Origin of the ankle in the UHECR spectrum and extragalactic protons below it

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Cosmic Neutrinos: What's Next?
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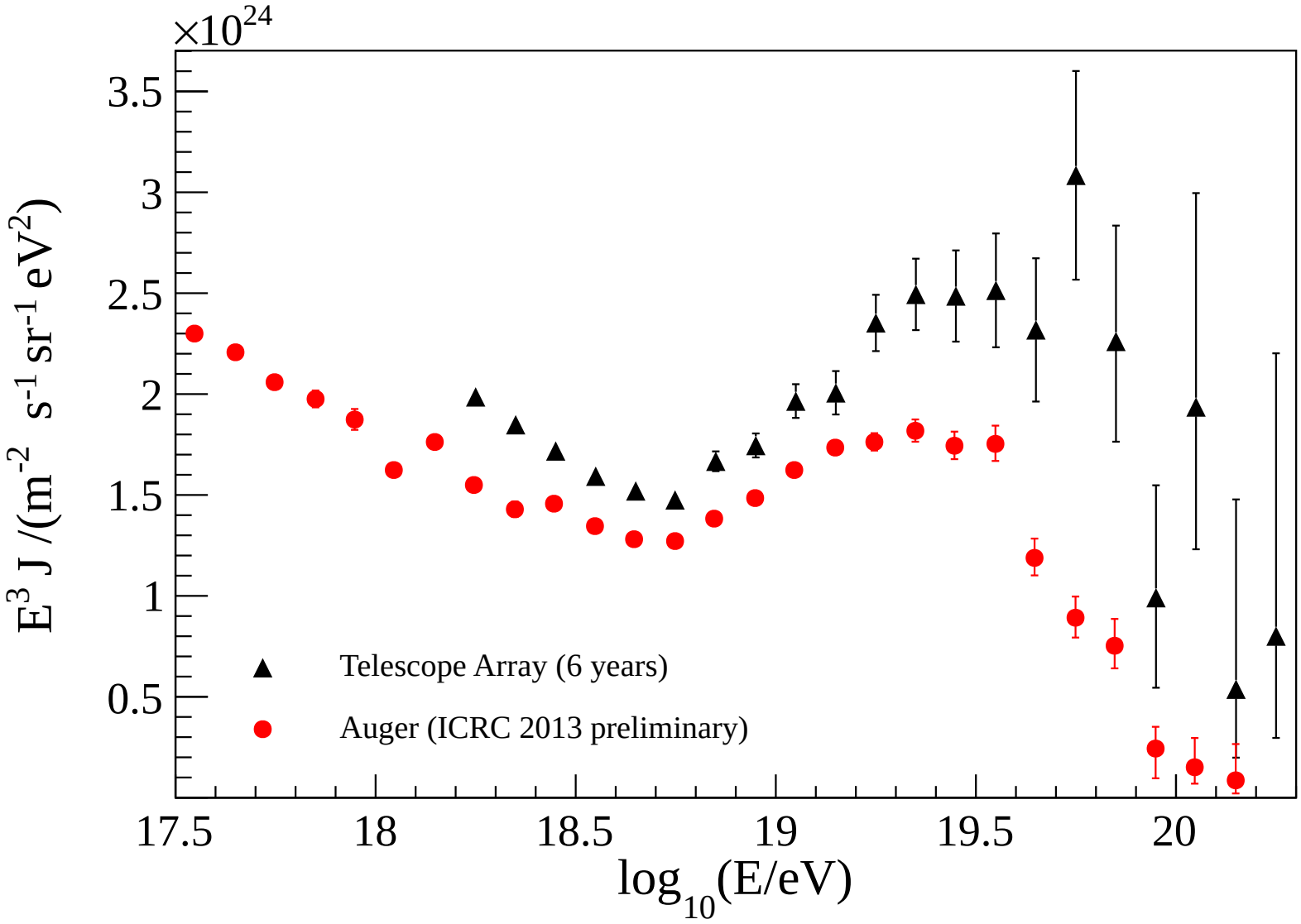
High energy end of CR spectrum

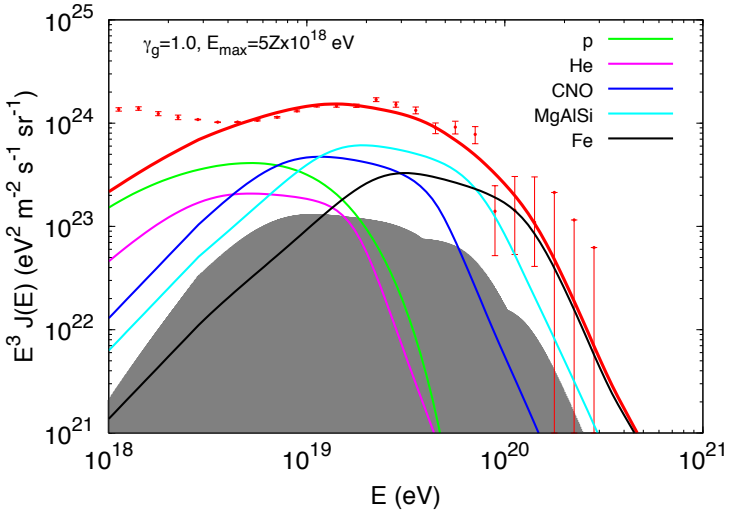


UHECR conundrum

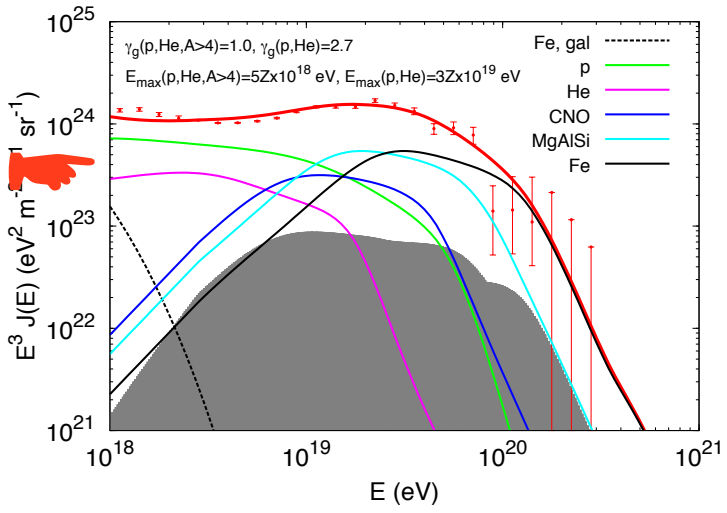
1. Ankle shape readily produced by superposition of two power-laws
   Natural candidate: transition between GCRs and EGCRs
   - Original models ☞ transition from Galactic ^{56}Fe to EG protons
     (Bird+,1993)
   - Recent models ☞ transition from G ^{56}Fe to EG heavies
     (Allard-Olinto-Parizot,2007)
2. Ankle feature also naturally arises as dip in spectrum
   from e^+e^- energy loss of EG protons propagating in CMB
   (Berezinsky-Gazizov-Grigorieva,2002)
3. Auger data ☞ light but EG component near and below ankle
   + intermediate composition above
   (Auger Collaboration,2014)
4. Recent models ☞ fit Auger spectrum and composition
   at price of adding an *ad hoc* light EG component below ankle
   with a steep injection spectrum $\propto E^{-2.7}$

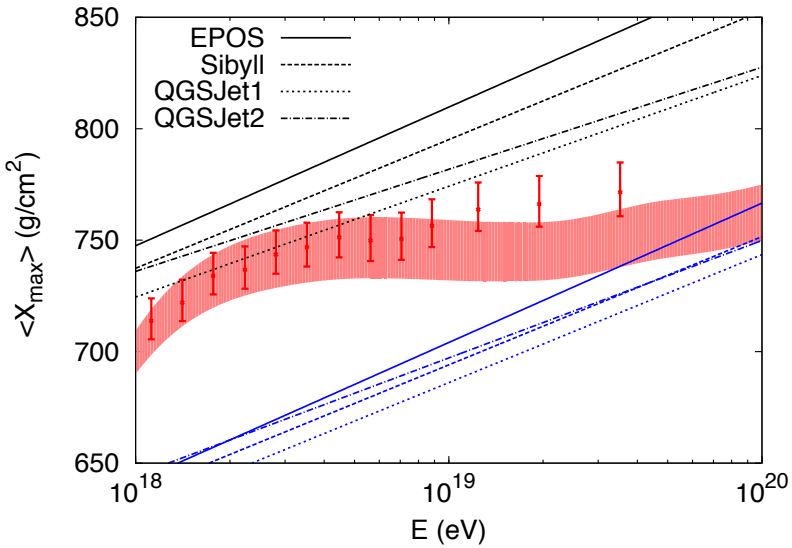
(Gaisser-Stanev-Tilav,2013;Aloisio-Berezinsky-Blasi,2014)

Example of 4 (Aloisio-Berezinsky-Blasi, 2014)



p-He EG





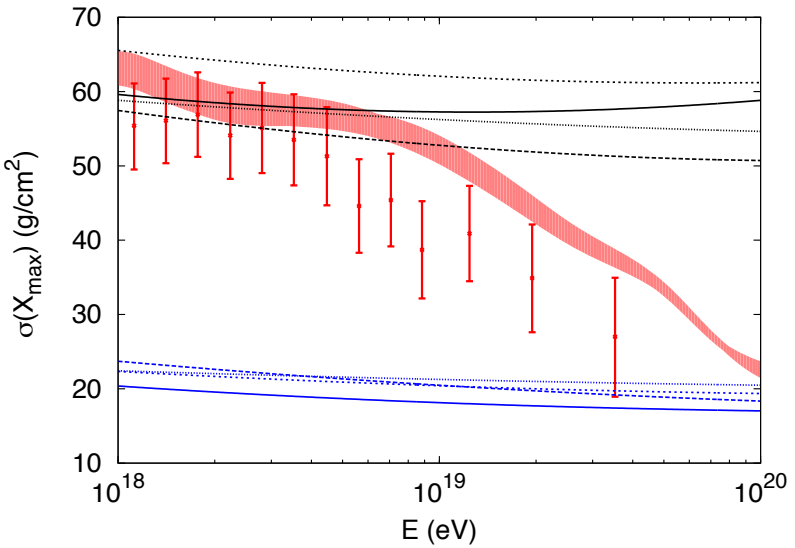
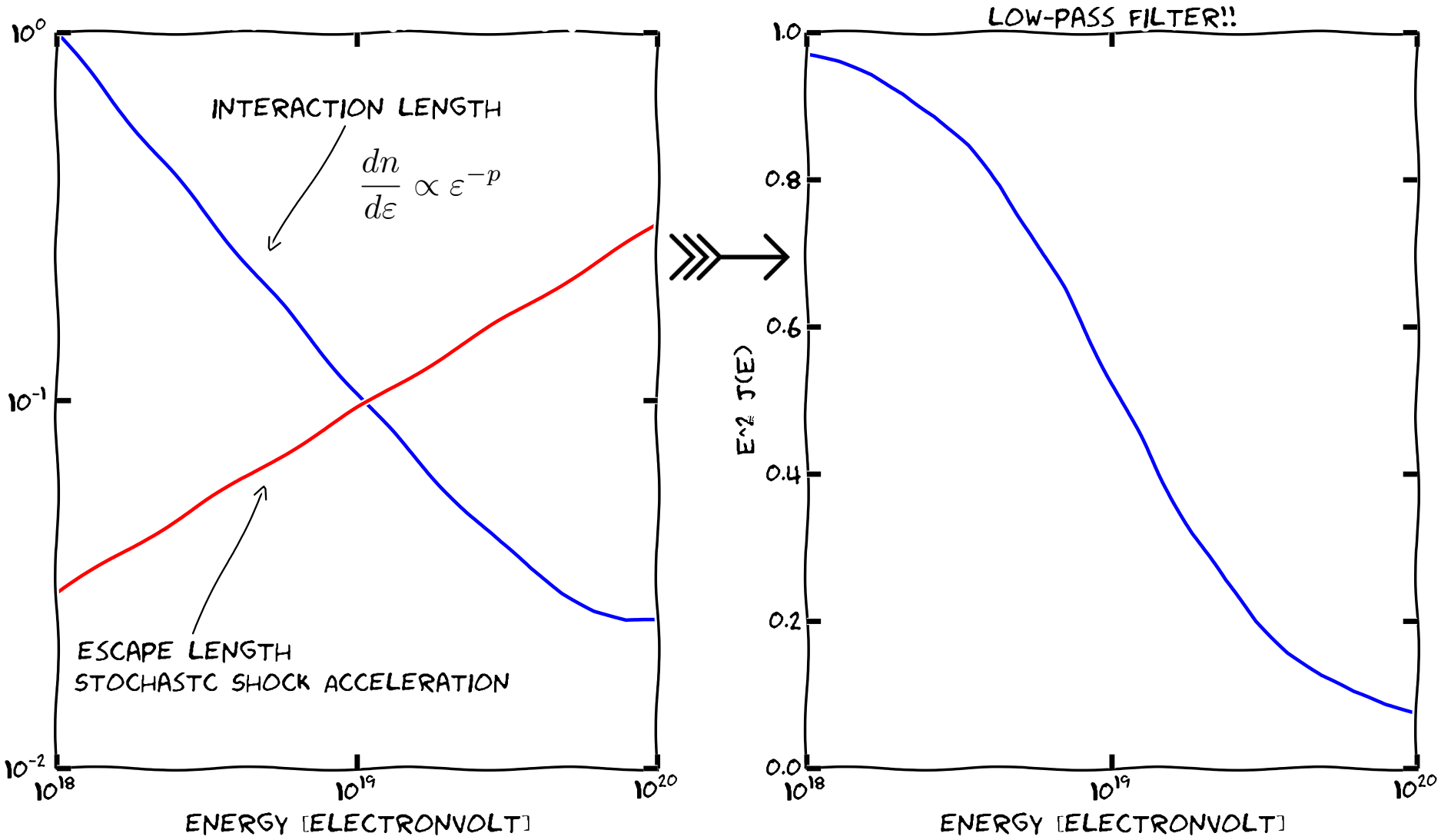
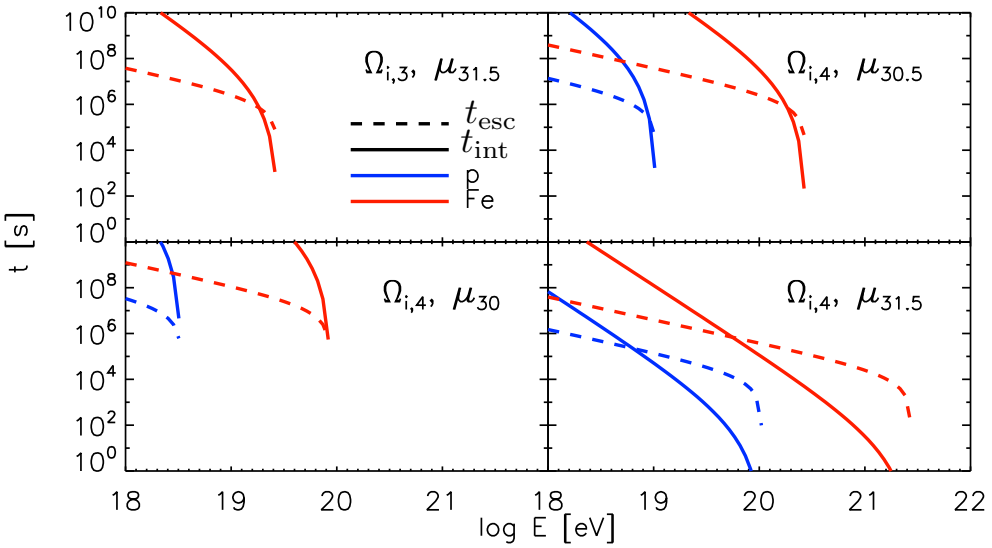
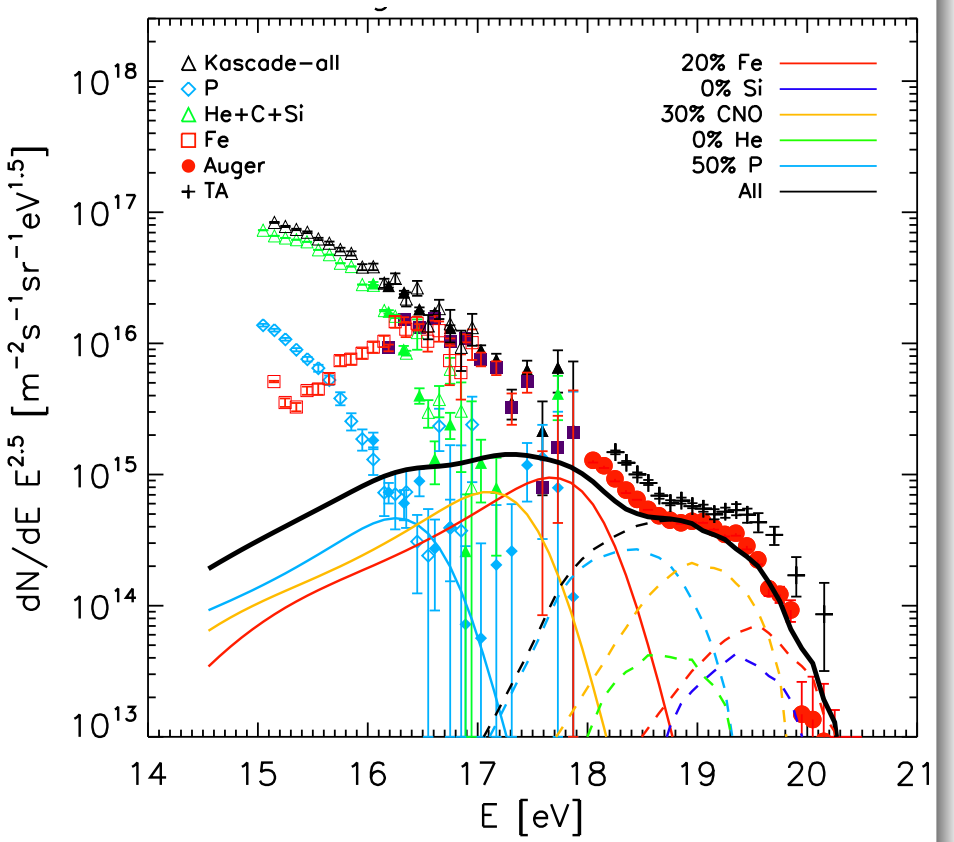


Photo-nuclear interactions during acceleration



Example (Fang-Kotera-Olinto, 2012-2014)

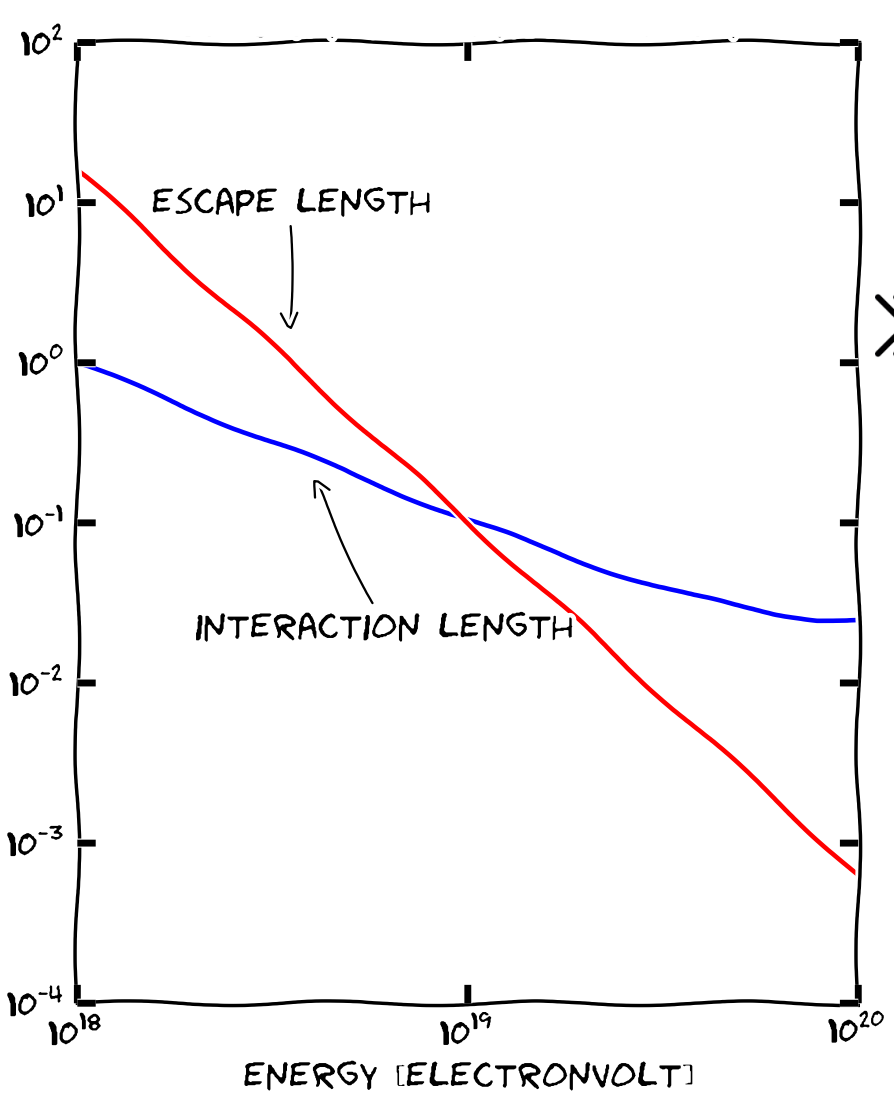


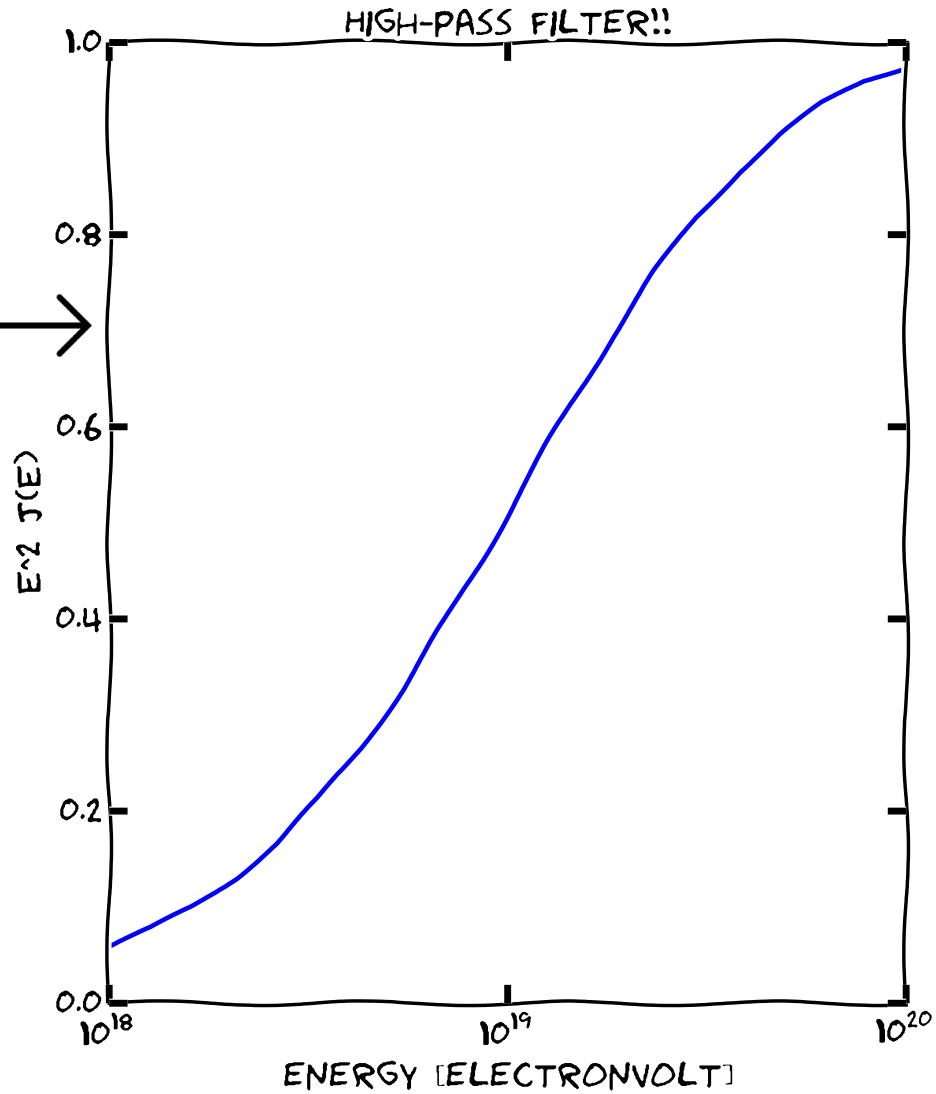


Newly-born pulsars embedded in core-collapse supernovae

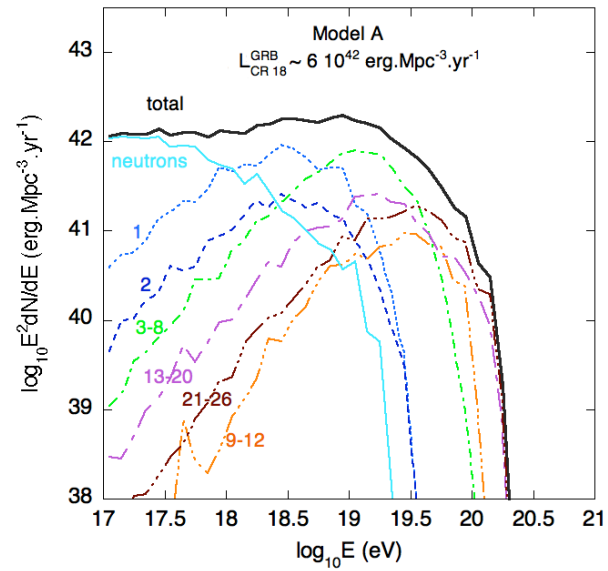
- initial rotational velocity: $\Omega_i = 10^3, 10^4$ s^{-1}
- magnetic dipole moment: $\mu = 10^{30}, 10^{31.5}$cgs
- need GCR population (solid lines) to fill-in spectrum below ankle

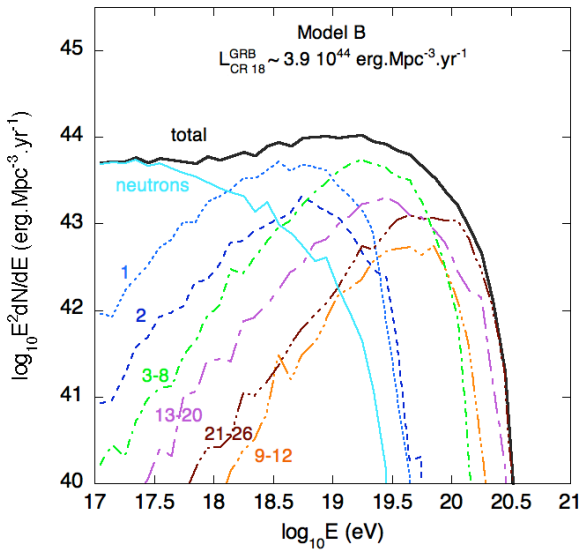
New idea: photodisintegration after acceleration

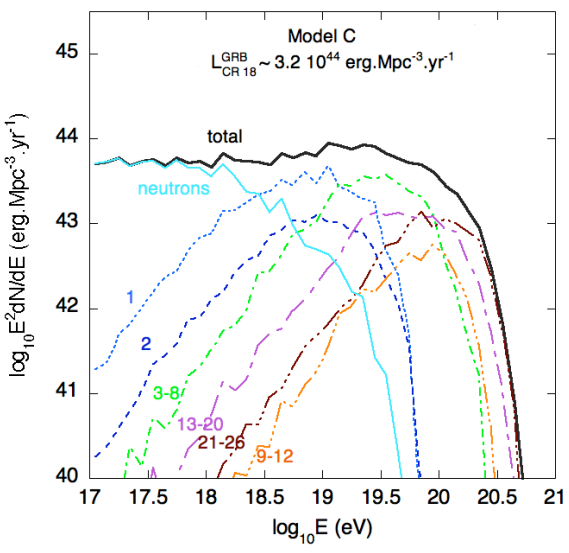


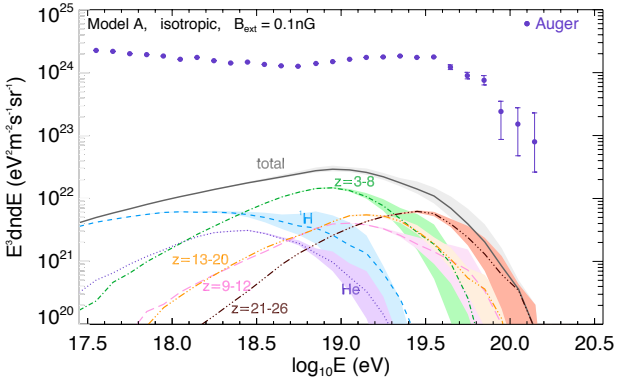


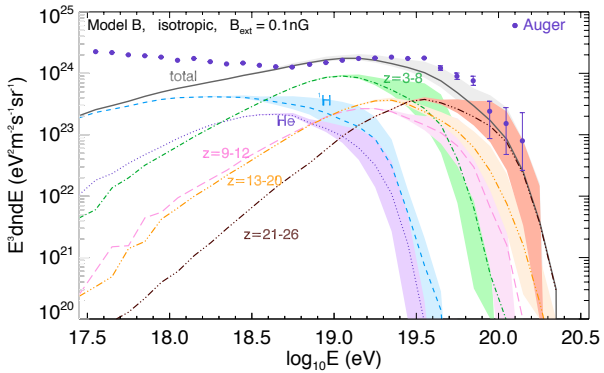
Example that doesn't create ankle (Globus+,2014)

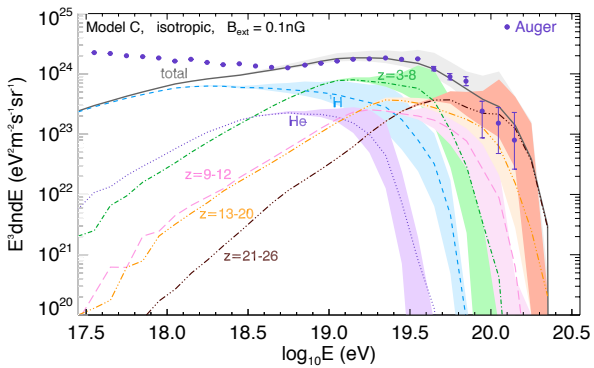












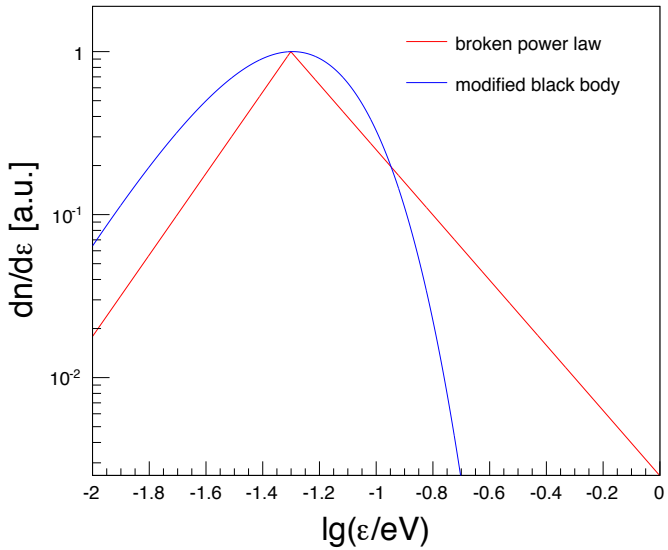
Still requires some new EG component

(Globus-Allard-Mochkovitch-Parizot,2014)

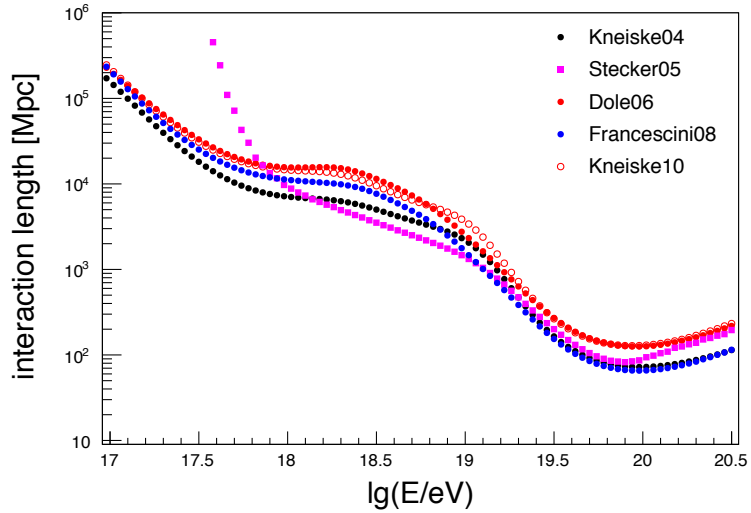
Our model: Photodisintegration in medium outside the accelerator

- injection spectrum $\propto E^{-\gamma}$
- mass of injected nuclei: A
- UHECR power density: $\dot{\epsilon}$
- source evolution with z ☞ SFR
- interaction/escape time: $t_{\rm int}/t_{\rm esc}$
- maximum energy: $E_{\rm p}^{\rm max}$

Uncertainties



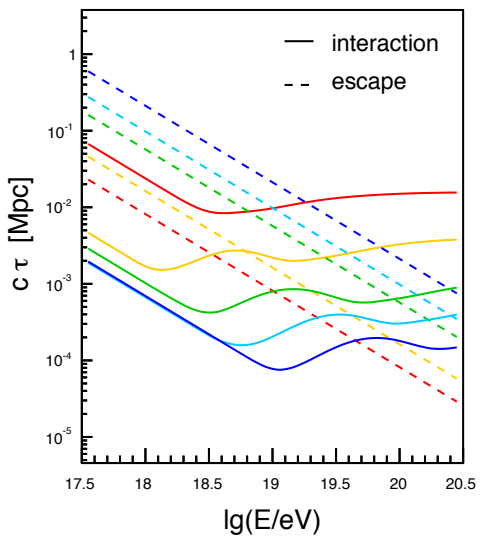
Photon field sourrounding source



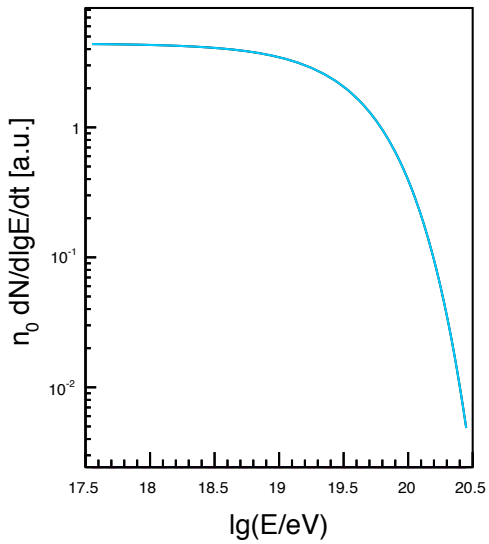
EG background light

Impact of source environment depends on photon field

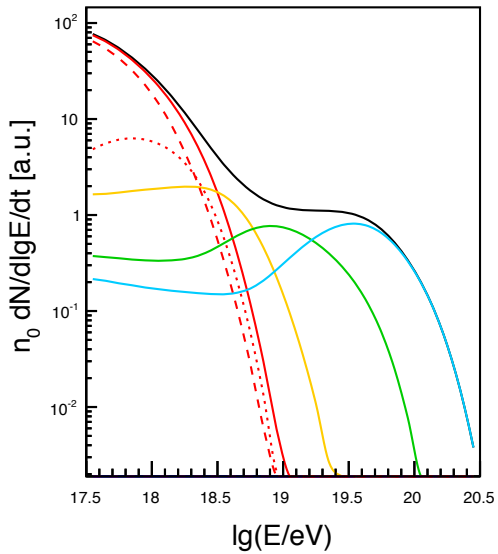
broken power law



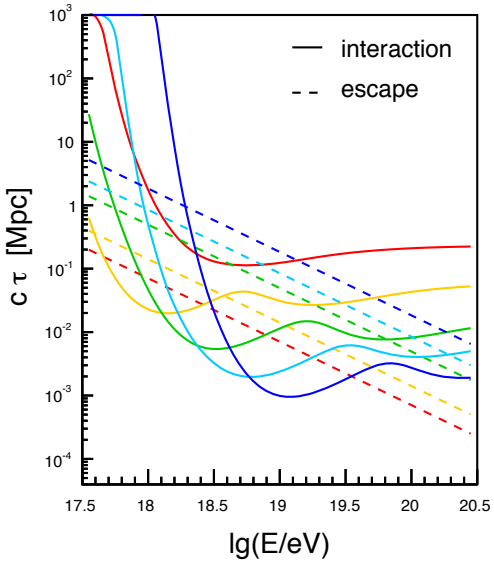
injected



escaping



greybody



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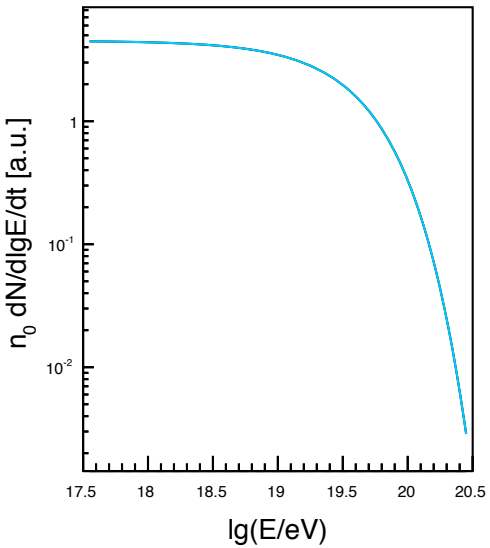
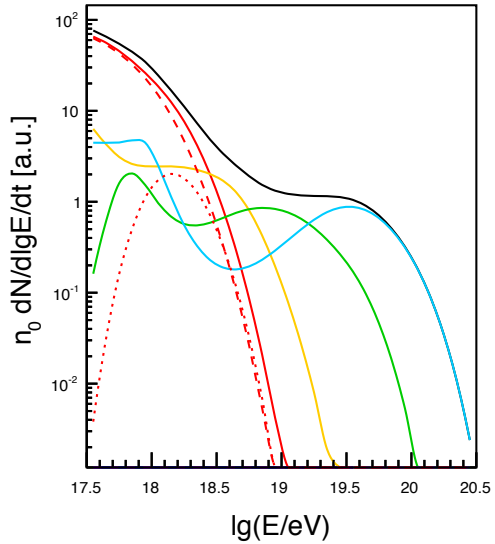
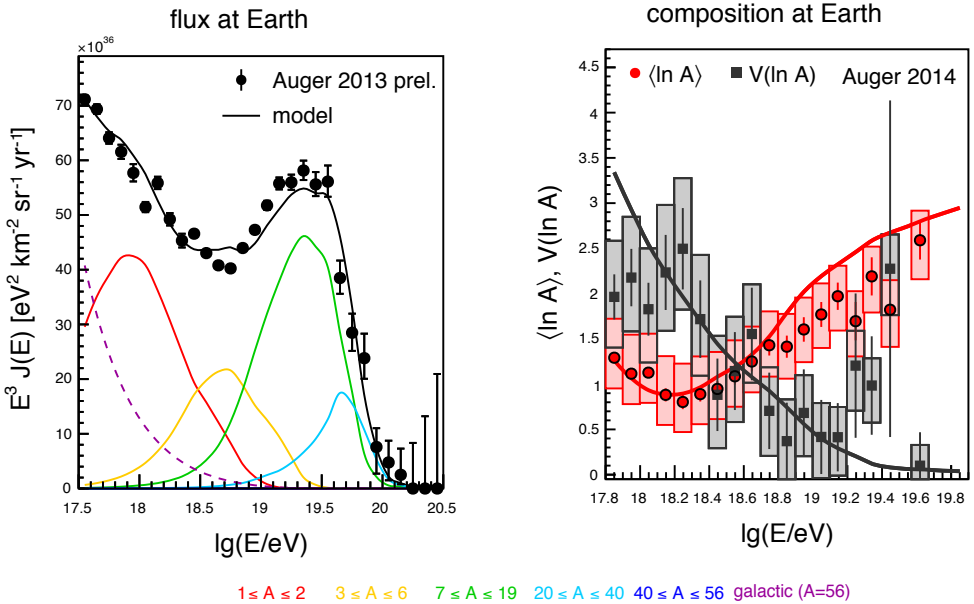


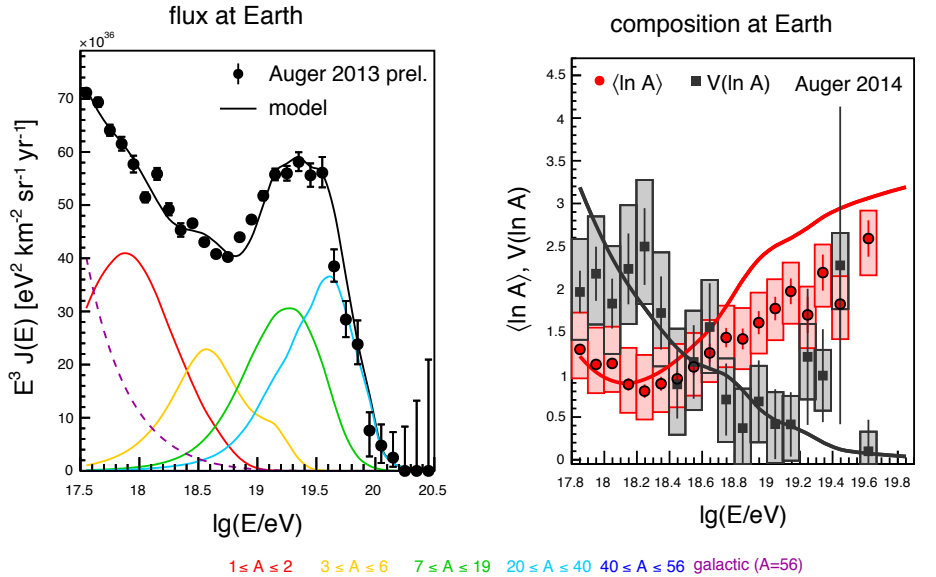
escaping



Example fit: broken power law



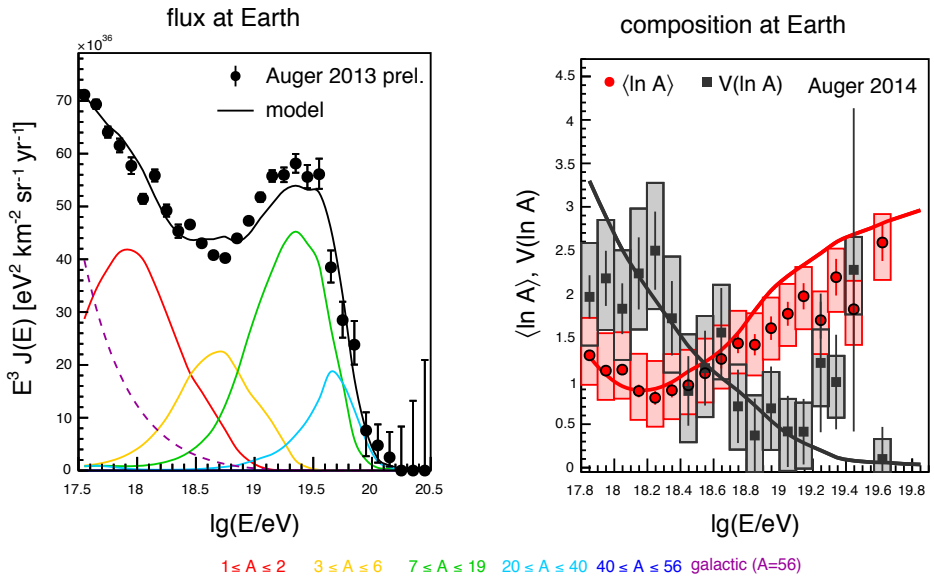
- Assuming $\gamma = 1$, Kneiske10
- $\log(E_p^{\max}/\mathrm{eV}) = 18.6$
- $A = 23$



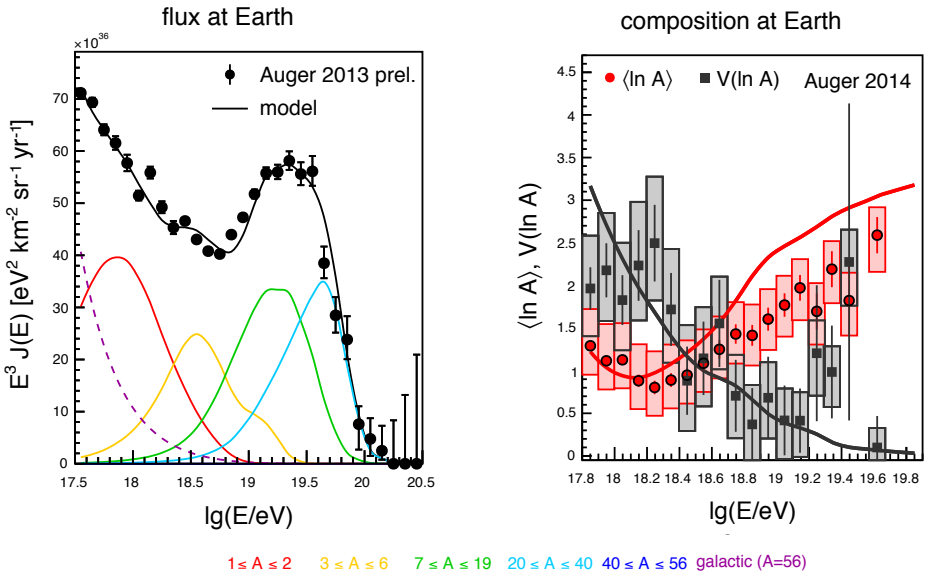
- Assuming $\gamma = 1$, Kneiske04
- $\log(E_p^{\max}/\mathrm{eV}) = 18.5$
- $A = 28$

tail of GCRs (dashed line)

Example fit: greybody



- Assuming $\gamma = 1$, Kneiske10
- $\log(E_p^{\max}/\mathrm{eV}) = 18.6$
- $A = 23$

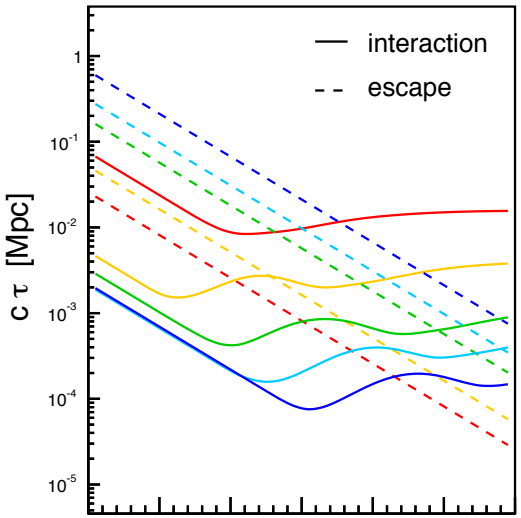


- Assuming $\gamma = 1$, Kneiske04
- $\log(E_p^{\max}/\mathrm{eV}) = 18.5$
- $A = 27$

tail of GCRs (dashed line)

Systematic sensitivity (spectrum $1\sigma \uparrow$ and $\langle X_{\max} \rangle$ $1\sigma \downarrow$)

broken power law



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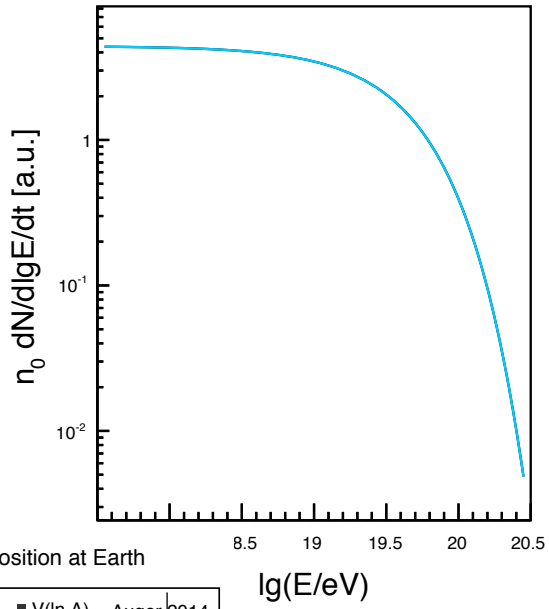
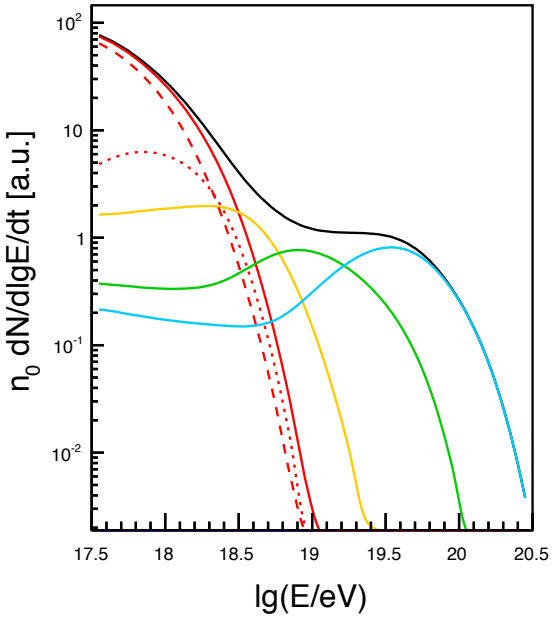
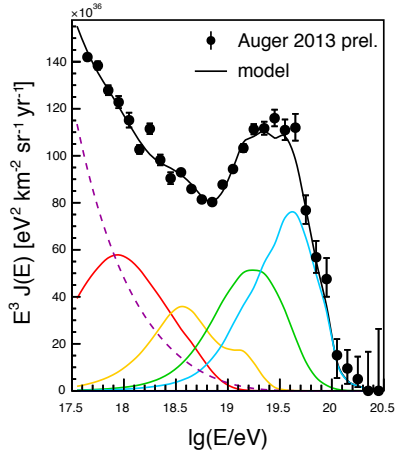


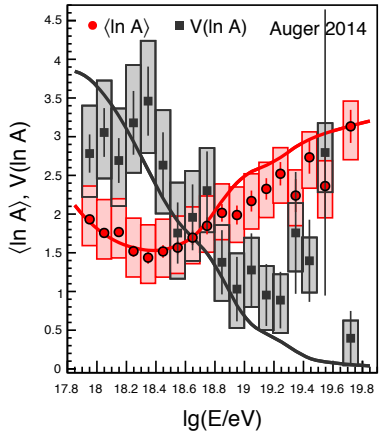
escaping



flux at Earth



composition at Earth

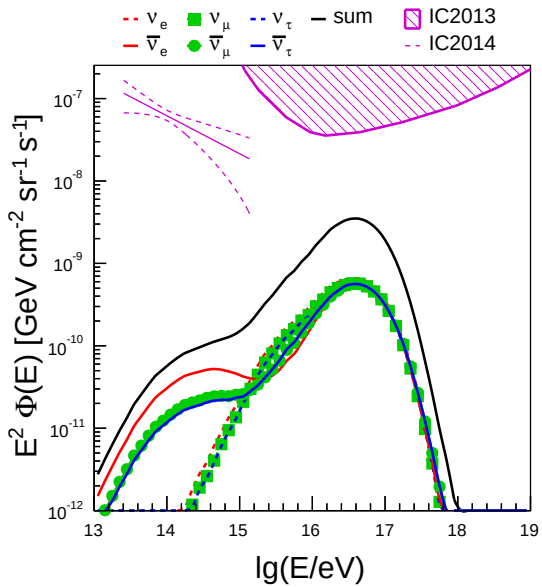


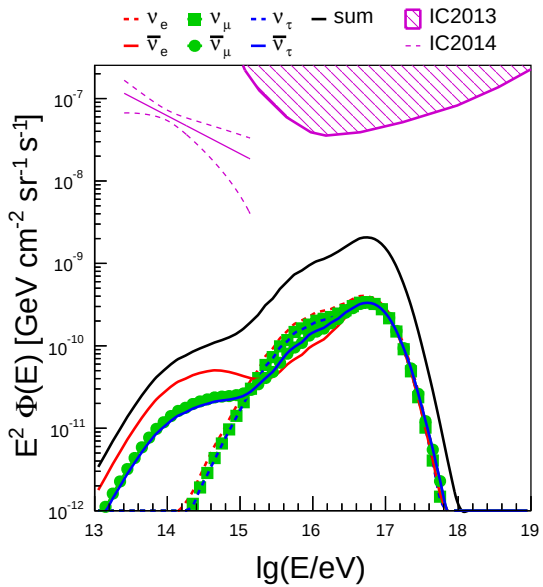
1 ≤ A ≤ 2 3 ≤ A ≤ 6 7 ≤ A ≤ 19 20 ≤ A ≤ 40 40 ≤ A ≤ 56 galactic (A=56)

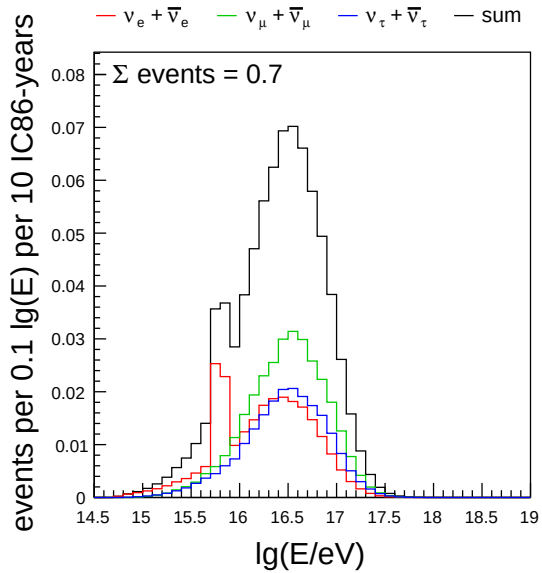
- Assuming $\gamma = 1$, Kneiske04
- $\log(E_p^{\max}/\mathrm{eV}) = 18.6$
- $A = 28$

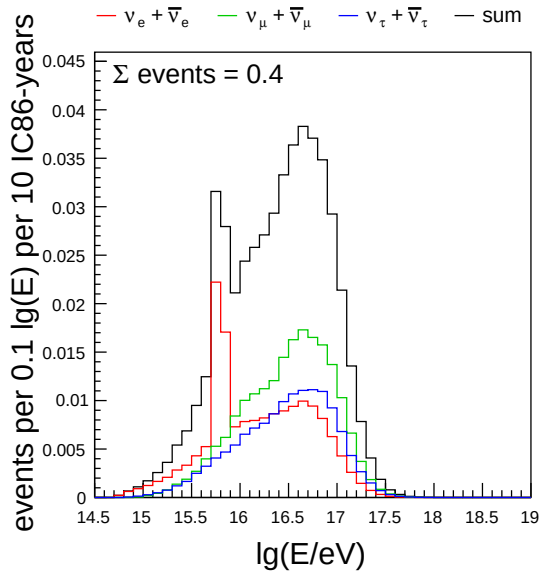
tail of GCRs (dashed line)

Distinctive ν signal ☞ broken power law (left) and greybody (right)



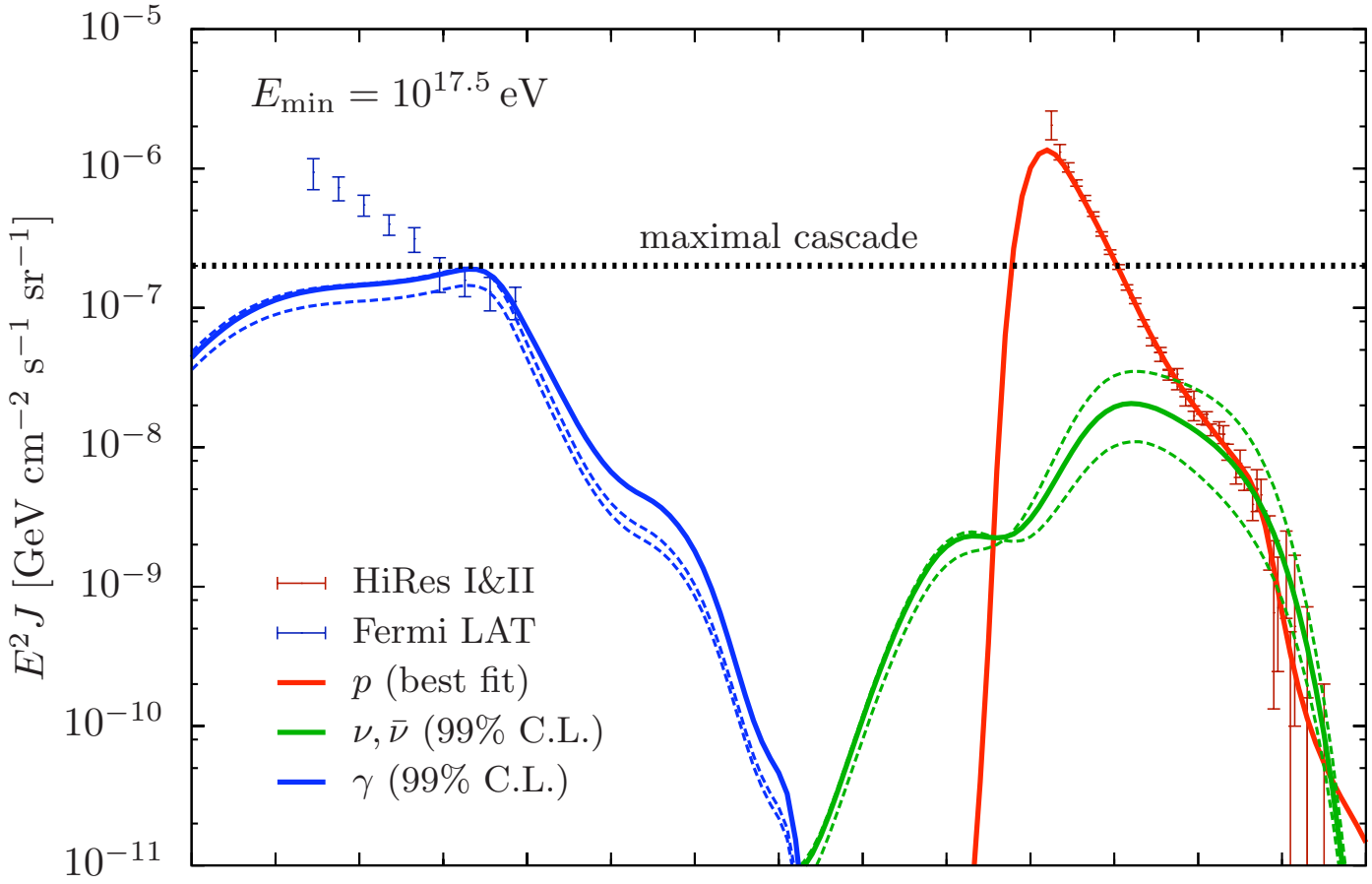






EM cascades from γ-rays

- Cosmogenic neutrinos safely below upper limit set by *Fermi*-LAT flux



(Ahlers+,2010)

- γ's from nucleus de-exitation ☞ negligible contribution to EM cascades

(Anchordoqui,2015)

Take home message

- Ankle and light extragalactic CRs below it, can be explained by photodisintegration of UHECRs *in region surrounding accelerator*
  - Auger composition *and* spectrum explained within systematics
  - Distinctive signature in neutrino flavors ☛ testable
- Astrophysical realizations being studied – stay tuned to arXiv...