Constraints on UHECR Sources and their Environments

from fitting UHECR spectrum & composition data, neutrinos, and gamma-rays

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Madison, WI, USA

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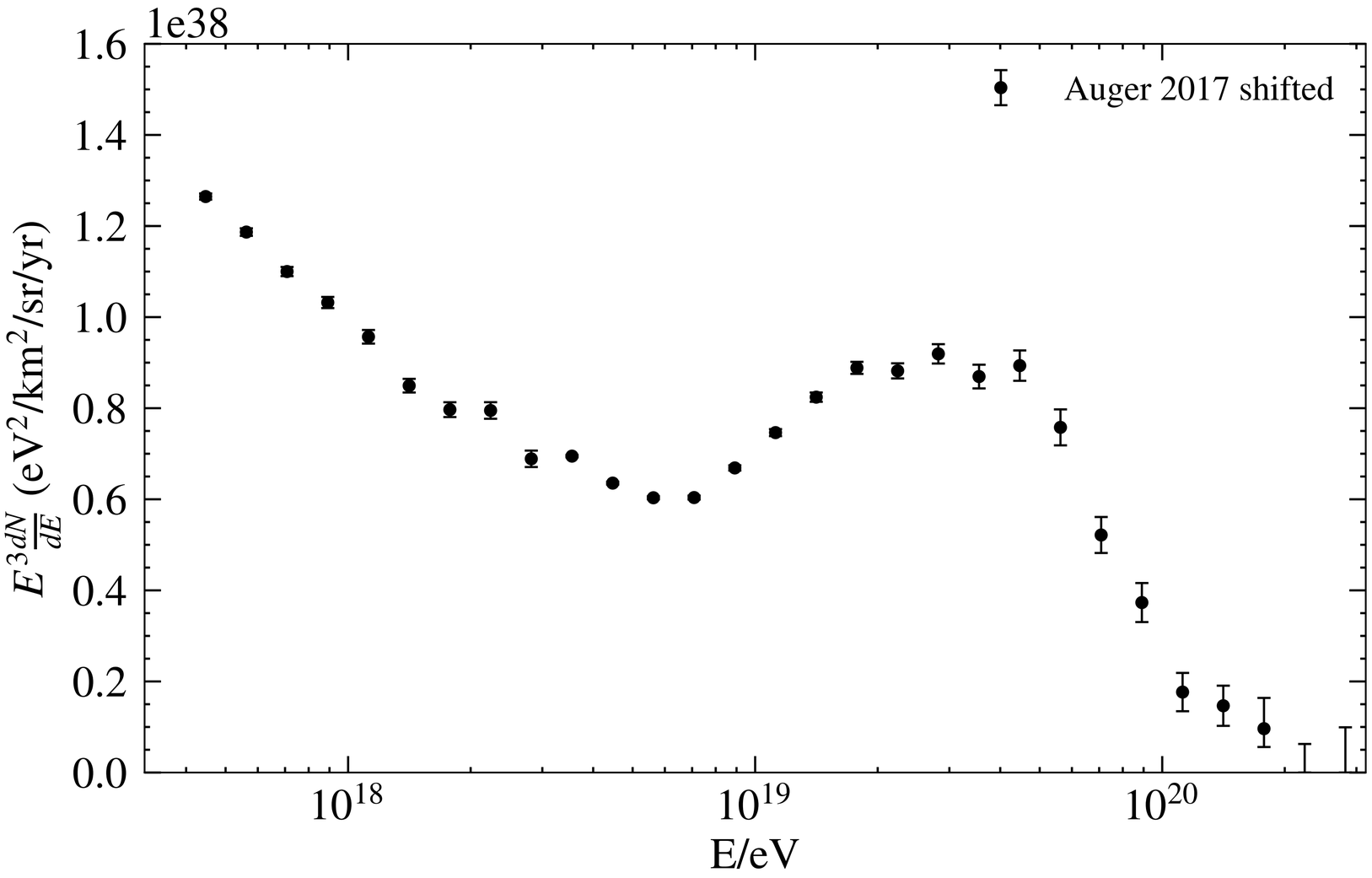
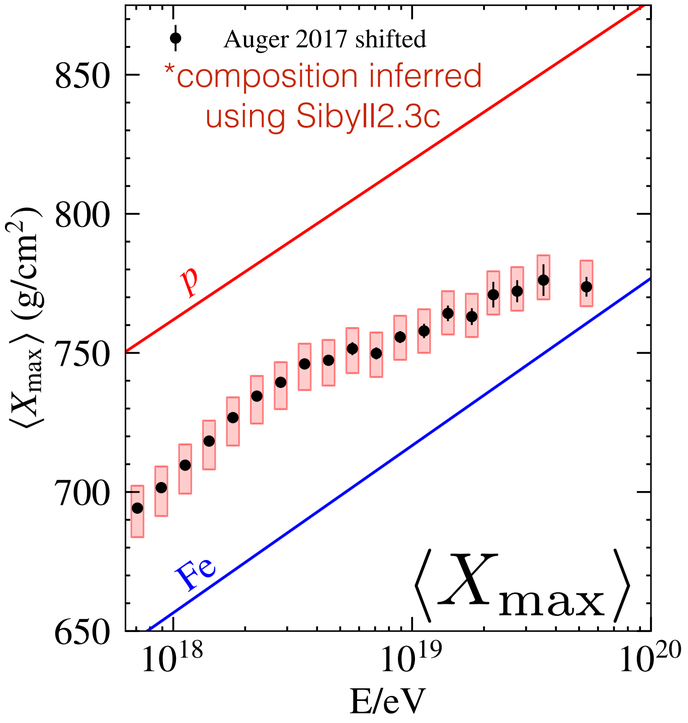
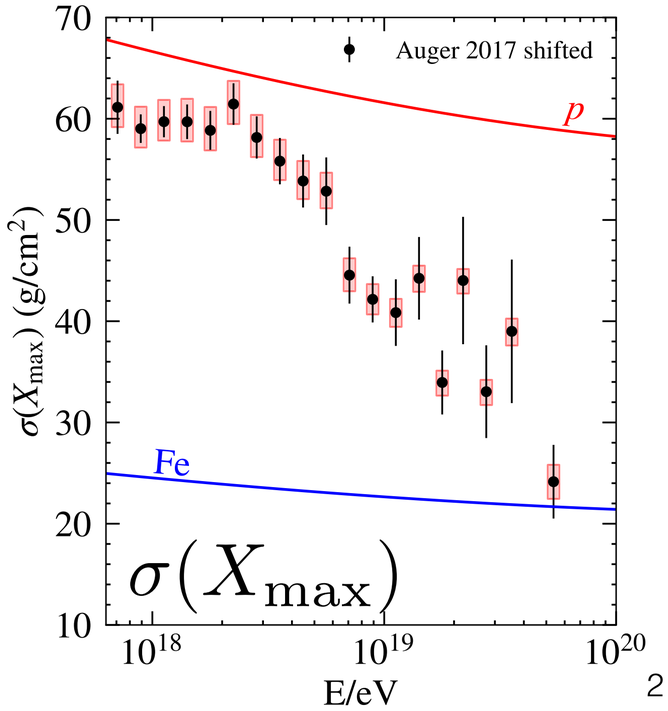






How do we characterize UHECR sources?

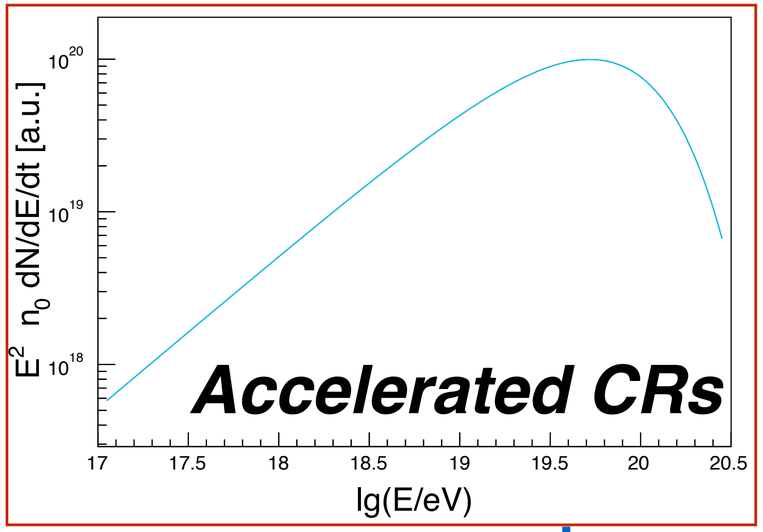
☛Build UHECR source models

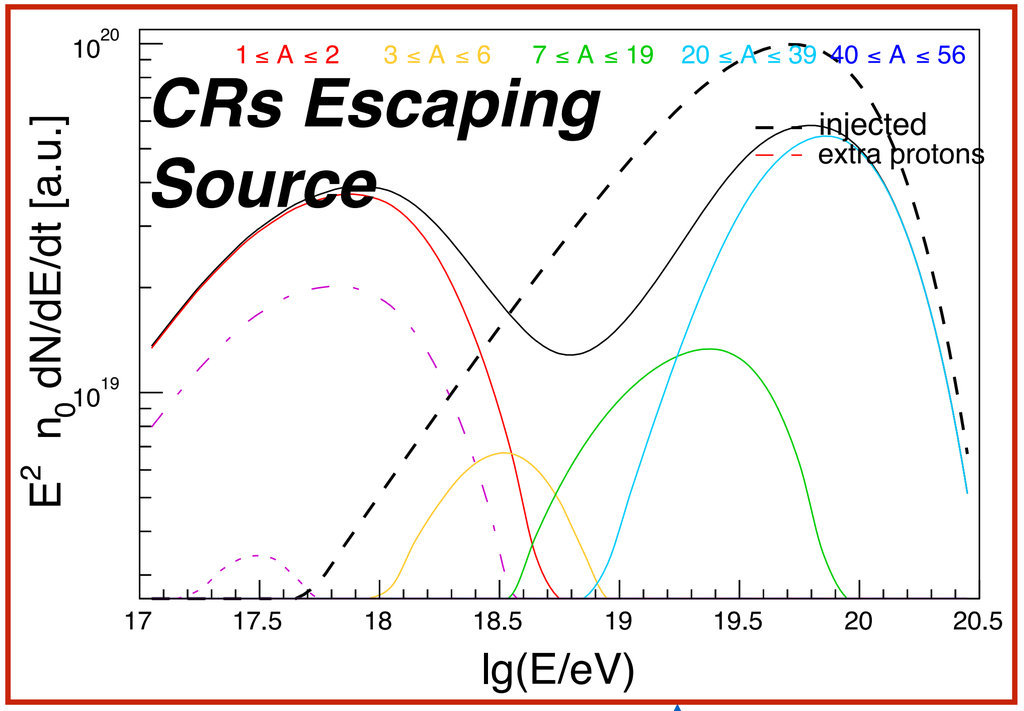
UFA Model

Unger, Farrar, Anchordoqui (2015), PRD

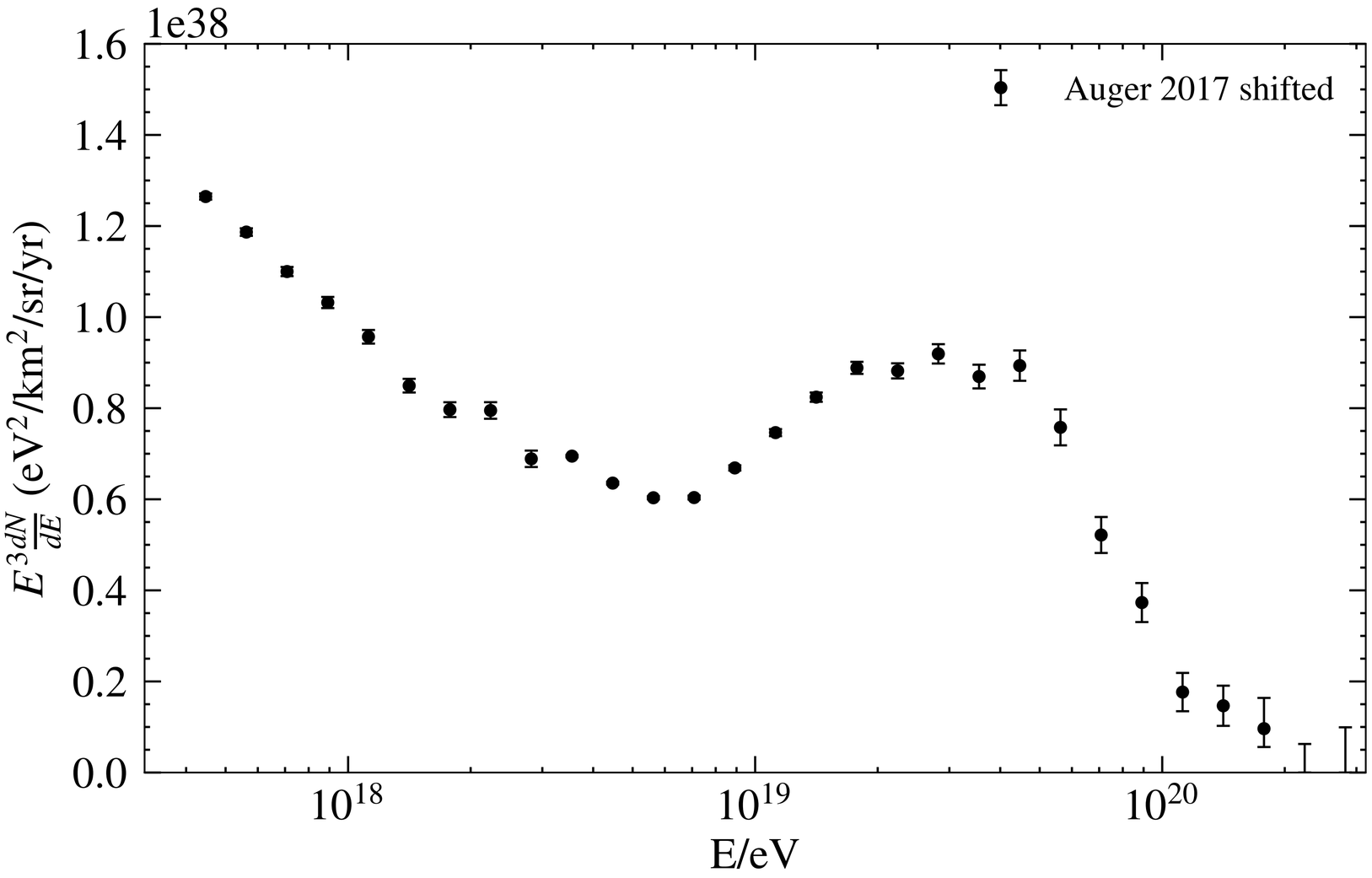
Model Parameters:

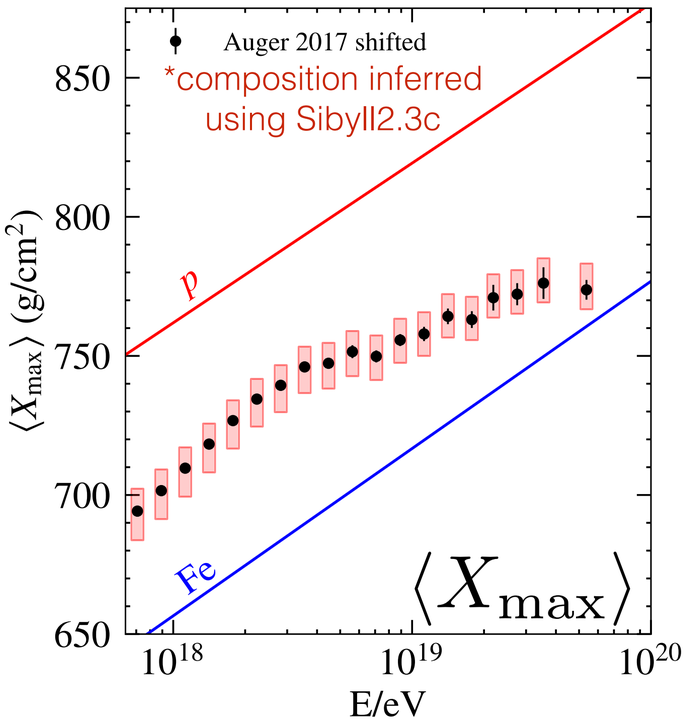
- Injected composition
- Injection index
- Rigidity cut-off
- Average number of interactions
- CR power density
- Source evolution
- Photon field
- Galactic spectrum

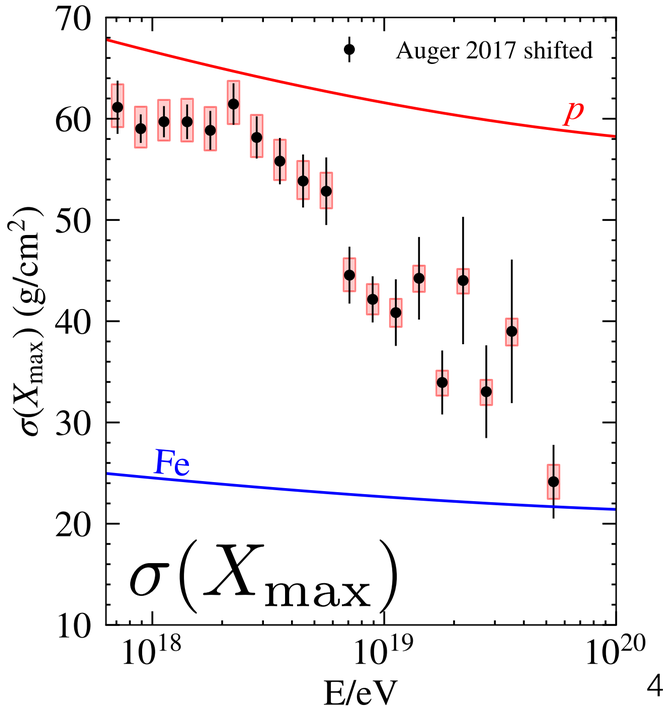


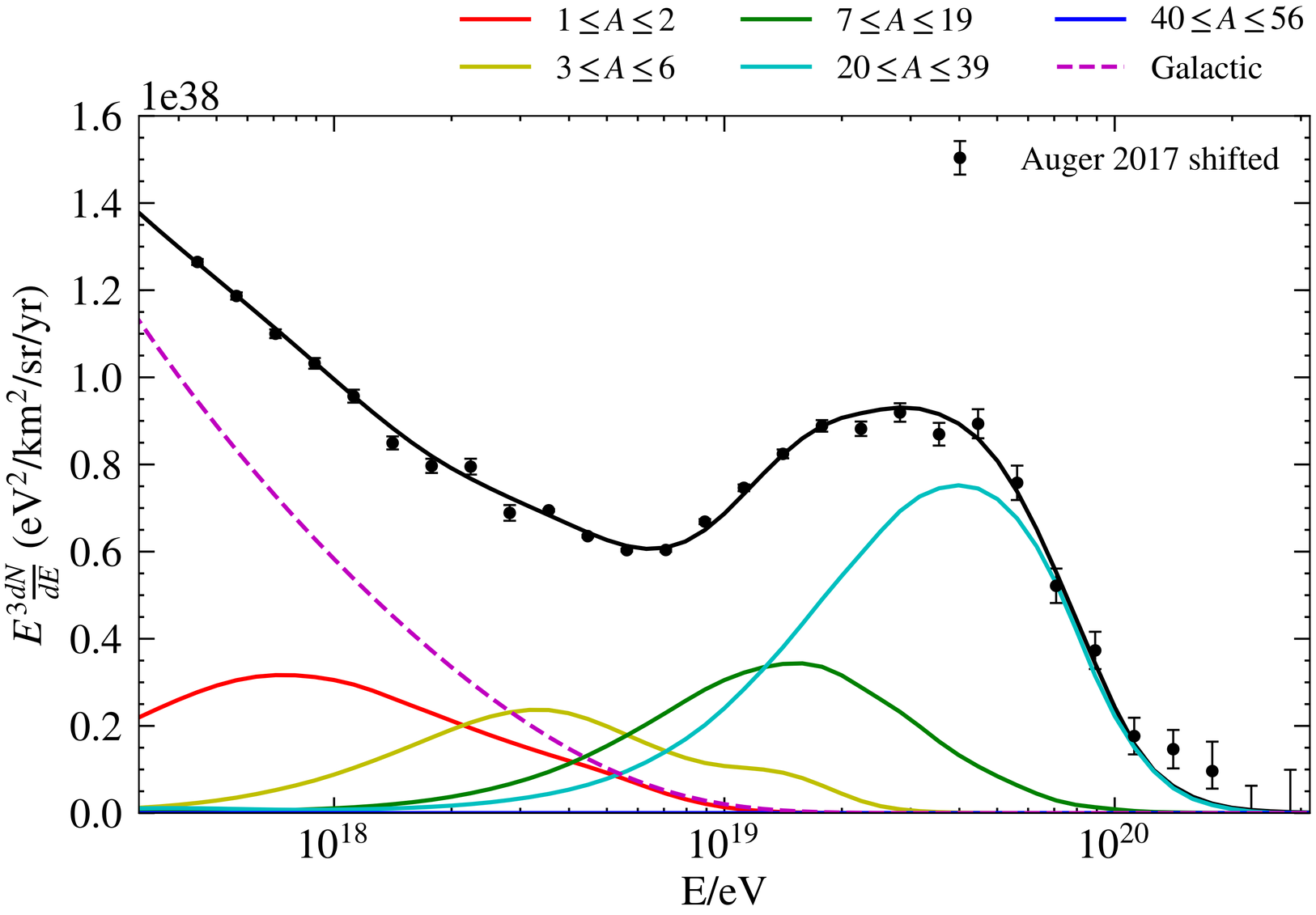


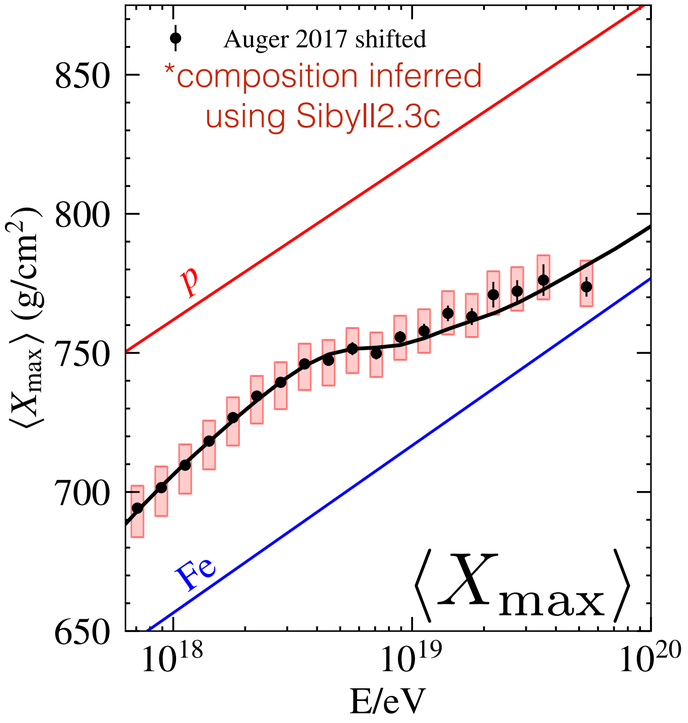
Photohadronic processing in source environment

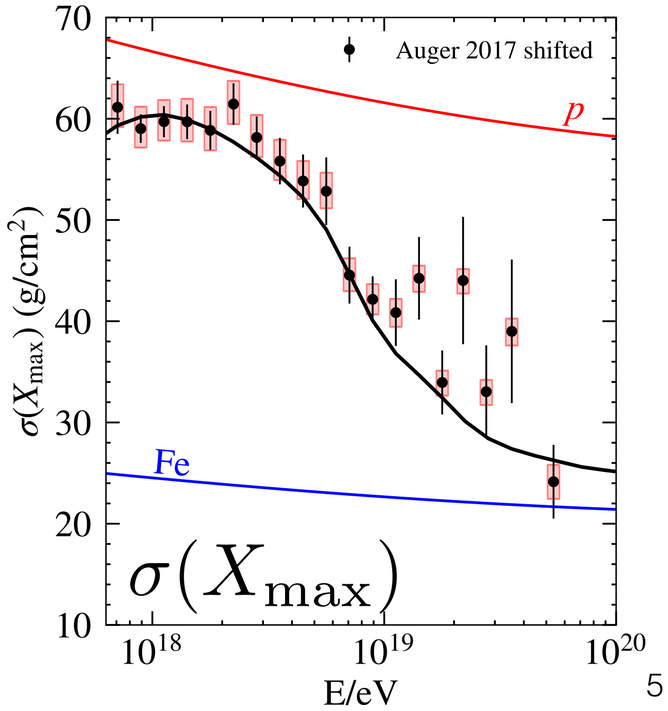

1e38
Auger 2017 shifted
$E^3 \frac{dN}{dE}$ (eV^2/km^2/sr/yr)
E/eV


Auger 2017 shifted
*composition inferred using Sibyll2.3c
p
Fe
$\langle X_{max} \rangle$
$\langle X_{max} \rangle$ (g/cm^2)
E/eV


Auger 2017 shifted
p
Fe
$\sigma(X_{max})$
$\sigma(X_{max})$ (g/cm^2)
E/eV

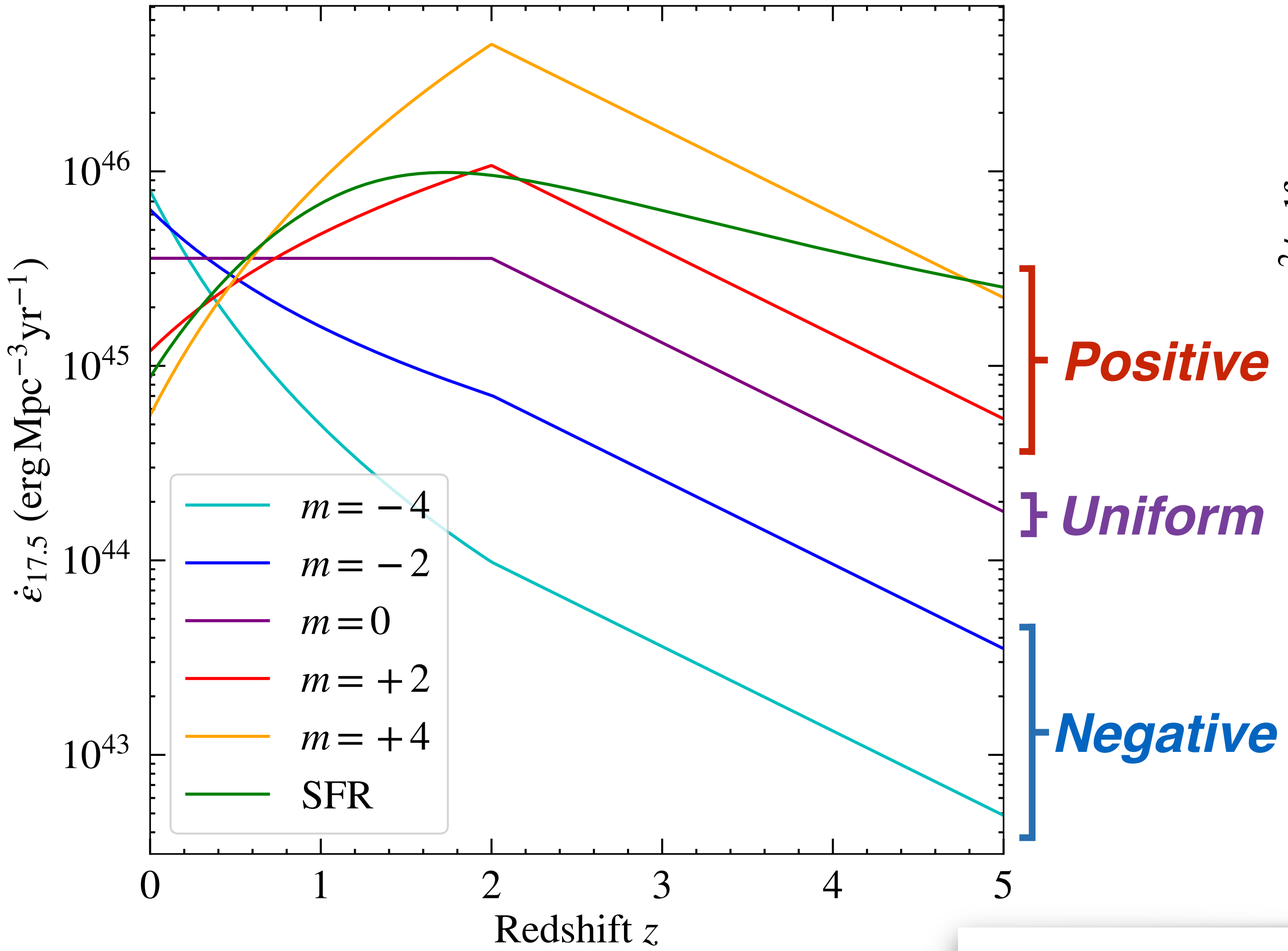


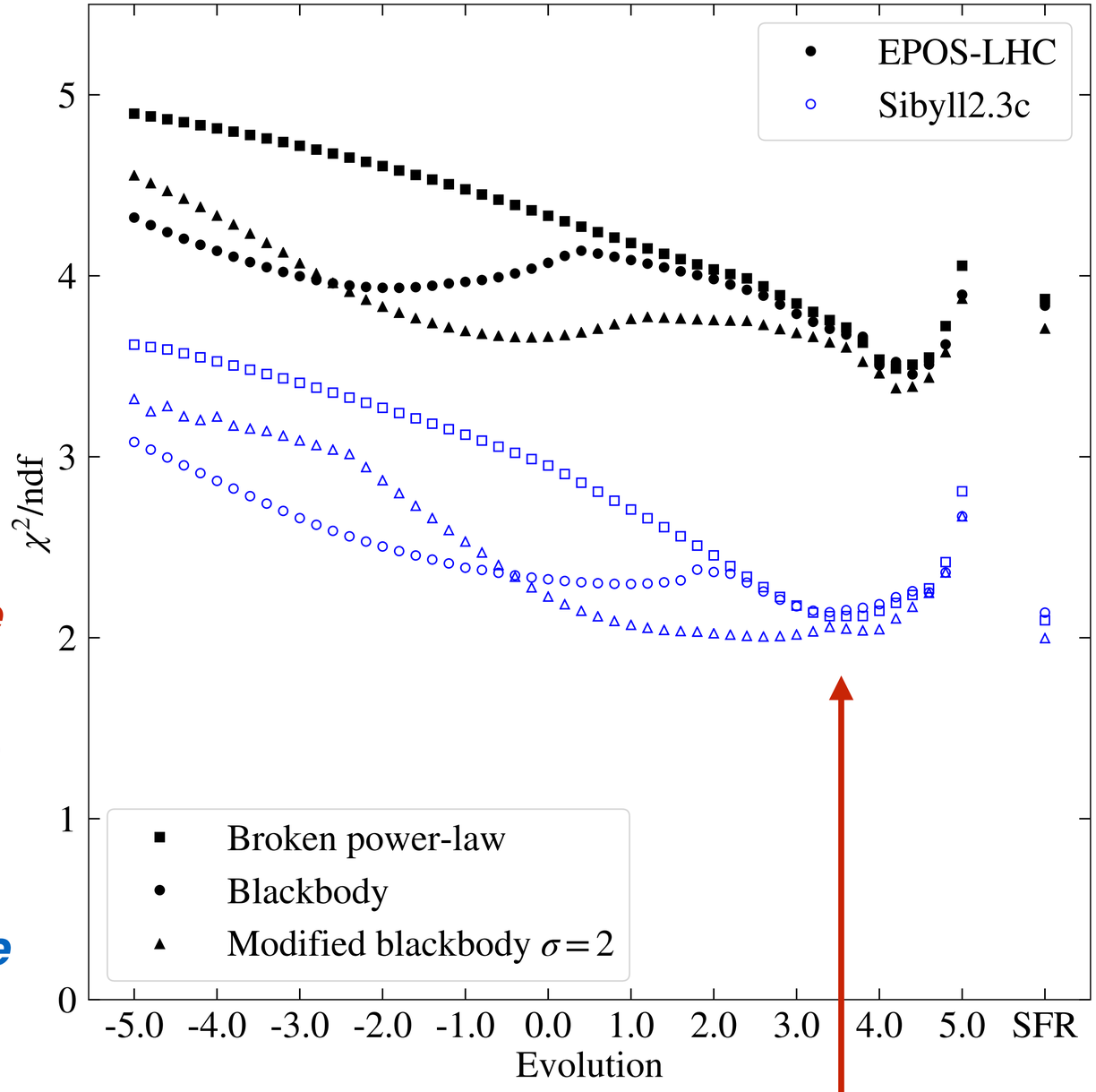




- ☛Fits characterized by source model parameters
- ☛Exclude parameters far from best-fits (>3σ)

What does UFA have to say about source evolution?



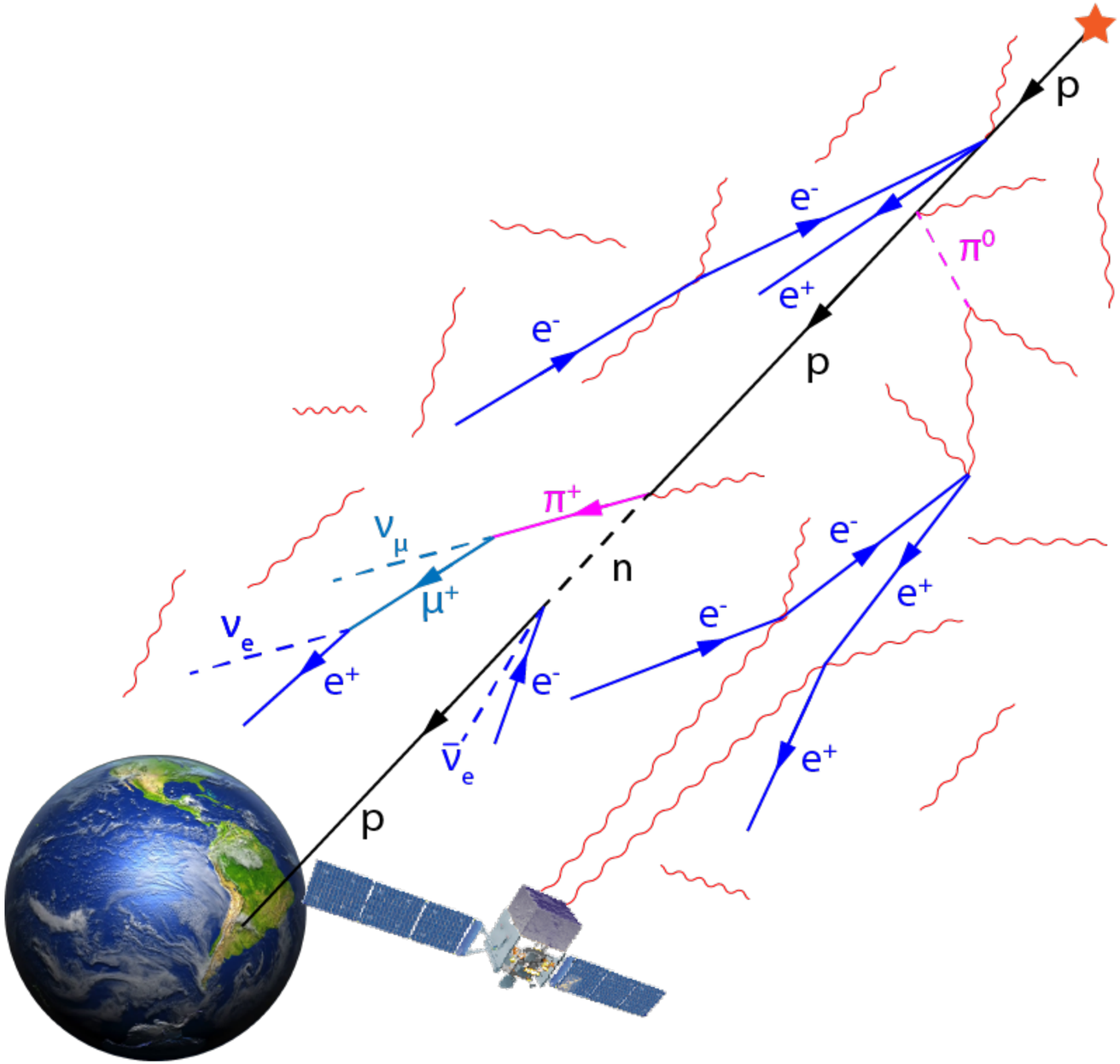


Positive source evolutions slightly favored

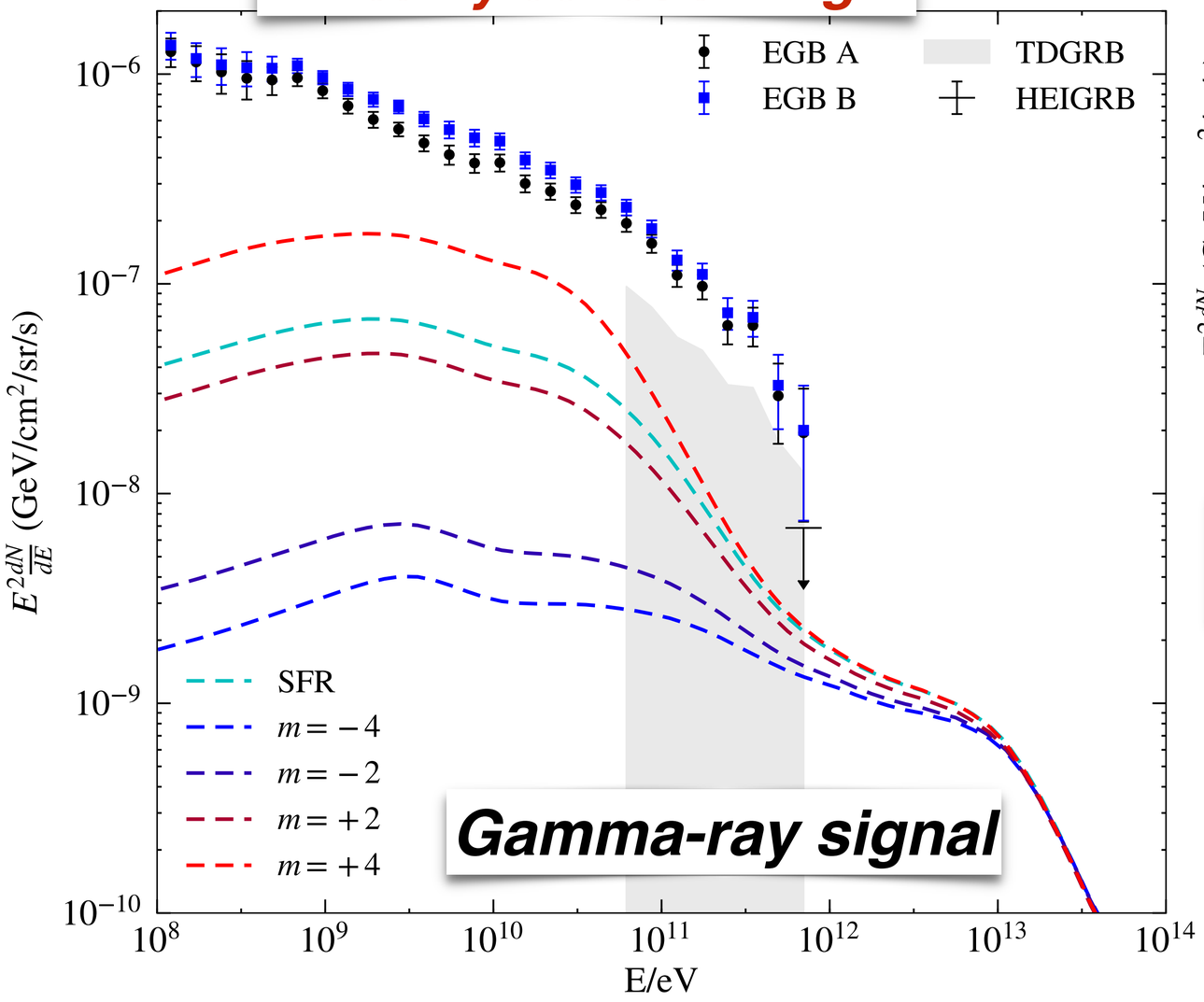
Constraints from Neutral Messengers

- Neutral secondaries produced by interactions in source and during extragalactic propagation
- **IceCube** and **Auger** give **upper-bounds on the neutrino flux** above ~3 PeV
- **Fermi-LAT** provides **upper-bounds on diffuse gamma-ray flux** in 100 MeV to ~ TeV range

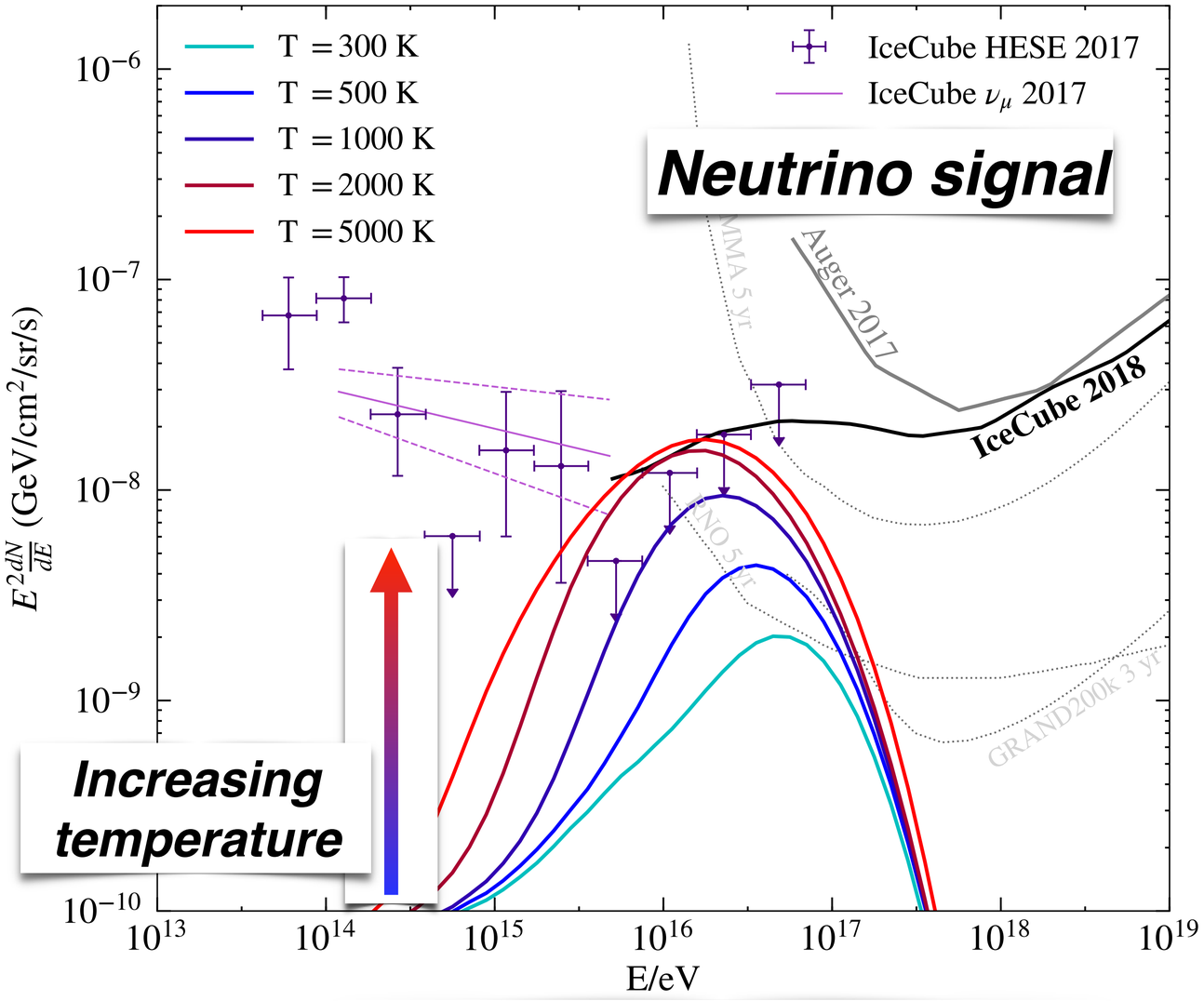
☛Exclude fit parameters which violate these bounds



Current Fermi-LAT gamma-ray data only weakly constraining



Gamma-ray signal



Neutrino signal

Increasing temperature

Neutrino bounds constrain source temperature: < 4000 K (< 500 meV)

Constraining Injected Composition?

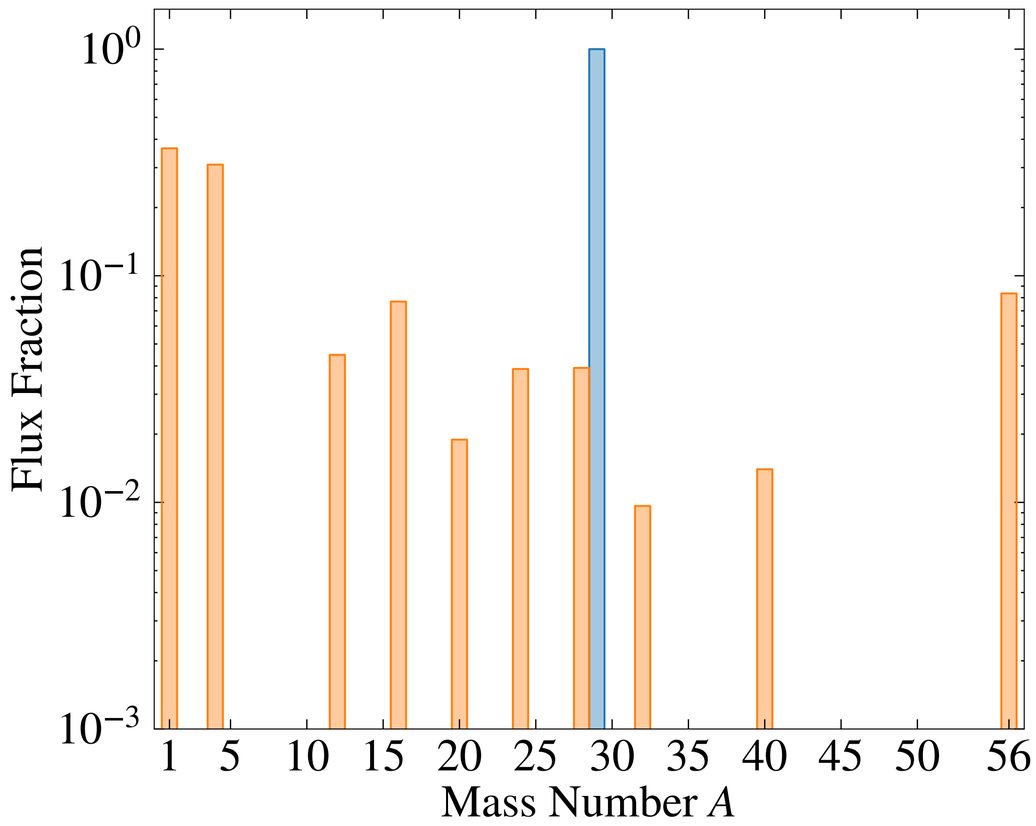
Characterizing injected composition:

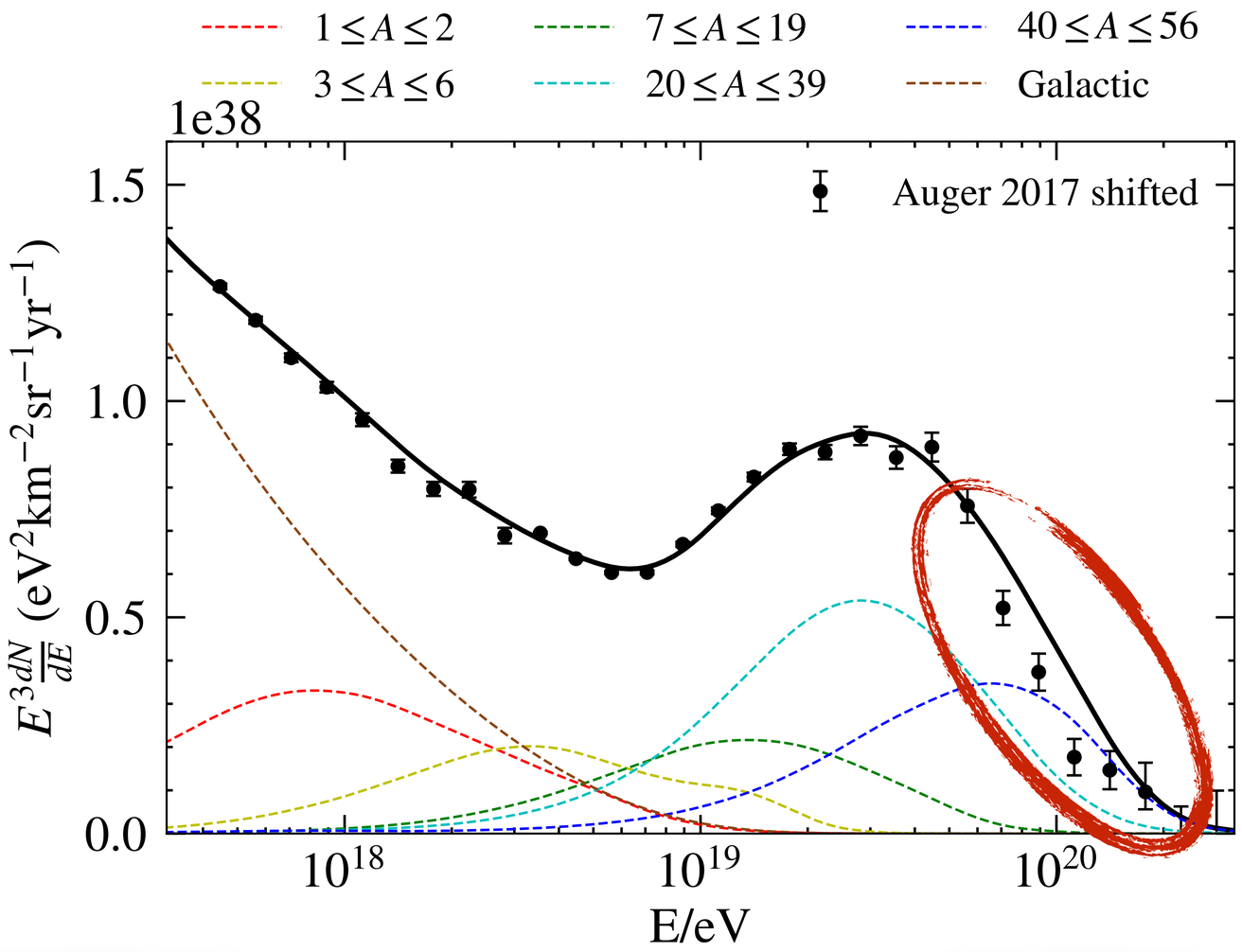
narrow mass range

or

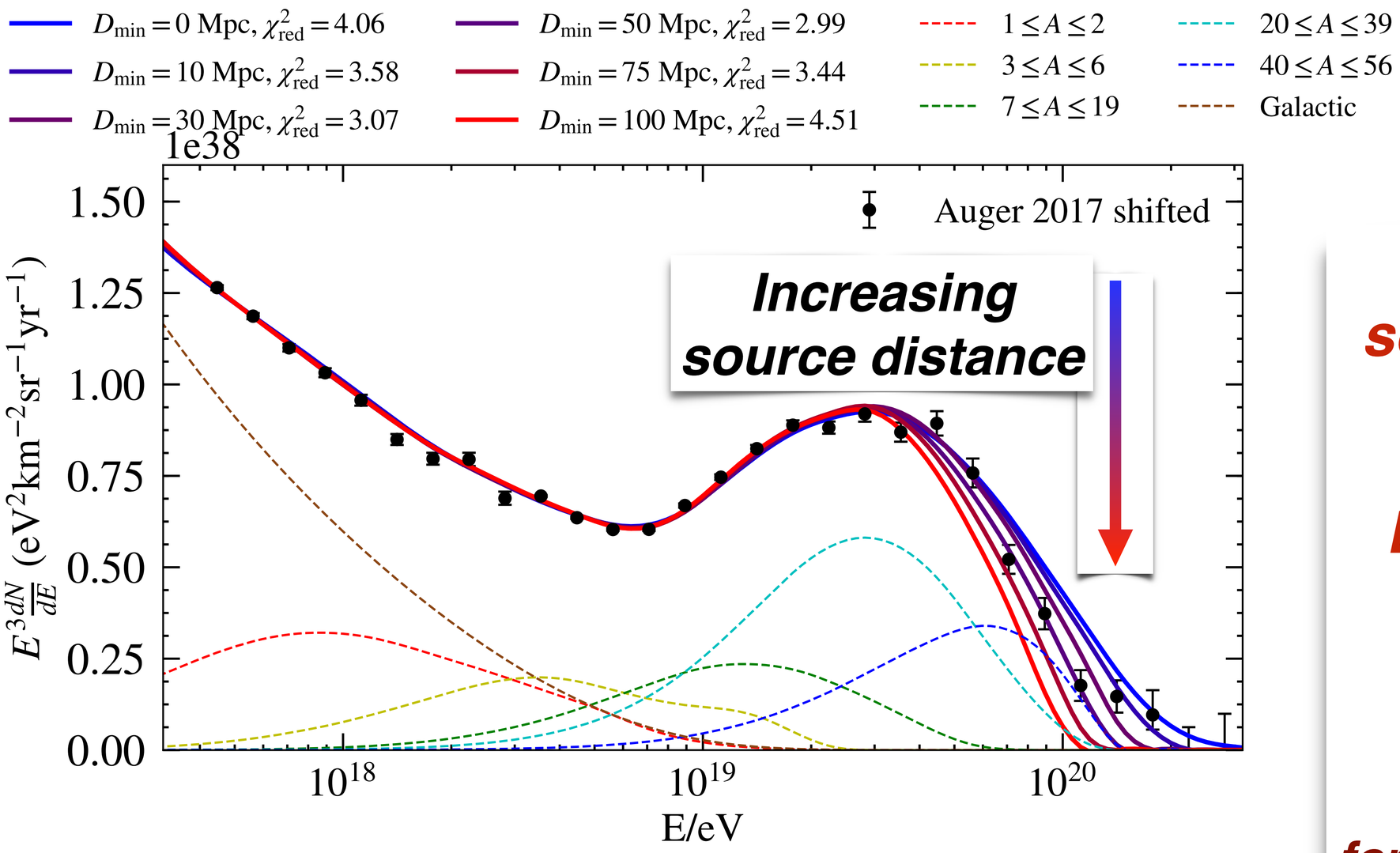
extended, Milky Way-like

composition?





Milky Way-like compositions produce overshoot of the spectrum at the cutoff



$$\xi(z) = \begin{cases} 0 & z < z_0(D_{\min}) \\ SFR & z \geq z_0(D_{\min}) \end{cases}$$

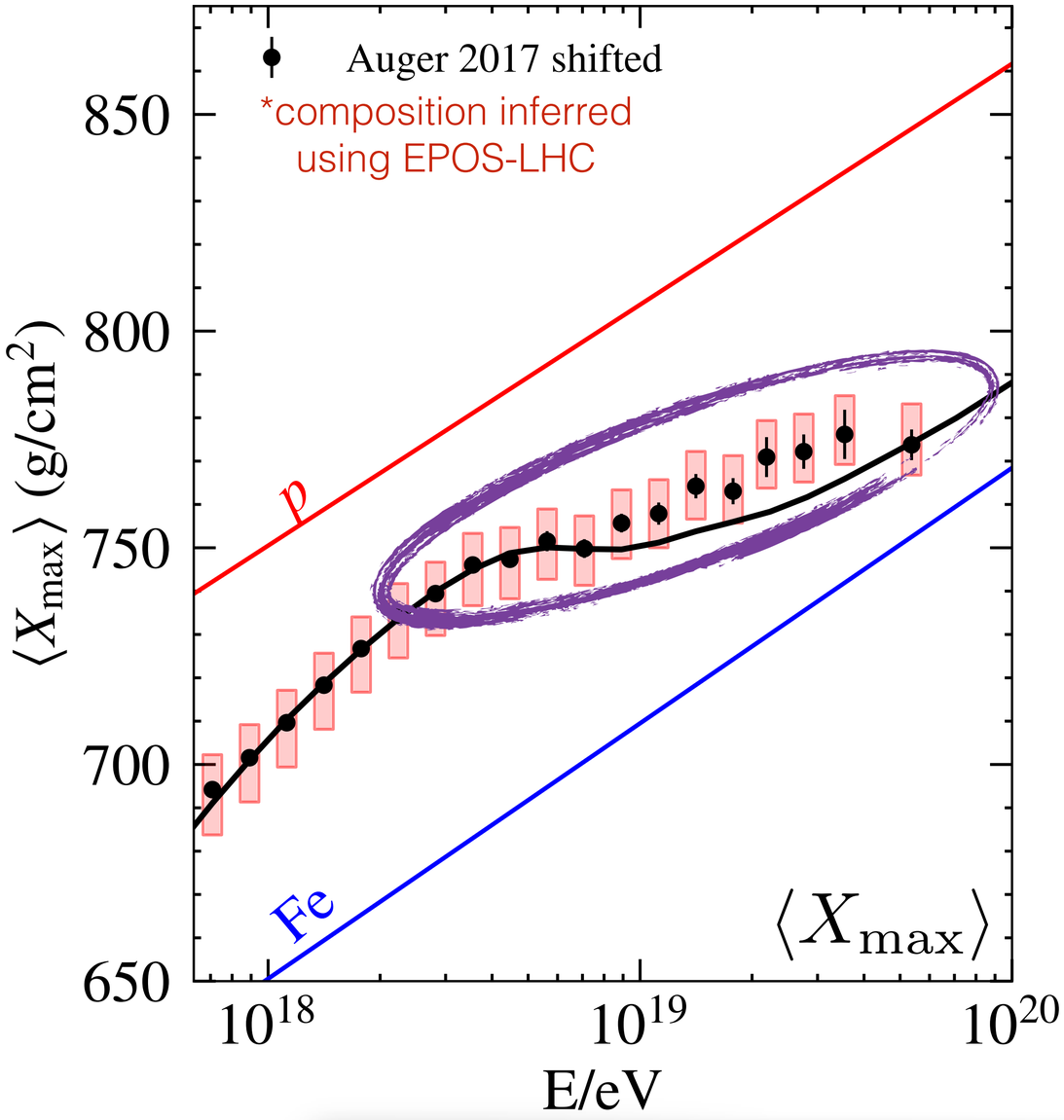
Best-fit nearest source distance is constrained:

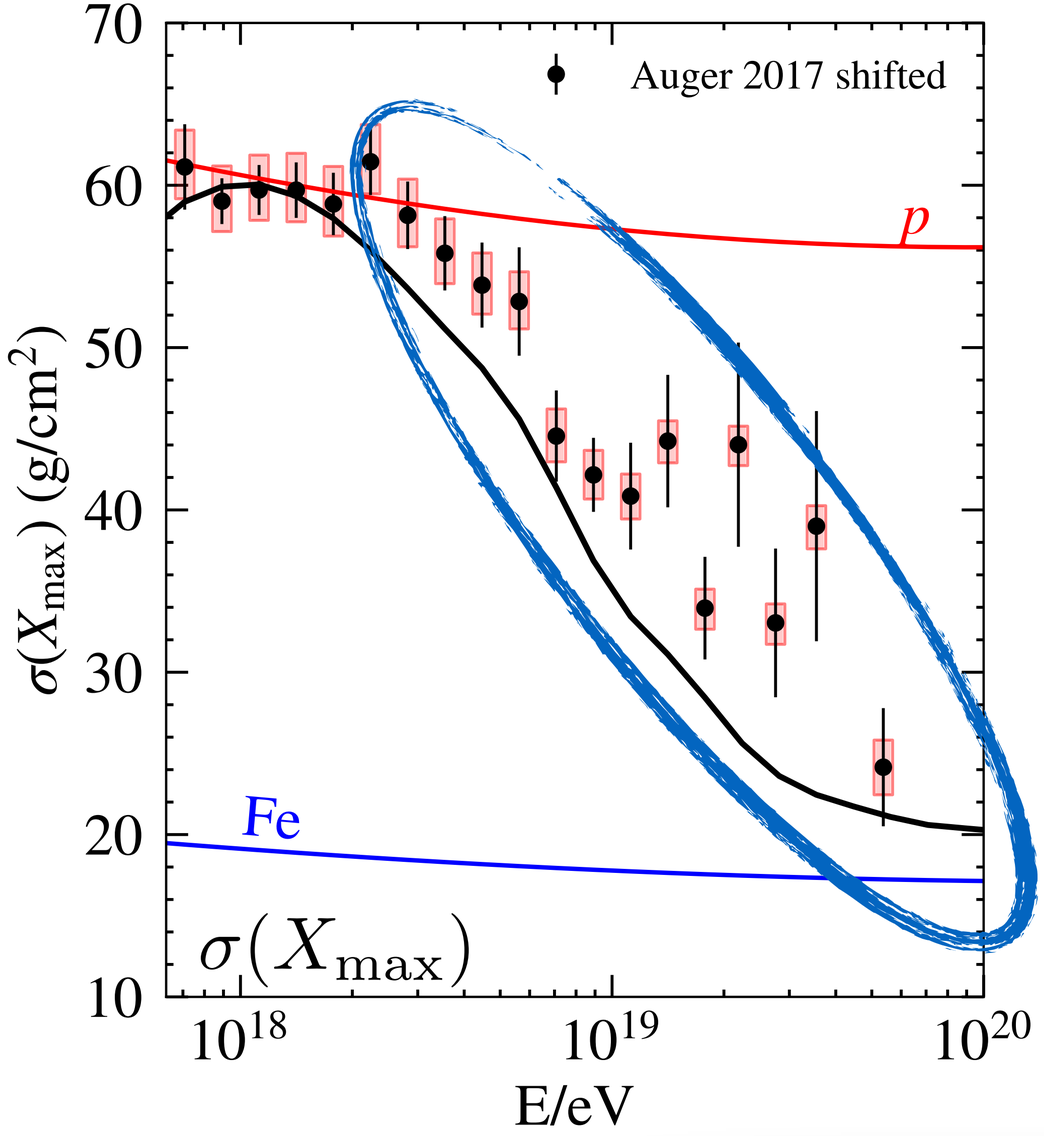
D_{min} ~ 30-50 Mpc
for Milky Way-like composition,

$D_{min} \lesssim$ 5 Mpc
for narrow composition*

*dependent on systematic uncertainties

Room for Improvement





Predicted composition is too heavy & too pure above the ankle

Could there be a pure-proton component to the spectrum?

- Pure-proton component:
  - Spectral index of -1 escaping source
  - Exponential cutoff in 10-1000 EeV range

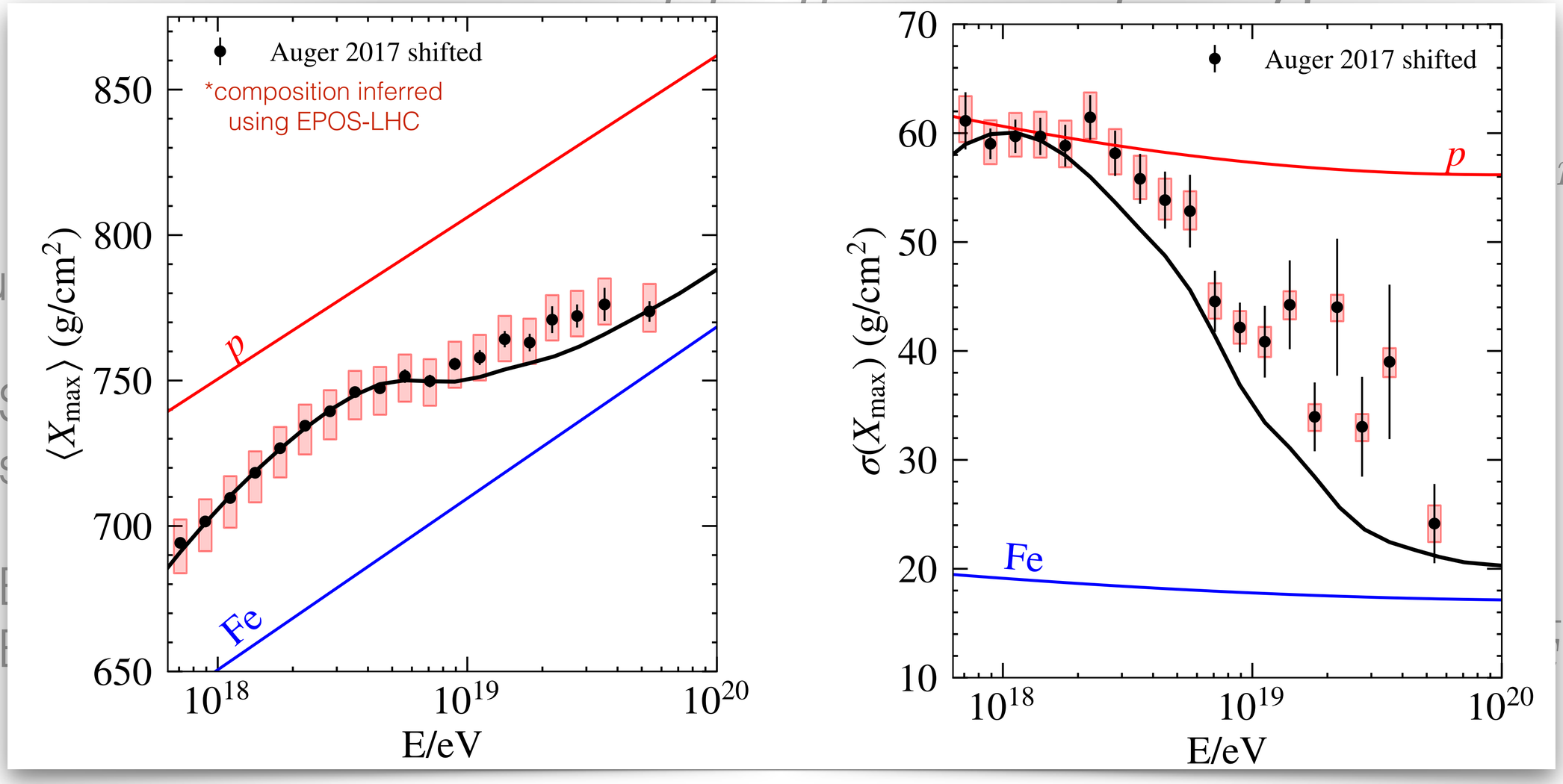
$$\Phi_p \sim \underbrace{f_p}_{} E^{-1} e^{-E/E_{max}^{\mathrm{UHE}p}}$$

Measures strength of pure-proton component as:

$$f_p = \frac{\int_{E_{\mathrm{ref}}}^{\infty} E\phi_p \mathrm{d}E}{\int_{E_{\mathrm{ref}}}^{\infty} E(\phi_p + \phi_{\mathrm{UFA}})\mathrm{d}E}$$

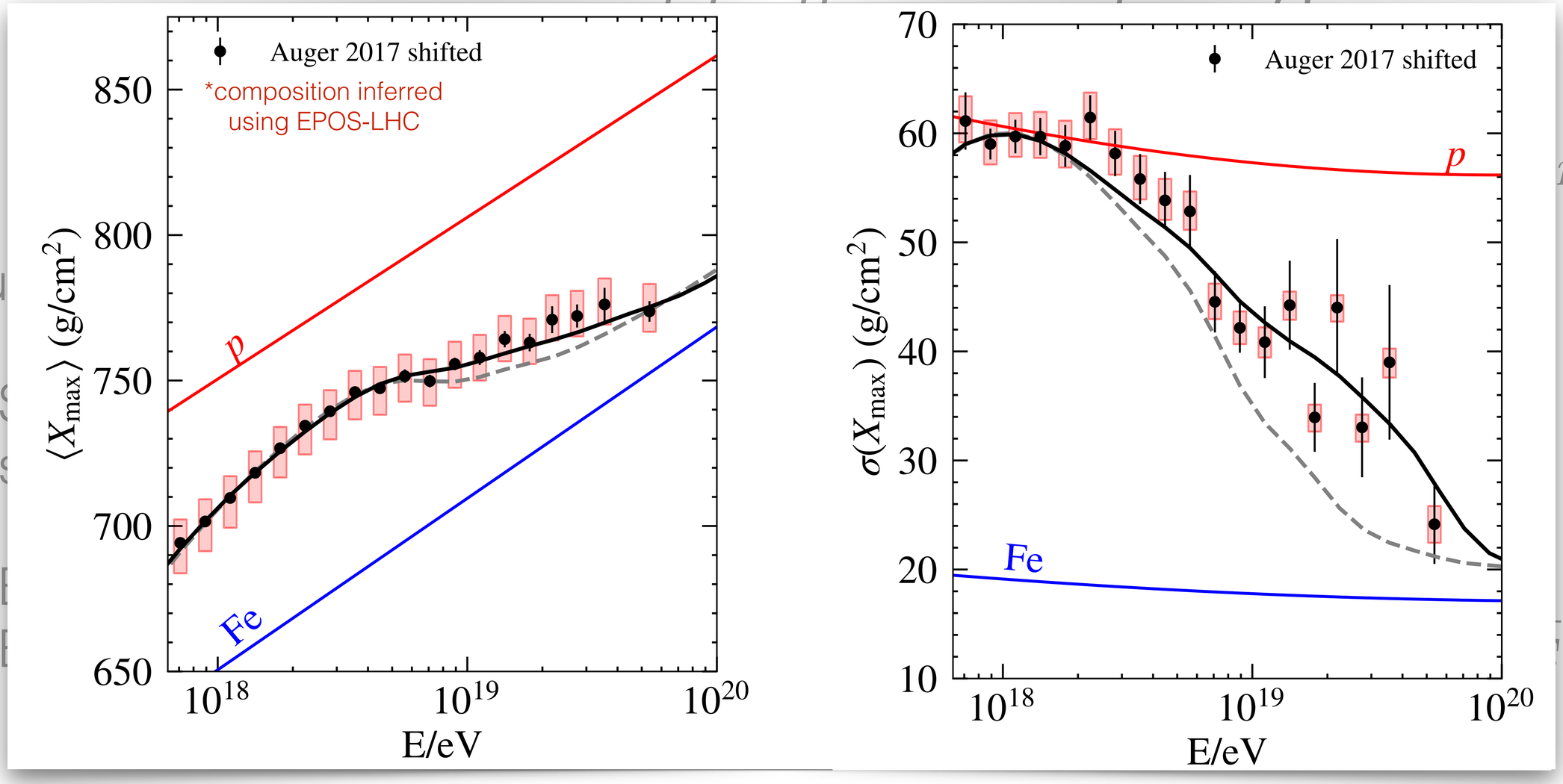
$$E_{\mathrm{ref}} = 10^{19}\ \mathrm{eV}$$

Could there be a pure-proton

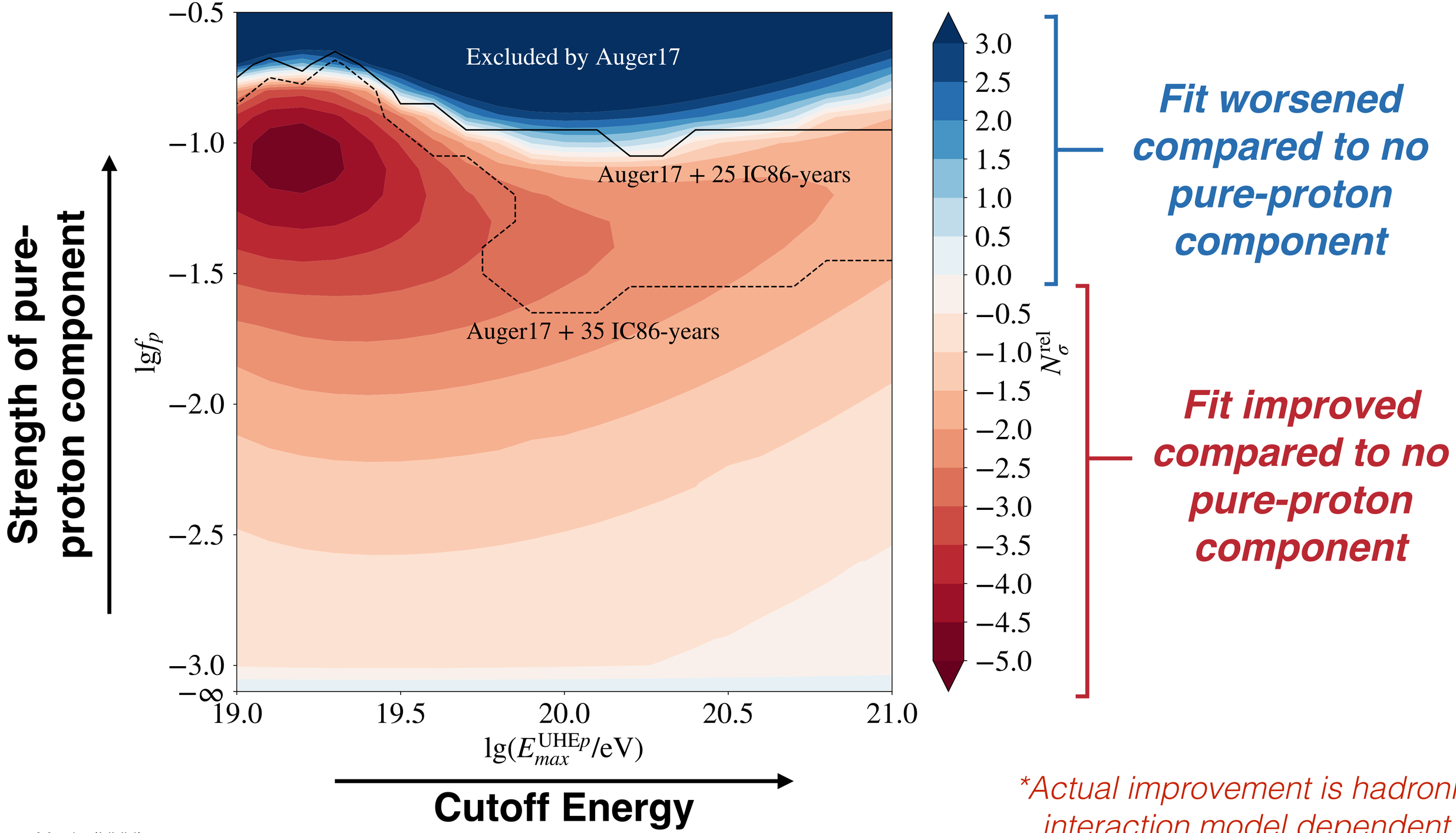


$E_{\rm ref} = 10^{19}$ eV

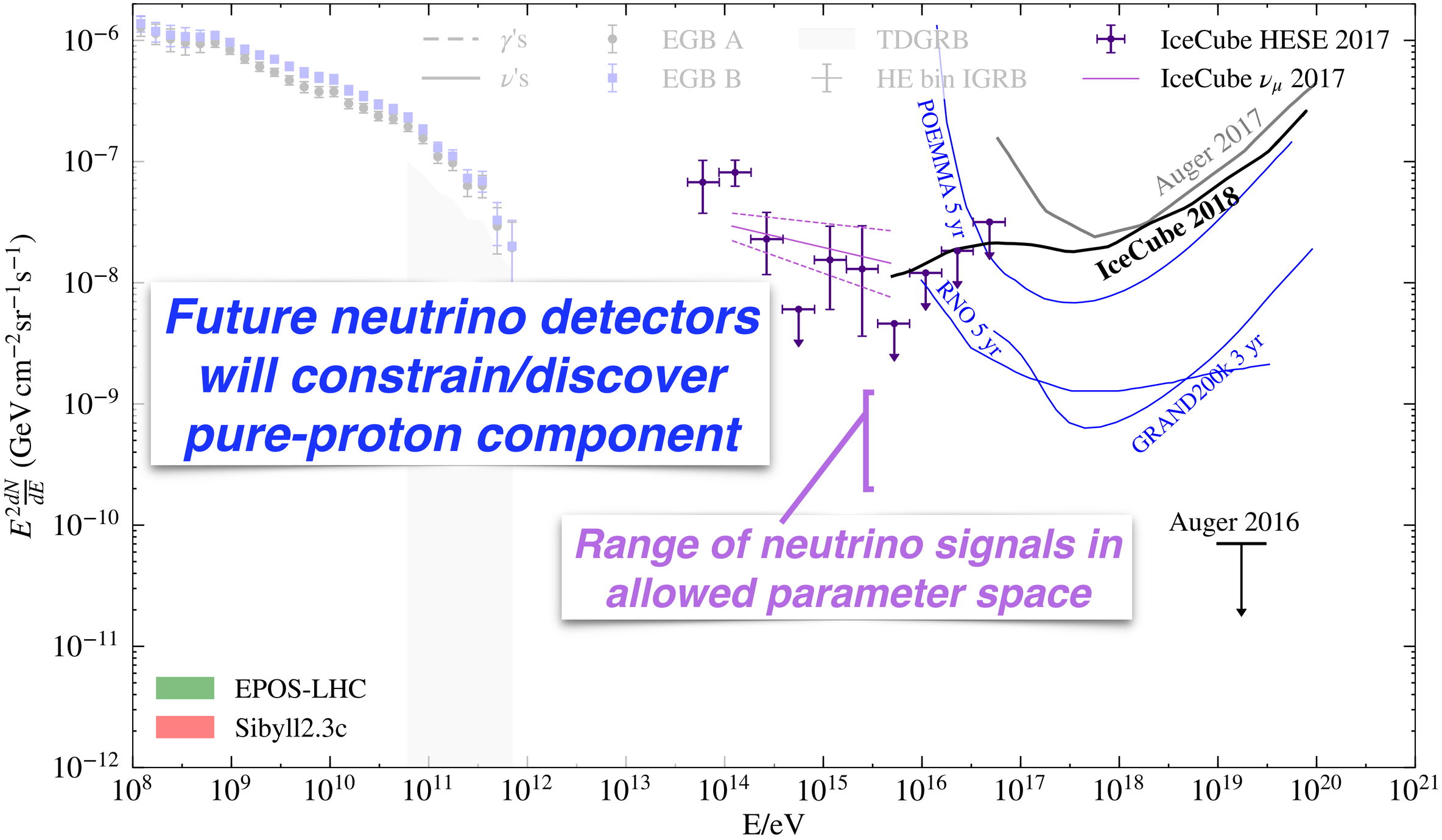
Could there be a pure-proton



$E_{\rm ref} = 10^{19}$ eV



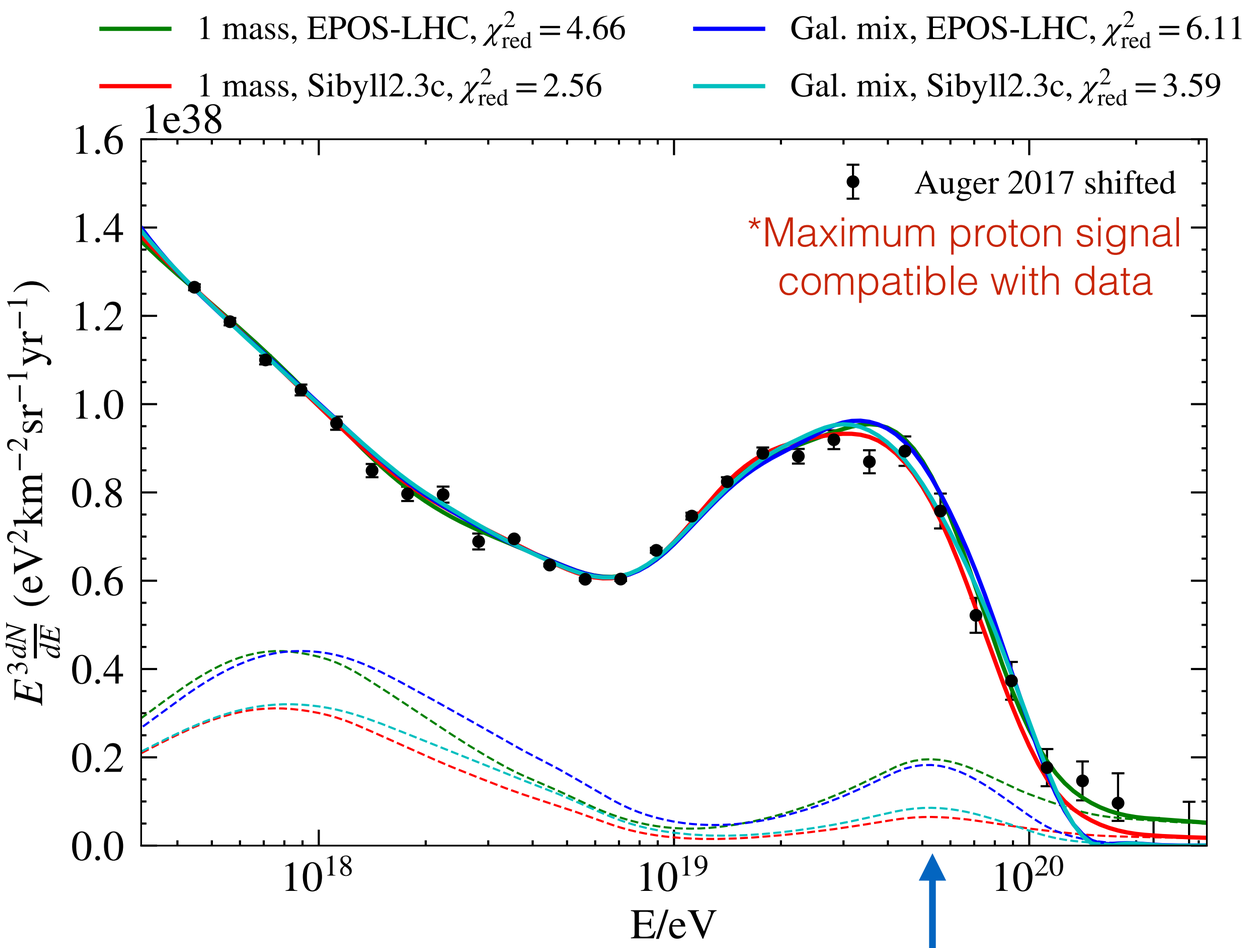
*Actual improvement is hadronic interaction model dependent



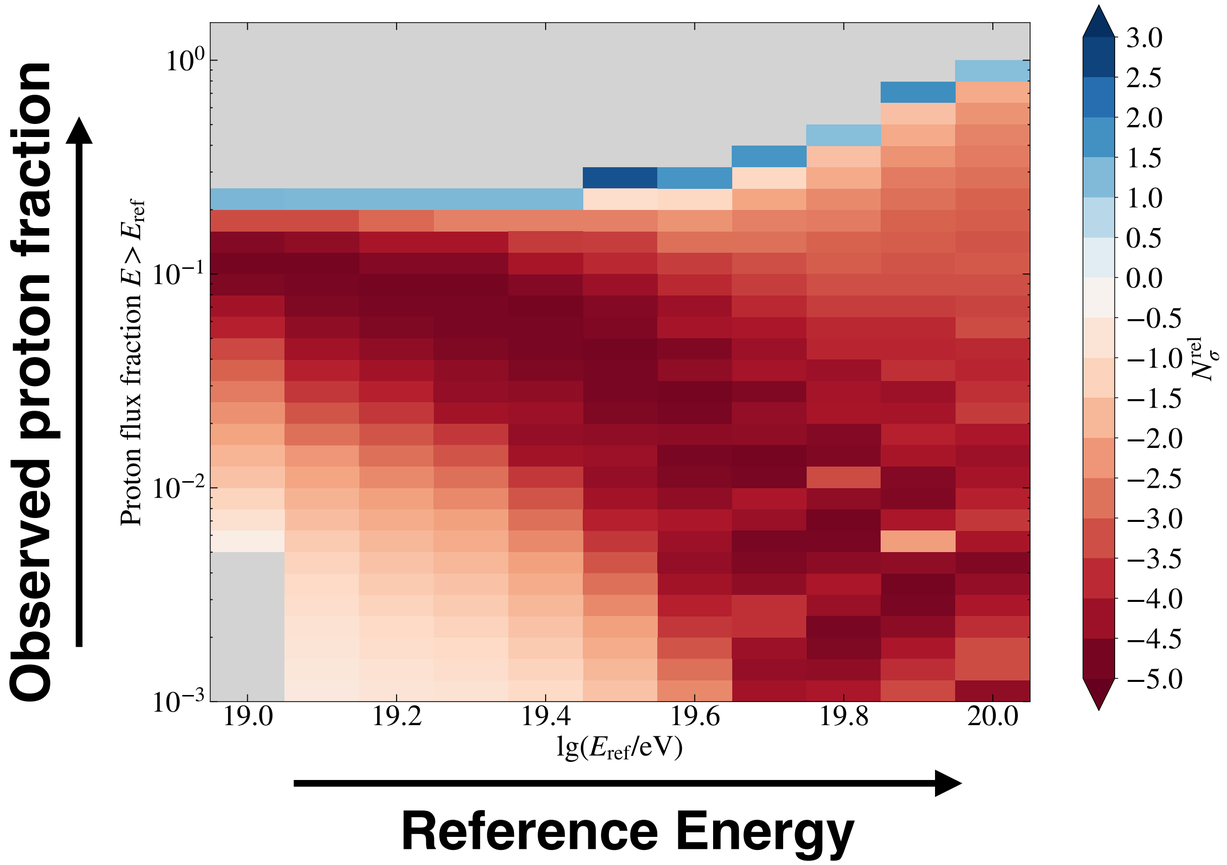
Future neutrino detectors will constrain/discover pure-proton component

Range of neutrino signals in allowed parameter space

All hadronic interaction models are compatible with > 10% CRs above 50 EeV being protons

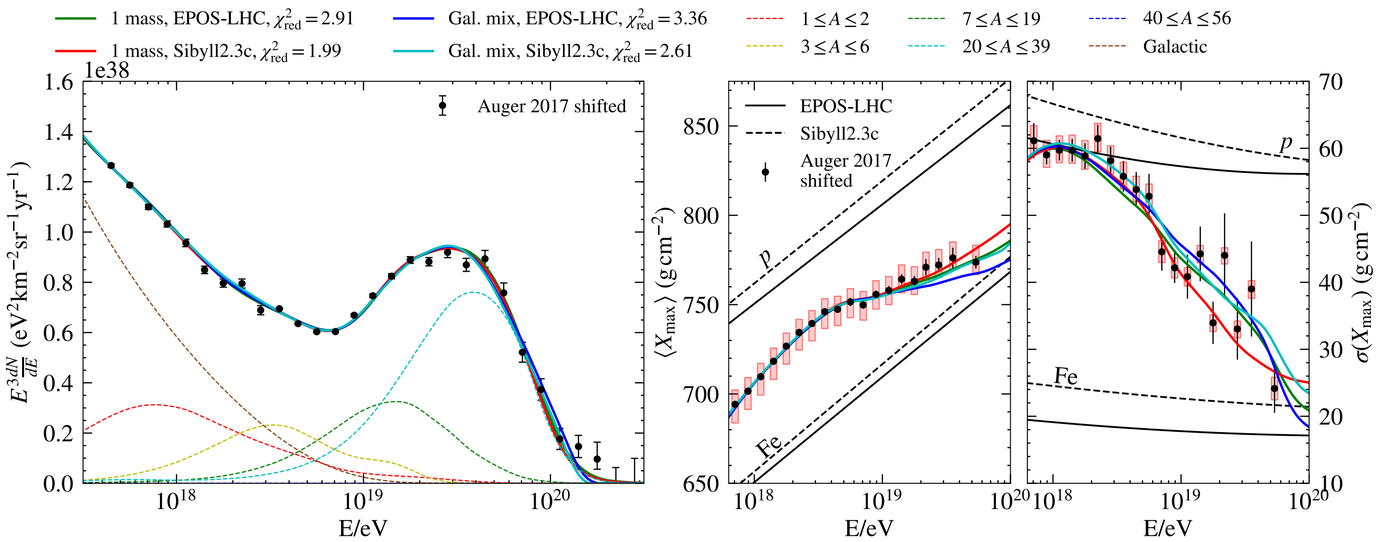


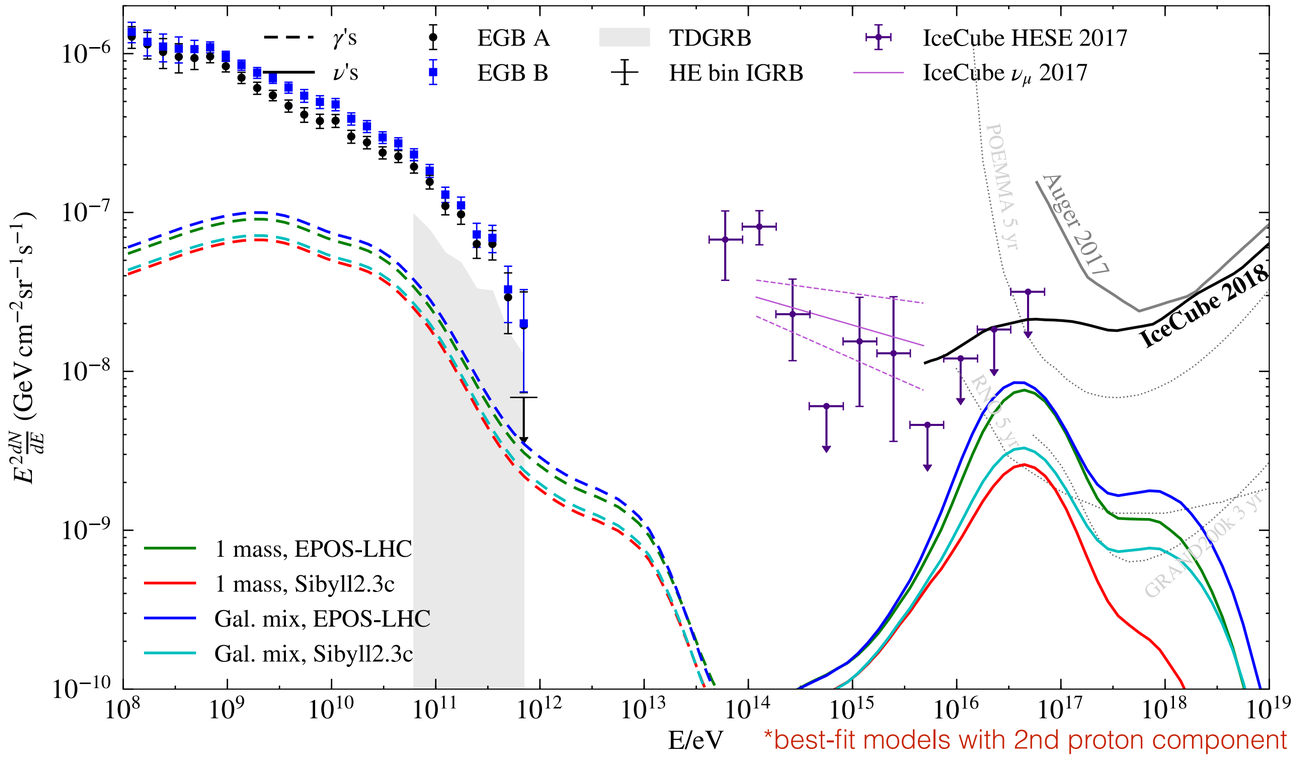
Observed high energy protons



Summary

- **UFA framework** gives **excellent fit** to all UHECR data (spectrum & composition)
- **Pure-proton component** of 10-1000 EeV CRs escaping source **improves fit**
  - Predicts possibility of >10 EV rigidity protons & >10% protons above 50 EeV
  - Future neutrino & mass sensitive UHECR experiments (e.g. AugerPrime & POEMMA) can constrain this possibility
- **Source temperatures > 4000 K** (peak energies > 500 meV) **excluded by neutrino data**
- Current gamma-ray data only weakly constraining

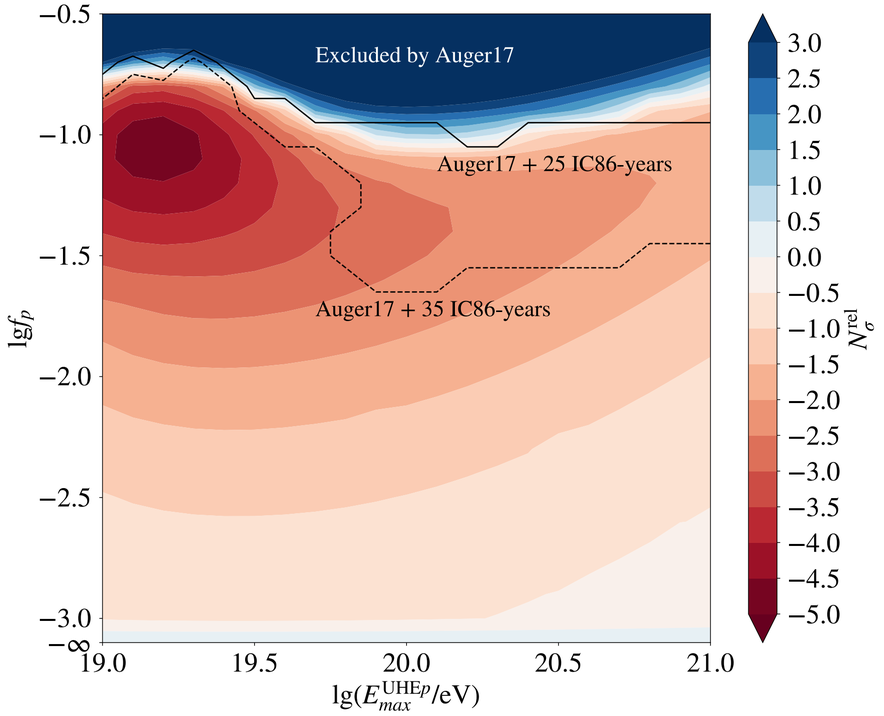


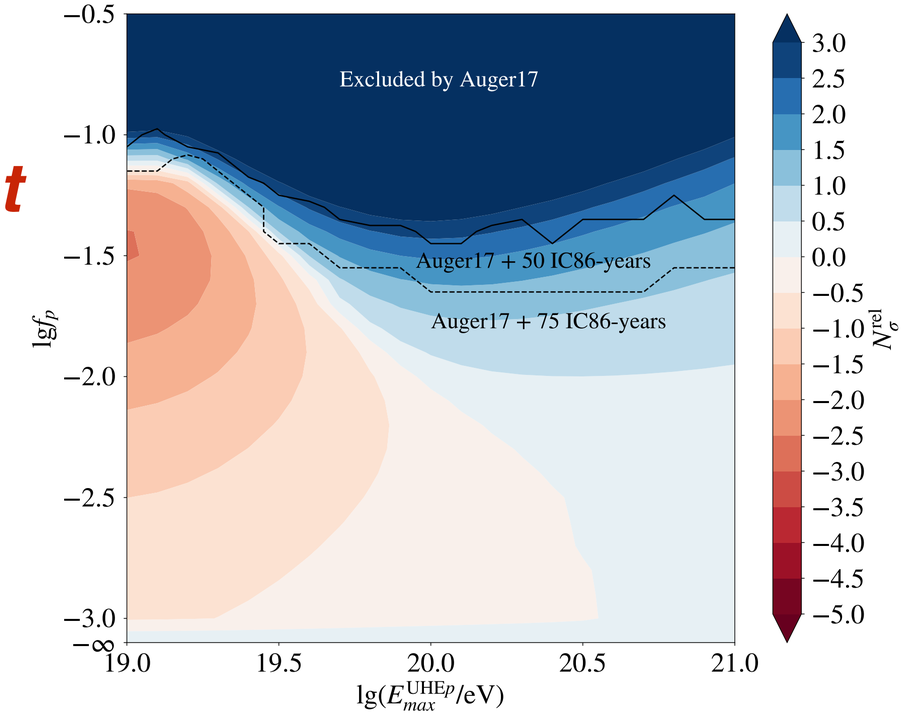


*best-fit models with 2nd proton component

Backup

Fit Improvement with Pure-Proton Component

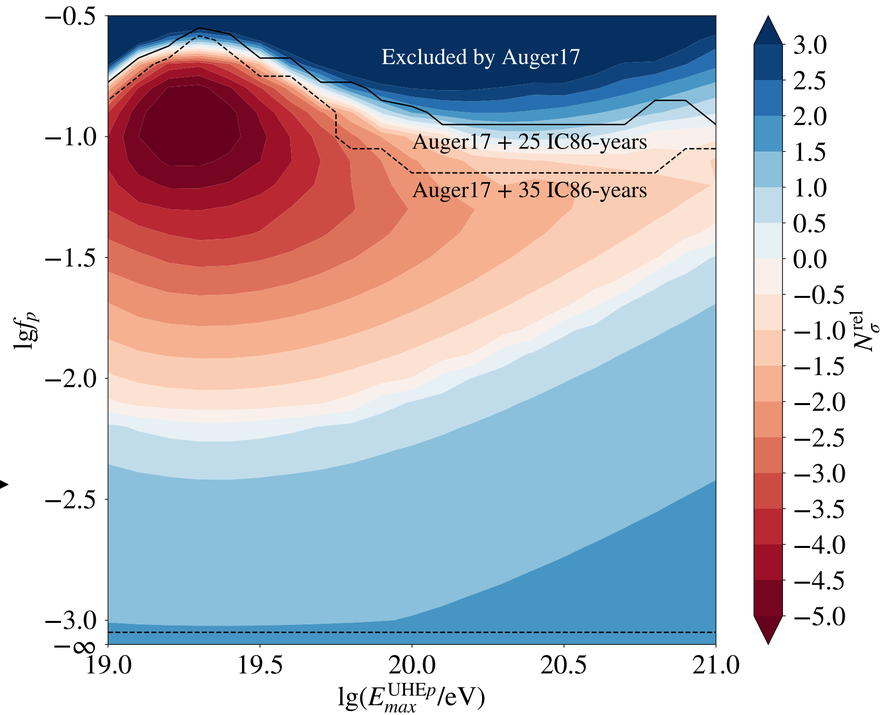


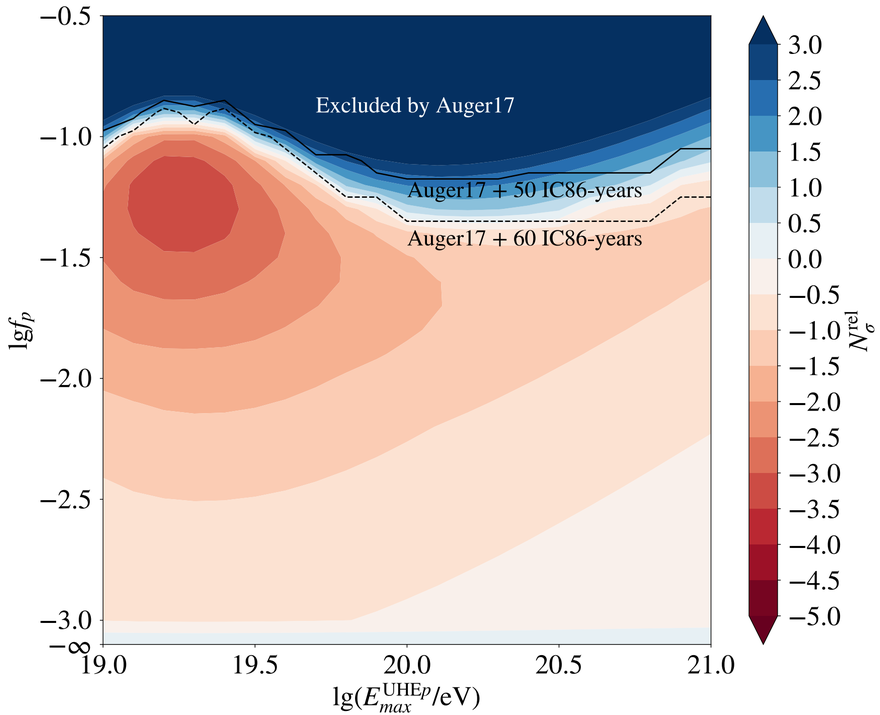


Single-mass composition

Milky Way-like composition

EPOS-LHC





Sibyll2.3c