astroparticle probes of quantum gravity : cosmological propagation uncertainties

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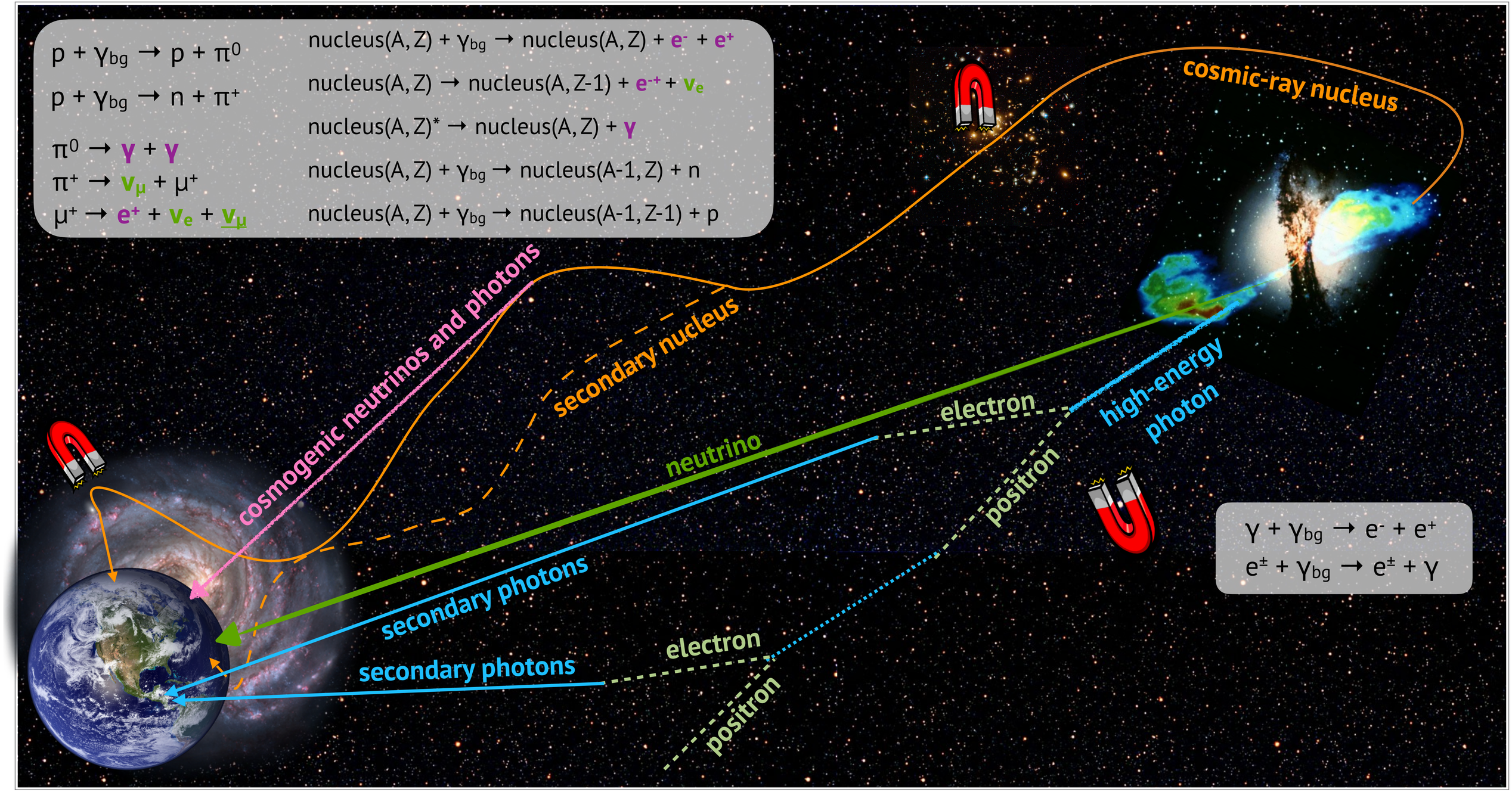
Workshop on Theoretical and Experimental Advances in Quantum Gravity
COST Action CA18108
01-03 September 2022
Belgrade, Serbia

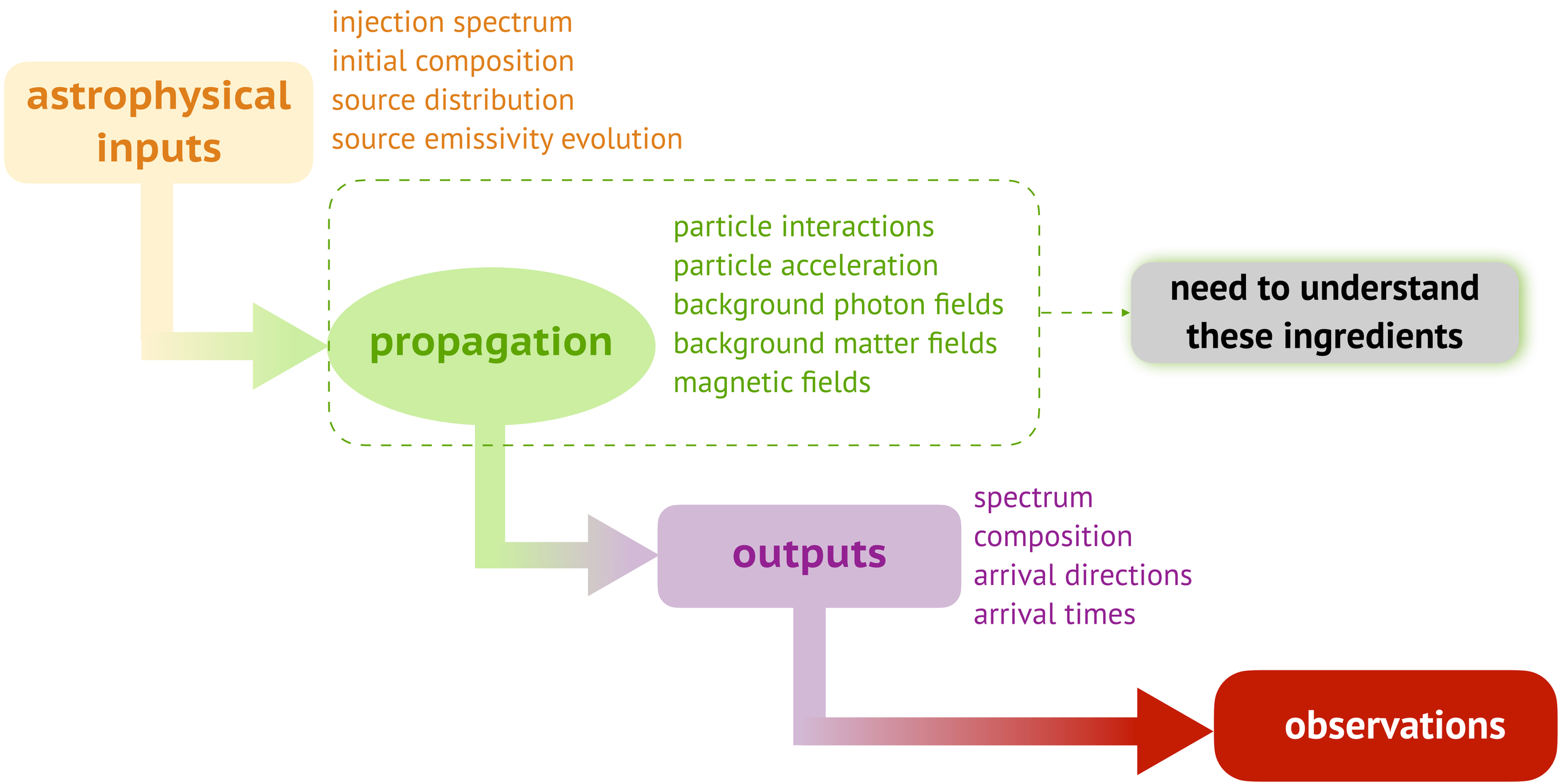
overview of this talk

- **propagation of high-energy cosmic messengers**
  - ultra-high-energy cosmic rays (UHECRs)
  - gamma rays
- **phenomenological observables**
  - particle fluxes
  - time delays
- conclusions & outlook

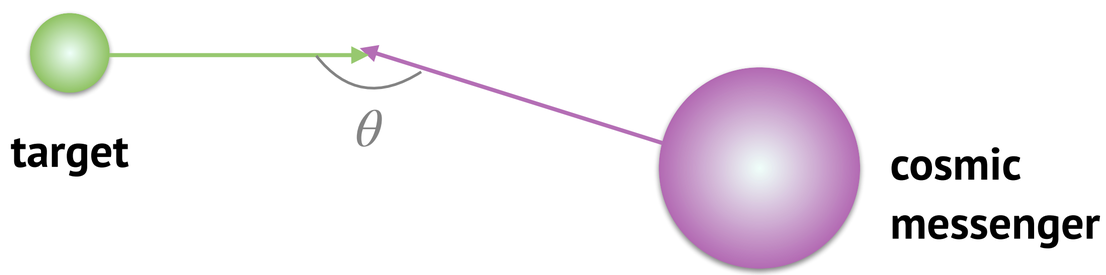
(intergalactic) propagation picture



cookbook for astroparticle transport



propagation ingredients: interactions



$$s = m^2 + 2E\varepsilon(1 - \beta\cos\theta)$$

(inverse) mean free path

$$\lambda^{-1}(E,z) = \frac{1}{8\beta E^2}\int_0^\infty \int_{s_{\min}}^{s_{\max}(\varepsilon,E)} \frac{1}{\varepsilon^2}\underbrace{\frac{\mathrm{d}n(\varepsilon,z)}{\mathrm{d}\varepsilon}}_{\text{photon backgrounds}}(s-m^2)\sigma(s)\underbrace{\Theta(\varepsilon-\varepsilon_{\min})}_{\text{interaction threshold}}\,\mathrm{d}s\,\mathrm{d}\varepsilon$$

interaction threshold

$$\varepsilon_{\min} = \frac{s_{\min} - m^2}{2E(1+\beta)}$$

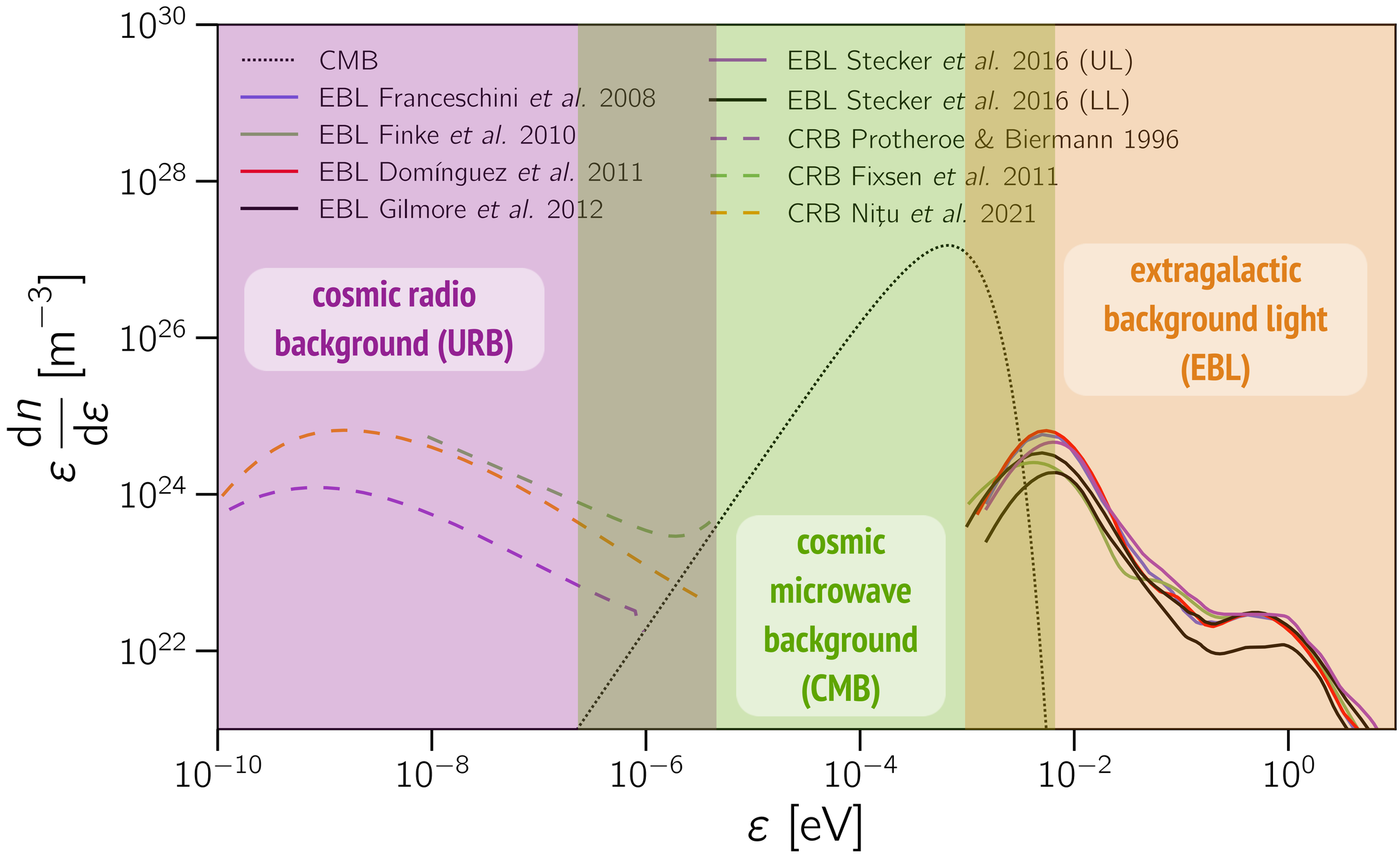
Lorentz invariance violation

$$E_i^2 = m_i^2 + p_i^2 + \sum_{n=0}^{\infty}\delta_{i,n}p_i^{n+2}$$

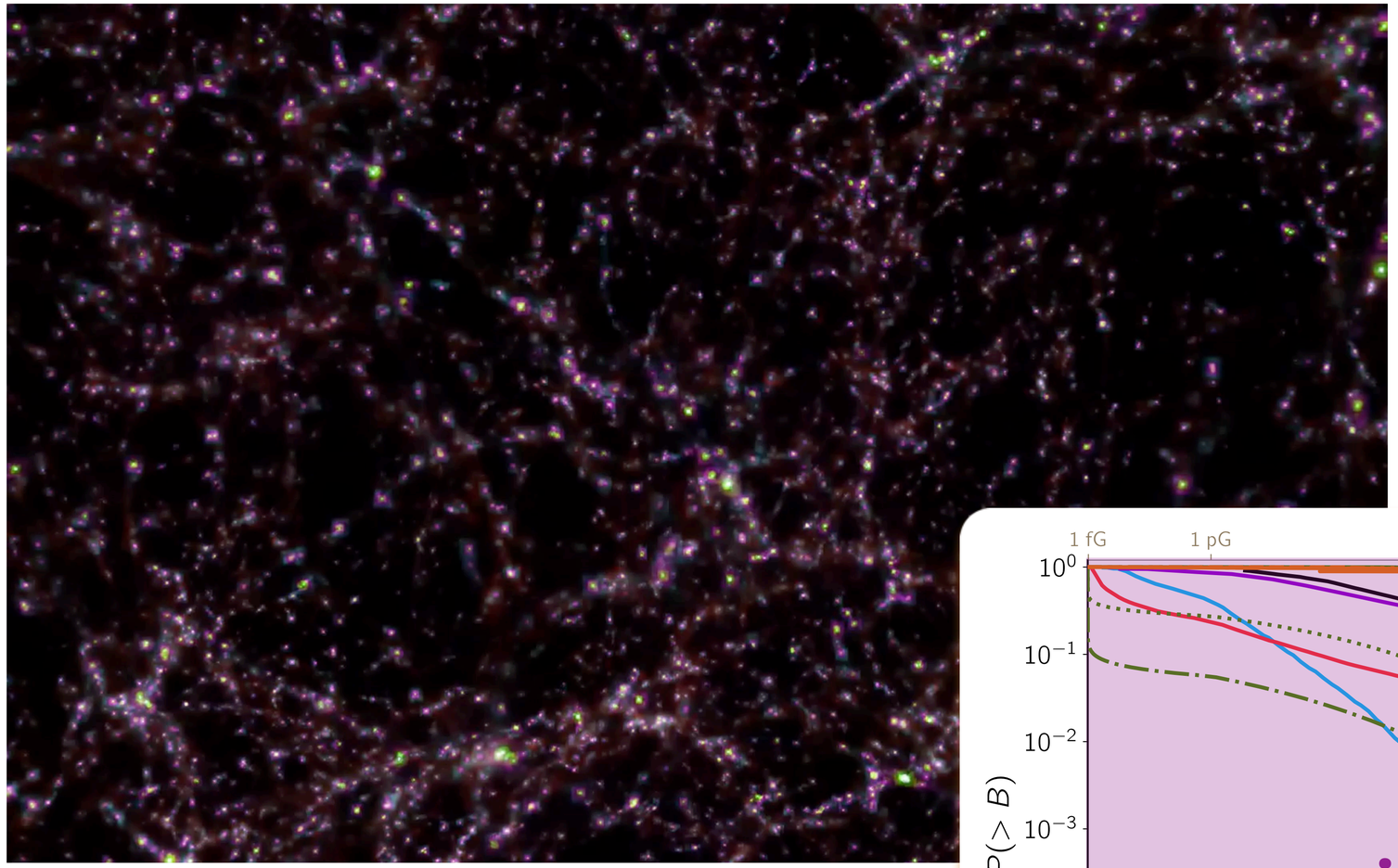
$$\delta_{i,n} = \frac{\eta_n}{M_{\mathrm{QG},n}}$$

interaction thresholds sensitive to QG effects

propagation ingredients: photon fields



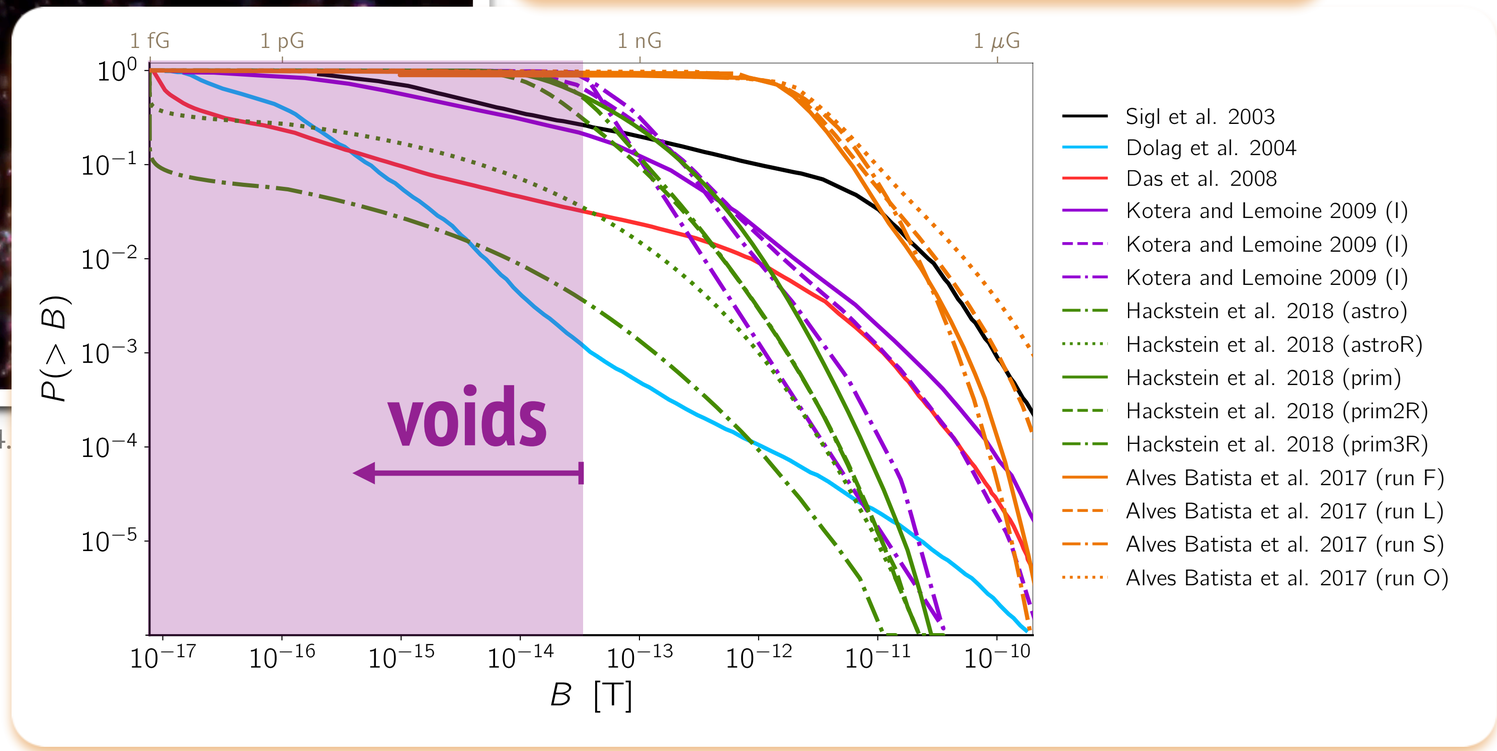
propagation ingredients: cosmic magnetic fields



Alves Batista, Shin, Devriendt, Semikoz, Sigl. PRD, 96 (2017) 023010. arXiv:1704.

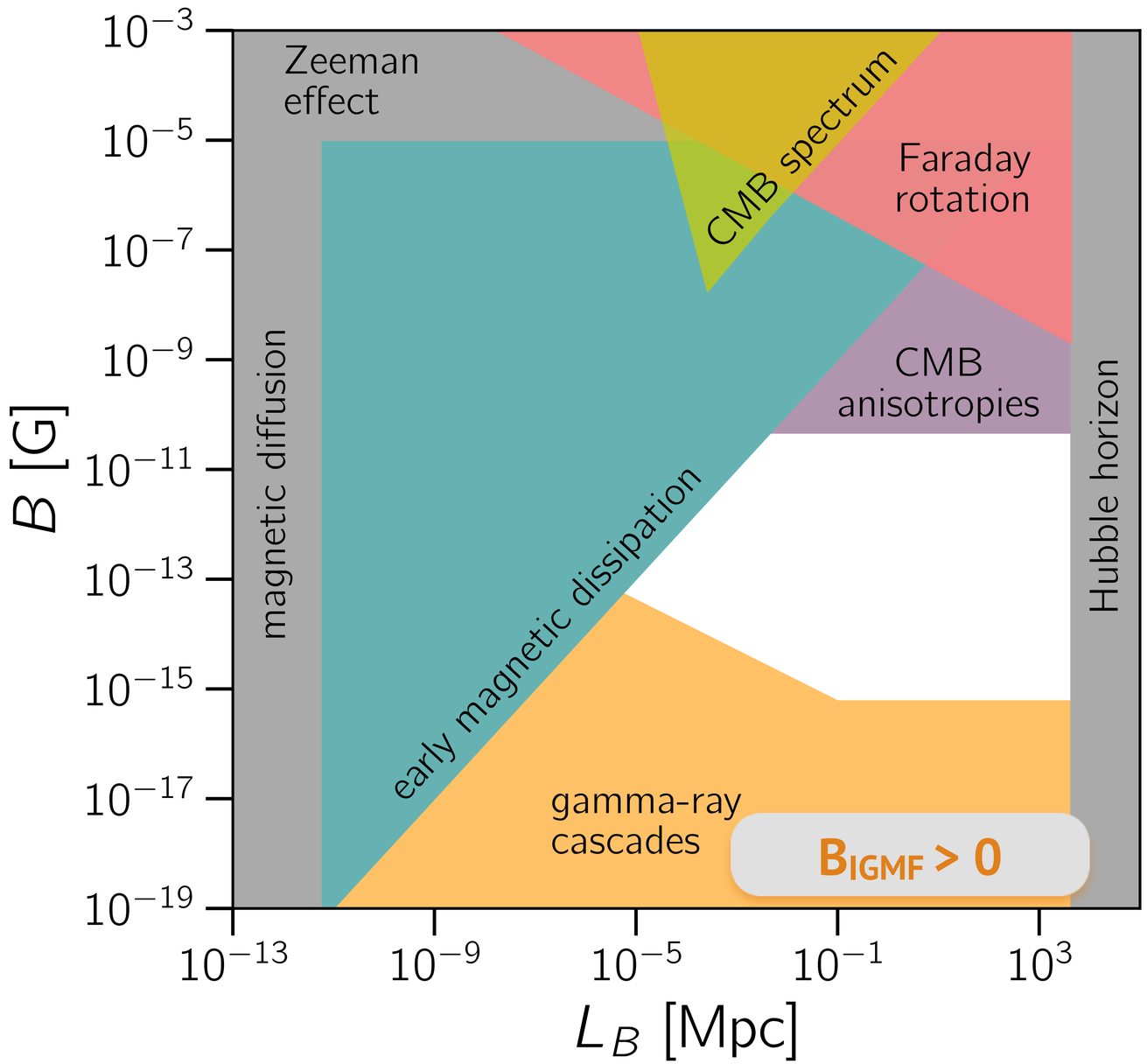
magnetic fields in voids are the most uncertain

contribution of voids dominate over cosmological distances



propagation ingredients: cosmic magnetic fields

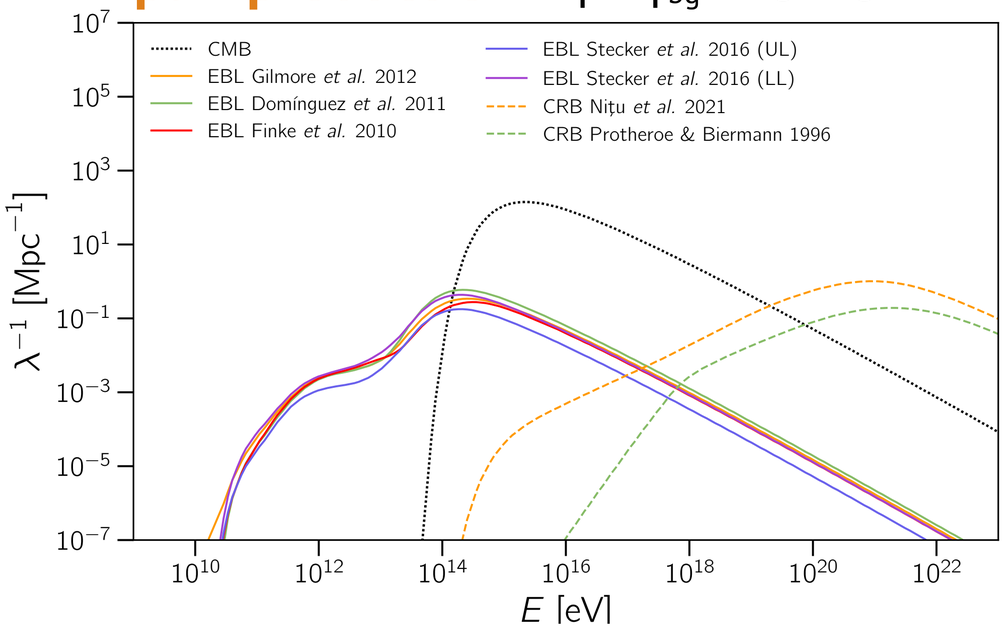
Alves Batista & Saveliev. Universe 7 (2021) 223. arXiv:2105.12020



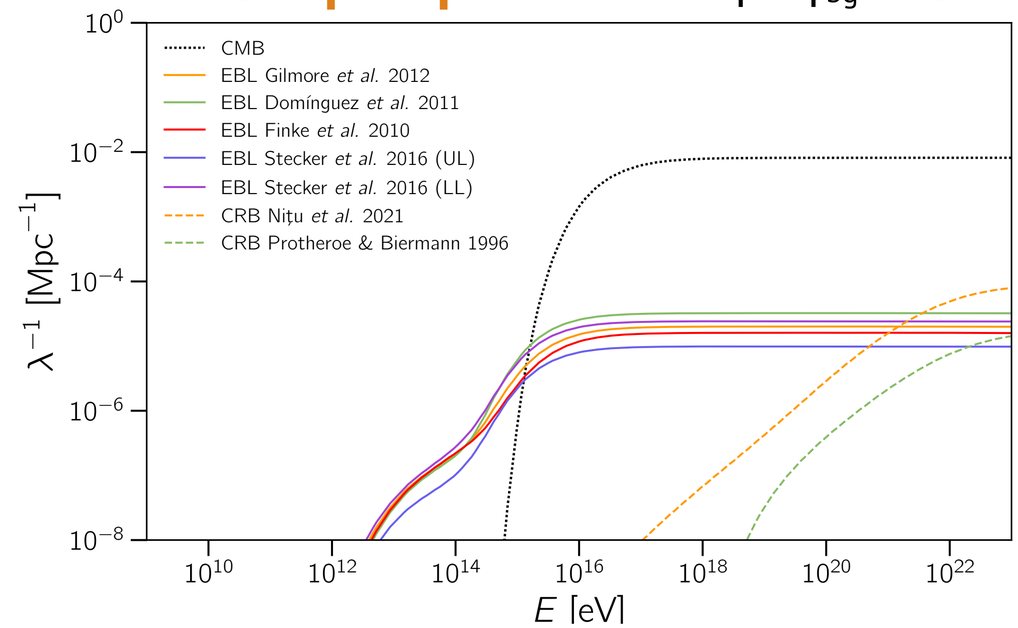
gamma rays

gamma rays: interactions during cosmological propagation

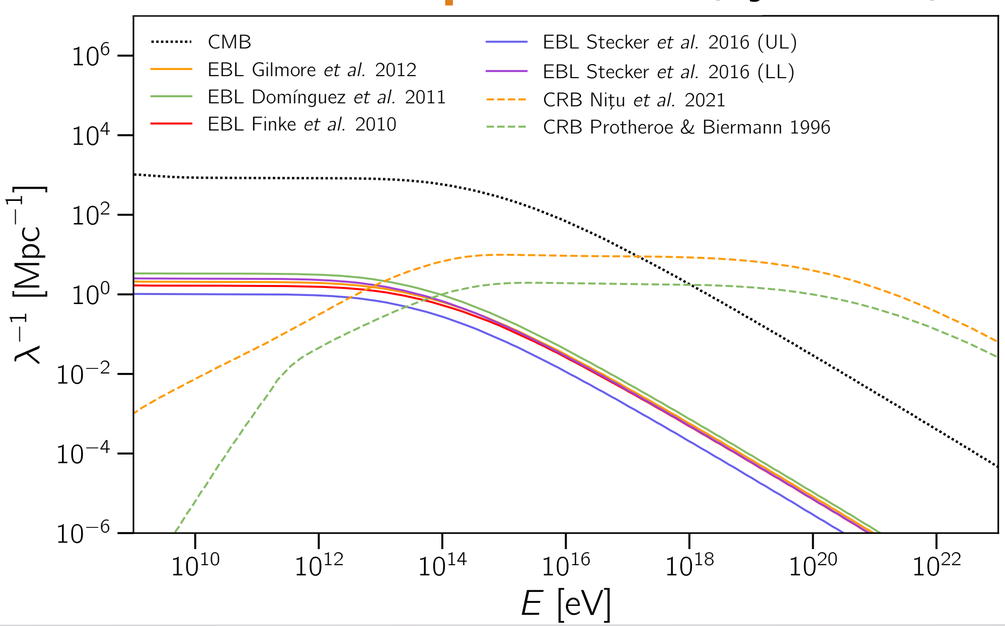
pair production $\gamma + \gamma_{bg} \rightarrow e^- + e^+$



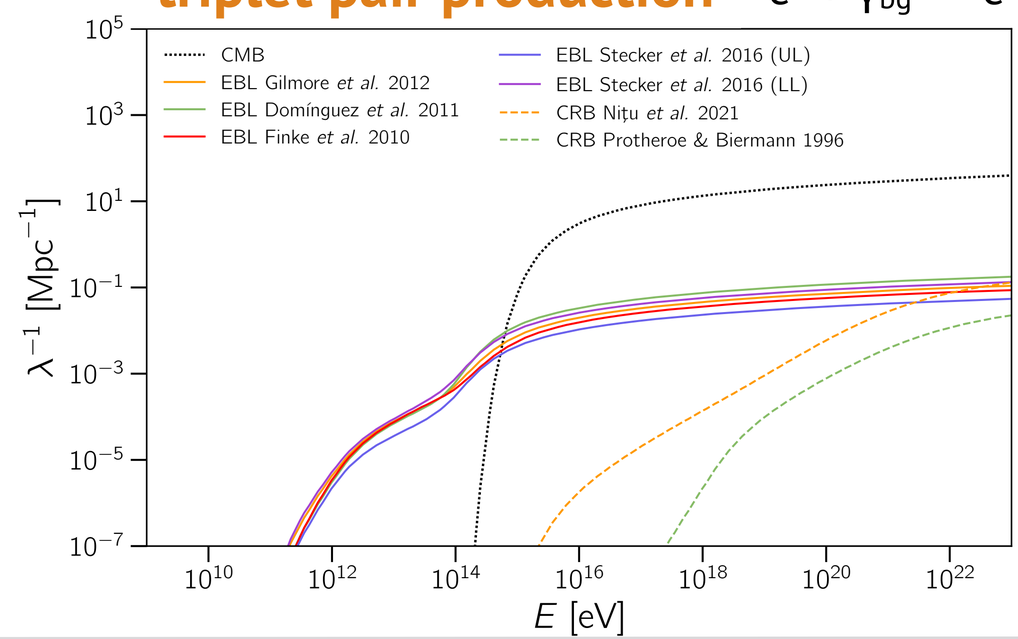
double pair production $\gamma + \gamma_{bg} \rightarrow e^- + e^+ + e^- + e^+$



inverse Compton $e^\pm + \gamma_{bg} \rightarrow e^\pm + \gamma$

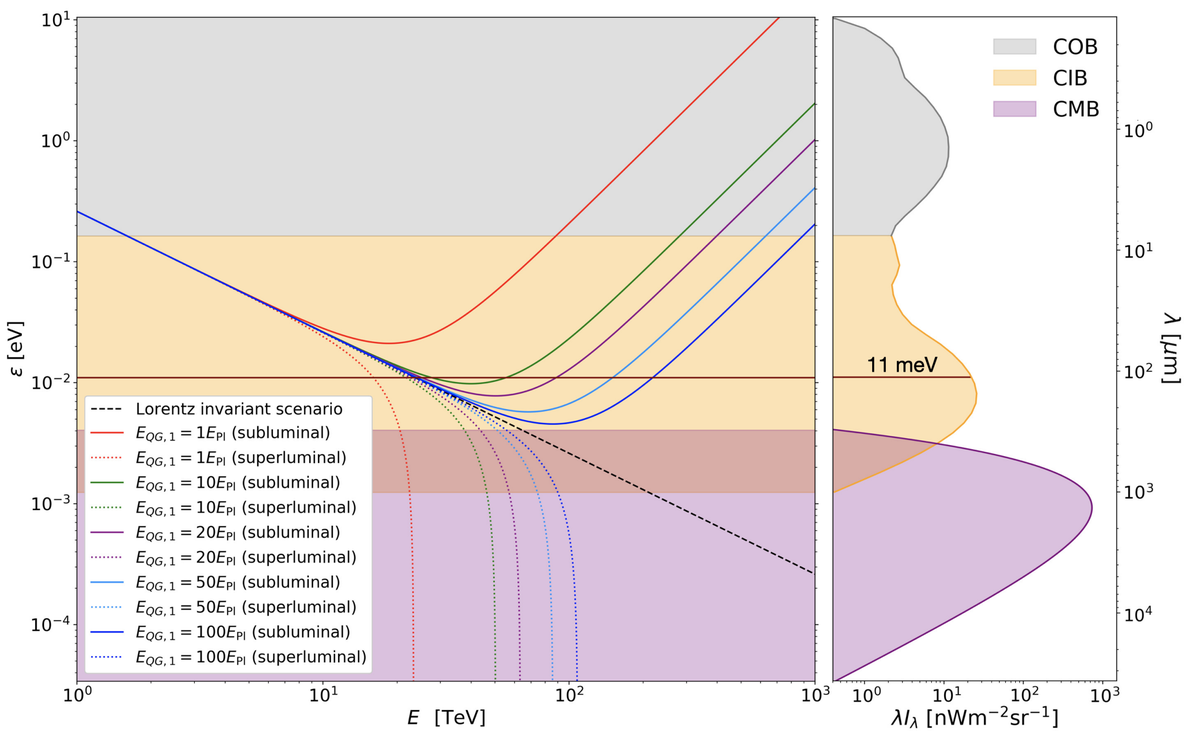


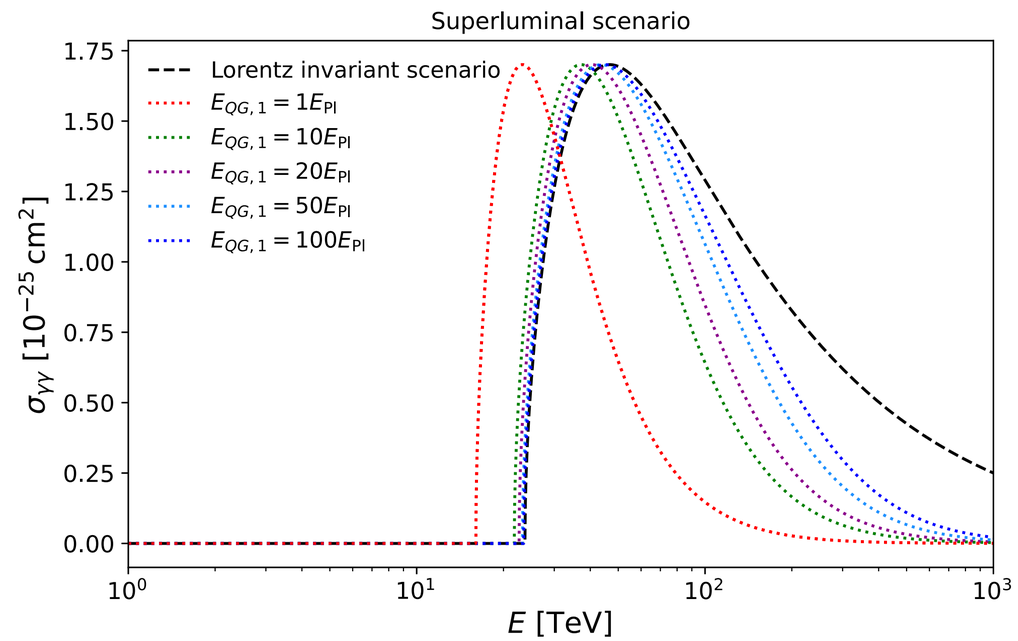
triplet pair production $e^\pm + \gamma_{bg} \rightarrow e^\pm + e^- + e^+$

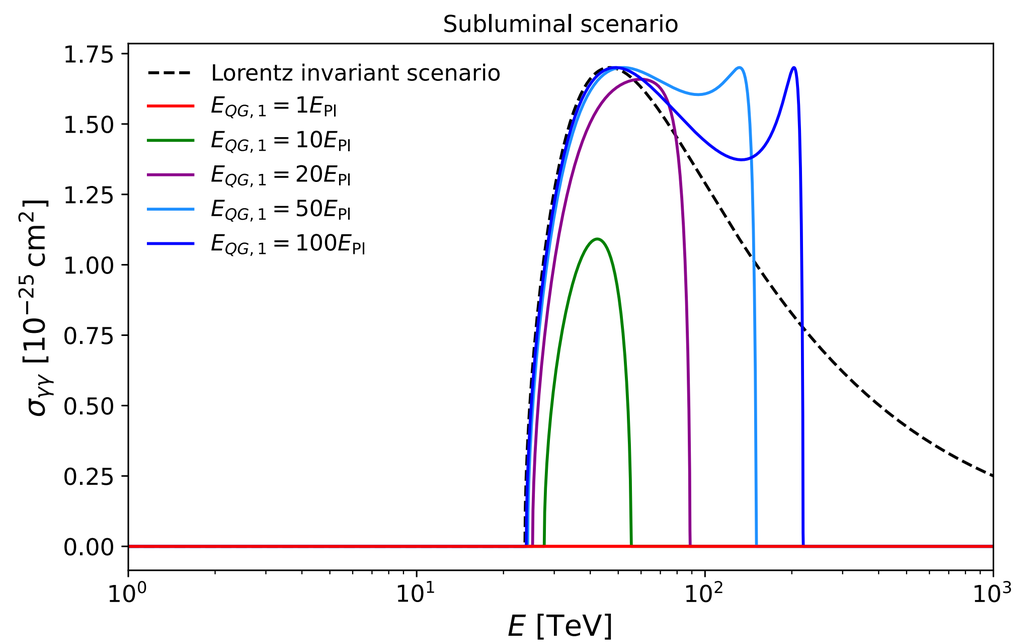


gamma rays: modification of interaction thresholds by QG

- Breit-Wheeler pair production: $\gamma + \gamma_{bg} \rightarrow e^- + e^+$
- QG: $$E_\gamma^2 = p_\gamma^2 \left[1 + \sum_{n=1}^{\infty} \eta_{\gamma,n} \left(\frac{E_\gamma}{E_{QG}} \right)^n \right]$$







Terzic et al. Universe 7 (2021) 345. arXiv:2109.09072

gamma rays: Lorentz invariance violation and time delays

question: how can we constrain LIV using gamma-ray observations?

flux attenuation

$$\Phi_{\rm o}(E_{\rm o}; z_{\rm s}) = \Phi_{\rm s}(E_{\rm o,s}) \exp\left[-\tau(E_{\rm o}, z_{\rm s})\right]$$

- $E_{\rm o}$: observed energy
- $z_{\rm s}$: source redshift
- $\Phi_{\rm s}(E_{\rm o,s})$: emitted flux
- $\tau(E_{\rm o}, z_{\rm s})$: optical depth

optical depth

$$\tau\left(E_{\rm o}; z_{\rm s}\right) = \int_0^{z_{\rm s}} {\rm d}z \, \frac{{\rm d}\ell}{{\rm d}z} \, \lambda_{\rm PP}^{-1}\left(E_{\rm o,s}, z\right)$$

- ${\rm d}\ell/{\rm d}z$: line of sight
- $\lambda_{\rm PP}^{-1}$: mean free path for pair production

LIV: modified dispersion relation

$$E = p\left[1 + \xi \frac{n+1}{2}\left(\frac{E}{E_{\rm QG}}\right)^n\right]$$

$$v = v(E) \approx 1 + \xi \frac{n+1}{2}\left(\frac{E}{E_{\rm QG}}\right)^n$$

- $v(E)$: energy-dependent velocity

time delays

$$\Delta t_{\rm obs} = \Delta t_{\rm QG} + \mathfrak{T} + \Delta t_B$$

- $\Delta t_{\rm QG}$: QG time delay
- $\mathfrak{T}$: intrinsic source time delay
- Δt_B: IGMFs

do time delays give truly meaningful constraints on LIV?

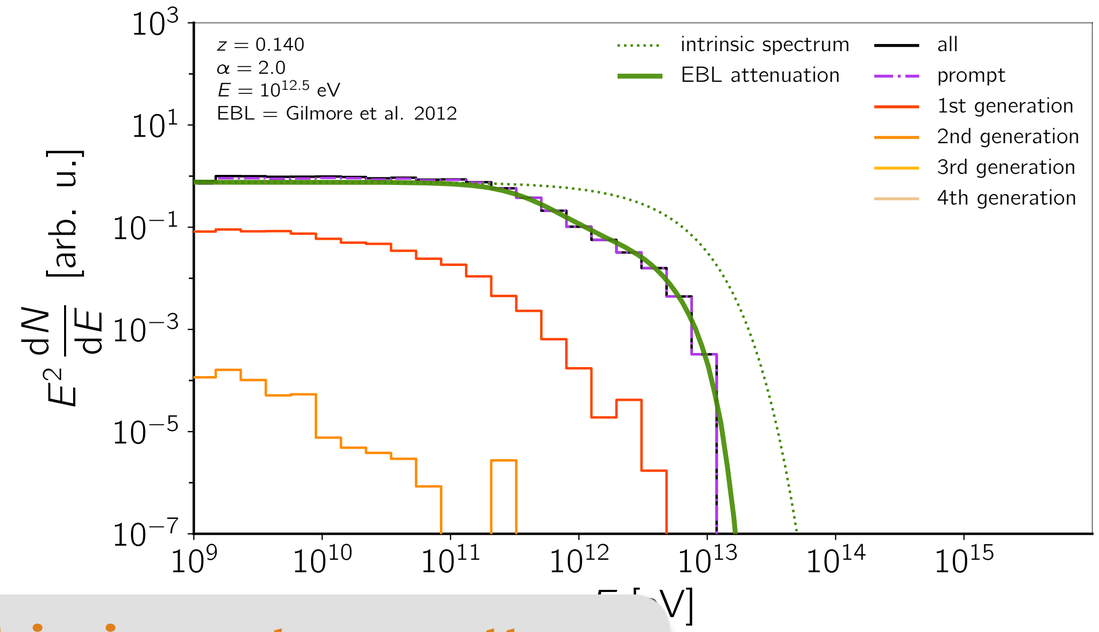
gamma rays: intrinsic spectrum uncertainties

information about the source

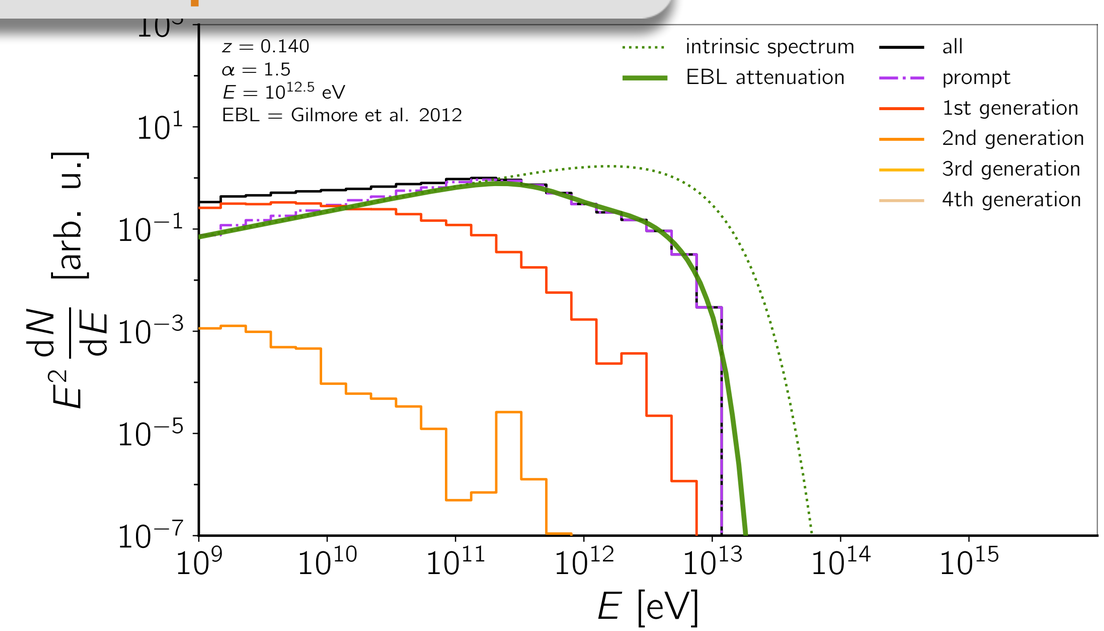
flux attenuation

$$\Phi_o(E_o; z_s) = \Phi_s(E_{o,s}) \exp\left[-\tau(E_o, z_s)\right]$$

how good is this approximation?



intrinsic spectrum matters



simulations performed with CRPropa

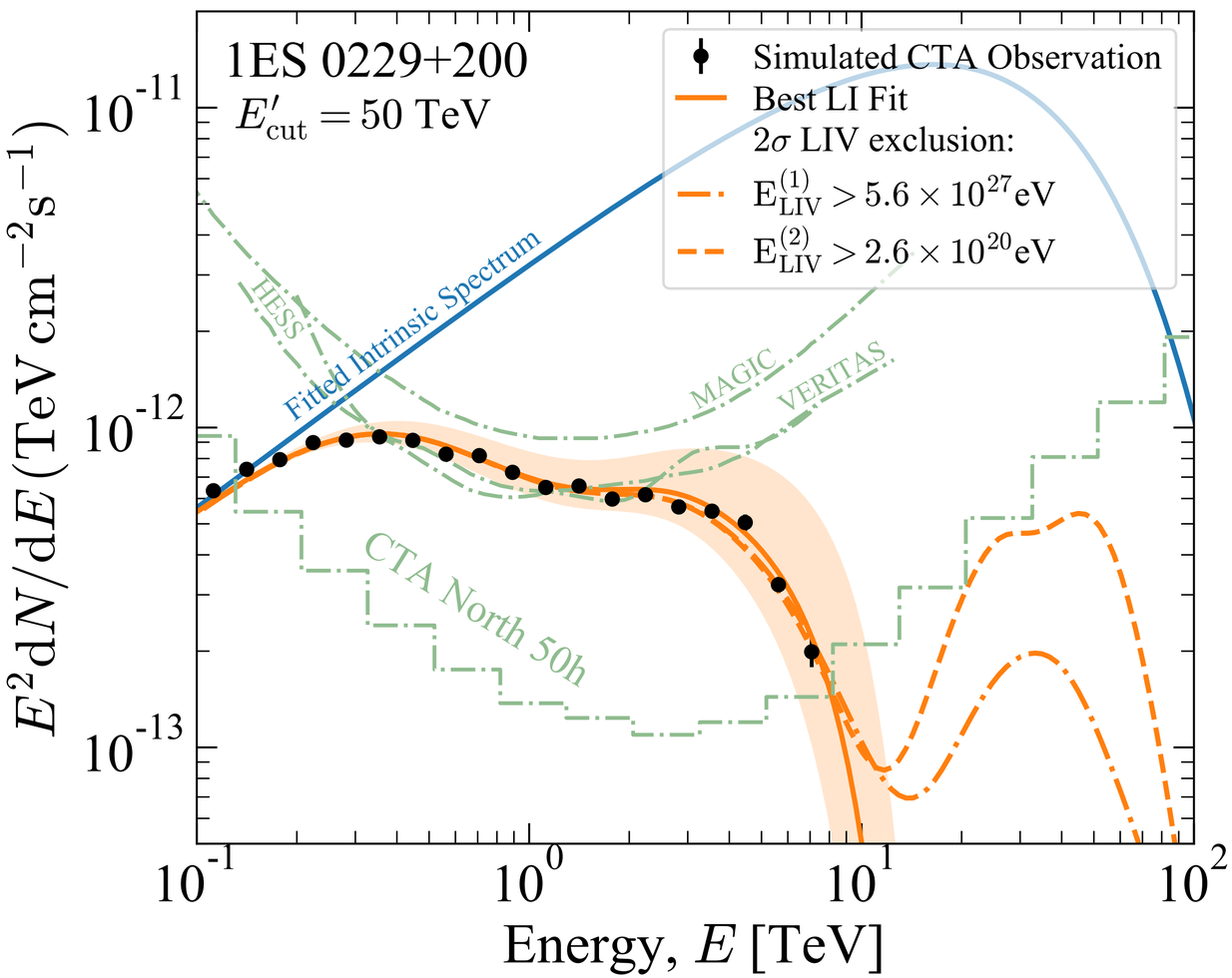
Alves Batista et al. JCAP 05 (2016) 038. arXiv:1603.07142

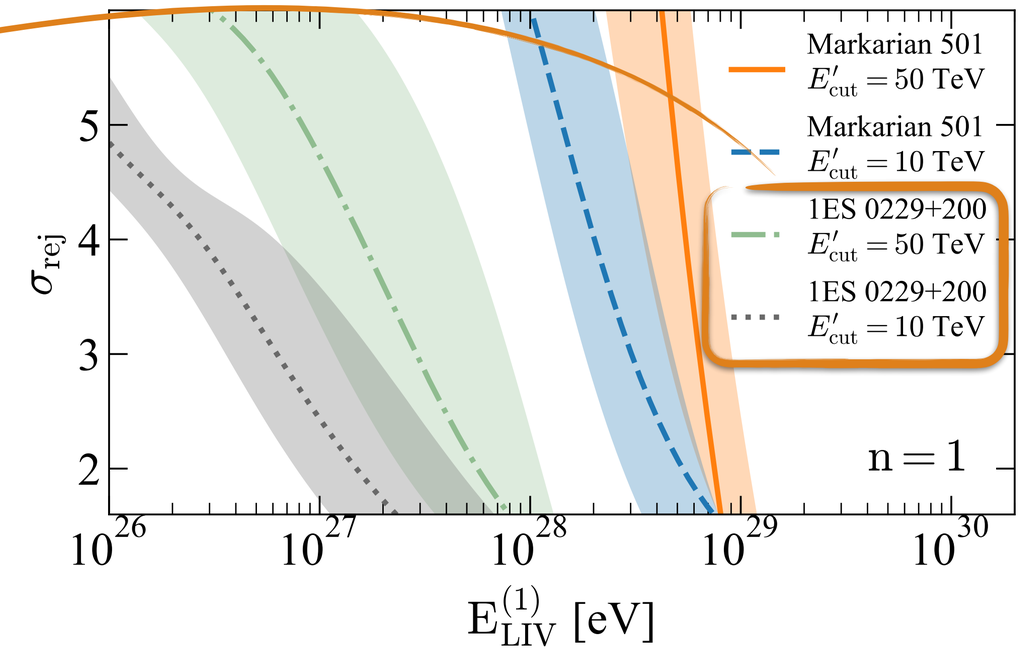
Alves Batista et al. arXiv:2208.00107

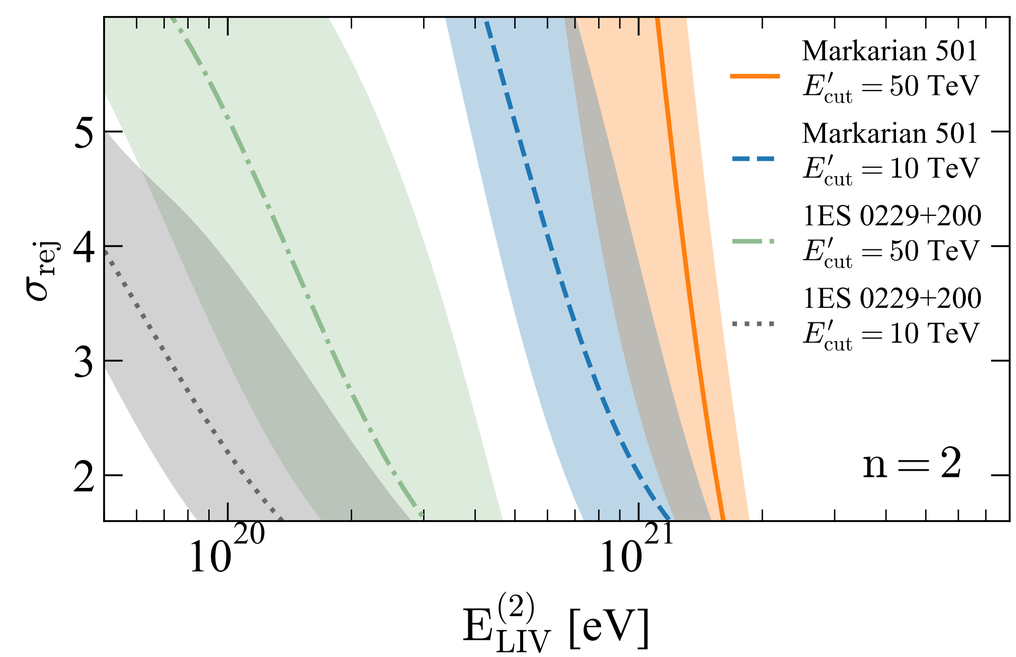
gamma rays: intrinsic spectrum uncertainties and constraints on LIV

CTA Consortium. JCAP 02 (2021) 048. arXiv:2010.01349

QG energy scale depends on intrinsic spectrum (spectrum cut-off energy)

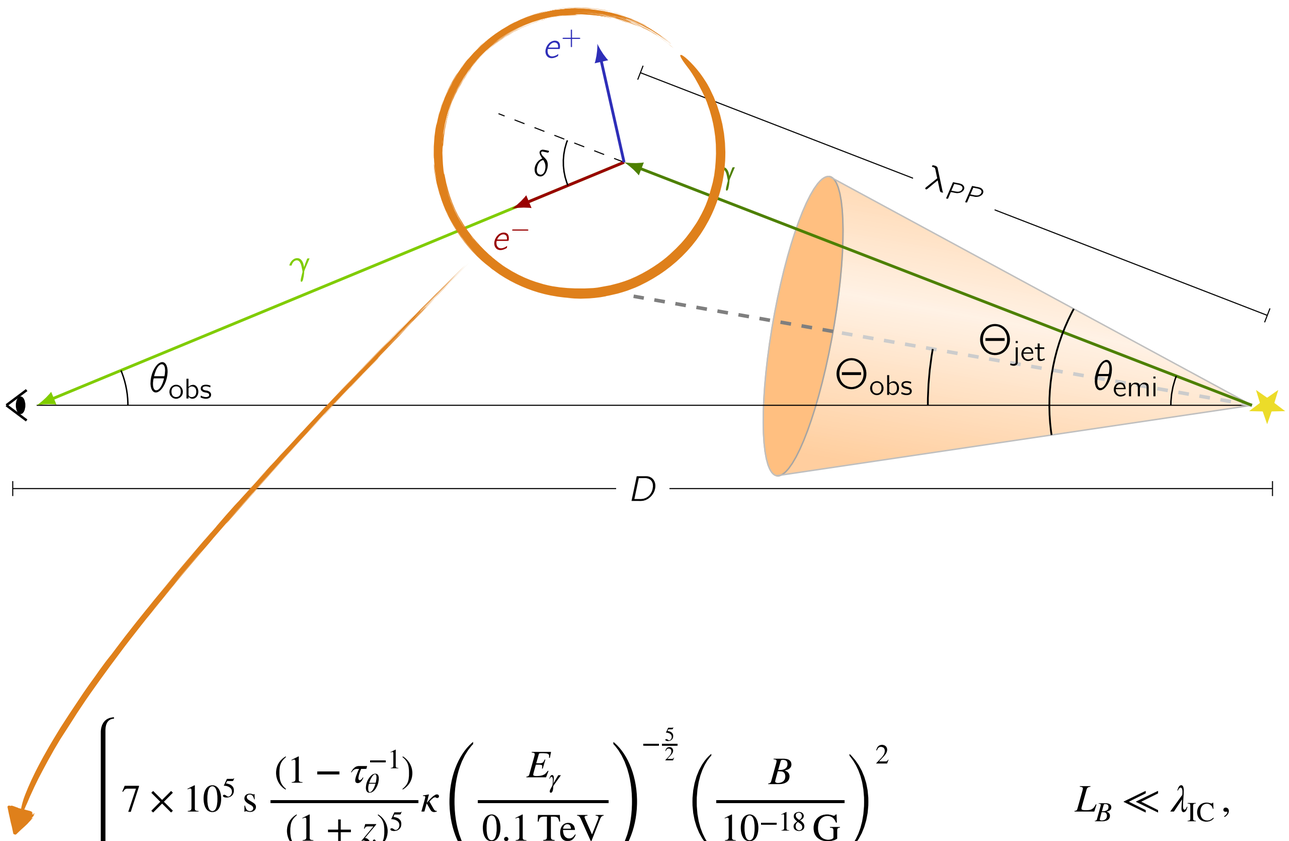






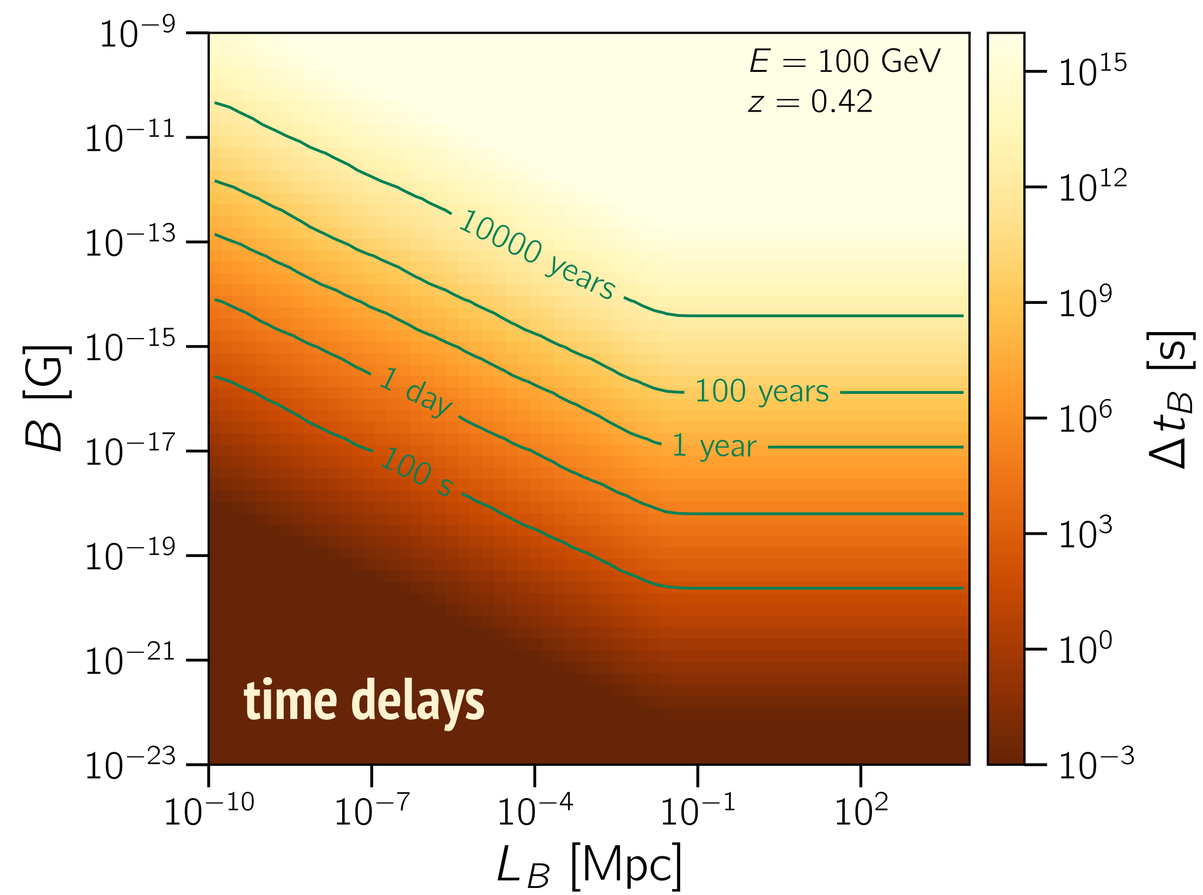
gamma rays: QG signatures through time delays

Alves Batista & Saveliev. Universe 7 (2021) 223. arXiv:2105.12020

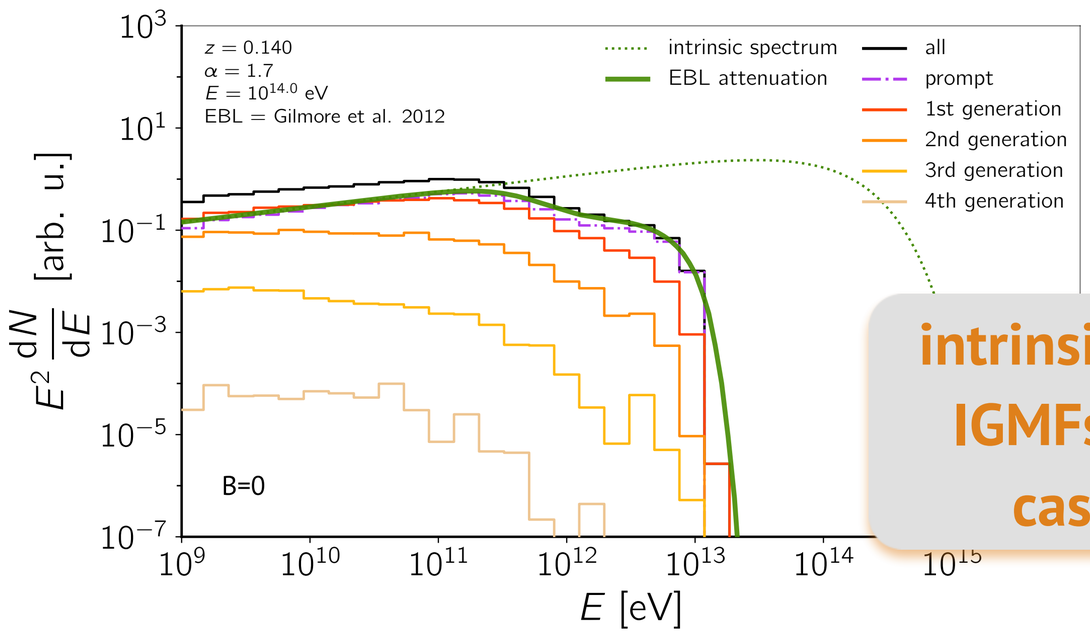


$$\Delta t_B \simeq \begin{cases} 7\times10^5\,\mathrm{s}\,\dfrac{(1-\tau_\theta^{-1})}{(1+z)^5}\kappa\left(\dfrac{E_\gamma}{0.1\,\mathrm{TeV}}\right)^{-\frac{5}{2}}\left(\dfrac{B}{10^{-18}\,\mathrm{G}}\right)^2 & L_B \ll \lambda_{\rm IC}\,, \\ 1\times10^4\,\mathrm{s}\,\dfrac{(1-\tau_\theta^{-1})}{(1+z)^2}\kappa\left(\dfrac{E_\gamma}{0.1\,\mathrm{TeV}}\right)^{-2}\left(\dfrac{B}{10^{-18}\,\mathrm{G}}\right)^2\left(\dfrac{L_B}{1\,\mathrm{kpc}}\right) & L_B \gg \lambda_{\rm IC}\,. \end{cases}$$

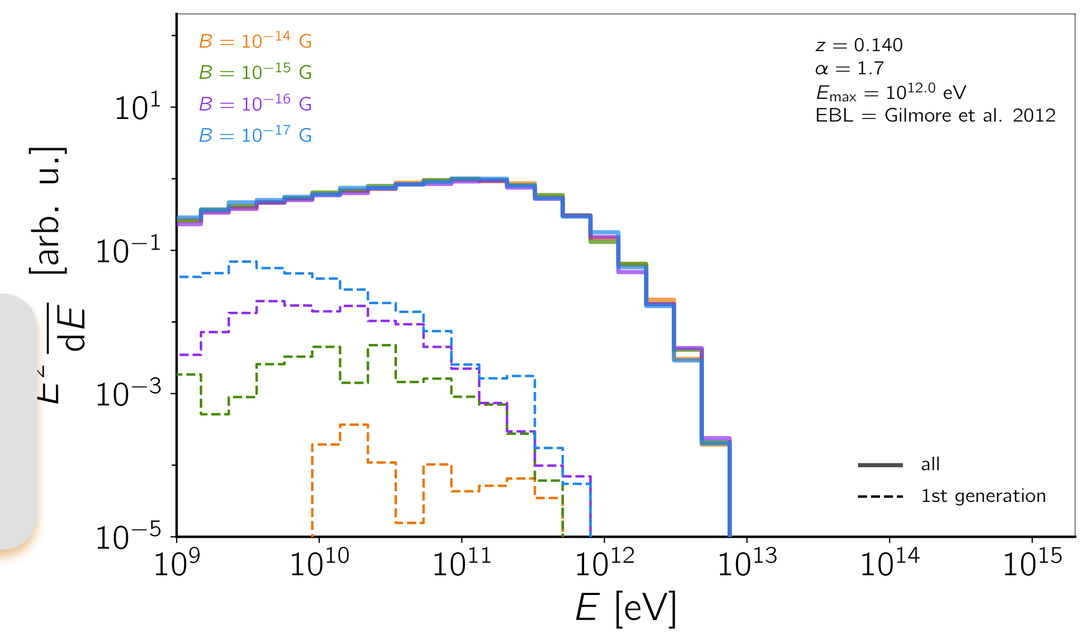
what fraction of the observed gamma-ray flux can be time-delayed?



gamma rays: detailed simulations of gamma-ray propagation

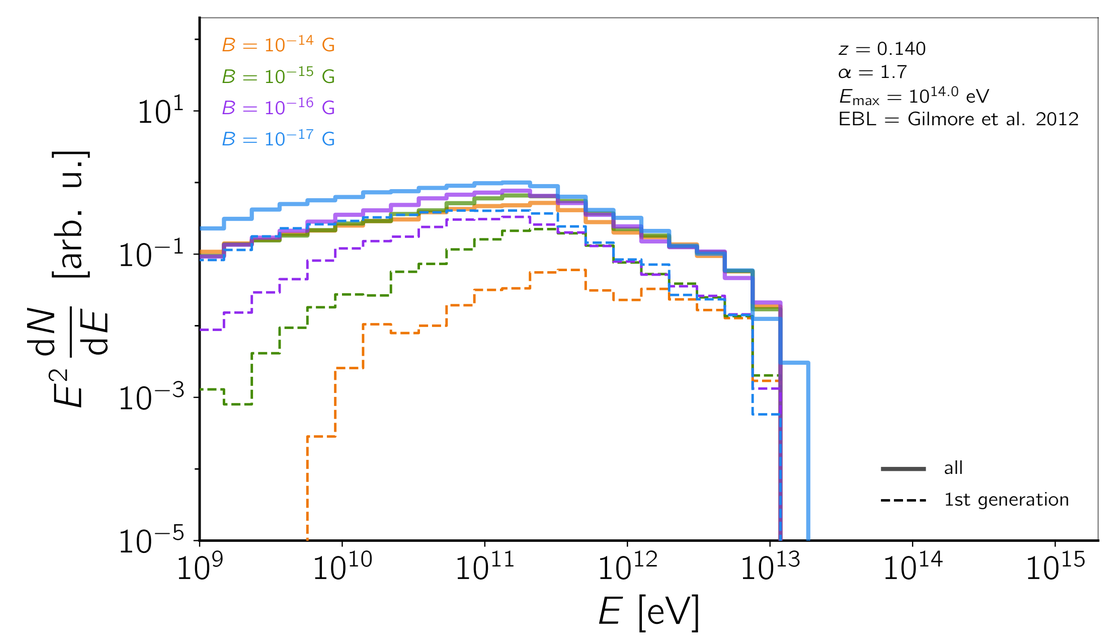


intrinsic spectrum + IGMFs determine cascade flux



$$\Delta t_{obs} = \Delta t_{QG} + \mathfrak{T} + \Delta t_B \longrightarrow \mathfrak{T} + \Delta t_B \overset{?}{\gg} \Delta t_{QG}$$

difficult to identify QG signatures with confidence



simulations performed with CRPropa

Alves Batista et al. JCAP 05 (2016) 038. arXiv:1603.07142

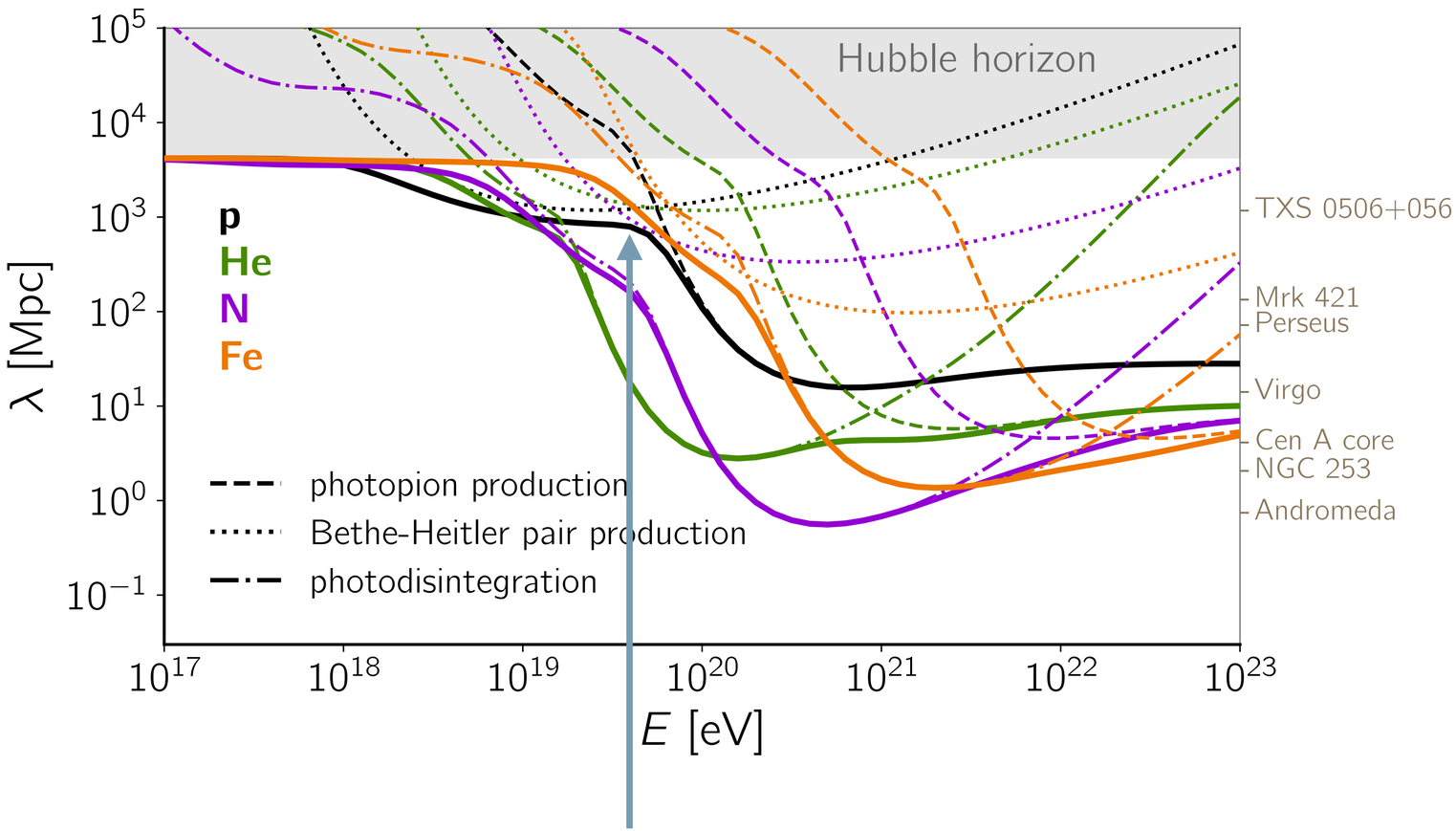
Alves Batista et al. arXiv:2208.00107

how to connect QG phenomenology with observations?

- given a set of gamma-ray observations, what can we really say about QG effects *(with confidence)*?
  - observables: arrival directions, arrival times, fluxes
  - 🙂 sources are generally known
  - 😐 knowledge of source properties barely satisfactory
  - 🙂 good statistics
  - ☹️ IGMFs affect all observables
  - 🙂 physics is known → we can just build better models and cover the whole parameter space

UHECRs

UHECRs: interactions during cosmological propagation



$$s = m^2 + 2E\varepsilon(1 - \beta\cos\theta)$$

$$s = (m_p + m_\pi)^2 \simeq m^2 + 2E_p\varepsilon_{\rm CMB}$$

$$E_{\rm GZK} \simeq 6\ {\rm EeV} \equiv 6 \times 10^{19}\ {\rm eV}$$

photopion production

$p + \gamma_{bg} \rightarrow p + \pi^0$ $\quad$ $\pi^0 \rightarrow \gamma + \gamma$

$p + \gamma_{bg} \rightarrow n + \pi^+$ $\quad$ $\pi^+ \rightarrow \nu_\mu + \mu^+$

$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

(similar for nuclei)

Bethe-Heitler pair production

$\text{nucleus}(A,Z) + \gamma_{bg} \rightarrow \text{nucleus}(A,Z) + e^- + e^+$

photodisintegration

$\text{nucleus}(A,Z) + \gamma_{bg} \rightarrow \text{nucleus}(A\text{-}1,Z) + n$

$\text{nucleus}(A,Z) + \gamma_{bg} \rightarrow \text{nucleus}(A\text{-}1,Z\text{-}1) + p$

...

nuclear decays

$\text{nucleus}(A,Z) \rightarrow \text{nucleus}(A\text{-}4,Z\text{-}2) + \alpha$

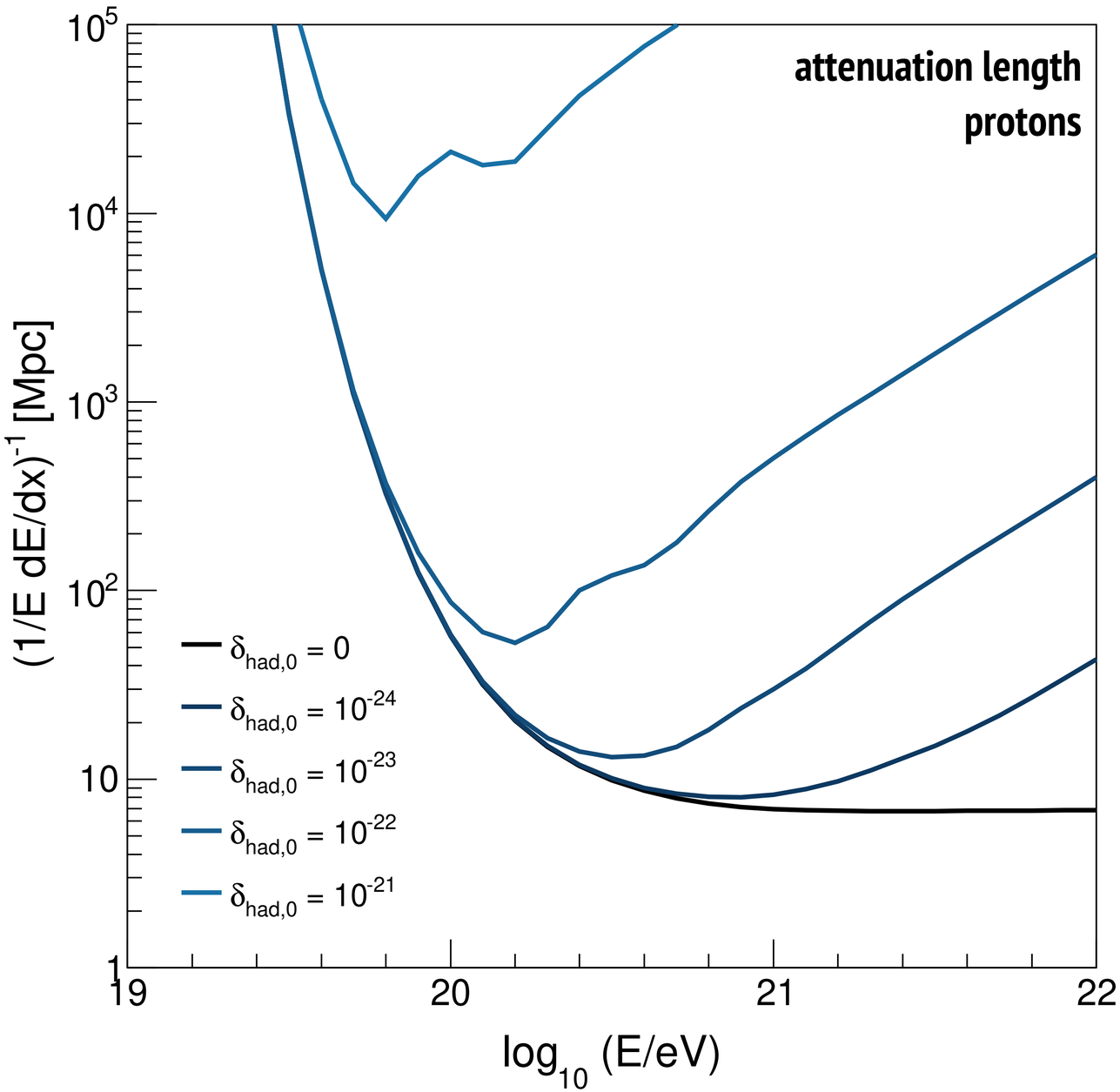
$\text{nucleus}(A,Z) \rightarrow \text{nucleus}(A,Z\text{+}1) + e^- + \bar{\nu}_e$

$\text{nucleus}(A,Z) \rightarrow \text{nucleus}(A,Z\text{-}1) + e^{-+} + \nu_e$

$\text{nucleus}(A,Z)^* \rightarrow \text{nucleus}(A,Z) + \gamma$

UHECRs: modification of interaction thresholds by QG

Pierre Auger Collaboration. JCAP 01 (2022) 023. arXiv:2112.06773



photopion production

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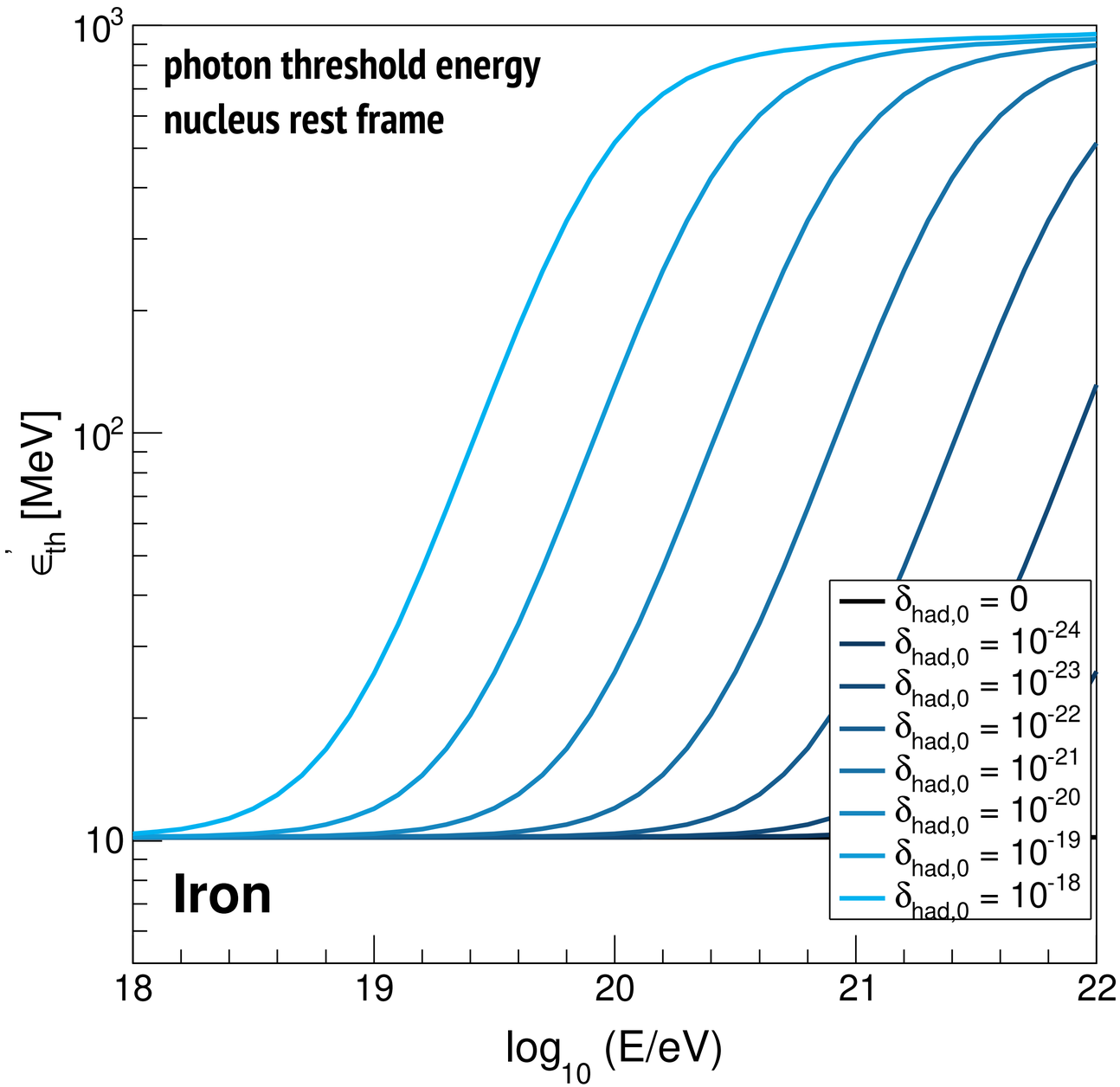


photodisintegration

nucleus(A, Z) + γ_{bg} → nucleus(A-1, Z) + n

nucleus(A, Z) + γ_{bg} → nucleus(A-1, Z-1) + p

...

UHECRs: the GZK effect and the QG scale

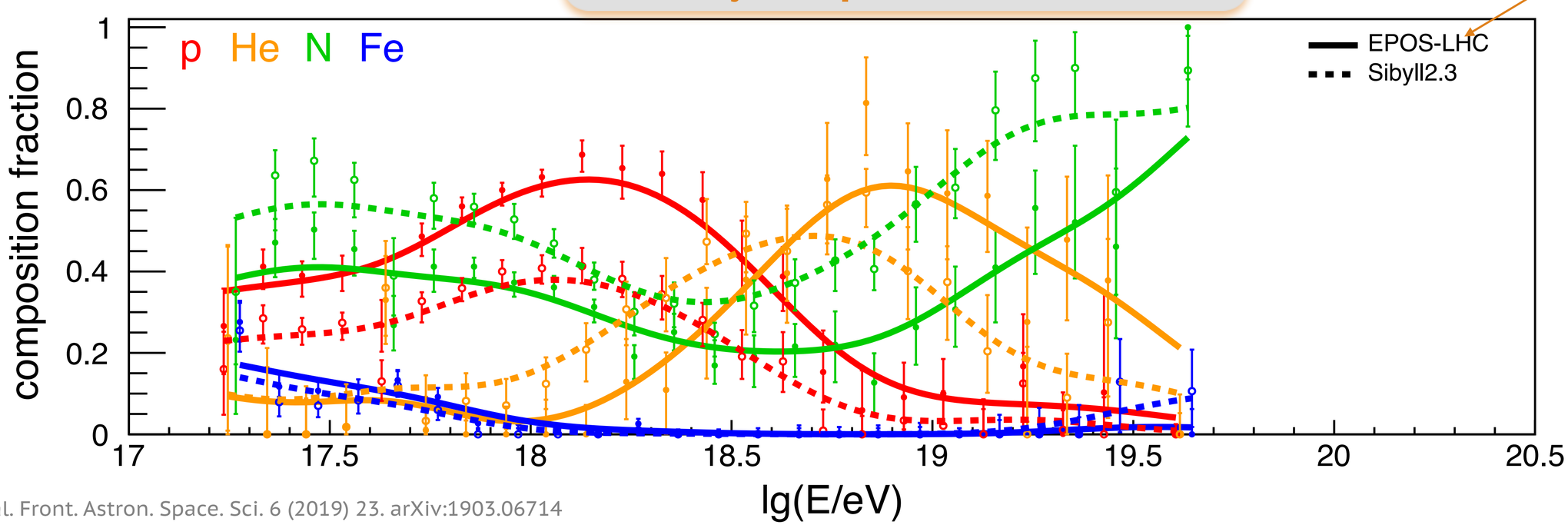
is the GZK effect is one of the best observables to search for QG effects?

necessary conditions

- UHECR sources are known (or incredibly high statistics)
- significant fraction of protons above the GZK threshold
- no other spectral effect that mimics the GZK suppression

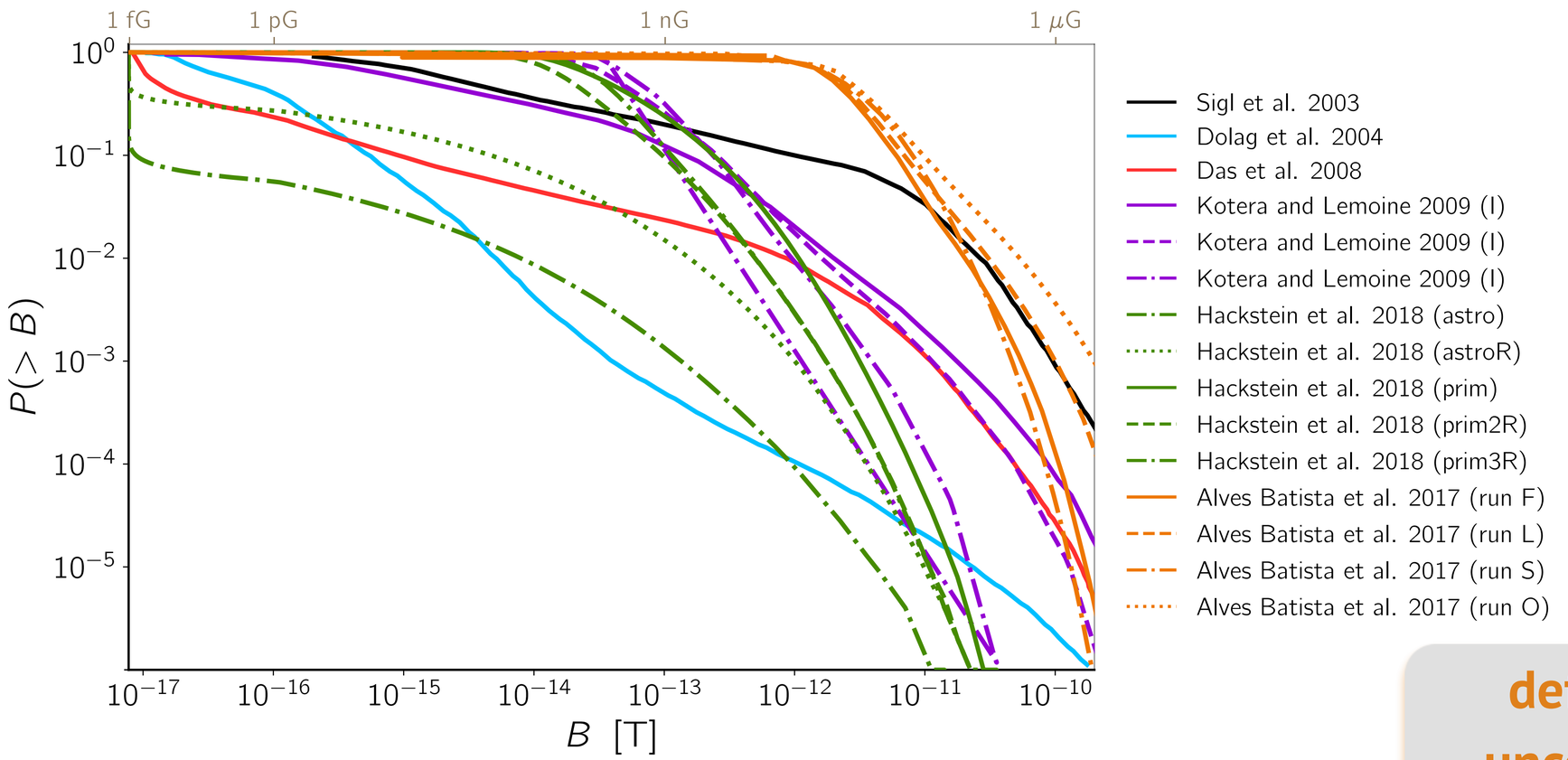
hadronic interaction models (air showers)

very few protons at UHE!



Alves Batista et al. Front. Astron. Space. Sci. 6 (2019) 23. arXiv:1903.06714

UHECRs: deflections in magnetic field



deflections are completely uncertain (they can be huge)

deflections

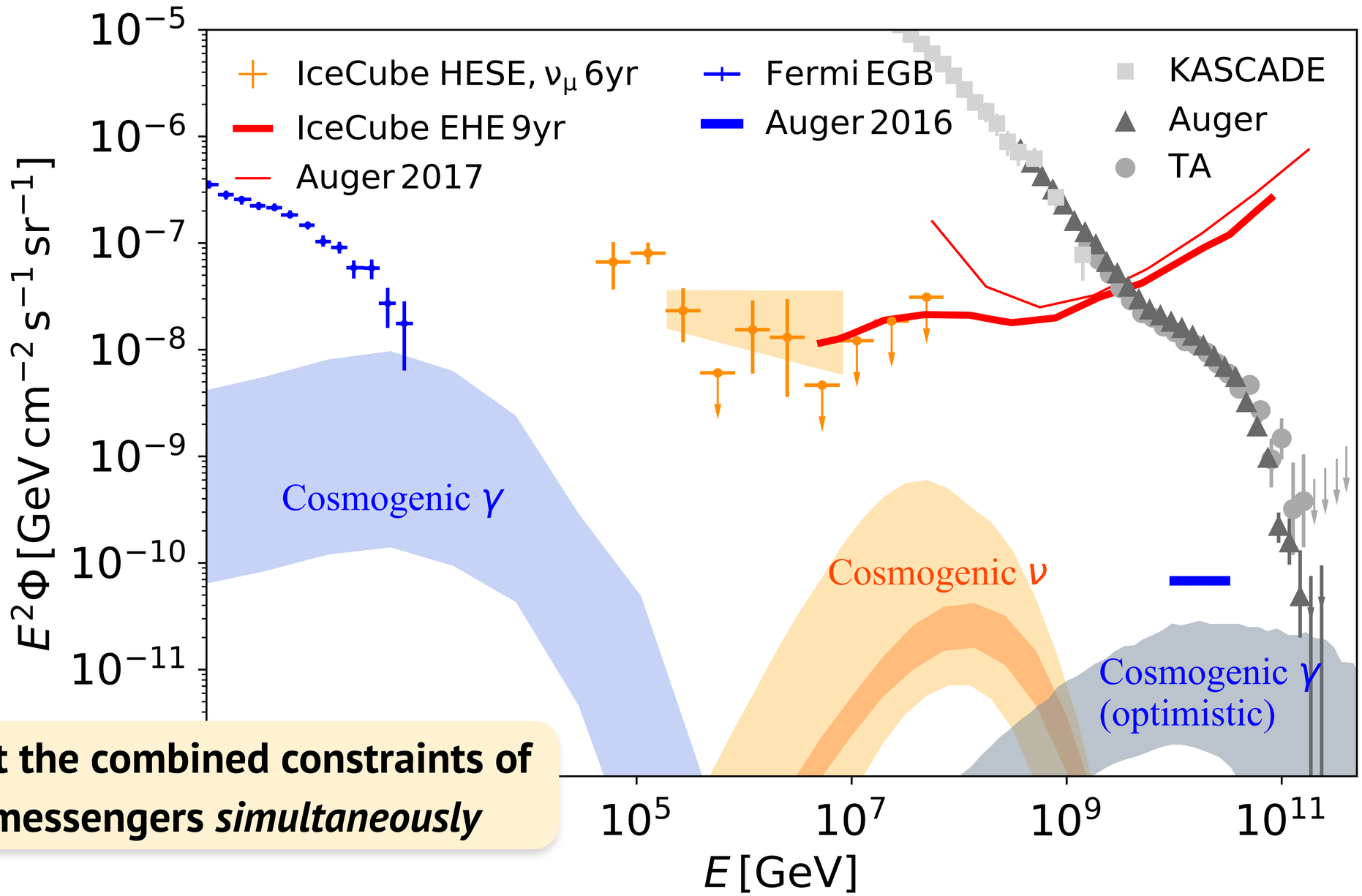
$$\delta \simeq \begin{cases} 0.05^\circ Z \left(\frac{E}{100\ \mathrm{EeV}}\right)^{-1} \left(\frac{B}{\mathrm{nG}}\right) \left(\frac{D}{\mathrm{Mpc}}\right) & \text{if } D \ll L_B \\ 0.05^\circ Z \left(\frac{E}{100\ \mathrm{EeV}}\right)^{-1} \left(\frac{B}{\mathrm{nG}}\right) \left(\frac{D}{\mathrm{Mpc}}\right)^{\frac{1}{2}} \left(\frac{L_B}{\mathrm{Mpc}}\right)^{\frac{1}{2}} & \text{if } D \gg L_B \end{cases}$$

how to connect QG phenomenology with observations?

- given a set of UHECR observations, what can we really say about QG effects *(with confidence)*?
  - UHECR observables: spectrum, composition, arrival directions
  - 🙁 cannot infer composition of individual CRs (+ air-shower physics is complicated)
  - 🙁 sources are unknown
  - 🙁 parameter space is huge to be fully covered
- modified interaction thresholds → changes fluxes of **cosmogenic neutrinos and photons**
  - 🙁 how to distinguish cosmogenic fluxes from other contributions?

outlook & summary

the way forward: multimessenger approach



exploit the combined constraints of all messengers *simultaneously*

Alves Batista et al. Front. Astron. Space. Sci. 6 (2019) 23. arXiv:1903.06714

a summary

- uncertainties in astroparticle propagation pose *severe difficulties* in detecting QG signatures
- with the current state of the art, claims of detection and some constraints should critically examined
- UHECRs are complicated on their own → *(my unpopular opinion)* do not seem a promise road for successfully finding QG effects (at the moment)
- electromagnetic cascades might spoil searches for QG signals using gamma rays → but they can be accounted for

- ***can we really detect QG signatures using high-energy cosmic messengers in the near future?***
  - true multimessenger studies can validate/exclude the oversimplified models employed today
  - *(the devil is in the details)*

thank you 😊

"la Caixa" Foundation