Combining Lorentz invariance violation of photons in the extragalactic propagation and in the detection stage

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Based on

- Morais, DB, Lobo, Salamida & Bezerra PoS UHECR2024;
- DB, Bezerra, Giammarco, Lobo & Salamida arxiv:2509.14753v1 (ICRC2025);
- Master Thesis, M. Giammarco, Oct 2025, University of L'Aquila

TeV Particle Astrophysics Conference

3-7 November 2025, Valencia, Spain

Introduction

- At high enough energies, a **violation of space-time symmetries of special relativity** could be manifest

- When Lorentz invariance is broken, the modified dispersion energy-momentum relation for photons can be ⟶ $E_i^2 - p_i^2 = \sum \eta_{i,n} \frac{E_i^{2+n}}{M_{Pl}^n}$ $\delta_{i,n} = \frac{\eta_{i,n}}{M_{Pl}^n}$

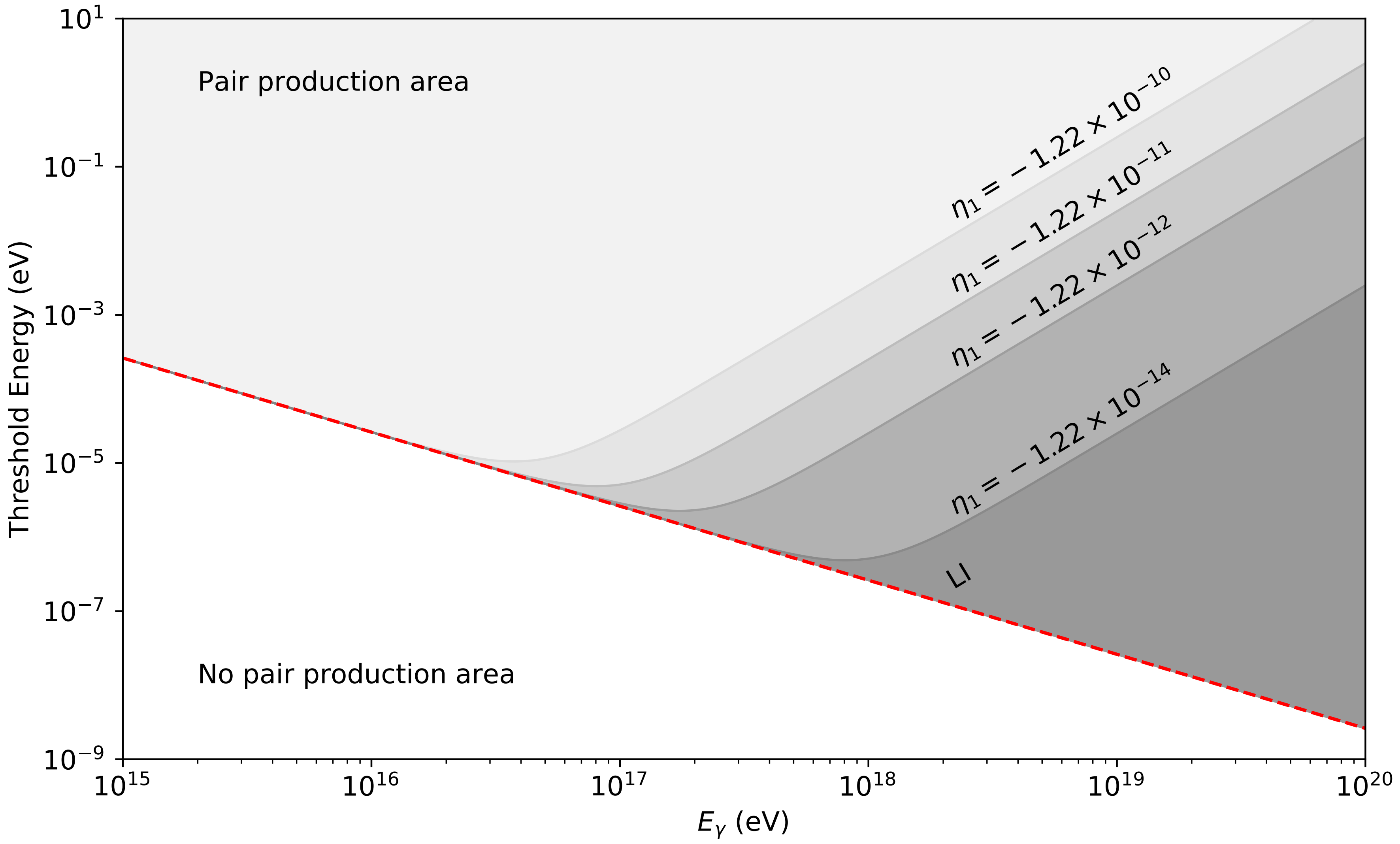
- Lorentz invariance violation (LIV) can affect the threshold of the interactions as well as their cross sections; see Addazi+ Prog.Part.Nucl.Phys. 125 (2022) for a review on quantum gravity phenomenology studies in multimessenger astrophysics

- How to constrain LIV?
  - We compute
    - the typical interaction length
    - the probability of interacting in a medium
    - the modified flux
  - We compare the modified propagated flux (model) to the measured energy spectrum - or to existing limits

LIV in extragalactic propagation of photons

- Modification of threshold (focus on subluminal case, so the threshold increases with LIV), as reported in Lang+ ApJ 2018

$$\epsilon \geq \frac{4m_e^2 - m_{\rm eff}^2}{4E_\gamma}$$

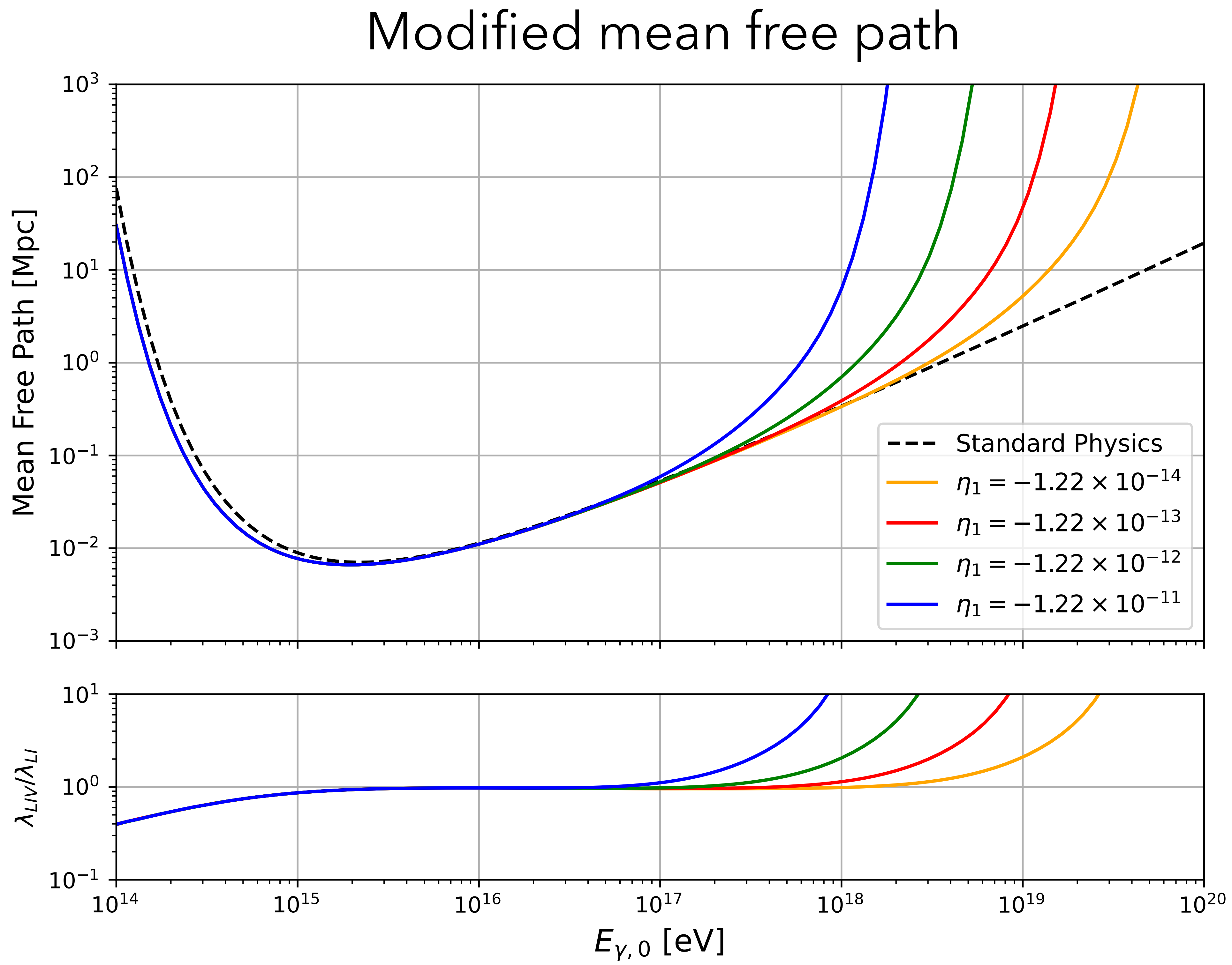


$$\gamma + \gamma_{\rm bkg} \rightarrow e^+ + e^-$$

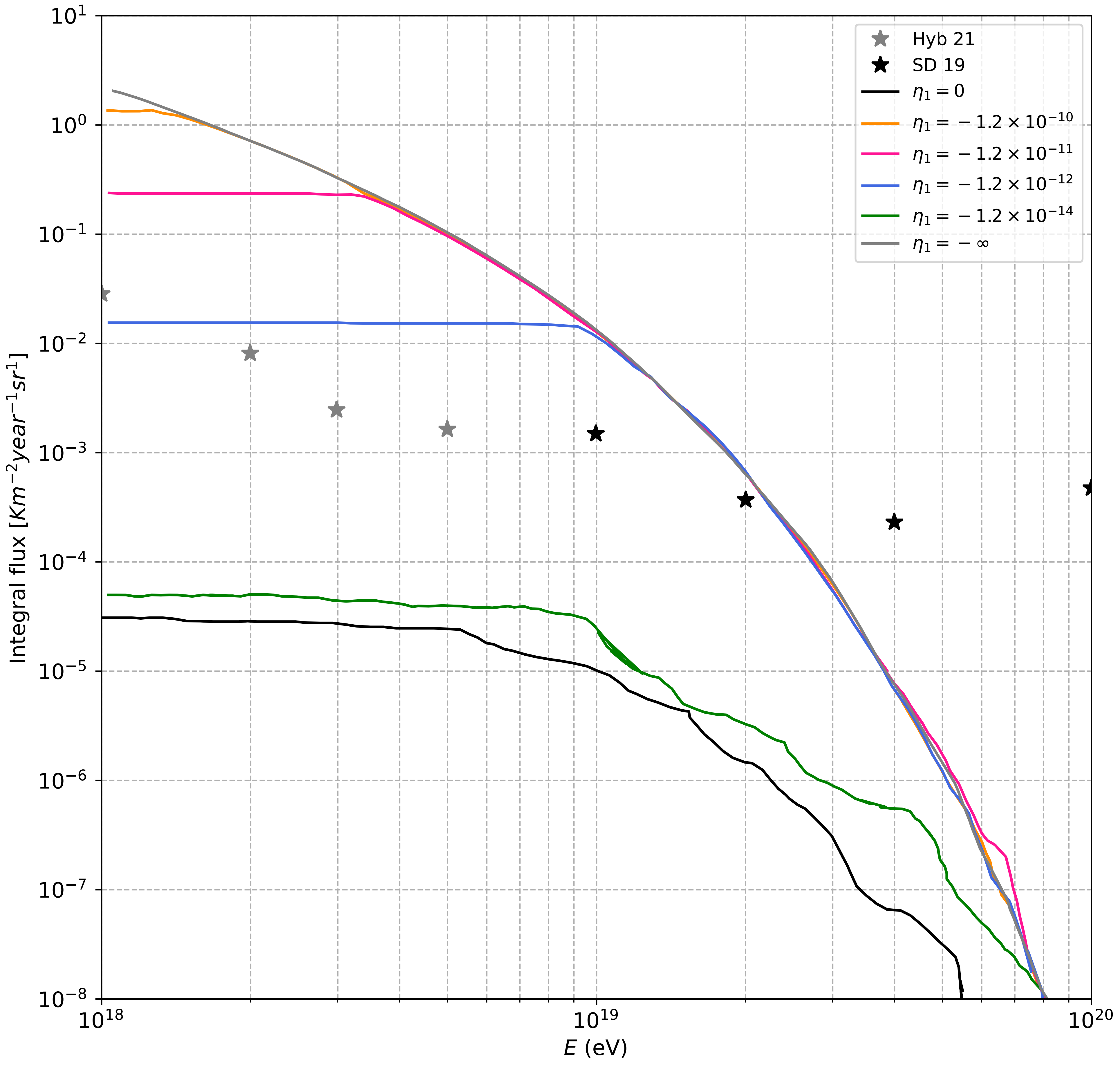
- See also Carmona+ PRD 2024 for a refined treatment of cross section modifications

$$\frac{1}{\lambda(E)} = \frac{c}{2\Gamma^2}\int_{\varepsilon'_{\rm th}}^{\infty} \sigma(\varepsilon')\varepsilon' \int_{\varepsilon'/2\Gamma}^{+\infty} \frac{n_\gamma(\varepsilon)}{\varepsilon^2} d\varepsilon d\varepsilon'$$

$$P_{prop}(E, d_s(z)) \approx \exp(-d_s/\lambda(E))$$



LIV in extragalactic propagation of photons



- Redshift and energy of **cosmogenic photons** (as produced by interactions of UHECRs with background photons) computed with *SimProp*, Aloisio, DB, di Matteo, Grillo, Petrera & Salamida JCAP2017
- Mass composition and spectral characteristics of UHECRs at their sources determined through a fit of measured spectrum and mass composition, see Auger JCAP 2017; JCAP 2023
    - Additional proton component (as allowed from Auger data) to increase the production of cosmogenic particles (see Muzio+ PRD 2019 for details)

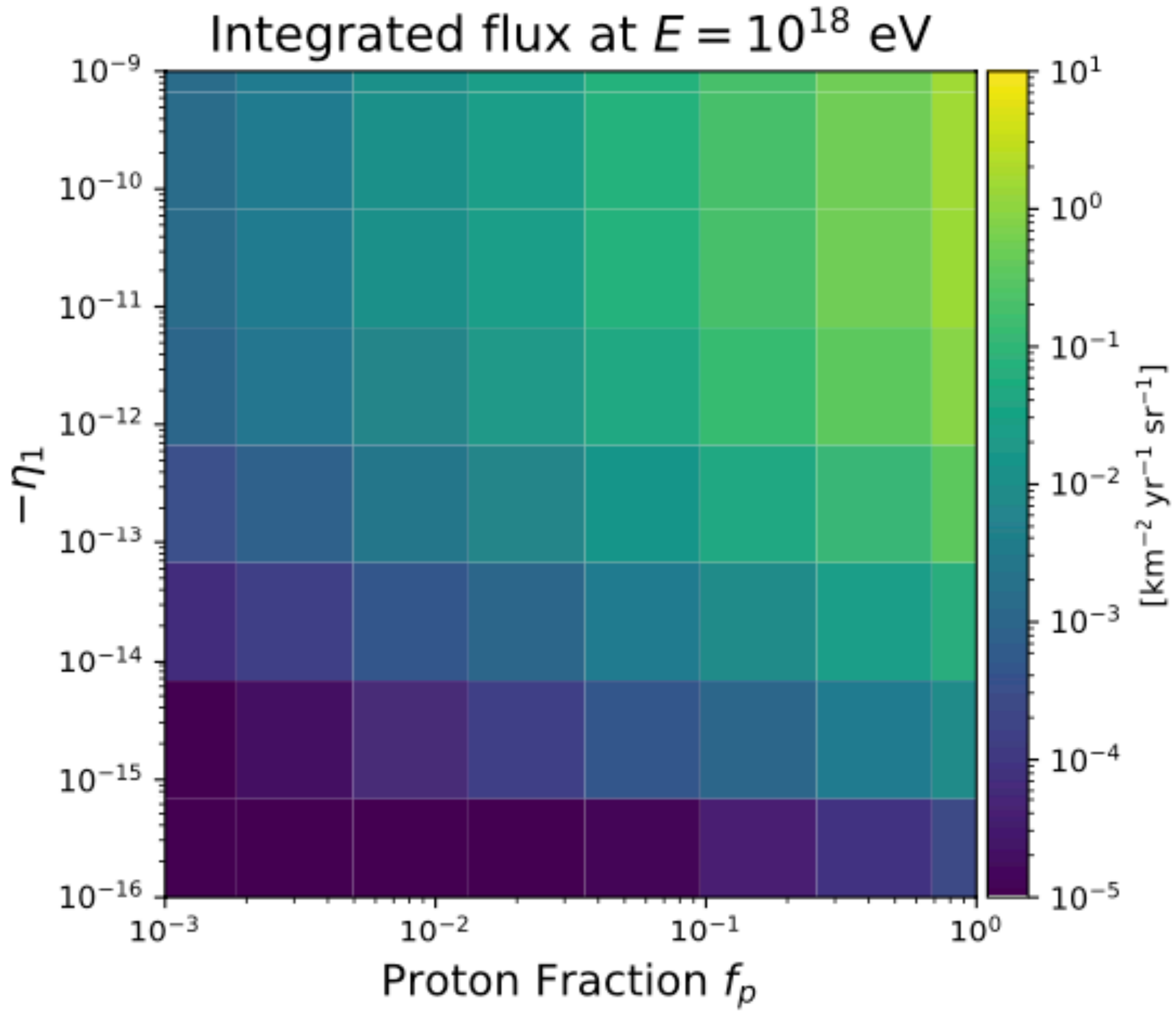
$$\left(\frac{dn_\gamma(E, z=0,\eta)}{dE}\right)_{top-of-atm} = \sum_{z_i} P_{prop}(E, z_i, \eta) \frac{dn_\gamma(E, z_i)}{dE}$$

→ Cosmogenic photons, as produced with SimProp

- LIV modifications allow for a larger photon flux to reach the top of the atmosphere
- LIV parameters corresponding to fluxes larger than the upper limits (as set by Auger, see Auger PRD 2024) can be excluded

LIV in extragalactic propagation of photons

- While fixing the other astrophysical parameters linked to the UHECR flux (spectral index, maximum energy of acceleration, mass composition), a scan over the proton fraction in UHECRs and LIV parameter can be performed
- Large proton fraction as well as large LIV parameter increase the expected photon flux



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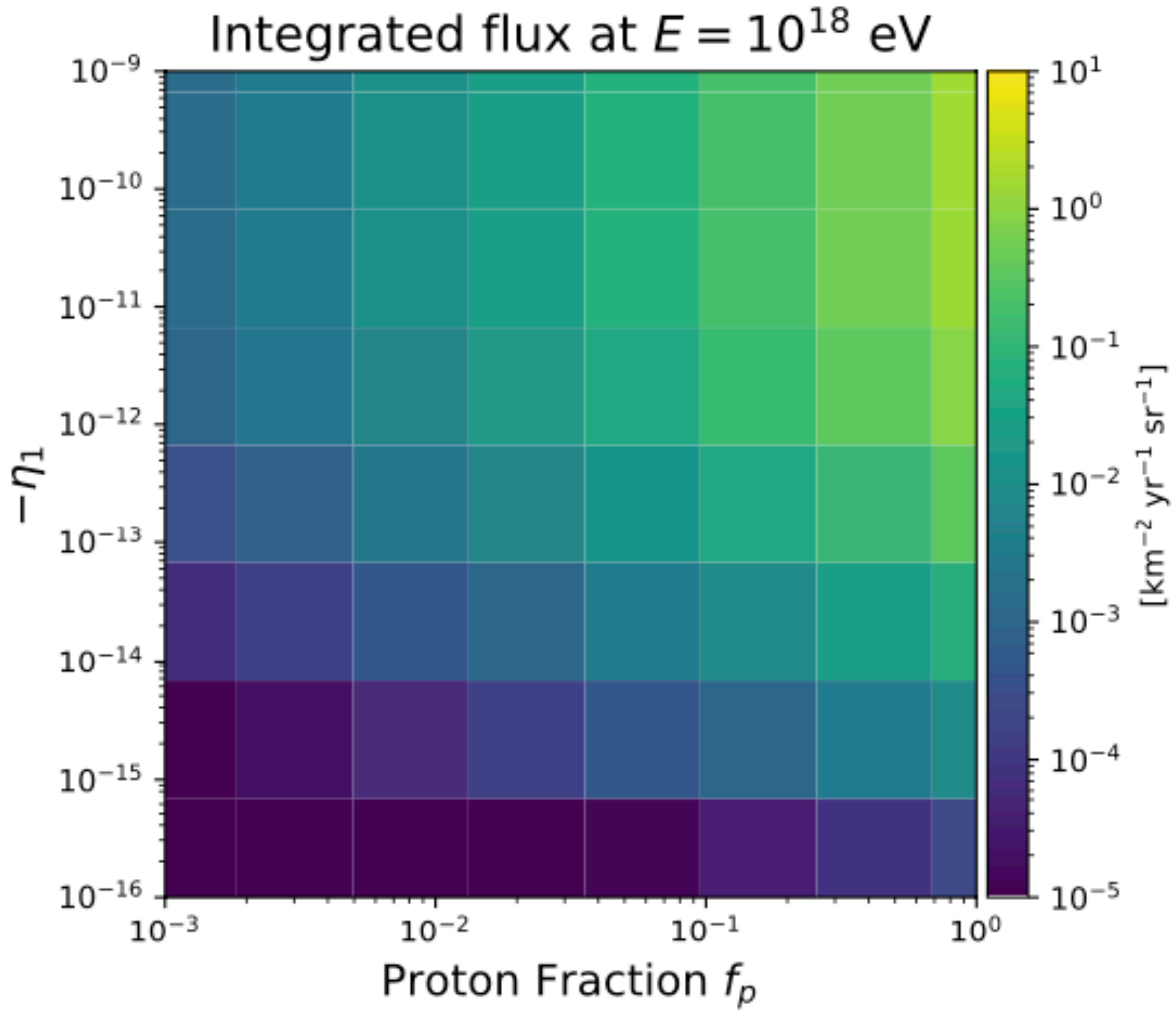
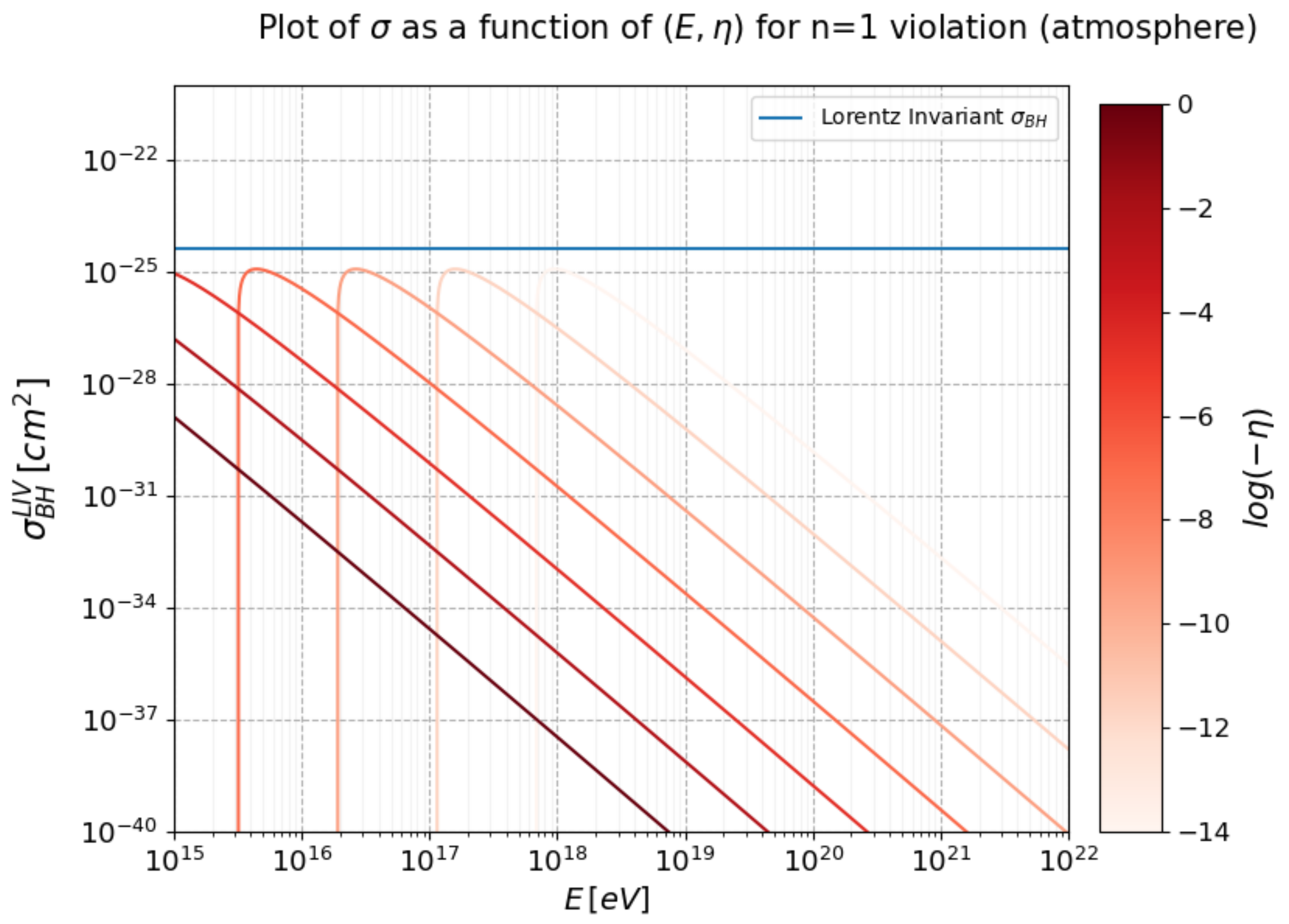


- Observation of UHE photons happens through the development of showers in atmosphere
  - To be considered for LIV searches

LIV in development of atmospheric showers initiated by photons

- Modification of cross section as reported in Rubtsov, Satunin & Sibiryakov, PRD 2012; 2014

$$\gamma + N_{\rm atm} \rightarrow N_{\rm atm} + e^+ + e^-$$



$$|\eta| \gg m_e^2 \frac{M_{Pl}^n}{E^{n+2}}$$

Validity of modification

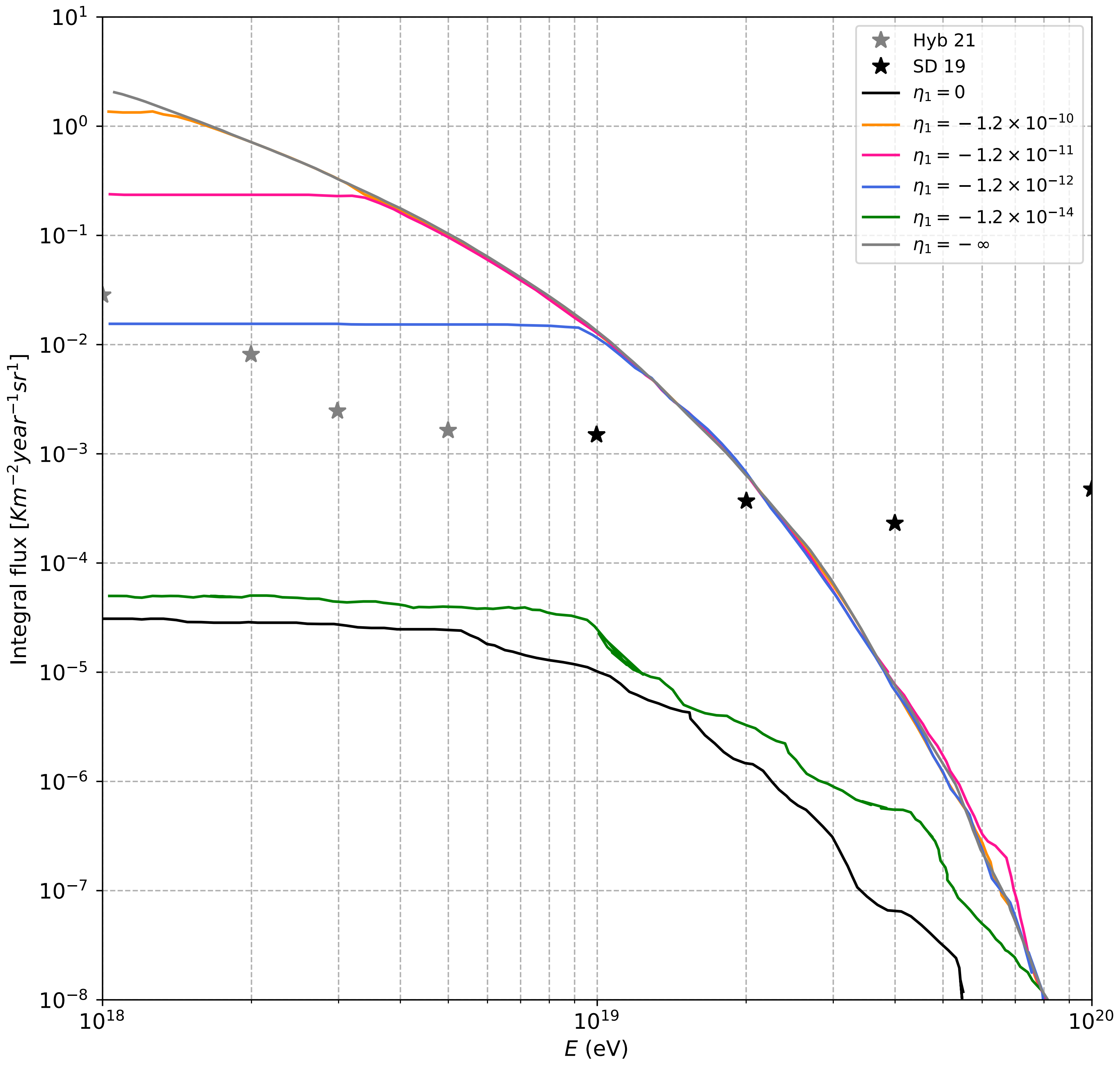
$$P_{atm}(E,\eta) = \int_0^{X_{\rm atm}} dX_0 \frac{e^{-X_0/\langle X_0\rangle_{\rm LIV}}}{\langle X_0\rangle_{\rm LIV}} = 1 - e^{-X_{\rm atm}/\langle X_0\rangle_{\rm LIV}}$$

$$\langle X_0\rangle_{\rm LIV} = \frac{\sigma^{\rm LI}}{\sigma^{\rm LIV}}\langle X_0\rangle_{\rm LI}$$

Probability to produce a pair in atmosphere

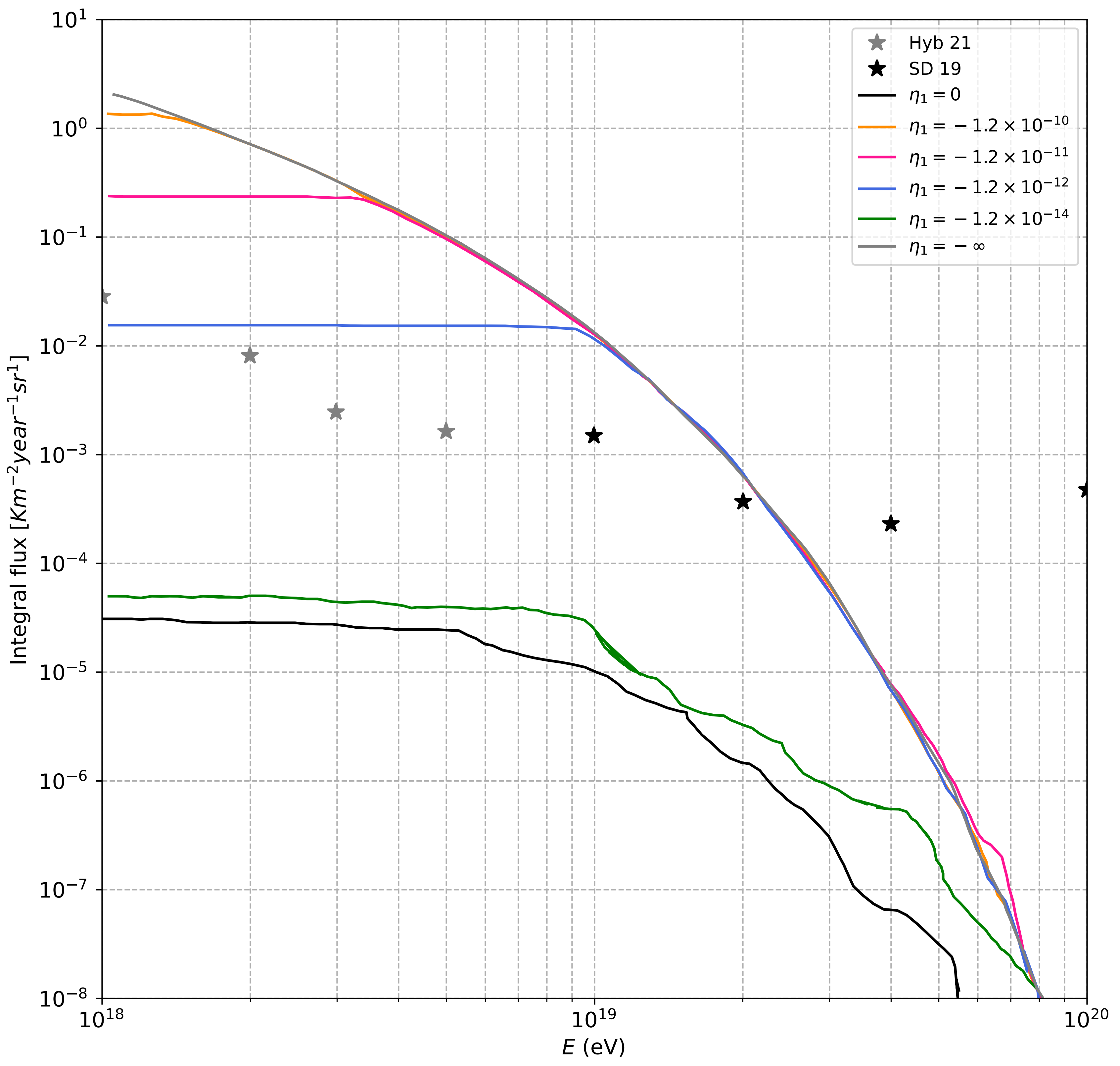
- For other tests of LIV in atmospheric showers: see
  - Photon sector: Duenkel+ PRD 2023; PRD 2021; Klinkhamer+ PRD 2017
  - Effects in Xmax predictions: DB+ ICRC2015
  - Fluctuation of the number of muons: Auger ICRC2021

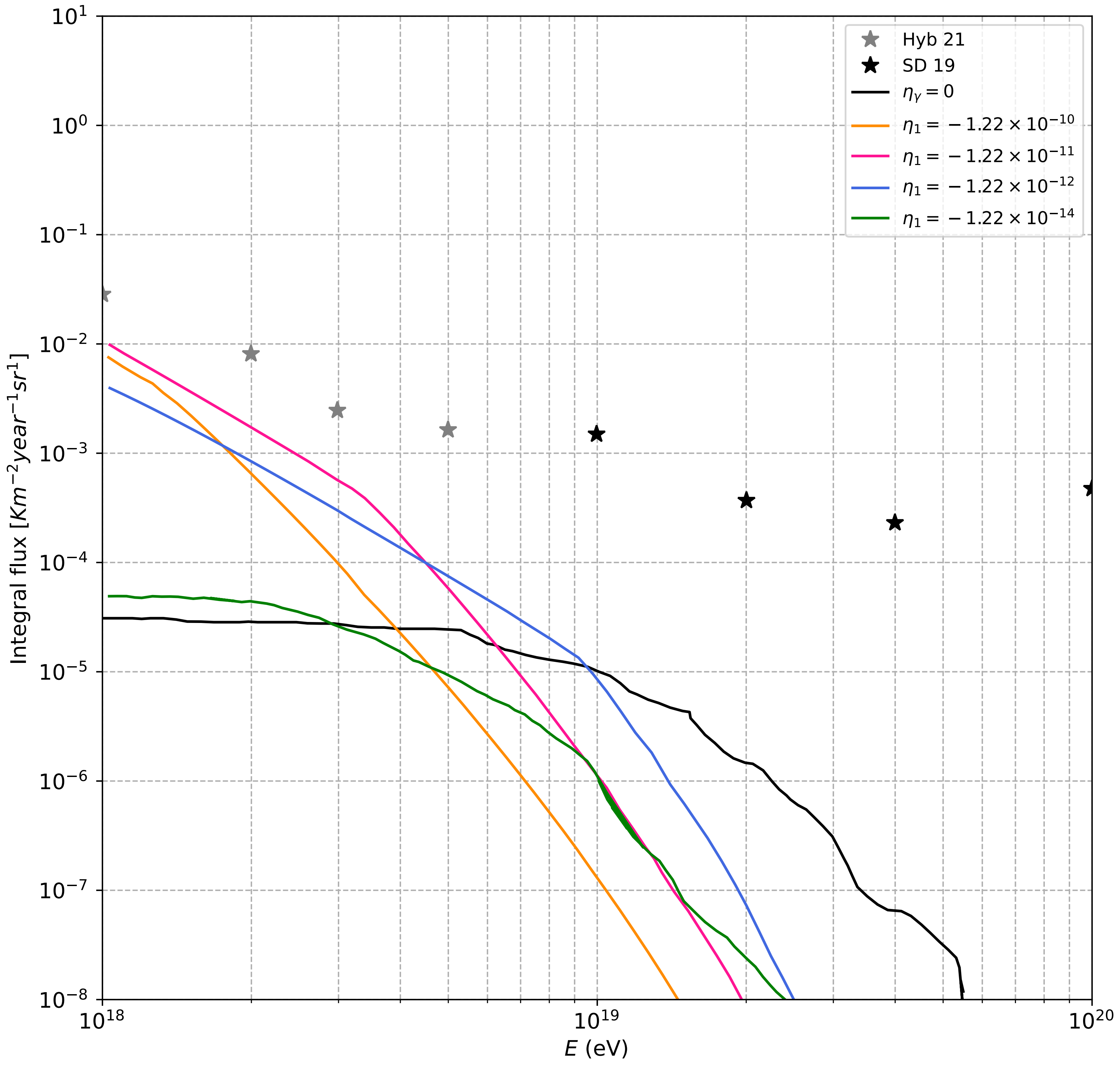
Effect of LIV in extragalactic propagation



- LIV modifications -> increase the threshold for pair production
  - allows for more photons to reach the top of the atmosphere

Effect of LIV in extragalactic propagation and in the atmosphere



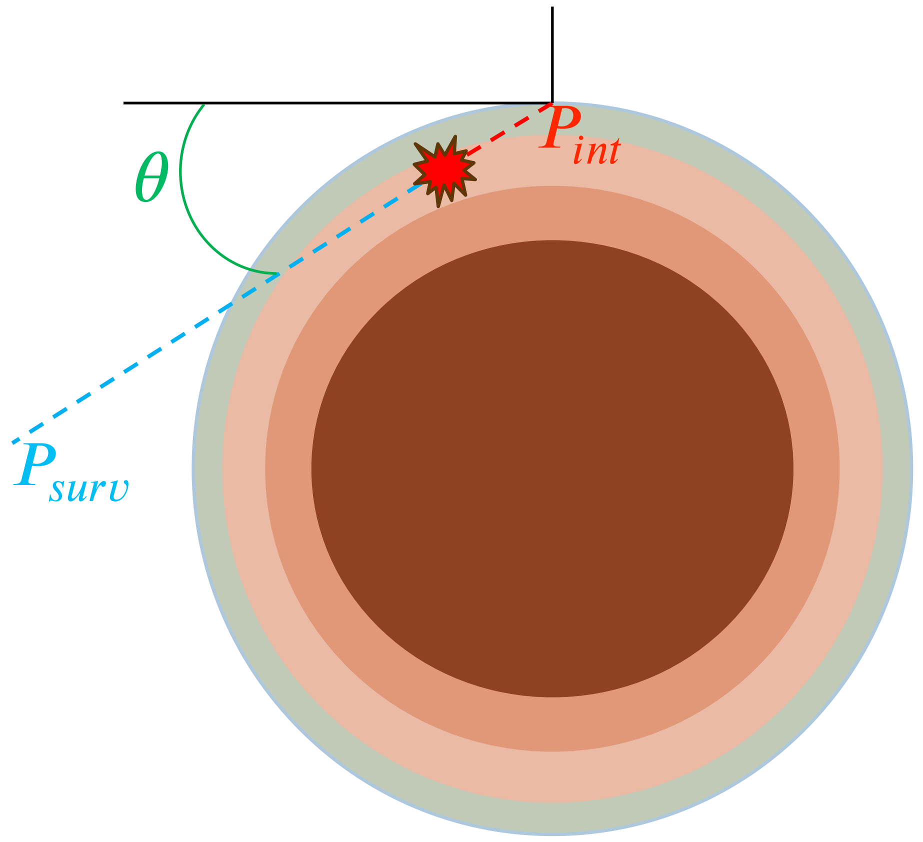


- LIV modifications -> increase the threshold for pair production
  - allows for more photons to reach the top of the atmosphere
  - allows for more photons to reach the Earth surface

$$\left(\frac{dn_\gamma(E, z=0,\eta)}{dE}\right)_{Earth} = P_{atm}(E,\eta)\left(\frac{dn_\gamma(E, z=0,\eta)}{dE}\right)_{top-of-atm}$$

- First attempt of connecting different stages of the life of an astroparticle for constraining LIV → Less optimistic result, but more realistic!

Cascade of particles initiated by photons in the Earth



- Test of **pair production in the Earth** -> same cross section as in the atmosphere, different target nuclei
- Compute the survival of photons so that they can initiate showers next to the surface
  - **Upward-going showers**, as expected from neutrinos? (inspired to B. Yue for the Auger Collab. ICRC23)

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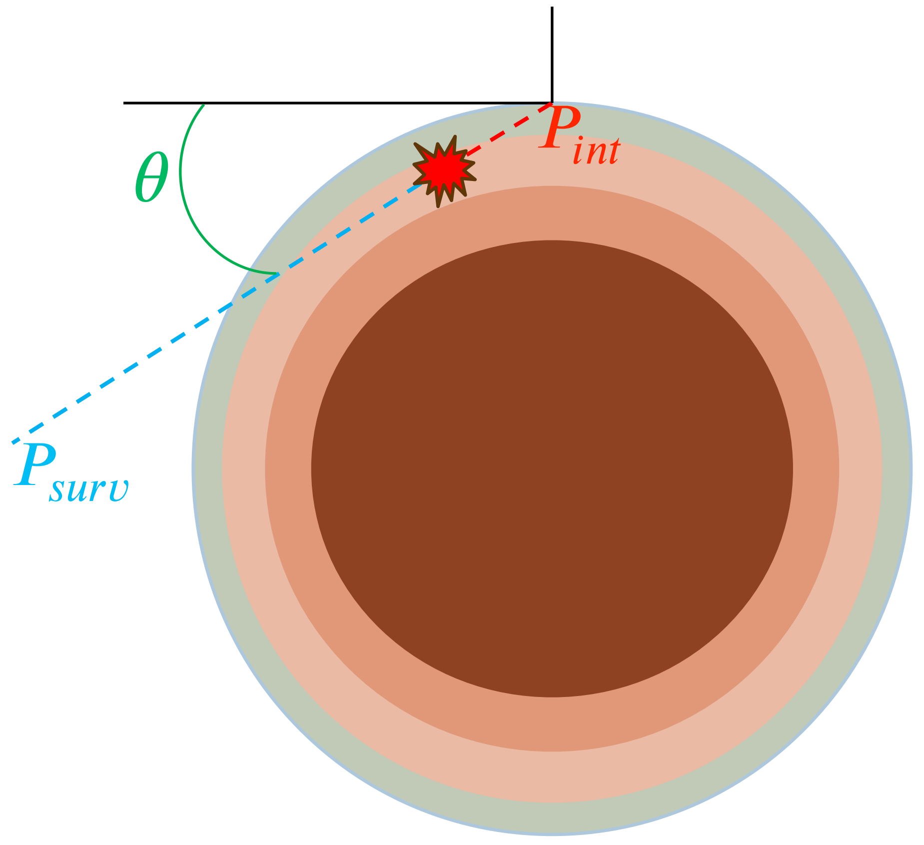

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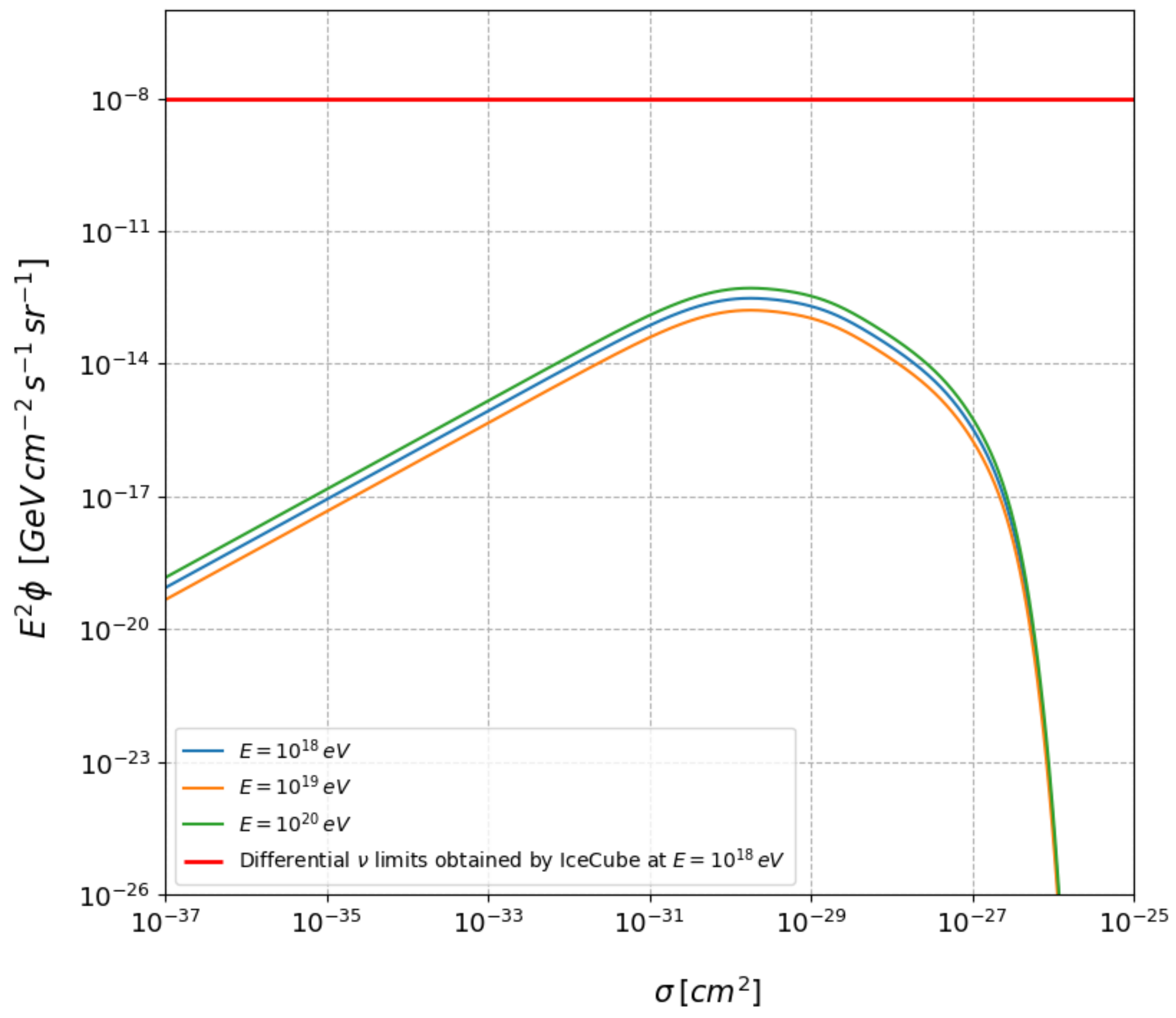
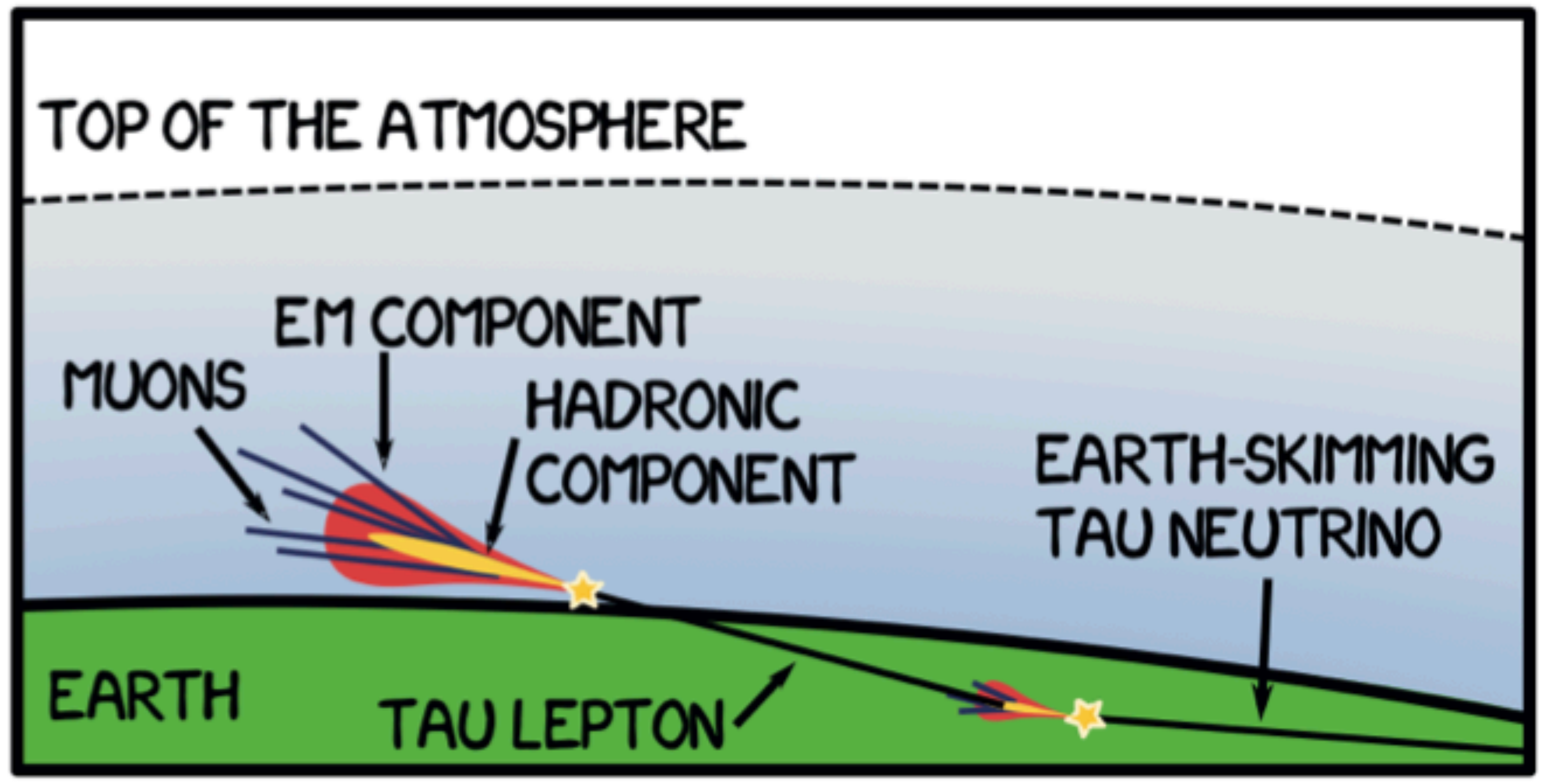




- As for the pair production in the atmosphere: the larger the energy, the more sensitive to LIV
- **The expected flux as a function of the cross section is compared to the current UHE neutrino limits**
  - A primary photon misinterpreted as a primary neutrino…

Summary

- **LIV can be tested with astroparticles at UHE**
  - See also Auger JCAP 2021 for LIV in UHECR propagation
- **Focus on photons: the propagation and detection stages**

Overall effect of accounting for LIV in propagation and detection stage: smaller LIV parameter space is constrained, but it is more realistic than considering just one stage!

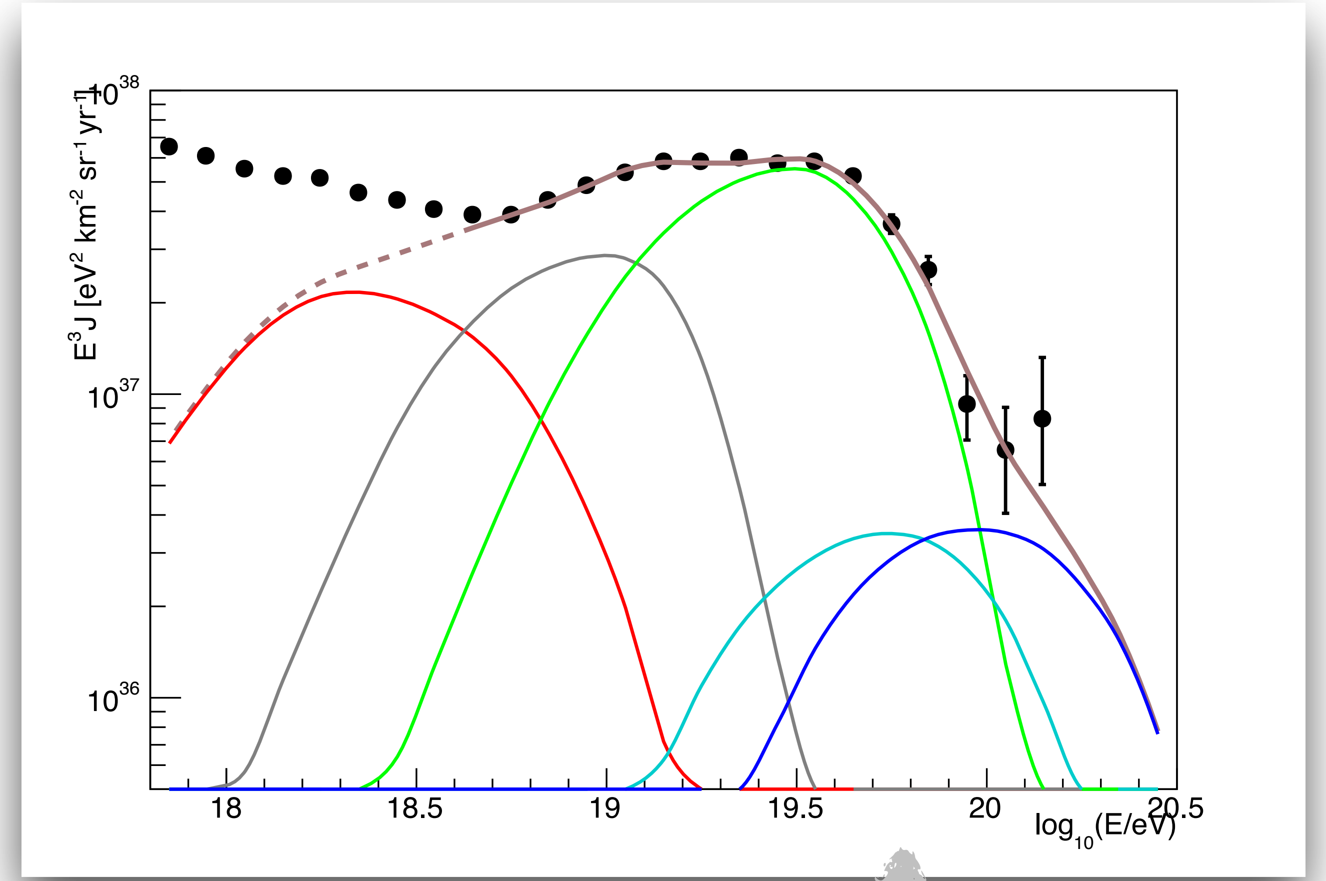
LIV in Earth crust similar to effect expected in atmosphere: Could the nature of astroparticles be misintepreted because of LIV?

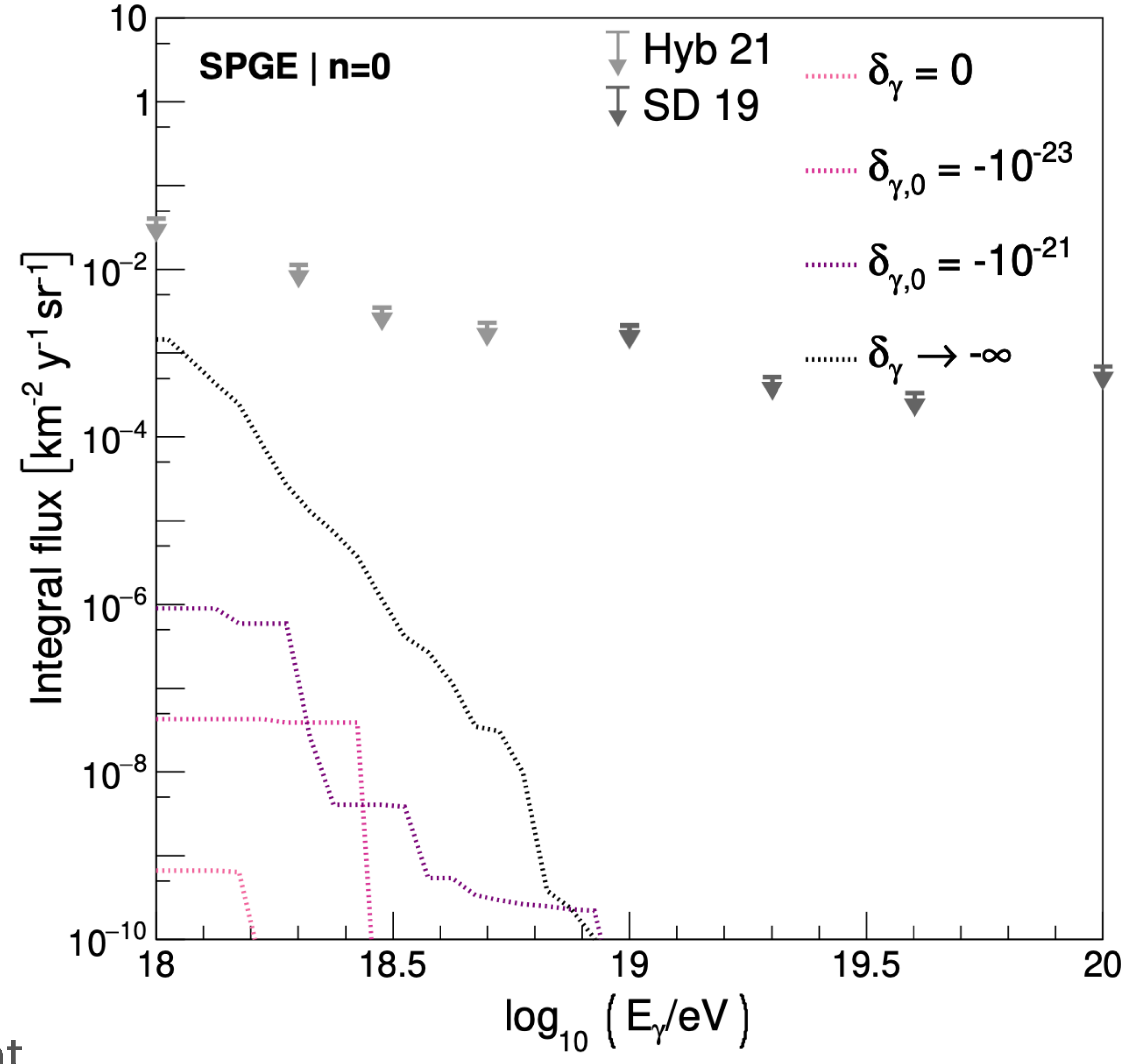
For a roadmap about quantum gravity phenomenology see Alves Batista+ Class.Quant.Grav. 42 (2025)

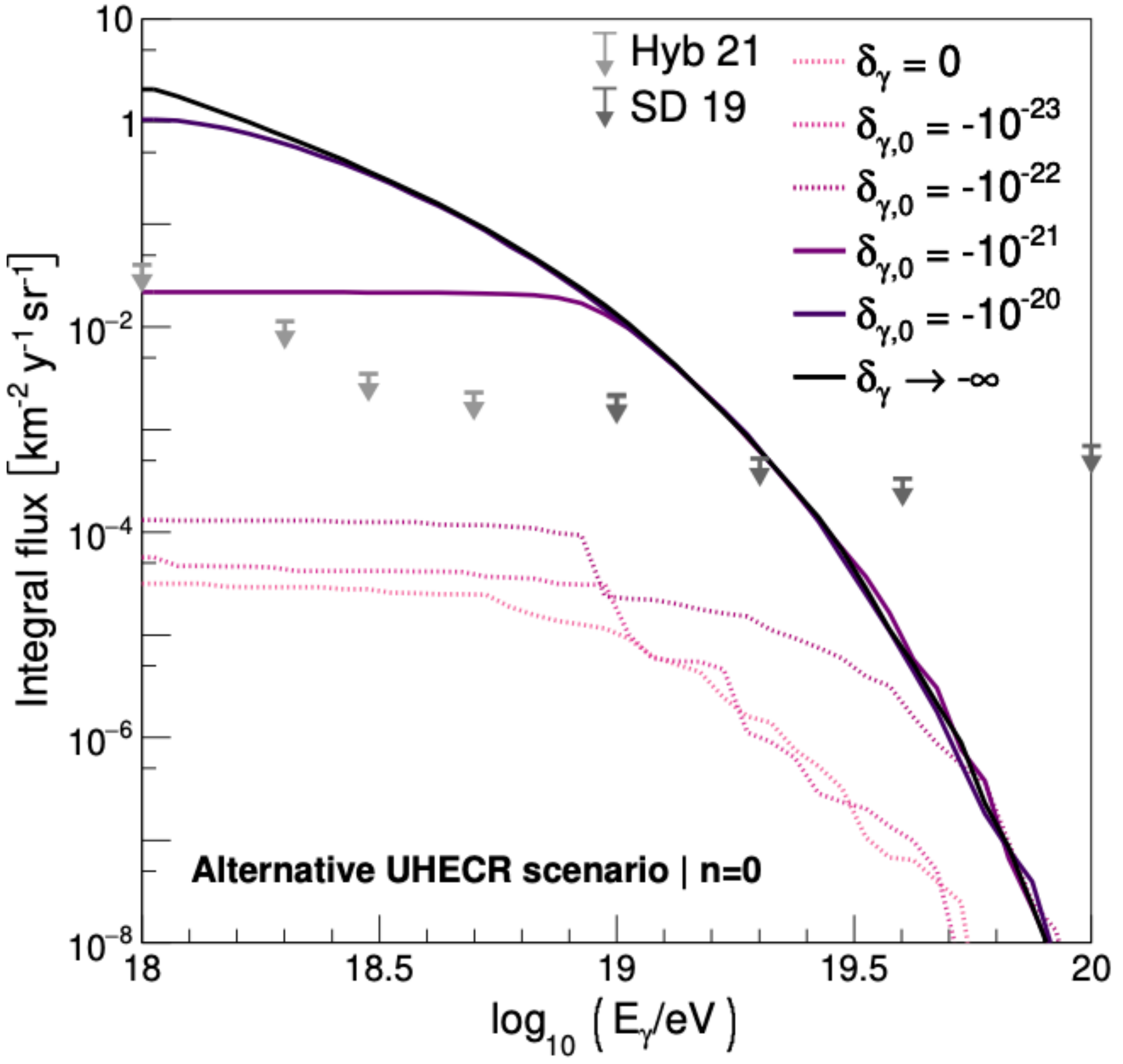
BACKUP SLIDES

Expected UHE photon flux

The Auger Collab, JCAP 2022







- **Photons** produced in extragalactic propagation by UHECRs;
  - **additional proton component** (compatible with mass composition data) is accounted for at high energy!

$\delta^{(0)} > -10^{-21}$ $\quad \delta^{(1)} > -10^{-40}\,\mathrm{eV}^{-1}$ $\quad \delta^{(2)} > -10^{-58}\,\mathrm{eV}^{-2}$

- Warning: photon production is connected to UHECR mass composition

LIV contraints - photons

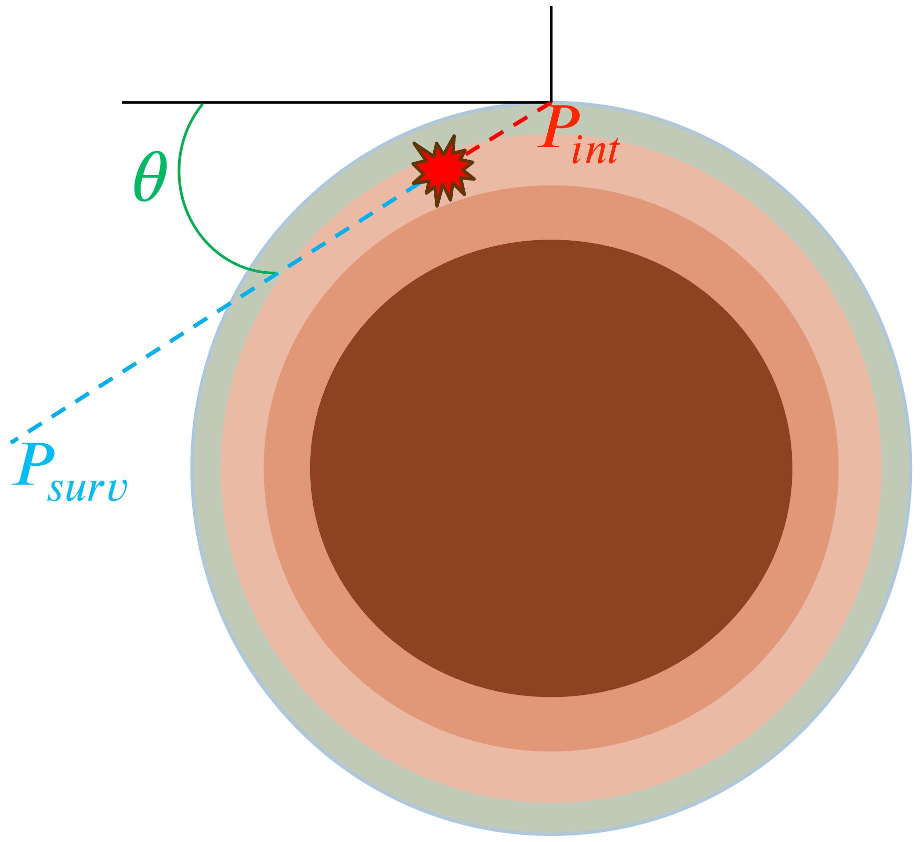
- Comparison of different tests of LIV on gamma rays: see Terzic+ Universe 2021
- Present work: focus on subliminal photons
  - n=1 constrained by birefringence effects
  - n=2 superluminal constrained by the absence of vacuum pair production or photon splitting

- In Rubtsov+ PRD2012; 2014
  - Calculation of corrections at energies far above the threshold; modifications also introduced in the fermionic sector
- More refined approach in Carmona+ PRD2024

$$\sigma_{BH} = \frac{28Z^2\alpha^3}{9m_e^2}\left(\log\frac{183}{Z^{\frac{1}{3}}} - \frac{1}{42}\right)$$

$$\sigma_{BH}^{LIV} = \frac{8Z^2\alpha^3}{3\,|m_{\gamma,\mathrm{eff}}^2|}\log\frac{1}{\alpha Z^{\frac{1}{3}}}\log\frac{|m_{\gamma,\mathrm{eff}}^2|}{m_e^2}$$

LIV photons in the Earth



$$P_{\mathrm{surv,Earth}}(\theta) = \exp\left(-\frac{N_A \sigma_{\mathrm{BH}}}{M} \sum_{i=1}^{n(\theta)} l_i(\theta)\rho_i\right)$$

$$P_{\mathrm{int,Earth}} = 1 - \exp\left(-\frac{N_A \sigma_{\mathrm{BH}}}{M} d\rho\right)$$

$$P_{\mathrm{gen}}(\theta) = P_{\mathrm{int,Earth}} P_{\mathrm{surv,Earth}}(\theta)$$

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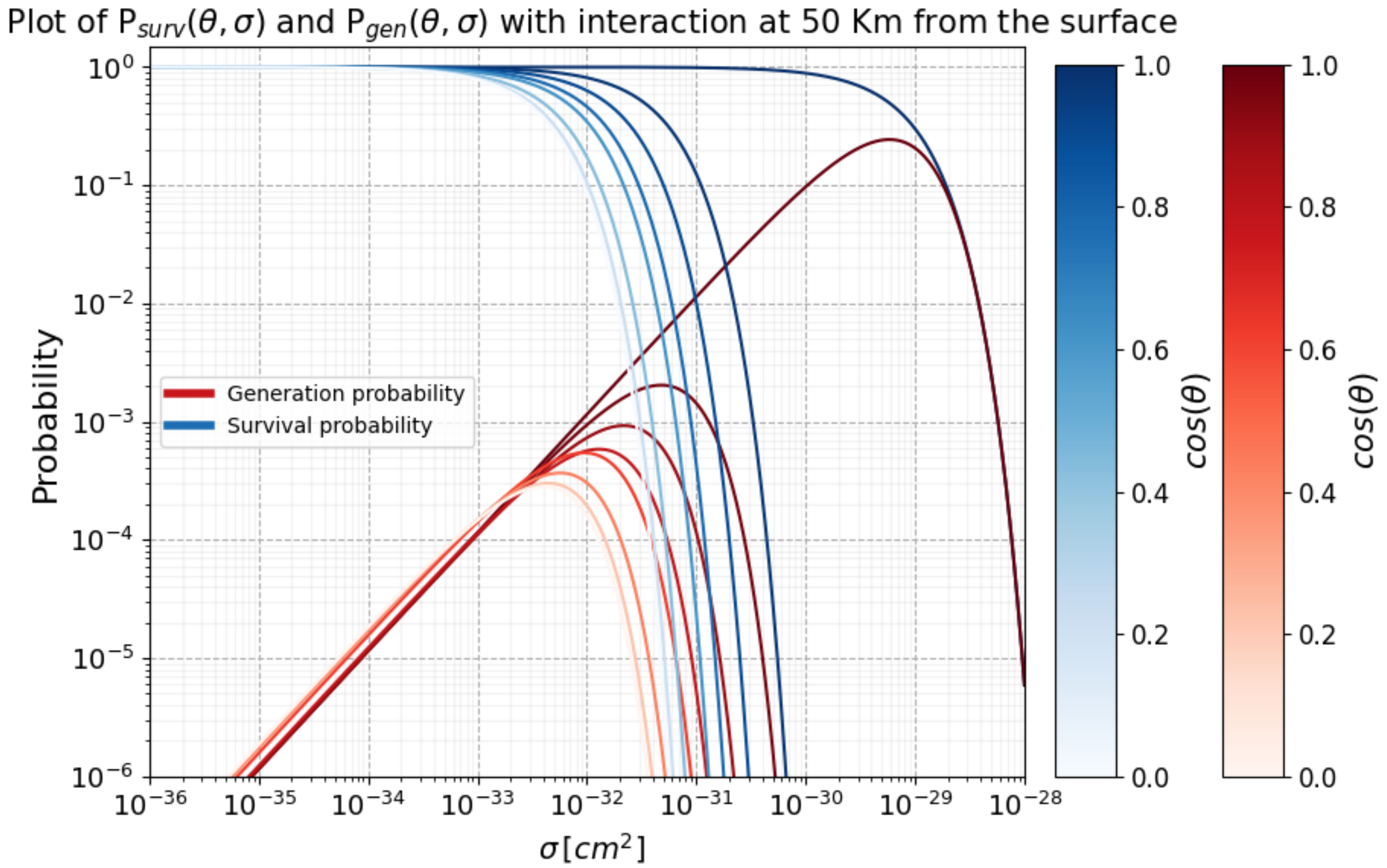

DB, Bezerra, Giammarco, Lobo, Morais & Salamida, ICRC2025