astroparticle probes of quantum gravity : cosmological propagation uncertainties

Rafael Alves Batista

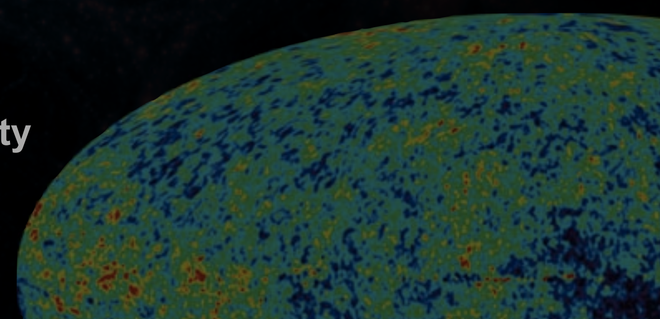
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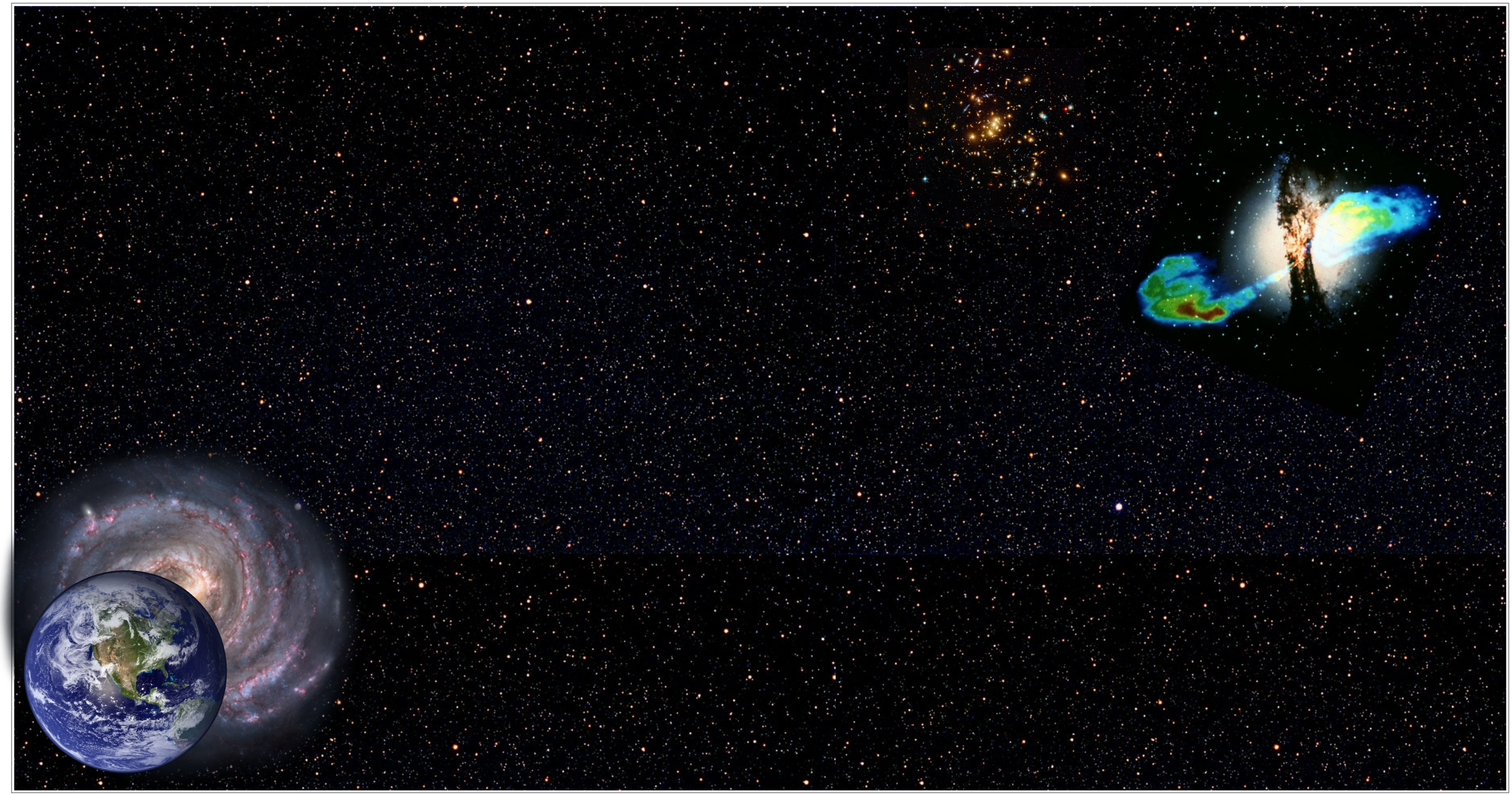


Workshop on Theoretical and Experimental Advances in Quantum Gravity
COST Action CA18108
01-03 September 2022
Belgrade, Serbia

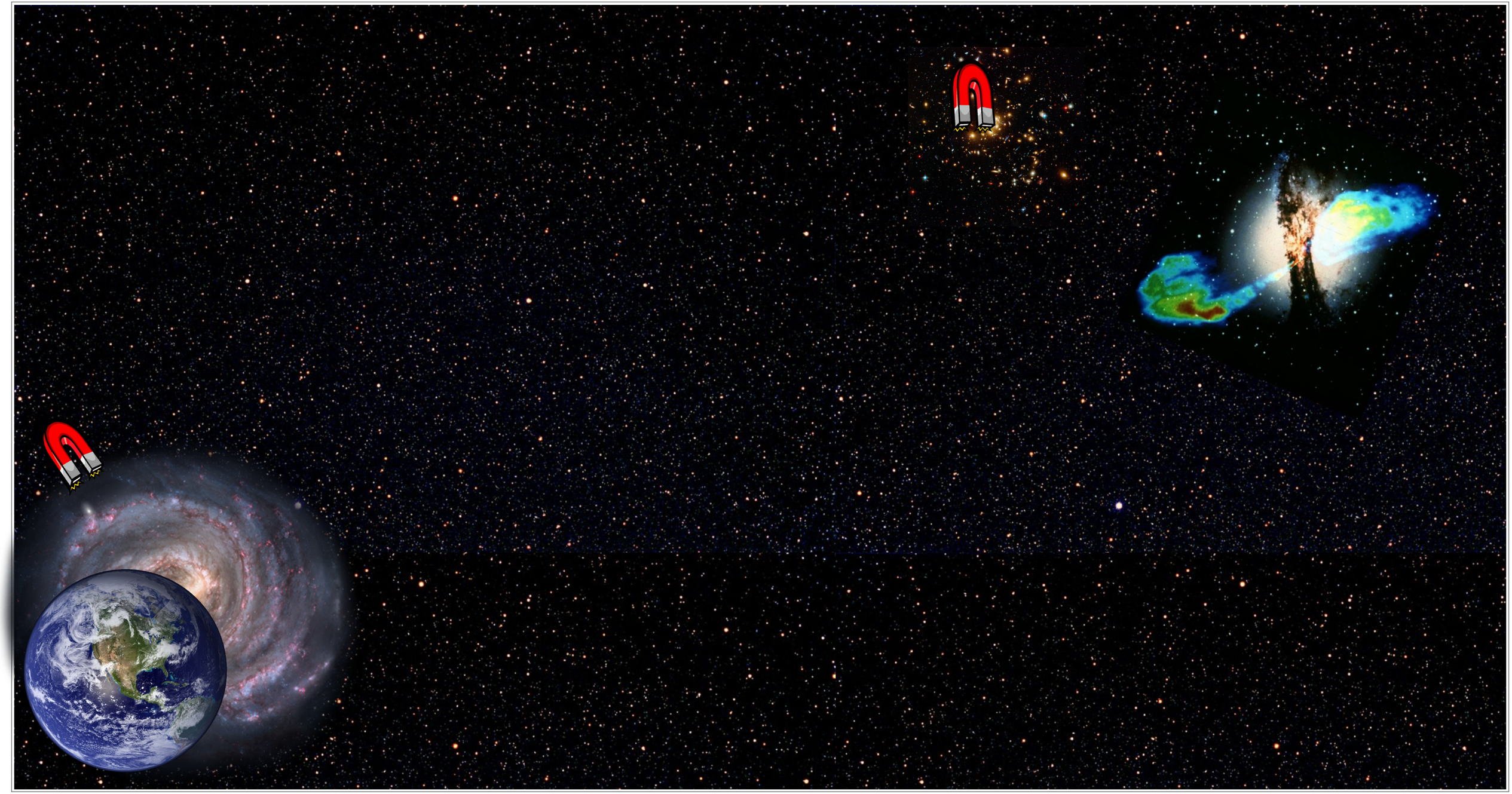
overview of this talk

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

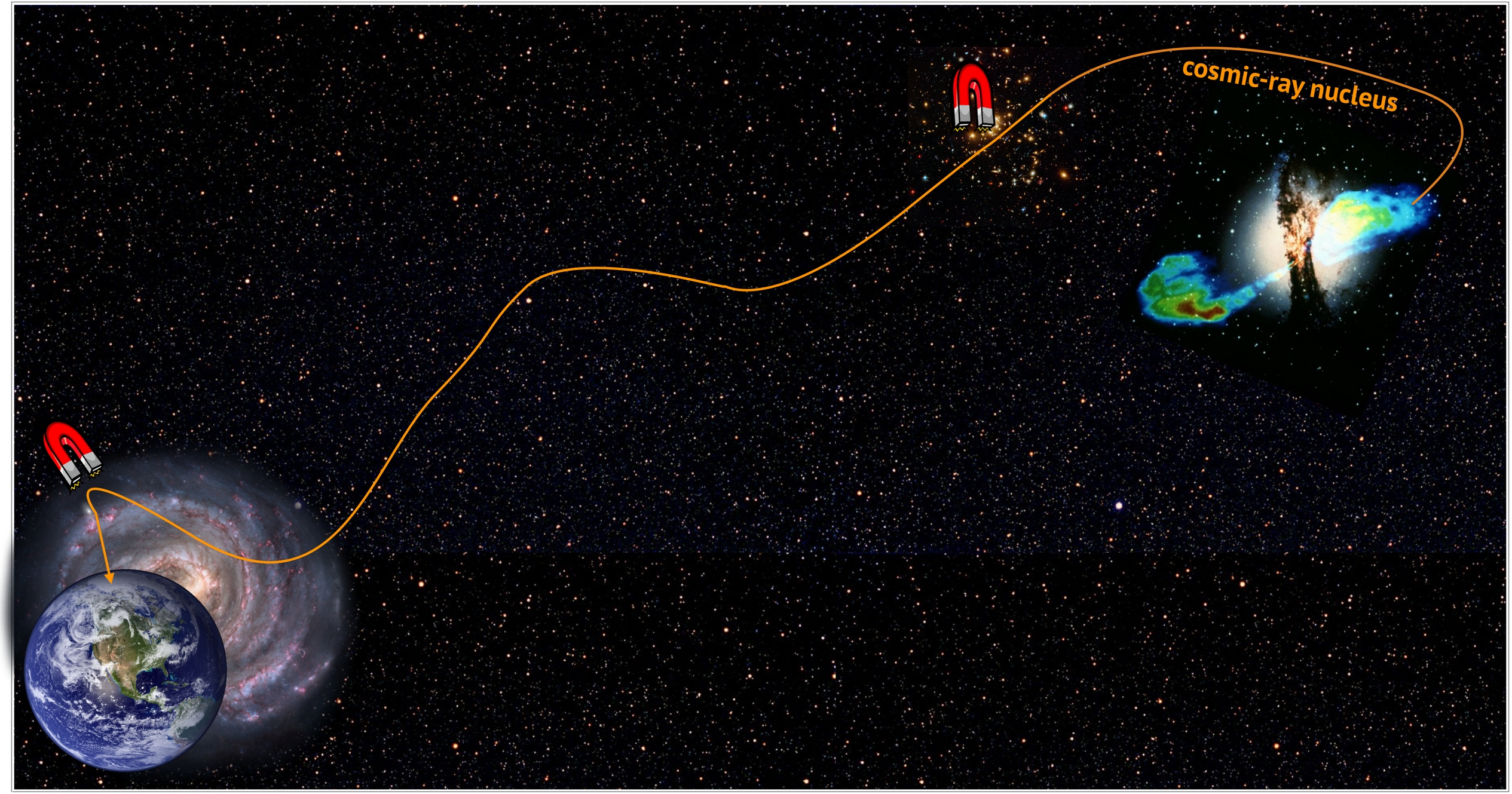
(intergalactic) propagation picture



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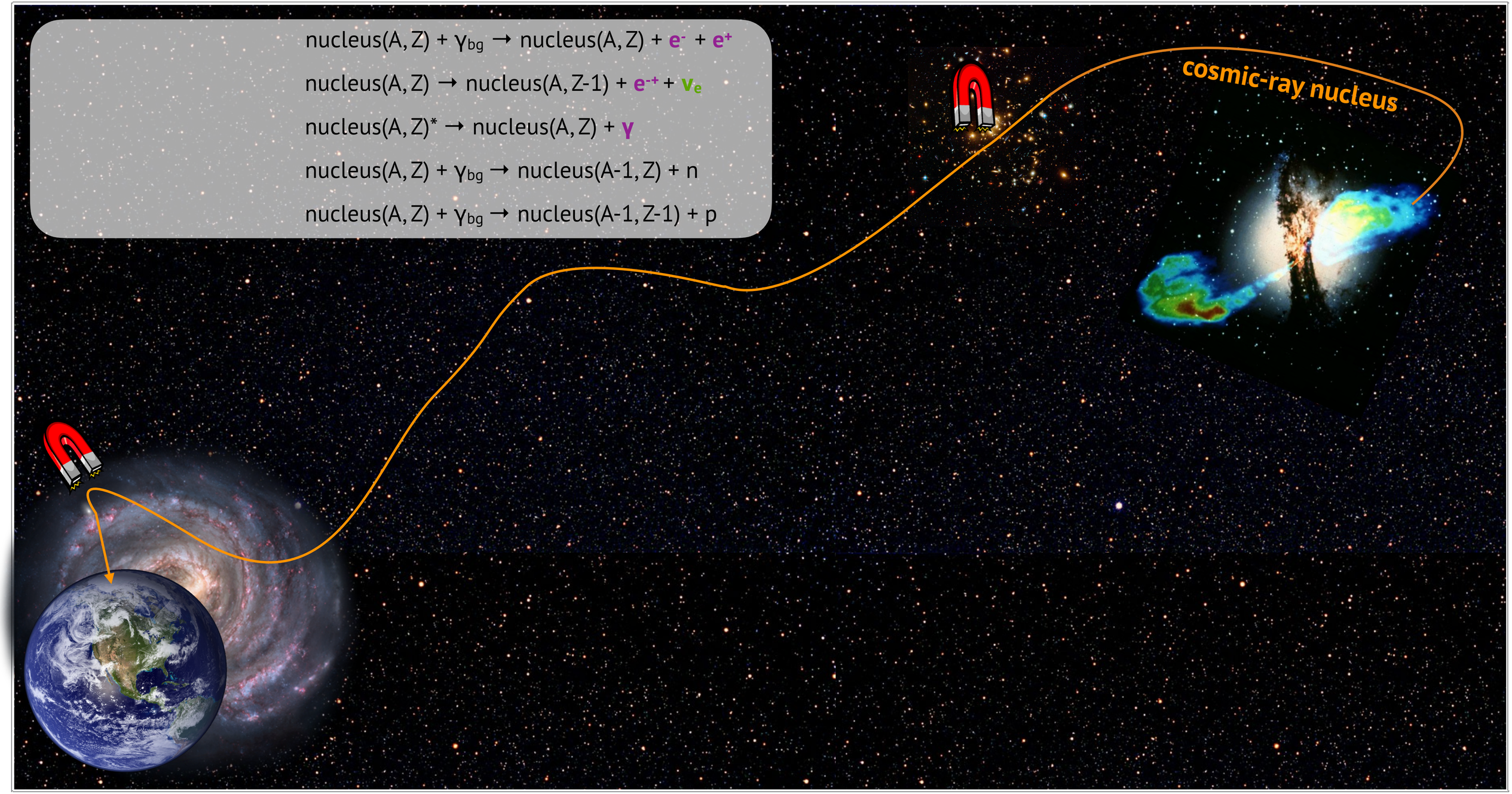
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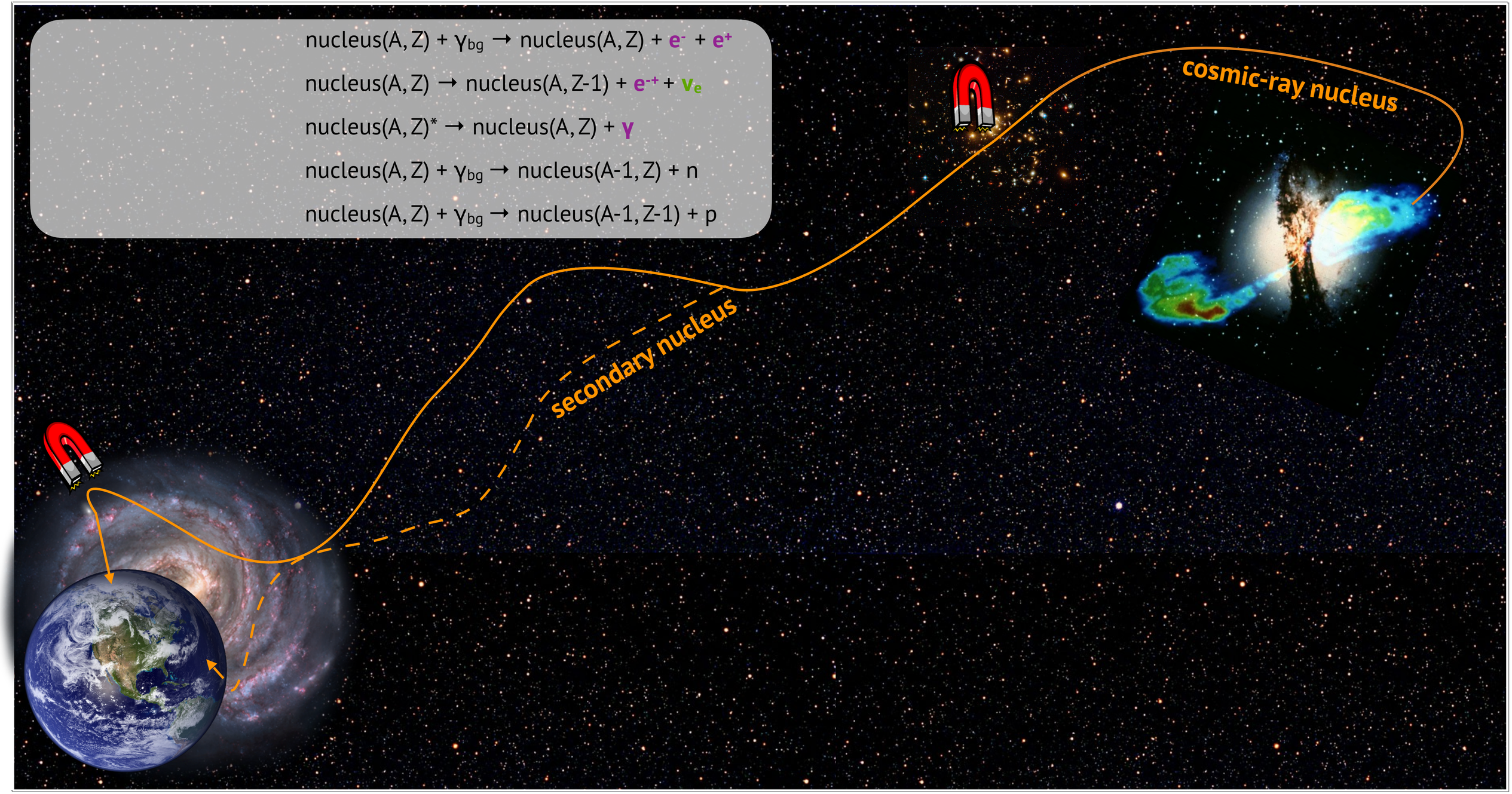
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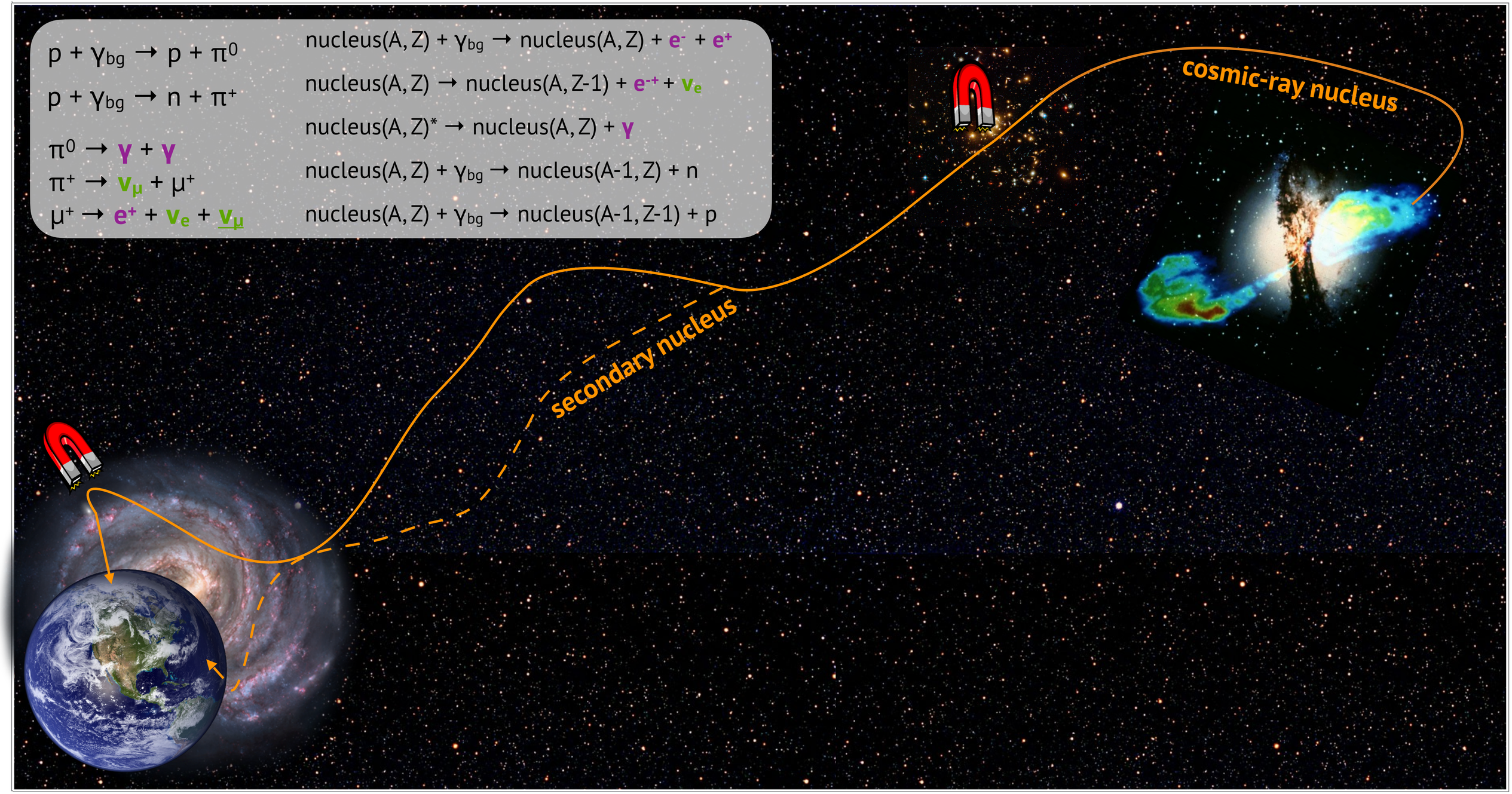
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secondary nucleus

cosmogenic neutrinos and photons

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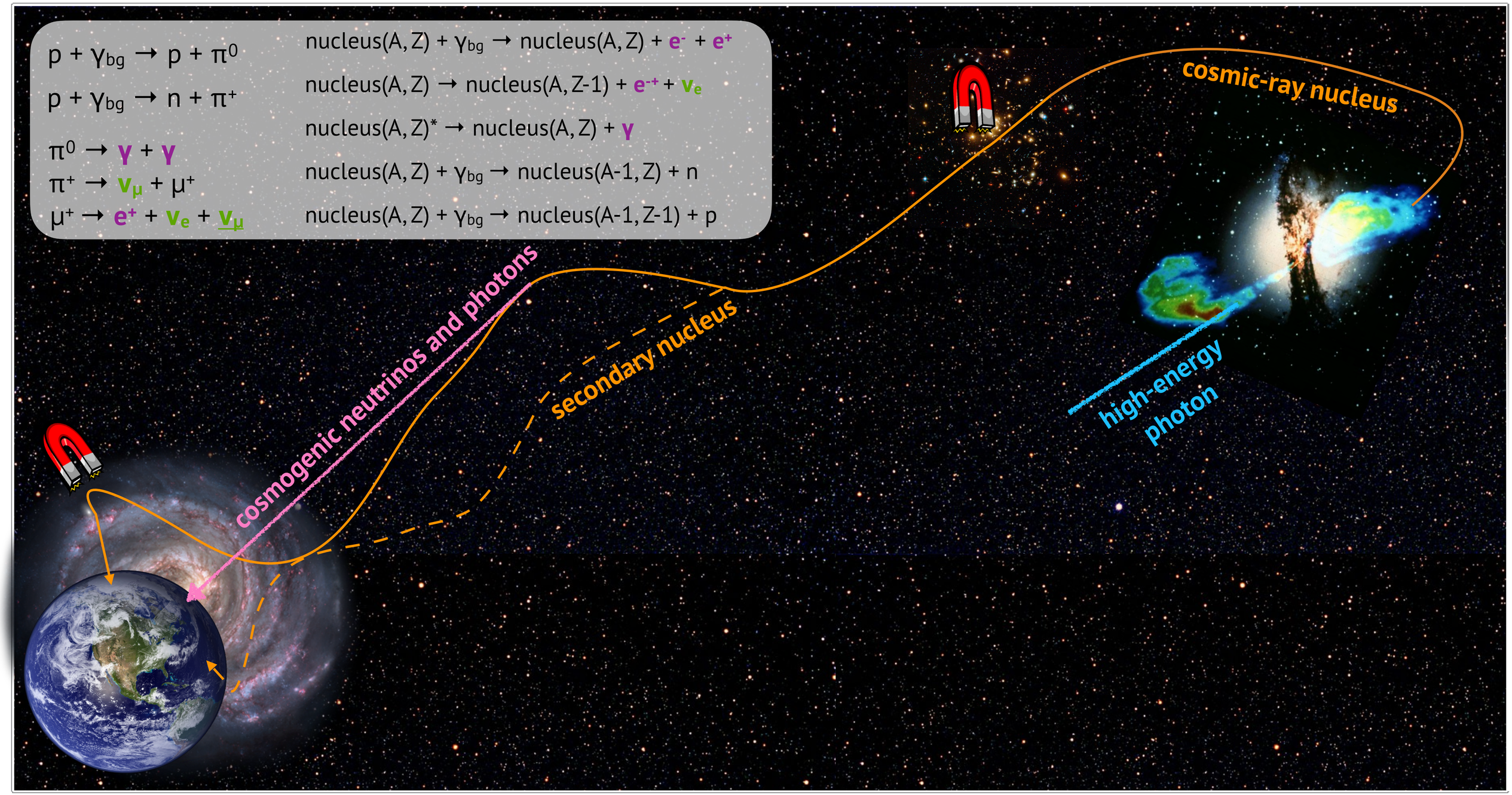
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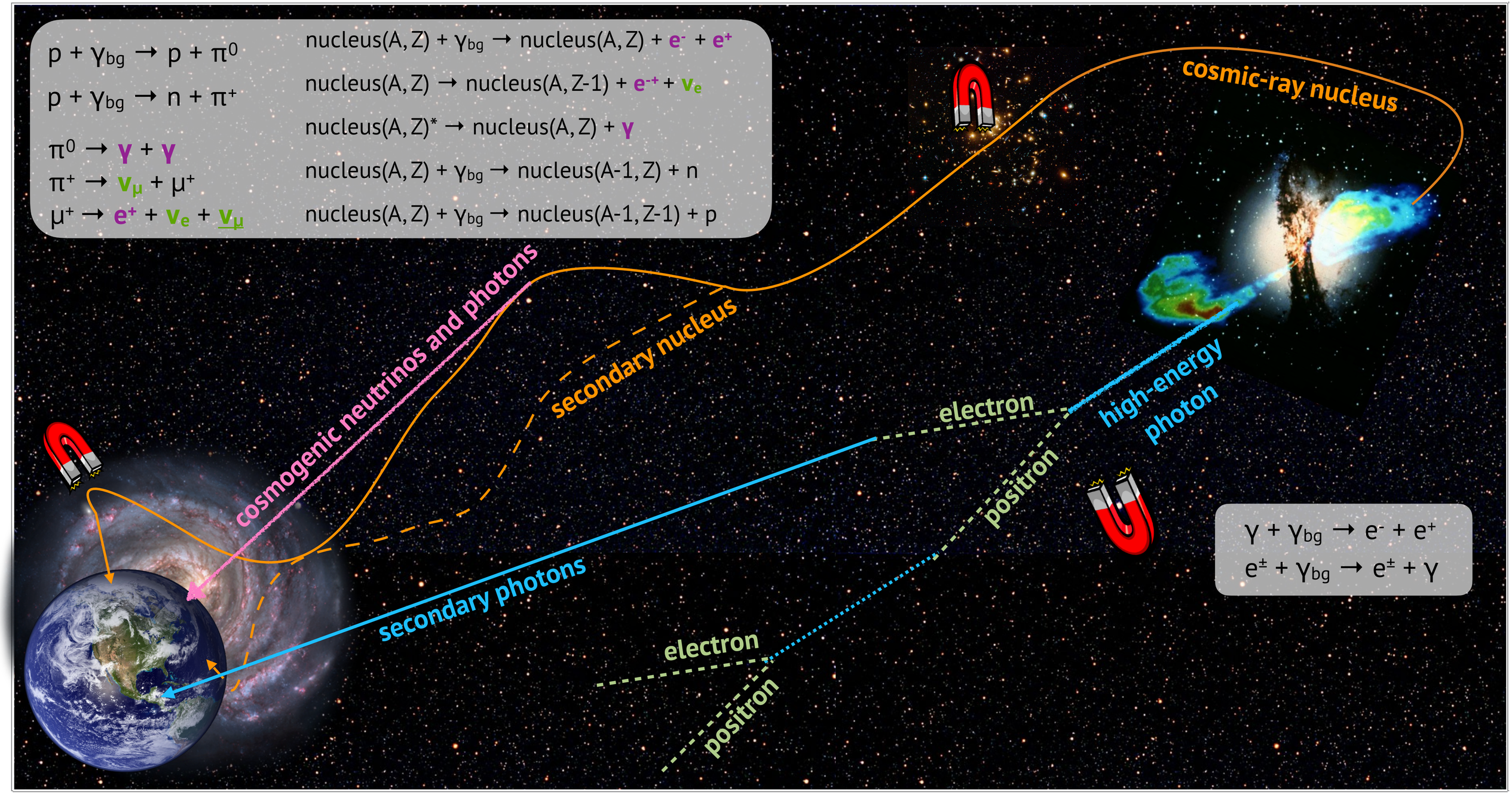
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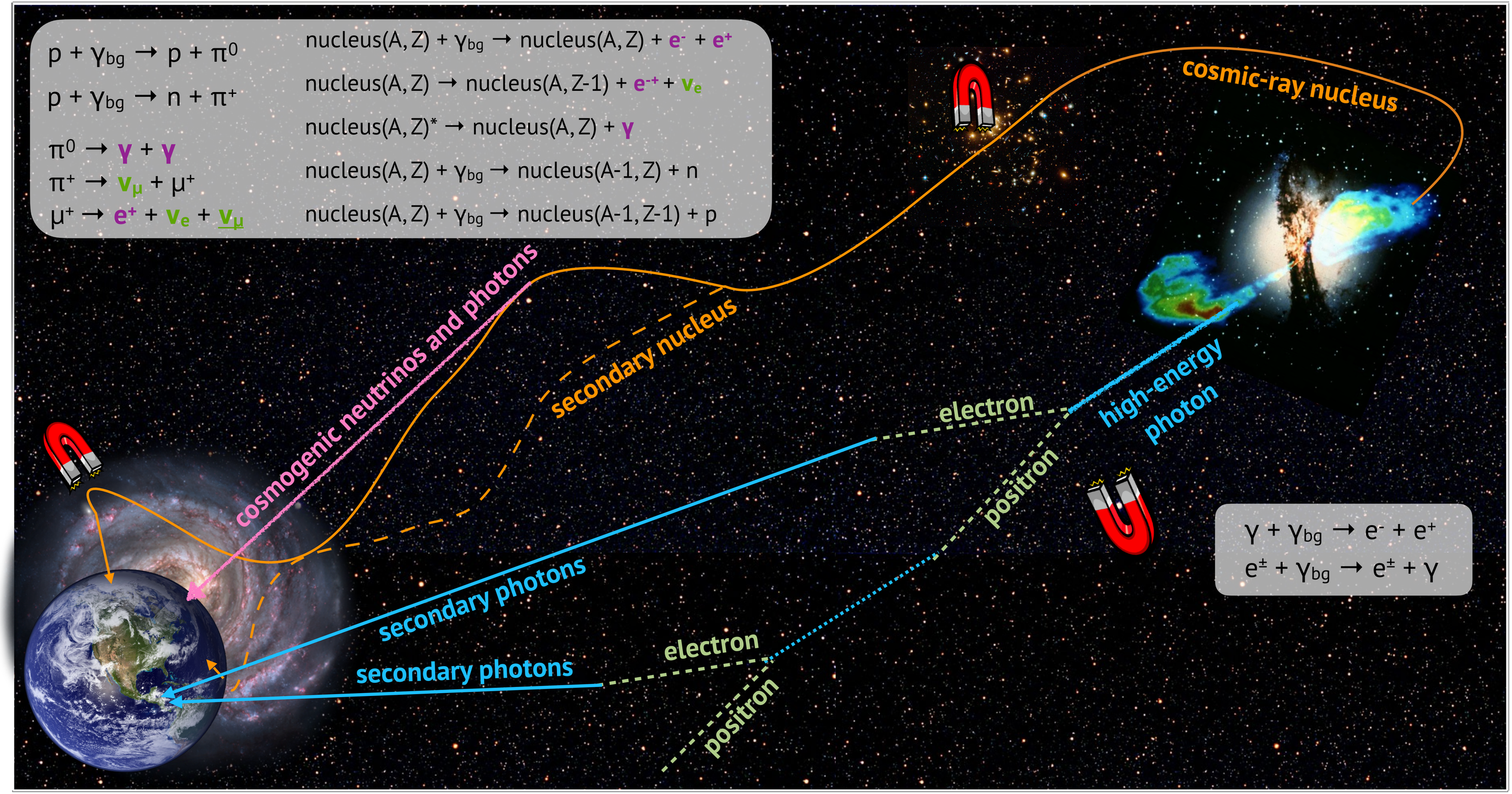
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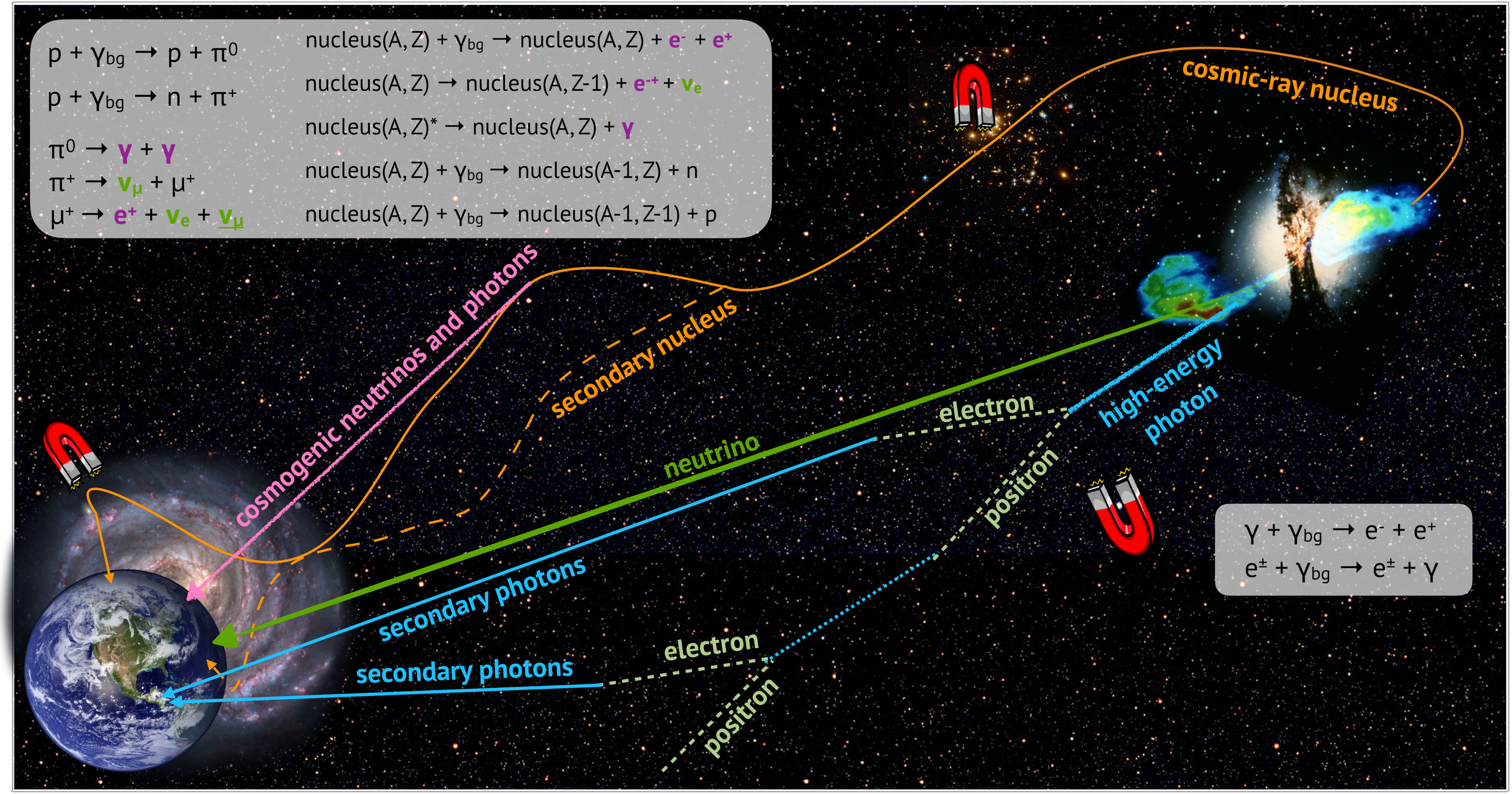
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astrophysical inputs

cookbook for astroparticle transport

astrophysical inputs

injection spectrum
initial composition
source distribution
source emissivity evolution

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propagation

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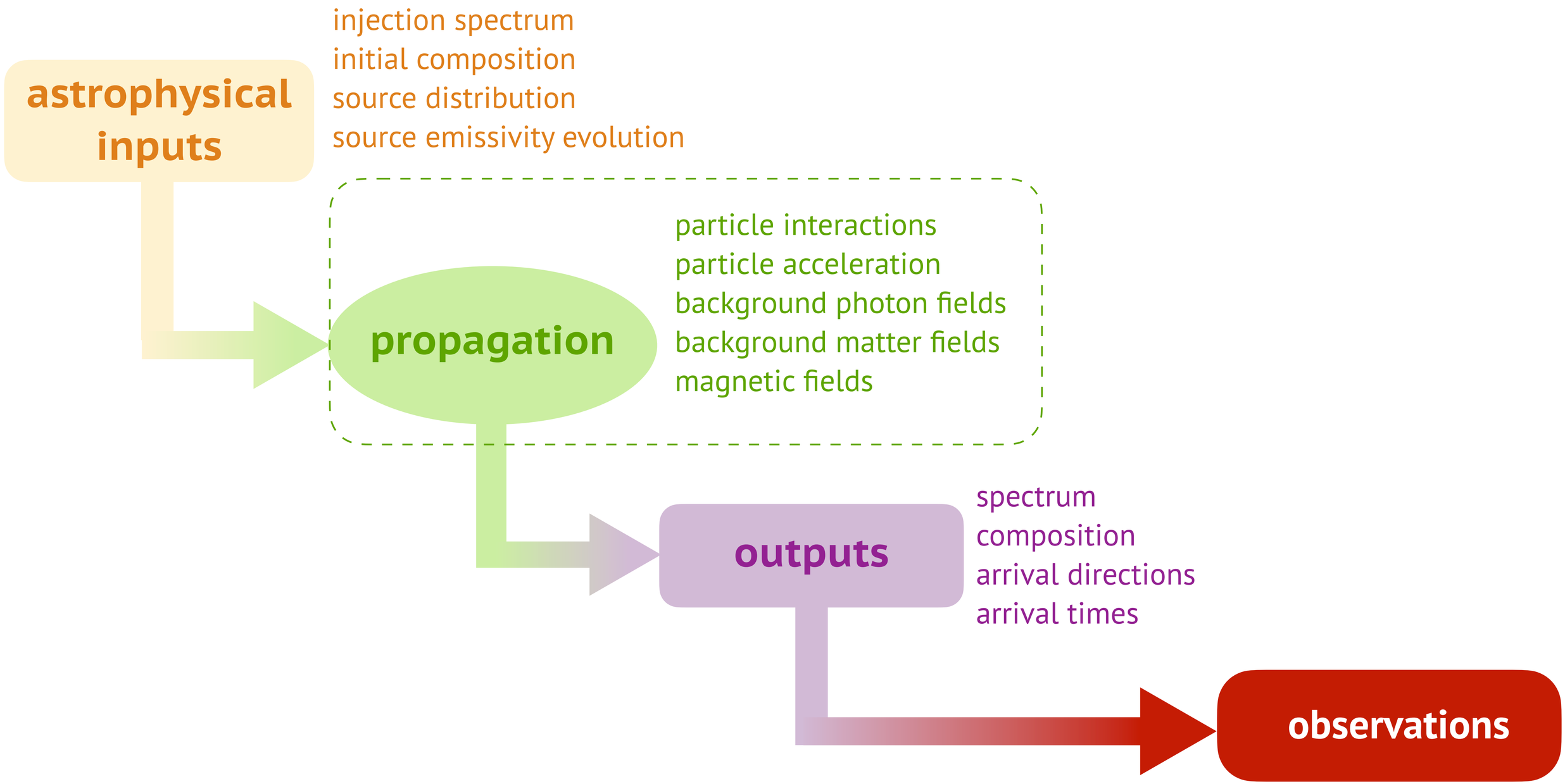
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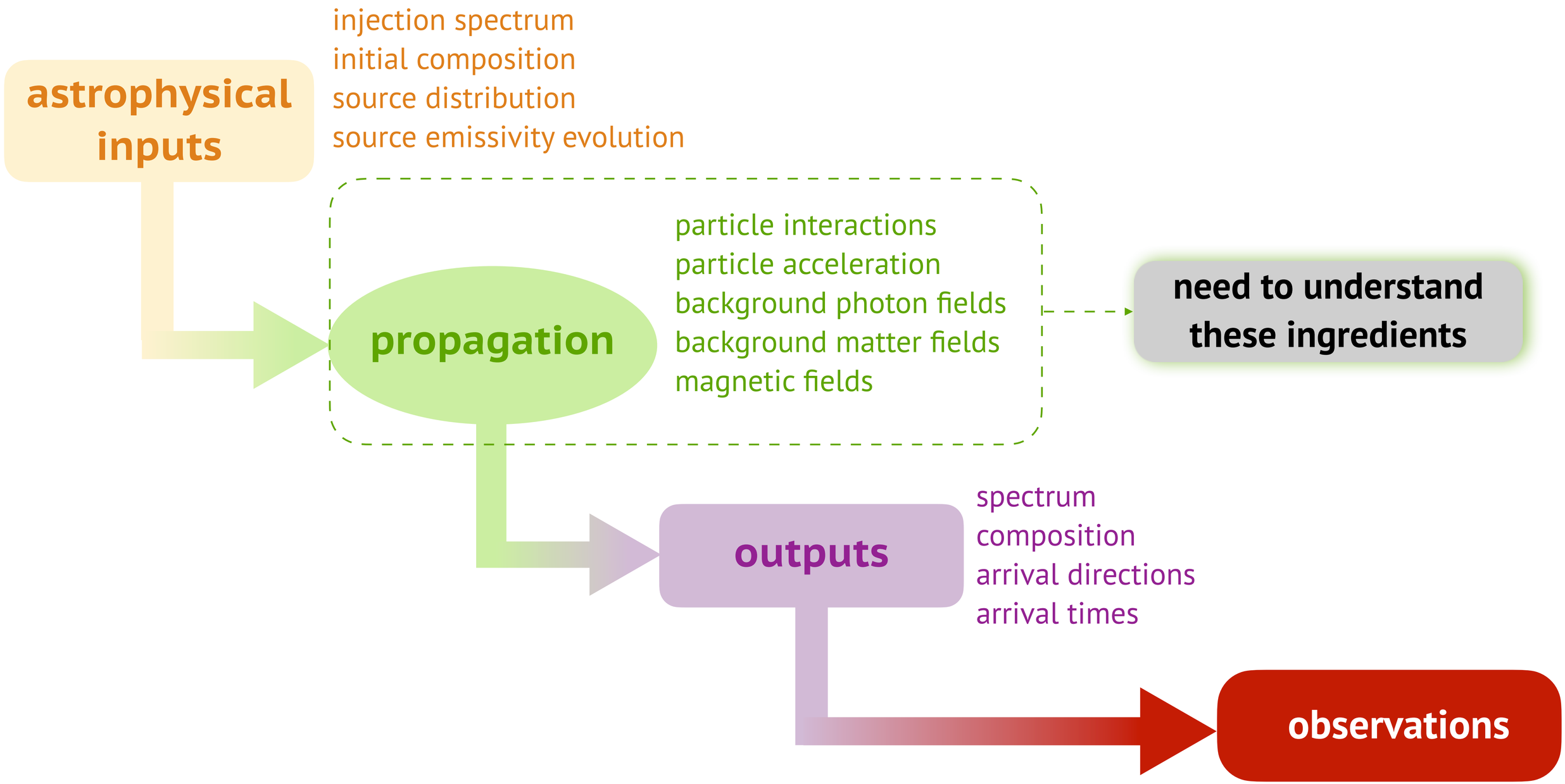
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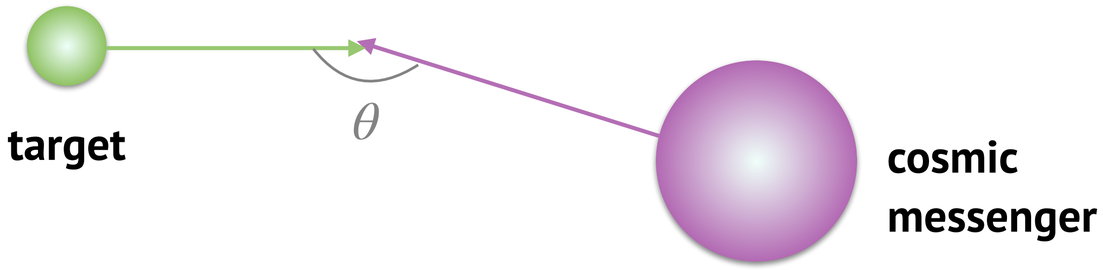

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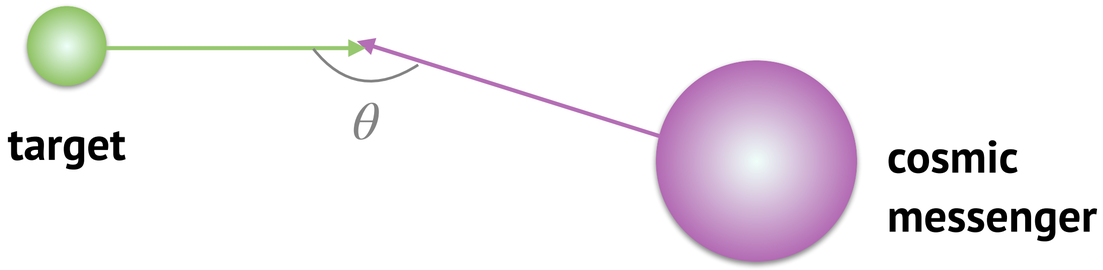


propagation ingredients: interactions

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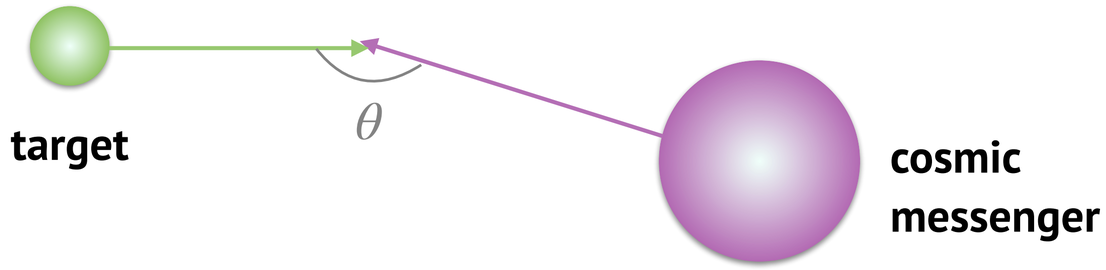


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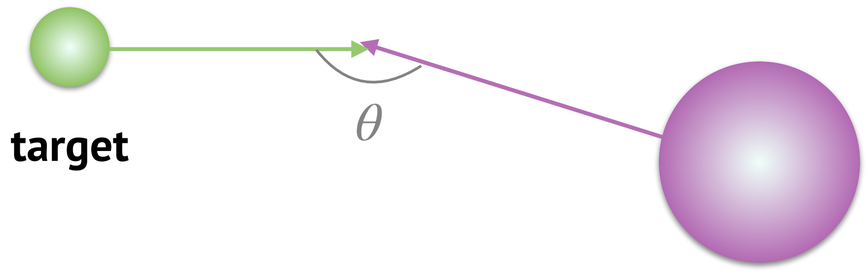
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propagation ingredients: interactions



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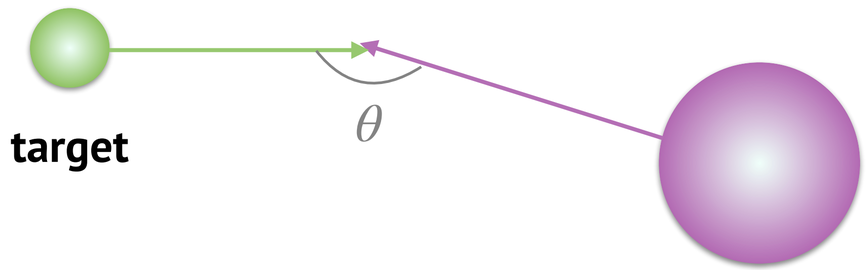
(inverse)
mean free path



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(inverse)
mean free path

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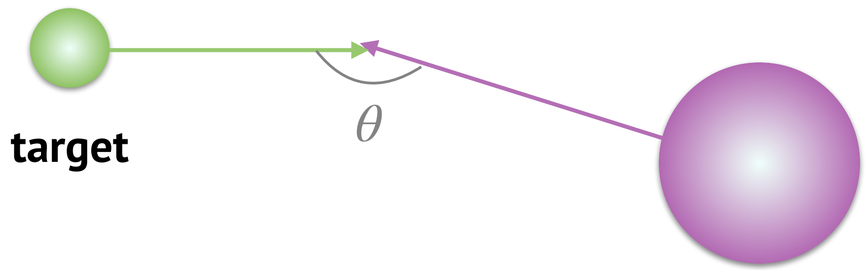


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photon
backgrounds



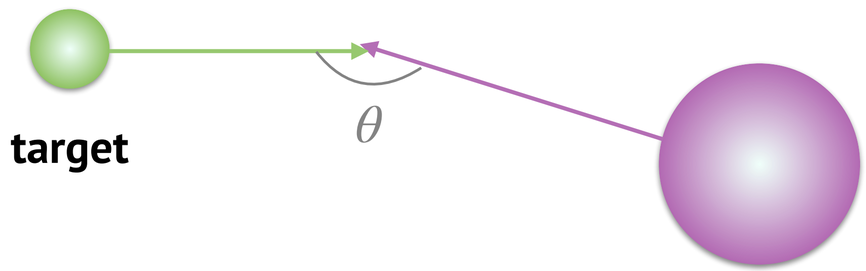
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photon backgrounds

interaction threshold



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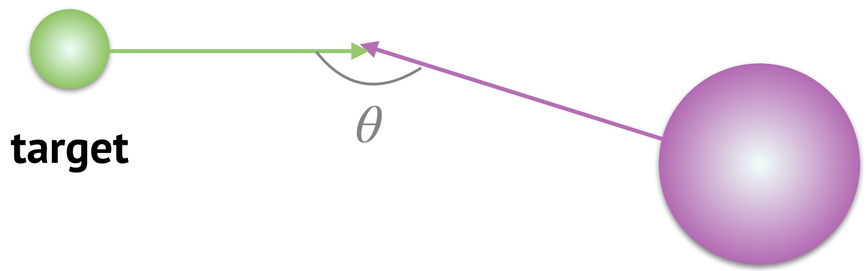
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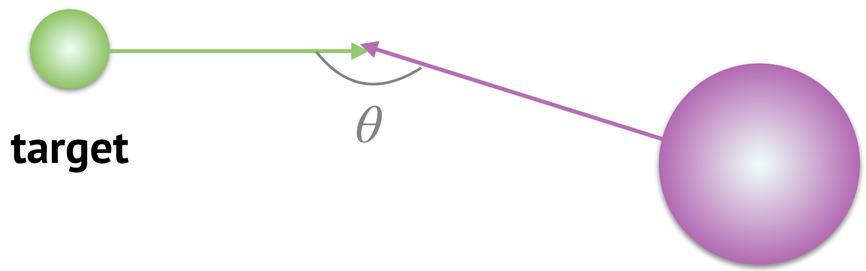
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photon backgrounds

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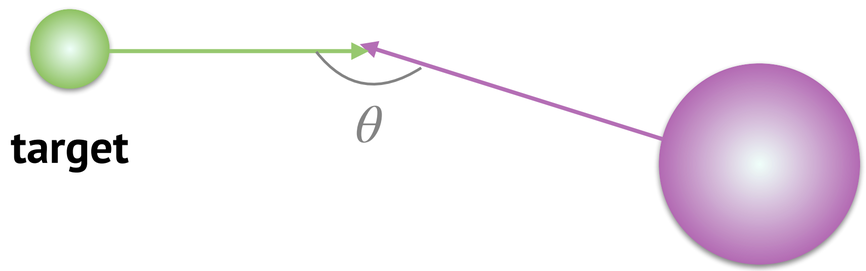
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Lorentz invariance violation



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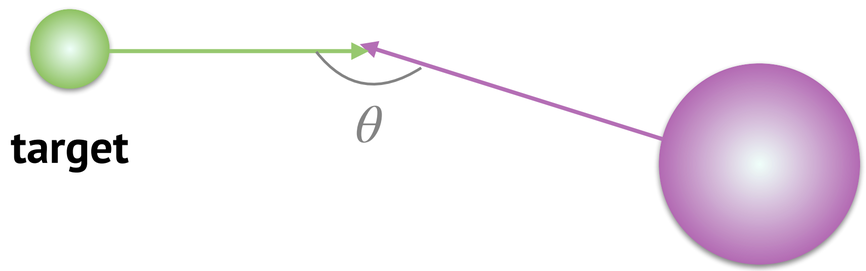
interaction threshold

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

Lorentz invariance violation

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

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



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

(inverse) mean free path

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

photon backgrounds

interaction threshold

interaction threshold

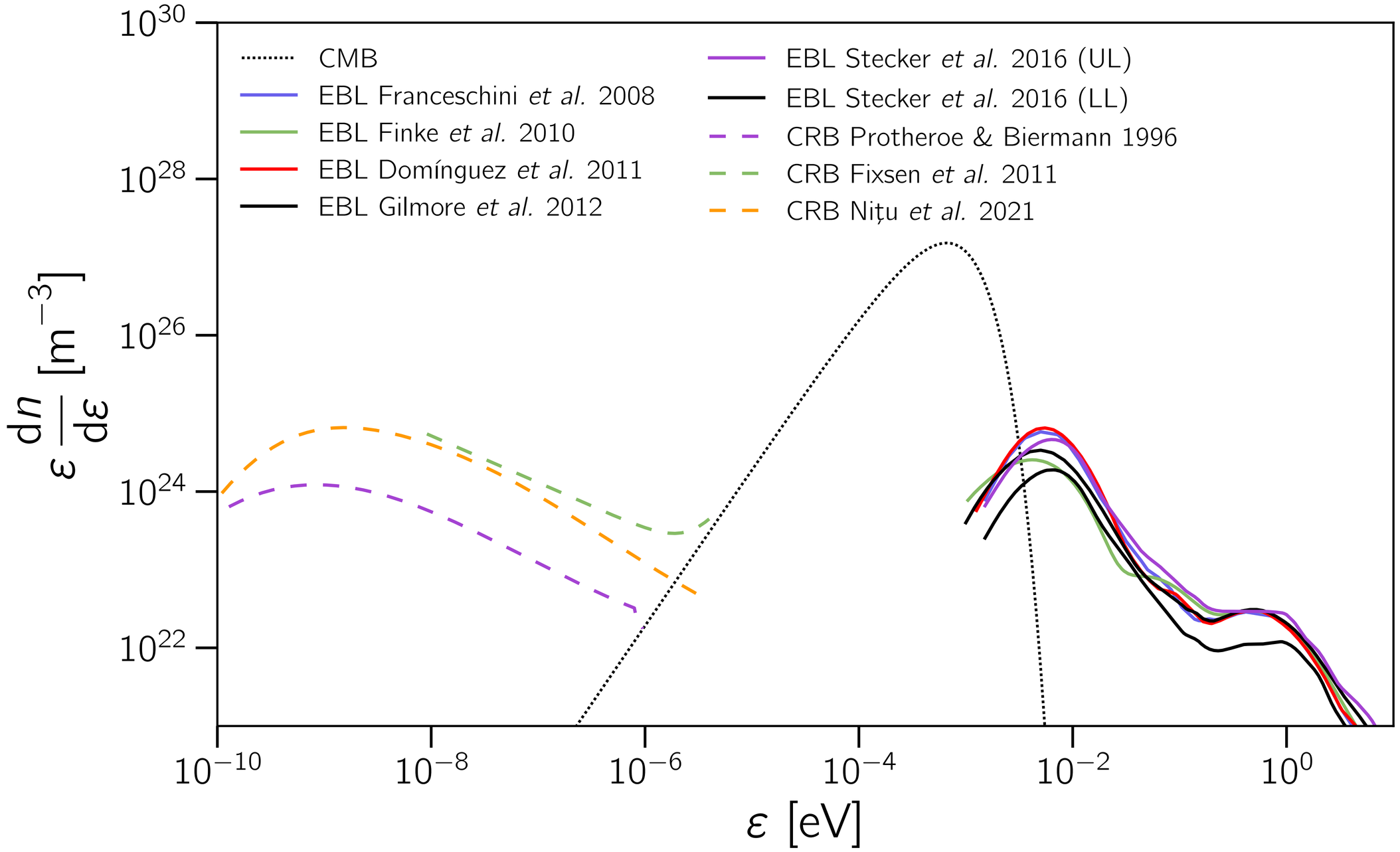
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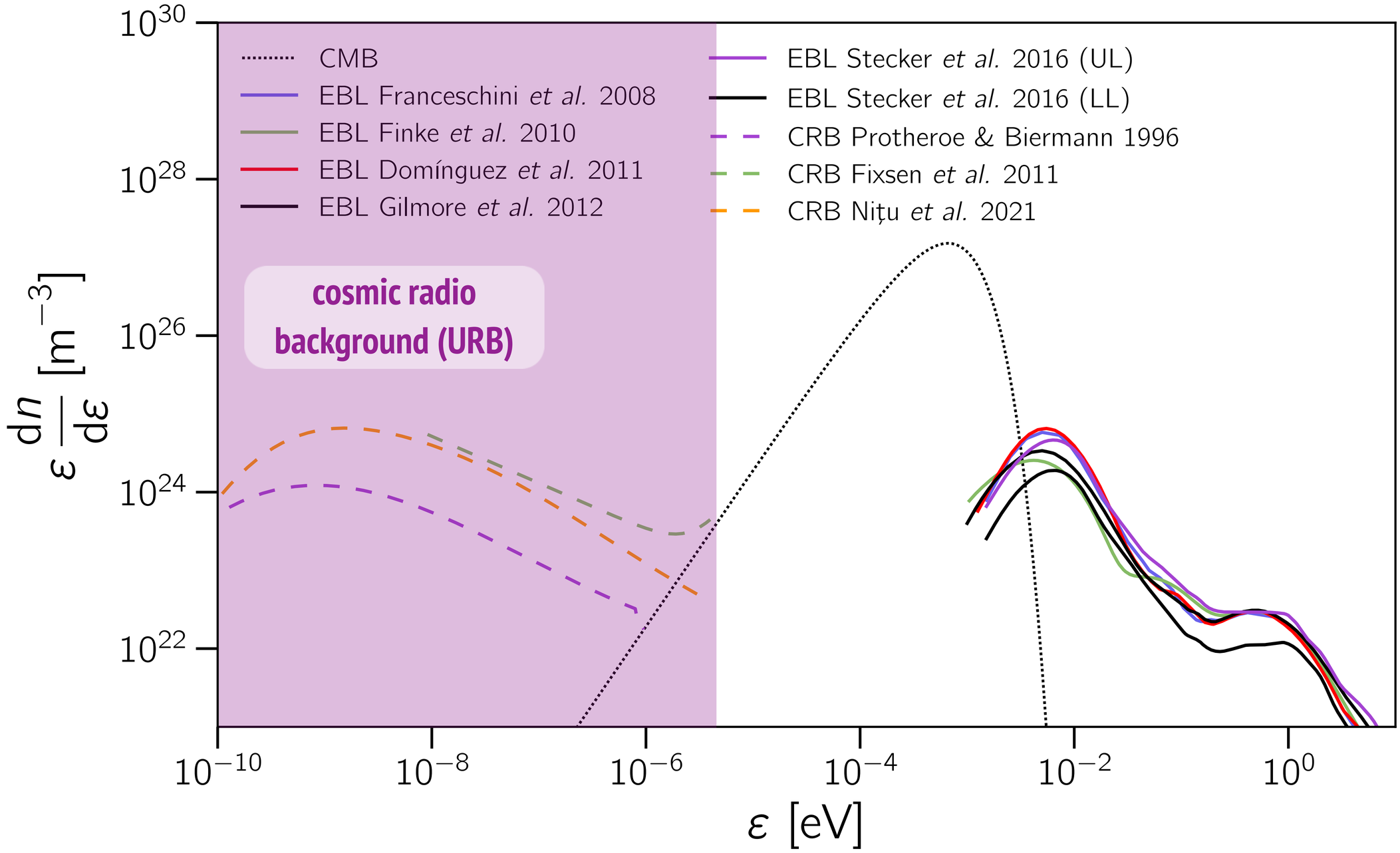
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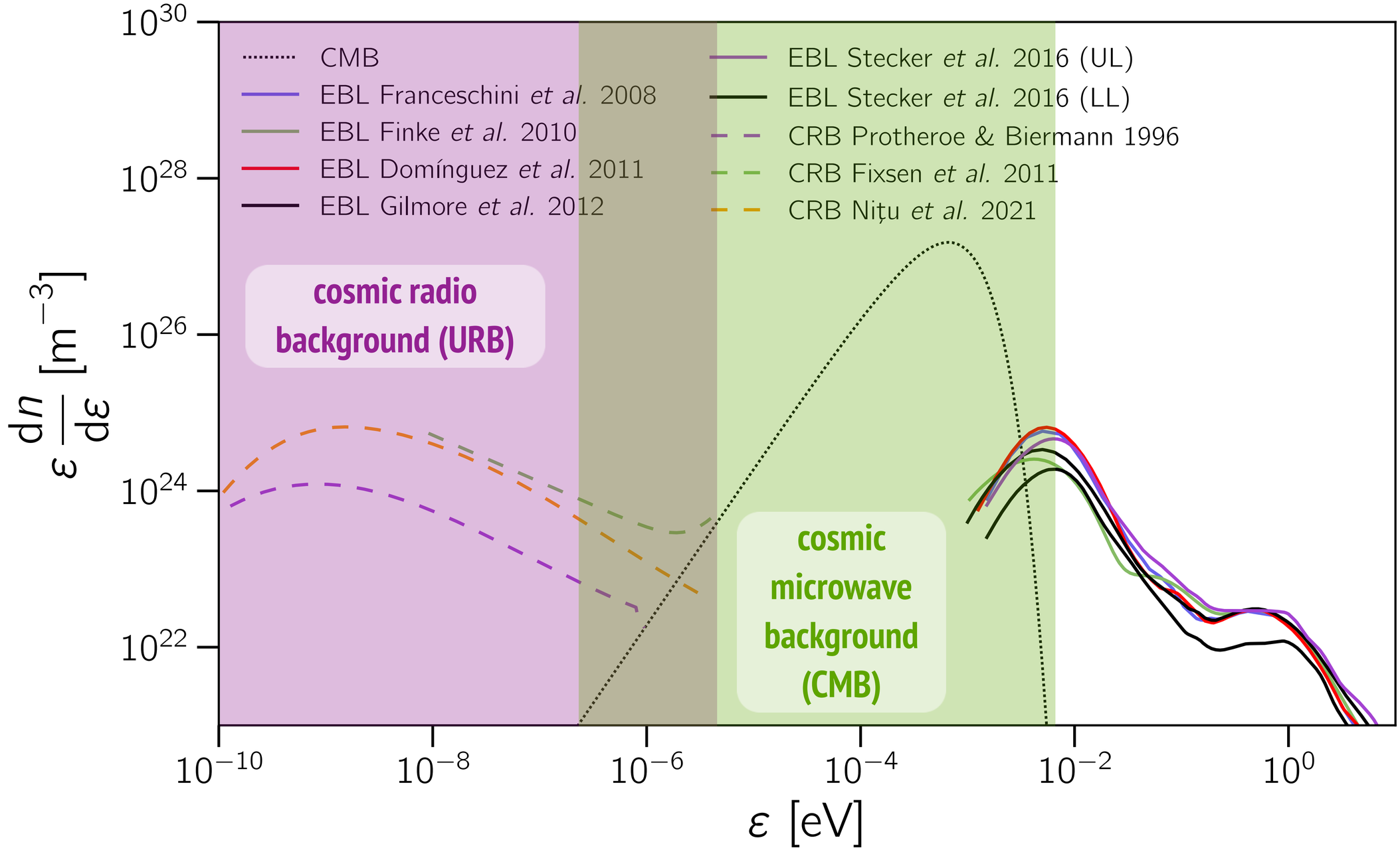
$$\delta_{i,n} = \frac{\eta_n}{M_{\mathrm{QG},n}}$$

interaction thresholds sensitive to QG effects

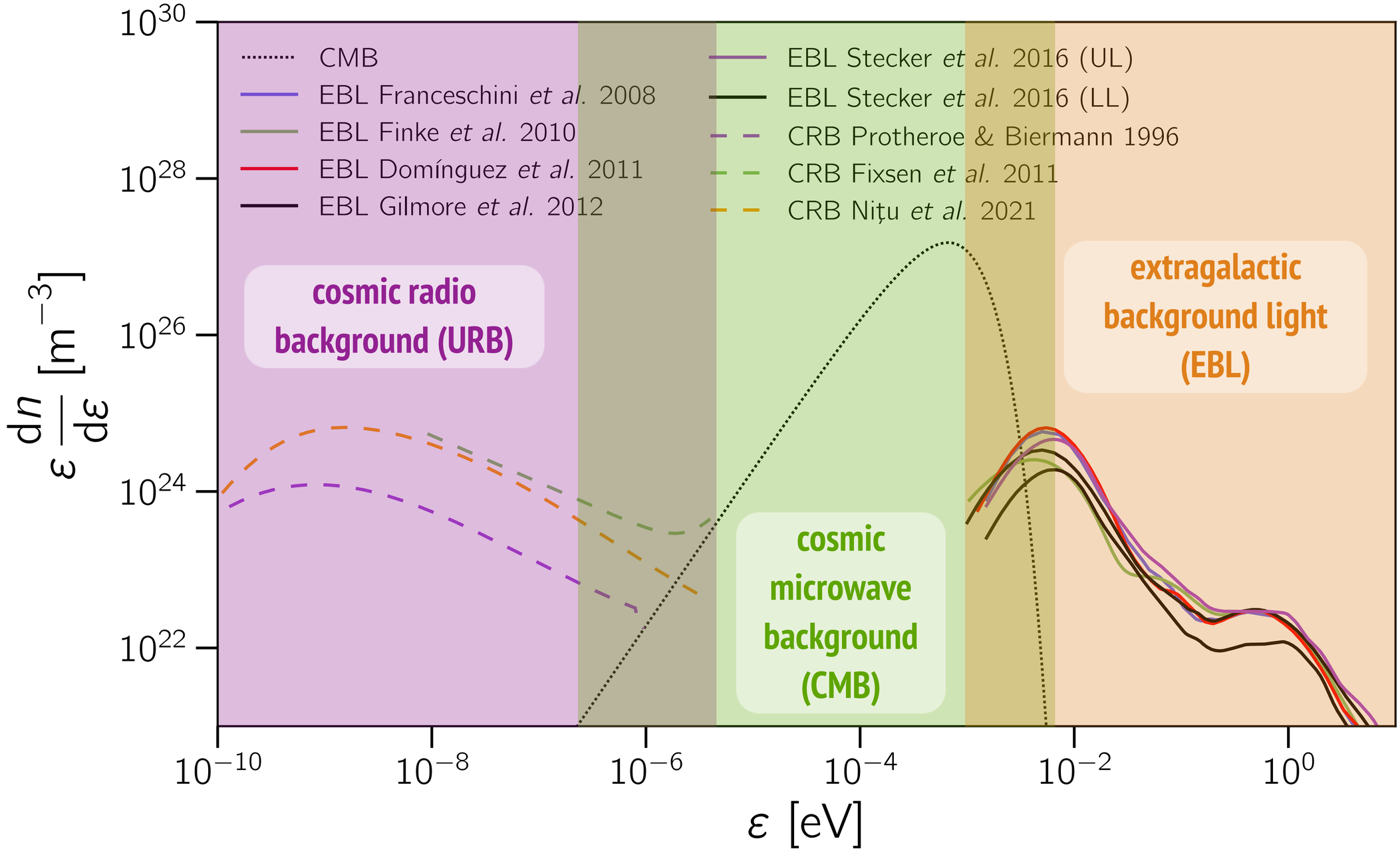

CMB
EBL Franceschini *et al.* 2008
EBL Finke *et al.* 2010
EBL Domínguez *et al.* 2011
EBL Gilmore *et al.* 2012
EBL Stecker *et al.* 2016 (UL)
EBL Stecker *et al.* 2016 (LL)
CRB Protheroe & Biermann 1996
CRB Fixsen *et al.* 2011
CRB Nițu *et al.* 2021
$\varepsilon \frac{dn}{d\varepsilon}$ [m^{-3}]
10^{30}
10^{28}
10^{26}
10^{24}
10^{22}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
ε [eV]


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CRB Protheroe & Biermann 1996
CRB Fixsen *et al.* 2011
CRB Nițu *et al.* 2021
cosmic radio background (URB)
$\varepsilon \frac{dn}{d\varepsilon}$ [m^{-3}]
10^{30}
10^{28}
10^{26}
10^{24}
10^{22}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
ε [eV]

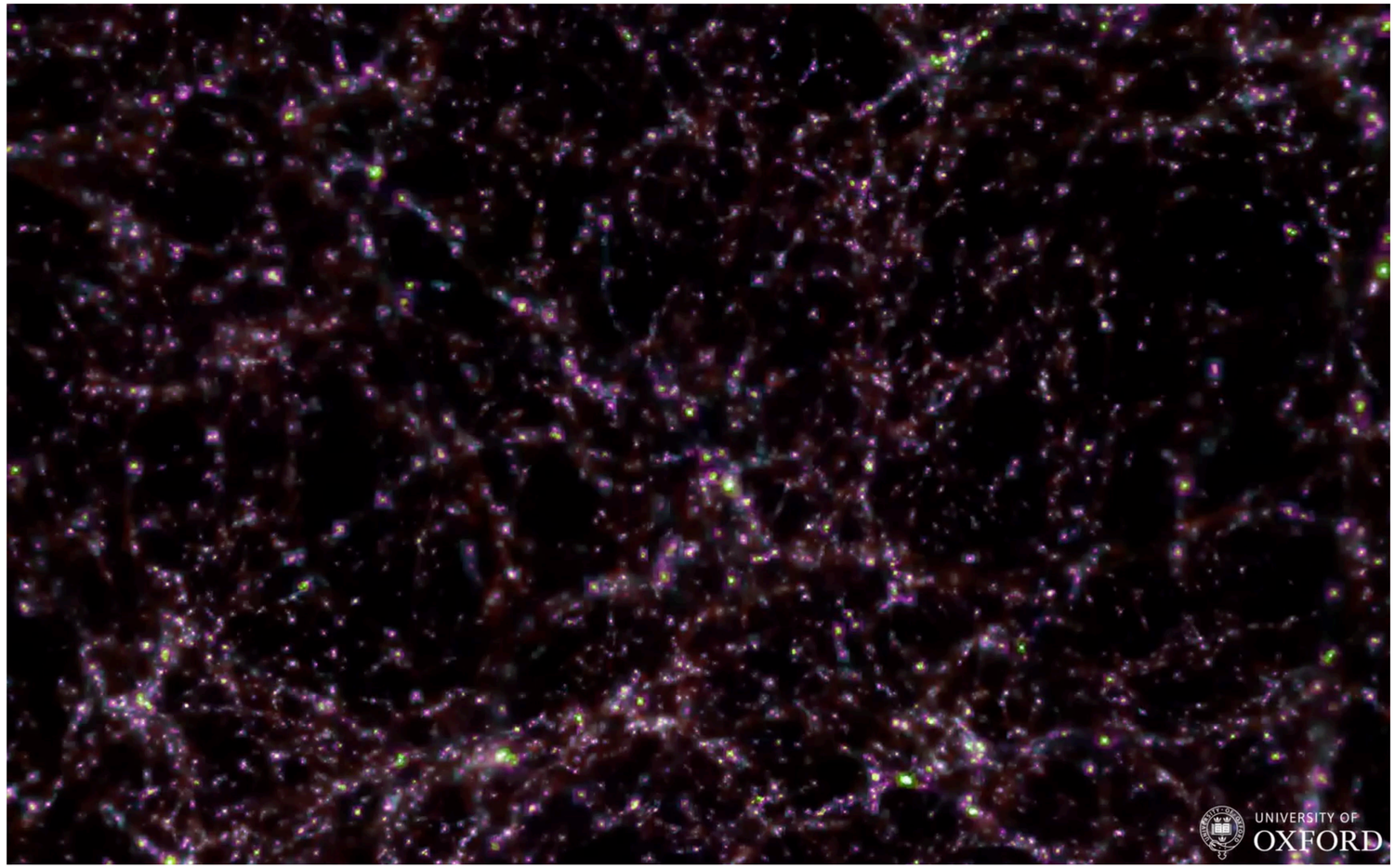
propagation ingredients: photon fields



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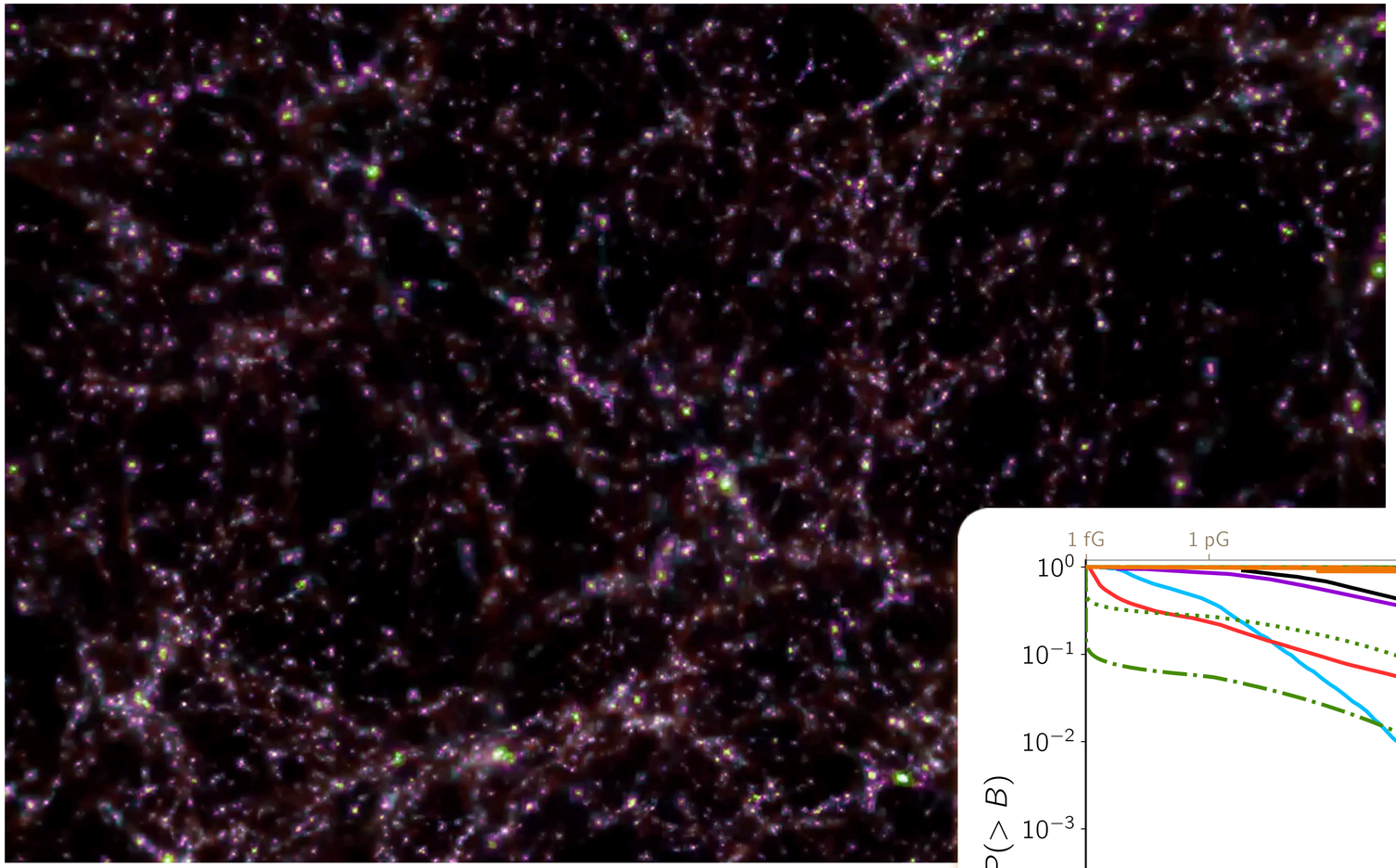


propagation ingredients: cosmic magnetic fields

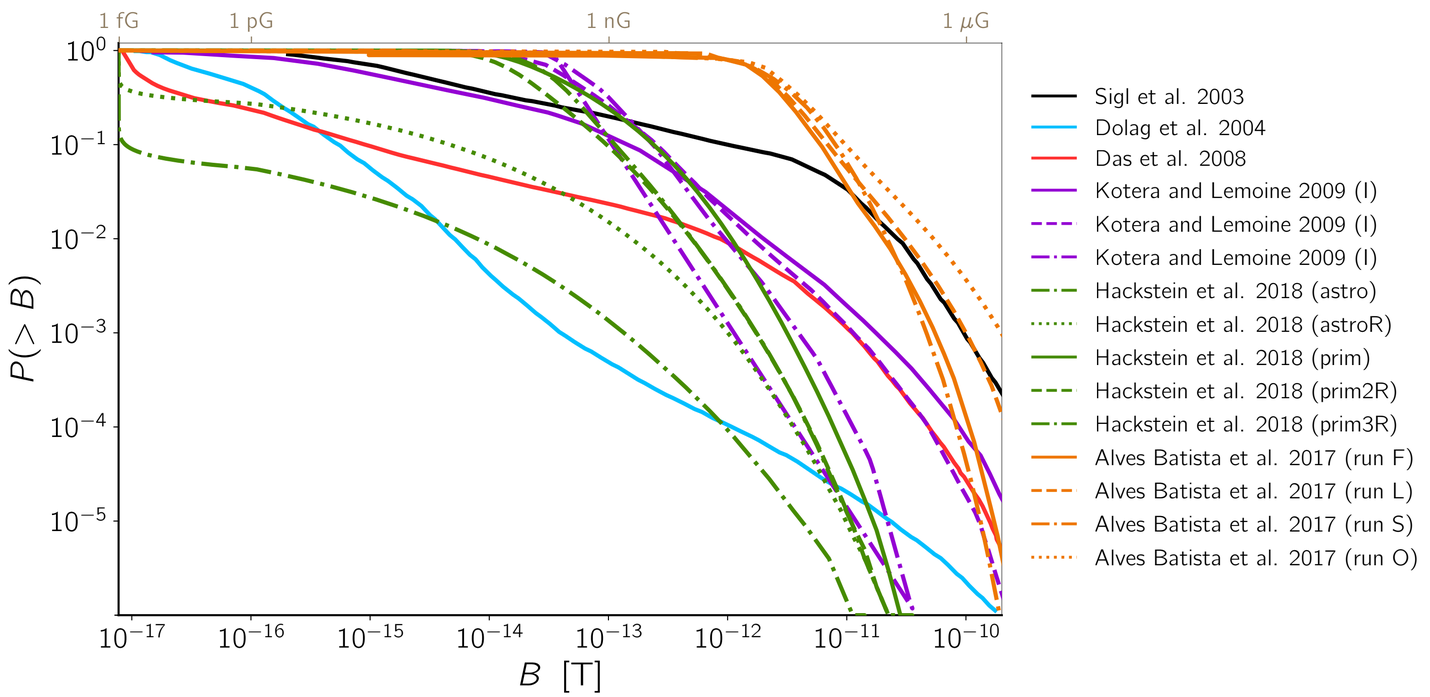


Alves Batista, Shin, Devriendt, Semikoz, Sigl. PRD, 96 (2017) 023010. arXiv:1704.05869

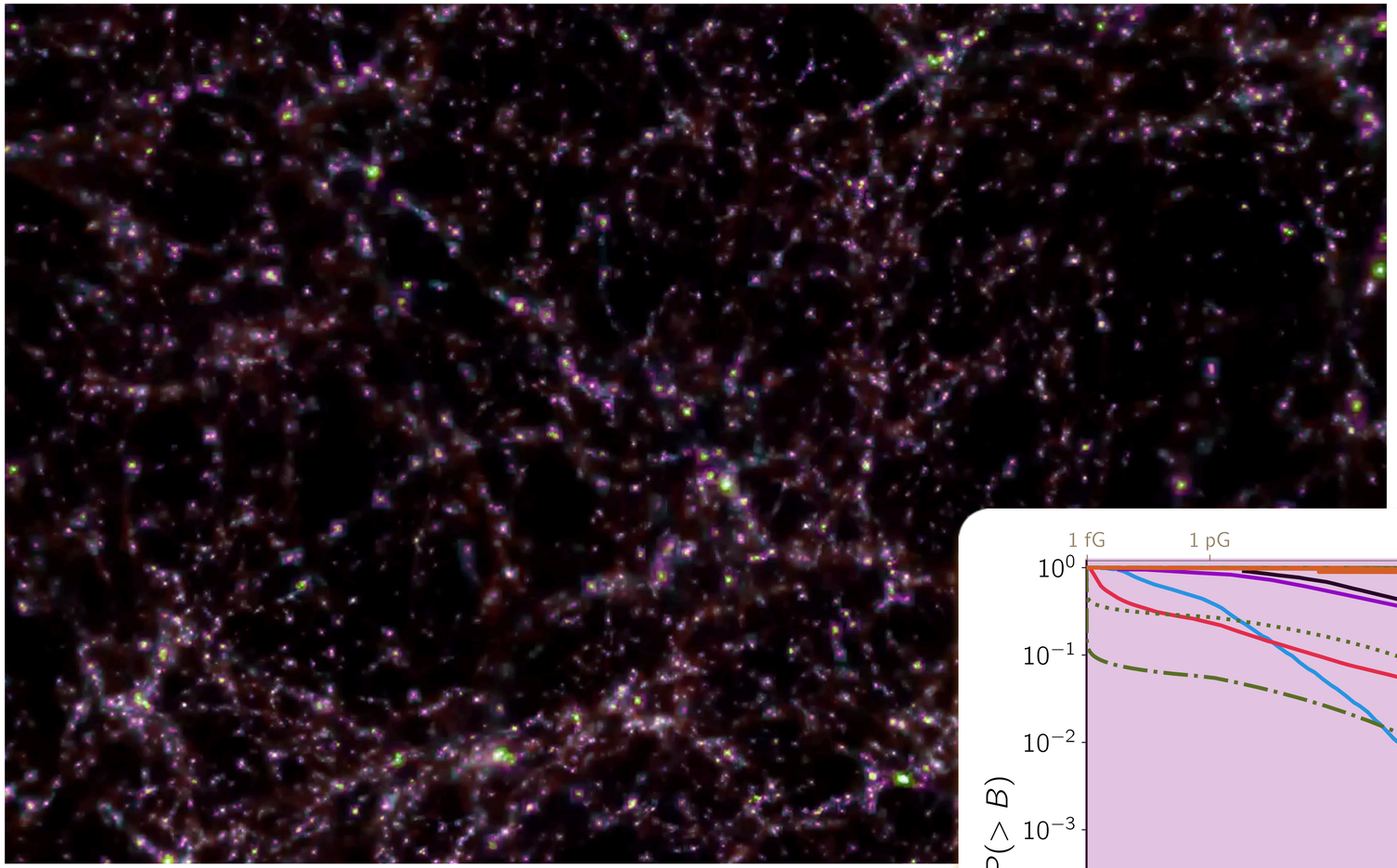
propagation ingredients: cosmic magnetic fields



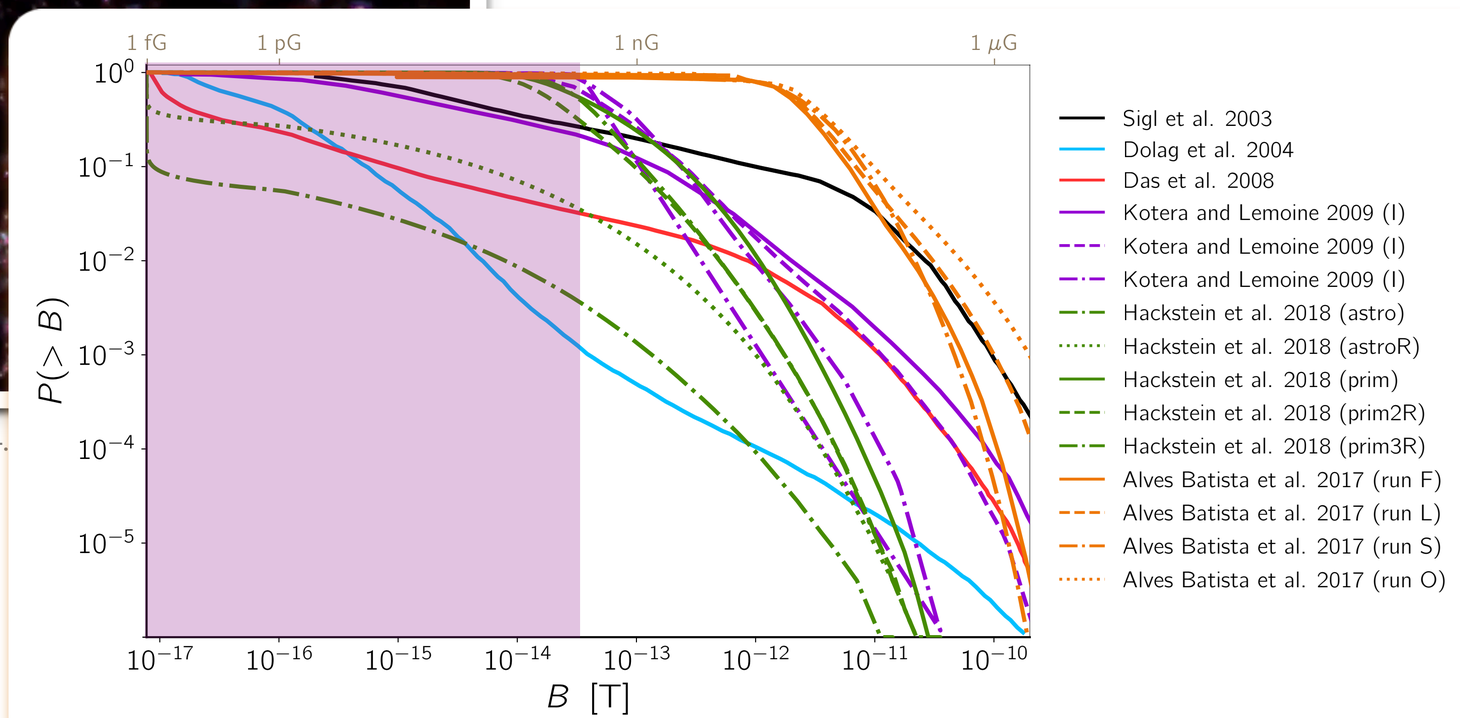
Alves Batista, Shin, Devriendt, Semikoz, Sigl. PRD, 96 (2017) 023010. arXiv:1704.



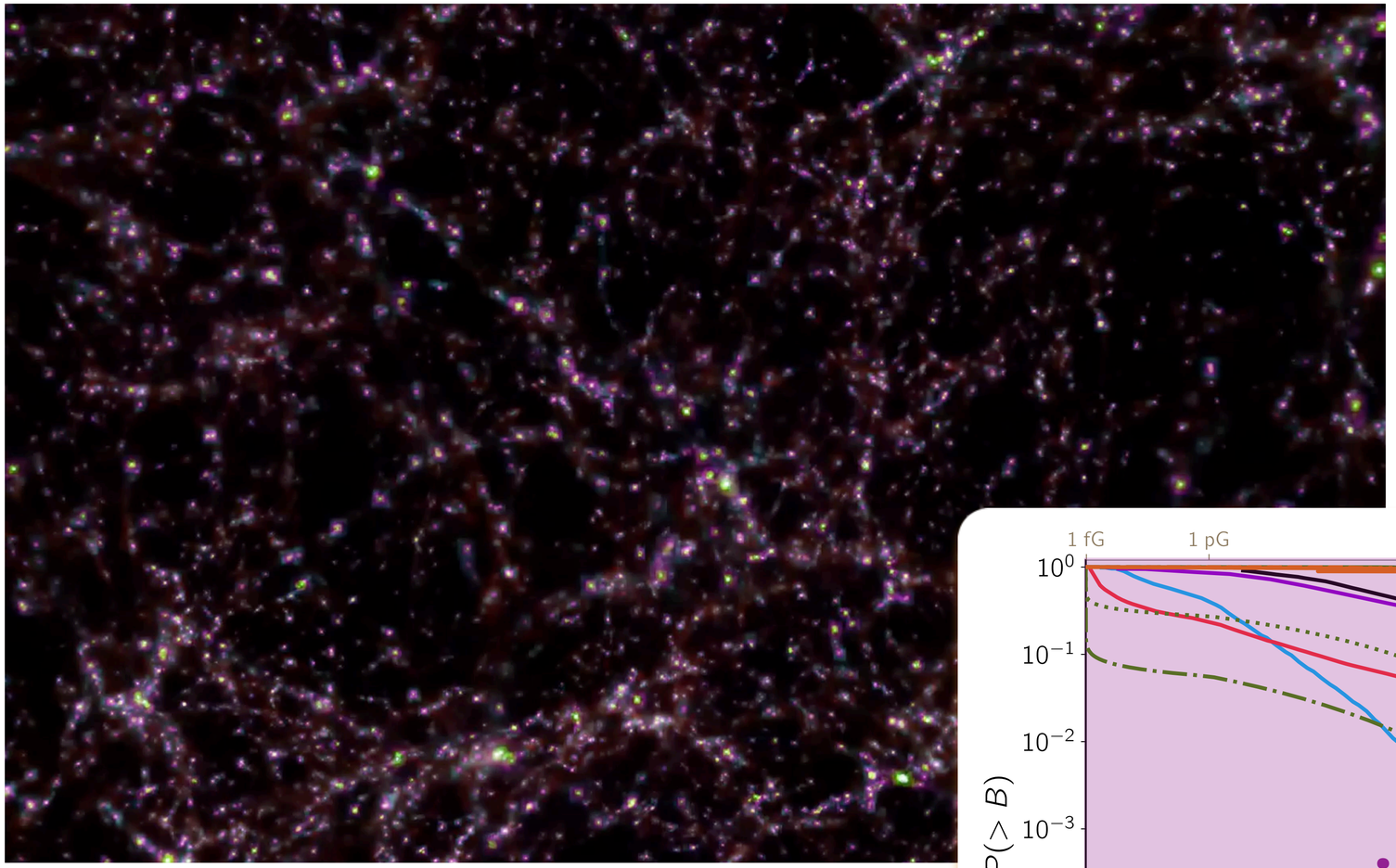
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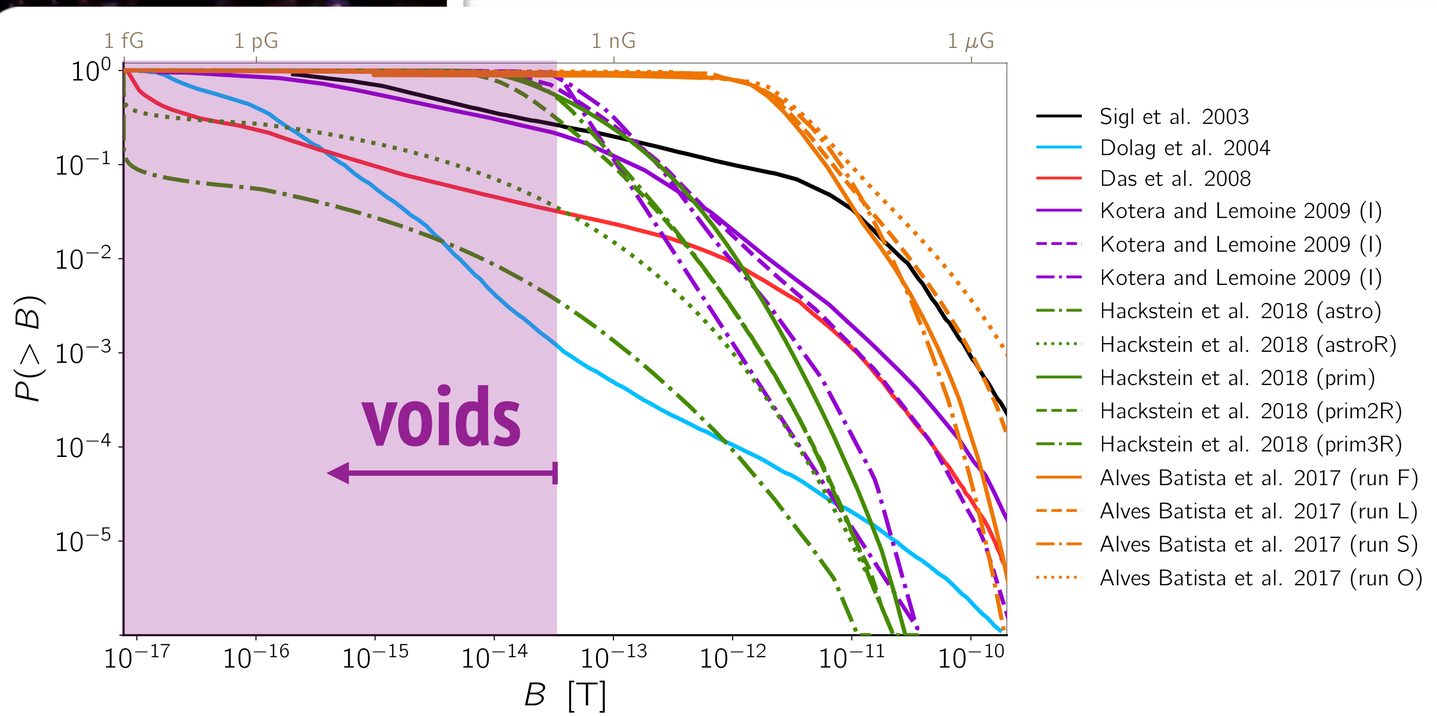
Alves Batista, Shin, Devriendt, Semikoz, Sigl. PRD, 96 (2017) 023010. arXiv:1704.



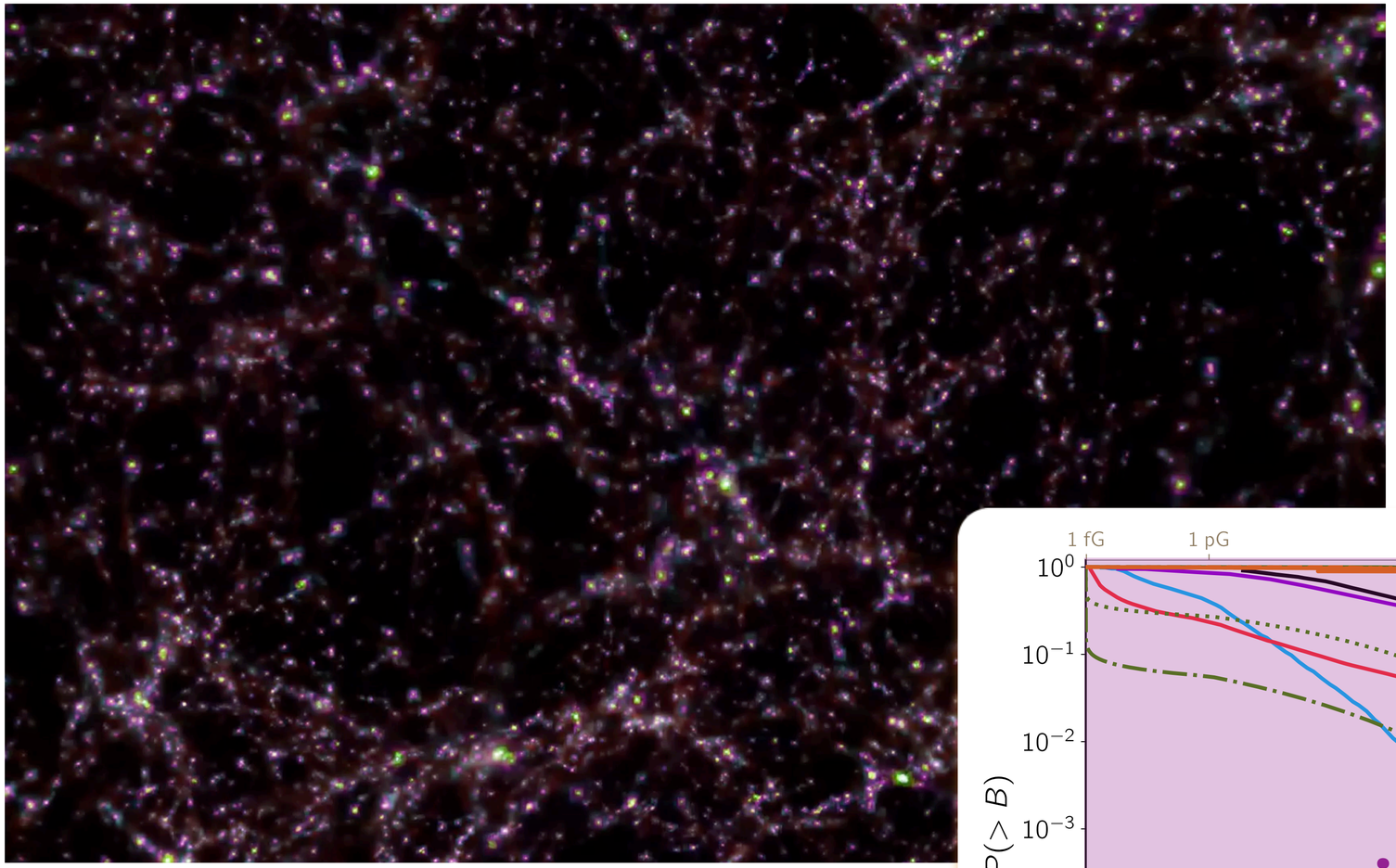
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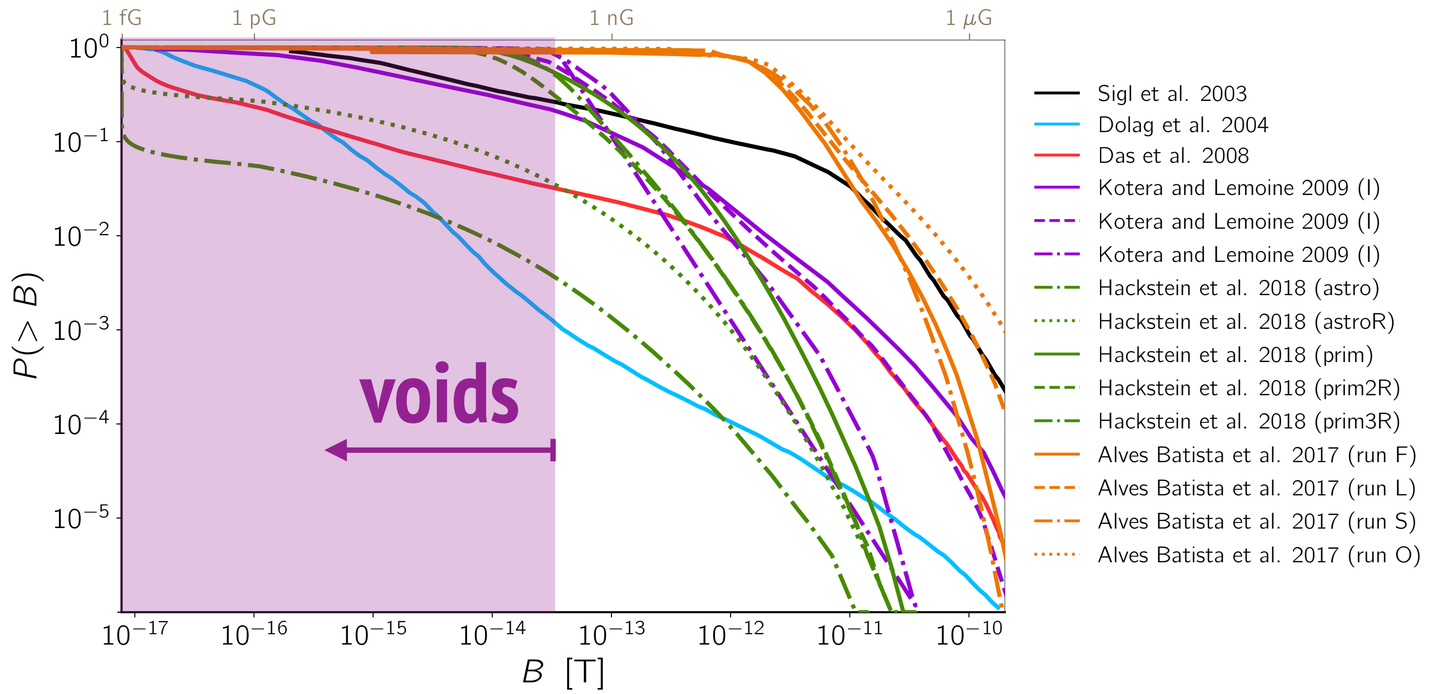


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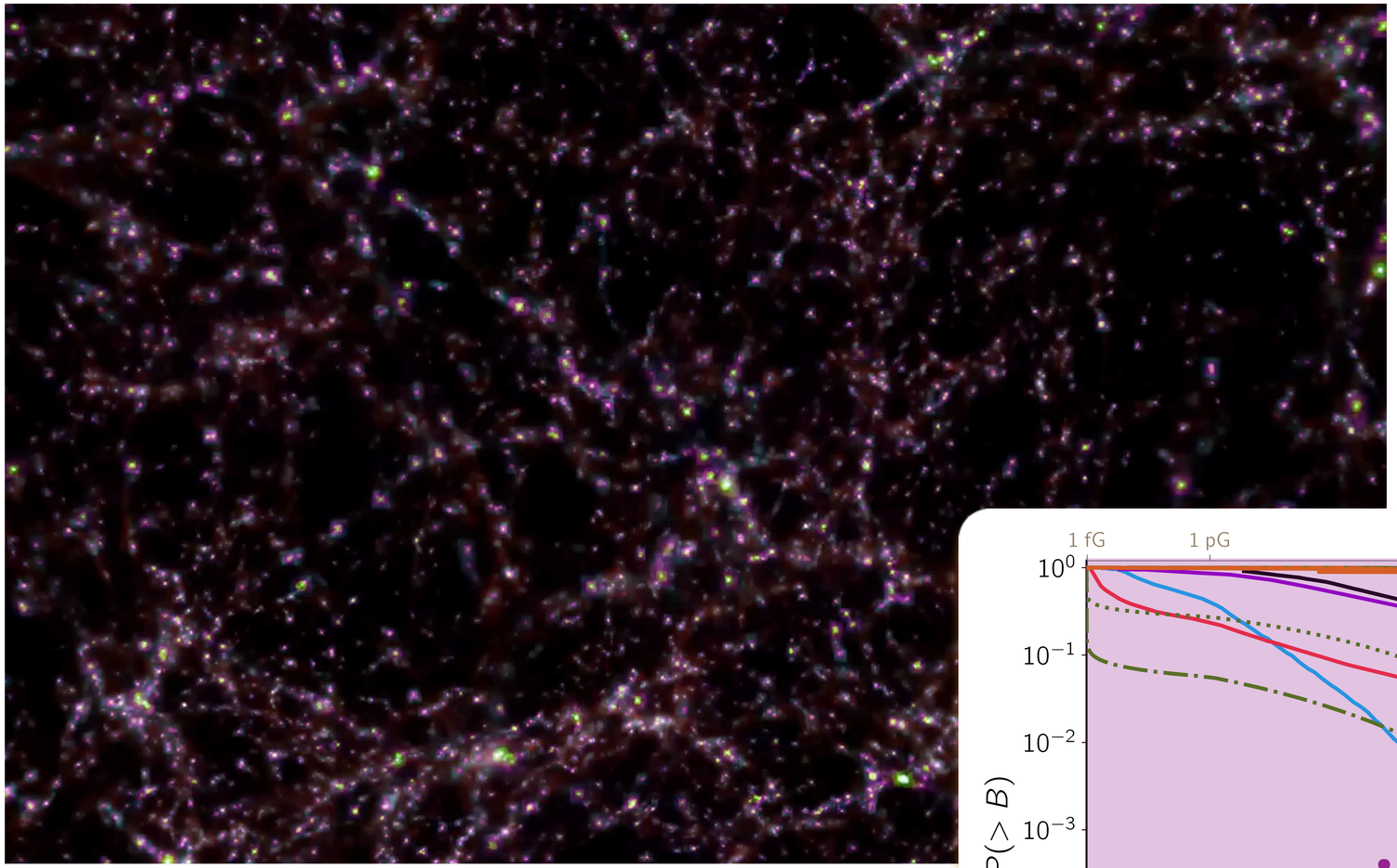


Alves Batista, Shin, Devriendt, Semikoz, Sigl. PRD, 96 (2017) 023010. arXiv:1704.

contribution of voids dominate over cosmological distances



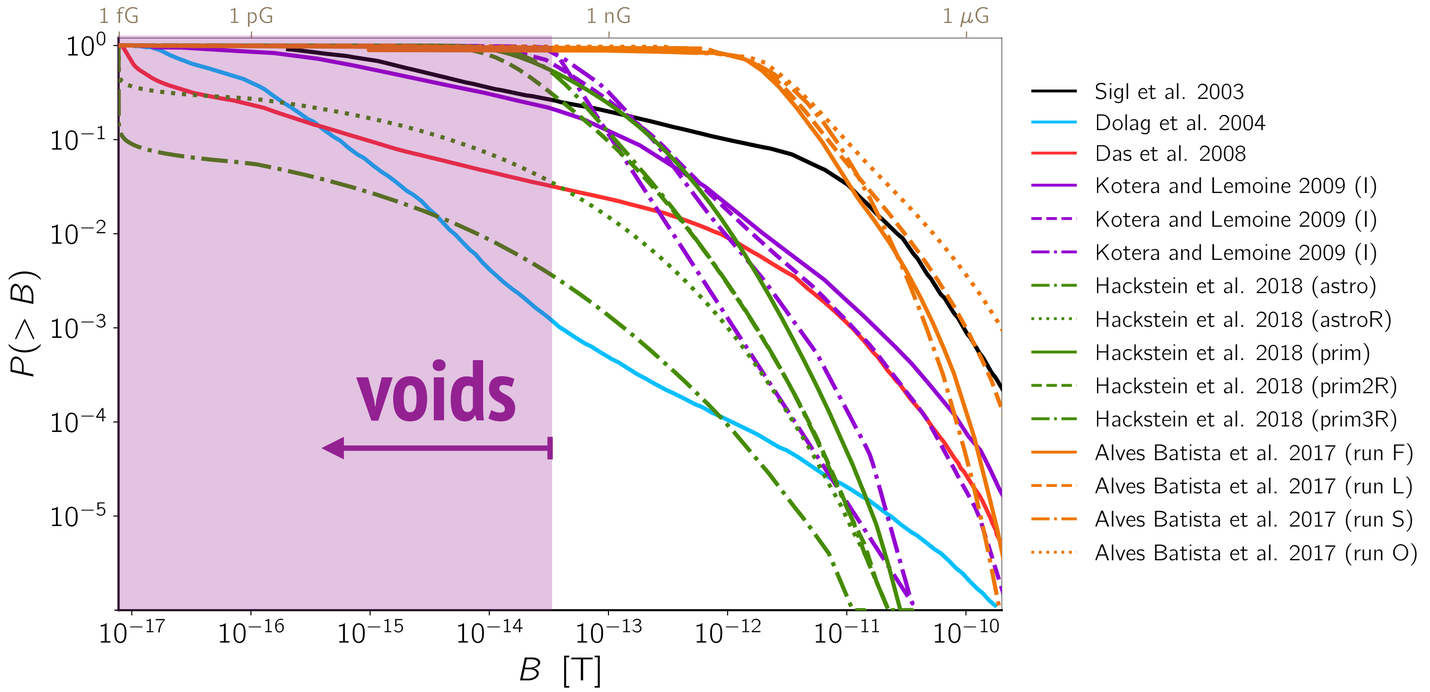
propagation ingredients: cosmic magnetic fields



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

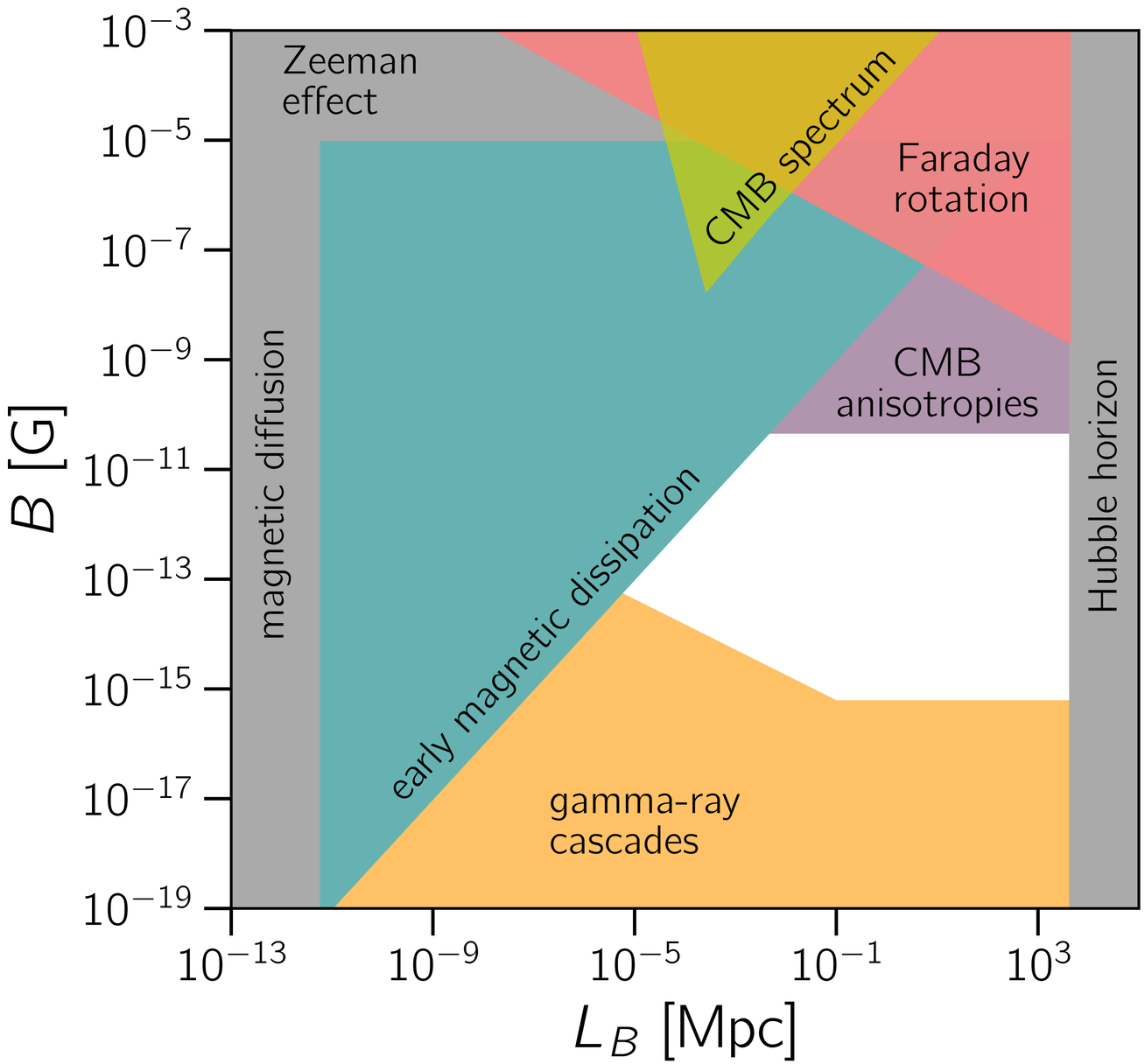
magnetic fields in voids are the most uncertain

contribution of voids dominate over cosmological distances



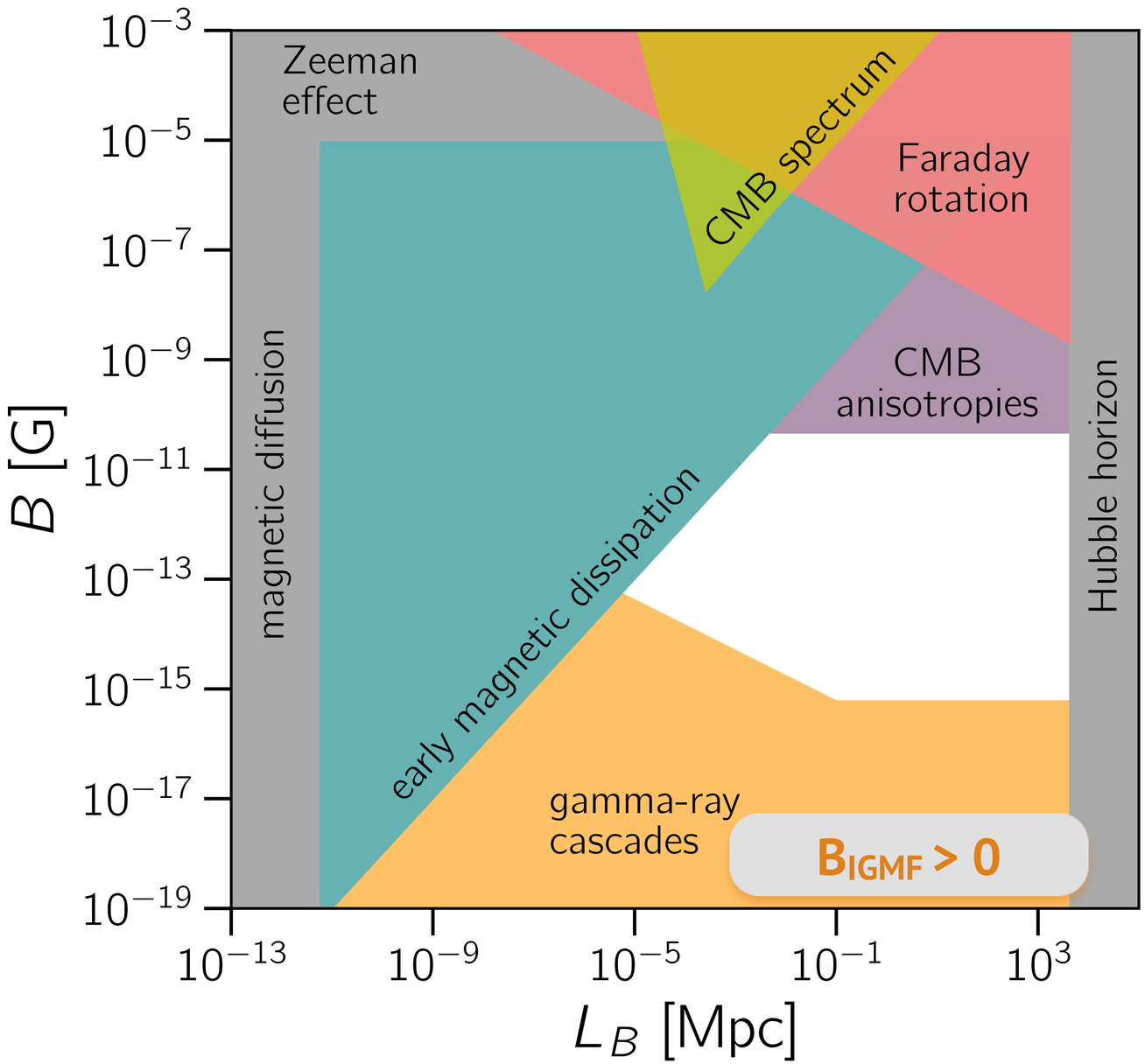
propagation ingredients: cosmic magnetic fields

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



propagation ingredients: cosmic magnetic fields

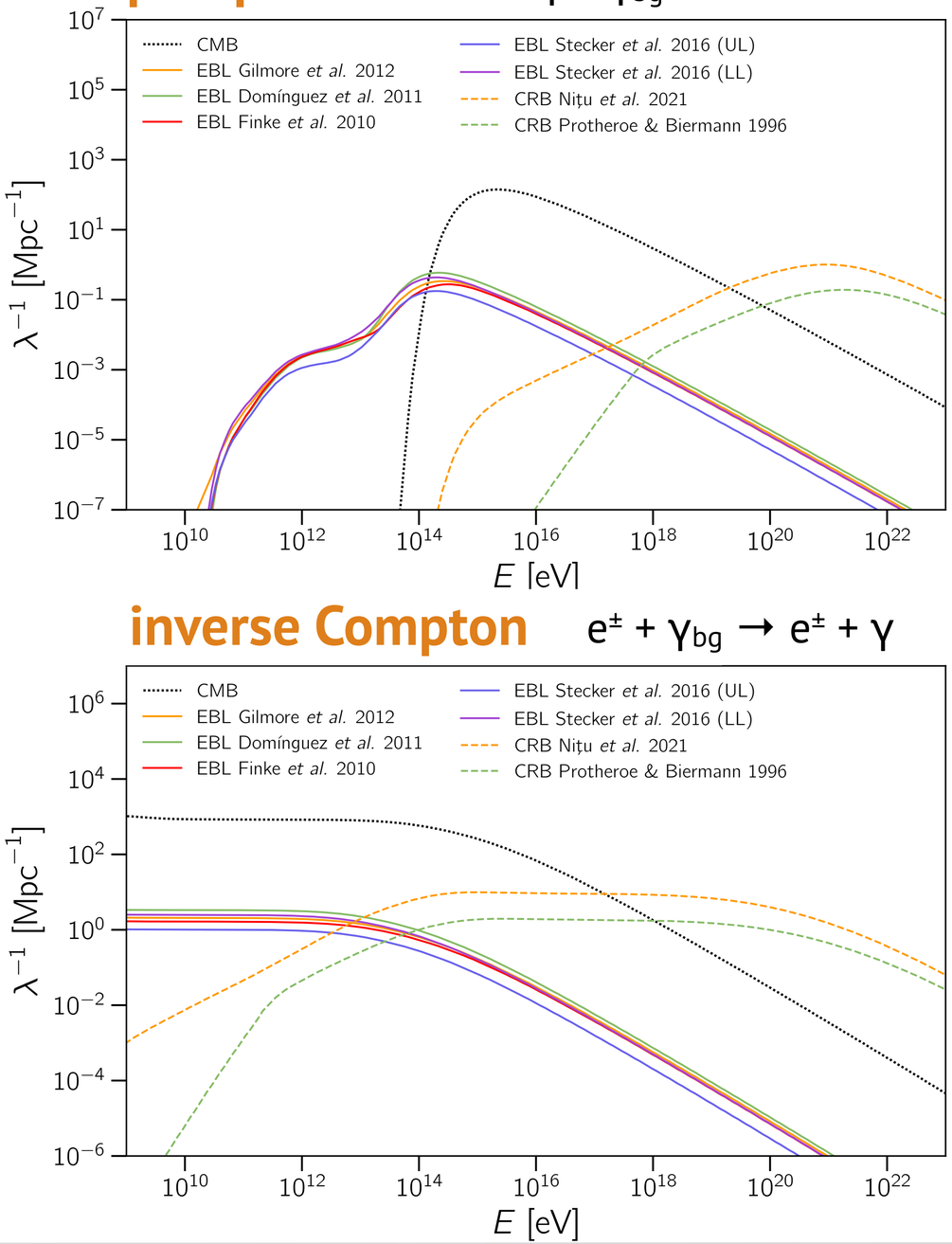
Alves Batista & Saveliev. Universe 7 (2021) 223. arXiv:2105.12020



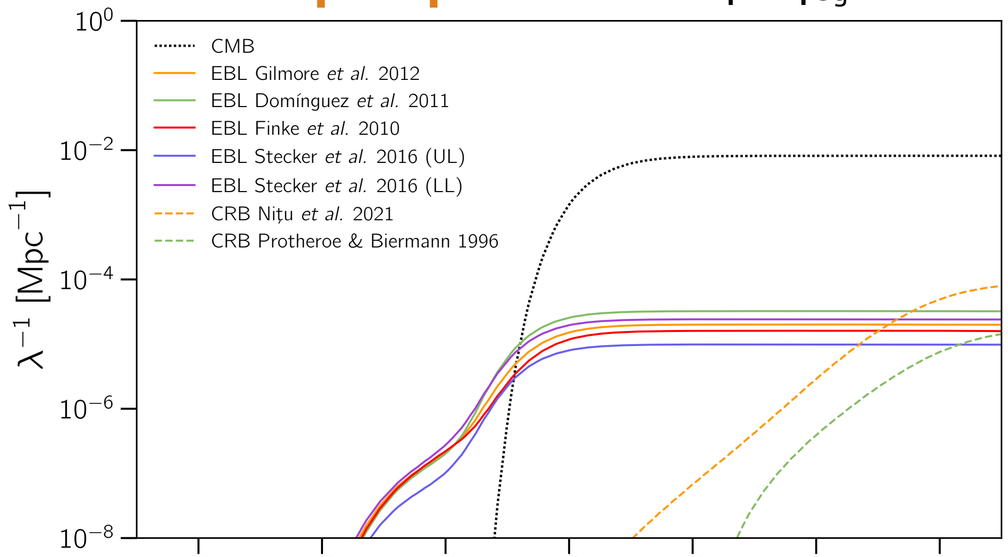
gamma rays

gamma rays: interactions during cosmological propagation

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

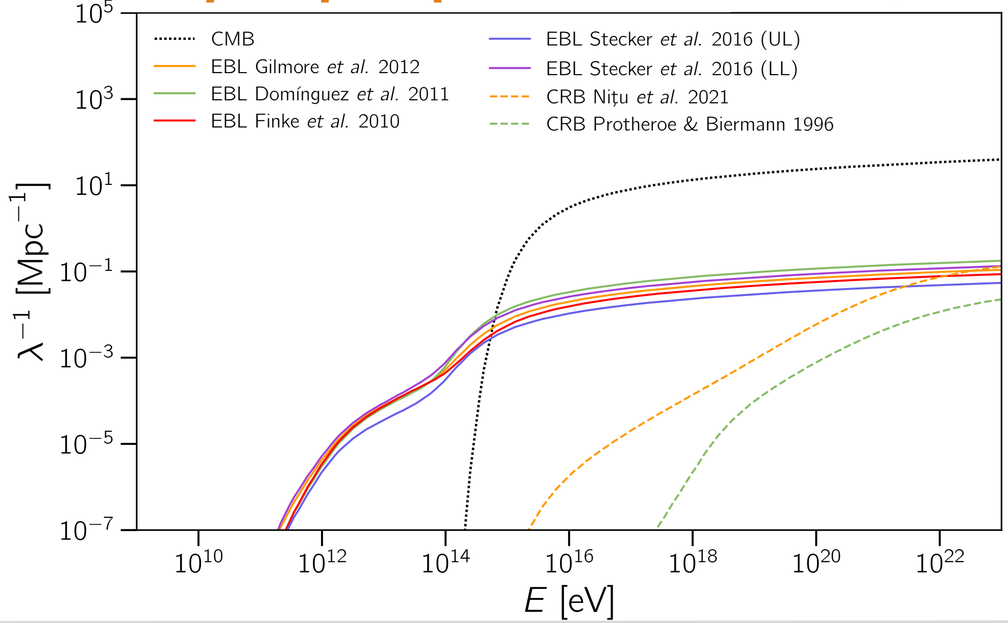


double pair production $\gamma + \gamma_{bg} \rightarrow e^- + e^+ + e^- + e^+$



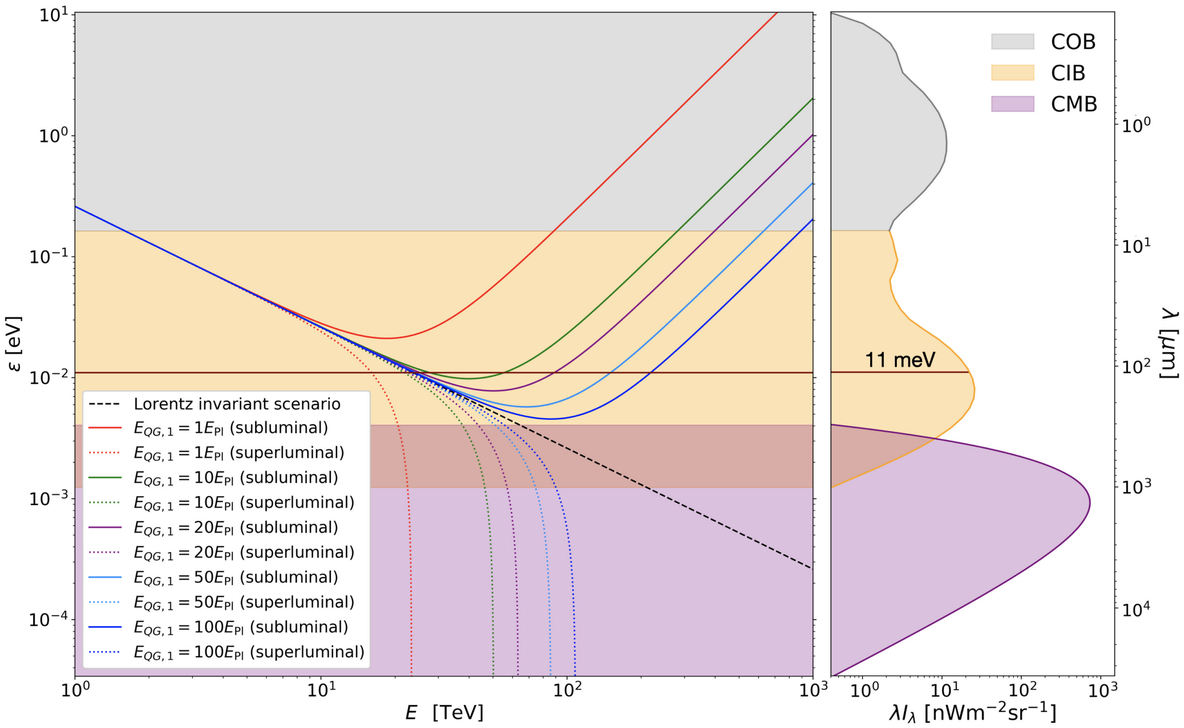
inverse Compton $e^\pm + \gamma_{bg} \rightarrow e^\pm + \gamma$

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

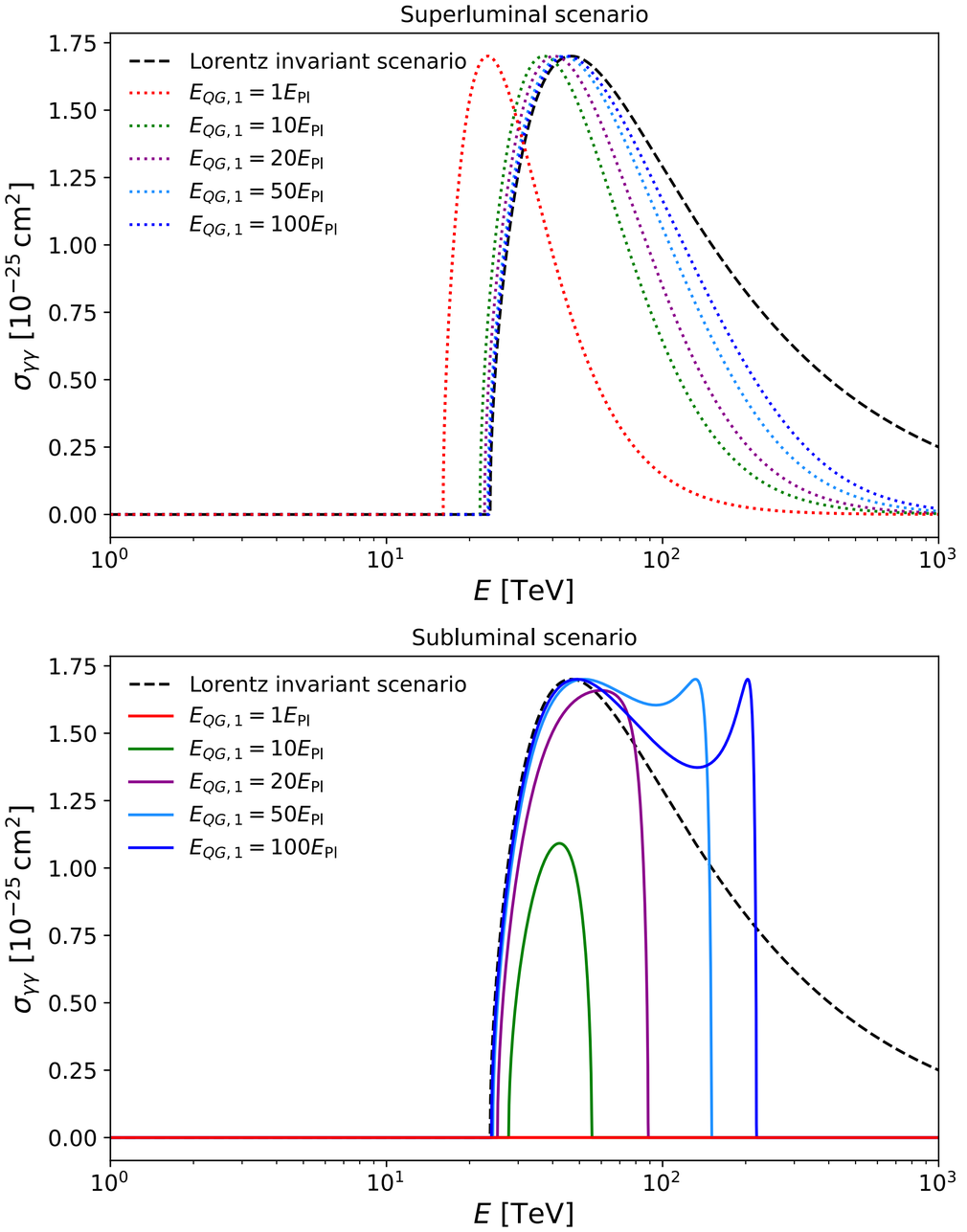


gamma rays: modification of interaction thresholds by QG

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



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



gamma rays: Lorentz invariance violation and time delays

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

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LIV: modified dispersion relation

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LIV: modified dispersion relation

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

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

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

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flux attenuation

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

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observed energy

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energy-dependent velocity

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optical depth

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

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

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

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

LIV: modified dispersion relation

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

$$v = \underbrace{v(E)}_{\text{energy-dependent velocity}} \approx 1 + \xi \frac{n+1}{2}\left(\frac{E}{E_{\rm QG}}\right)^n$$

time delays

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

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

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
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do time delays give truly meaningful constraints on LIV?

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information about the source

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simulations performed with CRPropa

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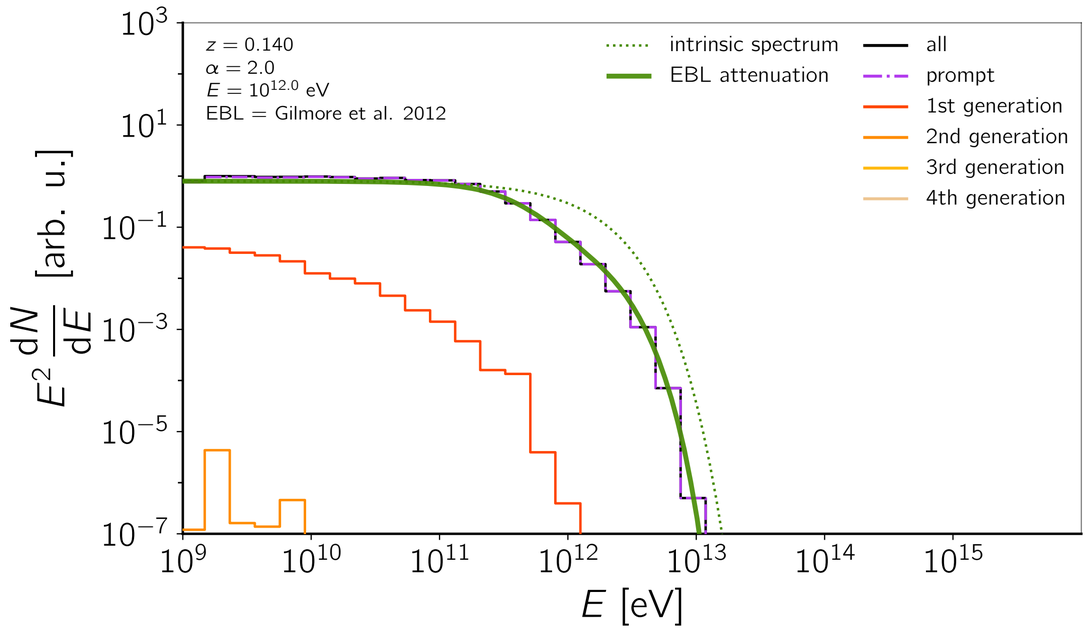
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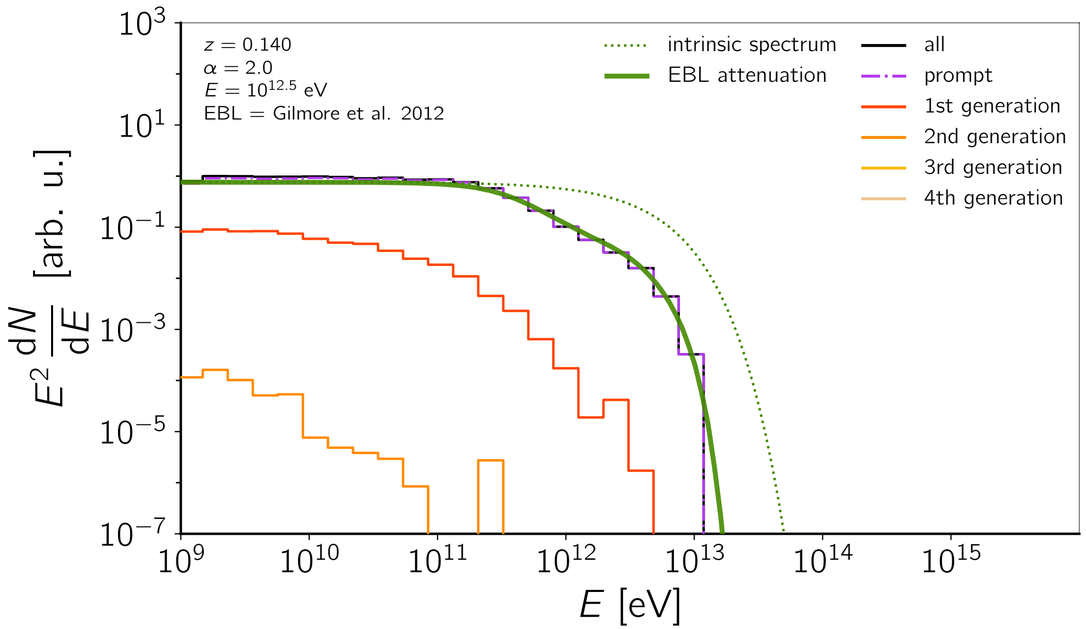
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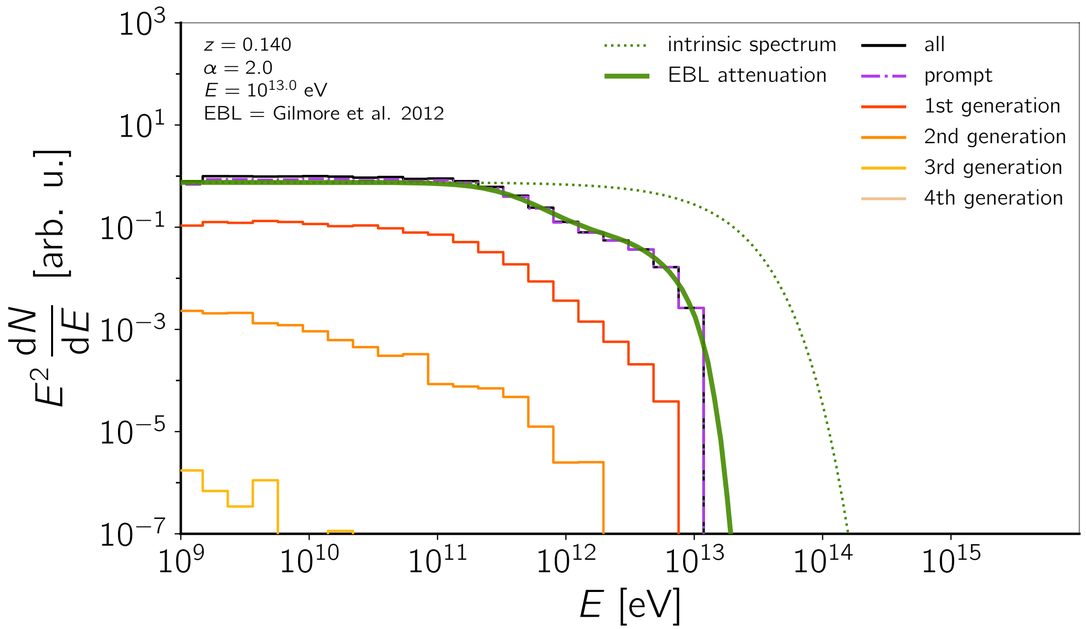
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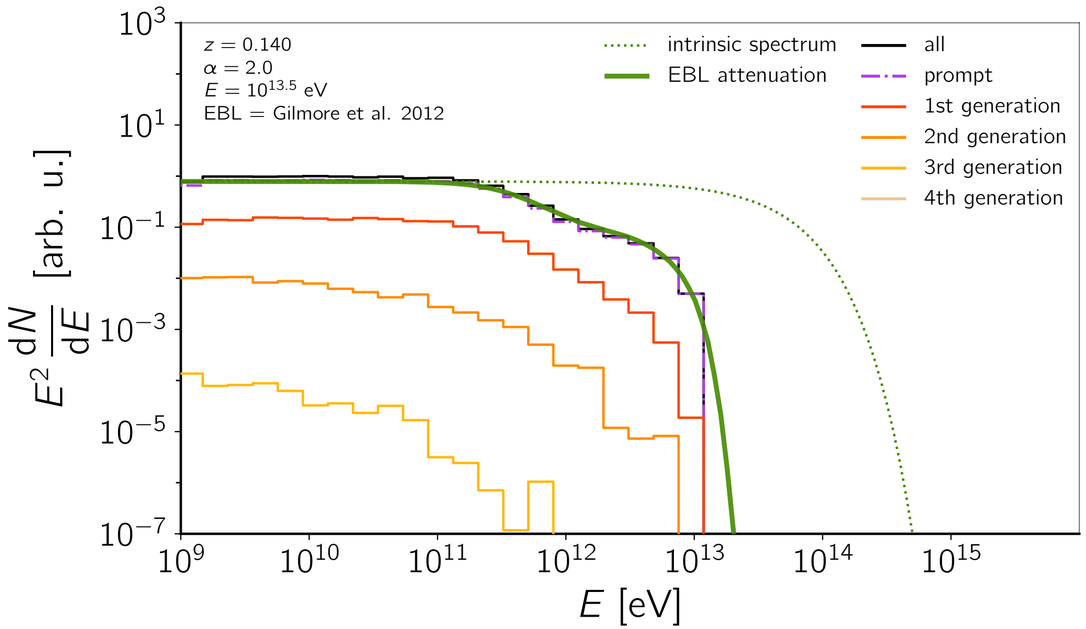
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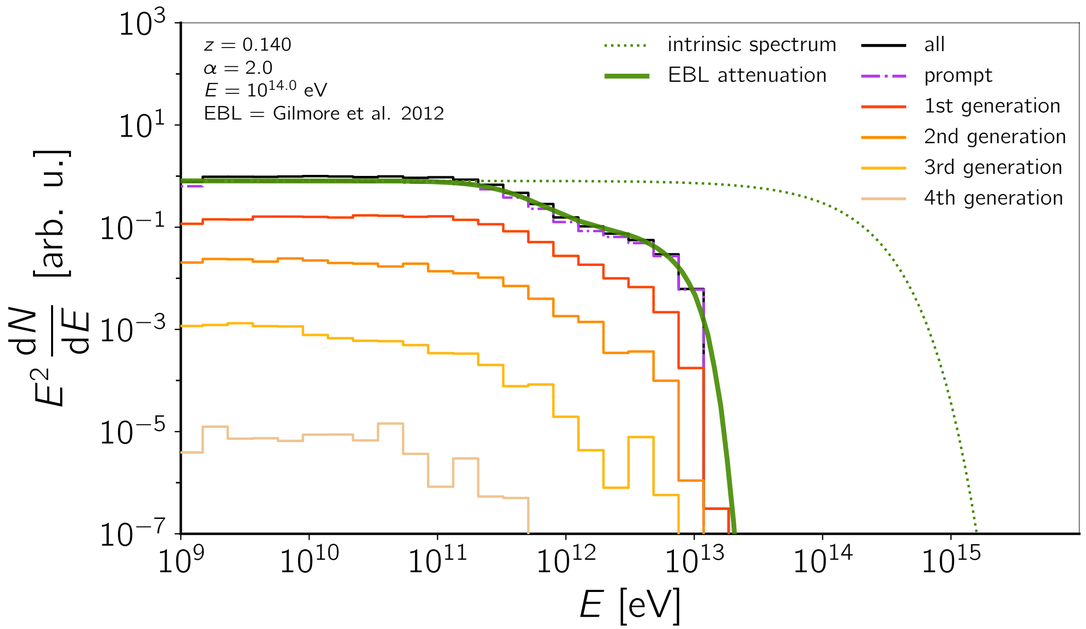
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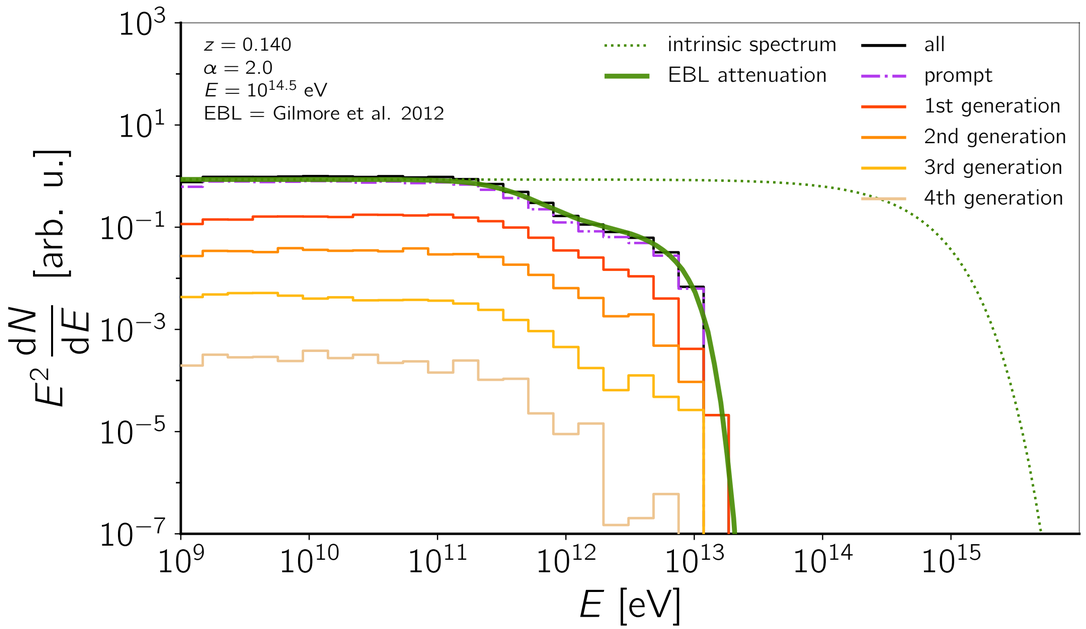
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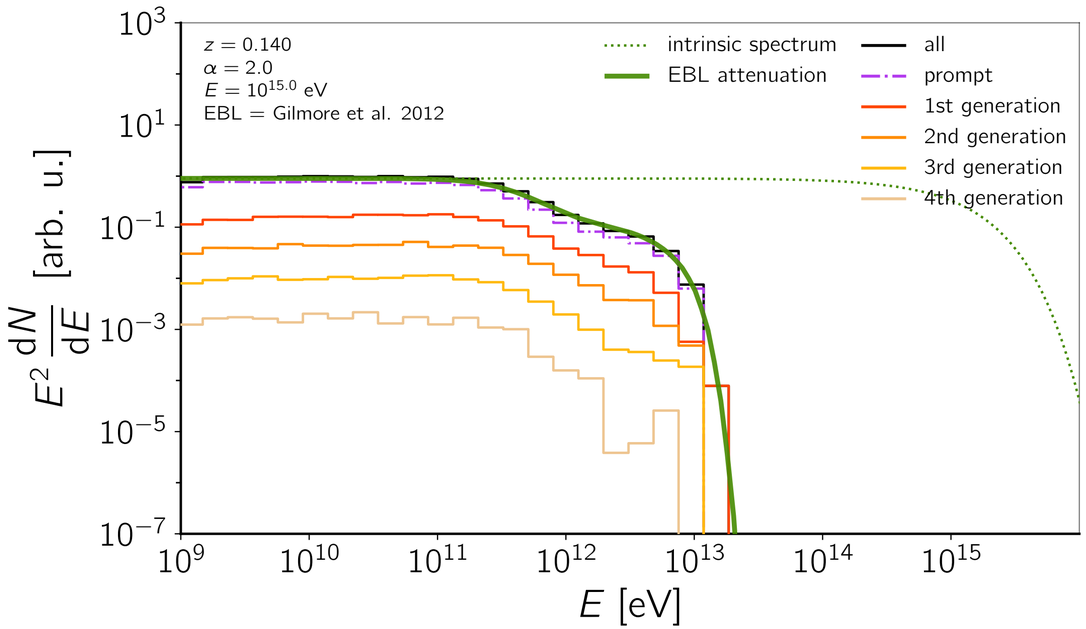
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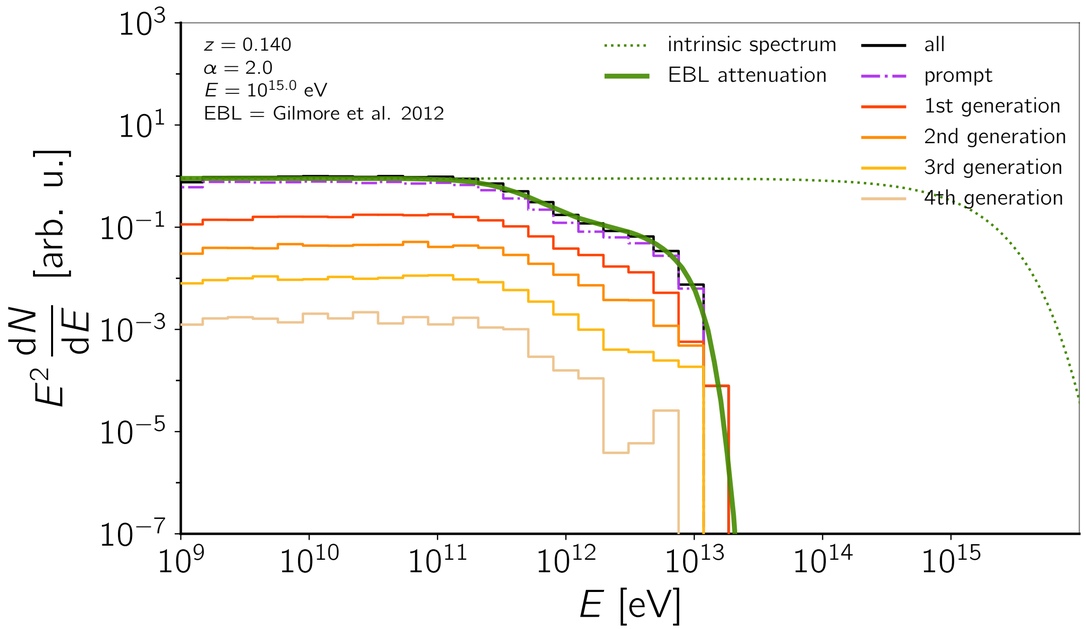
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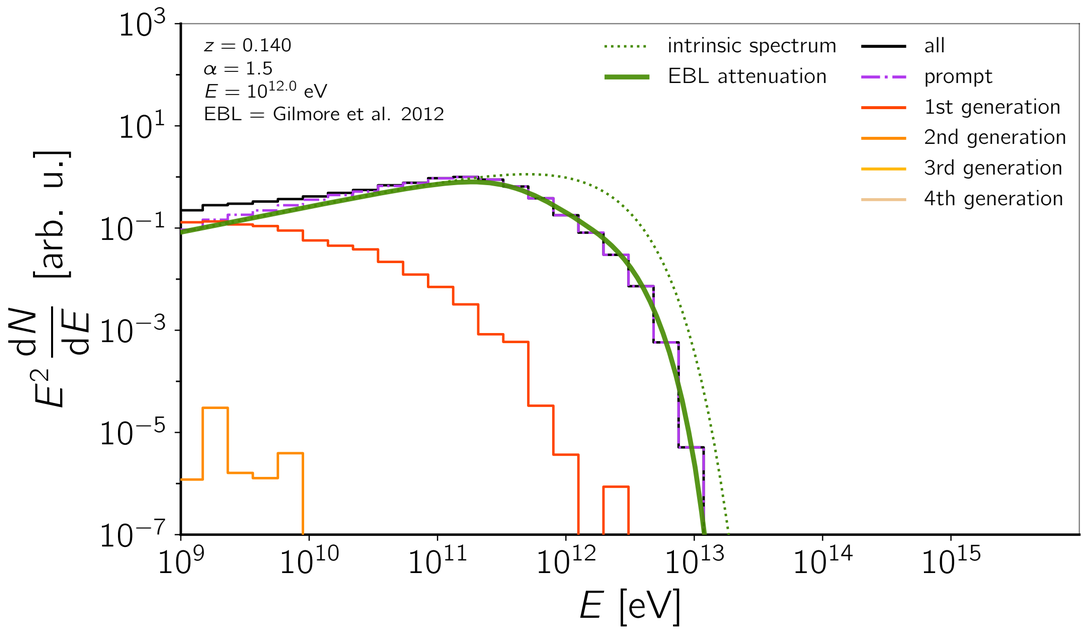
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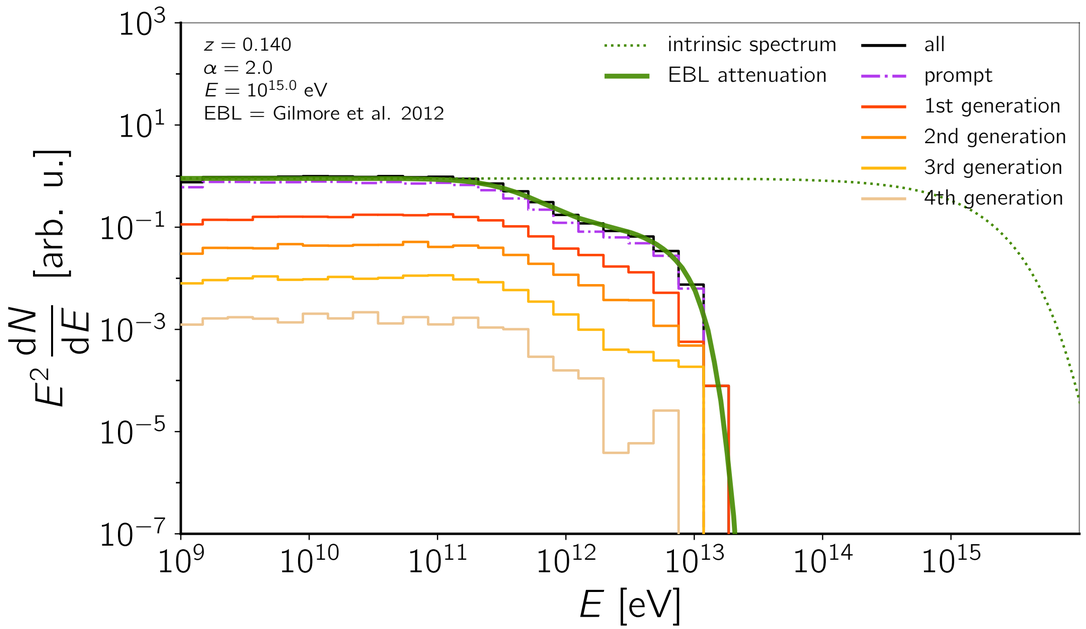
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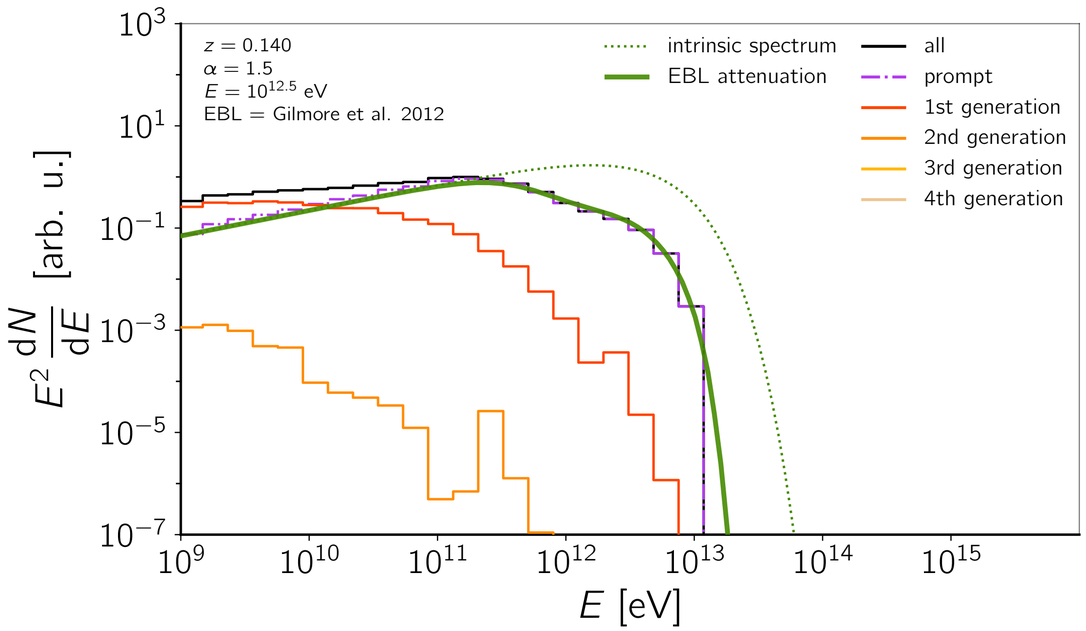
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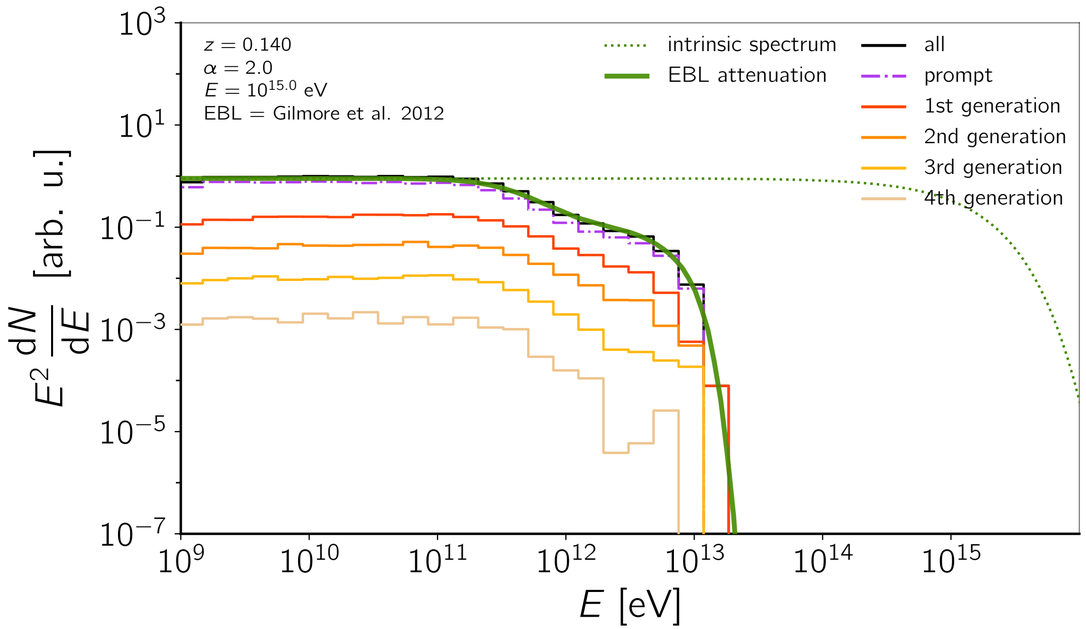
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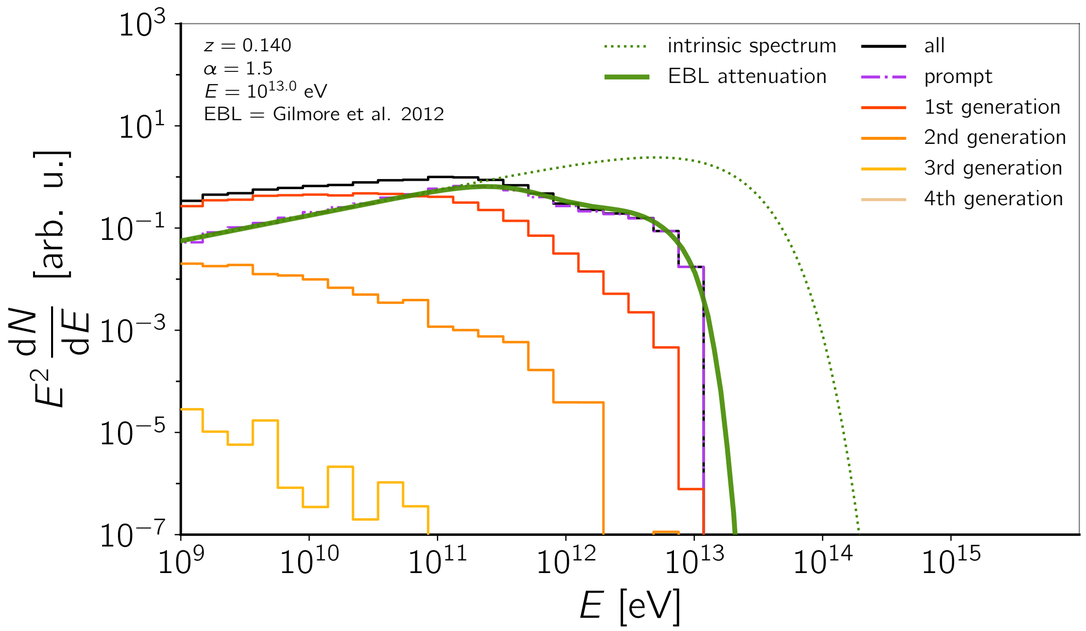
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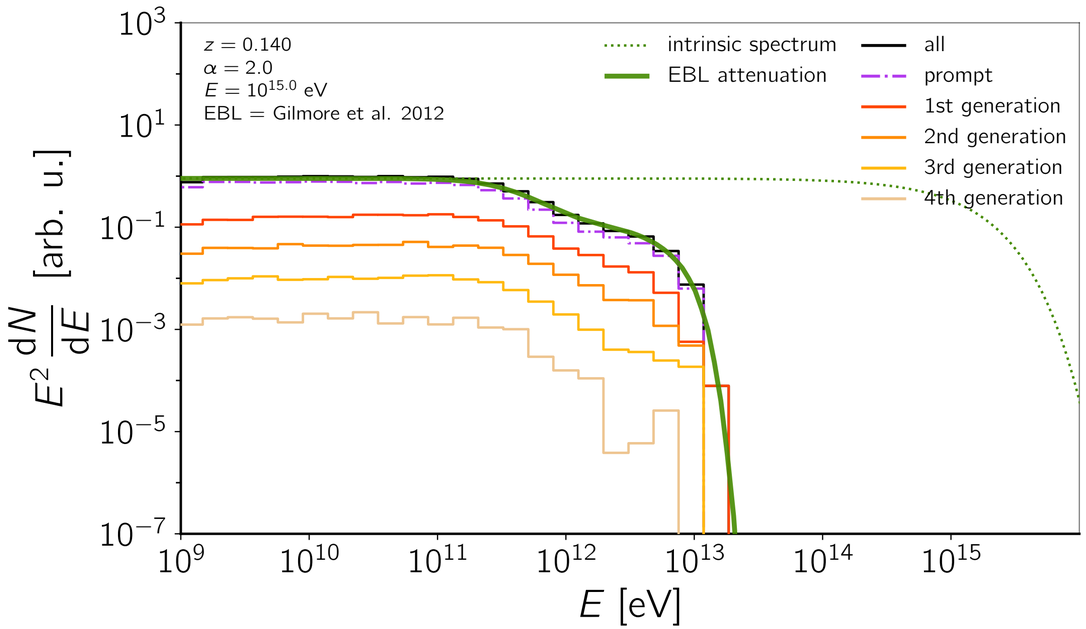
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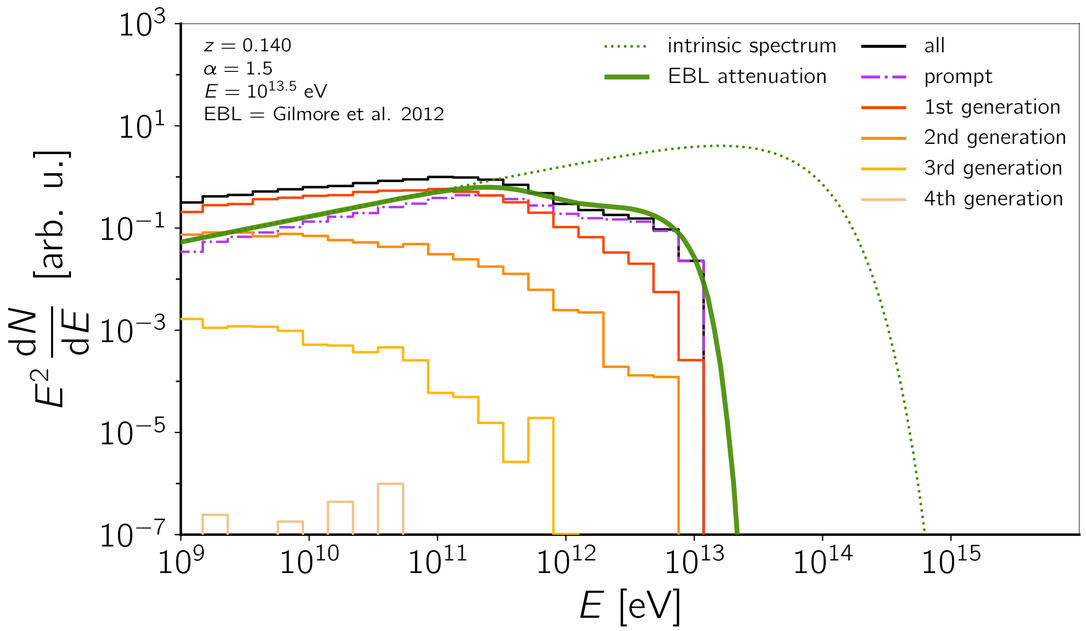
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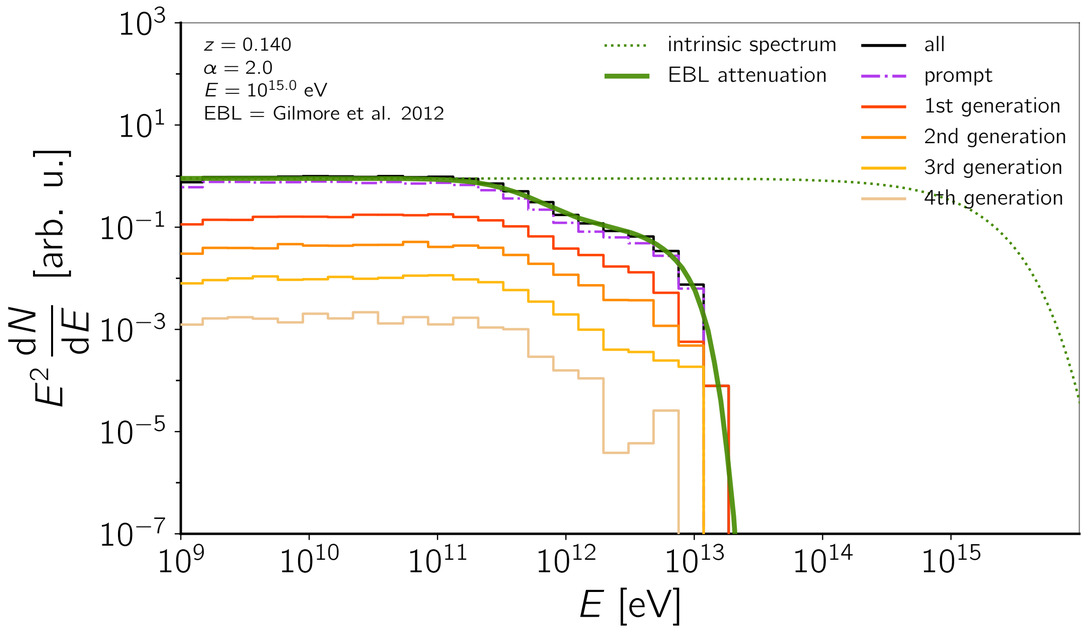
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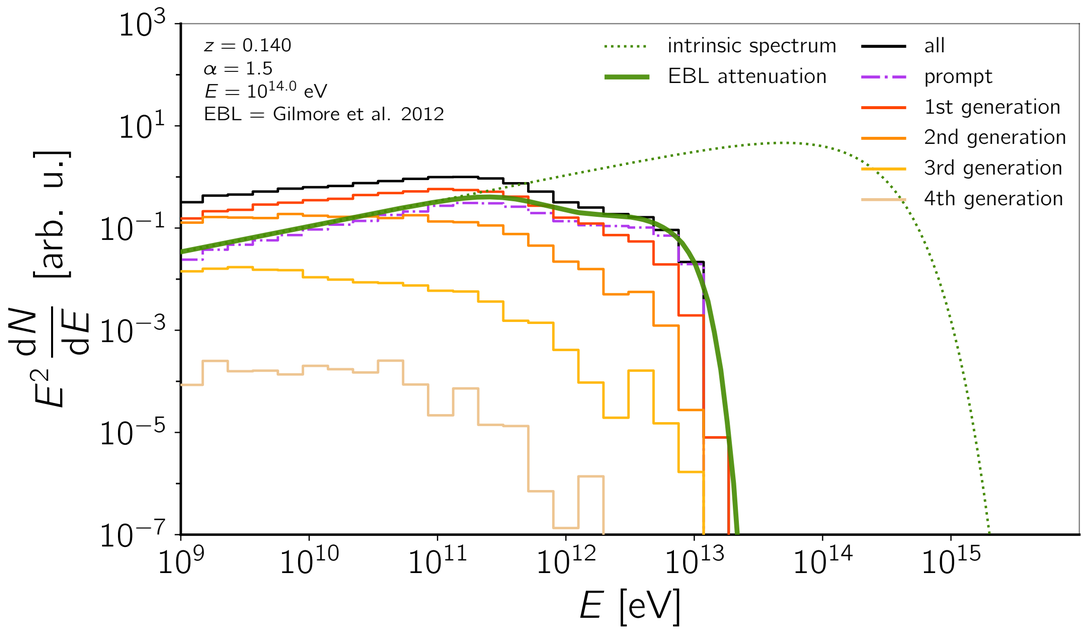
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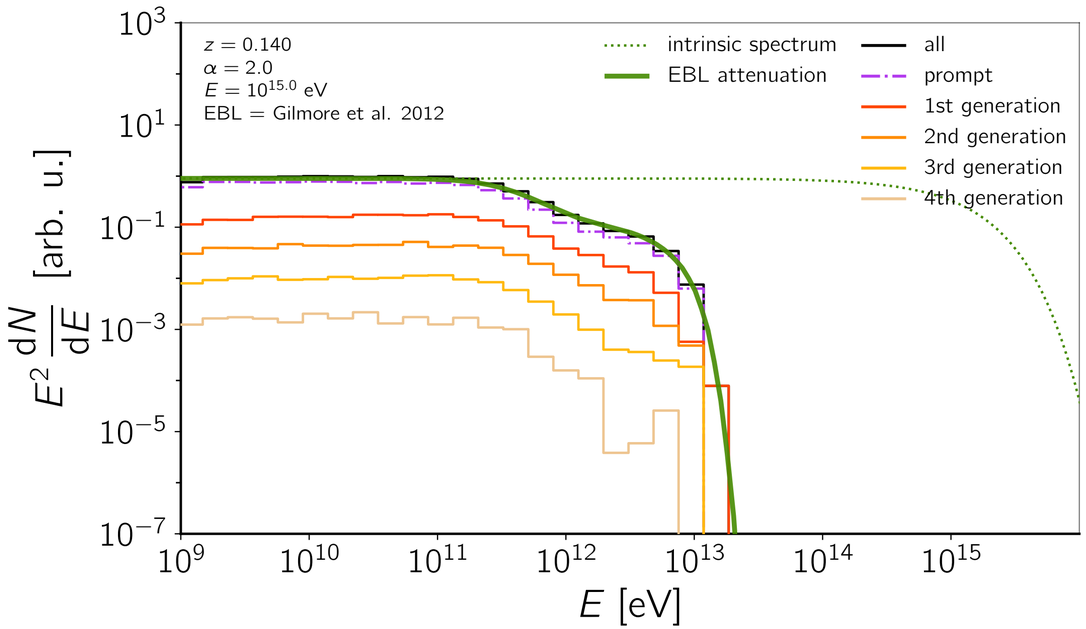
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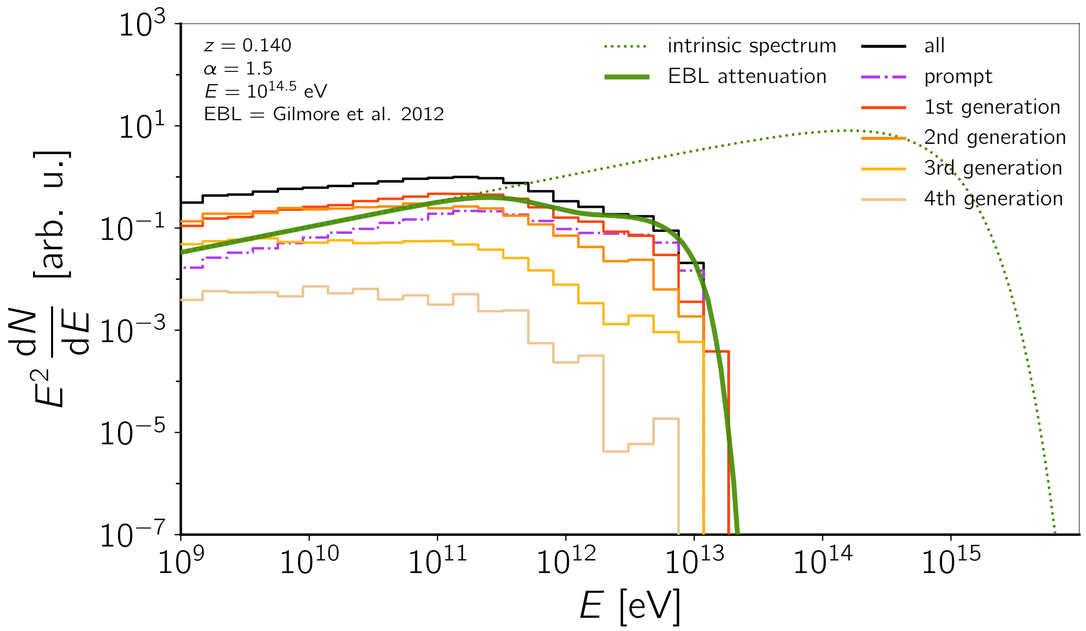
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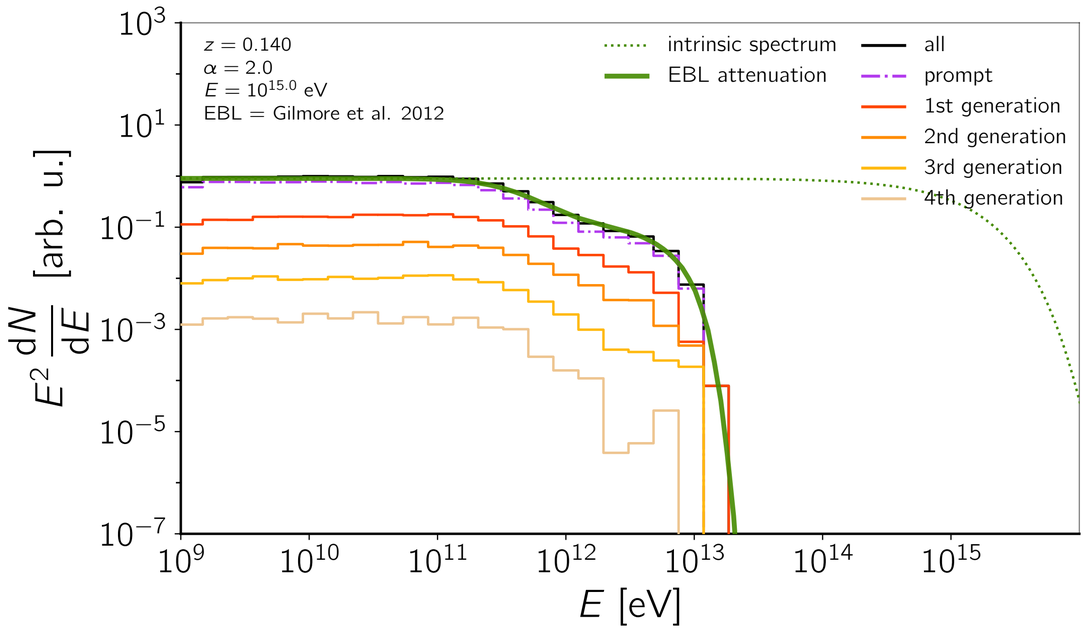
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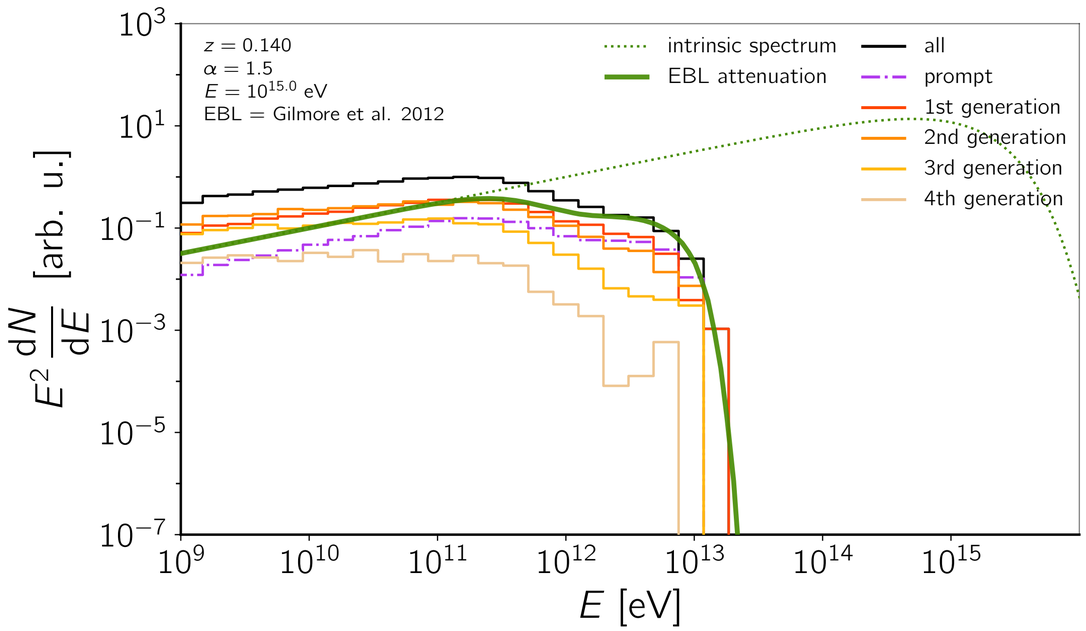
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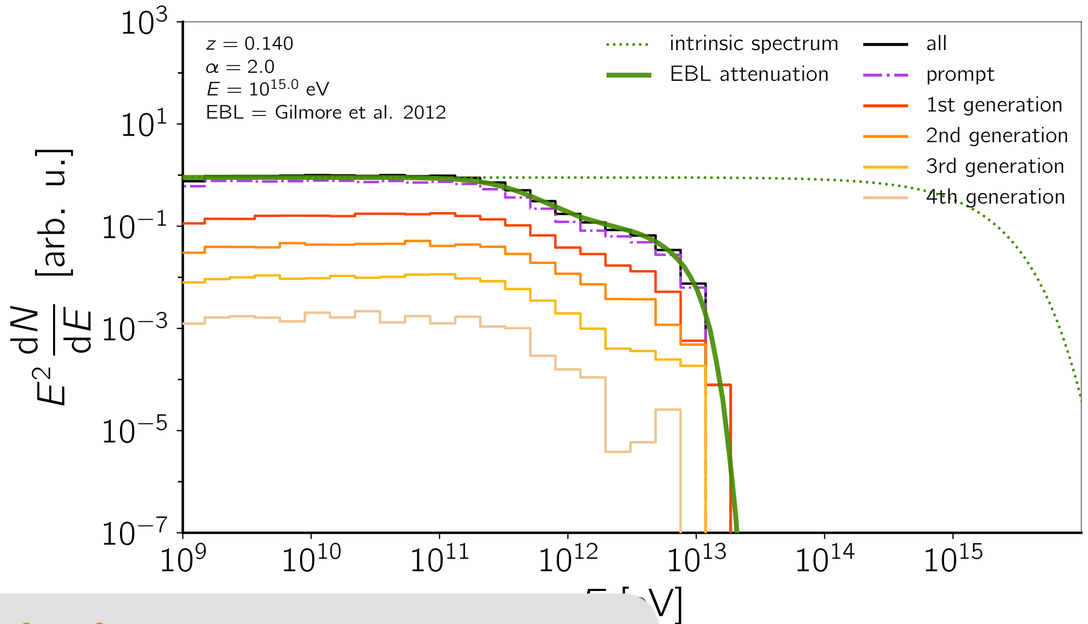
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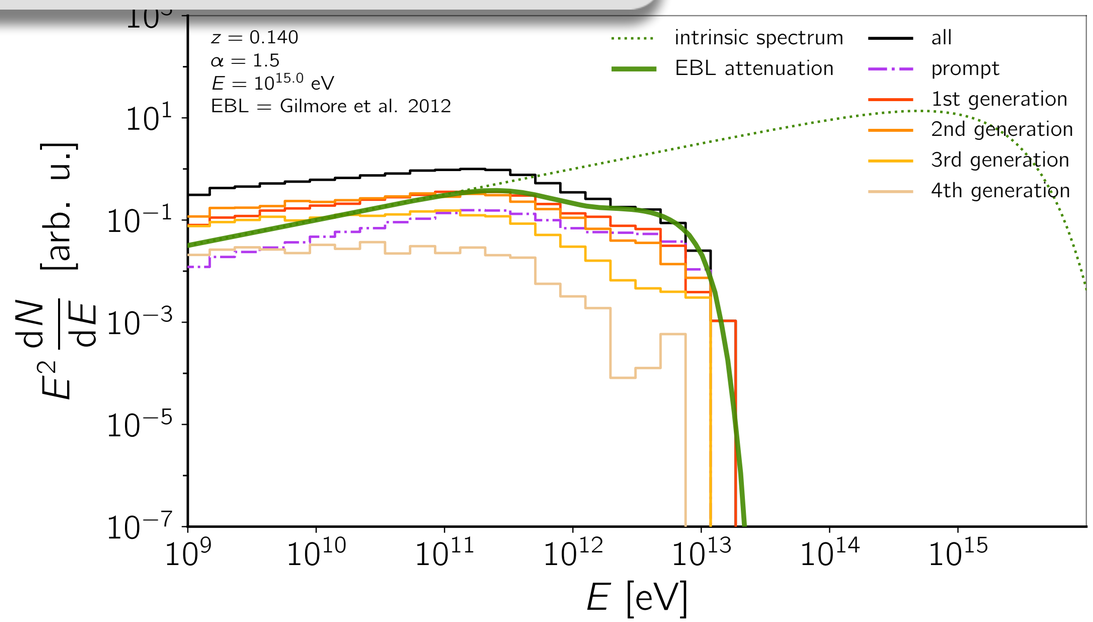
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intrinsic spectrum matters



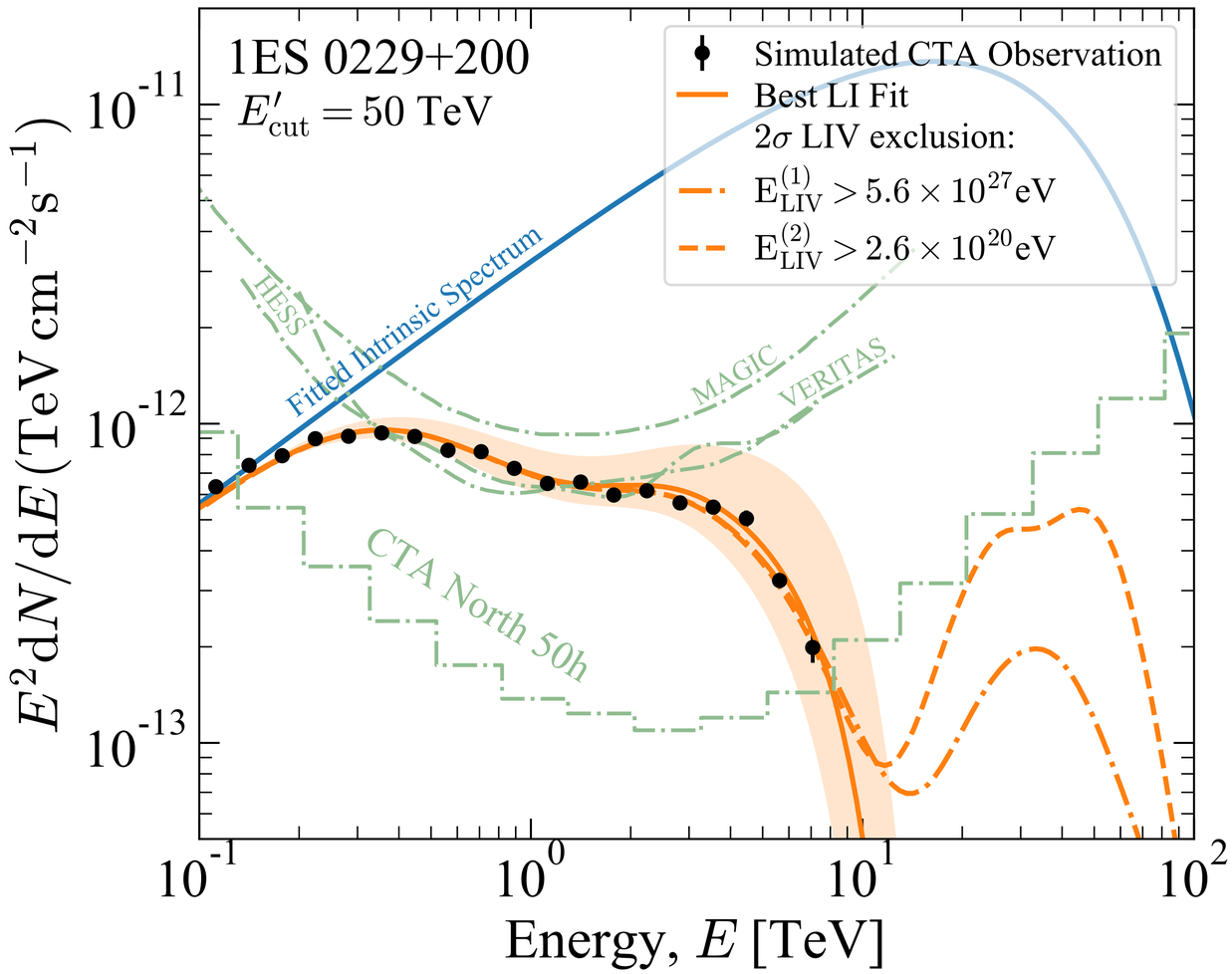
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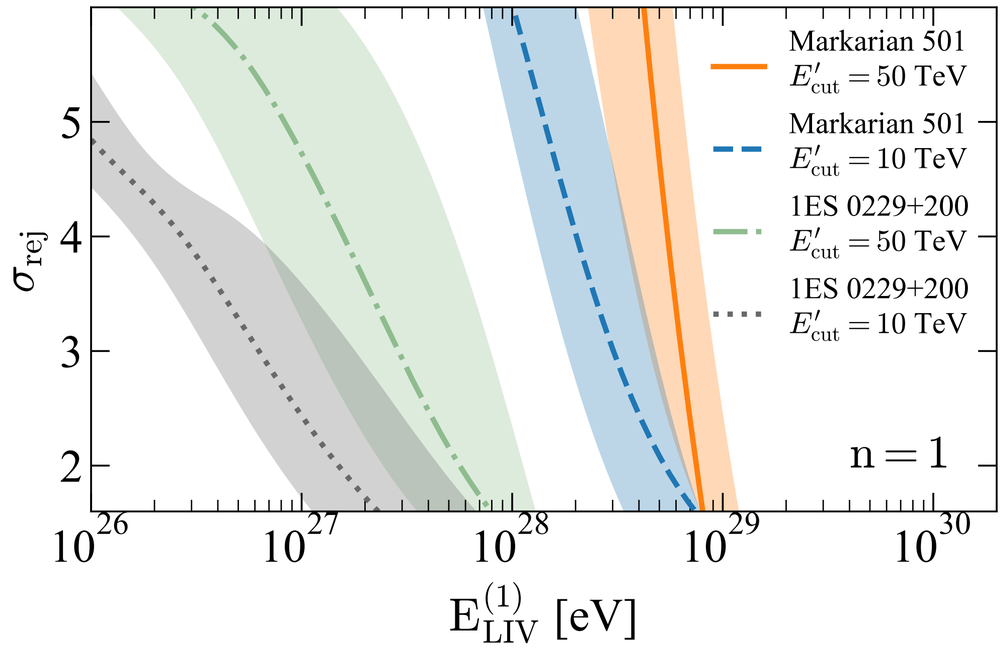
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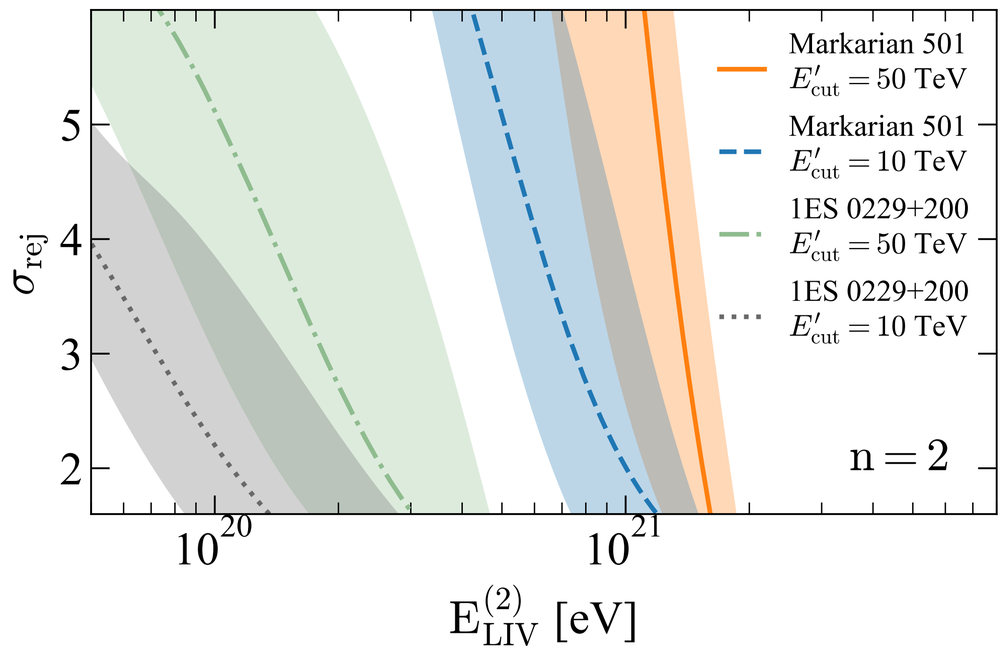
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gamma rays: intrinsic spectrum uncertainties and constraints on LIV

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

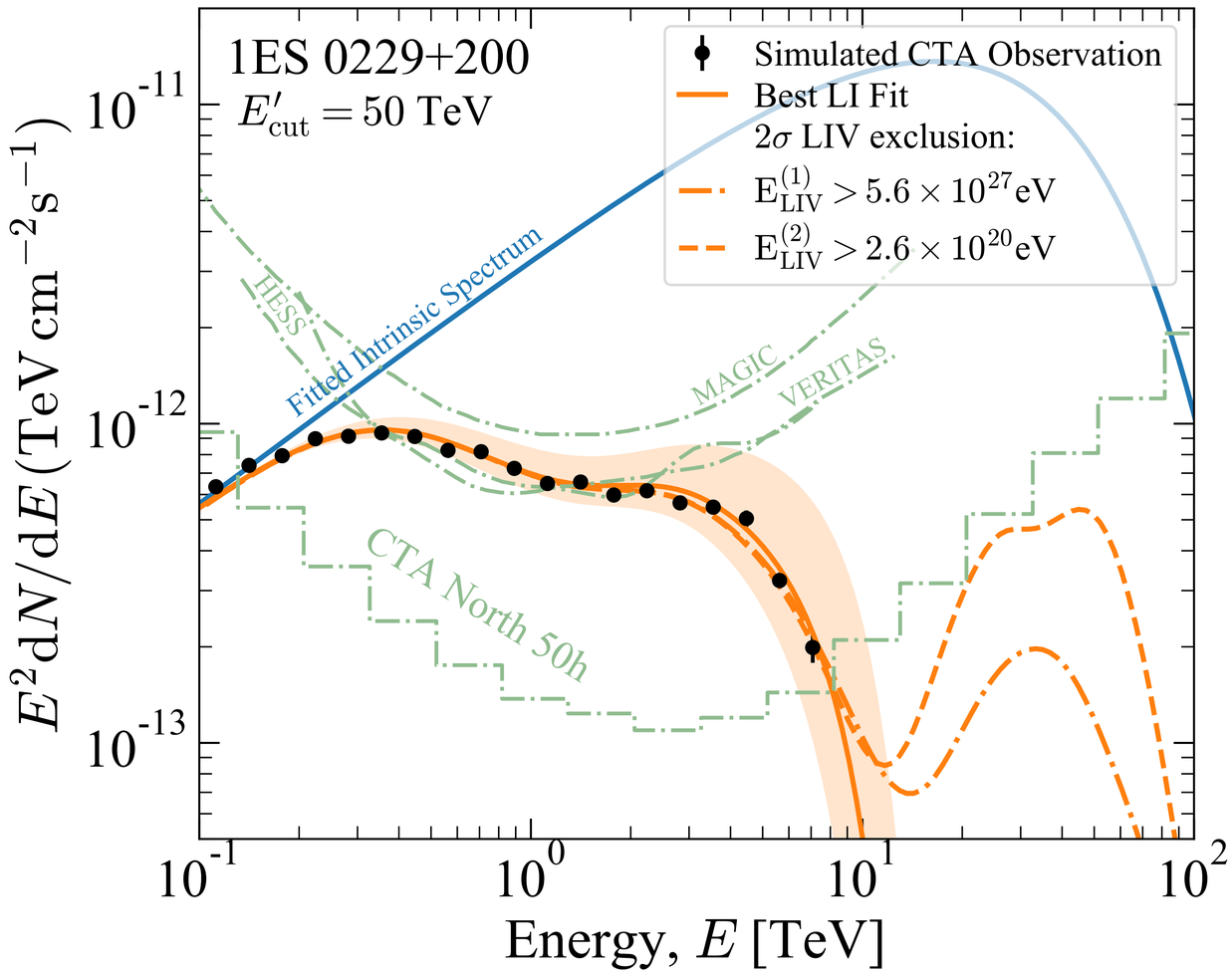


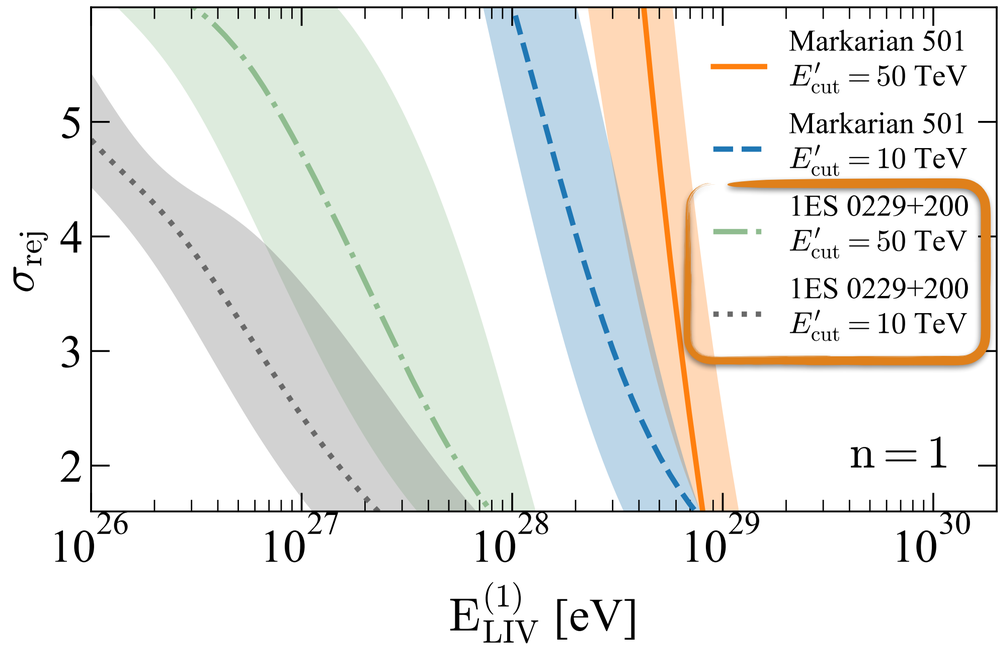


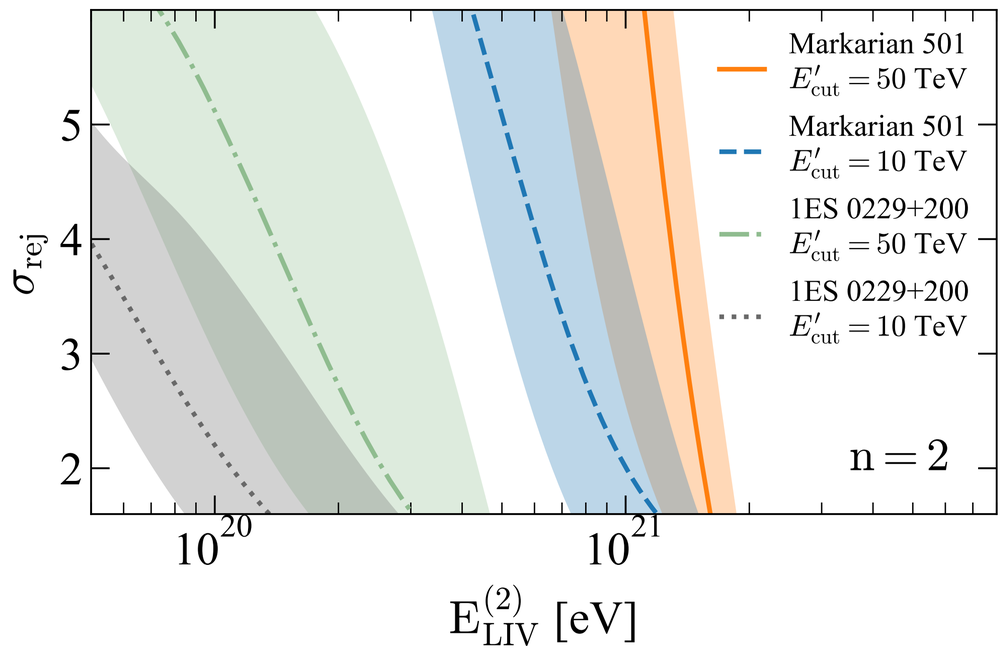


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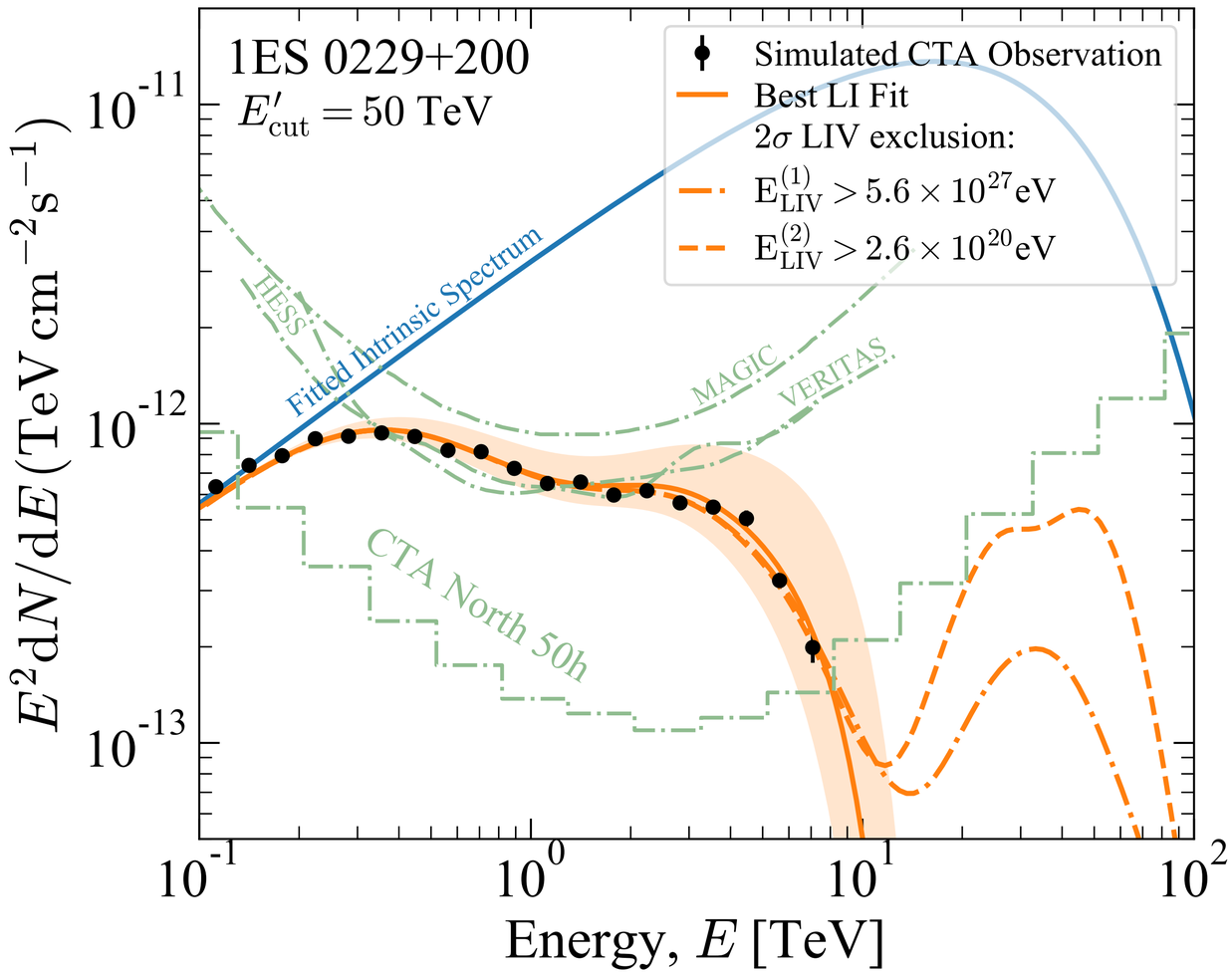


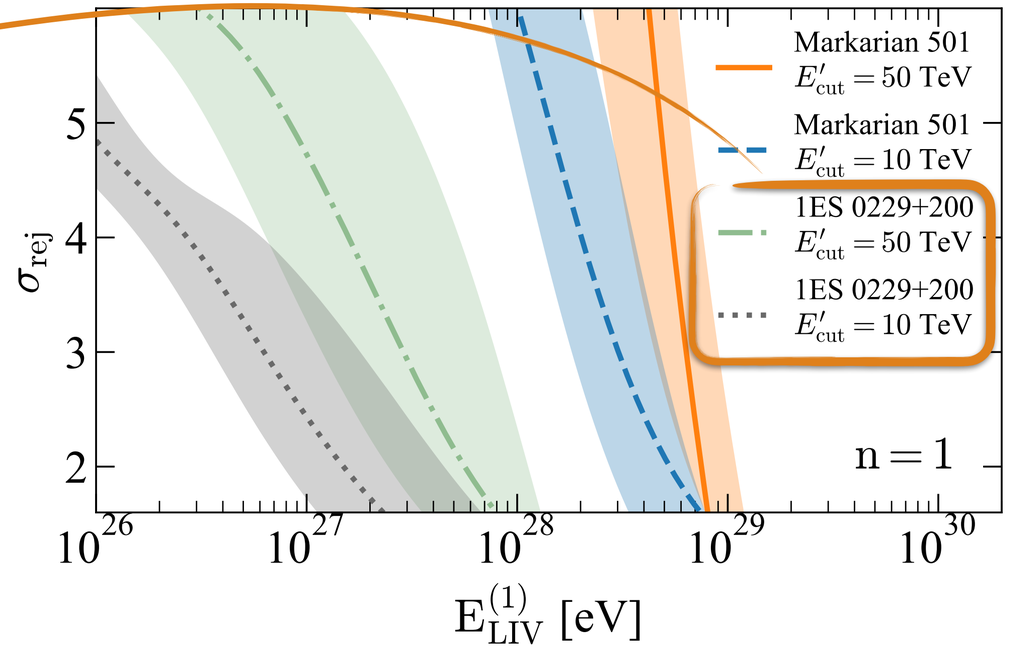


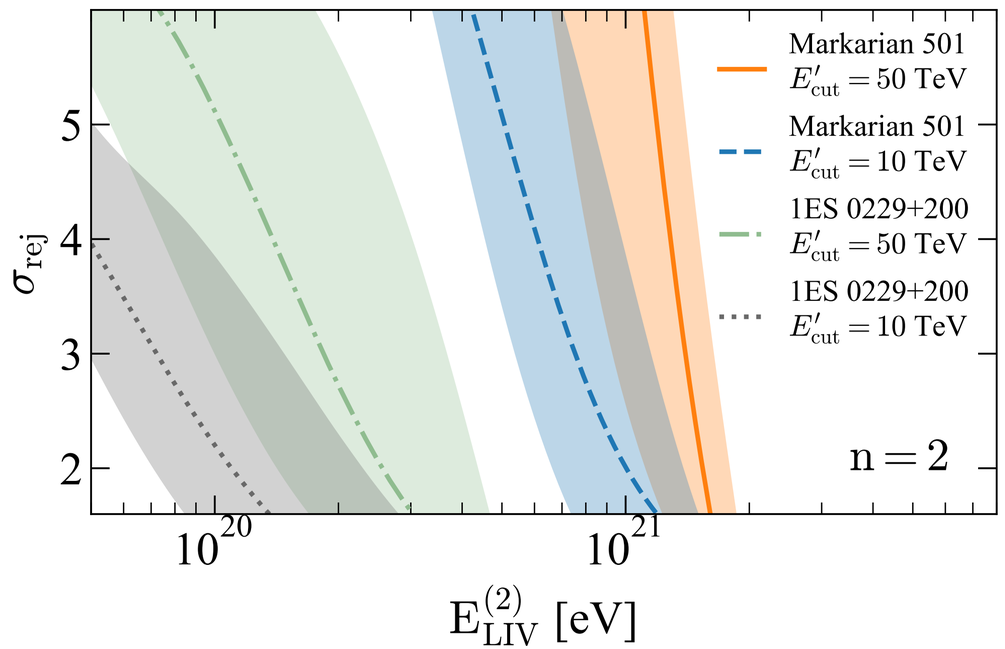
gamma rays: intrinsic spectrum uncertainties and constraints on LIV

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

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

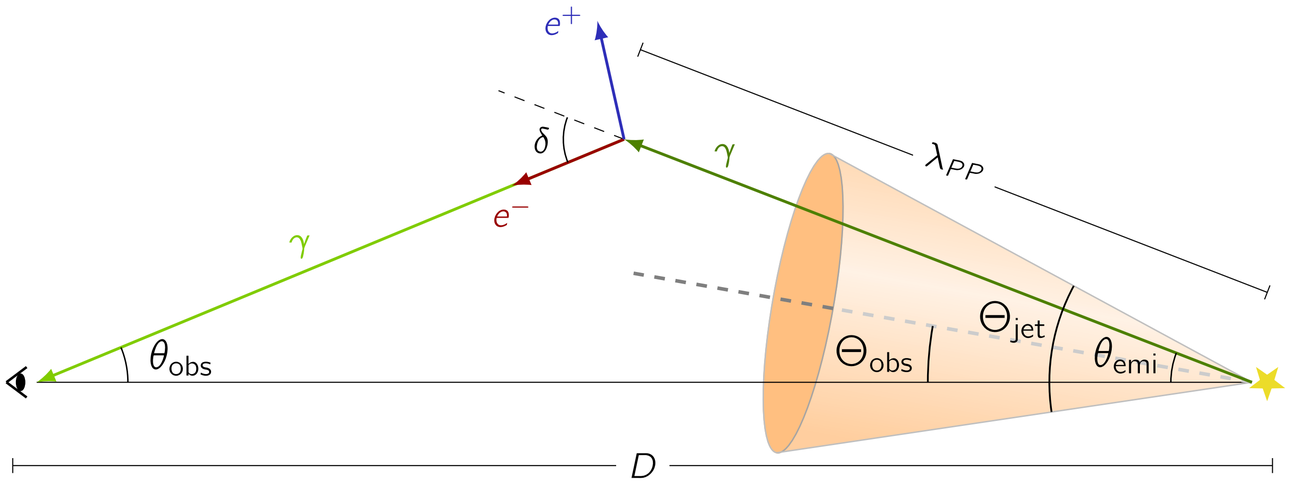






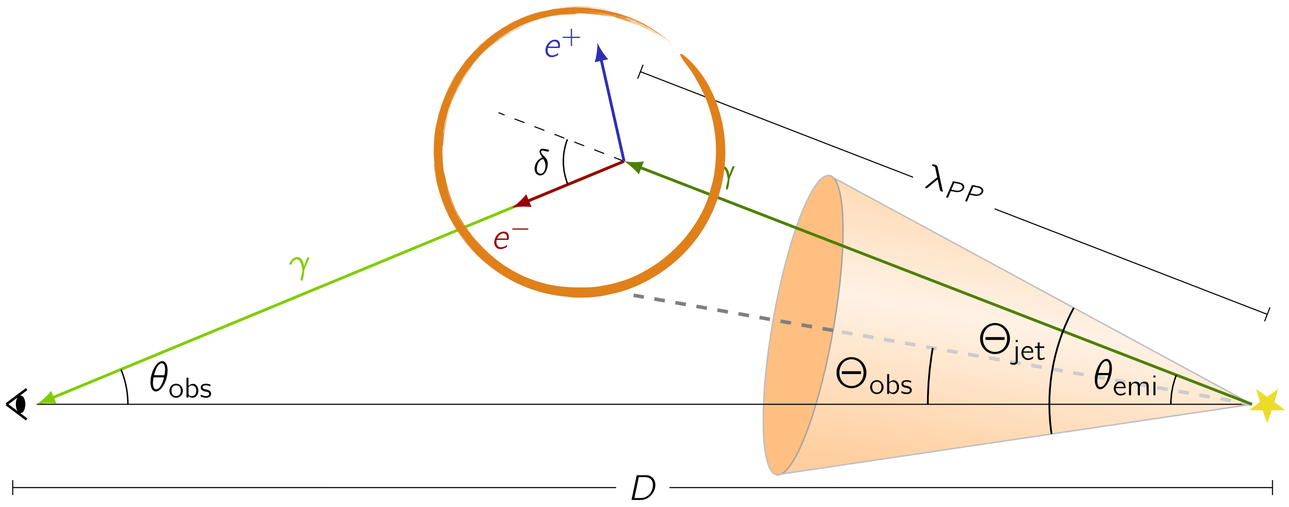
gamma rays: QG signatures through time delays

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



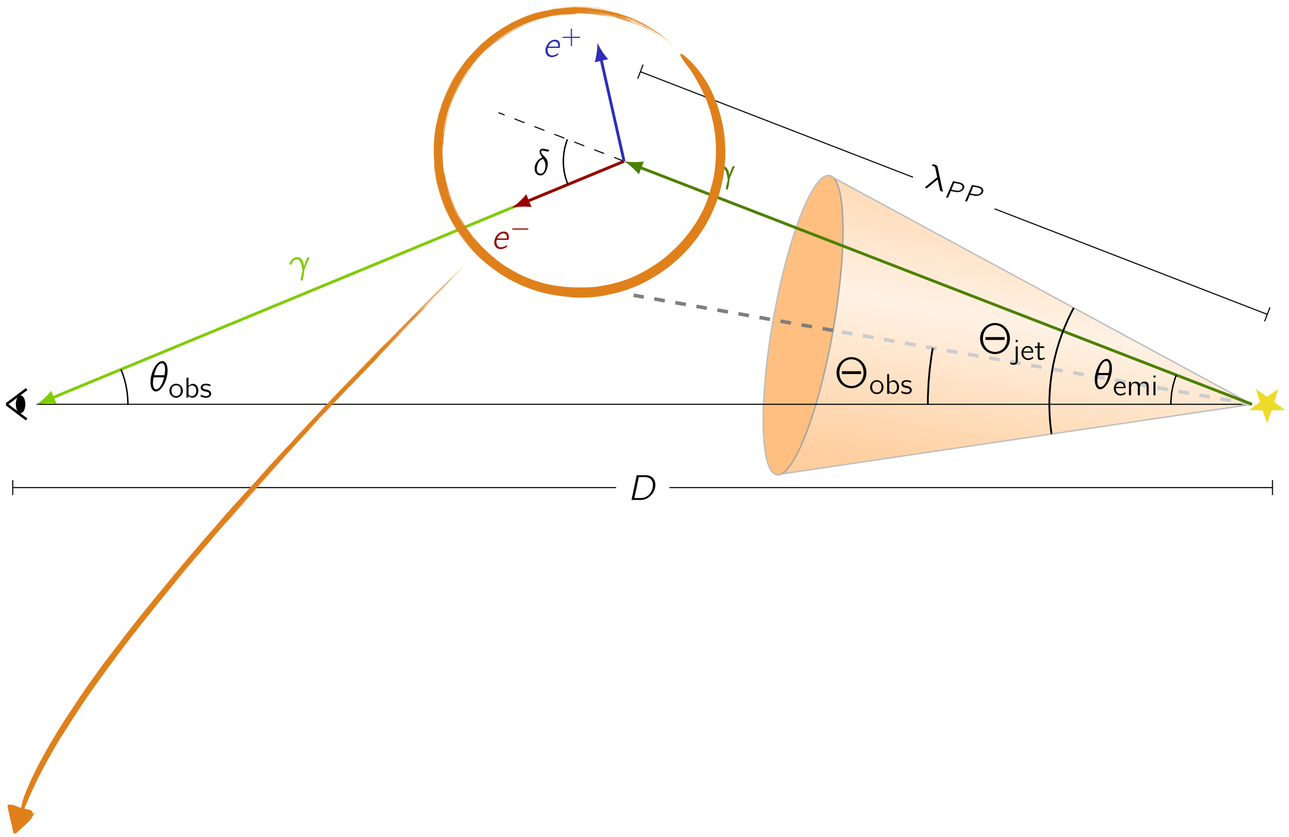
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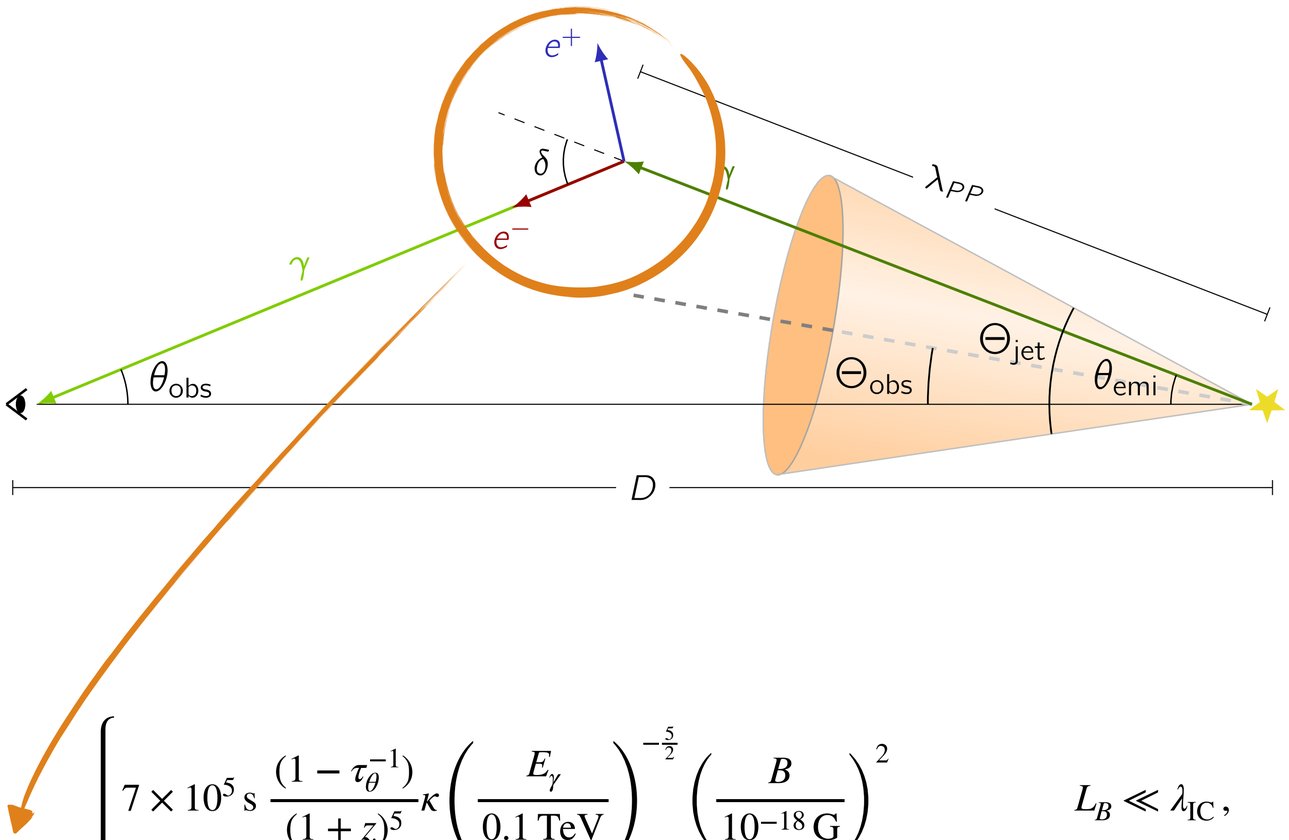
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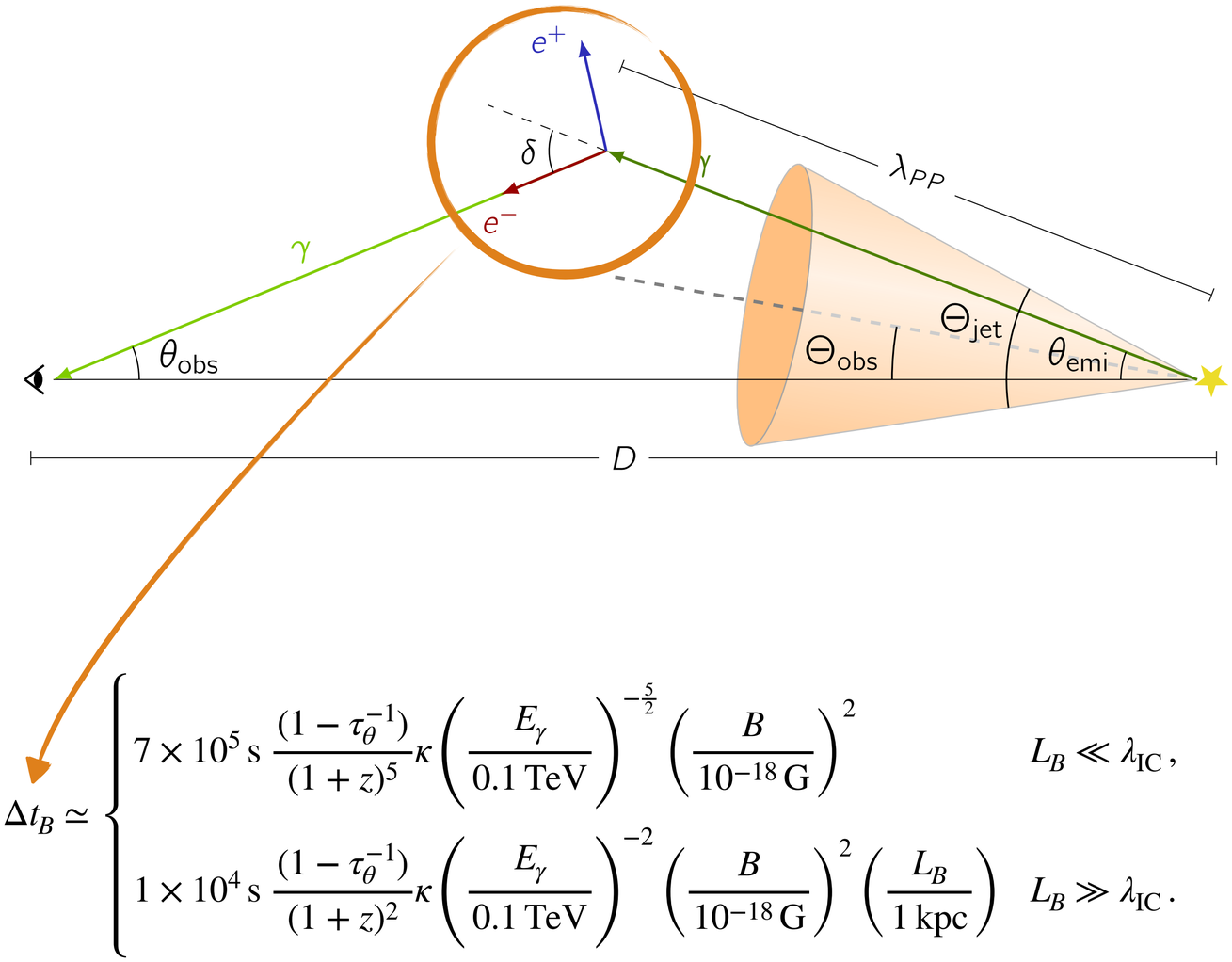
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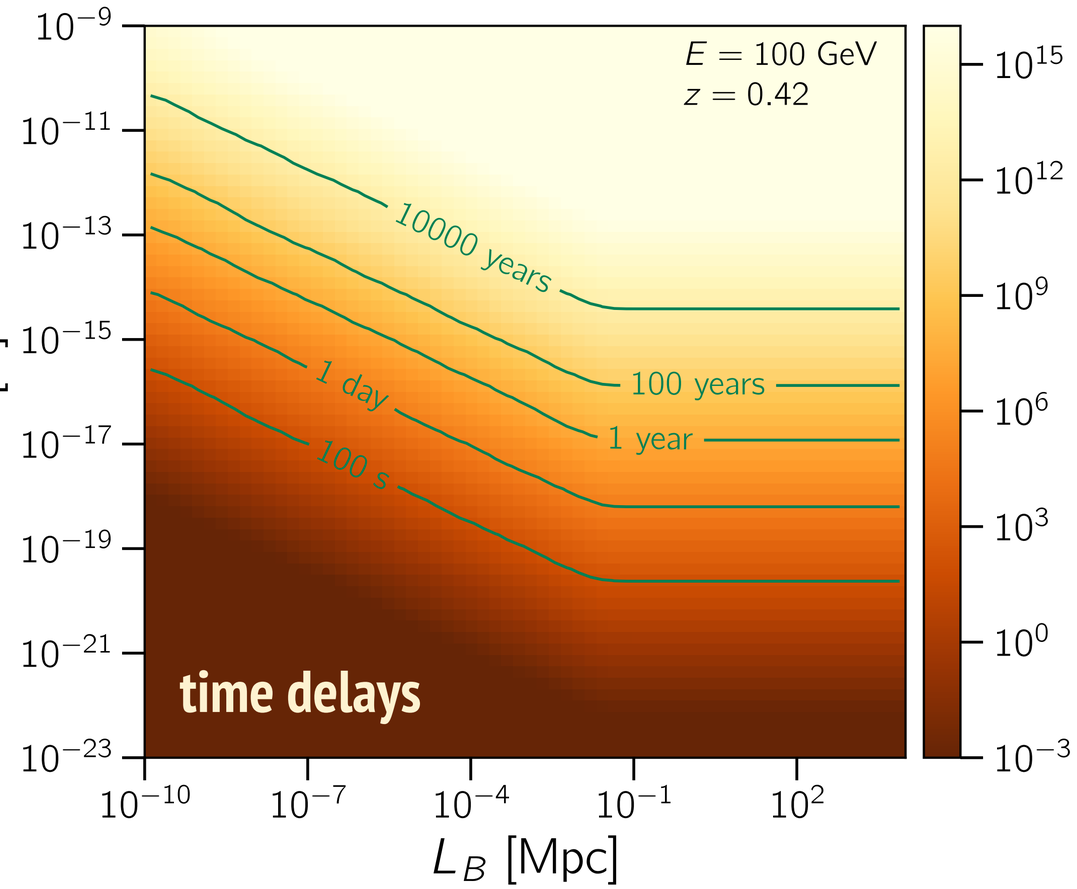
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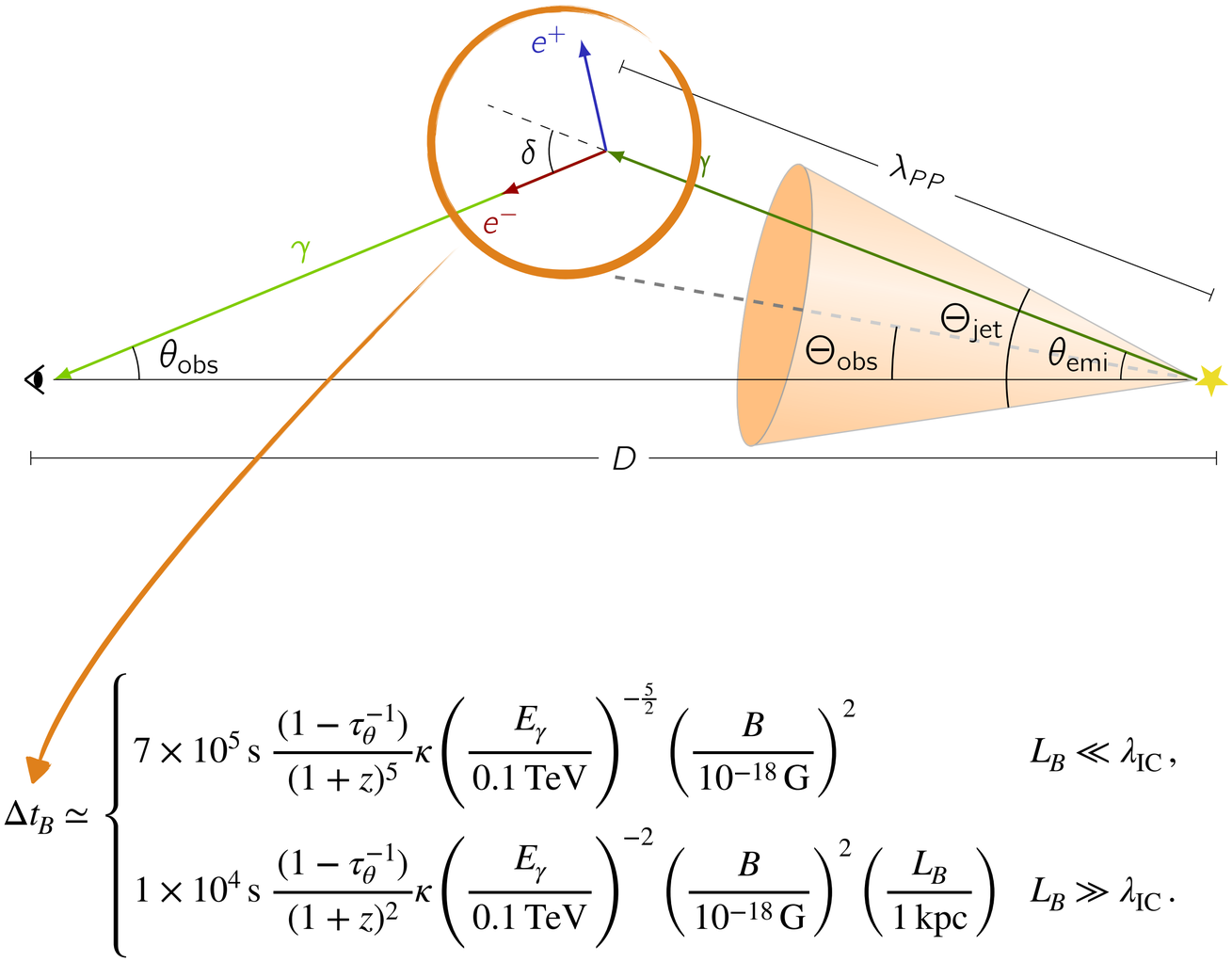


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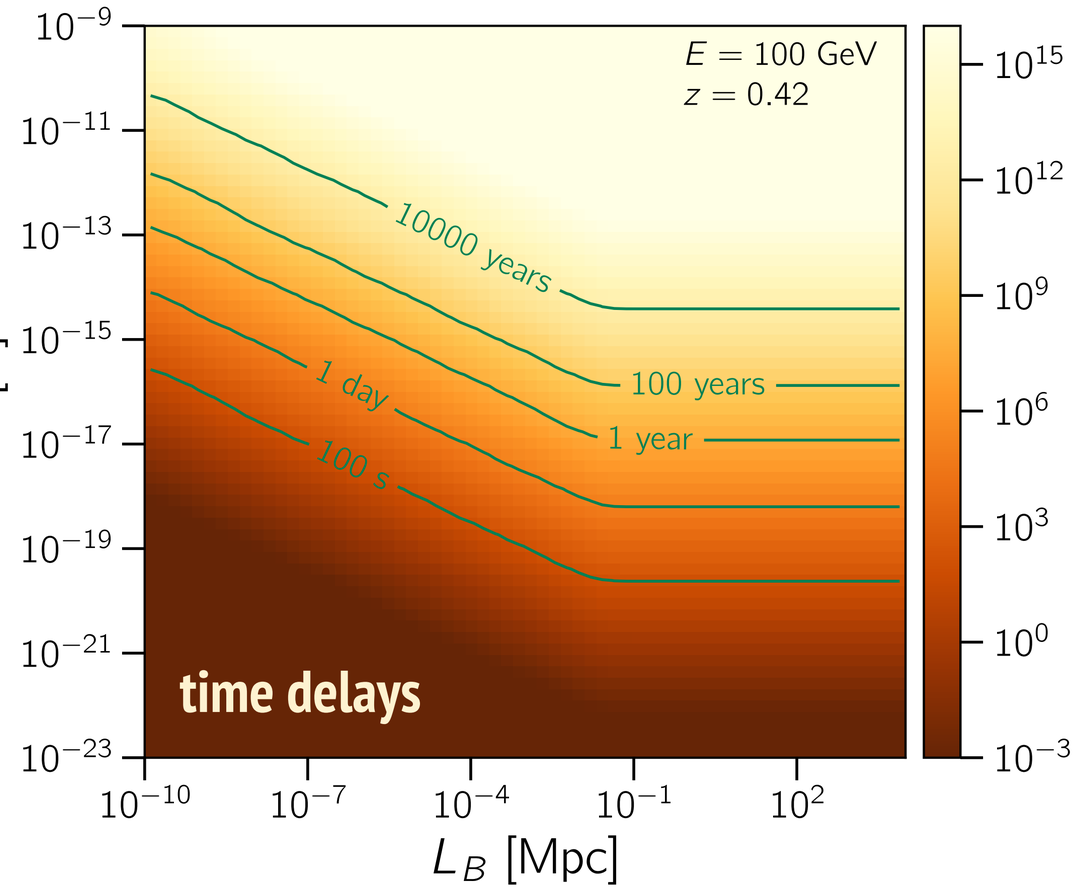
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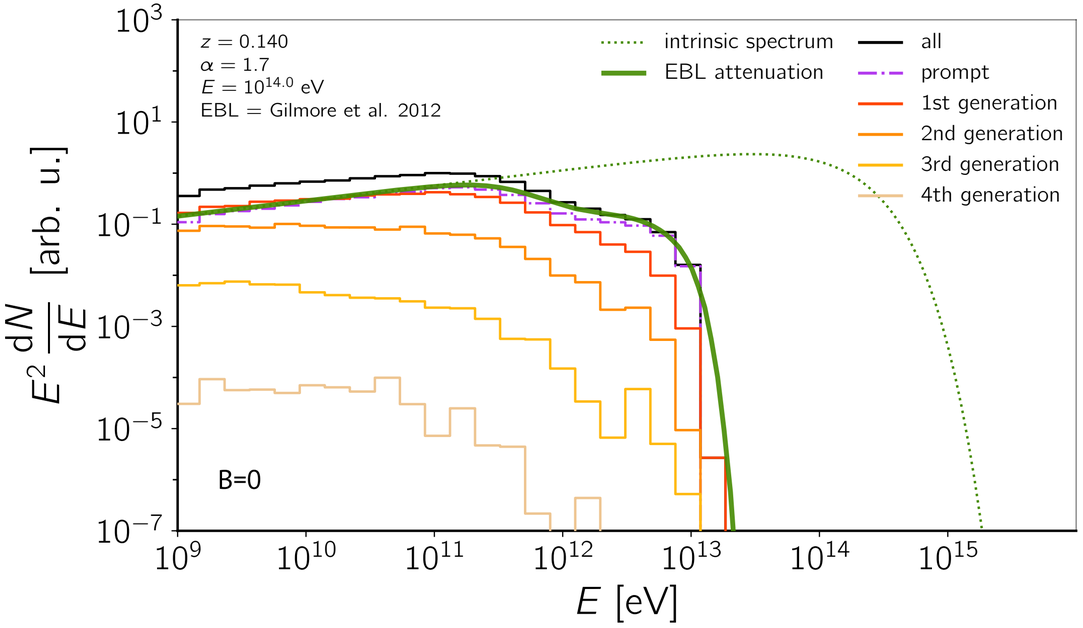


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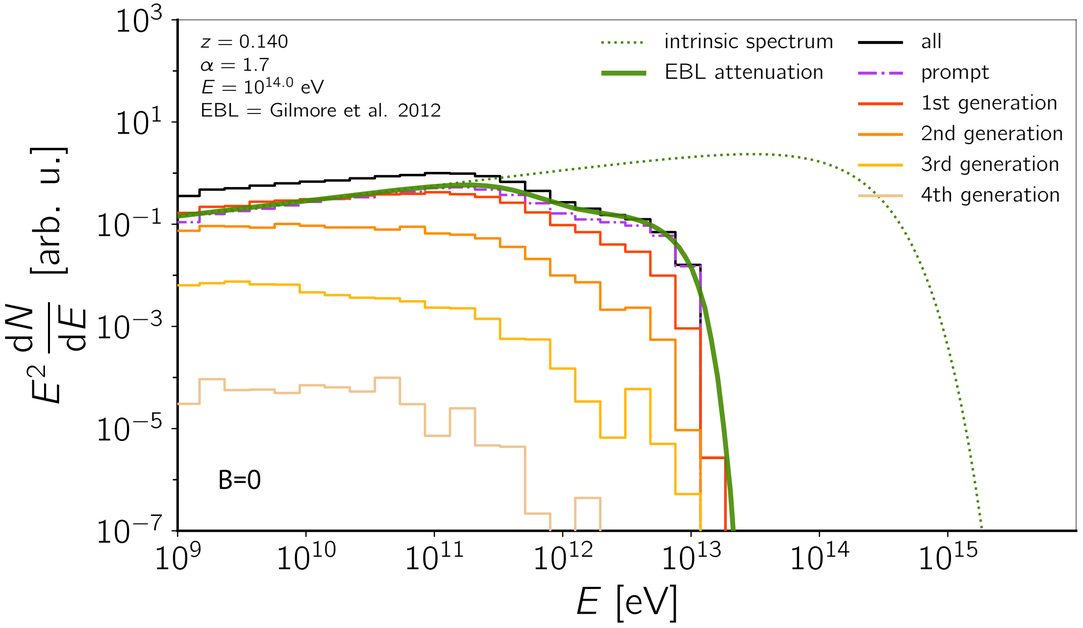
what fraction of the observed gamma-ray flux can be time-delayed?



gamma rays: detailed simulations of gamma-ray propagation



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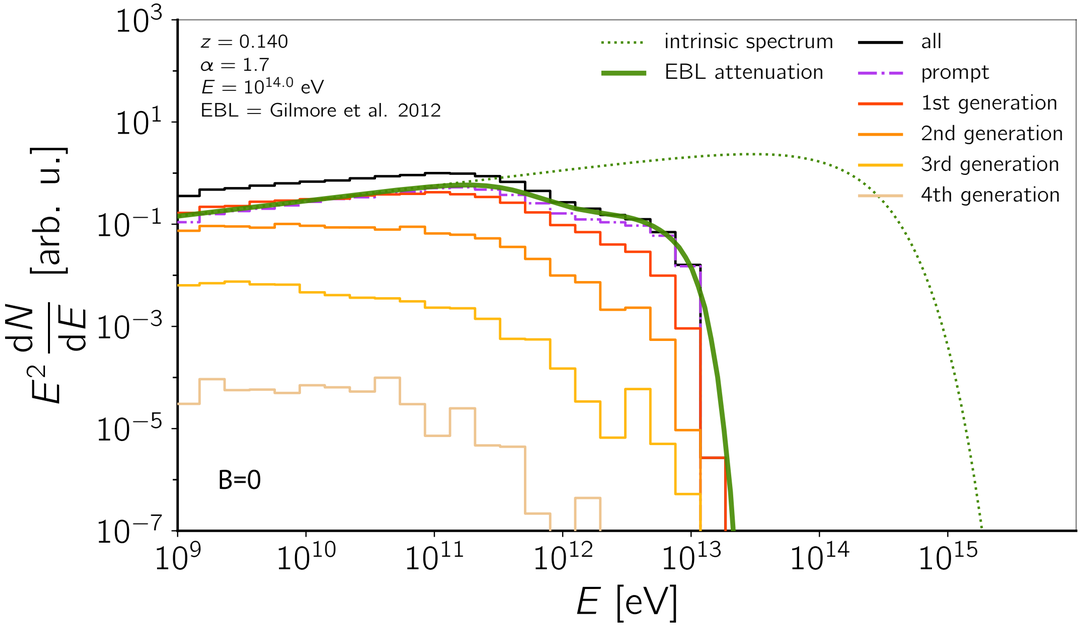


simulations performed with CRPropa

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

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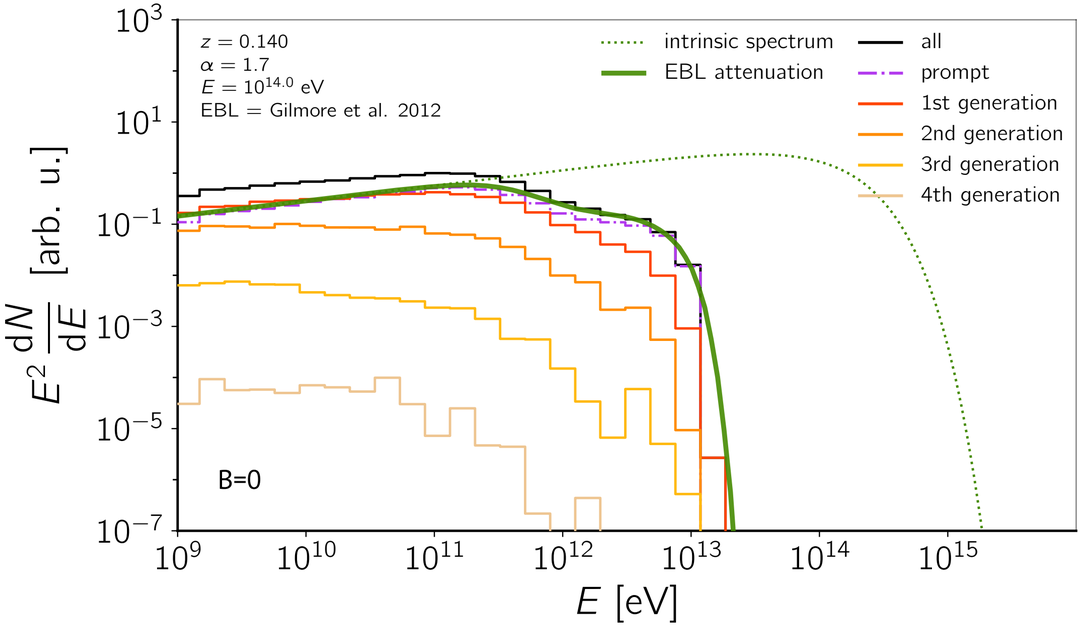
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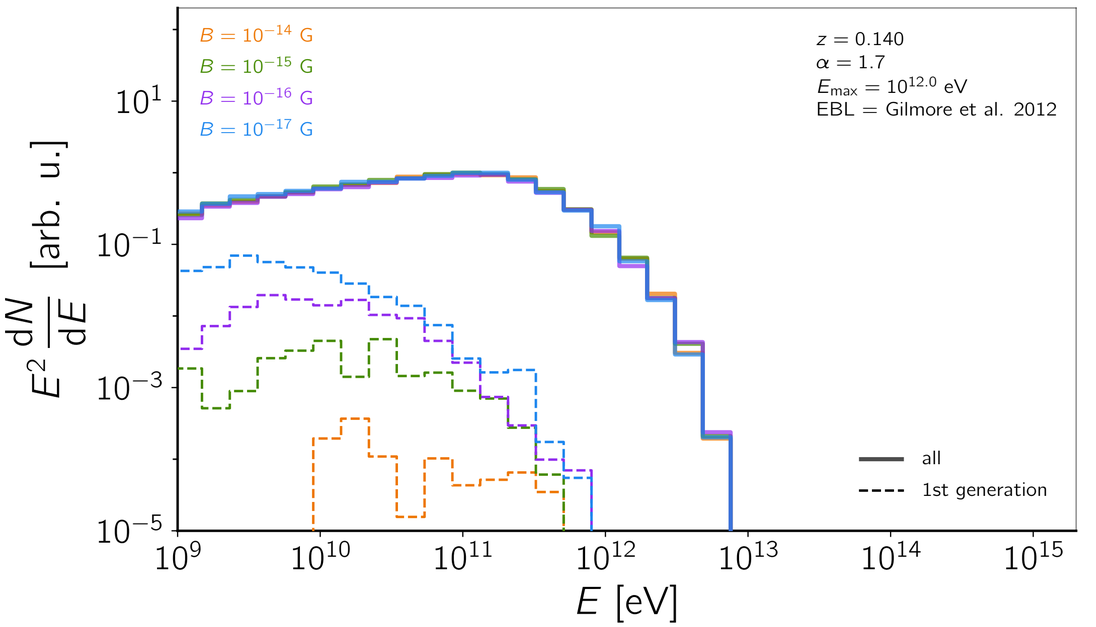
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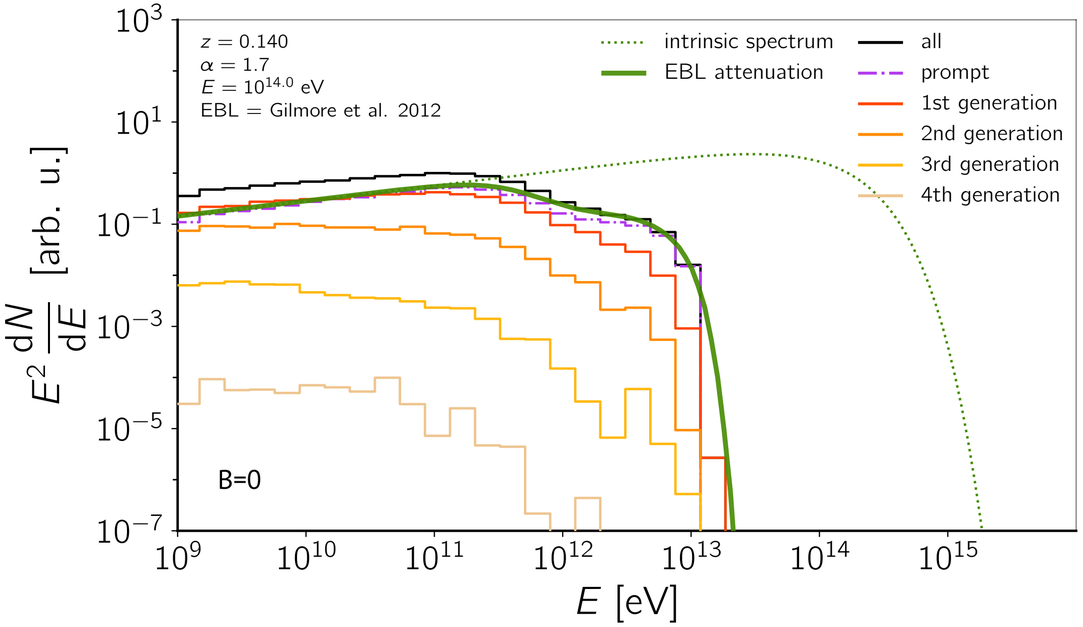
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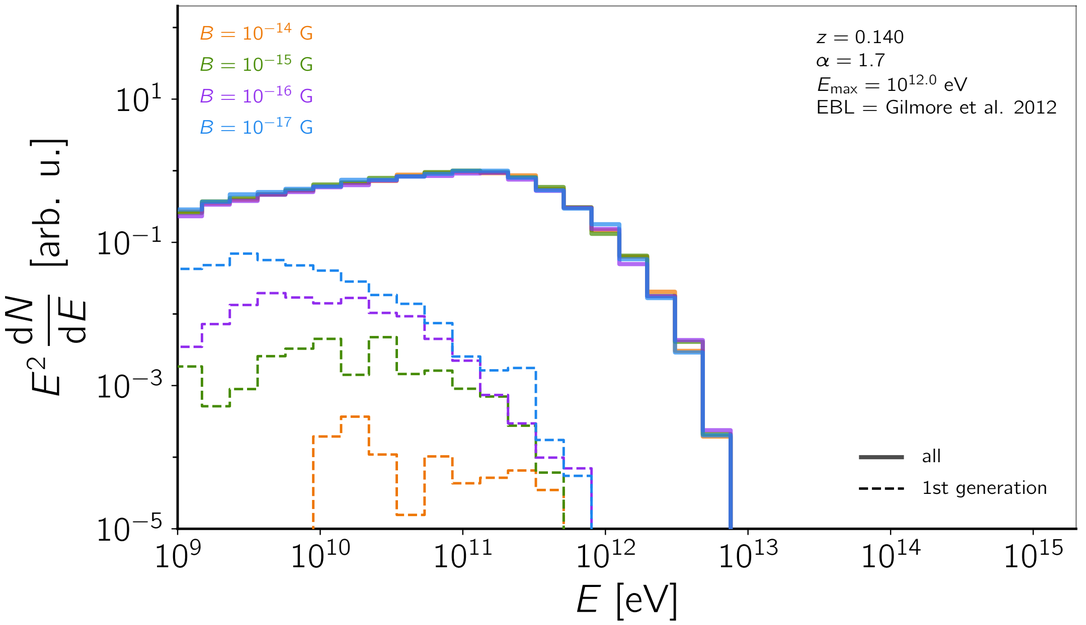
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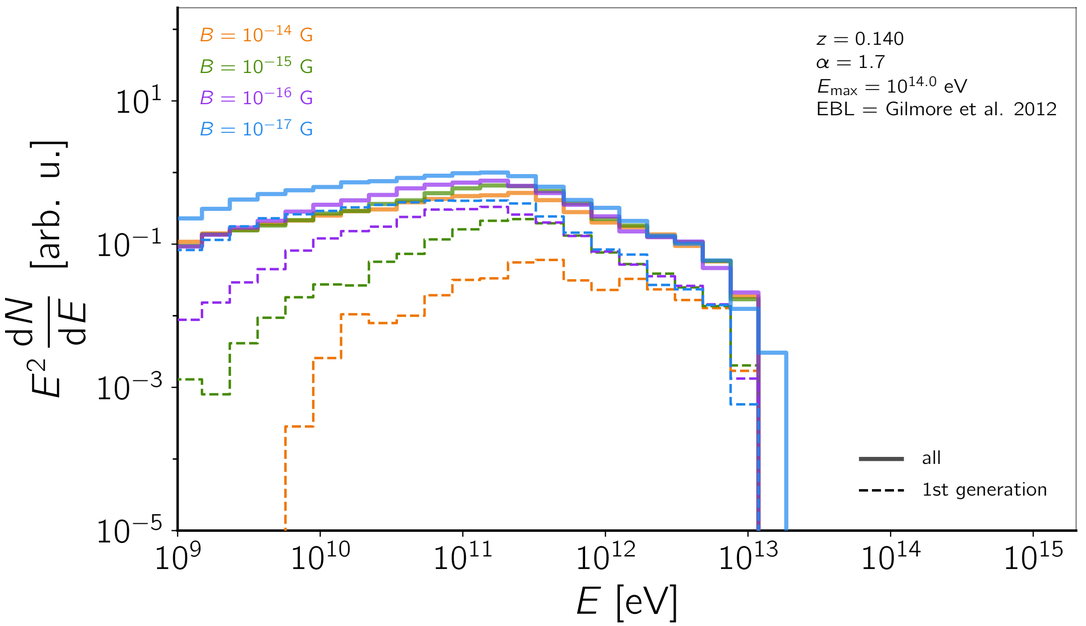
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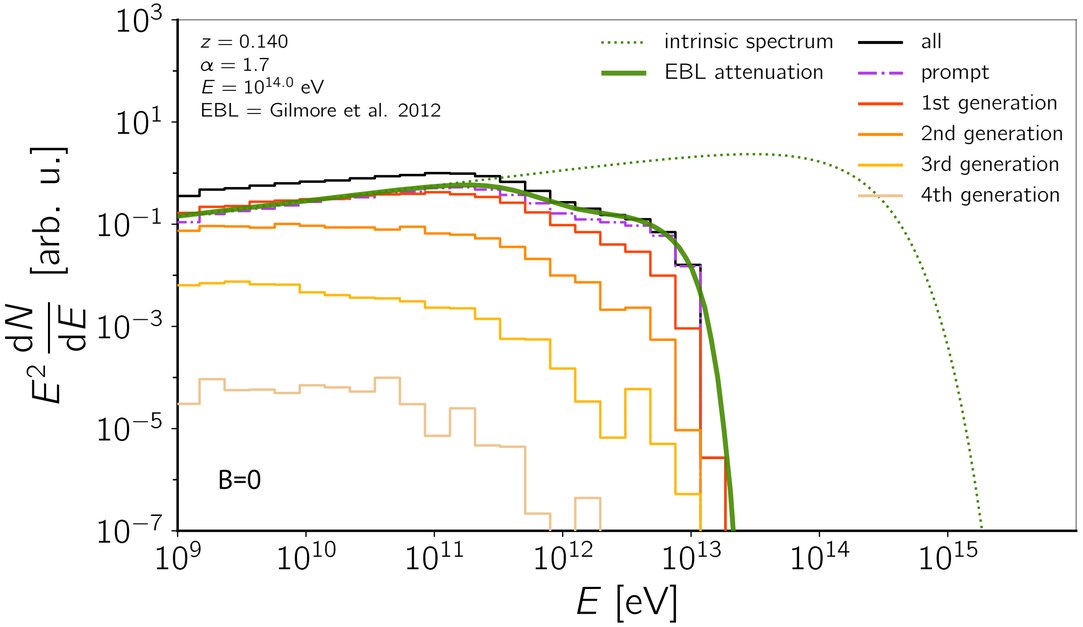


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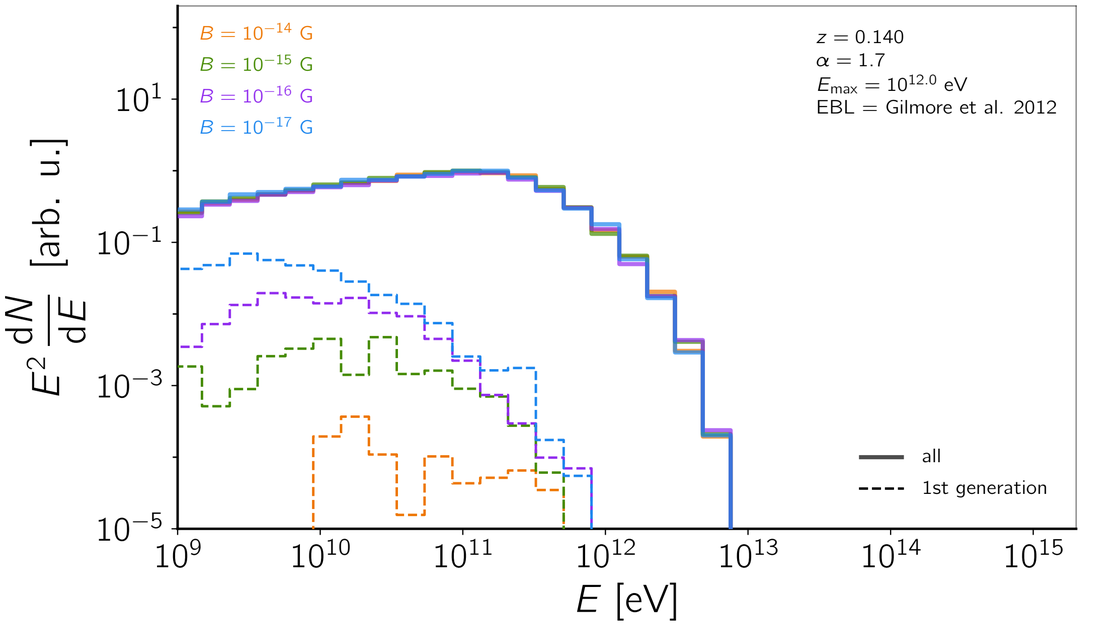
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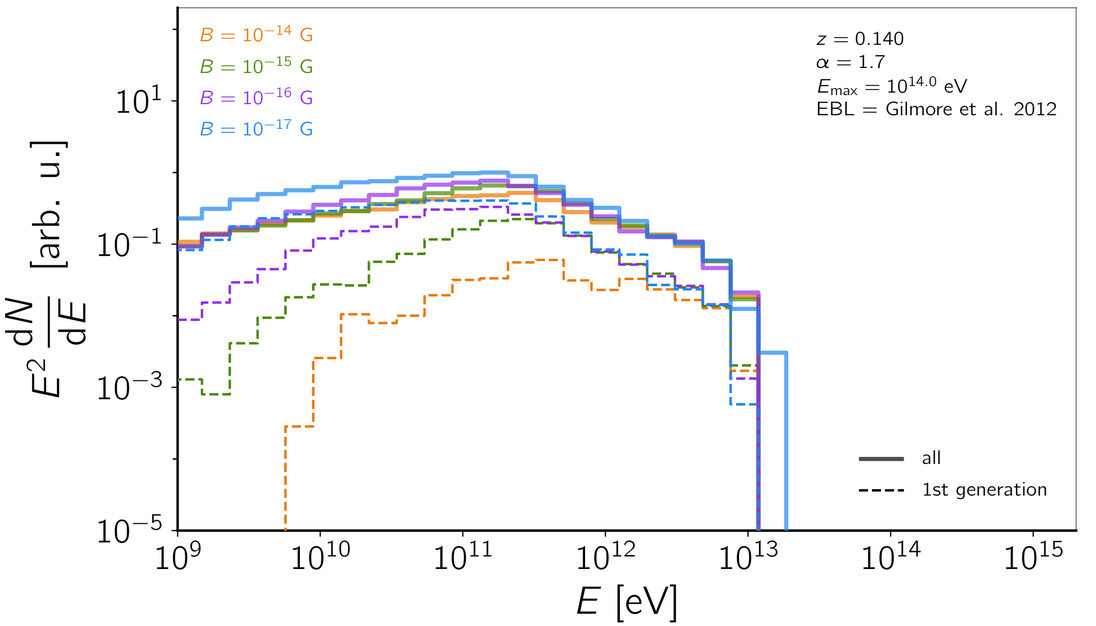
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difficult to identify QG signatures with confidence



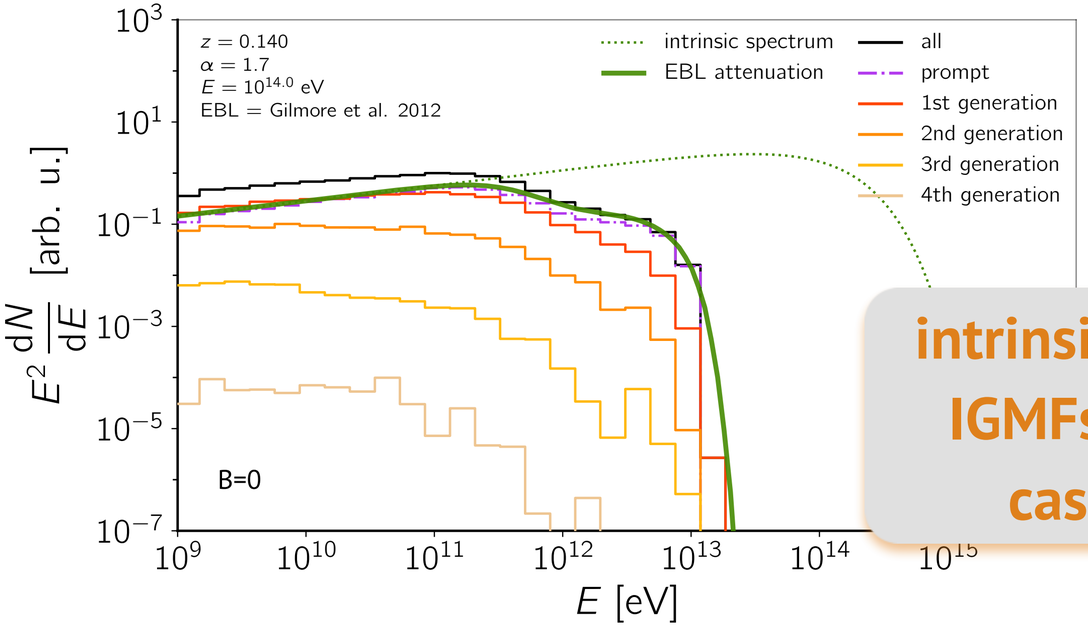


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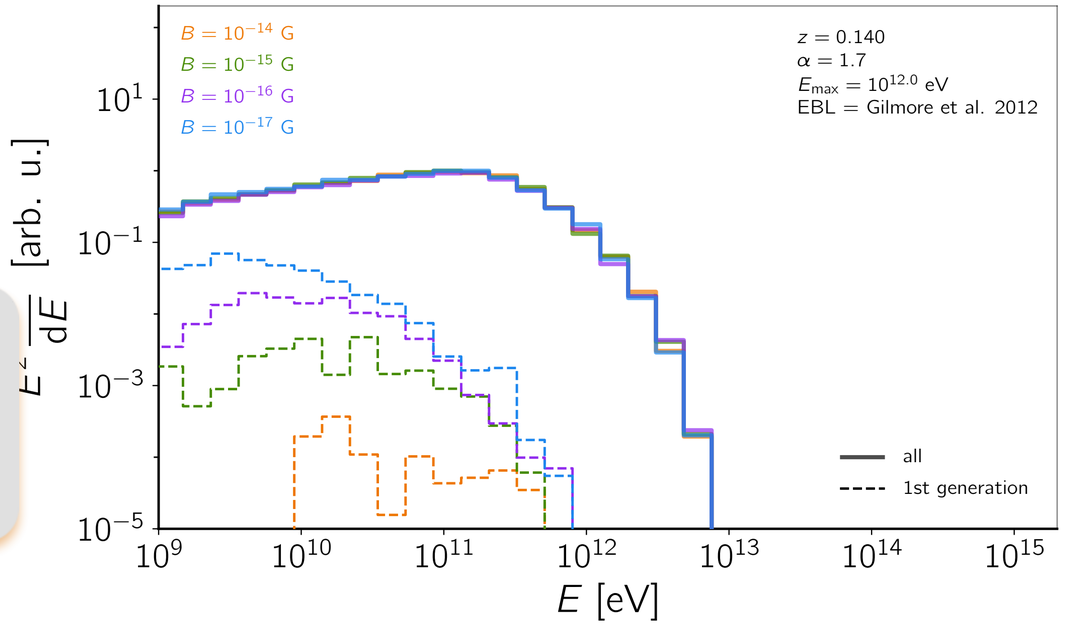
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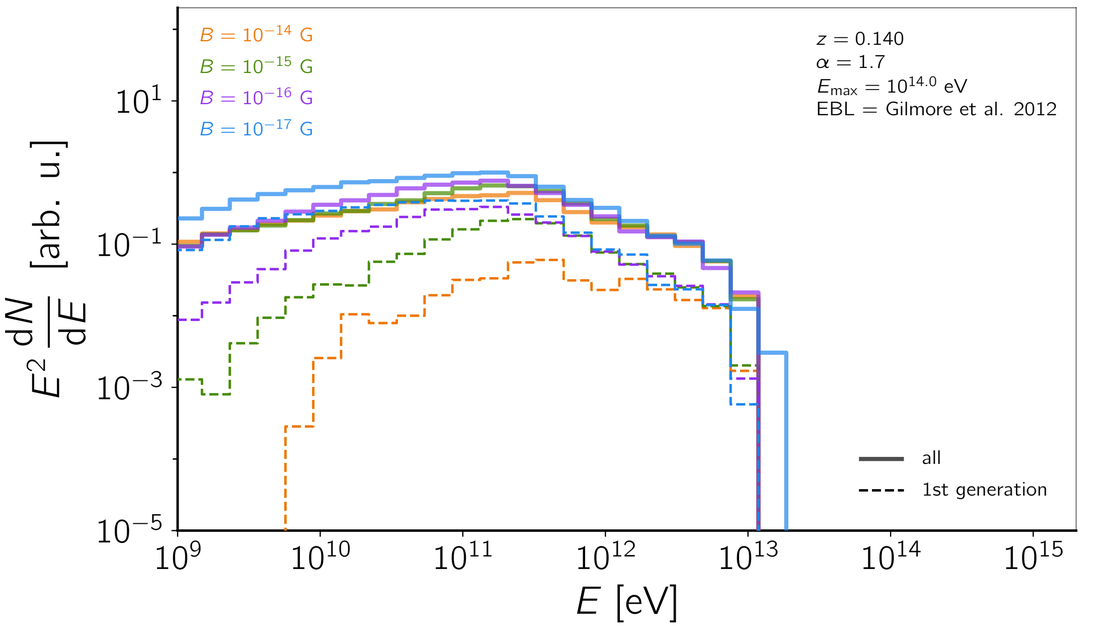


intrinsic spectrum + IGMFs determine cascade flux



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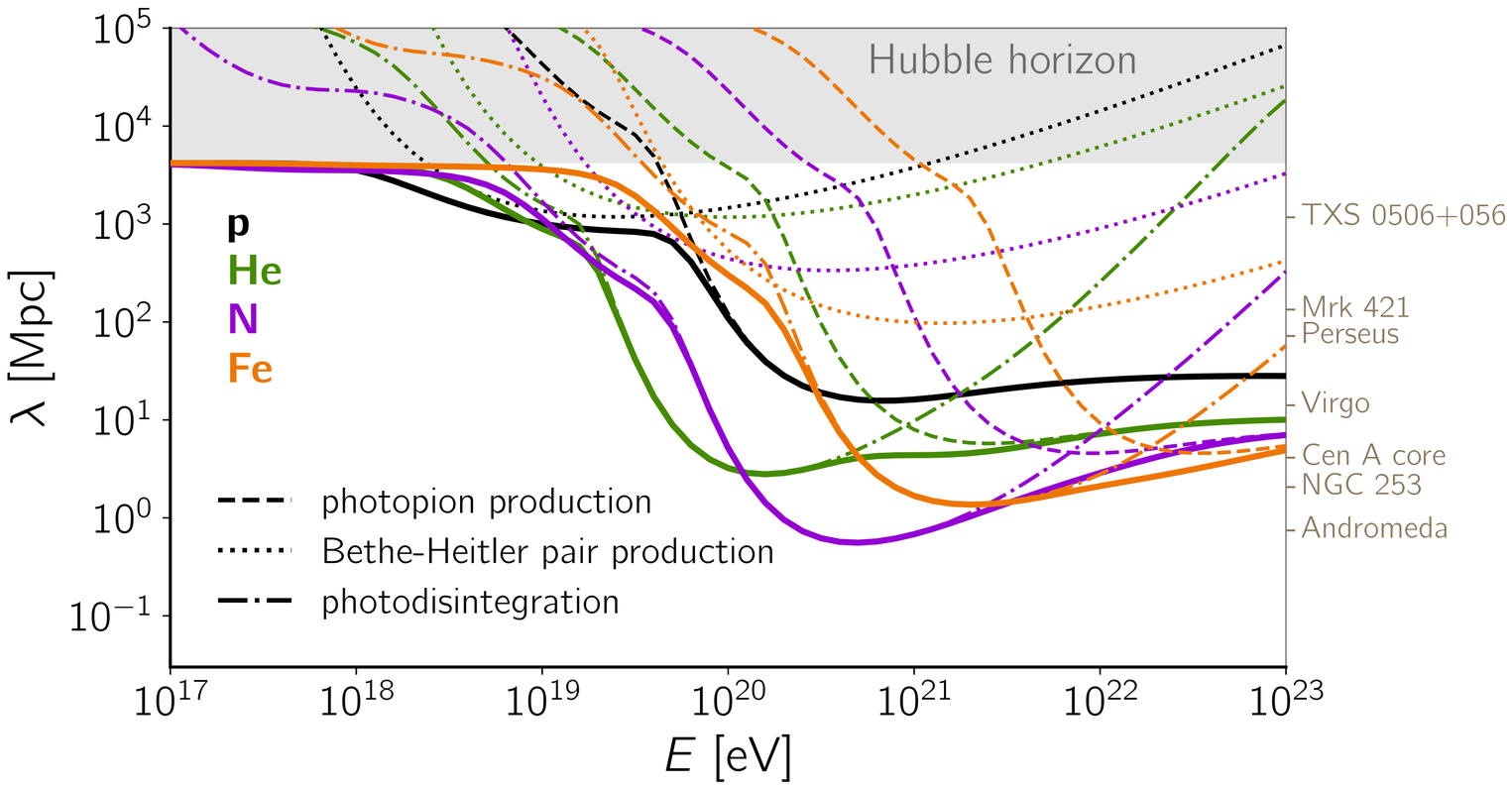
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how to connect QG phenomenology with observations?

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UHECRs

UHECRs: interactions during cosmological propagation



photopion production

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

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

$\mu^+ \rightarrow e^+ + \nu_e + \underline{\nu_\mu}$

(similar for nuclei)

Bethe-Heitler pair production

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nuclear decays

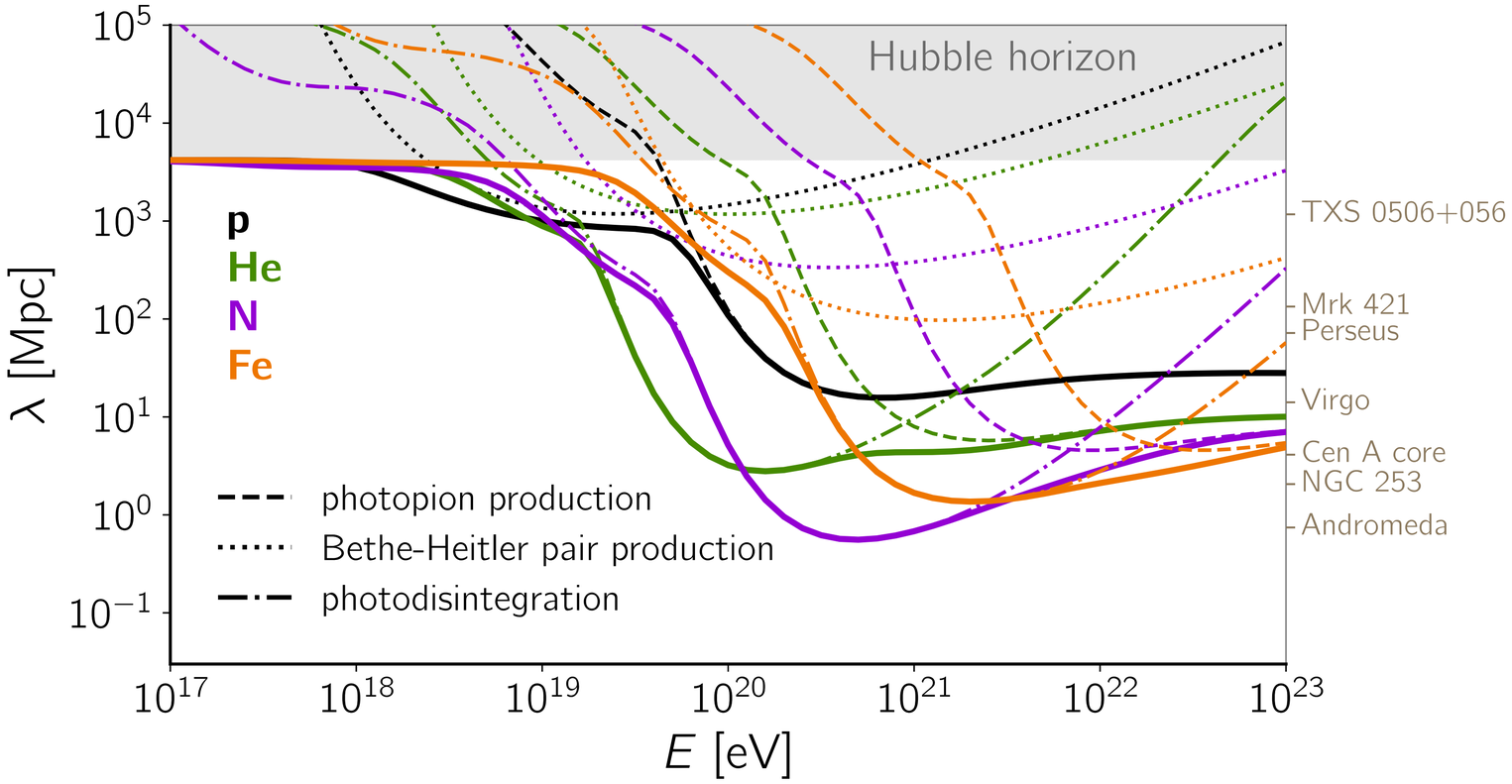
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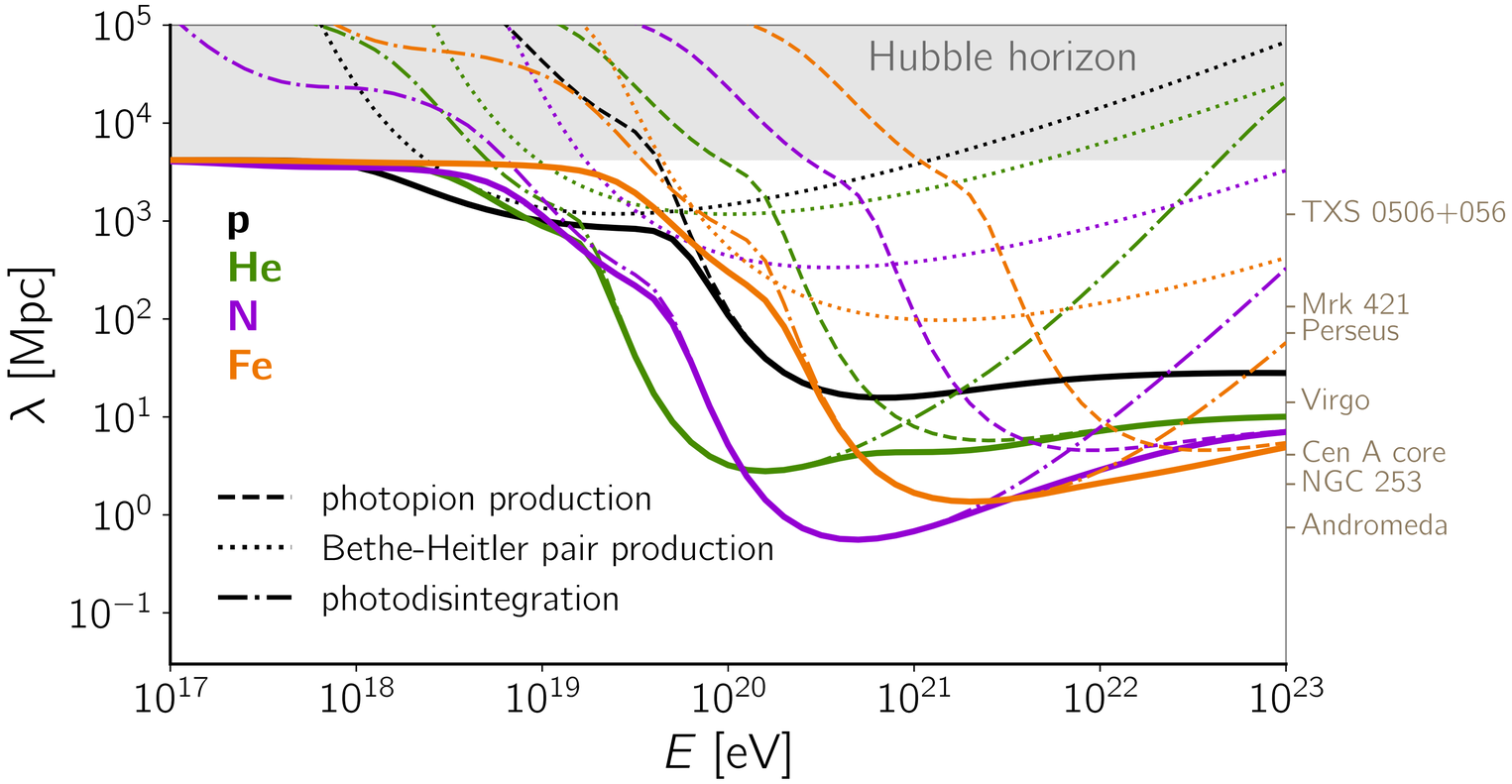
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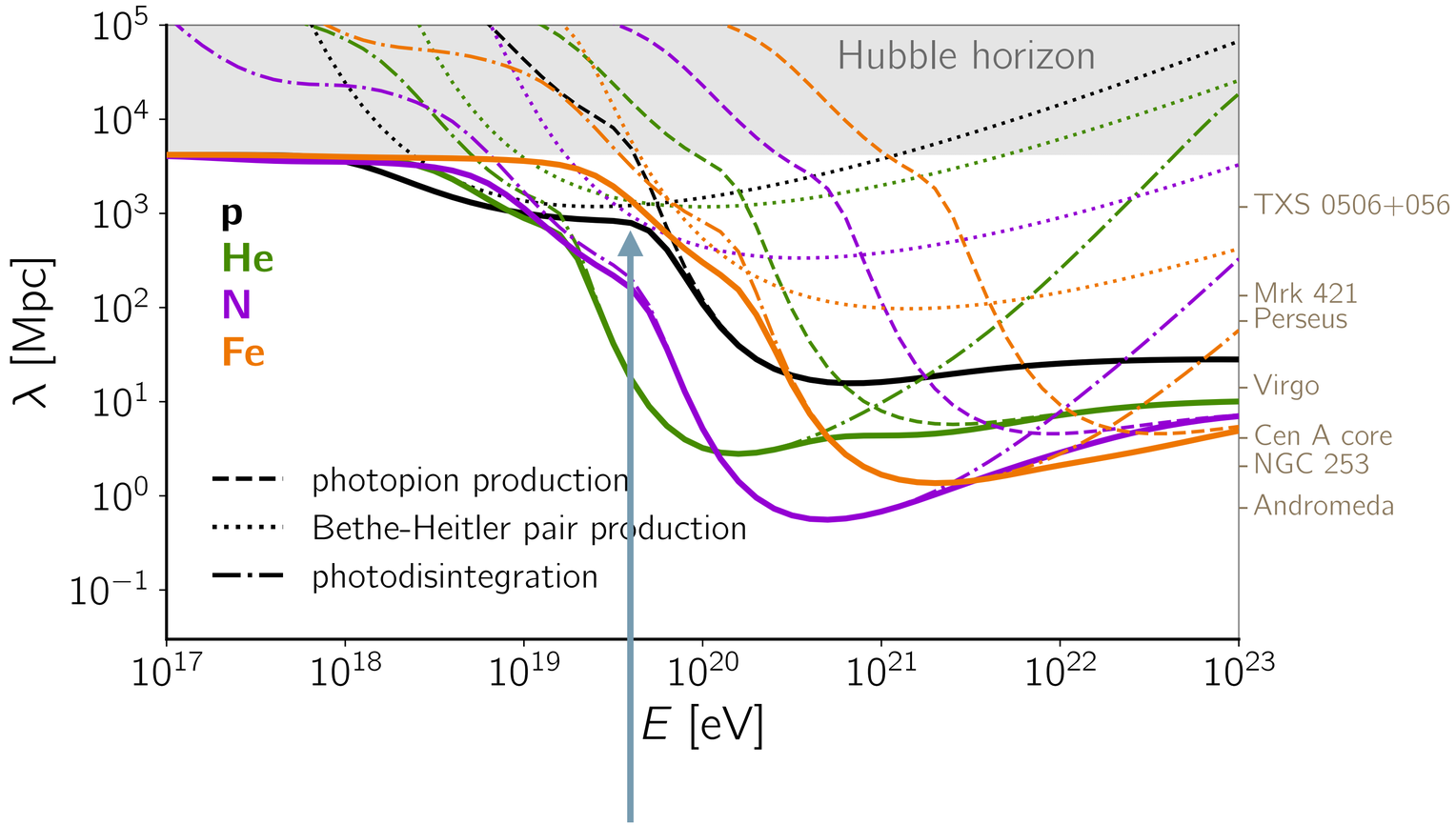
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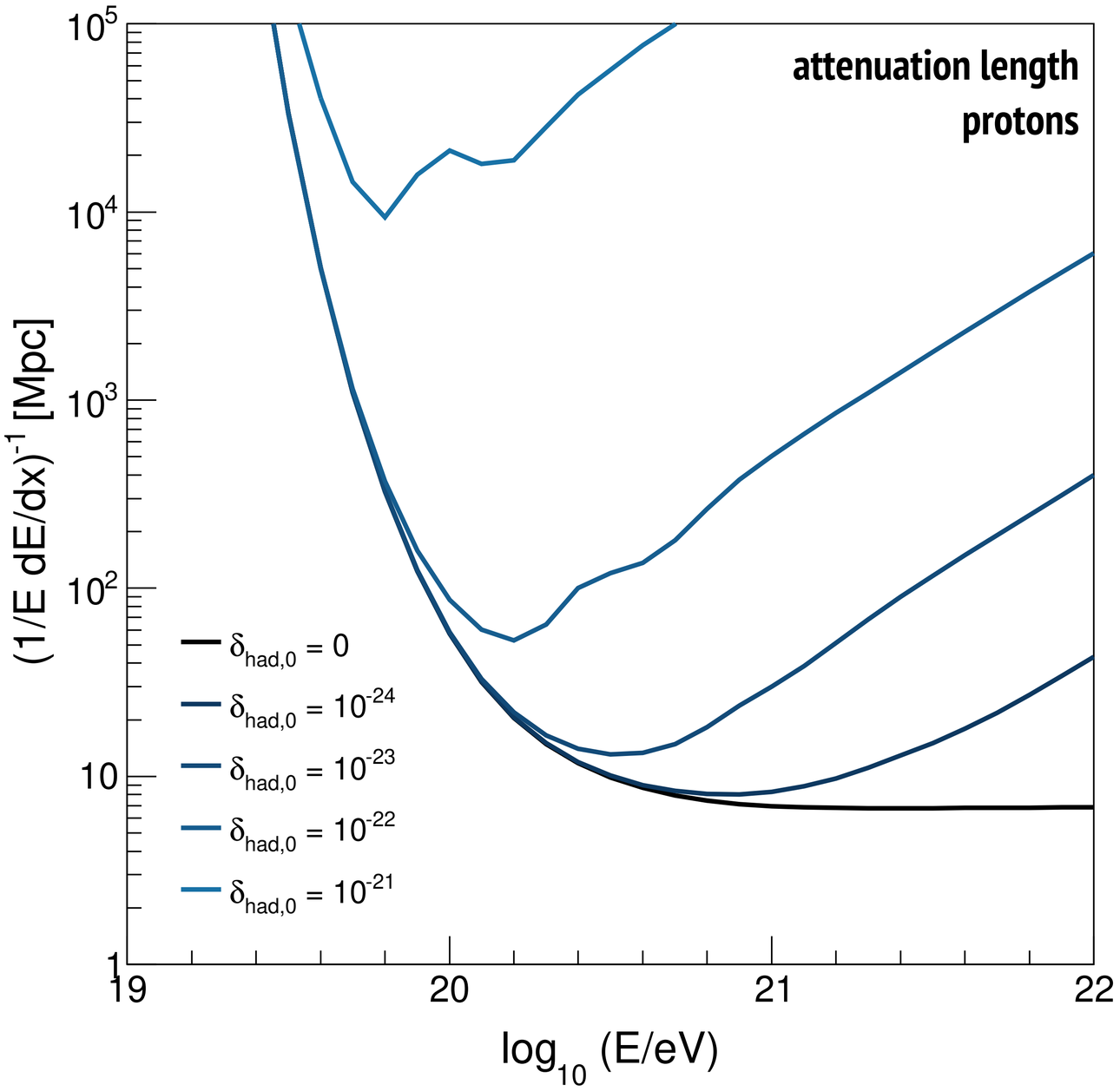
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UHECRs: modification of interaction thresholds by QG

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



photopion production

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

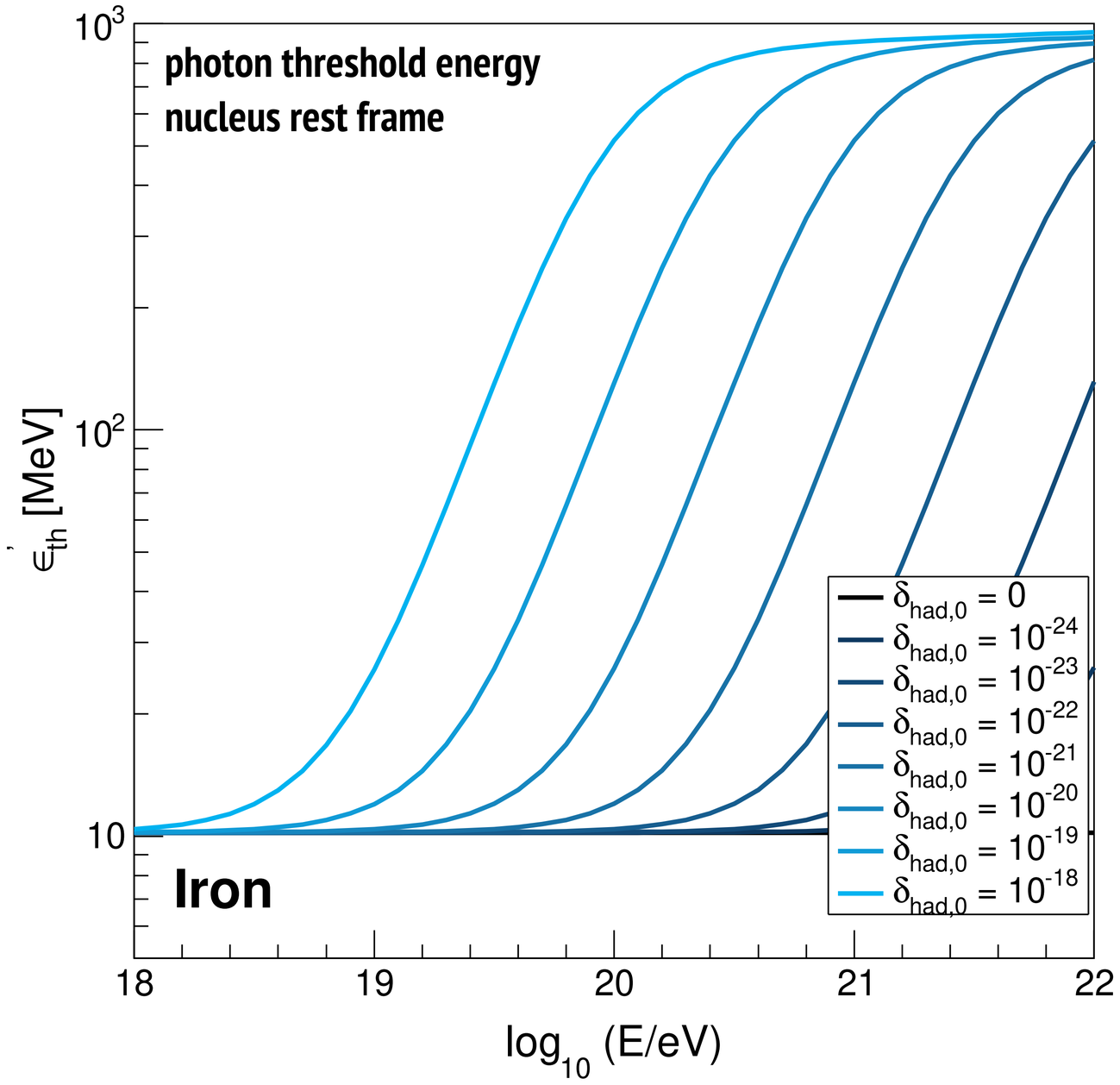
$p + \gamma_{bg} \rightarrow n + \pi^+$ $\quad$ $\pi^+ \rightarrow \nu_\mu + \mu^+$

$\mu^+ \rightarrow e^+ + \nu_e + \underline{\nu_\mu}$

(similar for nuclei)

UHECRs: modification of interaction thresholds by QG

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



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

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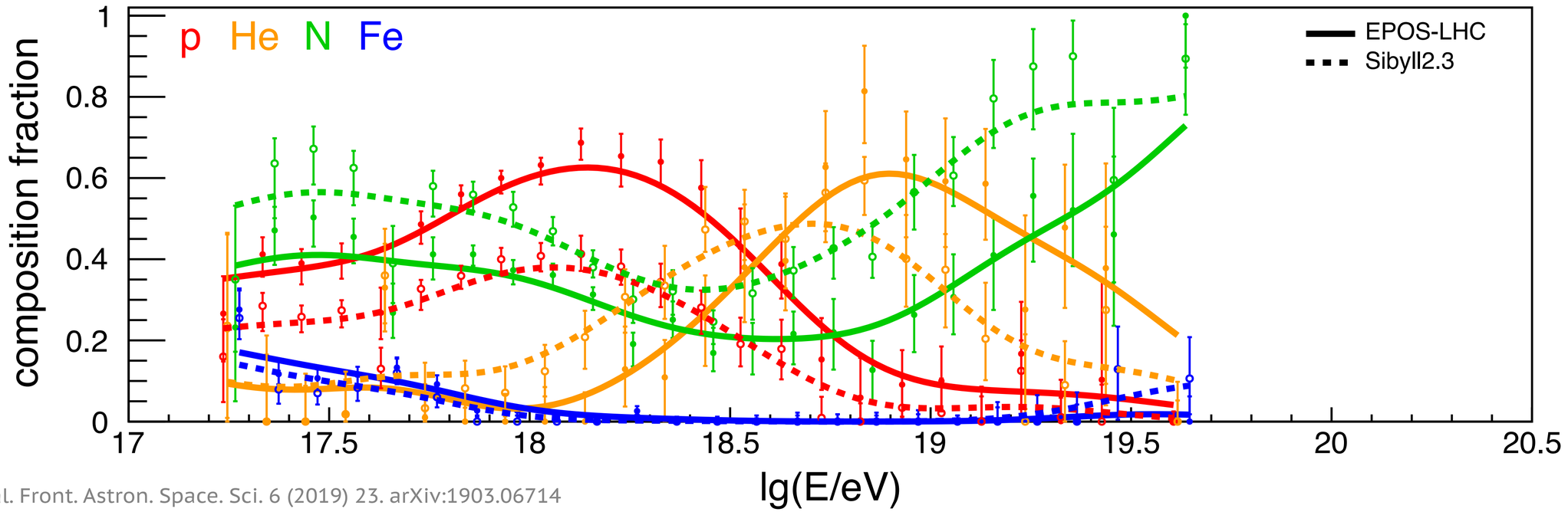
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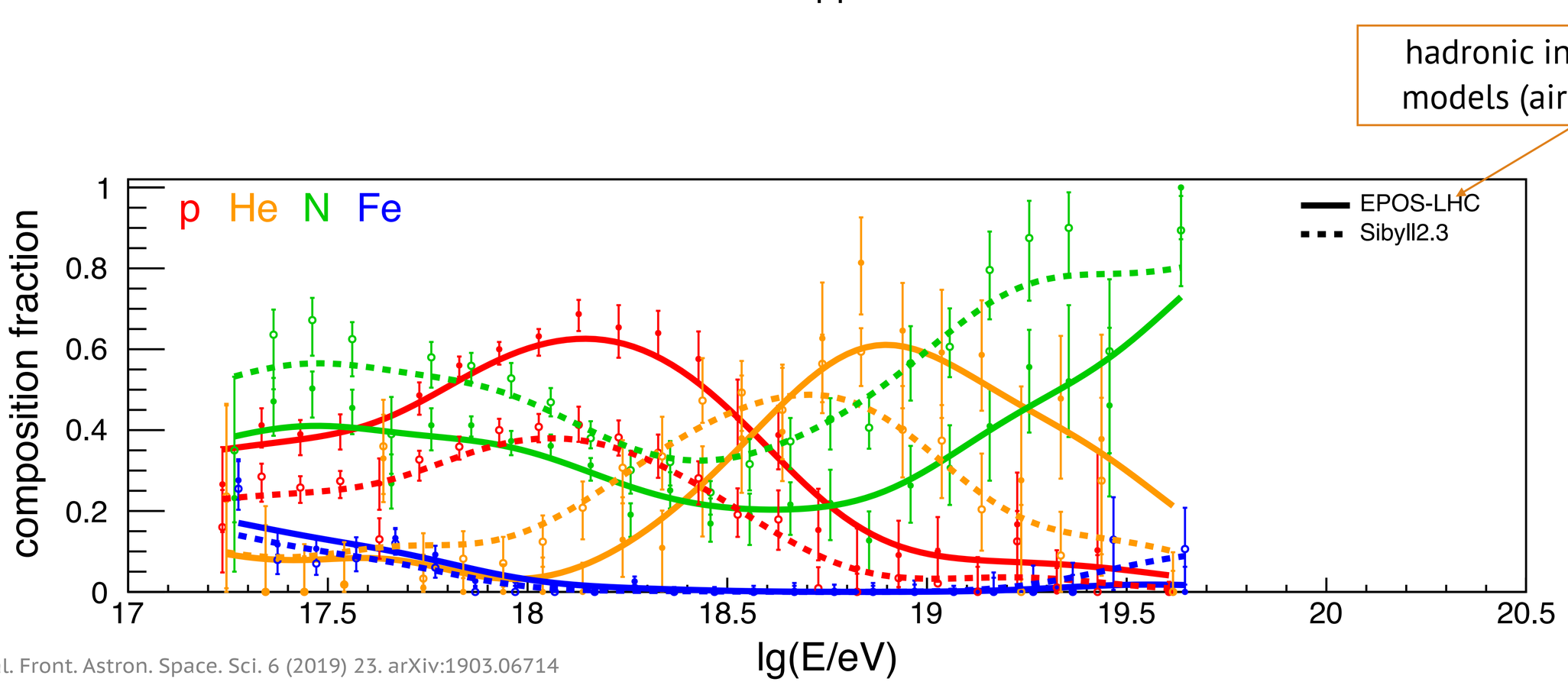
Alves Batista et al. Front. Astron. Space. Sci. 6 (2019) 23. arXiv:1903.06714

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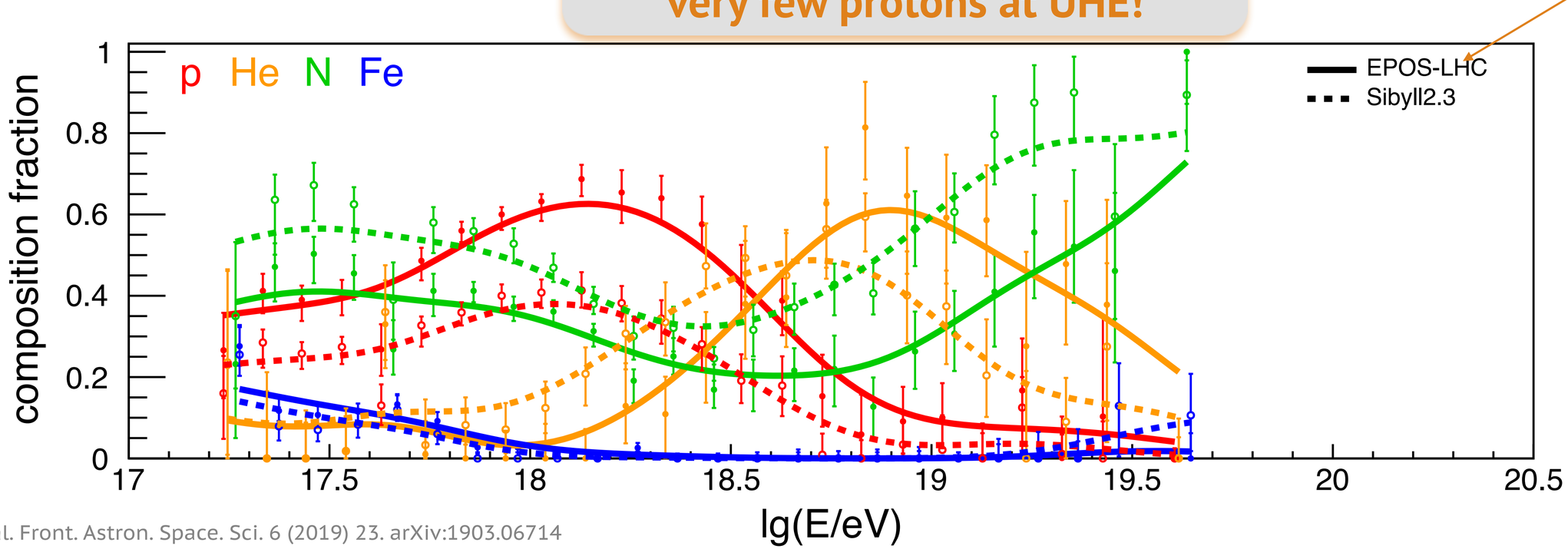
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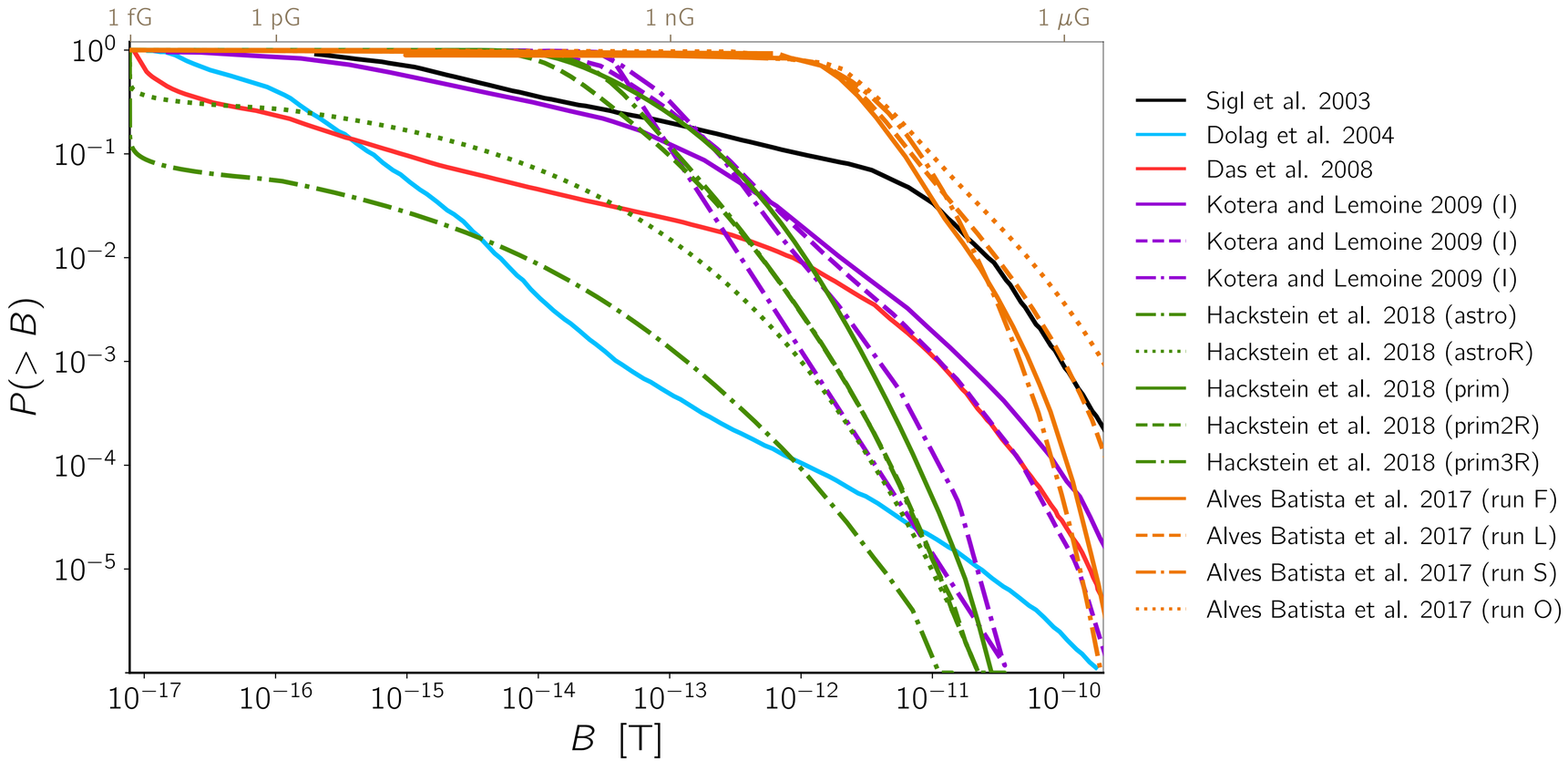
very few protons at UHE!

hadronic interaction models (air showers)

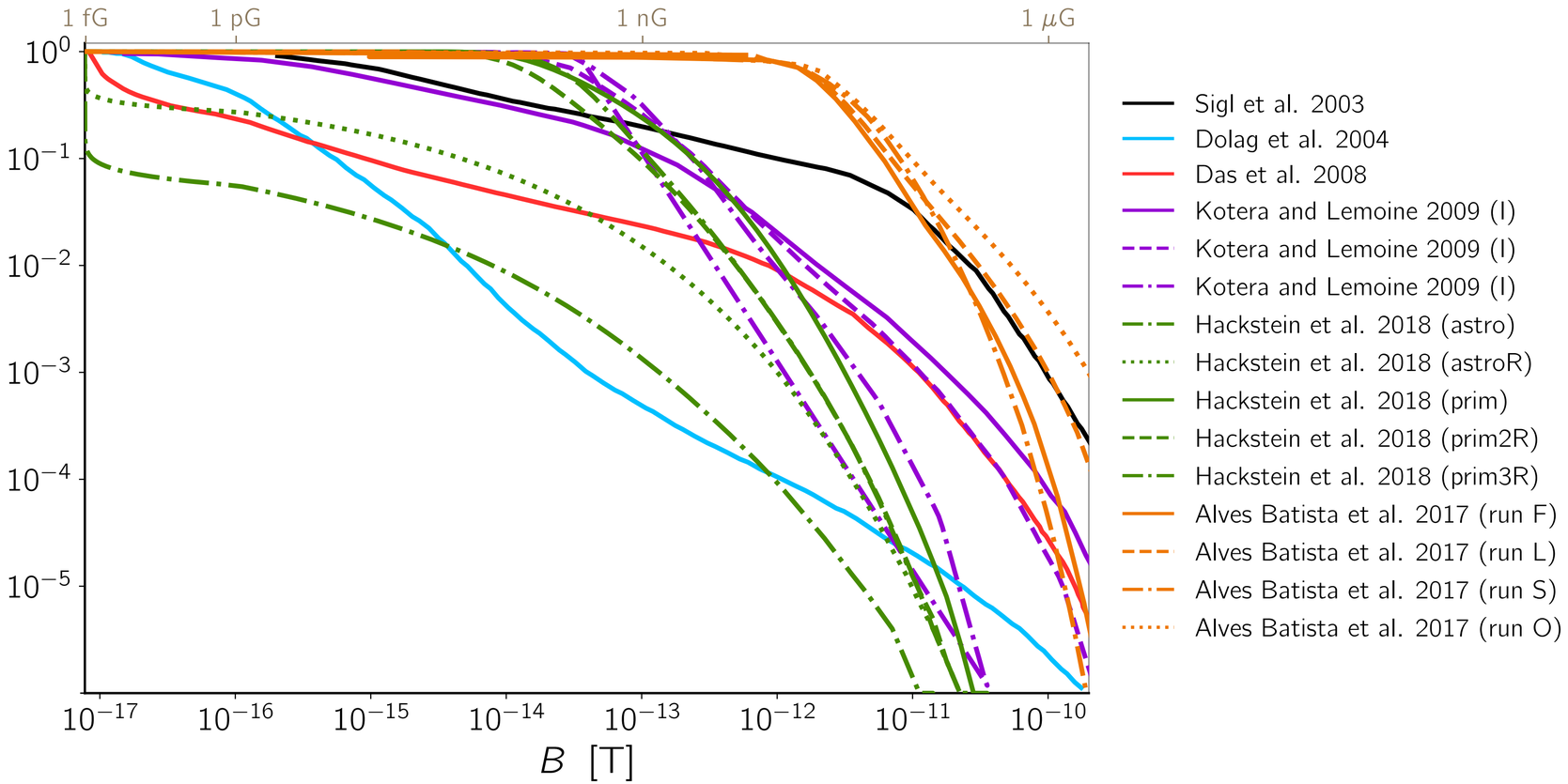


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UHECRs: deflections in magnetic field

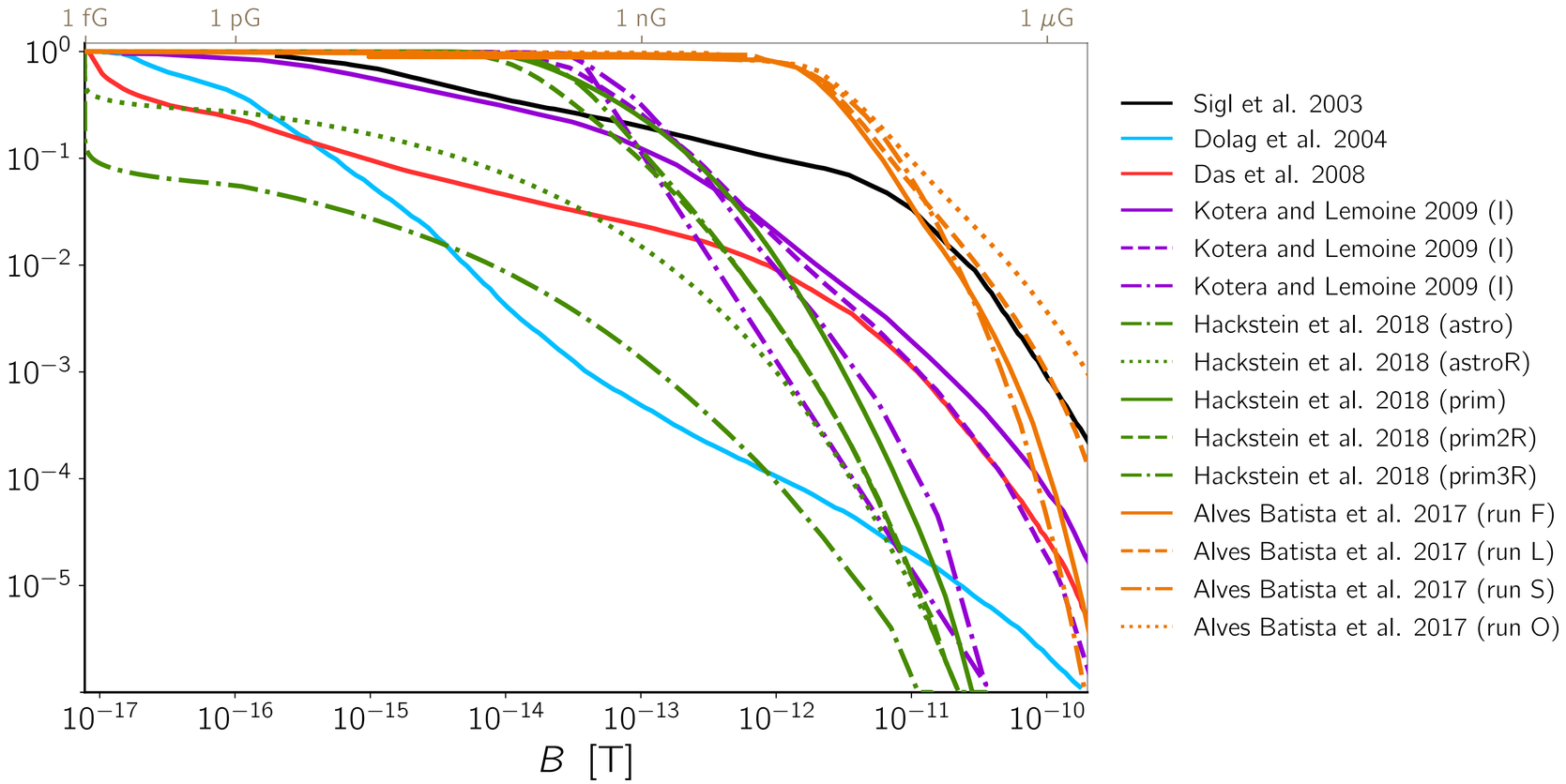


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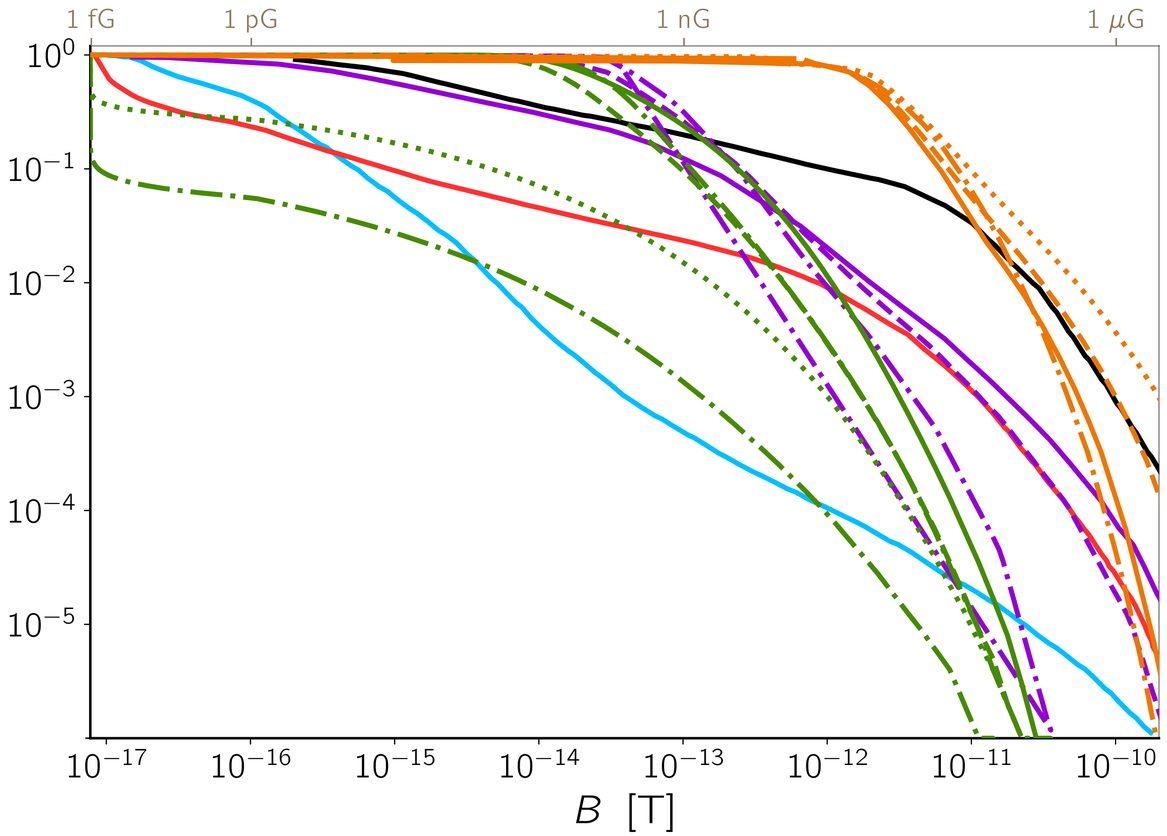
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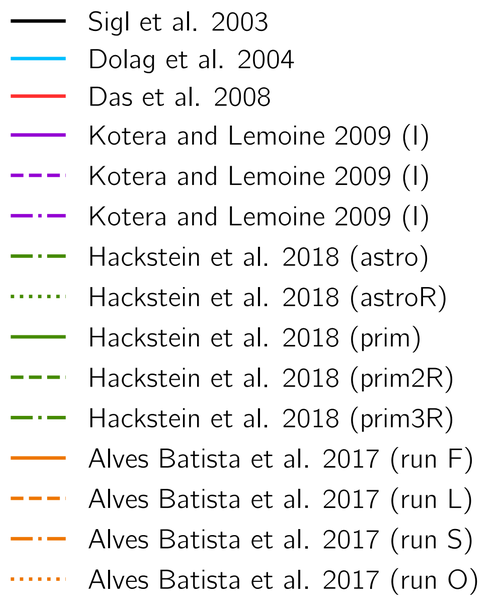


deflections

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

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deflections are completely uncertain (they can be huge)

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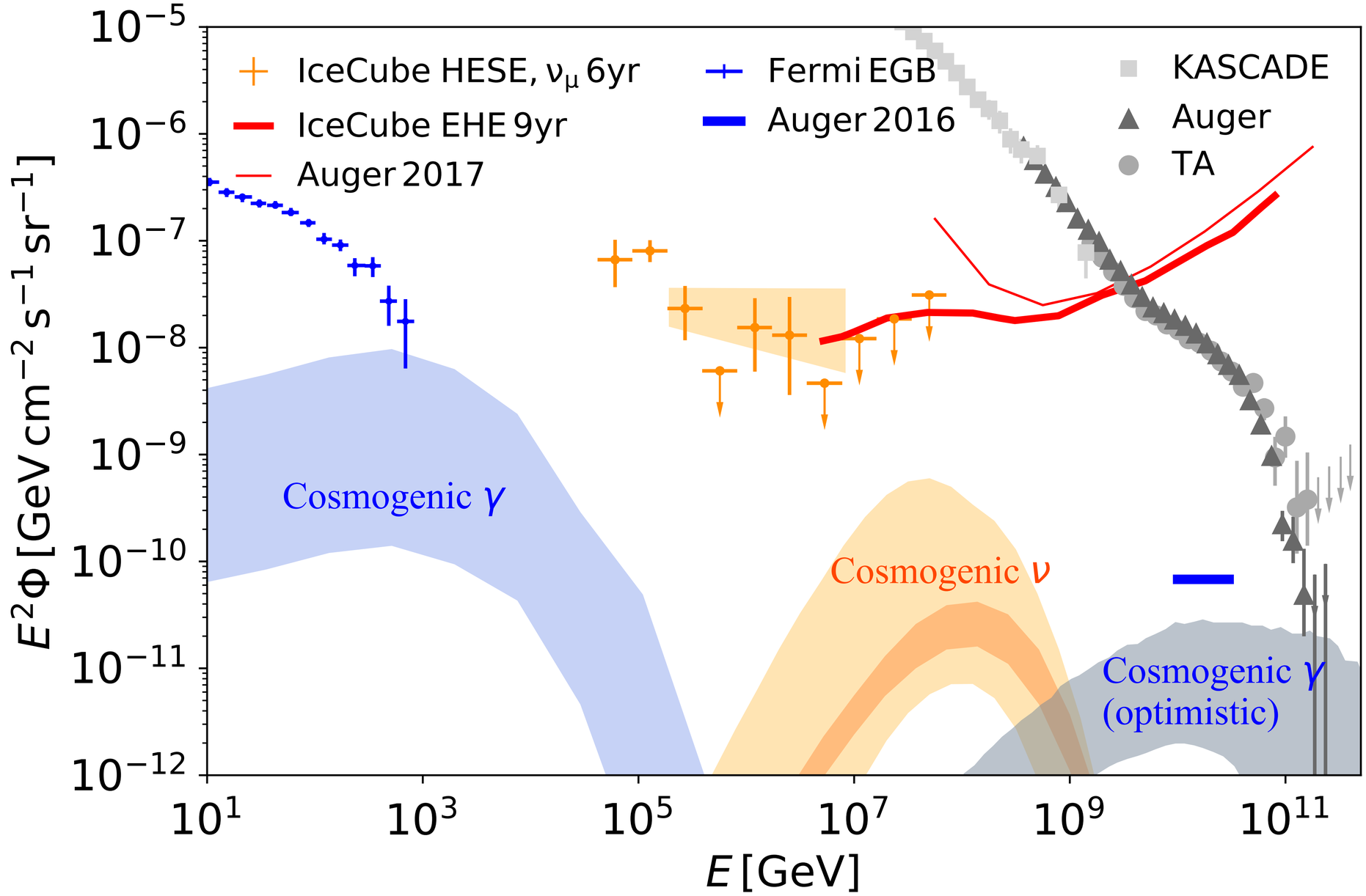
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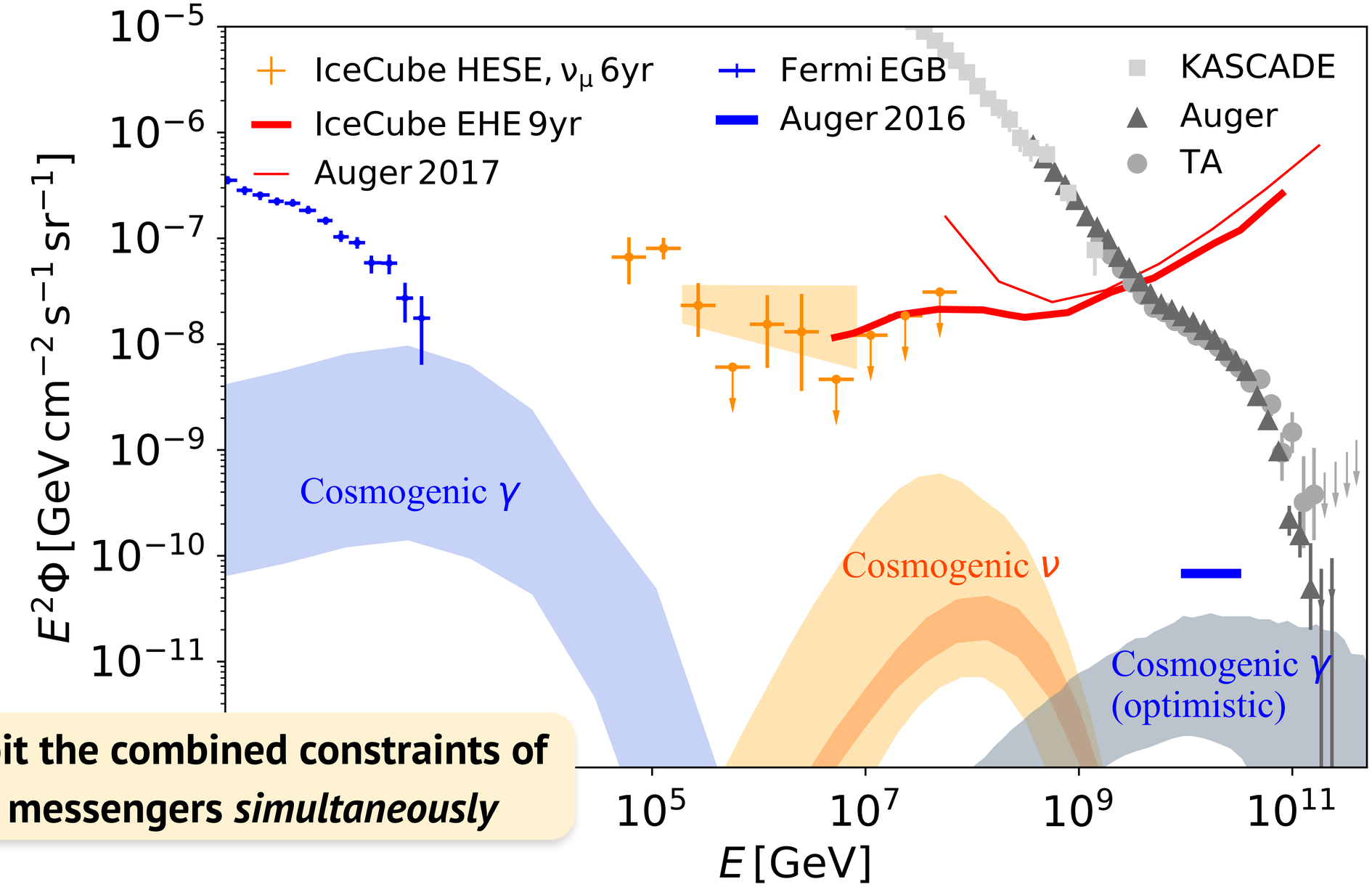
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outlook & summary



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



exploit the combined constraints of all messengers *simultaneously*

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  - *(the devil is in the details)*

acknowledgements

thank you 😊

"la Caixa" Foundation