Astrophysical Searches for Quantum Gravity: what multi-messenger observations can (and cannot) tell us

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BridgeQG Workshop

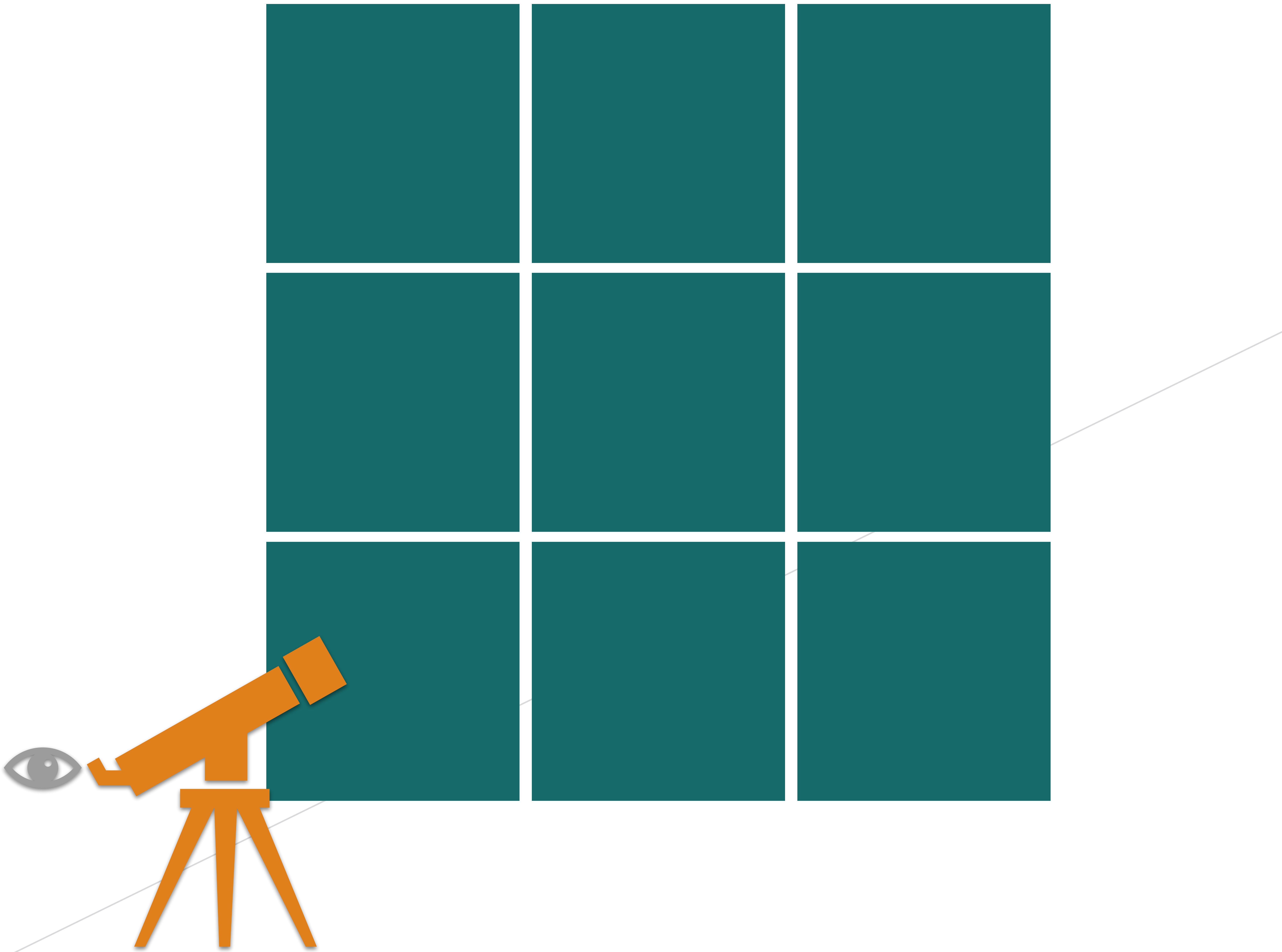
Annecy, February 4-6 2026

what if there are already QG signatures in the data?

what if there are already QG signatures in the data?

would we be able to tell?

what do we observe?



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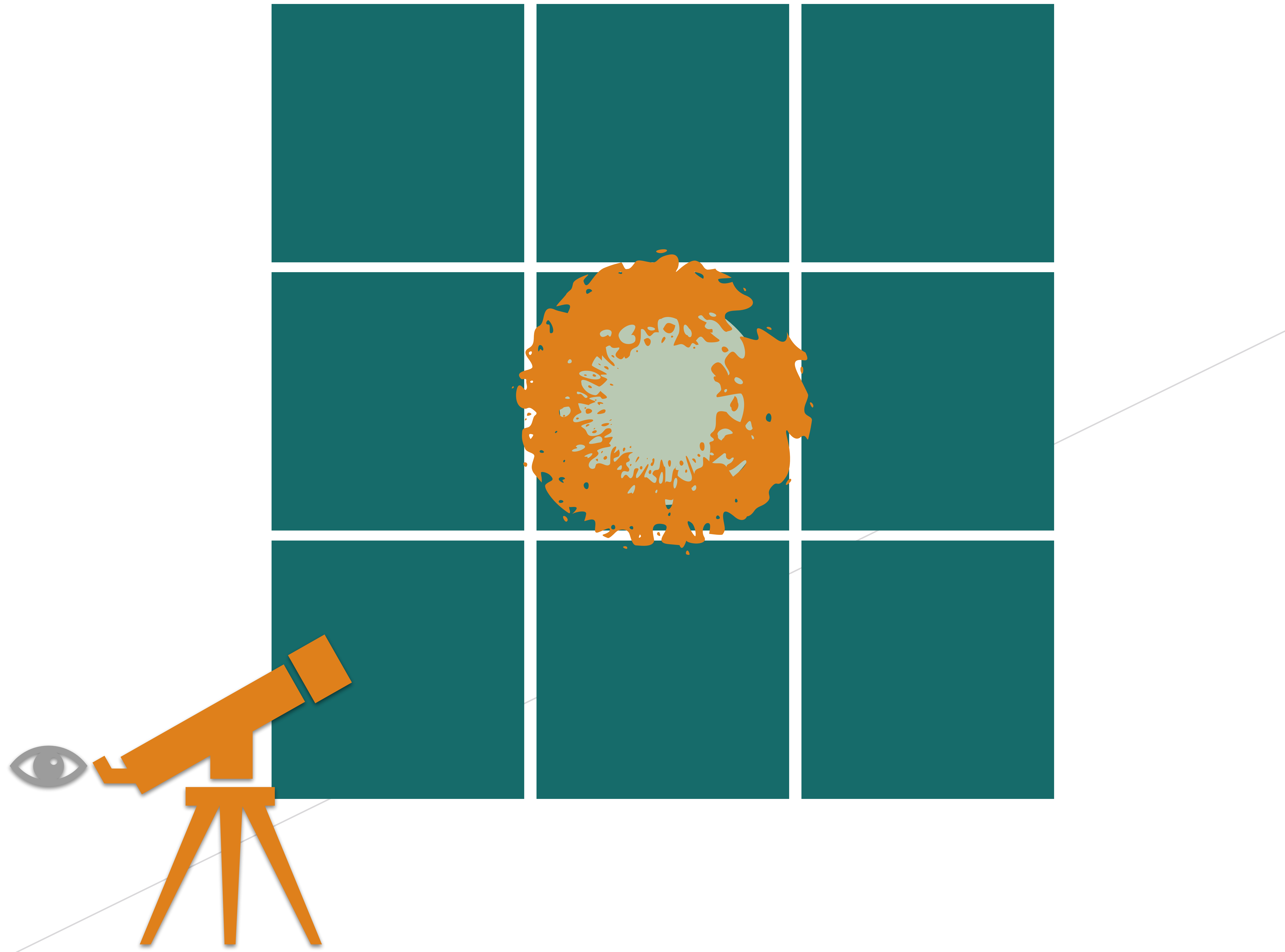

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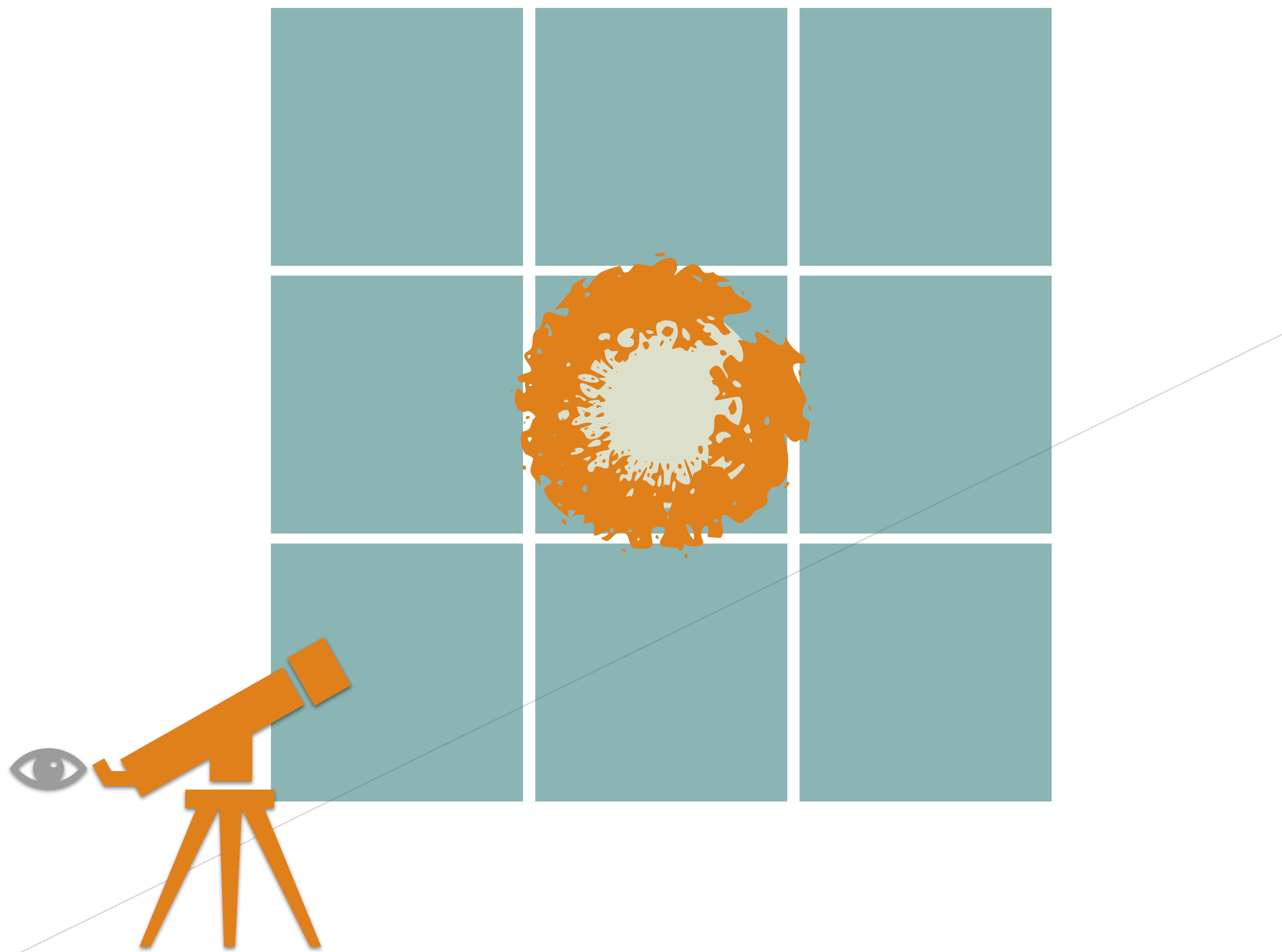
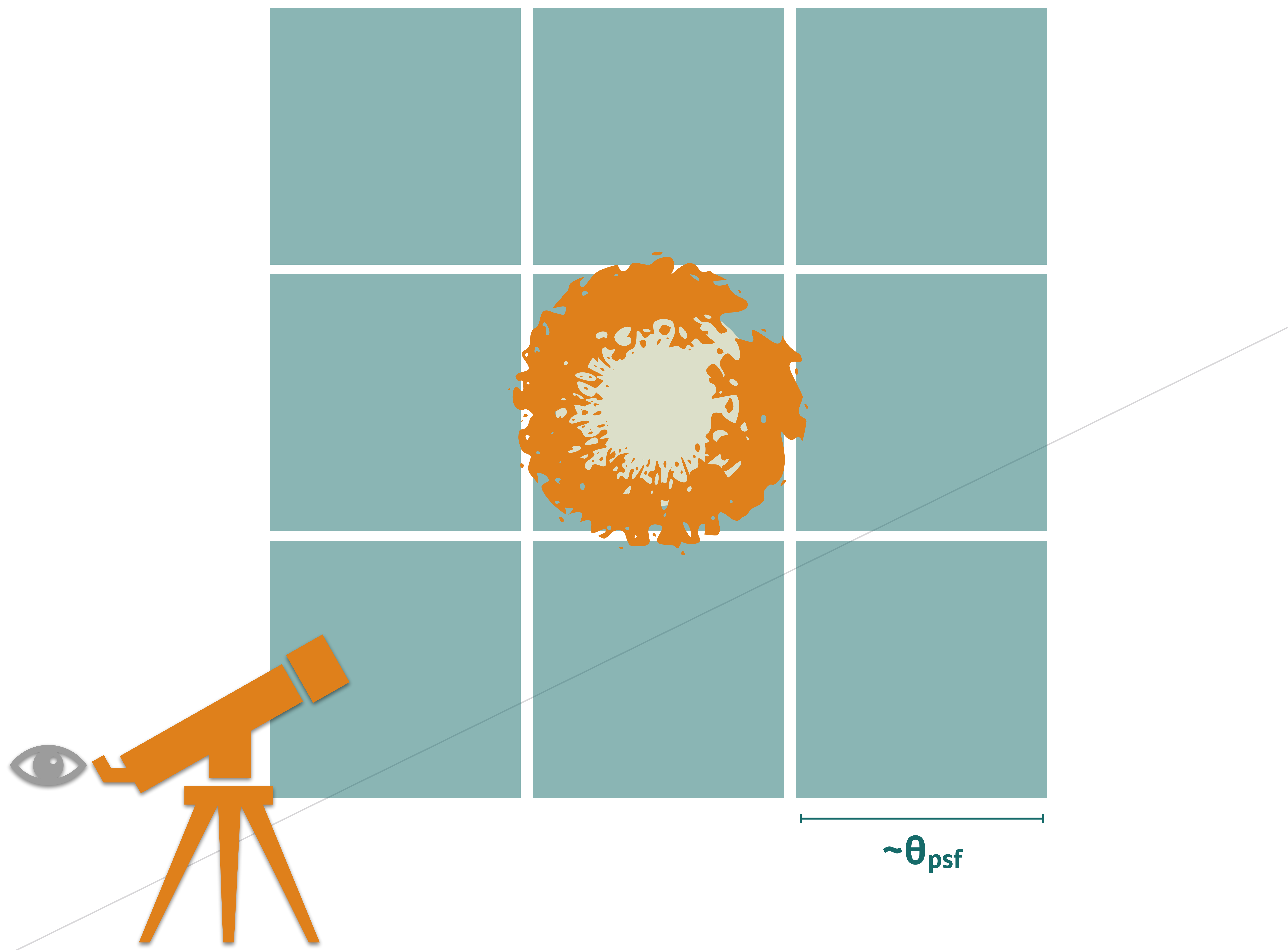
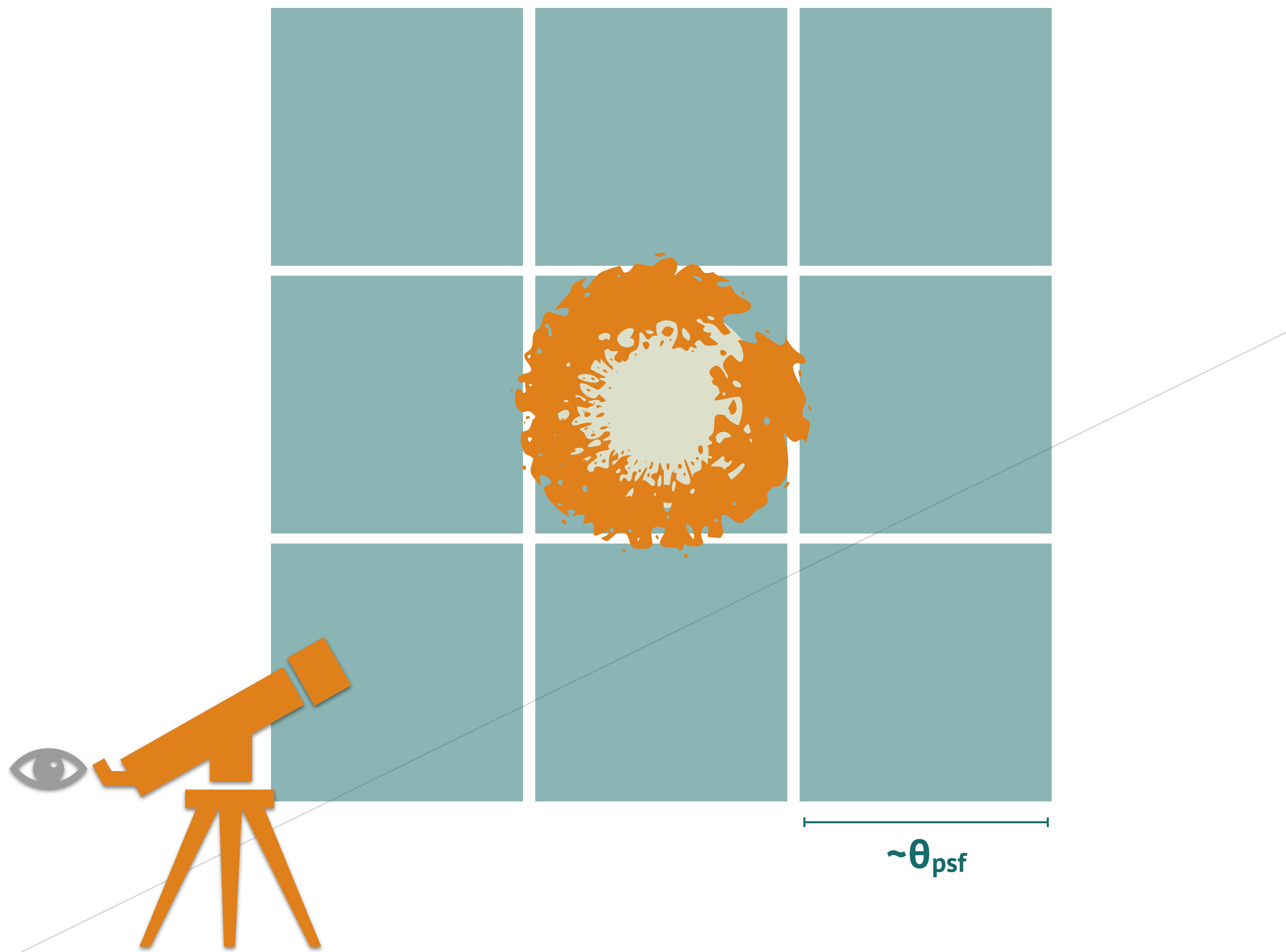



~θ_{psf}

arrival directions



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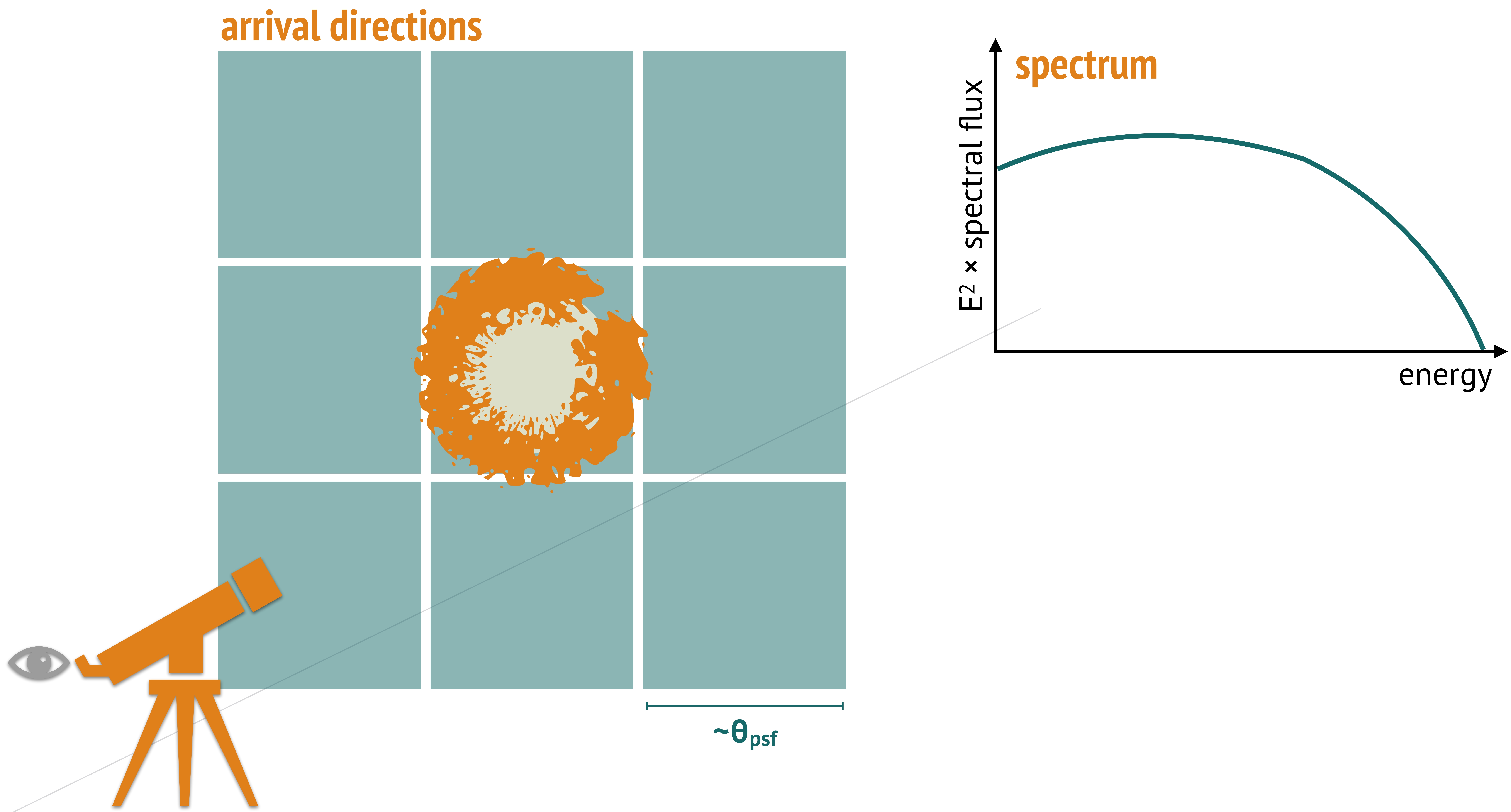

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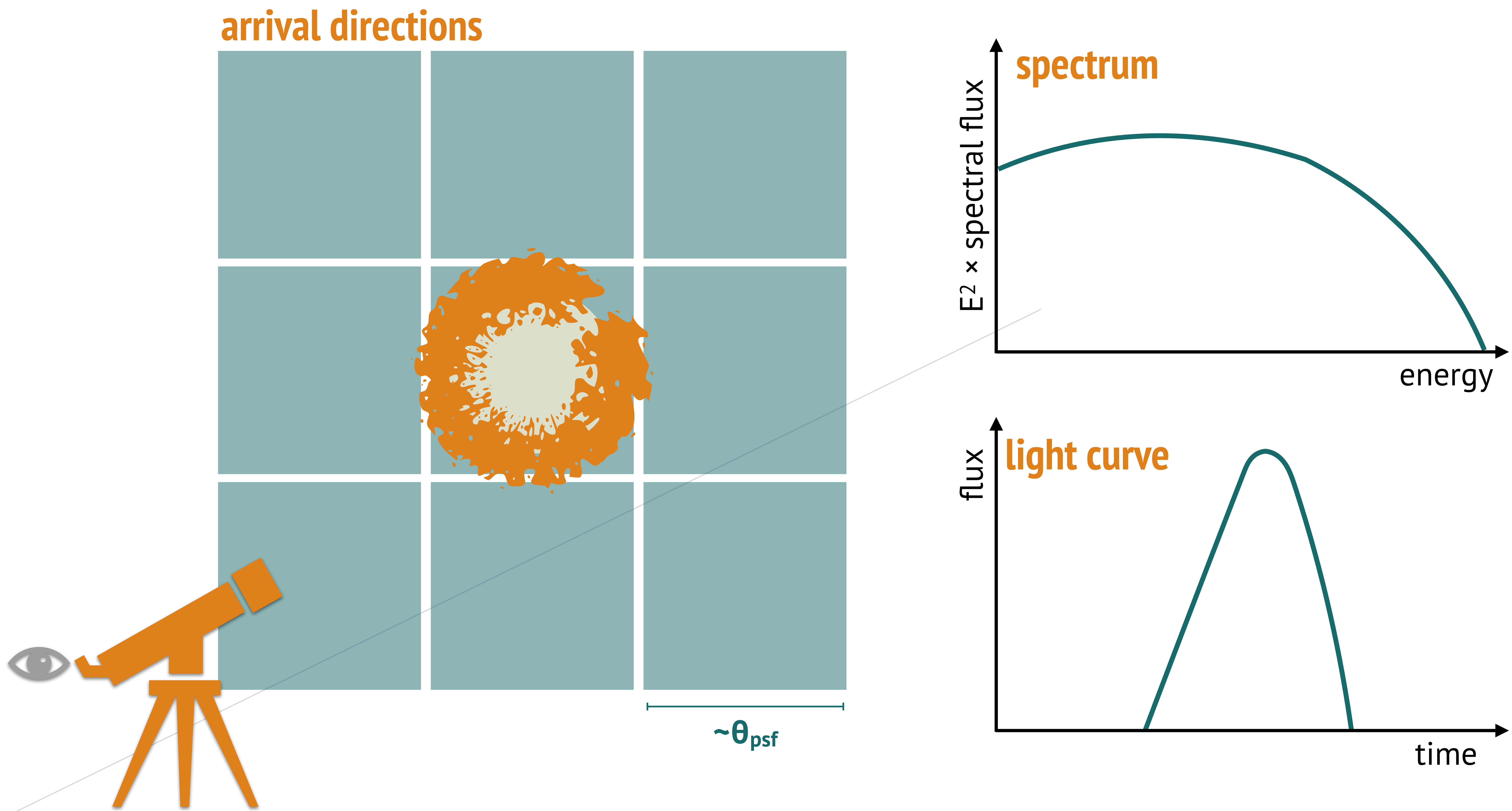

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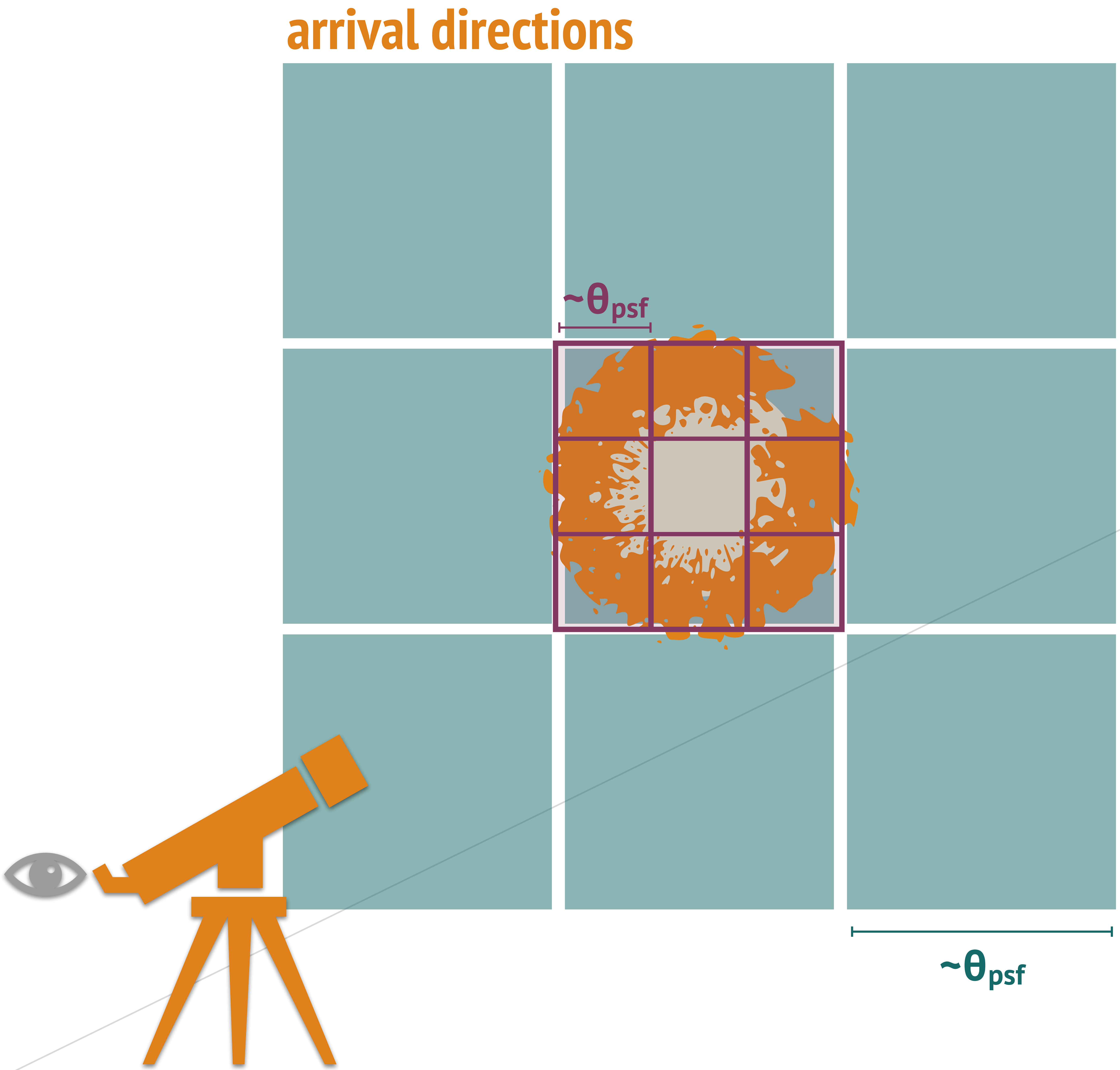

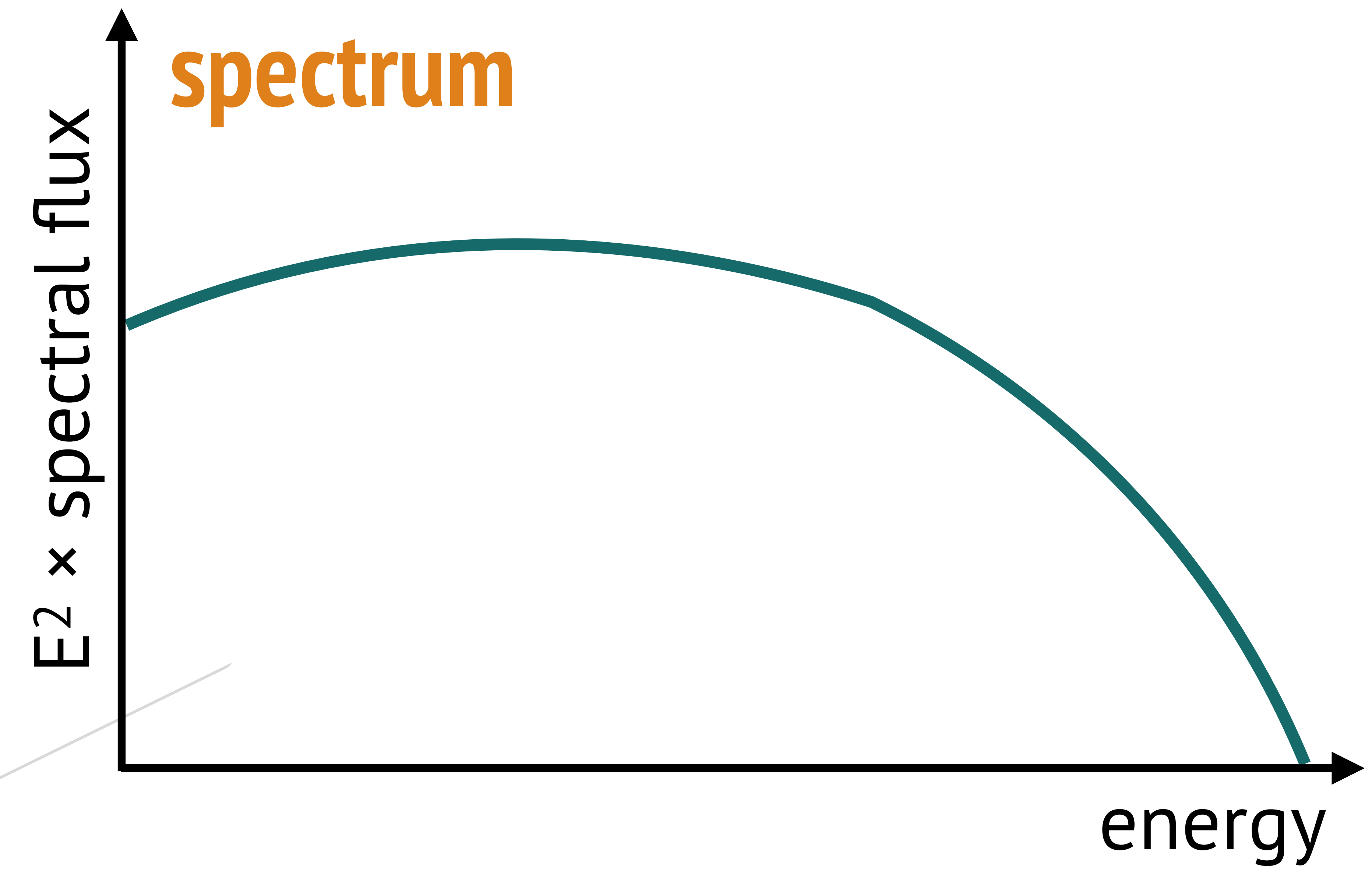

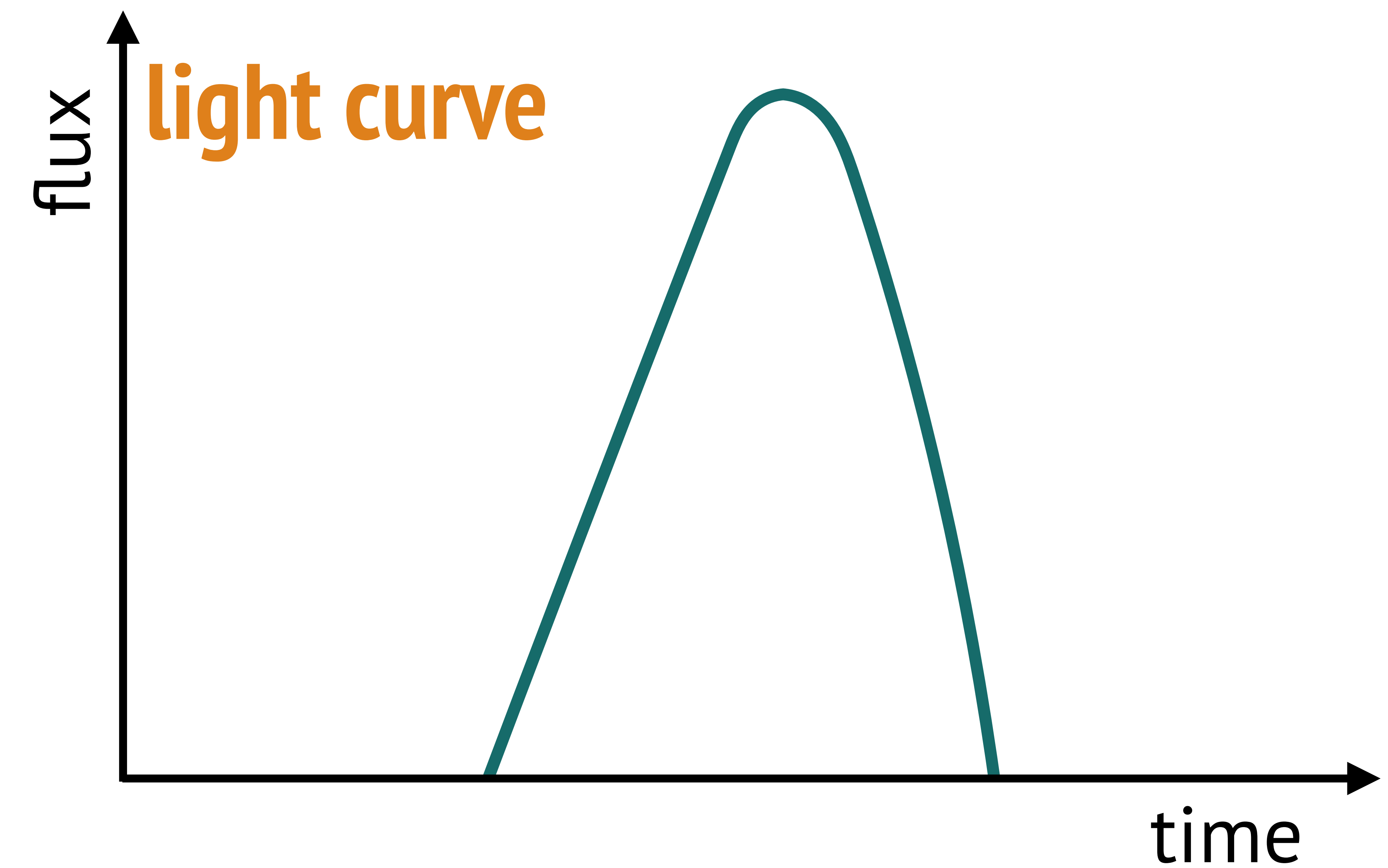

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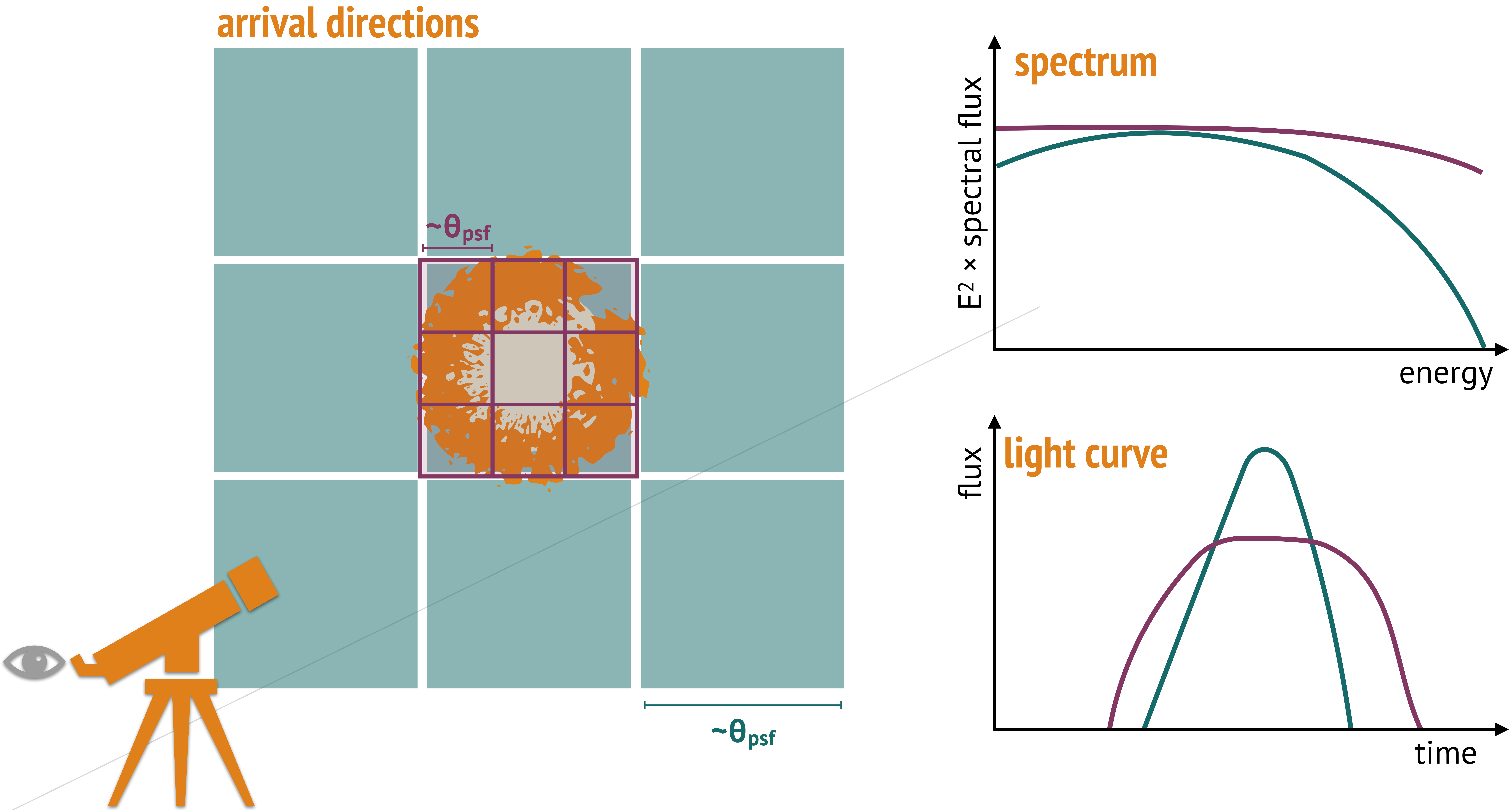
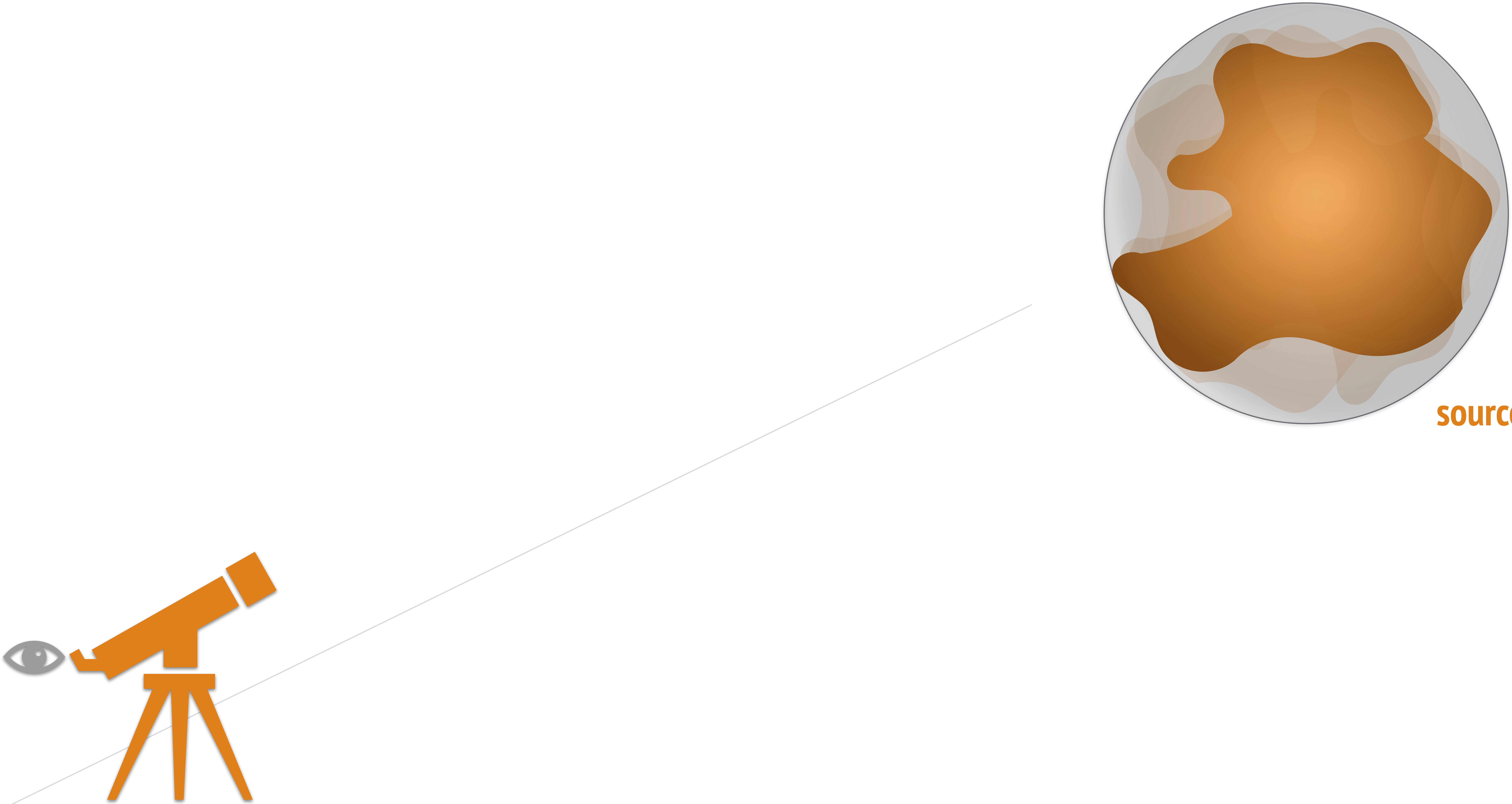


observations

observations

source properties. ingredients



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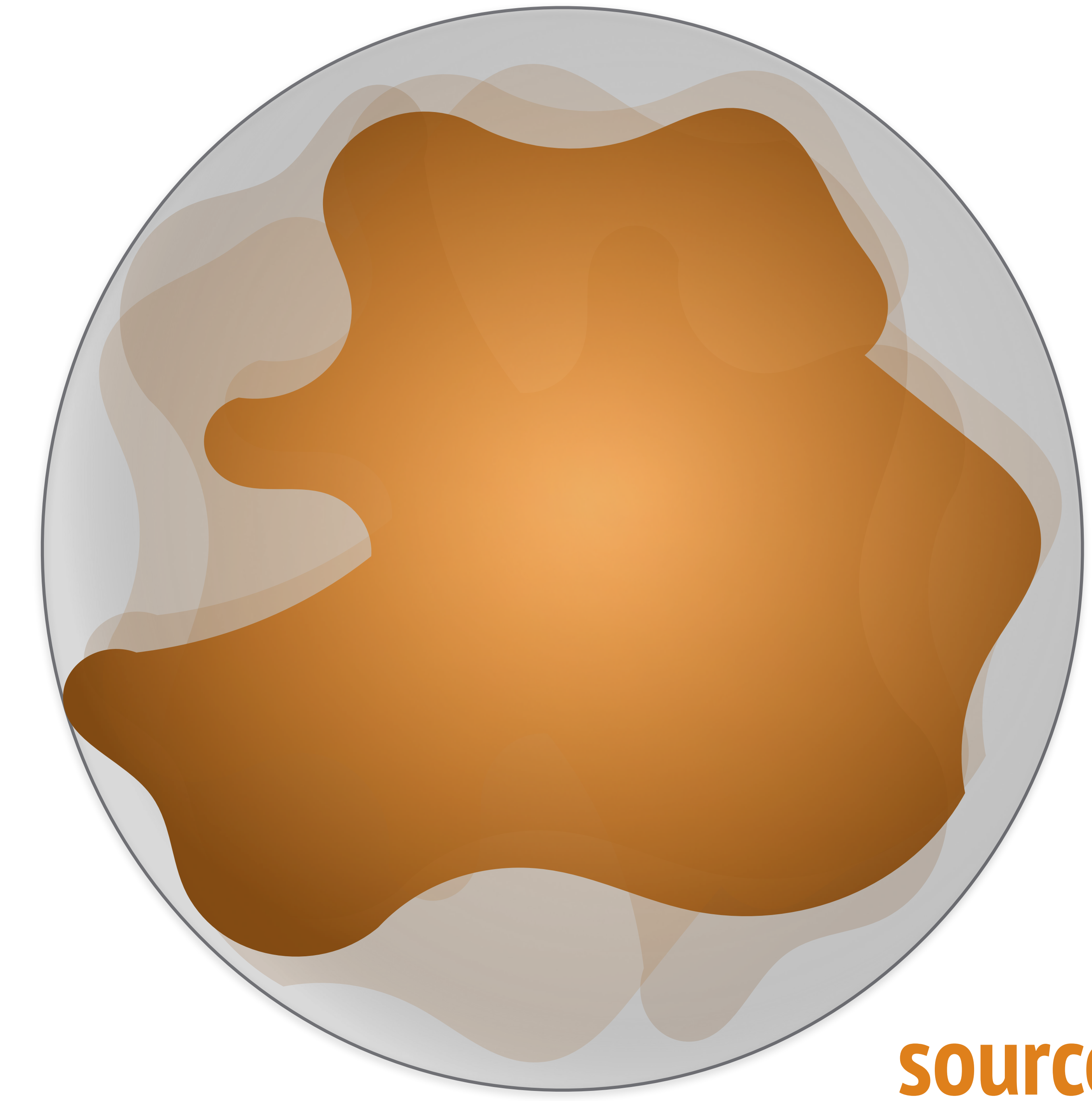
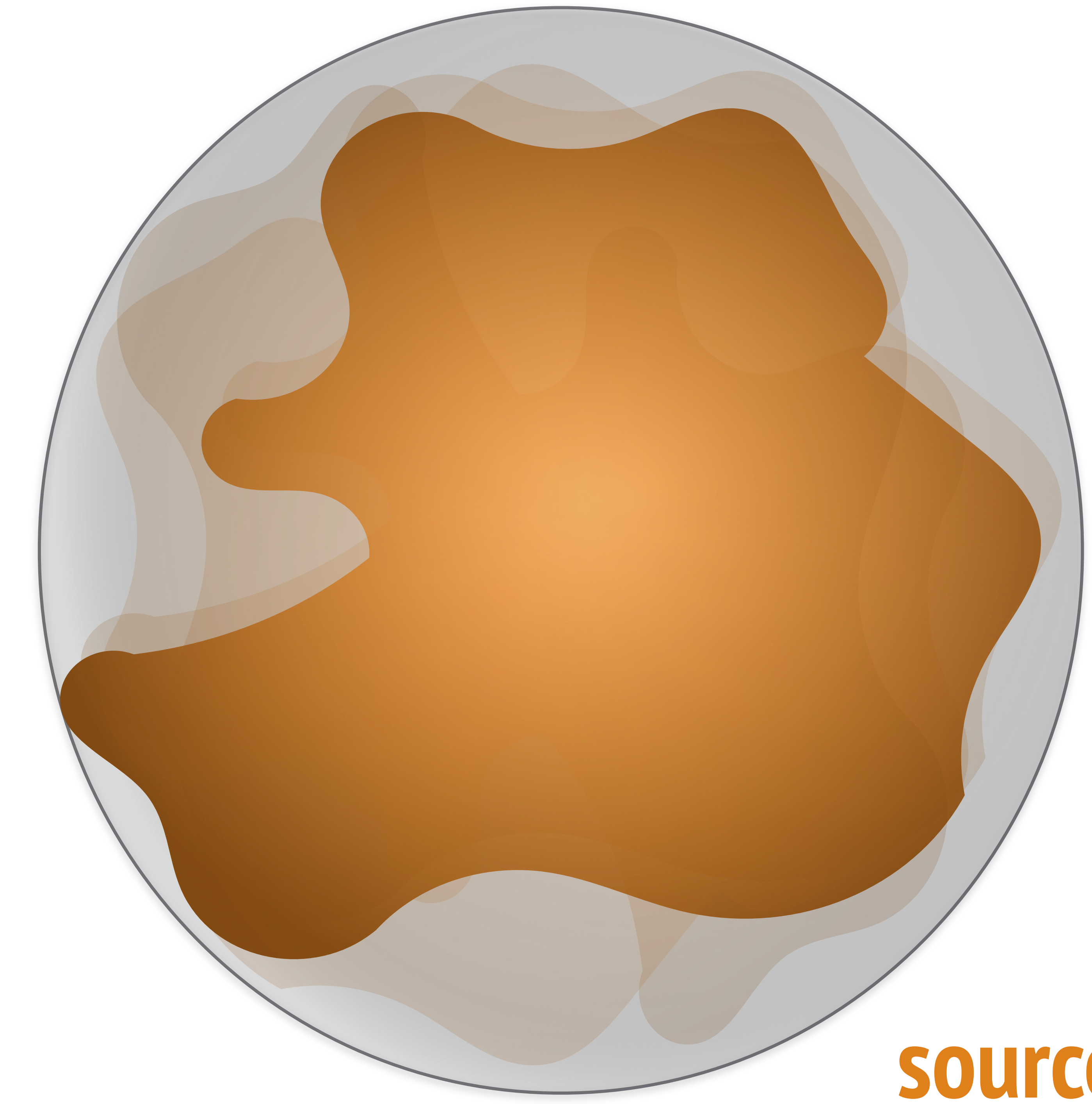


$$\frac{\textbf{number of particles}}{\text{(intervals of) } \textbf{solid angle} \times \textbf{energy} \times \textbf{time}}$$



source

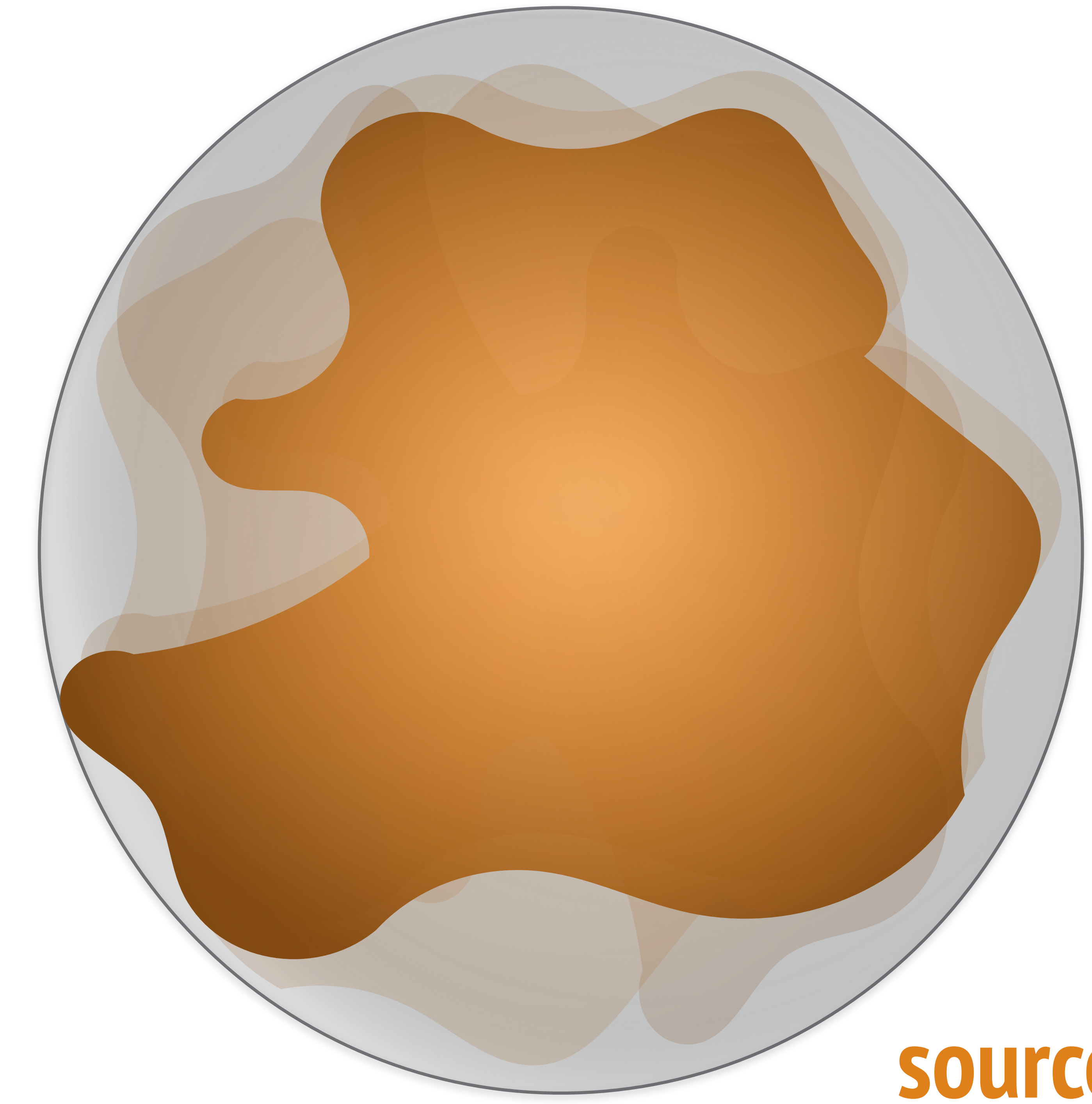
type of particle

composition, flavour

number of particles

(intervals of) **solid angle** × **energy** × **time**

source properties. ingredients



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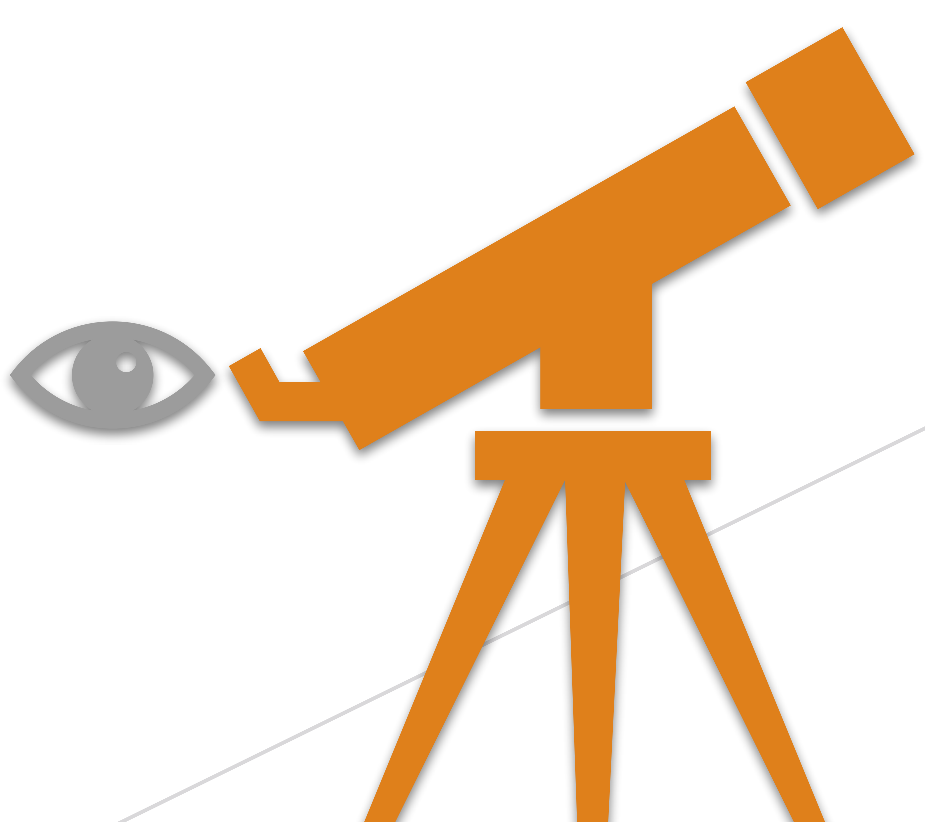

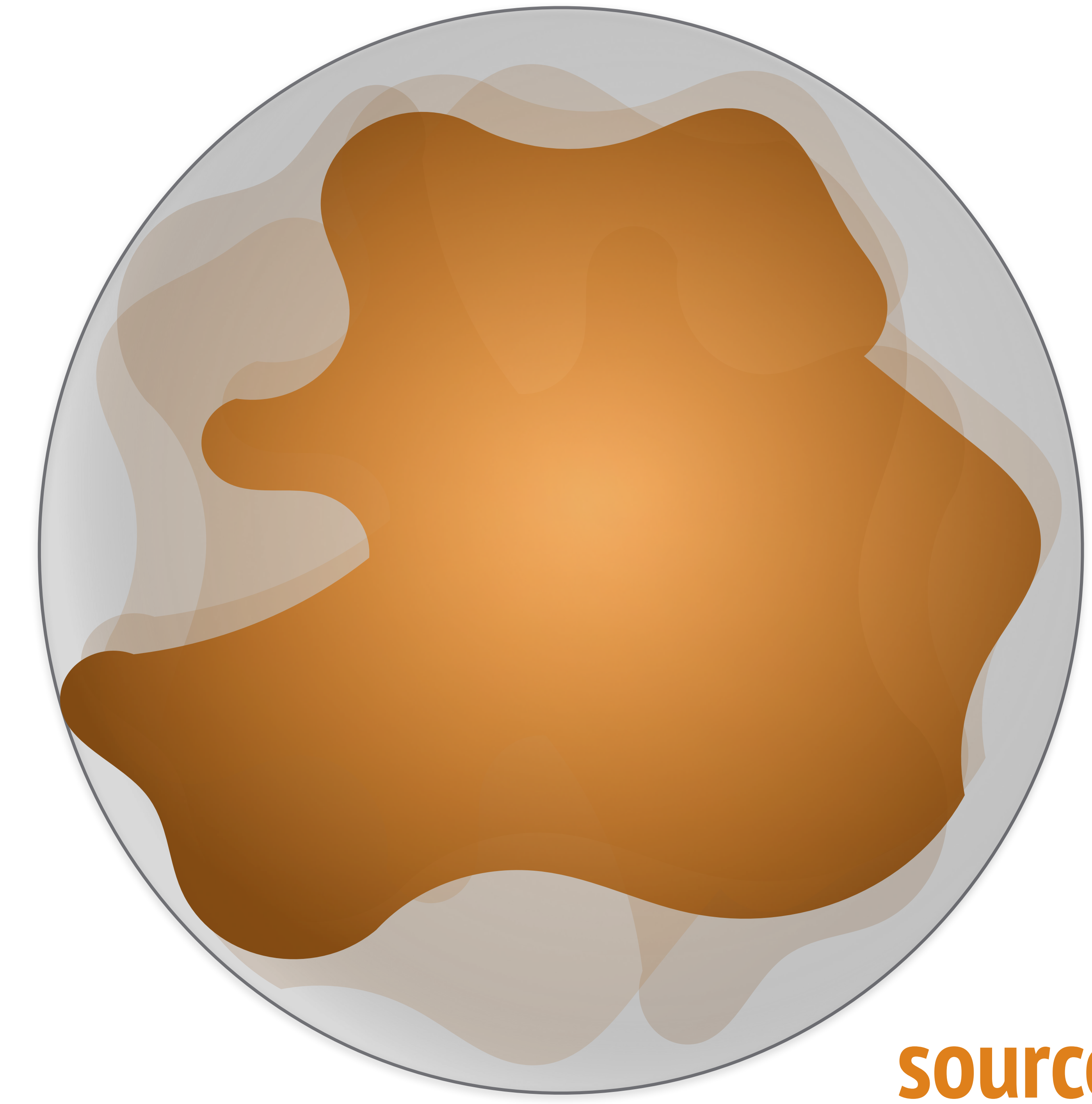

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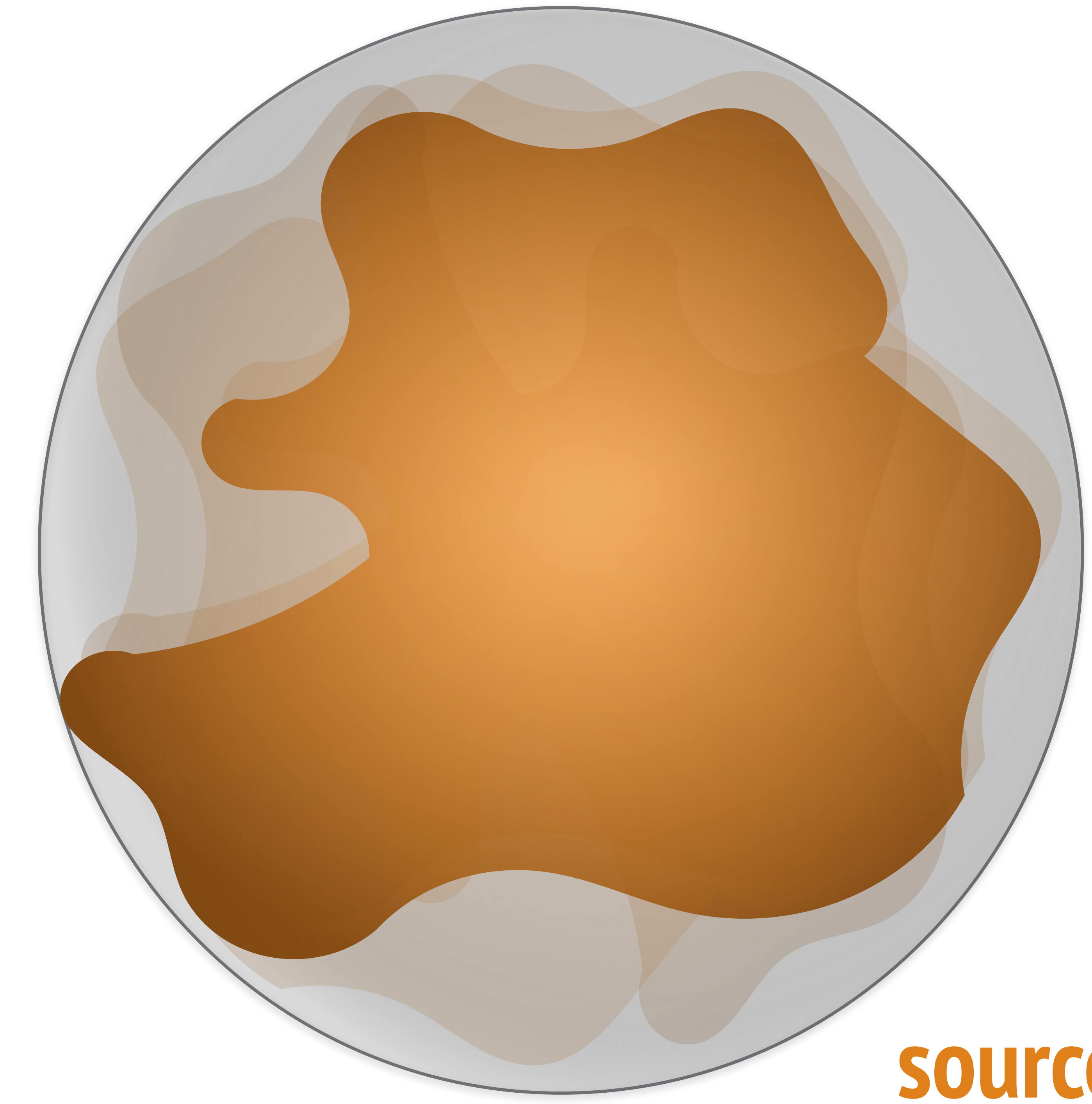

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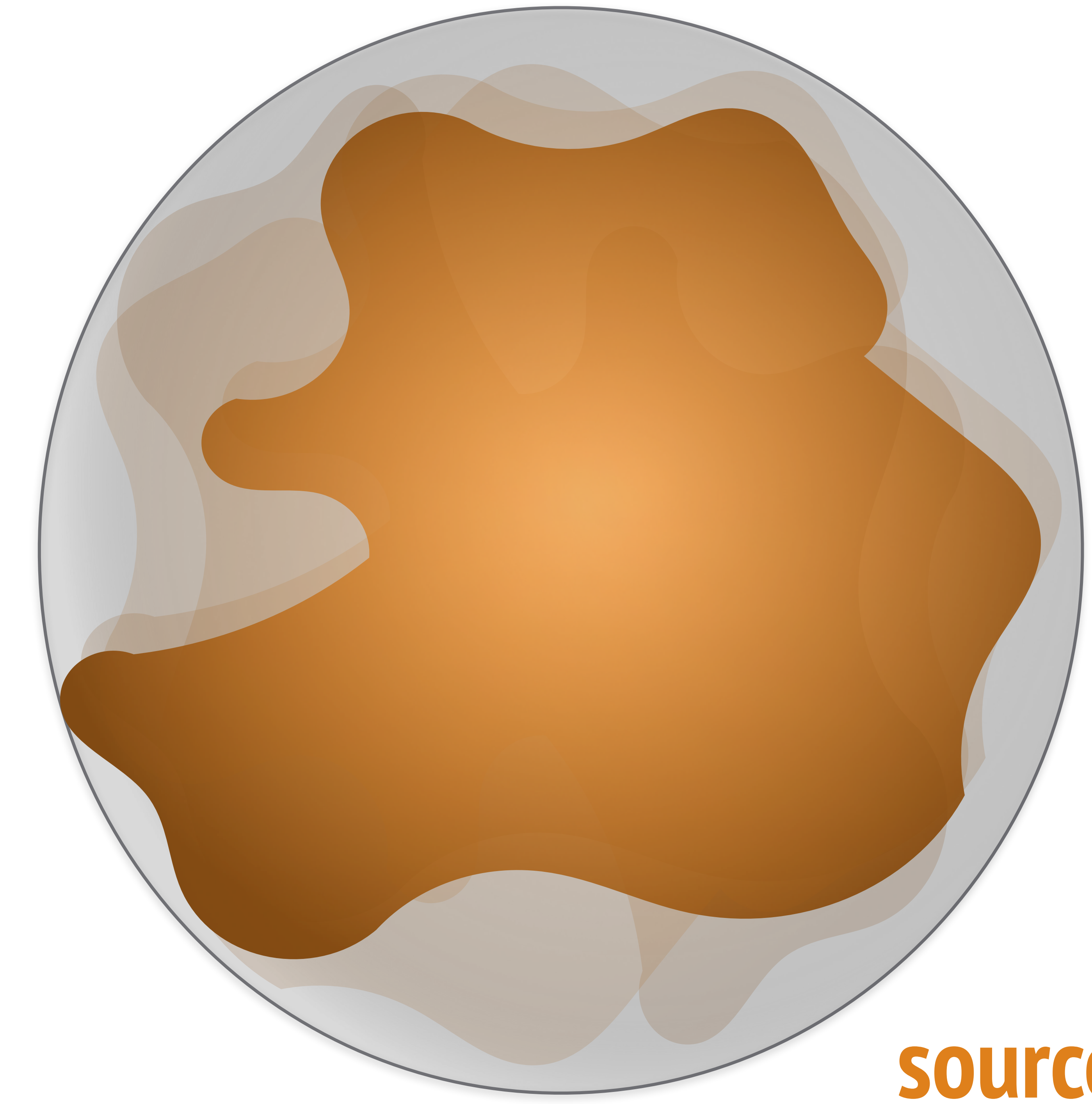

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number of events in each energy bin

geometry of emission

isotropic, jet

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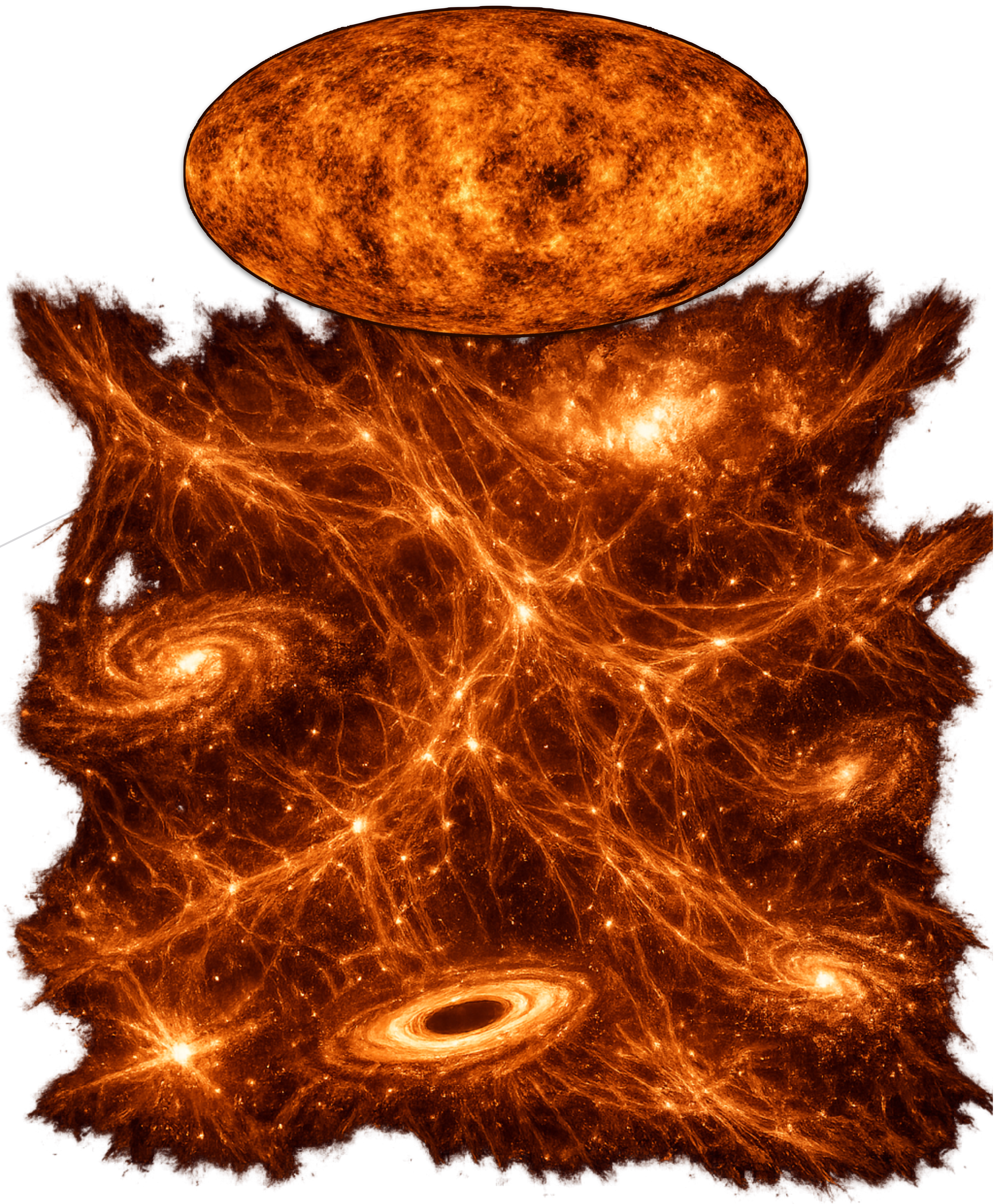
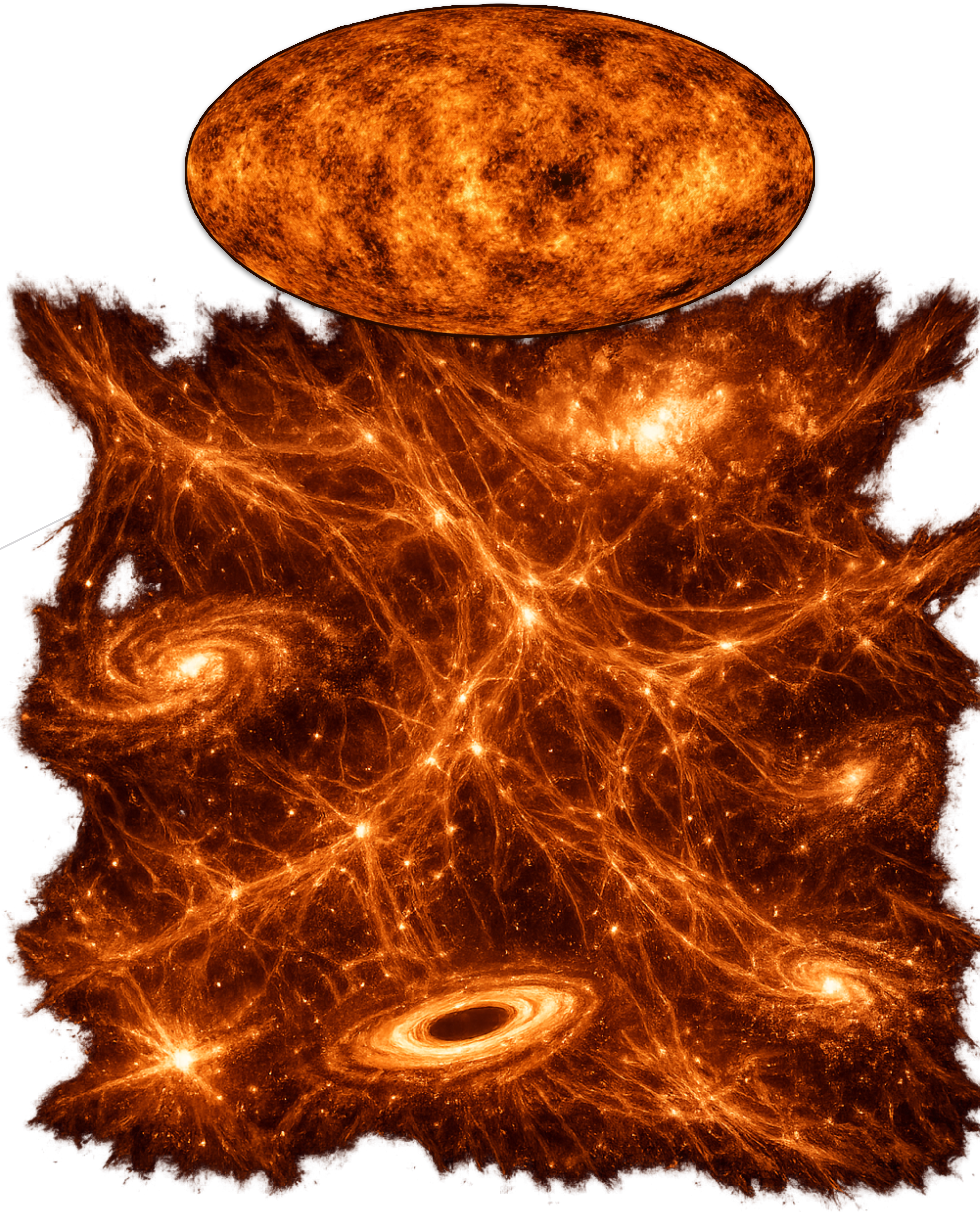


in-between

target distributions

photons (e.g., CMB, EBL)



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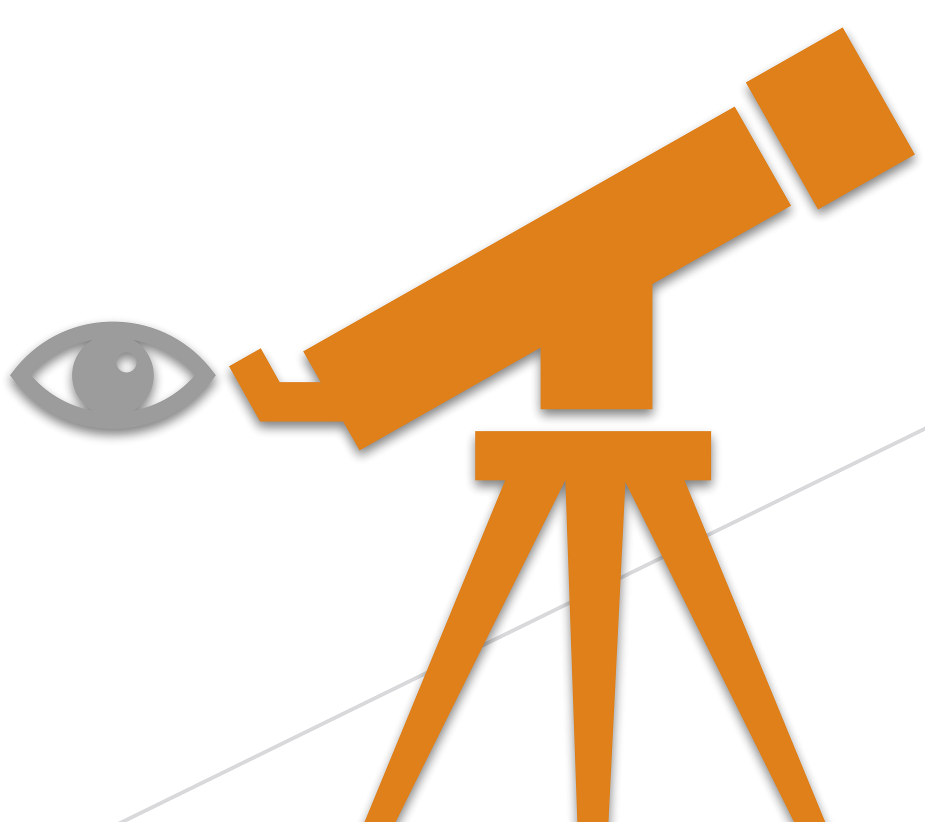
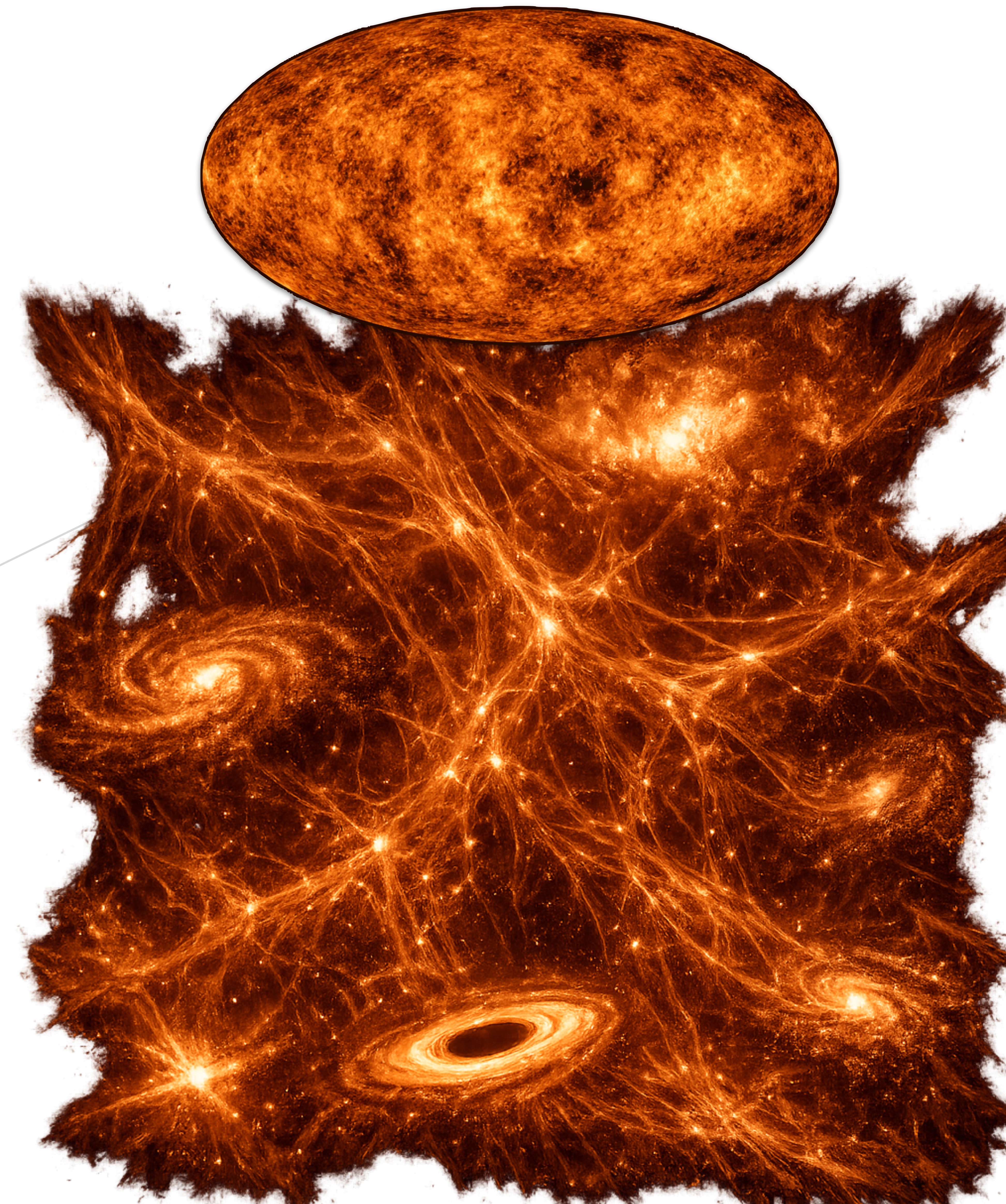
magnetic fields

galactic, extragalactic





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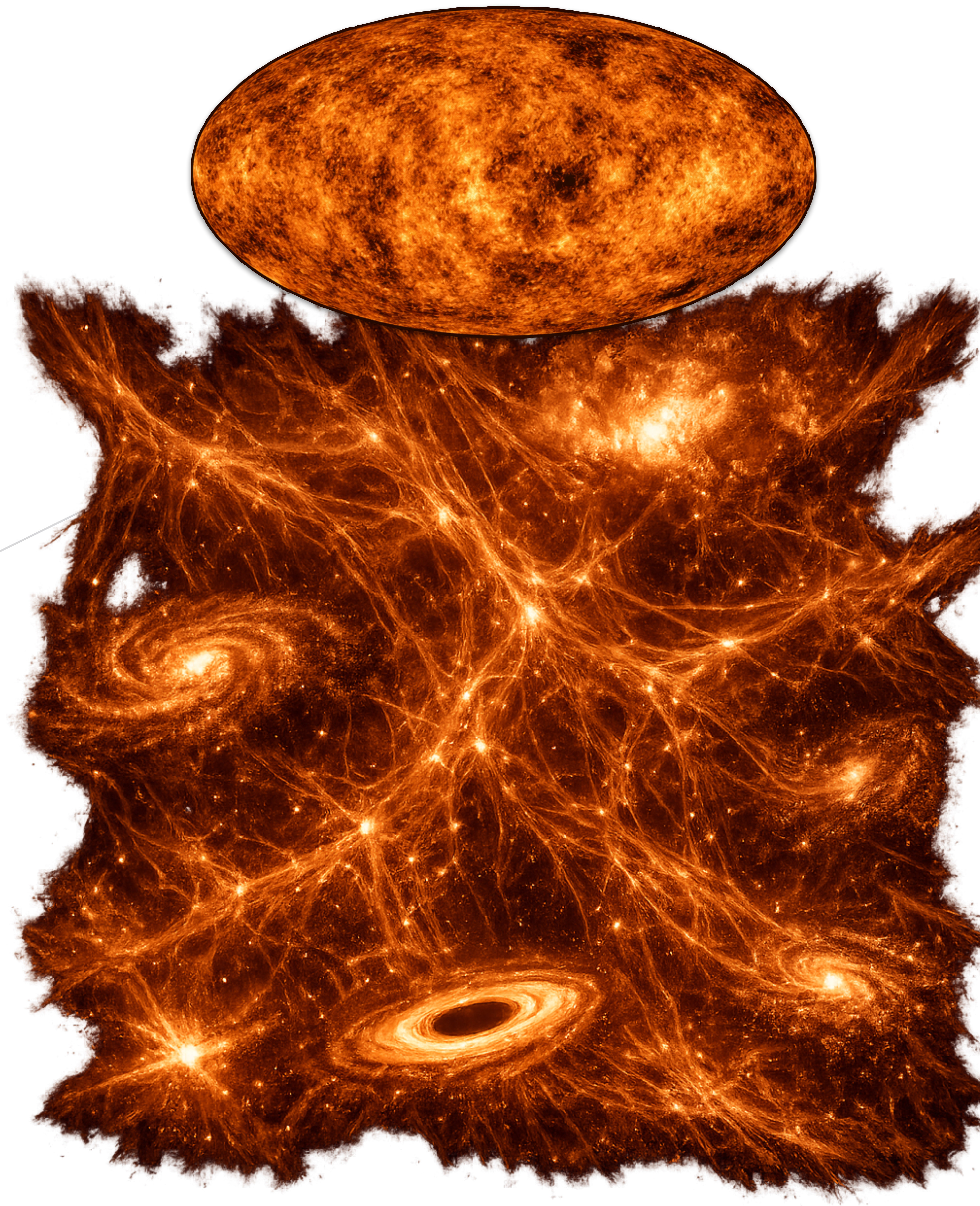
gravitational fields

lenses



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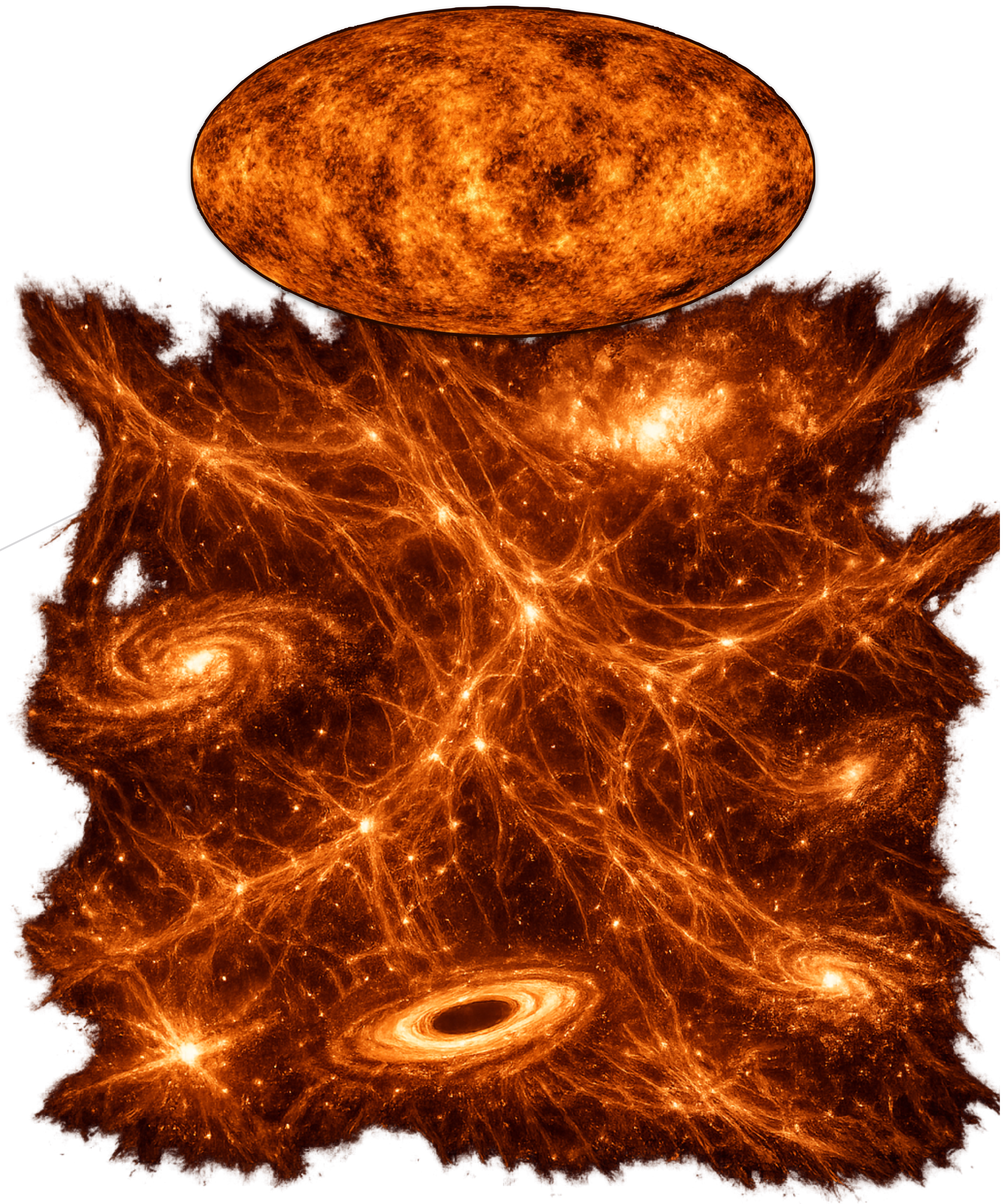
physics of interactions

cross sections, ….



in-between

propagation. ingredients

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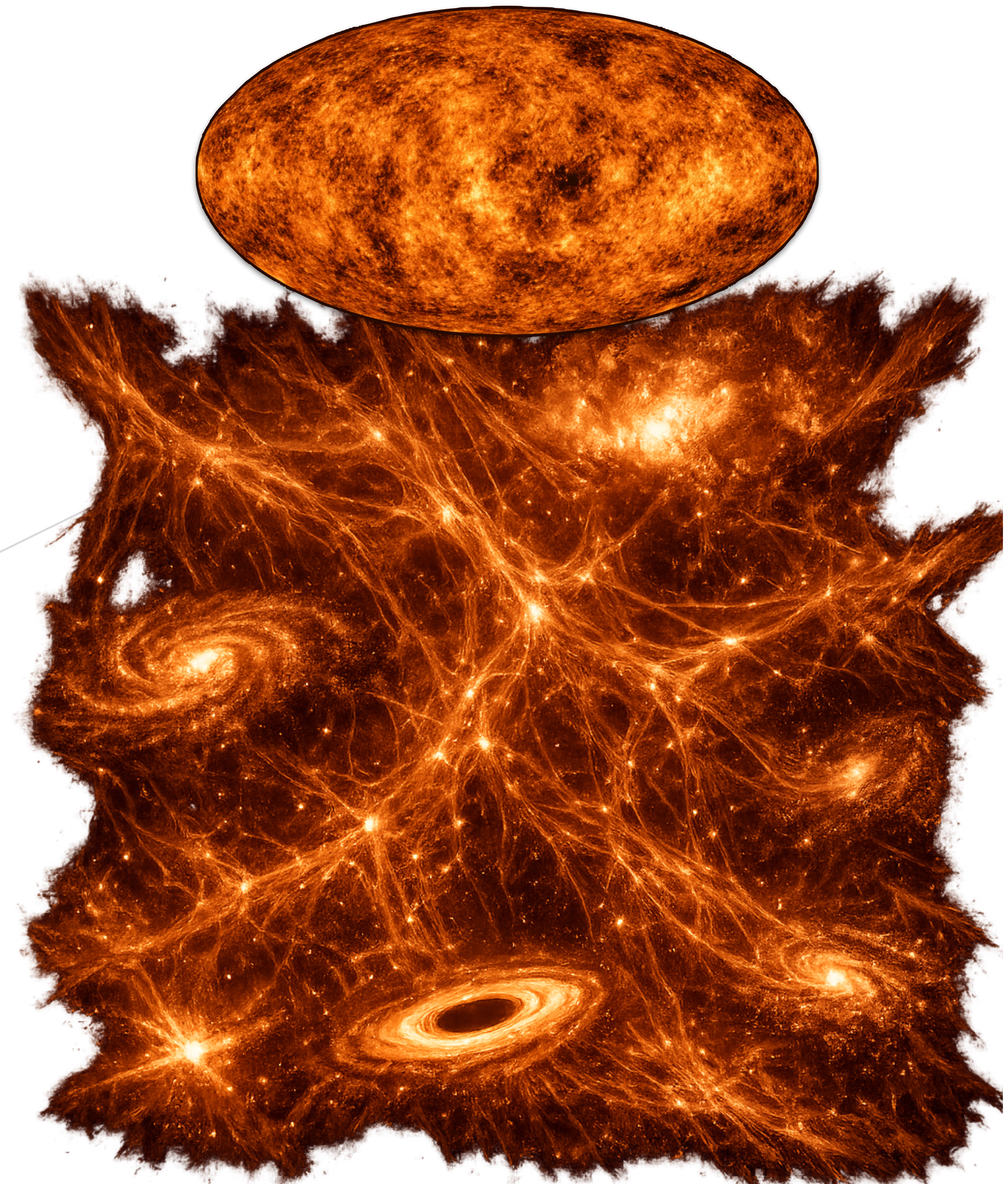
lenses

physics of interactions

cross sections, ...

mesoscale physics

collective phenomena



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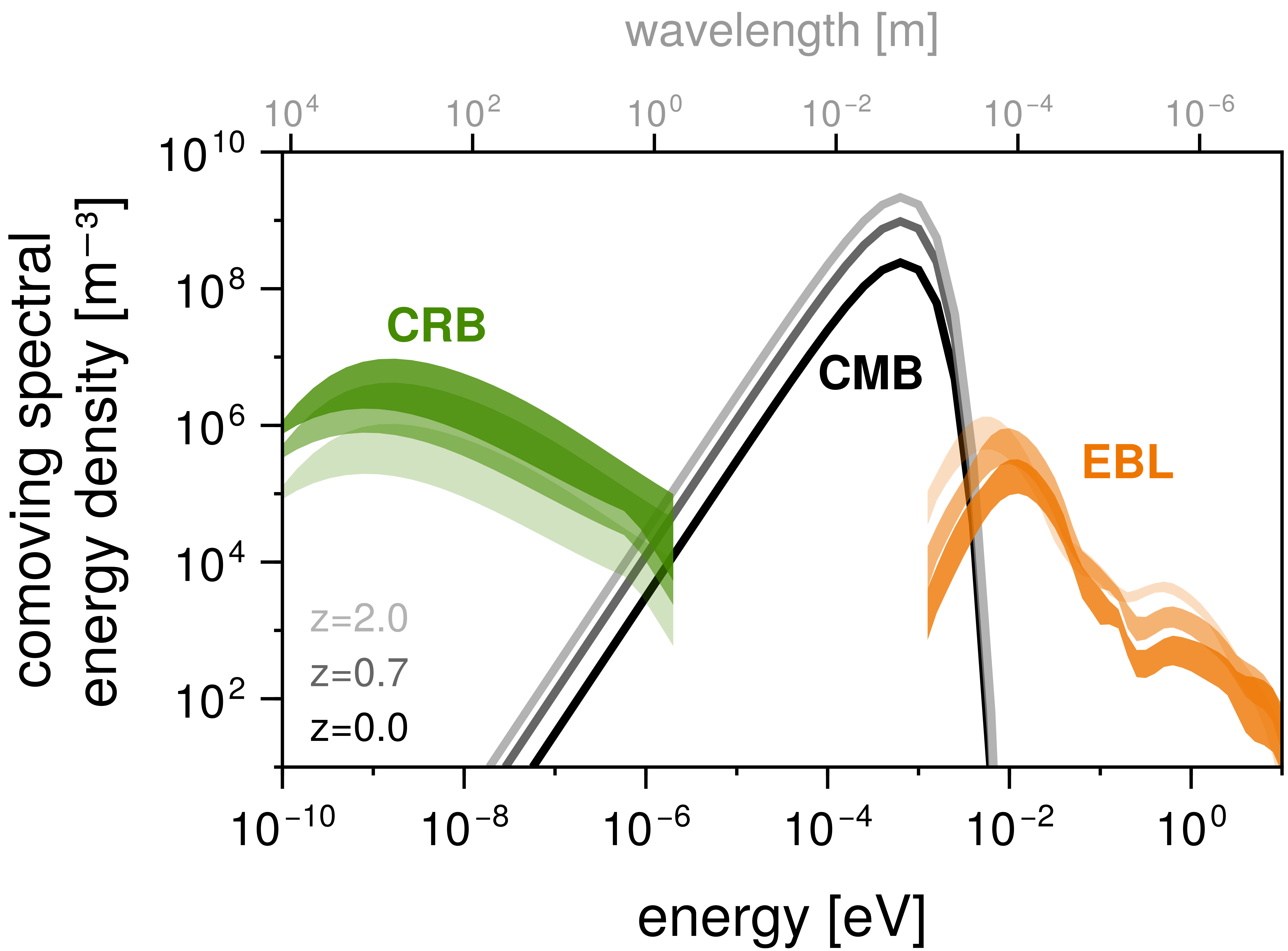
wavelength [m]
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{10}
10^8
10^6
10^4
10^2
comoving spectral energy density [m^{-3}]
CRB
CMB
EBL
z=2.0
z=0.7
z=0.0
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^0
energy [eV]

interactions and mean free path

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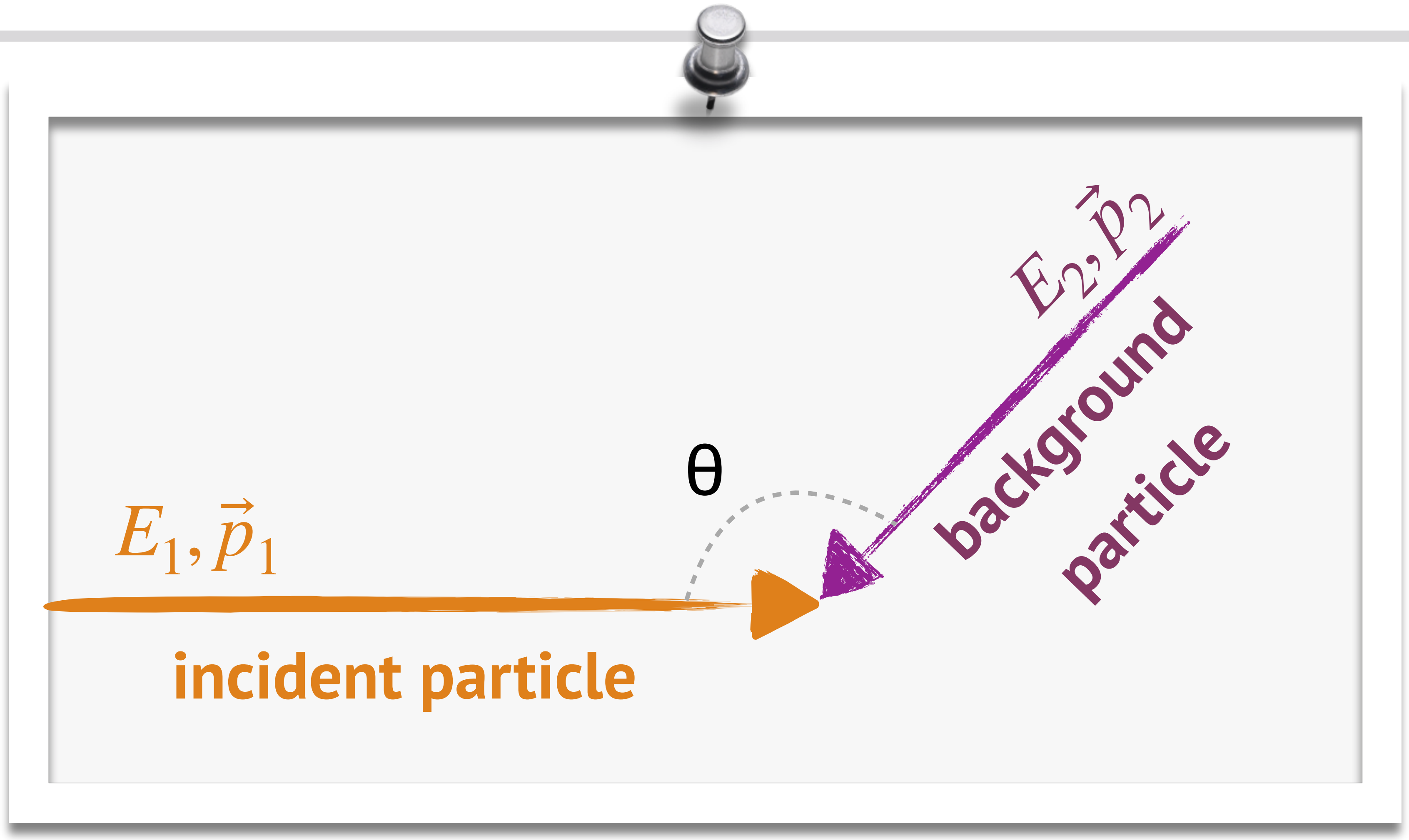
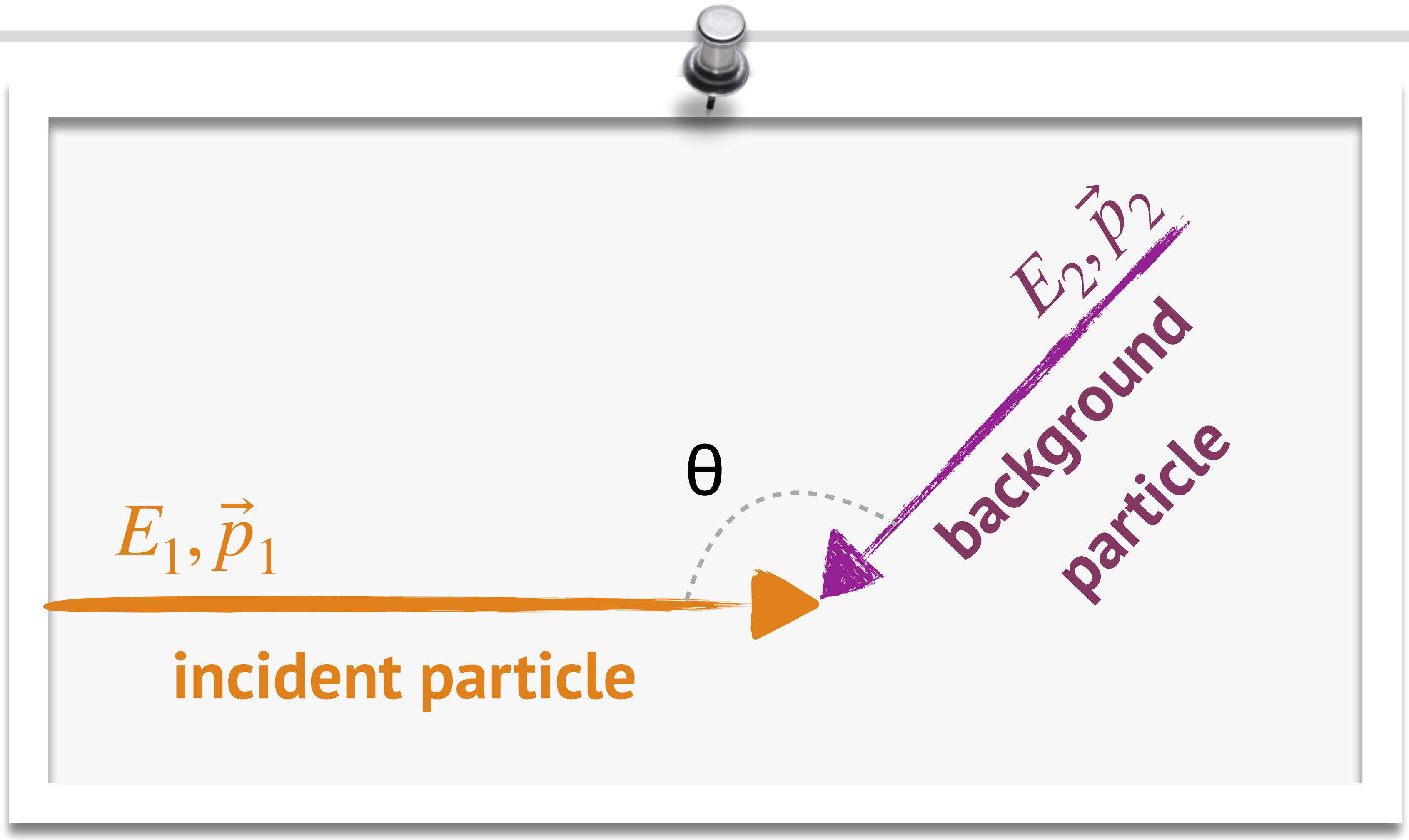
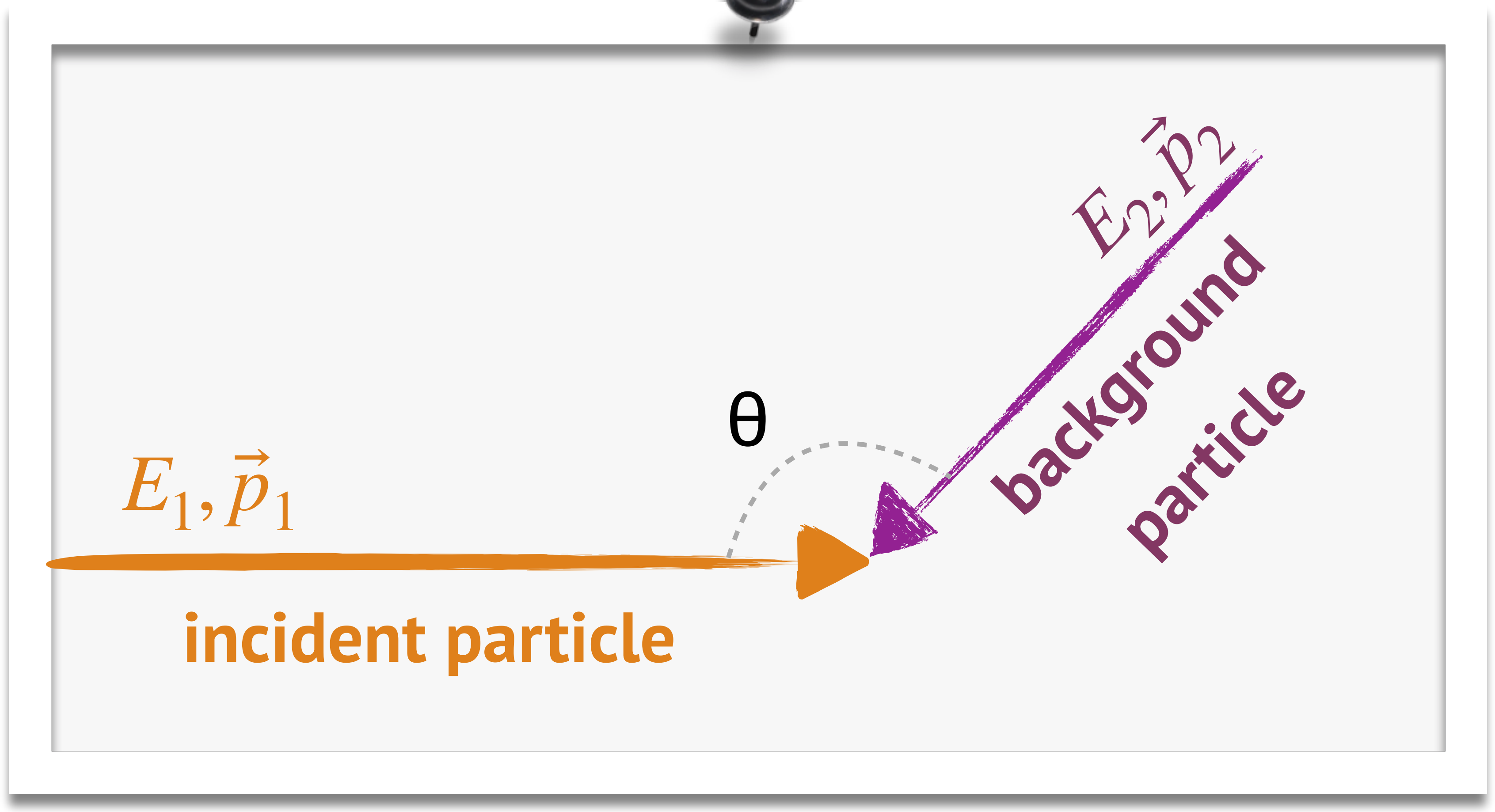




centre of mass energy

$$s = m_1^2 c^4 + m_2^2 c^4 + 2E_1 E_2 (1 - \beta_1 \beta_2 \cos\theta)$$



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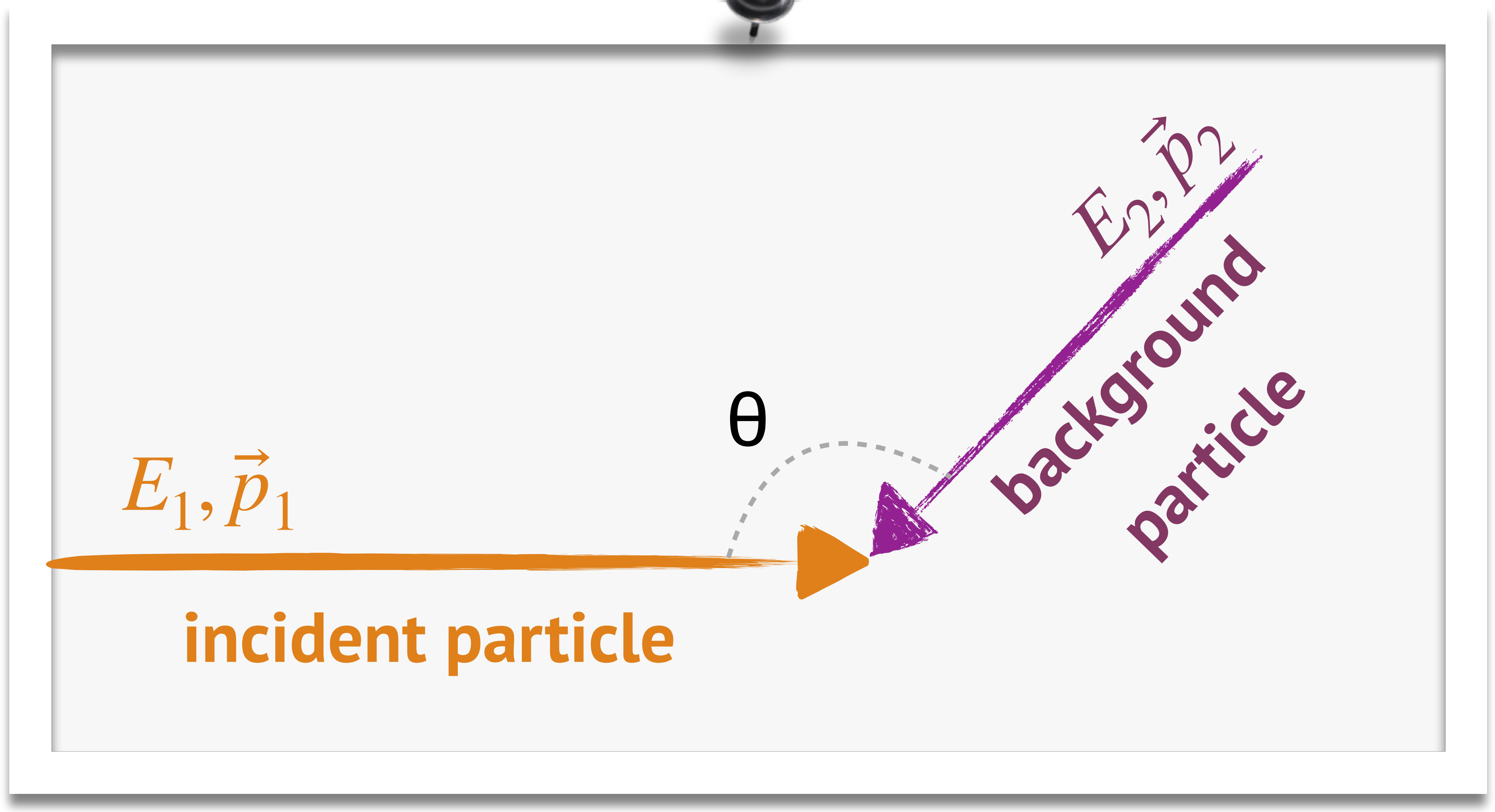
$$\beta_{\rm rel} = \sqrt{\frac{(P_1 \cdot P_2)^2 - (m_1 m_2 c^2)^2}{(P_1 \cdot P_2)^2}}$$

interactions and mean free path



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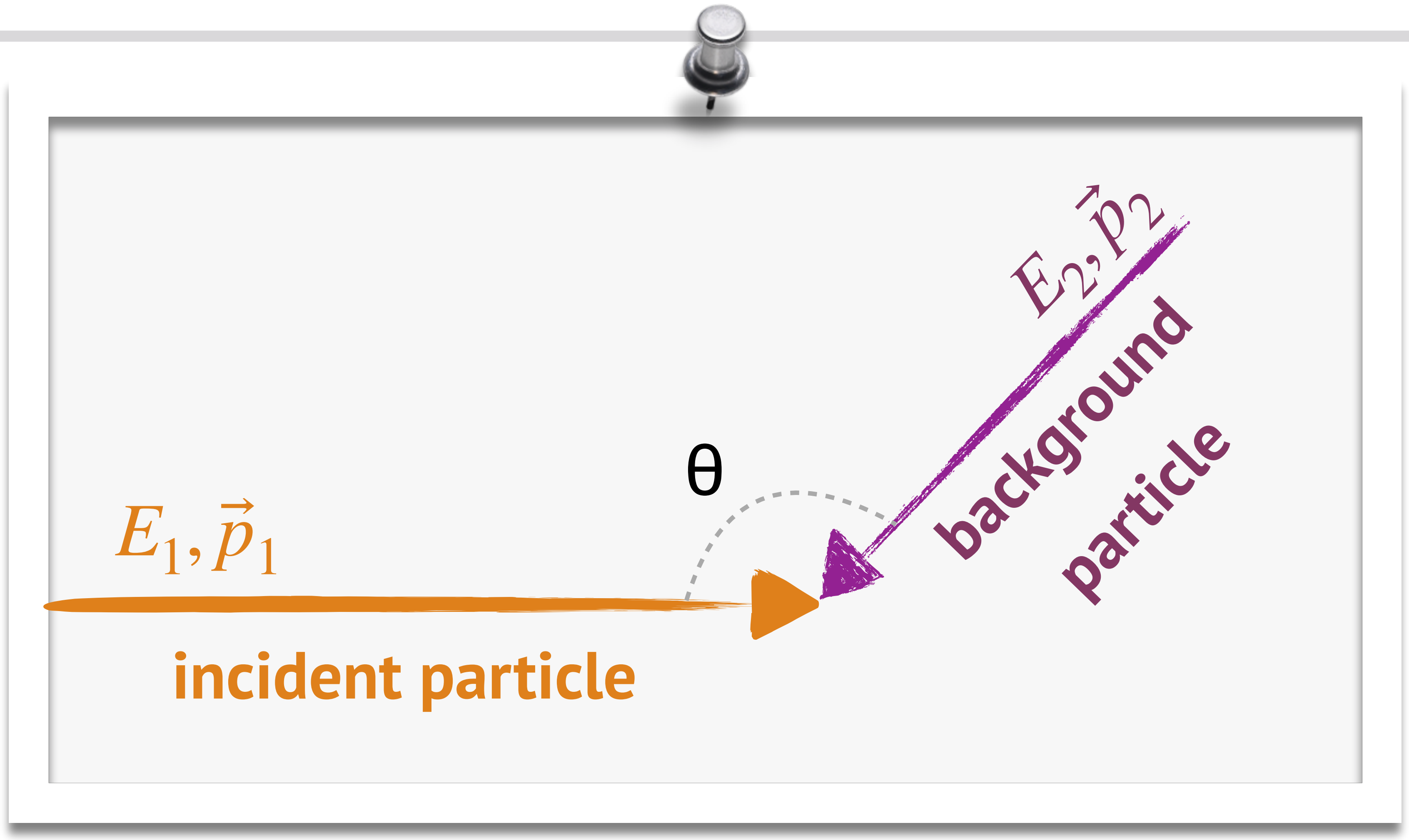
interaction length

for particle of type 1
interacting with (isotropic)
background of type 2



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interaction length

generic

$$\lambda^{-1} = \frac{1}{2} \iint \mathrm{d}p_2 \, \mathrm{d}\cos\theta \;\; \sigma(s) \; \beta_{\rm rel}(P_1, P_2) \; \left(1 - \beta_1 \beta_2 \cos\theta\right) \frac{\mathrm{d}n_2(\vec{p}_2)}{\mathrm{d}p_2}$$

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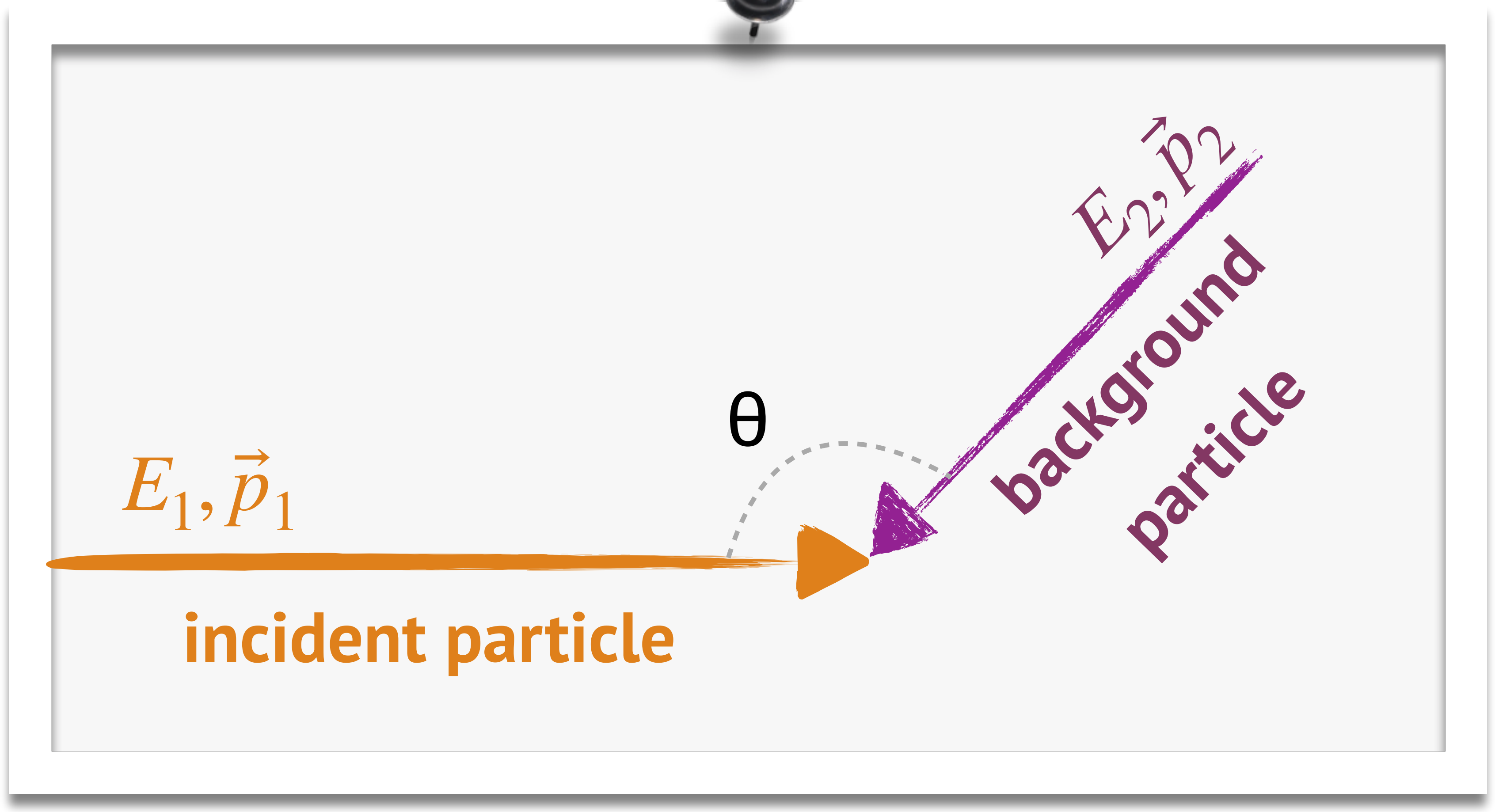

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photons

$$\lambda^{-1}(E, z) = \frac{1}{8\beta E^2} \int\limits_{\varepsilon_{\rm min}(E)}^{+\infty} \frac{1}{\varepsilon^2} \frac{dn(\varepsilon, z)}{d\varepsilon} \int\limits_{s_{\rm min}}^{s_{\rm max}(E,\varepsilon)} (s - m^2 c^4) \sigma(s) \, {\rm d}s {\rm d}\varepsilon$$

modified interactions with photon backgrounds

$$\lambda^{-1} = \frac{1}{2} \iint \mathrm{d}p_2 \, \mathrm{d}\cos\theta \;\; \sigma(s) \, \beta_{\mathrm{rel}}(P_1, P_2) \, \left(1 - \beta_1 \beta_2 \cos\theta\right) \, \frac{\mathrm{d}n_2(\vec{p}_2)}{\mathrm{d}p_2}$$

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can we use the same equation with Lorentz violation?

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change:

$\varepsilon_{\min}, s, s_{\min}, s_{\max}, \beta_{\rm rel}$

can we use the same equation with Lorentz violation?

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necessary conditions to state the a flux of a messenger is primary

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- know the **intrinsic spectrum** well to exclude **cascade contribution**
  - *but:* unobserved gamma rays at higher energies

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necessary conditions to state the a flux of a messenger is primary

- know the **intrinsic spectrum** well to exclude **cascade contribution**
  - *but:* unobserved gamma rays at higher energies
- know the **flux of other particles** along the **line of sight**
  - degeneracy between absorption of parent and observations of the messenger

cosmic rays

LIV-induced modifications

$$E^2 = m_a^2 c^4 + p^2 c^2 + f_a(E, \vec{p})$$

$$f_a\left(E, \vec{p}\right) \approx f_a\left(p\right) = p^2 c^2 \sum_{n=0}^{\infty} \chi_n^{(a)} \left(\frac{pc}{E_\star}\right)^n$$

modified interaction thresholds

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photodisintegration

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

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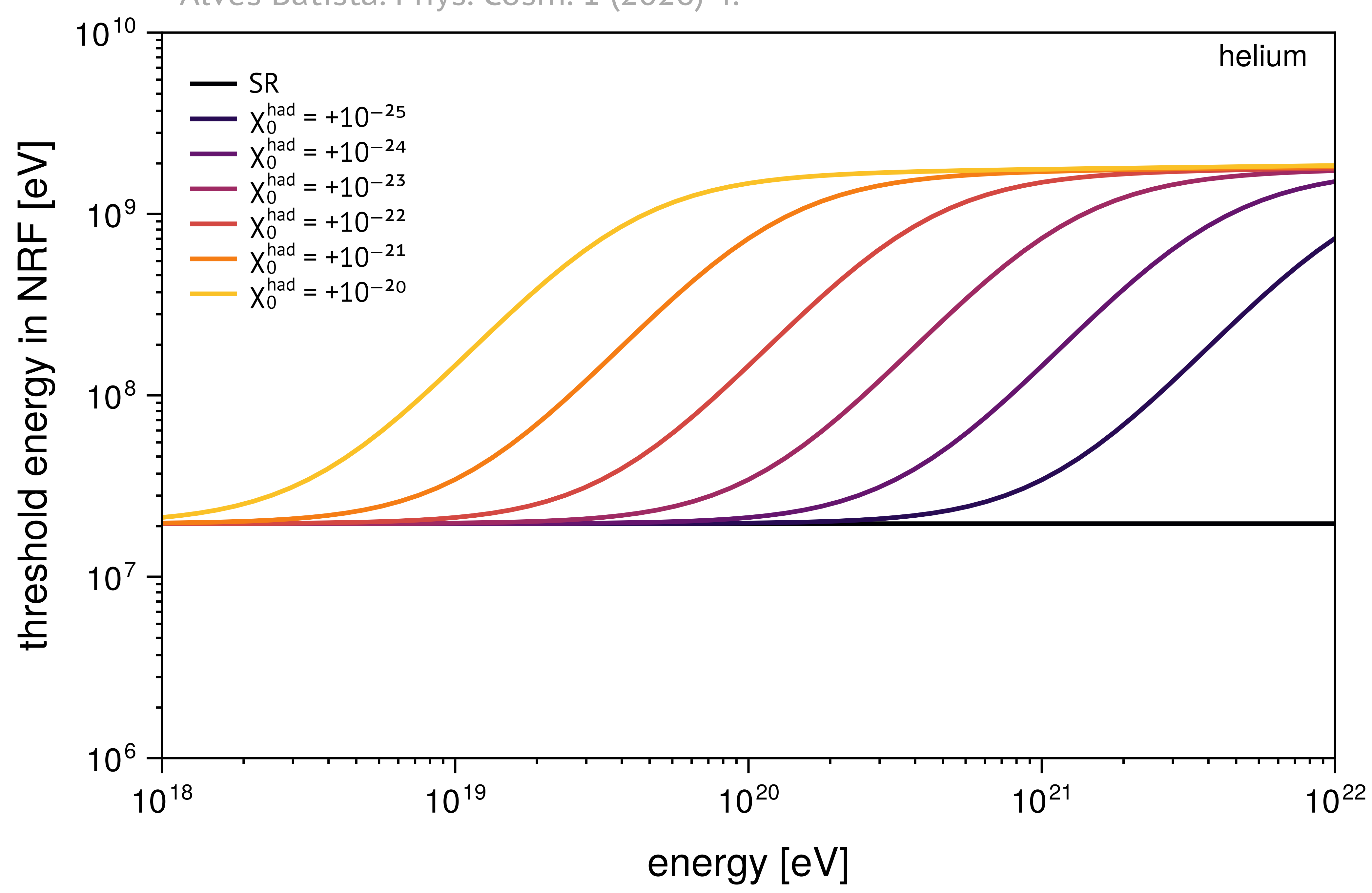

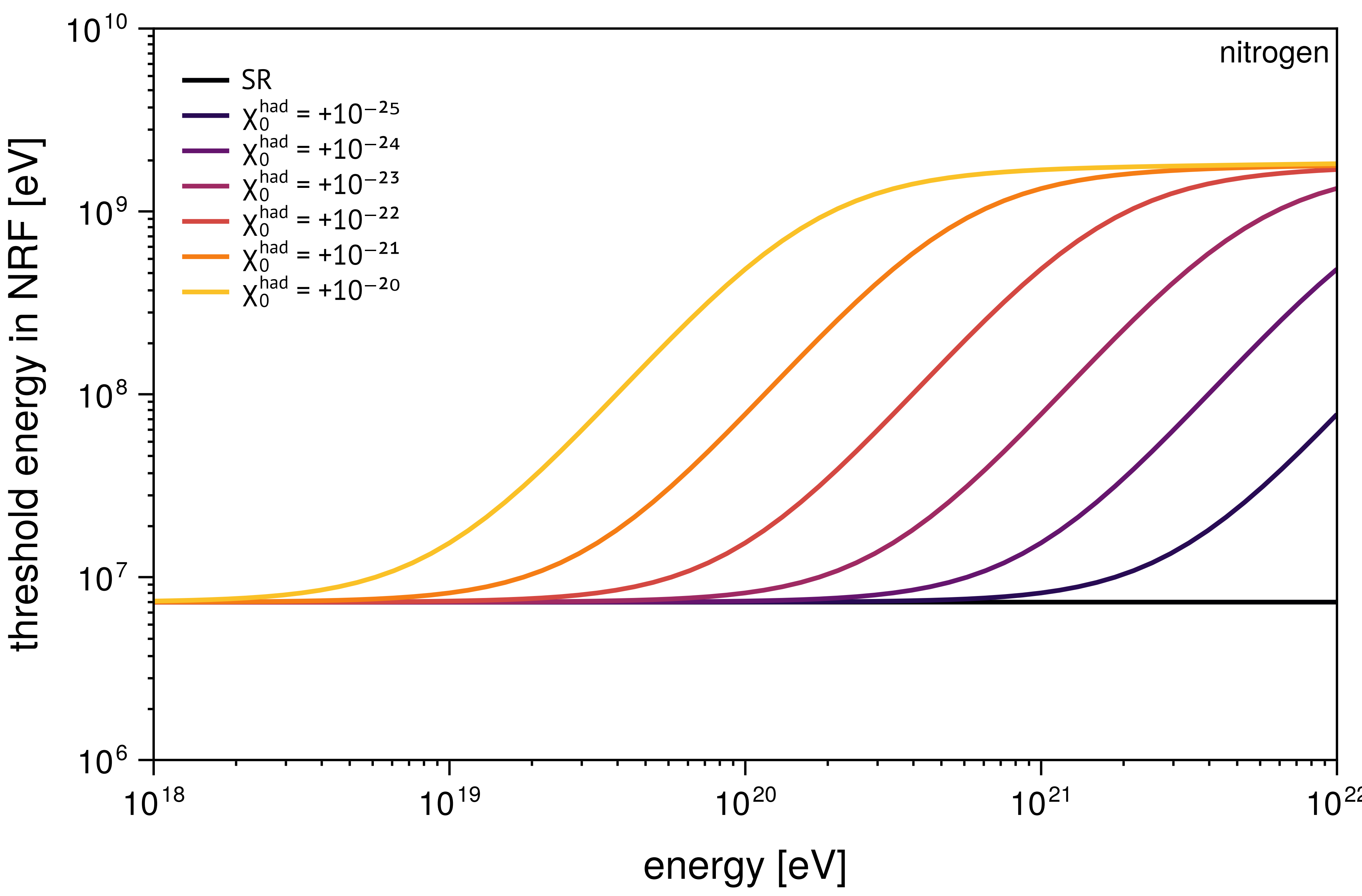

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n → p + e- + $\bar{\nu}_e$

cosmogenic particles

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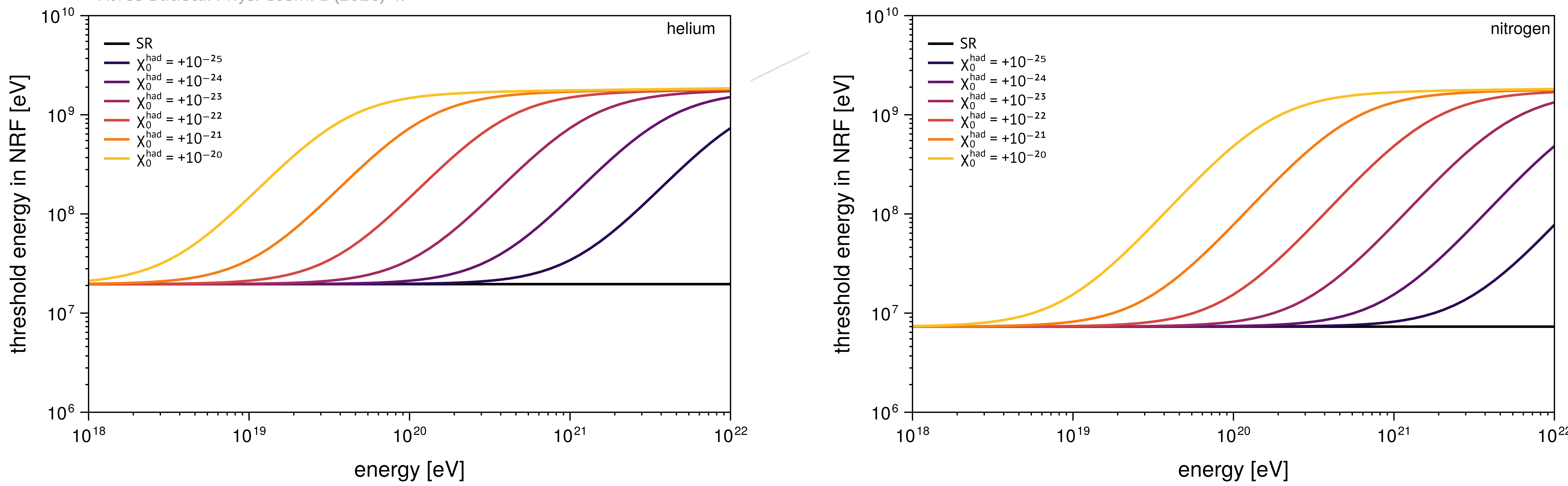

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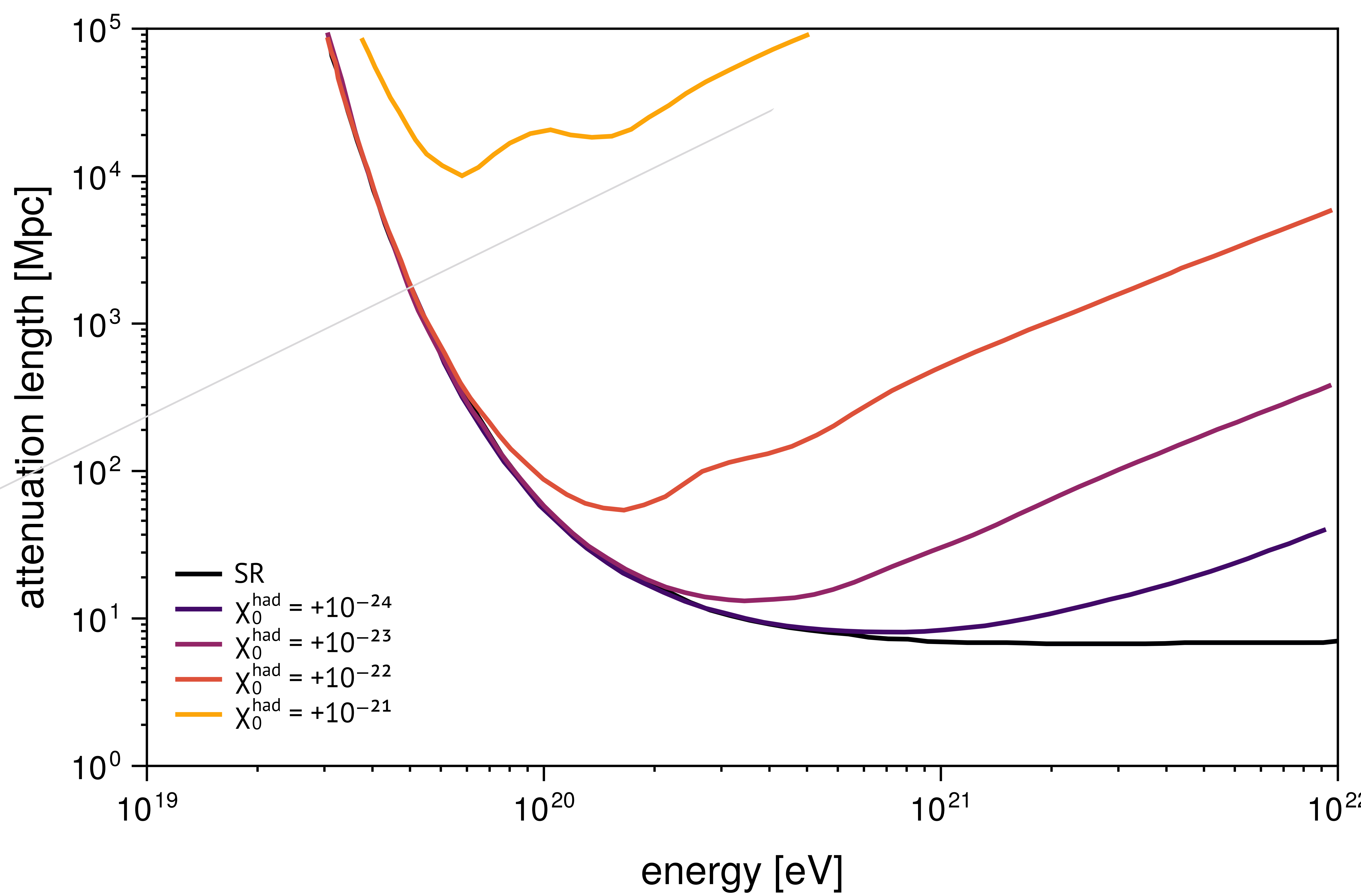

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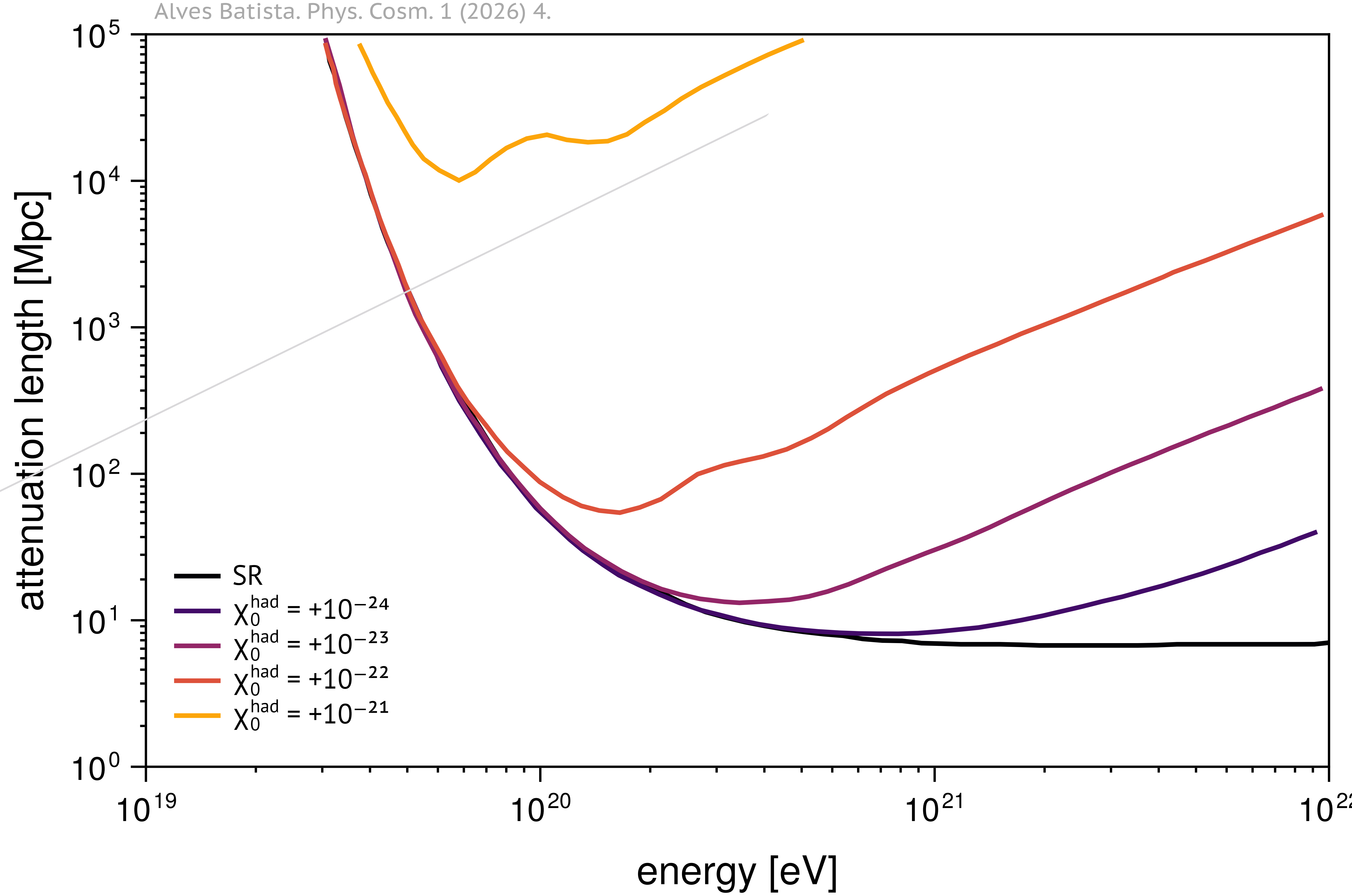

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(similar for nuclei)

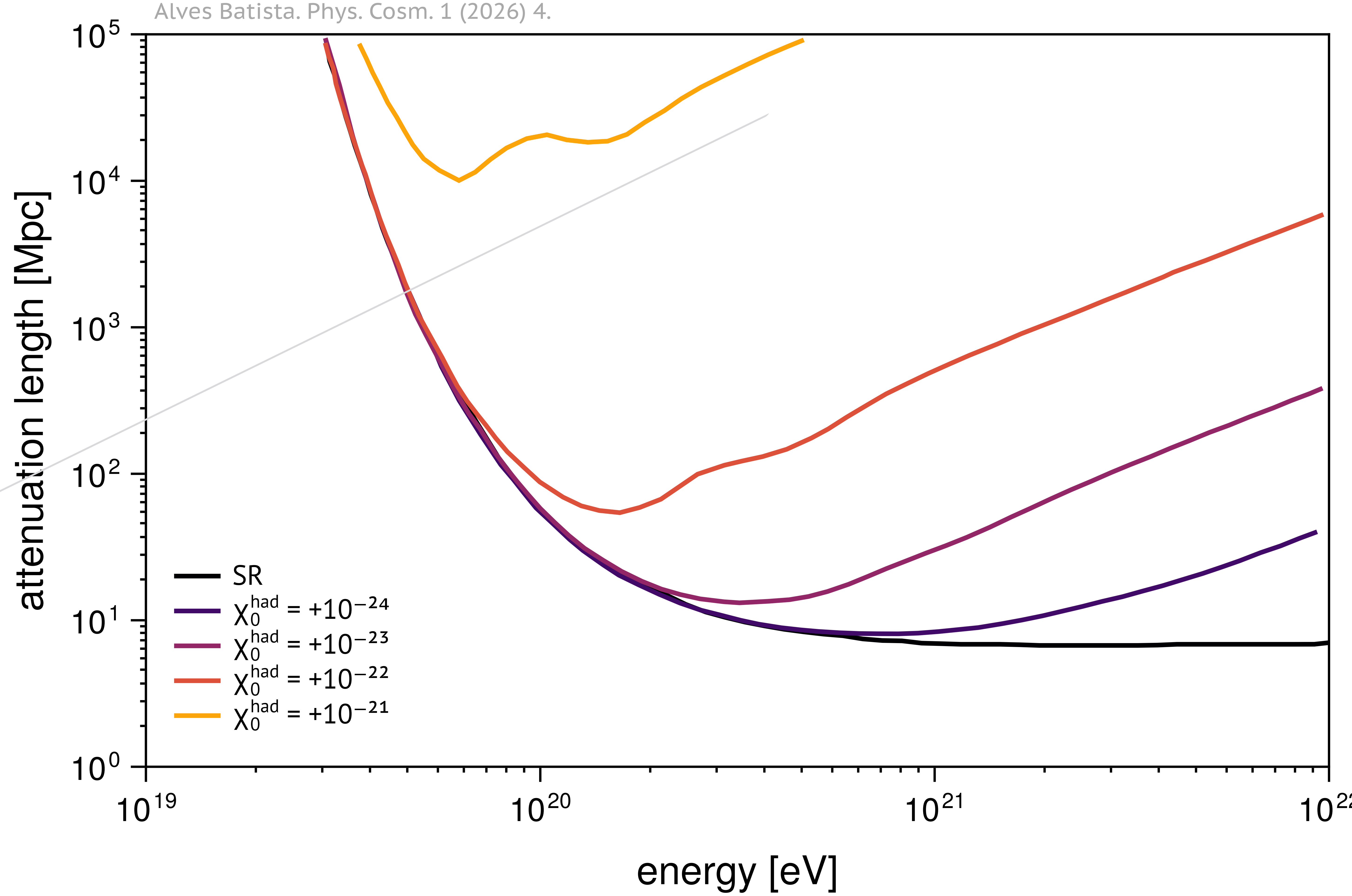
$\pi^0 \rightarrow \gamma + \gamma$

$\pi^+ \rightarrow \nu_\mu + \mu^+$

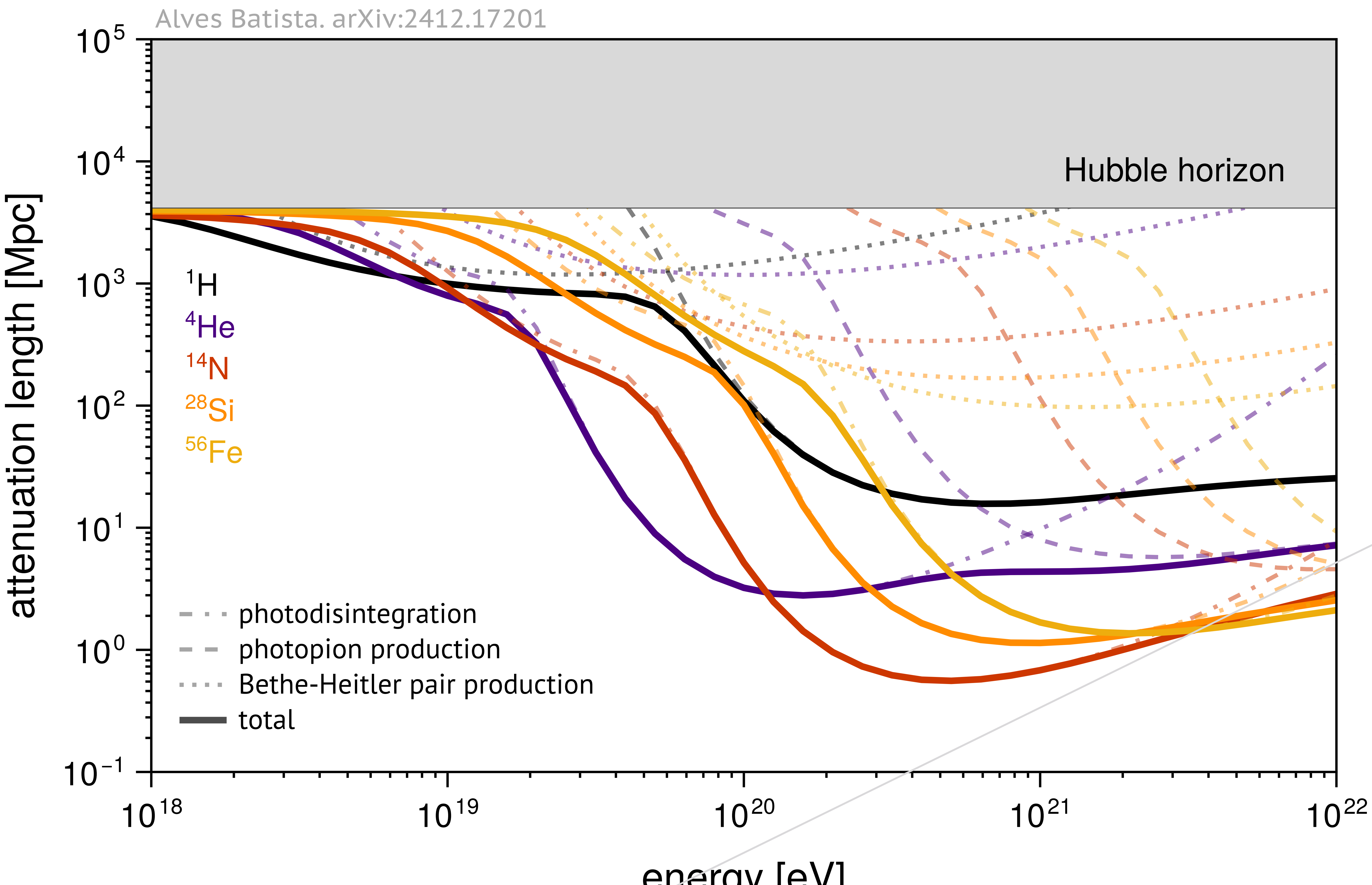
$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

cosmogenic particles

Alves Batista. Phys. Cosm. 1 (2026) 4.



UHECR propagation



photoproduction of mesons

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

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

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

(similar for nuclei)

Bethe-Heitler pair production

nucleus(A, Z) + γ_{bg} → nucleus(A, Z) + e^- + e^+

photodisintegration

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

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

...

nuclear decays

nucleus(A, Z) → nucleus(A-4, Z-2) + α

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

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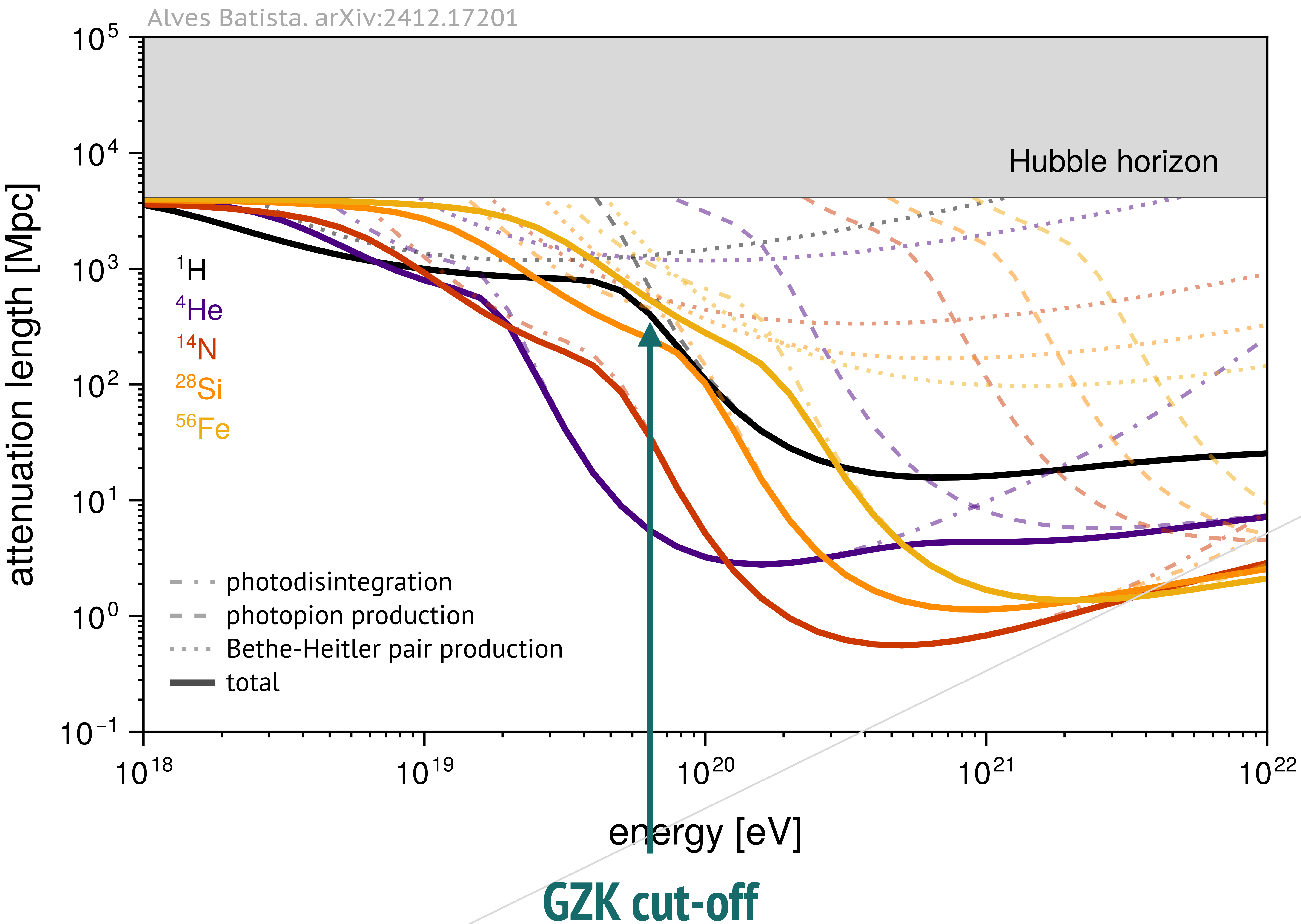
nucleus(A, Z)* → nucleus(A, Z) + γ



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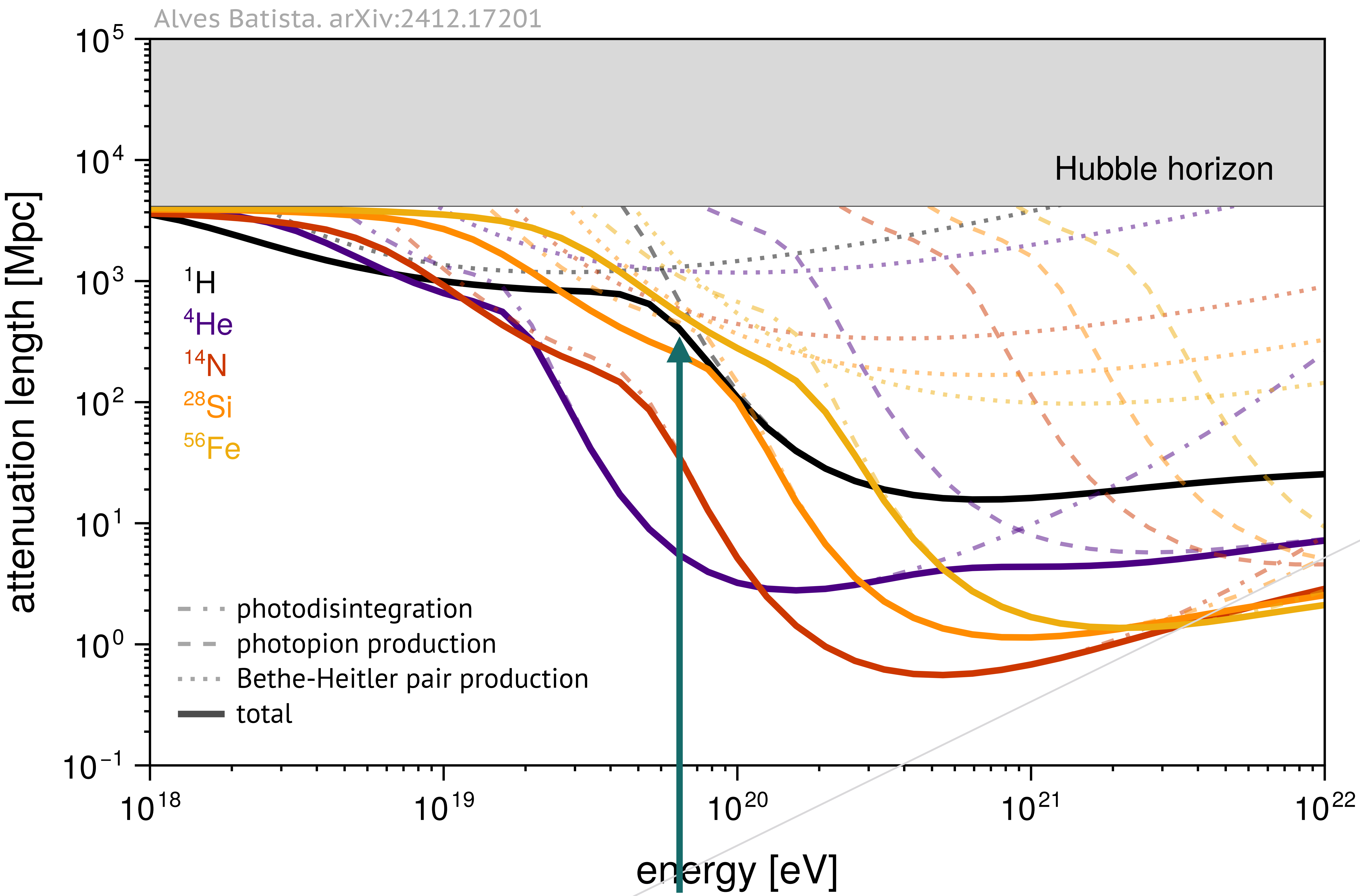
$\text{nucleus}(A, Z)^* \rightarrow \text{nucleus}(A, Z) + \gamma$



GZK cut-off

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

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

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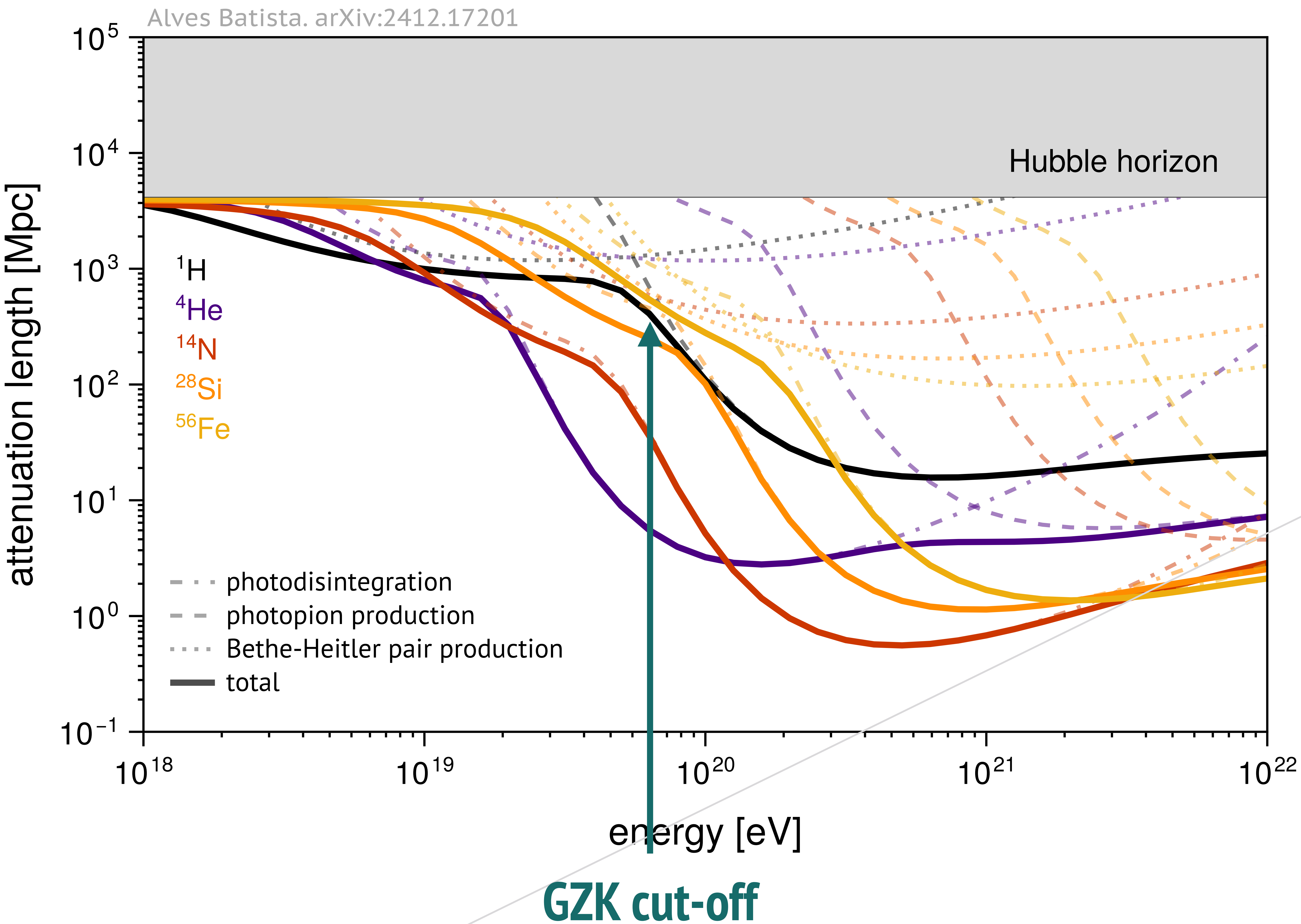

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$E_{\rm GZK} \simeq 6\ {\rm EeV} \equiv 6 \times 10^{19}\ {\rm eV}$

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Coleman et al. Astroparticle Physics 149 (2023) 102819. arXiv:2205.05845

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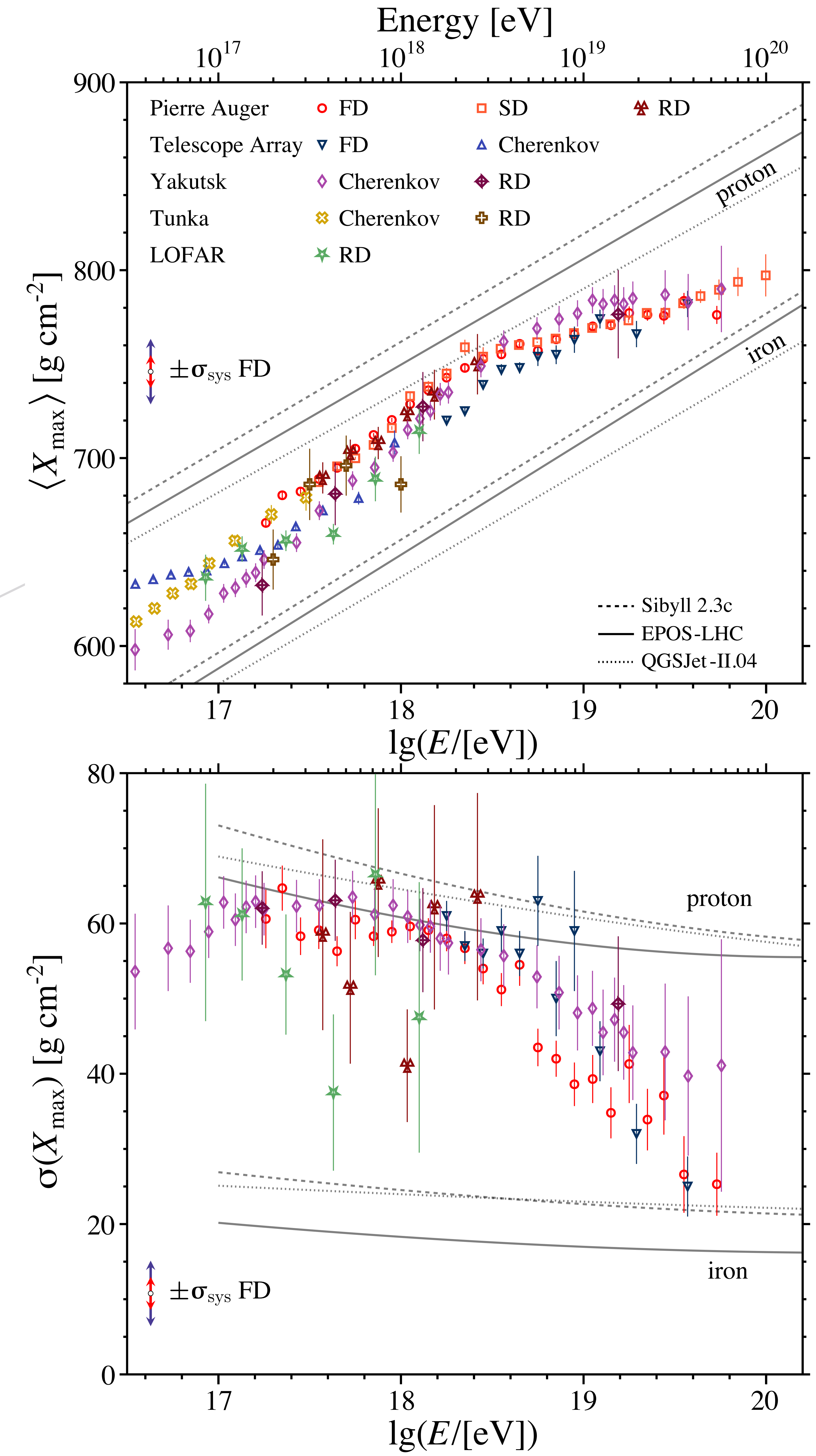
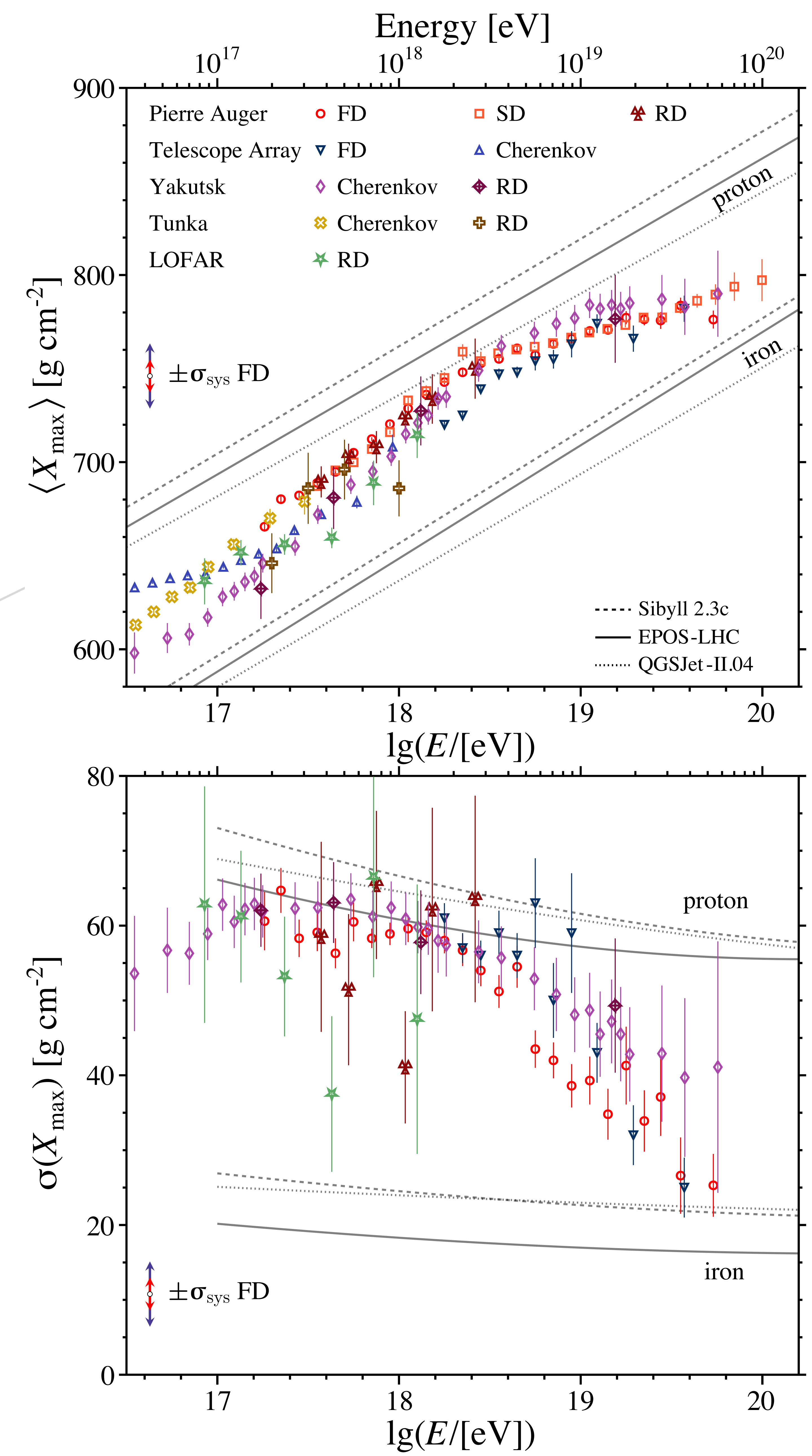


self-consistent constraints in hadronic sector

Coleman et al. Astroparticle Physics 149 (2023) 102819. arXiv:2205.05845

- **problem:** effects in the hadronic sector also affects the showers
- what we measure is X_{max}
- **how to tackle that?** LIV-CORSIKA working group



gamma rays

the usual approach to gamma-ray propagation

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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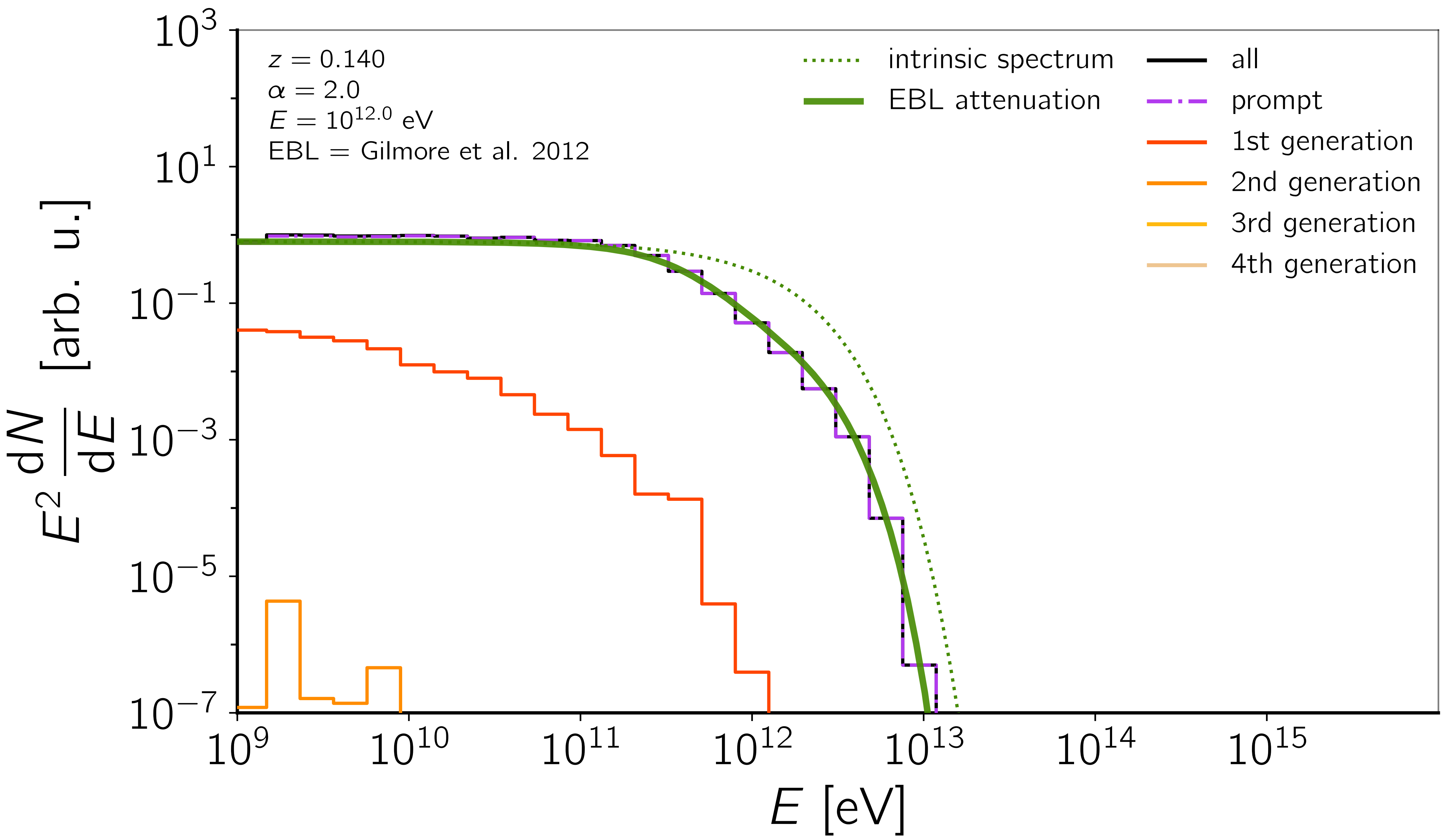

simulations performed with CRPropa

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

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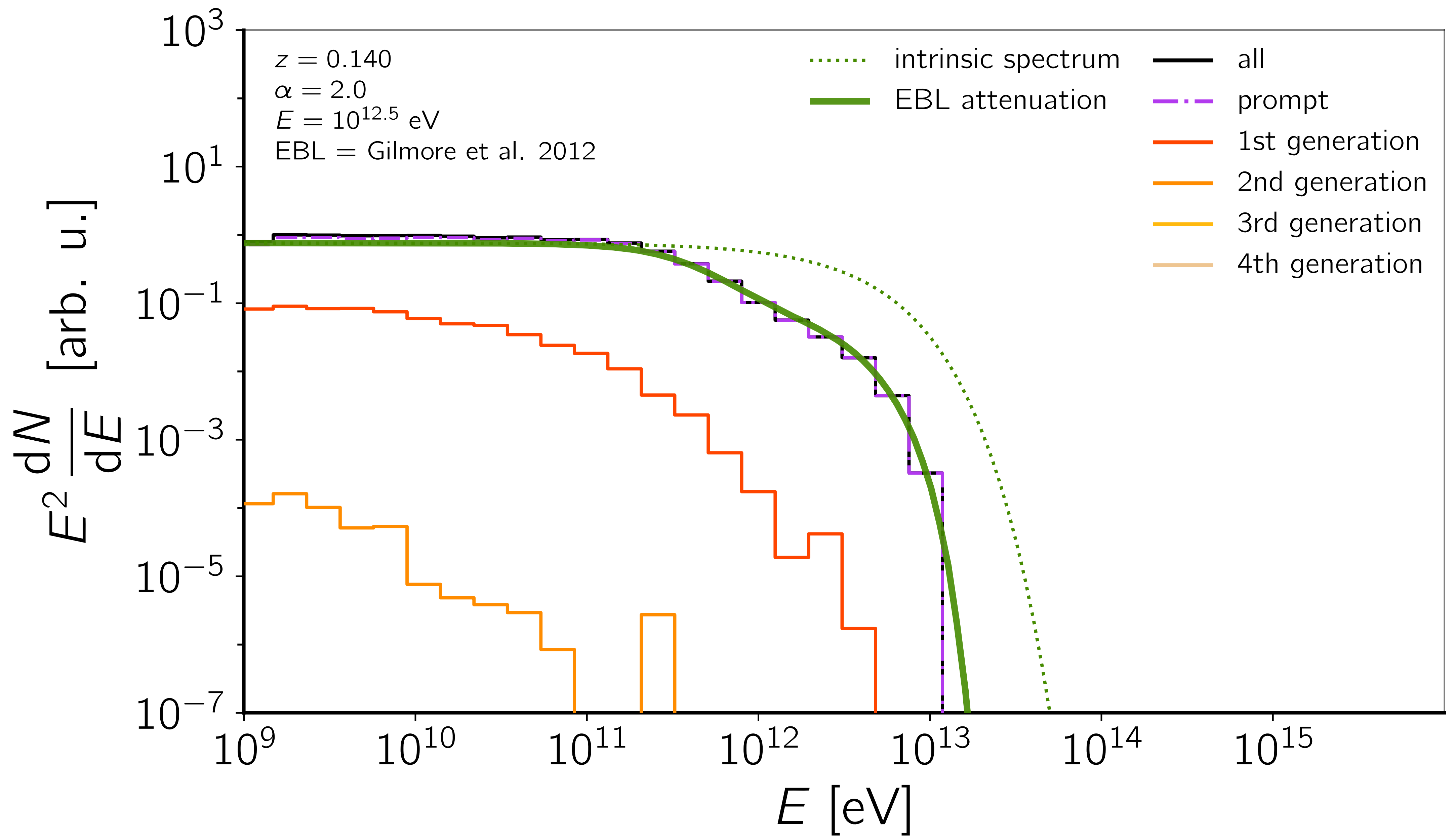

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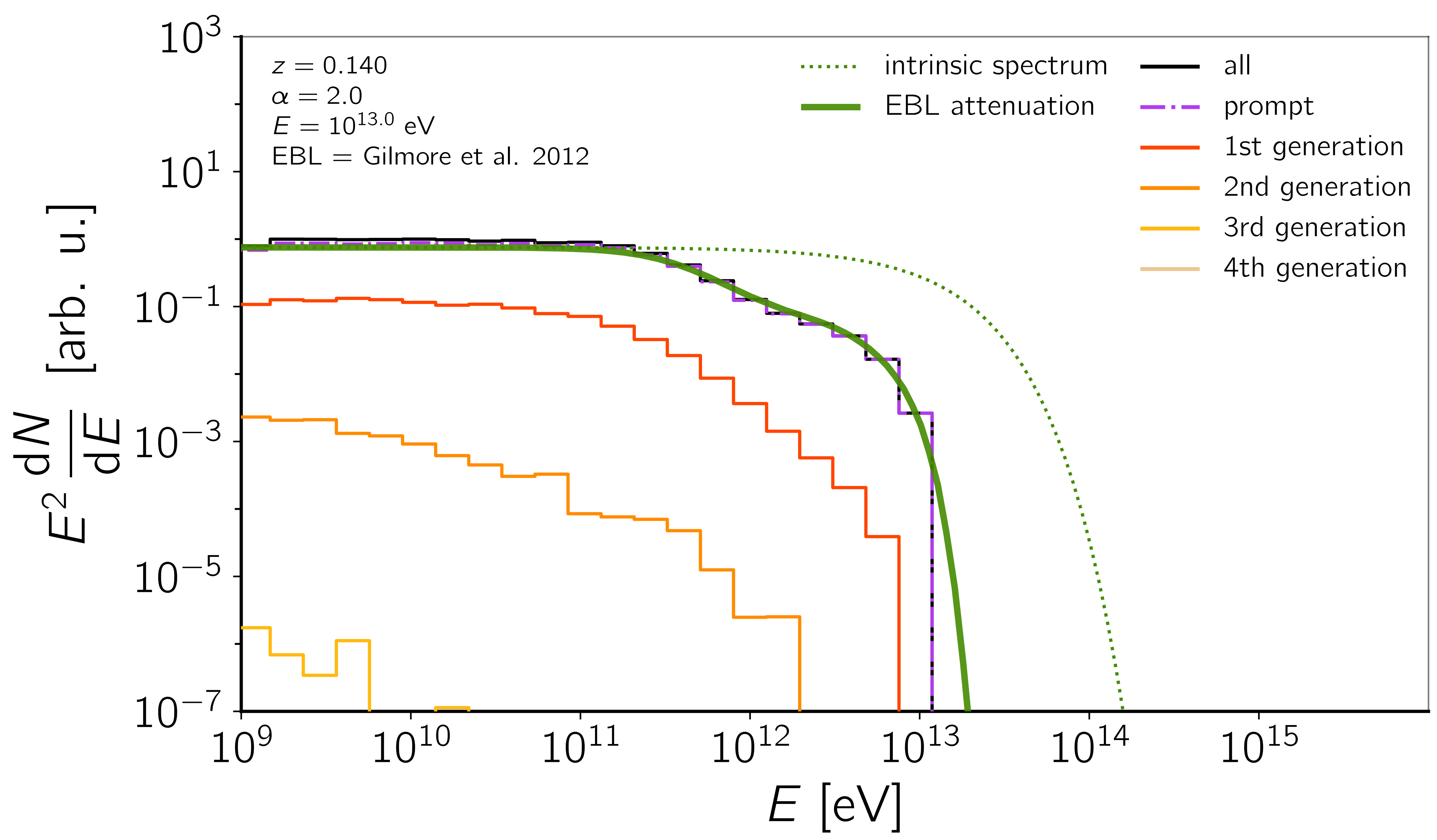

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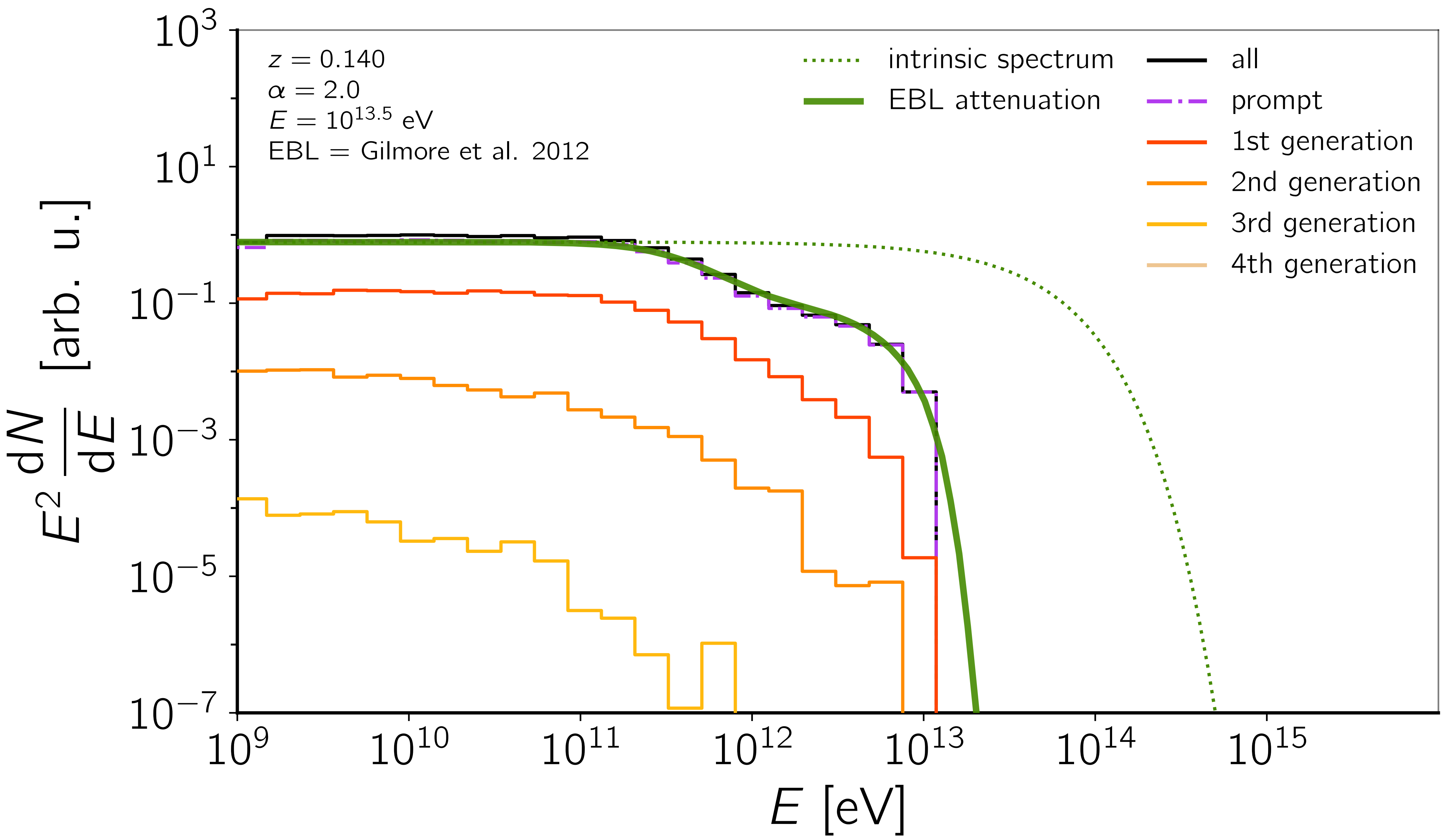

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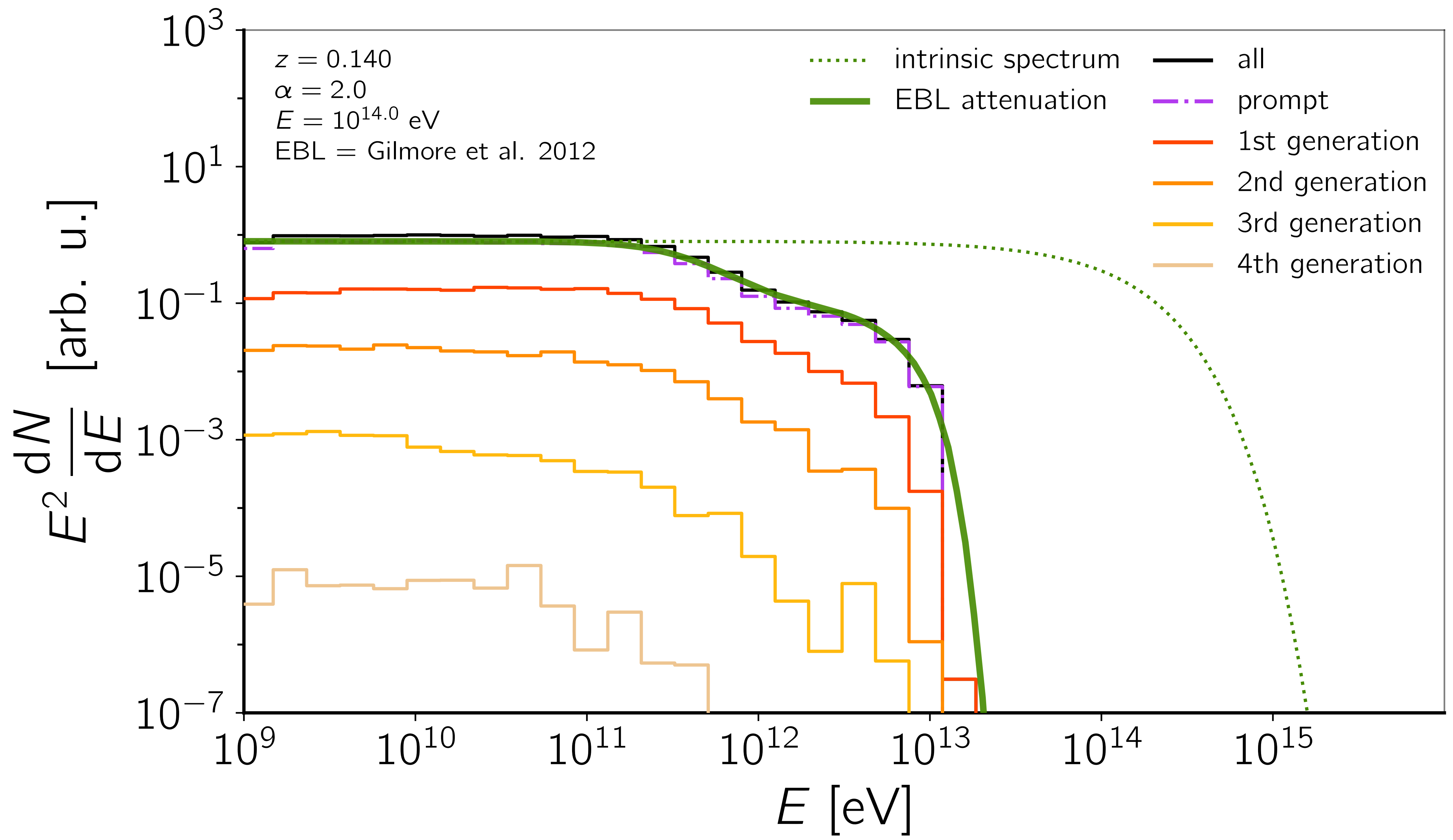

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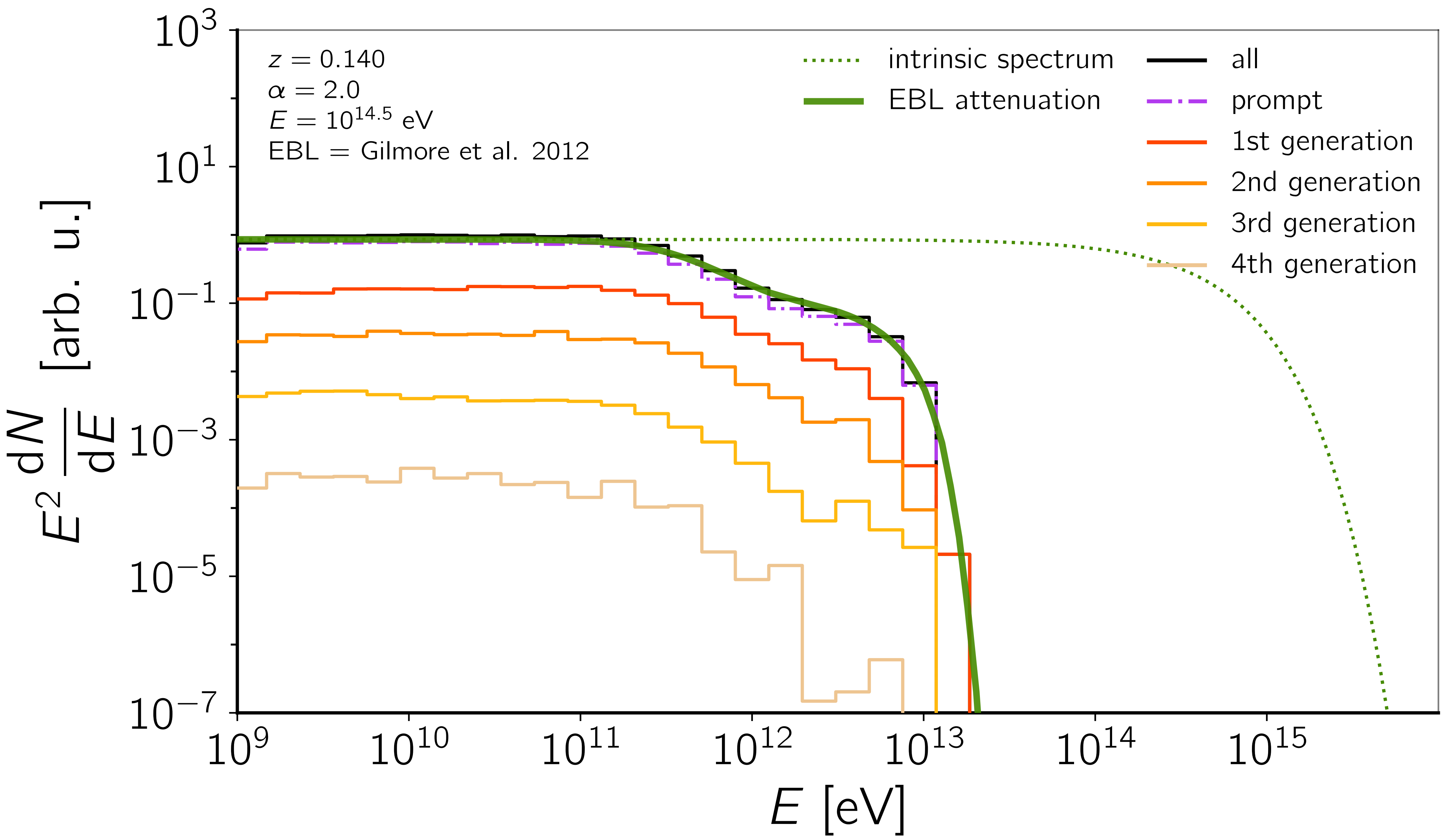

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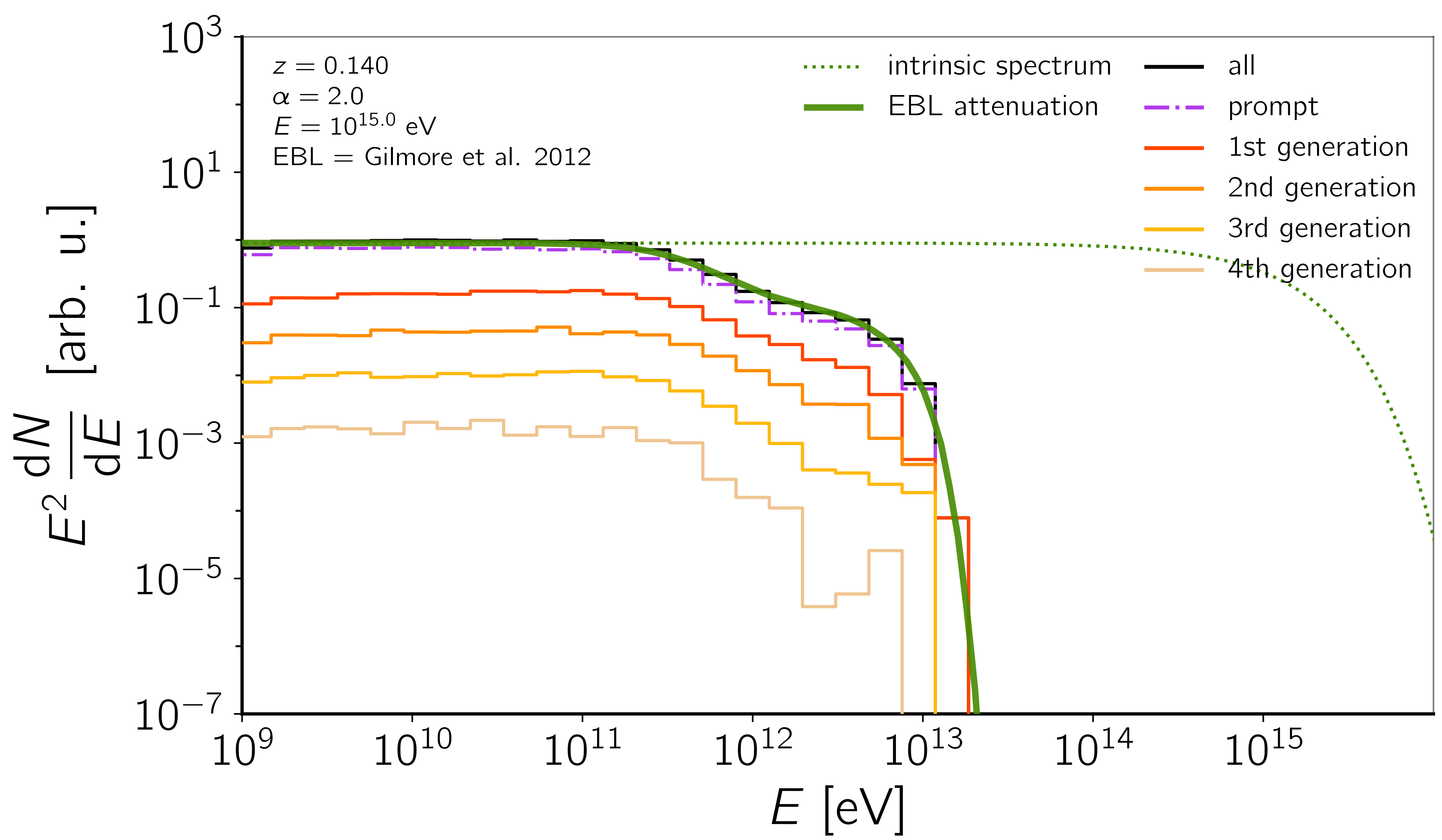

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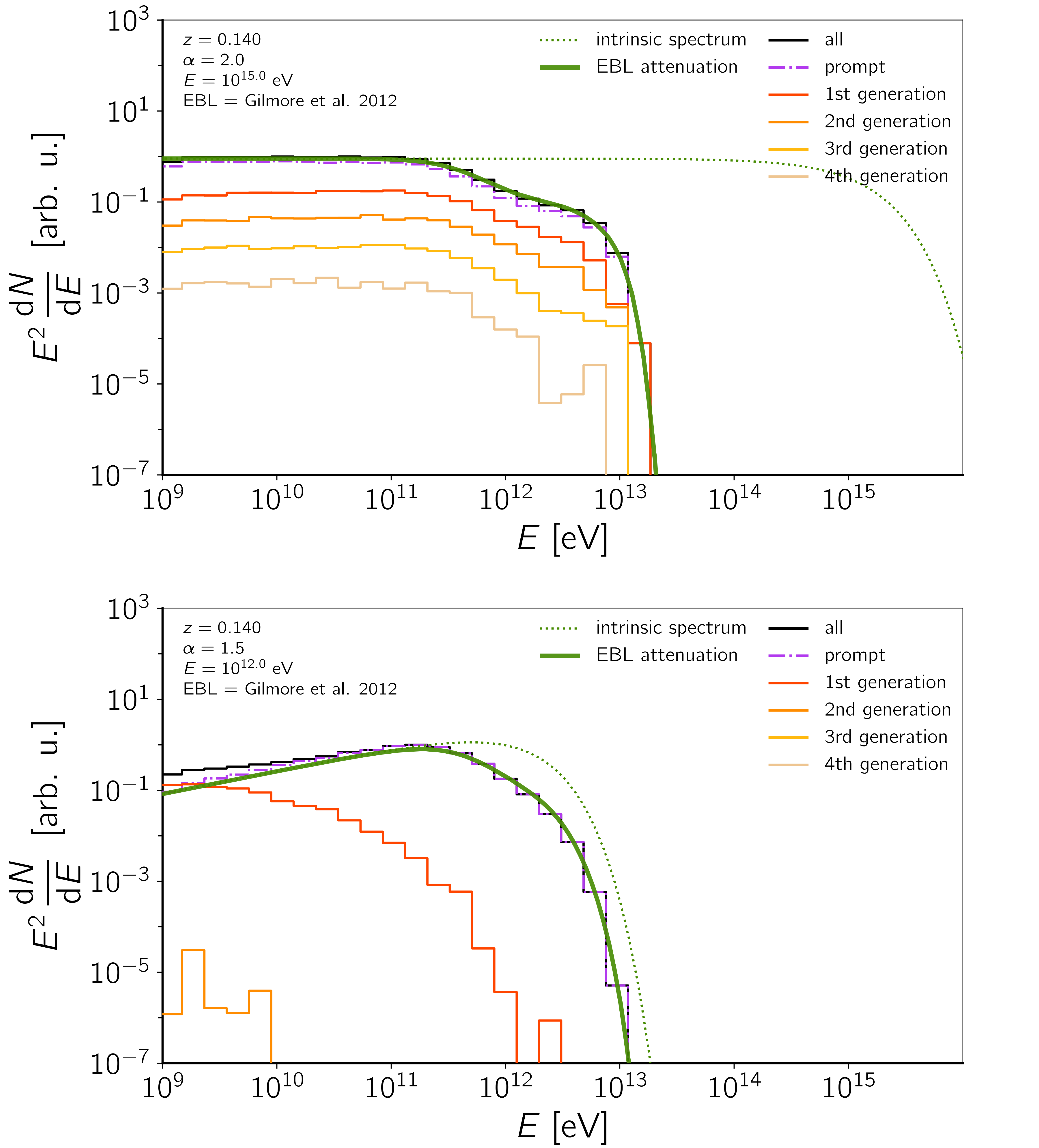

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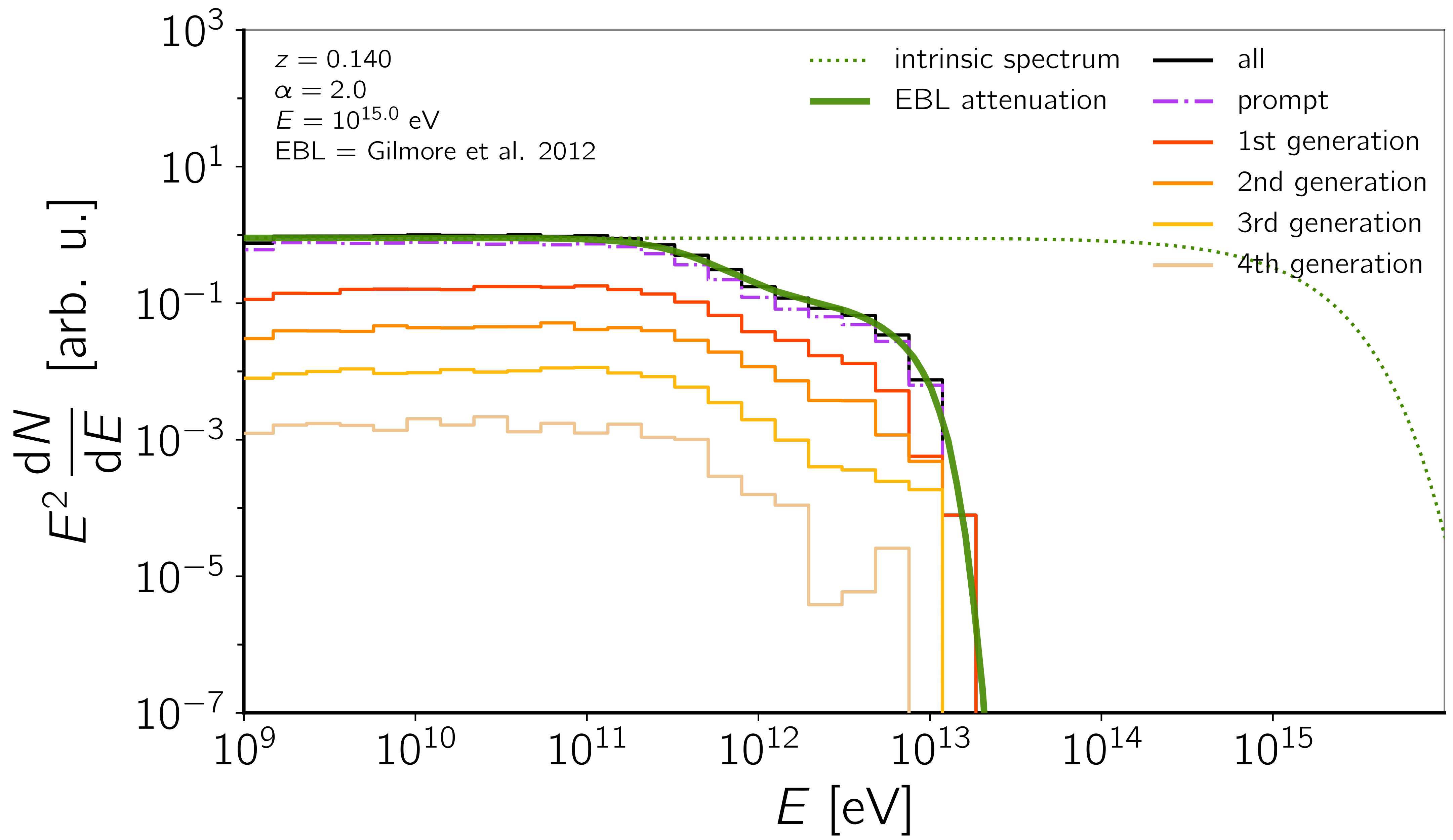

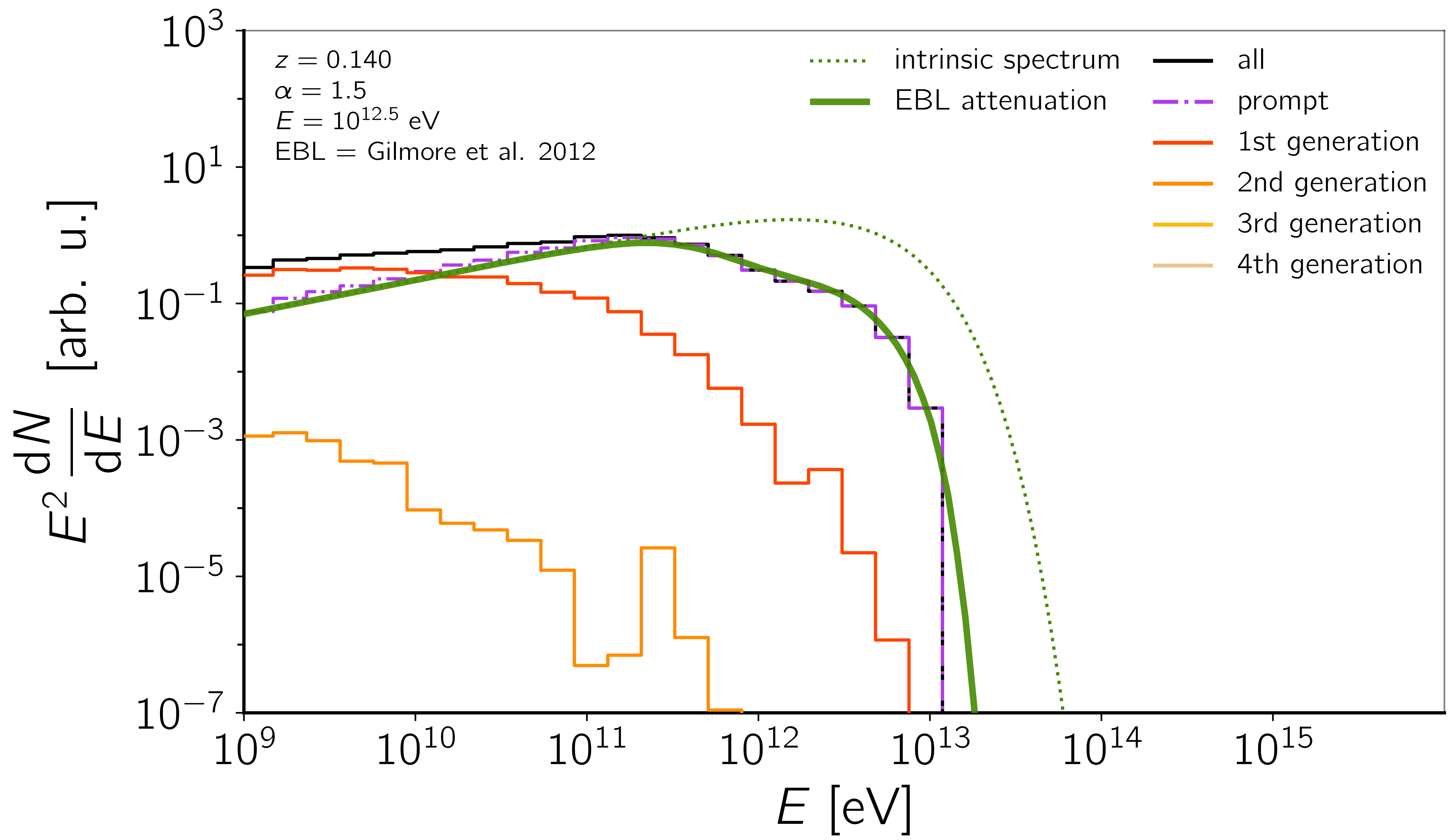

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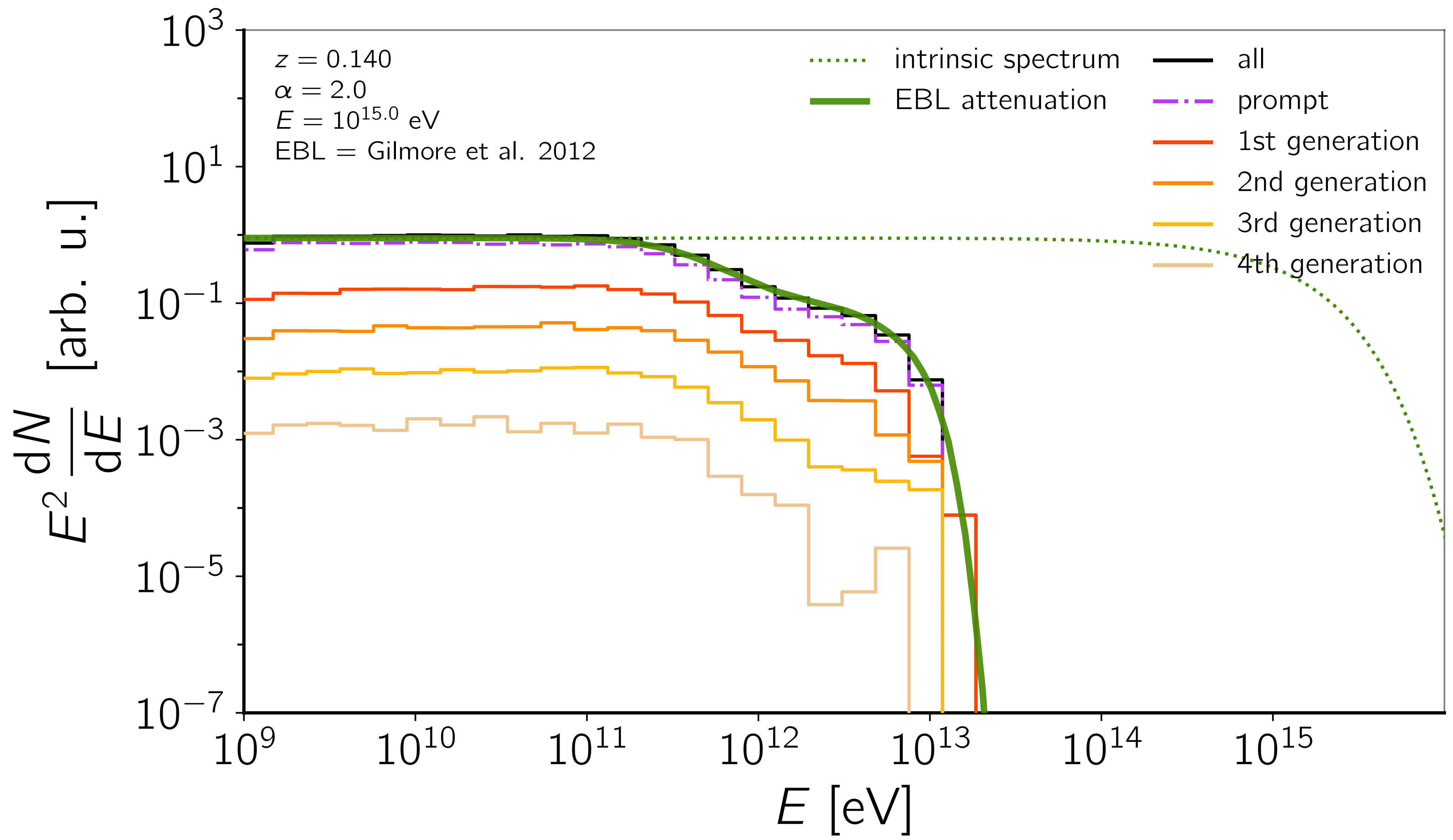

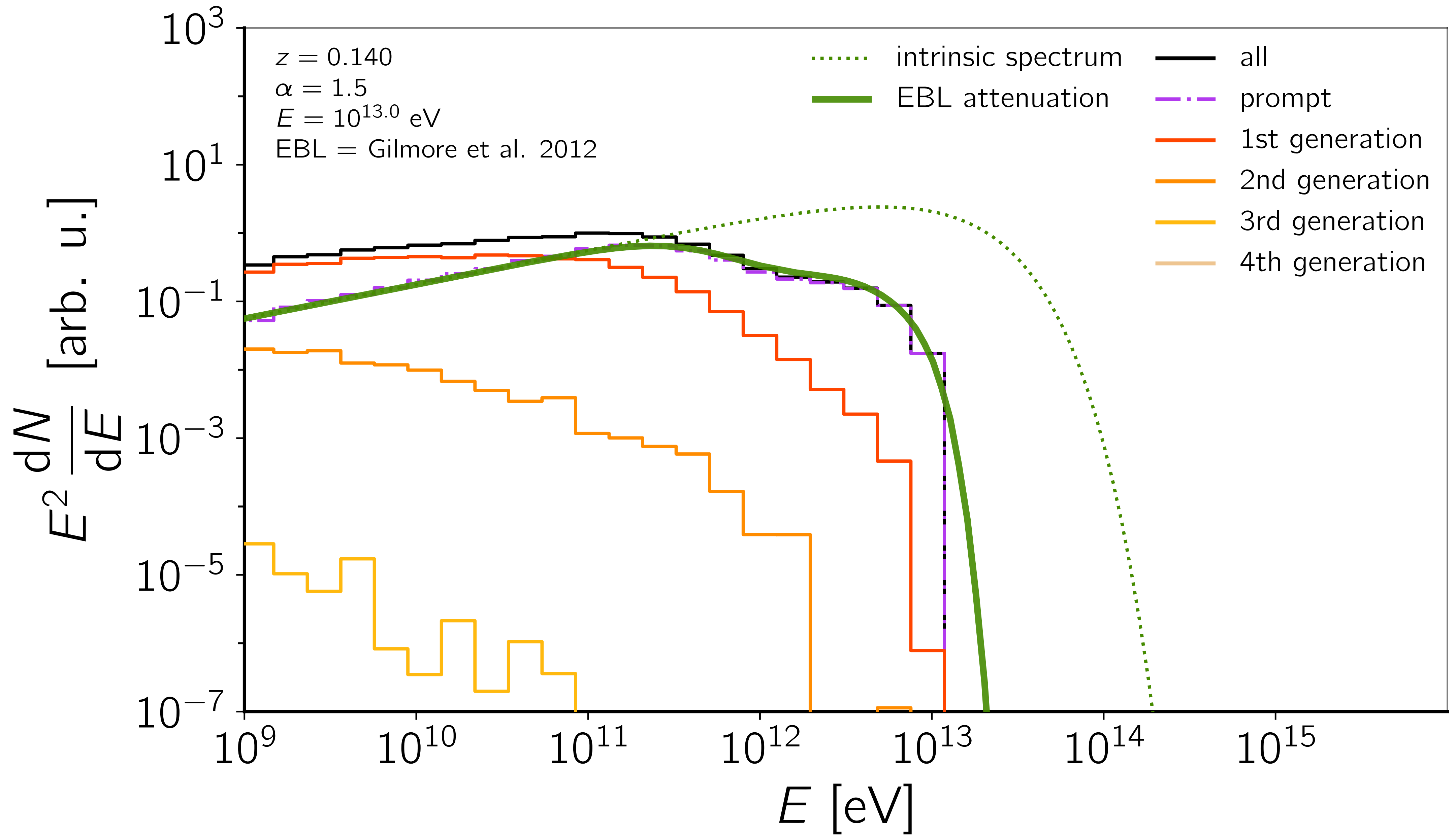

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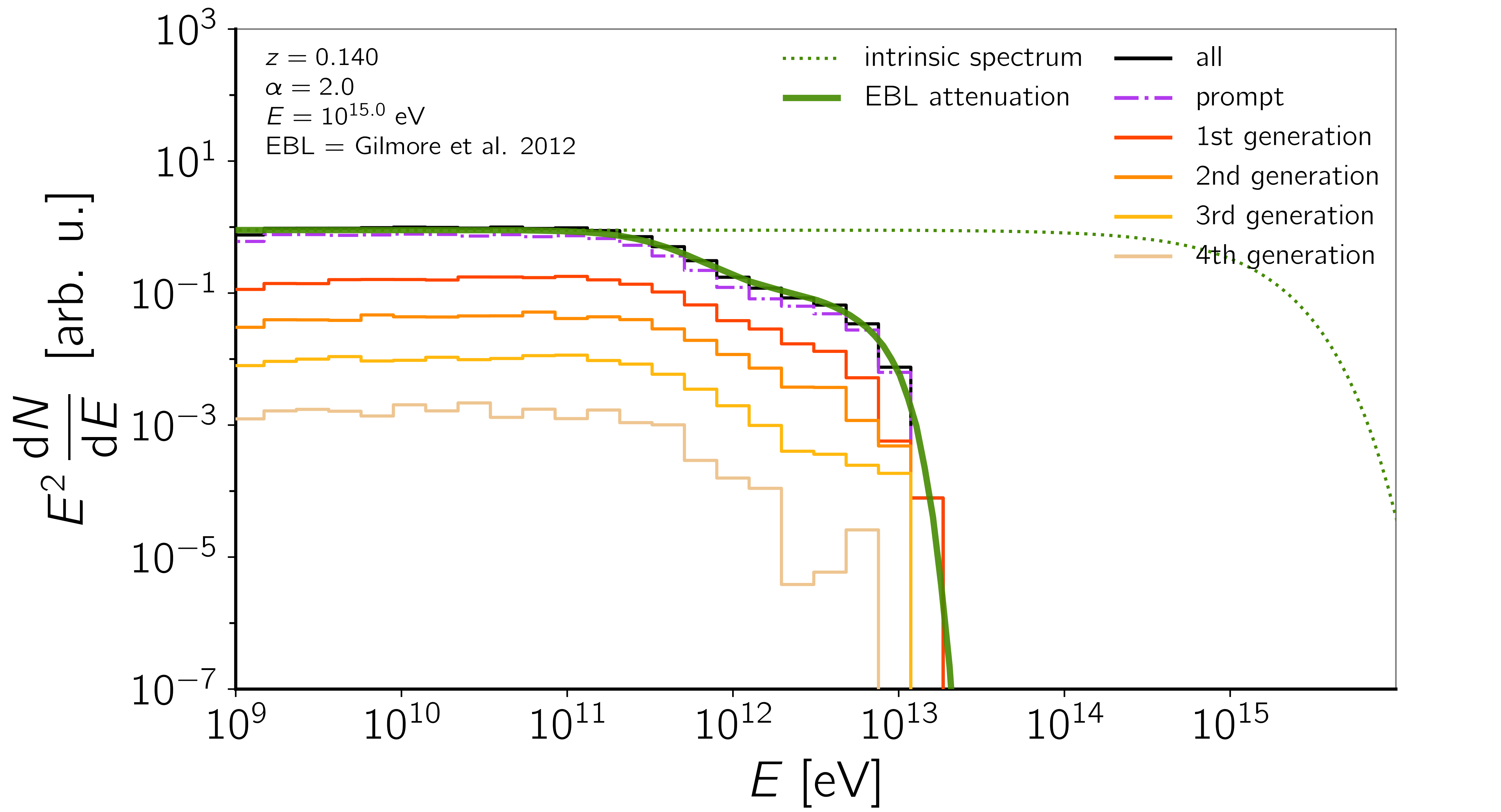

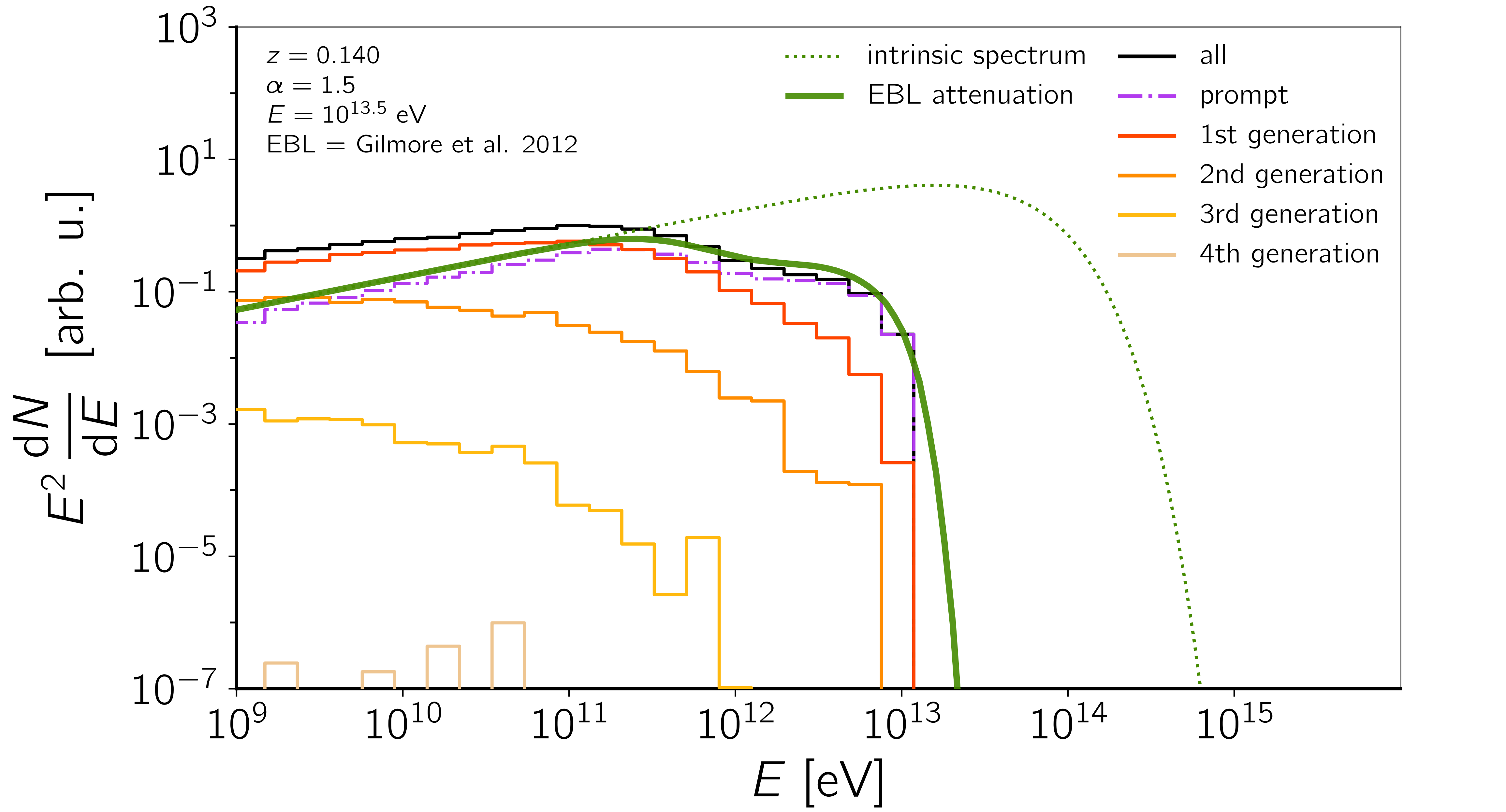

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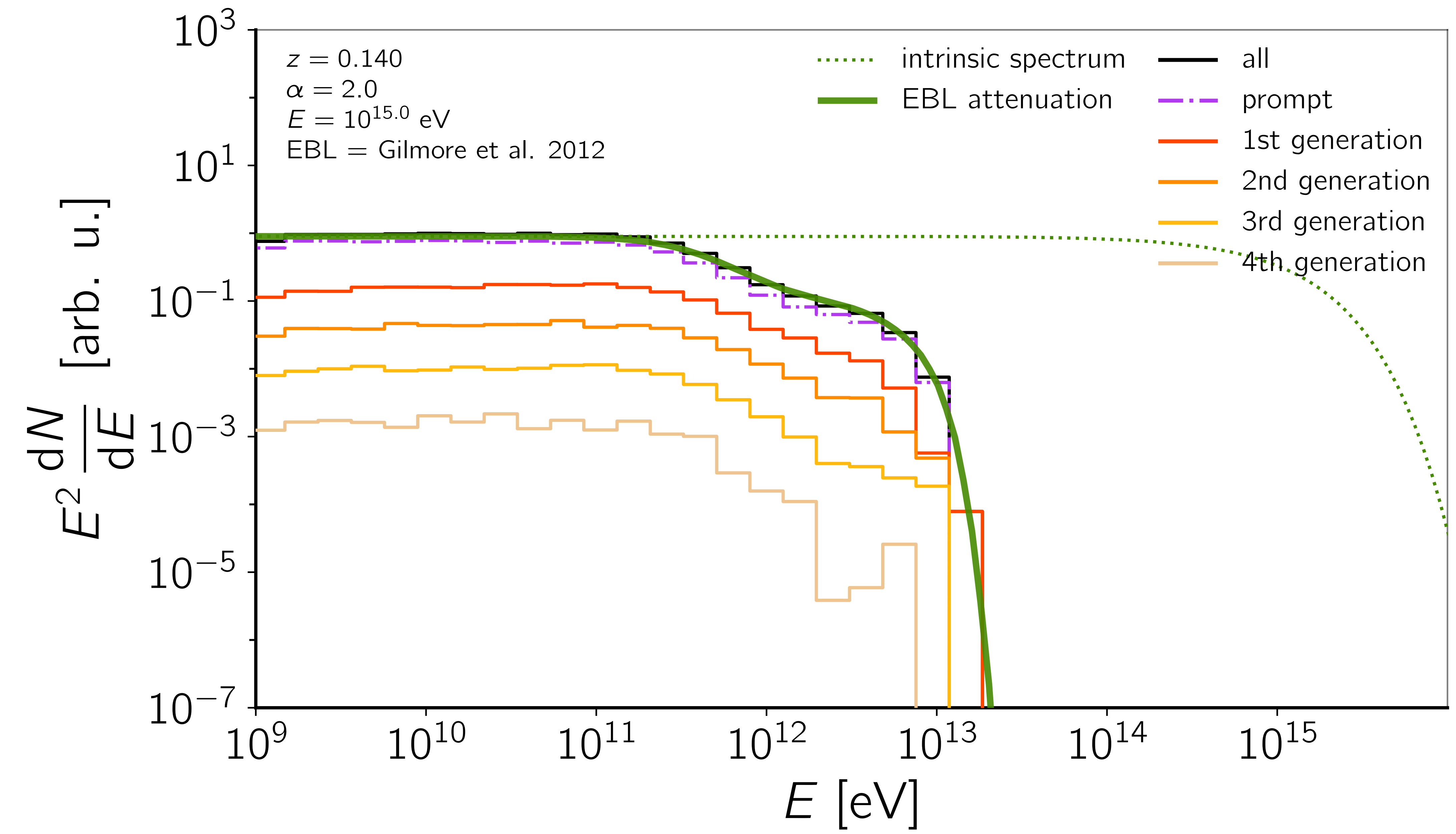

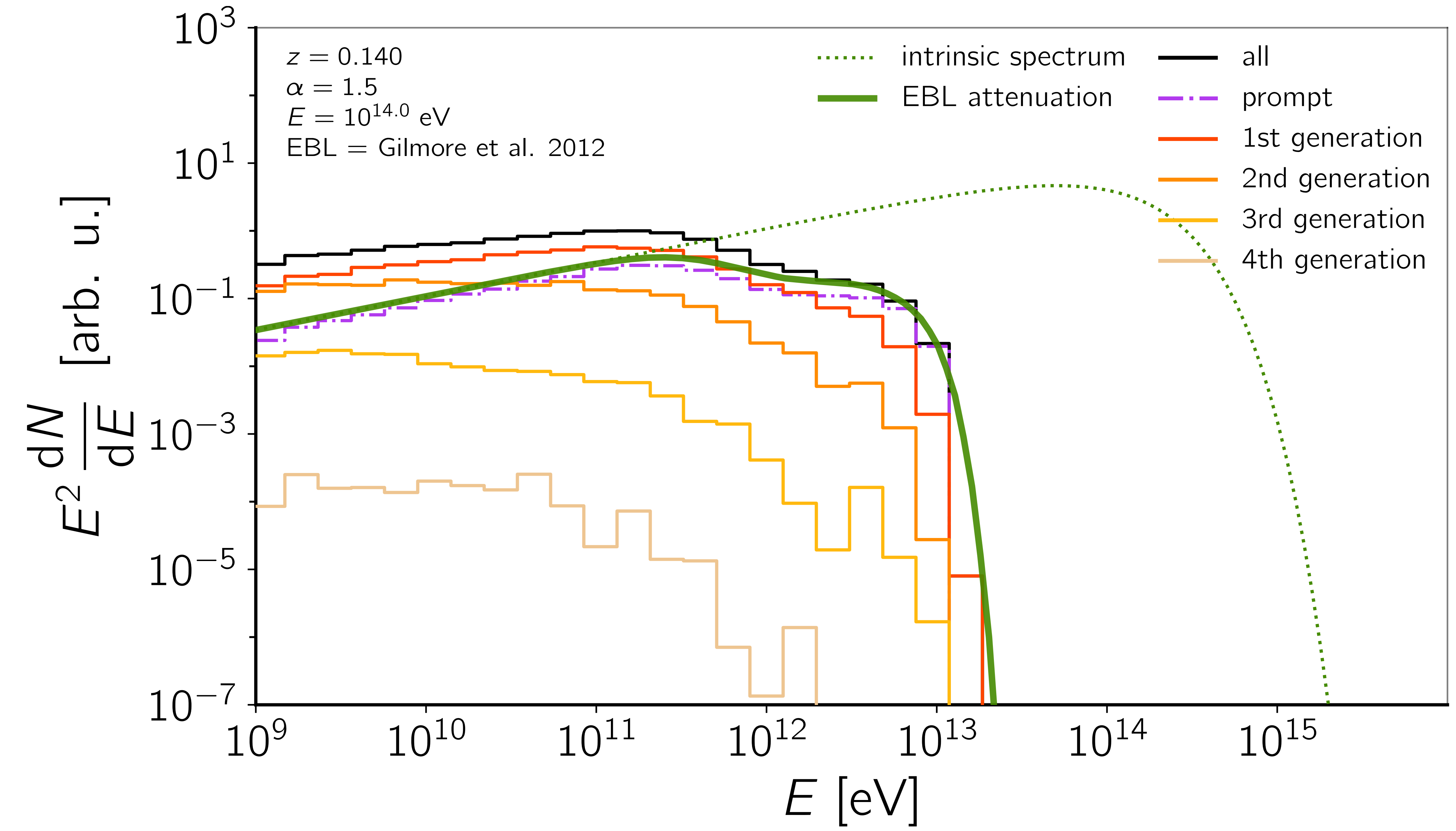

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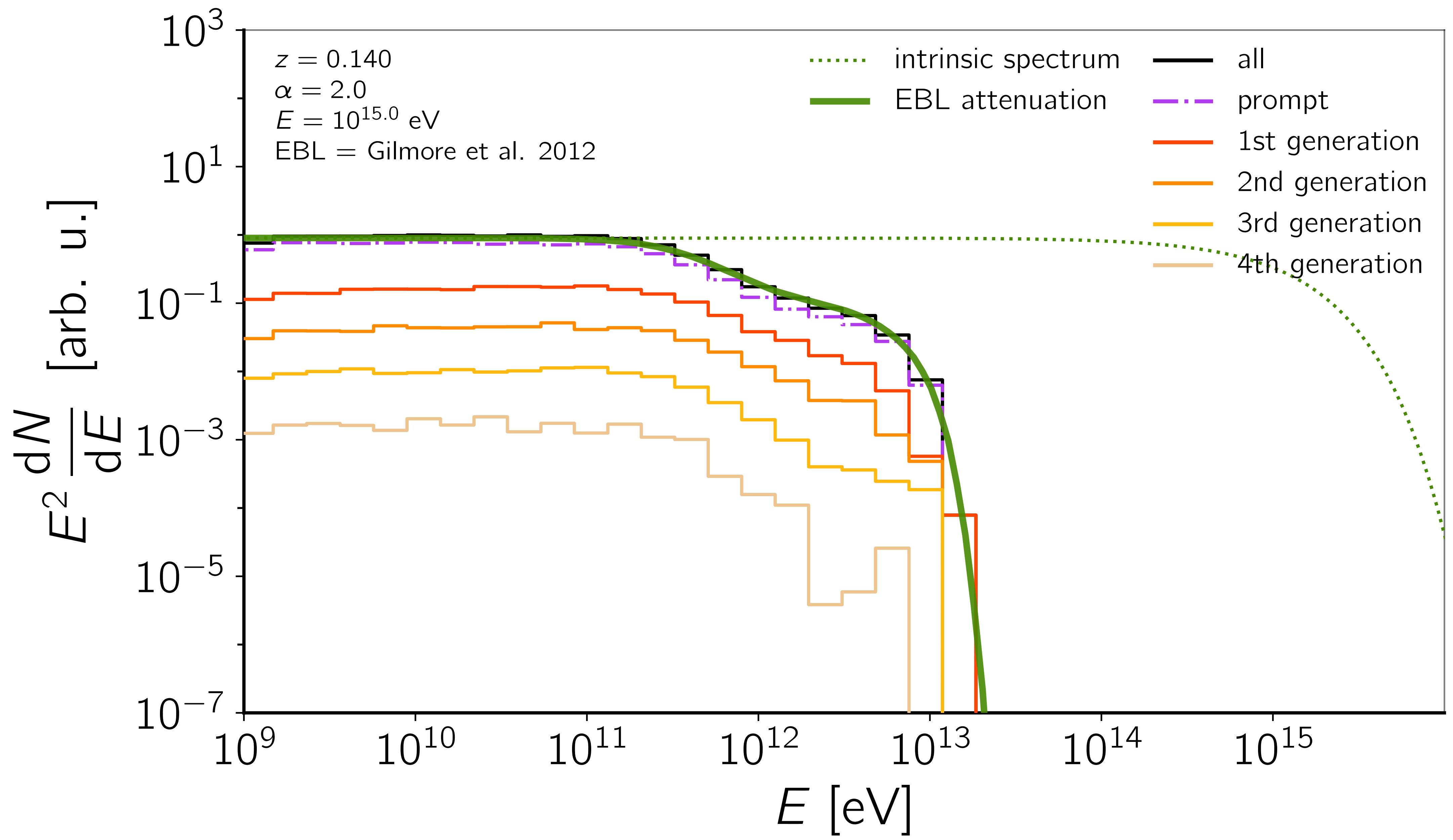

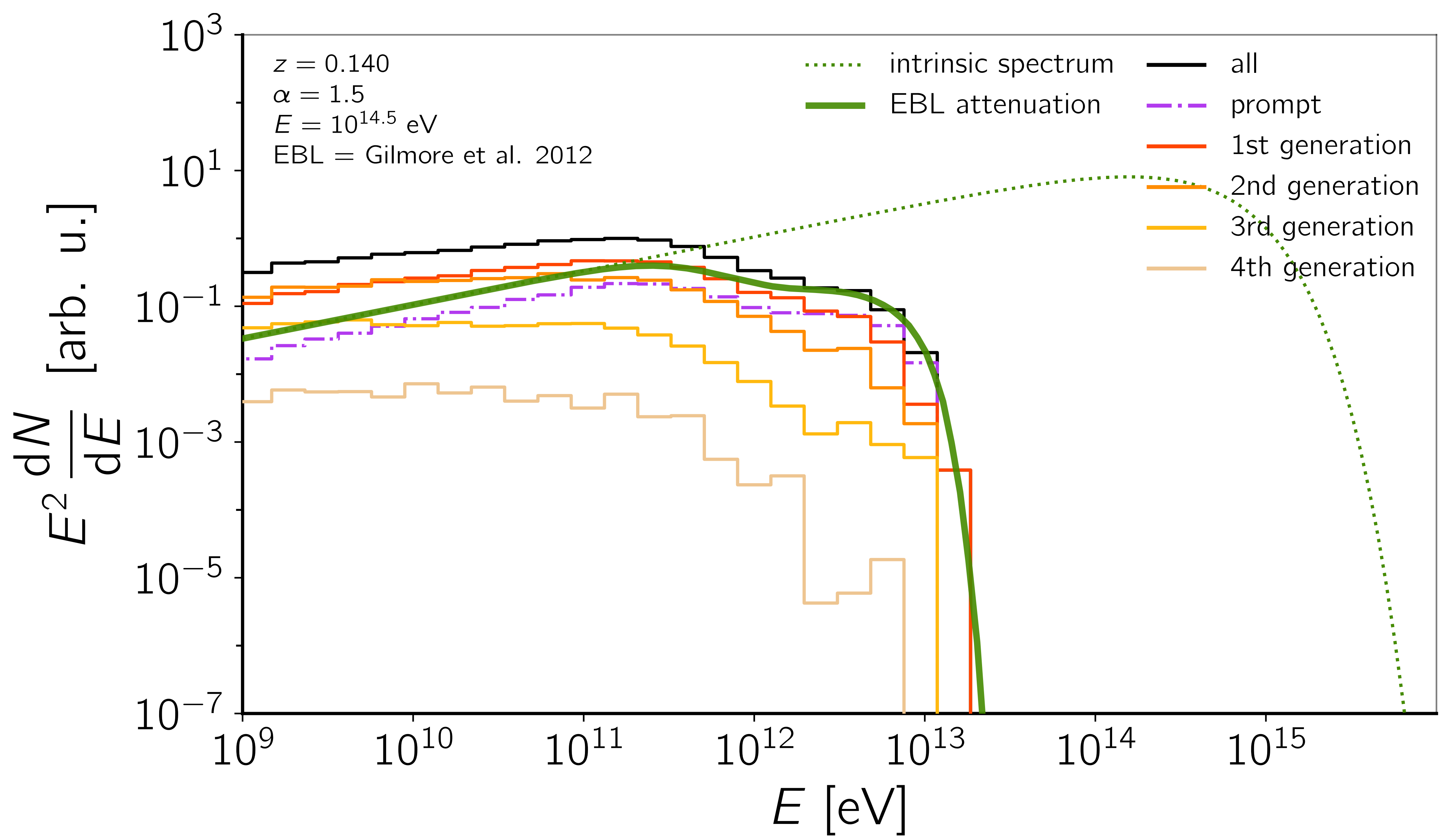

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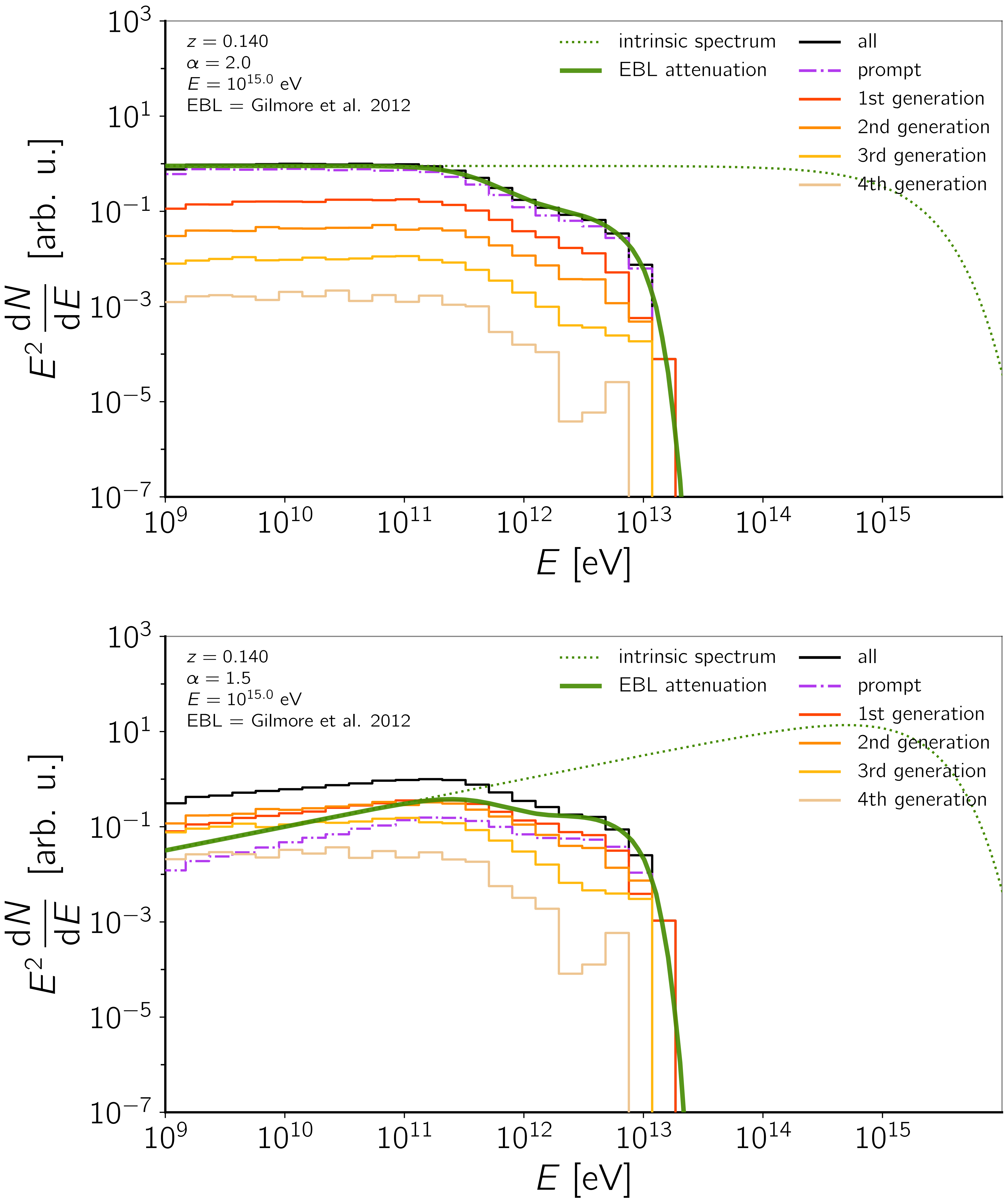

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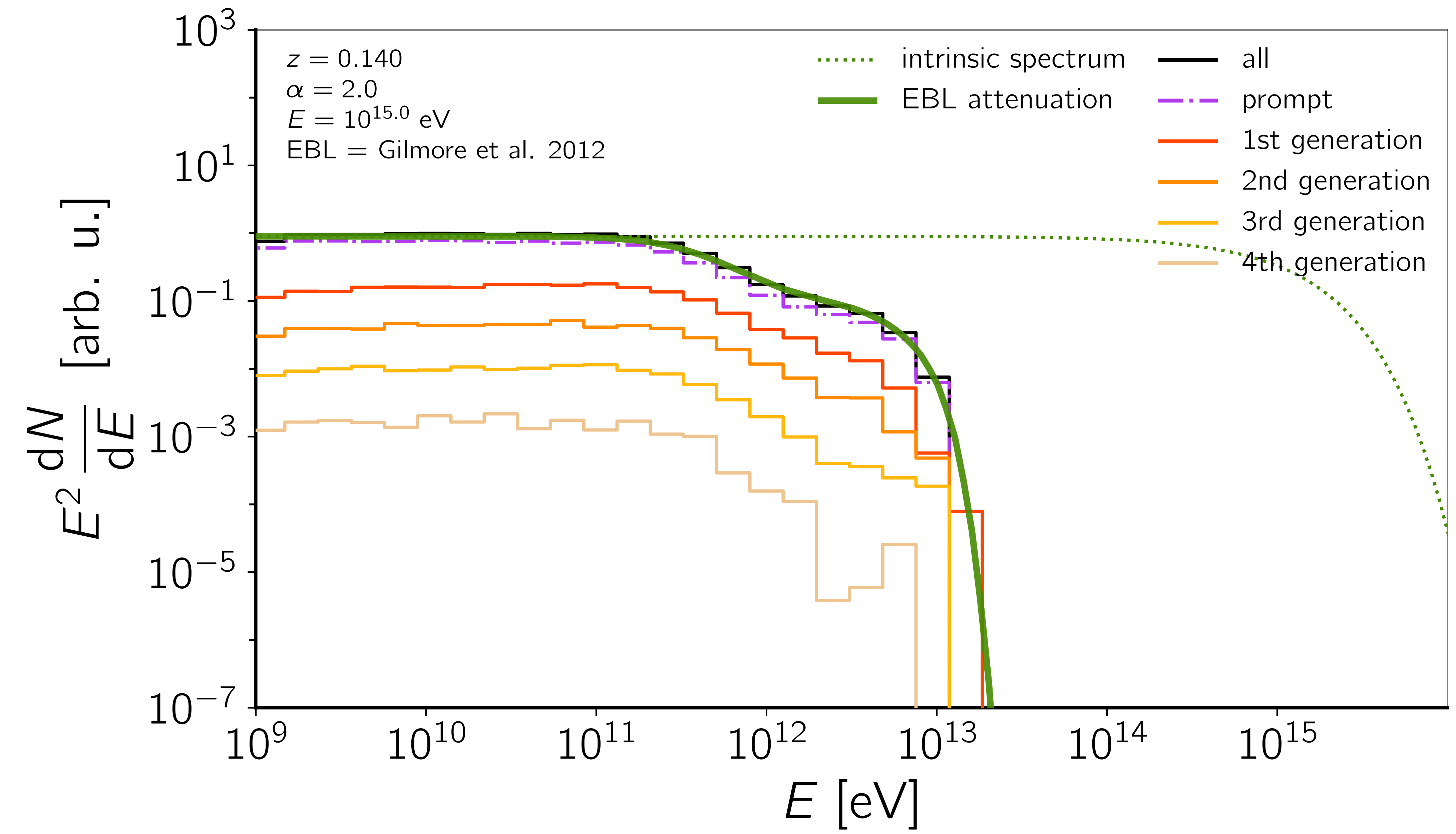
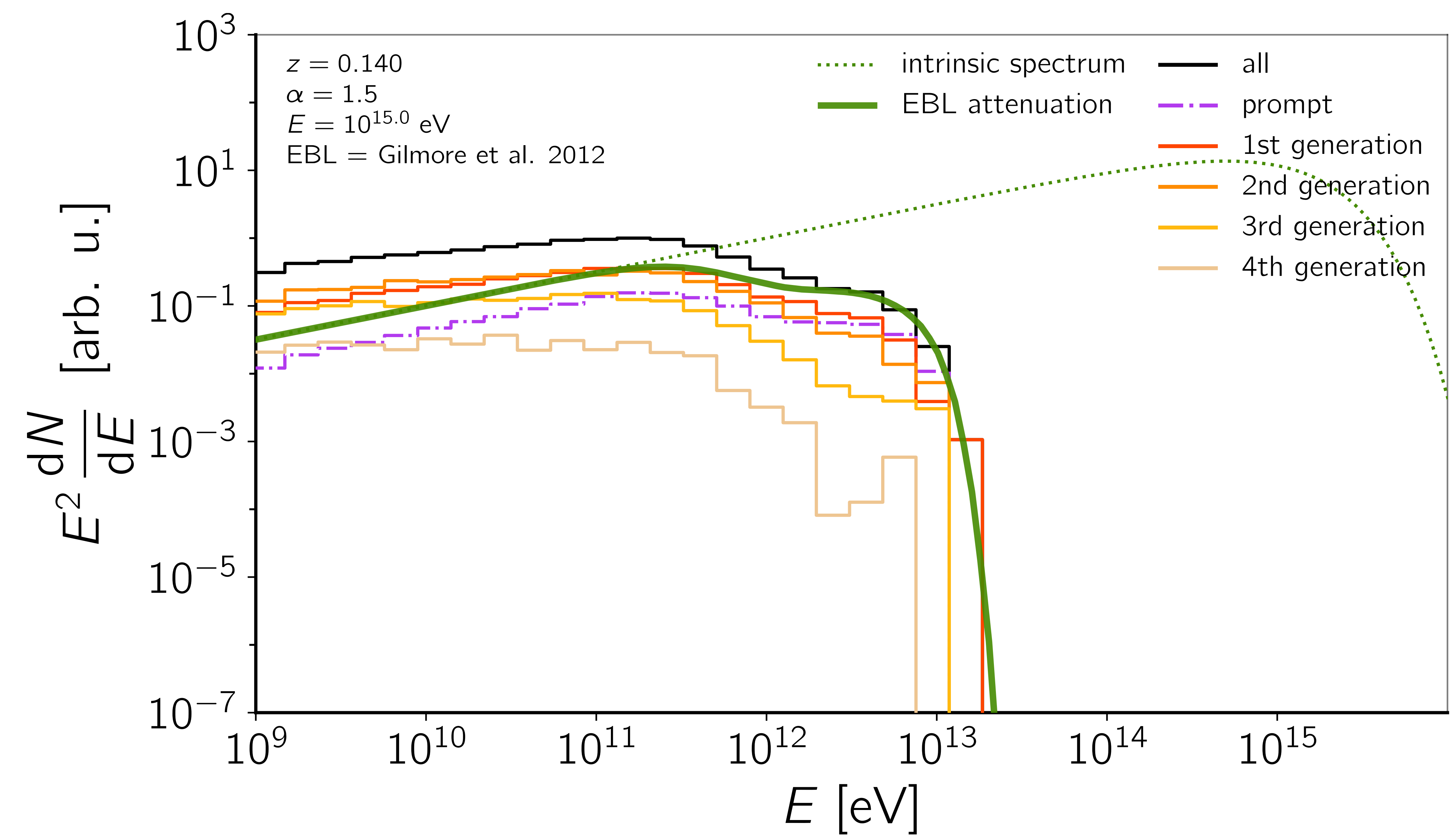
- **other processes can be important**
  - inverse Compton in this case
- it is always better to perform full simulations
  - *but not faster* 😕





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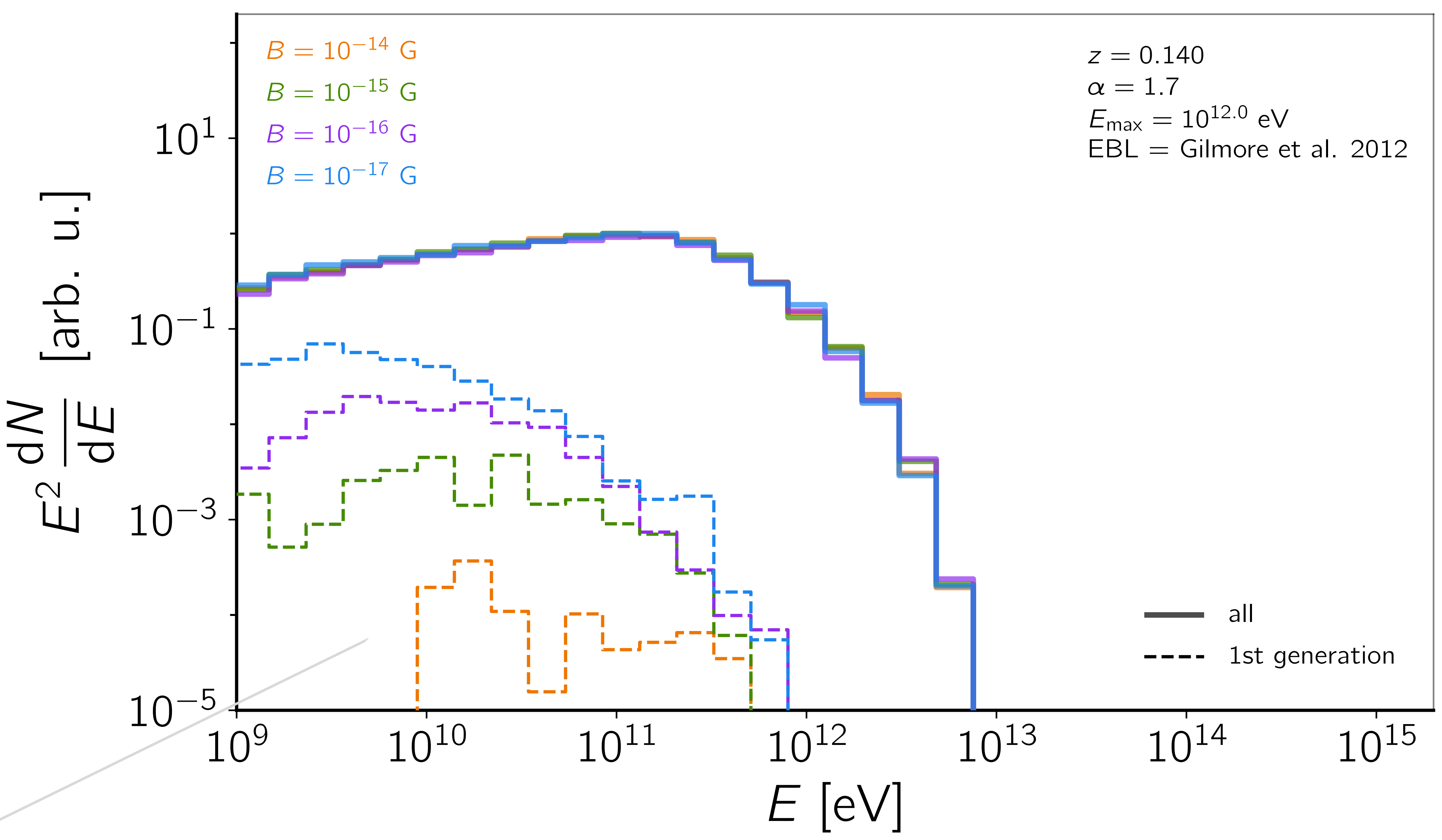

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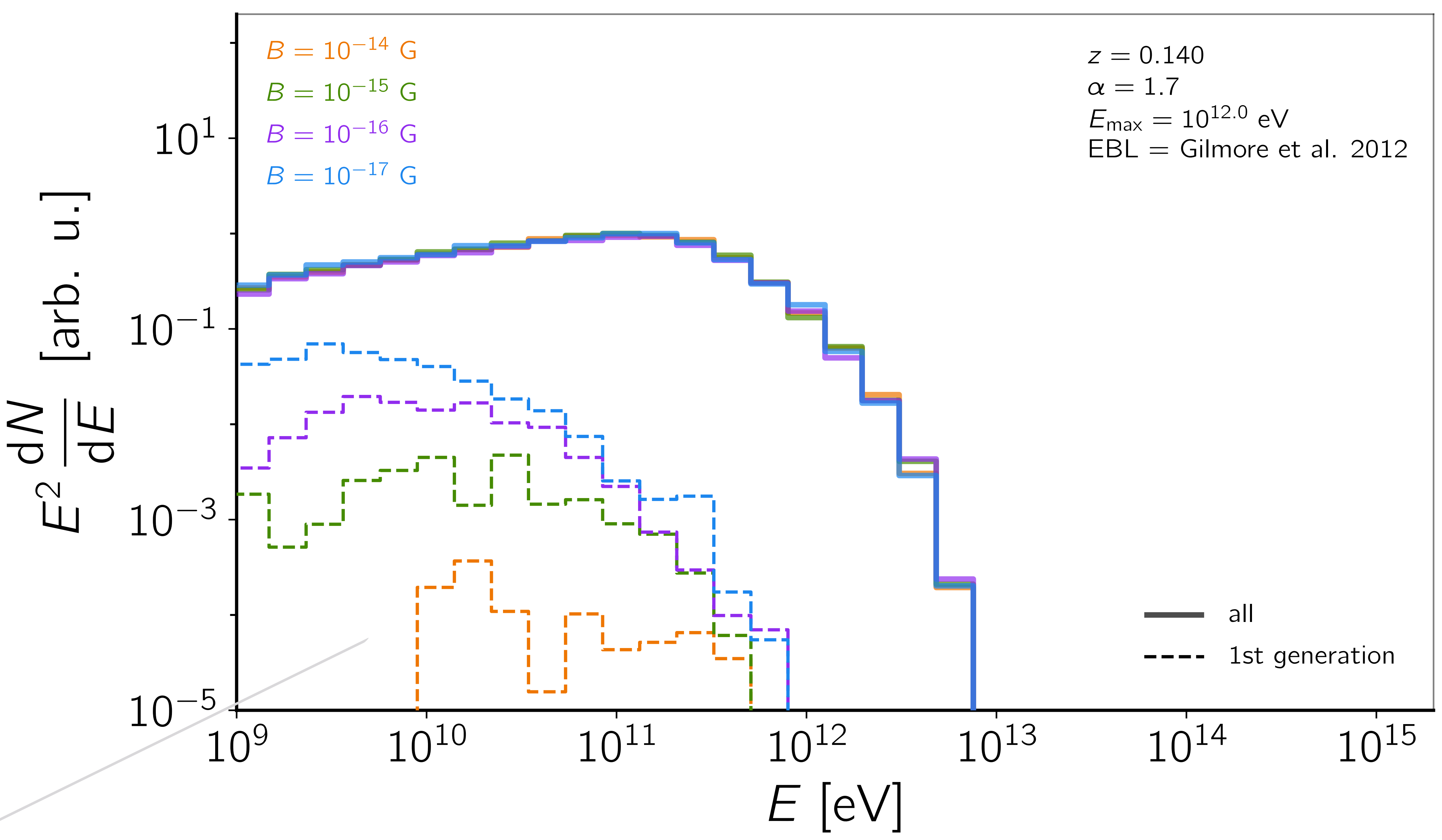
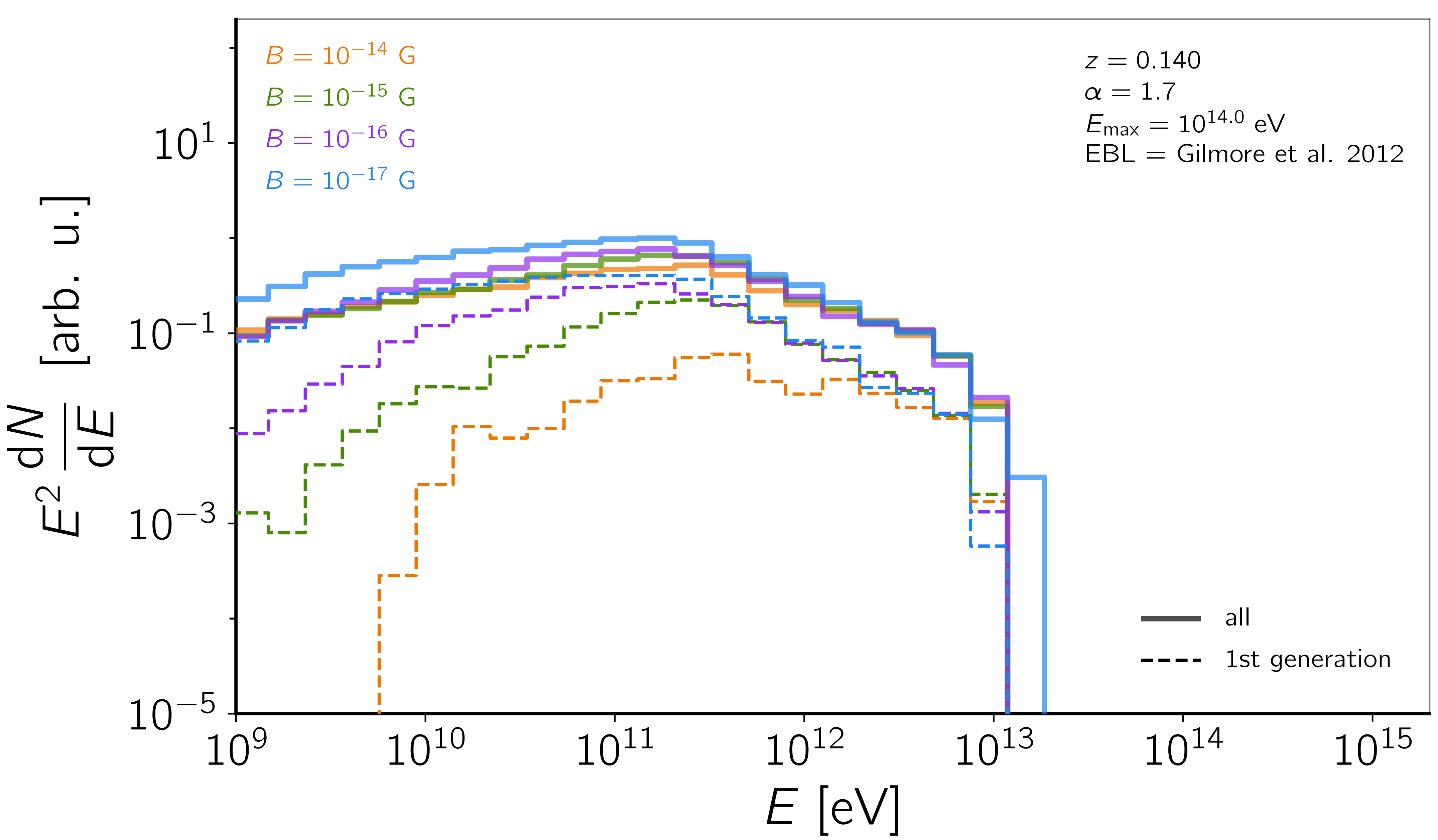
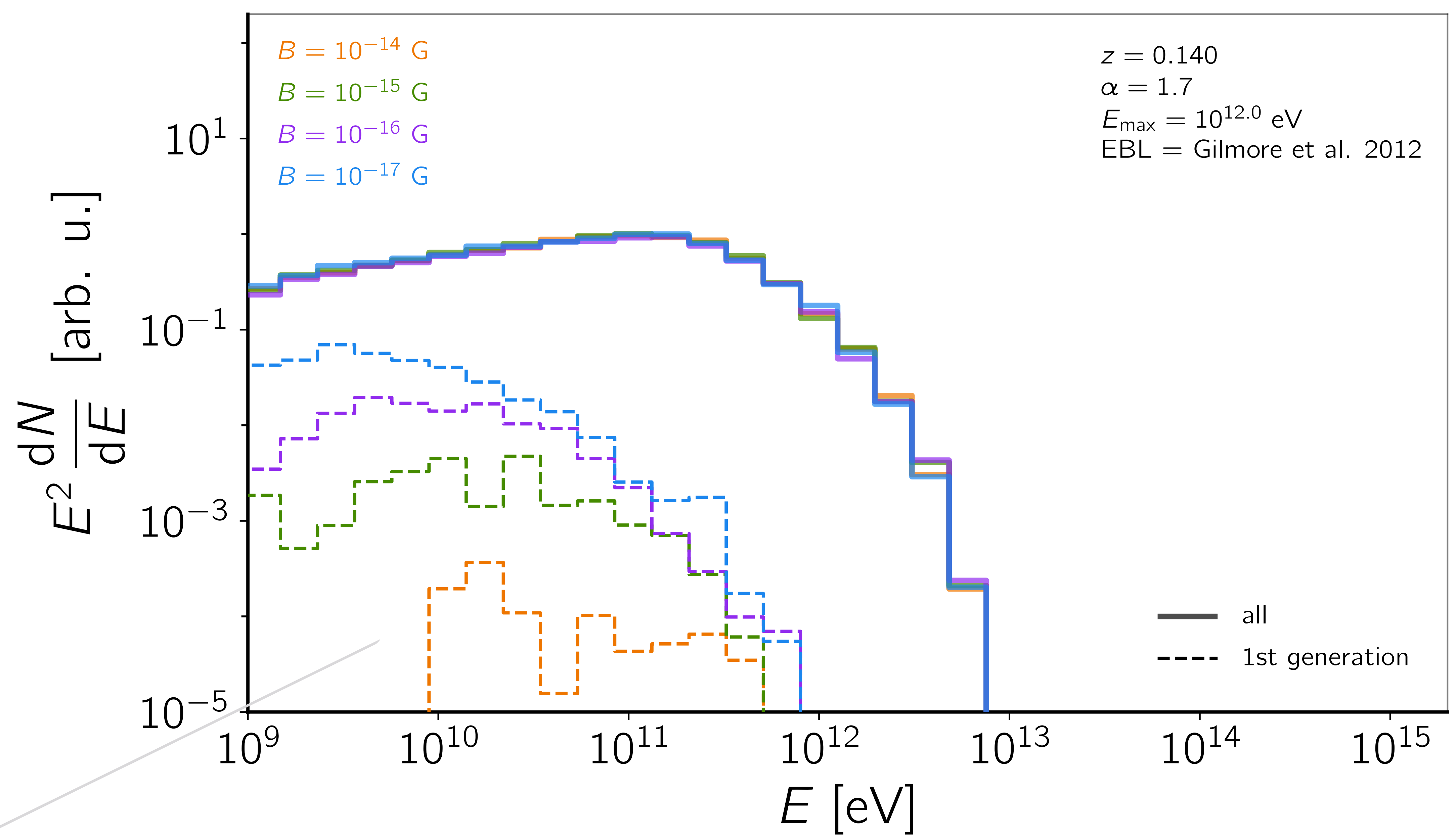
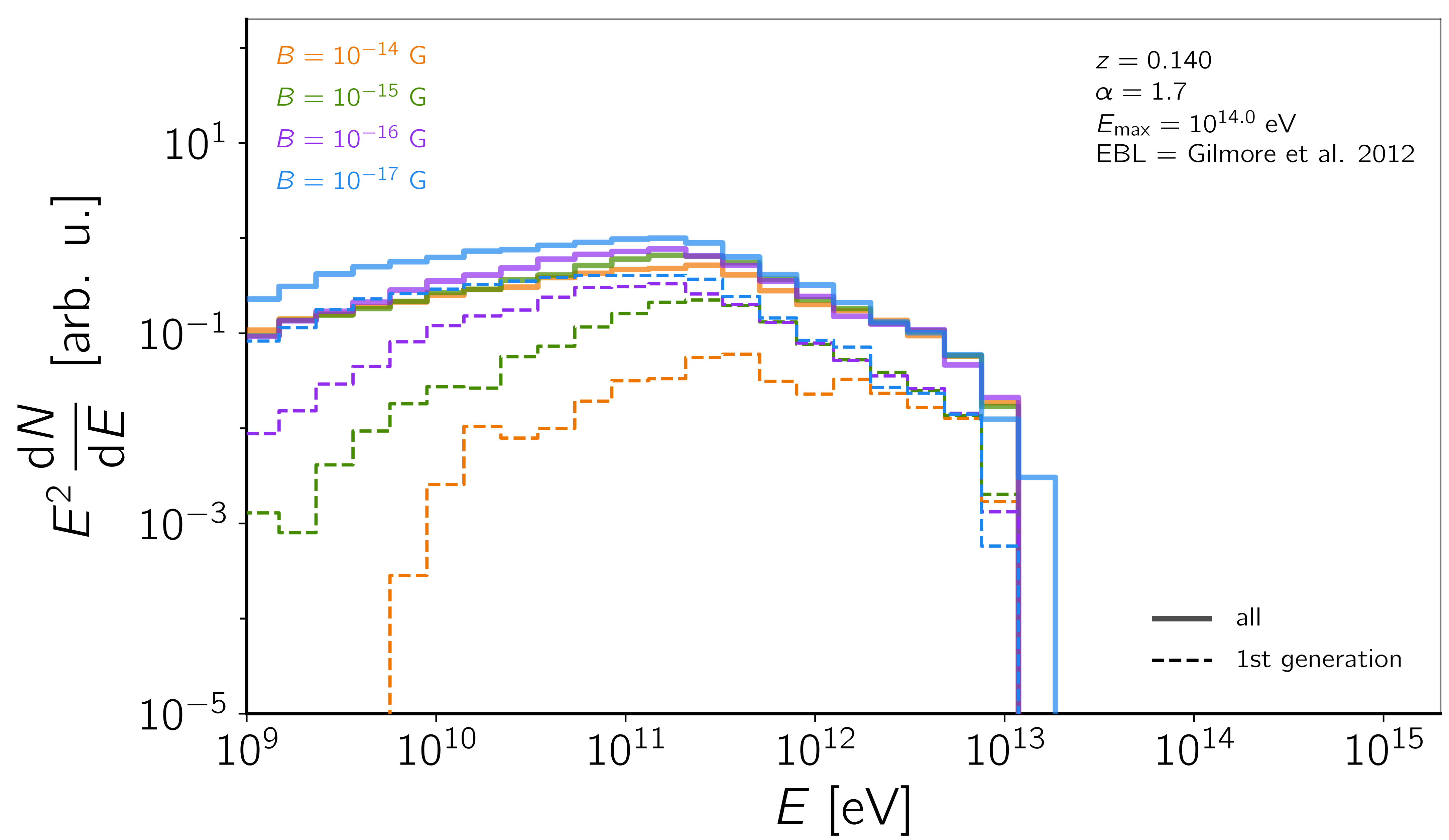




$$\Delta t_{\rm obs} = \Delta t_{\rm QG} + \mathfrak{T} + \Delta t_B + \cdots$$

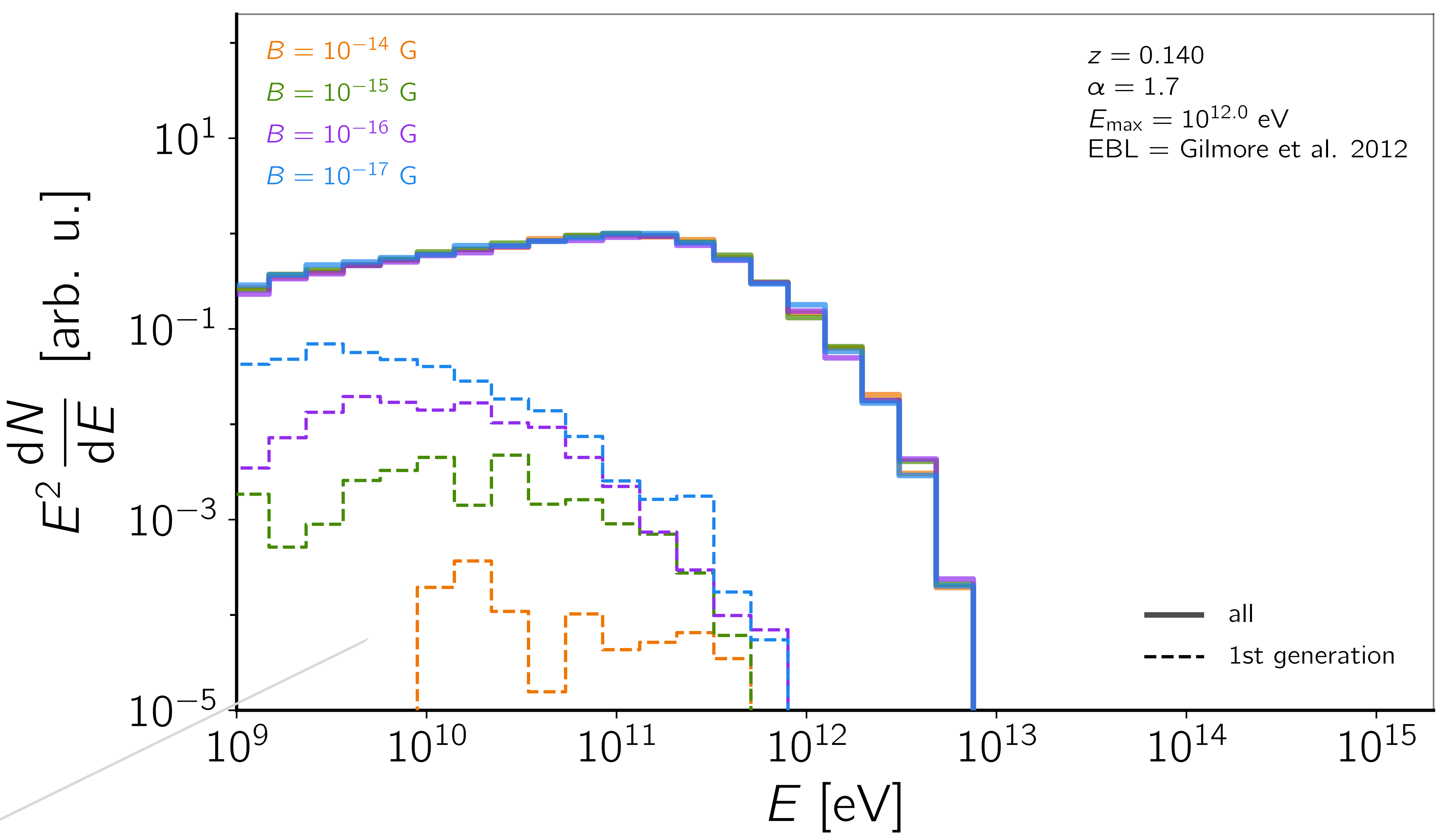


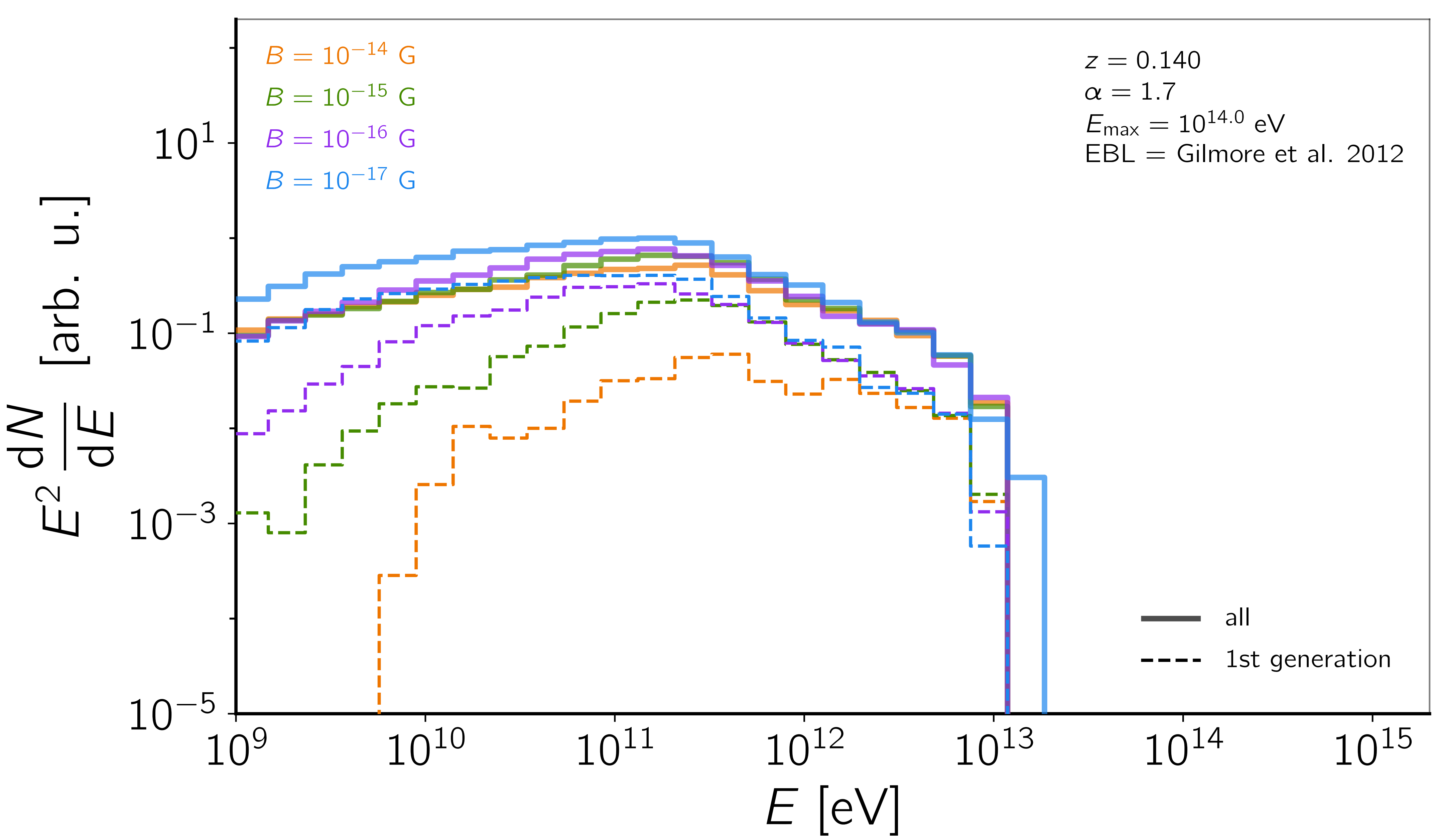


the usual approach to gamma-ray propagation

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

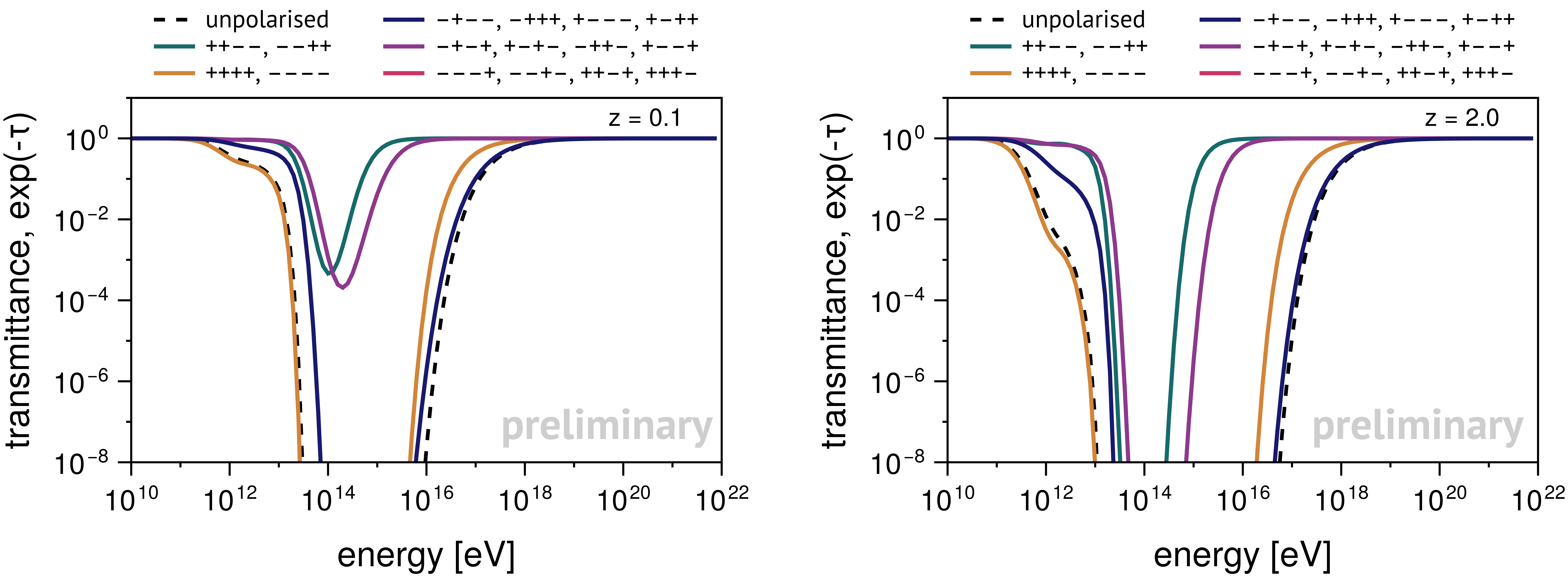
difficult to identify QG signatures with confidence





gamma-ray propagation. polarisation-dependent effects

Alves Batista, Cermeño, Mantoni. In preparation.



complete simulations of gamma-ray propagation with LIV

complete simulations of **gamma-ray propagation with LIV**

- **complete simulations** including LIV
  - modification of pair production
  - including inverse Compton scattering
  - including vacuum Cherenkov
  - including photon decay

Saveliev & Alves Batista. Class. Quant. Grav. 41 (2024) 115011. arXiv:2312.10803

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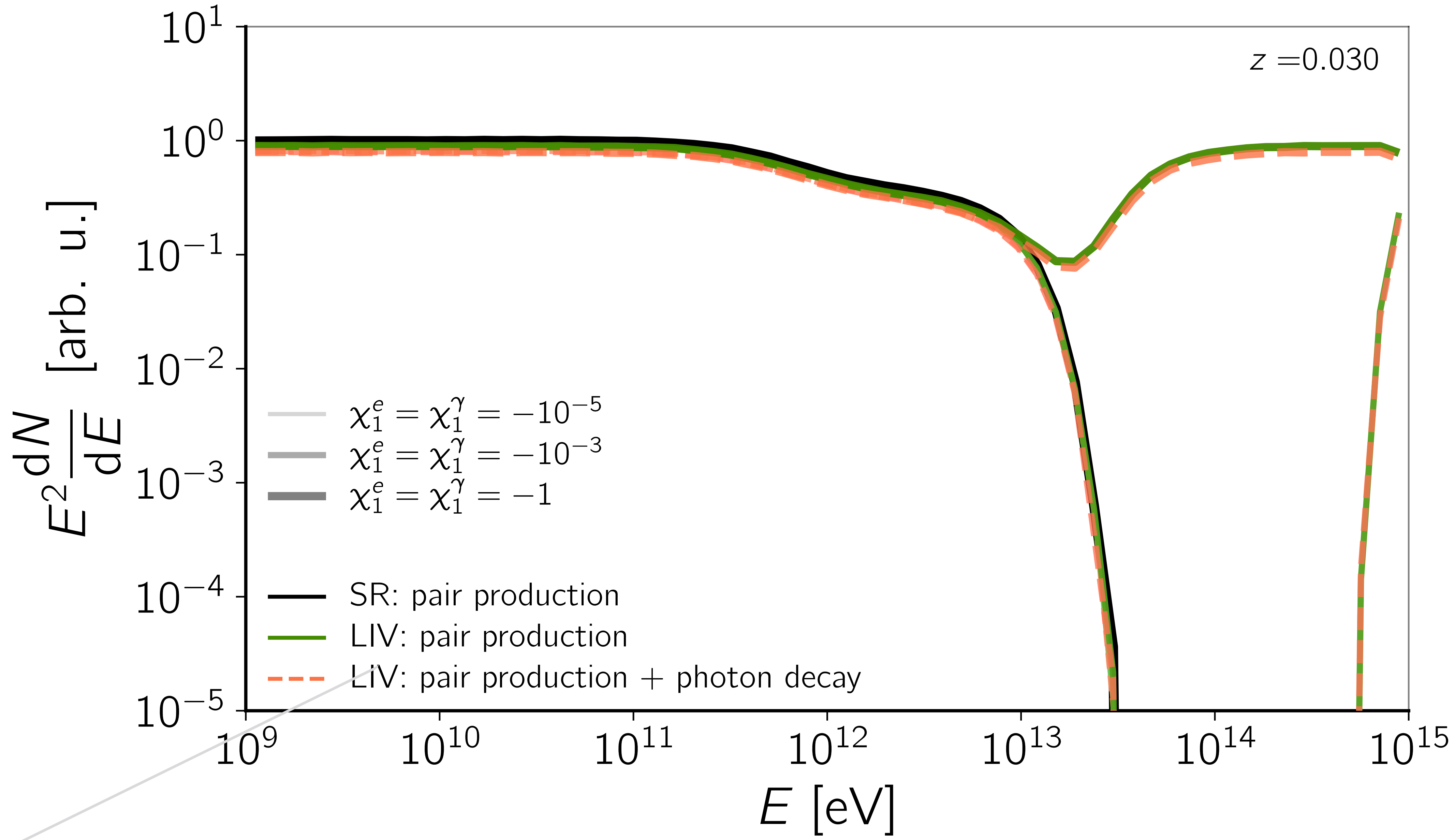

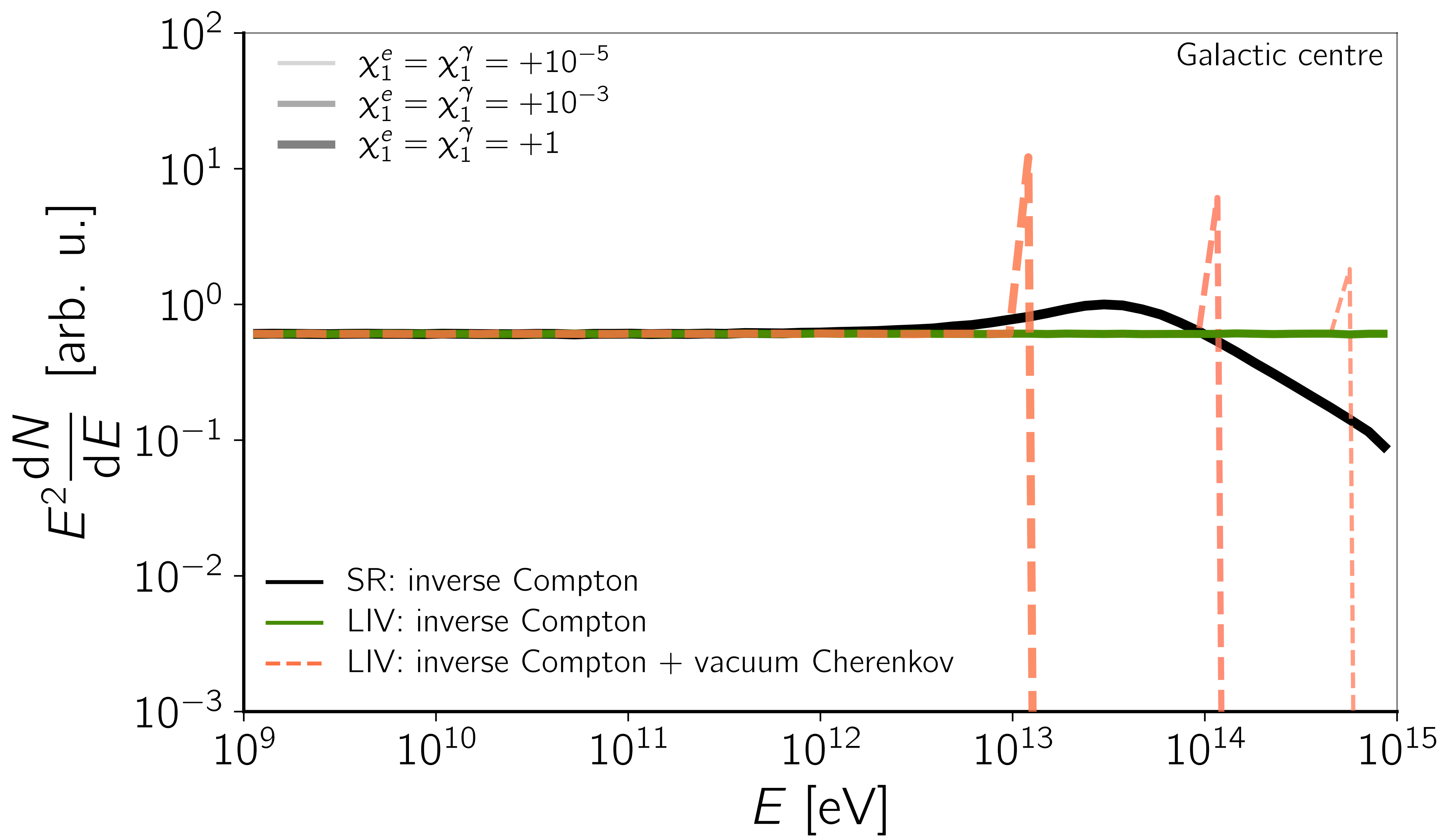

complete simulations of gamma-ray propagation with LIV

Saveliev & Alves Batista. Class. Quant. Grav. 41 (2024) 115011. arXiv:2312.10803

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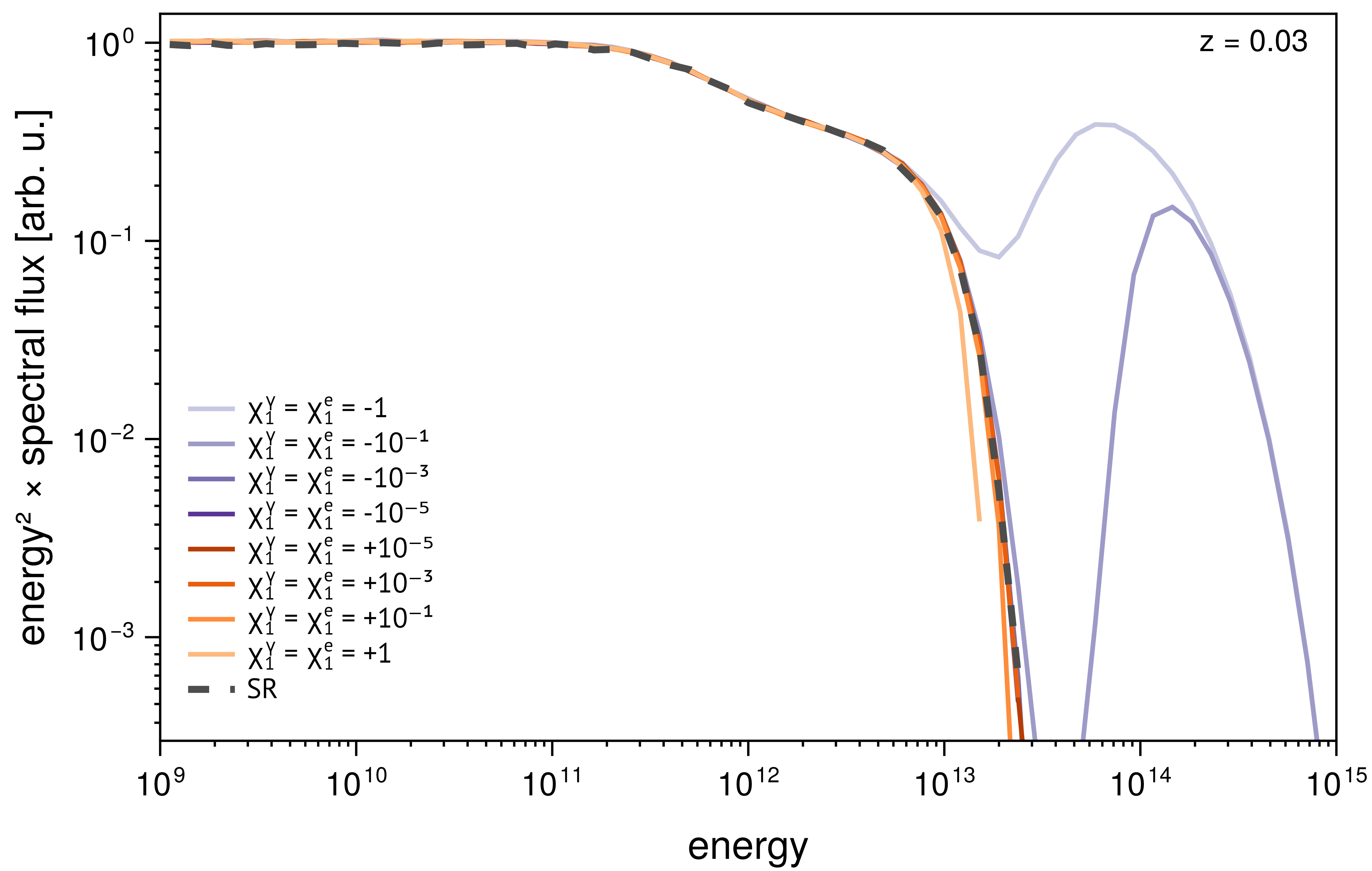
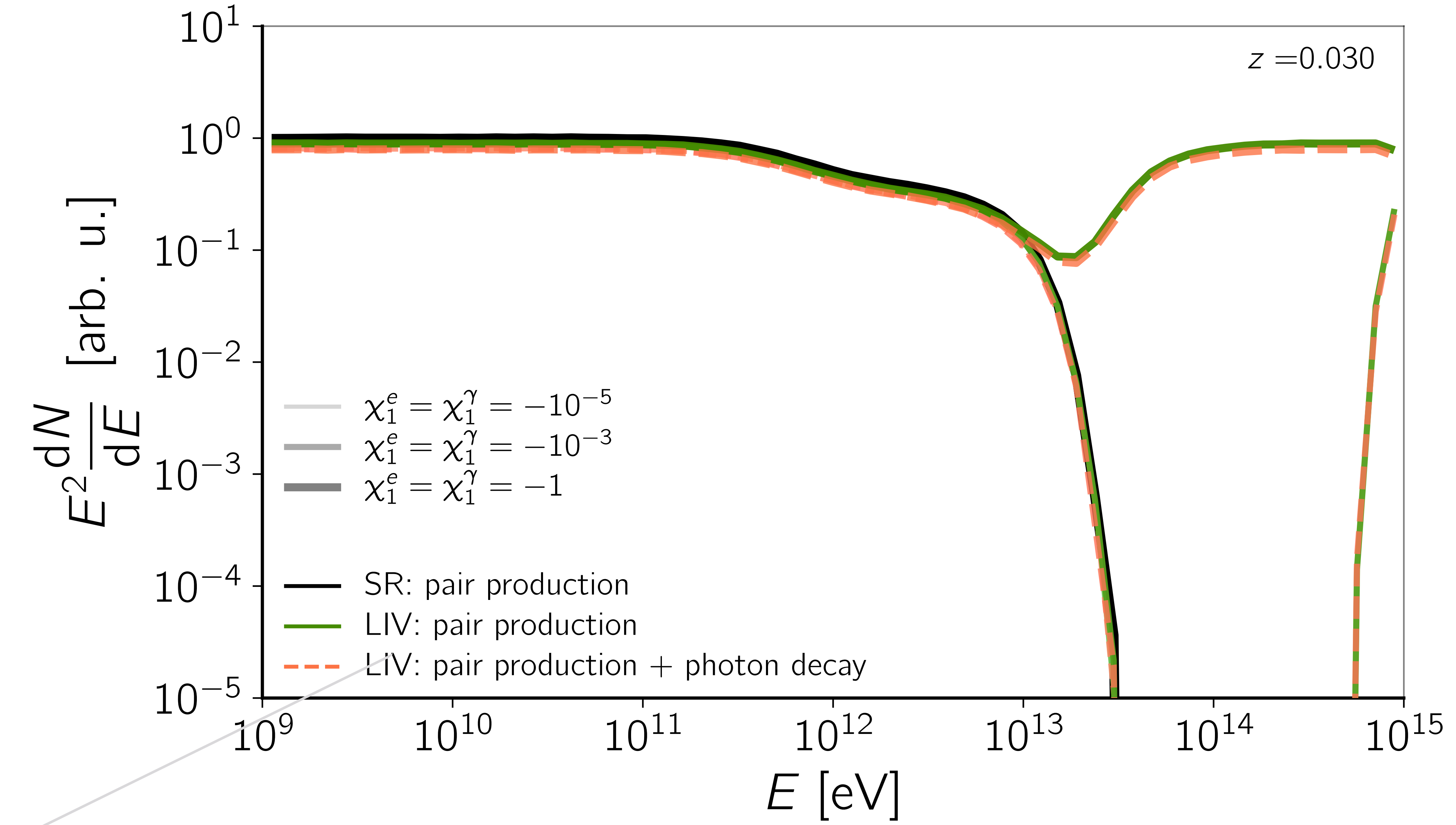
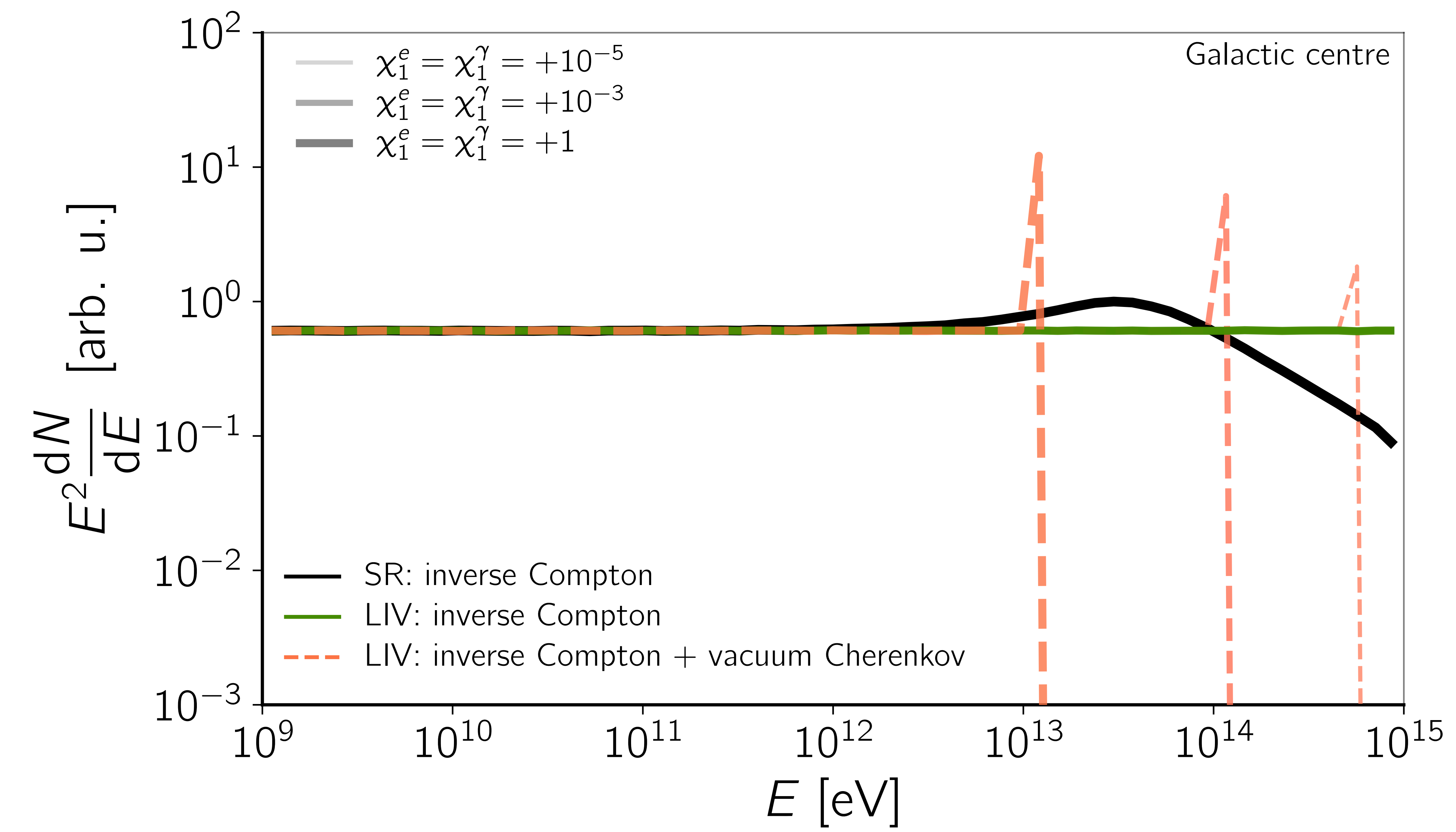
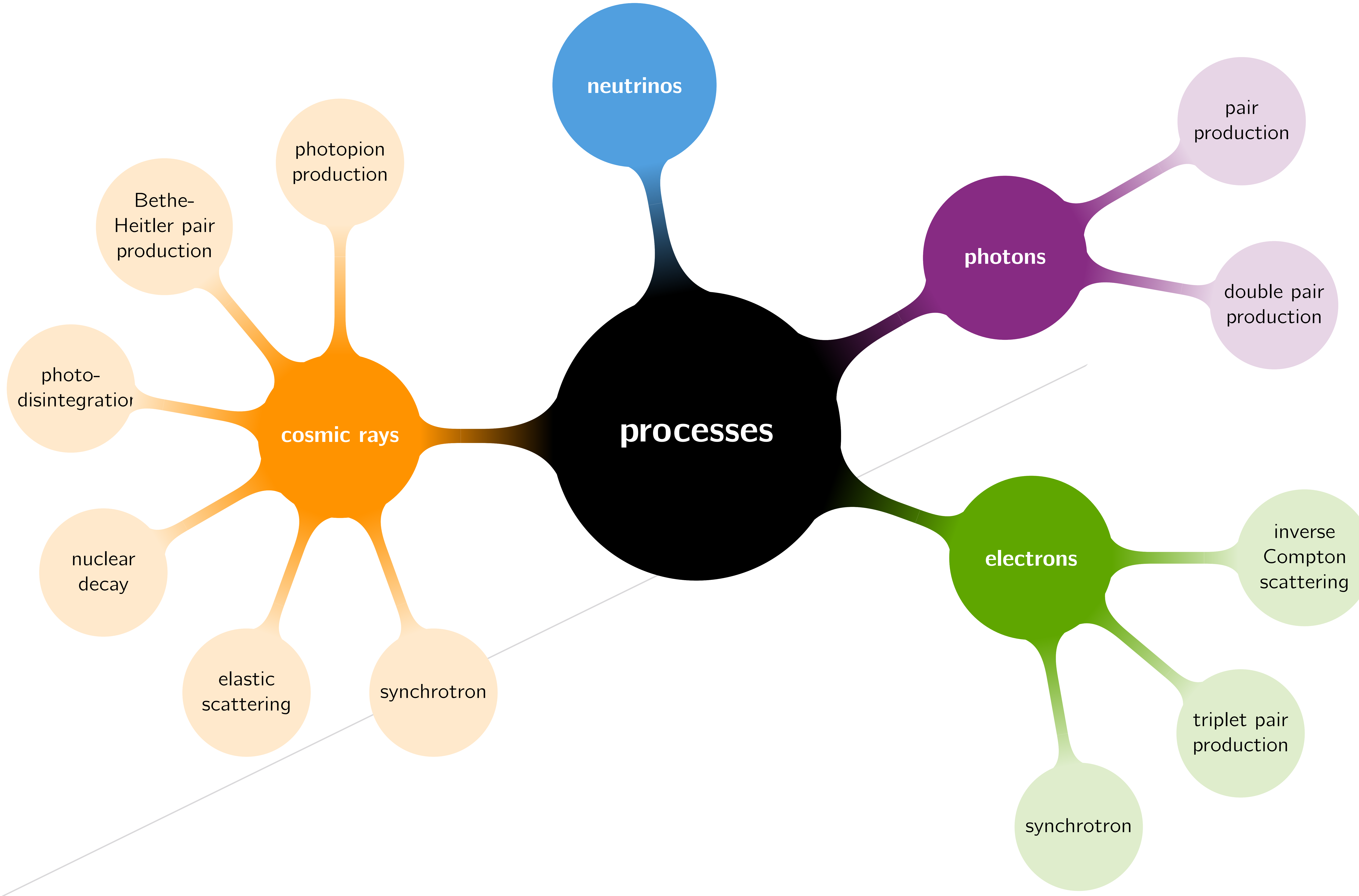
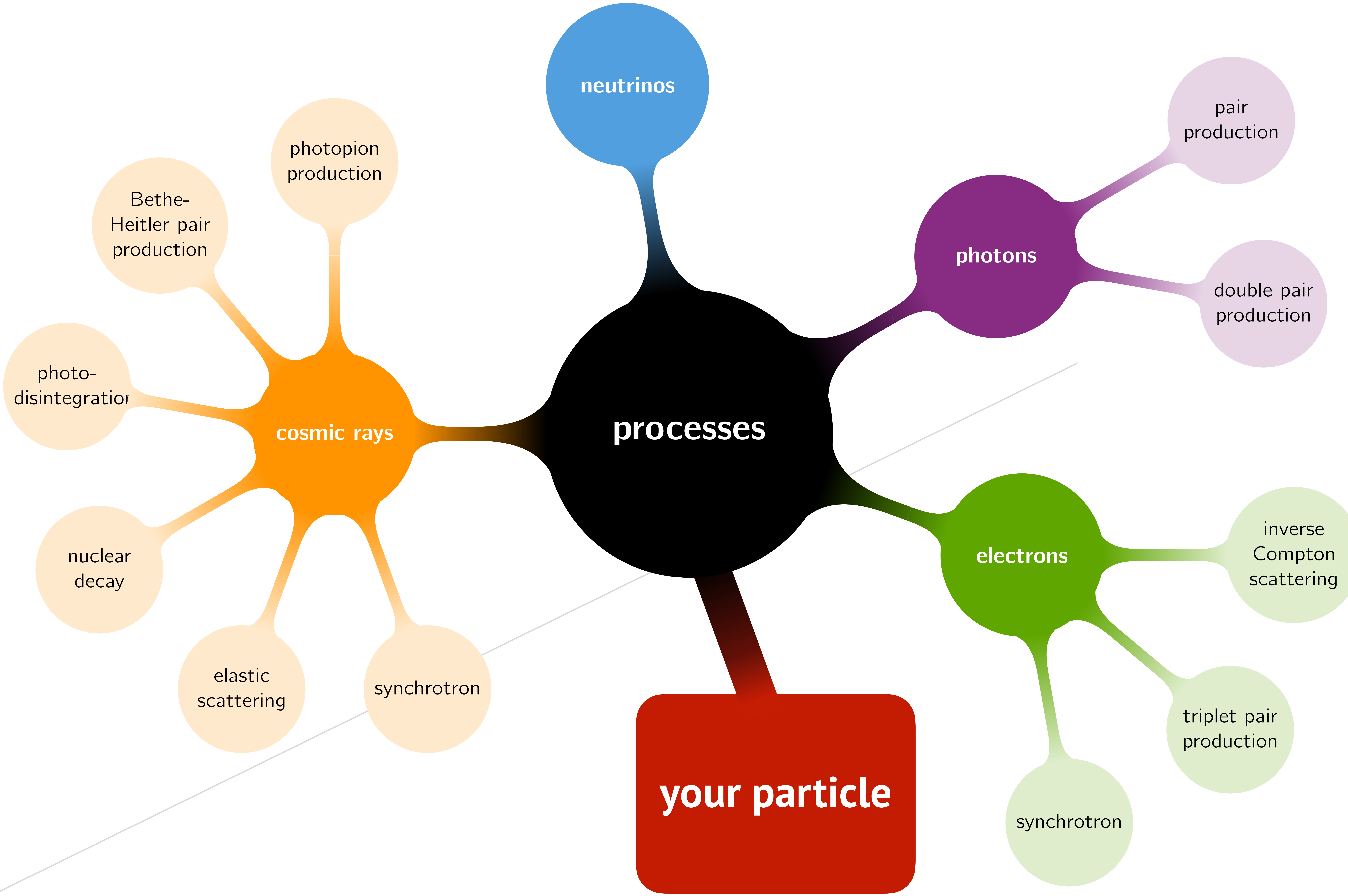







neutrinos
pair production
photopion production
Bethe-Heitler pair production
photons
double pair production
photo-disintegration
cosmic rays
processes
nuclear decay
electrons
inverse Compton scattering
elastic scattering
synchrotron
triplet pair production
synchrotron

the LIVPropa plugin for CRPropa



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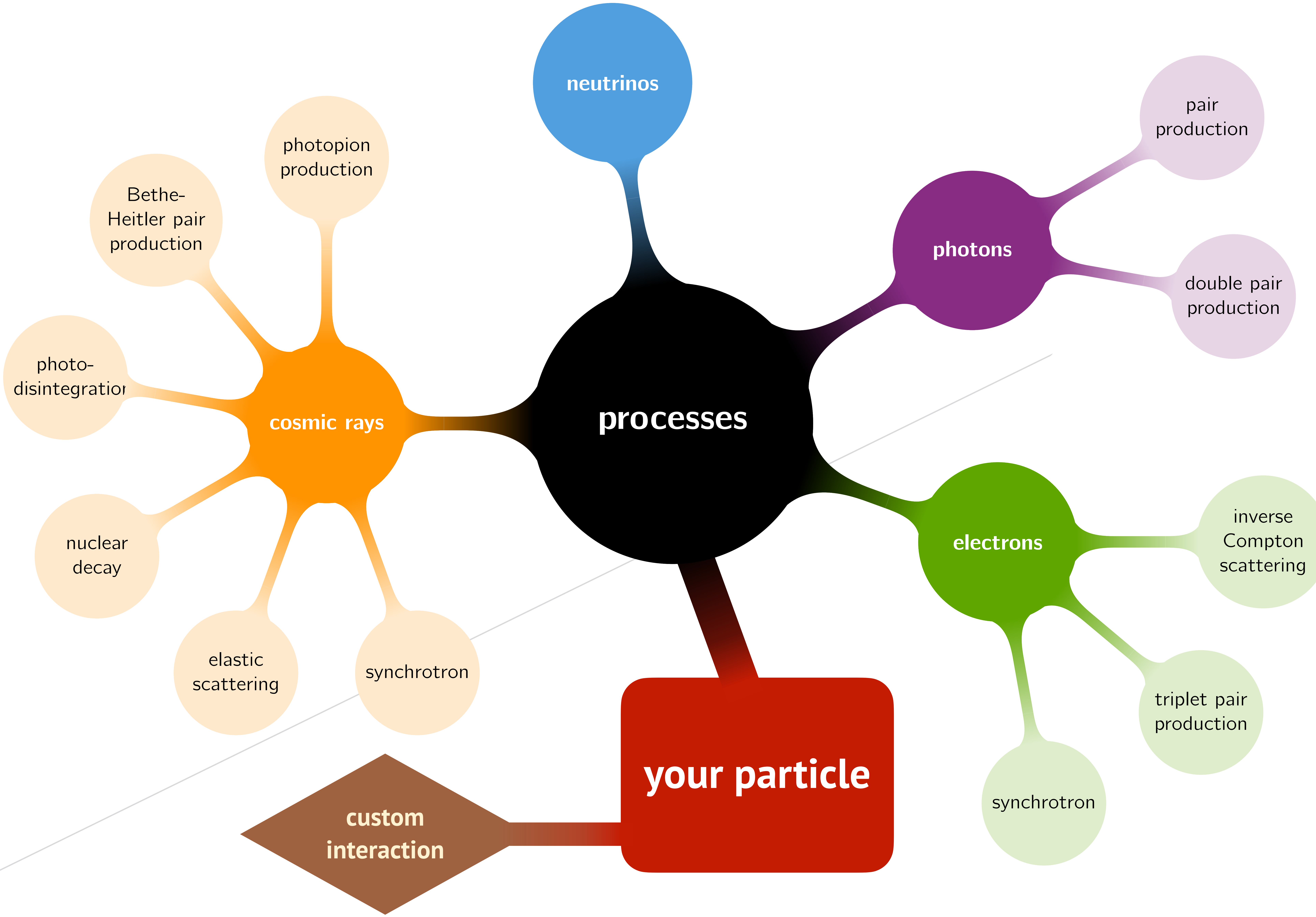

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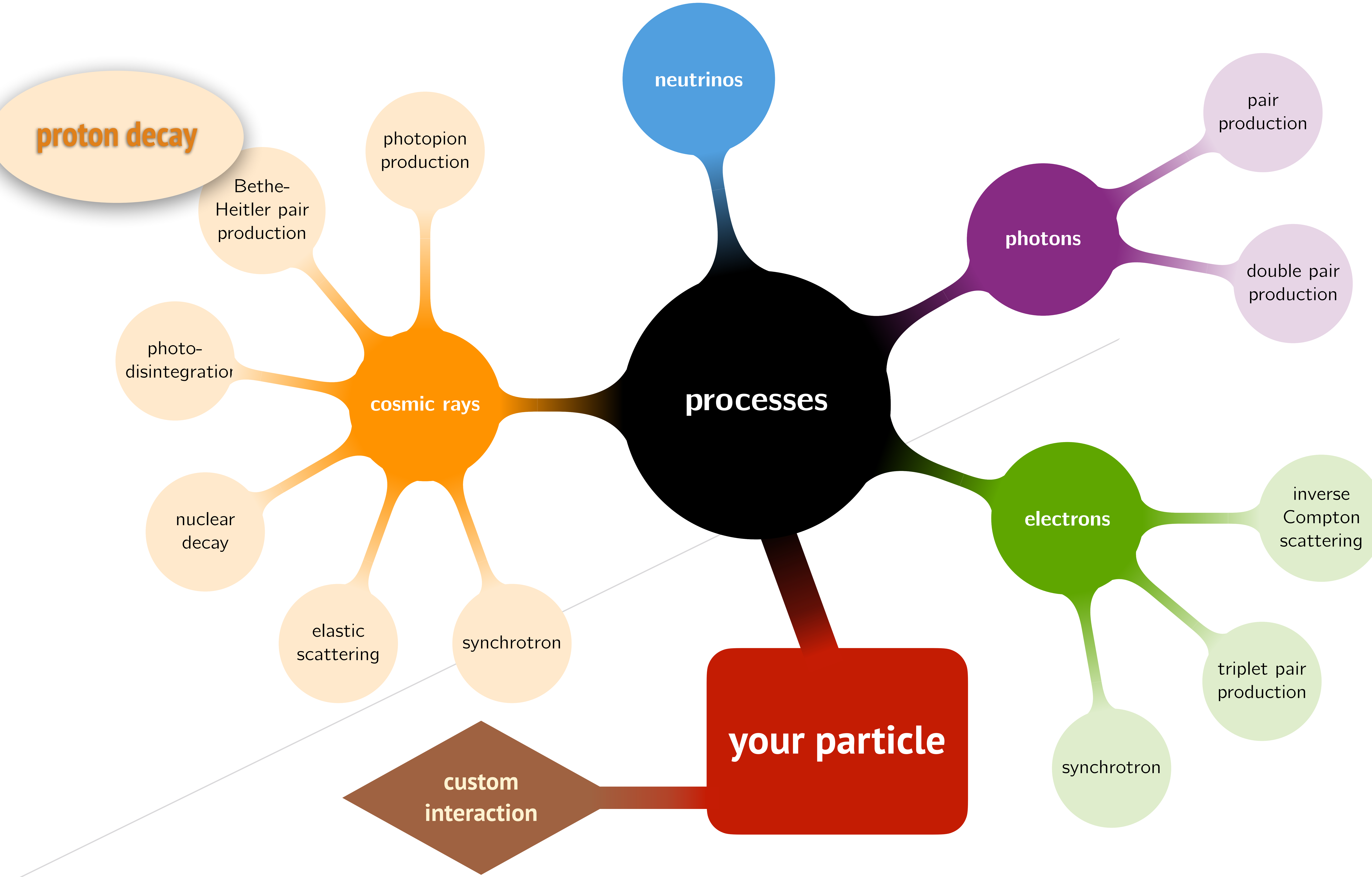

the LIVPropa plugin for CRPropa

the LIVPropa plugin for CRPropa

on time lags

$$\Delta t_{\text{obs}}\left(E_1, E_2\right) =$$

$$\Delta t_{\mathrm{obs}}(E_1, E_2) = \Delta t_{\mathrm{acc}}(E_1, E_2)$$

acceleration

$$\Delta t_{\rm obs}(E_1, E_2) = \Delta t_{\rm acc}(E_1, E_2) + \Delta t_{\rm emi}(E_1, E_2)$$

acceleration **emission**

$$\Delta t_{\mathrm{obs}}(E_1, E_2) = \Delta t_{\mathrm{acc}}(E_1, E_2) + \Delta t_{\mathrm{emi}}(E_1, E_2) + \Delta t_G(E_1, E_2)$$

acceleration **emission** **gravitational**

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acceleration **emission** **gravitational** **magnetic**

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acceleration **emission** **gravitational** **magnetic** **QG signal**

charged particles

$$\Delta t_B \approx \begin{cases} q^2 c \dfrac{B^2 L_{\rm src}^2 L_B}{18E^2} = 10^6 \left(\dfrac{q}{e}\right)^2 \left(\dfrac{B}{10^{-15}\ {\rm T}}\right)^2 \left(\dfrac{E}{100\ {\rm EeV}}\right)^{-2} \left(\dfrac{L_{\rm src}}{100\ {\rm Mpc}}\right)^2 \left(\dfrac{L_B}{1\ {\rm Mpc}}\right)\ {\rm yr} & \text{if } L_{\rm src} \gg L_B\,, \\ q^2 c \dfrac{B^2 L_{\rm src}^3}{24E^2} = 4200 \left(\dfrac{q}{e}\right)^2 \left(\dfrac{B}{10^{-15}\ {\rm T}}\right)^2 \left(\dfrac{E}{100\ {\rm EeV}}\right)^{-2} \left(\dfrac{L_{\rm src}}{100\ {\rm Mpc}}\right)^3\ {\rm yr} & \text{if } L_{\rm src} \ll L_B\,. \end{cases}$$

$$\Delta t_{\rm obs}(E_1, E_2) = \Delta t_{\rm acc}(E_1, E_2) + \Delta t_{\rm emi}(E_1, E_2) + \Delta t_G(E_1, E_2) + \Delta t_B(E_1, E_2) + \Delta t_{\rm QG}(E_1, E_2) + \cdots$$

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acceleration **emission** **gravitational** **magnetic** **QG signal**

gamma rays (approximation including cascade effects) [Neronov & Semikoz 2009]

$$\Delta t_B \simeq \begin{cases} 1.0 \times 10^4 \, \dfrac{\kappa\left(1 - \tau_\theta^{-1}\right)}{(1 + z_{\rm src})^2} \left(\dfrac{E}{1~{\rm TeV}}\right)^{-2} \left(\dfrac{B}{10^{-21}~{\rm T}}\right)^2 \left(\dfrac{L_B}{1~{\rm kpc}}\right) {\rm s} & \text{if } \dfrac{L_B}{1 + z_{\rm src}} \ll \lambda_{\rm IC}\,, \\ 2.2 \times 10^5 \, \dfrac{\kappa\left(1 - \tau_\theta^{-1}\right)}{(1 + z_{\rm src})^5} \left(\dfrac{E}{1~{\rm TeV}}\right)^{-\frac{5}{2}} \left(\dfrac{B}{10^{-21}~{\rm T}}\right)^2 {\rm s} & \text{if } \dfrac{L_B}{1 + z_{\rm src}} \gg \lambda_{\rm IC}\,, \end{cases}$$

$$\Delta t_{\rm obs}(E_1, E_2) = \Delta t_{\rm acc}(E_1, E_2) + \Delta t_{\rm emi}(E_1, E_2) + \Delta t_G(E_1, E_2) + \Delta t_B(E_1, E_2) + \Delta t_{\rm QG}(E_1, E_2) + \cdots$$

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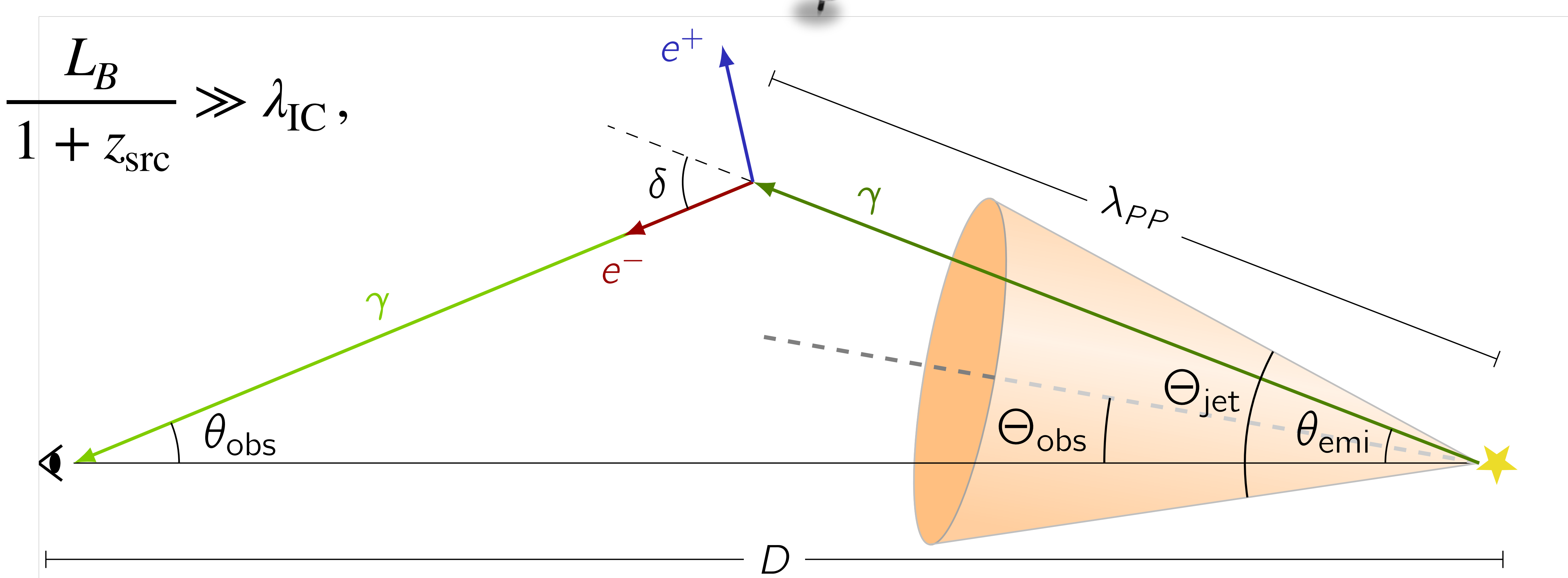

Alves Batista & Saveliev. Universe 7 (2021) 223. arXiv:2105.12020

discussion

two approaches: lamp and lighthouse

lamp approach

rigorous focused approach

look at few observables / effects at a time

phenomenologically-motivated

excellent for clean signals

empirically adequate

allow for inconsistencies

parsimonious and descriptive

lighthouse approach

complex brute-force approach

exploits correlations → reduces parameter space

phenomenologically- or theoretically-motivated

weaker but sturdier constraints

empirically adequate

imposes internal consistency

complex and more explanatory

are there QG signatures in the data?

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$$p\left(\theta_{\mathrm{QG}} \mid D\right) \propto p\left(D \mid \theta_{\mathrm{QG}}\right) \, p(\theta_{\mathrm{QG}})$$

are there QG signatures in the data?

$$p\left(\theta_{\rm QG} \,|\, D\right) \propto p\left(D \,|\, \theta_{\rm QG}\right)\, p(\theta_{\rm QG})$$

$$p\left(D \,|\, \theta_{\rm QG}\right) = \iiint$$

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$$p\left(D \,|\, \theta_{\mathrm{QG}}\right) = \iiint p\left(D \,|\, \theta_{\mathrm{QG}} \qquad\qquad \right)$$

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$$p\left(\theta_{\mathrm{QG}} \,|\, D\right) \propto p\left(D \,|\, \theta_{\mathrm{QG}}\right)\, p(\theta_{\mathrm{QG}})$$

propagation uncertainties

$$p\left(D \,|\, \theta_{\mathrm{QG}}\right) = \iiint p\left(D \,|\, \theta_{\mathrm{QG}}, \theta_{\mathrm{prop}} \qquad \right)\; p(\theta_{\mathrm{prop}}) \qquad \mathrm{d}\theta_{\mathrm{prop}}$$

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propagation uncertainties

source uncertainties

$$p\left(D \mid \theta_{\mathrm{QG}}\right) = \iiint p\left(D \mid \theta_{\mathrm{QG}}, \theta_{\mathrm{prop}}, \theta_{\mathrm{src}} \right) \, p(\theta_{\mathrm{prop}}) \, p(\theta_{\mathrm{src}}) \, \mathrm{d}\theta_{\mathrm{src}} \mathrm{d}\theta_{\mathrm{prop}}$$

are there QG signatures in the data?

$$p\left(\theta_{\mathrm{QG}} \,|\, D\right) \propto p\left(D \,|\, \theta_{\mathrm{QG}}\right)\, p(\theta_{\mathrm{QG}})$$

propagation uncertainties

source uncertainties

$$p\left(D \,|\, \theta_{\mathrm{QG}}\right) = \iiint p\left(D \,|\, \theta_{\mathrm{QG}}, \theta_{\mathrm{prop}}, \theta_{\mathrm{src}}, \quad \right)\, p(\theta_{\mathrm{prop}})\, p(\theta_{\mathrm{src}})\, \mathrm{d}\theta_{\mathrm{src}}\mathrm{d}\theta_{\mathrm{prop}}$$

are there QG signatures in the data?

$$p\left(\theta_{\mathrm{QG}} \,|\, D\right) \propto p\left(D \,|\, \theta_{\mathrm{QG}}\right)\, p(\theta_{\mathrm{QG}})$$

propagation uncertainties

source uncertainties

$$p\left(D \,|\, \theta_{\mathrm{QG}}\right) = \iiint p\left(D \,|\, \theta_{\mathrm{QG}}, \theta_{\mathrm{prop}}, \theta_{\mathrm{src}}, \theta_{\mathrm{inst}}\right)\, p(\theta_{\mathrm{prop}})\, p(\theta_{\mathrm{src}})\, \mathrm{d}\theta_{\mathrm{src}}\mathrm{d}\theta_{\mathrm{prop}}$$

are there QG signatures in the data?

$$p\left(\theta_{\mathrm{QG}} \,|\, D\right) \propto p\left(D \,|\, \theta_{\mathrm{QG}}\right)\, p(\theta_{\mathrm{QG}})$$

propagation uncertainties — source uncertainties — instrumental uncertainties

$$p\left(D \,|\, \theta_{\mathrm{QG}}\right) = \iiint p\left(D \,|\, \theta_{\mathrm{QG}}, \theta_{\mathrm{prop}}, \theta_{\mathrm{src}}, \theta_{\mathrm{inst}}\right)\, p(\theta_{\mathrm{prop}})\, p(\theta_{\mathrm{src}})\, p(\theta_{\mathrm{inst}})\, \mathrm{d}\theta_{\mathrm{inst}}\mathrm{d}\theta_{\mathrm{src}}\mathrm{d}\theta_{\mathrm{prop}}$$

- **sink terms** affecting propagation are considered
- rarely new **source terms** are considered on top of standard ones (new processes)
- results are only as good as the models on which they are based
- problem with lamp strategy: *dutch book argument*
- combine **multiple messengers**
- build models covering **larger parameter space**
  - dimensional reduction from correlations / couplings
- epistemic goal: coherence over tightness