

# Multimessenger constraints on the UHECR source evolution in the AugerPrime era

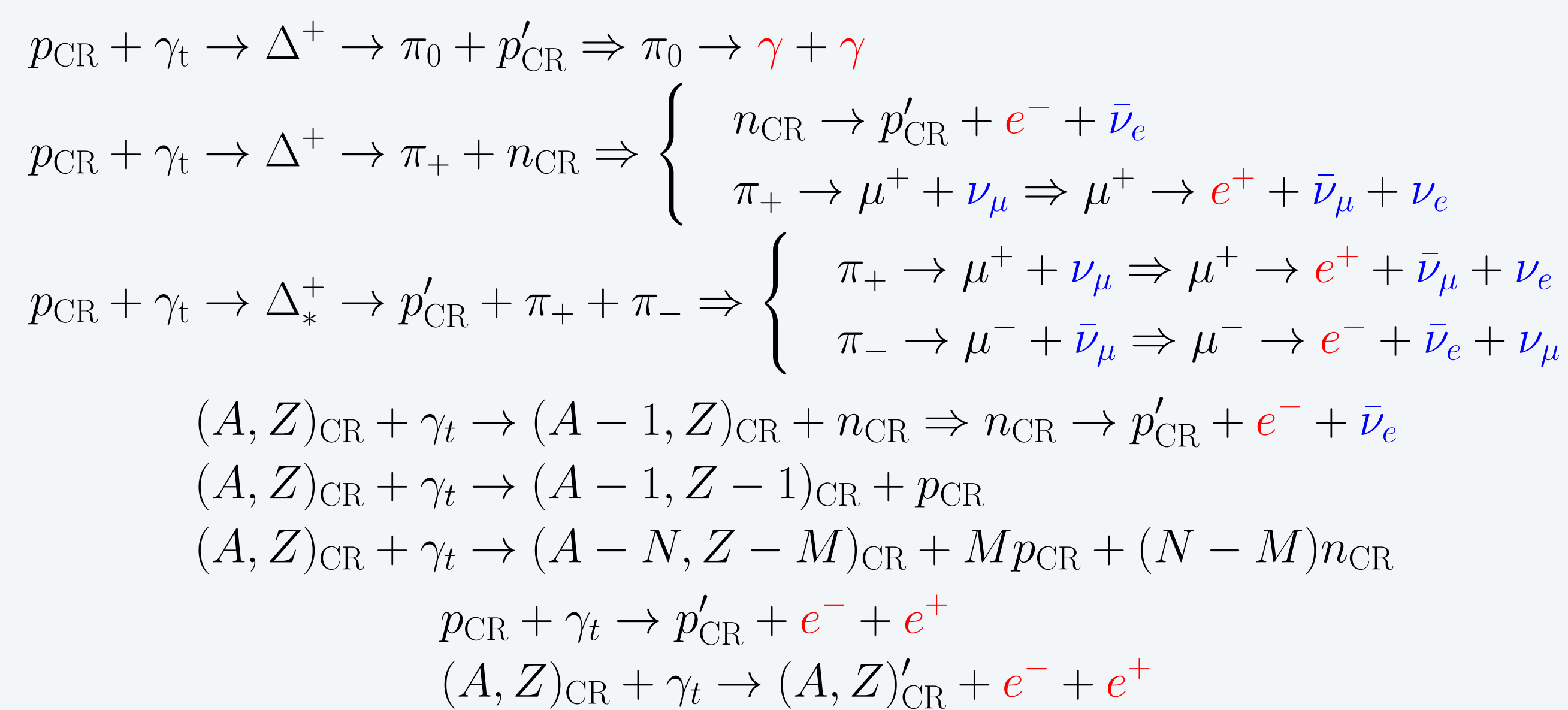
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## Scientific goals of *GammaProp*

With the ongoing advancements at the *Pierre Auger Observatory*, a new era in multi-messenger cosmic ray astrophysics is unfolding, promising to deepen our search for UHECR sources:

- Build a robust multimessenger framework, *GammaProp*, to constrain UHECR source models through VHE neutrino and gamma-ray observations.
- Integrate the development of electromagnetic cascades during extragalactic propagation.
- Investigate differences across Monte Carlo propagation codes.

## Production of VHE Neutrinos, Photons & Leptons by UHECR



## Cosmological transport

$$\frac{dn(\Gamma, z)}{dz} = \left| \frac{dt}{dz} \right| \left[ -3H(z) + \frac{\partial}{\partial \Gamma} (n(\Gamma, z)b(\Gamma, z)) + \frac{n(\Gamma, z)}{\tau_A(\Gamma, z)} + Q^I(\Gamma, z) + Q^{II}(\Gamma, z) \right]$$

## Injection & Interactions

- $3H(z)$ : expansion of the Universe.
- $b(\Gamma, z)$ : continuous energy-losses:
  - ALL: Adiabatic energy losses.
  - Protons: pair production + photopion.
  - Nuclei: pair production.
  - Photons: Pair Production on CMB + EBL.
  - Leptons: Inverse Compton on CMB.
  - Neutrinos: No interaction for  $z \lesssim 10$ .
- **Photodisintegration (only nuclei)**: Survival prob.  $\eta = \int dz \left| \frac{dt}{dz} \right| \frac{1}{\tau_A(\Gamma, z)}$
- **Primary Injection  $Q^I(\Gamma, z)$** :
  - Cosmic Rays: Injection from astrophysical sources
  - $\tilde{Q}(\Gamma, z) \propto L \times (1+z)^m \times \Gamma^{-\gamma} \times f_{\text{cut}}(Z, \Gamma)$ .
  - Neutrinos & Photons & Leptons: Injection from cosmic rays:
  - $Q(E_x, z) \propto n_{\text{CR}}(E_{\text{CR}}, z) \times R(E_{\text{CR}}, E_x, z)$ .
- **Secondary Injection  $Q^{II}(\Gamma, z)$** :
  - Protons: Injection from all-nuclei photodisintegration:
$$Q_{IIp}(E) \propto \sum_A \frac{n_A(AE, z)}{\tau_A(AE, z)}$$
  - Nuclei: Injection from heavier nuclei photodisintegration:
$$Q_{II(A,Z)}(E) \propto \frac{n_{A+1}(\frac{A+1}{A}E, z)}{\tau_{A+1}(\frac{A+1}{A}E, z)}$$
  - Photons & Leptons: Inverse Compton Scattering + Pair Production
$$\begin{cases} Q_\gamma \propto \tilde{n}_e \times R_{\text{ICS}} \\ Q_e \propto \tilde{n}_\gamma \times R_{\text{PP}} \end{cases}$$

## Cosmogenic Neutrinos

The two main Monte Carlo codes for UHECR transport, *SimProp* & *CRPropa*, show differences in the cosmogenic neutrino flux.:

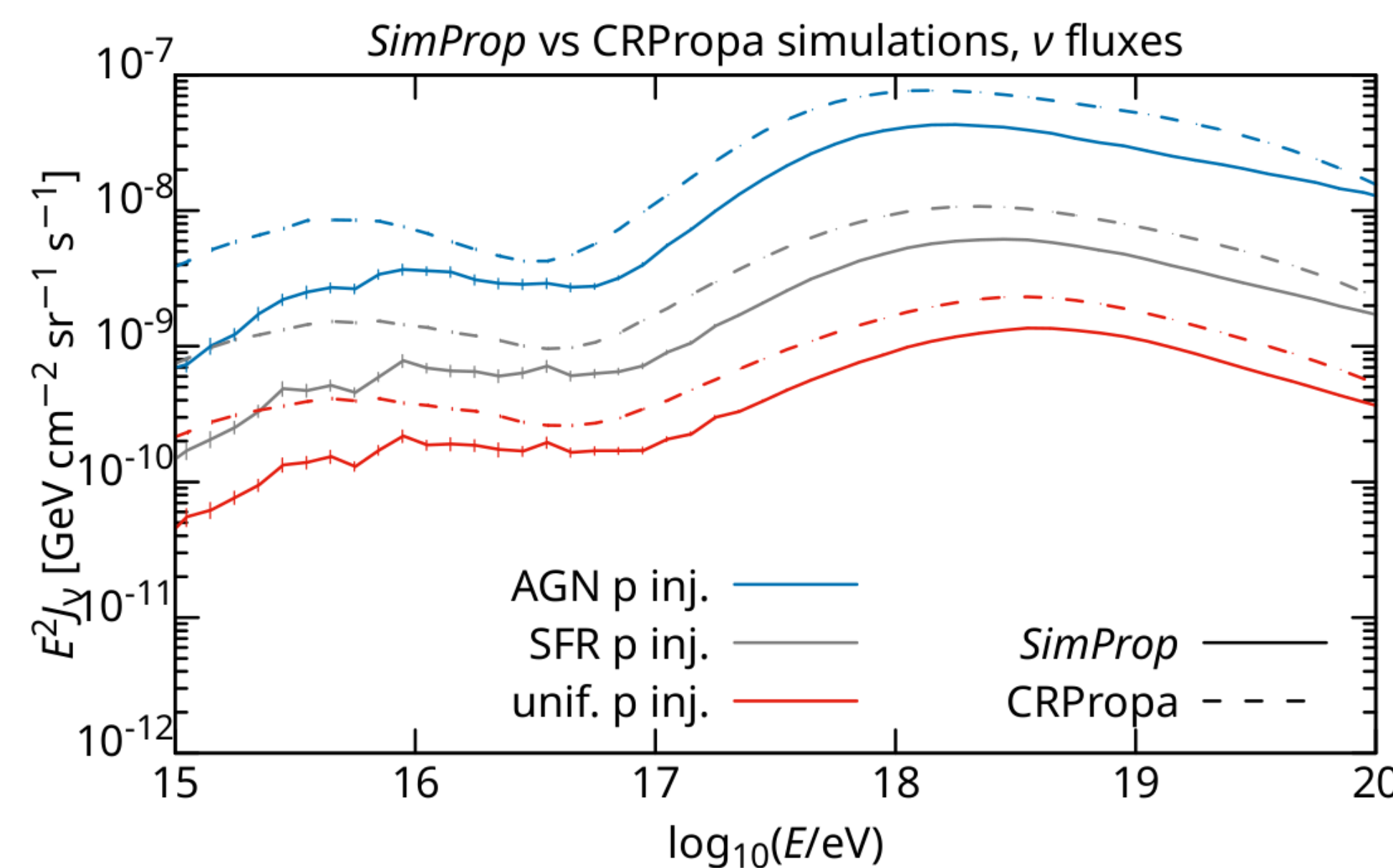
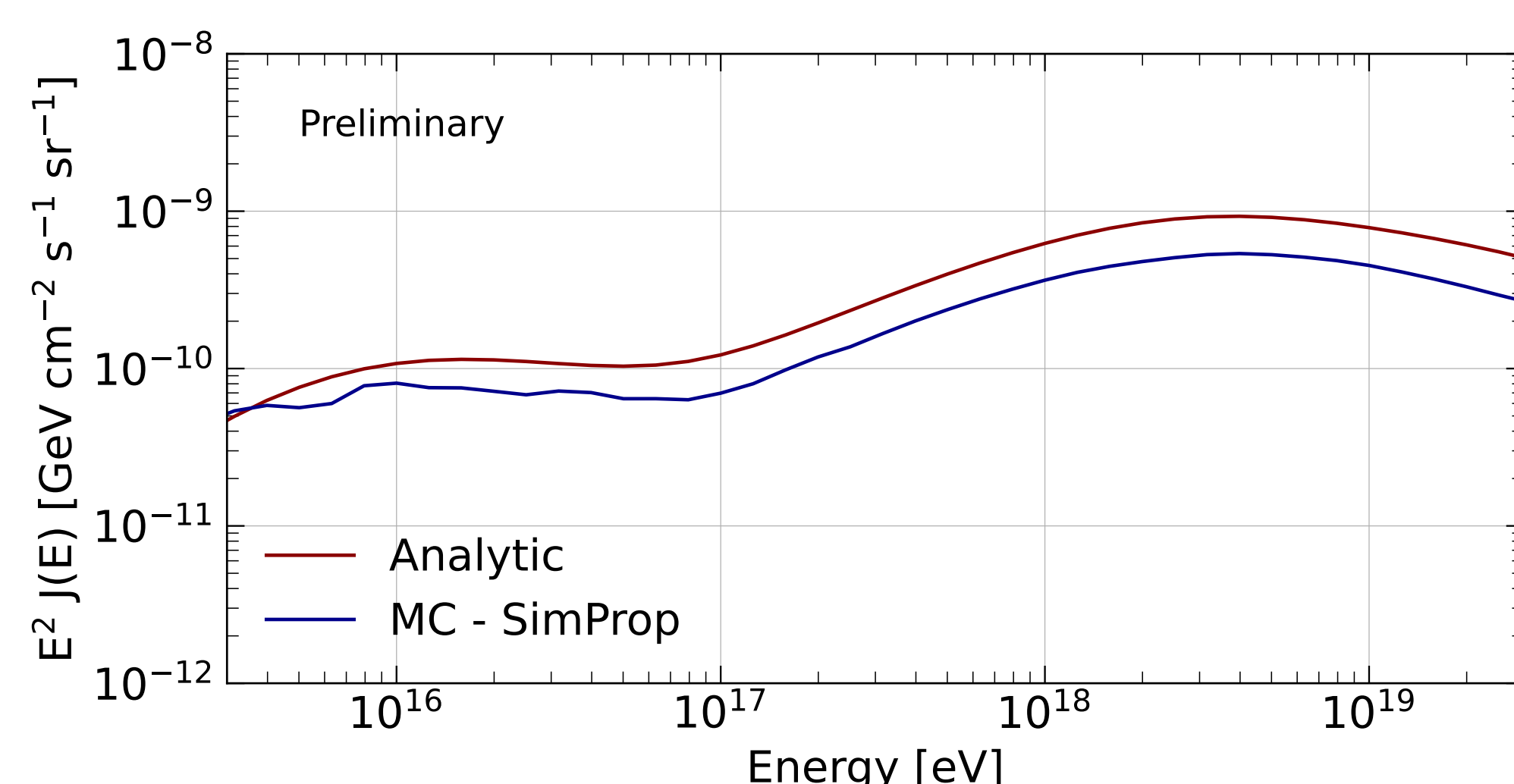
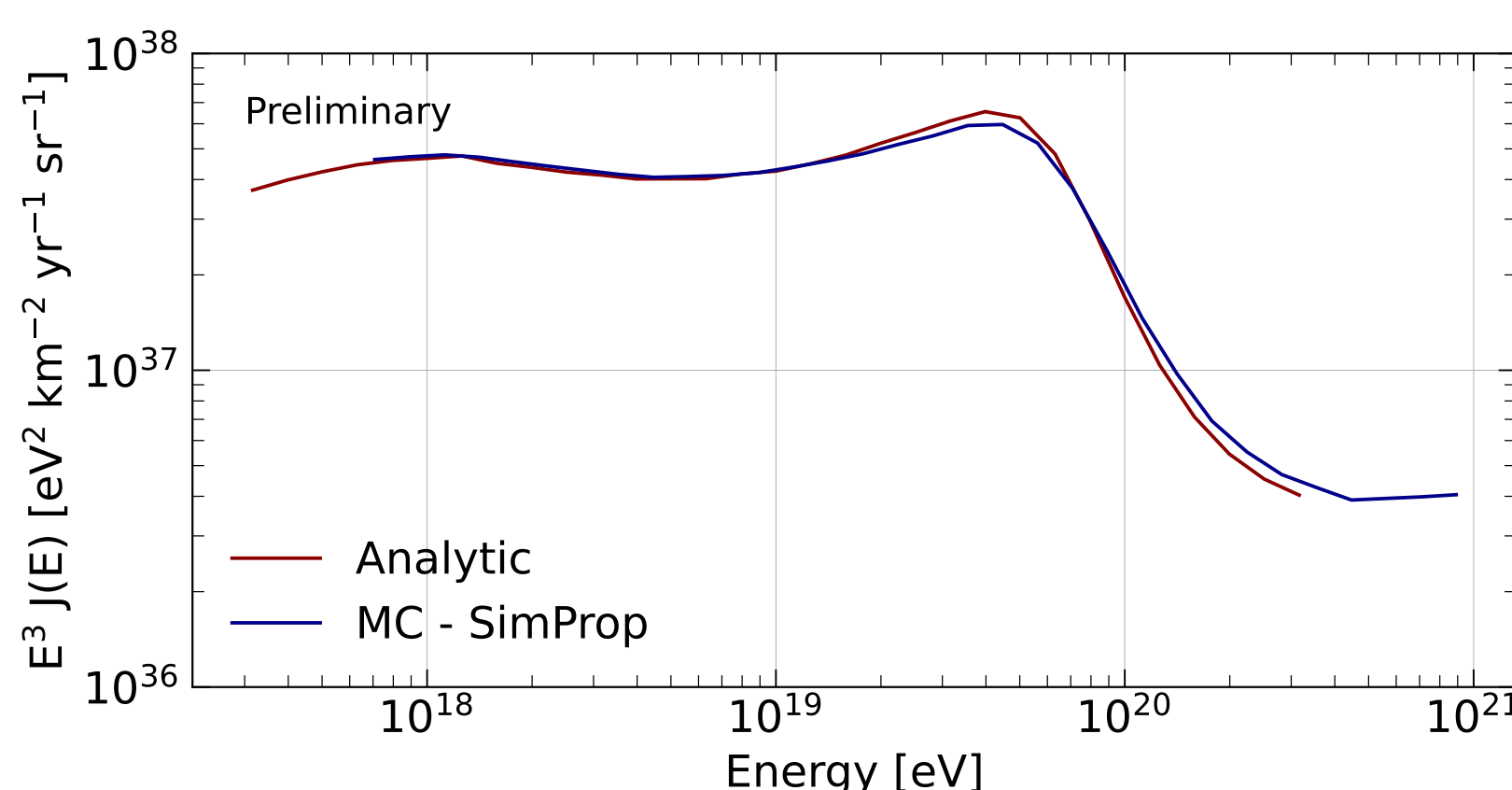


Figure: from Batista, R. A., et al. JCAP 2019/05

- *CRPropa*: use of an integrated particle physics code, *Sophia*, which simulates the interaction. (Mücke, A. et al., CPC 2000/02)
- *SimProp* single-pion production, with BR from isospin invariance and angular distribution of the outgoing pion isotropic in the CoM frame. (Batista, R. A., et al. JCAP 2019/05)

## Test of the difference

We compare the results on the cosmogenic neutrino flux obtained through an analytical calculation, making use of a parametrization of *Sophia*, with the flux obtained with *SimProp*. (Kelner, S. et al., PRD 2010/11)



## Gamma-ray cascade processes

$$\text{PP: } \gamma + \gamma_{\text{EBL}} \rightarrow e^+ + e^-, E_{\gamma, \text{th}}^{\text{EBL}} < E_{\gamma, \text{th}}^{\text{CMB}}$$

$$\text{IC: } e + \gamma_{\text{CMB}} \rightarrow \gamma_{\text{HE}} + e, n_{\text{CMB}} \gg n_{\text{EBL}}$$

## Development of the cascade

- **Stage I: leading particles**:
  - UHE-Photons with  $E_\gamma > E_{\text{th, CMB}}^{\text{PP}} = \frac{m_e^2}{\epsilon_{\text{CMB}}} \approx 400$  TeV produce leptons pairs with  $E_e \approx E_\gamma/2$ .
  - VHE-Leptons with  $E_e \gtrsim 400$  TeV, upscatter CMB photons mainly in **Klein-Nishina regime**,  $E_{\gamma'} \approx E_e$ .
- **Stage II: multiplication regime**:
  - HE-Photons with  $E_\gamma > E_{\text{th, EBL}}^{\text{PP}} = \frac{m_e^2}{\epsilon_{\text{EBL}}} \approx 300$  GeV produce leptons pairs with  $E_e \approx E_\gamma/2$ .
  - He-Leptons with  $E_e \lesssim 200$  GeV, upscatter CMB photons in **Thompson regime**,  $E_\gamma = \frac{4}{3} \frac{E_e^2}{m_e^2} \epsilon_{\text{CMB}} \approx 100$  MeV
- **Stage III: low energy regime** with no more  $\gamma$ -rays with  $E_\gamma \gtrsim 300$  GeV to produce pairs on EBL; the cascade only proceeds through the **ICS of remnant leptons on the CMB**.

## Universal spectrum approximation

Monte Carlo codes for extragalactic propagation implement a simple but effective approximation based on **ICS kinematics**:

$$\frac{dn_\gamma(E_\gamma)}{dE_\gamma} \propto \frac{q_e(E_e)}{E_e E_\gamma}, E_\gamma \propto E_e^2, \epsilon_X(z) = \frac{\epsilon_{\text{th, EBL}}^{\text{PP}}(z) \epsilon_{\text{CMB}}(z)}{3 \epsilon_{\text{EBL}}(z)}$$

$$Q_\gamma(E, z) \approx \omega_{\text{casc}}(z) \times \begin{cases} \left( \frac{E_\gamma}{\epsilon_X(z)} \right)^{-\frac{3}{2}} & \text{if: } E_\gamma \leq \epsilon_X(z) \\ \left( \frac{E_\gamma}{\epsilon_X(z)} \right)^{-2} & \text{if: } \epsilon_X(z) < E_\gamma \leq \epsilon_{\text{th, EBL}}^{\text{PP}}(z) \\ 0 & \text{if: } E_\gamma > \epsilon_{\text{th, EBL}}^{\text{PP}}(z) \end{cases}$$

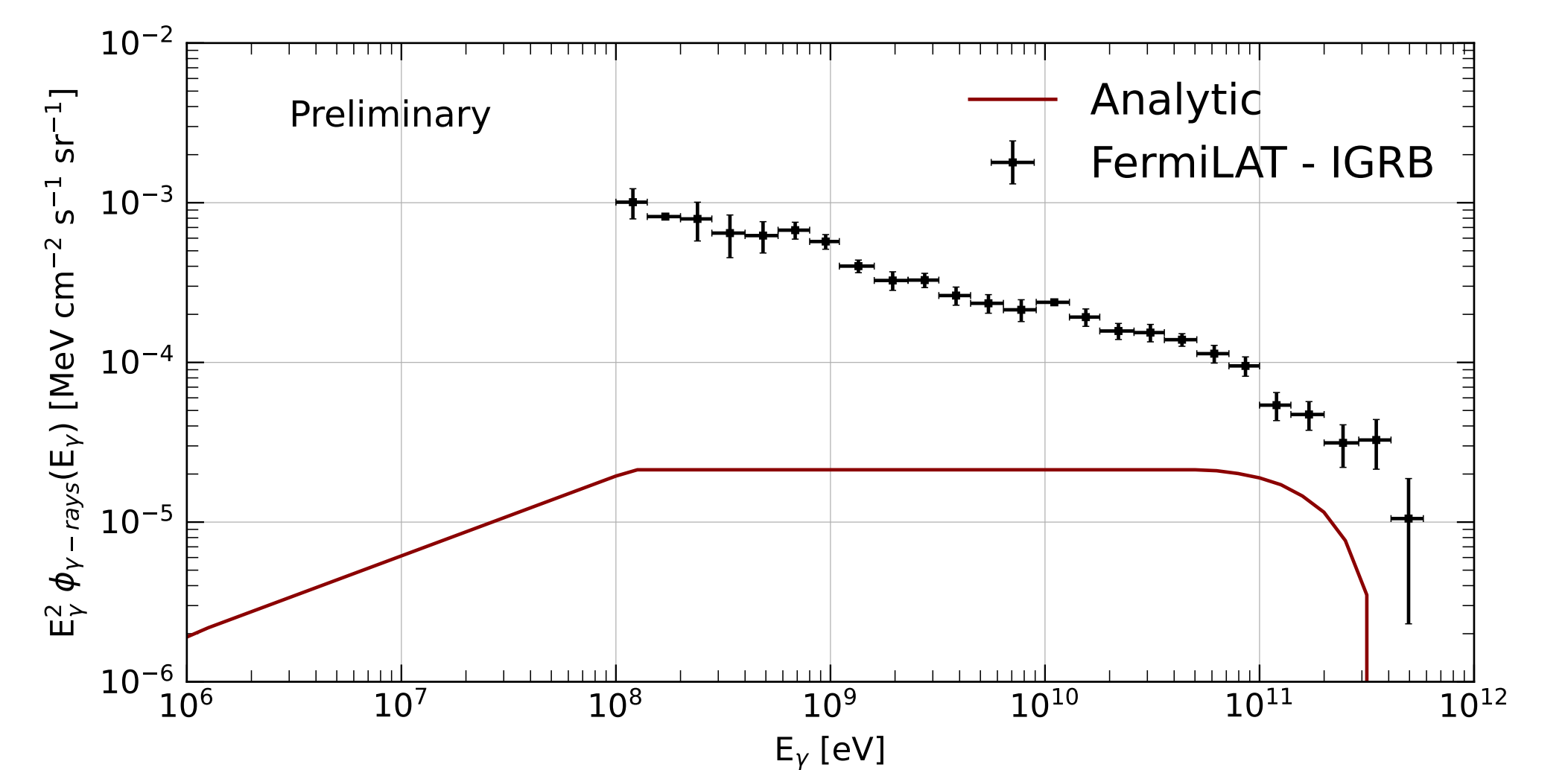


Figure: Data from Ackermann, M. et al., The Astrophysical Journal 799.1 (2015)

- **Conservation of energy in stage I**:
$$\omega_{\text{casc}}(z) = \int dEE [Q_{e^-}(E, z) + Q_{e^+}(E, z) + Q_\gamma(E, z)]$$
- **Equipartition of energy between photons and leptons in stage II: pair are continuously produced**

$$E_{\text{tot}} = E(q_e(E) + q_\gamma(E)) \rightarrow q_e(E_e) \approx \frac{2E_{\text{tot}}}{3E_e}$$
- **Leptons are no more produced in stage III:  $q_e(E_e) \approx \text{const.}$**

## Work in progress

- Finalizing implementation of full EM cascades
- Developing coupling with the new *SimProp*.
- Providing benchmark models to test *CRPropa* and *SimProp* accuracy.
- **Comprehensive exploration of UHECR source parameter space.**