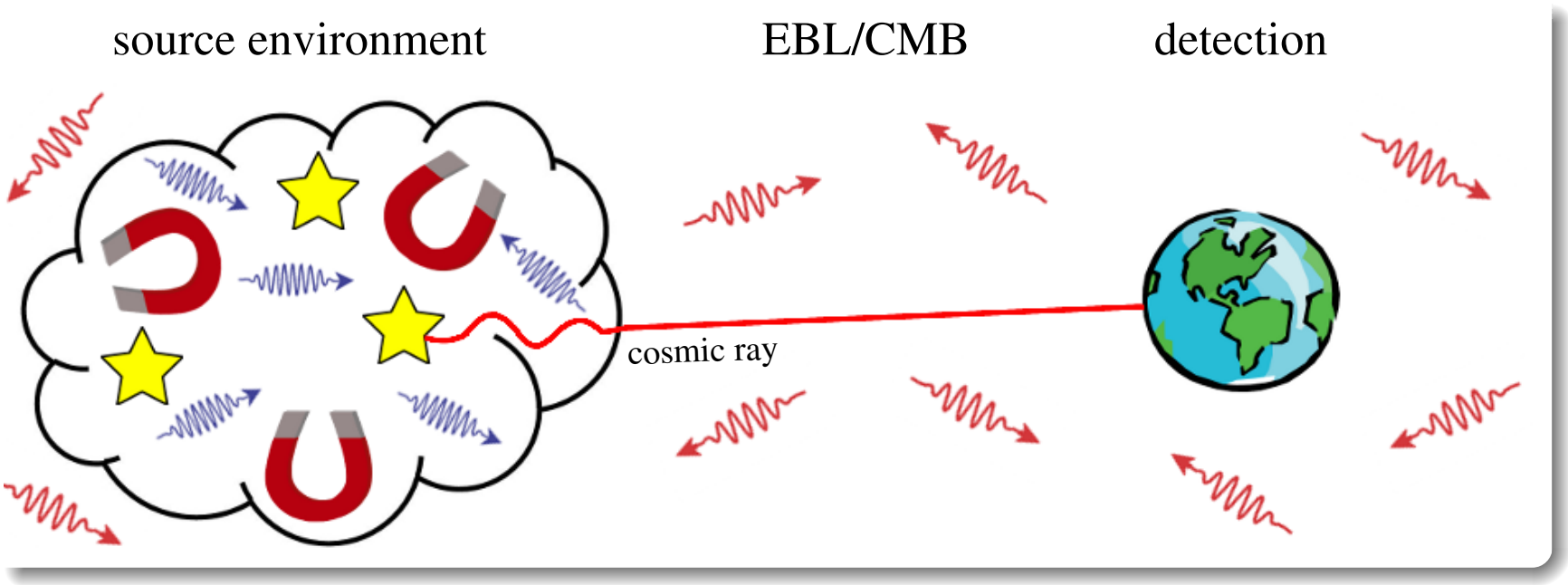
Origin of the Ankle and the Light Composition at EeV Energies

L. Anchordoqui, G. Farrar, M. Unger

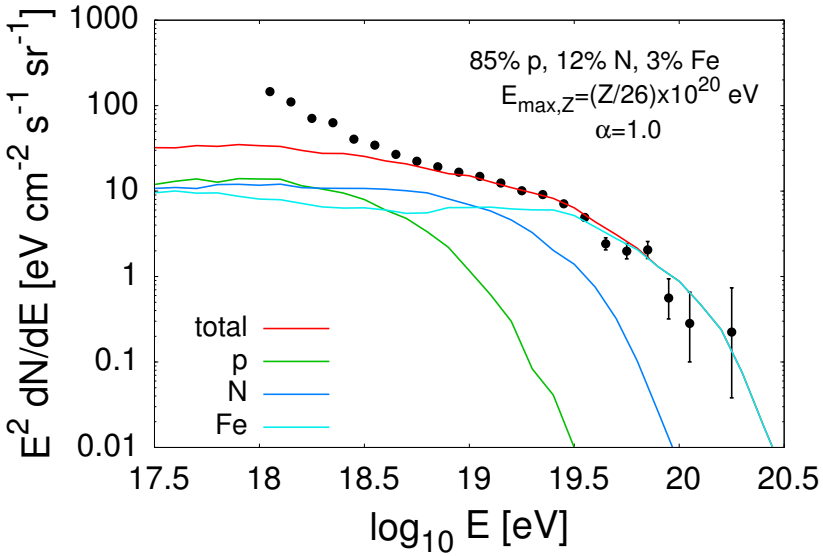


MU, G.F. Farrar & L.A. Anchordoqui Phys.Rev. **D92** (2015) 123001, arXiv:1505.02153

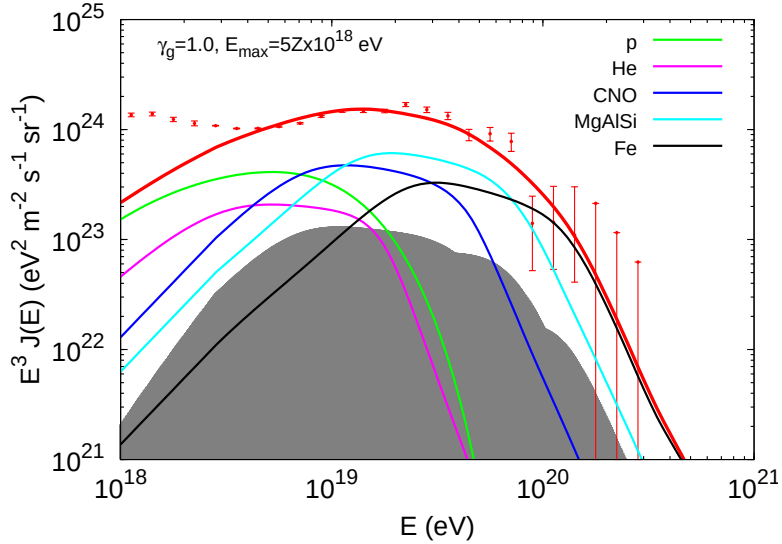
Previous Mixed Composition Models

e.g.

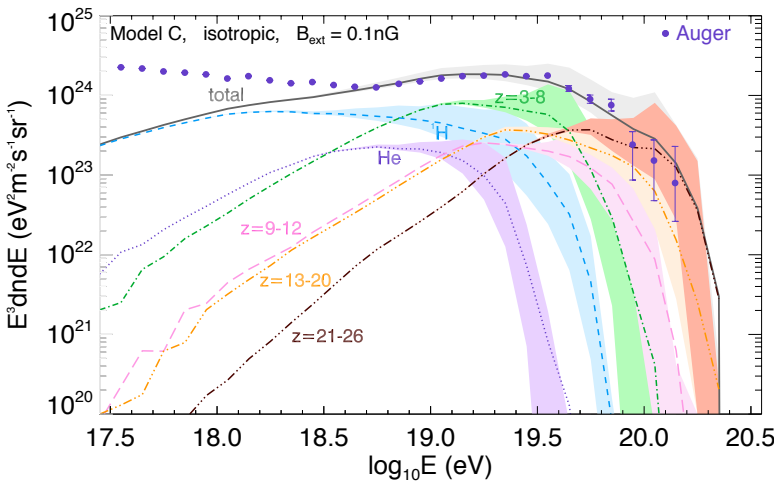
Taylor et al. 2014



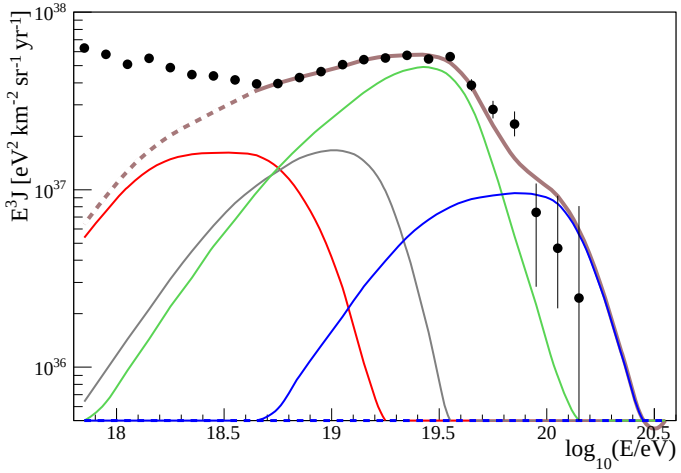
Aloisio et al 2014



Globus et al 2014



Auger ICRC15



Previous Mixed Composition Models

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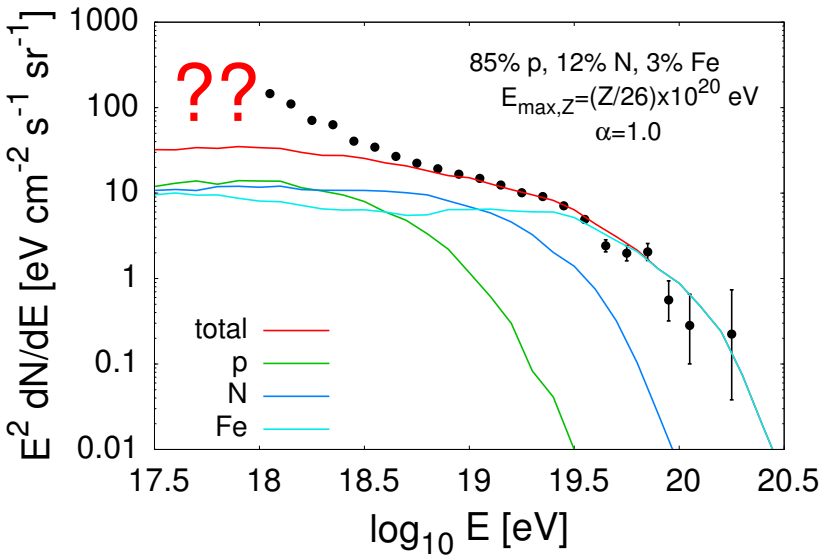
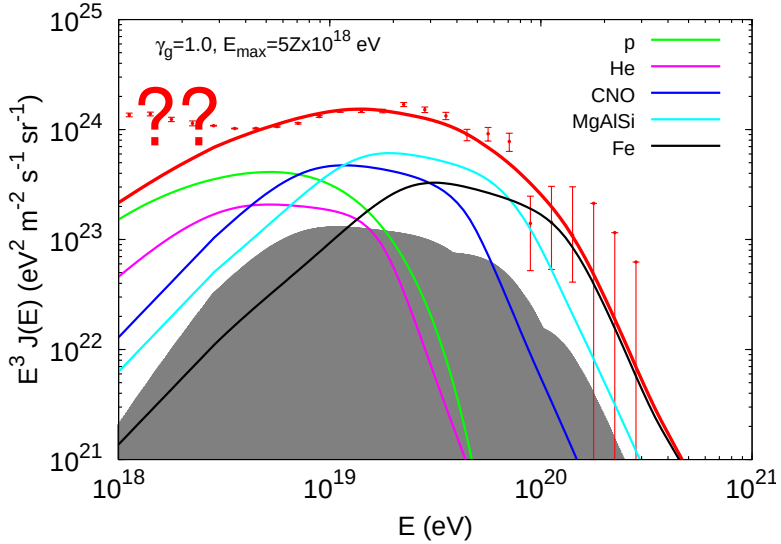
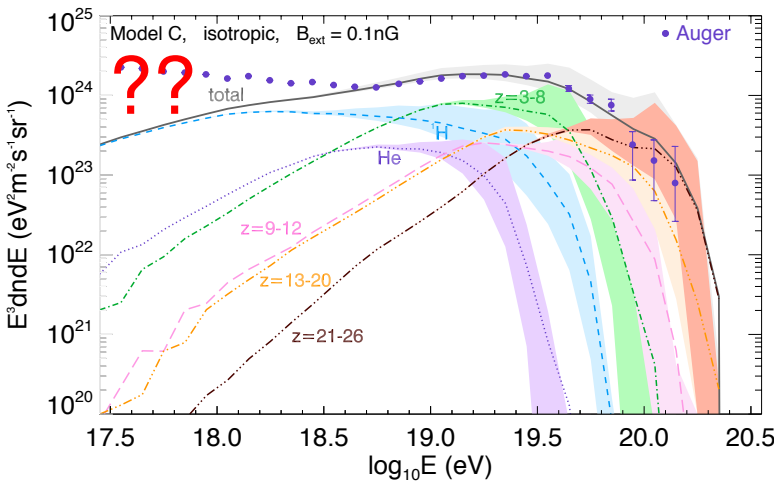


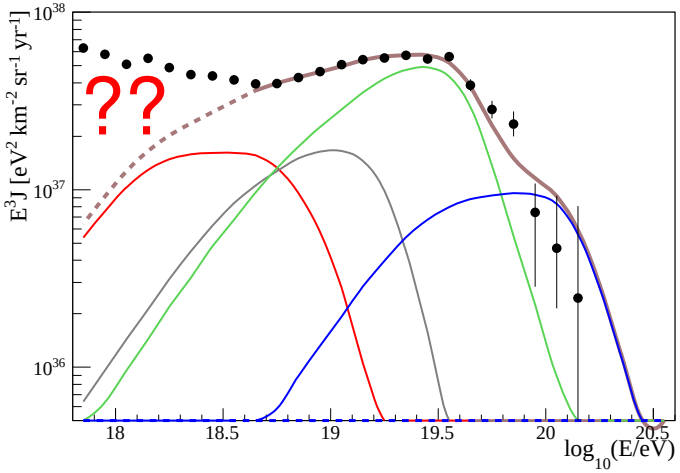
Aloisio et al 2014



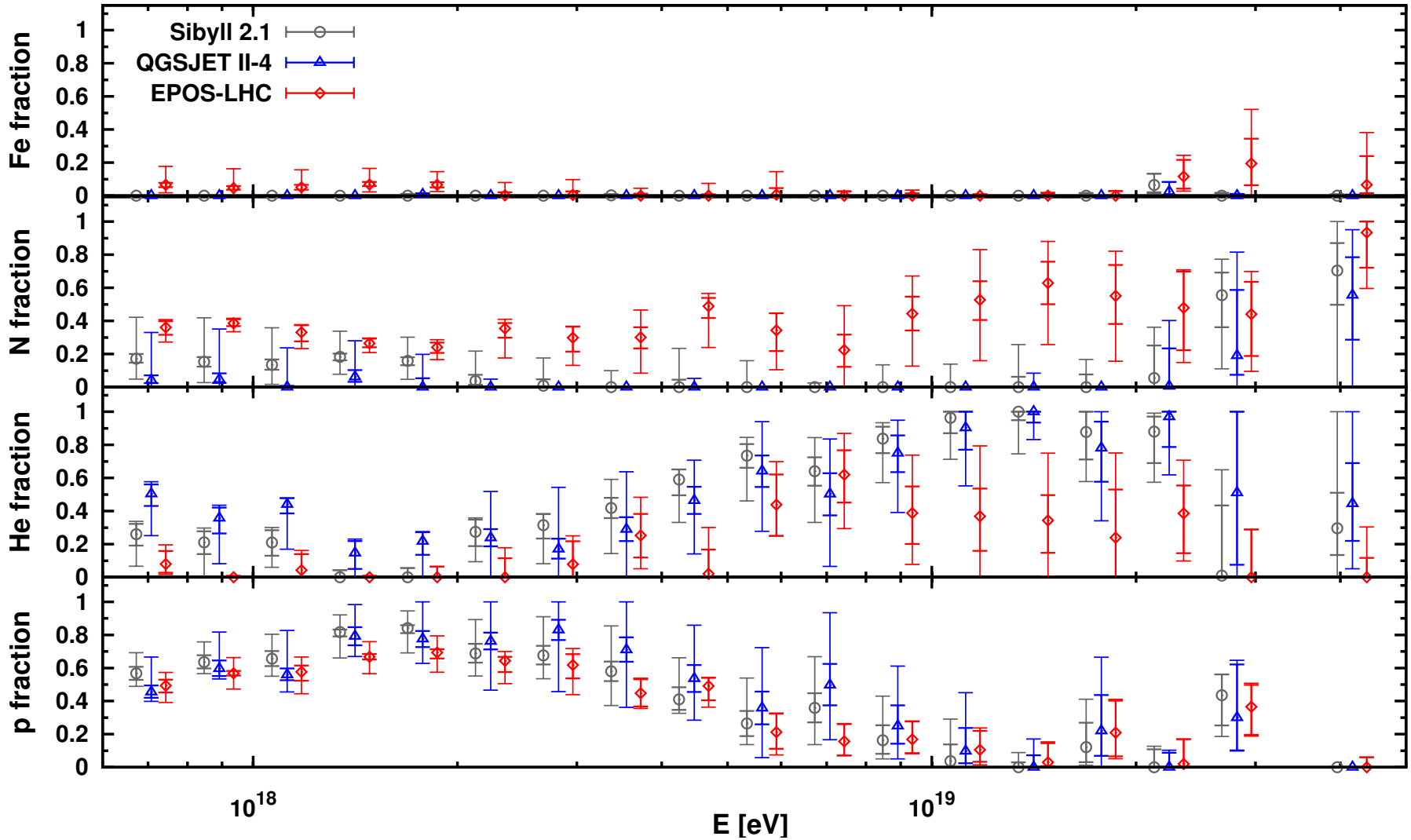
Globus et al 2014



Auger ICRC15



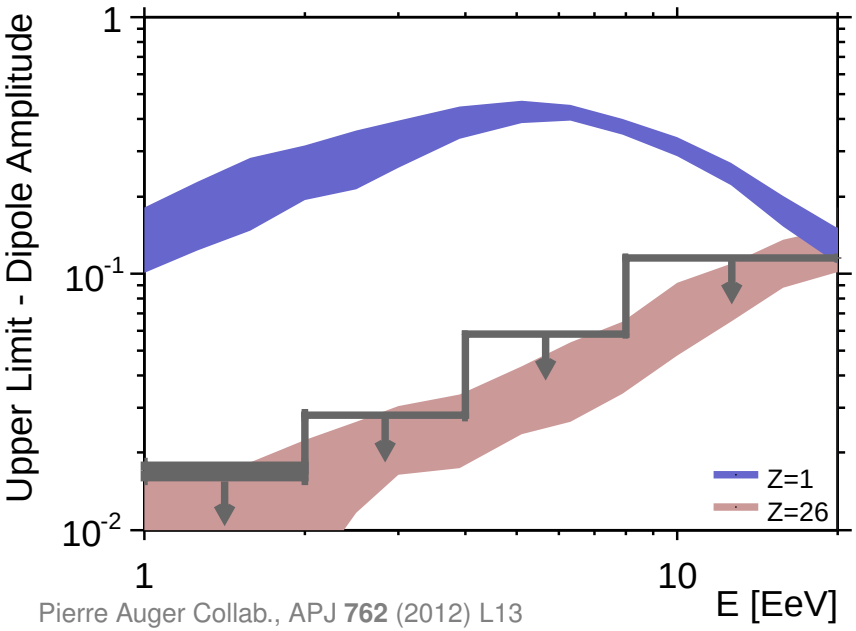
Light Composition around 10^{18} eV ...



Pierre Auger Coll., PRD **90** (2014) 12, 122006

… but no Anisotropy

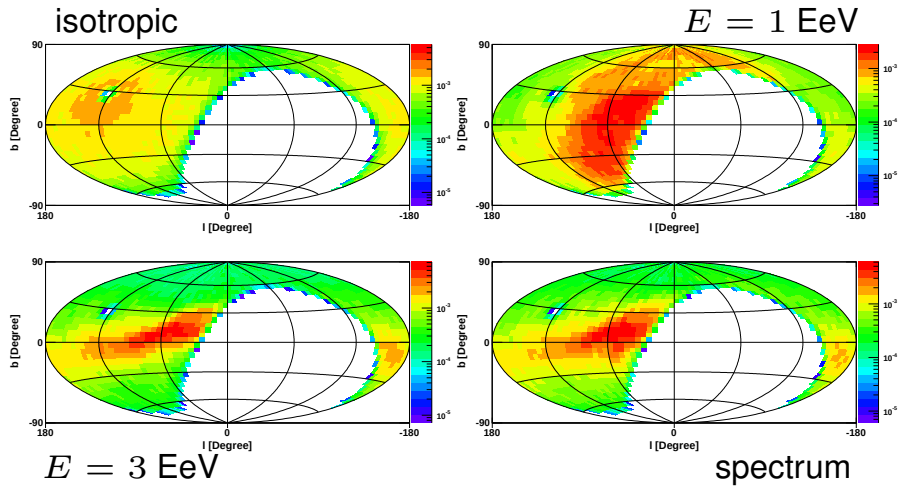
Auger dipole amplitude limits:

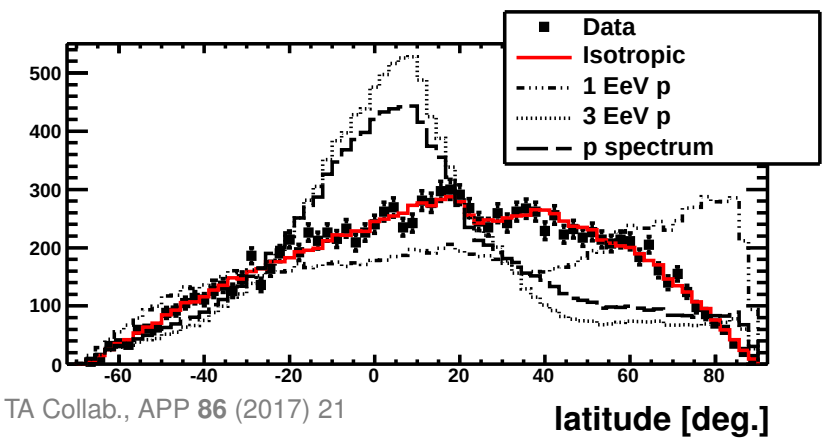


Pierre Auger Collab., APJ **762** (2012) L13

→ extragalactic origin!

TA latitude distribtion:

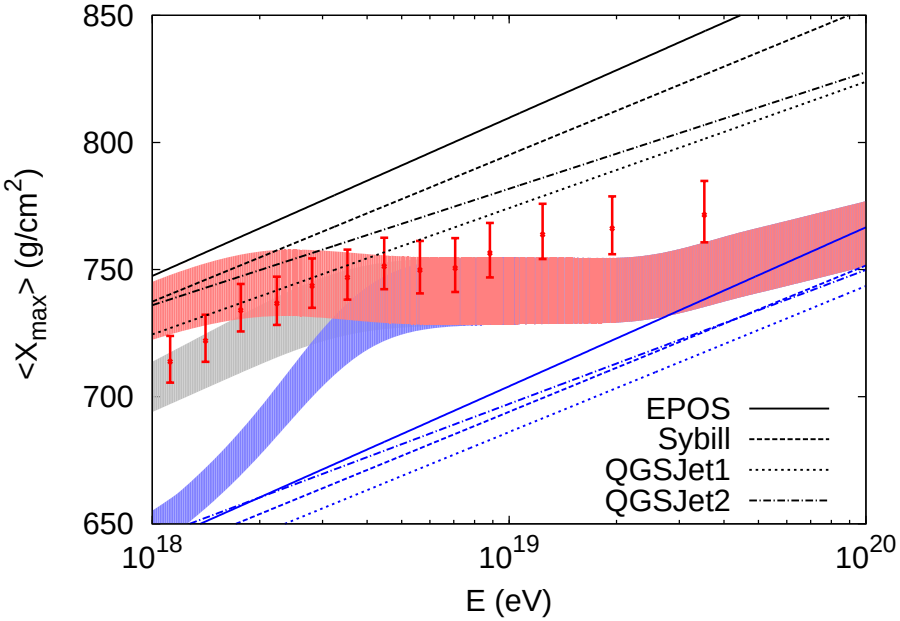


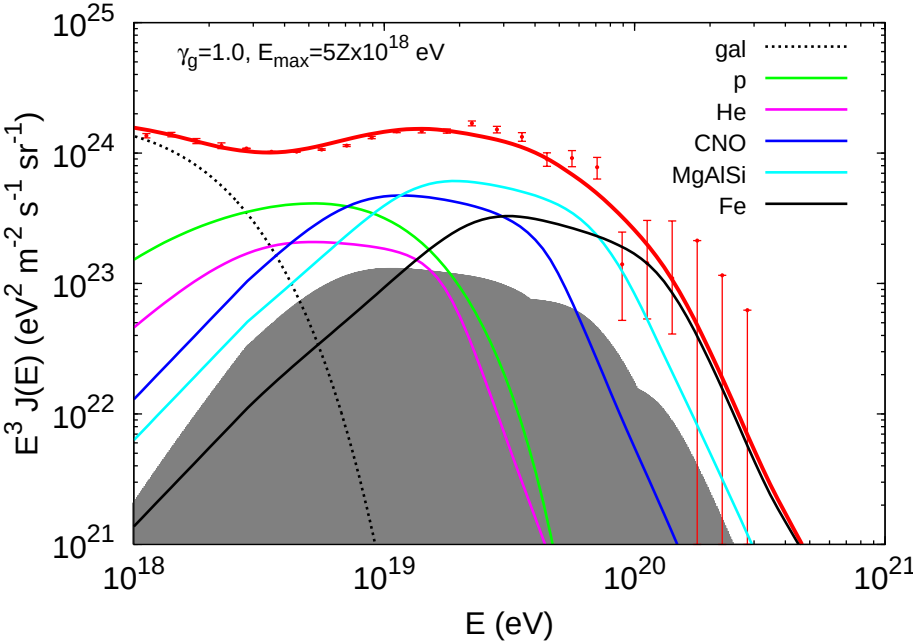


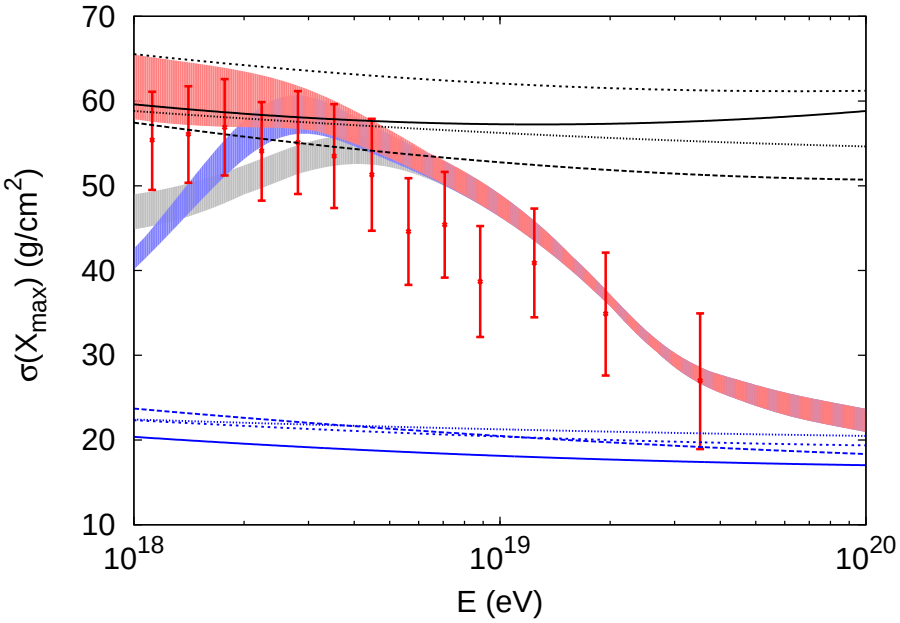
TA Collab., APP **86** (2017) 21

Mixed Composition Model plus "Component X"

- $E_{\max} \propto Z$
- hard injection spectrum $\gamma \approx 1$
- ad-hoc composition fractions
- ad-hoc low-E light component

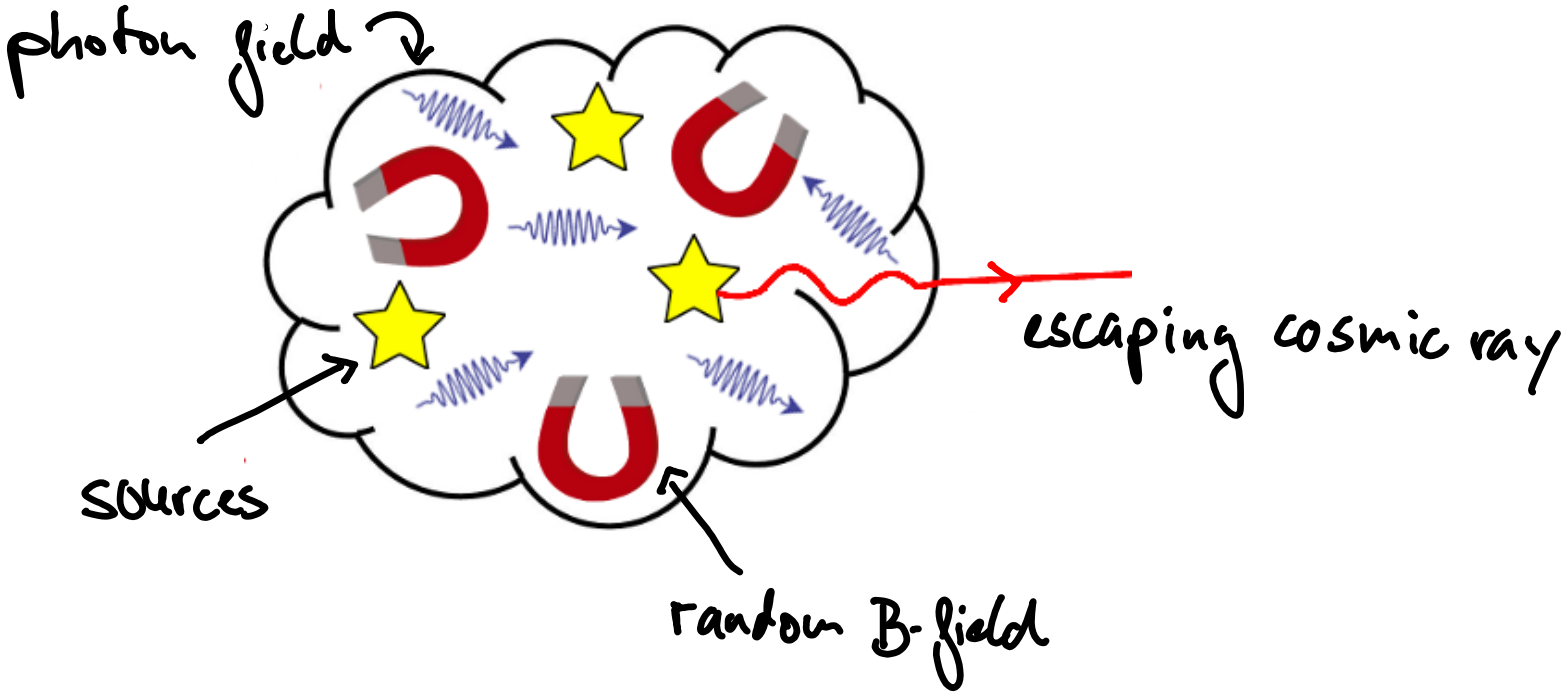






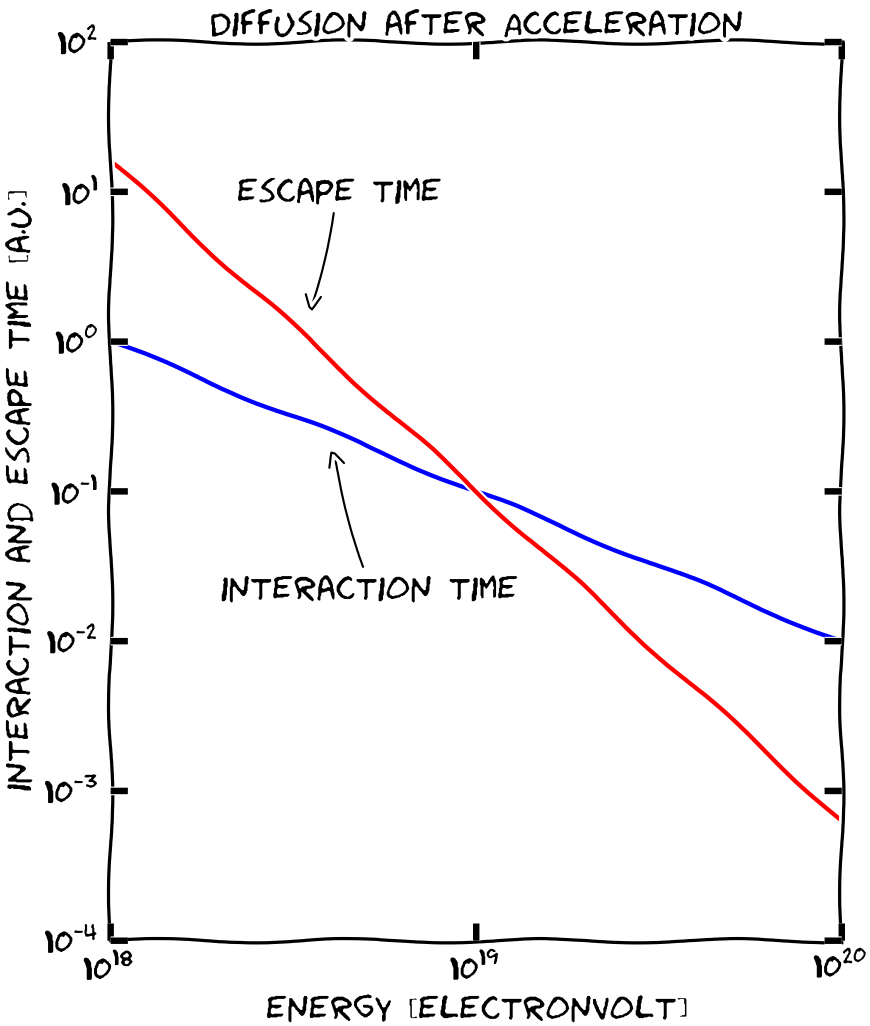
R. Aloisio, V. Berezinsky&P. Blasi JCAP **1410** (2014) 020

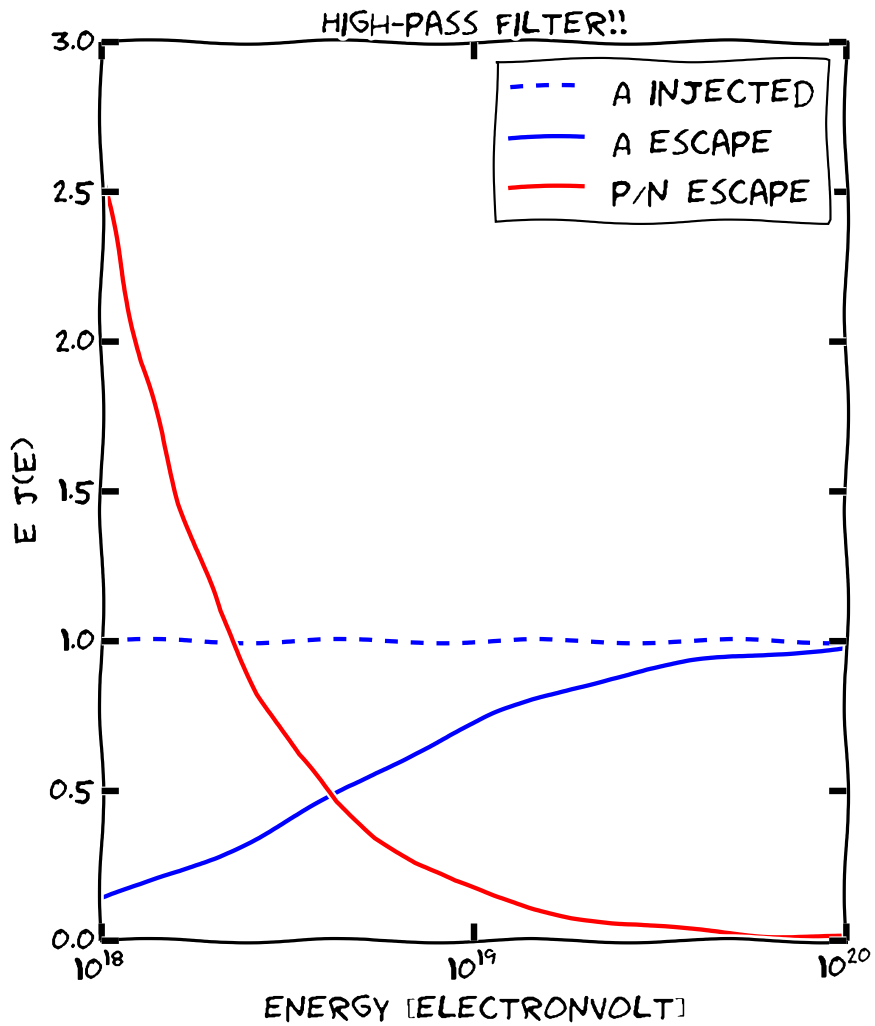
Photonuclear Interactions in Source Environment?



Photonuclear Interactions in Source Environment?

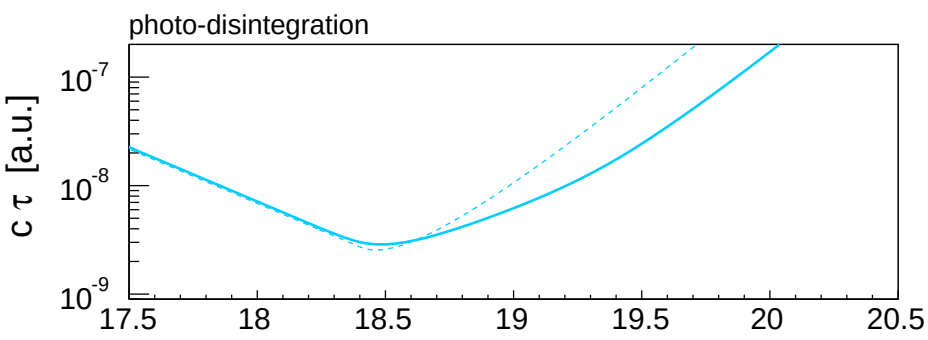
analytic example: full spallation of nucleus A, diffusion $\tau_{\rm esc} \propto E^{\alpha}$, $\tau_{\rm int} \propto E^{\beta}$

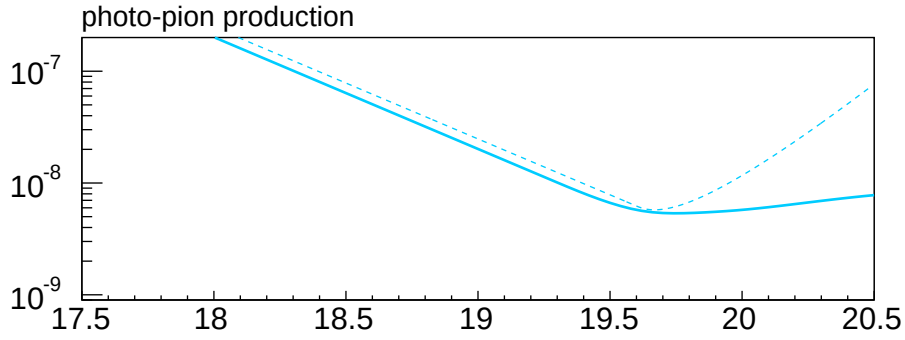


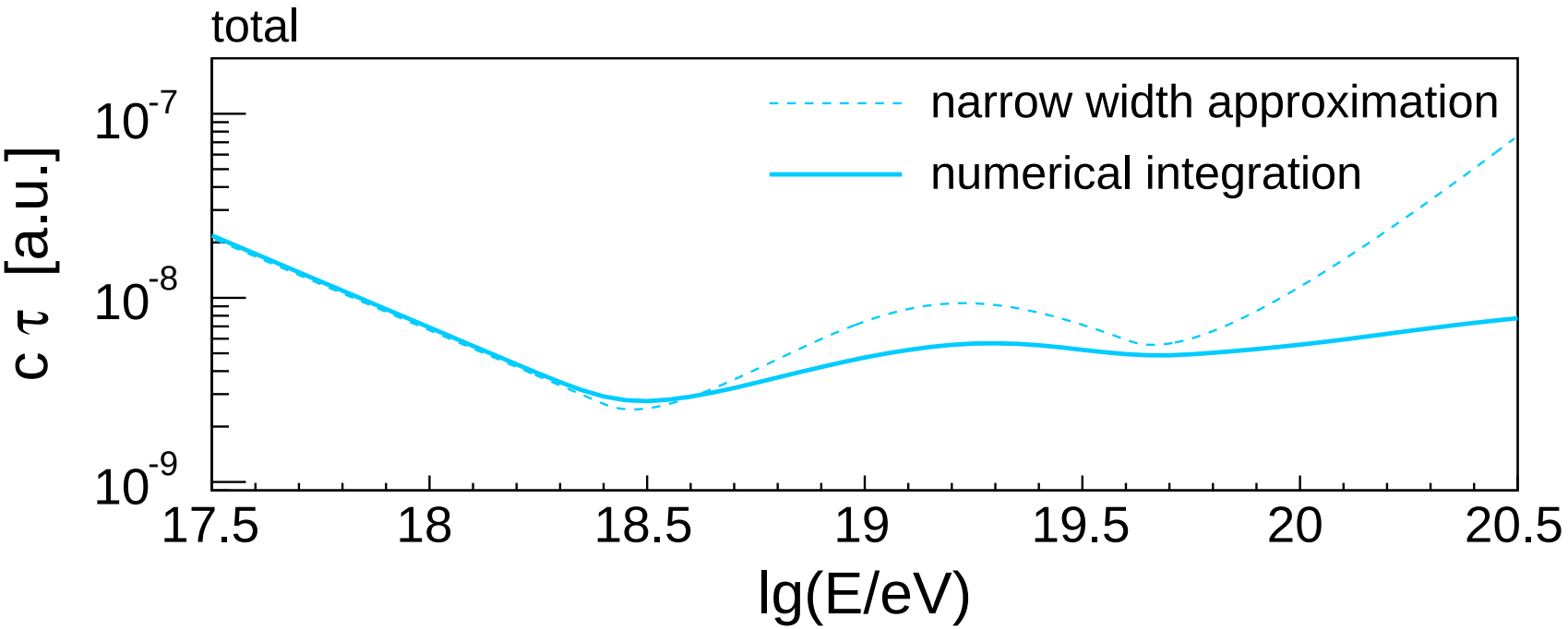


High-pass filter for injected nuclei, soft low-E nucleon spectrum

Photonuclear Interactions in a “peaky” Photon Field



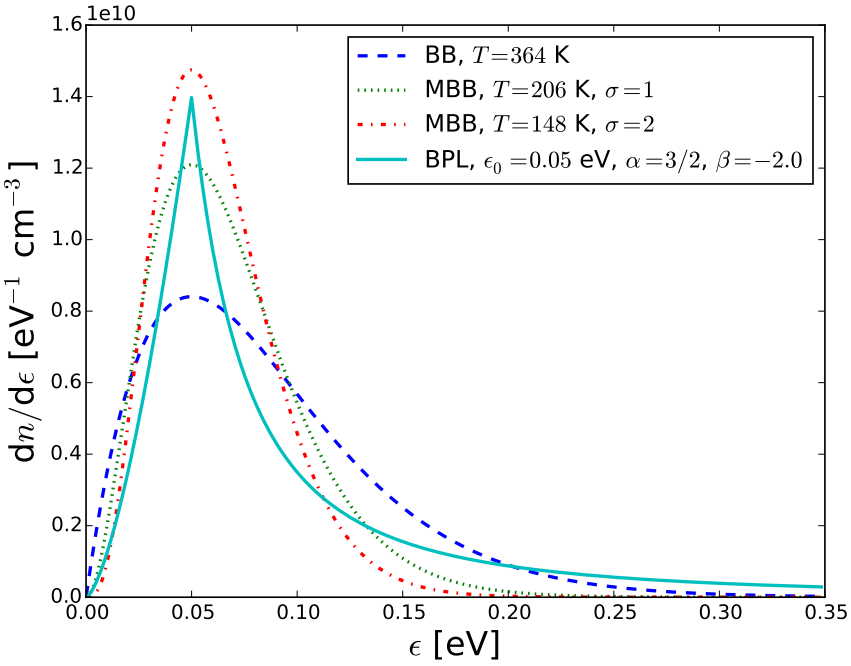


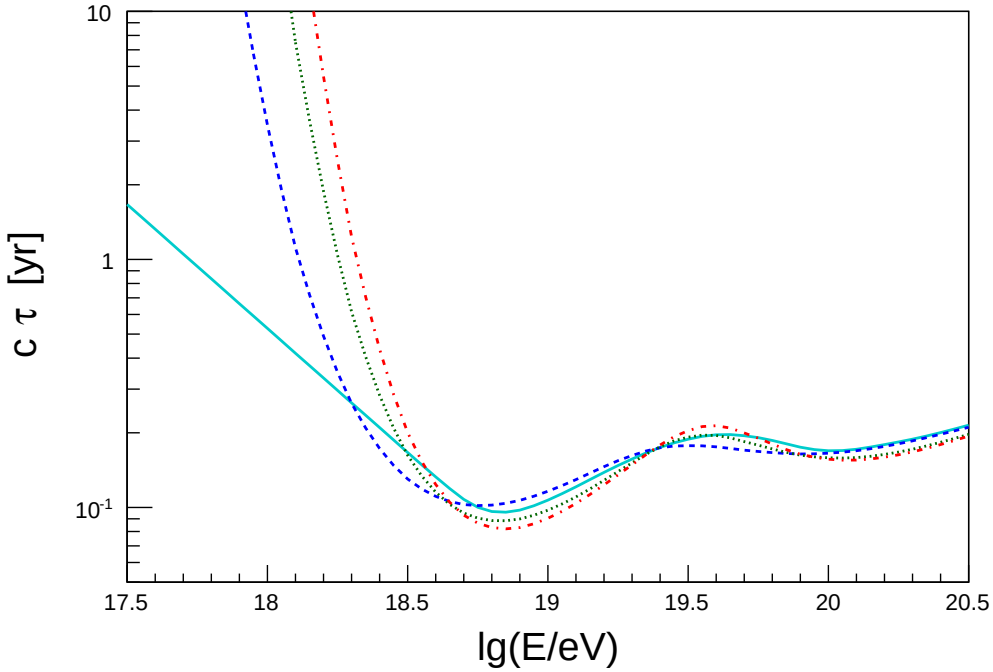


^{28}Si in a broken power-law photon field, $\alpha = \frac{3}{2}$, $\beta = -1$ and $\varepsilon_0 = 0.11$ eV

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

Details of Calculation

- PSB chain with TALYS cross sections and branching ratios
- Lorentz-factor conservation $E \approx E_i/A$
- recursive "trickle-down" calculation of production rates $\mathcal{Q}$

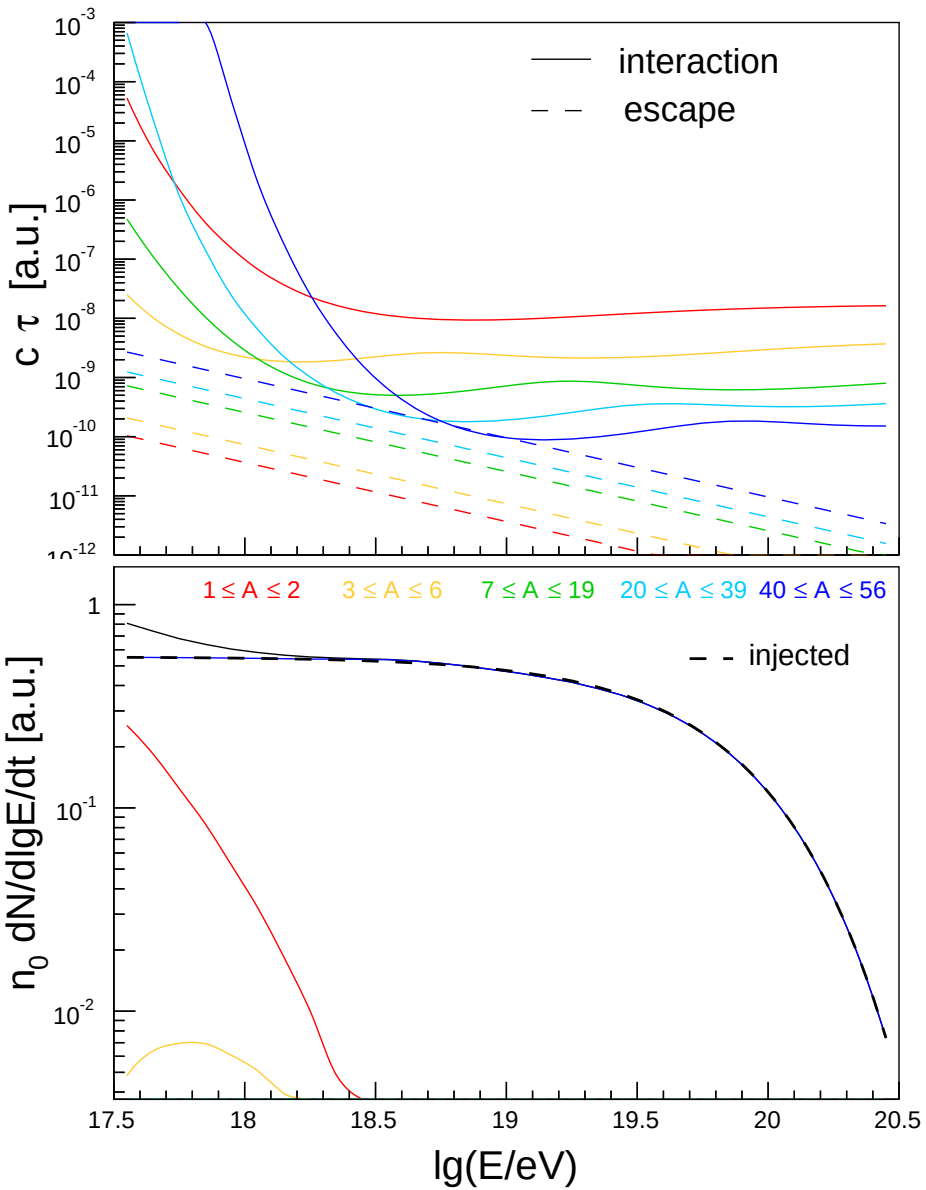
$$\mathcal{Q}(E,\ A) = \sum_{A'>A} \sum_{i=1}^{A'-A} b(E_i,\ A, A+i)\, \eta\,(E_i,\ A+i)\, \mathcal{Q}(E_i,\ A+i) \left| \frac{dE_i}{dE} \right|$$

injected nuclei A', secondary A, branching ratio b, interaction fraction η

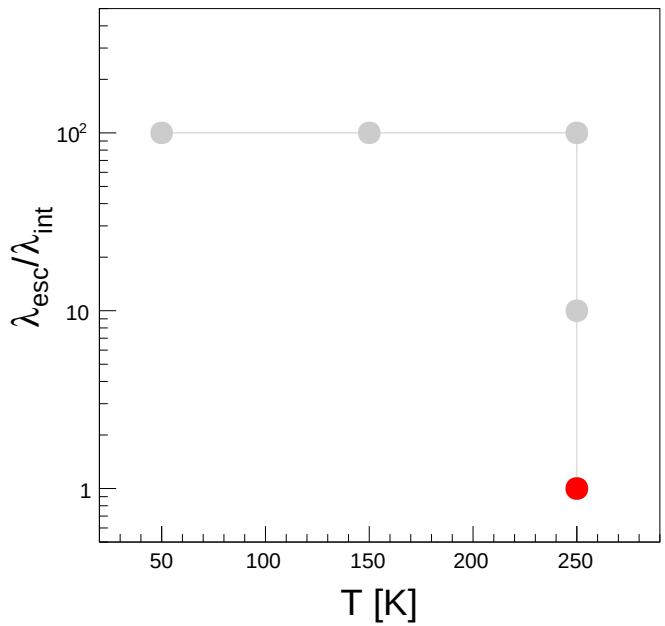
- fixed pion inelasticity for photo-pion: $\kappa_{PP} = 0.8$
- full decay kinematics of neutron and pion decay
- neutrino oscillation over astronomical distances
- end of Galactic spectrum: power law mass A_{gal}
- fast intergalactic propagation using propagation matrices (CRPropa)

$\rightarrow$ full calculation of CR spectrum and composition at Earth in $\mathcal{O}(100\ \mathrm{ms})$

Examples of Spectra Escaping from Source Environments



- 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



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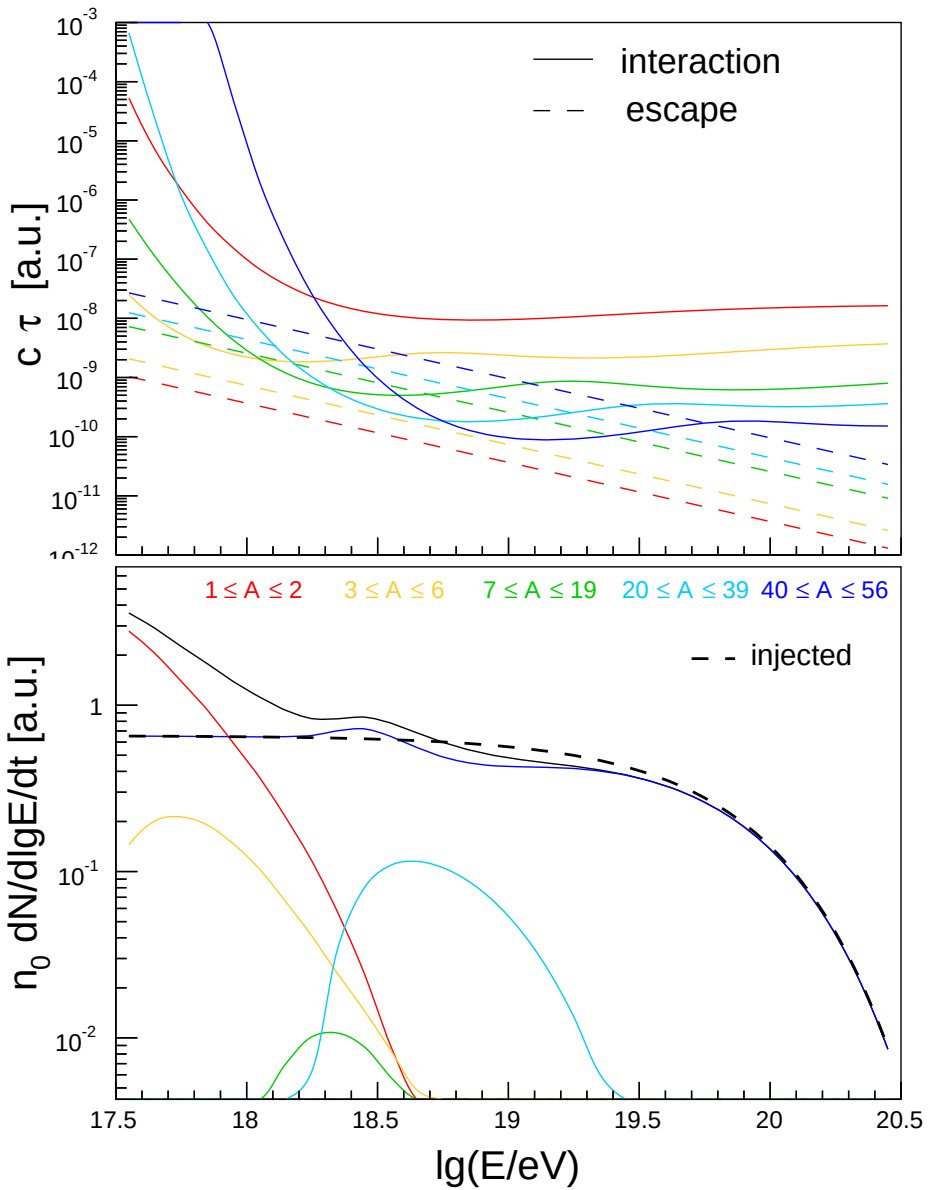
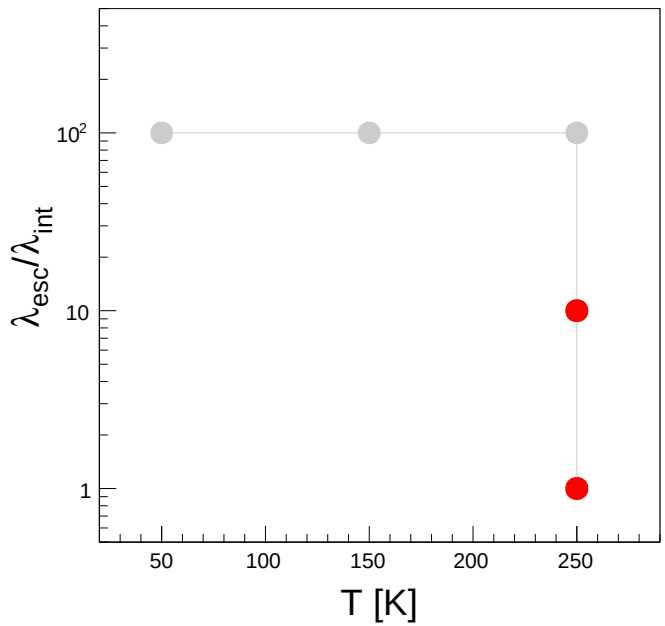


- injected mass: Fe
- $\gamma = -1$
- $E_{\rm max}({\rm Fe}) = 10^{19.8}$ eV
- photon field: black body, T=250 K
- $\lambda_{\rm esc} = 10 \times \lambda_{\rm int}$ at 10^{19} eV



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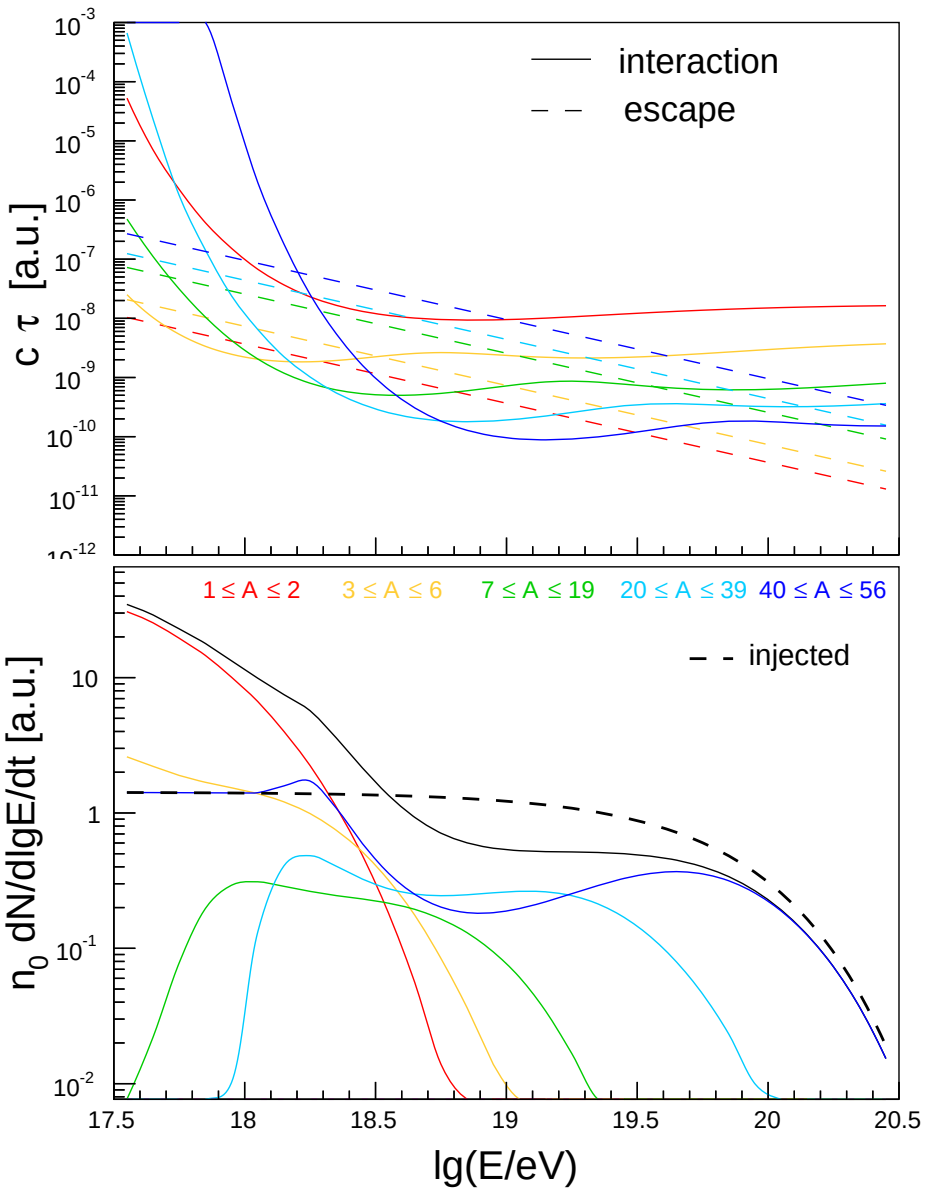
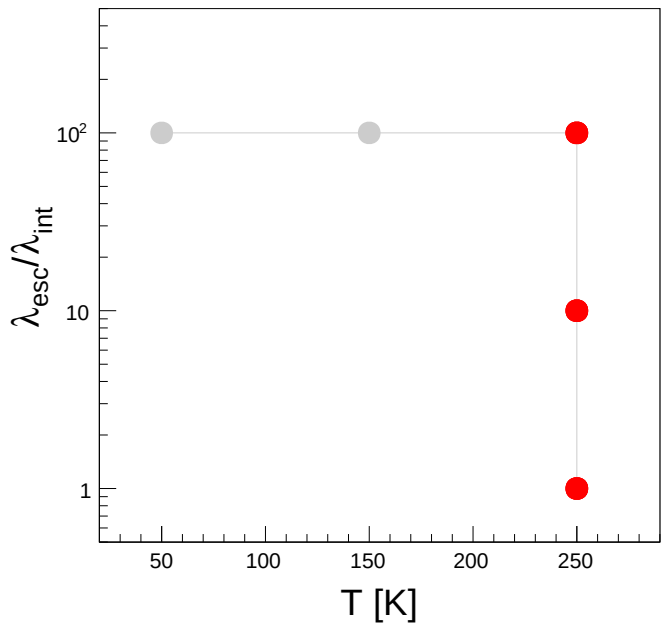
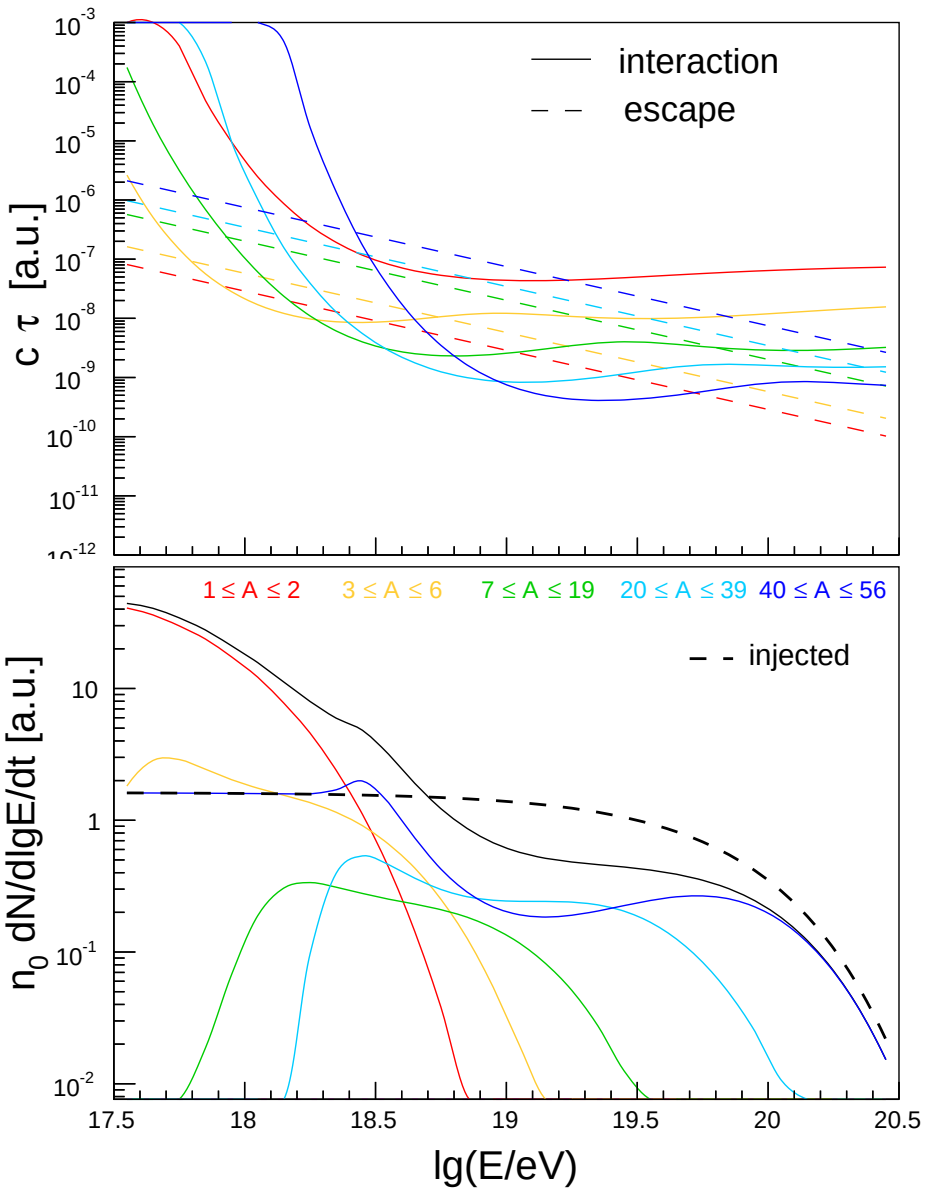


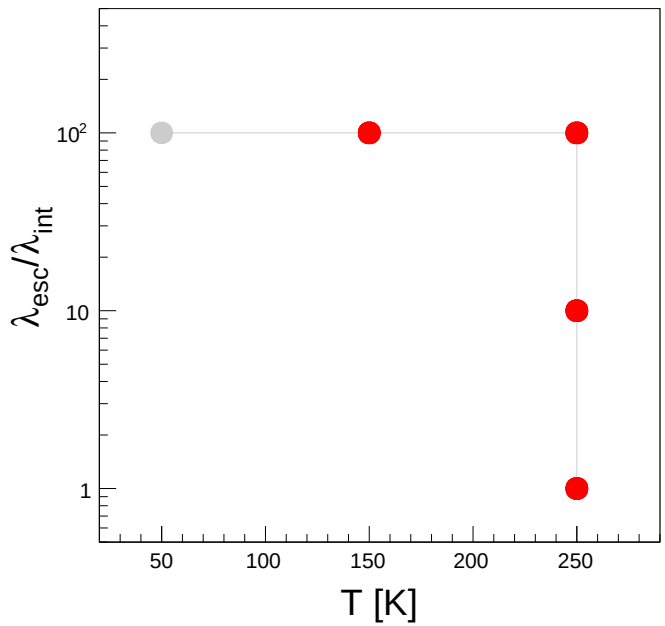
- injected mass: Fe
- $\gamma = -1$
- $E_{\rm max}({\rm Fe}) = 10^{19.8}$ eV
- photon field: black body, T=250 K
- $\lambda_{\rm esc} = 100 \times \lambda_{\rm int}$ at 10^{19} eV



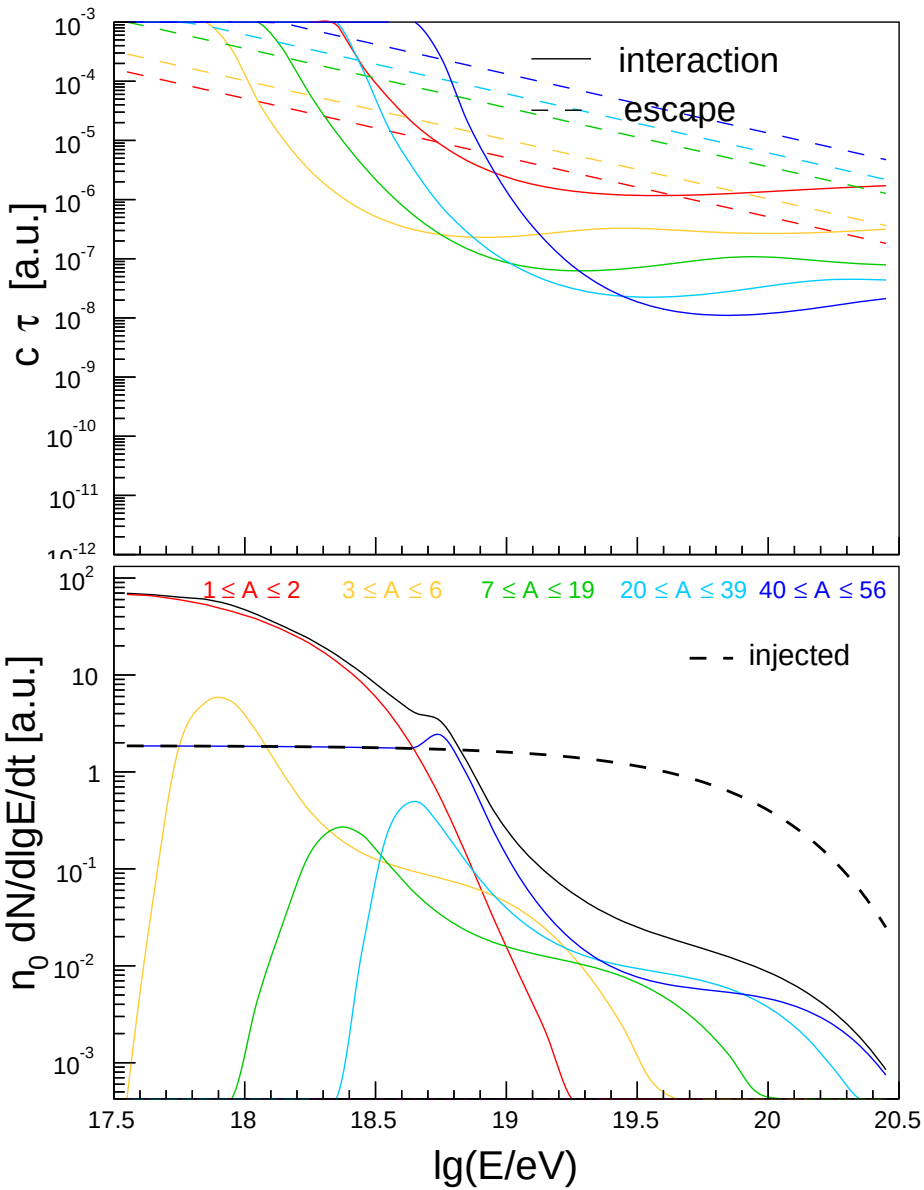
Examples of Spectra Escaping from Source Environments



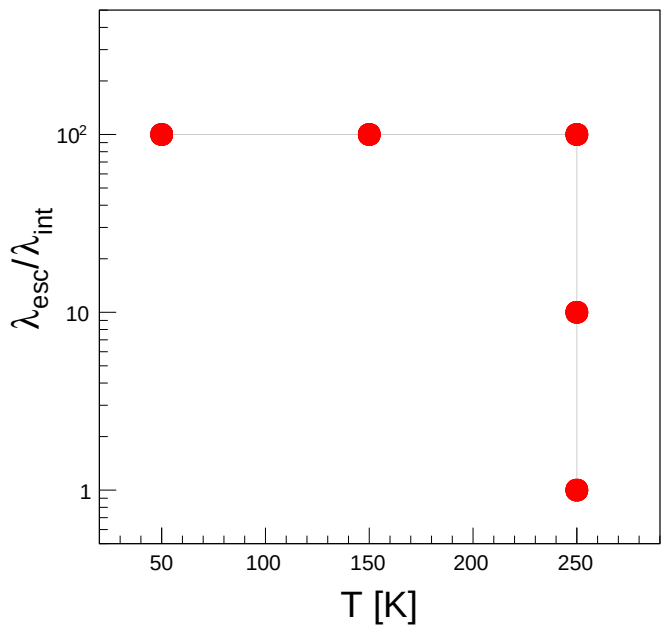
- injected mass: Fe
- $\gamma = -1$
- $E_{\max}(\mathrm{Fe}) = 10^{19.8}$ eV
- photon field: black body, T=150 K
- $\lambda_{\mathrm{esc}} = 100 \times \lambda_{\mathrm{int}}$ at 10^{19} eV



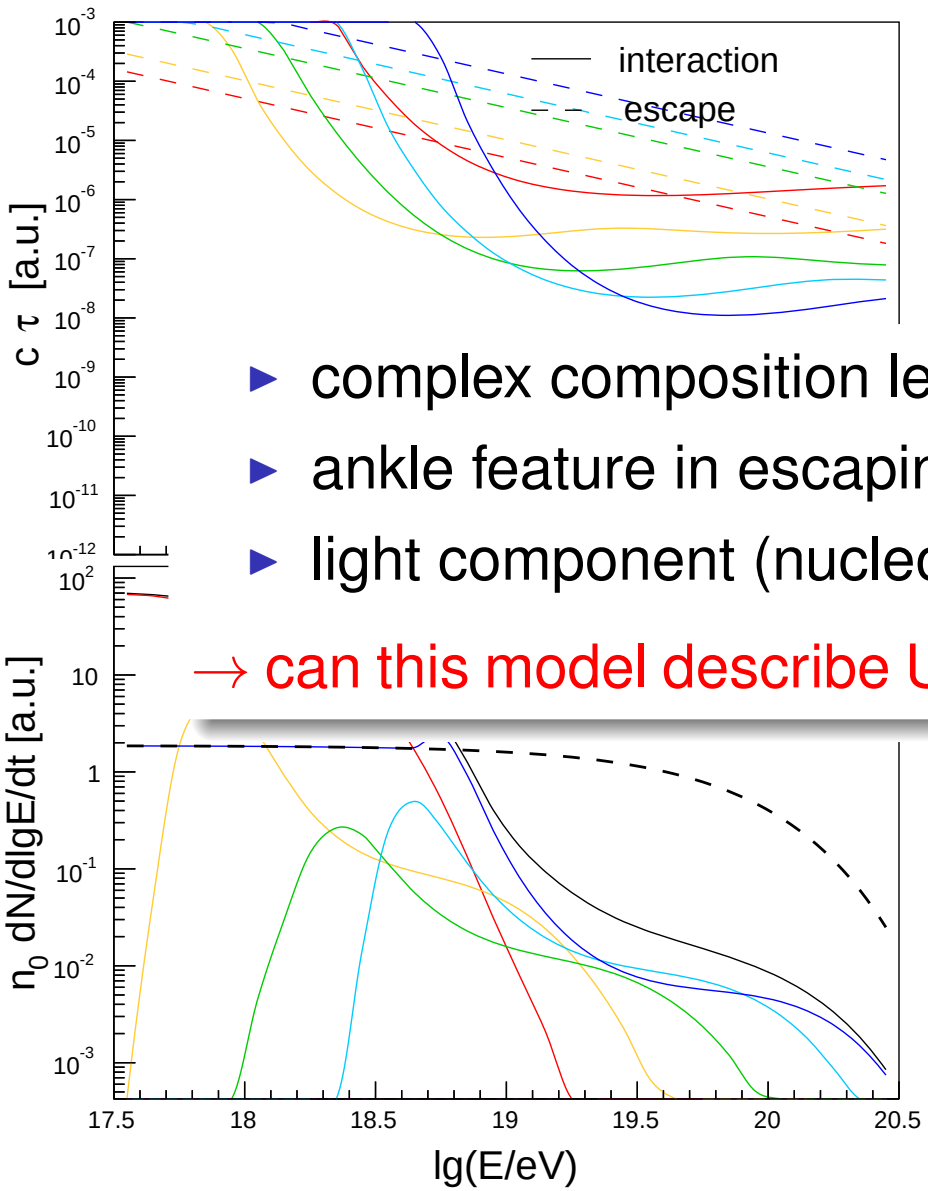
Examples of Spectra Escaping from Source Environments



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



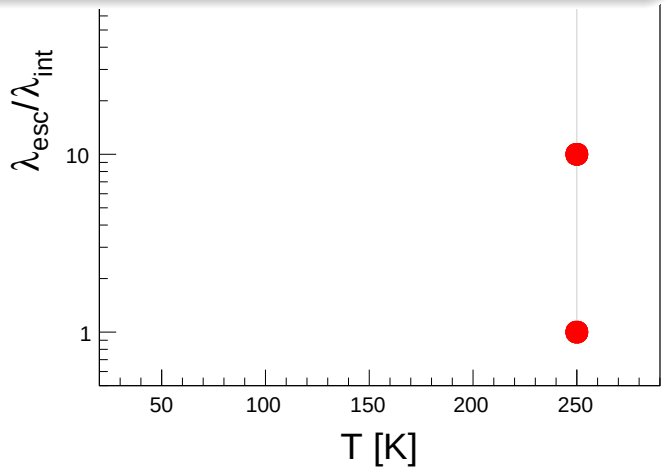
Examples of Spectra Escaping from Source Environments



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

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

→ can this model describe UHECR flux and composition?



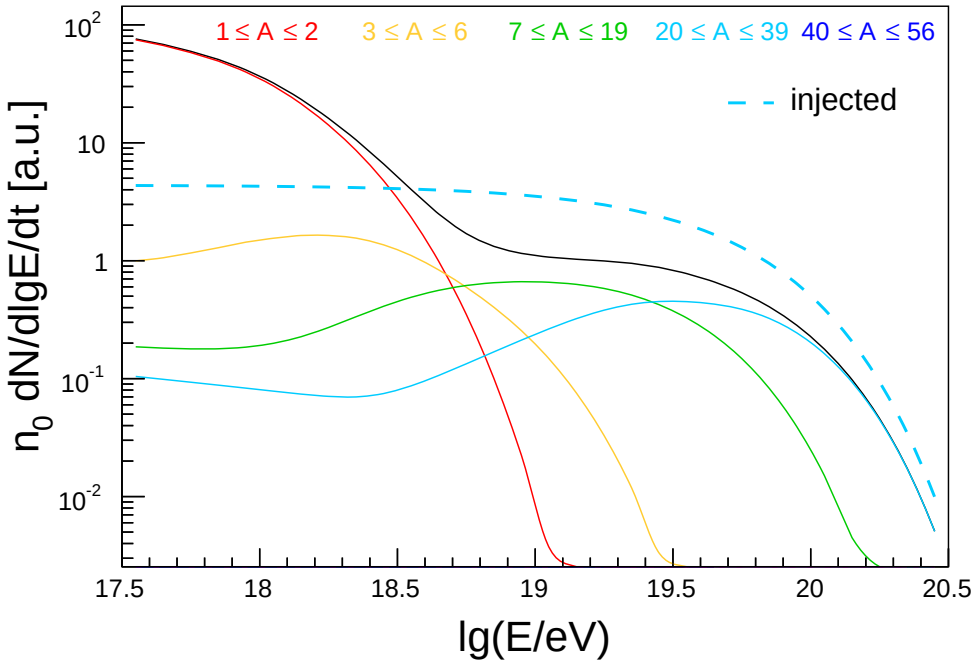
Fiducial Scenario

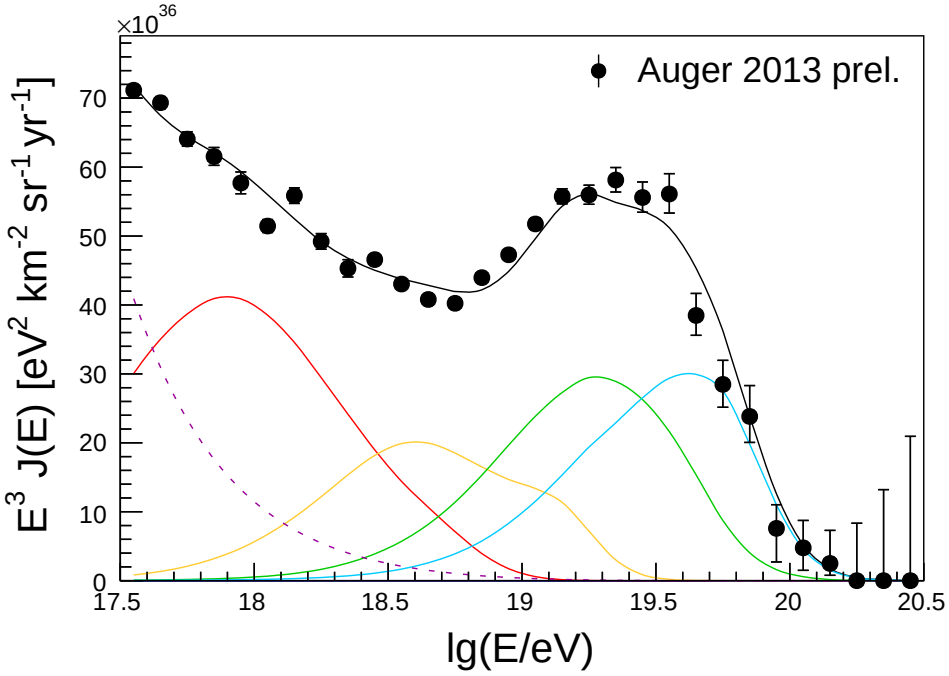
source parameters			
power law index of injected nuclei	γ	fix	-1
mass number of injected nuclei	A	free	28 (29)
maximum energy	$E^p_{\rm max}$	free	$10^{18.5\ (18.6)}$ eV
cosmic ray power density, $E > 10^{17.5}$ eV	$\dot{\epsilon}_{17.5}$	free	9.2 (13) $\times 10^{44}$ erg Mpc^{-3} yr^{-1}
evolution	$\xi(z(t))$	fix	star formation rate [60]
source environment			
energy of maximum of photon field density	ε_0	free	0.11 (0.07) eV
power law index of photon spectrum ($\varepsilon < \varepsilon_0$)	α	fix	$+\frac{3}{2}$
power law index of photon spectrum ($\varepsilon \geqslant \varepsilon_0$)	β	fix	-2
power law index of escape length	δ	free	-0.77 (-0.94)
ratio of interaction and escape time	$R^{\rm Fe}_{19}$	free	4.4 (3.7) $\times 10^2$
propagation to Earth			
infra-red photon background	–	fix	Gilmore12 [61]
spectrum of Galactic cosmic rays			
power law index at Earth	$\gamma_{\rm gal}$	free	-4.2 (-3.7)
mass number of Galactic nuclei	$A_{\rm gal}$	fix	56
flux fraction at $10^{17.5}$ eV	$f_{\rm gal}$	free	57 (72) %

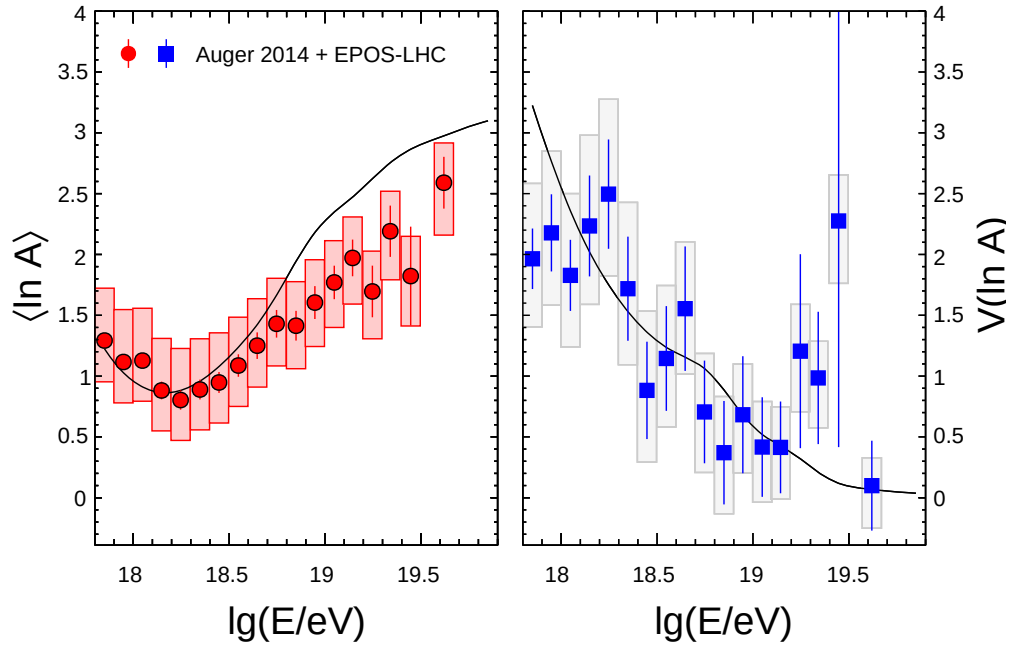
Fiducial Scenario

^{29}Si injected, escaping flux at source

flux and composition at Earth



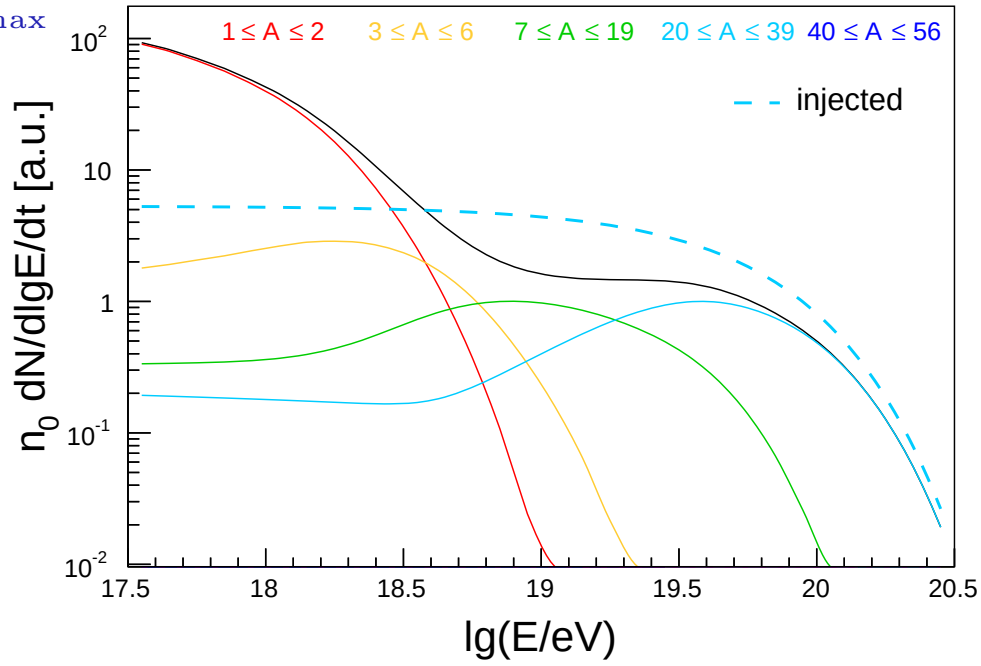


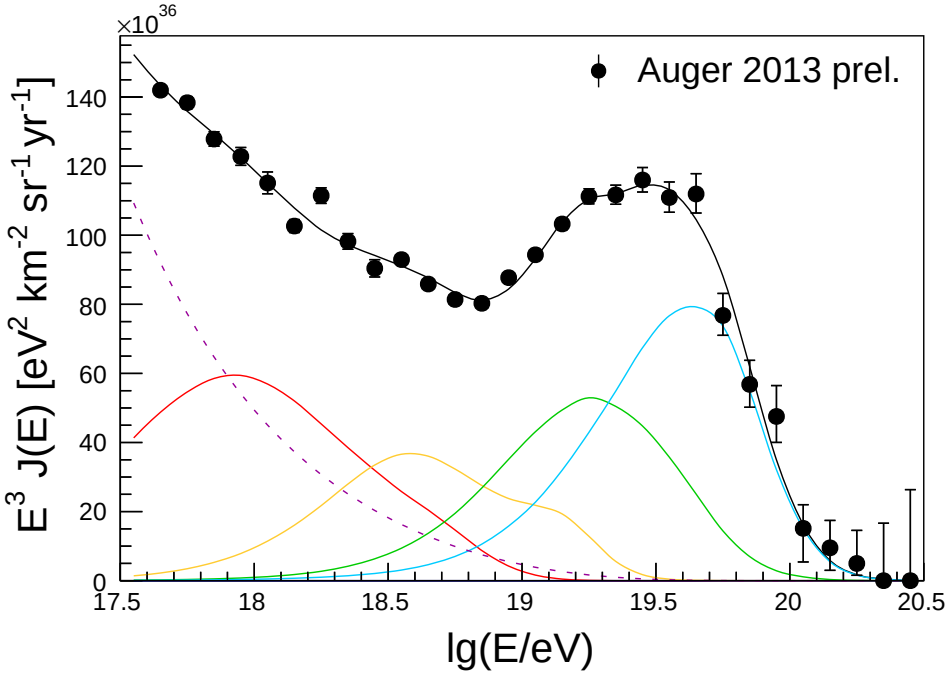


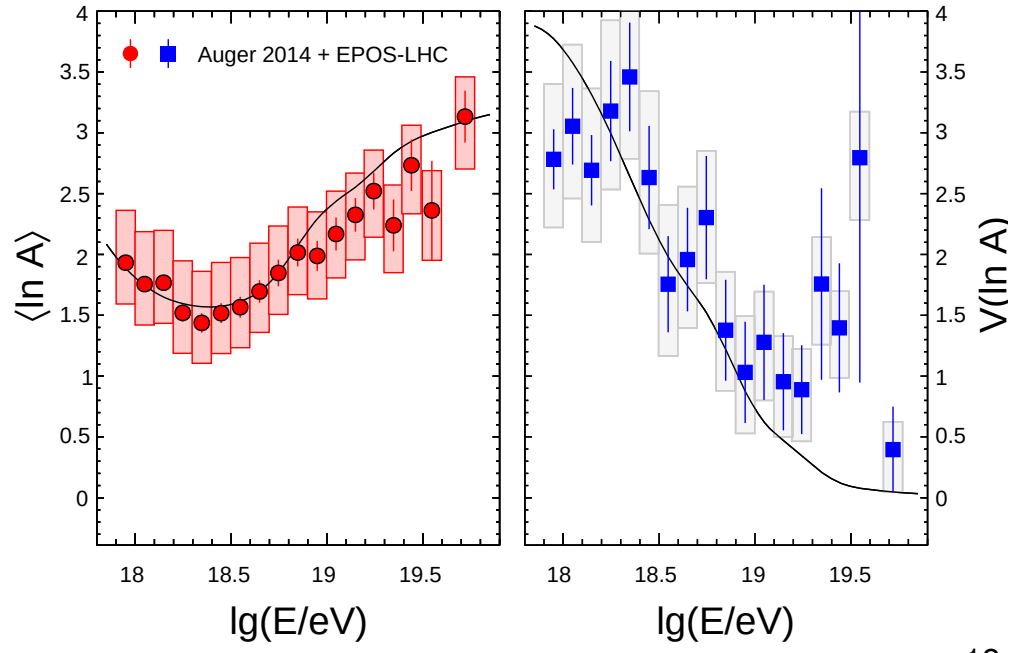
Fiducial Scenario $+1\sigma_{\mathbf{E}}\ -1\sigma_{\mathbf{X_{max}}}$

^{29}Si injected, escaping flux at source

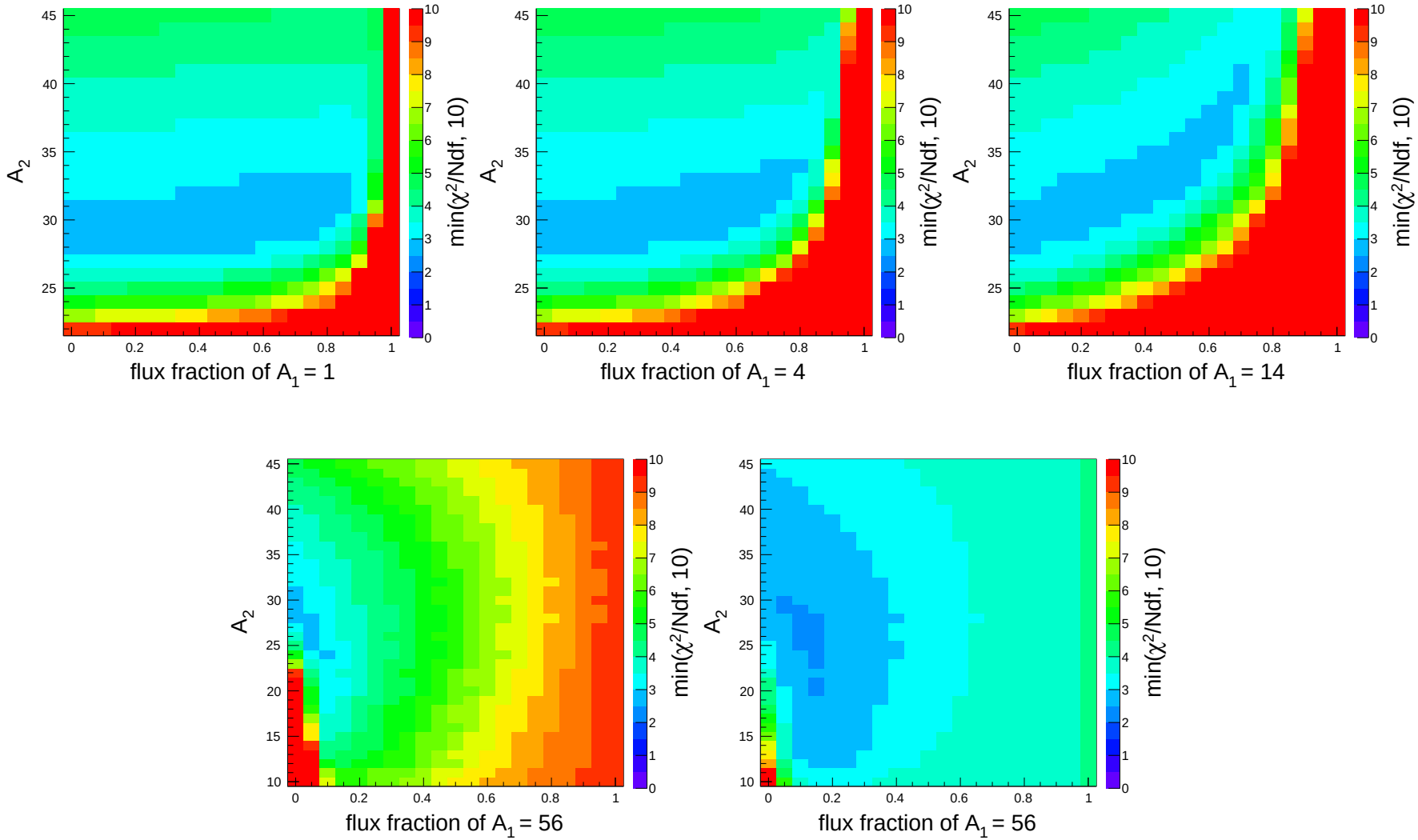
flux and composition at Earth







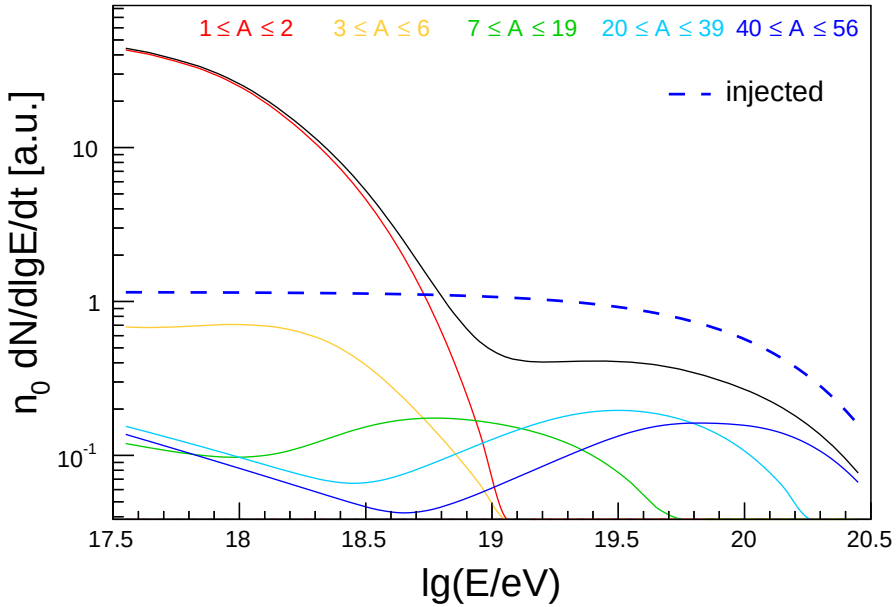
What about Mixed Injected Composition?

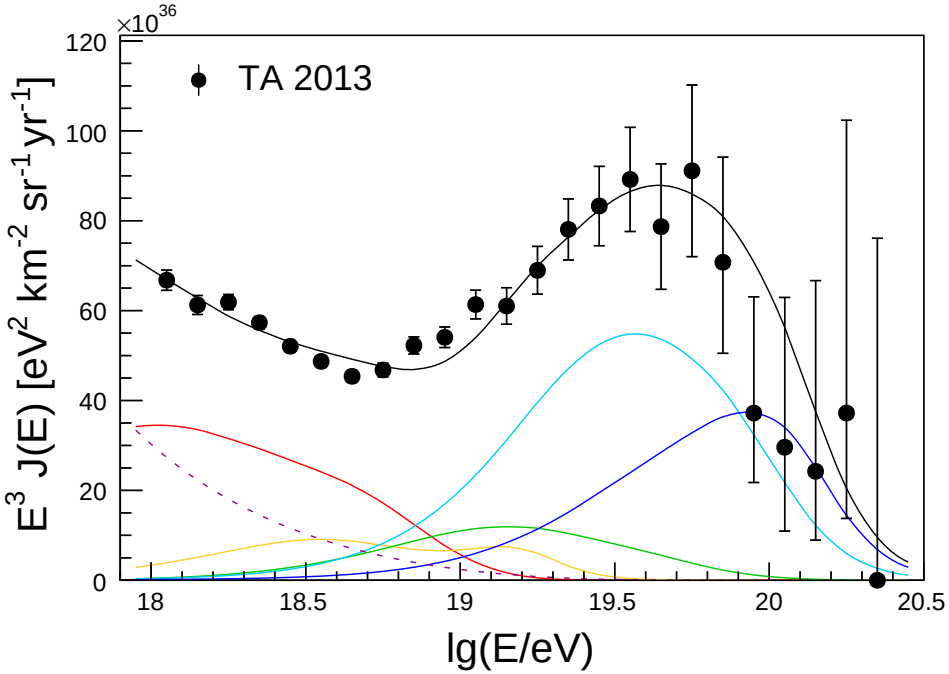


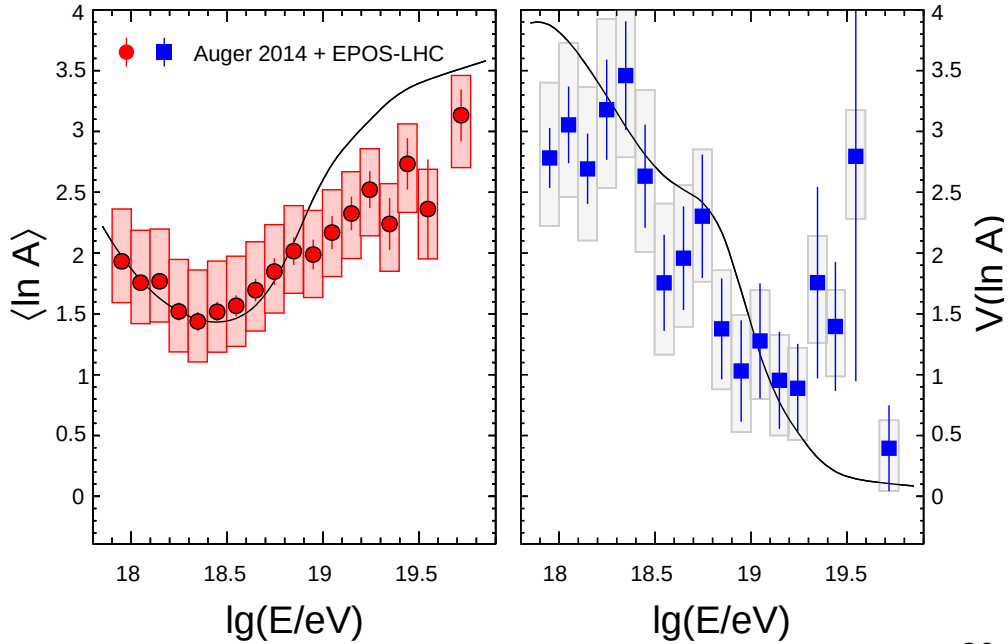
Fit using TA Spectrum, 100% Iron at Injection

^{56}Fe injected, escaping flux at source

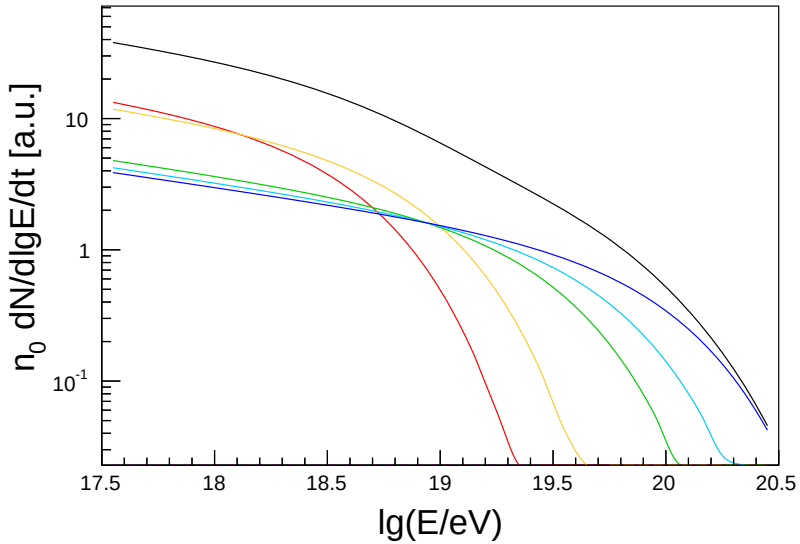
flux and composition at Earth

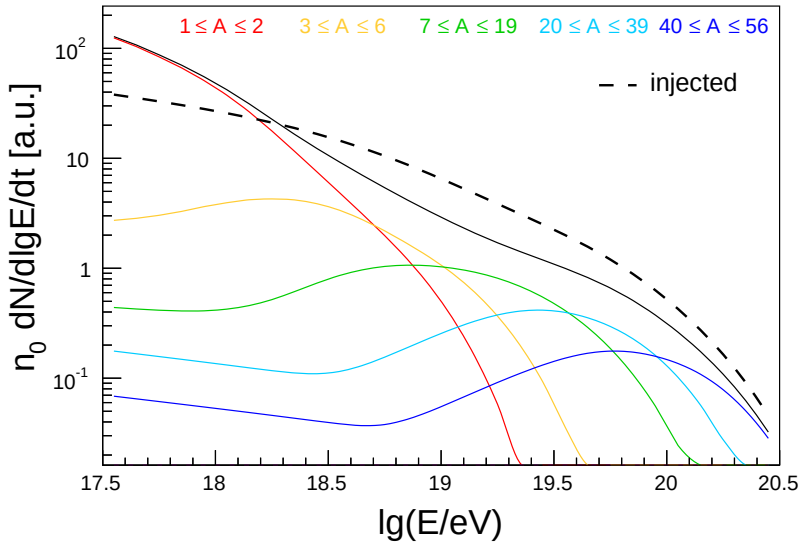


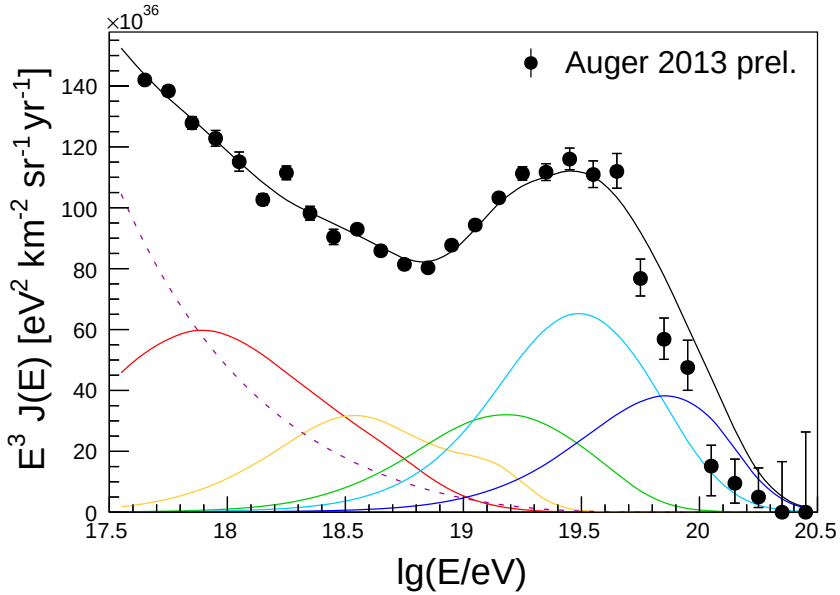


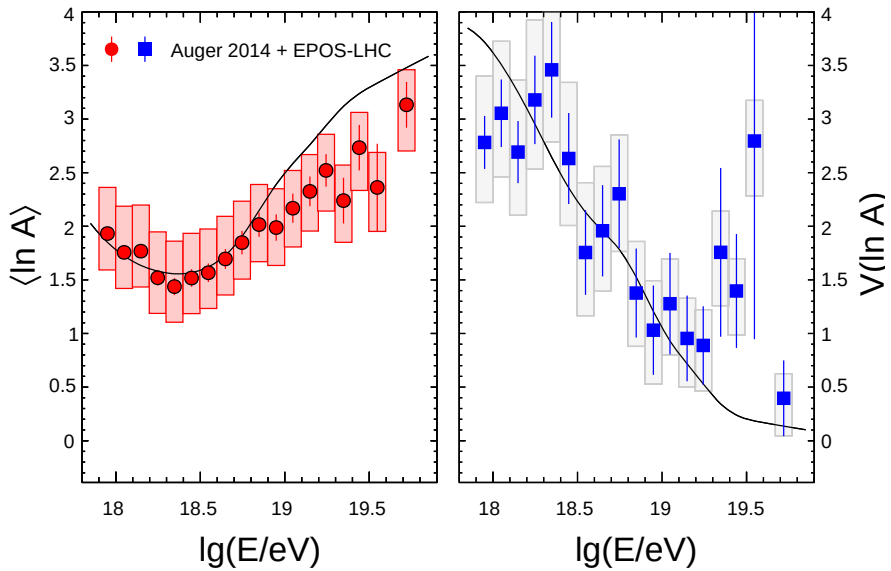


Fit injecting Galactic Mix*





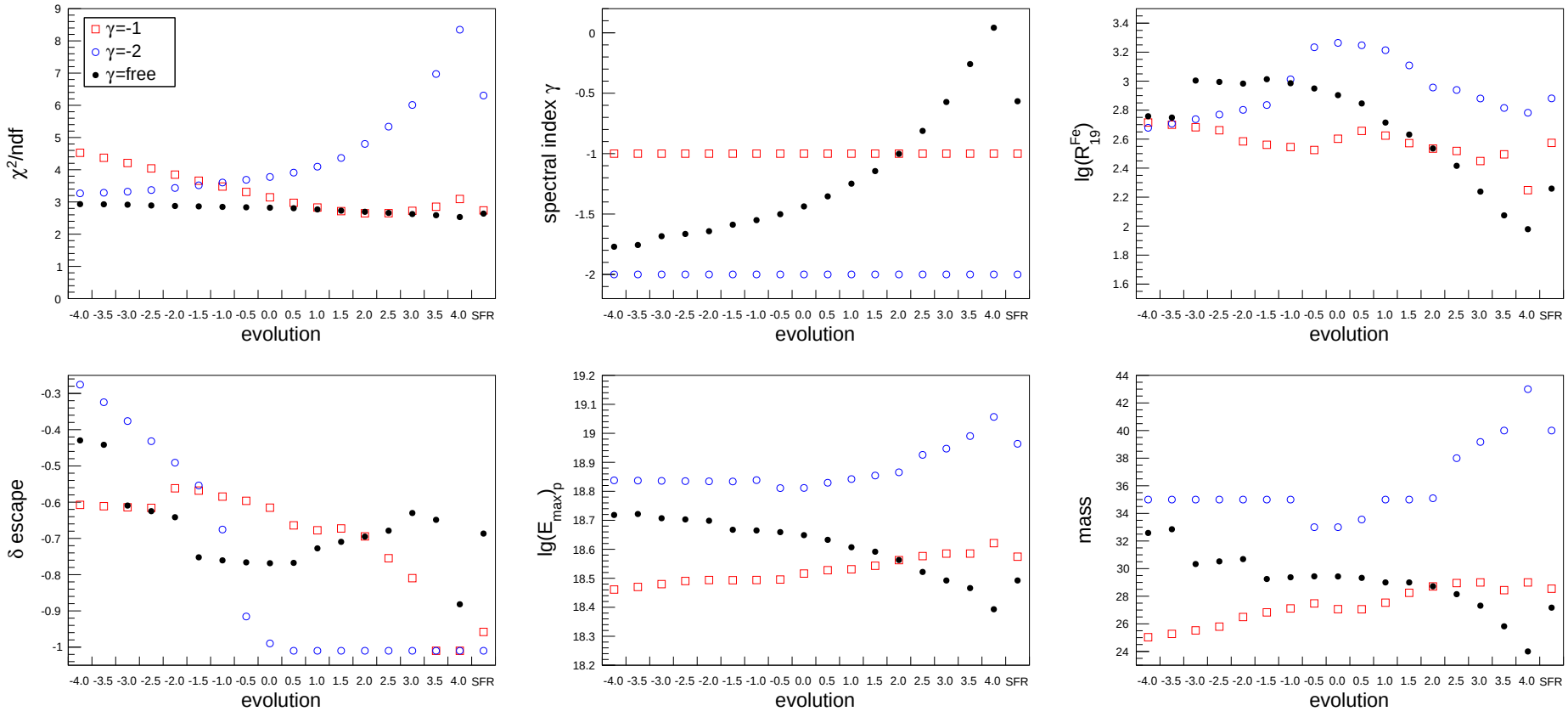




energy scale $+1\sigma_{\rm syst}$, $X_{\rm max}$ scale $-1\sigma_{\rm syst}$

* direct measurements of Galactic flux at TeV

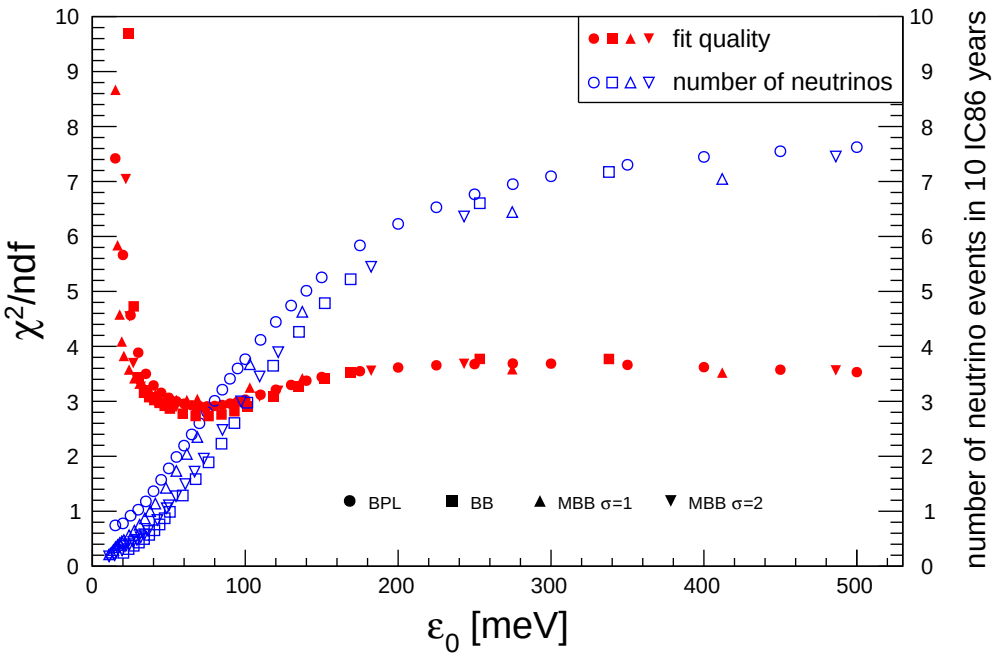
Effect of Source Evolution



- source evolution $\propto (1+z)^m$
- test $-4 < m < 4$ and star formation rate
- $m = 0$: no evolution
- $m < 0$: local sources dominate (à la Taylor et al 2015)

Photon Peak Energy and Neutrino Predictions

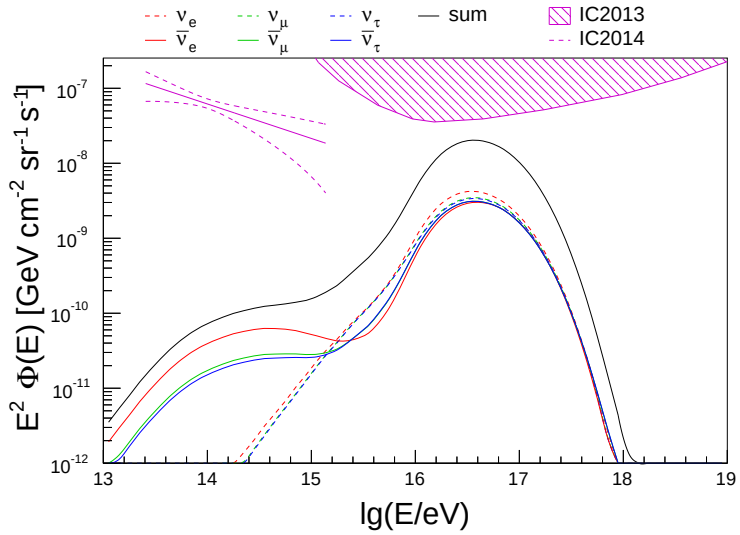
χ^2/Ndf and N_ν vs. peak energy



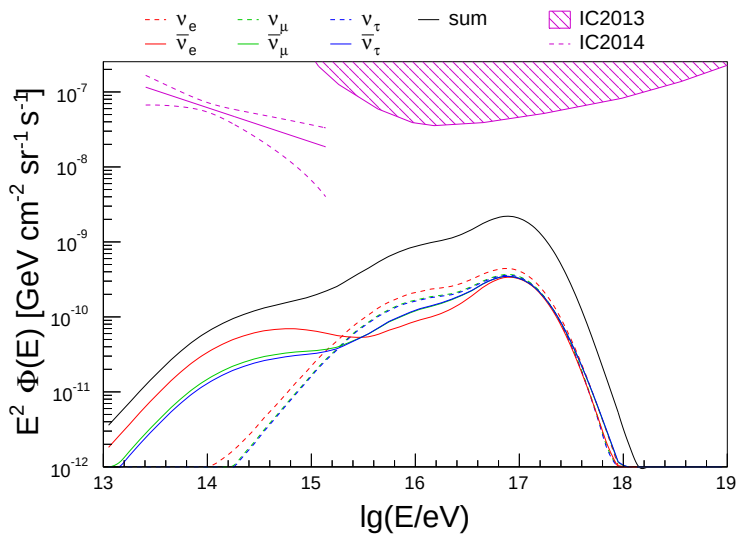
$T \geq 180$ K, 125 K and 100 K

for BB $\sigma = 0$, 1 and 2 at 3 σ

neutrinos at best fit ε_0



3σ lower limit (minimum ε_0)



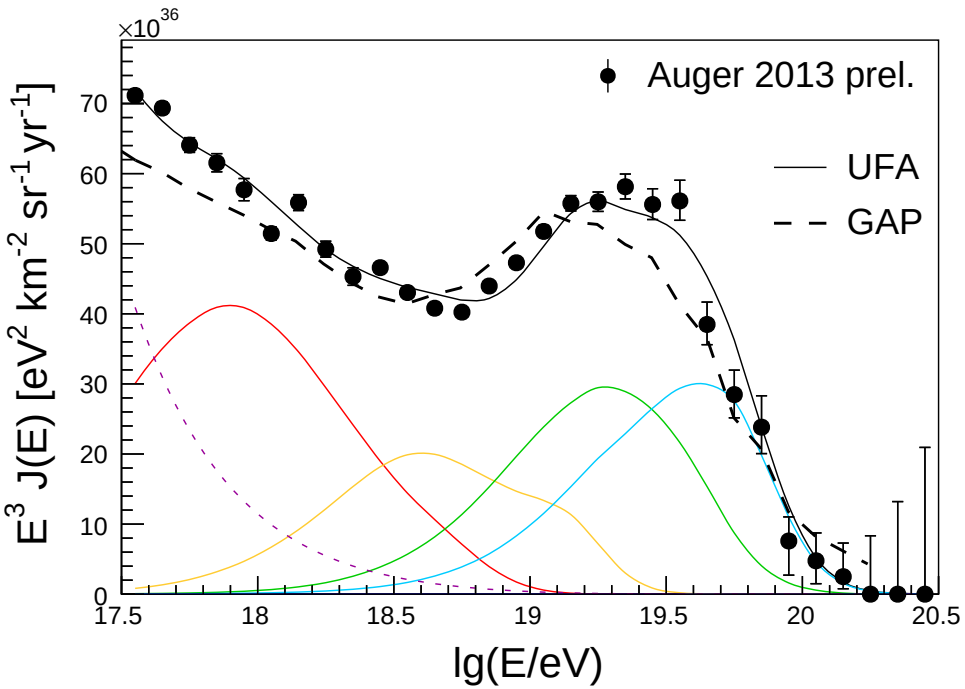
Summary

Previous mixed-comp. scenarios

- 🙂 $E_{\max} \propto Z$
- 😐 hard injection spectrum $\gamma \approx 1$
- ☹ ad-hoc composition fractions
- ☹ ad-hoc low-E light component

Photonuclear interactions at source

- 🙂 $E_{\max} \propto Z$
- 🙂 works with Galactic composition
- 🙂 explain ankle and low-E protons
- 😐 hard injection spectrum $\gamma \approx 1$
- 😐 source properties: additonal doF



see also:

- photonuclear interactions in GRBs
  N. Globus et al 2015, D. Biel et al 2017
- p+p interactions at source
  M. Kachelriess et al. 2017
- galactic-extragalactic transition
  S. Thoudam et al 2016