ALPs and CTA

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SUMMARY

1 – EXTRAGALACTIC OBSERVATIONS

2 – WHAT ARE ALPs?

3 – PROPERTIES OF PHOTON-ALP MIXING

4 – REDUCING THE VHE OPACITY

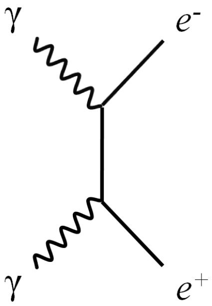
5 – PHOTON SURVIVAL PROBABILITY

1 – EXTRAGALACTIC OBSERVATIONS

Beautiful as it is, the CTA – just like HAWC (High-Altitude Water Cherenkov Observatory), GAMMA-400 (Gamma Astronomical Multifunctional Modular Apparatus), LHAASO (Large High Altitude Air Shower Observatory) and HiSCORE (Hundred Square km Cosmic Origin Explorer) – is afflicted by a BIG PROBLEM: the existence of the EBL (extragalactic background light).

The EBL = (light emitted by all galaxies till now) dominates the Universe in the infrared/optical/ultraviolet band.

Consider an extragalactic source e.g. a blazar. Accordingly hard beam photons emitted by it with energy E scatter off soft EBL photons through the Breit-Wheeler scattering – namely $\gamma\gamma \to e^+e^-$ – which depletes the beam.



How large is such depletion? Because $\sigma(\gamma\gamma \to e^+e^-)$ gets maximized for

$$\epsilon \simeq \left(\frac{900\,\mathrm{GeV}}{E}\right)\,\mathrm{eV}\ , \tag{1}$$

for $E = 70\,\mathrm{GeV} - 100\mathrm{TeV}$ we get $\epsilon = (0.009 - 13)\,\mathrm{eV}$, JUST where EBL dominates.

So, photons emitted by a blazar at redshift z have a survival probability

$$P_{\gamma \to \gamma}(E_0, z) = e^{-\tau_\gamma(E_0, z)} \ , \tag{2}$$

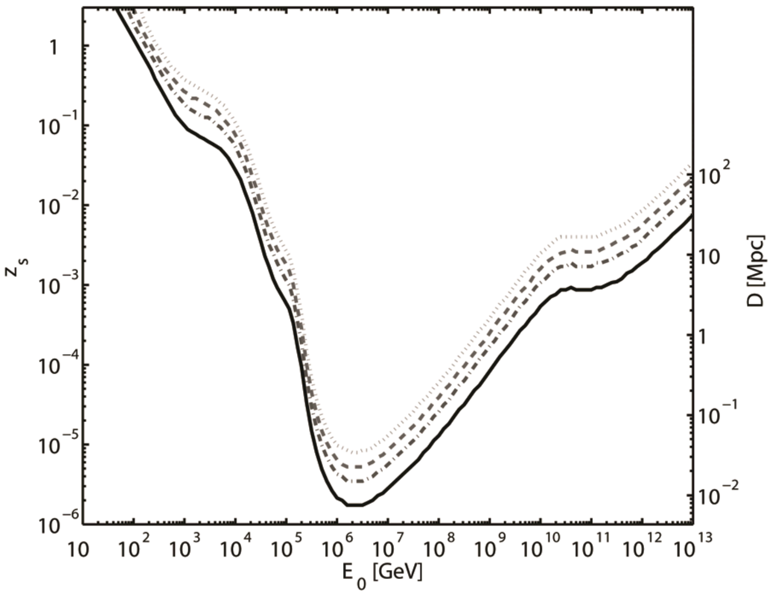
where the optical depth $\tau_\gamma(E_0, z)$ is evaluated in a standard fashion in terms of $\sigma(\gamma\gamma \to e^+ e^-)$ and the spectral number density of the EBL. Recalling that

$$\Phi_{\rm obs}(E_0, z) = e^{-\tau_\gamma(E_0, z)} \, \Phi_{\rm em}\big(E_0(1+z)\big) \tag{3}$$

we end up with

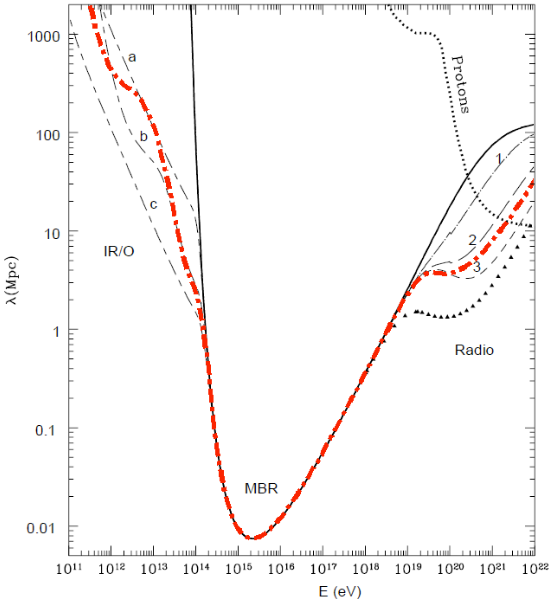
$$\Phi_{\rm obs}(E_0, z) \ll \Phi_{\rm em}\big(E_0(1+z)\big) \ . \tag{4}$$

Below, the source redshifts z_s is shown at which the optical depth takes fixed values as a function of the observed hard photon energy E_0. The curves from bottom to top correspond to a photon survival probability of $e^{-1} \simeq 0.37$ (the horizon), $e^{-2} \simeq 0.14$, $e^{-3} \simeq 0.05$ and $e^{-4.6} \simeq 0.01$. For $z_s < 10^{-6}$ the photon survival probability is larger than 0.37 for any value of E_0 computed for the EBL model of Franceschini, Rodighiero & Vaccari (2008) (De Angelis, Galanti & Roncadelli, MNRAS, **432**, 3245 (2013)).



1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
z_s
10 10² 10³ 10⁴ 10⁵ 10⁶ 10⁷ 10⁸ 10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³
E_0 [GeV]
10²
10
1
10⁻¹
10⁻²
D [Mpc]

Discarding cosmic expansion $P_{\gamma\to\gamma}(E,D) = e^{-D/\lambda_\gamma(E)}$



2 – WHAT ARE ALPs?

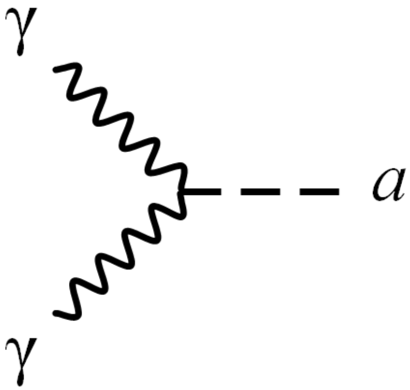
Axion-like particles (ALPs) are $s = 0$, neutral and very light pseudo-scalar particles a. They are a generic prediction of many extensions of the SM, especially of those based on the M-theory encompassing superstrings and superbranes. They are similar to the axion apart from 2 features.

- ALPs couple almost only to two photons through $g_{a\gamma}\, a\, \mathbf{B} \cdot \mathbf{E}$ (very small couplings to fermions are allowed but here they are discarded because they do not give rise to any interesting effect).
- The two-photon coupling $g_{a\gamma}$ is totally UNRELATED to the ALP mass m.

Hence ALPs are described by the Lagrangian

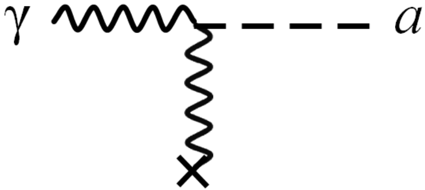
$$\mathcal{L}^0_{\rm ALP} = \frac{1}{2}\,\partial^\mu a\,\partial_\mu a - \frac{1}{2}\,m^2\,a^2 + g_{a\gamma}\,a\,\mathbf{E}\cdot\mathbf{B}\ . \qquad (5)$$

So, for ALPs the only new thing with respect to the Standard Model is shown in



which – at this stage – should be regarded as "God given".

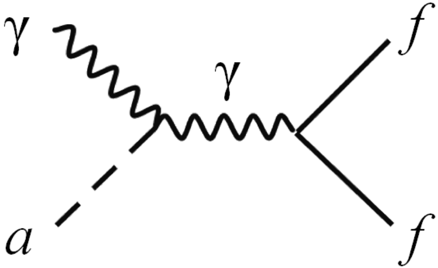
ALPs are produced in the core of MS stars (like the Sun) through the Primakoff process in the Coulomb field **E** of ionized matter



where $X = \mathbf{E}$.

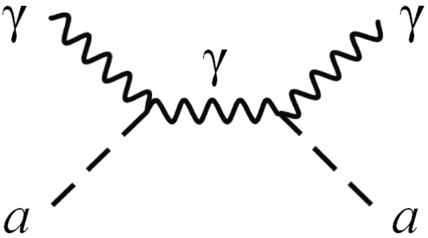
The CAST experiment at CERN was looking at the Sun and found nothing, thereby deriving $g_{a\gamma} < 0.88 \cdot 10^{-10}\,\mathrm{GeV}^{-1}$. Recent analysis of globular clusters gives $g_{a\gamma} < 0.66 \cdot 10^{-10}\,\mathrm{GeV}^{-1}$.

ALPs interact with NOTHING. Denote by f a generic fermion and consider the diagram for the scattering $a\gamma \to f\bar{f}$ with f a generic fermion



In the s-channel it describes the $a\gamma \to f\bar{f}$ scattering, while in the t-channel the $af \to af$ scattering. The cross-section is $\sigma \sim \alpha\, g_{a\gamma}^2$. So the previous bound yields $\sigma < 10^{-50}\,\mathrm{cm}^2$.

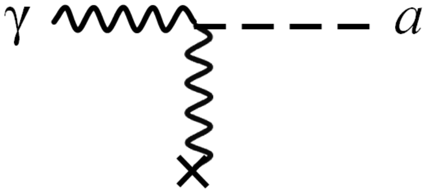
Moreover, for $a\gamma \to a\gamma$ scattering



the cross-section is $\sigma \sim s\, g_{a\gamma}^4$, and so we get

$$\sigma < 7 \cdot 10^{-69} \left(\frac{s}{\mathrm{GeV}^2}\right) \mathrm{cm}^2 \ . \tag{6}$$

We will henceforth consider a monochromatic photon beam of energy E and assume that an external magnetic field $\mathbf{B}$ is present. Hence in $g_{a\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$ the term $\mathbf{E}$ is the electric field of a beam photon while $\mathbf{B}$ is the external magnetic field. So $\gamma \to a$ conversions can occur



where now and in the following $X = \mathbf{B}$.

Needless to say, also the inverse process $a \rightarrow \gamma$ can equally well take place. As a consequence, as the beam propagates we can have photon-ALP oscillations

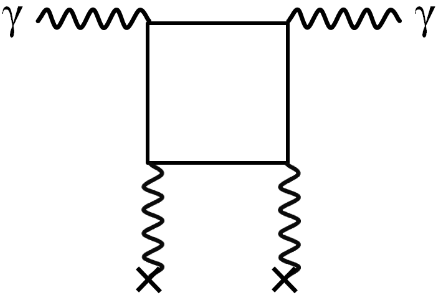
This is quite similar to what happens for massive neutrinos of different flavor apart from the need of the external field to compensate for the spin mismatch.

N. B. a REAL

Sometimes in the presence of an an external magnetic field also QED one-loop vacuum polarization effects have to be taken into account. They are described by

$$\mathcal{L}'_{\rm ALP} = \mathcal{L}_{\rm ALP} + \frac{2\alpha^2}{45 m_e^4} \left[\left(\mathbf{E}^2 - \mathbf{B}^2 \right)^2 + 7 \left(\mathbf{E} \cdot \mathbf{B} \right)^2 \right] \;, \qquad (7)$$

which gives an additional diagonal contribution to the γa mass matrix.



3 – PROPERTIES OF PHOTON-ALP MIXING

We suppose that our monochromatic γ/a beam of energy E is in the X-ray or γ-ray band and propagates along the y direction from a far-away astronomical source reaching us.

In the approximation $E \gg m$ the beam propagation equation becomes a Schrödinger-like equation in y, hence the beam is FORMALLY described as a 3-LEVEL NON-RELATIVISTIC UNSTABLE QUANTUM SYSTEM.

Consider the simplest possible case, where no photon absorption takes place and **B** is homogeneous. Taking the z-axis along **B**, we have

$$P_{\gamma \to a}(E; 0, y) = \left(\frac{g_{a\gamma} \, B}{\Delta_{\rm osc}} \right)^2 \sin^2 \left(\frac{\Delta_{\rm osc} \, y}{2} \right) \; , \qquad (8)$$

with

$$\Delta_{\rm osc} \equiv \left\{ \left[\frac{m^2 - \omega_{\rm pl}^2}{2E} + \frac{3.5\,\alpha}{45\pi} \left(\frac{B}{B_{\rm cr}} \right)^2 E \right]^2 + \left(g_{a\gamma}\, B \right)^2 \right\}^{1/2} , \quad (9)$$

where $B_{\rm cr} \simeq 4.41 \cdot 10^{13}\,{\rm G}$ is the critical magnetic field and $\omega_{\rm pl}$ is the plasma frequency of the medium.

Define

$$E_L \equiv \frac{|m^2 - \omega_{\rm pl}^2|}{2\,g_{a\gamma}\,B} , \quad (10)$$

and

$$E_H \equiv \frac{90\pi}{7\alpha} \frac{B_{\rm cr}^2\, g_{a\gamma}}{B} . \quad (11)$$

Accordingly

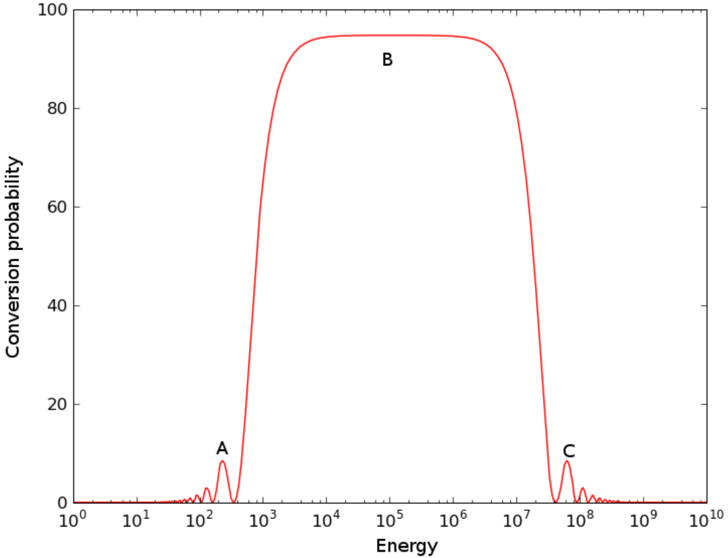
- For $E \ll E_L$ and $E \gg E_H$ then $P_{\gamma \to a}(E; 0, y) = 0$.
- For $E \sim E_L$ and $E \sim E_H$ then $P_{\gamma \to a}(E; 0, y)$ rapidly oscillates with E: WEAK-MIXING regime.
- For $E_L \ll E \ll E_H$ then $P_{\gamma \to a}(E; 0, y)$ maximal and independent of both m and E: STRONG-MIXING regime, where

$$\Delta_{\rm osc} \simeq g_{a\gamma}\, B \tag{12}$$

and

$$P_{\gamma \to a}(E; 0, y) \simeq \sin^2 \left(\frac{g_{a\gamma}\, B y}{2} \right) \,, \tag{13}$$

which is MAXIMAL.



100
80
60
40
20
0
Conversion probability
A
B
C
10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10}
Energy

4 – REDUCING THE VHE OPACITY

The key-idea is as follows (De Angelis, Roncadelli & Mansutti, 2007). Imagine that photon-ALP oscillations take place in the extragalactic magnetic field. Then they provide a photon with a SPLIT PERSONALITY: sometimes it travels as a TRUE PHOTON and sometimes as an ALP. When it propagates as a photon it undergoes EBL absorption, but when it propagates as an ALP in does NOT. Therefore, the EFFECTIVE optical depth $\tau_{\rm eff}(E,z)$ in extragalactic space is SMALLER than $\tau(E,z)$ as computed according to conventional physics. Hence

$$P^{\rm ALP}_{\gamma \to \gamma}(E,z) = e^{-\tau_{\rm eff}(E,z)} ~. \tag{14}$$

So, even a SMALL decrease of $\tau_{\rm eff}(E,z)$ produces a LARGE increases in $P^{\rm ALP}_{\gamma \to \gamma}(E,z)$. In this way EBL absorption gets considerably REDUCED.

ASSUMPTIONS

- Extragalactic magnetic field **B** modeled as a domain-like structure with $L_{\rm dom} = (1 - 10)\,{\rm Mpc}$, $B = (0.1 - 1)\,{\rm nG}$ in all domains, random direction in any domain: STRONGLY MOTIVATED by primeval galaxy outflow models.
- Since the physics depends only on $g_{a\gamma}\,B$, we work with $\xi \equiv \left(g_{a\gamma}\,10^{11}\,{\rm GeV}\right)\left(B/{\rm nG}\right)$.
- EBL described by the Franceschini & Rodighiero (FR) 2017 model.
- Vacuum polarization induced by the CMB becomes IMPORTANT for $E > 5\,{\rm TeV}$.
- STRONG MIXING REGIME implies $m < 5 \cdot 10^{-10}\,{\rm eV}$.
- Benchmark values: $\xi = 0.1, 0.5, 1, 5$; $L_{\rm dom} = 4\,{\rm Mpc}, 10\,{\rm Mpc}$.
- Polarization UNKNOWN: we have to deal with the POLARIZATION DENSITY MATRIX.

Now, for $E < 5\,\mathrm{TeV}$ the oscillation length is anyway LARGER than $L_{\rm dom}$, and so $P^{\rm ALP}_{\gamma \to \gamma}(E, z)$ is INSENSITIVE to the shape of the **B** domain. But for $E > 5\,\mathrm{TeV}$ the oscillation length is SMALLER than $L_{\rm dom}$ due to the CMB-induced vacuum polarization, so $P^{\rm ALP}_{\gamma \to \gamma}(E, z)$ DEPENDS on the domain's shape. So, in order to avoid such a dependence as well as a **B** jump between neighboring domains, we smooth them out as shown in the next Figure.

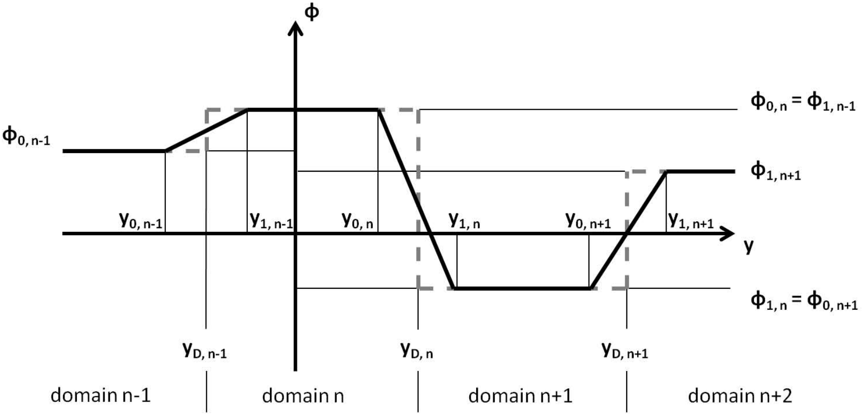


Figura: Behavior of the angle ϕ between $\mathbf{B}_T$ and the fixed z-axis concerning the propagation of the beam in the y-direction: the solid black line is the new smooth version, while the broken gray line represents its usual jump from one domain to the next. Partially, the horizontal solid and broken lines overlap.

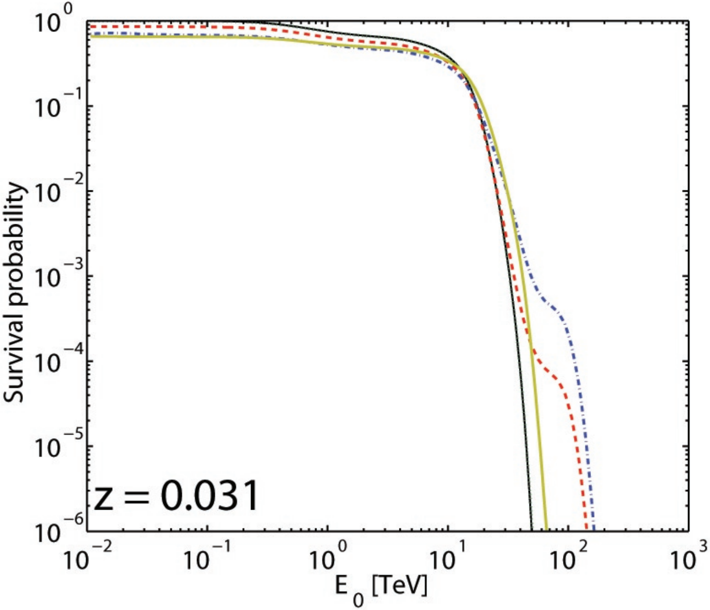
5 – PHOTON SURVIVAL PROBABILITY

PREDICTIONS FOR MOCK BLAZARS AT DIFFERENT REDSHIFT

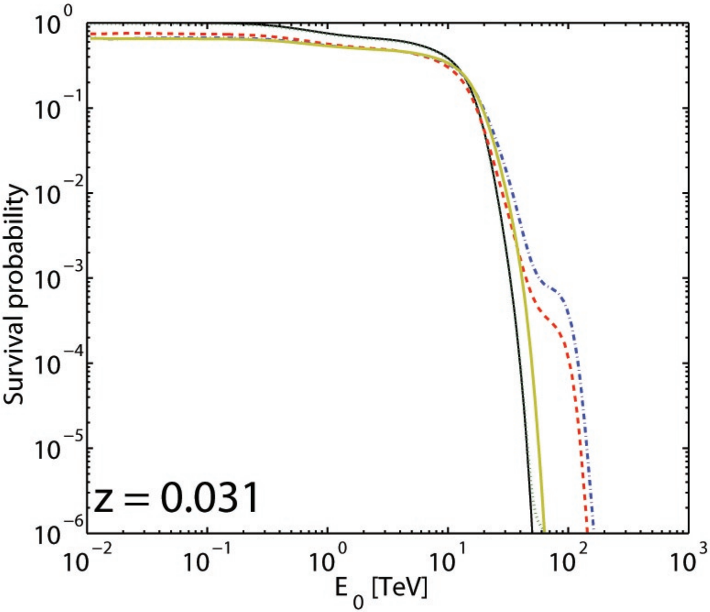
In the next Figures:

- Solid black line = conventional physics.
- Dotted green line: $\xi = 0.1$.
- Dashed red line: $\xi = 0.5$.
- Dotted-dashed blue line: $\xi = 1.0$.
- Solid yellow line: $\xi = 5.0$.
- σ = smoothing factor.

$L_{\mathrm{dom}} = 4\,\mathrm{Mpc}$. No CMB, $\sigma = 0$. EXERCISE.



$L_{\mathrm{dom}} = 10\,\mathrm{Mpc}$. No CMB, $\sigma = 0$. EXERCISE.



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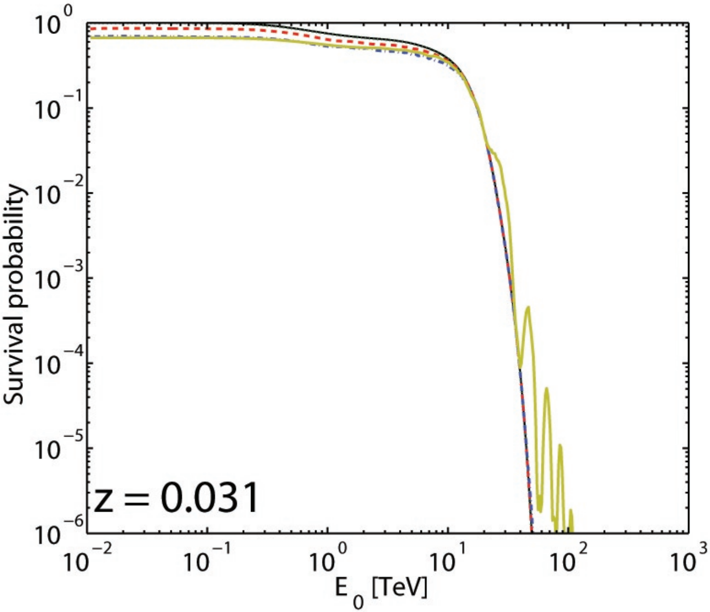

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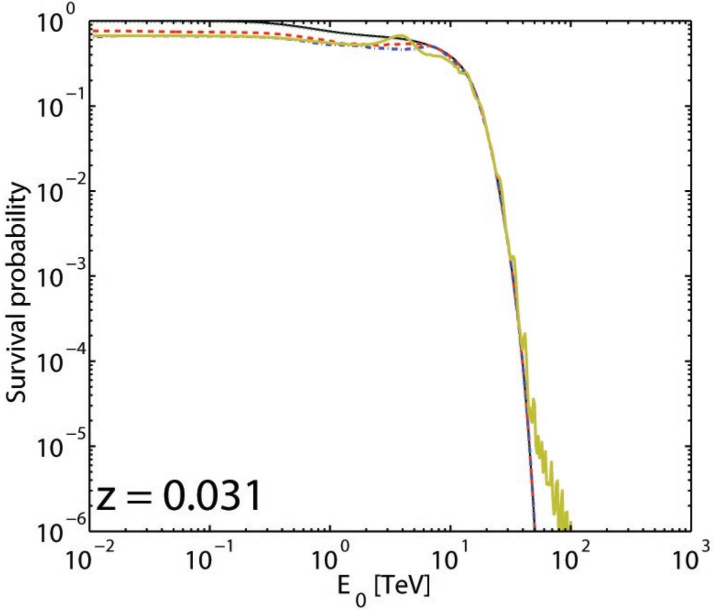
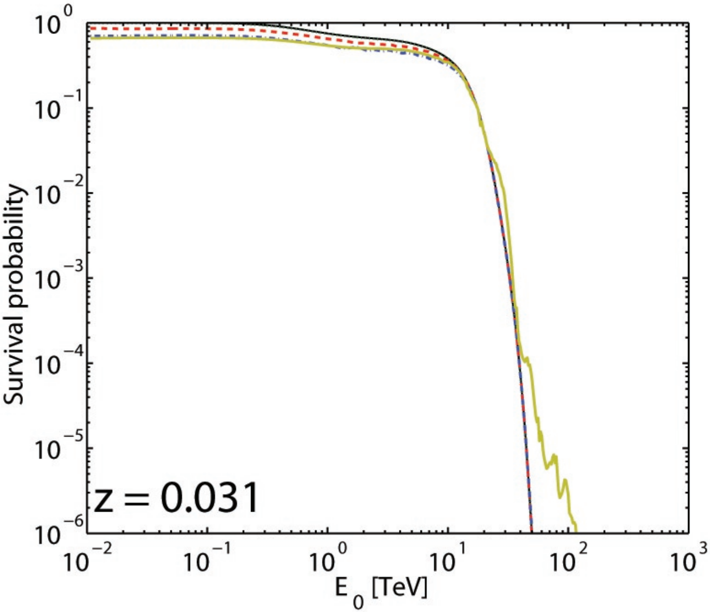


$L_{\rm dom} = 4\,{\rm Mpc}$. CMB, $\sigma = 0.1$. PHYSICAL.



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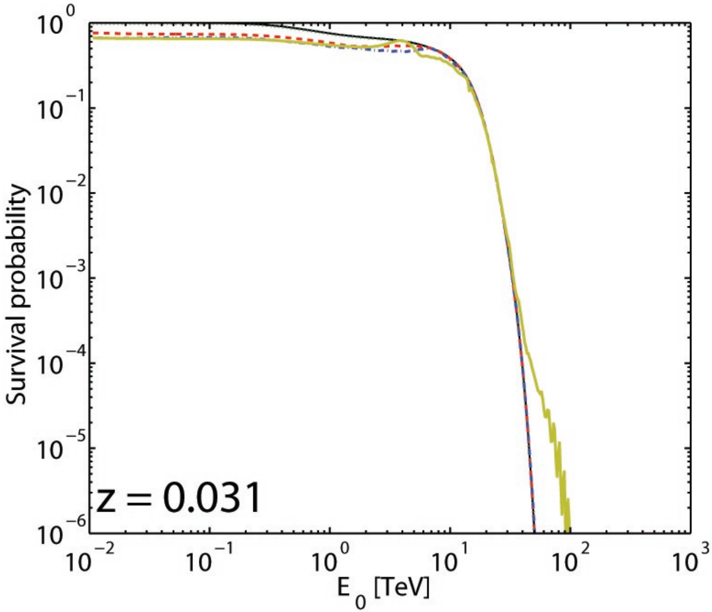

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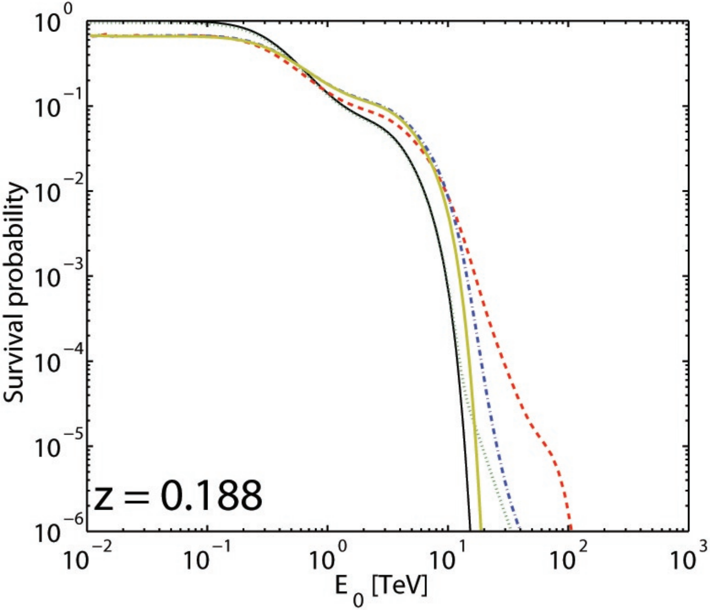

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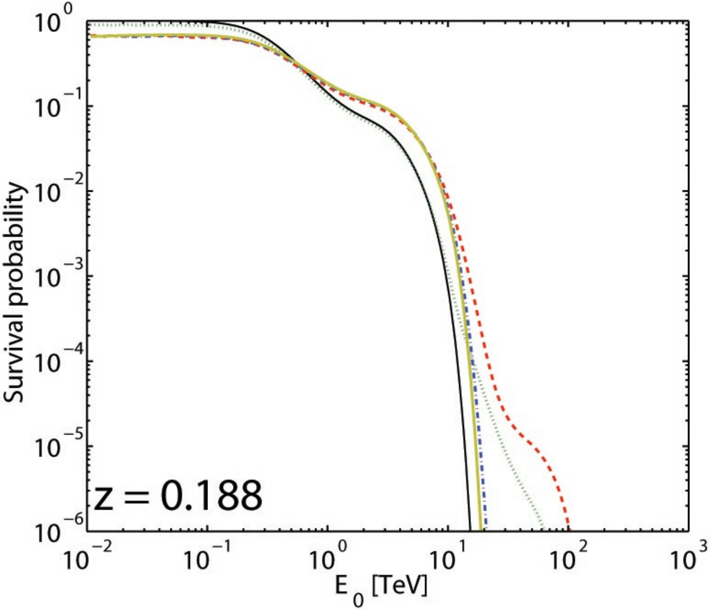

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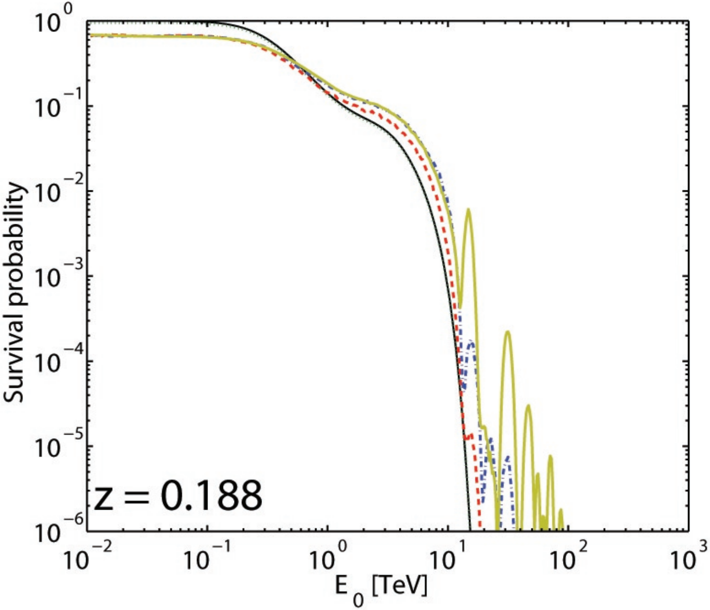

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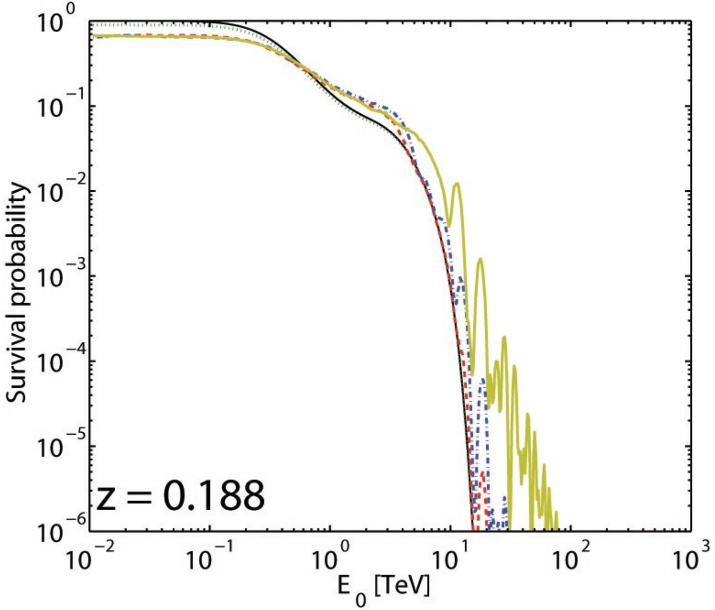

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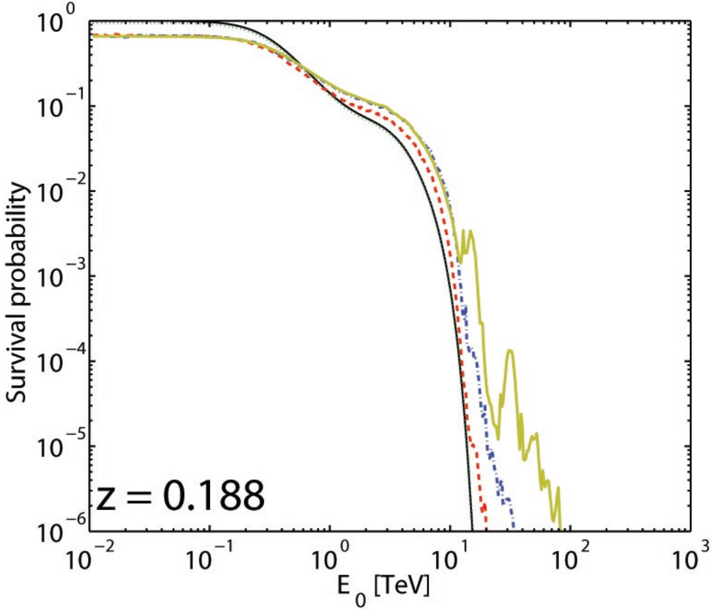

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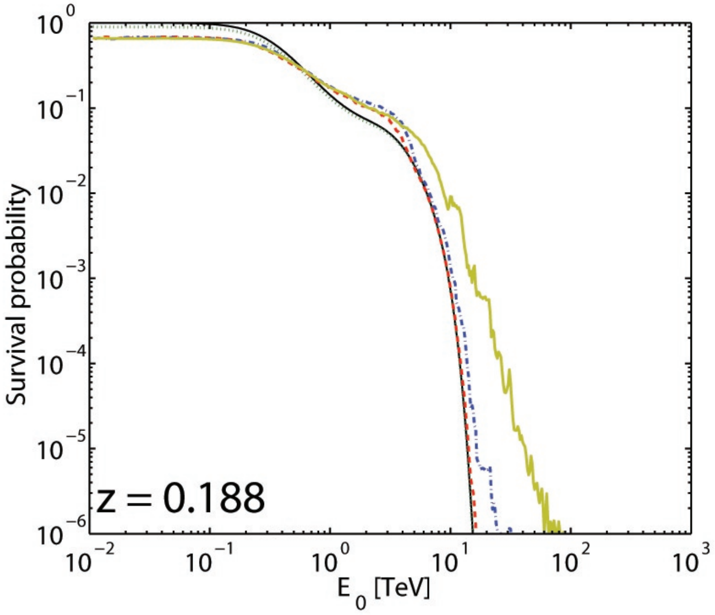

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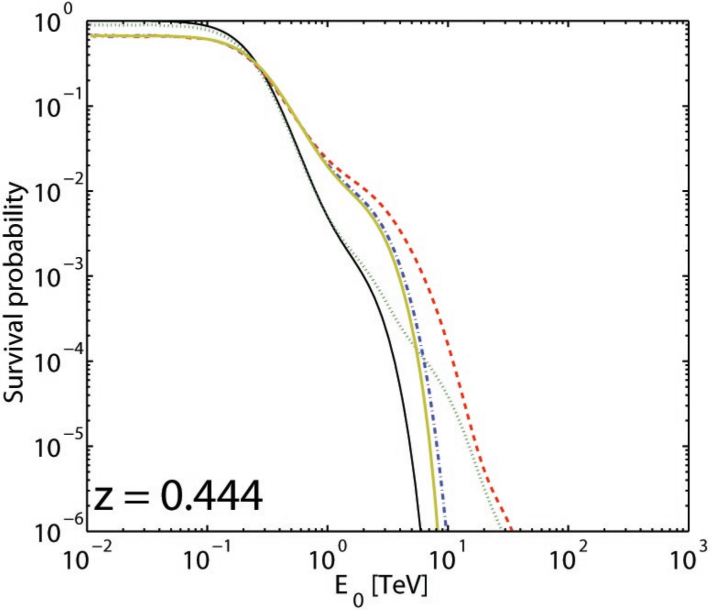

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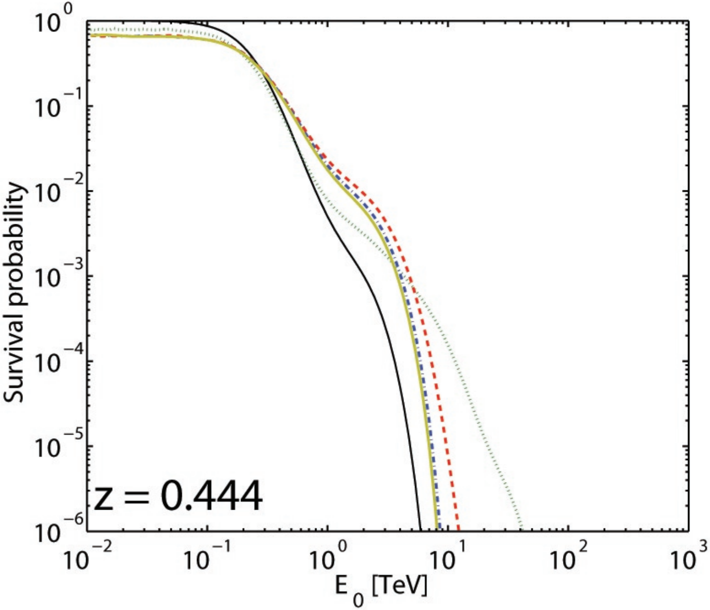

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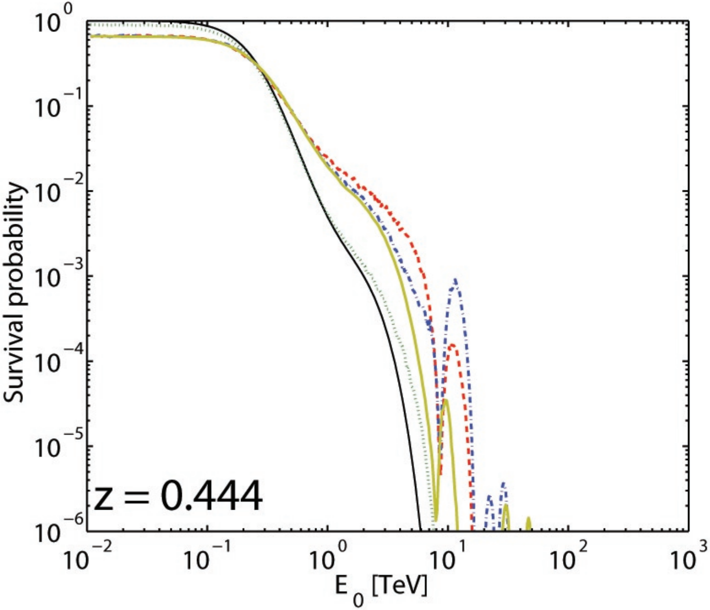

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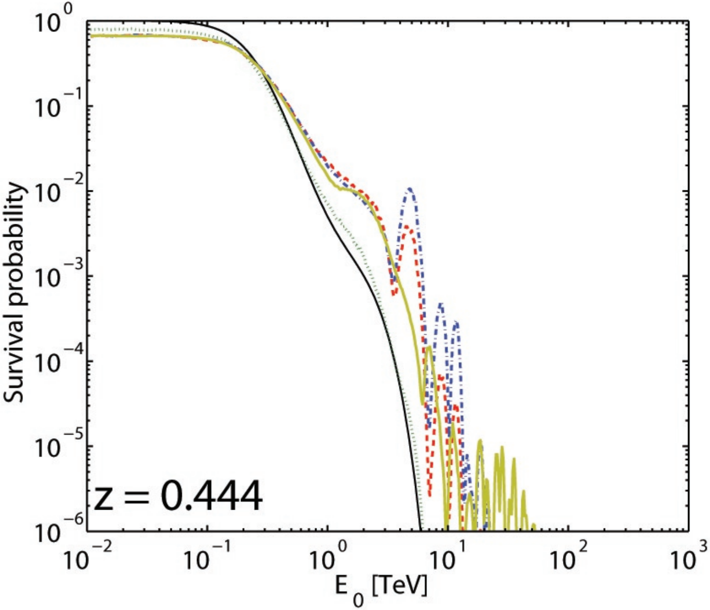

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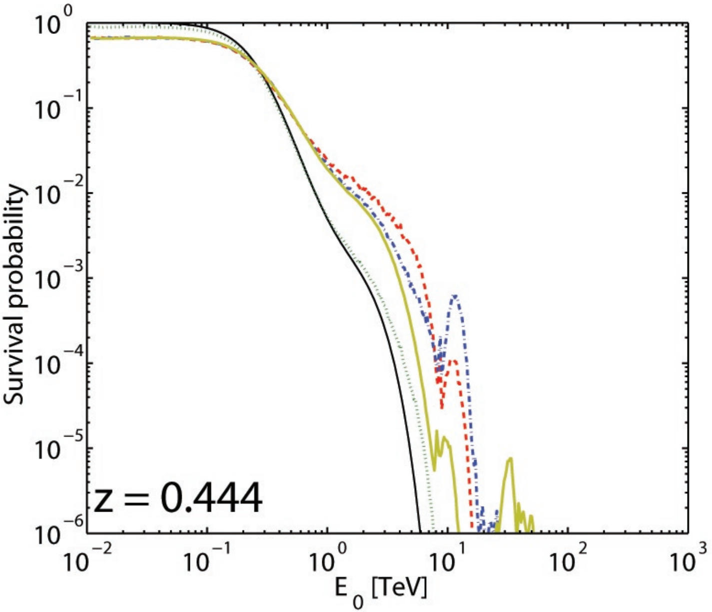

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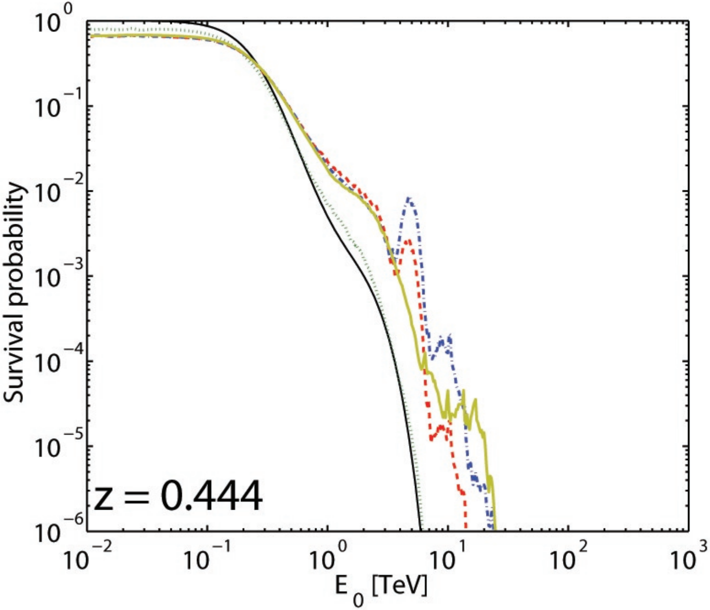

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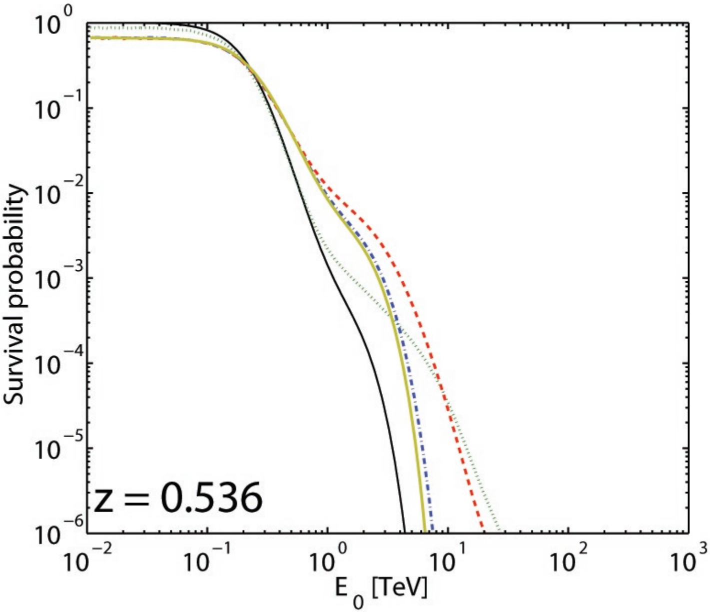

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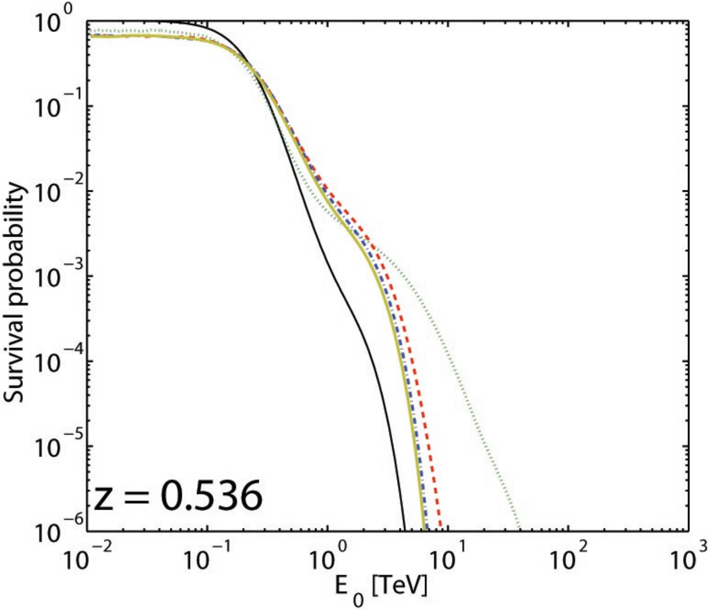

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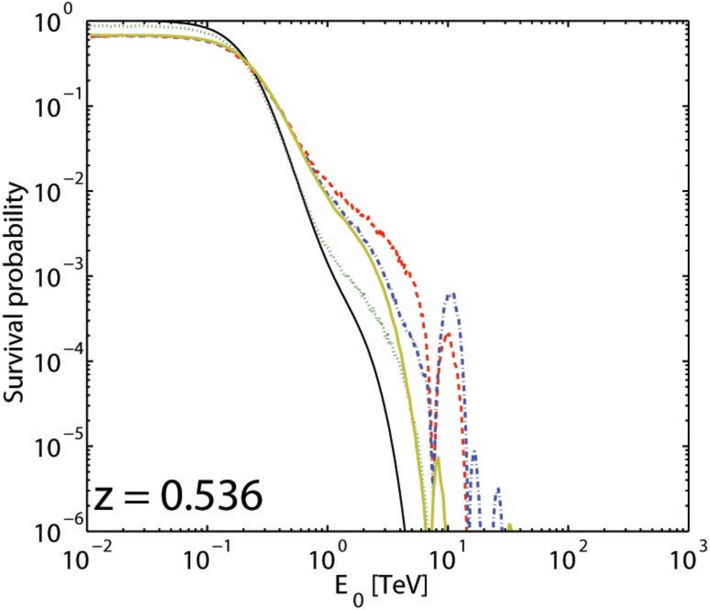

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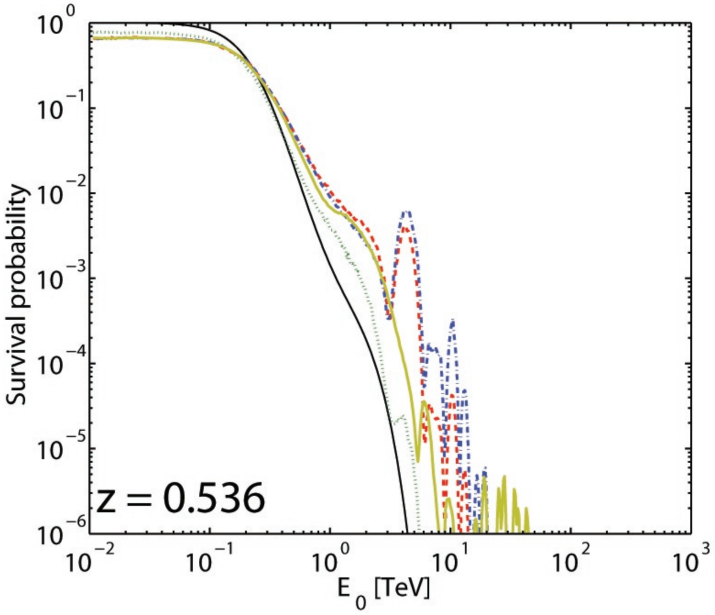

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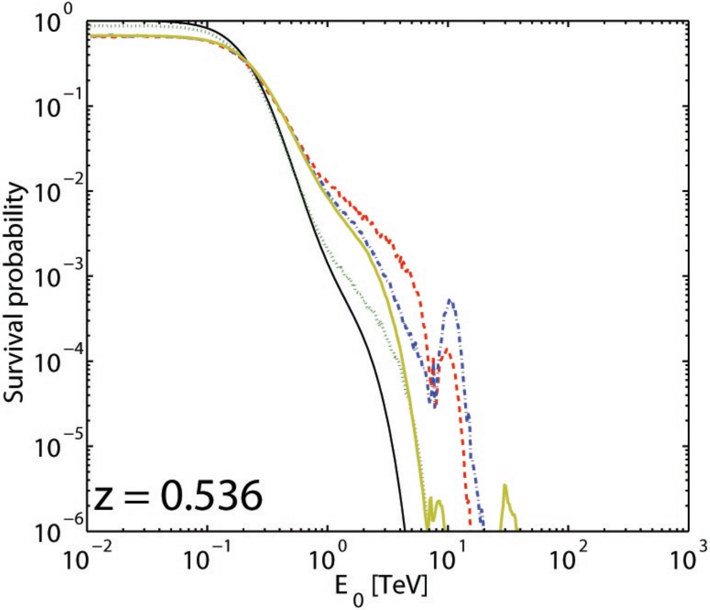

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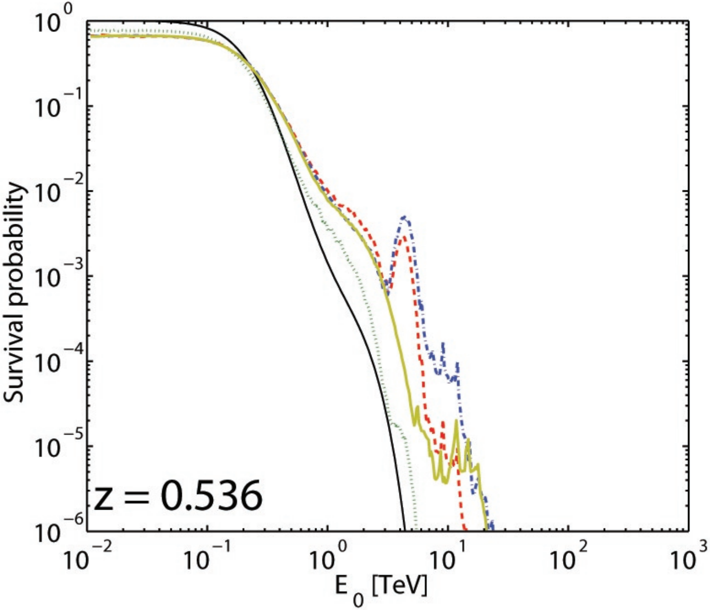

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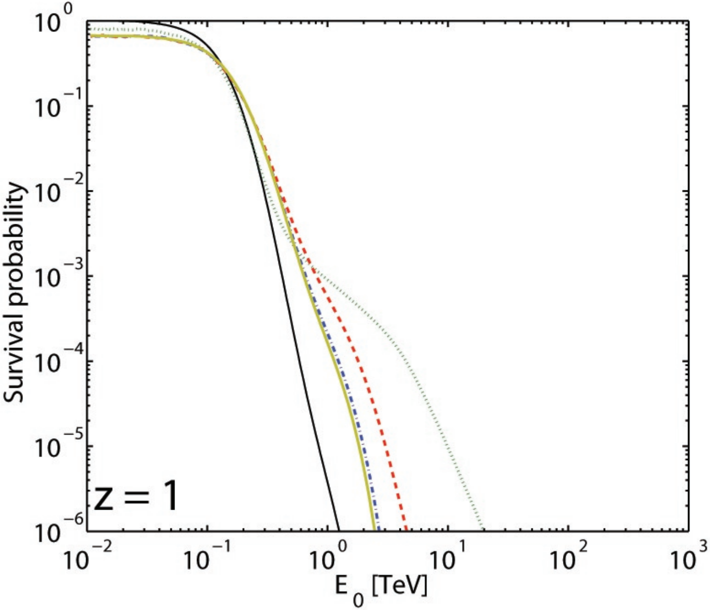

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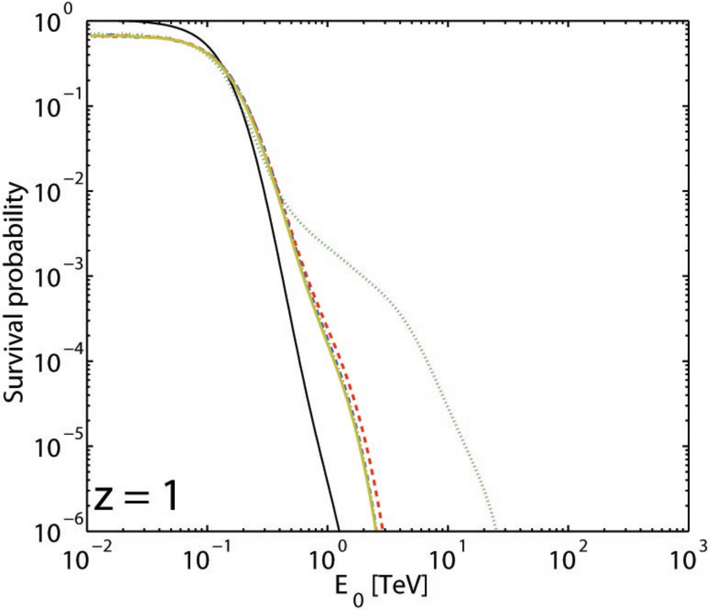

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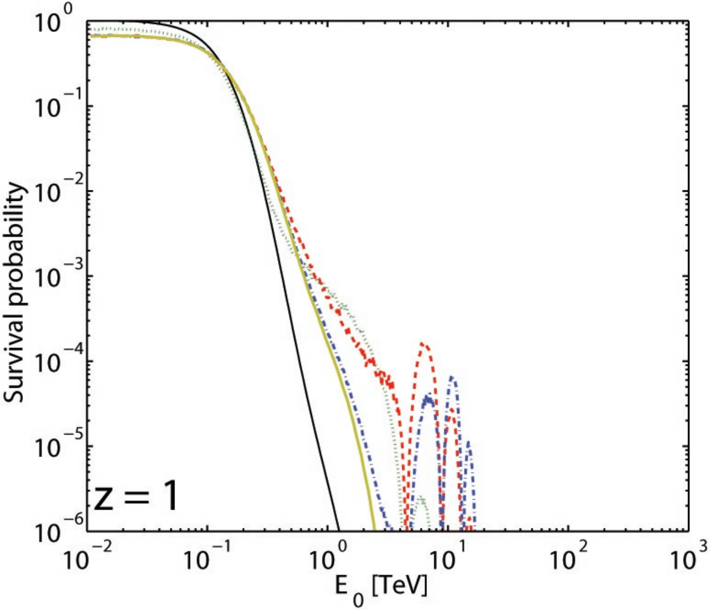

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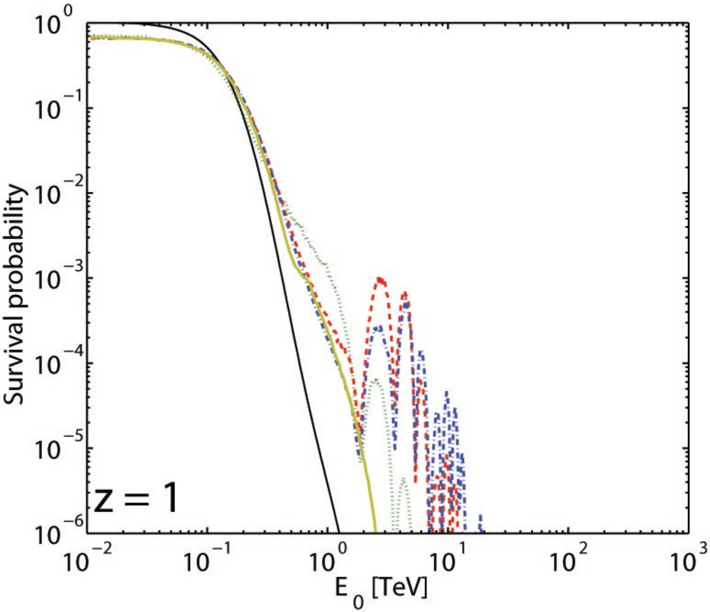
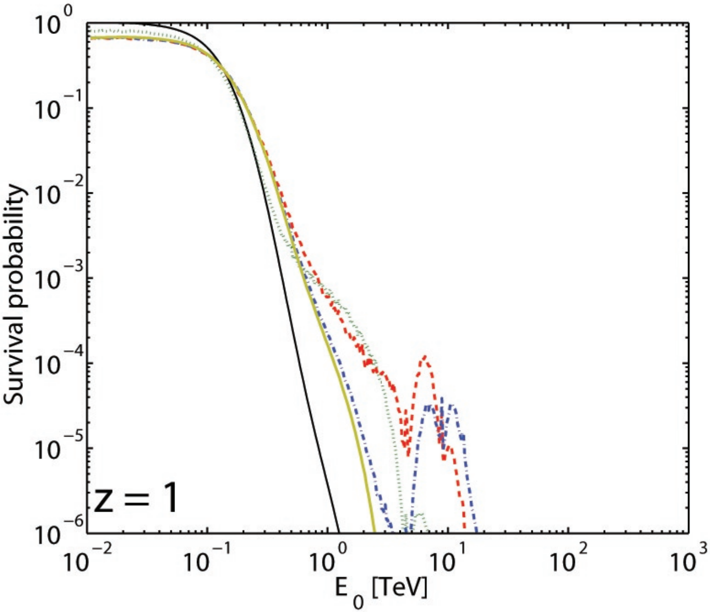


$L_{\mathrm{dom}} = 4\,\mathrm{Mpc}$. CMB, $\sigma = 0.1$. PHYSICAL.



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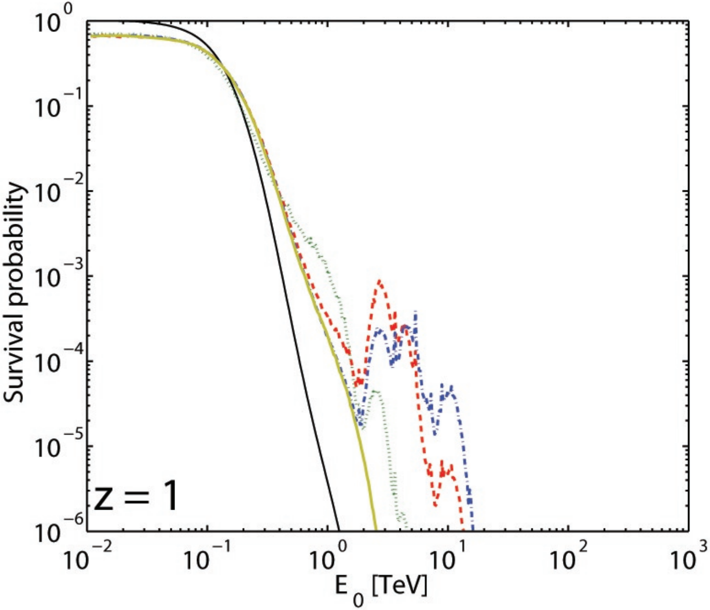
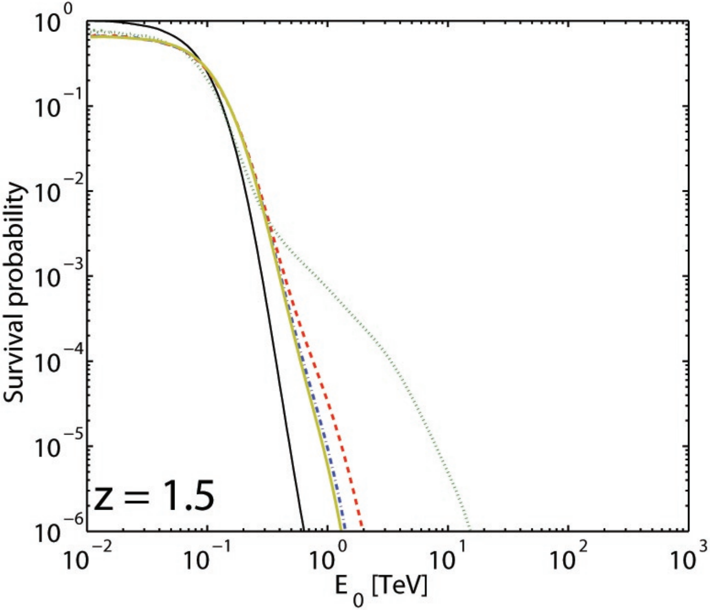


$L_{\rm dom} = 4\,{\rm Mpc}$. No CMB, $\sigma = 0$. EXERCISE.



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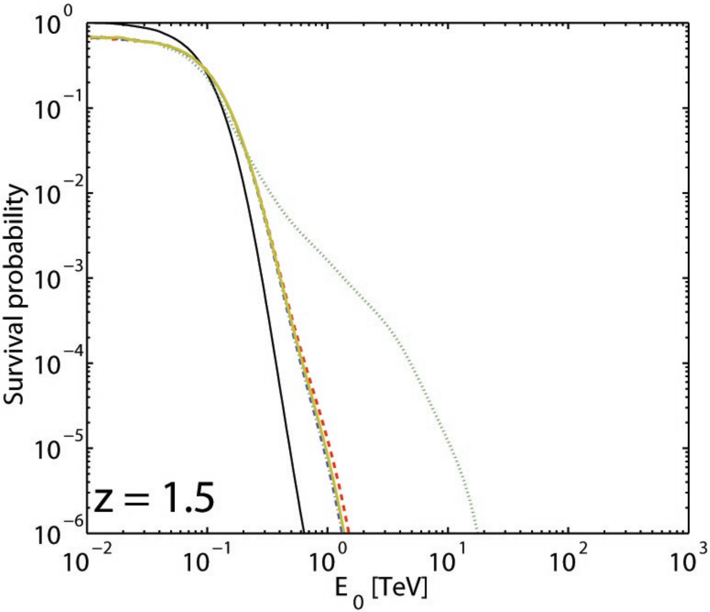

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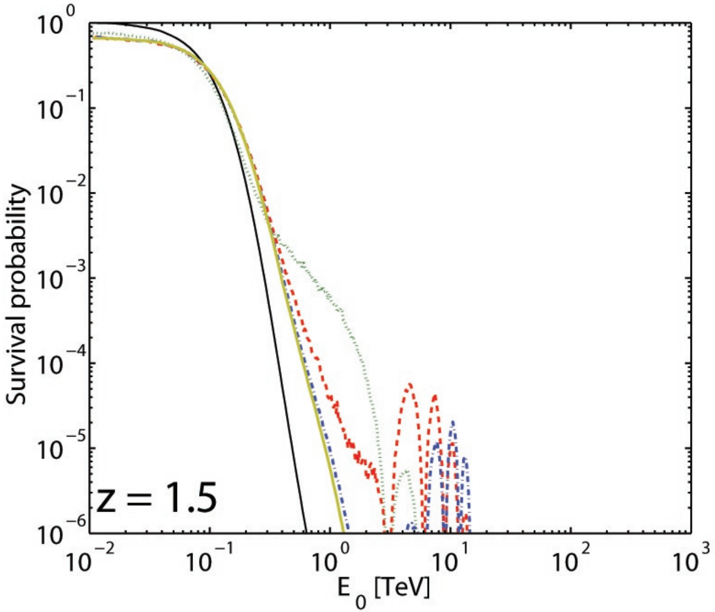

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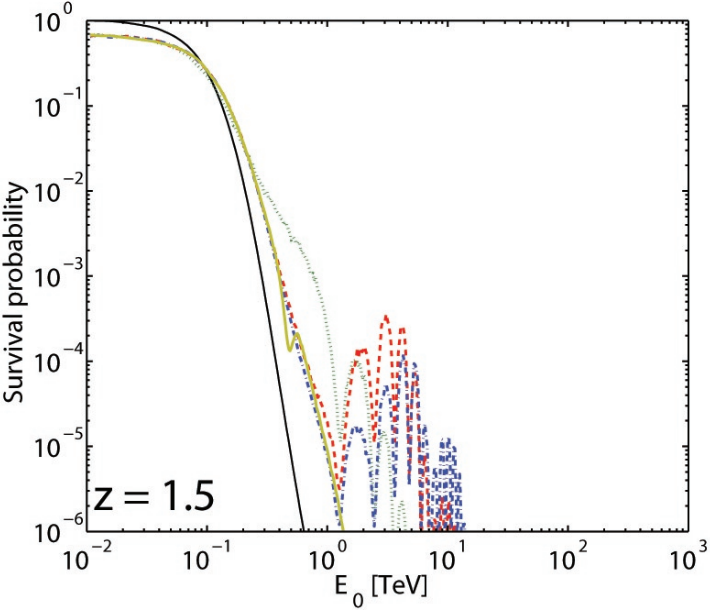

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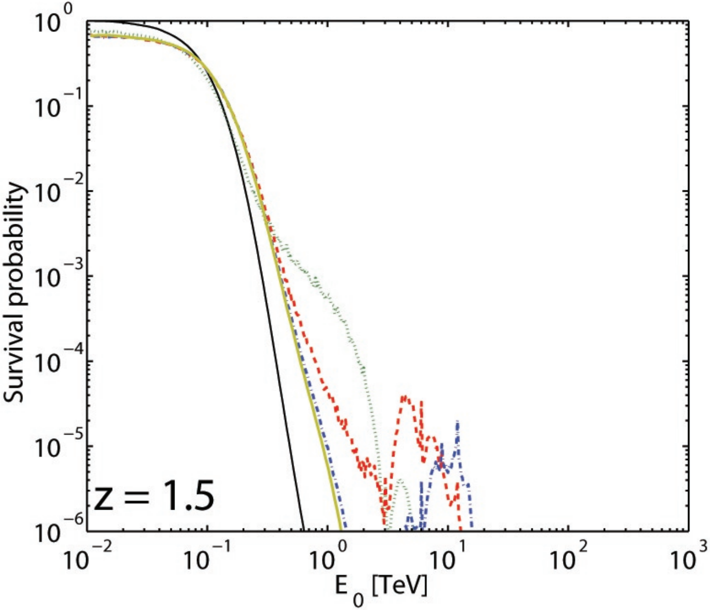

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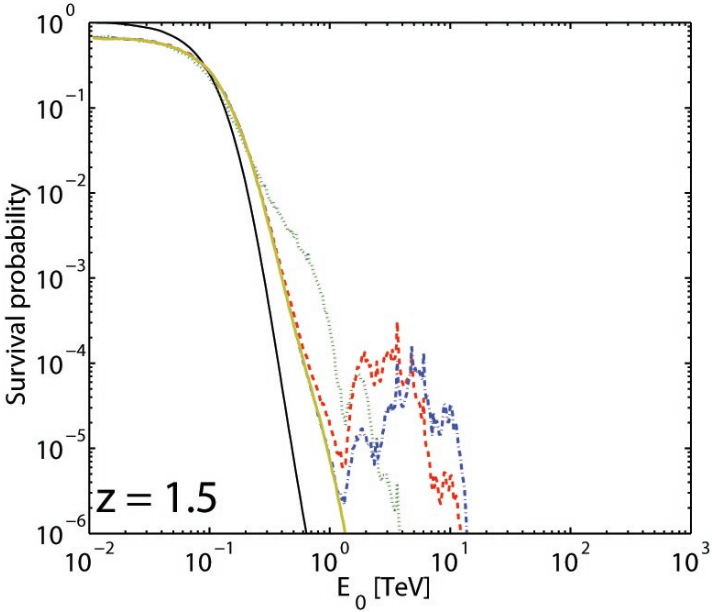
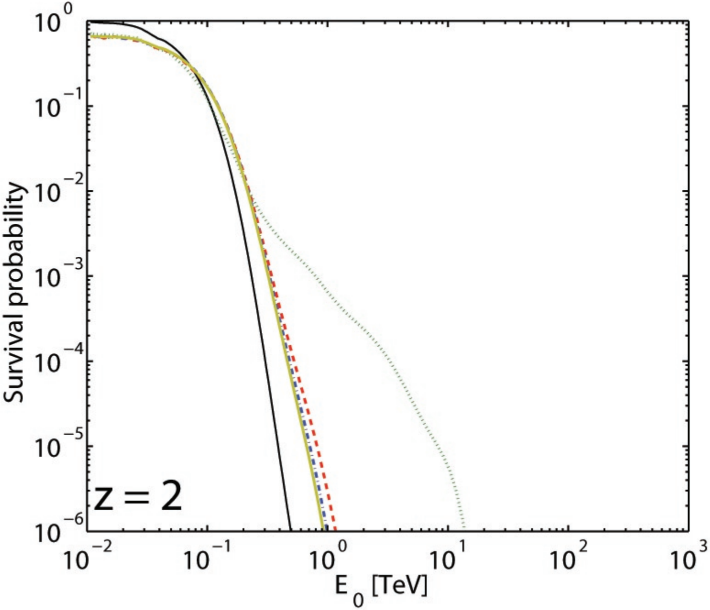


$L_{\mathrm{dom}} = 4\,\mathrm{Mpc}$. No CMB, $\sigma = 0$. EXERCISE.



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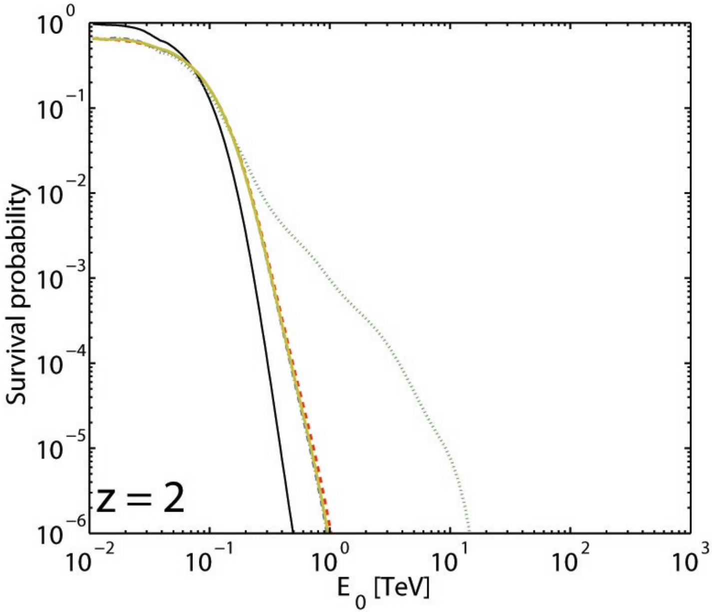

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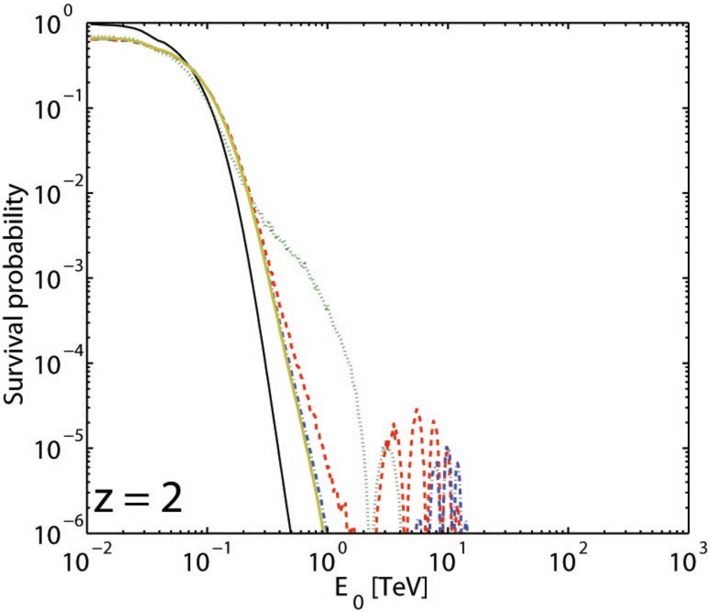

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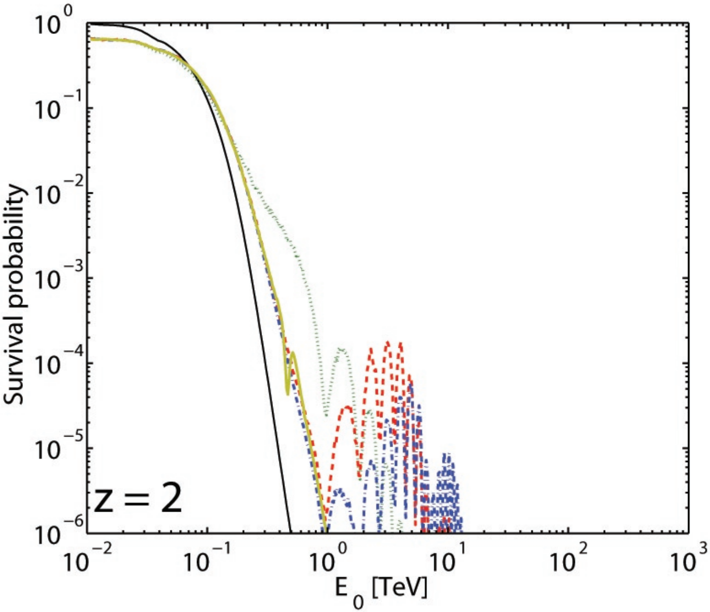

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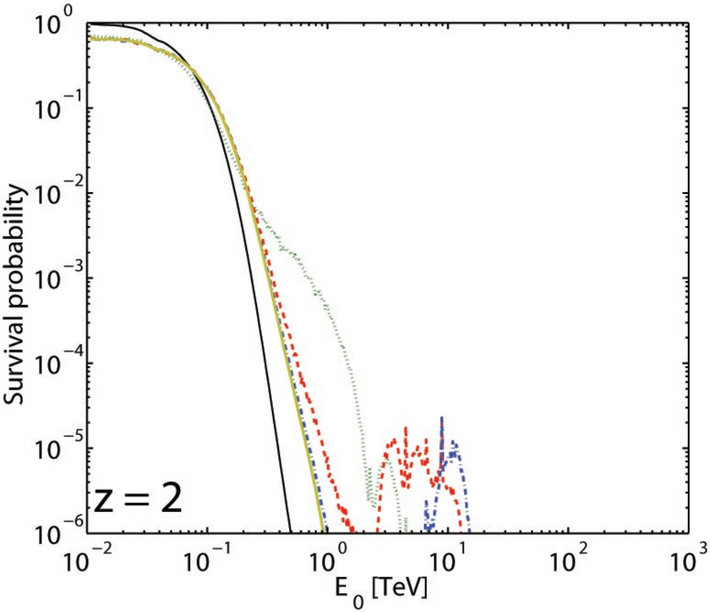

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