INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

PIERRE AUGER OBSERVATORY

Multimessenger constraints on the UHECR source evolution in the AugerPrime era

Speaker: A. Cermenati, authors: R. Aloisio, C. Evoli, A. Ambrosone, L. A. Dourado

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

$$p_{\rm CR} + \gamma_t \to \Delta^+ \to \pi_0 + p'_{\rm CR} \Rightarrow \pi_0 \to \gamma + \gamma$$

$$p_{\rm CR} + \gamma_t \to \Delta^+ \to \pi_+ + n_{\rm CR} \Rightarrow \begin{cases} n_{\rm CR} \to p'_{\rm CR} + e^- + \bar{\nu}_e \\ \pi_+ \to \mu^+ + \nu_\mu \Rightarrow \mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e \end{cases}$$

$$p_{\rm CR} + \gamma_t \to \Delta^+_* \to p'_{\rm CR} + \pi_+ + \pi_- \Rightarrow \begin{cases} \pi_+ \to \mu^+ + \nu_\mu \Rightarrow \mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e \\ \pi_- \to \mu^- + \bar{\nu}_\mu \Rightarrow \mu^- \to e^- + \bar{\nu}_e + \nu_\mu \end{cases}$$

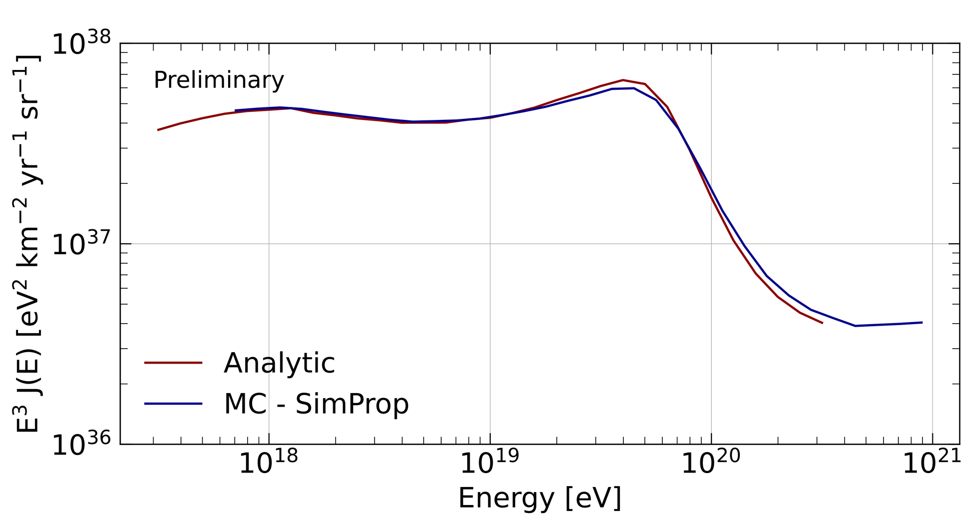
$$(A,Z)_{\rm CR} + \gamma_t \to (A-1,Z)_{\rm CR} + n_{\rm CR} \Rightarrow n_{\rm CR} \to p'_{\rm CR} + e^- + \bar{\nu}_e$$
$$(A,Z)_{\rm CR} + \gamma_t \to (A-1,Z-1)_{\rm CR} + p_{\rm CR}$$
$$(A,Z)_{\rm CR} + \gamma_t \to (A-N,Z-M)_{\rm CR} + Mp_{\rm CR} + (N-M)n_{\rm CR}$$
$$p_{\rm CR} + \gamma_t \to p'_{\rm CR} + e^- + e^+$$
$$(A,Z)_{\rm CR} + \gamma_t \to (A,Z)'_{\rm CR} + e^- + e^+$$

Cosmological transport

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

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
    $\widetilde{Q}(\Gamma,z) \propto L \times (1+z)^m \times \Gamma^{-\gamma} \times f_{\rm cut}(Z,\Gamma)$.
  - Neutrinos & Photons & Leptons: Injection from cosmic rays:
    $Q(E_{\rm x},z) \propto n_{\rm CR}(E_{\rm CR},z) \times R(E_{\rm CR},E_{\rm x},z)$.
- Secondary Injection $Q^{II}(\Gamma,z)$:
  - Protons: Injection from all-nuclei photodisintegration:
    $$Q_{IIp}(E) \propto \Sigma_A \frac{n_A(AE,z)}{\tau_A(AE,z)}$$
  - 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
    $$\begin{cases} Q_\gamma \propto \widetilde{n}_e \times R_{\rm ICS} \\ Q_e \propto \widetilde{n}_\gamma \times R_{\rm PP} \end{cases}$$



Cosmogenic Neutrinos

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

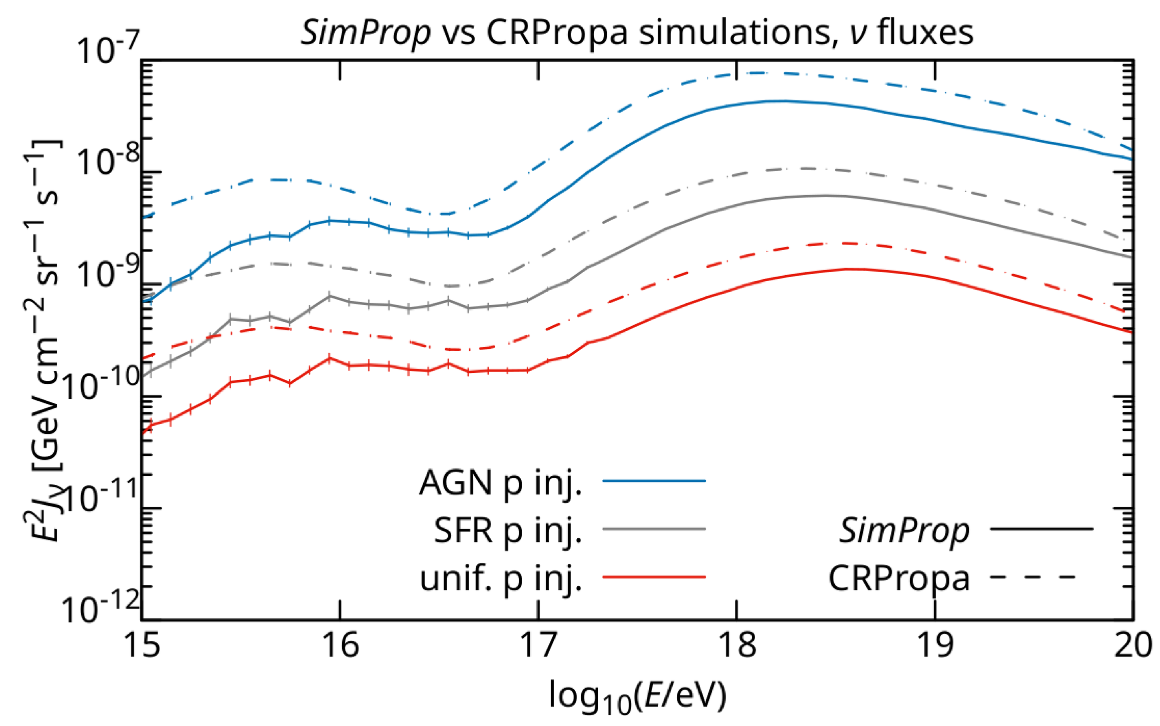
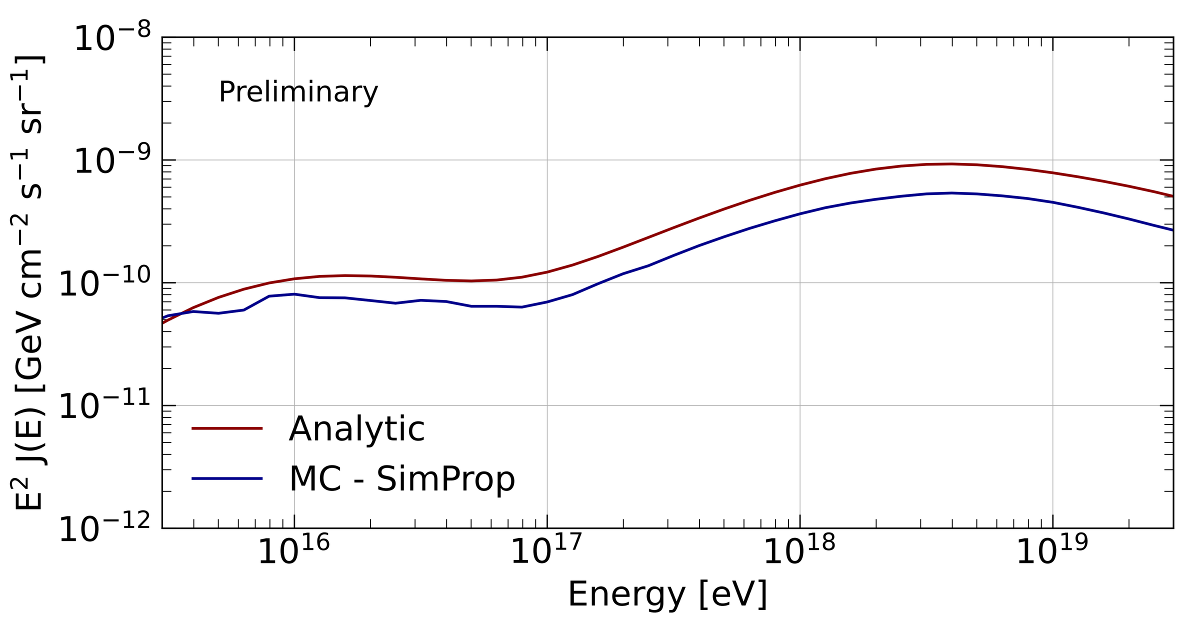


Figure: from Batista, R. A., et al. JCAP 2019/05

- *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

PP: $\gamma + \gamma_{\rm EBL} \to e^+ + e^-$, $E^{\rm EBL}_{\gamma,th} < E^{\rm CMB}_{\gamma,th}$
IC: $e + \gamma_{\rm CMB} \to \gamma_{\rm HE} + e$, $n_{\rm CMB} >> n_{\rm EBL}$

Development of the cascade

- Stage I: leading particles:
  - UHE-Photons with $E_\gamma > E^{PP}_{\rm th,\,CMB} = \frac{m_e^2}{\epsilon_{\rm CMB}} \approx 400$ 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 $E_\gamma > E^{PP}_{\rm th,\,EBL} = \frac{m_e^2}{\epsilon_{\rm EBL}} \approx 300$ 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, $E_\gamma = \frac{4}{3}\frac{E_e^2}{m_e^2}\epsilon_{CMB} \approx 100$ MeV
- Stage III: low energy regime with no more γ-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 kinematic:
$\frac{dn_\gamma(E_\gamma)}{dE_\gamma} \propto \frac{q_e(E_e)}{E_e E_\gamma}$, $E_\gamma \propto E_e^2$, $\epsilon_{\rm X}(z) = \frac{\epsilon^{\rm PP}_{\rm th,EBL}(z)}{3}\frac{\epsilon_{\rm CMB}(z)}{\epsilon_{\rm EBL}(z)}$

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

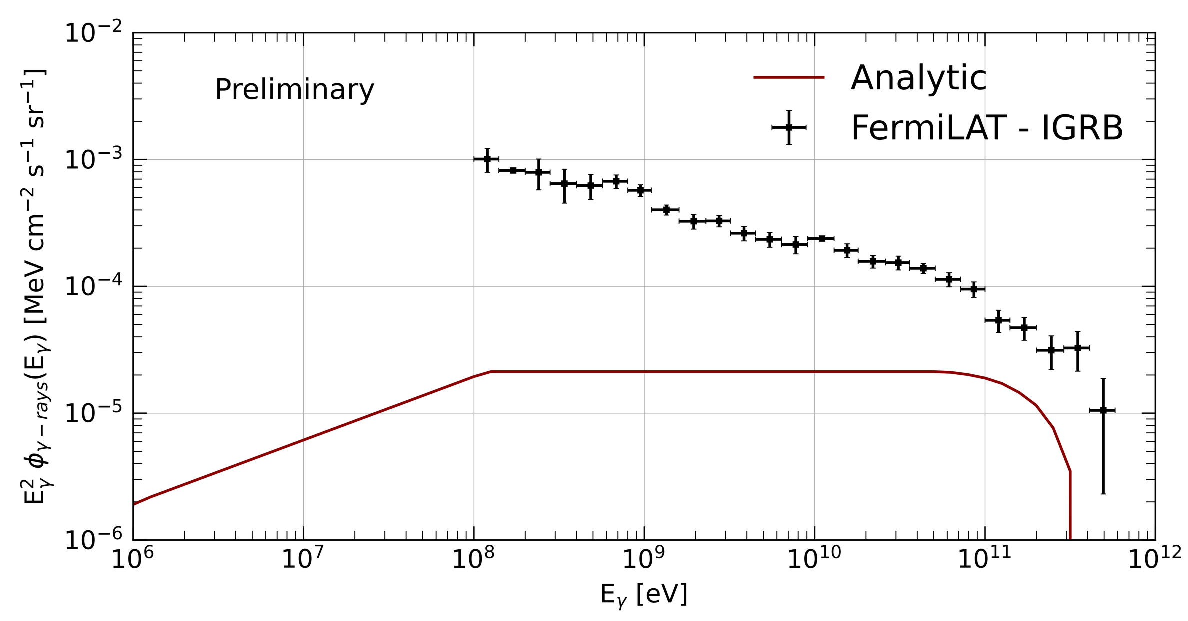


Figure: Data from Ackermann, M. et al., The Astrophysical Journal 799.1 (2015)

- Conservation of energy in stage I:
  $$\omega_{\rm casc}(z) = \int dEE\,[Q_{e^-}(E,z) + Q_{e^+}(E,z) + Q_\gamma(E,z)]$$
- Equipartition of energy between photons and leptons in stage II: pair are continuously produced
  $$E_{\rm tot} = E(q_e(E) + q_\gamma(E)) \to q_e(E_e) \approx \frac{2E_{\rm tot}}{3E_e}$$
- Leptons are no more produced in stage III: $q_e(E_e) \approx$ const.

Work in progress

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