Closing in on UHECR sources: A multimessenger approach

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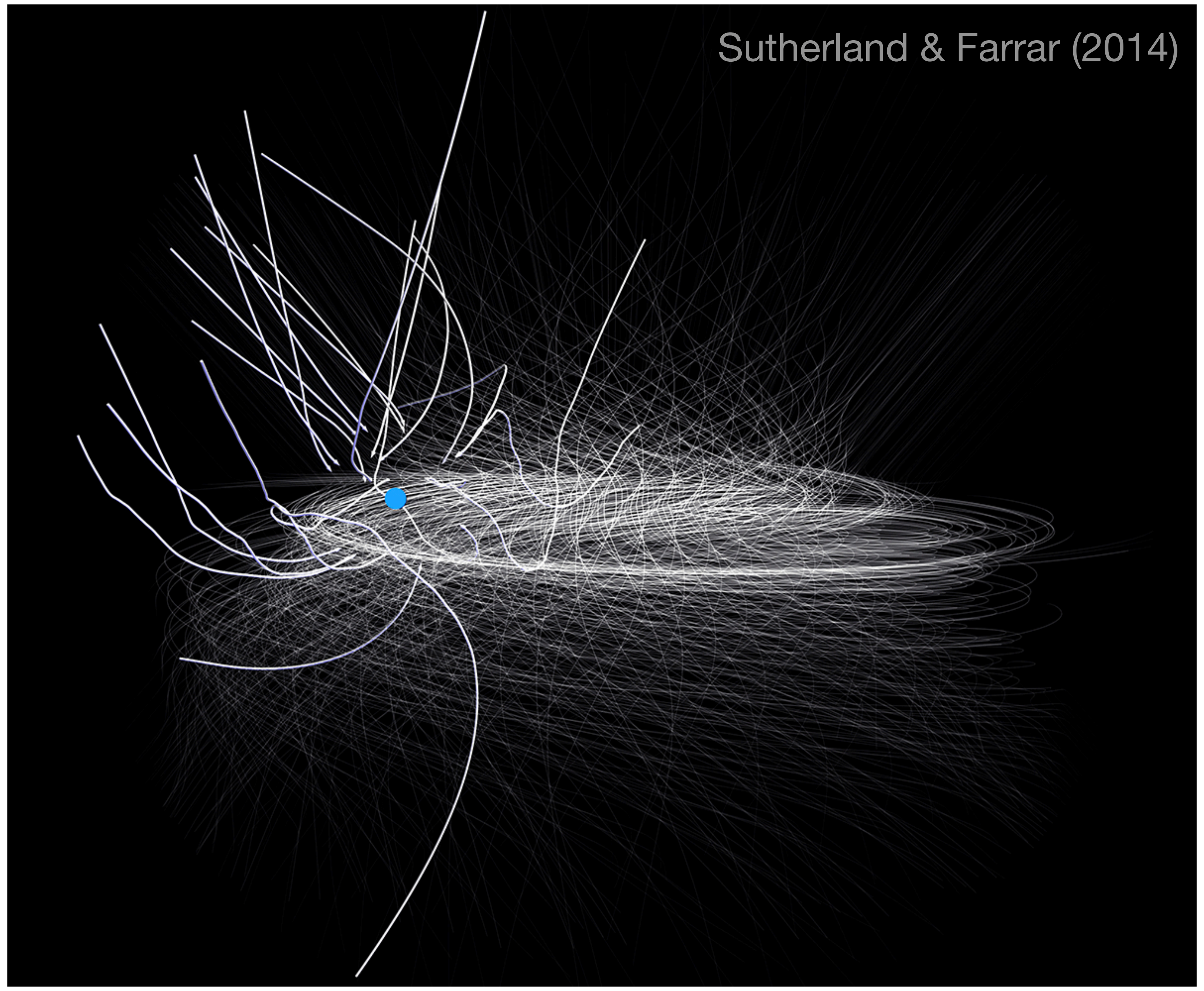
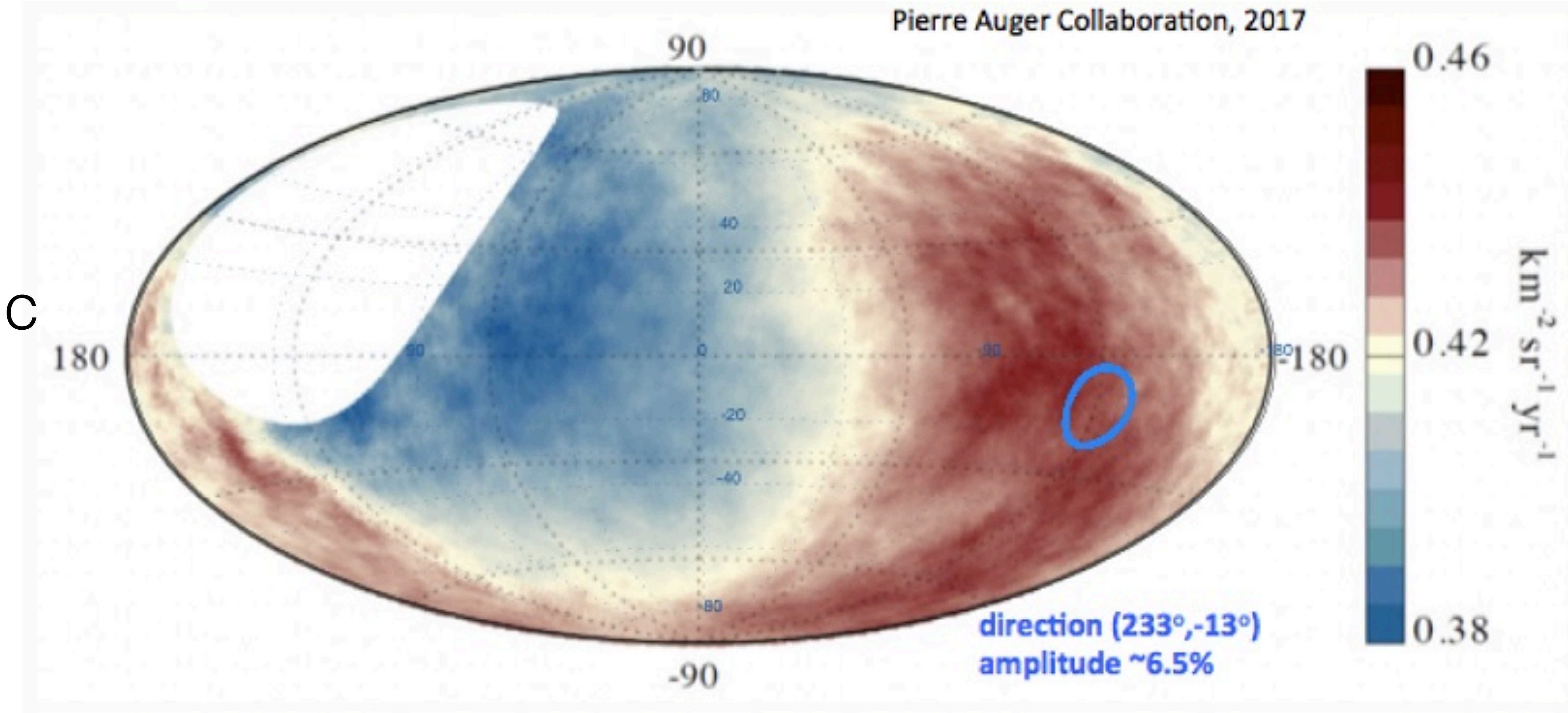
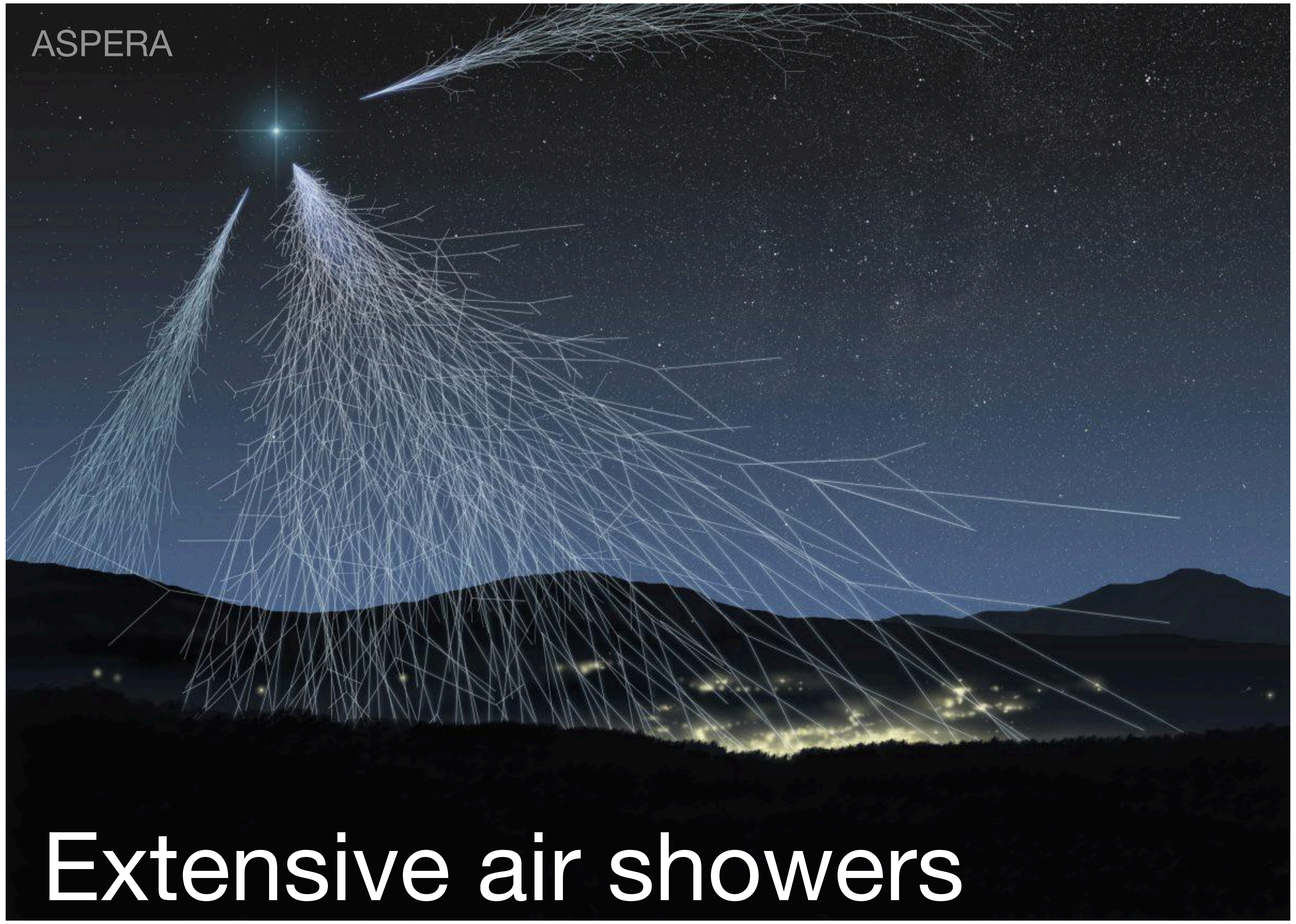
What are cosmic rays?

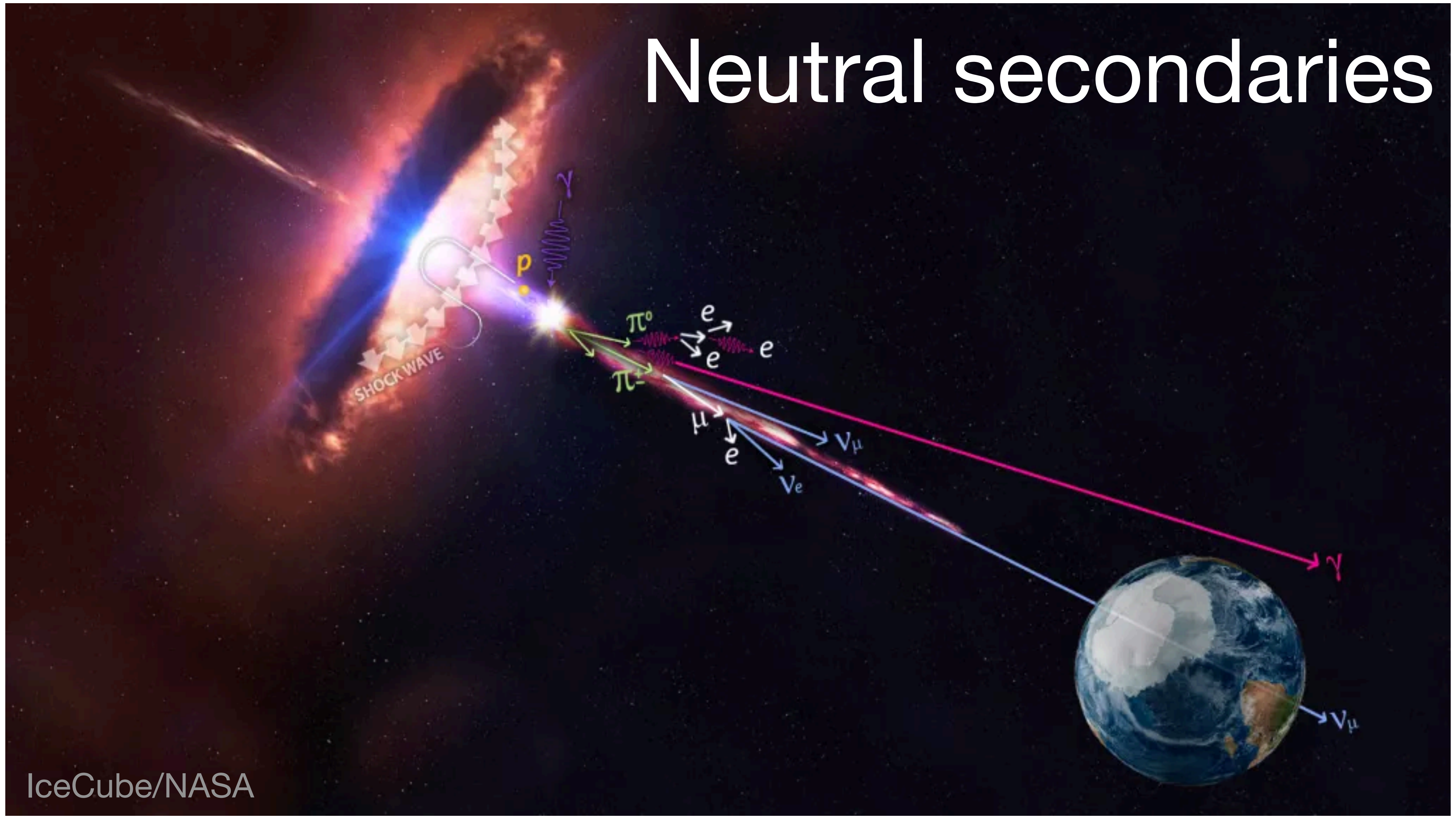
- **Charged nuclei**
- Reach **extreme energies**, more than 10^{20} eV = 100 EeV
  - Those above 10^{18} eV =1 EeV are called **ultrahigh energy (UHE)**
- **Source(s) unknown**, especially at the highest energies
- Of **extragalactic origin** beyond ~1 EeV
  - Dipole detected above 8 EeV
- Observational challenges:
  - **Magnetic deflections**, Galactic & extragalactic
  - **Extremely low flux** at the highest energies, < 1 CR/km^2/century





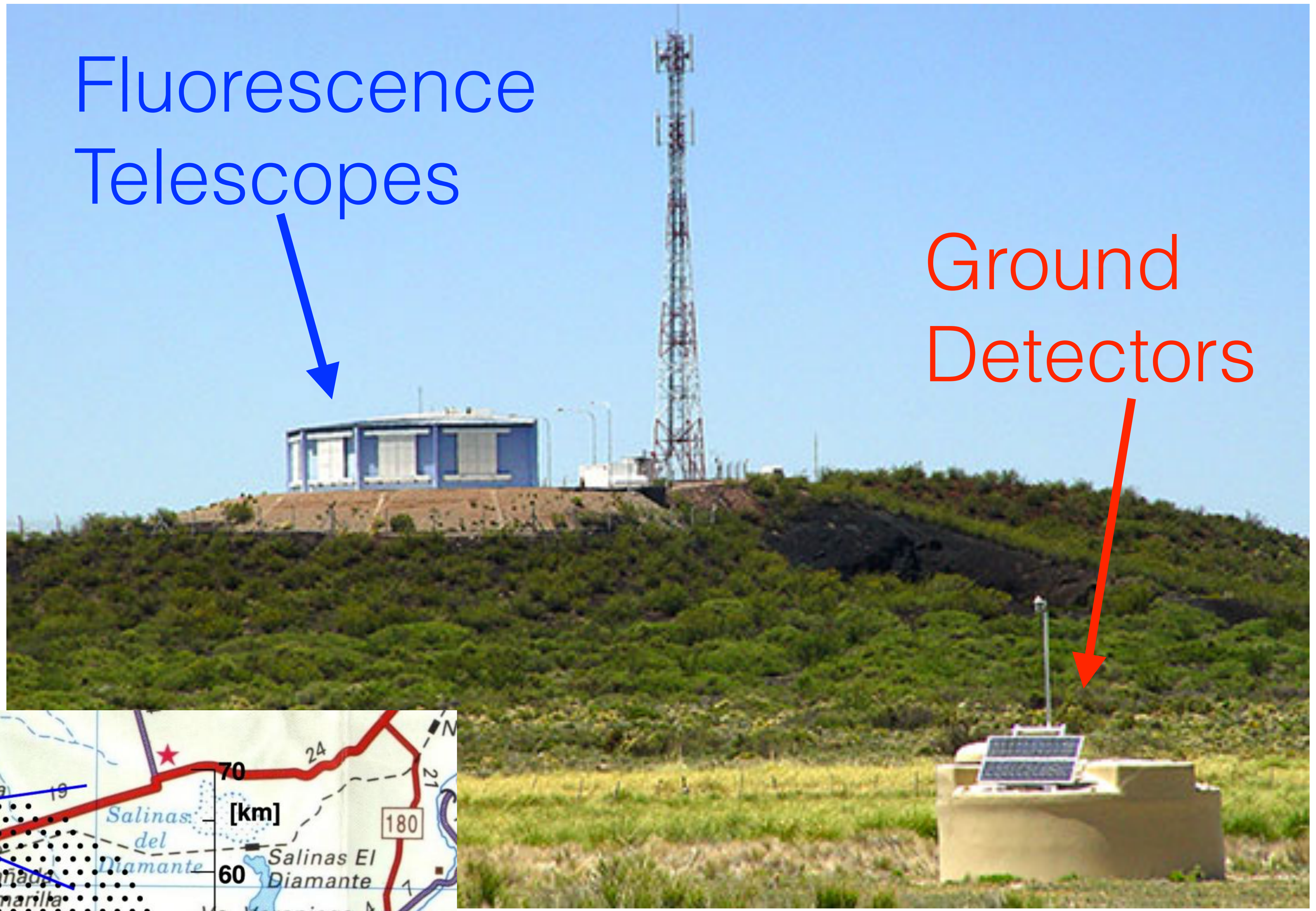
How do we detect UHECRs?

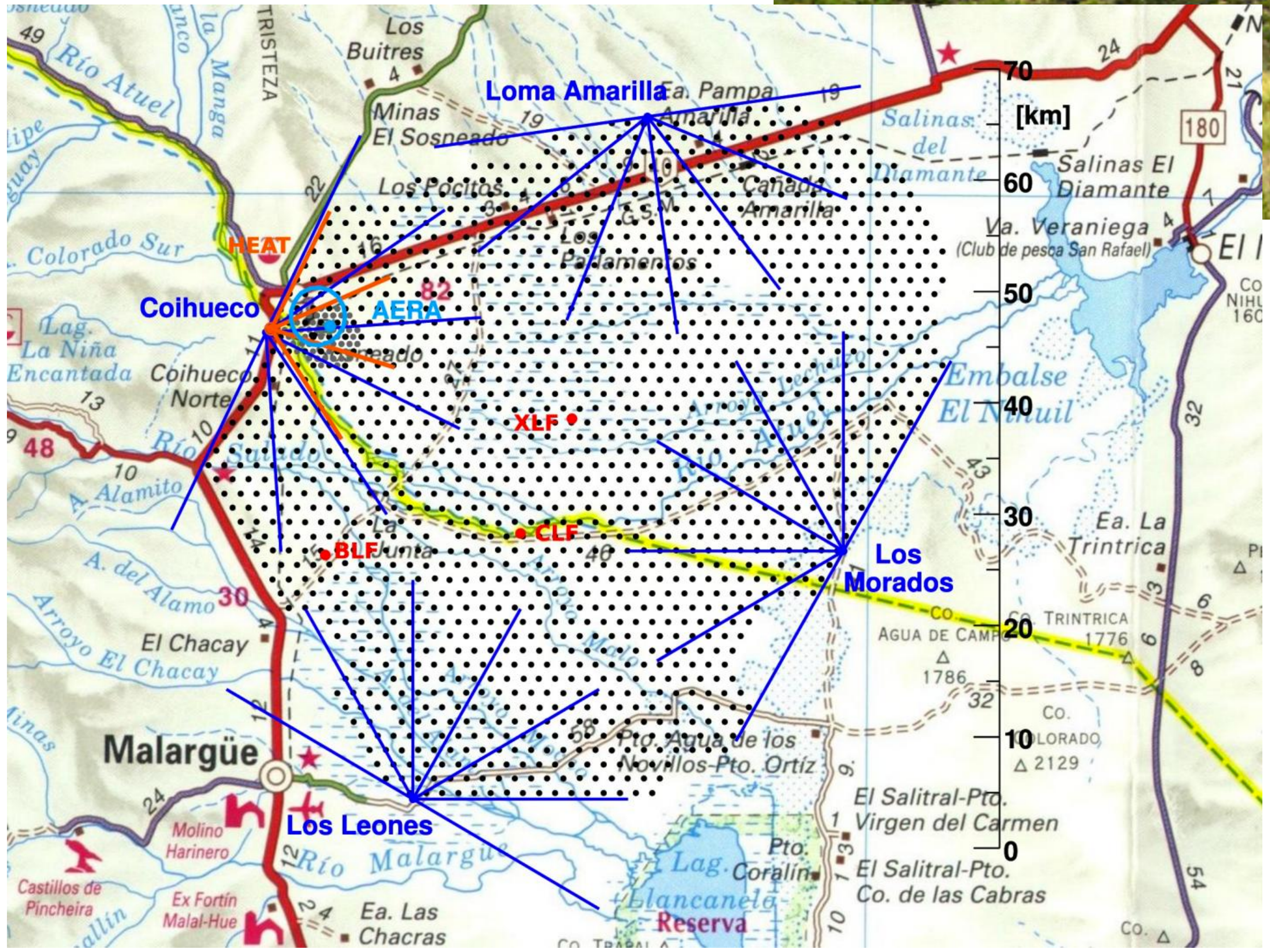




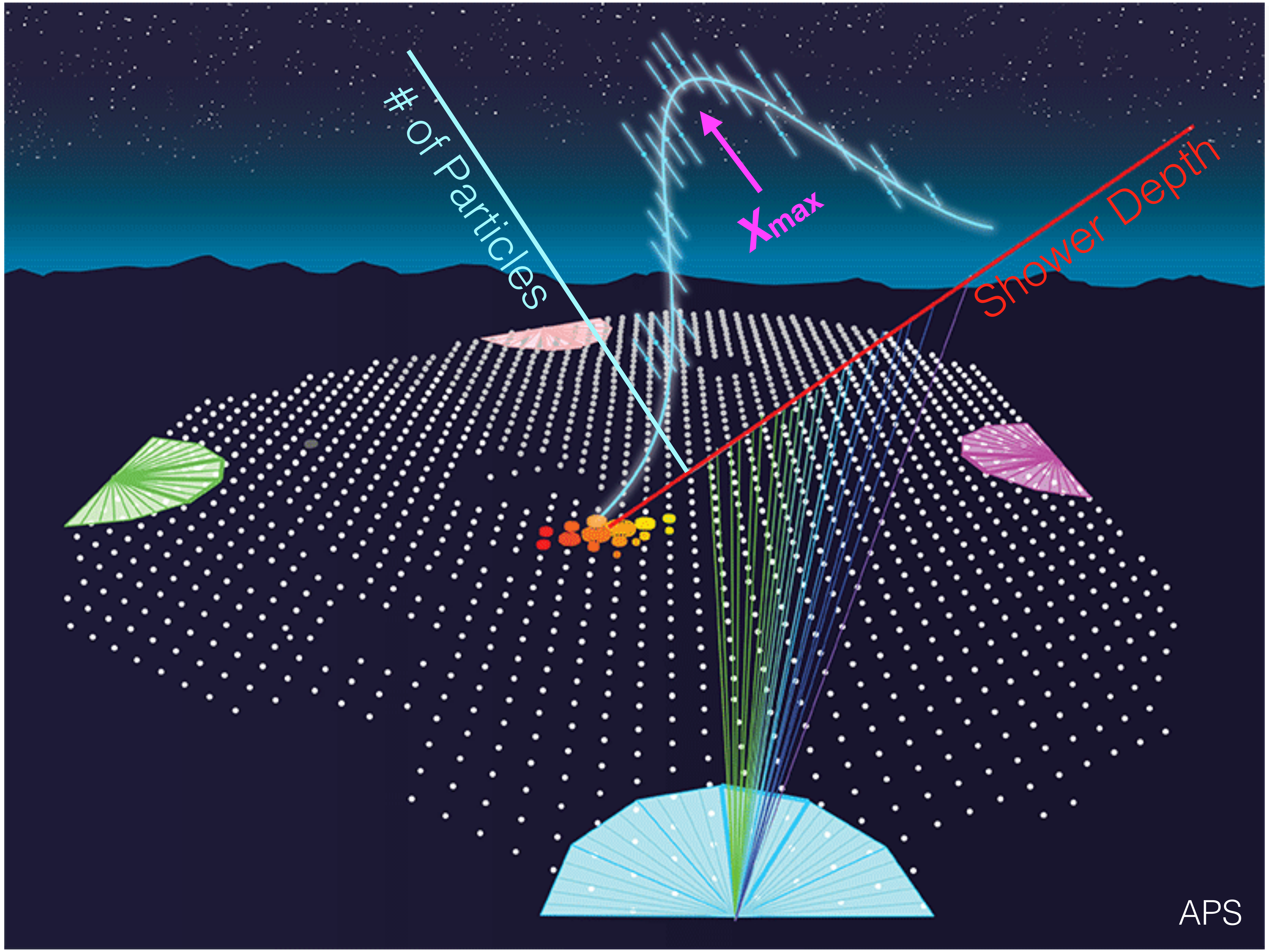
Hybrid (UHE)CR Detectors

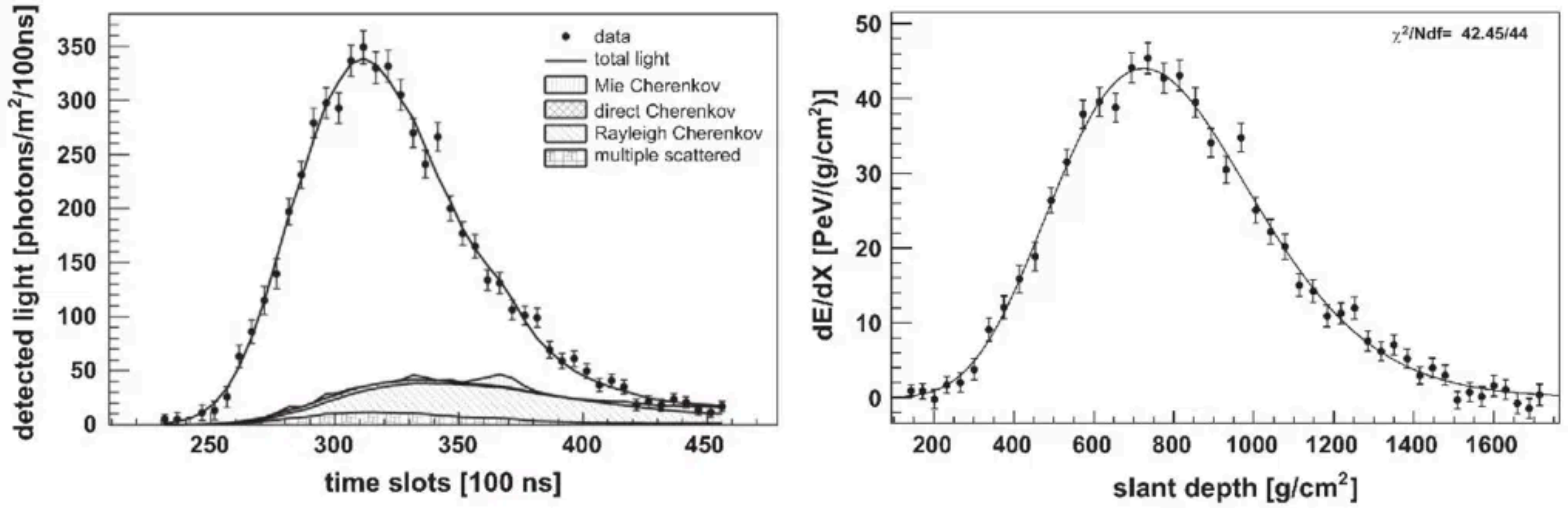
- Encompass enormous area to overcome low flux
  - Telescope Array (US)
  - Pierre Auger Observatory (Argentina)
- Employ hybrid detection method:
  - Surface detector array
  - Fluorescence detector telescopes





Pierre Auger Observatory



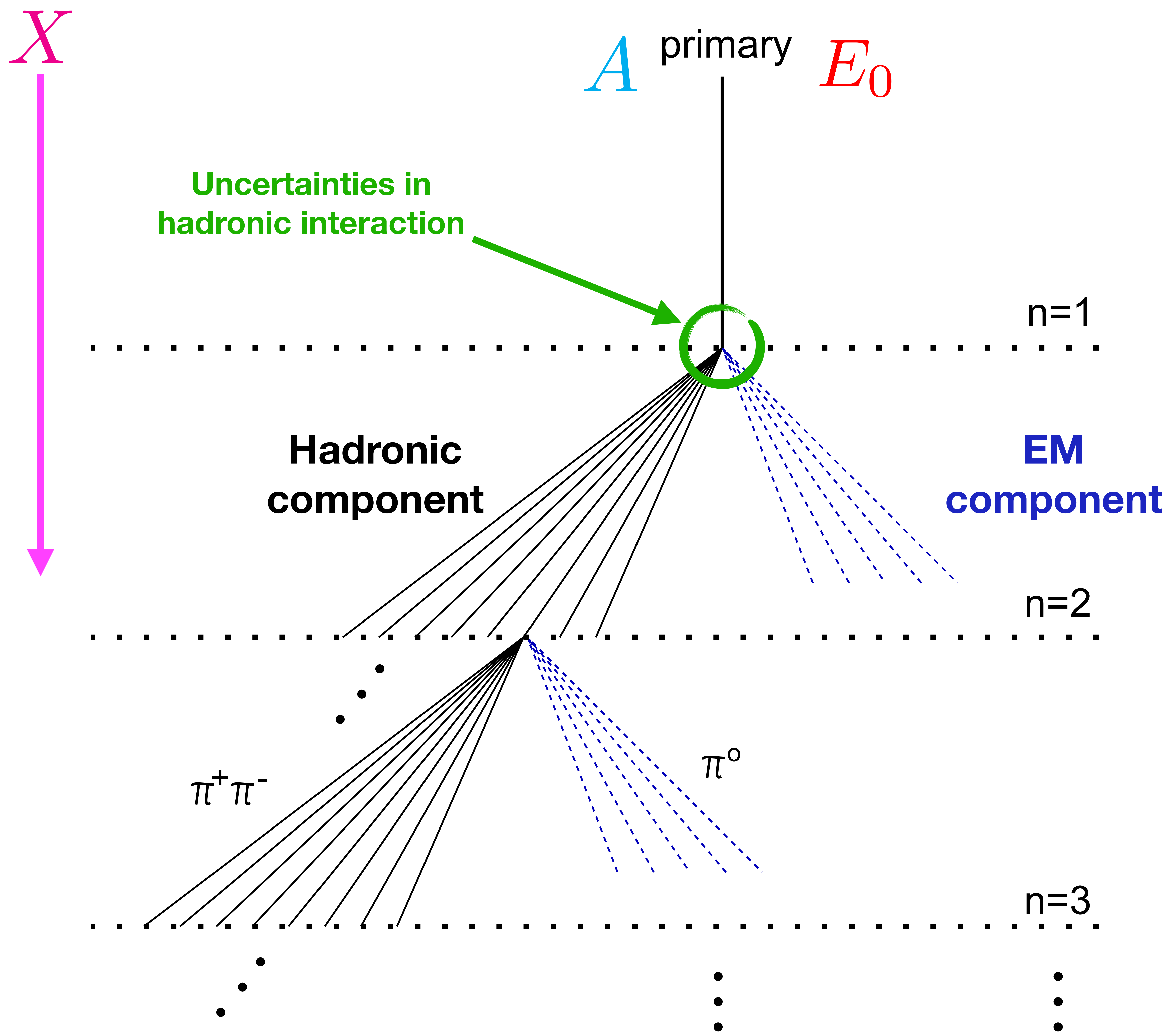


$$E_{\text{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\mathrm{d}X$$

- **Fluorescence detector measures** shower X_{max} **directly and primary energy** to high precision
- **Ground signal estimate of primary energy**, calibrated to fluorescence detection

Why measure X_{max}?

Heitler-Matthews model



- Ex: Proton initiates shower
  - Higher energy primary = more particles in shower (more generations to maximum)

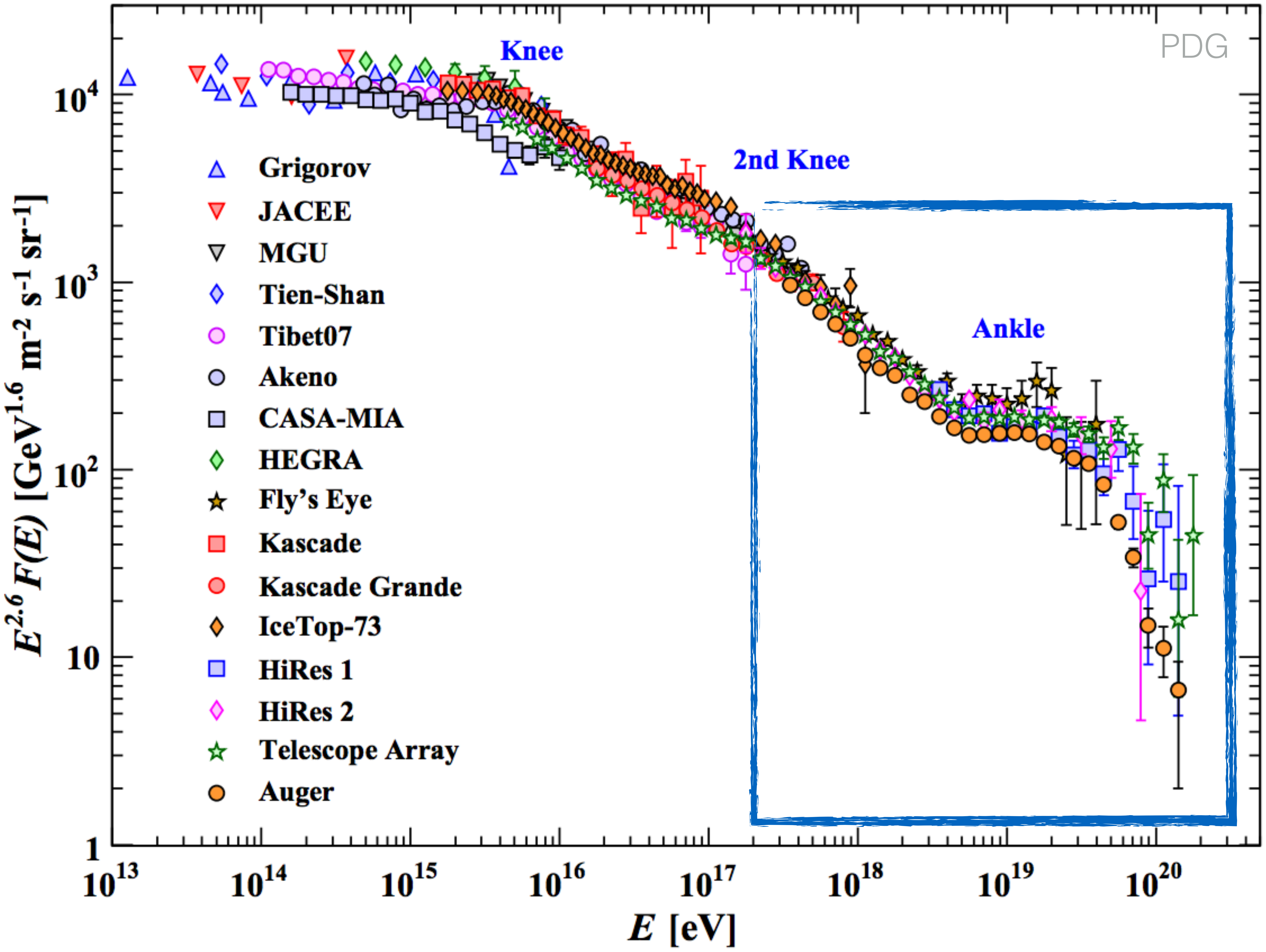
$$X_{\max} \sim \ln E_0$$

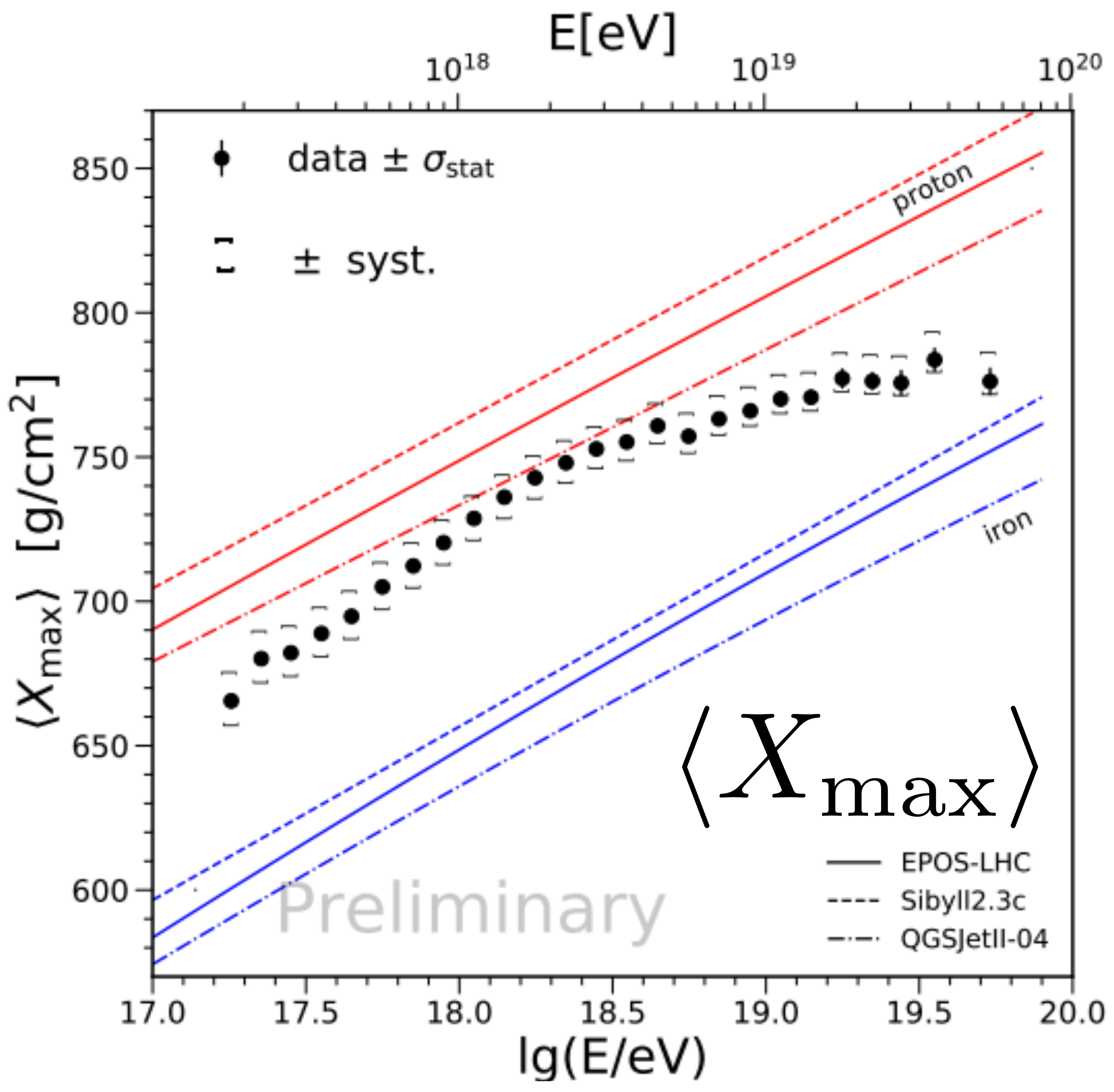
- Ex: Nucleus *A* initiates shower
  - Superposition approximation: nucleus *A* ≃ *A* nucleons
  - *A* showers initiated with energy E_0/A

$$X_{\max} \sim \ln\left(E_0/A\right)$$

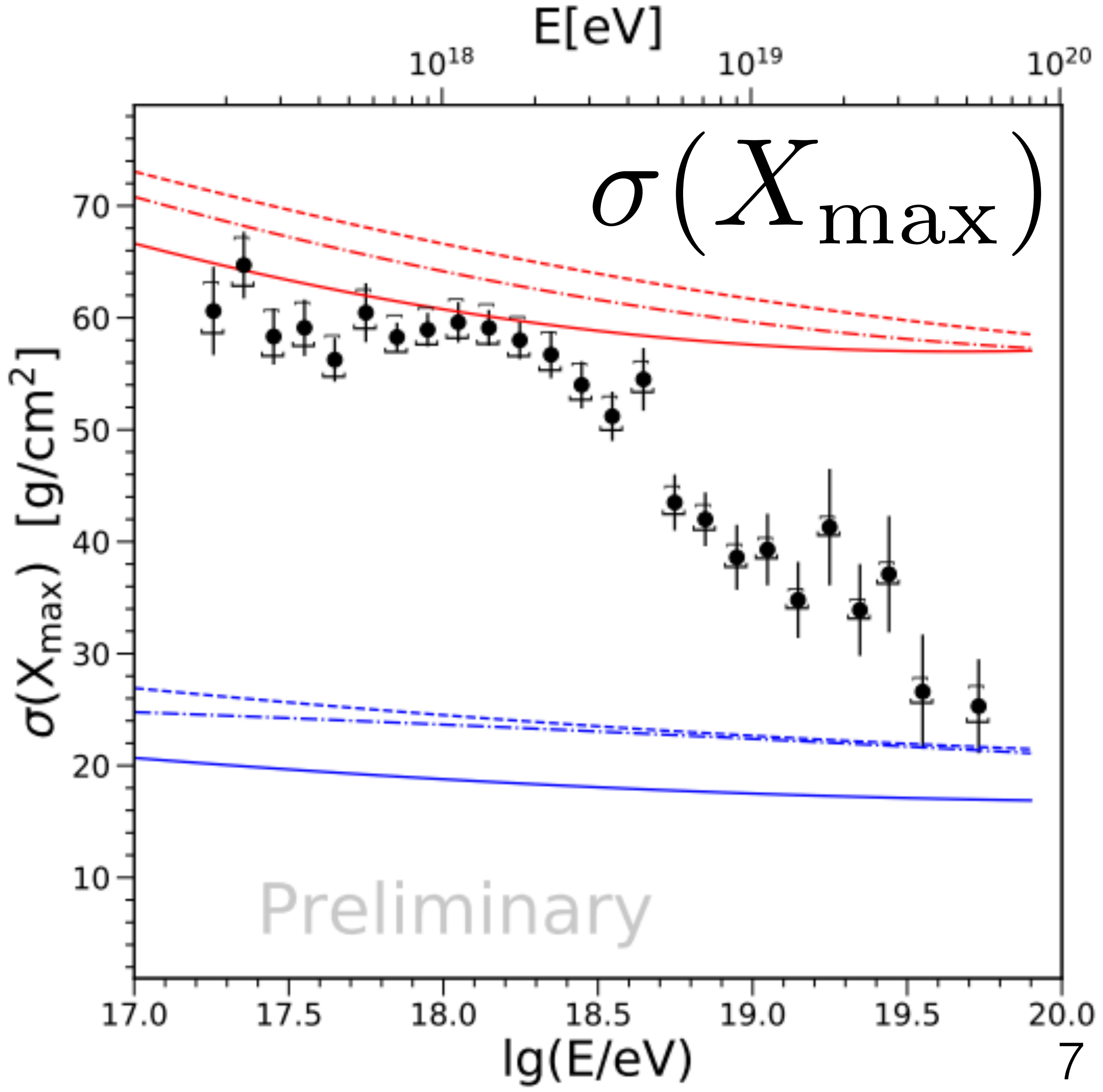
Measuring X_{max} probes primary particle energy & composition

CR Spectrum

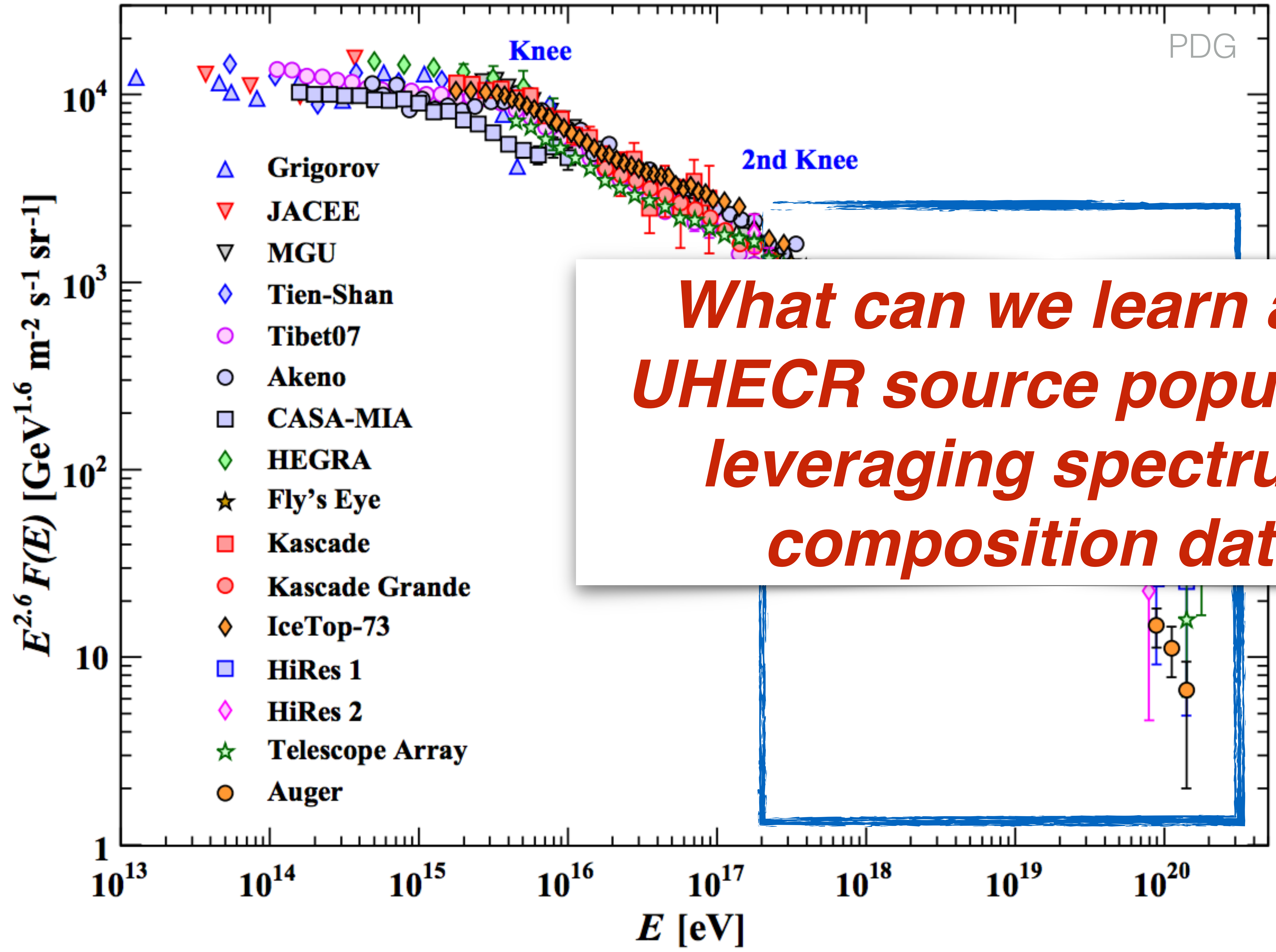




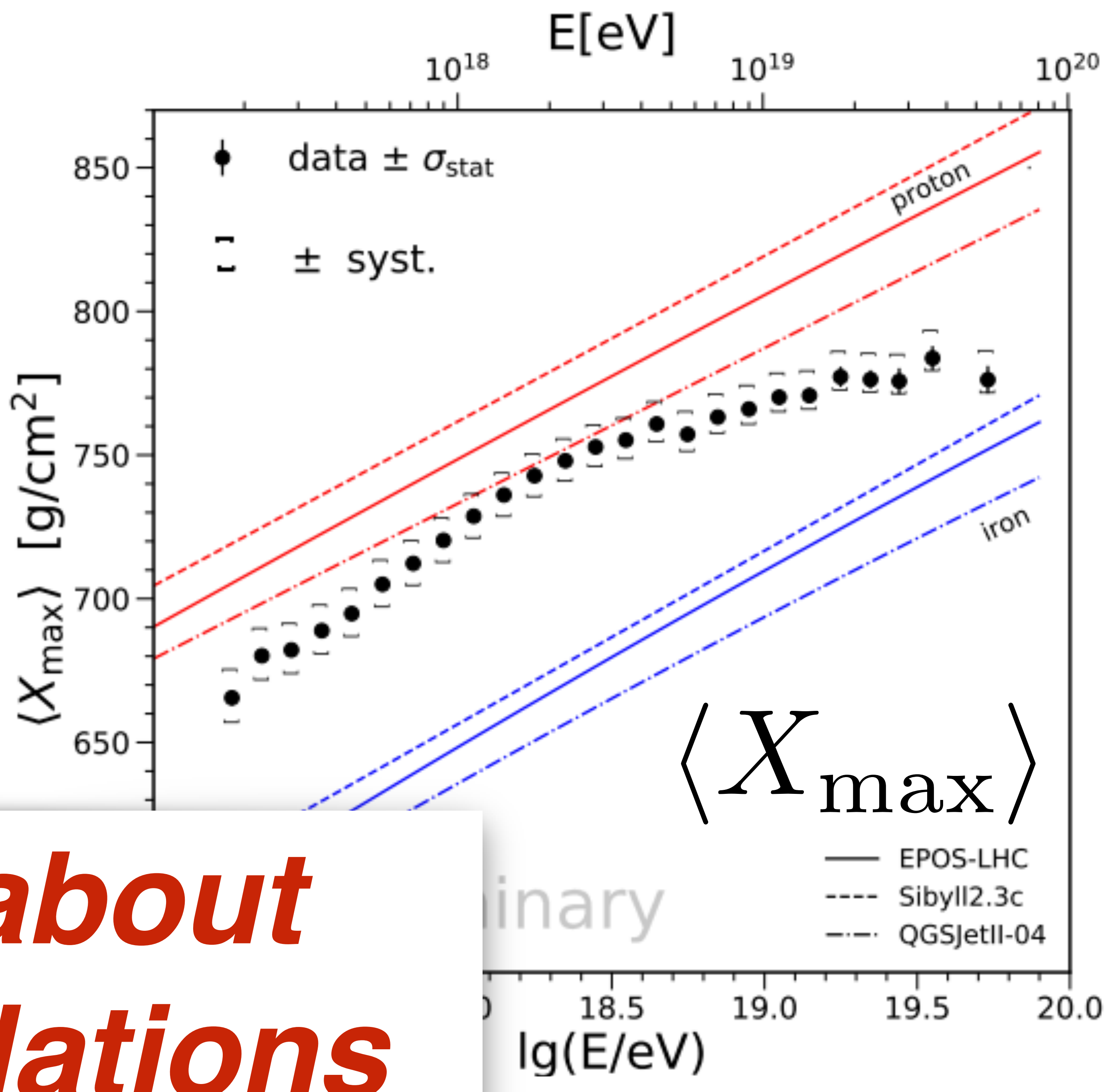
CR Composition



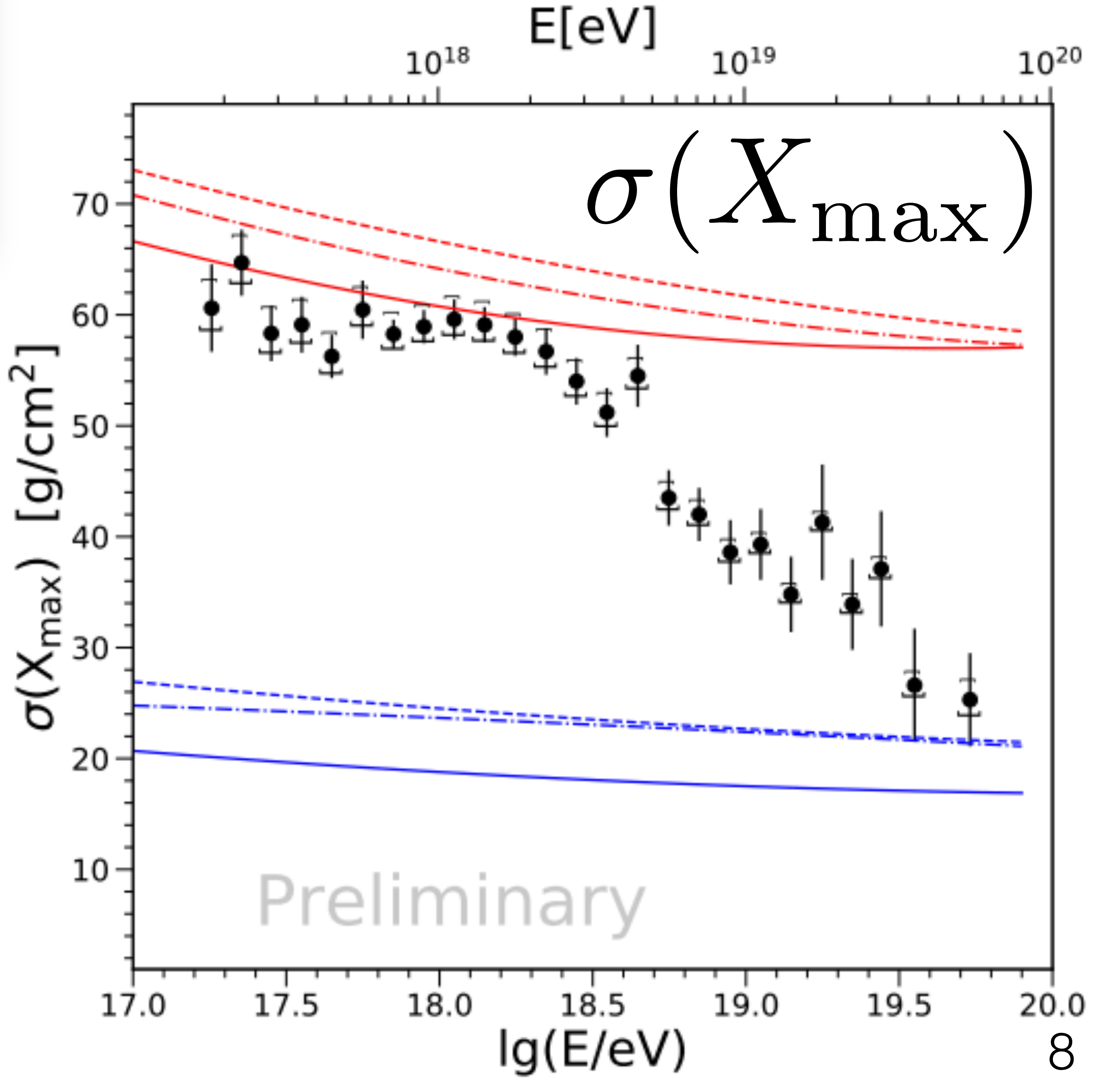
CR Spectrum



What can we learn about UHECR source populations leveraging spectrum & composition data?

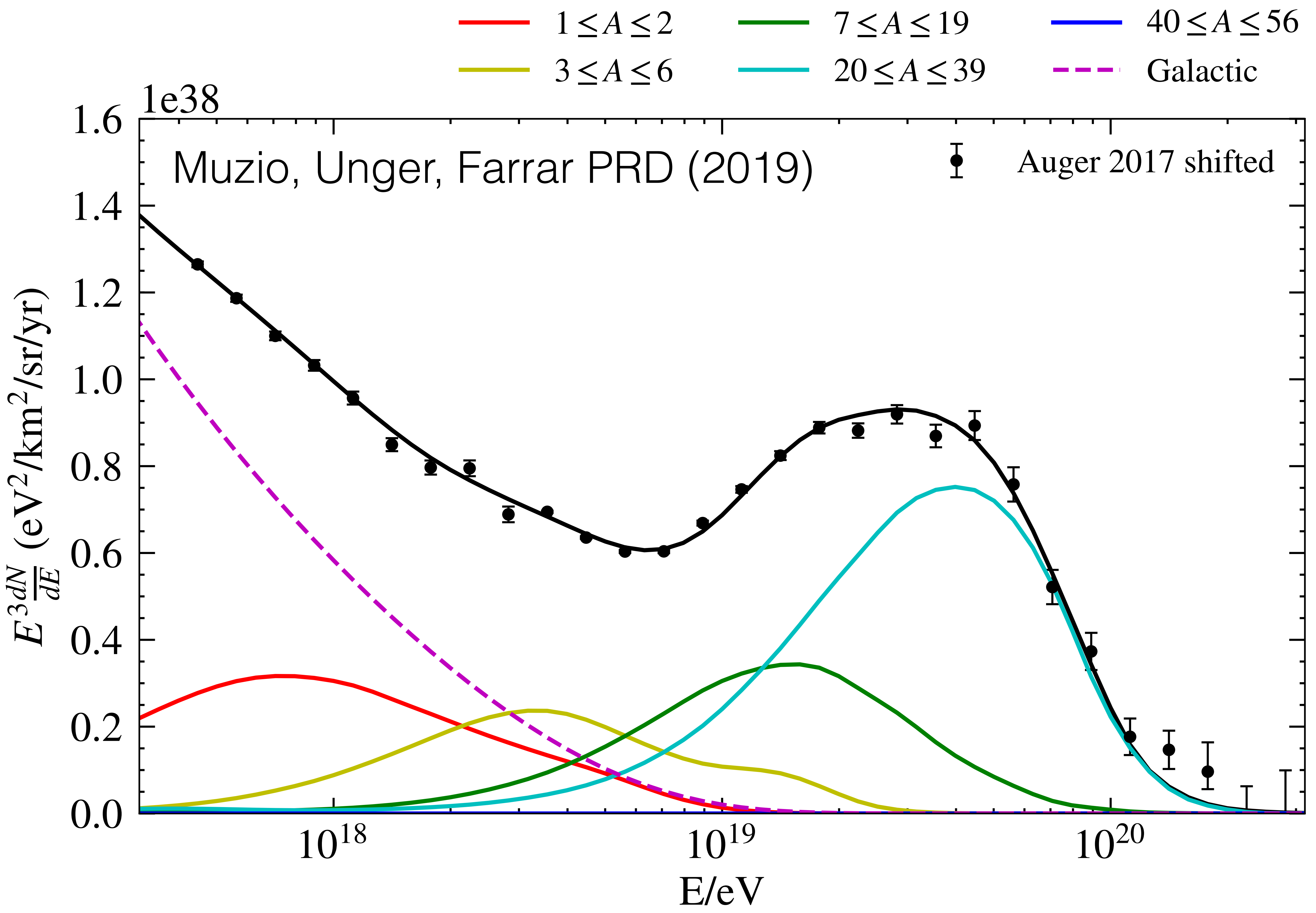


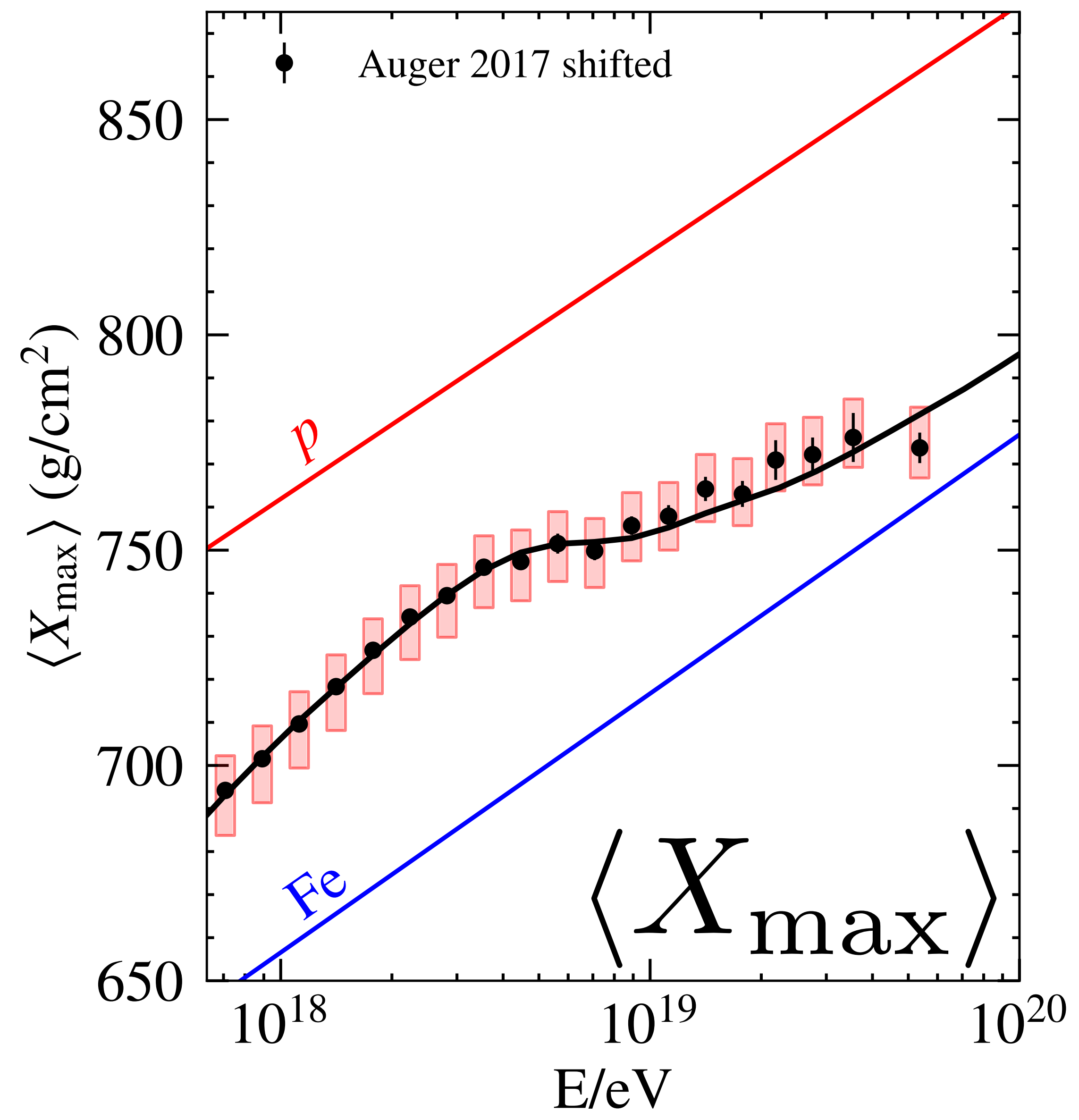
CR Composition

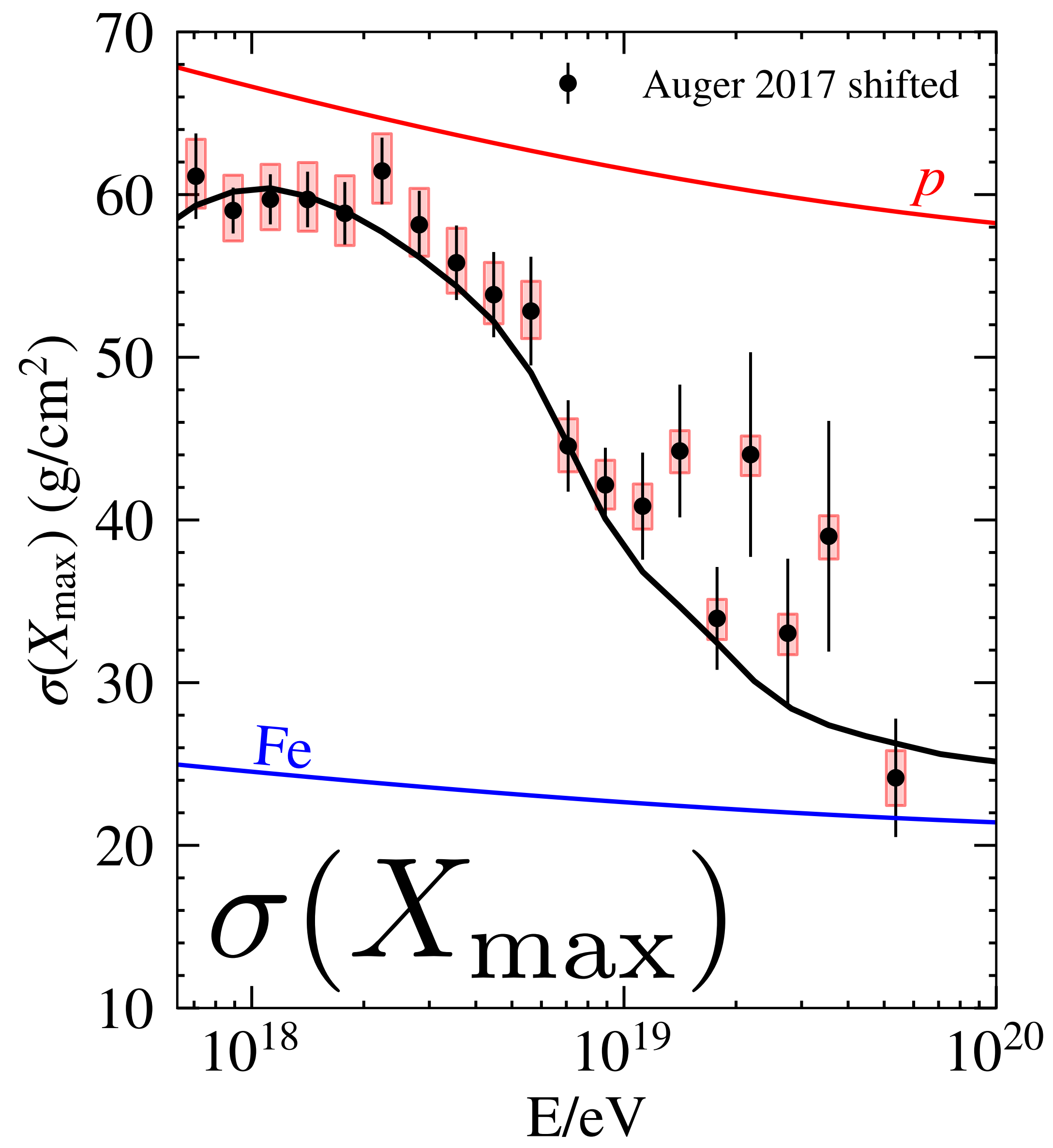


CR Source Model

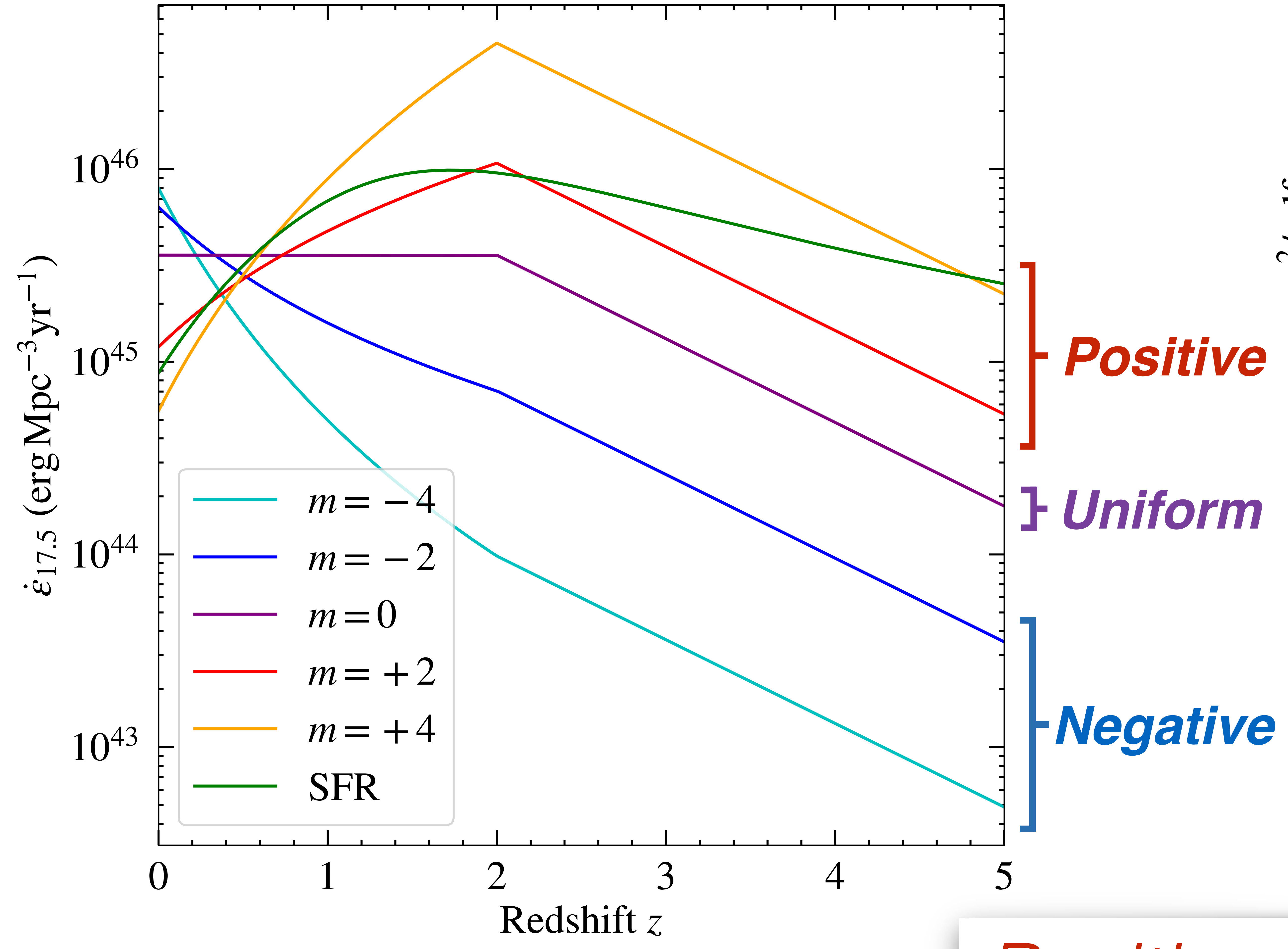
- Unger-Farrar-Anchordoqui model (UFA, 2015 PRD):
  1. Inject CRs into source environment
  2. **CRs processed by *photon* interactions**
  3. CRs escape source environment
  4. CRs propagate to Earth
- Accounts for observed spectrum (>$10^{17.5}$ eV) & composition (>$10^{17.8}$ eV)

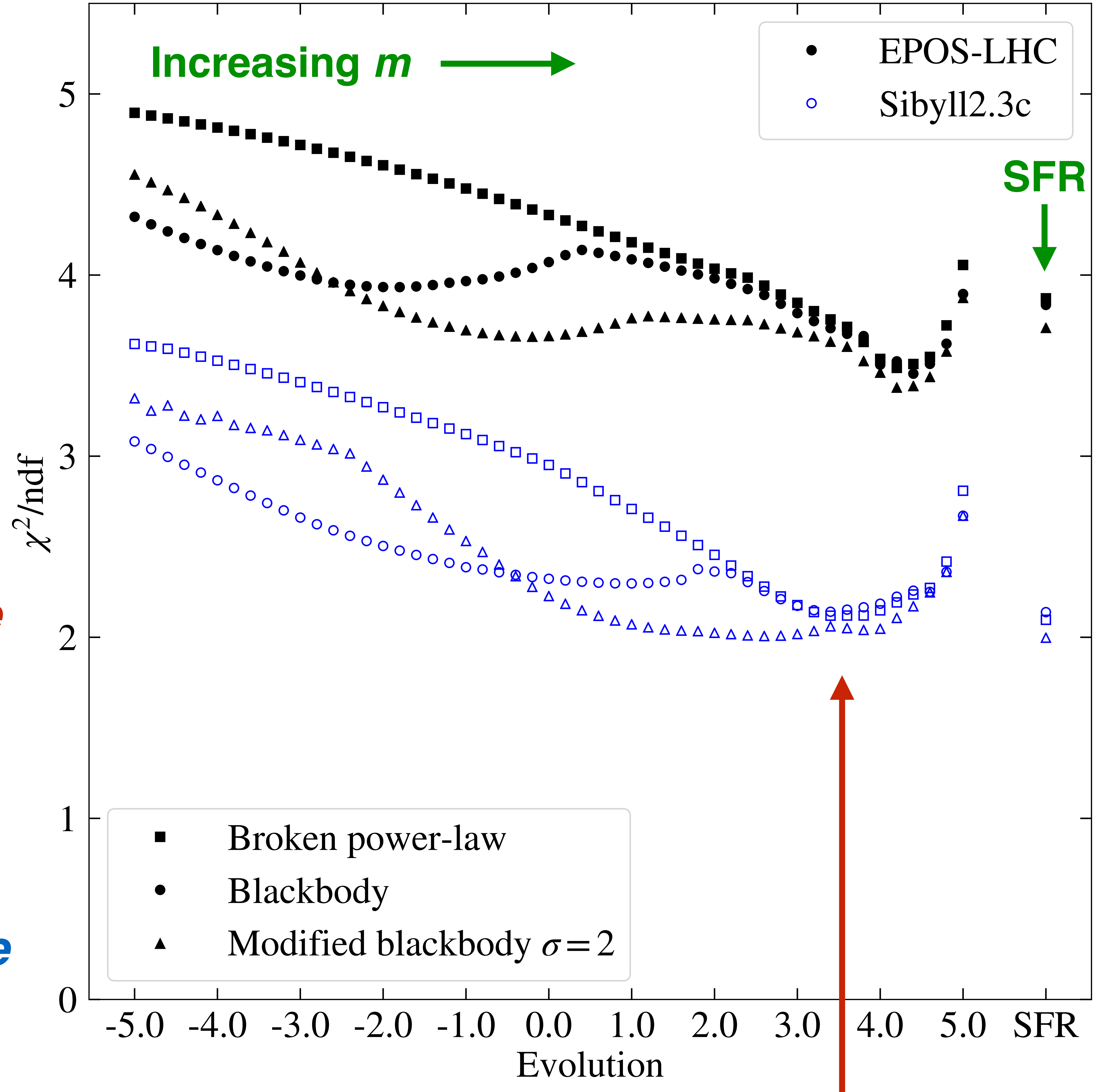




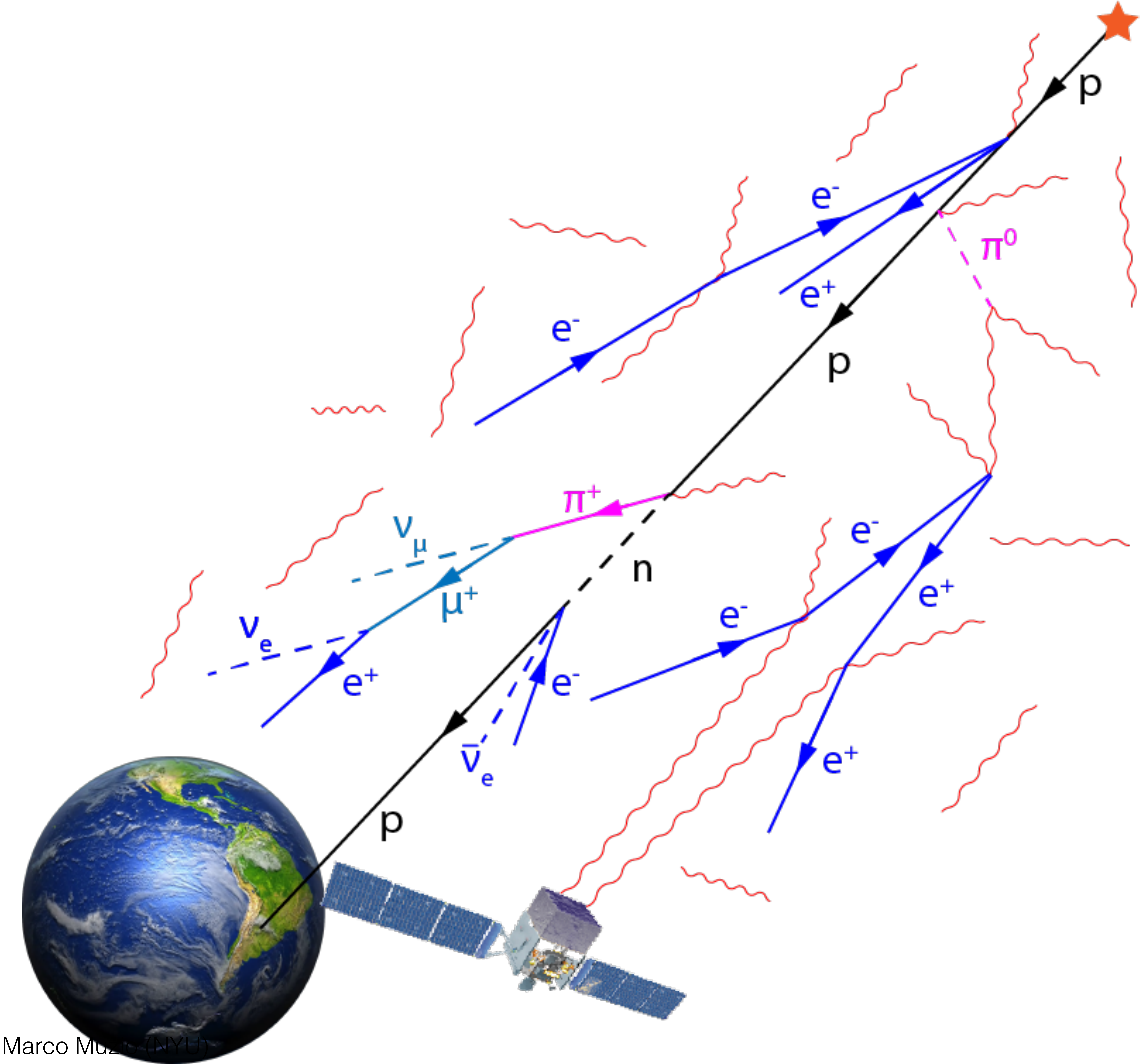


What does UFA have to say about source evolution?

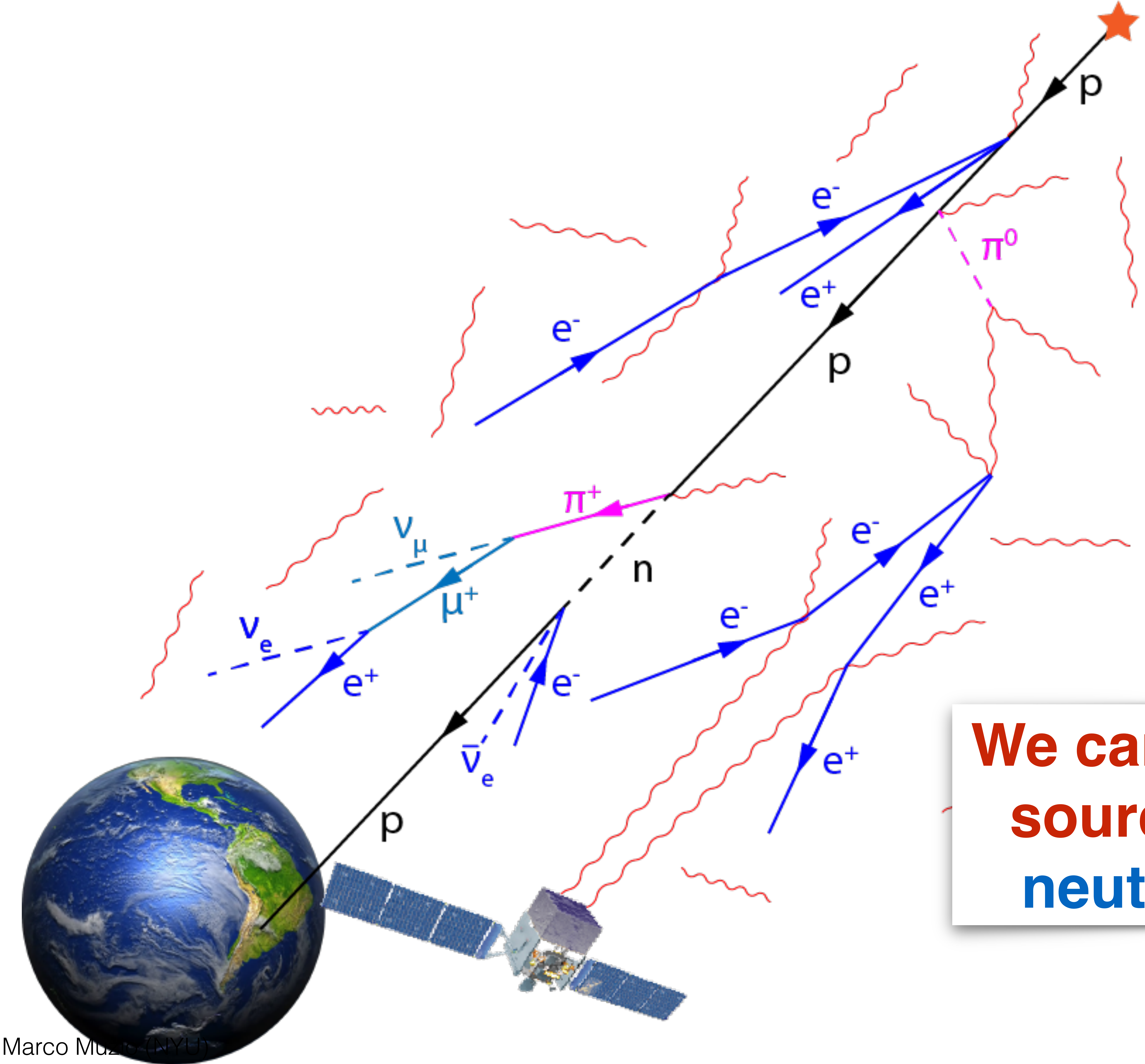




Positive source evolutions slightly favored

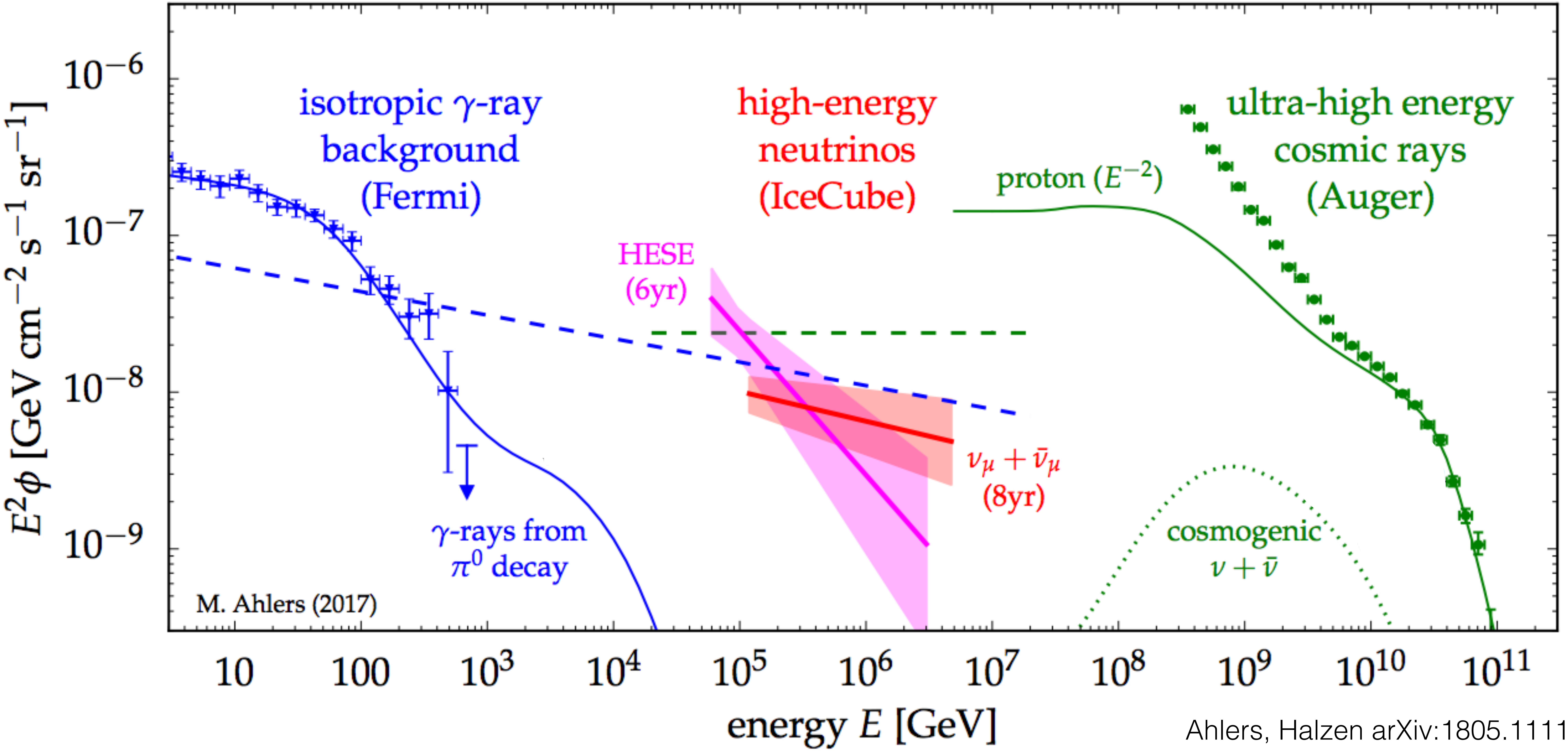


UHECRs produce gamma-rays & neutrinos through interactions *in their source environment* and *in propagation*



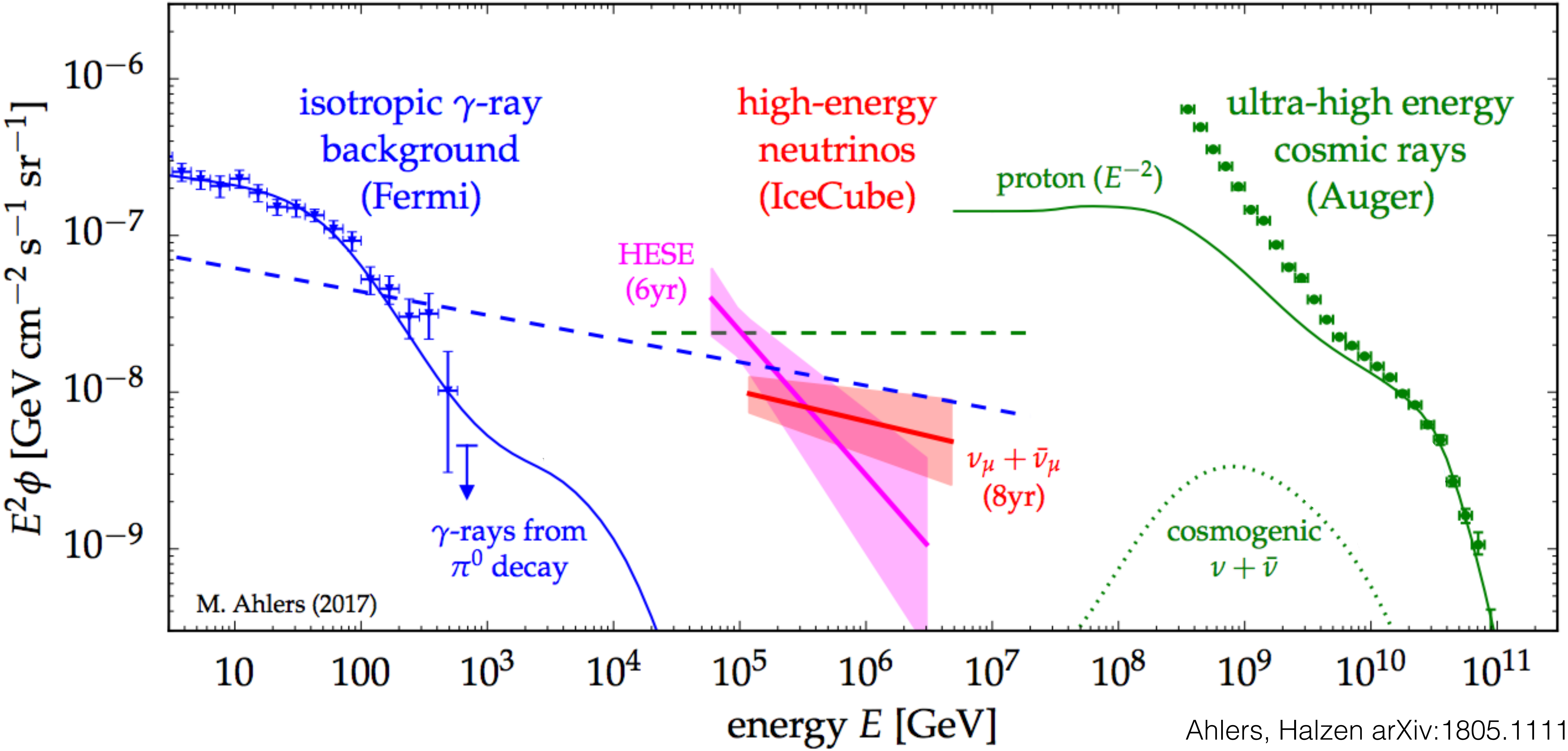
UHECRs produce gamma-rays & neutrinos through interactions *in their source environment* and *in propagation*

We can also constrain UHECR source *environments* using neutrino & gamma-ray data



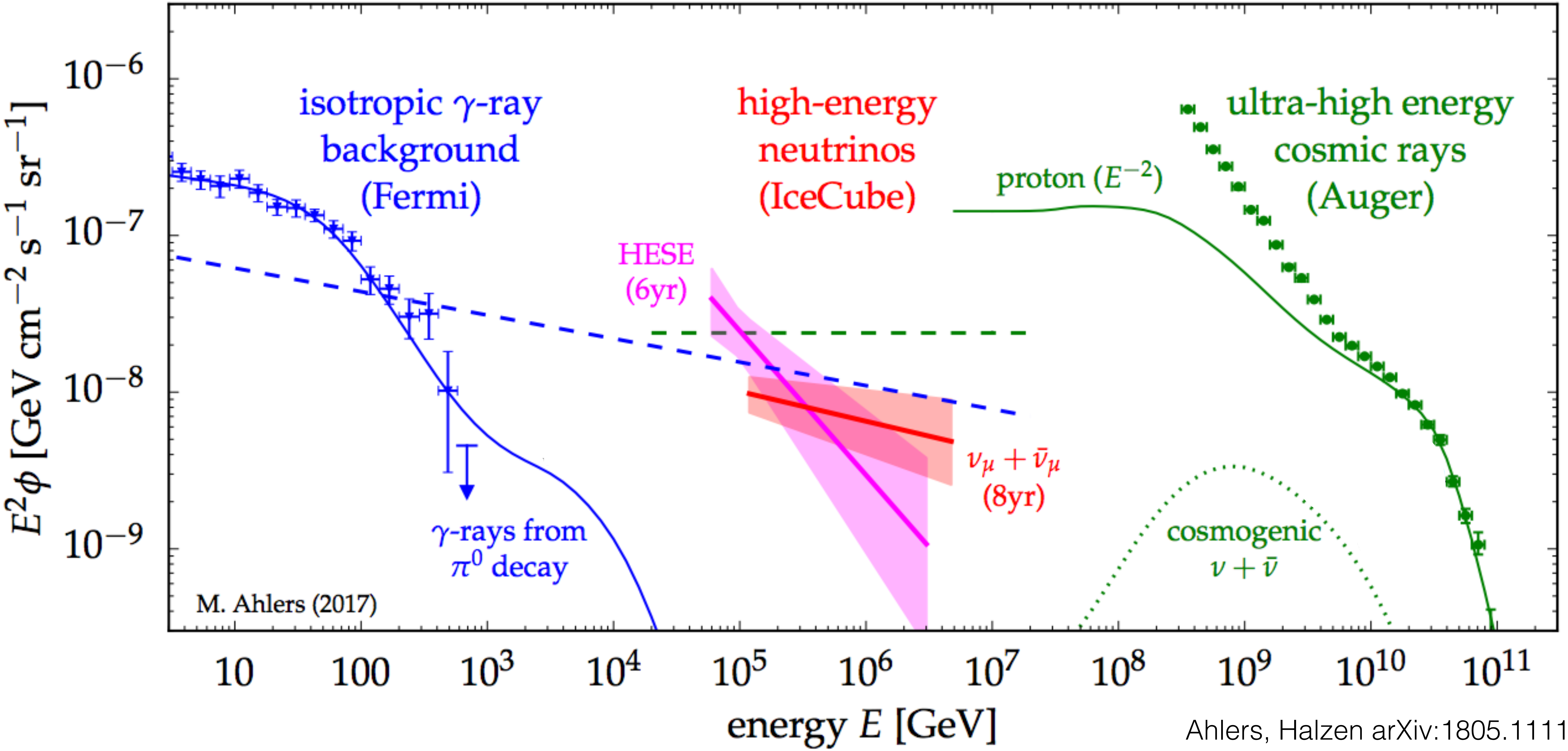
Ahlers, Halzen arXiv:1805.11112

Well-measured UHECR spectrum above ~0.1 EeV



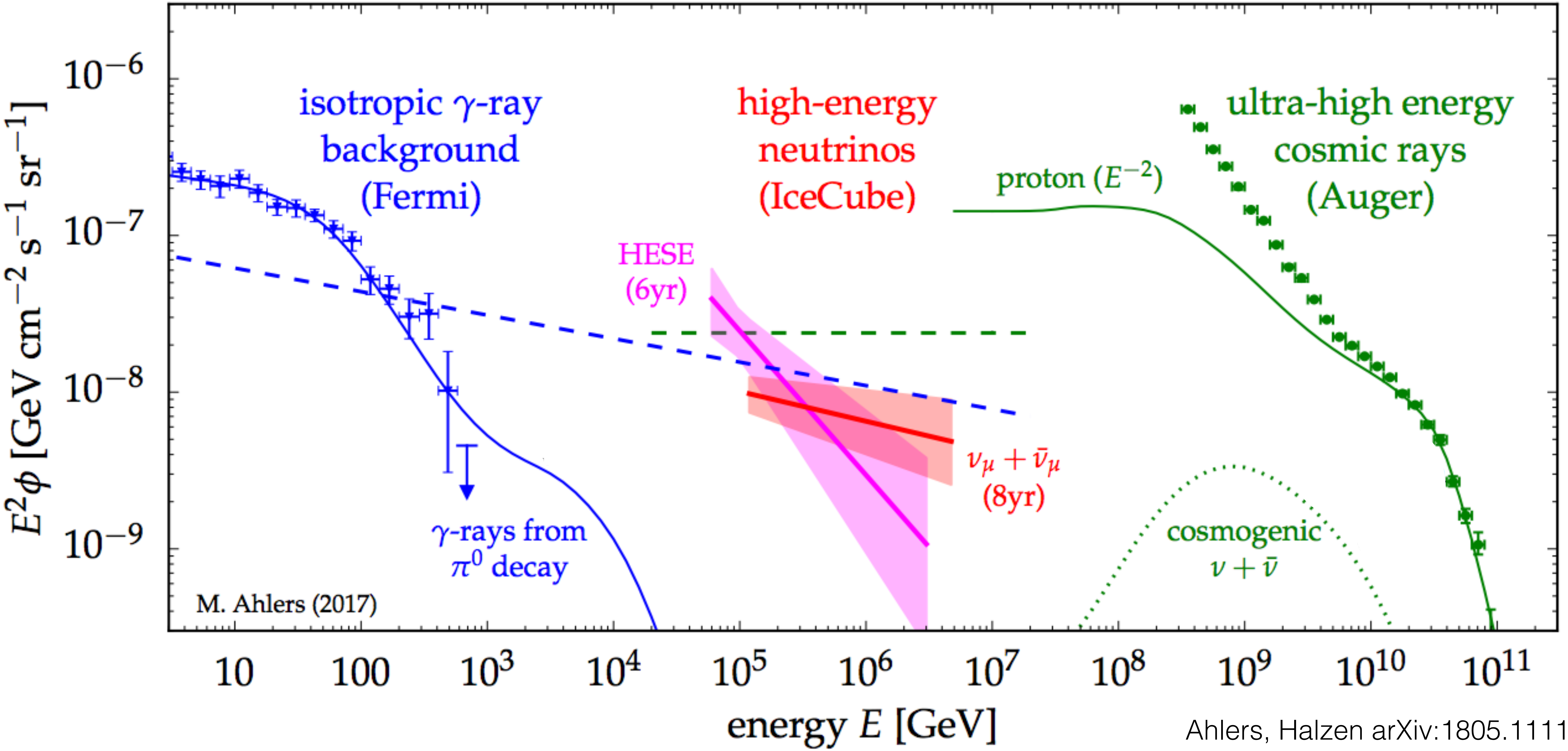
Ahlers, Halzen arXiv:1805.11112

Well-measured extragalactic gamma-ray background up to ~TeV



Ahlers, Halzen arXiv:1805.11112

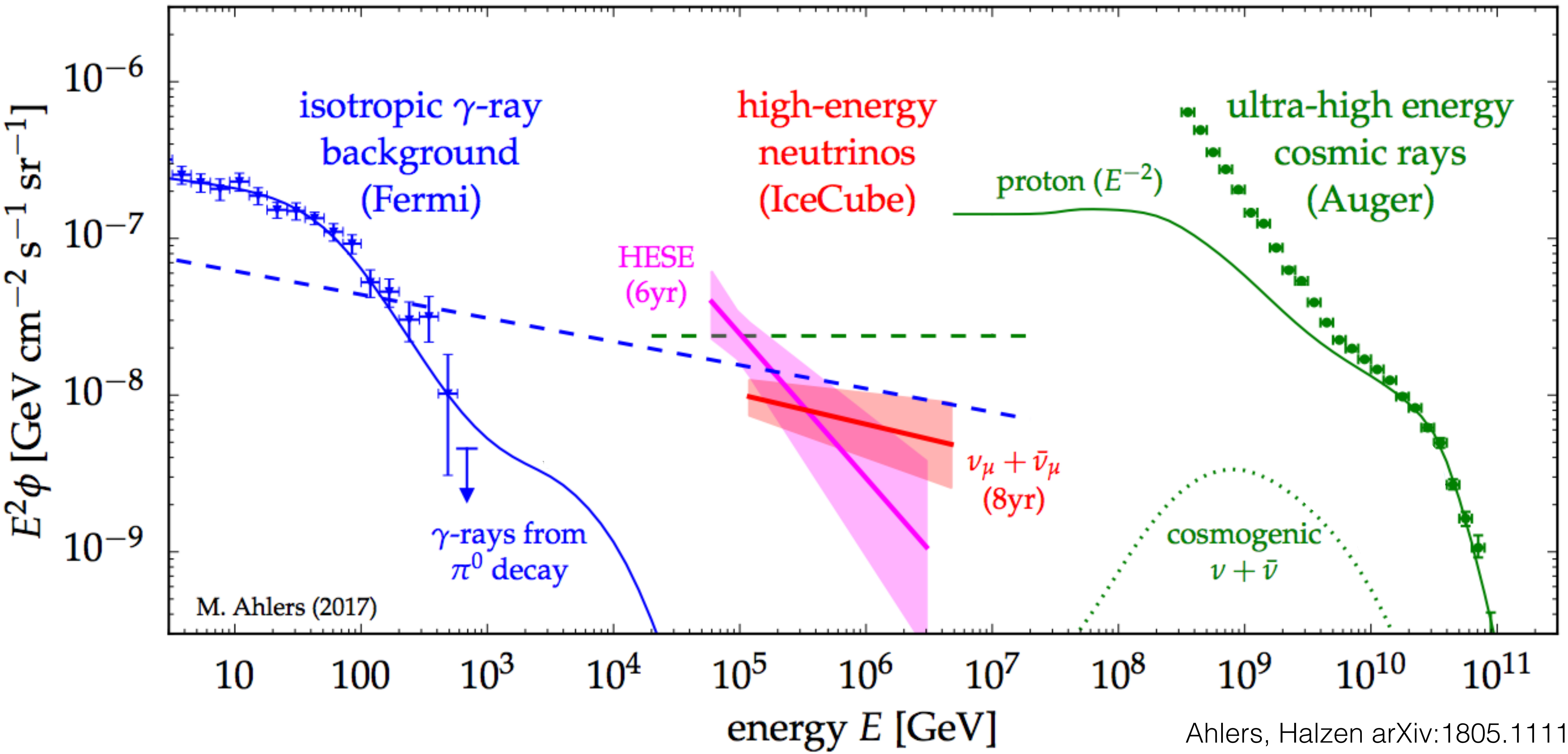
Astrophysical neutrino flux ~100 TeV to ~5 PeV



Ahlers, Halzen arXiv:1805.11112

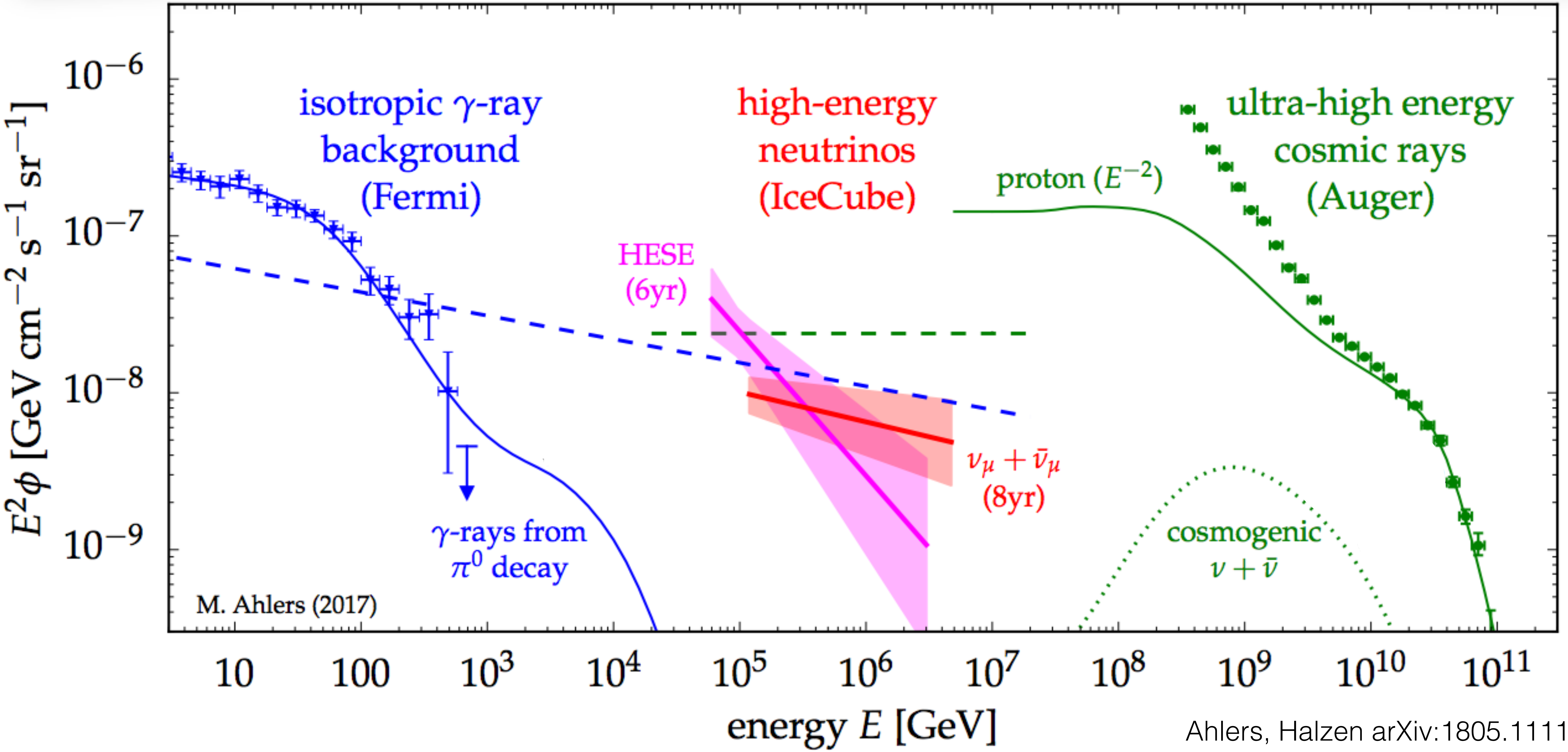
Astrophysical neutrino flux ~100 TeV to ~5 PeV

No neutrinos above ~5 PeV



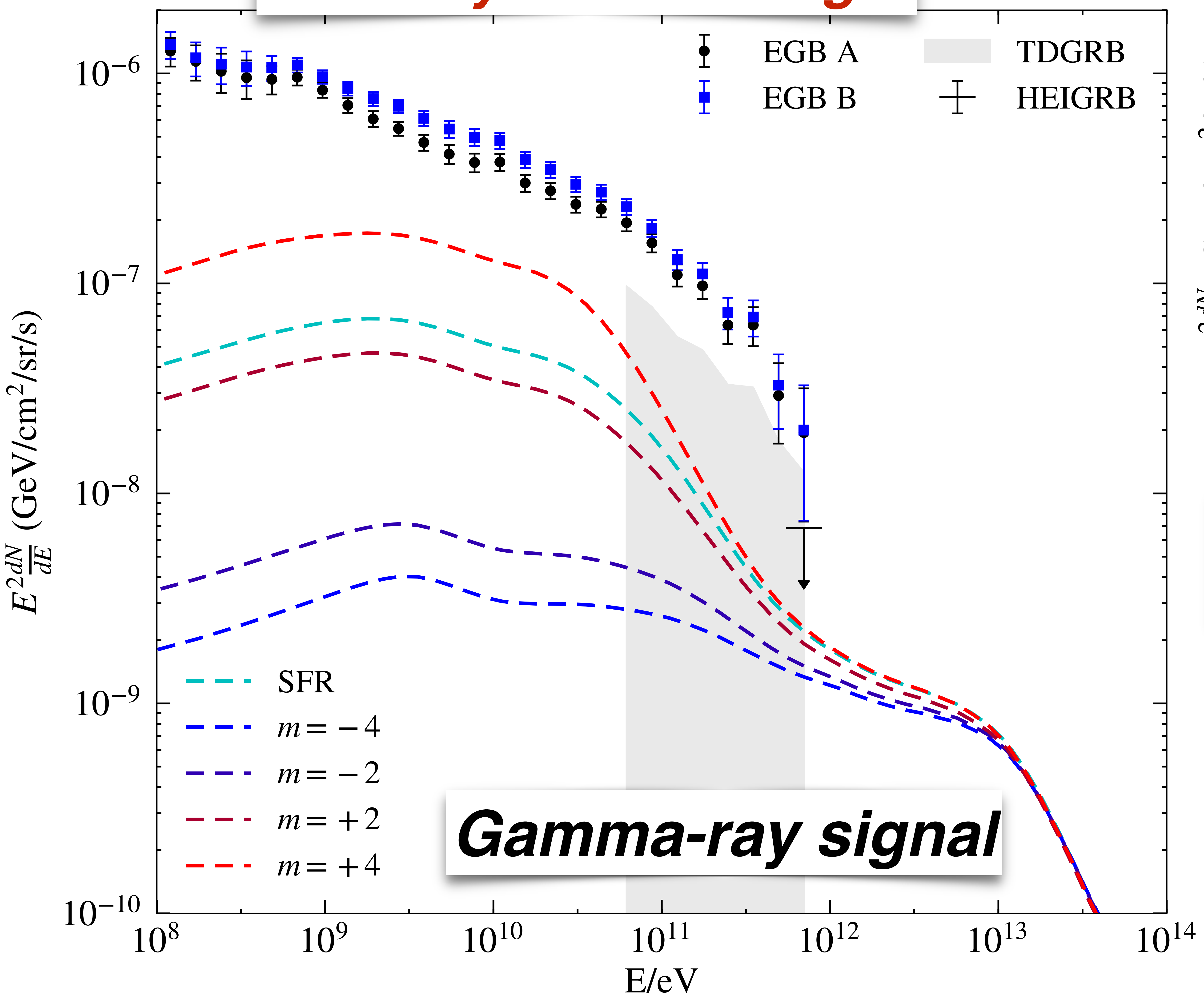
Ahlers, Halzen arXiv:1805.11112

Exclude model parameters that violate multimessenger bounds, constraining UHECR source environments

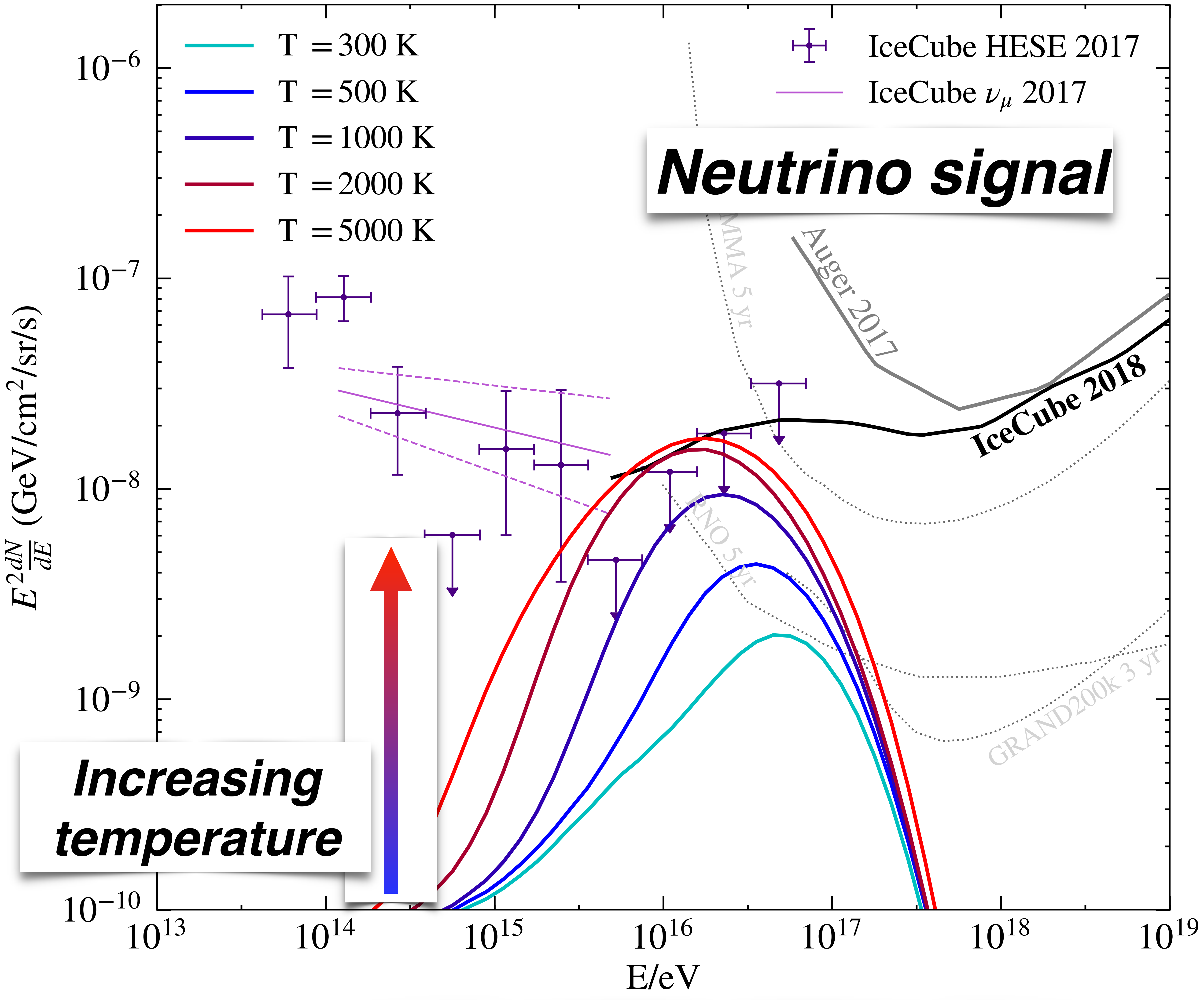


Ahlers, Halzen arXiv:1805.11112

Current Fermi-LAT gamma-ray data only weakly constraining



Gamma-ray signal

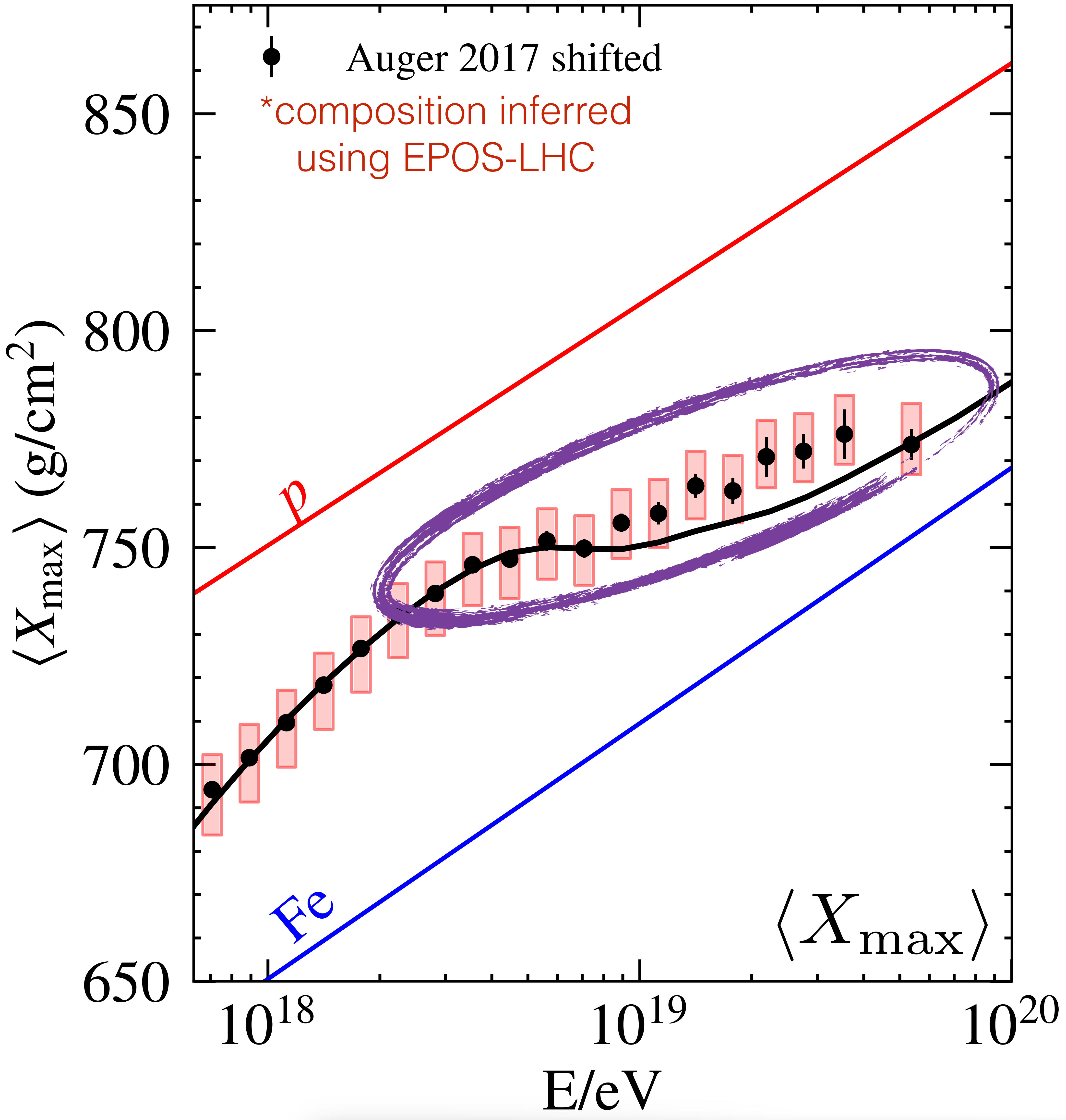


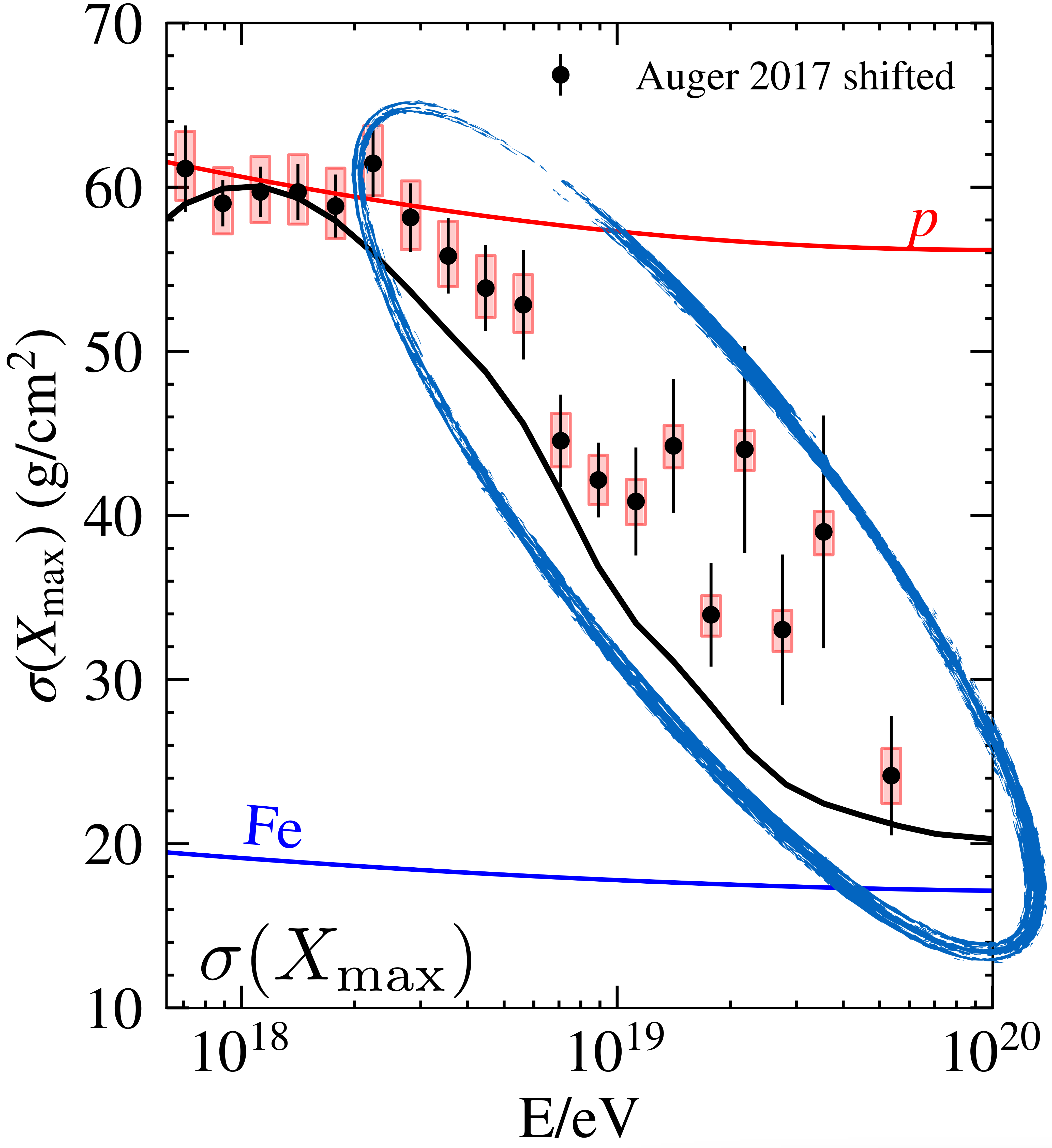
Neutrino signal

Increasing temperature

Neutrino bounds constrain source temperature to be < 4000 K (BPL < 500 meV)

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
- Can neutrinos and gamma-rays constrain this possibility?

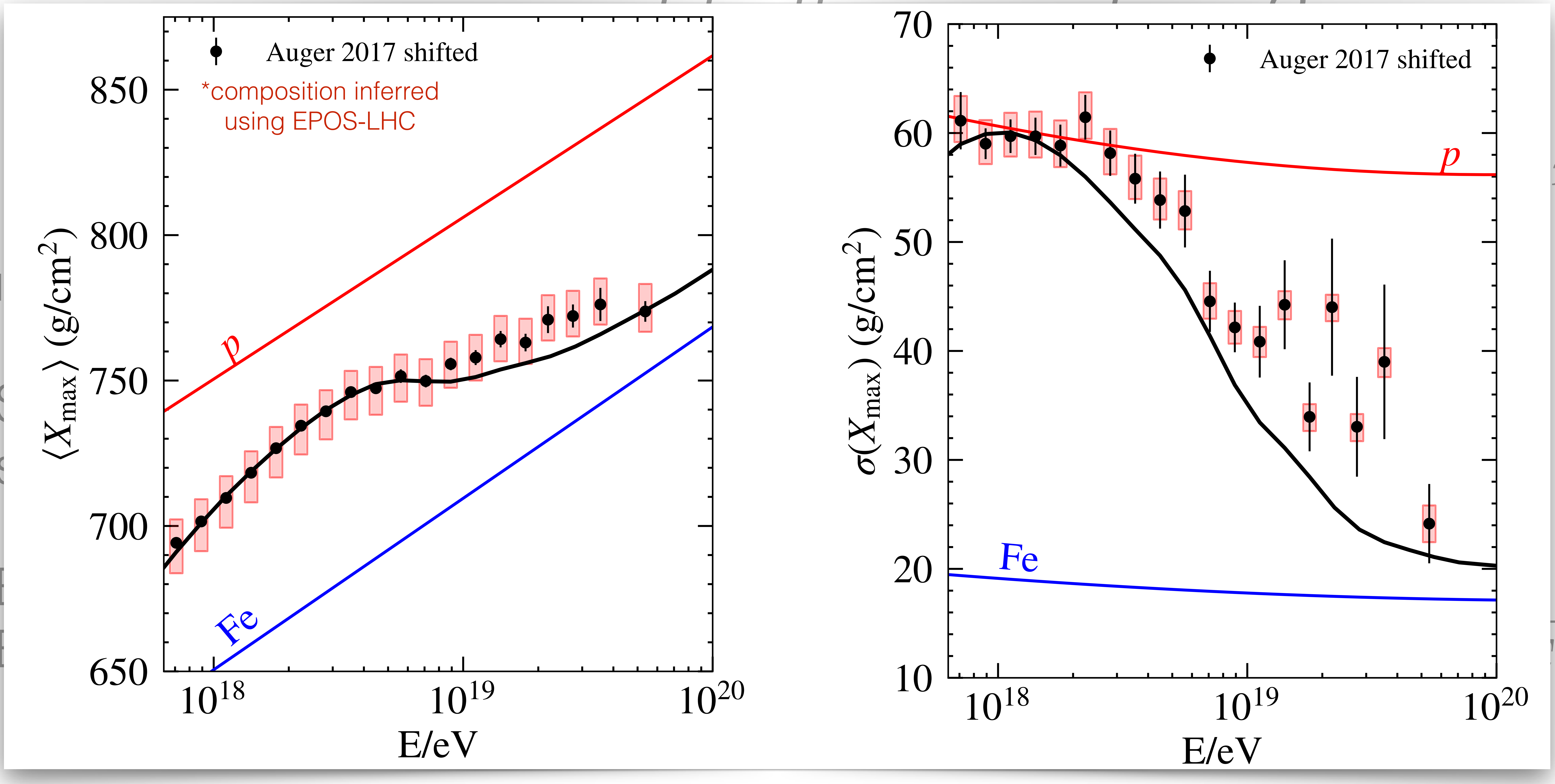
$$\Phi_p \sim f_p E^{-1} e^{-E/E_{max}^{\mathrm{UHE}p}}$$

Measures strength of pure-proton component as:

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

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

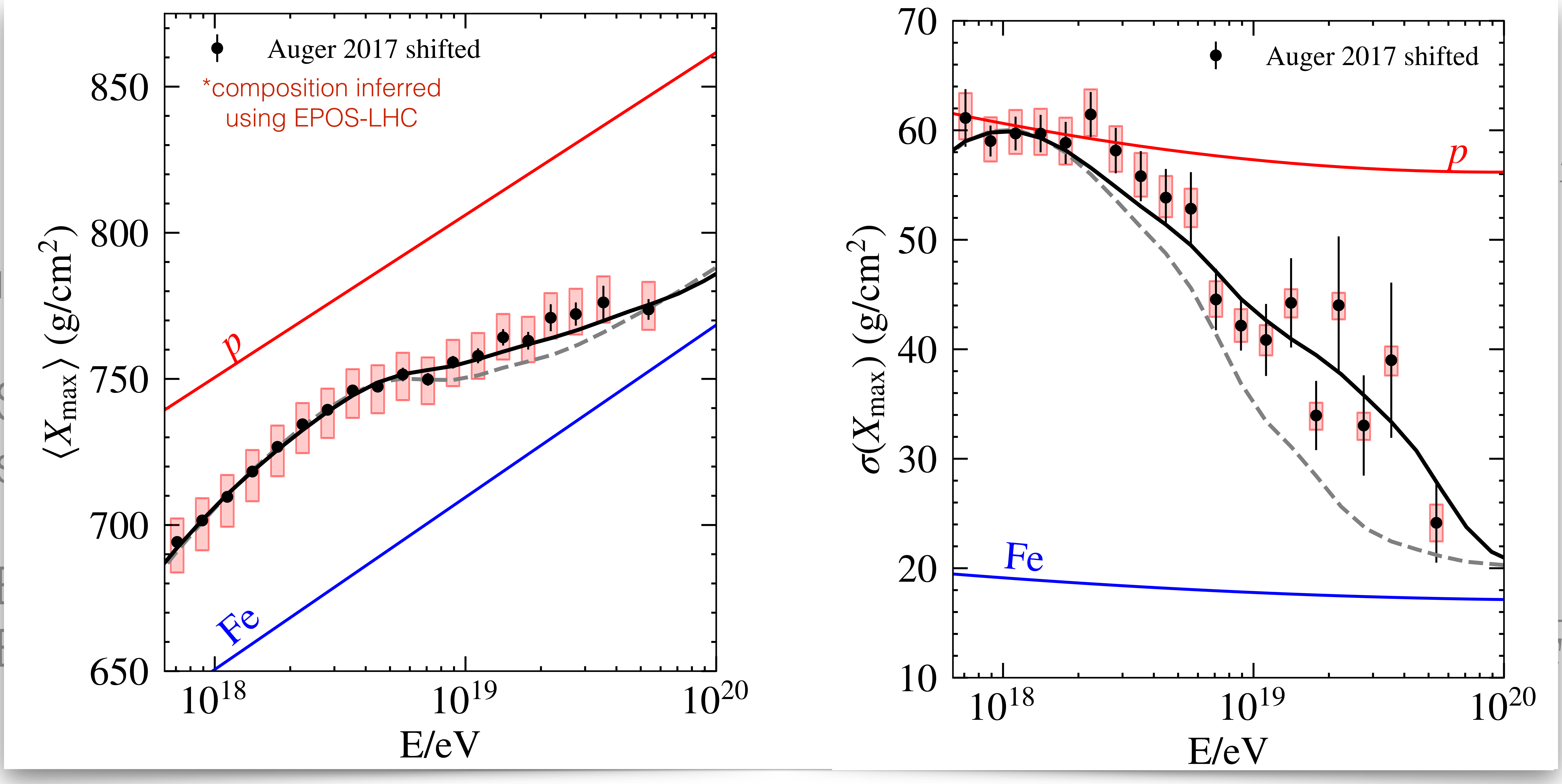
Could there be a pure-proton



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

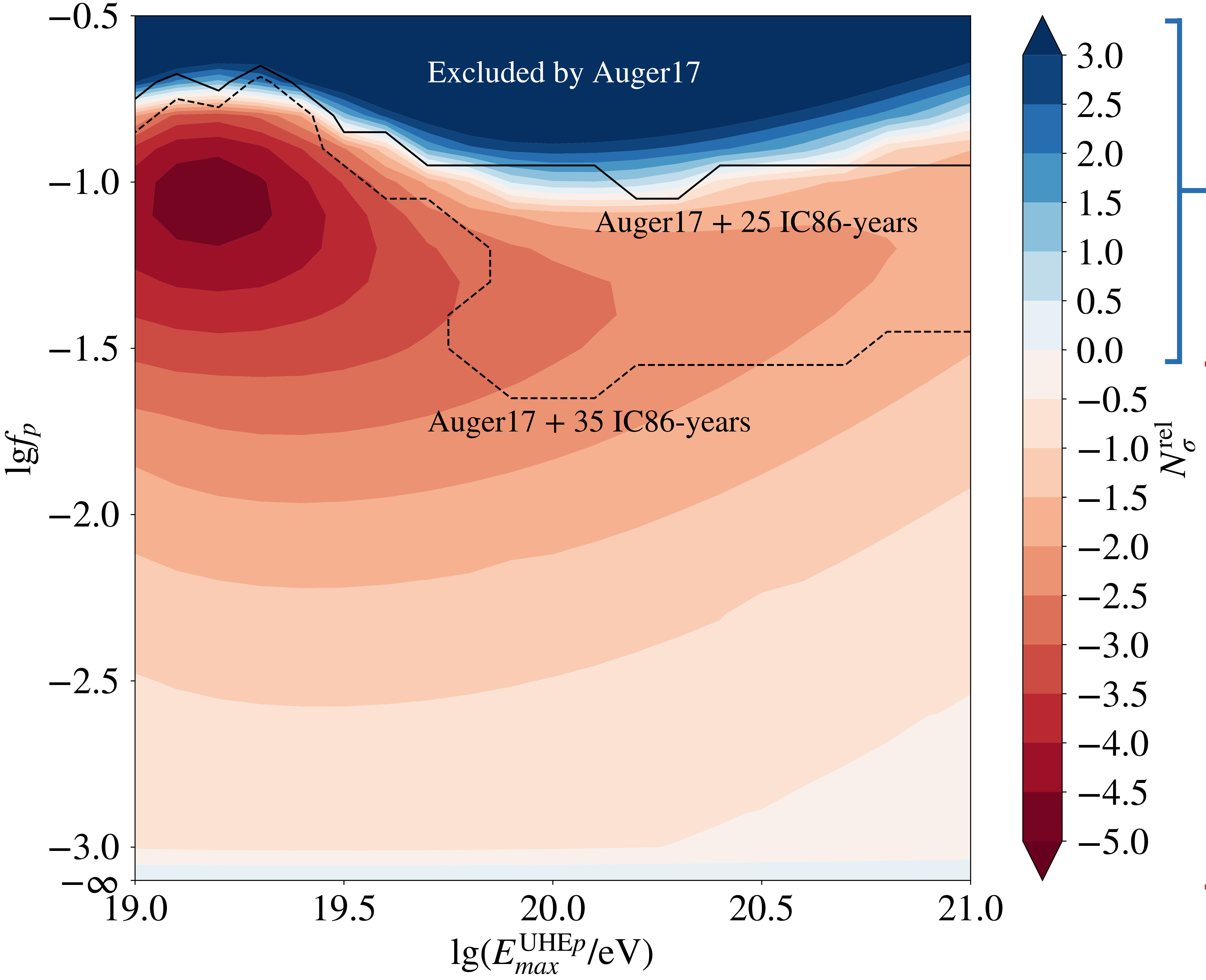
Could there be a pure-proton

- Pu



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

Strength of pure-proton component

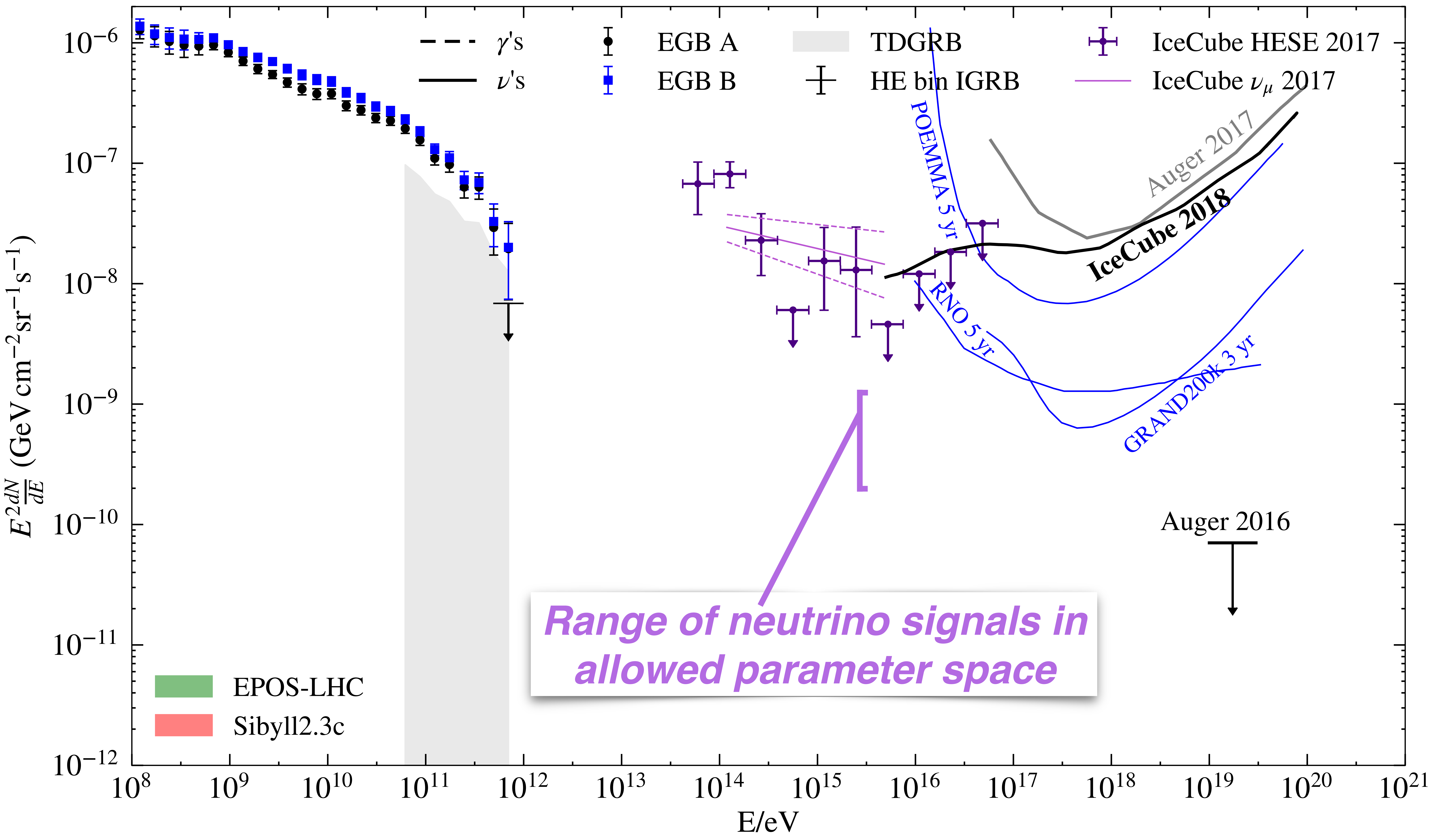


Cutoff Energy

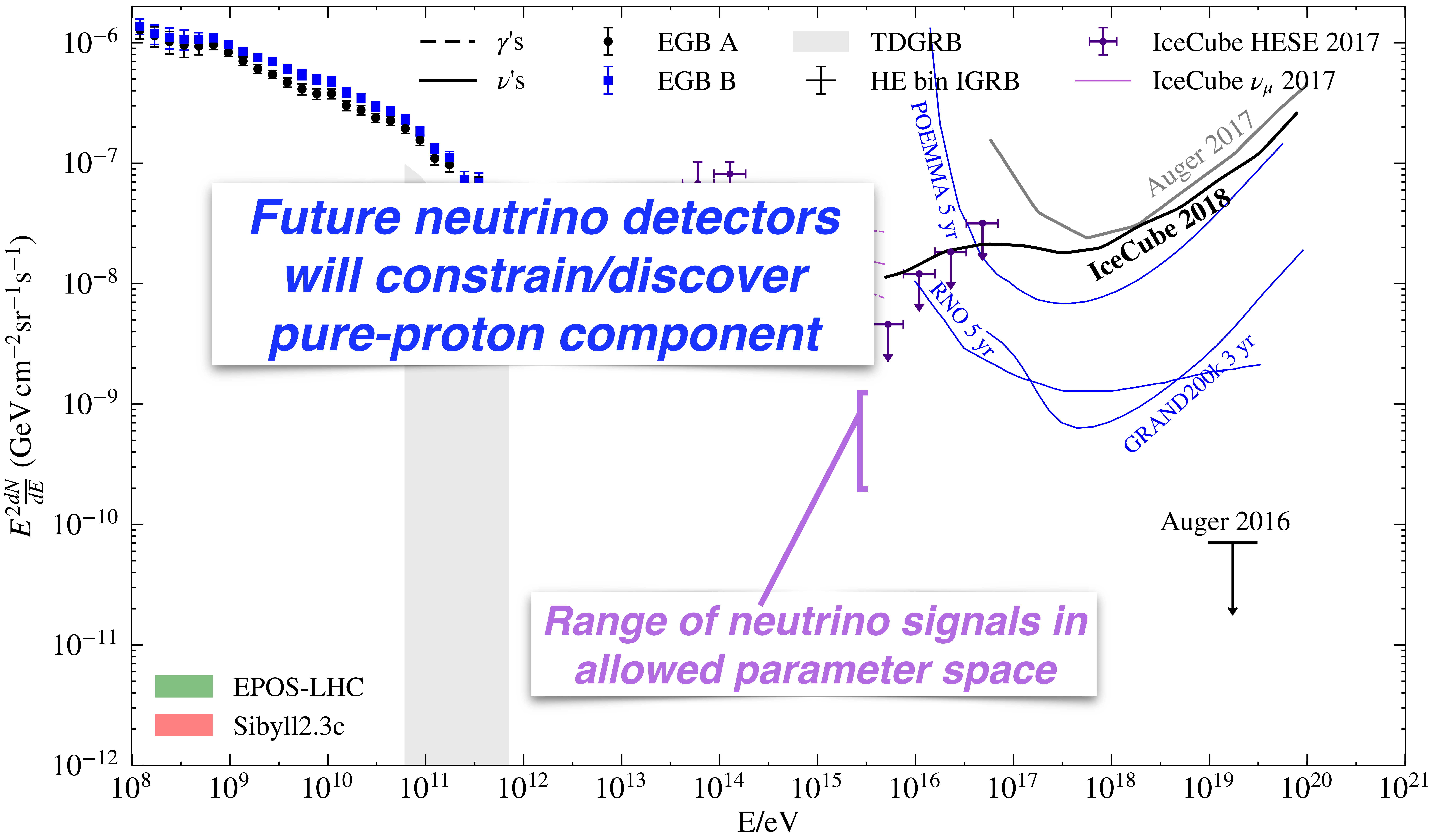
Fit worsened compared to no pure-proton component

Fit improved compared to no pure-proton component

**Actual improvement is hadronic interaction model dependent*



γ's
ν's
EGB A
EGB B
TDGRB
HE bin IGRB
IceCube HESE 2017
IceCube ν_μ 2017
POEMMA 5 yr
Auger 2017
IceCube 2018
RNO 5 yr
GRAND200k 3 yr
Auger 2016
EPOS-LHC
Sibyll2.3c
$E^2 \frac{dN}{dE}$ (GeV cm^{-2}sr^{-1}s^{-1})
E/eV
Range of neutrino signals in allowed parameter space


γ's
ν's
EGB A
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Future neutrino detectors will constrain/discover pure-proton component
POEMMA 5 yr
Auger 2017
IceCube 2018
RNO 5 yr
GRAND200k 3 yr
Auger 2016
Range of neutrino signals in allowed parameter space
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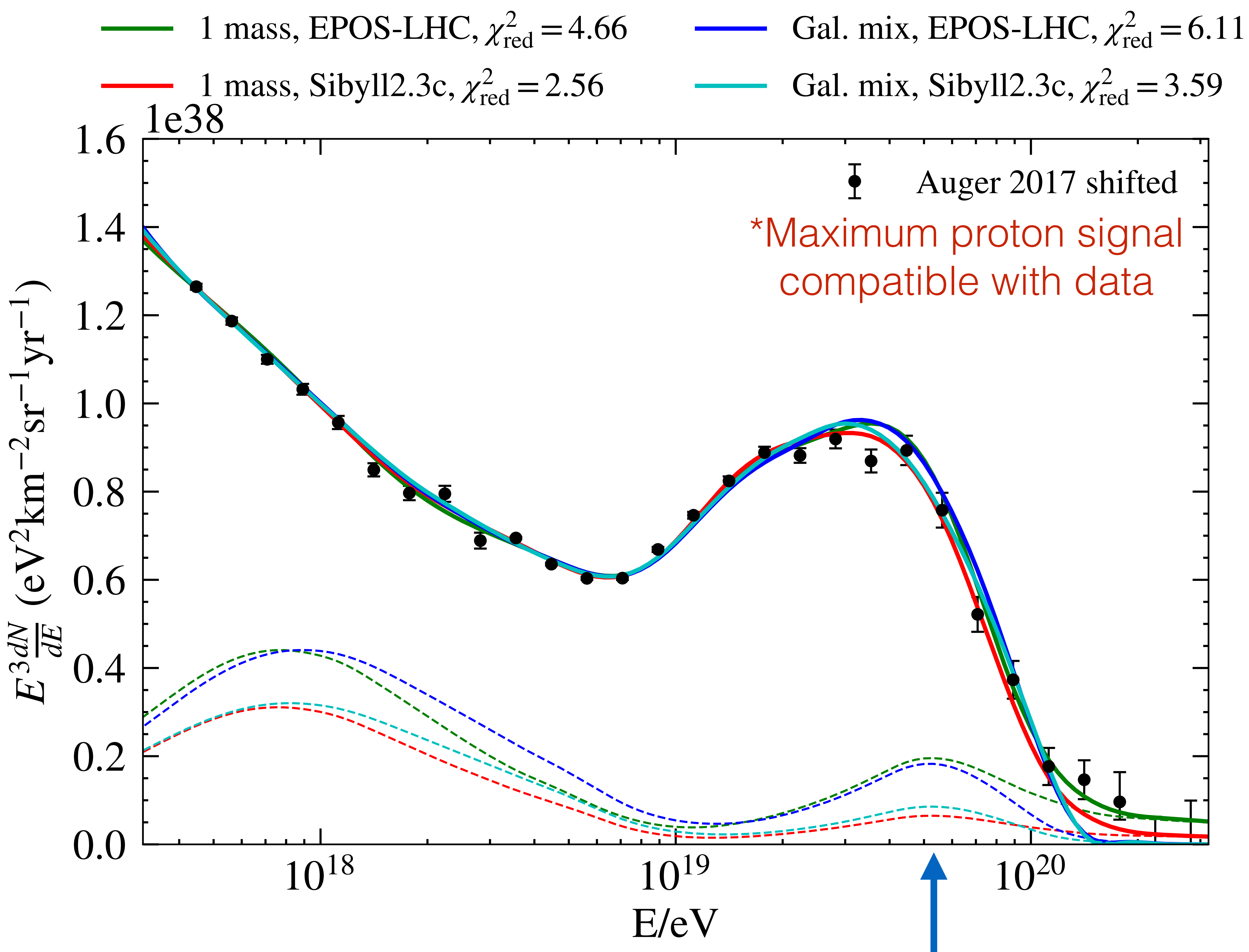
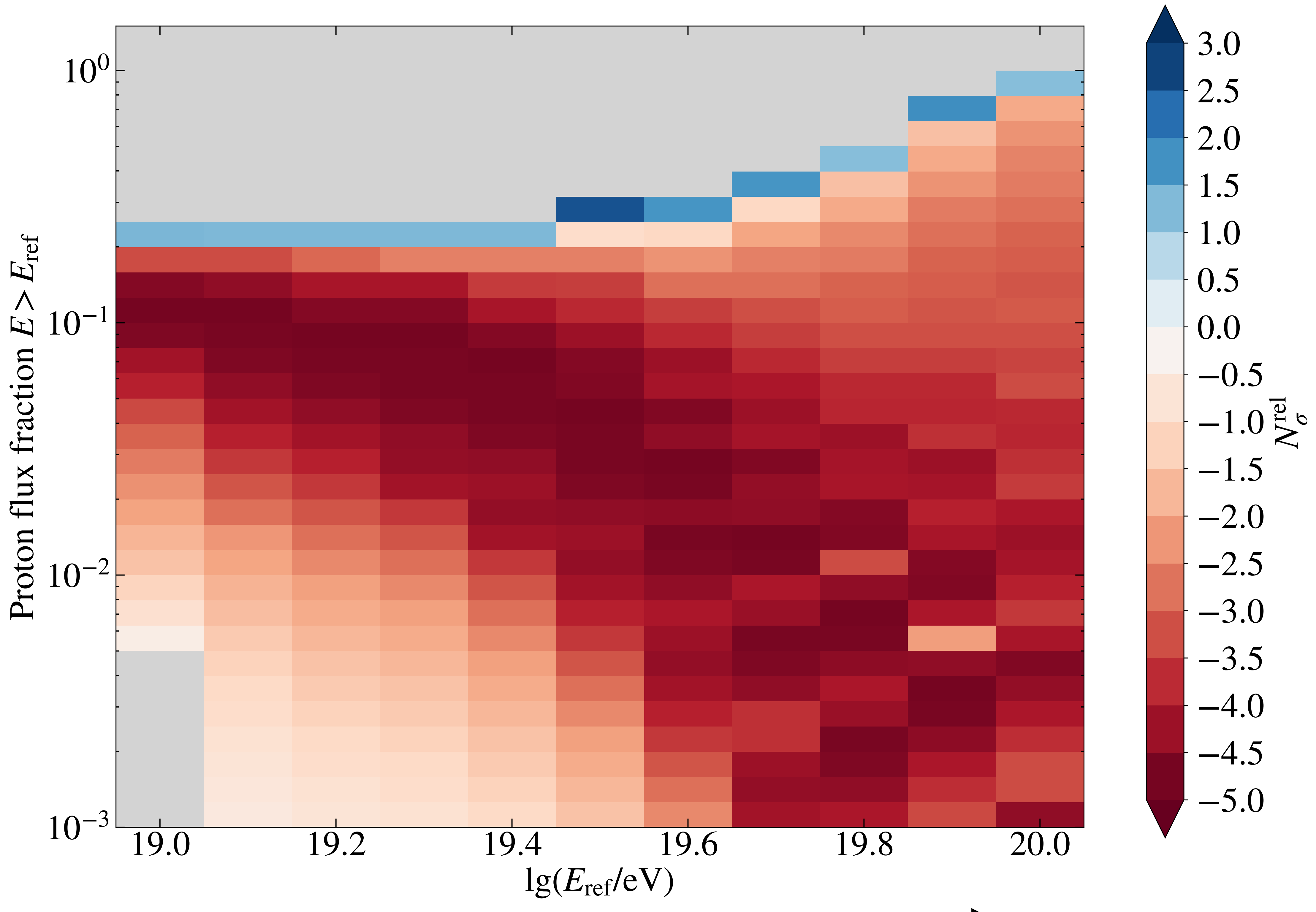
$E^2\frac{dN}{dE}$ (GeV cm^{-2}sr^{-1}s^{-1})
E/eV

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



Observed high energy protons

Observed proton fraction

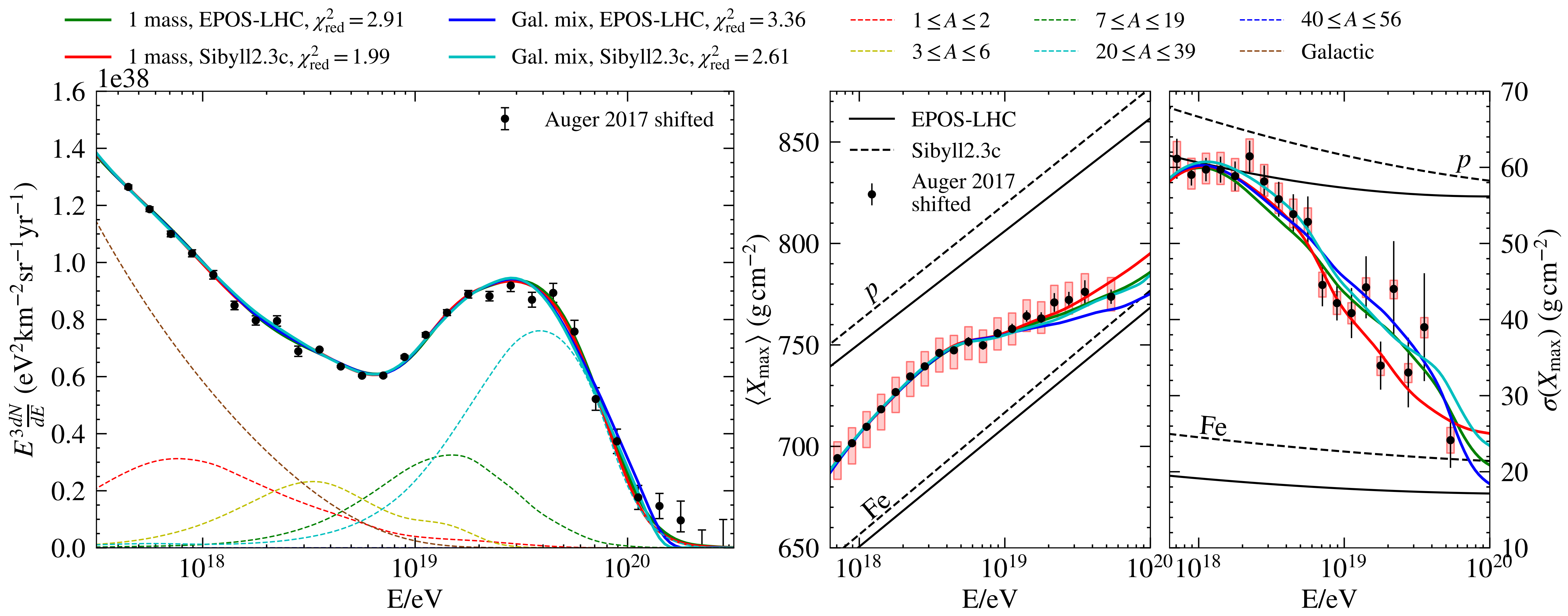


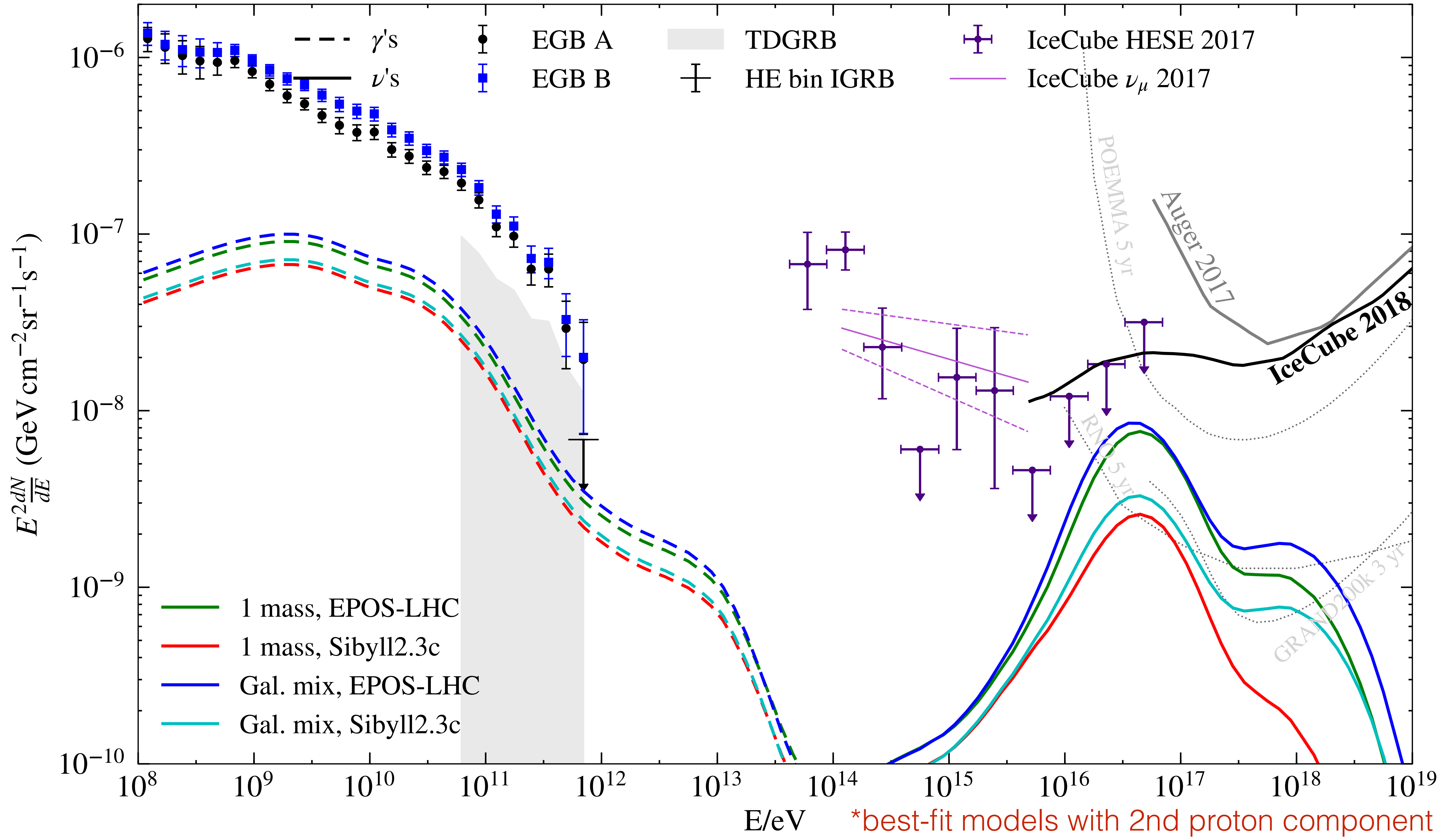
Reference Energy

Summary: Part I

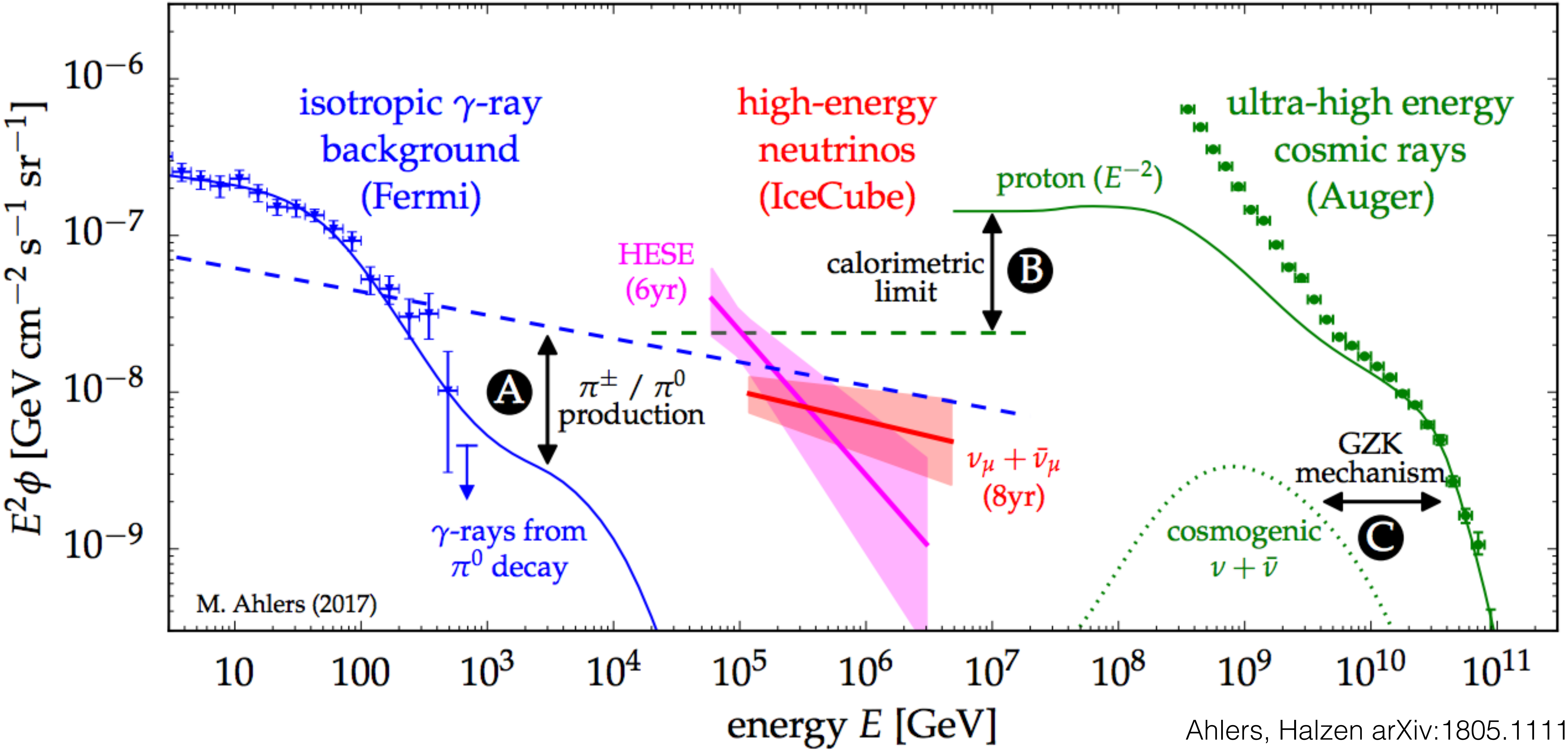
MM et al (2019)
arXiv:1906.06233

- **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 crucial in evidence against pure-proton CR models



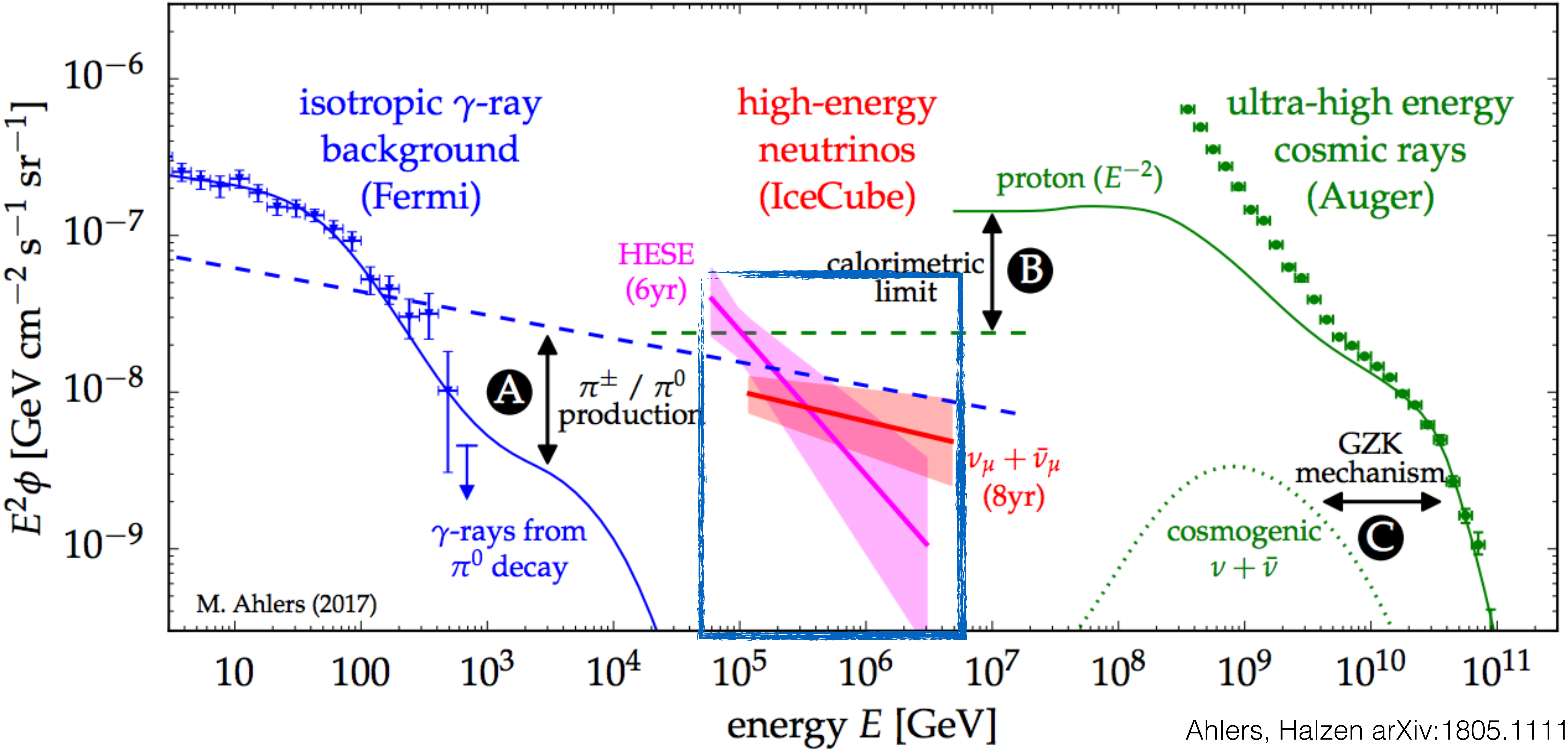


*best-fit models with 2nd proton component



Ahlers, Halzen arXiv:1805.11112

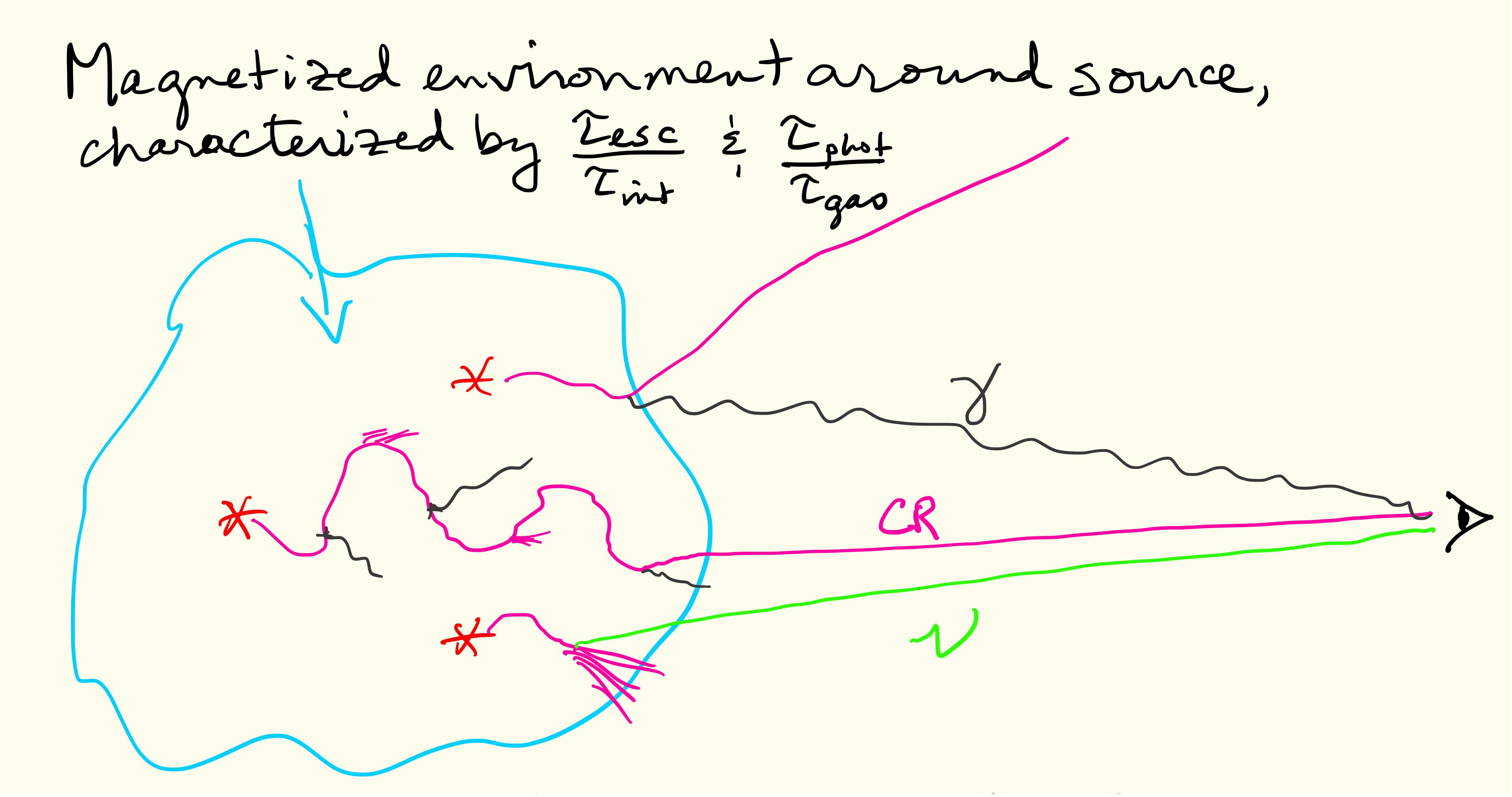
Could astrophysical neutrinos have common origin with UHECRS?



Ahlers, Halzen arXiv:1805.11112

What about gas in the source environment?

- **This work**
  - **Addition of gas in source** environment (single zone) — hadronic interactions
    - Calculated interaction matrices with CRMC using Sibyll2.3c and EPOS-LHC
  - **Realistic rigidity-dependent diffusion coefficient**, allowing for transition between diffusive, Bohm, & ballistic regimes



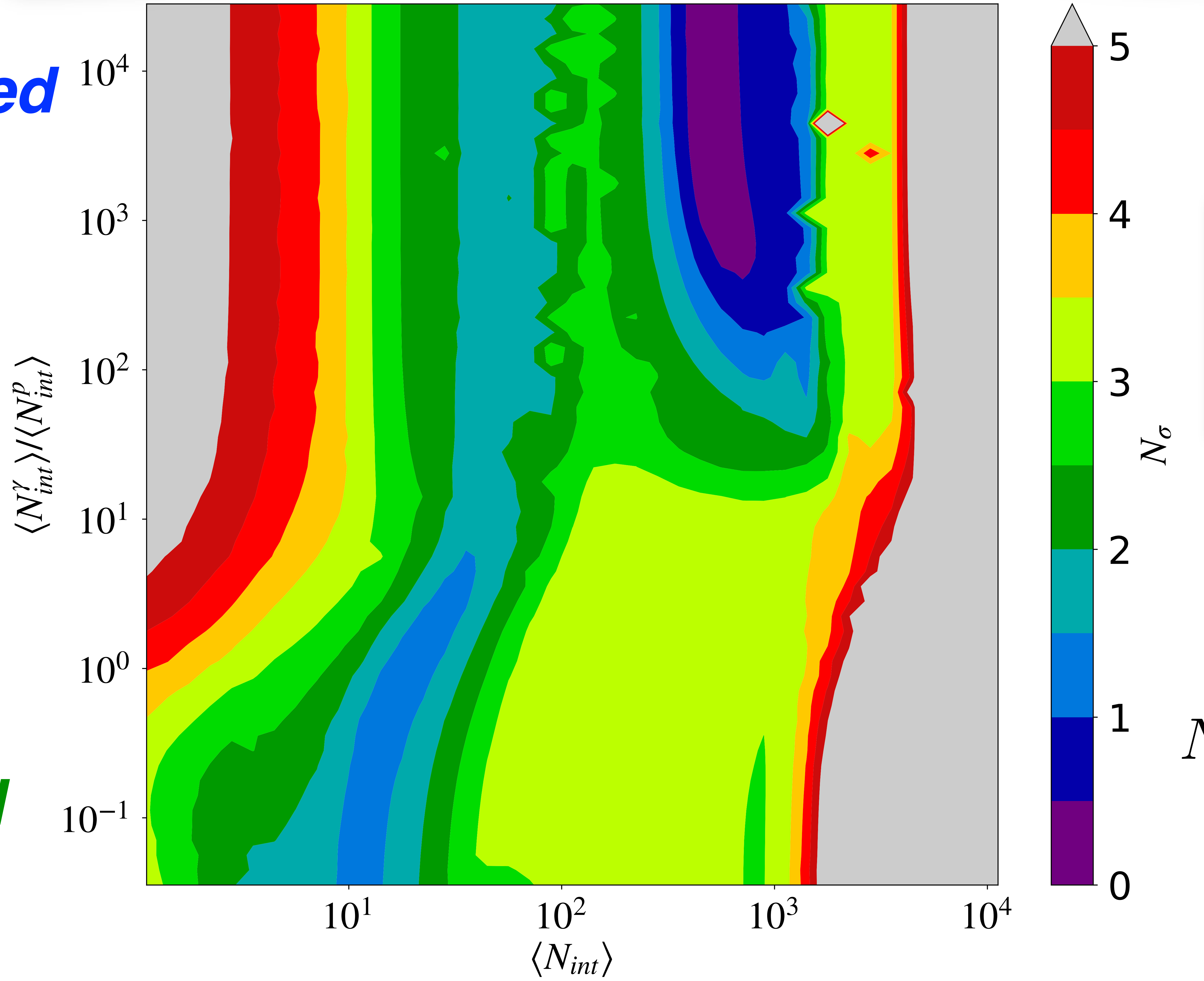
- Model doesn't rely on specific astrophysical model
- Model parameters (10 EeV Fe-56 as the reference)
  - Average # interactions $\langle N_{int} \rangle$
  - Ratio of photon-to-gas interactions $\frac{\langle N^{\gamma}_{int} \rangle}{\langle N^{p}_{int} \rangle}$
- Preferred astrophysical properties constrained by model parameters

Both gas- and photon-dominated sources can give good fits to CR data

CRs: No clear preference between gas- and photon-dominated sources

Photon dominated

Gas dominated

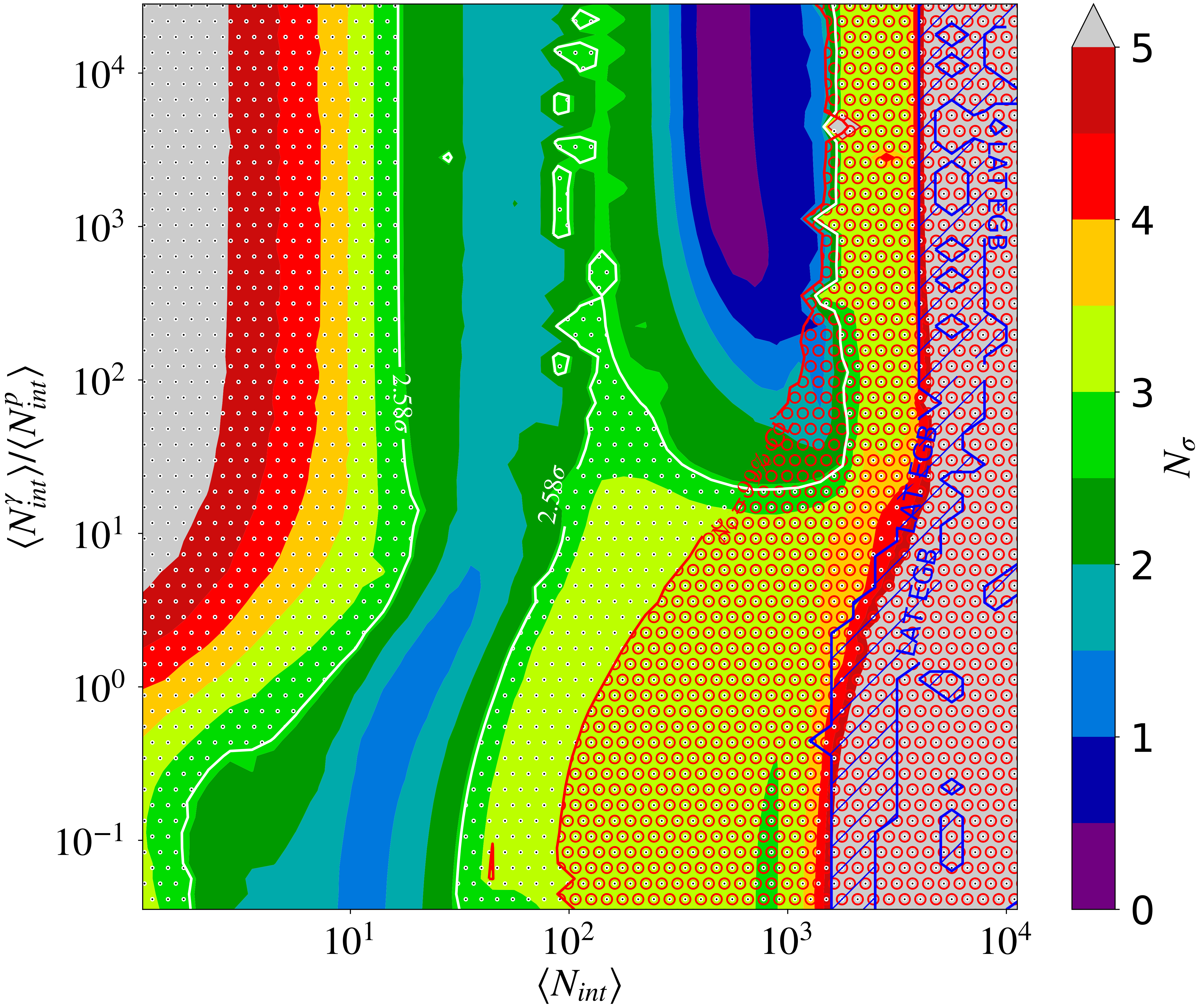


Average number of interactions

Photon-dominated sources less constrained

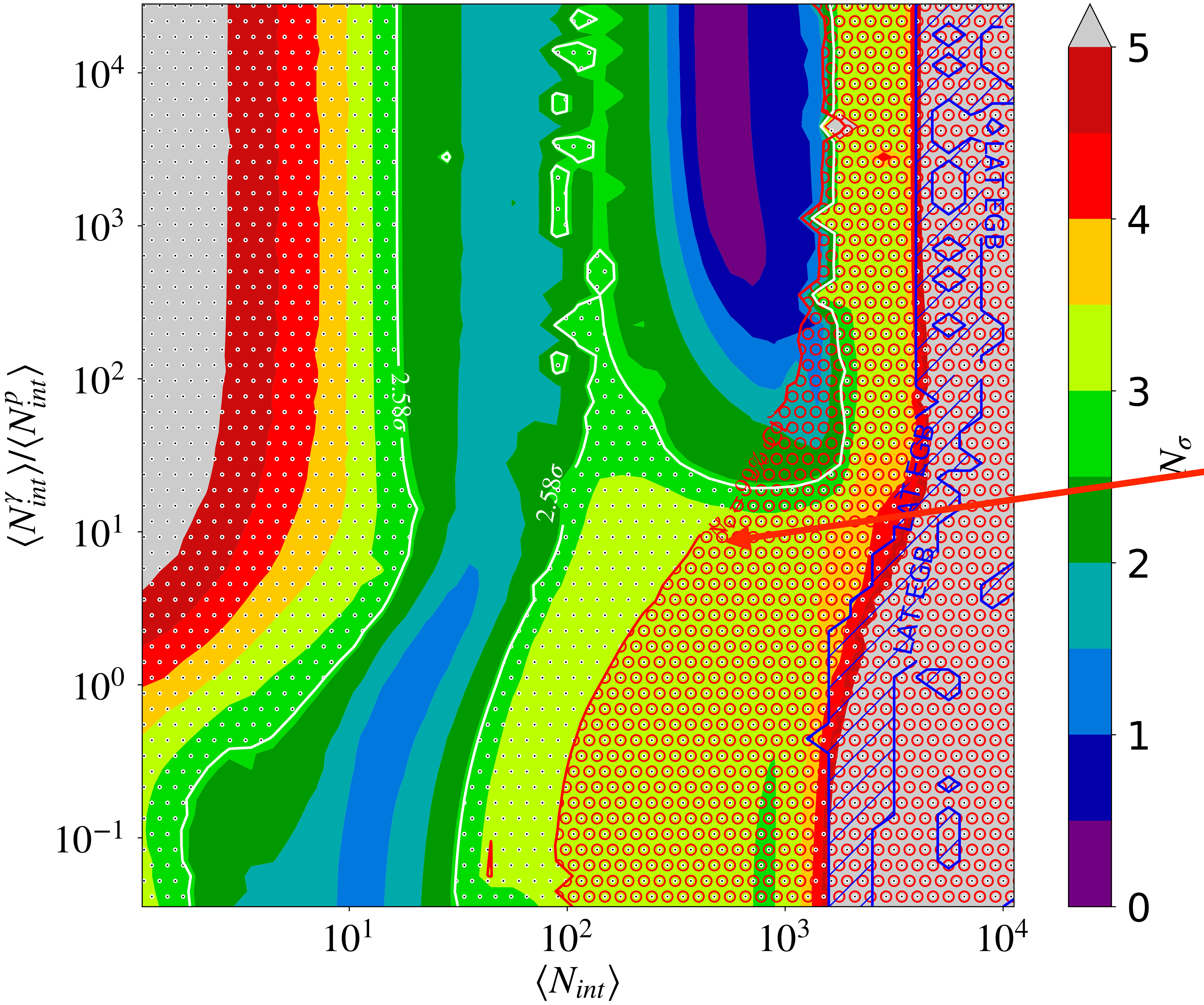
$$N_\sigma = \sqrt{N_{dof}\frac{(\chi^2 - \chi^2_{min})}{\chi^2_{min}}}$$

Multimessenger Constraints



Multimessenger Constraints

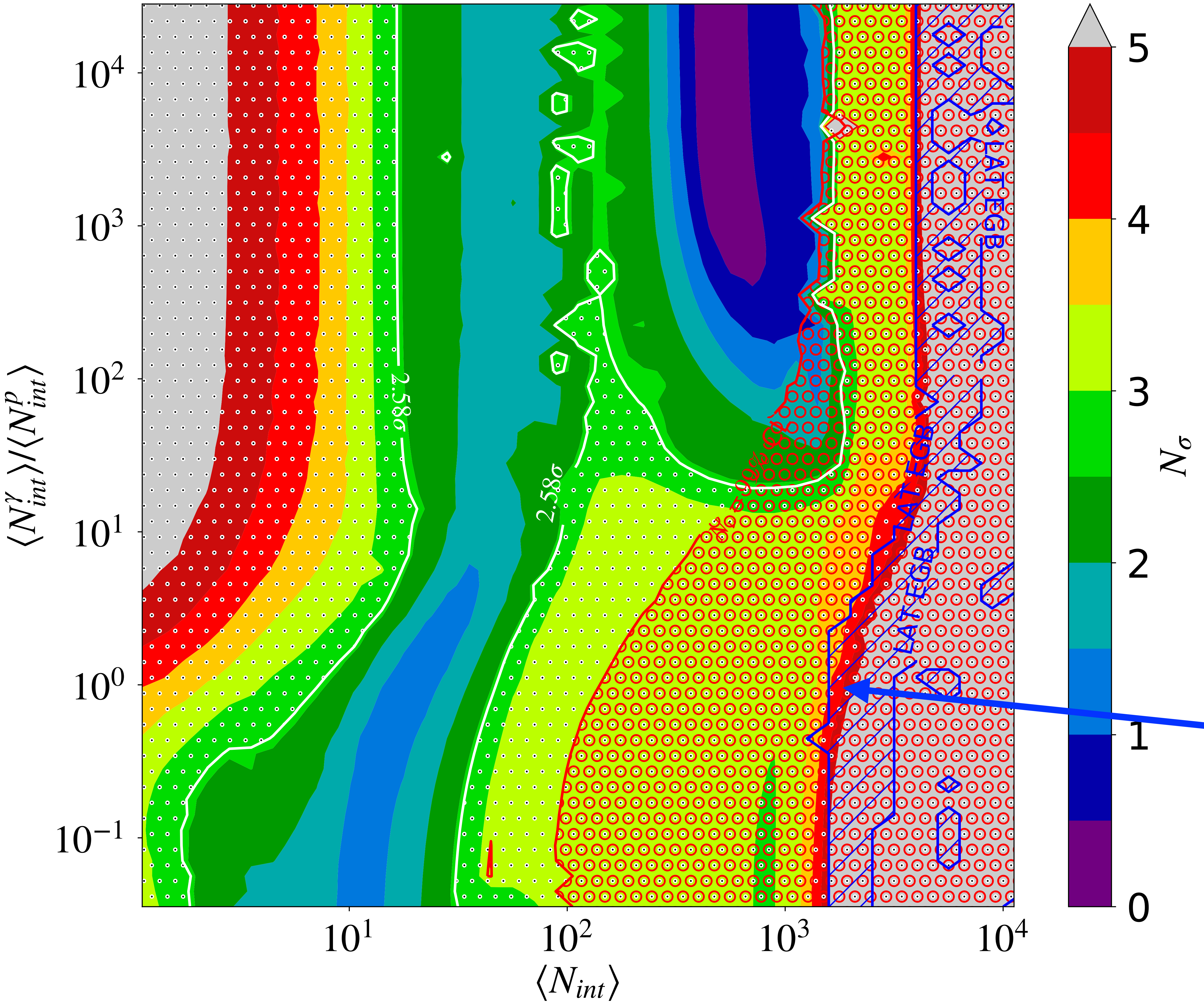
Multimessenger Constraints



$N_\sigma > 2.58$ **UHECR Constraint**

$N_\nu > 4.77$ **UHE ν Constraint**

Multimessenger Constraints

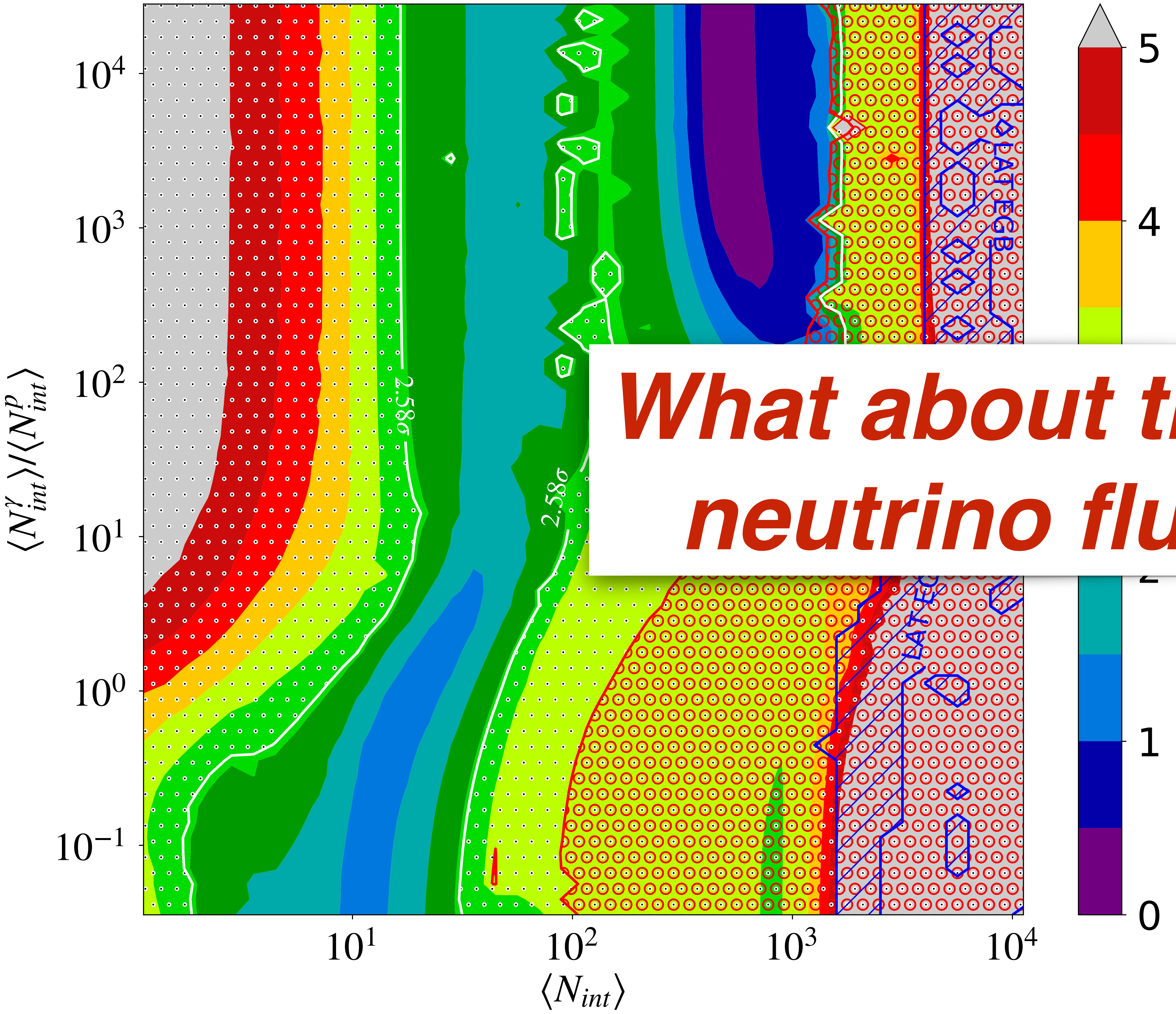


$N_\sigma > 2.58$ **UHECR Constraint**

$N_\nu > 4.77$ **UHE ν Constraint**

γ-ray flux > EGB + 1σ
(always weaker than ν-bound)

Multimessenger Constraints



$N_\sigma > 2.58$ **UHECR Constraint**

What about the astrophysical neutrino flux description?

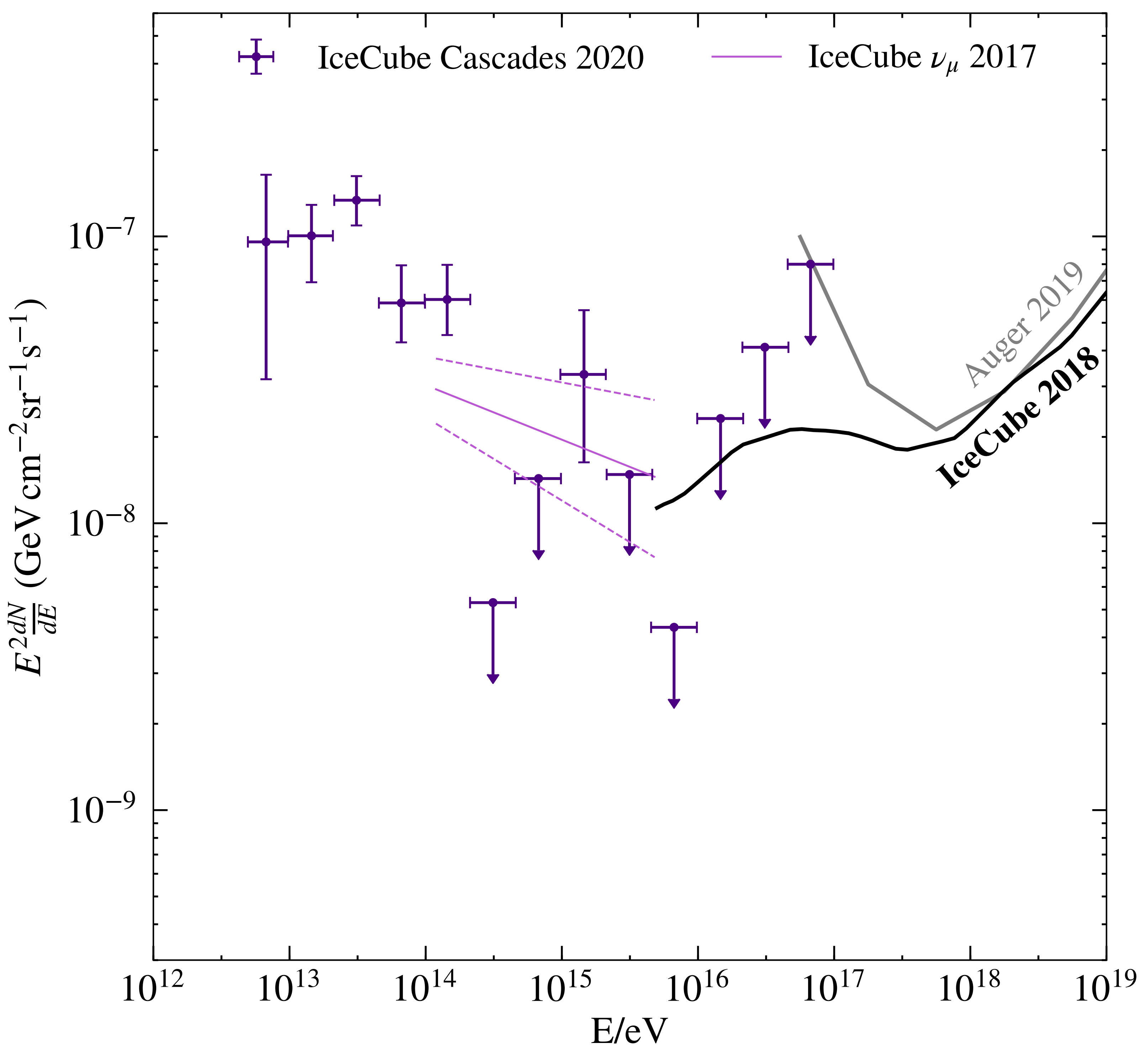
HE ν Constraint

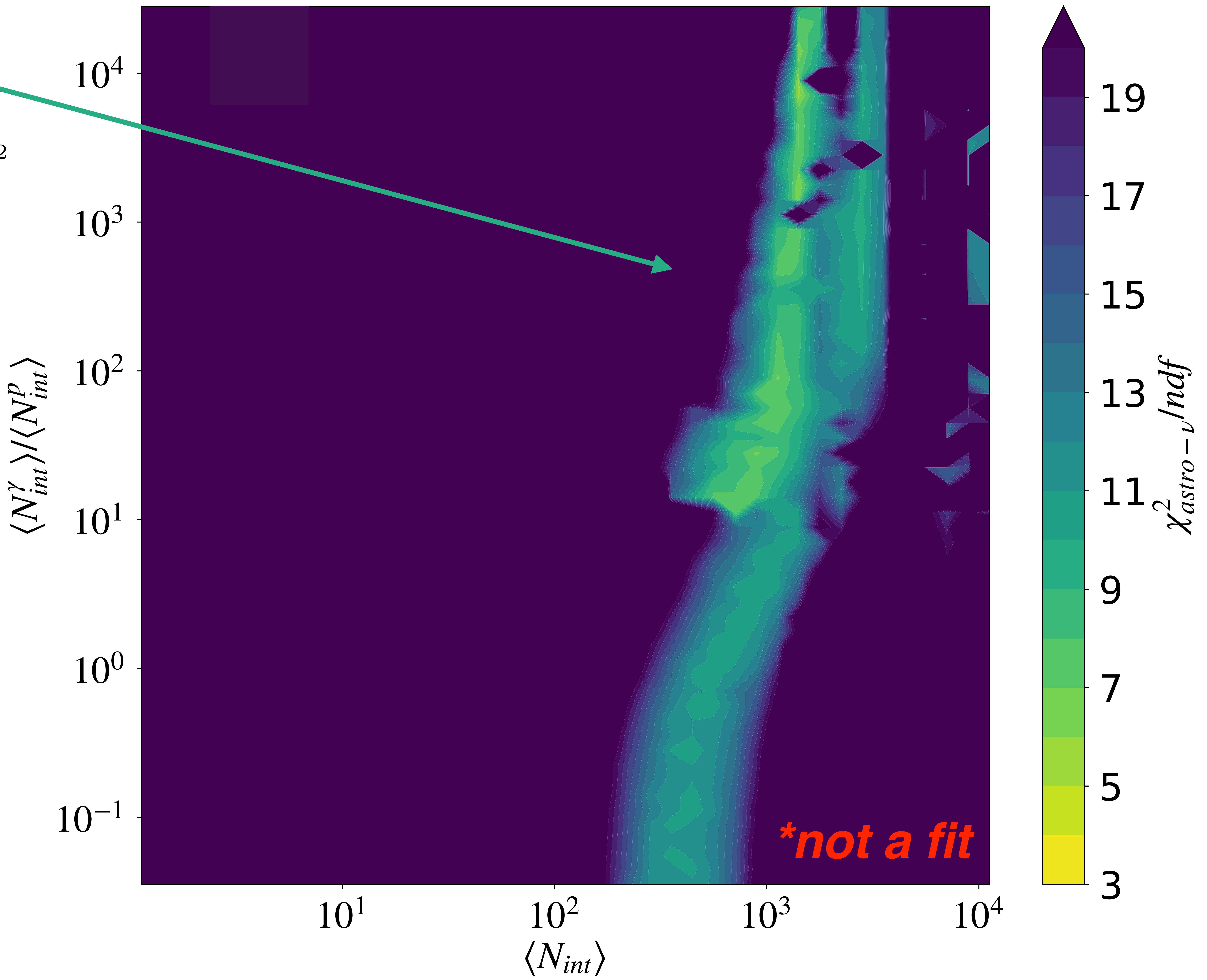
γ-ray flux > EGB + 1σ (always weaker than ν-bound)

$$\chi^2_{\mathrm{astro}-\nu} = \chi^2_{\log} + \sum_i 2n_i$$

$$\chi^2_{\log} = \sum_i \left(\frac{\log_{10}(y_i) - \log_{10}(m_i)}{\log_{10}(y_i + \sigma_i^{\mathrm{up}}) - \log_{10}(y_i - \sigma_i^{\mathrm{lo}})} \right)^2$$

n_i = predicted number of events in bins with zero observed events

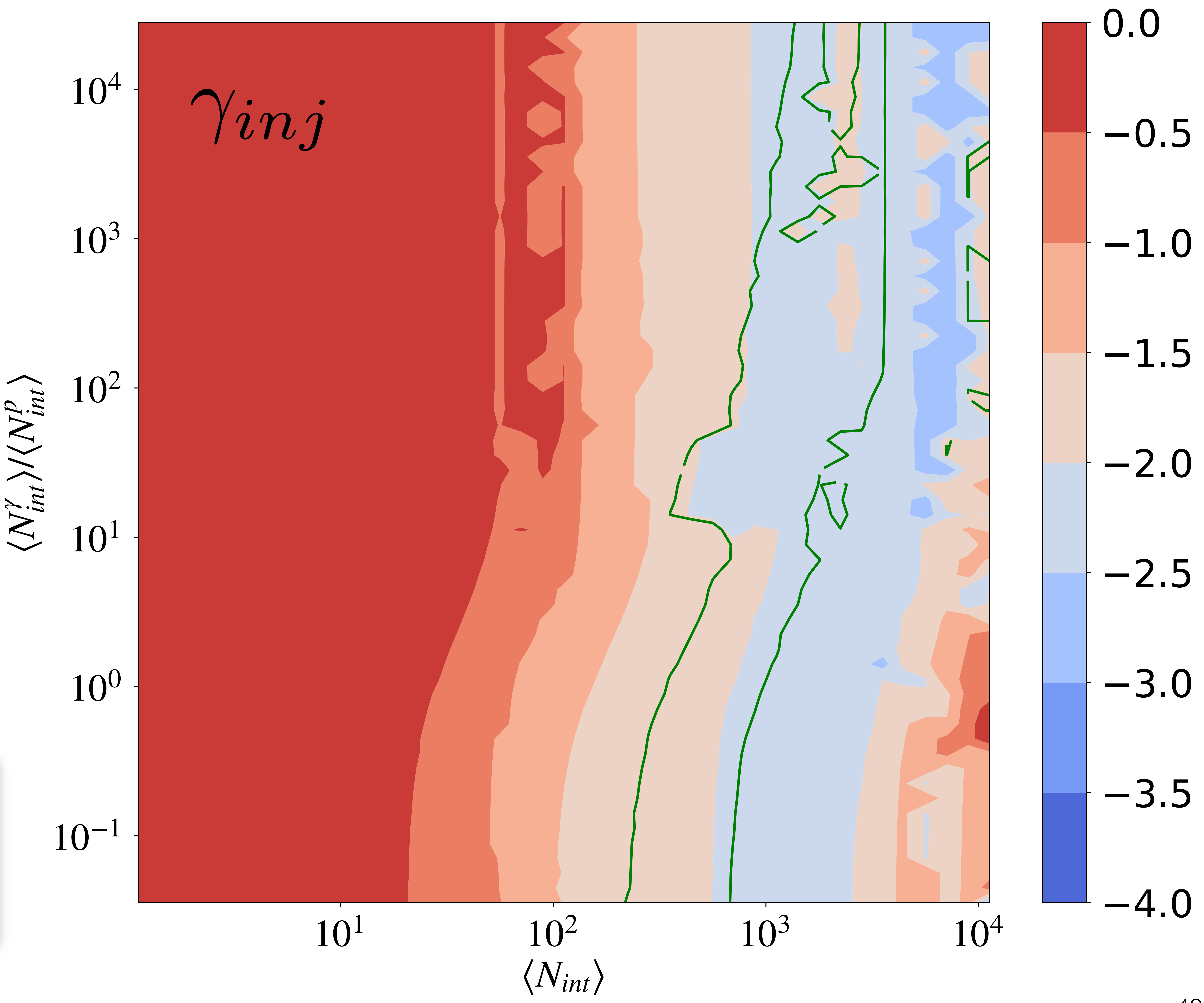


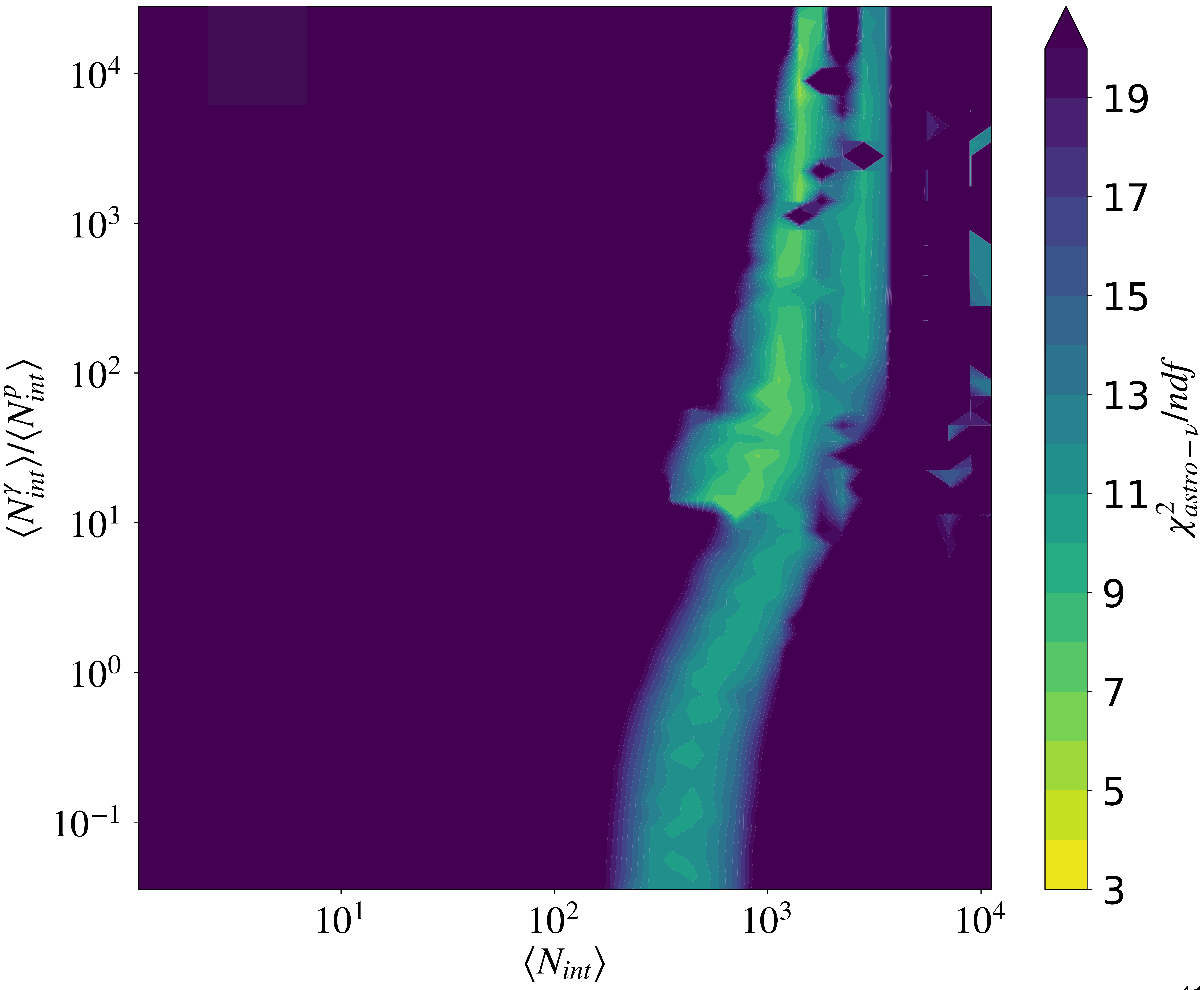


$$\phi \sim E^{\gamma_{inj}} e^{-E/E_{max}}$$

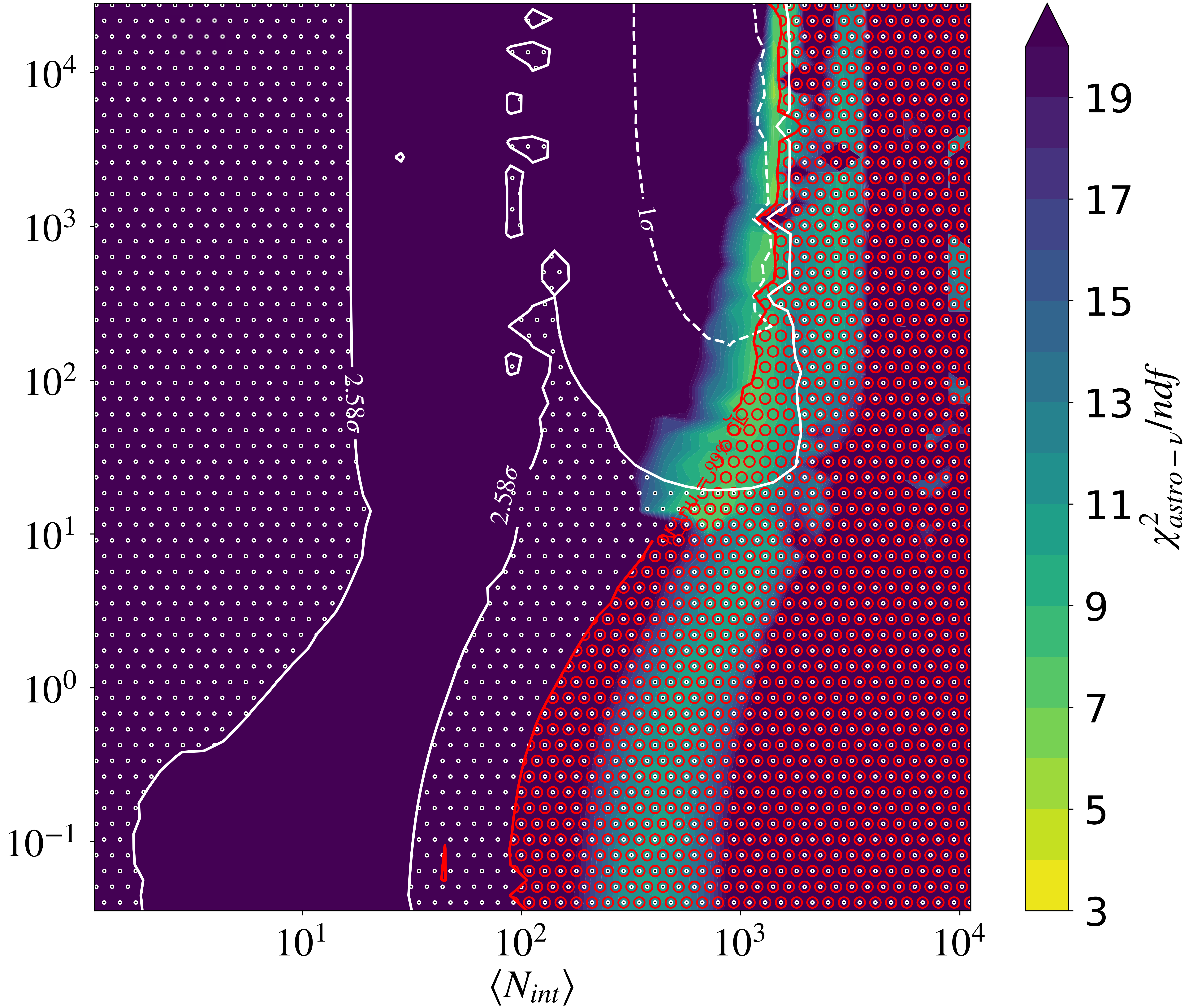
Shape of HE neutrinos driven by spectral index of injected CRs & number of interactions

Softer injection indices, *-2.0 to -2.5, lead to* ***most similar HE neutrino spectra***

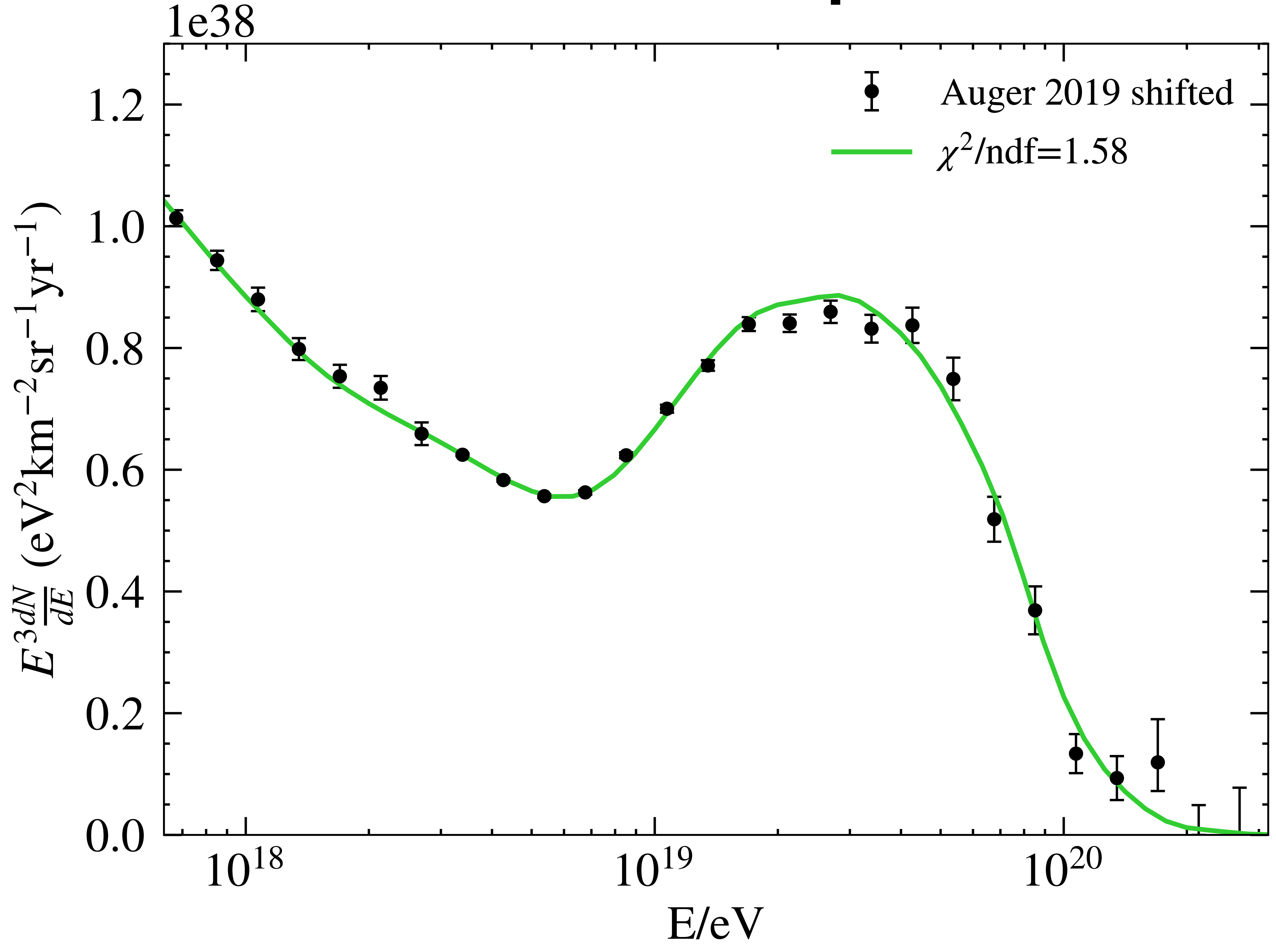


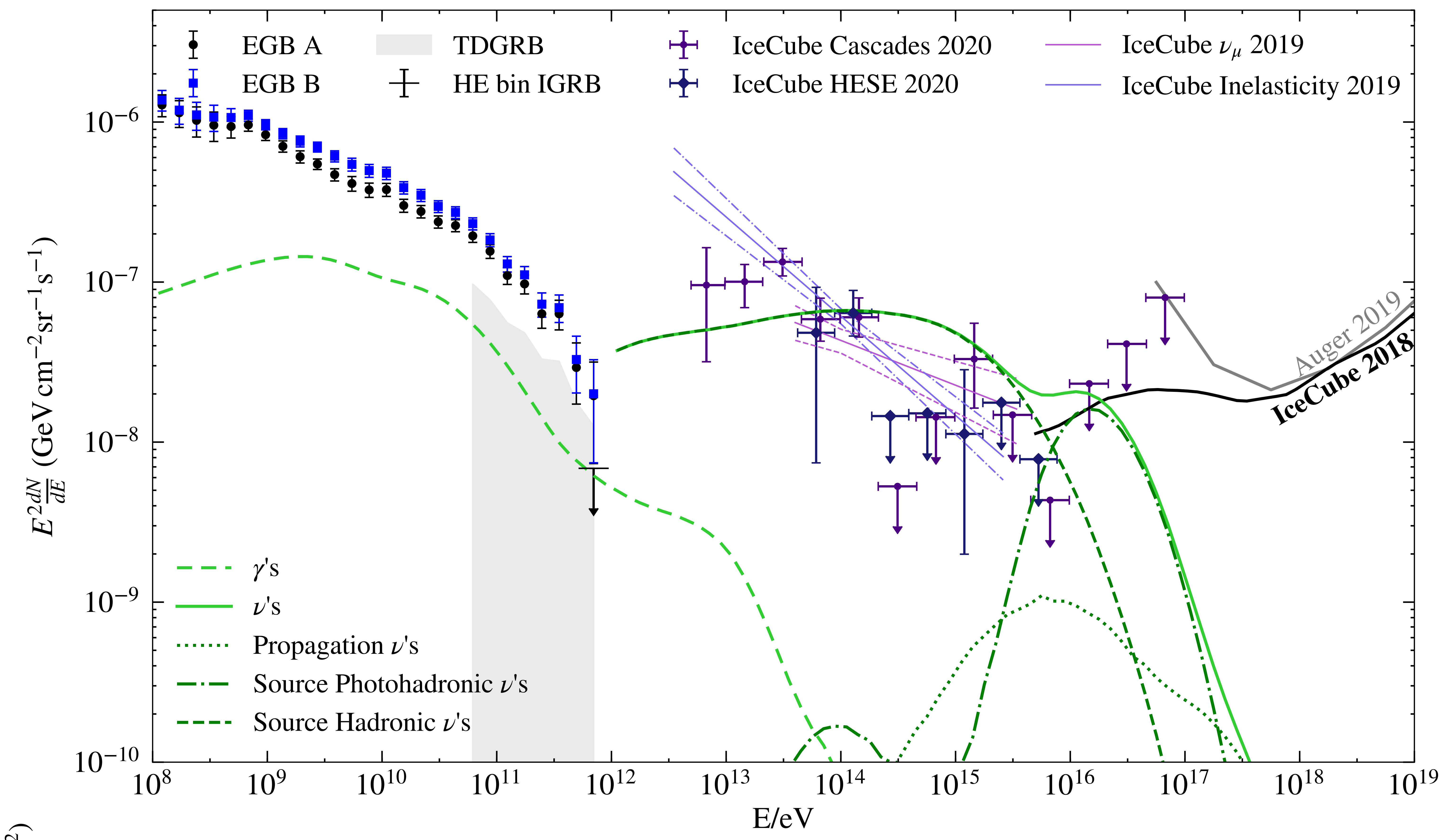

10^4
10^3
10^2
10^1
10^0
10^{-1}
$\langle N_{int}^{\gamma} \rangle / \langle N_{int}^{p} \rangle$
10^1
10^2
10^3
10^4
$\langle N_{int} \rangle$
19
17
15
13
11
9
7
5
3
$\chi^2_{astro-\nu}/ndf$

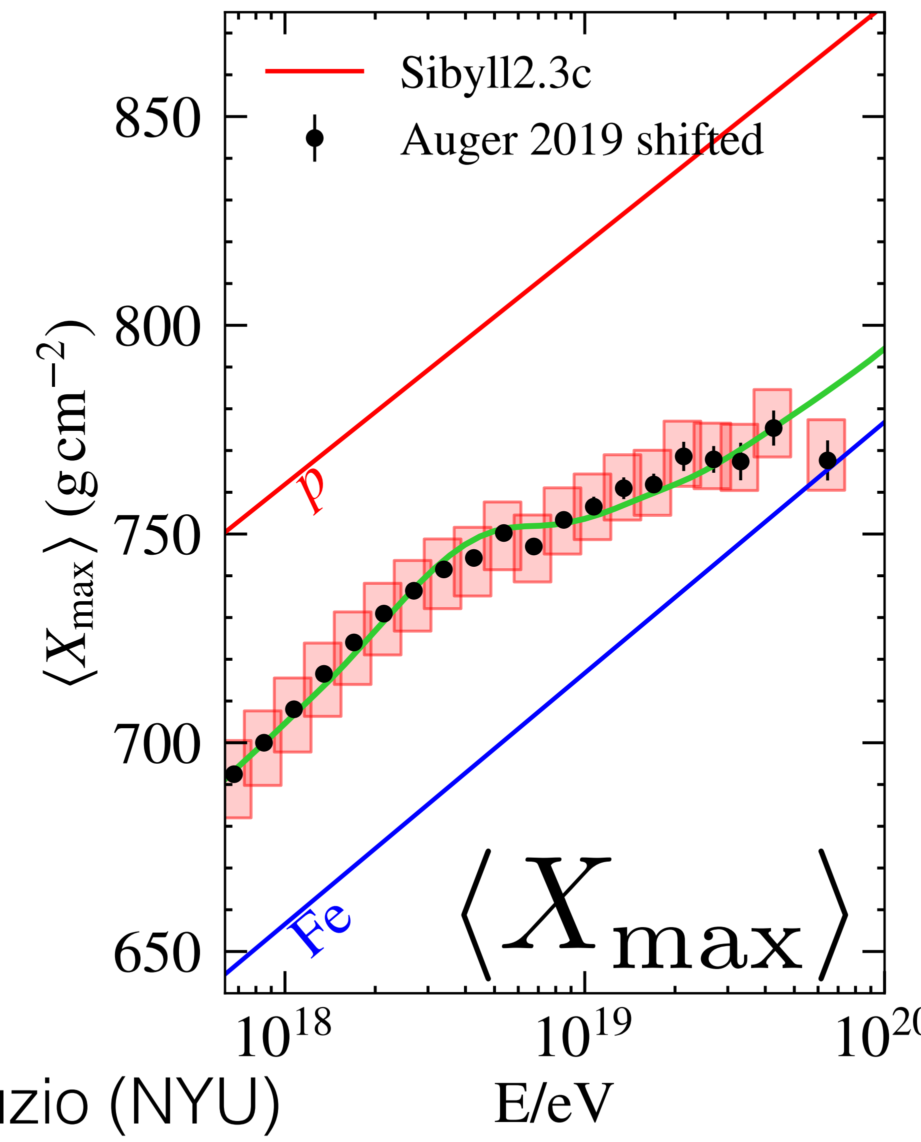
Best description of astrophysical neutrino flux compatible with UHECR & neutrino data, highly constrained

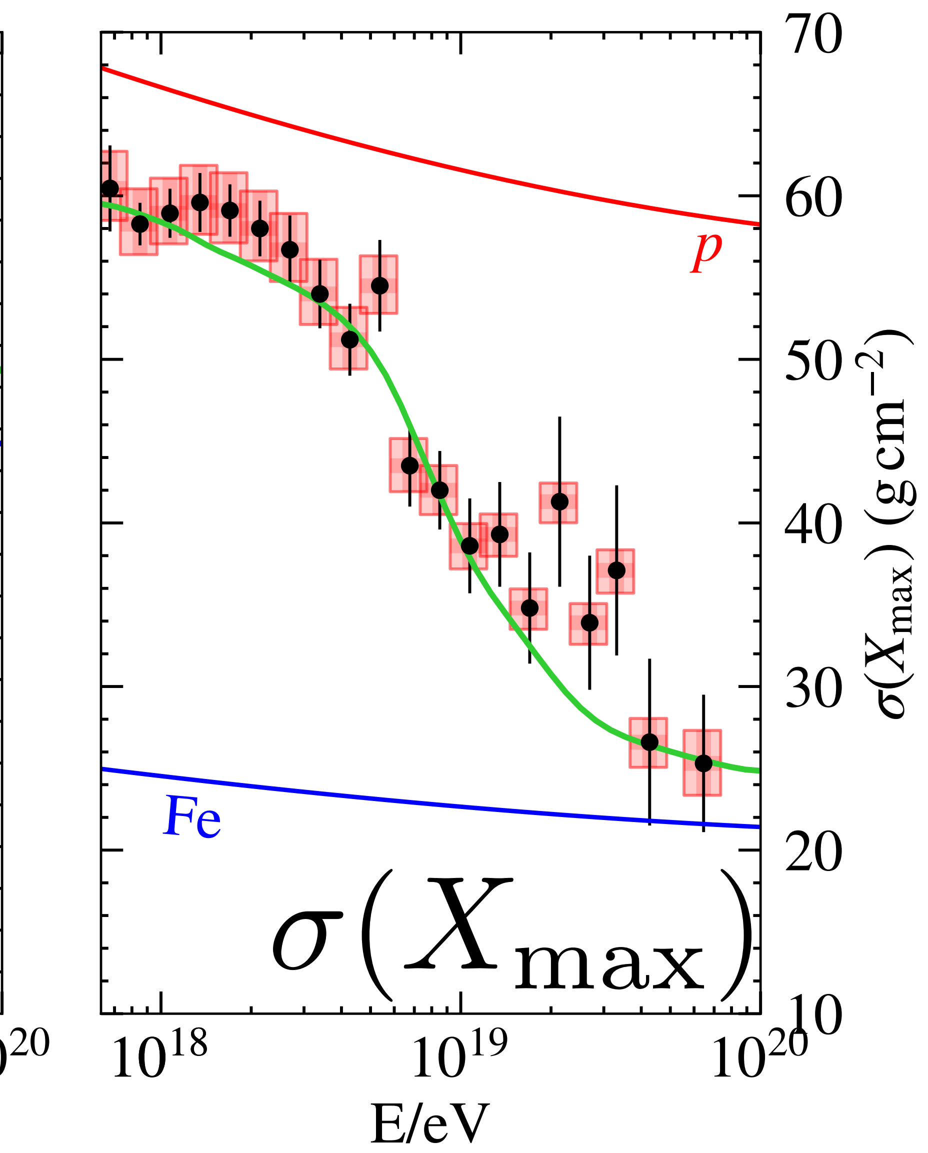


Best Description of Astrophysical Neutrino Flux









Inferred Source Parameters:

$$\langle N_{int} \rangle = 1413 \qquad T_{\mathrm{BB}} = 718 \text{ K}$$

$$\frac{\langle N_{int}^{\gamma} \rangle}{\langle N_{int}^{p} \rangle} = 1413 \qquad \gamma_{inj} = -2.2$$

$$R_{\mathrm{diff}} = 10^{16.3} \text{ V}$$

Next Steps: Narrowing in on Possible Sources

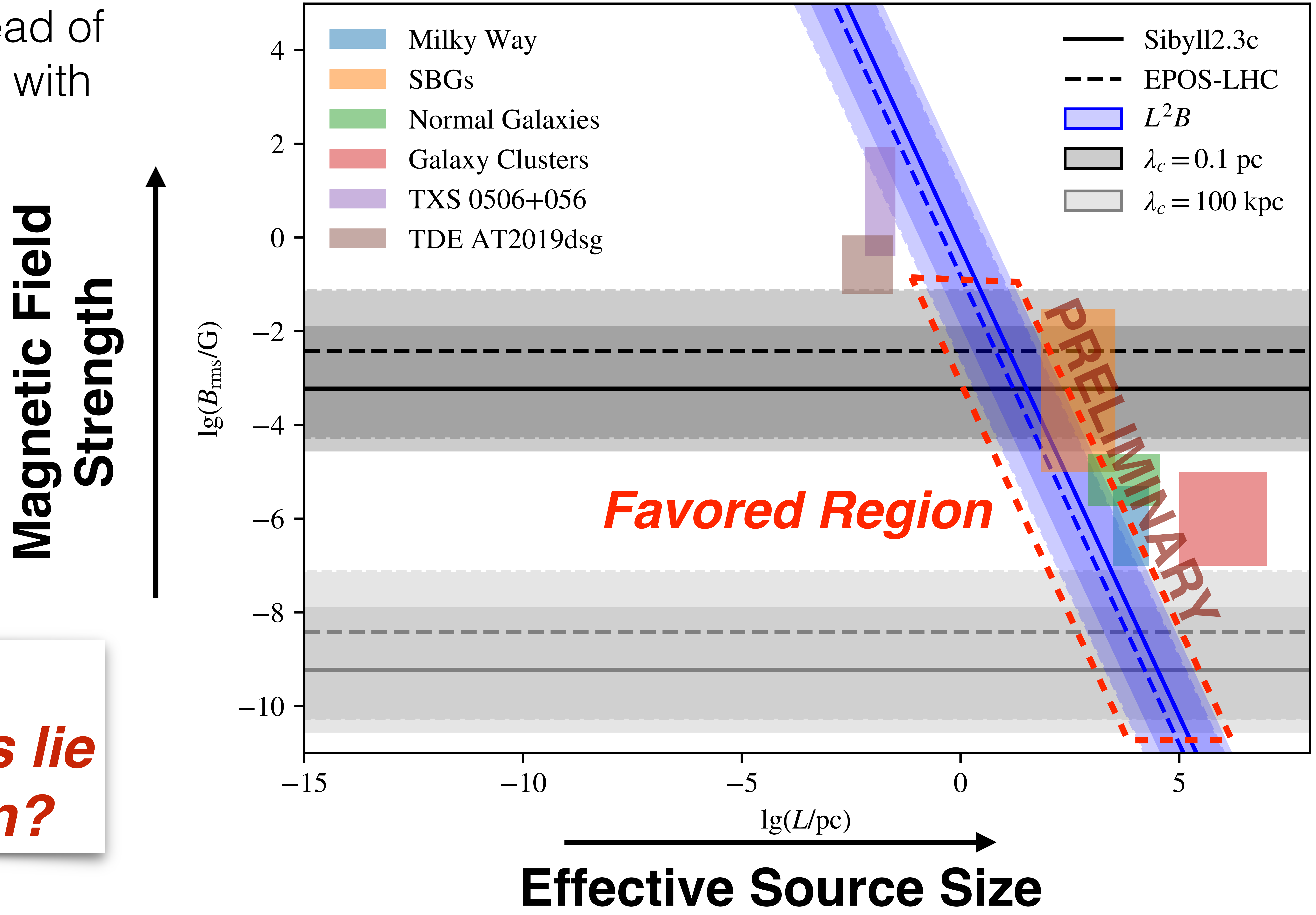
Performed MCMC to find spread of parameter values compatible with data and constraints

$$B\lambda_c = 2.2\pi \left(\frac{R_{\text{diff}}}{\text{EV}}\right) \ \mu\text{G}\cdot\text{kpc}$$

Under the assumption of blackbody photon field:

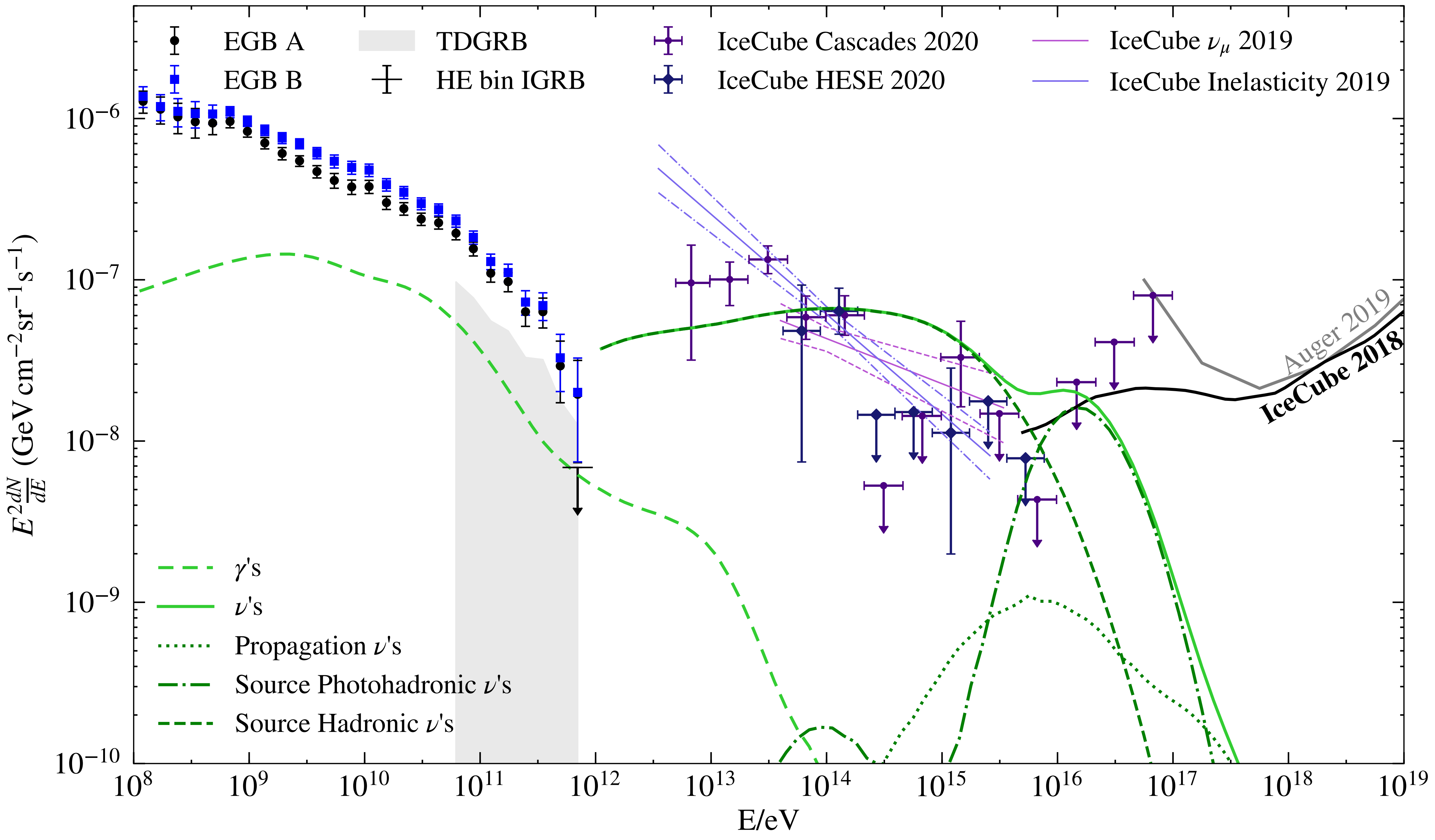
$$L^2 B = f(\{\theta_i\})$$

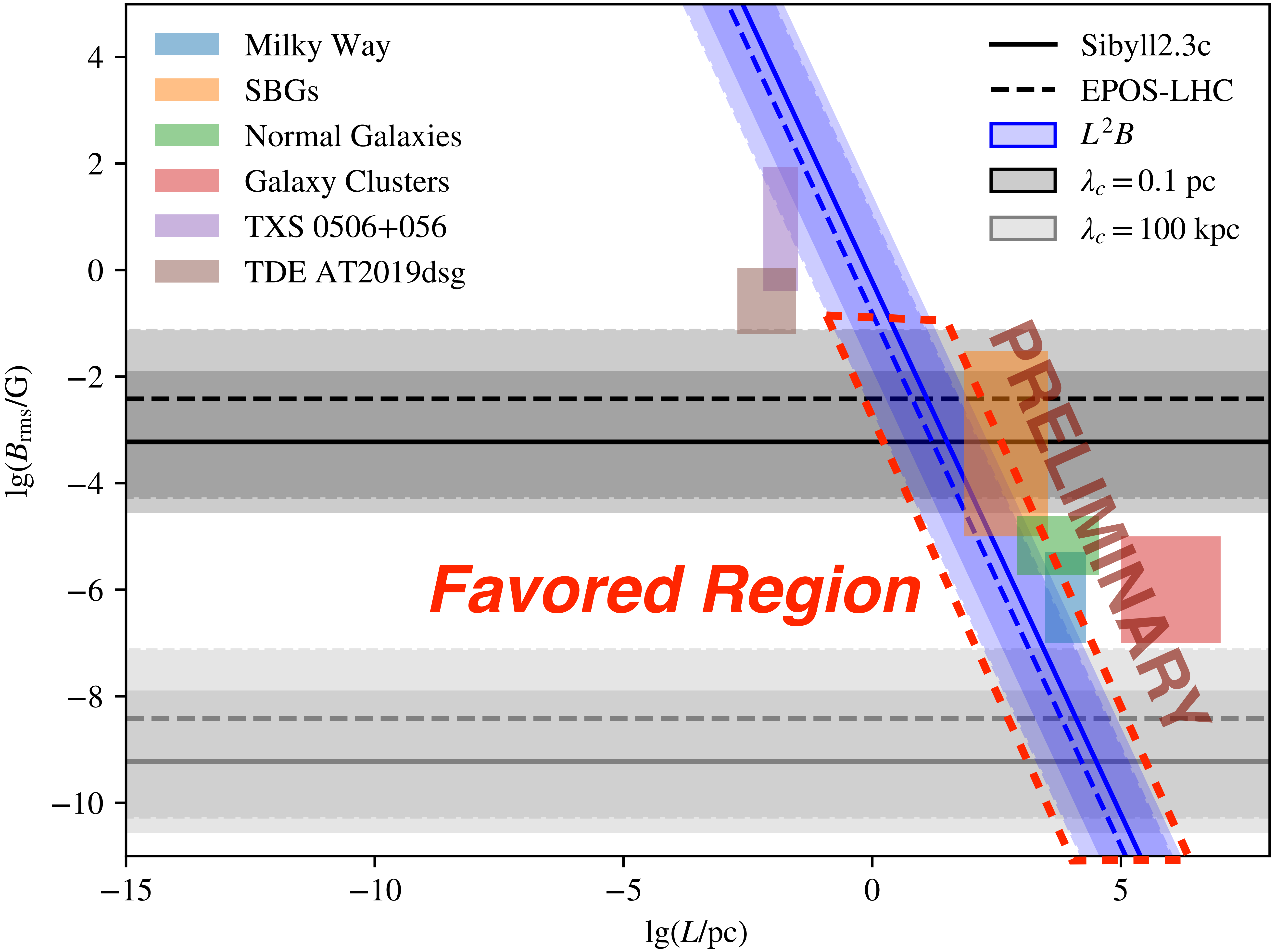
What known astrophysical sources lie in the favored region?



Summary: Part II

- Current UHECR data compatible with gas- and photon-dominated source environments
- **Common origin** of UHECRs & astro. ν's **possible, but tightly constrained**
- Leveraging multimessenger data we can **determine preferred astrophysical sources** for common origin or UHECRs alone



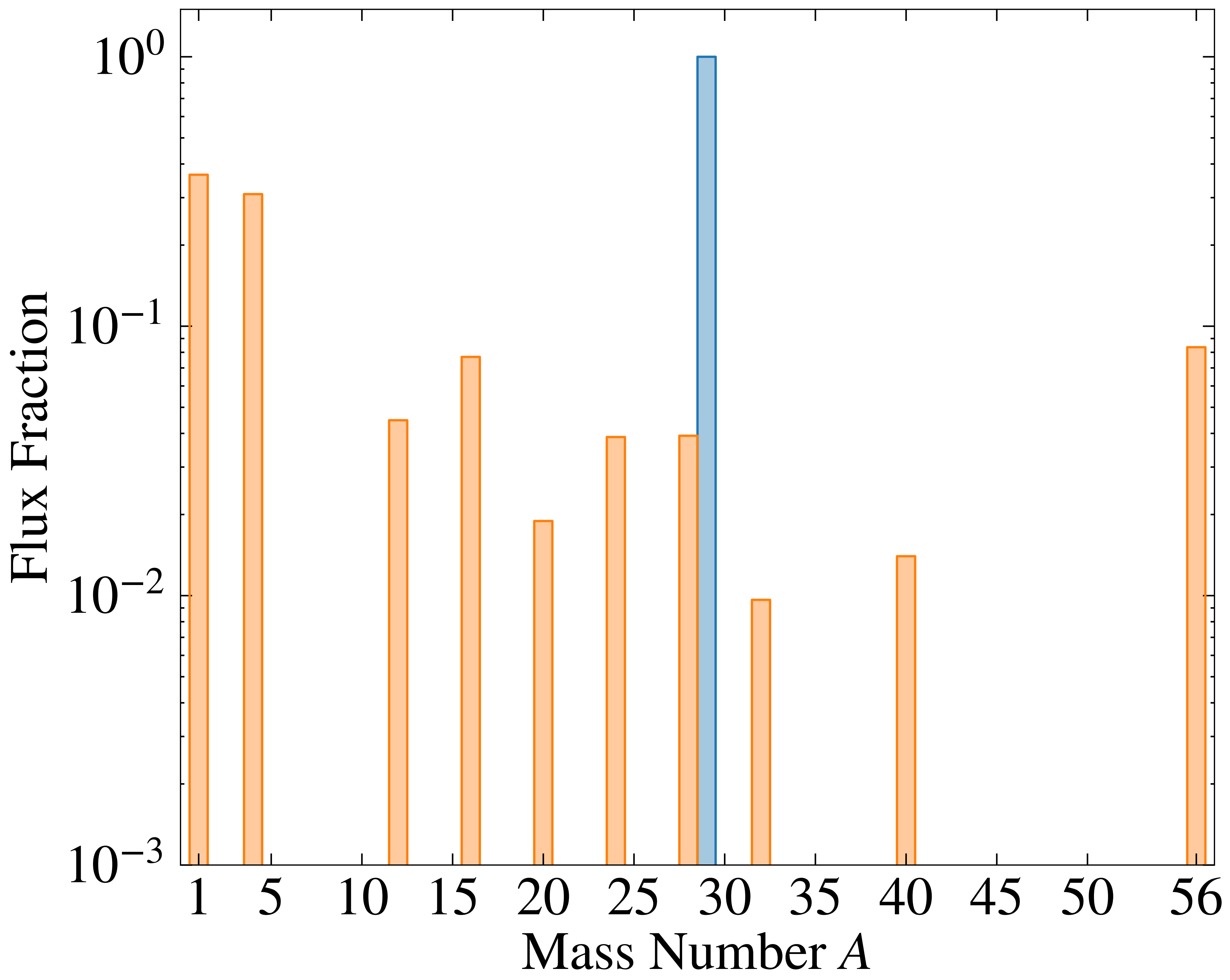


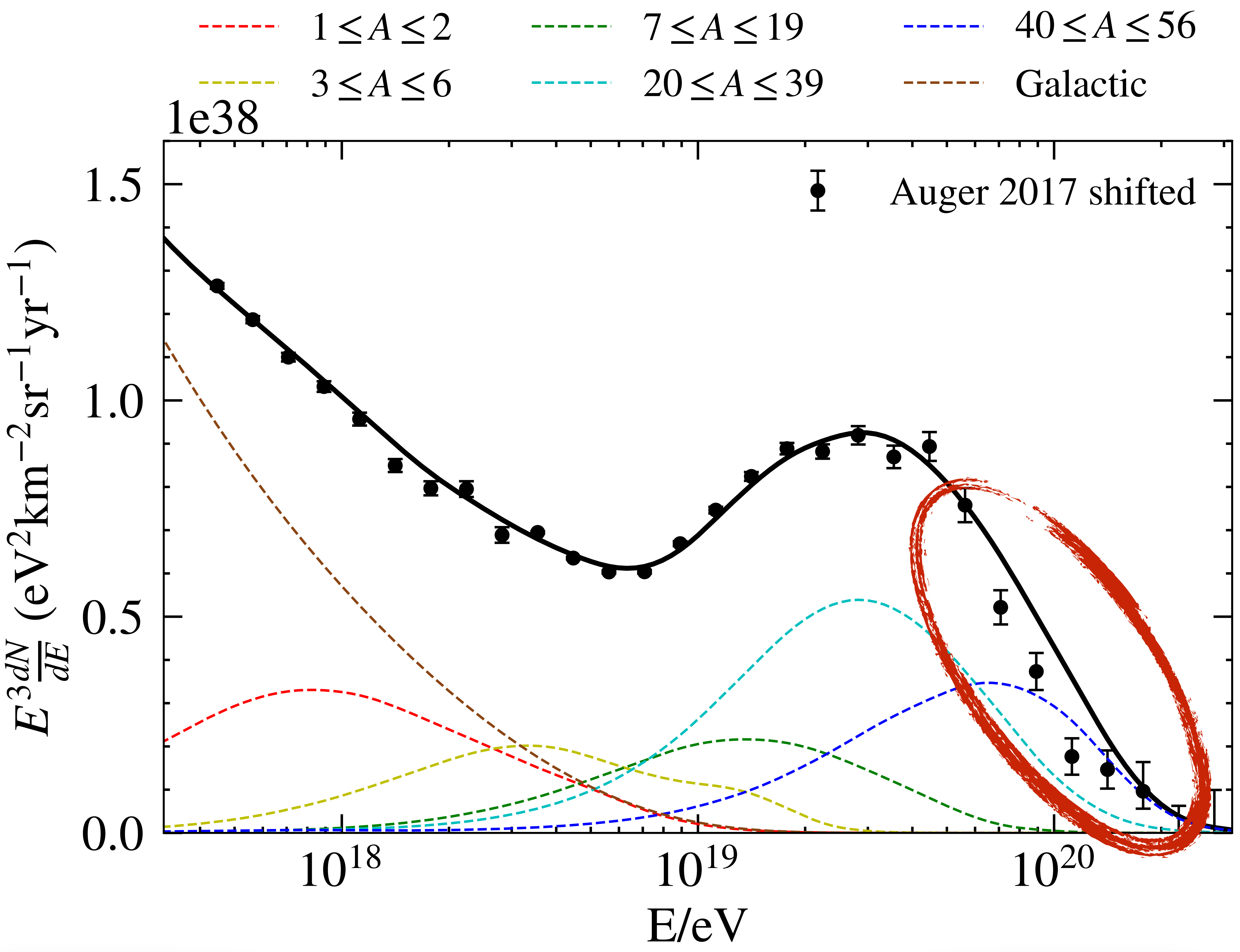

Thank you!

Backup

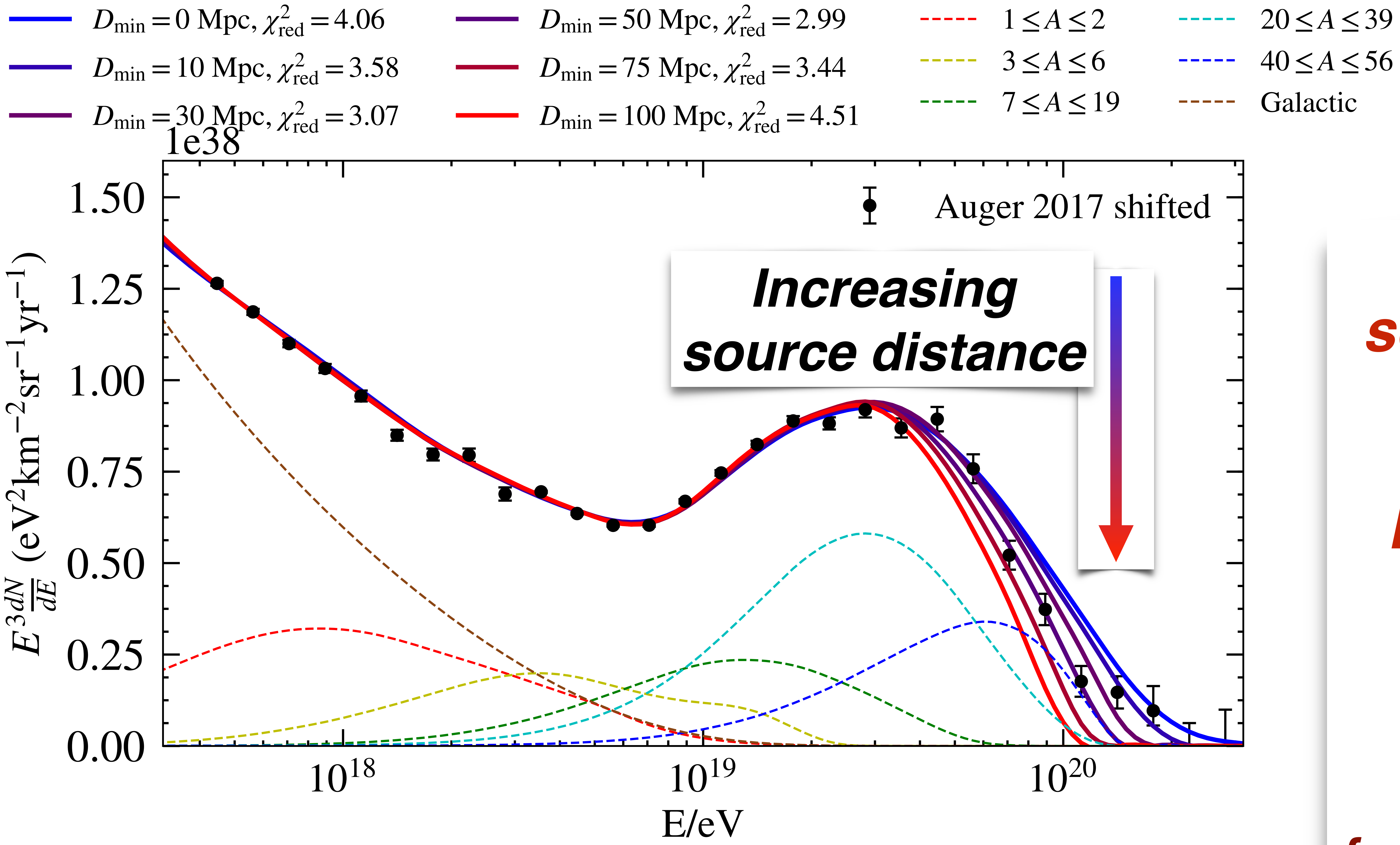
Constraining Injected Composition?

Characterizing injected composition:
narrow mass range
or
extended, Milky Way-like
composition?





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



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

Best-fit nearest source distance is constrained:

D_{min} ~ 30-50 Mpc

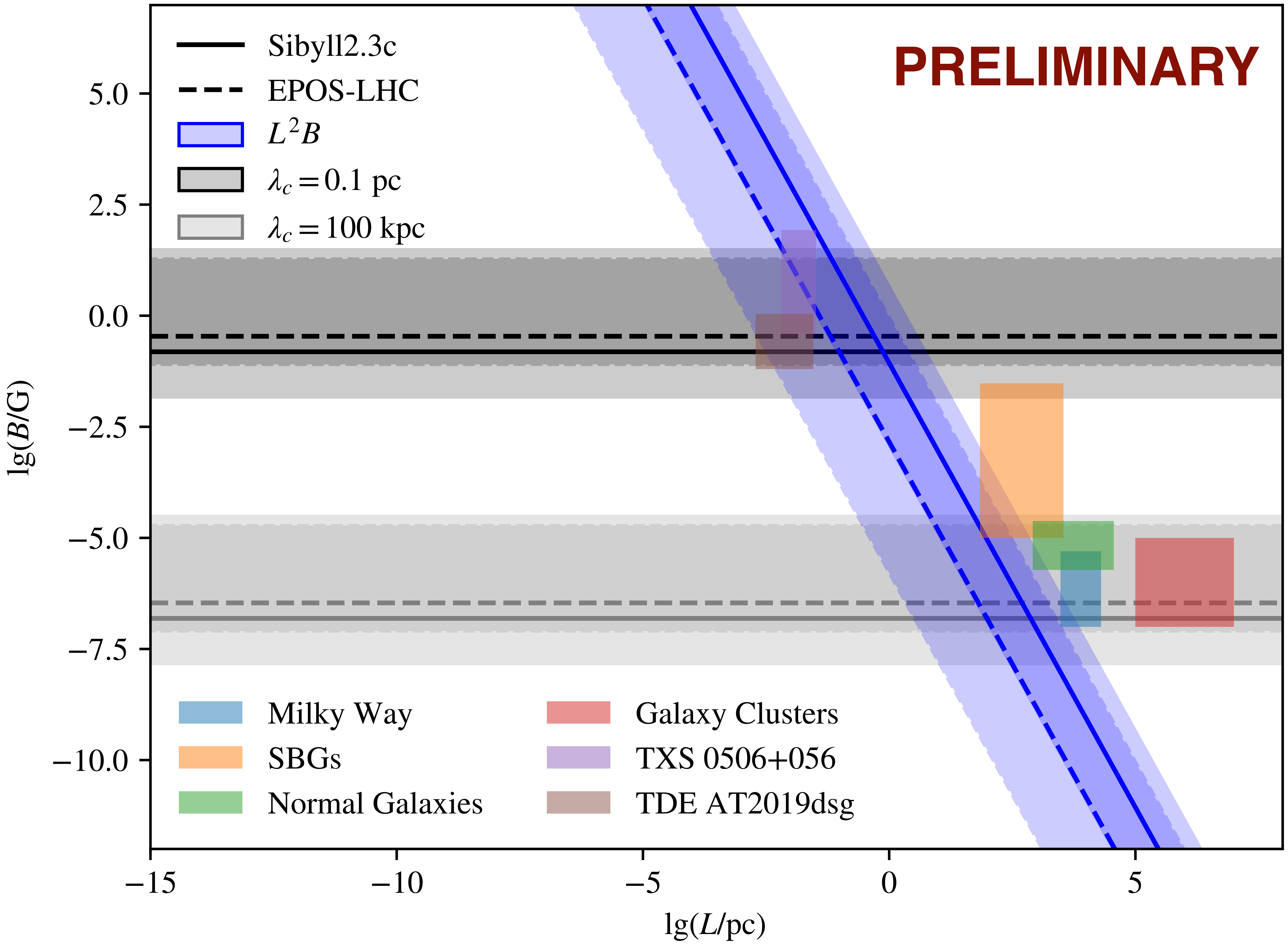
for Milky Way-like composition,

$D_{min} \lesssim 5$ Mpc

for narrow composition*

*dependent on systematic uncertainties

Constraints on UHECR sources



$$\frac{1}{\tau_{\rm esc}(R)} \propto \frac{c\lambda_c}{6\pi}\left[\left(\frac{R}{R_{\rm diff}}\right)^{1/3} + \frac{1}{2}\left(\frac{R}{R_{\rm diff}}\right) + \frac{2}{3}\left(\frac{R}{R_{\rm diff}}\right)^{2}\right]$$

Gas interactions always dominate at low-energies

Break in power-law for escape length is sensitive to turbulent magnetic field properties