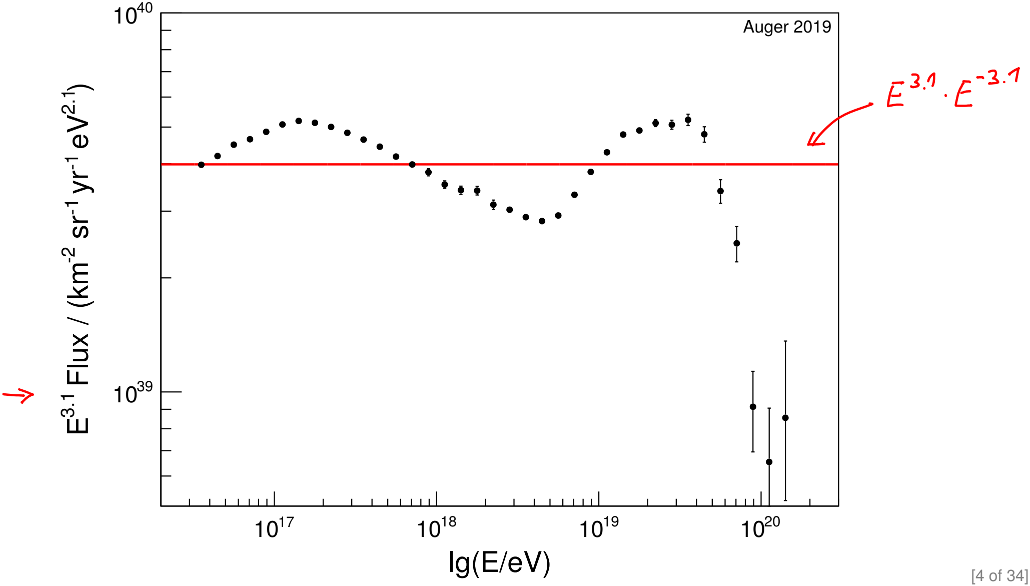


$E_{beam}^{LHC} = 7 \cdot 10^{12}$ eV

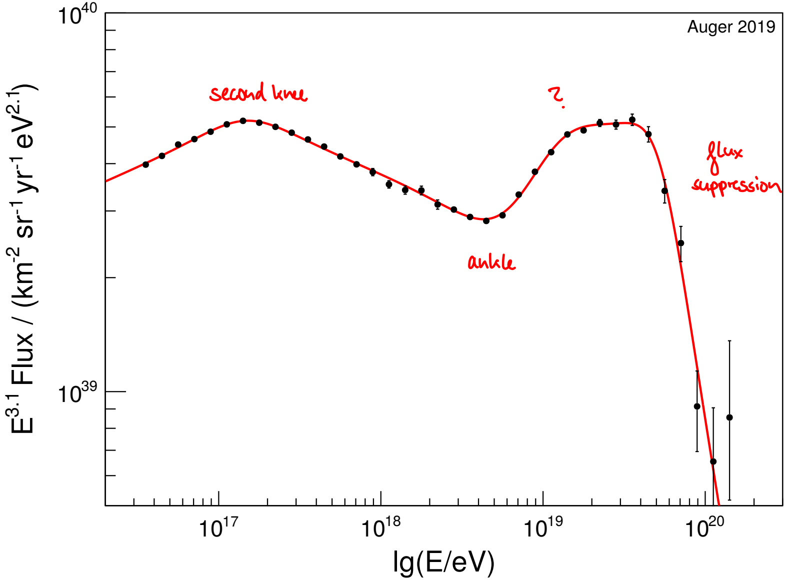
Energy Spectrum of Ultrahigh-Energy Cosmic Rays



Energy Spectrum of Ultrahigh-Energy Cosmic Rays



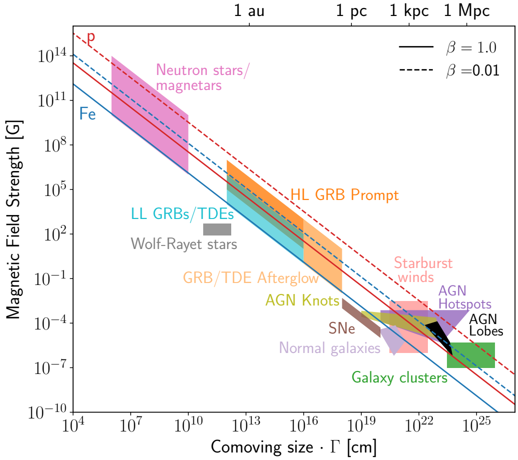
Energy Spectrum of Ultrahigh-Energy Cosmic Rays

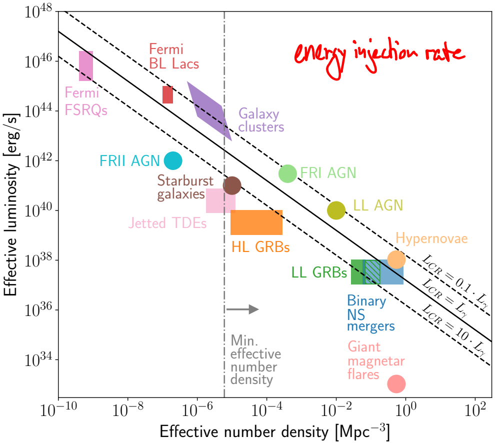


UHECR Source Candidates

Hillas criterion for maximum energy

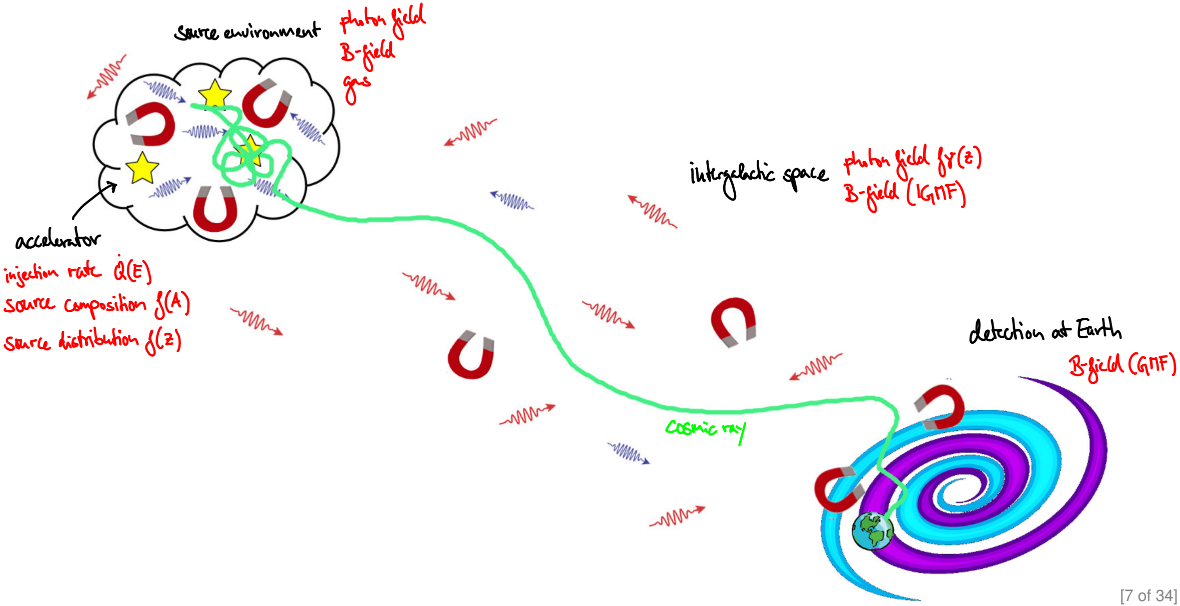
$E_{max} = \beta Z B R$



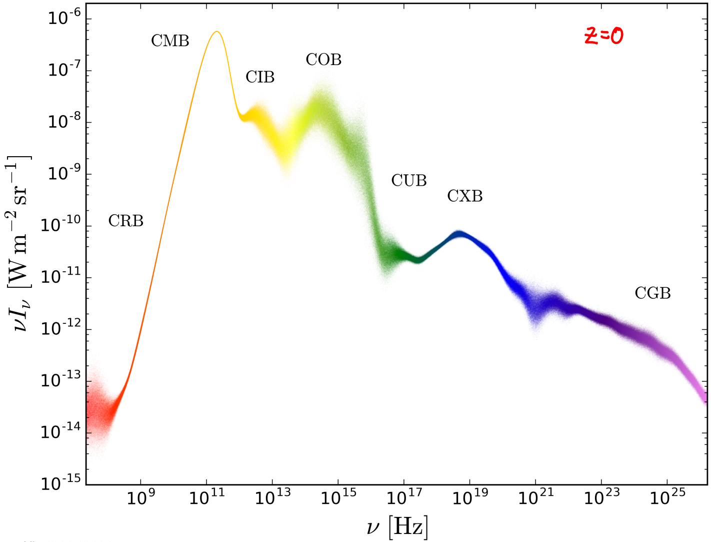


MIAPP review, Front.Astron.Space Sci. 6 (2019) 23

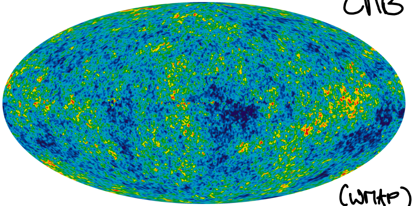
Generic Source Model



Propagation of UHECRs in Photon Fields



CMB



(WMAP)

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

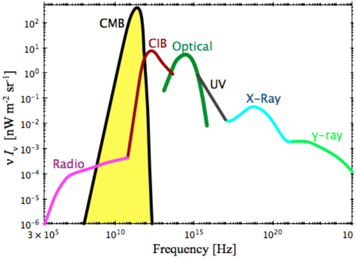
GZK

Greisen-Zatsepin-Kuzmin effect

arXiv:1802.03694

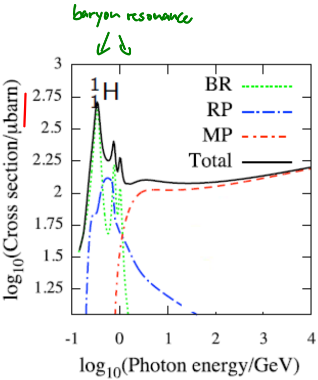
Propagation of UHECRs in Photon Fields

• interaction with photon fields:

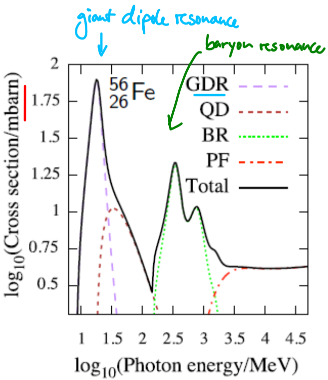


http://www.andrewjaffe.net

proton at rest



iron at rest



De Domenico, Lyberis, Settimo

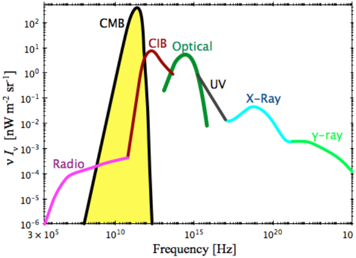
GZK: $s(p+\gamma_{CMB}) = (m_p + m_\pi)^2 \longrightarrow E_p \sim 10^{20}\,\text{eV}$ for $E_\gamma = k_B(2.7\,\text{K})$

Propagation of UHECRs in Photon Fields

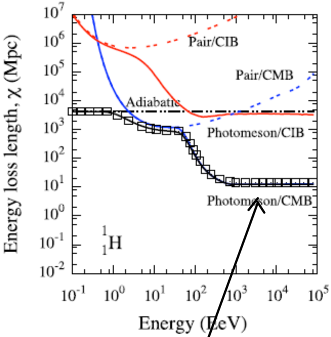
- interaction length:

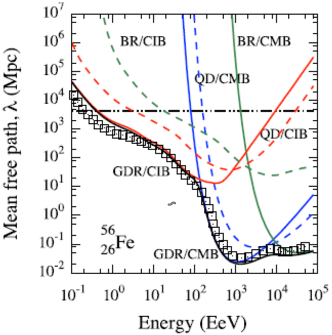
$\lambda = (\sigma \cdot n)^{-1}$ (σ: cross section, n: number density)

e.g. $n_{CMB} = 400/cm^3$, $\sigma_{photopion} \approx 0.5\,mb$ → $\lambda \approx 2\,Mpc$



http://www.andrewjaffe.net





De Domenico, Lyberis, Settimo

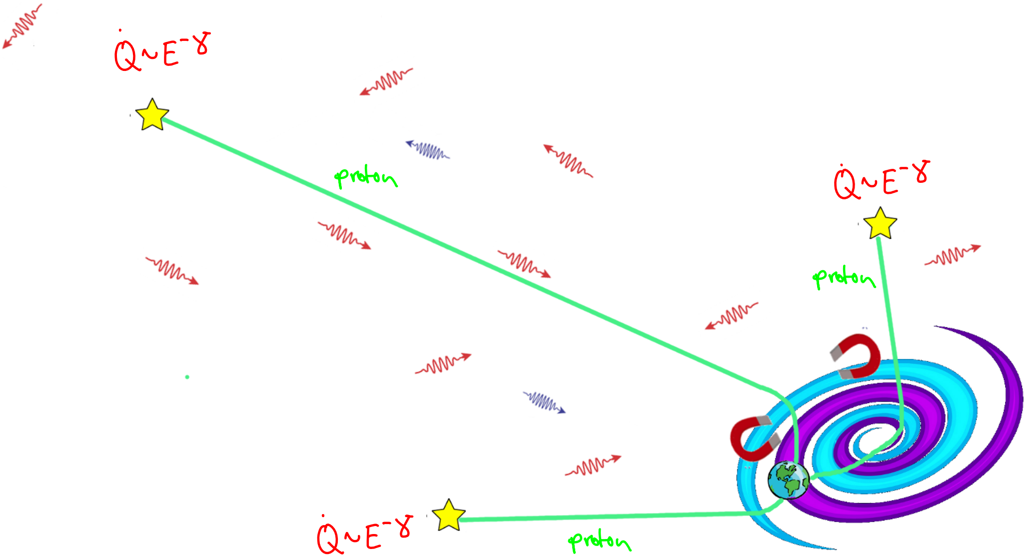
energy loss per interaction: $\kappa = 0.2$ (photopion) $\kappa = \frac{1}{A}$ (photonuclear)

- energy loss length: $\chi = \left(\frac{1}{E}\frac{dE}{dx}\right)^{-1} = \frac{\lambda}{\kappa}$ e.g. photopion: $\chi \approx 10\,Mpc$

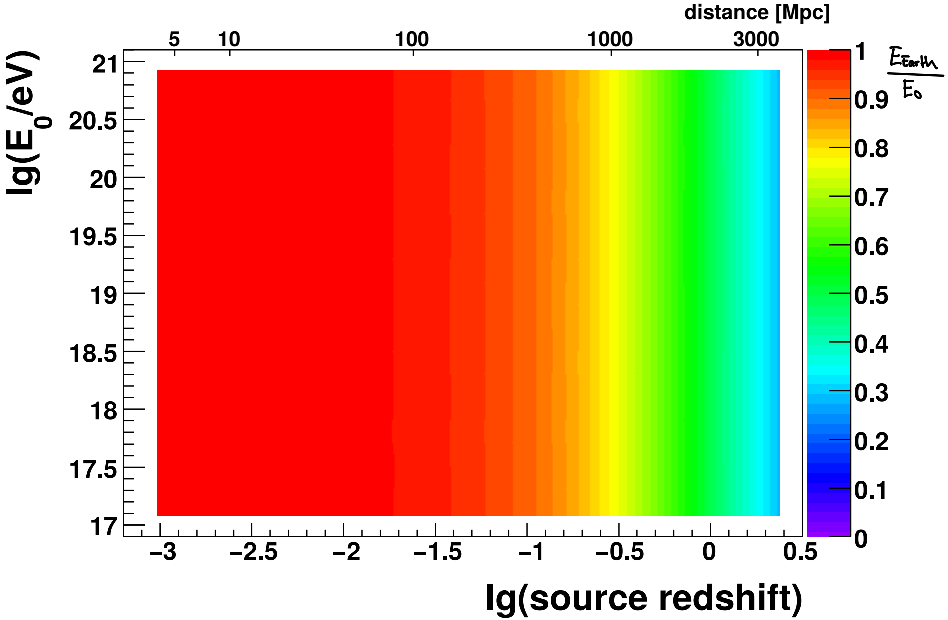
- expansion of universe: (z: redshift)

$E_{earth} = E_{source} / (1 + z_{source})$

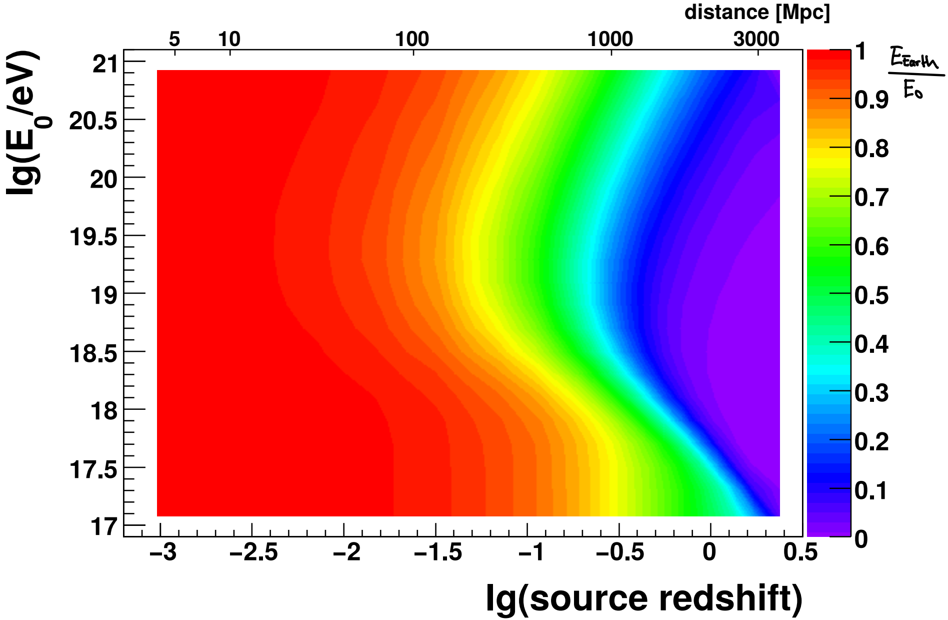
Proton Source Model ("Dip Model")



Propagation of UHE Protons



Propagation of UHE Protons



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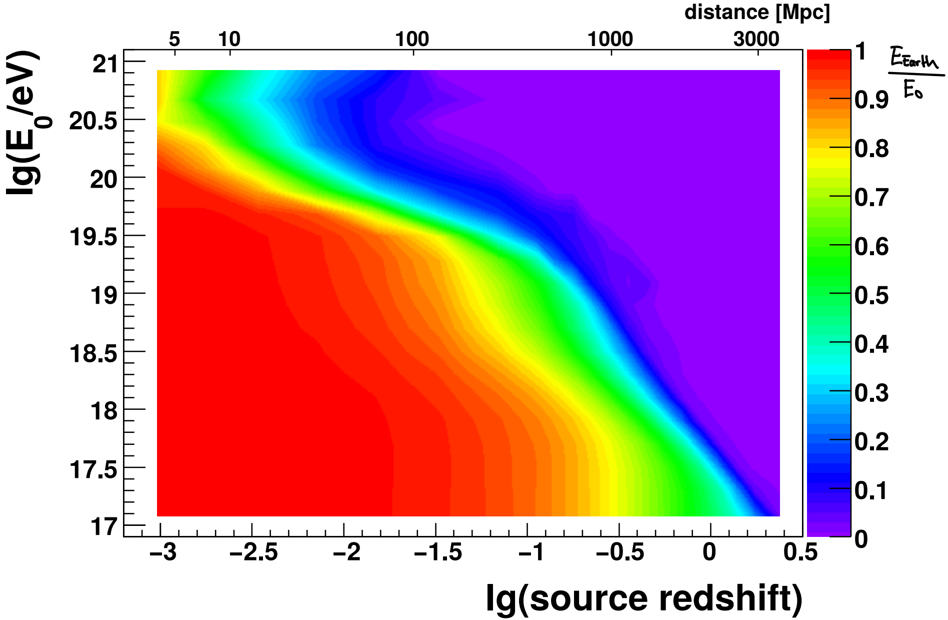

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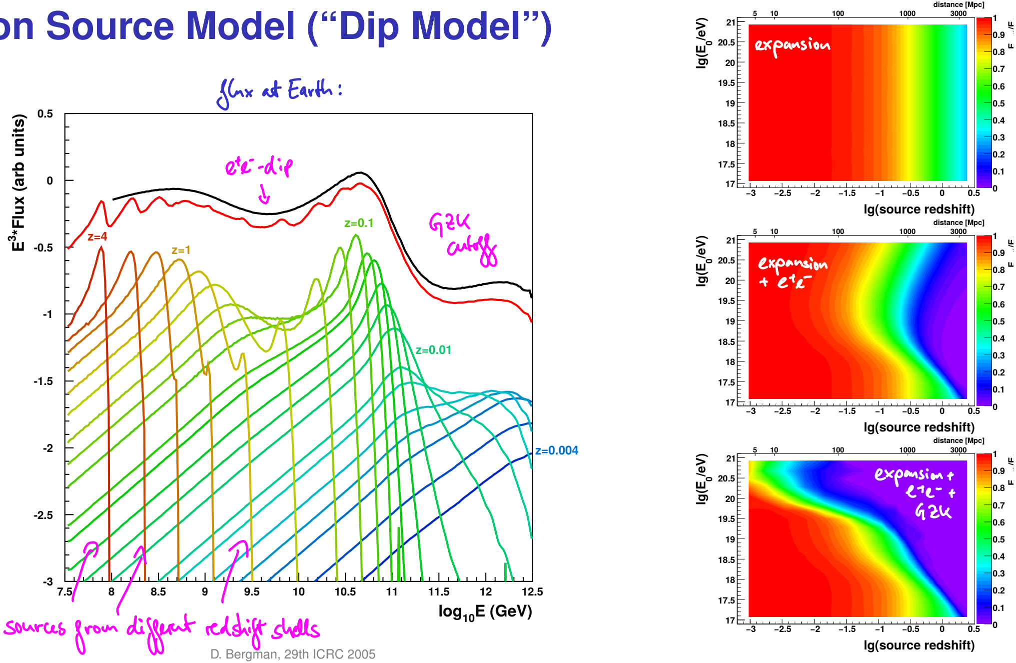

D. Bergman, 29th ICRC 2005

Proton Source Model ("Dip Model")

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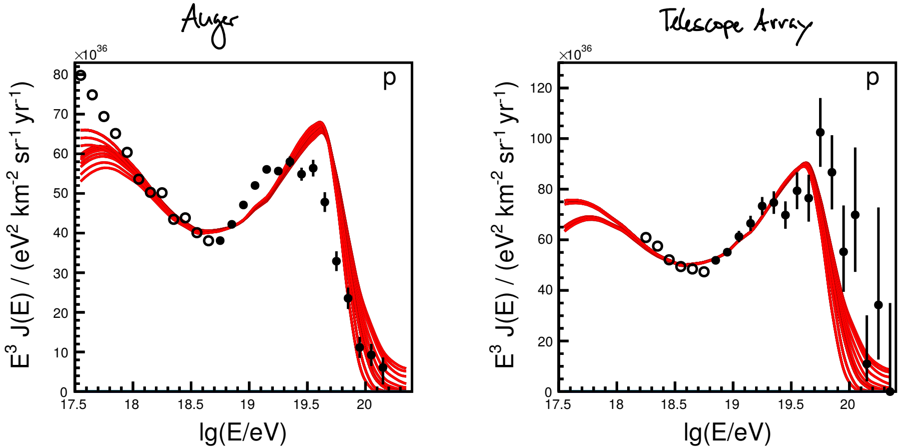
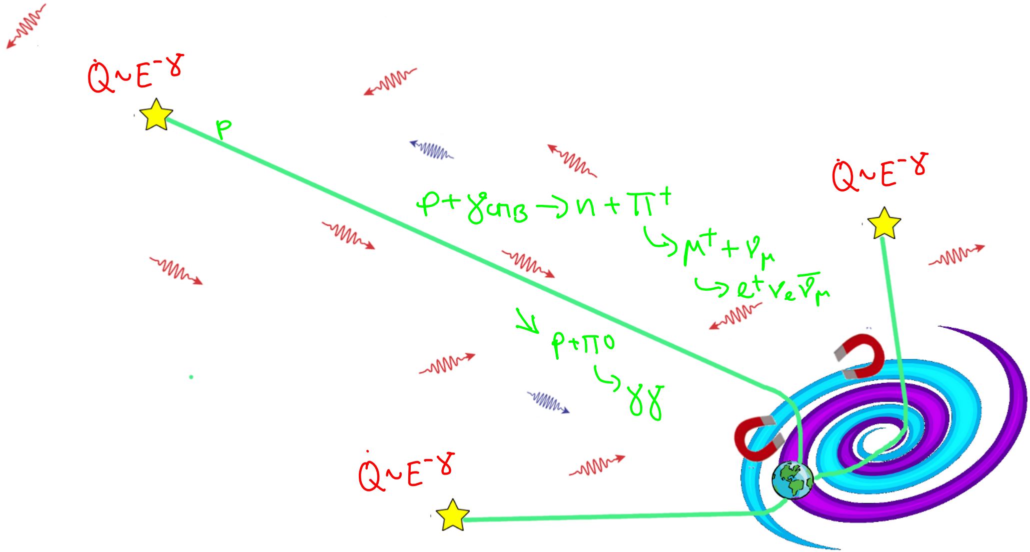
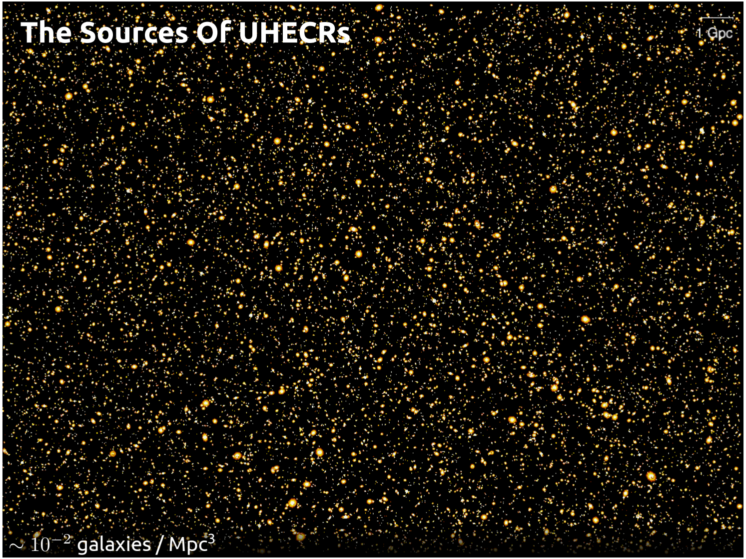


$E_{max} = 10^{22}$ eV , D_{min} = 1…100 Mpc, source evolution : SFR or AGN

Secondaries in Proton Source Model



Protons and Neutrinos at Earth



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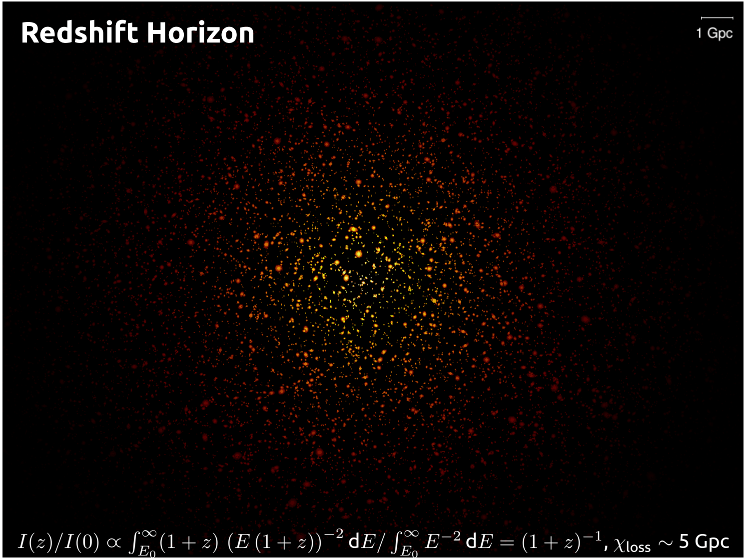

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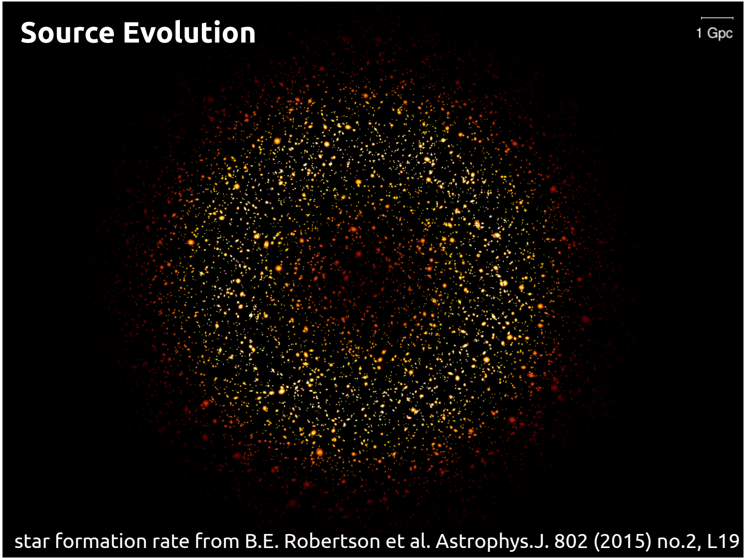

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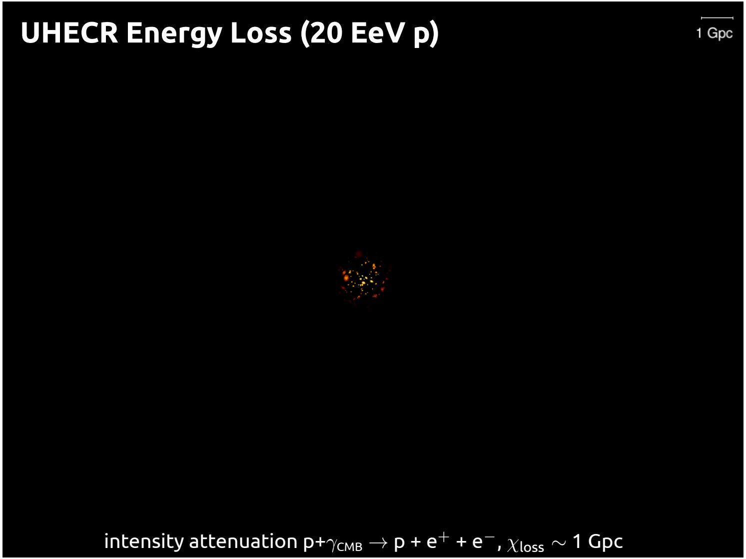

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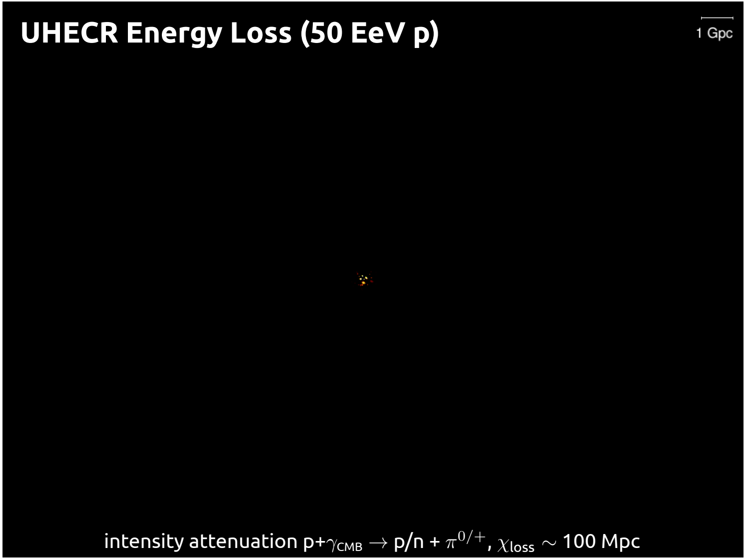
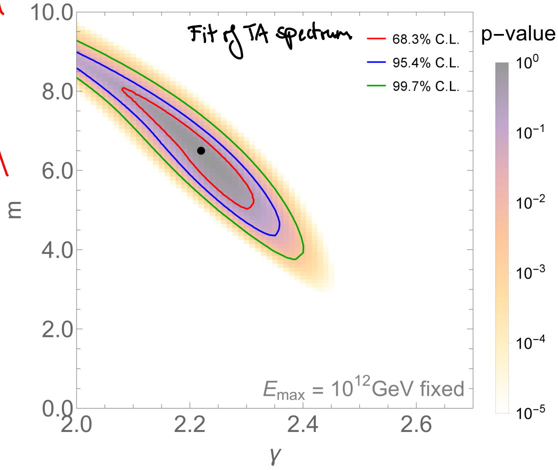
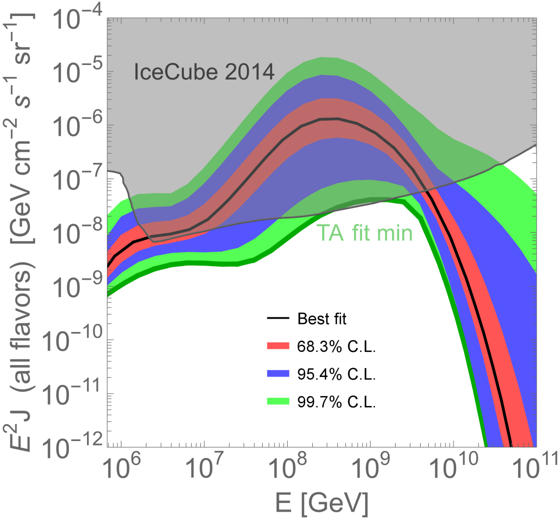


Secondaries in Proton Source Model

source evolution ~ $(1+z)^m$

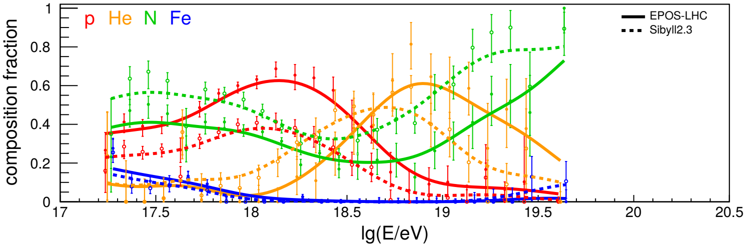




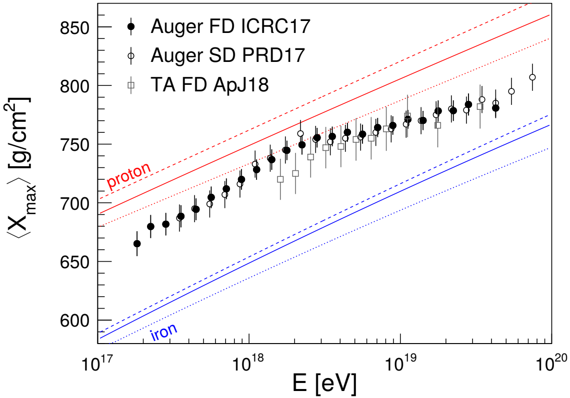
$Q \sim E^{-\gamma}$

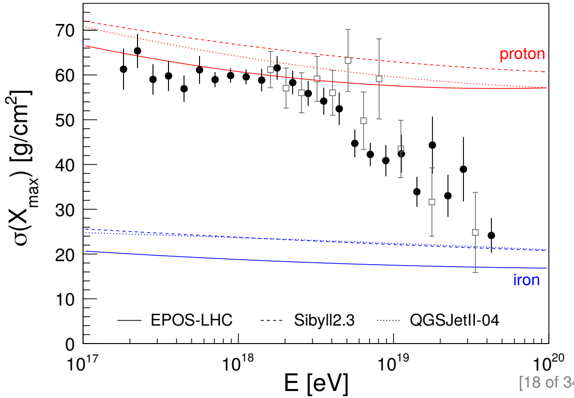
J. Heinze et al. ApJ **825** (2016) 122

UHECR Composition

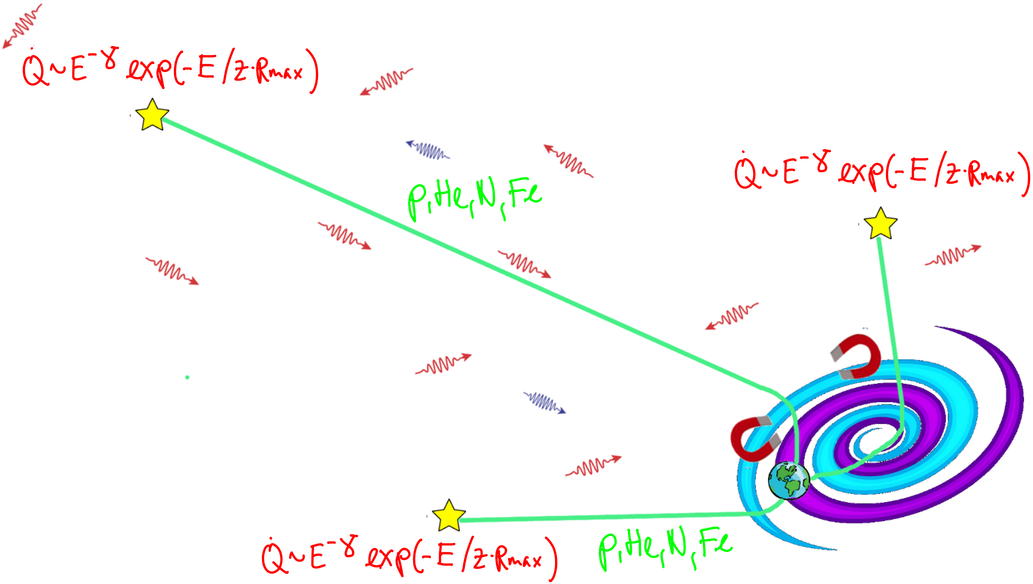


MIAPP review, Front.Astron.Space Sci. 6 (2019) 23





Mixed-Composition Model



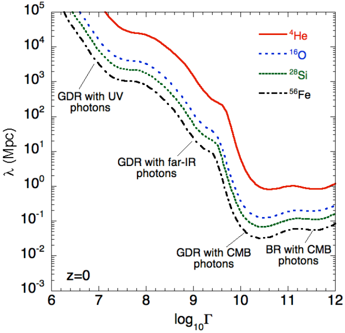
Propagation of UHE Nuclei

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

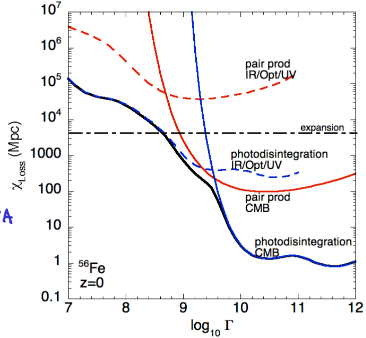
individual γ-nucleon interactions

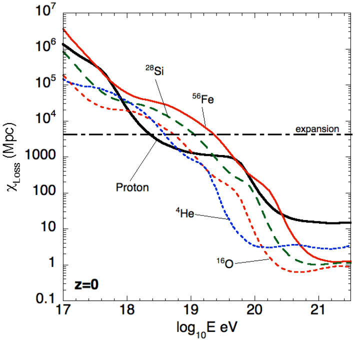
$\to \sqrt{s}\,(E/A)$

energy loss per interaction: $\kappa \sim \frac{1}{A}$ $\Rightarrow \kappa(He) = 0.25$, $\kappa(Fe) = 0.018$



σ ~ A

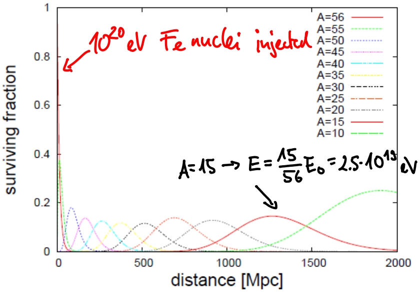




Lorentz-factor $\Gamma = E/A$

D. Allard, APP 39 (2012) 33

Propagation of UHE Nuclei



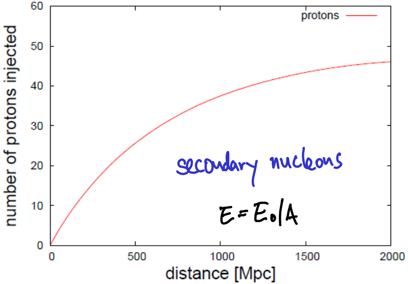
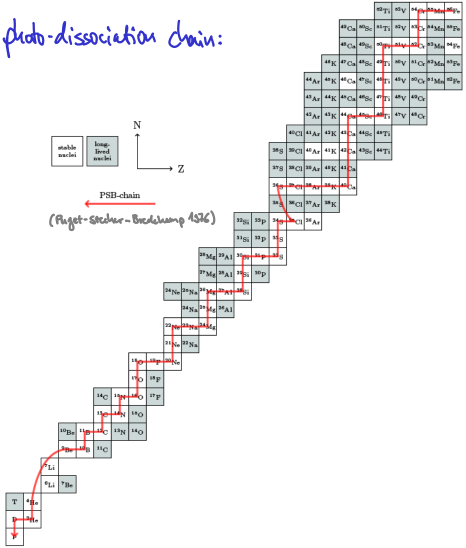


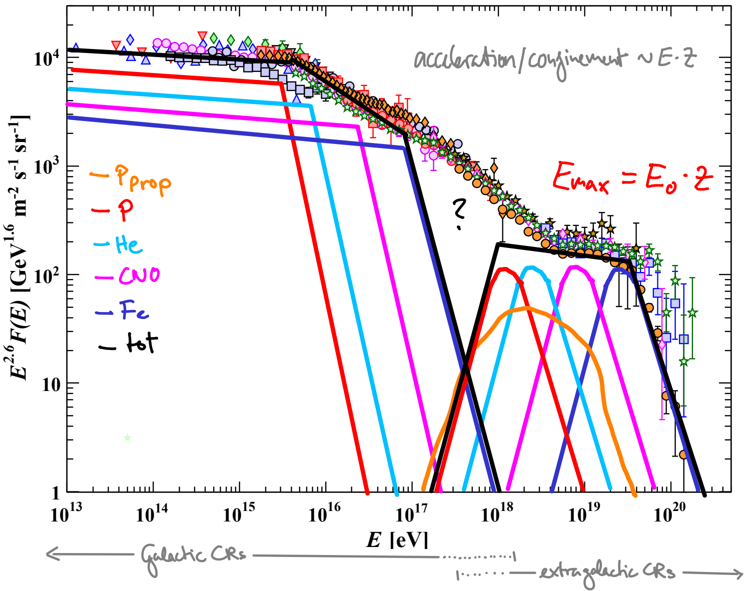
photo-dissociation chain:



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

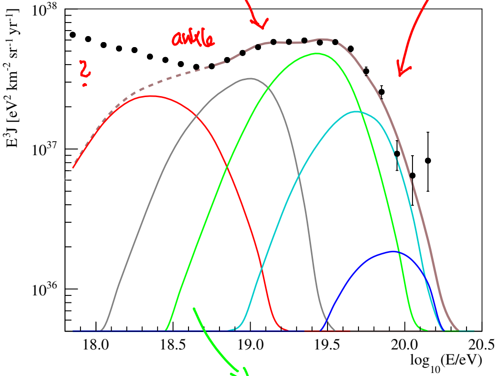
“Peters Cycle” at Source

B. Peters, Nuovo Ciemento **22** (1961) 800



Mixed-Composition Model

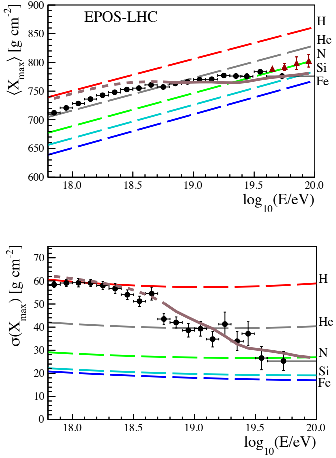
Spectrum:



supression ∓ GZK ?!

very hard injection spectrum! ($\sim E^{-1}$)

Composition:

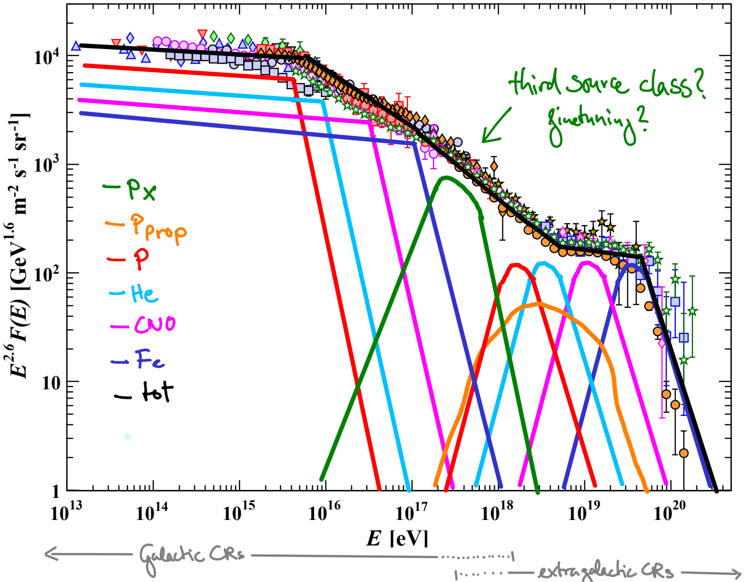


$R_0 \sim 10^{18.7}$ V

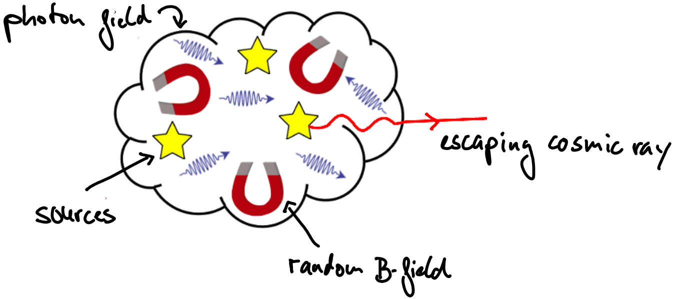
($E_{max} = Z \cdot e\, R_0$)

Auger ICRC19 and JCAP **1704** (2017) 038

Origin of Ankle and EeV Protons?



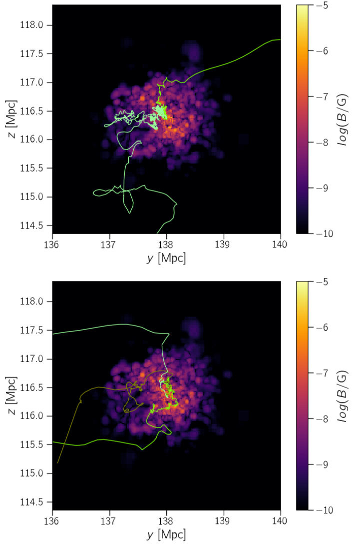
Photonuclear Interactions in Source Environment?



escape time $\sim (E/Z)^{-\alpha}$ in turbulent field ($\alpha = 1$: Bohm Diffusion)

$A + \gamma \to (A-1) + p/n$ ← escapes immediately if $R < \gamma c\tau$

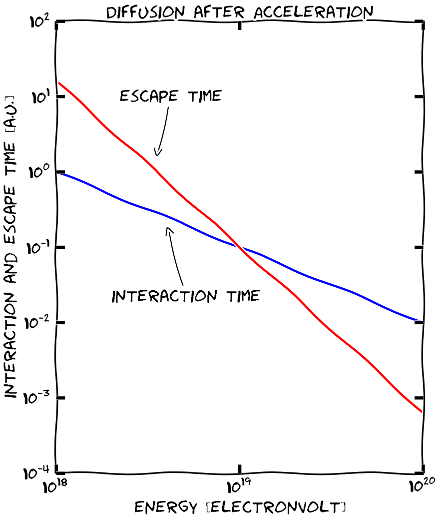
MU, G. Farrar, L. Anchordoqui, PRD **92** (2015) 123001 and M. Muzio, MU, G. Farrar arXiv:1906.06233
see also Globus+15, Biel+17, Kachelriess+17, Supanitsky+18

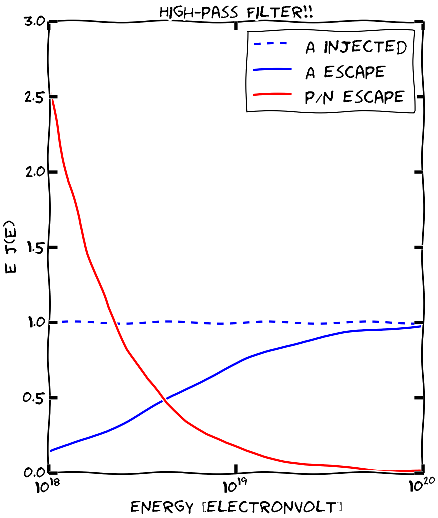


Virgo Cluster sim., R.A. Batista et al, arXiv:1811.03062

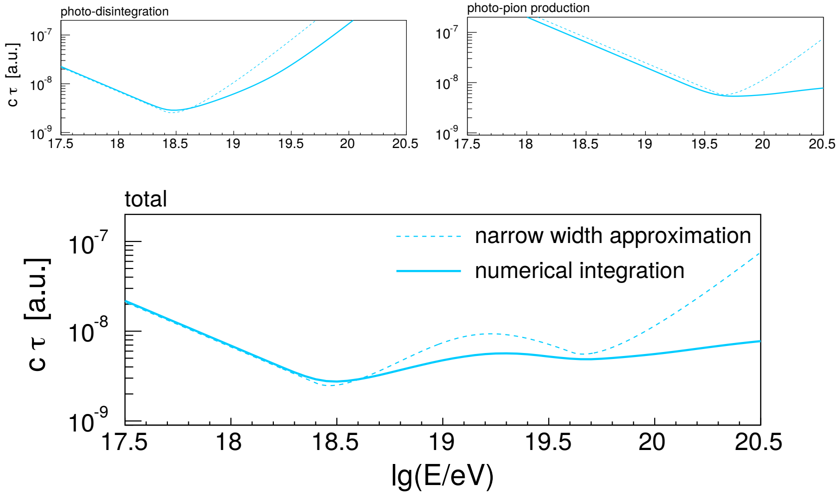
Photonuclear Interactions in Source Environment?

analytic example: full spallation of nucleus A, diffusion $\tau_{\rm esc} \propto E^{\alpha}$, $\tau_{\rm int} \propto E^{\beta}$





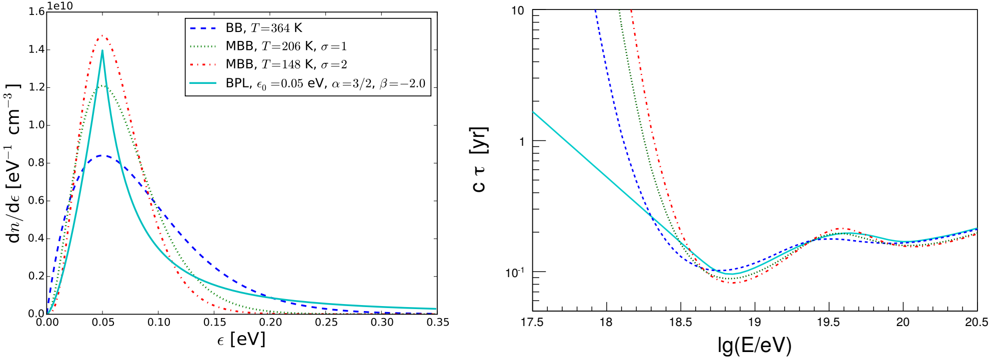
Photonuclear Interactions in a “peaky” Photon Field



^{28}Si in a broken power-law photon field, $\alpha = \frac{3}{2}$, $\beta = -1$ and $\varepsilon_0 = 0.11 \text{ eV}$

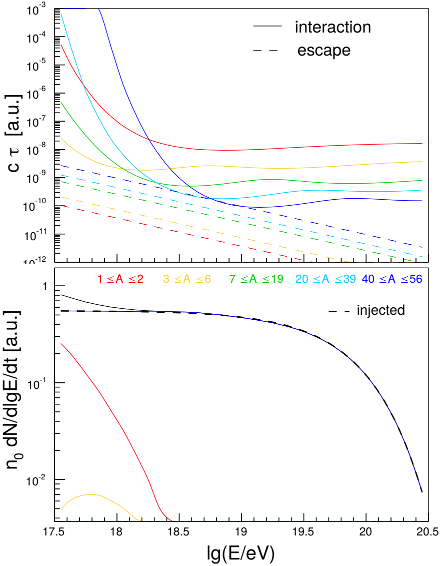
Photonuclear Interactions in a "peaky" Photon Field

broken power law (BPL), black body (BB), modified black body (MBB)

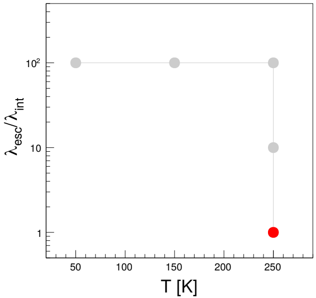


Near-universal "L-curve" depending mostly on peak position

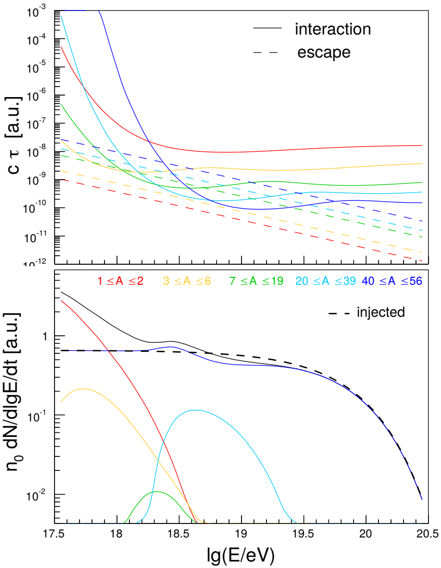
Example Escaping Photonuclear Cascade



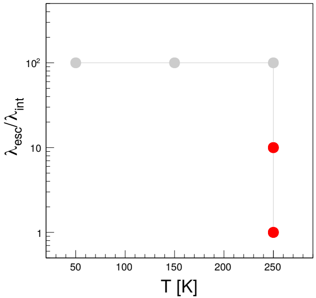
- injected mass: Fe
- $\gamma = -1$
- $E_{\max}(\mathrm{Fe}) = 10^{19.8}$ eV
- photon field: black body, T=250 K
- $\lambda_{\mathrm{esc}} = 1 \times \lambda_{\mathrm{int}}$ at 10^{19} eV



Example Escaping Photonuclear Cascade



- injected mass: Fe
- $\gamma = -1$
- $E_{\text{max}}(\text{Fe}) = 10^{19.8}$ eV
- photon field: black body, T=250 K
- $\lambda_{\text{esc}} = 10 \times \lambda_{\text{int}}$ at 10^{19} eV



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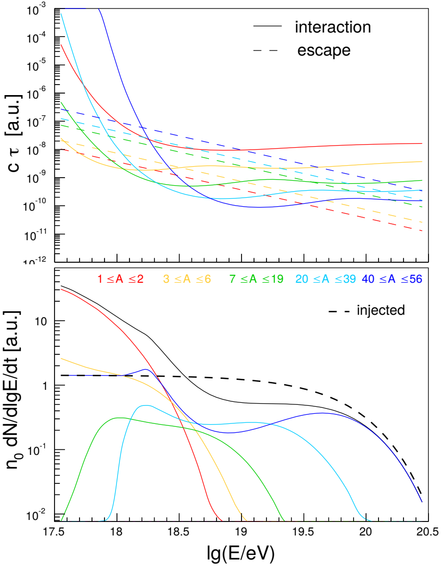
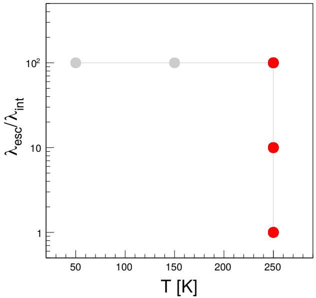
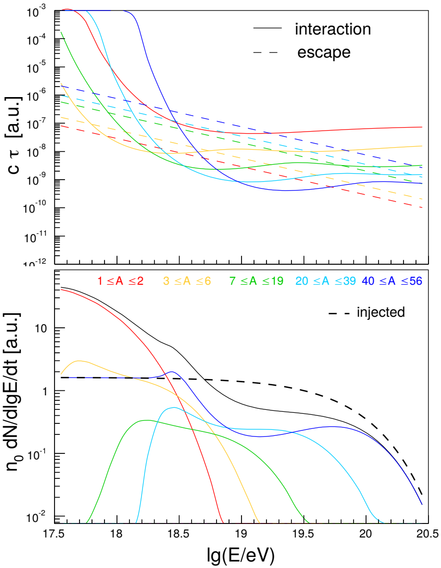


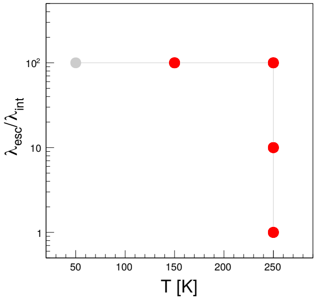
- injected mass: Fe
- $\gamma = -1$
- $E_{\max}(\mathrm{Fe}) = 10^{19.8}$ eV
- photon field: black body, T=250 K
- $\lambda_{\mathrm{esc}} = 100 \times \lambda_{\mathrm{int}}$ at 10^{19} eV



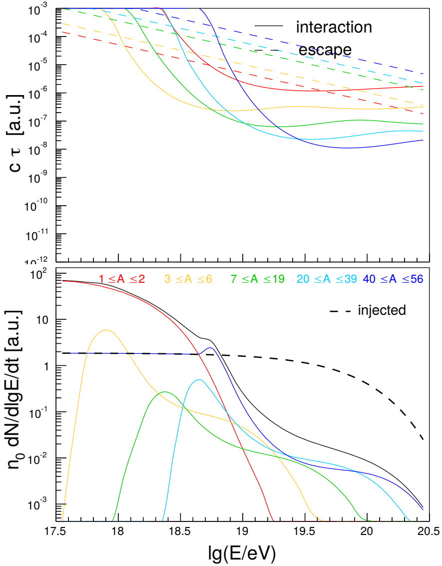
Example Escaping Photonuclear Cascade



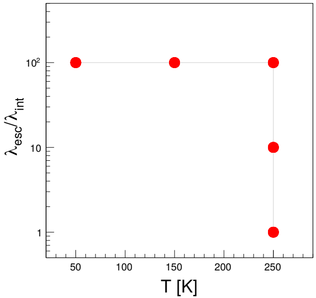
- injected mass: Fe
- $\gamma = -1$
- $E_{\max}(\mathrm{Fe}) = 10^{19.8}$ eV
- photon field: black body, T=150 K
- $\lambda_{\mathrm{esc}} = 100 \times \lambda_{\mathrm{int}}$ at 10^{19} eV



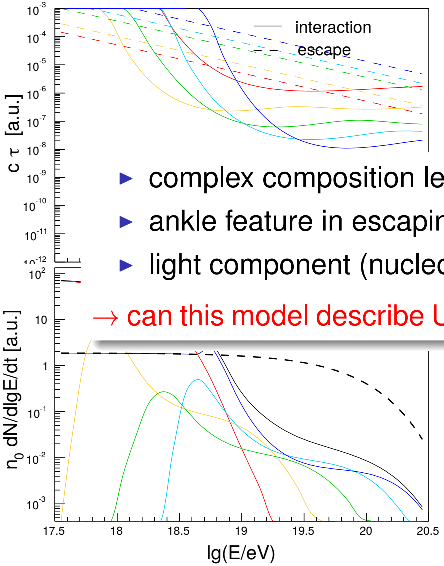
Example Escaping Photonuclear Cascade



- injected mass: Fe
- $\gamma = -1$
- $E_{\mathrm{max}}(\mathrm{Fe}) = 10^{19.8}$ eV
- photon field: black body, T=50 K
- $\lambda_{\mathrm{esc}} = 100 \times \lambda_{\mathrm{int}}$ at 10^{19} eV



Example Escaping Photonuclear Cascade

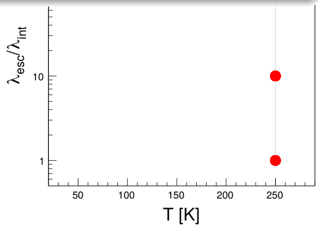


- injected mass: Fe
- $\gamma = -1$
- $E_{\mathrm{max}}(\mathrm{Fe}) = 10^{19.8}$ eV
- photon field: black body,

eV

- complex composition leaving source
- ankle feature in escaping flux
- light component (nucleons) below ankle

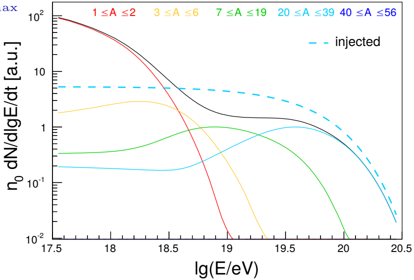
→ can this model describe UHECR flux and composition?



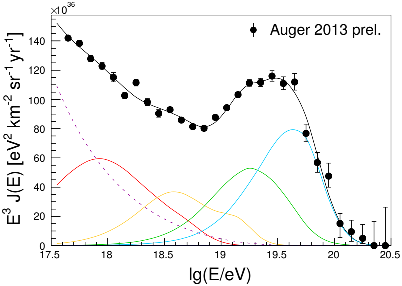
Fit of Spectrum and Composition At Earth (single mass)

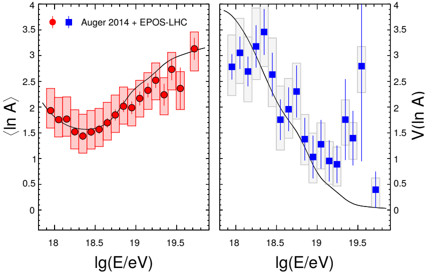
Fiducial Scenario $+1\sigma_{\mathrm{E}}$ $-1\sigma_{\mathrm{X_{max}}}$

^{29}Si injected, escaping flux at source

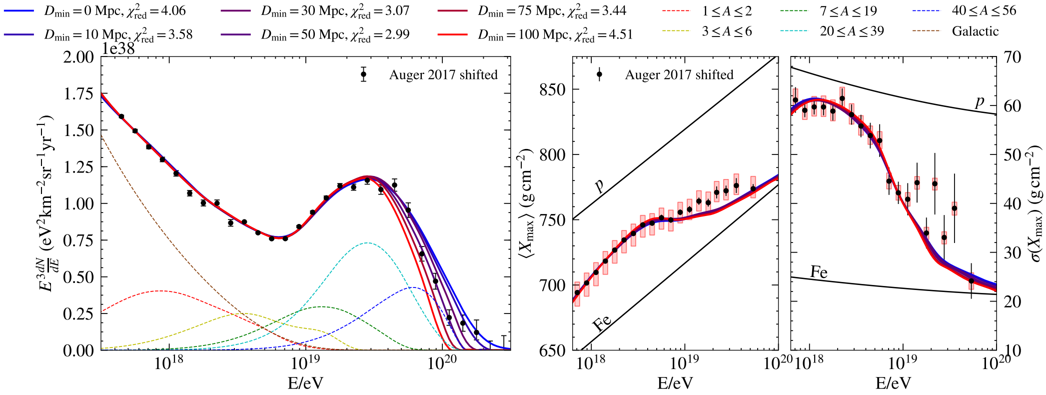


flux and composition at Earth

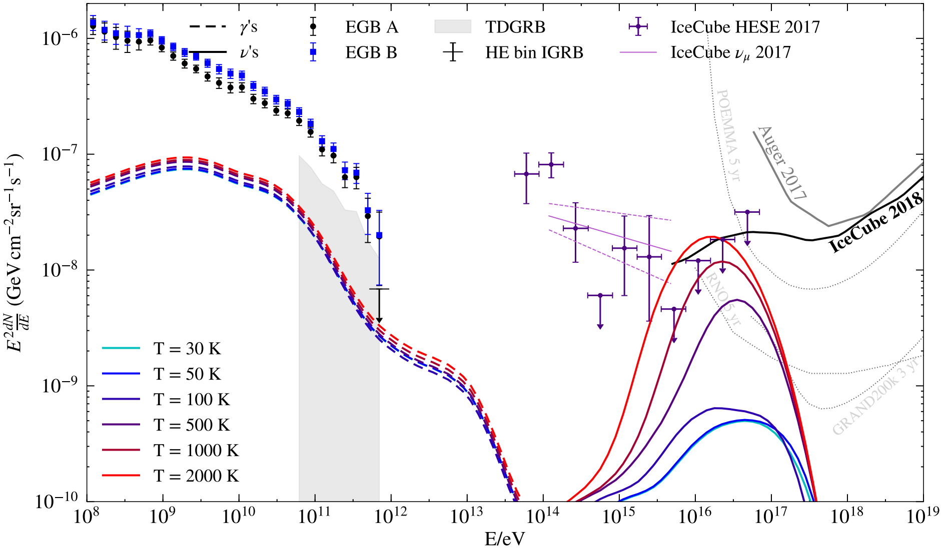




Fit of Spectrum and Composition At Earth (Galactic Mix)



Secondaries vs. Photon Field Temperature

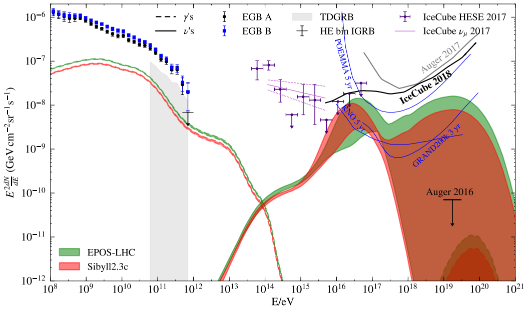


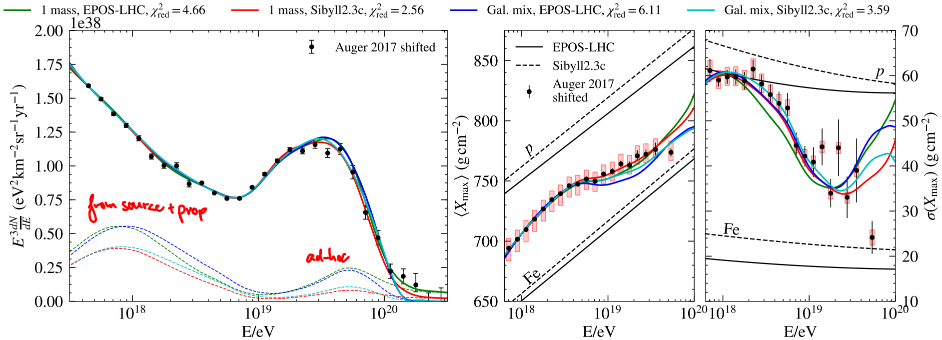
Protons at UHE?

add ad-hoc proton component $E^{-1} \cdot \exp\left(-\frac{E}{E_{max}'}\right)$

⇒ data does not constrain p σ(10%) > 50 EeV

(fits get actually better!)





Summary of Generic Source Models of UHECRs

- **dip model (pure proton)**
  - elegant, very few parameters
  - disfavoured by secondaries (ν, γ)
  - excluded by UHE composition
- **mixed composition**
  - fits UHE composition and flux
  - low secondary fluxes $\to$ not excluded
  - low secondary fluxes $\to$ hard to detect
  - hard injection spectrum $\gamma \approx 1$
  - ad-hoc composition fractions
  - ad-hoc low-E light component needed
- **photonuclear interactions at source**
  - fits UHE composition and flux
  - works with Galactic composition
  - explains ankle and low-E protons
  - detectable secondary fluxes (falsifiable)
  - hard injection spectrum $\gamma \approx 1$
  - source properties: additonal doF