Simulating the Propagation of Ultra-High-Energy Cosmic Rays and Cosmogenic Neutrinos

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A coupled proton–neutrino transport solver reveals how UHECR energy losses and source redshift shape the proton and cosmogenic-neutrino fluxes observed at Earth.

1. Physical Motivation

Ultra-high-energy cosmic rays (UHECRs) are the most energetic particles observed in nature, yet their astrophysical origin remains uncertain.

During propagation through intergalactic space, UHECR protons interact with the **cosmic microwave background (CMB)** and the **extragalactic background light (EBL)**. These interactions modify the spectrum observed at Earth and, at the highest energies, lead to the **Greisen–Zatsepin–Kuzmin (GZK) suppression**, caused mainly by photopion interactions.

They also generate secondary **cosmogenic neutrinos**, which provide a complementary probe of the distant UHECR source population.

2. Propagation Model

The comoving proton density $Y_p(E_p, z)$ evolves according to

$$\frac{\partial Y_p}{\partial z} = -\frac{\partial}{\partial E_p}\left[Y_p(E_p, z)\frac{dE_p}{dz}\right] - \frac{Q_p(E_p, z)}{H(z)(1+z)},$$

with proton energy losses from cosmological expansion, Bethe–Heitler electron-positron pair production, and photopion production.

The total fractional proton energy-loss rate is

$$\beta_{\rm tot} = \beta_{\rm adiab} + \beta_{\rm pair} + \beta_{\rm pion}.$$

The relevant interaction channels considered are

$$p + \gamma \to p + e^+ + e^-, \qquad p + \gamma \to n + \pi^+ \to \nu + \cdots,$$

The neutrino population then evolves as

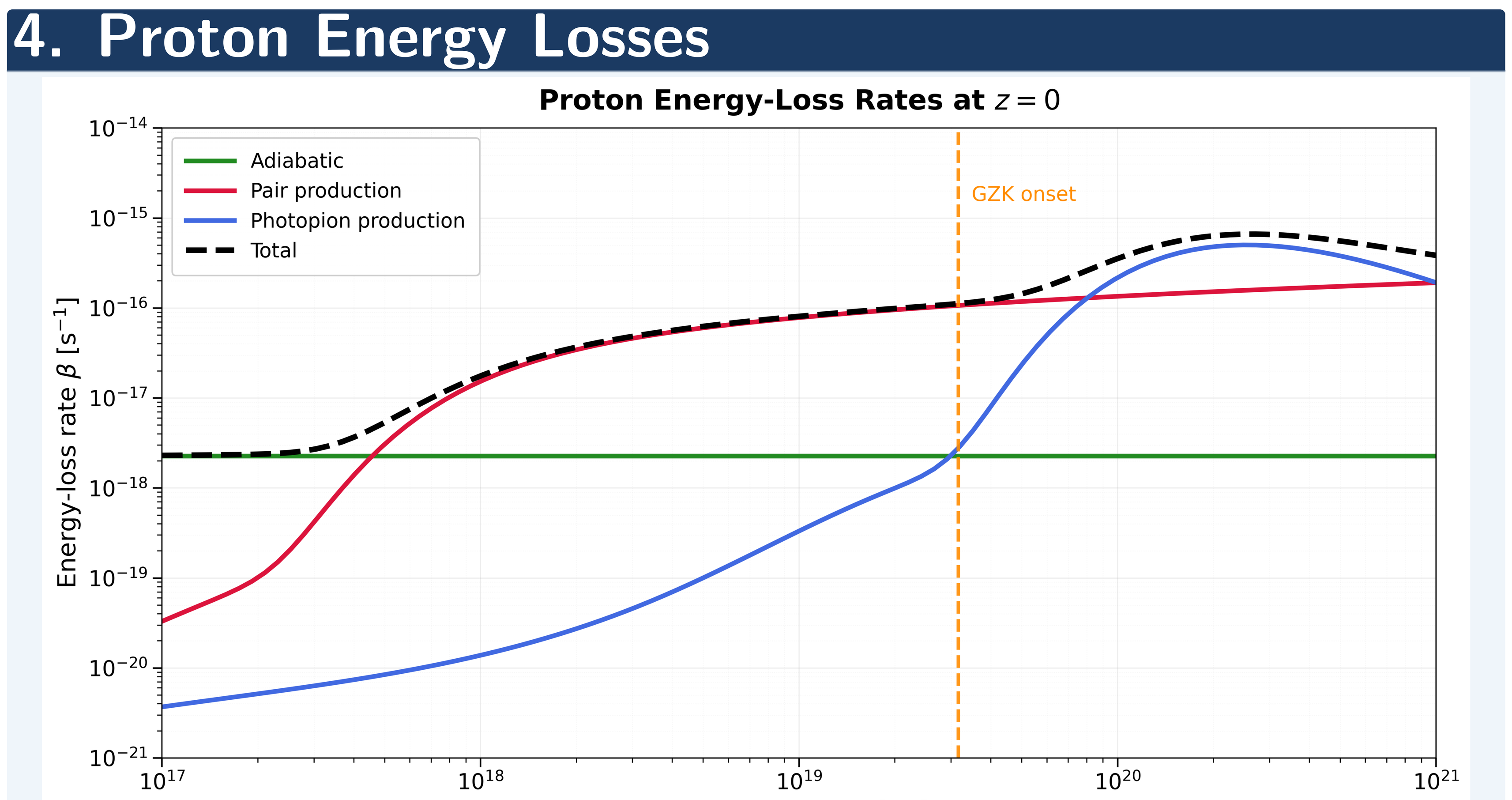
$$\frac{\partial Y_\nu}{\partial z} = -\frac{\partial}{\partial E_\nu}\left[Y_\nu(E_\nu, z)\frac{E_\nu}{1+z}\right] - \frac{Q_\nu(E_\nu, z)}{H(z)(1+z)}.$$

After production, neutrinos propagate essentially freely, losing energy only through cosmological redshift.

3. Numerical Method

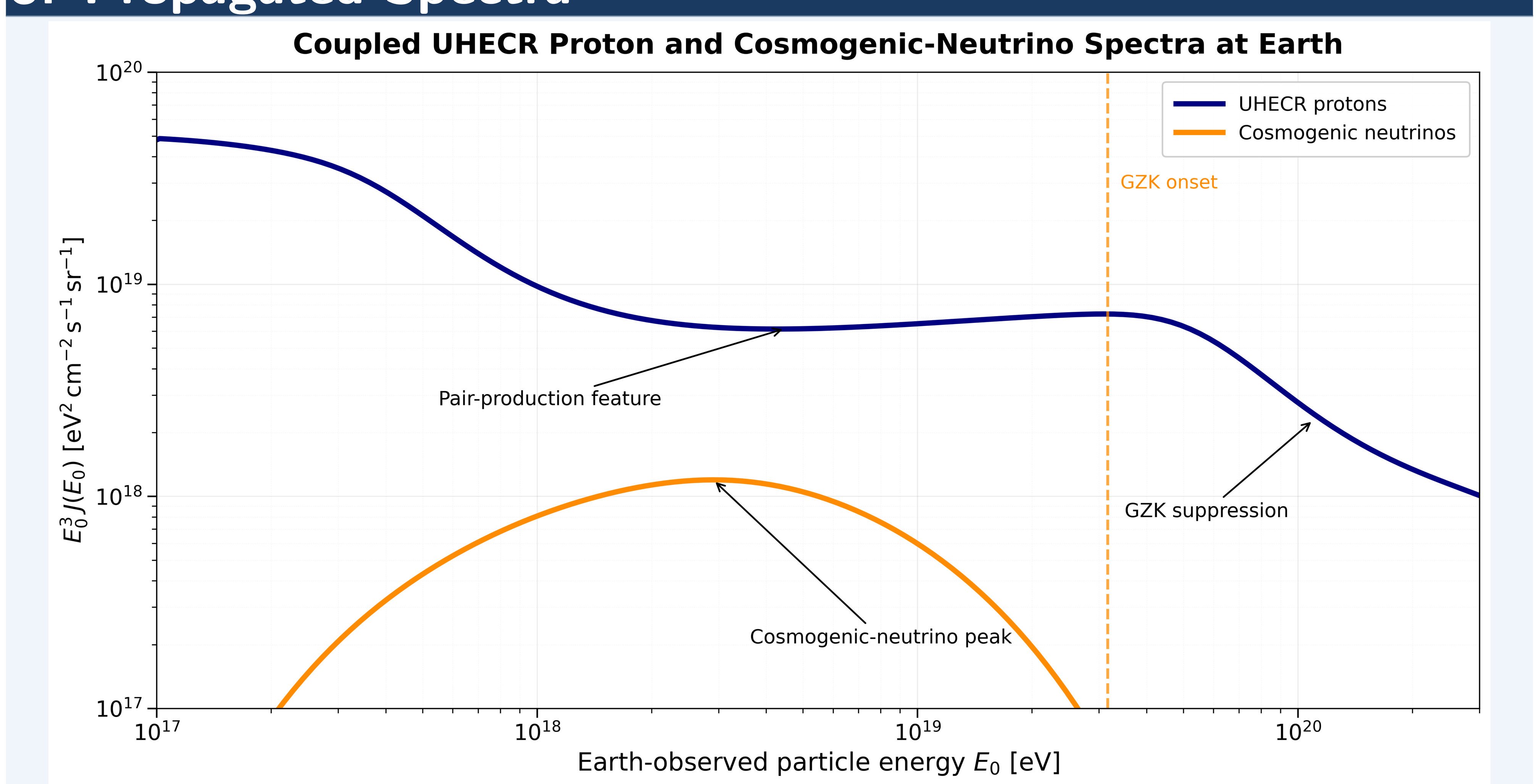
1. **Set cosmology, photon backgrounds and grids**
   CMB + EBL photon backgrounds, E-grid, z-grid
2. **Pre-compute interaction loss rates**
   $\beta_{\rm pair}(E, z)$ and $\beta_{\rm pion}(E, z)$
3. **Discretize energy transport**
   Logarithmic grid + upwind finite differences
4. **Solve the coupled transport system**
   Backward differentiation formula (BDF) **via** `solve_ivp`, $z = 4 \to 0$
5. **Extract Earth-observed differential fluxes**
   $J_p(E_0)$, $J_\nu(E_{\nu,0})$ and redshift-shell contributions

4. Proton Energy Losses



Bethe–Heitler pair production dominates the interaction losses at intermediate energies, while photopion losses rise rapidly in the GZK regime and strongly attenuate the highest-energy protons.

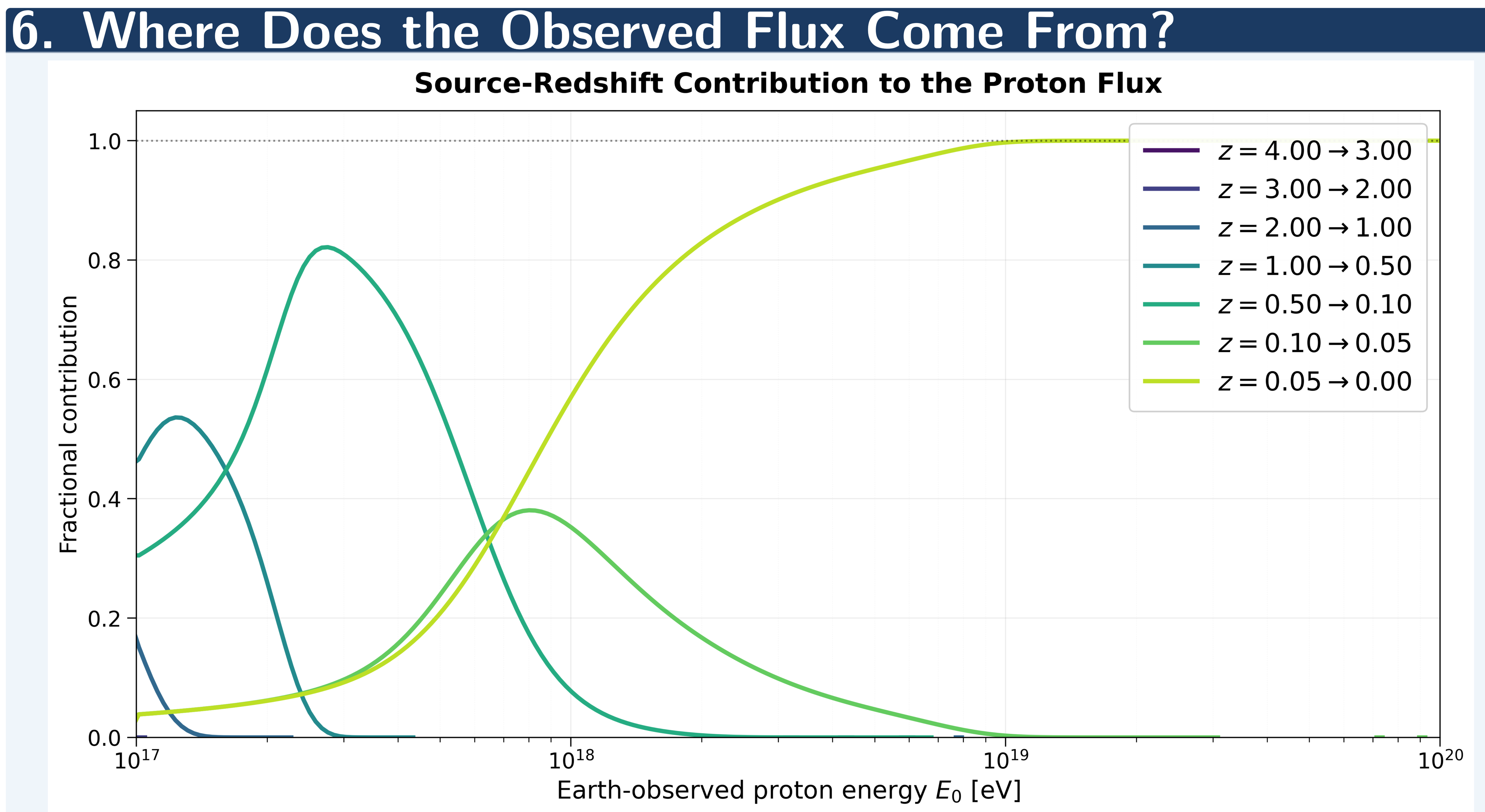
5. Propagated Spectra



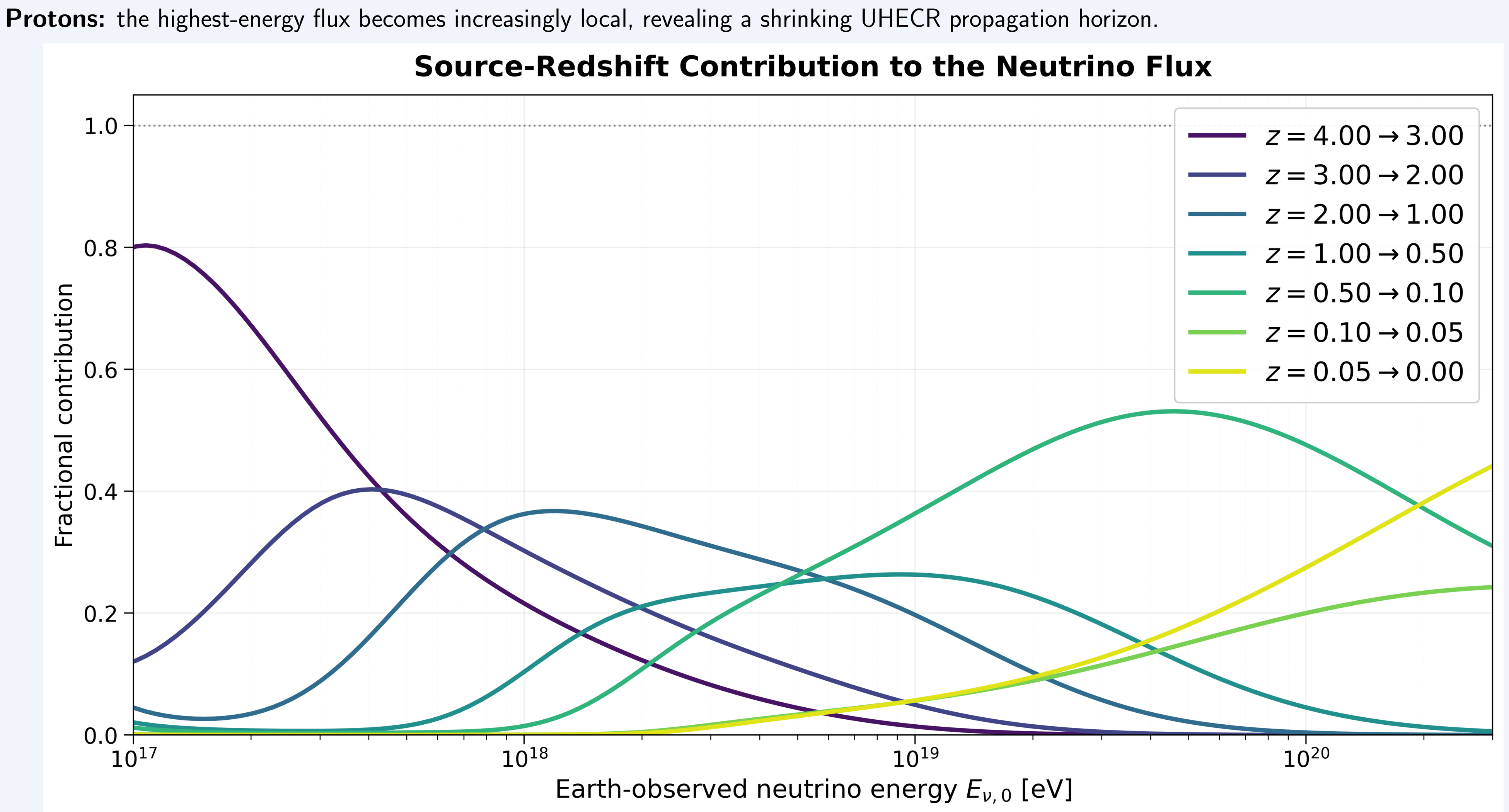
UHECR protons: Bethe–Heitler pair production produces the intermediate-energy spectral feature, while photopion losses drive the high-energy GZK suppression.

Cosmogenic neutrinos: the energy-weighted spectrum peaks at a few EeV, reflecting the transfer of UHECR proton energy to secondary neutrinos through photopion interactions.

6. Where Does the Observed Flux Come From?



Protons: the highest-energy flux becomes increasingly local, revealing a shrinking UHECR propagation horizon.



Neutrinos: the observed flux receives substantial contributions from proton sources over a broad range of cosmological redshifts.

7. Conclusions

- Bethe–Heitler pair production and photopion interactions shape distinct regions of the propagated UHECR proton spectrum.
- Photopion interactions drive the high-energy GZK suppression while simultaneously generating the cosmogenic-neutrino flux.
- The energy-weighted cosmogenic-neutrino spectrum peaks below the proton GZK-suppression regime.
- The highest-energy UHECR proton flux is predominantly local, whereas cosmogenic neutrinos retain sensitivity to a much broader source-redshift distribution.

References

[1] K. Greisen, *End to the cosmic ray spectrum?*, *Phys. Rev. Lett.* **16**, 748–750 (1966).

[2] G. T. Zatsepin and V. A. Kuzmin, *Upper limit of the spectrum of cosmic rays*, *JETP Lett.* **4**, 78–80 (1966).

[3] M. Ahlers, L. A. Anchordoqui, M. C. Gonzalez-Garcia, F. Halzen, and S. Sarkar, *GZK Neutrinos after the Fermi-LAT Diffuse Photon Flux Measurement*, *Astropart. Phys.* **34**, 106–115 (2010).

[4] R. Alves Batista *et al.*, *Open Questions in Cosmic-Ray Research at Ultrahigh Energies*, *Front. Astron. Space Sci.* **6**, 23 (2019).

[5] M. Ahlers, L. A. Anchordoqui, and S. Sarkar, *Neutrino diagnostics of ultra-high energy cosmic ray protons*, *Phys. Rev. D* **79** (2009)

[6] A. Franceschini, G. Rodighiero, and M. Vaccari, *The extragalactic optical-infrared background radiations, their time evolution and the cosmic photon-photon opacity*, *Astron. Astrophys.* **487**, 837 (2008).

[7] M. J. Chodorowski, A. A. Zdziarski, and M. Sikora, *Reaction Rate and Energy-Loss Rate for Photopair Production by Relativistic Nuclei*, *Astrophys. J.* **400**, 181 (1992).