

**PIERRE  
AUGER**  
OBSERVATORY

# Testing effects of Lorentz Invariance Violation in the propagation of astroparticles with the Pierre Auger Observatory

## The Pierre Auger Collaboration

JCAP 01 (2022) 023

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# Layout

Motivation

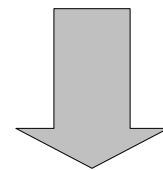
Method

Results

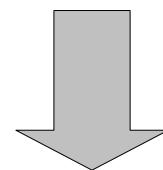
Conclusion



Postulates  
+  
Causality

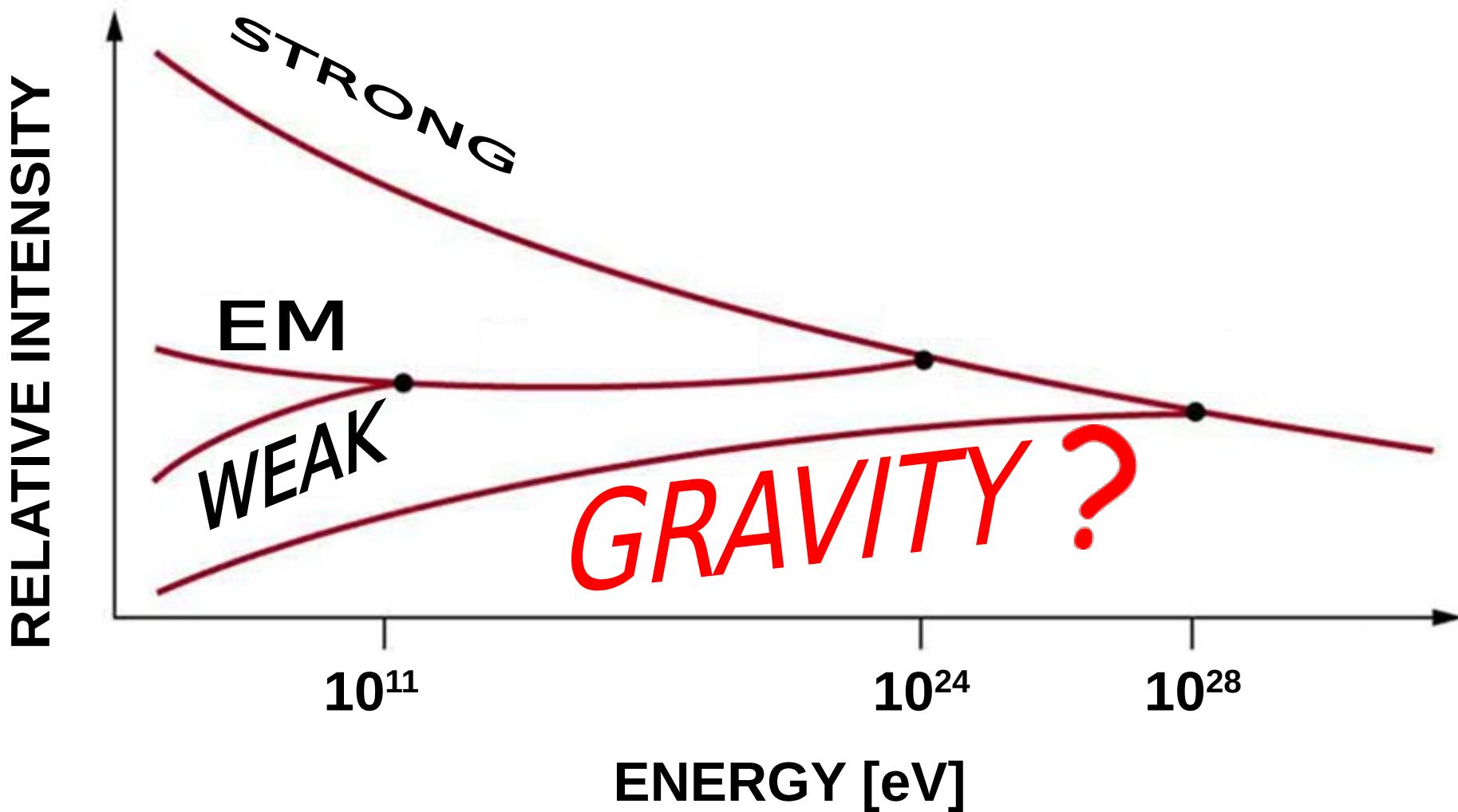


Lorentz  
Invariance  
(LI)

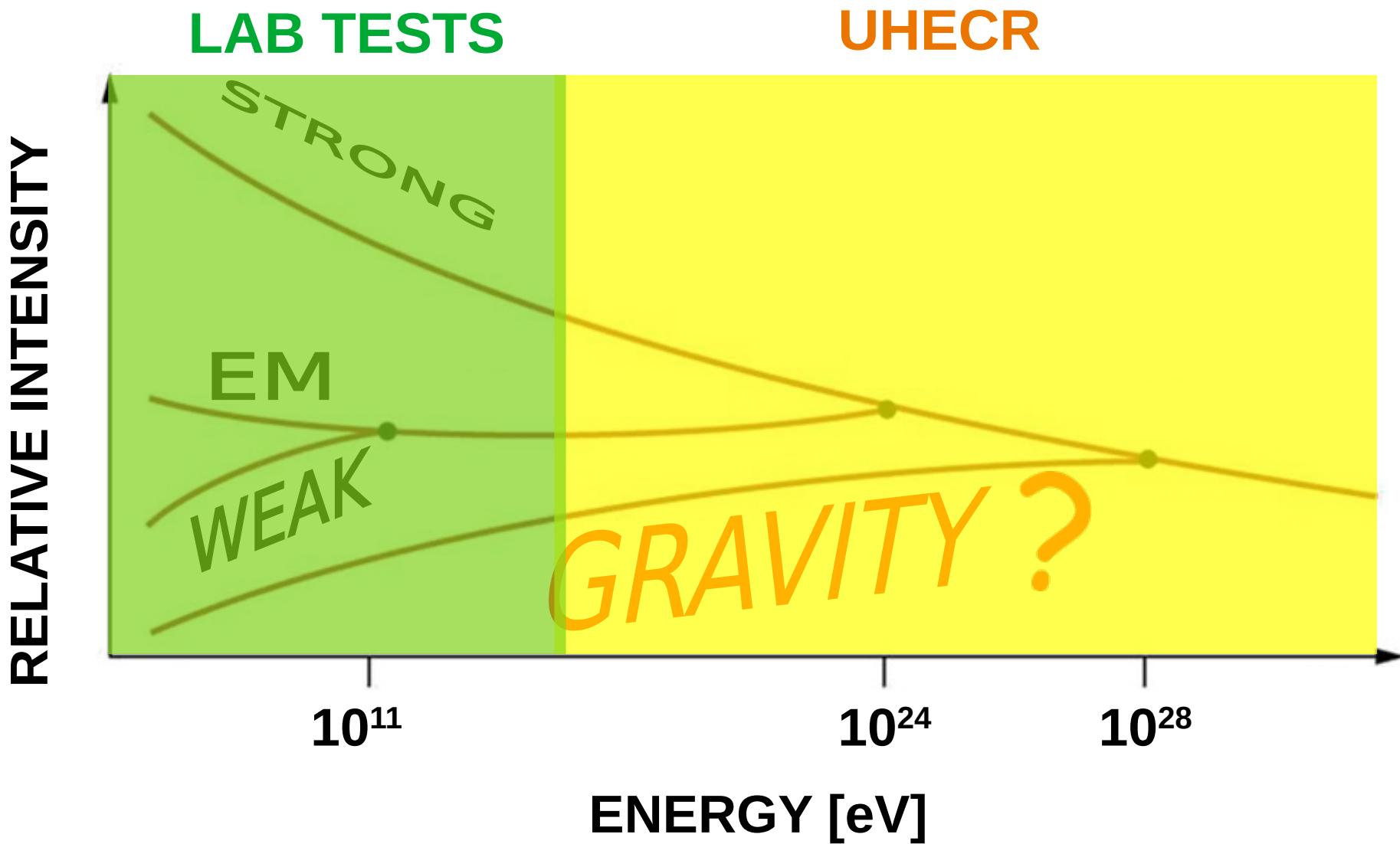


Laws of Physics are  
invariant under  
Lorentz  
Transformation

# Lorentz Invariance Violation - LIV Promissing hypothesis



# Lorentz Invariance Violation - LIV Promissing hypothesis



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# UHECR SCENARIO

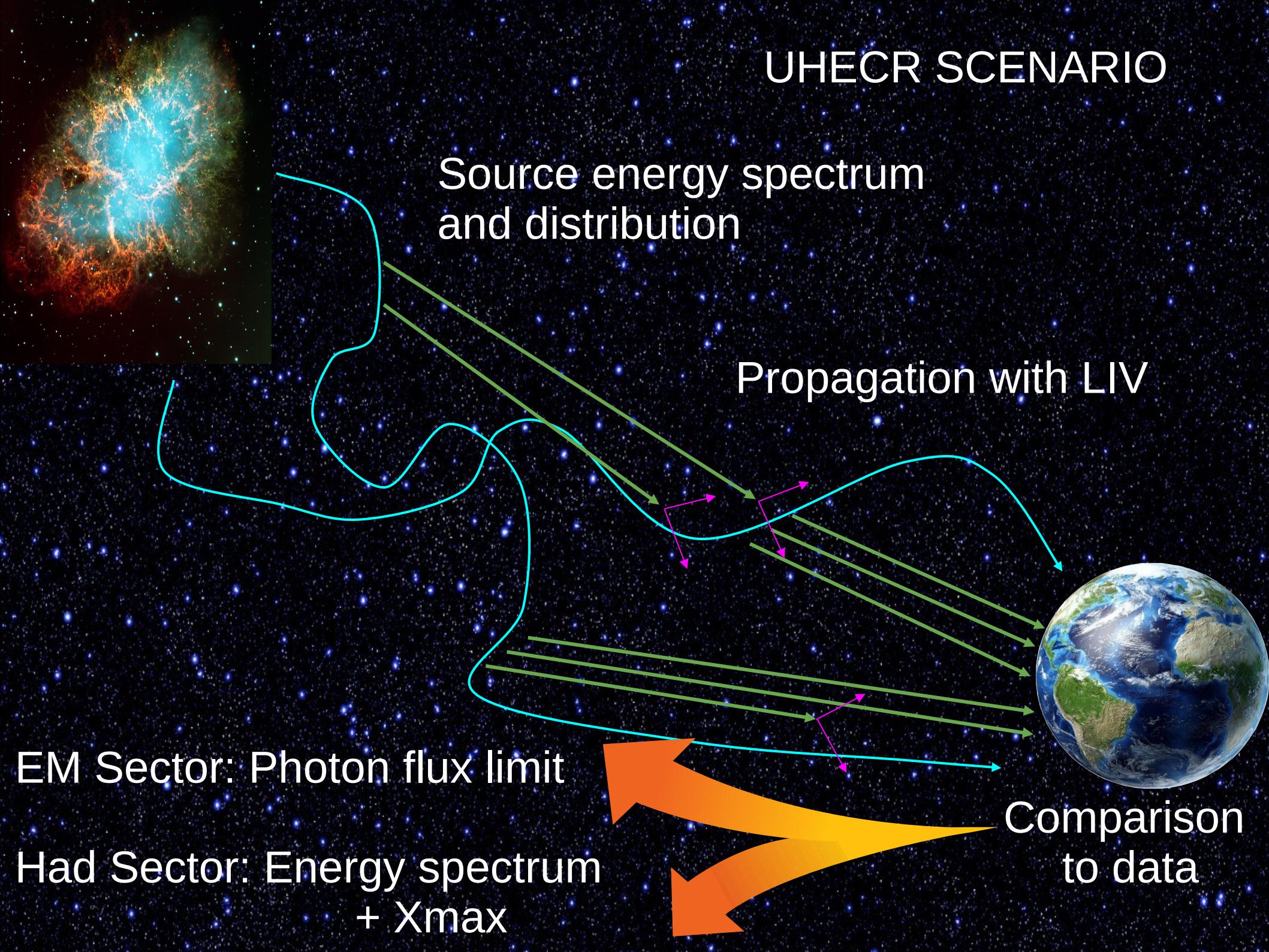
Source energy spectrum  
and distribution

Propagation with LIV



Comparison  
to data

# UHECR SCENARIO



# Method: Challenges

- **Excellent data**

- Pierre Auger Coll.

- **Energy spectrum**

- PRL, 125(12):121106, 2020
    - PRD, 102(6):062005, 2020

- **Xmax distributions**

- PRD, 90(12):122005, 2014
    - ICRC 2019 - arXiv:1909.09073

- **Limit on photon flux**

- JCAP, 04:009, 2017
    - ICRC 2019 - arXiv:1909.09073
    - PoS, ICRC2021:373, 2021

- **Solve interactions under LIV**

- Coleman&Glashow:  
PRD,59:116008, 1999

- Galaverni&Sigl: PRL,  
100:021102, 2008

- R. Lang: doi:  
[10.11606/D.76.2017.tde-13042017-143220](https://doi.org/10.11606/D.76.2017.tde-13042017-143220)

- R. Lang et al., *Astrophys. J.*,  
853(1):23, 2018

- R. Lang et al. *PRD*, 99  
(4):043015, 2019

# Phenomenological approach for LIV

$$E_a^2 = p_a^2 + m_a^2 + \sum_{n=0}^{\infty} \delta_{a,n} E_a^{(n+2)}$$

# Phenomenological approach for LIV

$$E_a^2 = p_a^2 + m_a^2 + \sum_{n=0}^{\infty} \delta_{a,n} \frac{E_a^{(n+2)}}{E_a}$$

Perturbative expansion

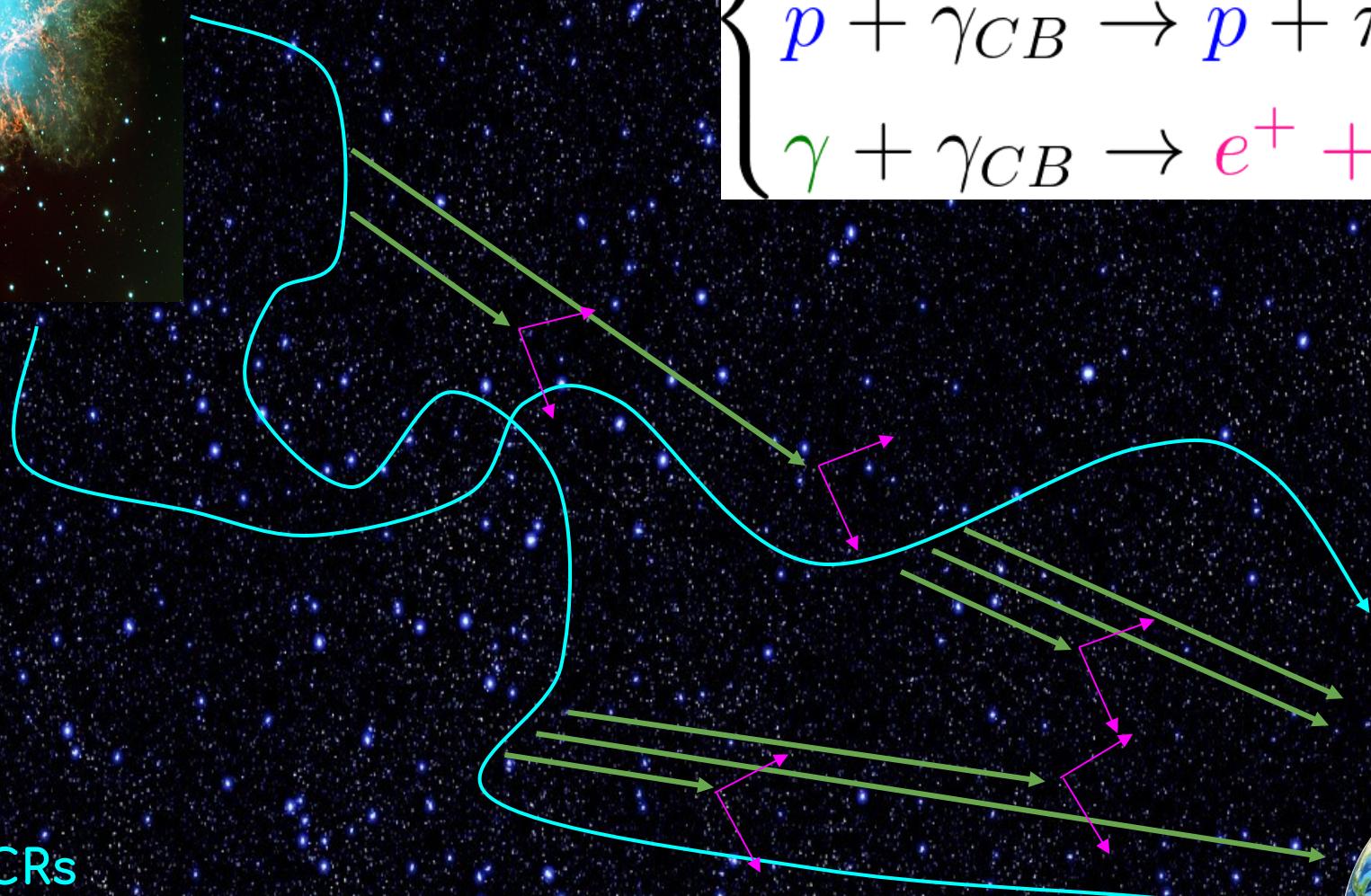
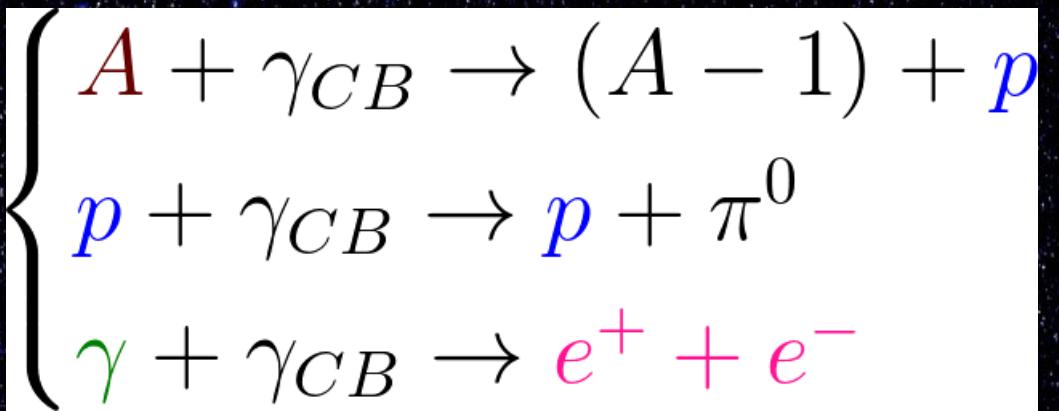
LIV coefficient

Particle species

Suppressed for lower energies

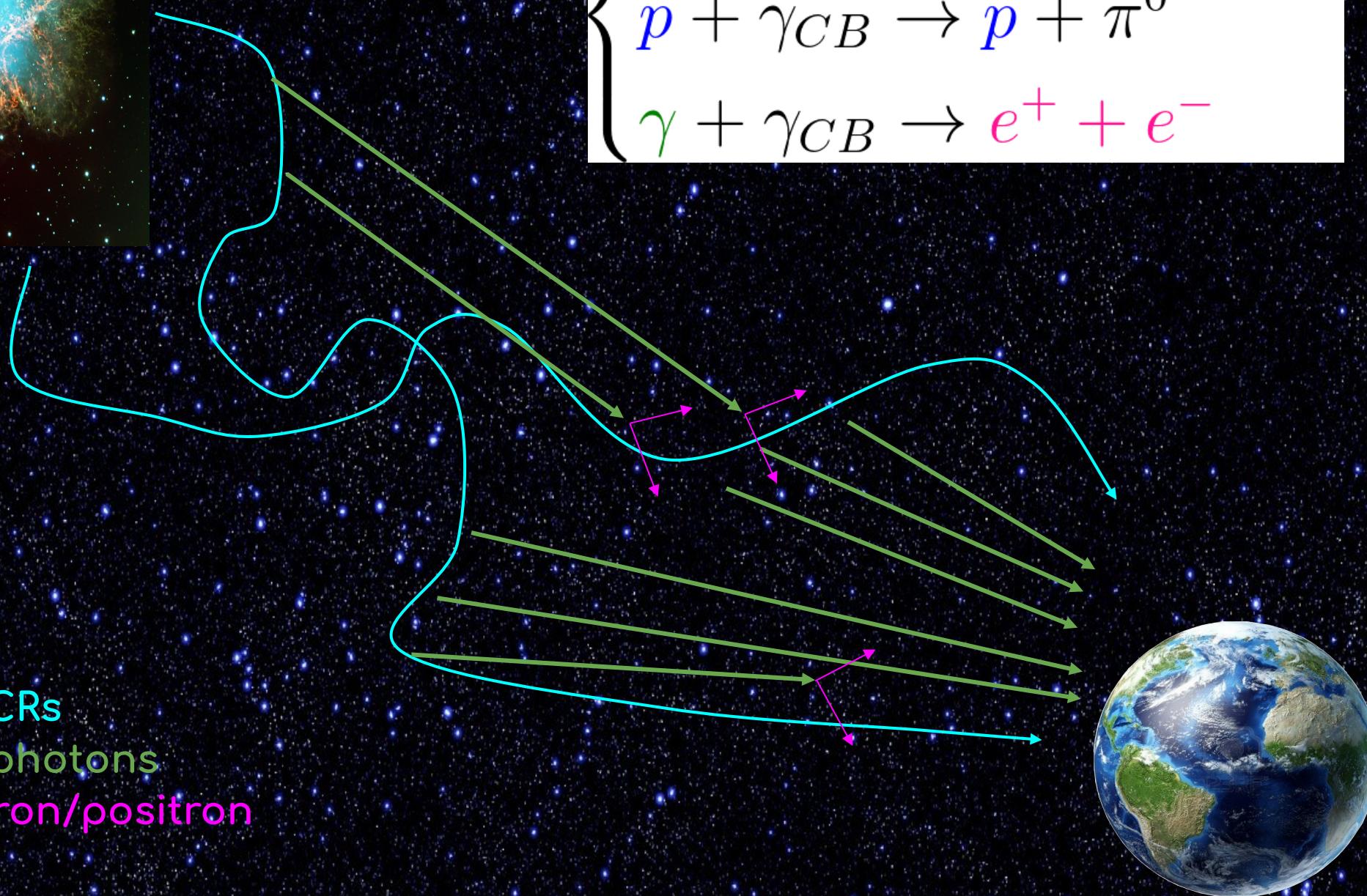
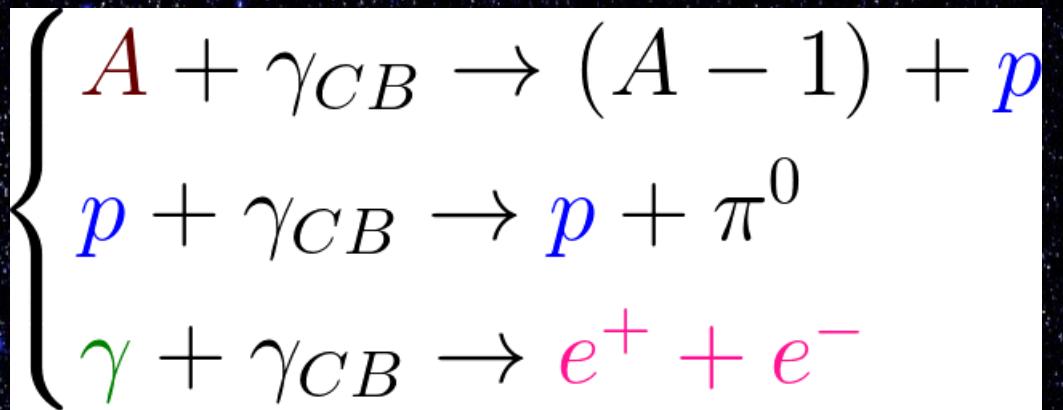


LI

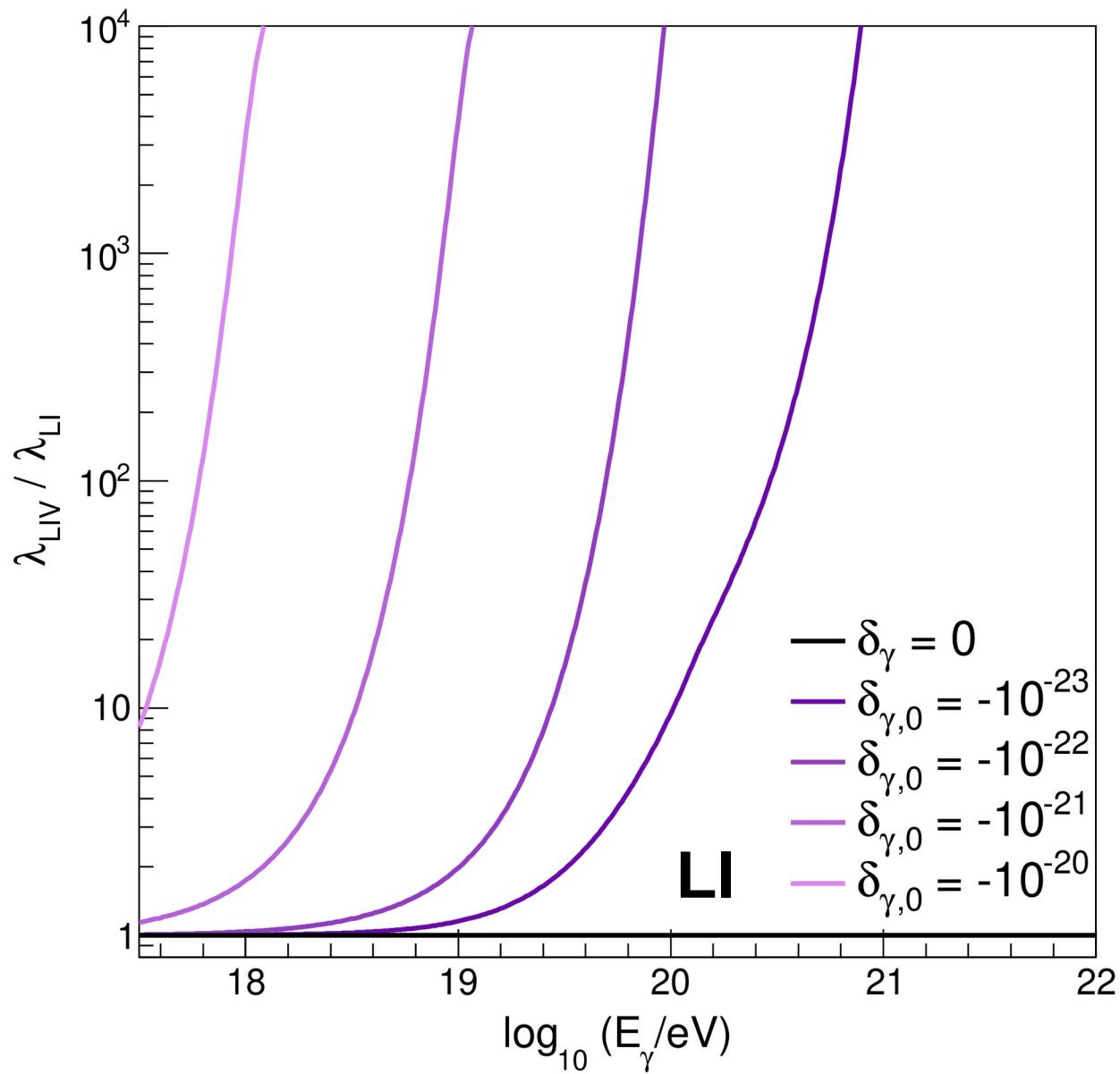


- UHECRs
- GZK photons
- Electron/positron

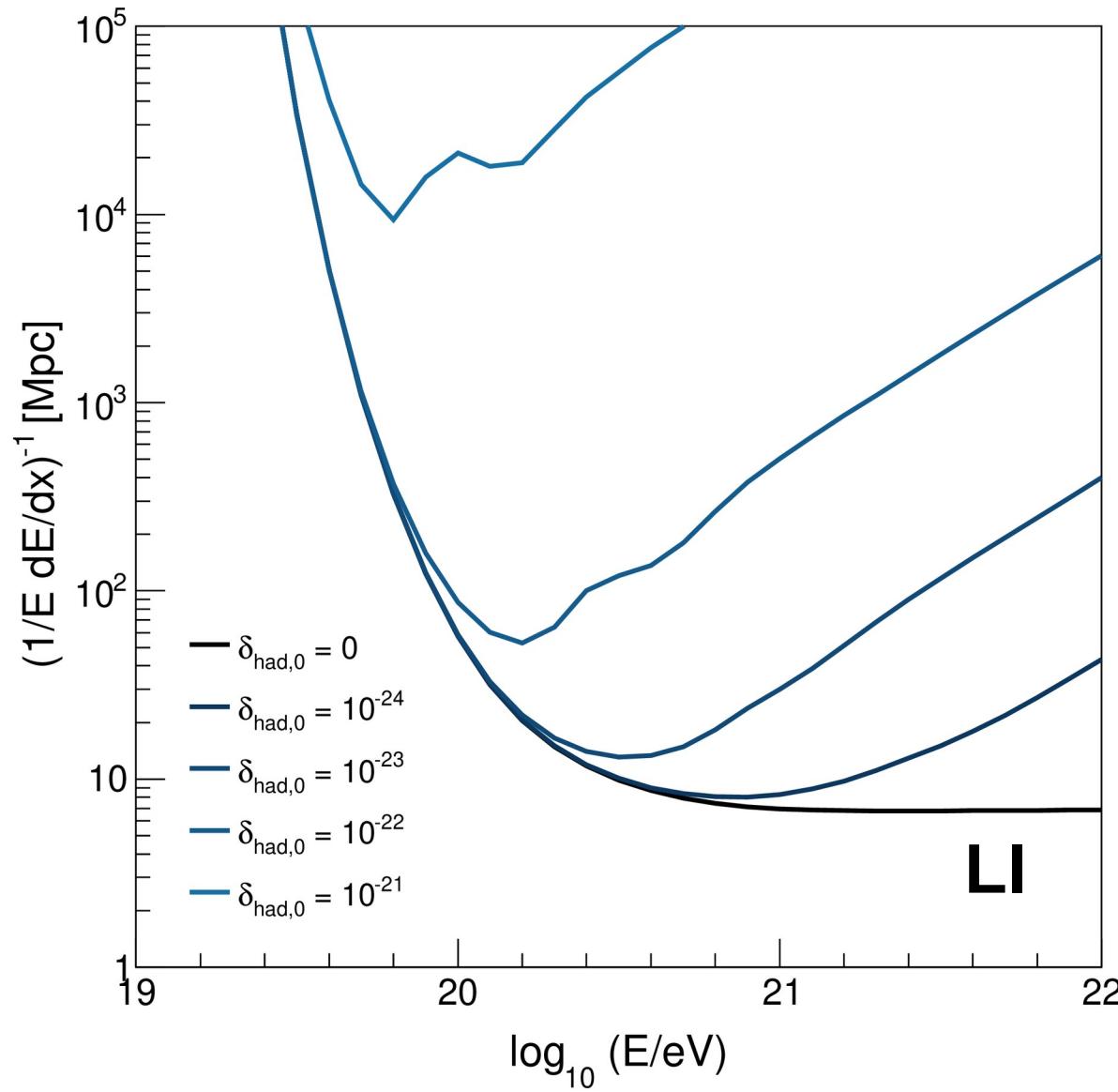
LIV



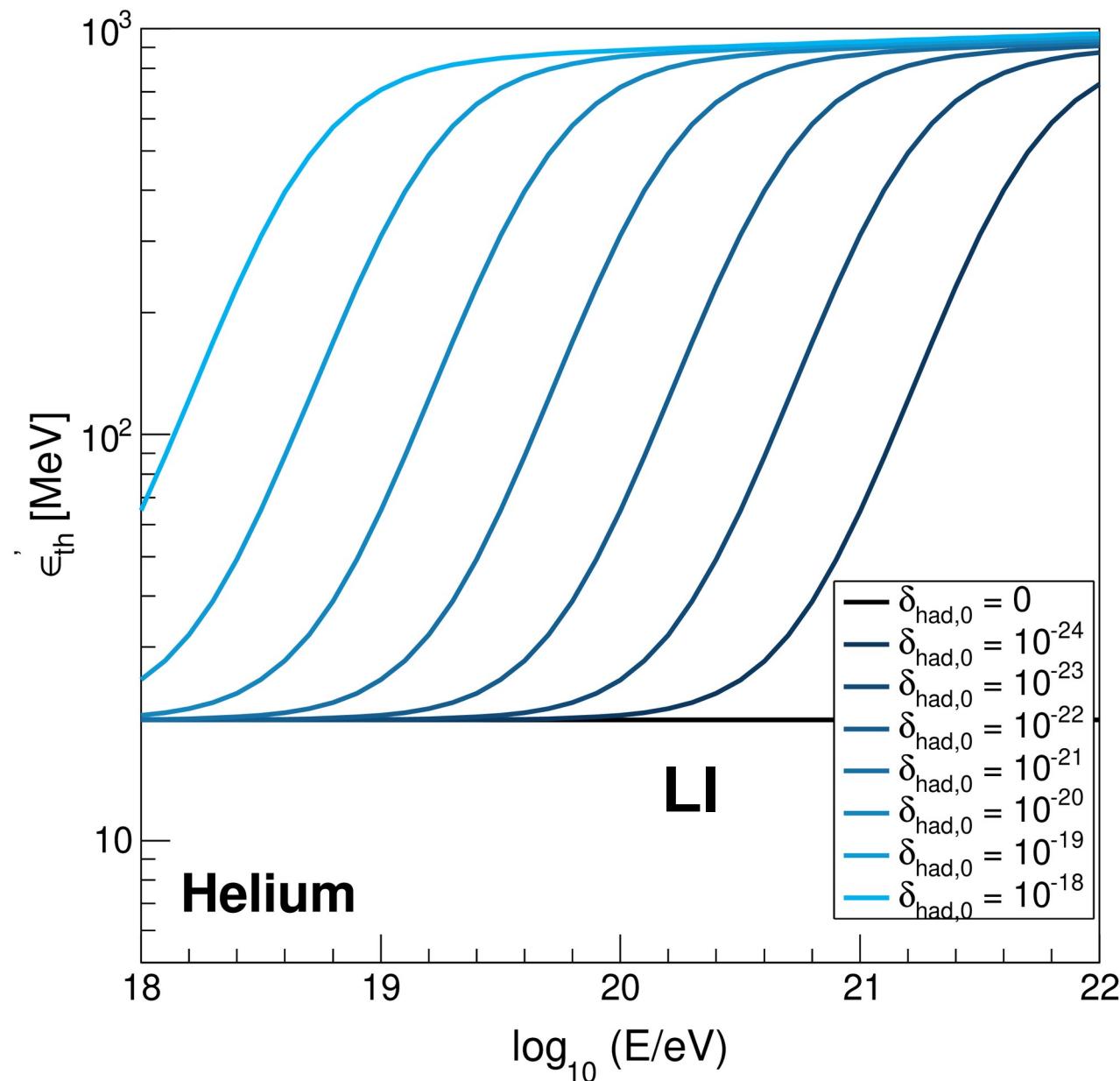
# Pair production with LIV



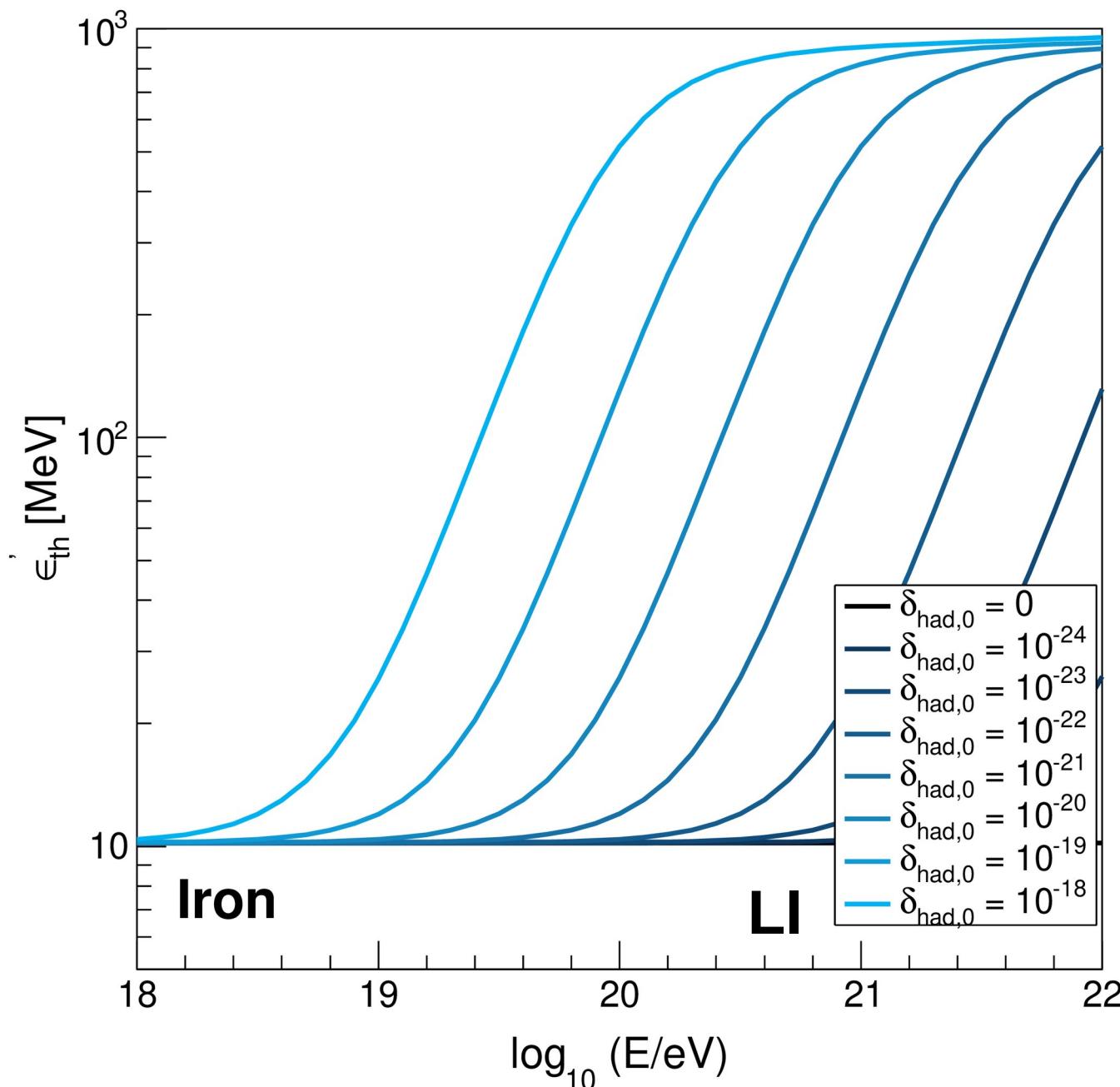
# Pion attenuation lenght with LIV



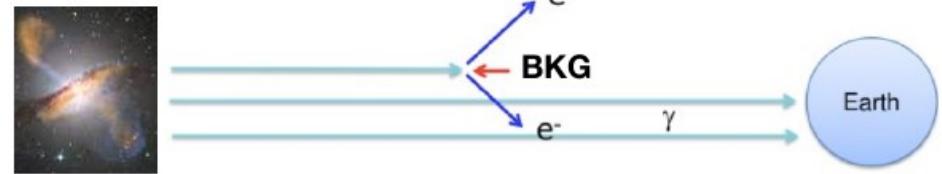
# Helium photo-desintegration with LIV



# Iron photo-desintegration with LIV



$$\tau(E_\gamma, z, \eta) =$$



$$\int_0^z dz \frac{c}{H_0(1+z)\sqrt{\Omega_\Lambda + \Omega(1+z)^3}}$$

Expansion

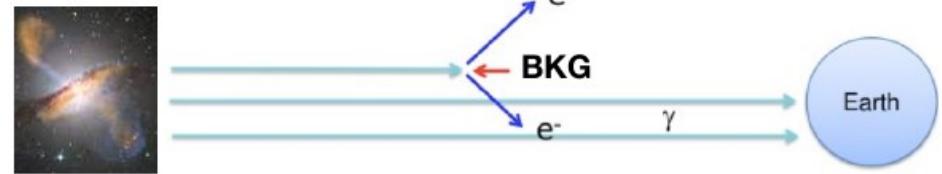
$$\bigotimes \int_{\epsilon_{th}}^{\infty} d\epsilon \ \eta(\epsilon, z)$$

Cosmic  
Background

$$\bigotimes \int_{-1}^1 d(\cos \theta) \frac{1 - \cos \theta}{2} \ \sigma(E_\gamma, \epsilon)$$

Interaction

$$\tau(E_\gamma, z, \eta) =$$



$$\int_0^z dz \frac{c}{H_0(1+z)\sqrt{\Omega_\Lambda + \Omega(1+z)^3}}$$

Expansion

$$\otimes \int_{\epsilon_{th}}^{\infty} d\epsilon \eta(\epsilon, z)$$

$$\epsilon_{th}^{LIV} = \frac{m_e c^2}{4E_\gamma K(1-K)} - \frac{\delta_1 E_\gamma^2}{4}$$

Cosmic  
Background

$$\otimes \int_{-1}^1 d(\cos \theta) \frac{1 - \cos \theta}{2} \sigma(E_\gamma, \epsilon)$$

Interaction

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# UHECR SCENARIO

- 1) 
$$\frac{dN_A}{dE} = J_0 f_A \left( \frac{E}{10^{18} \text{ eV}} \right)^{-\Gamma} \times \begin{cases} 1, & \text{for } R < R_{\text{cut}} \\ \exp(1 - R/R_{\text{cut}}), & \text{for } R \geq R_{\text{cut}} \end{cases}$$
- 2) Source isotropically distributed with a cosmological evolution  $(1 + z)^m$

Scenario	Cross sections	EBL	Hadronic interactions
SPGE	PSB [24, 25]	Gilmore [26]	EPOS-LHC [27]
STGE	Talys [28]	Dominguez [29]	EPOS-LHC
SPDE	PSB	Gilmore	EPOS-LHC
SPGS	PSB	Gilmore	Sibyll 2.3c [30]

3) Propagation

4) Xmax Distribution

# EM Sector

- Two UHECR Scenarios
  - Auger Standard LI Scenario

JCAP, 04:038, 2017

$$\Gamma = -1.3 \quad - \quad \log_{10}(R_{\text{cut}}/V) = 18.22 \quad - \quad m = 0$$

$$f_H = 13\% \quad - \quad f_{He} = 43\% \quad - \quad f_N = 28\% \quad - \quad f_{Si} = 14\% \quad - \quad f_{Fe} = 0.08\%$$

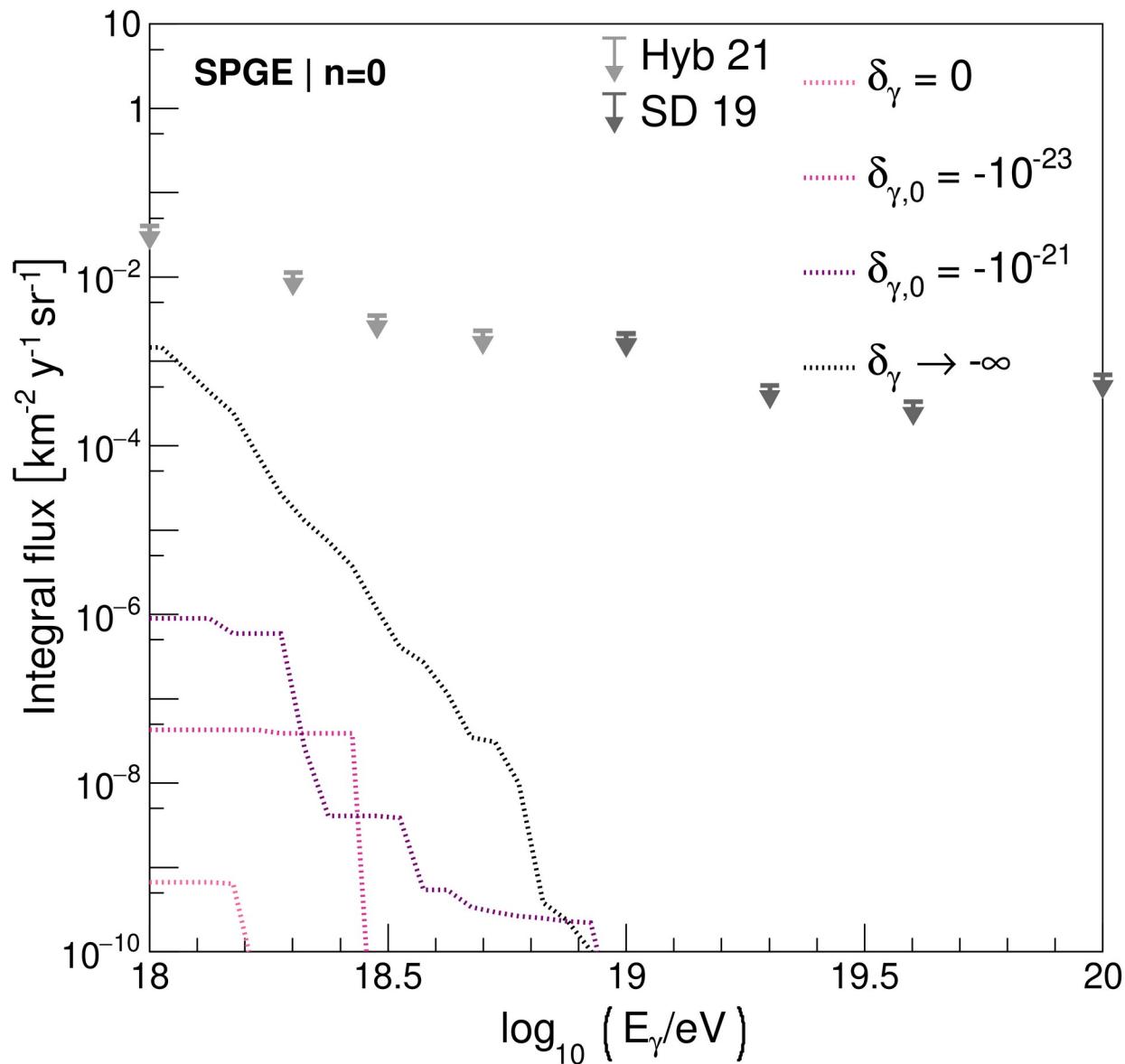
- Alternative Scenario: Proton enhanced

PRD, 100(10):103008, 2019

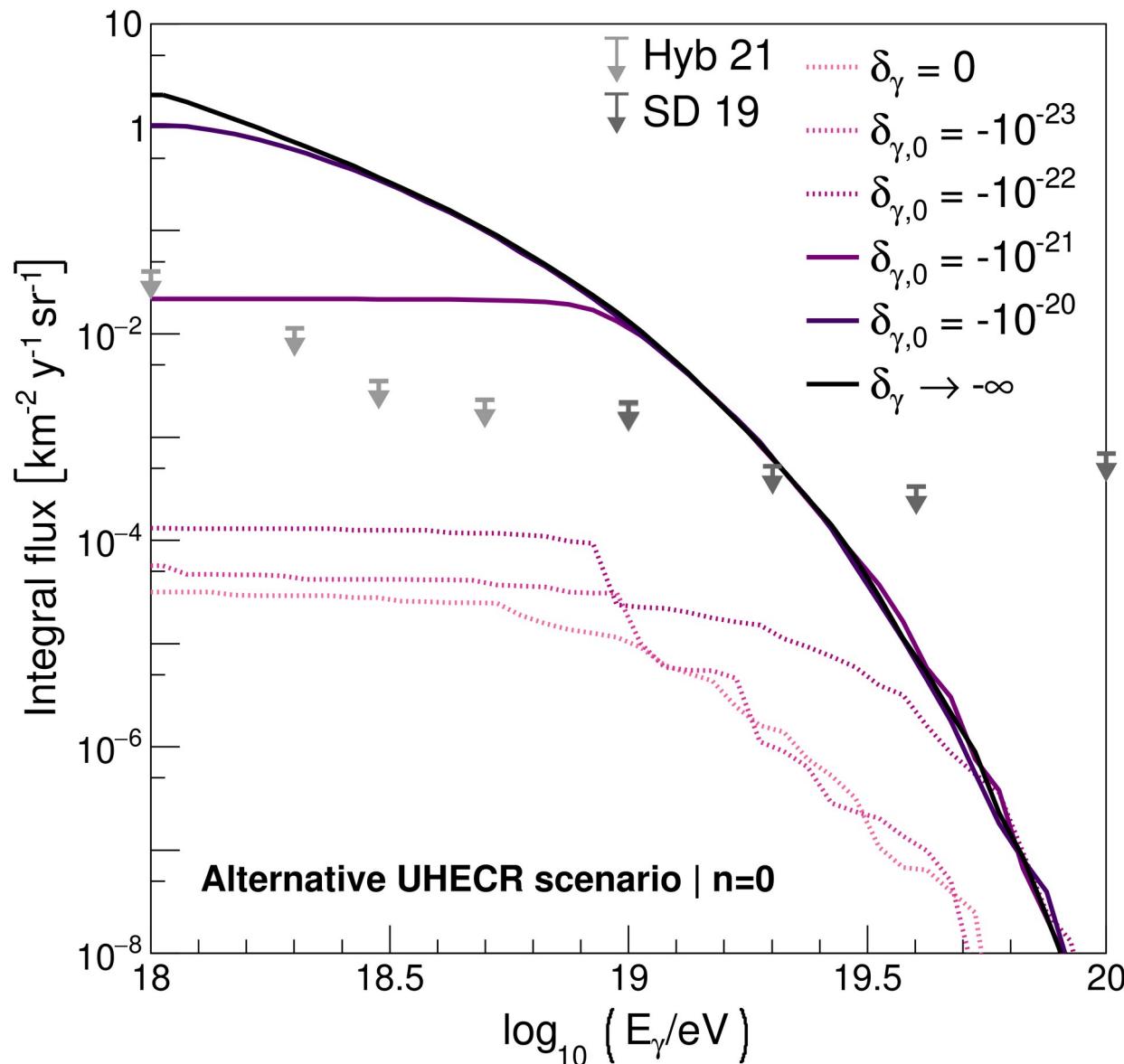
$$f_H = 31\%$$

Limit the maximum Lorentz coefficient allowed  
by the limit on the photon flux

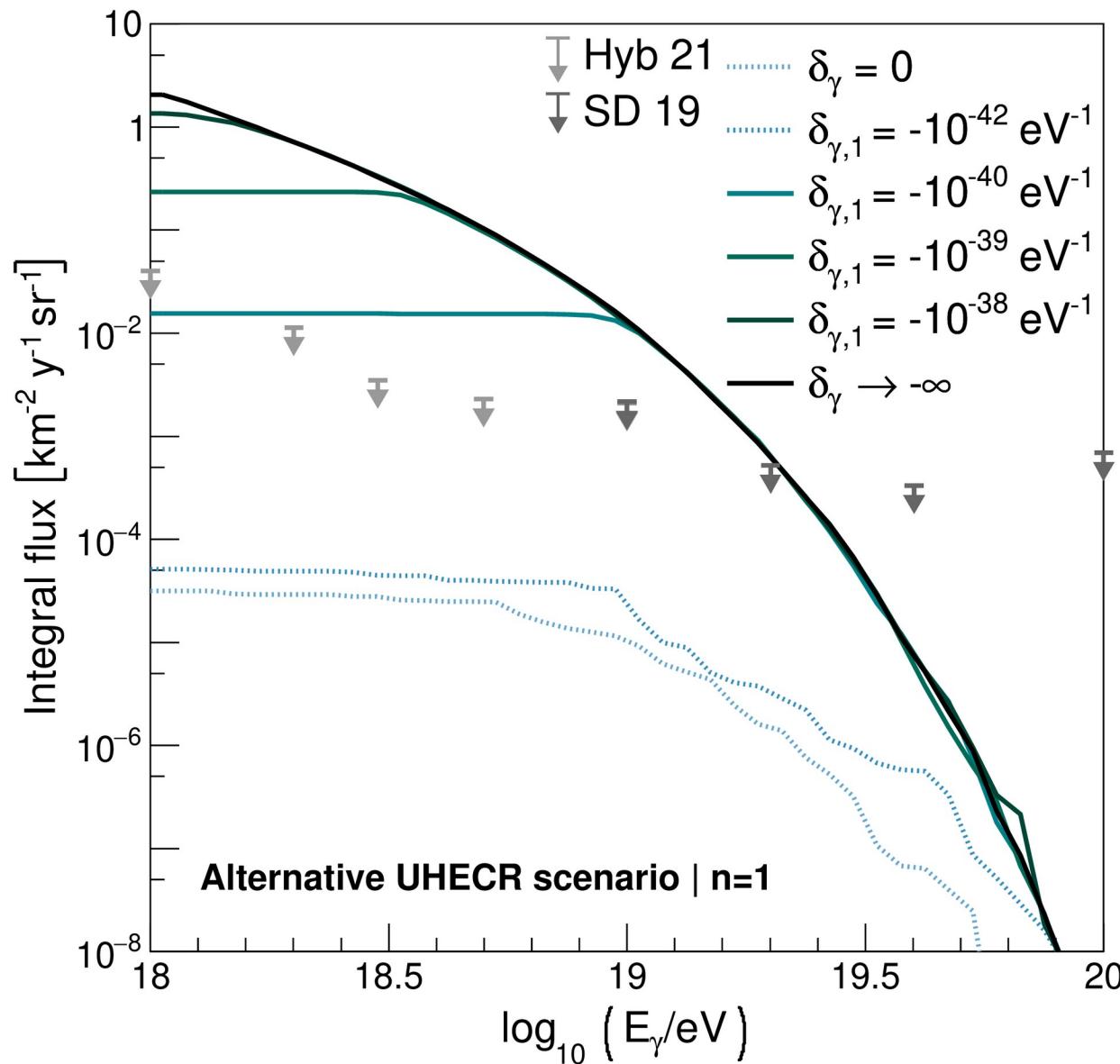
# EM Sector Auger Standard LI Scenario



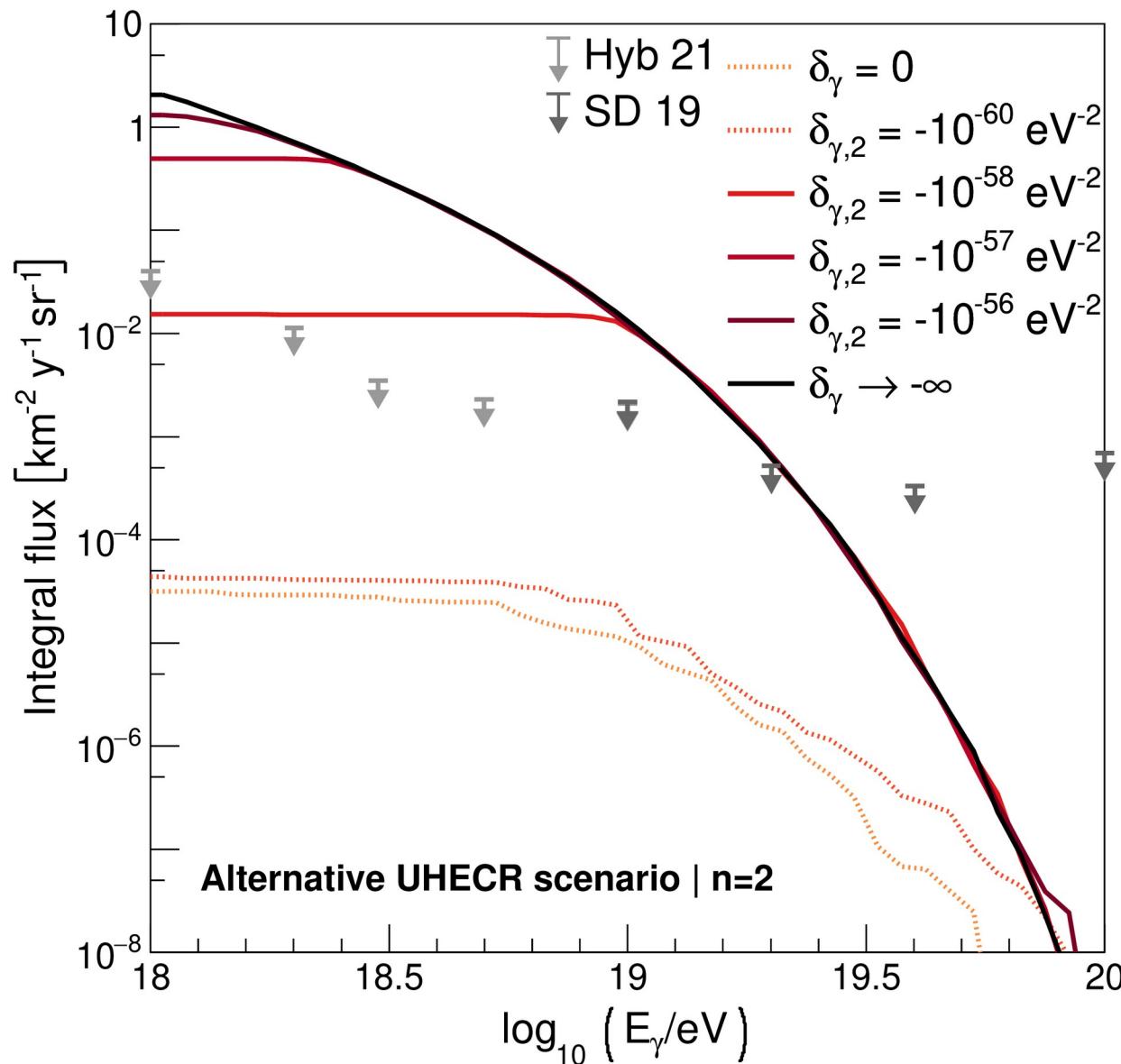
# EM Sector: Alternative UHECR scenario proton enhanced



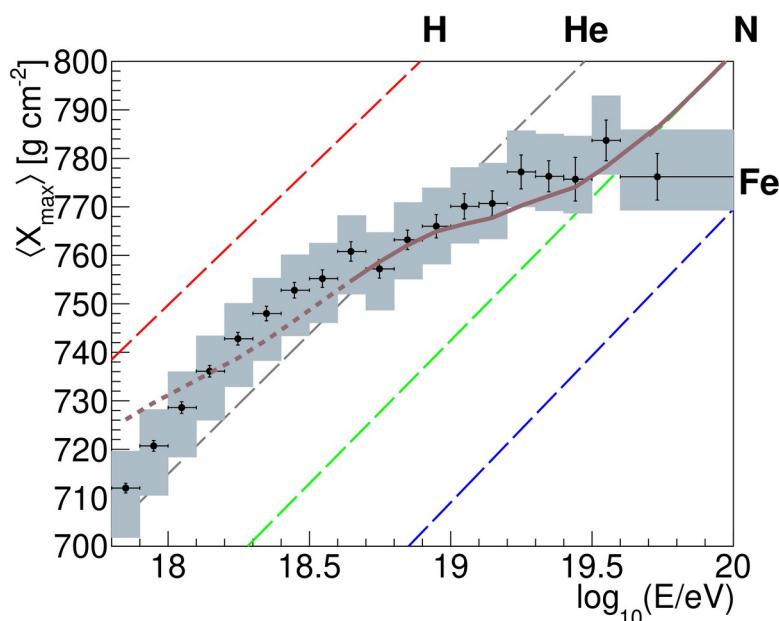
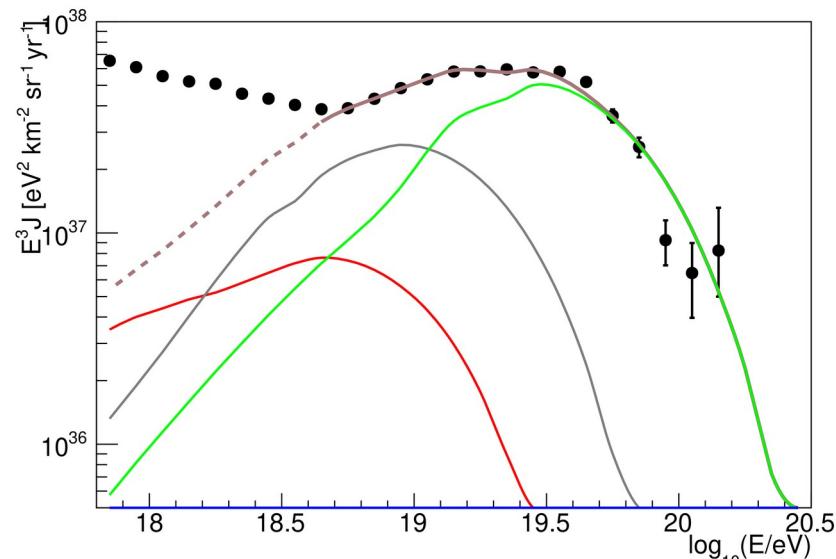
# EM Sector: Alternative UHECR scenario proton enhanced



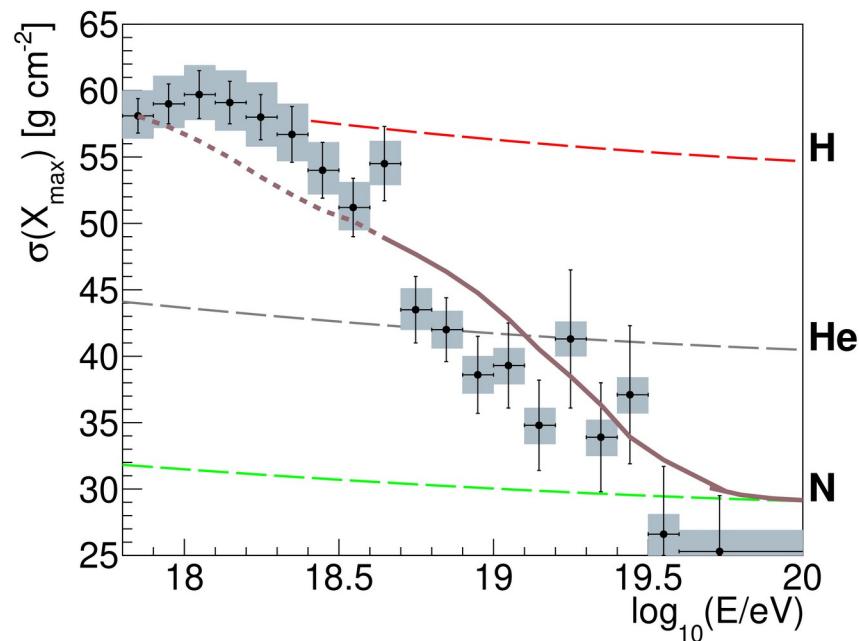
# EM Sector: Alternative UHECR scenario proton enhanced

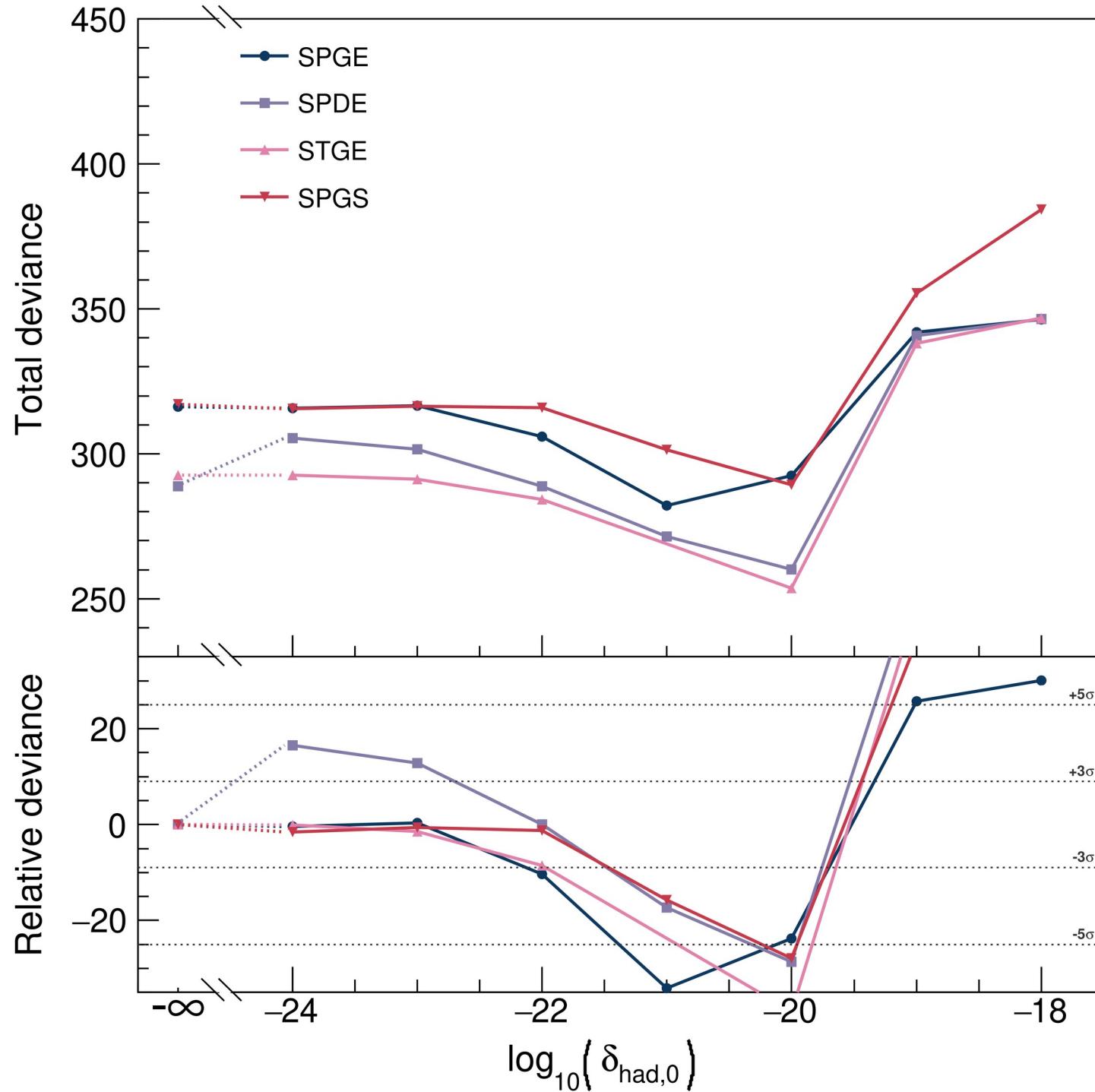


# Had Sector



Search for the  $\Gamma$ ,  $R_{\text{cut}}$ ,  $m$ ,  
 $f_H$ ,  $f_{\text{He}}$ ,  $f_N$ ,  $f_{\text{Si}}$ ,  $f_{\text{Fe}}$  and  $\delta_{\text{had}}$   
which best describe the  
measured energy  
spectrum and  $X_{\max}$   
distributions





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- EM Sector

- Auger LI Standard Scenario: no limits
- Proton enhanced Scenario

$$\delta_{\gamma,0} > -10^{-21} \quad \delta_{\gamma,1} > -10^{-40} \text{ eV}^{-1}$$

$$\delta_{\gamma,2} > -10^{-58} \text{ eV}^{-2}$$

- Had Sector

$$\delta_{\text{had},0} < 10^{-19} \quad \delta_{\text{had},1} < 10^{-38} \text{ eV}^{-1}$$

$$\delta_{\text{had},2} < 10^{-57} \text{ eV}^{-2}$$

