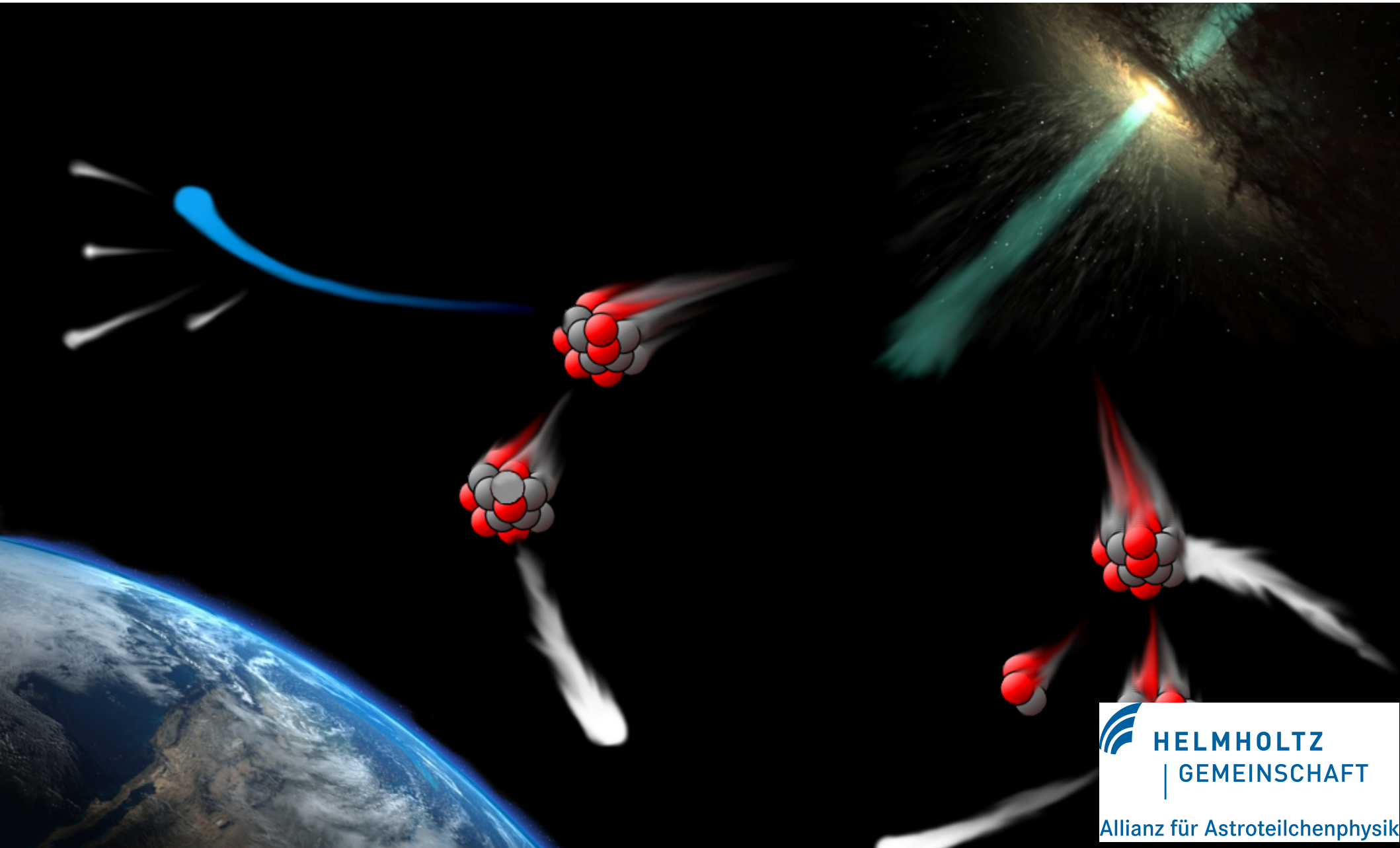
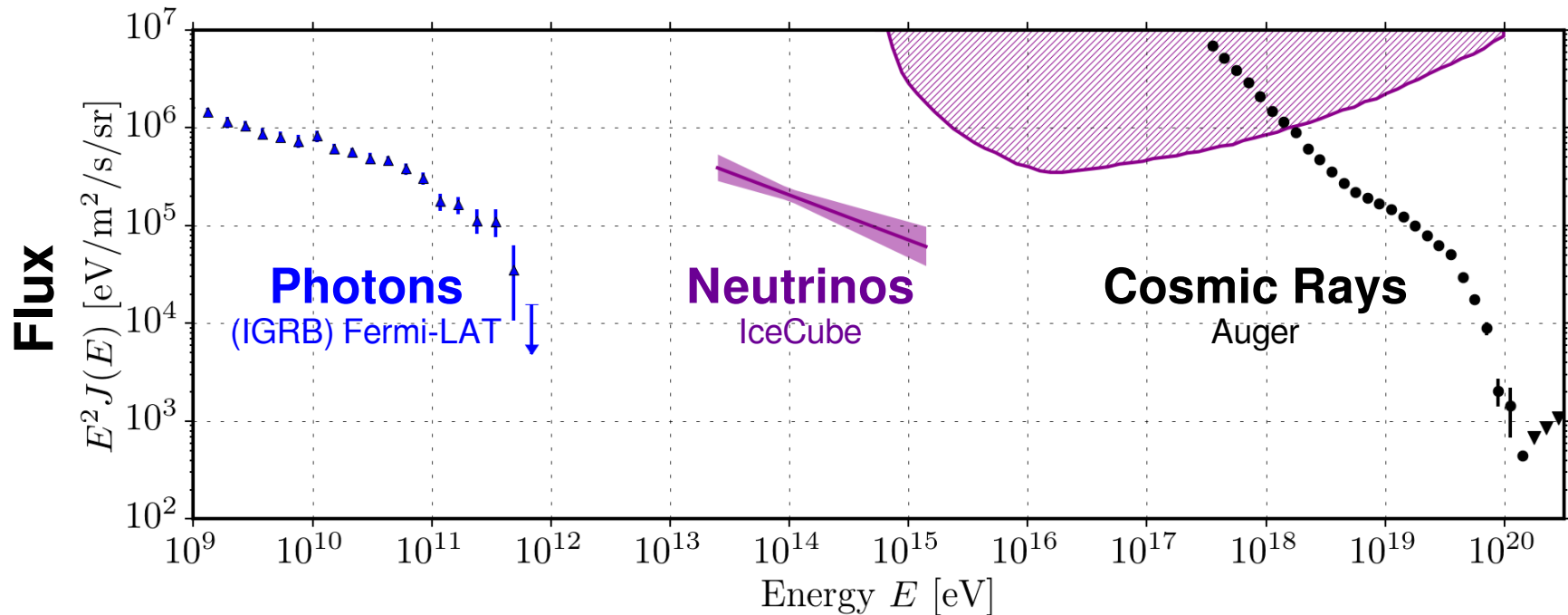


Multimessenger simulations with CRPropa 3



Multimessenger Approach



■ Constrain UHECR scenarios with ν and γ -ray measurements

- » Heinze et al., ApJ 825 (2016)
- » Gavish and Eichler, ApJ 822 (2016)
- » Berezinsky et al., Astropart. Phys. 84 (2016)
- » Liu et al., Phys. Rev. D 94 (2016)
- » Supanitsky, Phys. Rev. D 94 (2016)
- » van Vliet, arXiv:1609.03336 (2016)

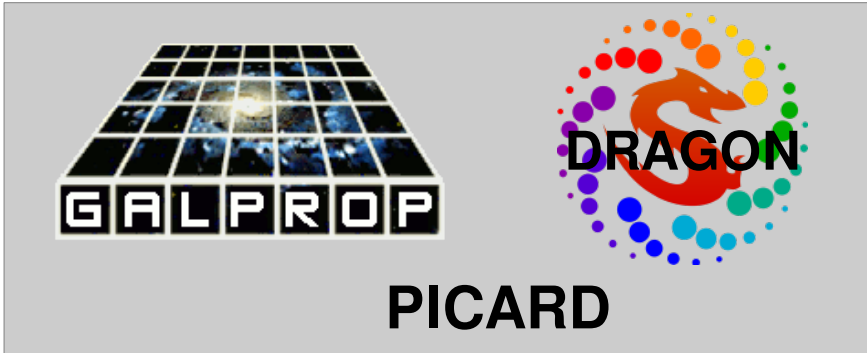


need accurate
cosmic ray simulations

Propagation Codes

- Multi particle approach → Fokker Planck equations

galactic



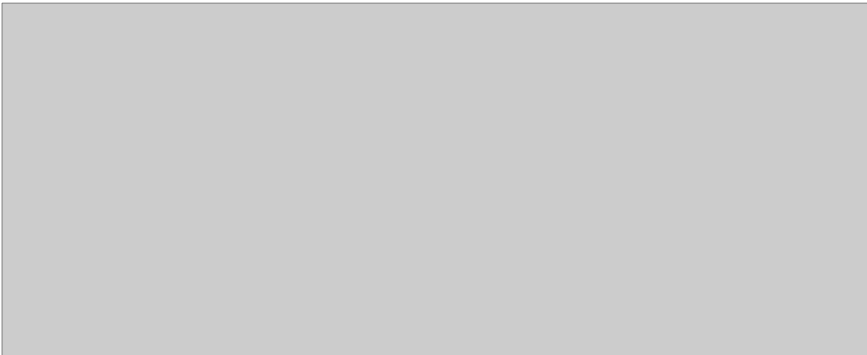
extragalactic

TransportCR DINT

+ many private codes

- Single particle approach → Particle tracking

galactic

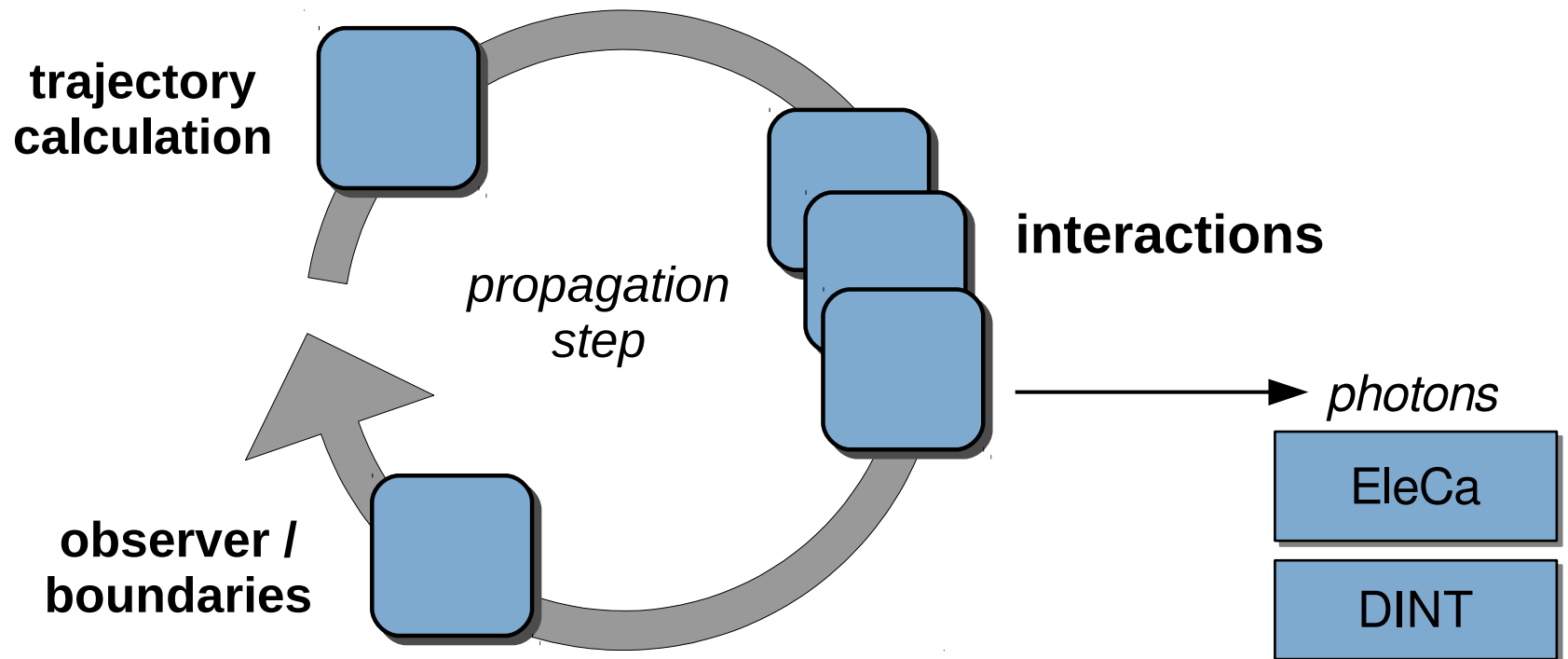
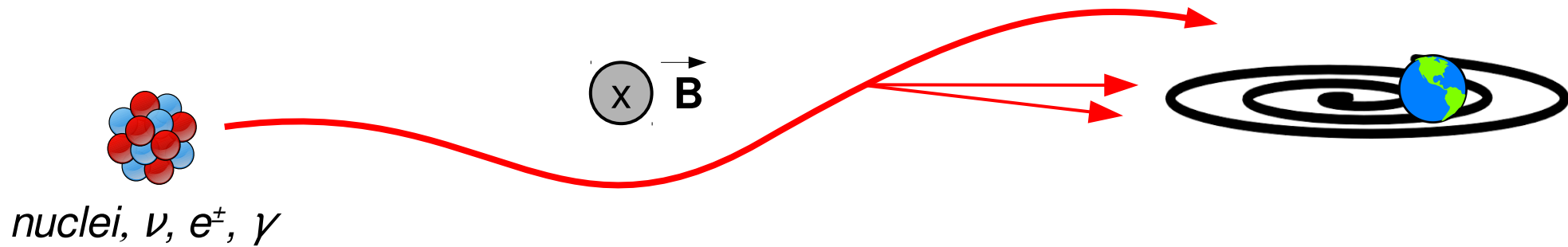


extragalactic

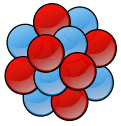
CR/Propa SimProp

CRT Hermes / EleCa

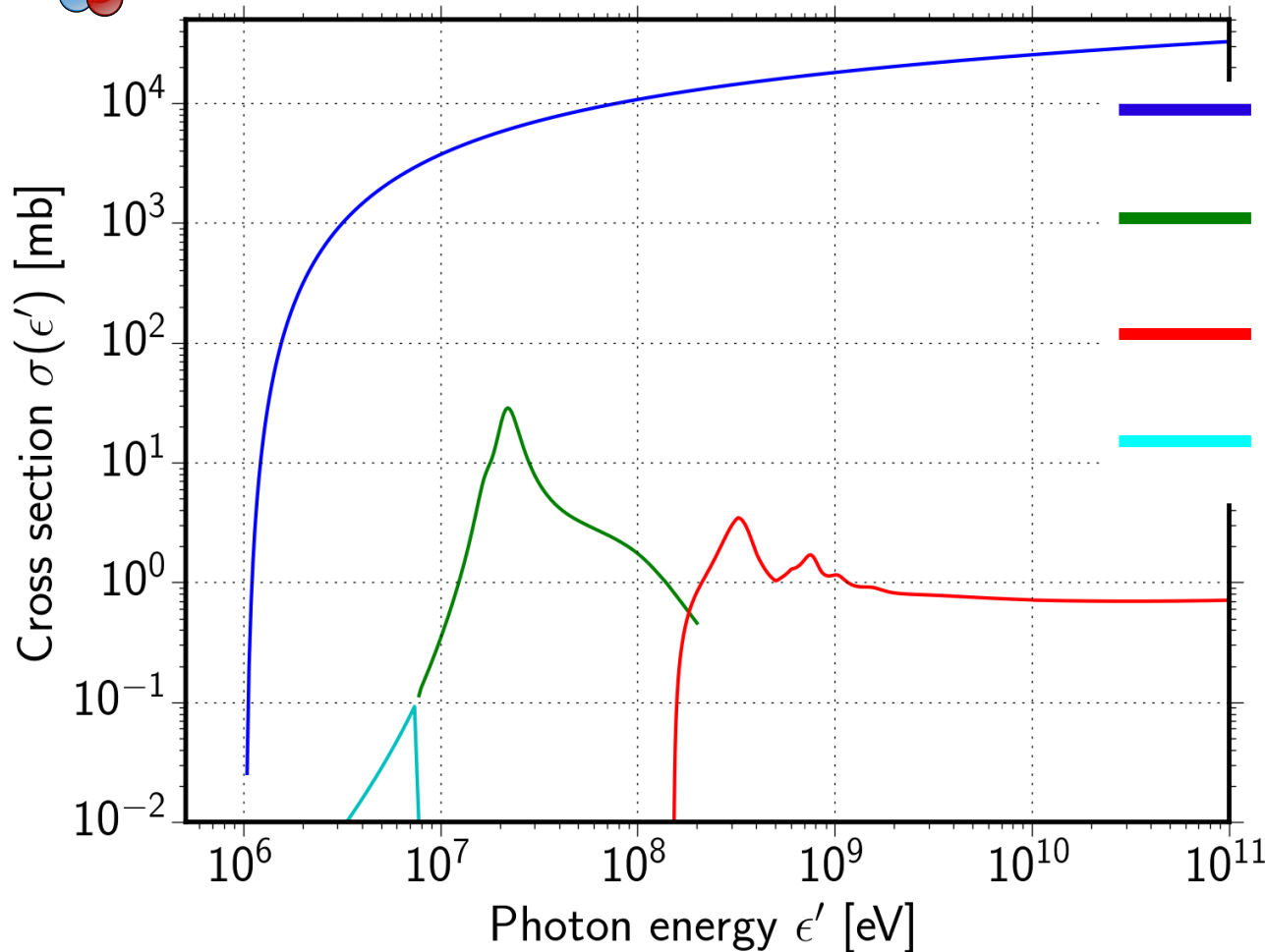
CRPropa 3 in a Nutshell



Interactions for Nuclei



nitrogen-14



process

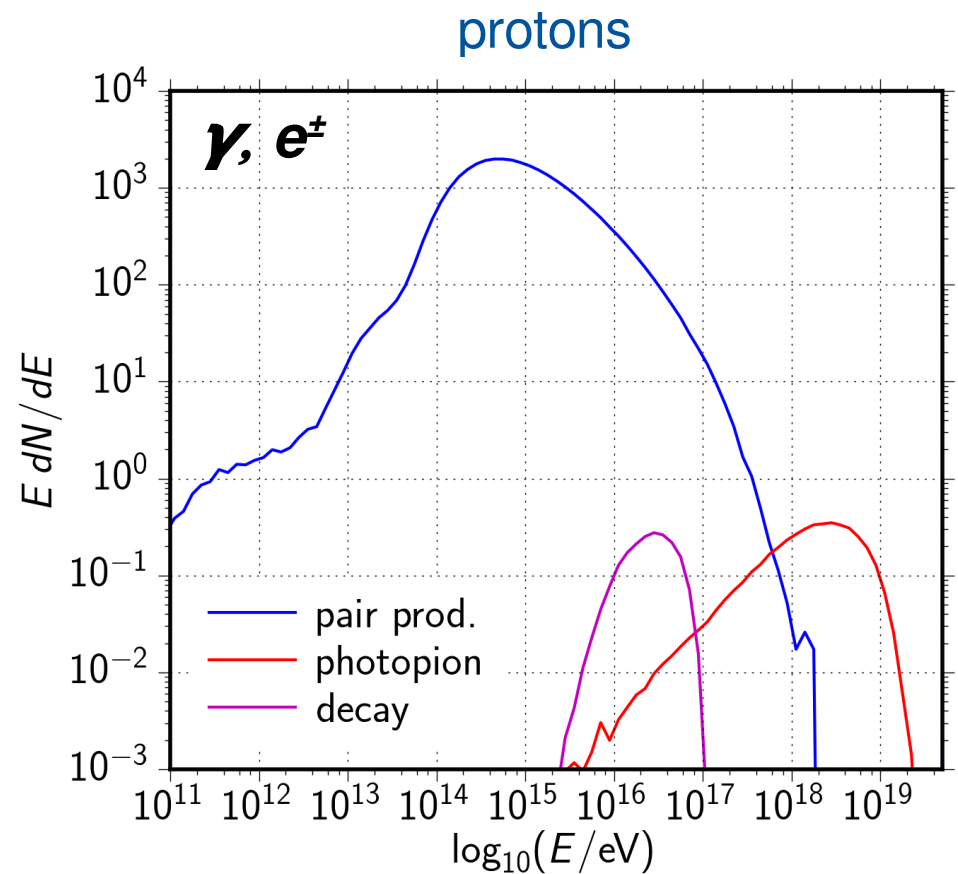
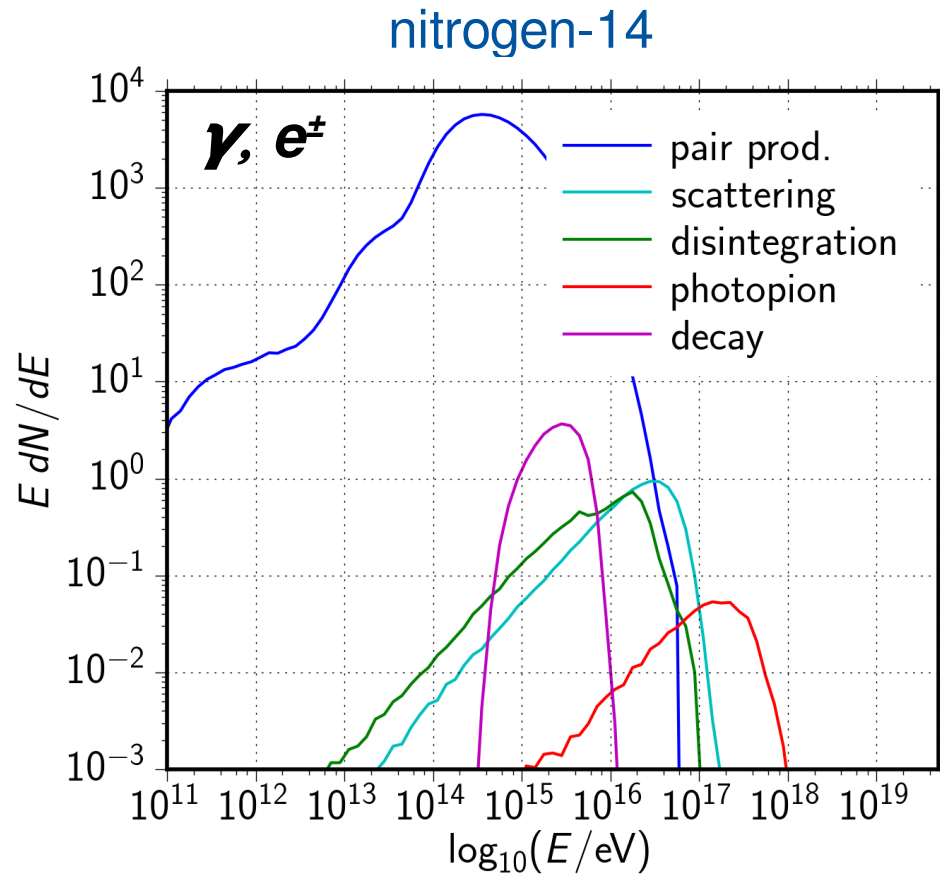
secondaries

(new)

- pair production $\rightarrow e^{\pm}$
- disintegration $\rightarrow \gamma$
- pion production $\rightarrow e^{\pm}, \nu, \gamma$
- elastic scattering $\rightarrow \gamma$
- $\rightarrow e^{\pm}, \nu, \gamma$ nuclear decay

Secondary EM Particles

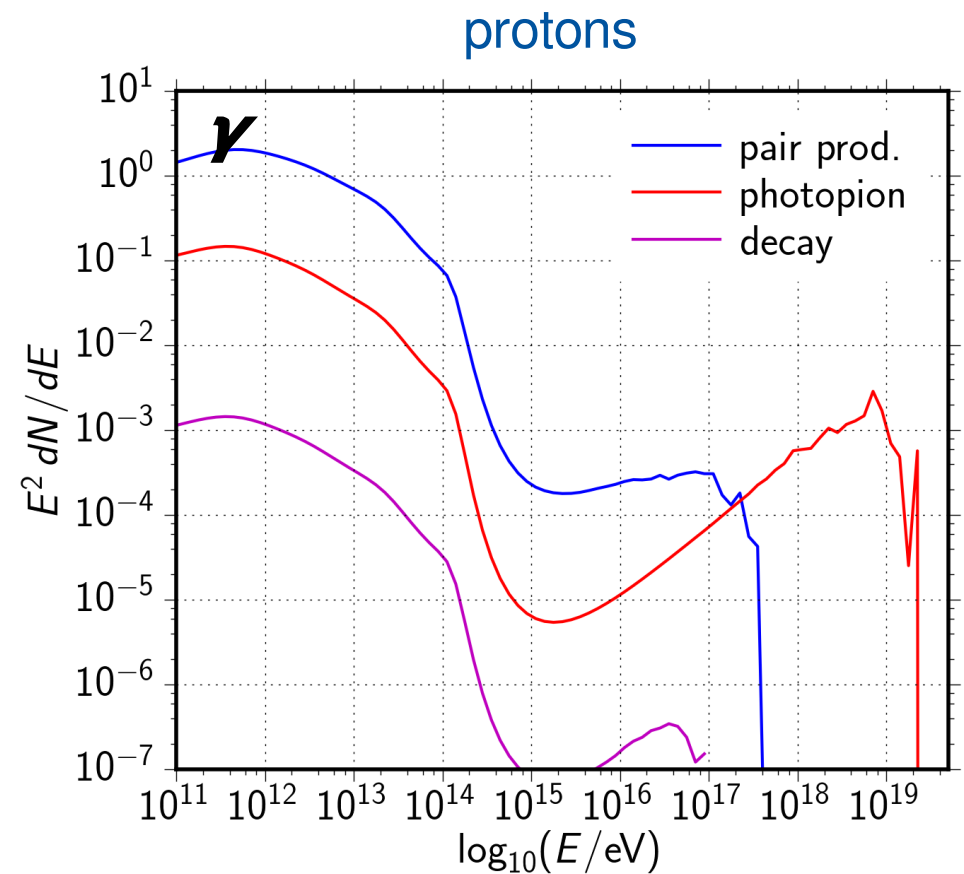
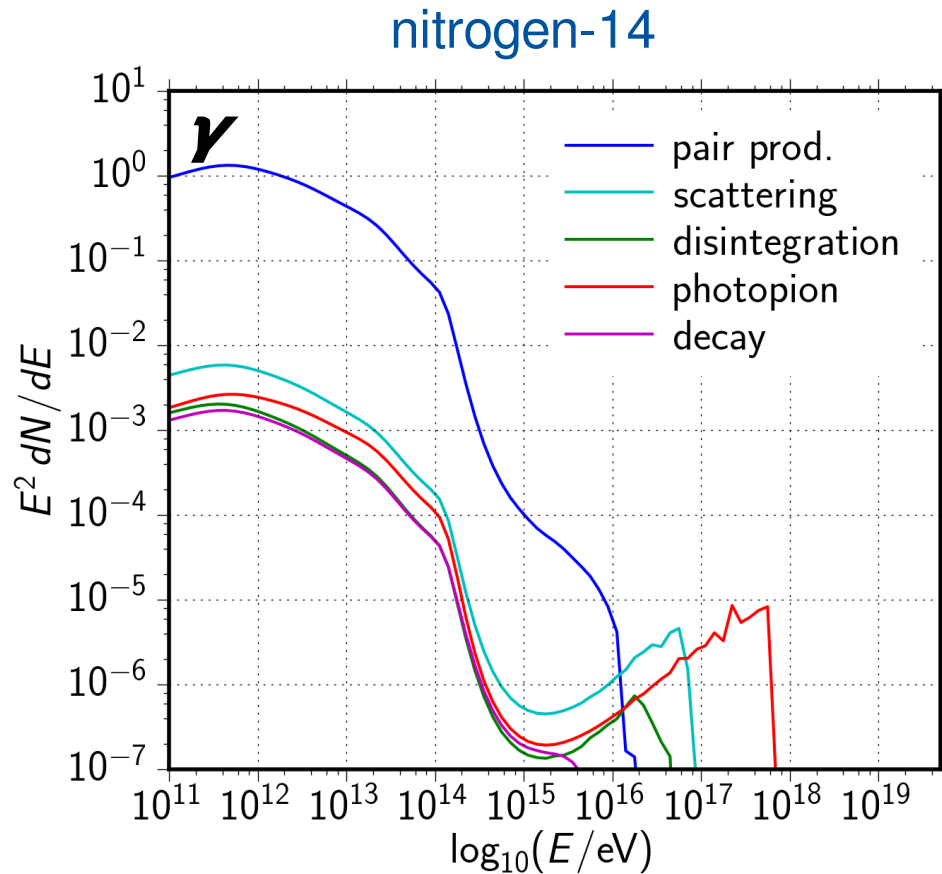
- Example: cosmic rays with 50 EeV from 1-1000 Mpc
 - produced photons and electrons



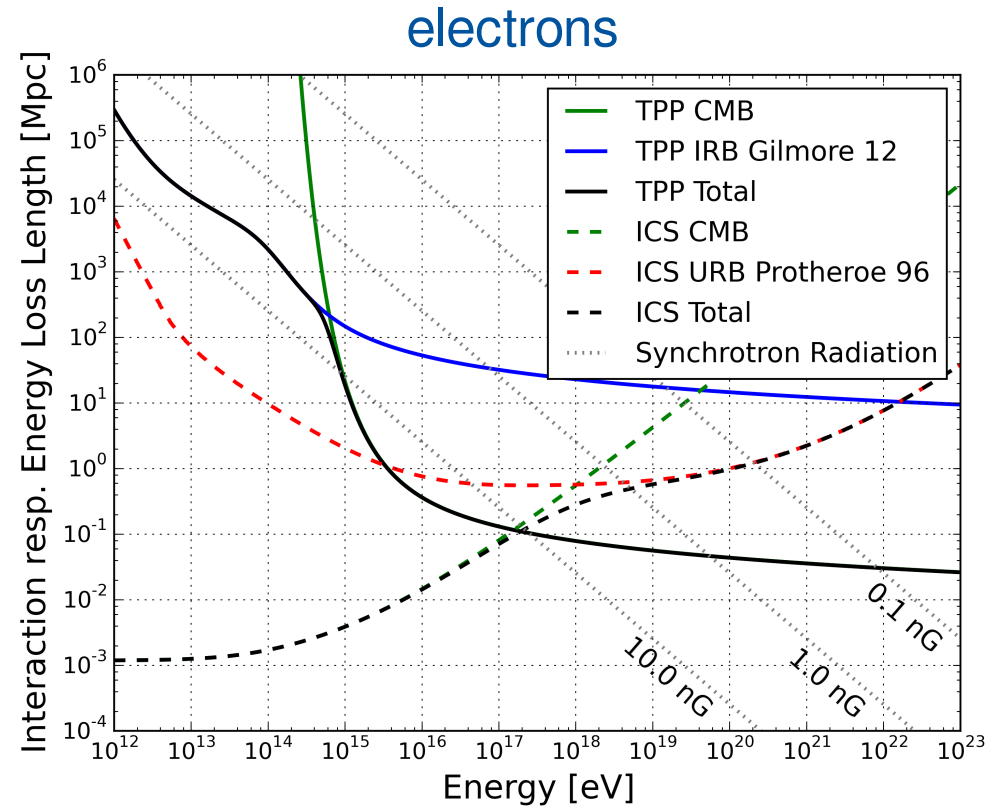
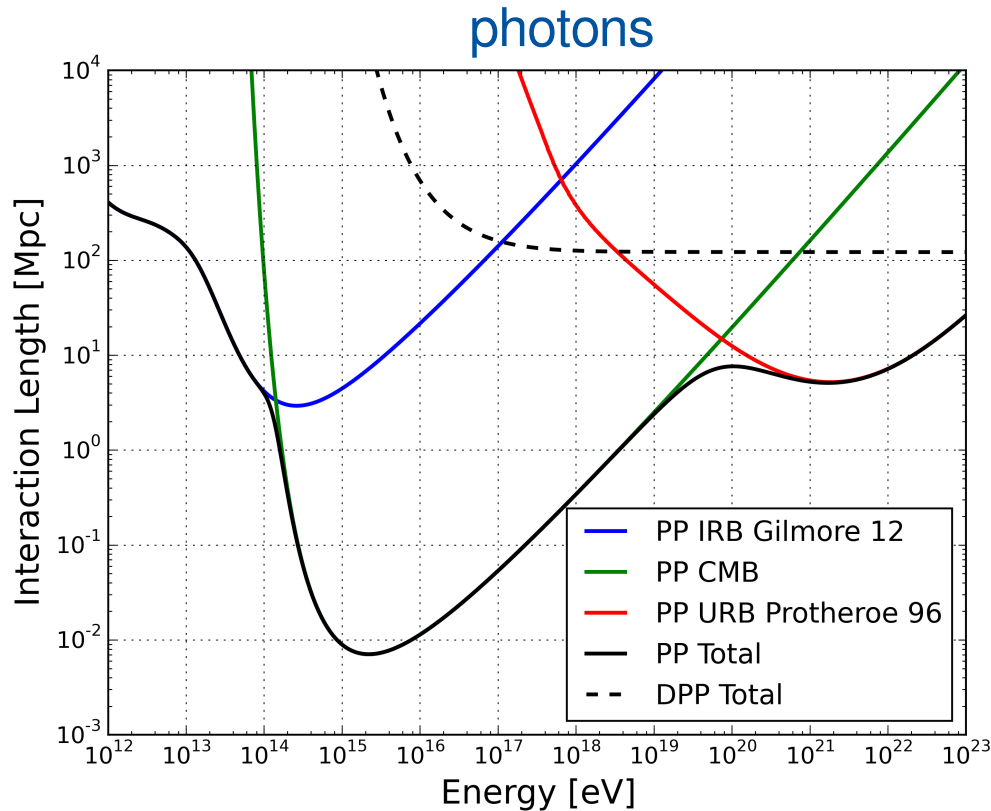
Secondary EM Particles

- Example: cosmic rays with 50 EeV from 1-1000 Mpc
→ observed photons (propagated with DINT)

DINT



EM Cascade in CRPropa

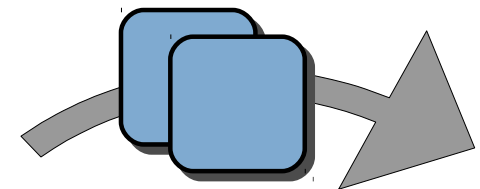


■ **New:** photon / electron interactions directly in CRPropa

→ γ : (double) pair production

→ e^\pm : triplet pair production, inverse compton, synchrotron radiation

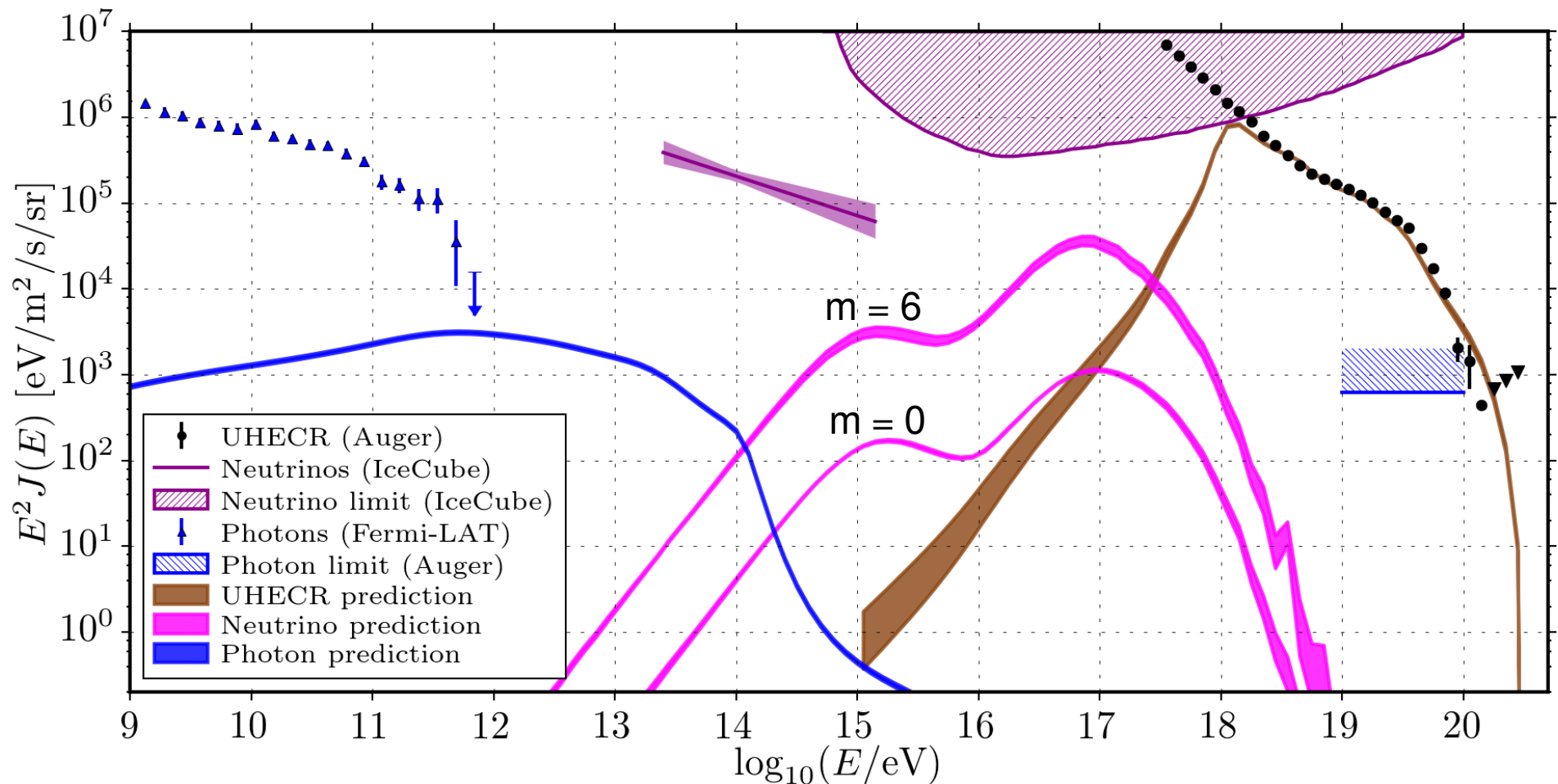
→ Suitable for EM cascade $E > 10^{16}$ eV



Multimessenger Example (1)

- Fit to Auger flux and X_{\max} measurements, for method see *A. di Matteo, ICRC 2015*

$$J_0(Z_0, E_0) = \phi_0 a(Z_0) f_{\text{cut}} \left(\frac{E_0/Z_0}{R_{\text{cut}}} \right) \left(\frac{E_0}{1 \text{ EeV}} \right)^{-\gamma} \frac{\log_{10}(R_{\text{cut}})}{18.56^{+0.02}_{-0.01}} \quad \gamma \quad \text{H} [\%] \quad \text{He} [\%] \quad \text{N} [\%] \quad \text{Fe} [\%]$$

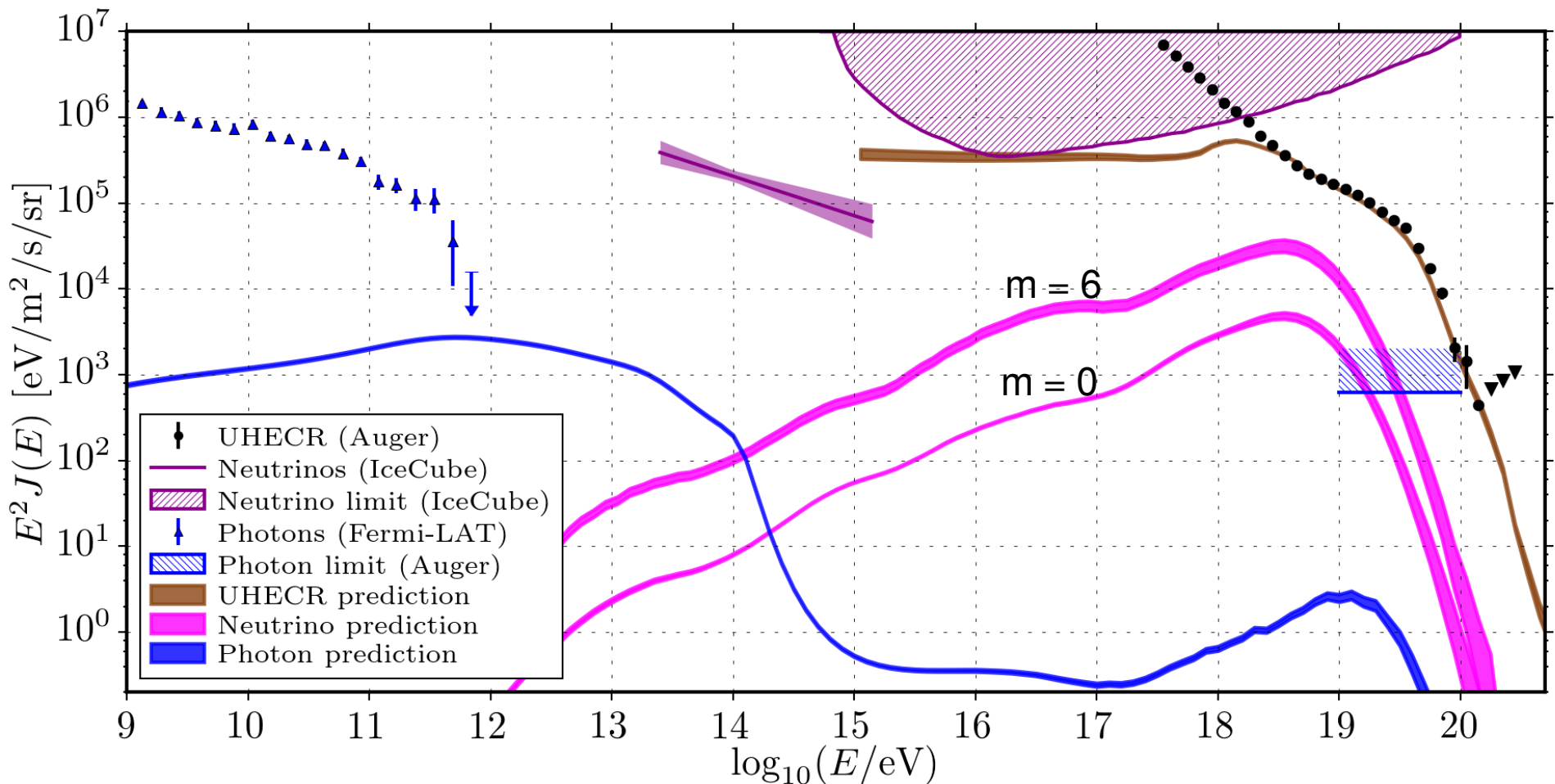


Multimessenger Example (2)

- Fit to Auger flux and X_{\max} measurements, for method see *A. di Matteo, ICRC 2015*

$$J_0(Z_0, E_0) = \phi_0 a(Z_0) f_{\text{cut}} \left(\frac{E_0/Z_0}{R_{\text{cut}}} \right) \left(\frac{E_0}{1 \text{ EeV}} \right)^{-\gamma}$$

$\log_{10}(R_{\text{cut}})$	γ
$19.87^{+0.02}_{-0.02}$	$2.0^{+0.0}_{-0.0}$



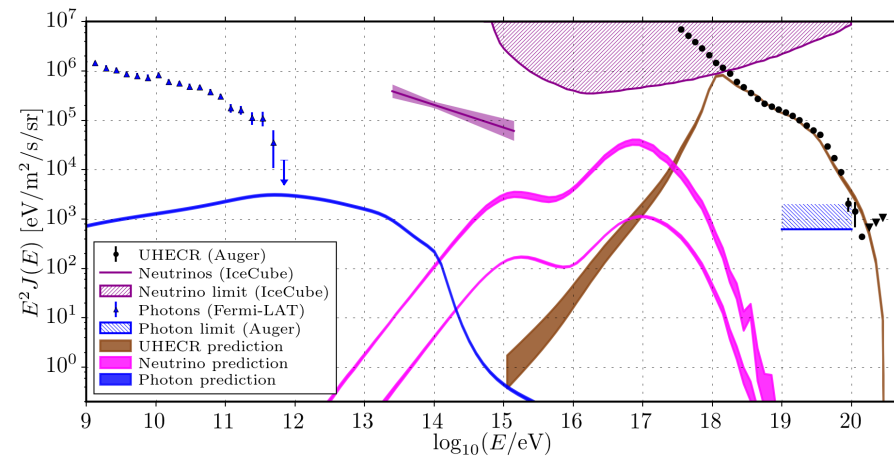
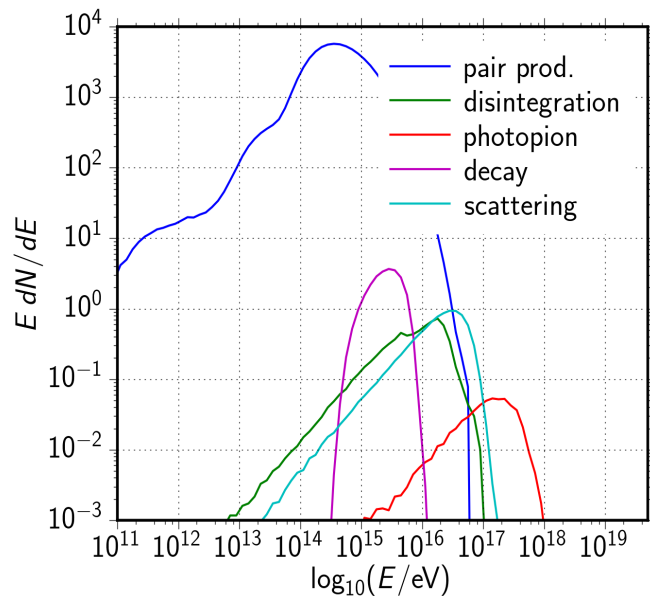
Summary

■ Photon propagation with CRPropa

- Low energies: External cascade simulation **DINT**
- High energies: EM cascade inside CRPropa ($E > 10^{16}$ eV) **new**

■ Photon production in CRPropa

- **New channels:** elastic scattering, photodisintegration, nuclear decay

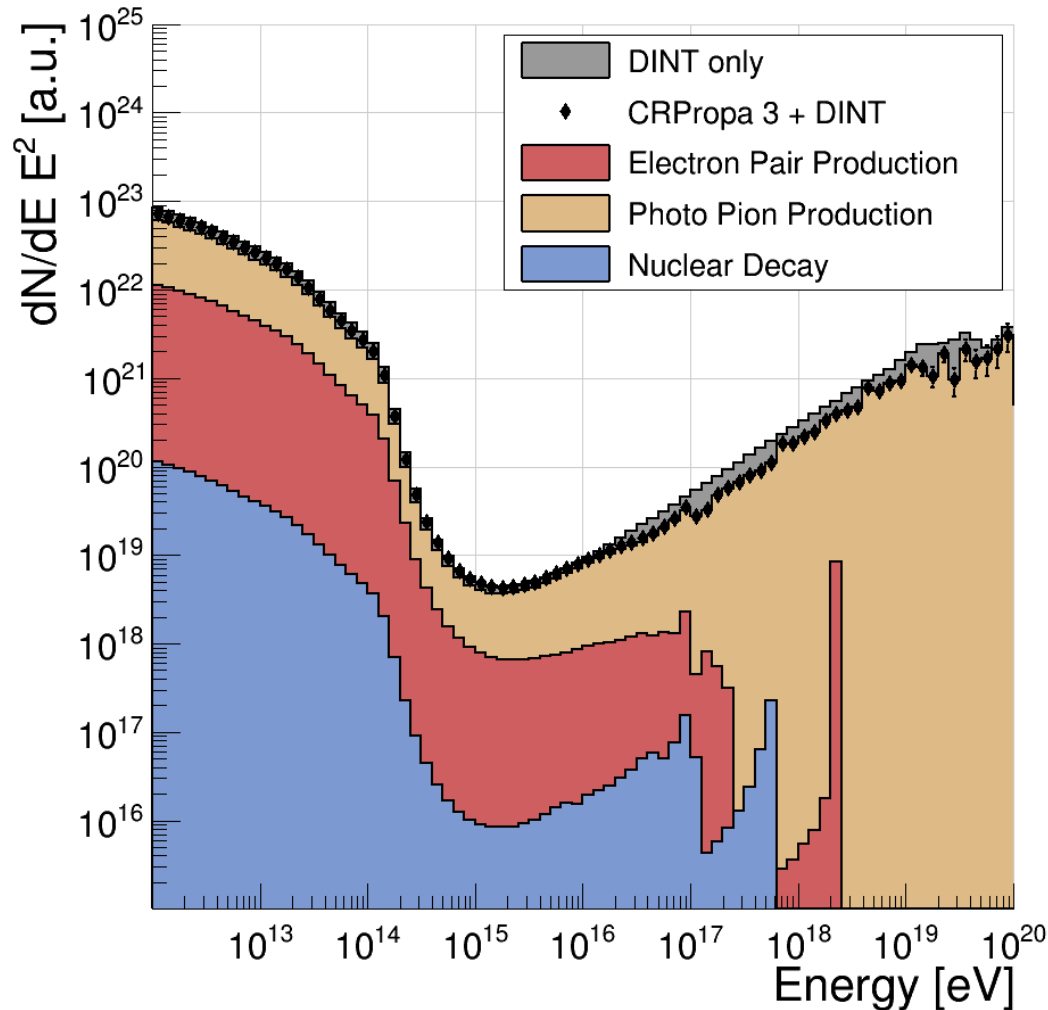


CRPropa

<https://github.com/CRPropa/CRPropa3>

Combination of DINT + CRPropa

Injected Protons



Injected Iron

