

Positron signal from the early Universe

Leo Stodolsky 

Max-Planck-Institut für Physik, Boltzmannstr. 8, 85748 Garching, Germany

Joseph Silk

Institut d'Astrophysique de Paris, UMR7095:CNRS UPMC-Sorbonne University, F-75014, Paris, France;

Department of Physics and Astronomy, The Johns Hopkins University

3400 N. Charles Street Baltimore, Maryland 21218, USA;

and BIPAC, University of Oxford, 1 Keble Road, Oxford, OX1 3RH, United Kingdom



(Received 9 October 2024; revised 3 February 2025; accepted 12 June 2025; published 27 June 2025)

Bursts from the very early Universe may lead to a detectable signal via the production of positrons, whose annihilation gives an observable x-ray signal. Using the absorption parameters for the annihilation photons of 511 keV, it is found that observable photons would originate at a redshift around $z \approx 200$ –300, resulting in soft x-rays of energy ~ 2 –3 keV at present. Positrons are expected to be absent at these times or redshifts in the standard picture of the early universe. Detection of the x-rays would thus provide dramatic support for the hypothesis of the bursts, explosive events at very early times. We urge the search for such a signal.

DOI: [10.1103/897z-1k7m](https://doi.org/10.1103/897z-1k7m)

We have contemplated [1] the possibility that in the very early Universe, rare but explosive events take place, analogous to the supernovas seen in the presently observable Universe. These might be induced by such processes as the collapse of massive regions to black holes or the formation of “baby” [2] or “pocket” [3] universes”, or perhaps “little bangs” connected with phase transitions [4]. Although such events might lead to regions of spacetime which are physically disconnected from us, it is plausible that during their formation, peripheral or transient phenomena occur, as is familiar for the optical or neutrino bursts accompanying core-collapse supernovae. Just as for the supernovae, a quiescent remnant may be left behind, while a dramatic explosive effect reaches the “outer world.”

The most plausible carriers of energy or information among the presently established particles would be neutrinos. Since they are neutral and have purely weak interactions, they are the most likely to “escape” from the dense environments of the very early Universe. This would also be analogous to the core-collapse supernovas, where essentially all the energy is carried away by neutrinos.

Observation or detection of such events would evidently open a new chapter in observational cosmology. But there is a great difficulty in directly detecting such early time

events, namely the high redshift to be anticipated. The particles, produced at high redshift, will arrive to us with very low energy, $a(t_{\text{em}})E_{\text{em}}$, where E_{em} is the energy in the rest frame of their emission, and $a(t_{\text{em}})$ is the cosmological expansion parameter at the emission time t_{em} of the burst. Thus neutrinos emitted from an event at cosmic time $t_{\text{em}} = 1$ second will have their energies reduced by a factor (2×10^{-10}) when arriving at the present. Since the neutrino cross section for detection is strongly energy dependent, this would seem to make direct detection of the bursts practically impossible, even if we find [1] that the flux factor stops decreasing for very early emission times.

However another approach suggests itself, based on the thought that there could be processes induced by the burst particles at high redshift, where they are more energetic. This might then lead to observable signals [5]. The question is somewhat subtle, since a signal created at high redshift may not be able to “escape” the dense environments to reach the present epoch. In this note we would like to briefly report on one of the most intriguing and novel cases where this may be however possible: the production of positrons.

If neutrinos with MeV energies or more arrive to the recombination epoch or later, the production of positrons, whose subsequent annihilation gives an observable soft x-ray signal, is possible.

That is, we consider

$$\bar{\nu} + p \rightarrow e^+ + n \quad e^+ + e^- \rightarrow \gamma + \gamma \quad (1)$$

giving 511 keV photons, whose redshift to the present gives a soft x-ray, as we shall explain.

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Open access publication funded by the Max Planck Society.

The detection of such a signal would be very characteristic for bursts. We shall see that the relevant redshift factor z for the origin of observable x-rays is on the order of some hundreds. However the temperature of the universe at such times is well below an eV, as may be judged from the fact that already at the much earlier time around recombination with $z \sim 10^3$, the temperature has already fallen to the order of the binding energy of the hydrogen atom, or some eV's. Thus with only sub-eV energies available in the purely thermal equilibrium picture, positrons should be entirely absent.

In principle, there are other, presumably subdominant, reactions which can lead to positrons via decay chains, such as $\bar{\nu}_\mu p \rightarrow \mu^+ n$, followed by $\mu^+ \rightarrow e^+ \nu \bar{\nu}$. There can also be the production of π mesons via hadron channels, as in $\nu p \rightarrow e^- \Delta^{++}$ followed by $\Delta^{++} \rightarrow \pi^+ p$, where Δ is the resonance with mass 1240 MeV and the pion then decays to a muon. An amusing possibility in this connection would be the production of π^0 mesons as in $\Delta^+ \rightarrow \pi^0 p$. The pion will give two “prompt” 70 MeV photons, which would profit from the higher transparency for high energy photons. However, all such channels should be subdominant due to the fact that, in addition to the complicated branching fractions involved, they have much higher energy thresholds than the ~ 1 MeV for Eq. (1). For the muon reaction this will be near the muon mass or 110 MeV and for the Δ reactions around 400 MeV. Due to the great redshift for the bursts, we expect the incoming neutrino spectrum to be strongly peaked towards low energy, making higher threshold processes subdominant [6].

In principle there is also a 2.2 MeV γ signal from capture of the neutron on hydrogen, but due to the low matter density at early times the 14 minute decay of the neutron is much faster.

The quantity of interest is $N_\gamma(t_{\text{now}})$, the present density of annihilation photons, which gives our detection rate. In particular we are interested in its energy spectrum $\frac{dN_\gamma(t_{\text{now}})}{d\omega}$, where ω is the present energy of an annihilation photon.

Although the annihilation of a positron on a stationary electron leads to a “line” at 511 keV, various effects lead to a spread of the photon spectrum. There is the thermal motion of the atoms and the motion of the bound electron in the atom. However, the most important effect in our present problem will be due to the spread of the redshifts in the origin of the gamma ray. There is essentially a one-to-one relation between the redshift of origin z and ω

$$\omega = (1/z) 511 \text{ keV} \quad d\omega = (2/3) z^{1/2} \frac{dt}{t_{\text{now}}} 511 \text{ keV}. \quad (2)$$

Since we will find that the relevant times are well into the matter dominated epoch, for z we use $z = (t_{\text{now}}/t)^{2/3}$, with $t_{\text{now}} = (2.9 \times 10^{17})$ seconds [1]. The second relation shows how a spread in production times dt gives a band of present energies $d\omega$.

A time interval dt at redshift z thus gives a contribution to the present density of the annihilation photons with energy $\omega = (1/z) 511 \text{ keV}$

$$dN_\gamma(t_{\text{now}}) = C(z) dt = C(z) \frac{1}{z^{1/2}} (3/2) \frac{t_{\text{now}}}{511 \text{ keV}} d\omega \quad (3)$$

where C is the factor for the conversion of neutrinos into photons, and the propagation of the photons to the present time. This will involve presently unknown features of the fluxes from the bursts, their spectrum and intensity. The most significant feature, due to the high redshift anticipated for the sources, should be the peaking of the neutrino spectrum toward low energy. For our present purposes we leave questions pertaining to the absolute magnitude of C open and only consider those affecting the shape of the spectrum.

The most important of these will be the factor in C for the absorption of the photons during their propagation. While of course positrons will be produced all along the path of a neutrino pulse, only those conversions which are close enough so that the annihilation photon can “escape” to the present time are potentially observable.

The absorption is governed by an attenuation factor $\mathcal{A}$. That is, the probability of an emitted photon to reach us is

$$\mathcal{A} = \exp(-\tau/\tau_o) \quad (4)$$

where τ is the column density or “thickness” of the matter traversed, and τ_o is a parameter characterizing the matter. This parameter is usually given in grams/cm² and for 500 keV photons in hydrogen one has [7]

$$\tau_o \approx 6 \text{ grams/cm}^2. \quad (5)$$

This parameter is energy dependent and so $\mathcal{A}$ will be somewhat affected by the redshift of the traveling photons. However, most of the absorption will take place close to the time of production and for the present rough estimates we will simply use Eq. (5).

To evaluate Eq. (4) in the cosmological situation, we take the intervening matter to be essentially hydrogen (the correction for helium is at the 10% level) and we estimate the column density from the present back to an earlier time t or equivalently to an $a(t)$ or $z = 1/a$. One first needs the density, which we take to be

$$\rho(t) = \rho_o \left(\frac{t_{\text{now}}}{t} \right)^2, \quad (6)$$

where ρ_o is the present density of hydrogen and the density scales as $1/a^3$, using $a = (t/t_{\text{now}})^{2/3}$.

One thus has for the column density

$$\begin{aligned}\tau &= \int_{t_{\text{now}}}^t \rho(t) dt = \rho_o t_{\text{now}} \left(\frac{t_{\text{now}}}{t} \right) \\ &= \rho_o t_{\text{now}} \times a^{-3/2} = \rho_o t_{\text{now}} \times z^{3/2},\end{aligned}\quad (7)$$

and thus for the absorption factor expressed in terms of z

$$\mathcal{A} = \exp\left(-\frac{\rho_o t_{\text{now}}}{6 \text{ grams/cm}^2} z^{3/2}\right) = \exp(-(z/z_o)^{3/2}) \quad (8)$$

where we introduce the quantity $z_o = (\frac{\rho_o t_{\text{now}}}{6 \text{ grams/cm}^2})^{-2/3} \approx 130$, which characterizes the absorption distance in terms of z . We have taken ρ_o at 5% of the critical density, namely $\rho_o = (5 \times 10^{-31}) \text{ grams/cm}^3$.

In addition to $\mathcal{A}$ which favors nearby production of the positrons, there are countervailing factors favoring higher redshift, namely the higher density of target protons for Eq. (1) at early times, and the smaller downshift of the original neutrino emission energy.

Two other possible factors of this type cancel each other in their z or a dependence. If a is the expansion parameter at the time the positrons are produced, then there is a factor $\sim 1/a^3$ for the dilution of the original neutrino burst and at the same time a factor $\sim a^3$ for the closeness of the production time of the annihilation photons to the present. This cancellation is due to the fact that photon and neutrino densities redshift in the same way.

The increasing density of proton targets with redshift gives a factor $\sim (1/a)^3 = z^3$. As for the neutrino energy factor in the cross section [8], this will depend on whether we are in the fully relativistic regime $E^\nu > 1 \text{ GeV}$ for the neutrino energy at production where the cross section is linear with energy, or at lower energy, where the behavior is closer to quadratic. In addition to the absorption factor we thus anticipate a power factor in the z dependence of C with a power in the vicinity 4–5 (dashes are meant to indicate a range).

The combination of these factors with Eq. (3) gives the spectrum for the possibly observable density of annihilation photons $N_\gamma(t_{\text{now}})$

$$\frac{dN_\gamma(t_{\text{now}})}{d\omega} \sim z^p \mathcal{A} = z^p \times \exp(-(z/z_o)^{3/2}). \quad (9)$$

with $p = 3.5\text{--}4.5$.

The product of increasing and decreasing functions leads to a peak at some z , namely at $z = (\frac{2}{3}p)^{2/3} \times z_o$. We thus have a peak at z_{peak}

$$z_{\text{peak}} \approx (1.8\text{--}2.1) \times z_o \approx (230\text{--}280), \quad (10)$$

implying that the original 511 keV photon appears at present as a soft x-ray in the vicinity of 2 or 3 keV

The distribution is rather broad. Reexpressing Eq. (9) in terms of ω

$$\frac{dN_\gamma(t_{\text{now}})}{d\omega} \sim (1/\omega)^p \exp(-(3.9/\omega)^{3/2}) \quad (11)$$

with ω in keV and p in the vicinity 3.5–4.5. Because of the range in redshift for production, the original annihilation “line” has become a broad and somewhat asymmetric “bump”. A plot of Eq. (11) is shown in Fig. 1.

Since a certain threshold neutrino energy is required for the positron production, and since a high redshift for the origin of the bursts requires an even higher emission energy, there will be a limitation on how early the bursts can originate. Those bursts that are emitted too early will either have their energies redshifted below threshold when arriving at the production epoch, or be absorbed due to their high energy. Estimates [5] using standard neutrino and early universe parameters suggest that neutrinos can “escape” to later times when their emission time t_{em} fulfills the condition $t_{\text{em}}/\text{sec} > (7 \times 10^{-1}) E_{\text{em}}^\nu/\text{GeV}$ (emission in the radiation dominated epoch). Reexpressing this relation in terms of the energy E_{200} after the redshift to $z \sim 200$, one has $t_{\text{em}}/\text{sec} > (6 \times 10^4) (E_{200}^\nu/\text{GeV})^{2/3}$. Thus to have the threshold energy of $\sim 1 \text{ MeV}$ at $z \sim 200$ one finds that a neutrino must have been emitted at earliest $\sim (6 \times 10^2)$ seconds. Or if one asks for an energy of 1 GeV to give a higher production rate, the earliest time is about $\sim (6 \times 10^4)$ seconds. Hence evidence for the positrons would imply significant burst activity around these epochs.

A question that might arise if there is a flux of 511 keV photons following recombination is that this could lead to significant reionizations of the newly formed hydrogen atoms. However we expect the bursts to be rare and an estimate [5] shows that their intrinsic probability would have to be very large for this reionization to be important. However, should it be that our simple estimates are too

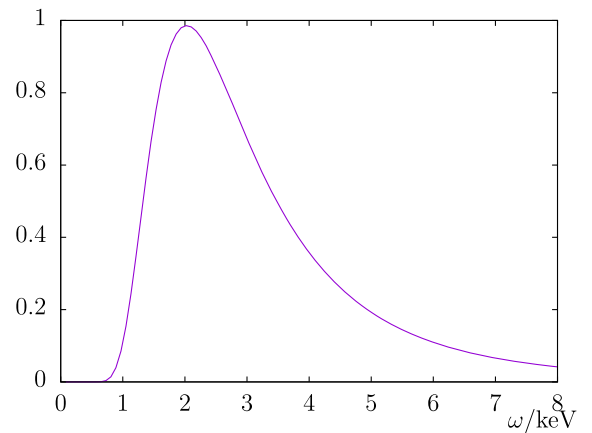


FIG. 1. Plot of the photon spectrum Eq. (11). The power p has been set to 4. The horizontal axis is in keV. Arbitrary normalization.

small, then there could be small ionized patches after recombination. This could be a target for future generation ground-based 21 cm and CMB observations which should be capable of detecting patchy reionization [9–12].

In the energy range under discussion, the soft x-ray sky is dominated by local emission. Observed fluxes are from diffuse gas in the local hot bubble, the Milky Way diffuse hot gas [13] and even the circumgalactic hot gas [14].

Our predicted x-ray is an “all-sky” effect, which could be helpful in suppressing such backgrounds. It is possible that the characteristic form of the “bump” in the spectrum could allow it, in refined observations, to be picked out among these broad backgrounds. Observation of this signal would indicate the existence of explosive events in the very early universe, not detectable in classical astronomy. We urge looking for it.

-
- [1] J. Silk and L. Stodolsky, Bursts from the very early universe, *Phys. Lett. B* **639**, 14 (2006), In the present note we use the parameters as described in the appendix to this earlier paper. However, the parameter t_{now} , for the matter-dominated epoch we need here, $a(t) = (t/t_{\text{now}})^{2/3}$ should, in view of more recent data, be set to $t_{\text{now}} \approx (2.9 \times 10^{17})$ seconds.
 - [2] S. W. Hawking and R. Laflamme, *Phys. Lett. B* **209**, 39 (1988).
 - [3] A. H. Guth, *Phys. Rep.* **333**, 555 (2000).
 - [4] See for example C. P. Korthals Altes, QCD: Some like it hot or why there have been small bangs, in *Gauge Theories*, edited by R. Akhoury *et al.* (World Scientific, Singapore, 1992).
 - [5] L. Stodolsky and J. Silk, Signals of bursts from the very early universe, *Astrophys. J.* (to be published).
 - [6] If one would like nevertheless to pursue the idea of the π^0 channel, the methods of this note lead to a photon distribution at present with a peak in the vicinity of 50 keV.
 - [7] See the x-ray mass attenuation tables of NIST, available at <https://physics.nist.gov/cgi-bin/Xcom/xcom2?Method=> Elem&Output2=Hand We consider only hydrogen, the contribution from helium may be seen to be small.
 - [8] See Fig. 50.1 of the Particle Physics Booklet, 2016. A discussion is at rpp2023-rev-nu-cross-sections.pdf; or in J. A. Formaggio and G. P. Zeller, *Rev. Mod. Phys.* **84**, 1307 (2012).
 - [9] P. M. Keller, B. Nikolic, N. Thyagarajan, C. L. Carilli, G. Bernardi, and N. Charles, *Mon. Not. R. Astron. Soc.* **524**, 583 (2023).
 - [10] H. T. J. Bevens, A. Fialkov, E. d. Acedo, W. J. Handley, S. Singh, and R. Subrahmany, *Nat. Astron.* **6**, 1473 (2022).
 - [11] S. Munshi *et al.*, *Astron. Astrophys.* **681**, A62 (2024).
 - [12] R. A. Monsalve, A. E. E. Rogers, J. D. Bowman, and T. J. Mozdzen, *Astrophys. J.* **847**, 64 (2017).
 - [13] M. Ueda, H. Sugiyama, S. B. Kobayashi, K. Fukushima, N. Y. Yamasaki, and K. Sato, *Publ. Astron. Soc. Jpn.* **74**, 1396 (2022).
 - [14] G. Ponti, X. Zheng, N. Locatelli, S. Bianchi, Y. Zhang, K. Anastasopoulou, J. Comparat, K. Dennerl, and M. Freyber, *Astron. Astrophys.* **674**, A195 (2023).