

Light Black Holes from Light

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(Received 22 May 2025; accepted 24 November 2025; published 26 December 2025)

Álvarez-Domínguez *et al.* [Phys. Rev. Lett. **133**, 041401 (2024)] have suggested that “it is not possible to concentrate enough light to precipitate the formation of an event horizon. We argue that the dissipative quantum effects coming from the self-interaction of light (such as vacuum polarization) are enough to prevent any meaningful buildup of energy that could create a black hole in any realistic scenario,” and “the dissipation of energy via Schwinger effect alone is enough to prevent the formation of kugelblitze with radii ranging from 10^{-29} to 10^8 m.” I agree that, with the very restrictive assumption of Álvarez-Domínguez *et al.* of an adiabatic influx of electromagnetic energy, it is indeed highly implausible that black holes will form mainly from light in our actual Universe, either naturally or by any foreseeable human activity. However, if instead a rapidly changing influx is allowed, there are many idealized theoretical processes (though probably not occurring naturally or possible for humans to engineer) for forming black holes of any size down to near the Planck length (about 10^{-35} m) purely from photons, such as from colliding approximately plane-wave pulses, with only a small fraction of the energy escaping the black hole as scattered light or electron-positron pairs.

DOI: 10.1103/physrevlett.135.261402

Introduction—Álvarez-Domínguez *et al.* [1] (see also Refs. [2–6]) have noted that if one has an adiabatically inflowing gas of photons of mass less than about $10^5 M_\odot$ [which in Planck units is about 1.8×10^{43} , close to $1.6 \times 10^{43} \approx q/(\pi m^2)$ that is one definition, when π is included, of the reciprocal of the critical electric field for the pair production of electrons and positrons of charge magnitude $q = \sqrt{\alpha} \sim \sqrt{1/137}$ and mass $m \approx 4.2 \times 10^{-23}$ in Planck units], when it gets sufficiently compacted that it would form a black hole if the photons interacted purely gravitationally, actually the production of electron-positron pairs will lead to the dissipation of the energy before a black hole can form. Under realistic situations in our Universe, such as their assumption of photons traveling largely in random directions at each location, their conclusion seems to be valid, though I would also expect it to be in practice impossible for black holes to form from light in the present Universe even if there were no pair production.

However, I shall argue that their assumptions (such as assuming “a constant influx f of electromagnetic energy into the sphere” of radius R over an influx time $T \gg R/c$ [1]) and conclusions (taken out of the context of their various assumptions) are not so universally valid as many

of their statements suggest. Instead, there certainly exist idealized situations (initial states with virtually all of the energy in photons) which can form black holes of any mass greater than approximately the minimum mass for a black hole, which is presumably near the Planck mass (about 2.2×10^{-8} kg or $1.1 \times 10^{-38} M_\odot$), with a minimum size near the Planck length (about 1.6×10^{-35} m), nearly 43 orders of magnitude smaller than the lower limit of 10^8 m (not counting black hole radii less than 10^{-29} m that are not disallowed in [1]) proposed by Álvarez-Domínguez *et al.* [1].

To allow the photon energy to collapse into a black hole, the main situation to be avoided is for many different photons to be traveling in significantly different directions at the same location to produce many electron-positron pairs (as would be the case with the significantly restrictive assumption of [1] of a putative influx timescale T much larger than the light crossing time $2R/c$), until the photon energy gets concentrated enough to form a black hole that engulfs the electron-positron pairs and prevents them from escaping. For slowly varying classical electromagnetic fields, one generally needs to keep a combination of the Lorentz invariants $\mathbf{E}^2 - \mathbf{B}^2$ and $\mathbf{E} \cdot \mathbf{B}$ from getting near the Schwinger critical value, say, $\sqrt{\mathbf{E}^2 - \mathbf{B}^2} = \pi m^2/q$ for m and q the mass and charge of the positron, for the rapid production of electron-positron pairs before the energy becomes sufficiently concentrated that it forms a black hole. These invariants are zero for plane electromagnetic waves, and if one keeps the energy in approximate plane waves (the photons traveling in nearly the same direction)

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in each region before that region becomes engulfed by a black hole, significant pair production to disperse the energy can be avoided.

In the limit that one has a single photon, since it will be in a superposition of plane-wave states, each of which will not interact with itself to form electron-positron pairs, the superposition state will also not form pairs. Of course, such a one-photon quantum state also cannot form a black hole. However, if one takes a two-photon state with total center-of-momentum (COM) energy M sufficiently larger than the minimum needed to form a black hole, then their collision can form a black hole, with a cross section that will be of the order of M^2 in Planck units:

$$\hbar = c = G = 4\pi\epsilon_0 = 1. \quad (1)$$

In contrast, the Breit-Wheeler cross section [7,8] for the formation of electron-positron pairs (each particle with the electron mass m and with charge magnitude $q = \sqrt{\alpha}$, using q instead of the more common e for the elementary charge to avoid confusion with the e that I use many times below as the exponential of 1) for $M^2 \sim 1$ is $\approx 16\pi\alpha^2 \ln(M/m)M^{-2} \sim 0.14M^{-2}$, which is less than the cross section $\sim M^2$ to form a black hole for $M > 1$. Thus a pair of photons with COM total energy M sufficiently larger than the Planck energy will be significantly more probable to form a black hole than an electron-positron pair.

Furthermore, since when $M \gg 1$, in the COM frame the wavelength of each of the two highly energetic photons, being of the order of $1/M \ll 1$, is small enough so that in principle one can focus the two photons into a region smaller than the size $\sim M$. Thus the collapse into a black hole can not only be much more probable than pair production, but also can have a probability near unity.

When one considers the case of many photons, each of angular frequency or energy ω much less than the Planck energy (1 in my units here), the wavelength $2\pi/\omega \gg 1$ puts a limit on how small a region the photons can be focused into before gravitational collapse can take over. This limit gives an order-of-magnitude limit $M > 1/\omega$ for the mass and hence linear size of the black hole, and therefore a minimum number of photons $N > M/\omega > 1/\omega^2$ of angular frequency ω that can be focused to form a black hole.

One can now take these N photons, each of angular frequency $\omega \gtrsim 1/\sqrt{N}$, and put them into two truncated approximately parallel plane-wave pulses approaching each other, with characteristic pulse length of the order of L along the direction of propagation (say, along the z axis) and radial size r in the transverse directions (parallel to the x - y plane, so $\sqrt{x^2 + y^2} < r$), obeying the following inequalities:

$$\omega^{-1} \leq L < r/2 < M = N\omega > \sqrt{N} > \omega^{-1}. \quad (2)$$

Although $L < r/2$ violates the adiabaticity assumption of [1], there is no physical obstruction to approximately

saturating these inequalities and still avoiding dissipating the energy into electron-positron pairs that escape the black hole, so for a number of photons N that is not too large, one can form a black hole of mass M not much larger than $\sqrt{N}$ and hence not much larger than the Planck mass.

Colliding antiparallel polarized plane-wave pulses—To give a concrete model for forming a black hole of mass of any mass larger than some lower limit near the Planck mass, I shall put the electromagnetic energy into two colliding pulses (violating the adiabatic influx assumption of [1]) that are respectively functions of the null coordinates $u = t - z$ and $v = t + z$, plane waves parallel to the x - y plane, for radial distances $\sqrt{x^2 + y^2} < r$ from the z axis, but with the energy density dropping off for greater transverse distances so that most of the energy is within the plane-wave region of radius r . To minimize the pair production, I shall take the two pulses to be antiparallel polarized, so that the invariant $\mathbf{E}^2 - \mathbf{B}^2$ is negative everywhere that the pulses overlap, and with nowhere a frame in which there is a pure electric field and no magnetic field:

$$\begin{aligned} E_x &= E_0 \exp\left(-\frac{(t-z)^2}{2L^2}\right) - E_0 \exp\left(-\frac{(t+z)^2}{2L^2}\right), \\ B_y &= E_0 \exp\left(-\frac{(t-z)^2}{2L^2}\right) + E_0 \exp\left(-\frac{(t+z)^2}{2L^2}\right). \end{aligned} \quad (3)$$

This electromagnetic field has the invariants $\mathbf{E} \cdot \mathbf{B} = 0$ and

$$\mathbf{E}^2 - \mathbf{B}^2 = -4E_0^2 \exp\left(-\frac{u^2 + v^2}{2L^2}\right) = -4E_0^2 \exp\left(-\frac{t^2 + z^2}{L^2}\right). \quad (4)$$

These mean that at each location in spacetime there is a frame in which only the magnetic field is nonzero, of magnitude

$$\begin{aligned} B &= \sqrt{\mathbf{B}^2 - \mathbf{E}^2} = 2E_0 \exp\left(-\frac{u^2 + v^2}{4L^2}\right) \\ &= 2E_0 \exp\left(-\frac{t^2 + z^2}{2L^2}\right). \end{aligned} \quad (5)$$

An observer at rest in that frame at that location is moving along the z axis with rapidity $\psi = tz/L^2$ in the COM frame of the two pulses.

Because at each event there is a frame in which the electric field is zero, the locally constant field approximation (LCFA) gives zero pair production for this field. However, it is plausible that derivatives of the electromagnetic field may lead to pair production even though it would not if the field were constant at the value it has at any location. Therefore, I shall show that even for an extremely conservative upper limit for the pair production, black holes

of masses not much larger than the Planck mass can form and engulf almost all possible pair production and prevent the energy from dissipating before gravitational collapse occurs.

The energy density ρ of the two pulses together, for $x^2 + y^2 < r^2$, is

$$\rho = \frac{E_0^2}{4\pi} \left(e^{-u^2/L^2} + e^{-v^2/L^2} \right) = \frac{E_0^2}{4\pi} \left(e^{-(t-z)^2/L^2} + e^{-(t+z)^2/L^2} \right). \quad (6)$$

The integral over the entire z coordinate of this energy density gives a mass M per cross-sectional area A of

$$\frac{M}{A} = \frac{E_0^2 L}{2\sqrt{\pi}}. \quad (7)$$

A conservative sufficient condition for a black hole to form at $t = 0$ (when the two pulses completely overlap, giving a pure magnetic field in the COM frame), using the hoop conjecture [9], is that the energy M in the COM frame inside a sphere of radius $R = \sqrt{x^2 + y^2 + z^2}$ gives a Schwarzschild radius $2M > R$, or $2M/R > 1$. To evaluate this condition, it is helpful to define

$$\begin{aligned} F &\equiv \frac{R}{L}, \\ \epsilon &\equiv E_0^2 L^2, \\ K(F) &\equiv \left(F - \frac{1}{2F} \right) \sqrt{\pi} \operatorname{erf}(F) + e^{-F^2} \\ &= \sqrt{\pi} \left(F - \frac{1}{2F} \right) + O(e^{-F^2}). \end{aligned} \quad (8)$$

I shall assume that $e^{-F^2} \ll 1$ and $\epsilon \ll 1$. Then the integral of the energy density ρ over all $x^2 + y^2 + z^2 < R^2$ at $t = 0$, divided by $R/2$, gives

$$\frac{2M}{R} = \epsilon K(F) \approx \sqrt{\pi} \epsilon \left(F - \frac{1}{2F} \right), \quad (9)$$

which is greater than 1 for

$$F > f(\epsilon) \equiv \frac{1}{2} \left(\frac{1}{\sqrt{\pi} \epsilon} + \sqrt{\frac{1}{\pi \epsilon^2} + 2} \right) \approx \frac{1}{\sqrt{\pi} \epsilon}. \quad (10)$$

Then the minimum mass black hole that can be formed with the two counterpropagating pulses with parameters E_0 and L is approximately

$$M_0 \sim \frac{1}{2} R = \frac{1}{2} L F \sim \frac{L}{2\sqrt{\pi} \epsilon} = \frac{1}{2\sqrt{\pi} E_0^2 L}. \quad (11)$$

A black hole near this minimum mass for each set of the parameters E_0 and L will only occur if the transverse width

of the pulse is not much greater than $R = Lf(E_0^2 L^2)$. Otherwise, if the pulse has field values roughly E_0 extending transversely to $R \gg Lf(E_0^2 L^2)$, the mass of the black hole will be of the order of $M \sim E_0^2 L R^2 \sim (E_0^4 L^2 R^2) M_0 = (\epsilon F)^2 M_0$. The point is that by making the transverse width not much greater than necessary, one can form a black hole of mass $M \sim Lf(E_0^2 L^2)$, which for $\epsilon = E_0^2 L^2 \ll 1$ is $M \sim 1/(E_0^2 L) \sim L/\epsilon$, which can be not too much larger than 1 (the Planck mass). However, so far this analysis ignores the energy escaping from outside the possible formation of a black hole, to which we now turn.

Conservative upper bound on pair production—Now I wish to find conservative upper bounds to the number of electron-positron pairs produced and energy dissipated that can escape the putative black hole, possibly preventing its formation.

For a constant electromagnetic field with the Lorentz invariants $\mathbf{E}^2 - \mathbf{B}^2$ and $\mathbf{E} \cdot \mathbf{B}$, one can define the subsidiary nonnegative invariants,

$$\begin{aligned} E &= \sqrt{\frac{1}{2} \sqrt{(\mathbf{E}^2 - \mathbf{B}^2)^2 + 4(\mathbf{E} \cdot \mathbf{B})^2} + \frac{1}{2} (\mathbf{E}^2 - \mathbf{B}^2)}, \\ B &= \sqrt{\frac{1}{2} \sqrt{(\mathbf{E}^2 - \mathbf{B}^2)^2 + 4(\mathbf{E} \cdot \mathbf{B})^2} - \frac{1}{2} (\mathbf{E}^2 - \mathbf{B}^2)}, \end{aligned} \quad (12)$$

which are the magnitudes of the electric and magnetic fields in any frame in which $\mathbf{E}$ and $\mathbf{B}$ are parallel or zero. In such a constant electromagnetic field, the pair-production rate, per time and per spatial volume, of electrons and positrons of charge magnitude $q = \sqrt{\alpha}$ and mass m is the first term in the infinite series for twice the imaginary part of the one-loop effective action per four-volume [10–15],

$$\mathcal{N} = \frac{(qE)(qB)}{(2\pi)^2} \coth\left(\frac{\pi B}{E}\right) \exp\left(-\frac{\pi m^2}{qE}\right). \quad (13)$$

In the limit that the invariant scalar B is taken to 0, this becomes

$$\mathcal{N} = \frac{q^2 E^2}{4\pi^3} \exp\left(-\frac{\pi m^2}{qE}\right). \quad (14)$$

However, for the colliding antiparallel polarized plane-wave pulses, the electric and magnetic fields given by Eq. (3) give the Lorentz invariant scalar $E = 0$ everywhere, so the LCFA gives $\mathcal{N} = 0$ everywhere, predicting no pair production.

Nevertheless, it seems implausible that there would actually be no pair production even though the LCFA gives $\mathcal{N} = 0$. Therefore, I shall take as a conservative upper limit what one would get from Eq. (14) if one took the maximum value of 1 for the exponential and in the prefactor replaced the invariant E with the invariant B

from Eq. (5), giving an upper limit for the pair-production rate per four-volume of

$$\mathcal{N}_{\max} = \frac{q^2 B^2}{4\pi^3} = \frac{q^2 E_0^2}{\pi^3} e^{-(t^2+z^2)/L^2}. \quad (15)$$

Assuming flat spacetime with no black hole formation, this very conservative upper limit for the pair production rate per four-volume would, when integrated over the entire infinite range of both t and z , give a maximum number of pairs, $N_{\max}$, per transverse area A , of

$$\frac{N_{\max}}{A} = \frac{q^2 E_0^2 L^2}{\pi^2} = \frac{\alpha \epsilon}{\pi^2}, \quad (16)$$

where $\alpha = q^2 \approx 1/137$ is the fine structure constant and where Eq. (8) gives $\epsilon \equiv E_0^2 L^2$ in terms of the maximum electric field magnitude E_0 of each plane-wave Gaussian pulse with length parameter L along the propagation direction $\pm z$.

Taking the photon frequency to be $\omega = 1/L$ and using Eq. (7) gives the number of photons per cross-sectional area as

$$\frac{N_\gamma}{A} = \frac{ML}{A} = \frac{E_0^2 L^2}{2\sqrt{\pi}} = \frac{\epsilon}{2\sqrt{\pi}}, \quad (17)$$

so the very conservative upper limit of the number of pairs produced, divided by the photon number, is

$$\frac{N_{\max}}{N_\gamma} = \frac{2\alpha}{\pi^{3/2}} \approx 0.002\,621. \quad (18)$$

Unless each charged particle can gain more energy than the typical photon energy $\omega = 1/L$, this may already suggest that the pair production has only a small effect on the evolution of the energy in the electromagnetic pulses. However, it is not clear that this is the case, since for a constant electromagnetic field, the individual photon frequency and energy is zero, so the pairs gain an infinite multiple of the individual photon energy. Of course, since the LCFA gives zero pair production for the two colliding antiparallel polarized plane-wave pulses, one might suppose in this case in which only the inhomogeneities in the electromagnetic field can lead to pair production, it might be plausible that the energy of each electron and positron is limited by the effective frequency $1/L$ of the electromagnetic field.

Nevertheless, I shall now show that there are theoretically possible ranges for the E_0 and L parameters so that the pair production outside the black hole region is so greatly exponentially suppressed by the $\exp[-(t^2+z^2)/L^2]$ factor outside the region where the black hole is expected to form that it cannot prevent a black hole from indeed forming.

Consider the formation of a black hole of Schwarzschild radius R such that $e^{-F^2} = e^{-R^2/L^2}$ is very small, so that $1/F = L/R$ is also small but need not be extraordinarily small. At first ignoring the pair production, this black hole will form from the electromagnetic energy inside a cylinder of radius $x^2 + y^2 = r^2 \sim R^2$, energy $\pi r^2 M/A = (\sqrt{\pi}/2) r^2 E_0^2 L$, which equals the black hole mass $M = R/2$ for

$$r \sim R \sim \frac{1}{E_0^2 L} \equiv \frac{L}{\epsilon}, \quad (19)$$

dropping $O(1)$ constants such as π . Within $x^2 + y^2 \lesssim r^2$, the total number of pairs produced outside the black hole region, $t^2 + z^2 \gtrsim R^2 \sim r^2$ will be conservatively bounded above by the transverse area πr^2 multiplying the integral of $\mathcal{N}_{\max} = (q^2 E_0^2 / \pi^3) e^{-(t^2+z^2)/L^2}$ over this outside region, which gives

$$N_{\text{outside}} \lesssim q^2 E_0^2 L^2 R^2 e^{-R^2/L^2} = \alpha \epsilon R^2 e^{-R^2/L^2}. \quad (20)$$

Now a conservative upper bound on the energy per pair is the energy that can be gained in the length $2R$ by the maximum electric field E_0 , which is $2qE_0R$, which gives a very conservative upper bound on the energy of the pairs as

$$\mathcal{E} \lesssim 2qE_0R N_{\text{outside}} \lesssim 2q^3 E_0^3 L^2 R^3 e^{-R^2/L^2}. \quad (21)$$

When using $M \sim 2R \sim 2/(E_0^2 L) \equiv 2L/\epsilon$ from Eq. (19), this leads to a very conservative upper limit on the ratio of the total energy of the pairs to the energy of the black hole as

$$\frac{\mathcal{E}}{M} \lesssim q^3 E_0^3 L^2 R^2 e^{-R^2/L^2} \sim \frac{q^3}{E_0} e^{-R^2/L^2} = \frac{q^3}{E_0} e^{-F^2} \sim \frac{q^3 M}{\sqrt{F}} e^{-F^2}. \quad (22)$$

Now one can show that if $F > \sqrt{\ln(M+3)}$, then $(q^3 M / \sqrt{F}) e^{-F^2} < q^3 \approx 0.000\,623$, which gives a very small conservative upper limit on the fraction of energy going into electron-positron pairs outside the black hole. Obeying this upper limit for $M = M_0 \sim \frac{1}{2} L F > \frac{1}{2} L \sqrt{\ln(M+3)}$ would require $L < 2M / \sqrt{\ln(M+3)}$, which is greater than the Planck length for any black hole greater than the Planck mass, so even if one wants to require that $L > 1$ (which is controversial), there is no theoretical obstruction, under idealized conditions, to converting electromagnetic energy to a black hole not much larger than the Planck size.

In qualitative terms, only a negligible fraction of the relevant energy gets dissipated into electron-positron pairs if energy M gets within a sphere of radius $R \approx 2M$ before there is any significant overlap of the two electromagnetic

pulses, each of length along the z direction of propagation of the order of $L \ll R = FL$. Thus indeed one can produce light black holes from light in such an idealized theoretically possible scenario, even though such a scenario is very unlikely to occur naturally.

Conclusions—Although I agree with the strong suggestion of Álvarez-Domínguez *et al.* [1] that “the formation of black holes solely from electromagnetic radiation is impossible, either by concentrating light in a hypothetical laboratory setting or in naturally occurring astrophysical phenomena” (though I doubt that this conclusion depends significantly on pair production), if instead one allows purely theoretical situations within the known laws of physics (violating the stringent adiabatic influx assumption of [1]), it is in principle possible to concentrate enough light to precipitate the formation of an event horizon. The trick, probably never actually occurring in our Universe either naturally or by human intervention, would be to concentrate the radiation into two plane pulses (each of which separately does not produce pairs) that do not overlap enough to give significant pair production before they have concentrated enough energy close enough to each other to form a black hole that would engulf any pair production that occurs when the two pulses do eventually get close enough together to produce many pairs inside the black hole.

Acknowledgments—I have benefited from communication with Eduardo Martín-Martínez, from insightful comments by Robert Wald on the implausibility of the assumptions of [1], and from referees’ comments. This research was supported by a grant from the Natural Sciences and Engineering Research Council of Canada.

Data availability—No data were created or analyzed in this study.

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