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Peer Review File

Backreaction of stimulated Hawking radiation in an optical analogue

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Version 0:

Reviewer comments:

Referee #1

(Remarks to the Author)
In this article, the authors use a strong laser pulse (pump laser) to induce a change in the refractive index of an optical fiber, creating an analogue black hole horizon. A weaker laser pulse (probe laser) is then used to stimulate analogue Hawking radiation emitted by the analogue black hole, and the Hawking radiation is measured in their experiment. The authors employ the pulse propagation equation to describe the generation of analogue Hawking radiation and experimentally measures the backreaction on the pump laser or the analogue black hole after the emission of analogue Hawking radiation. The measurement results are quite clear and are consistent with theoretical predictions, providing important insights into understanding the Hawking radiation process emitted by real black holes. However, I have the following questions that I hope the author can address:

The first question is about confirmation of Hawking radiation. The author reasonably infers that the negative frequency modes observed (in the co-moving coordinate system) are Hawking radiation based on the theoretical relationship between the frequencies of the emitted radiation and the probe laser. However, the main characteristic of Hawking radiation is thermal radiation, which is not demonstrated here. I believe that without displaying the thermal spectrum characteristics, it cannot be conclusively identified as analogue Hawking radiation. Moreover, since the article focuses on the backreaction of Hawking radiation, demonstrating the radiation spectrum or its impact on the thermal spectrum would be of significant physical relevance.

The second one is about Hamiltonian of Hawking radiation. The Hamiltonian obtained in this article for Hawking radiation is derived from the propagation equation of the laser pulse. Whether there exists the possibility of other forms of propagation equations under approximations? More importantly, does this Hamiltonian have general significance? It is noted that the Hamiltonian for the creation of Hawking radiation was also suggested for other analogous systems such as Bose-Einstein condensation, but it had the different form with that suggested in this article. On the other hand, in analogue black hole experiments, the black hole metric simulated by the physical systems used has the same form (it can also simulate different types of black holes, such as rotating black holes; here "the same" means simulating the same type of black hole), and the motion of Hawking radiation satisfies the Klein-Gordon equation in the curved spacetime. These are in a classical sense, but there should be a correspondence with the quantum mechanical description. What is the connection between the Hamiltonian for Hawking radiation given in this article and the general classical description?

The third one is about the frequency of Hawking radiation. Since the Hawking radiation is stimulated, its frequency is related to that of the probe laser. The calculations in the appendix, such as from (B.5) to (B.6), also reflect this. How should one understand the statement "Even in the limit of zero probe intensity, vacuum fluctuations will still trigger the spontaneous generation of Hawking quanta, …"?

The four one is about experimental results. The experimental signal in Figure 3 of the main text is obtained by subtracting the data with only the pump laser from the data with both the pump and probe lasers. Is the stimulated Hawking radiation embedded in the probe laser, or does the probe laser transform into Hawking radiation? How is it theoretically shown that this difference is Hawking radiation? This is my concern in the first point that whether the Hawking radiation claimed here is thermal. Additionally, can the stimulated Hawking radiation be captured and measured separately?

The fifth one is about an expression in the explanation under Figure 2.The Doppler formula used in Figure 2b seems inconsistent with equation (1). Were the variables v and u written in reverse?

Referee #2

(Remarks to the Author)
A. Summary of the key results

The manuscript presents an experimental and theoretical investigation into the mechanisms that produce Hawking radiation in a fiber-optical analogue of an event horizon, and reports on the observation of its backreaction. The results are explained in terms of a relatively simple wave-mixing process (conjugated cross–phase modulation). Remarkably, this appears to be a fairly generic mechanism if the backreaction (the interplay between the radiation and the analogue of the gravitational field) is bi-quadratic. This is the case in other analogue-gravity systems, such as BECs and photon superfluids, and possibly even in real gravity.

B. Originality and significance: if not novel, please include reference

Over the past decade, numerous analogue-gravity experiments have aimed to detect Hawking radiation. Evidence of this phenomenon has been observed in water tanks and in optical fibers, where highly sensitive spectral measurements in a setup similar to the one described in this manuscript allowed to identify a spectral peak corresponding to stimulated Hawking radiation. Additionally, observations have been made in Bose-Einstein condensates (BECs), where also first signatures of quantum effects have been claimed.
No signatures of backreaction due the Hawking process has been reported so far, not even at the classical level.

Here, the authors provide experimental evidence of stimulated Hawking radiation and claim to have observed its backreaction on a fiber-optical event horizon. This manuscript potentially holds significant interest for the community as it provides a first insight into a fundamental problem that will likely become a prominent research direction in the next generation of analogue gravity experiments. Overall, I greatly appreciate this experiment and I find the measurements and observations strikingly appealing.

C. Data & methodology: validity of approach, quality of data, quality of presentation

The experimental and theoretical approach is valid, as demonstrated by previous studies in this system (see, e.g., [11] and [12]). The manuscript is well-written, and the quality of the data are of high quality.

D. Appropriate use of statistics and treatment of uncertainties

Statistics and treatment of uncertainties are valid for Fig. 3c. For the spectra in Fig. 3b, I suggest including error bars if they represent averages of multiple measurements. In the Experimental Methods section it is stated that "the UV spectrum is scanned for each probe wavelength, taking a total of 3648 measurements within the UV region of 231nmto 235nm, each integrating a total time of approximately 12 hours of continuous measurement", but I didn't understand if the spectra displayed in Fig. 3 and Fig.2-3 of the methods are "single-shot" or averaged. I would ask the authors to clarify this issue.

E. Conclusions: robustness, validity, reliability

I can find robustness and reliability for the experimental results and for the theoretical interpretation. However, in my opinion a number of important issues need to be addressed and clarified to support the main claim. My comments and suggestions are listed below.

F. Suggested improvements: experiments, data for possible revision

1) The observation of the backreaction appears to be the main contribution of the manuscript, as experimental evidence of stimulated Hawking radiation in a similar setup was previously provided in Ref. [9]. In this respect, a primary question is to what extent these results can provide insight into the quantum mechanisms underlying Hawking radiation and its backreaction.

In the experiment, the vacuum fluctuations of the electromagnetic field are replaced with a classical state of coherent amplitude (the probe) to amplify the Hawking signal and facilitate its detection. In this sense, one can explain all the observed phenomena as a classical wave-mixing process, although resolved at the level of single-photon counting.
In a linear system (or at the level of linear dynamics), there is a correspondence between evolution of infinitesimal classical disturbances and quantum fluctuations. As a result, experiments using classical fields, which are technically less challenging, have frequently been employed to gain valuable insights into processes involving quantum noise. Examples of this approach can be found in various areas of physics and have been prominent in the first generation of analogue-gravity experiments (see e.g. the observation of negative-frequency modes [New J Phys. 10, 053015 (2008)] or spontaneous emergence of Hawking-like correlations [Phys. Rev. Lett. 117, 121301 (2016)], to name just a few.

However, such a correspondence does not necessarily extend to the nonlinear level, necessary to account for backreaction effects. In other words, there are likely significant differences between classical and quantum backreaction, and is the latter that would shed light on the information paradox, as correctly stated by the authors. I believe this is an important issue that deserves to be addressed and discussed in the manuscript.

2) At page 4 the authors state that "care must be taken for working in a regime of sufficiently high probe intensity for facilitating detection and sufficiently low intensity for avoiding perturbation, apart from the inevitable backreaction of Hawking radiation we have predicted here."
I think this is a crucial point that deserves further exploration.

Sufficiently strong probes will affect the pump possibly modifying the UV spectral features of stimulated Hawking signal. A compromise must be found by identifying a regime in which the backreaction due to the Hawking radiation exceeds the direct backreaction on the pump (which creates the horizon) induced by the probe.

The authors reported that "the pump is easily perturbed by probes with intensities as low as 10^−2 of the pump". This finding is consistent with measurements in Ref. [9], which demonstrated that with a probe power of approximately 1.5% of the pump peak power, the power of the UV Hawking peak saturates. This saturation indicates that the probe is affecting the pump, as the power of the stimulated signal would be expected to increase linearly with the probe power.

In their experiment, the authors achieved approximately 50% (30%) coupling efficiency for the pump (probe) into the interaction fiber, with average input powers of around 45 mW (4 mW) for the pump (probe). This results in a probe intensity of about 5% of the pump intensity. Given these probe powers, I would expect to be in a regime where the backreaction from the probe on the pump
dominates over the backreaction from the Hawking signal. This is shown in Fig. 3 where the excess in counts around 233.5nm is indeed attributed to the probe perturbing the pump pulse.

I think that this point should be clarified and that additional data showing the spectra as a function of the probe power would be necessary to support the claim and quantify the residual probe contribution to the backreaction in the spectral region around λ_B.

3) The authors showed that the locations of the Hawking and backreaction peaks agree with theoretical predictions and numerical simulations.
However, I didn't find any comment about the expected strength of these signals, particularly of the backreaction peak. In simplistic terms, given a background (order O(1)), and fluctuations of order O(\epsilon) << 1 (relative to the background), I would expect the backreaction of the fluctuations over the background to be of order O(\epsilon^2). Looking at the observed peak counts shown in e.g. in Fig. 3, the backreaction peak seems only slightly lower than the Hawking peak, and in Fig. 2b and 2c of the supplementary material for different probe wavelengths the two peaks even become comparable.

I would ask the authors to comment on this point and add a paragraph discussing the expected spectral amplitudes of both the Hawking signal and the corresponding backreaction signal. How does the experimental amplitudes compare with numerical spectra?
Additionally, it would be useful to include the infrared (IR) portion of the pump and probe spectra
corresponding to the ultraviolet (UV) spectra shown, at least for those probe wavelengths where the UV backreaction peak is more evident.

4) The authors observe some sidebands attributed to the interference between the Hawking and backreaction signals, but this effect is not exhaustively discussed. Do the authors have any insights into their origin? While the UV spectra clearly point to some mixing between the Hawking signal and its backreaction, could such mixing mirror IR interactions between the pump and probe components, or be due to existing spectral fringes in the pump in the IR?
Is the pump experiencing any filamentation phenomenon?

In spite of its conceptual simplicity, the system here studied is extremely complex,
with a plethora of nonlinear optical effects that could come into play. Therefore, even in this case a quantitative comparison with numerical spectra and a quantitative estimation of the expected amplitudes of these peaks would be extremely helpful to clarify their origin.

As a second remark related to this problem, the authors suggest that the observed interference, reproduced also by numerical simulations, is indeed an indication of the coherence between Hawking radiation and the backreaction signal. While I agree with this statement, I wonder if some incoherent signal (apart from spontaneous radiation) may arise in this system, given that the pump and probe are derived from the same laser source, thus inherently exhibiting coherence (unless they are recombined after delays longer than the coherence time).
If this is the case, I do not think that the observed sidebands can be used as an argument supporting the claim of observation of backreaction.

As a minor amendment, I find it more appropriate to refer to this phenomenon as mixing rather than interference. What is observed is indeed the generation of new frequencies produced at the sum/difference or more complex combinations of the original frequencies, whereas simple interference involves waves with the same frequency.

5) I didn't find any reference to the regime in which the analogue-gravity system is operating. I think it is in the regime of

strong dispersion, where the Hawking spectrum would deviate from the ideal Planckian behaviour. Although this fact does not invalidate the relevance of these measurements in any way, as widely discussed in the literature, I believe that a few lines of commentary on these aspects would provide a more complete picture for the non-expert reader.
In particular, could we expect any qualitative differences in the backreaction spectrum between the weak and strong dispersion regime?

6) While, as mentioned earlier, stimulated Hawking radiation can be considered a classical phenomenon, it would be still possible to exploit the same scheme to amplify quantum effects related to the Hawking process (not just its classical strength), provided that appropriate quantum initial states are chosen. For example, a non-classical (squeezed) probe is expected to affect the covariance of the final state and potentially enhance the entanglement generated by the Hawking process (see Ref. [11]). I wonder if a future perspective for this setup might involve the use of squeezed light. Additionally, have the authors considered any further developments in this direction to probe backreaction at the quantum level? If so, it would be beneficial to include a comment on this in the conclusions and draw some perspectives.

7) Page 3: "Now, if H_R governs the transfer of energy from our analogue of the gravitational field, the pump pulse A_1, then it must also describe how A_1 is affected by emitting Hawking radiation."
I agree, but I find this sentence not very clear. I would suggest something like:
"H_R fully encodes the interaction between our analogous gravitational field, the pumping pulse A_1, and the emitted Hawking radiation, describing in particular how this radiation affects A_1."

8) Page 3: "From the outgoing light we remove the pump contribution by dichroics and either detect its IR or UV spectrum." Please provide the pump extinction coefficient.

9) Page 4: "The backreaction of water waves on a draining bathtub vortex mimicking a rotating black hole was investigated as well [38], but so far all these studies were theoretical, whereas here we report on experimental results."

Ref. 38 actually reports also experimental results on the scattering of surface waves with a draining vortex to test the predicted backreaction effects. Moreover, backreaction has been experimentally studied also in photon fluids (Sci. Rep. 6, 23282 (2016)), where the self-steepening effect as as the result of the backreaction on the wave by its own effective metric. In none of the above works is the backreaction induced by Hawking radiation, but I think that the above statement should be modified.

10) Page 4: "In general relativity, the gravitational field is described by the metric tensor, which can be written in a quadratic form in terms of tetrads [39] such that the interaction between field and radiation becomes bi–quadratic, as in our case.

I think this is a very interesting point that should be further discussed. Adding an explanatory paragraph, possibly with additional references, in the Supplementary Material, would enhance the clarity and impact of the manuscript.

G. References: appropriate credit to previous work?
Yes.

H. Clarity and context: lucidity of abstract/summary, appropriateness of abstract, introduction and conclusions

Abstract, introduction and conclusions are clear. Some issues could be further discussed (see above Section F).

Referee #3

(Remarks to the Author)

This article reports on experimental results concerning optical systems in which the analogue of Hawking pair-production from causal horizons can be recreated. This is a fascinating topic, and experimental advances are of great relevance for the community.
In the optical analogues considered in this paper, the causal horizon is created by means of nonlinear interactions between electromagnetic waves, induced by the presence of the medium. More specifically, the presence of a strong pulse of radiation induces a change in the index of refraction other waves experience, modifying their speed of propagation. These modifications can be engineered in such a way that probe waves experience a causal barrier that moves with the strong pulse inducing it. This causal barrier bears some similarities to the horizon surrounding black holes. In particular, a phenomenon similar to that predicted by Hawking, consisting of the spontaneous emission of entangled pairs of quanta with thermal properties, has been predicted to occur. This opens an exciting opportunity to experimentally probe aspects of Hawking radiation in the laboratory. Although the fundamental equations behind this experiment are unrelated to the gravitational field equations—being just Maxwell's equations—one can still learn aspects of Hawking radiation that are universal, in the sense that they do not depend on Einstein's field equations. For other aspects of Hawking radiation which do depend on Einstein's field equations, or a suitable quantum generalization, one can still get useful insights from analogue experiments. One such aspect is analyzed in this article: back-reaction. This is the process by which the black hole loses mass as a result of emitting Hawking radiation. For optical systems, the role of the black hole is played by the strong pulse generating the horizon. It is expected that the pulse loses energy due to the emission of Hawking quanta.

This article reports experimental results on the observation of back-reaction in the context of optical black horizons. This is, to my knowledge, the first of this kind of experiment and, as such, I consider it of potential great relevance. The authors of this article are world experts on the topic, and the experimental platform they have put together looks impressive from a theorist's eyes.

But in spite of the intrinsic interest and potential relevance of this topic, there are a few aspects of this article that need to be further clarified.

1 One aspect of this article that puzzles me is the use of the term “back-reaction”. The authors clearly state in the abstract that the term refers to the process by which the emission of Hawking quanta extracts energy from the black hole. The abstract conveys the impression that the article is about the experimental observation of the energy extraction from the pump field generating the analogue black hole. But this is not what this article reports. Instead, the article reports the energy gained by the pump after probe radiation is injected into the system. The word “stimulated” in the title of the paper makes reference to this fact, but this is, to my eyes, insufficient. I feel there is tension between the abstract and the actual content of this article. I feel it is important that the authors make crystal clear what effect they are observing and how it relates to the process of back-reaction. I understand the authors may feel that they are probing a term in the Hamiltonian which is the one that would cause back-reaction if the system was not stimulated. Still, many could think they are not observing back-reaction, but merely a process related to it. A clear statement about what is being observed in this experiment and its relation to back-reaction seems to be needed.

2 The authors identify the term H_R in the Hamiltonian, written explicitly in Eqn. (3), as the term responsible for both back-reaction and the signal they observe. It is not obvious to understand how H_R could generate the observed signal (or back-reaction), simply because H_R is proportional to the number operator associated with the pump mode, and as such must conserve the number of quanta in the pump. For the probe, this Hamiltonian corresponds to a squeezer. Hence, I would expect H_R to create Hawking pairs in the probe field but to leave unchanged the number of quanta in the pump. Instead, the authors claim H_R would create quanta both in the probe and pump. They justify the claims using an argument based on frequencies, which seems a bit handwaving to my eyes. Further justification seems to be needed.

3 For the pump in numerical simulations (which, as far as I can see, mimics the one used in experiments), what is the value of the Hawking temperature? This can be computed from the properties of the pump profile at the location of the horizon. What is the value of δn for the probes used in the experiments? It would be useful to report these numbers in the supplemental material, since it has been unclear in the past whether the pump used was strong enough to actually generated a horizon (some of the observed signals would be present even if an actual horizon never forms). On the other hand, in Fig. 2, one can see that the UV part of the probe signal is largest around $\lambda \approx 1300$ nm. It decreases for longer and shorter wavelengths. Is this related to the value of the Hawking temperature?

4 I find the argument given in Fig. 1 a bit too heuristic. In gravitational black holes, there is no preferred notion of time and frequency at the location where the Hawking-partners cross the horizon. Consequently, there is no unambiguous sense in which the partners carry negative frequency. Although the simple picture of particles with opposite frequency is quite extended, it may be too heuristic to be included in a journal like this one.

Some of these questions point at the core of this article. Consequently, I cannot recommend it for publication in its present form. But, appreciating the potential of this experiment, I will be happy to reconsider my recommendation once these questions are addressed satisfactorily.

Version 1:

Reviewer comments:

Referee #1

(Remarks to the Author)
I have carefully read the revised manuscript by the authors as well as their responses to all reviewers. The authors' replies are generally thorough and candid. Although a few issues have not been fully resolved, I believe the current version is suitable for publication.

Additionally, there are two minor formal points for the authors' consideration:

1. In Figure 2, ω_h is not defined. This could easily confuse readers. Since the frequencies mentioned in the text (or those after frequency shifting) are all related to the pump or probe light, how is ω_h obtained?

2. The propagation or evolution equation (2) in the main text differs from equation (A.2) provided in the Methods section; it would be better to provide an explanation.

Referee #2

(Remarks to the Author)
The authors have engaged seriously with my comments and addressed most of the points. I appreciated their effort and the new material they added in the paper, in particular the unexpected results on "thermal features" of Hawking radiation in the strong dispersion regime. These results are interesting and potentially important. However, while the authors' interpretation

is reasonable and likely correct, the central claim appears somewhat stronger than what is rigorously supported by the data. In particular, two key issues remain either unresolved or addressed only at a qualitative level.

1) One of these issues is to what extent an experiment probing classical aspects of backreaction can can shed light on more general quantum backreaction mechanisms. (see point 1 of my first report). The authors respond by asserting that i) "in the approximation where the background is classical and fixed, Hawking radiation is a process where the vacuum states creates particle pairs. In the literature, it was not clear how the background reacts in response, in particular when it is quantum. In our paper we solve precisely this: we include the background and show the type of quantum processes involved in producing Hawking radiation" and ii) "Our theory and our experiment are primarily classical, but the theory is easy to quantize. The only problem is the ordering of operators."

This second part of the answer seems to contradict the first, and the resolution of the ambiguities about the order of the operators only partially addresses my point. The experiment is performed entirely with classical coherent states, even though the detection is performed at the single-photon level. Classical–quantum correspondence holds in linear systems because the evolution of quantum fluctuations (including vacuum noise) follows the same equations as infinitesimal classical disturbances. However, this correspondence breaks down in the nonlinear (backreaction) quantum regime, where the dynamics depend not only on mean fields but also on higher-order correlations that encode genuinely quantum effects, such as pair creation and entanglement. While operator ordering specifies how classical expressions are promoted to operators, the resulting dynamics depend on the quantum state through these correlations. The limitation is therefore not theoretical, but experimental: the present setup does not access observables sensitive to these quantum contributions. As a result, the measured backreaction reflects only the classical component of this nonlinear process and provides no direct information about quantum correlations.
While the authors already state that their experiment operates in a classical regime, I suggest they further remark that they are probing only classical aspects of backreaction, and include a brief discussion of which inherently quantum features do not survive in the classical limit. This will help to clarify what the present experiment is actually demonstrating and what instead cannot be probed yet.

2) The second issue concerns possible probe-induced backreaction effects, which may influence or even dominate the observed backreaction (see point 2 of my previous report). The estimated probe power of 1 mW corresponding to about 5% of the pump, lies in a regime where nonlinear interactions between probe and pump are not negligible. The authors identify a probe-induced frequency shift of the NRR, which they correct for. The subsequent removal of the excess signal, together with the emergence of a sideband structure consistent with the theoretical model, suggests that this shift indeed constitutes a significant contribution to the perturbation. However, more general modifications of the nonlinear probe–pump dynamics cannot be ruled out. In particular, the probe may alter the conversion efficiency and phase-matching conditions, perturb the pump evolution, or even generate additional nonlinear signals. All these effects influence spectral amplitudes and shapes, and cannot, in general, be removed by a rigid shift correction. Indeed, even in Fig. 3b the agreement is not uniform across the spectrum, in particular between 233.5nm and 234.2nm, as also noted by the authors.
As said in my previous report, in the absence of independent measurements, specifically, a systematic study of the signal as a function of probe power, it remains difficult to exclude that such effects contribute significantly to the observed backreaction signal.

The authors are, at present, unable to carry out these type of systematic measurements. They explained that such measurements are extremely challenging, as they require very long acquisition times and a high degree of system stability throughout the measurement run, given their sensitivity to long-term drifts that can cause significant variations in the Hawking power. While I can understand these difficulties, the manuscript advances a strong claim, which requires a correspondingly robust and unambiguous evidence. As said, the results are relevant and the proposed interpretation is plausible. However, the current experimental support does not yet suffice to establish the claim conclusively beyond reasonable doubt.
I thus suggest adding a statement along the following lines (e.g. in the conclusions): "In the absence of a systematic study of the signal as a function of probe power that would allow one to unambiguously separate genuine Hawking backreaction from direct probe-induced effects, it remains difficult to exclude the possibility that effects beyond a simple frequency shift contribute to the observed backreaction signal. These may include probe-induced modifications of phase-matching conditions, conversion efficiency, pump dynamics, or additional nonlinear mixing. Such measurements are experimentally very demanding, requiring long acquisition times (up to 12 hours) and stability against slow parameter drifts during the whole measurement run, which are not currently achievable in our setup. Nevertheless, the removal of excess signal near the NRR after applying the spectral shift (Fig. 3b), together with the emergence of a sideband structure consistent with our model, suggests that the frequency shift constitutes a significant contribution to the probe-induced backreaction effects."

I also have a few additional points regarding the new material included in this version.

3) The authors reported a novel interpretation of the sideband asymmetry as a “smoking gun” of backreaction. The interference term between Hawking and backreaction contributions survives at the level of each individual sideband, even after averaging over fluctuations in the propagation phase and can therefore contribute to the observed intensity asymmetry. While this makes the author's interpretation plausible, it does not uniquely establish that the asymmetry originates from backreaction, as similar interference effects may arise from other nonlinear processes. The analytic model provides nontrivial and quantitative predictions for the relative structure of the spectrum, including the scaling of sideband amplitudes, their phase relations, and the dependence on probe power. However, it does not capture absolute spectral amplitudes under

experimental conditions, which are strongly influenced by pump evolution and Raman effects, as acknowledged by the authors. As a result, while the agreement between the observed asymmetry and the analytic predictions is significant and supports the proposed interpretation, it cannot be regarded as an unambiguous signature of backreaction.
I would therefore suggest to replace the "smoking-gun" statement with something like "the agreement between the observed asymmetry and the analytic predictions is significant and supports the proposed interpretation, although alternative nonlinear processes producing similar effects cannot be explicitly ruled out".

4) The observation of an approximately thermal spectrum in a regime of strong dispersion is particularly intriguing and unexpected. In this regime, the standard notion of a well-defined horizon and the associated surface-gravity interpretation of the Hawking temperature are no longer applicable. Instead, the authors argue that the effective temperature is determined by the global temporal profile of the pump pulse, specifically by the exponential decay of its Fourier spectrum. This suggests that thermality may arise from the analytic structure of the background field rather than from local horizon properties, which is a conceptually novel and potentially far-reaching result. At the same time, this increased universality may reduce the specificity of thermality as a distinctive signature of the Hawking process, implying that its observation alone is not sufficient to uniquely identify Hawking radiation, at least within this class of systems. I believe the manuscript would benefit from a brief discussion of this point.

4a) A purely thermal spectrum, would correspond to a loss of information; in a consistent quantum description, this must be avoided through subtle deviations from exact thermality or the presence of correlations. In this context, the persistence of thermality even in the absence of a direct connection to surface gravity may have important implications for future tests of the analogue information paradox in this system. Could the authors comment on that?

5) In Fig. 3c, the authors plot the logarithm of the normalized Hawking radiation counts and the backreaction counts as a function of the frequency ratio. Both datasets have been fitted with linear models, and the corresponding slopes were extracted, yielding a ratio of 1.02. This is really remarkable. However, no error estimates for this ratio are reported. I think that the authors should report also the results of the individual fits for both Hawking and backreaction counts, including their uncertainties, and confidence intervals or error bars for the slope ratio to evaluate its statistical significance.
It would be also nice to see some goodness-of-fit metrics for each linear fit (e.g. residual analysis) to assess how well the linear model describes the data. Providing these details would strengthen the statistical basis of the claim and allow readers to judge the robustness of the observed scaling.

6) The decision to remove the comparison with numerical simulations is understandable in light of the acknowledged quantitative discrepancies and the introduction of the analytic model. However, including these simulations as a Supplementary Information, together with a clear discussion of their limitations, would be valuable. Even if they do not reproduce the amplitudes, the fact that they capture the spectral positions and qualitative features provides useful support for the underlying physical picture, while their failure highlights the role of additional effects such as Raman dynamics in this regime. In my opinion, presenting these results transparently would strengthen the manuscript by clarifying both the validity and the limitations of the current modeling.

Referee #3

(Remarks to the Author)
The revised version of this article clarifies several of the points raised in the previous reports. In their response, the authors acknowledge that the process of backreaction is subtle and have provided useful clarifications. However, I still feel that the claims are not yet fully aligned with the main results. The title and abstract make clear that the primary goal of the article is to provide a theoretical clarification of the origin of the pair-creation process, to understand the resulting backreaction on the pump (the analogue of the black hole), and to support these findings with observational data.

At the theoretical level, the key result (on which much of the analysis rests) is the identification of the term H_R in the Hamiltonian as the one responsible for the creation of Hawking pairs and for the backreaction on the pump field. I remain unconvinced that this interpretation is sufficiently clear or justified.

In particular, the component of H_R associated with the pump (the factor $a_1^\dagger a_1$) commutes with the total number of quanta $N_w := \int dw A_w^\dagger A_w$. Consequently, it cannot change the net number of quanta in the pump field. While H_R may indeed create pairs in the probe field, it does not appear capable of doing so in the pump. At most, it can redistribute quanta across frequencies. This frequency shift is consistent with the observations reported in the article. However, this raises a concern regarding energy conservation: it appears that the final state may contain more energy than the initial state, both in the pump and in the probe. This seems in tension with the standard interpretation of backreaction, as summarized in the abstract “The energy of Hawking radiation must come from the gravitational field around the black hole.”

I would therefore ask the authors to address the following points:

-Improve the clarity in the main text regarding what type of transformation H_R generates. In the current version, although it is said that it creates pairs of probe quanta, its effect on the pump is not stated explicitly enough. This is important for the reader to understand what type of “back reaction” H_R generates.

-Explain how the effects attributed to H_R are compatible with energy conservation, which underlies standard arguments about backreaction. I see two possible scenarios (i) The process induced by H_R, combining pair creation in the probe and frequency redistribution in the pump, does conserve energy (though this is not obvious to me). (ii) The process induced by H_R is not enough by itself, and additional terms in the Hamiltonian must be included to account for the full energy balance.

The authors’ discussion invoking the analogy with the Unruh effect seems to point toward the second possibility. However, I would strongly encourage the authors to state this explicitly, rather than relying on this analogy. In the present context (consistent merely in photons subject to an effective interaction) any additional contributions to the energy balance must arise from other terms in the Hamiltonian. The comparison with the Unruh effect, which involves a complicated process in which a detector experiences an effective friction, may obscure rather than clarify this point, since complications of the physical effects producing this friction are absent in the problem under consideration in this article.
If other terms in the Hamiltonian are indeed necessary to explain the origin of the energy in Hawking radiation, then it would not be accurate to attribute this role solely to H_R, as the current version of the article does. In that case, I would encourage the authors to moderate their claims accordingly.

In my view, the issues raised in my report are central to the paper and should be addressed with full clarity in the main text, as they underpin the entire analysis. That said, I believe the authors are likely on the right track, and a careful clarification of these points would significantly enhance both the clarity and the impact of the work. For this reason, I encourage the authors to revise the manuscript accordingly.

Version 2:

Reviewer comments:

Referee #2

(Remarks to the Author)
The authors have satisfactorily addressed all the points raised in my report and have revised the manuscript accordingly. I am satisfied with the changes made and therefore recommend publication.

Referee #3

(Remarks to the Author)
The authors have appropriately addressed my comments and, in doing so, have substantially clarified the theoretical and conceptual content of this article. I therefore recommend publication.

Referee 1

The referee writes: The measurement results are quite clear and are consistent with theoretical predictions, providing important insights into understanding the Hawking radiation process emitted by real black holes. However, I have the following questions that I hope the author can address:

1. The first question is about confirmation of Hawking radiation. The author reasonably infers that the negative frequency modes observed (in the co-moving coordinate system) are Hawking radiation based on the theoretical relationship between the frequencies of the emitted radiation and the probe laser. However, the main characteristic of Hawking radiation is thermal radiation, which is not demonstrated here. I believe that without displaying the thermal spectrum characteristics, it cannot be conclusively identified as analogue Hawking radiation. Moreover, since the article focuses on the backreaction of Hawking radiation, demonstrating the radiation spectrum or its impact on the thermal spectrum would be of significant physical relevance.

   In the revised manuscript we show now that both the Hawking radiation and the backreaction have a thermal spectrum (in the limit of large frequencies) despite the fact that we operate in a regime of strong dispersion. The dispersion is strong when the difference between group index $n_g = \mathrm{d}(n\omega)/\mathrm{d}\omega$ and phase index n exceeds the nonlinear contribution δn to the index that plays the role of the gravitational potential. In our case $n_g - n \sim 10^{-2}$ and $\delta n \sim 10^{-3}$, so we definitely are in this regime. Referee 2 writes in Point F5: I think it is in the regime of strong dispersion, where the Hawking spectrum would deviate from the ideal Planckian behaviour. Although this fact does not invalidate the relevance of these measurements in any way, as widely discussed in the literature ... . Nevertheless, we show theoretically in Secs. B and D and experimentally in Fig. 3c that the spectrum is thermal, which is a new and unexpected result for the case of strong dispersion. However, there is an important caveat: the Hawking temperature is no longer solely determined by the equivalent of the surface gravity, the logarithmic derivative of δn at the horizon, but by the asymptotics of the Fourier transform of δn. The effective temperature depends on the whole pulse profile and not on δn and its derivative at the horizon. It has been anticipated in the literature that, in the regime of strong dispersion, the Hawking radiation depends on the entire profile; in Sec B we have made this quantitative and precise in the regime of short pump pulses. Interestingly, for a soliton pump and large δn we get the exact same result for the Hawking temperature as in the non–dispersive case. A soliton is a stable nonlinear wave where the nonlinearity balances the dispersion. Astrophysical black holes are classically stable and perhaps some trans–Planckian dispersion softens the singularity to something resembling a soliton. So this intriguing result in optics might ring a bell for future theory in general relativity.

Experimentally, our main difficulty in measuring the Hawking temperature with sufficient precision is the fact that the steepness of the pump pulse at the moment of soliton fission depends on minute details beyond our control and varies from day to day, presumably due to the Raman effect. The steepness when the pump reaches nearly a single cycle dominates the Hawking radiation and the backreaction, but the soliton fission depends on the Raman effect, which results in variations of the Hawking temperature from day to day. Our method to overcome this difficulty is the use of the Negative Resonance Radiation (NRR) as a thermometer. The NRR is essentially Hawking radiation stimulated by the pump itself and therefore the NRR should go with the same exponent as stimulated Hawking radiation. We normalze the measured Hawking intensity with the measured probe intensity to remove variations in the stimulation and to make it proportional to the vacuum value. Then the ratio of the normalized Hawking intensity and the NRR intensity should be a power of the frequency ratios, see Eq. (D.3). The logarithm should lie on a straight line. The data (Fig. 3c) show this to a good approximation. Furthermore, the backreaction should be thermal as well with the same temperature as the Hawking radiation. Figure 3c shows that the corresponding logarithm of the backreaction data also approximates a straight line. As the slopes of the two lines agree within 2% their temperatures can be considered equal. We thus confirm the thermality of the Hawking radiation (with the caveat mentioned) and add a new feature: the thermality of the backreaction with the same temperature.

2. The second one is about Hamiltonian of Hawking radiation. The Hamiltonian obtained in this article for Hawking radiation is derived from the propagation equation of the laser pulse. Whether there exists the possibility of other forms of propagation equations under approximations? More importantly, does this Hamiltonian have general significance? It is noted that the Hamiltonian for the creation of Hawking radiation was also suggested for other analogous systems such as Bose-Einstein condensation, but it had the different form with that suggested in this article. On the other hand, in analogue black hole experiments, the black hole metric simulated by the physical systems used has the same form (it can also simulate different types of black holes, such as rotating black holes; here "the same" means simulating the same type of black hole), and the motion of Hawking radiation satisfies the Klein-Gordon equation in the curved spacetime. These are in a classical sense, but there should be a correspondence with the quantum mechanical description. What is the connection between the Hamiltonian for Hawking radiation given in this article and the general classical description?

   In Methods Sec. E we consider theoretically the Hawking effect in atomic Bose–Einstein condensates and in gravity. We show that in both cases the interaction that gives rise to the effect can be described by exactly the same bi–quadratic form we have in nonlinear fibre optics. Bose–Einstein condensates represent the theoretically best understood and experimentally best demonstrated example of analogues of quantum Hawking radiation. As other analogues are similar our method should be universally applicable. Concerning gravity, we point out that in the tetrad formalism the interaction between the gravitational field and radiation fields is bi–quadratic. We illustrate this with the tetrads of the metric of analogues of gravity. The relationship between our case of fibre optics and this metric (and the corresponding Klein–Gordon equation) was shown in the Supplementary Information of Science **319**, 1367 (2008). Our Hawking Hamiltonian is thus applicable to other analogues and to gravity itself.

3. The third one is about the frequency of Hawking radiation. Since the Hawking radiation is stimulated, its frequency is related to that of the probe laser. The calculations in the appendix, such as from (B.5) to (B.6), also reflect this. How should one understand the statement "Even in the limit of zero probe intensity, vacuum fluctuations will still trigger the spontaneous generation of Hawking quanta, ..."?

   Indeed, the frequency of Hawking radiation is selected by the frequency of the probe pulse. The frequency ω_- we observe in the UV is the one where the comoving frequency ω'_- is the negative ω'_2 of the probe. Each probe corresponds to one spectral line. However, with several probes of different frequencies we can span a spectrum. In our experiment, we use our tuning method (based on the Raman effect in a separate fibre) to cover an as wide spectrum as possible, stretching from the edge of the capture range of the horizon (probe wavelength 1100nm) all the way across the red–shifting side with the pump pulse acting as a black hole to the blue–shifting side (1600nm) where the pump acts as a white hole. As the probe intensity varies with probe wavelength (due to our Raman method) we need to measure it and to normalize the Hawking counts by the count rate of the probe, which depends on the average coupled probe power divided by the probe frequency. The normalized probe intensities correspond to the uniform spectrum of vacuum fluctuations entering the horizon and being converted into the photon pairs of Hawking radiation, but it is stronger (by 10^3) than the vacuum noise and it is triggered, which helps us reduce the noise floor of the measurements. As the stimulated Hawking intensity is proportional to the vacuum Hawking intensity and as long as the proportionality factor, the probe photon number, is well calibrated we can measure the correct Hawking spectrum. Figure 3c illustrates that our calibration is correct, as otherwise we would not get a thermal spectrum.

4. The four one is about experimental results. The experimental signal in Figure 3 of the main text is obtained by subtracting the data with only the pump laser from the data with both the pump and probe lasers. Is the stimulated Hawking radiation embedded in the probe laser, or does the probe laser transform into Hawking radiation? How is it theoretically shown that this difference is Hawking radiation? This is my concern in the first point that whether the Hawking radia-

tion claimed here is thermal. Additionally, can the stimulated Hawking radiation be captured and measured separately?

Part of the probe pulse is transformed into Hawking radiation by the pump. In turn, part of the pump is transformed into the backreaction. Both add to the total electromagnetic field near and in the spectral window of the NRR, but as we argue in Methods Sec. D they are incoherent with respect to the NRR, apart from one sideband that shares exactly the comoving frequency $-\omega_1'$ of the NRR. Their intensities should simply add to the NRR. Subtracting the UV counts with and without the probe should give us our signal. However, in practice, the probe also influences the NRR; it shifts the frequency of the NRR by a relative amount in the order of 10^{-3}. We correct for this by shifting the measured NRR by a frequency we determine empirically by optimization. Previously, in PRL **122**, 010404 (2019) and also in the initial version of this paper, we did not perform such corrections and got partially negative differences between the photon counts with the probe and the counts without. We still see indications of interference between the NRR and the Hawking radiation/ backreaction in one of the sidebands (the one with $-\omega_1'$). But the correction removes most of the artefacts and reveals a new sideband previously hidden in "negative data" with the correct intensity (Fig. 3b). This indicates that our correction method is correct.

The fact that the NRR and the Hawking radiation are incoherent, apart from one sideband, could allow us to remove the lion share of the NRR by interference. This is something we are considering for the future. Experimentally it is not easy, but not impossible. The role of the NRR reminds us on the saying "Yesterday's sensation (the NRR) is today's calibration (for the temperature measurements) and tomorrow's background."

5. The fifth one is about an expression in the explanation under Figure 2.The Doppler formula used in Figure 2b seems inconsistent with equation (1). Were the variables v and u written in reverse?

   We corrected the typo; thank you for paying attention to detail.

Referee 2

The referee writes: Over the past decade, numerous analogue-gravity experiments have aimed to detect Hawking radiation. ... No signatures of backreaction due the Hawking process has been reported so far, not even at the classical level. Here, the authors provide experimental evidence of stimulated Hawking radiation and claim to have observed its backreaction on a fiber-optical event horizon. This manuscript potentially holds significant interest for the community as it provides a first insight into a fundamental problem that will likely become a prominent research direction in the next generation of analogue gravity experiments. Overall, I greatly appreciate this experiment and I find the measurements and observations strikingly appealing. Then the referee asks a series of penetrating, good questions:

D Statistics and treatment of uncertainties are valid for Fig. 3c. For the spectra in Fig. 3b, I suggest including error bars if they represent averages of multiple measurements. In the Experimental Methods section it is stated that "the UV spectrum is scanned for each probe wavelength, taking a total of 3648 measurements within the UV region of 231nmto 235nm, each integrating a total time of approximately 12 hours of continuous measurement", but I didn't understand if the spectra displayed in Fig. 3 and Fig.2-3 of the methods are "single-shot" or averaged. I would ask the authors to clarify this issue.

The photon fluxes (counts per second) are based on averages over much longer times such that in the data plots (Figs. 3, D1 and D2) the statistical errors are smaller than the size of the data points; we accumulate enough statistics such that systematic variations and the noise background are more significant. In Fig. 3c the deviations of the data points from the theory lines are predominantly due to systematic errors. There we use a simple model [Eq. (D3)] solely based on the exponent of the NRR and the Hawking radiation/ backreaction [Eq. (D2)] and neglecting the prefactors that would come from the actual wave envelopes. Such systematic deviations are not well–characterized by error bars. Instead, we indicate them by connecting the data points with lines such that their systematic movement becomes visible.

E I can find robustness and reliability for the experimental results and for the theoretical interpretation. However, in my opinion a number of important issues need to be addressed and clarified to support the main claim. My comments and suggestions are listed below.

F 1. The observation of the backreaction appears to be the main contribution of the manuscript, as experimental evidence of stimulated Hawking radiation in a similar setup was previously provided in Ref. [9]. In this respect, a primary question is to what extent these results can provide insight into the quantum mechanisms underlying Hawking radiation and its backreaction.

in the approximation where the background is classical and fixed, Hawking radiation is a process where the vacuum states creates particle pairs. In the literature, it was not clear how the background reacts in response, in particular when it is quantum. In our paper we solve precisely this: we include thße background and show the type of quantum processes involved in producing Hawking radiation. We believe this mechanism is general for all bi-quadratic theories, including Bose-Einstein condensates and even gravity itself and underpin this in Methods Sec. E.

Our theory and our experiment are primarily classical, but the theory is easy to quantize. The only problem is the ordering of operators. In the Hawking Hamiltonian $\propto \widehat{a}_1^\dagger \widehat{a}_1 (\widehat{a}_2^{\dagger 2} + \widehat{a}_2^2)$ the order of operators is not an issue for the probe (described by the $\widehat{a}_2$ and $\widehat{a}_2^\dagger$ operators) but it is for the pump. If we would use symmetric ordering and replace $\widehat{a}_1^\dagger \widehat{a}_1$ by $\frac{1}{2}(\widehat{a}_1 \widehat{a}_1^\dagger + \widehat{a}_1^\dagger \widehat{a}_1) = \widehat{a}_1^\dagger \widehat{a}_1 + \frac{1}{2}$ for a single pump mode we would get an infinite amount of Hawking radiation generated by a vacuum pump, which is clearly unphysical. Therefore we use normal ordering as we state now in the paper.

2. Sufficiently strong probes will affect the pump possibly modifying the UV spectral features of stimulated Hawking signal. A compromise must be found by identifying a regime in which the backreaction due to the Hawking radiation exceeds the direct backreaction on the pump (which creates the horizon) induced by the probe.

   In their experiment, the authors achieved approximately 50% (30%) coupling efficiency for the pump (probe) into the interaction fiber, with average input powers of around 45 mW (4 mW) for the pump (probe). This results in a probe intensity of about 5% of the pump intensity. Given these probe powers, I would expect to be in a regime where the backreaction from the probe on the pump dominates over the backreaction from the Hawking signal. This is shown in Fig. 3 where the excess in counts around 233.5nm is indeed attributed to the probe perturbing the pump pulse.

   We measured the average coupled probe power: it is about 1mW (details in Sec. D). The probe causes a systematic frequency shift of the pump (in the order of 10^{-3} of the carrier frequency) that results in a frequency shift of the NRR. In the data analysis, we correct for this shift by not only taking the difference between the counts with and without probe, but by moving the NRR spectrum by an amount we obtain by optimization, see Sec. D. When we have done this, the excess is gone and the data reveal (Fig. 3b) an additional sideband with an amplitude we can predict from data analysis on the left and including the Hawking peak alone. This indicates that our correction procedure is indeed correct. Some discrepancy with theory still remains around the location of the first right sideband of the Hawking radiation (Fig. 3b) as this sideband interferes with the NRR — more details in point 4.

I think ... that additional data showing the spectra as a function of the probe power would be necessary to support the claim ... .

We tried to measure the dependance of the Hawking and backreaction intensity on the probe power, but were not successful. Such measurements require that the set-up works at peak performance such that we can take data over 12 hours continuously. This takes months in preparation. Then we need to lower the probe power in steps and just take data at the Hawking peak for each step. As minute day–to–day variations in the pump may cause significant variations in the Hawking power such measurements must be done within a day. The main difference between the experiment we report in this paper and our previous PRL **122**, 010404 (2019) are some technical improvements but mainly the ability to take data over long periods of time and keep the system stable, which takes exceptional experimental skill. Lorenzo Procopio, who had operated the experiment, had left for Paderborn in Germany and so far nobody of the same calibre did replace him at the Weizmann lab. Due to war and illness he was not able to do the measurements as we had planned (see the letter to the editor and the referees). However, we do have indirect evidence for the power dependance, as we explain in the next point.

3. The authors showed that the locations of the Hawking and backreaction peaks agree with theoretical predictions and numerical simulations. However, I didn't find any comment about the expected strength of these signals, particularly of the backreaction peak. In simplistic terms, given a background (order O(1)), and fluctuations of order $O(\epsilon) \ll 1$ (relative to the background), I would expect the backreaction of the fluctuations over the background to be of order $O(\epsilon^2)$. Looking at the observed peak counts shown in e.g. in Fig. 3, the backreaction peak seems only slightly lower than the Hawking peak, and in Fig. 2b and 2c of the supplementary material for different probe wavelengths the two peaks even become comparable.

   In Methods Sec. B we calculate the Hawking and backreaction field with an analytical theory. We find that both are exponentially suppressed. In optics terms, this suppression comes from the lack of phase matching. Phase matching depends on two conditions, energy and momentum conservation, which in the moving frame translates into the conservation of the comoving and the laboratory frequency. While the comoving frequencies ω' are matched, the laboratory frequencies ω are not. To generate a signal, the mismatch in the carrier frequencies must be compensated by the Fourier wings of the envelope, and they are exponentially small. Now, the exponent of the backreaction is larger than the exponent of the Hawking radiation. The backreaction goes with the square of the probe power, as the referee has pointed out, but its coefficient is significantly larger than the coefficient of Hawking radiation that is linear in the probe power. We have run our experiment such that the two are comparable.

Experimental evidence for the quadratic power dependance of the backreaction is contained in Fig. 3c where we plot the logarithm of the thermality relation, Eq. (D.3). There we need to divide by the square of the varying probe powers in order to get a good fit with a straight line, see the discussion in Sec. D. The probe power varies naturally (0.66 mW, 0.99 mW, 1.35 mW, 1.2 mW, 1.2 mW, 0.81 mW) resulting from controlled variations in the initial probe intensity in order to achieve a target wavelength by Raman shifting in the probe preparation fibre, and then due to .nonlinear wave propagation. These natural variations test the dependance of both the Hawking and backreaction on the probe power. Direct measurements would be better, but we still have sufficient indirect experimental evidence for the quadratic power law of the backreaction.

How do the experimental amplitudes compare with numerical spectra?

We did many computer simulations of the pump and probe propagation. While we could always reproduce the spectral positions of the Hawking radiation and backreaction, the amplitudes were wrong by orders of magniture. We discovered that small variations in the pump have an exponential effect, which is also consistent with our experiment where we measured significant variations in the NRR (by a factor of 3) from one day to the next without having made any visible changes in the set–up. We believe that this is due to the Raman effect influencing where the soliton fission occurs that generates most of the UV signal we see. We know from the location of the horizon and from direct measurements after the fibre that a few mm of fibre are enough for 8fs pulses to get Raman–shifted by several 100nm. Modeling the Kerr effect for near–single–cycle pulses is possible as the Kerr effect is almost instantaneous (its time scale is the time it takes for light to cross the Angstrom of an atom). But the Raman effect involves molecular vibrations of a much longer time scale. The usual model of the Raman dissipative nonlinearity works well for standard 100fs pulses, but fails in our extreme case. So far we can only do simulations without the Raman effect where an essential part of the physics of our system is missing. We decided to remove the discussion of numerical simulations from our paper altogether, although we have done many of those.

Additionally, it would be useful to include the infrared (IR) portion of the pump and probe spectra corresponding to the ultraviolet (UV) spectra shown, at least for those probe wavelengths where the UV backreaction peak is more evident.

We have taken those spectra, but did not see (Fig. 1 of this response to the referees) any important differences to our previously published spectra [PRL **122**, 010404 (2019)]. Although the new measurements are of better quality, we would prefer not to include them in our paper as they do not convey new information nor are important for explaining other, new results (unlike the dispersion Fig. 2). We also decided not to show the former Fig. 3c, the relative locations of λ_{H}, λ_{B} versus λ_{NRR}) which at the time of submission was the only evidence we had for correctly identifying the backreaction. Now we have much better, much more detailed, quantitative evidence. We state in the text that the measured wavelengths λ_{B} agree with the predicted ones, but we remove the figure (and also the comparison with numerics) for saving space. We plan to write up a comprehensive paper after our article has appeared where we would show such figures.

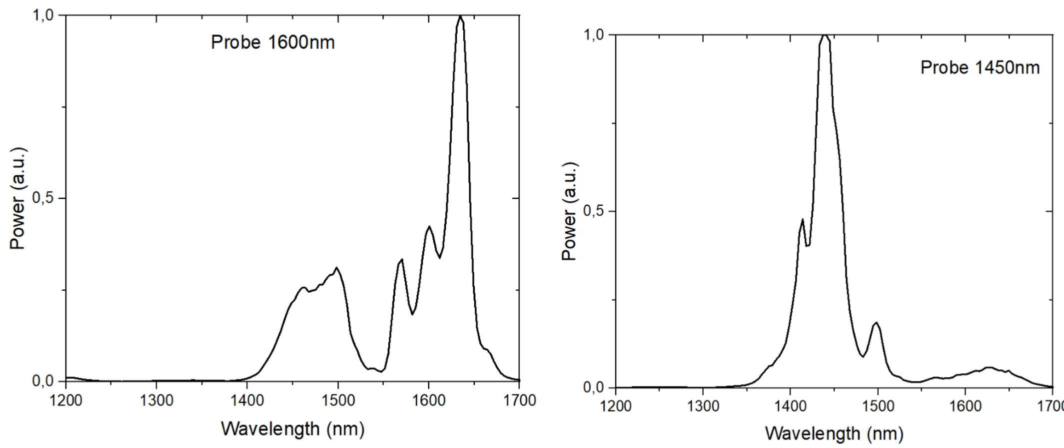

Figure 1: Frequency shifting. The left figure shows the IR spectrum for a probe that has experienced partial blueshifting, the right figure shows the IR spectrum of redshifting. The structures seen in the blueshifting spectrum originate from multiple interactions of the probe with the pump [PRA 94, 033811 (2016)].

4. The authors observe some sidebands attributed to the interference between the Hawking and backreaction signals, but this effect is not exhaustively discussed. Do the authors have any insights into their origin? While the UV spectra clearly point to some mixing between the Hawking signal and its backreaction, could such mixing mirror IR interactions between the pump and probe components, or be due to existing spectral fringes in the pump in the IR? Is the pump experiencing any filamentation phenomenon?

   The referee is right, the sidebands are due to a mixing of the pump and the probe. They do not fit spectral fringes of the pump and we have no indications of filamentation either.

   The most likely explanation of the sidebands – and an explanation that quantitatively agrees with our measurements — is frequency modulation. The Kerr nonlinearity does not distinguish between the pump a_1 and the probe a_2 such that the nonlinear δn is generated by the total light field $a_1 + a_2$. We get $\delta n \propto a_1^* a_1 + a_1^* a_2 + a_2^* a_1$ for $|a_2| \ll |a_1|$. The interference term $a_1^* a_2 + a_2^* a_1$ oscillates with the frequency difference of the pump and the probe, both with respect to comoving and laboratory frequencies. This frequency modulation of δn creates sidebands at integer multiples $m\delta'$ where δ' is the comoving frequency difference. Usually, a frequency modulation of strength χ generates sidebands with amplitudes given by the Fourier coefficients of $\exp[\mathrm{i}2\chi \sin(\delta'\zeta)]$. These are Bessel functions[1] $J_m(2\chi) \sim \chi^m/m!$ for $|\chi| \ll 1$. However, pouring over our data we discovered that in our case the sideband amplitudes go with the pure power law X^m — without the factorial — for all modulation strengths. Because of the missing factorial they were so well visible in our spectra. A power law is what one would naively expect: if the modulation creates the first sideband with amplitude X then the second sideband is made from the first with X as well and so goes with X^2 etc. So where does the factorial come from and why don't we have it?

In the standard regime, the frequency–modulated wave is still a single mode. Sidebands are excited with amplitude χ from each other, but those excitations are statistically indistinguishable. As the number of permutations of m distinguishable processes is $m!$ we need to divide χ^m by $m!$. In our regime of near–single–cycle pump pulses, all the sidebands are modes coupled all with each other by the modulation with equal strength χ. As those modes are distinguishable we must not divide by $m!$. To back up this heuristic reasoning, we derived an exact solution of the infinite set of coupled–mode equations (Sec. C) that gives an exact power law $\propto (-\mathrm{i}X)^{|m|}$ that agrees well with the data and a formula how X relates to χ.

But there is a problem. The sideband $m = -1$ to the left of the Hawking peak ($m = 0$) coincides with the main peak of the backreaction. In fact, all the bands of the Hawking radiation align with the bands of the backreaction. So how can we tell whether we have measured a sideband of stimulated Hawking radiation or the backreaction? The answer is that the bands are no longer symmetric, the amplitude right of and including the Hawking peak ($m \geq 0$) is proportional to the Hawking amplitude minus $\mathrm{i}X$ times the backreaction amplitude, whereas on the left ($m < 0$) we have the Hawking amplitude minus the backreaction amplitude divided by $\mathrm{i}X$. The bands are all generated coherently, but in our experiment we average over a modulation cycle of $2\pi/\delta'$ as the propagation time varies and the probe experiences a large number of such cycles (10^3 over 1mm of propagation). So despite all bands being created coherently, their coherences average out and their intensities just add up. As the backreaction appears in the imaginary part of the total amplitude the Hawking and backreaction intensities also just add up. The resulting asymmetry of the sidebands is the "smoking gun" of

[1] The astronomer Friedrich Wilhelm Bessel discovered the Bessel functions by studying periodic frequency modulations in celestial mechanics.

the backreaction.

But there is another problem. The sideband immediately to the right of the Hawking peak ($m = +1$) has the same comoving frequency as the NRR. It interferes with the field of the NRR that appears to have a complicated phase structure, and this interference does not average out. The sideband with the strongest asymmetry becomes completely useless for retrieving the backreaction (but it might become a future tool for exploring the NRR). In our data analysis, we therefore ignore the region of $m > 0$ and focus exclusively on $m \leq 0$. There we still have an asymmetry: between the Hawking peak ($m = 0$) and the peaks left to it ($m < 0$). Figure 3b shows that by fitting exclusively on the left side of the spectrum we can still retrieve the sideband $m = +2$ right from the NRR interference (Fig. 3b) This sideband is lifted from the negative dip in the difference between the counts with and without the probe by our NRR correction procedure, see point 2. Its correct prediction testifies to the consistency of the data correction, the right physical understanding of the sidebands, and the high quality of the data.

In spite of its conceptual simplicity, the system here studied is extremely complex, with a plethora of nonlinear optical effects that could come into play. Therefore, even in this case a quantitative comparison with numerical spectra and a quantitative estimation of the expected amplitudes of these peaks would be extremely helpful to clarify their origin.

We are aware of the complexities and we have experienced them firsthand in our unsuccessful attempts of precise numerical simulations. It is ironic that an analytical theory is more accurate than computer simulations. And we find it astonishing how well such a simple theory fits reality, despite all complexities. It reminds us on Wigner's famous phrase from his essay *The Unreasonable Effectiveness of Mathematics in the Natural Sciences*: it is "a gift we neither understand nor deserve."

5. I didn't find any reference to the regime in which the analogue-gravity system is operating. I think it is in the regime of strong dispersion, where the Hawking spectrum would deviate from the ideal Planckian behaviour. Although this fact does not invalidate the relevance of these measurements in any way, as widely discussed in the literature, I believe that a few lines of commentary on these aspects would provide a more complete picture for the non-expert reader.

   The referee is right, we are in the regime of strong dispersion. This is the regime where the difference between group and phase index is larger than the nonlinear δn that is analogous to the gravitational potential. In this regime, a Planck spectrum of Hawking radiation is not expected. However, we are also in the short–pulse regime where the envelope of the pump pulse is significantly shorter than the wavelength of the probe. In this regime, the Hawking effect simplifies even when the dispersion is strong and we get an approximate Planck spectrum (see Methods Sec. B). However, the Hawking temperature is no longer solely determined by the analogue of the surface gravity, the logarithmic derivative of δn at the horizon. When the probe wavelength is longer than the pump pulse, there simply is no longer a well–defined horizon, as the entire pulse is immersed in less than one cycle of the probe. The entire pulse contributes to the Hawking temperature. Mathematically, $k_B T$ is given by $\hbar/(2\pi\tau_0)$ where τ_0 is the exponent of the Fourier transform of the pump intensity profile in the limit of large laboratory frequencies or, equivalently, the lowest pole on the upper half complex plane of the pump intensity as a function of retarded time τ. The backreaction also follows the exponential tail of a Planck spectrum with the same temperature. We confirm by combining all of our measurements the thermality of both the Hawking radiation and the backreaction (Fig. 3c). How we do the analysis is explained in our answer to Point 1 of Referee 1 and in Methods Sec. D.

6. While, as mentioned earlier, stimulated Hawking radiation can be considered a classical phenomenon, it would be still possible to exploit the same scheme to amplify quantum effects related to the Hawking process (not just its classical strength), provided that appropriate quantum initial states are chosen. For example, a non-classical (squeezed) probe is expected to affect the covariance of the final state and potentially enhance the entanglement generated by the Hawking process (see Ref. [11]). I wonder if a future perspective for this setup might involve the use of squeezed light. Additionally, have the authors considered any further developments in this direction to probe backreaction at the quantum level? If so, it would be beneficial to include a comment on this in the conclusions and draw some perspectives.

   Yes, so far, we have explored the optical analogue of the Hawking effect with classical light. We plan to upgrade our experimental set–up and investigate options for going into the quantum regime of Hawking radiation. The experimental results of our paper show that there is very little noise in the UV window of stimulated Hawking radiation. We therefore have the chance of going all the way to the true quantum level of the Hawking effect, but there are some technical obstacles we need to overcome. The main bottleneck of our experiment is our UV detection. We spectrally resolve the light with a prison we can rotate with a piezo motor, send it through a narrow slit and detect it with a photomultiplier tube. This is a wasteful process where only a small portion of the light is detected. While currently our count rate of stimulated Hawking radiation lies in the order of 10^3 per second, the rate of spontaneous Hawking radiation would be 1 per second. We therefore plan to explore options for parallel detection that would give us higher count rates. Stimulation has another important advantage: it provides a trigger. We exploit this for reducing noise by taking data when the trigger is on and comparing it with data when the rigger is off. One could take advantage of the pair creation in spontaneous Hawking radiation and select for coincidences. However, while one of the two photons is in the UV the other is in the infrared around 1.6μm where the noise from other nonlinear process is not negligible. We plan to explore an alternative where we use the creation of photon pairs by four–wave mixing. This process naturally occurs in our pulses. David Bermudez and his team have experimentally shown that such single photons can undergo the typical redshifting at the analogue of the event horizon [under review in Nature Communications]. In our set–up we can use one photon for stimulating Hawking radiation and the other as a trigger for reducing noise. This would be a feasible step towards observing full quantum Hawking radiation in the laboratory. We briefly mention some of this in our revised paper.

7. Page 3: "Now, if H_R governs the transfer of energy from our analogue of the gravitational field, the pump pulse A_1, then it must also describe how A_1 is affected by emitting Hawking radiation."

   I agree, but I find this sentence not very clear. I would suggest something like: "H_R fully encodes the interaction between our analogous gravitational field, the pumping pulse A_1, and the emitted Hawking radiation, describing in particular how this radiation affects A_1."

   Thank you, we changed the wording.

8. Page 3: "From the outgoing light we remove the pump contribution by dichroics and either detect its IR or UV spectrum." Please provide the pump extinction coefficient.

   Our pump pulses are about eight orders of magnitude stronger than our UV signals, and they create a dispersive wave in the visible to near IR region. Despite the spectral separation between the UV signals and this supercontinuum, without spectral filtering, our monochromator generates stray visible light that floods our measurement with count rates of about 108Hz/nm. We verify the source of this noise by filtering out the UV signal at the PMT input with a coloured glass bandpass filter (Thorlabs FGB37M). Our dichroic filters reduce this background by two orders of magnitude, with only 10% loss in the deep UV. An additional bandpass filter (Edmund Optics 228nm central wavelength, 25nm FWHM) is used to remove the remaining stray light (with an optical density of over 4), at the expense of a 90% reduced transmission. We achieve a background noise level of about 100Hz/nm, while keeping the signal flux at about 10Hz/nm.

   As requested, we briefly mention this in the revised text.

9. Page 4: "The backreaction of water waves on a draining bathtub vortex mimicking a rotating black hole was investigated as well [38], but so far all these studies were theoretical, whereas here we report on experimental results."

Ref. 38 actually reports also experimental results on the scattering of surface waves with a draining vortex to test the predicted backreaction effects. Moreover, backreaction has been experimentally studied also in photon fluids (Sci. Rep. 6, 23282 (2016)), where the self-steepening effect as the result of the backreaction on the wave by its own effective metric.

In none of the above works is the backreaction induced by Hawking radiation, but I think that the above statement should be modified.

We agree and have modified this in the text.

10. Page 4: "In general relativity, the gravitational field is described by the metric tensor, which can be written in a quadratic form in terms of tetrads [39] such that the interaction between field and radiation becomes bi–quadratic, as in our case." I think this is a very interesting point that should be further discussed. Adding an explanatory paragraph, possibly with additional references, in the Supplementary Material, would enhance the clarity and impact of the manuscript.

    In Methods Sec. E we explain the tetrad formalism and how it gives rise to the same bi–quadratic interaction between gravity and radiation fields and hence the same Hawking Hamiltonian as in our paper.

Referee 3

The referee writes: This article reports on experimental results concerning optical systems in which the analogue of Hawking pair-production from causal horizons can be recreated. This is a fascinating topic, and experimental advances are of great relevance for the community. ...

This article reports experimental results on the observation of back-reaction in the context of optical black horizons. This is, to my knowledge, the first of this kind of experiment and, as such, I consider it of potential great relevance. The authors of this article are world experts on the topic, and the experimental platform they have put together looks impressive from a theorist's eyes.

But in spite of the intrinsic interest and potential relevance of this topic, there are a few aspects of this article that need to be further clarified.

1. One aspect of this article that puzzles me is the use of the term "back-reaction". The authors clearly state in the abstract that the term refers to the process by which the emission of Hawking quanta extracts energy from the black hole. The abstract conveys the impression that the article is about the experimental observation of the energy extraction from the pump field generating the analogue black hole. But this is not what this article reports. Instead, the article reports the energy gained by the pump after probe radiation is injected into the system. The word "stimulated" in the title of the paper makes reference to this fact, but this is, to my eyes, insufficient. I feel there is tension between the abstract and the actual content of this article. I feel it is important that the authors make crystal clear what effect they are observing and how it relates to the process of back-reaction. I understand the authors may feel that they are probing a term in the Hamiltonian which is the one that would cause back-reaction if the system was not stimulated. Still, many could think they are not observing back-reaction, but merely a process related to it. A clear statement about what is being observed in this experiment and its relation to back-reaction seems to be needed.

   The referee asks the right questions and exposes a paradox hidden in our paper. If the backreaction of Hawking radiation onto the gravitational field ultimately leads to an energy loss, how is it possible that it first appears as an energy gain? And what does our paper actually mean by the term backreaction? Are we not just probing the interface between the analogue of the graviational field (the pump) and the radiation field (the probe)?

   In our paper this interface is given by the Hawking Radiation Hamiltonian $H_{\mathrm{R}} \propto \widehat{a}_1^\dagger \widehat{a}_1 (\widehat{a}_2^{2\dagger} + \widehat{a}^2)$. It is important to understand the $\widehat{a}_1$ and $\widehat{a}_2$ as local quantum fields (each as the positive–frequency component of a bosonic quantum field evaluated at some position z and time t) and not as annihilation operators nor the corresponding $\widehat{a}_1^\dagger$ and $\widehat{a}_2^\dagger$ as creation operators — despite the notation. The fields $\widehat{a}$ can be decomposed into modes, $\widehat{a} = \sum_k \widehat{b}_k A_k(z,t)$, and now the $\widehat{b}_k$ are annihilation operators and the $\widehat{b}_k^\dagger$ creation operators in $\widehat{a}^\dagger = \sum_k \widehat{b}_k^\dagger A_k^*(z,t)$. The misunderstanding of the $\widehat{a}_1$ and $\widehat{a}_2$ and their Hermitian conjugates as annihilation and creation operators seems to be the core of the problem with understanding our paper — more on this in point 2. We hope to have explained this better in the revised paper.

But the referee exposes a perfectly valid paradox, and we are grateful for that and address it in our revised paper. It reminds us on the paradox of accelerated detectors from the perspective of Minkowski space, see Unruh and Wald, PRD **29**, 1047 (1984). Unruh discovered the Unruh effect by trying to find an explanation of Hawking radiation based on a simpler and physically more transparent system than the black hole. This system is the accelerated Unruh–DeWitt detector in the Minkowski vacuum. The detector perceives the vacuum as thermal radiation. This radiation corresponds to the Hawking radiation of the black hole. In PRD **29**, 1047 (1984) Unruh and Wald ask the question of how the detection of quanta from the vacuum appears from the perspective of Minkowski space. Detection is a real physical process and hence in GR it must be frame–independent. So how does a Minkowski observer see what an Unruh–DeWitt detector does? The detector absorbs quanta from empty space, from the quantum vacuum, so how does this absorption appear in the space it is absorbed from? The short answer is: as emission. Each detection event appears as the emission of a pair of quantum particles in Minkowski space. One may view this as the beginning of the backreaction in the Unruh effect. It is caused by the primary effect, the Unruh–DeWitt detection. But it is not the end of the story. The recoil of the particle emission acts on the accelerated detector. Many of such recoils averaged cause friction, slowing down the acceleration. This friction by Unruh–Dewitt detection corresponds in the black hole to its energy loss by evaporation.

In our case, the Hamiltonian H_R creates particle pairs of the probe. In each pair, the partners have to be of opposite comoving frequency ω_2' and $-\omega_2'$ due to energy conservation in the comoving frame, assuming a stationary pump in this frame. From the many modes of the probe such pairs are chosen. Now, from the perspective of the pump, two bundles of new quanta are generated in principle, one with negative comoving frequencies $\omega_1' - 2\omega_2'$ (negative as $\omega_2' > \omega_1'$) and one with positive comoving frequency $\omega_1' + 2\omega_2'$. In practice, the positive comoving frequency lies above the dispersion curve (Fig. 2a) and so cannot materialize as a propagating wave. We think the bundles of negative ω' quanta correspond in the Unruh effect to the particles created in Minkowski space due to Unruh–DeWitt detection. It is only the first step leading towards the friction of the accelerated detector or the evaporation of the black hole, or in our case, the energy loss of the pump that is the result of many such events and the reaction to them.

The eventual energy loss is extremely difficult to observe. For measuring the minute difference between two large energies — of the field after and before the emission of Hawking radiation — one would need an incredible precision. In our case, each pump pulse consists of 5×10^{23} photons, whereas about 10^{-8} Hawking photons are spontaneously emitted (and 10^{-5} stimulated) in each spectral bin of our detection apparatus (while our laser makes 80 million pulses per second). The vast difference between the number of pump and Hawking photons makes direct measurements of the energy transfer impossible.

Finally we note that our Hawking Hamiltonian is a new result. The community – us included — believed that Hawking radiation is a complicated, cascaded process. The fact it is actually simple came as a complete surprise. We calculated the backreaction of this Hamiltonian onto the pump, identified its spectral location, adapted and improved the experiment, and found it. Then it took a year of improvements for being able to take data of the quality we report here.

2. The authors identify the term H_R in the Hamiltonian, written explicitly in Eqn. (3), as the term responsible for both back-reaction and the signal they observe. It is not obvious to understand how H_R could generate the observed signal (or back-reaction), simply because H_R is proportional to the number operator associated with the pump mode, and as such must conserve the number of quanta in the pump. For the probe, this Hamiltonian corresponds to a squeezer. Hence, I would expect H_R to create Hawking pairs in the probe field but to leave unchanged the number of quanta in the pump. Instead, the authors claim H_R would create quanta both in the probe and pump. They justify the claims using an argument based on frequencies, which seems a bit handwaving to my eyes. Further justification seems to be needed.

   In the notation of our paper, the $\widehat{a}$ and $\widehat{a}^\dagger$ are not the usual annihilation and creation operators, but primarily the positive/ negative frequency parts of fields (with respect to laboratory–frame frequencies ω). Bosonic quantum fields $\hat{A}$ can be expressed in mode decompositions:

$$\hat{A} = \sum_k \left(\widehat{b}_k A_k(t,z) + \widehat{b}_k^\dagger A_k^*(t,z) \right) \quad \text{with} \quad [\widehat{b}_k, \widehat{b}_l^\dagger] = \delta_{kl}\,.$$

   The mode functions A_k obey the classical linear field equation and are normalized according to the corresponding Klein–Gordon–type scalar product. For monochromatic modes these are normalized stationary waves oscillating with positive frequencies ω. In this case (and only in this case) the total free–field energy is the sum of $\hbar\omega\,\hat{b}_k^\dagger \hat{b}_k$ and so $\hat{b}_k^\dagger \hat{b}_k$ is the usual photon–number operator. In our case

$$\widehat{a} = \sum_k \widehat{b}_k A_k(t,z) \quad \text{and} \quad \widehat{a}^\dagger = \sum_k \widehat{b}_k^\dagger A_k^*(t,z)\,.$$

   It follows from the commutation relation of the $\hat{b}_k$ and $\hat{b}_l^\dagger$ and the completeness of the mode functions that $[\widehat{a}(z_1,t), \widehat{a}^\dagger(z_2,t)] = \delta(z_1 - z_2)$. This means that the $\widehat{a}$ and $\widehat{a}^\dagger$ are local annihilation and creation operators as we call them now in the revised paper. For the classical fields primarily considered in the paper we chose $a = (q + \mathrm{i}p)/\sqrt{2}$ for denoting the positive–frequency part of the field, because we want to use Hamilton's equations ($\dot{q} = \partial H/\partial p$ and $\dot{p} = -\partial H/\partial q$) familiar from classical mechanics and known to most physicists, and not overload the paper with formalism from quantum field theory. The referee knows this formalism, but not necessarily the broad audience of Nature. Yet we also need to give the experts the proper definitions and hope to have improved this in our revision.

With our definition of $\widehat{a}$ and $\widehat{a}^\dagger$ it is then clear that $\widehat{a}^\dagger\widehat{a}$ is not the photon number, but rather the local photon flux (the number of photons per second at time t and position z). This is the quantity our photomultiplier tube would measure if it were placed at position z. The intensity is given by $\hbar\omega\,\widehat{a}^\dagger\widehat{a}$ and measured, e.g., with photodiodes (and typically expressed in mW). The quantity $\widehat{a}^\dagger\widehat{a}$ is not conserved, for otherwise pulses would not propagate. We could go into a frame comoving with the pump pulse (as we do in our paper) but due to the propagation of the probe pulse and the nonlinear interaction we are never in a stationary regime where $\langle\widehat{a}^\dagger\widehat{a}\rangle = \text{const}$.

Moreover, the $\widehat{a}$ and $\widehat{a}^\dagger$ consist of many modes, and one mode can be partially converted into another. In Methods Sec. A we sketch where the well–known unidirectional propagation equation (A.1) comes from. This equation is an excellent approximation for describing wave propagation in nonlinear fibre optics. The equation describes how the field propagates and how new frequencies are generated, which is the most prominent effect of Nonlinear Optics [Nobel Prize Bloembergen 1981]. Given an initial light field, the right–hand side acts as a source for fields of new frequencies on the left. In (A.2) we express the right–hand side in terms of a Hamiltonian. For example, for the part H_R of the total nonlinear Hamiltonian and for the given pump a_1 and probe a_2 a new mode becomes excited on the left–hand side of the equation that is driven by the frequency $a_1^* a_1\, a_2^*$ oscillates. In the comoving frame, this is $-\omega_2'$. Looking at the dispersion curve (Fig. 2) we can then read off whether and with which laboratory frequency ω this wave can propagate. The laboratory frequencies of the carriers are not matched, but we derive in Sec. B how the mode propagates in the regime of a pump pulse much shorter then the probe wavelength.

Neither is $\widehat{a}_1^\dagger\widehat{a}_1$ the total photon number of a single mode nor $\widehat{a}_2^{2\dagger} + \widehat{a}_2^2$ the squeezer of another single mode, but rather the generator of a wide spectrum of two–mode squeezing for modes with opposite comoving frequencies. The new Eqs. (B.1) and (C.1) and our frequency discussion are not just a handwaving argument, but establish a remarkably accurate theory that agrees well with data (Fig. 3). We understand that we need to explain this better and hope to have done this in the revised paper and the completely new Methods section. Referees are test readers, and if they struggle with something we thought we explained clearly, we need to make changes.

3. For the pump in numerical simulations (which, as far as I can see, mimics the one used in experiments), what is the value of the Hawking temperature? This can be

computed from the properties of the pump profile at the location of the horizon. What is the value of δn for the probes used in the experiments? It would be useful to report these numbers in the supplemental material, since it has been unclear in the past whether the pump used was strong enough to actually generated a horizon (some of the observed signals would be present even if an actual horizon never forms). On the other hand, in Fig. 2, one can see that the UV part of the probe signal is largest around $\lambda \approx 1300$ nm. It decreases for longer and shorter wavelengths. Is this related to the value of the Hawking temperature?

Computer simulations accurately reproduce the laboratory frequencies of the stimulated Hawking radiation, of the backreaction and also of the Negative Resonance Radiation (NRR) but they did not reproduce their intensities in our regime. The NRR can be calculated accurately for a different system [Opt. Exp. **21**, 31240 (2013)] where the pump is much longer (and still a significant NRR is produced) but not in our case, despite many months of effort. There is a fundamental reason for this difficulty. The emission of Hawking radiation (and also the backreaction and the NRR) depends exponentially on the logarithmic derivative of δn at the horizon (in the regime of weak dispersion) [Science **319**, 1367 (2008)]. In our experiment we generate a near–single–cycle pulse by soliton fission. It is not easy to predict the value of maximal steepness with exponential precision, in particular as the pulse propagation depends on the Raman effect of the glass in the fibre that is a dissipative nonlinearity acting on longer time scales than our pulses.

The same reason that makes the computer simulations difficult also causes day–to–day variations in the experiment. The referee has observed correctly that the 1300nm probe has produced the highest number of Hawking counts, but the NRR is also high. Both are related, NRR is essentially Hawking radiation, but with the pump itself as stimulant. As it is comoving with the pump — by definition — the pump does not run into itself (unlike the probe running into the pump) and so the rate of generating Hawking radiation by itself is low, but the pump is 10^2 more intense than the probe. One needs to calibrate the Hawking intensities by the NRR intensities, see the discussion of Point 1 of Referee 1. When we do this (and also correct for measured variations in probe power for the various probe intensities) we get a very good fit with the exponential tail of a Planck spectrum (Fig. 3c). The Hawking temperature $k_{\mathrm{B}}T$ is $\hbar/(2\pi\tau_0)$ for a soliton pump (Sec. B). It agrees with the prediction [Science **319**, 1367 (2008)] for large δn and can easily reach $10^3 - 10^4$K. However, the rate is reduced by an exponential prefactor we did not know in 2008 nor in 2019 [PRL **122**, 010404 (2019)] nor when we submitted this paper. Replying to the referee has inspired us for developing an analytic and accurate theory of the Hawking effect in the near–single–cycle regime, the relevant regime for optical analogues capable of demonstrating the Hawking effect.

4. I find the argument given in Fig. 1 a bit too heuristic. In gravitational black holes, there is no preferred notion of time and frequency at the location where the Hawking-partners cross the horizon. Consequently, there is no unambiguous sense in which the partners carry negative frequency. Although the simple picture of particles with opposite frequency is quite extended, it may be too heuristic to be included in a journal like this one.

   The referee is of course right; reducing the Hawking effect to an argument on positive and negative frequencies is a bit heuristic and not universally true; one should rather use positive or negative norms instead. But we believe it is best to keep the formal level of the paper low in view of the large and diverse readership of Nature and to rely on the simplest, intuitive models as much as possible. Furthermore, these frequencies are not meant to be local frequencies at the horizon, but global ones corresponding to the ω' and $-\omega'$ of our optics experiment. We would therefore much prefer to keep the figure as is.

Referee 1

The referee accepts the paper, but suggests two amendments:

1. In Figure 2, ω_h is not defined. This could easily confuse readers. Since the frequencies mentioned in the text (or those after frequency shifting) are all related to the pump or probe light, how is ω_h obtained?
2. The propagation or evolution equation (2) in the main text differs from equation (A.2) provided in the Methods section; it would be better to provide an explanation.

We have implemented these amendments. We explain in the amended figure caption that ω_h is the local maximum of the dispersion curve and that it corresponds to the horizon. Concerning point 2) we have now denoted the interaction term in Eq. (A2) by H_{int}, which resolves the confusion.

Thanks for the attention to detail!

Referee 2

We are grateful for the insightful comments and questions. Two questions have remained only partially answered after the first round; we address them below. Our revision had brought some new and unexpected results to light, and so it is completely understandable that the referee has some additional questions on the new material; we also answer them below.

1. While the authors already state that their experiment operates in a classical regime, I suggest they further remark that they are probing only classical aspects of backreaction, and include a brief discussion of which inherently quantum features do not survive in the classical limit. This will help to clarify what the present experiment is actually demonstrating and what instead cannot be probed yet.

   We have followed this suggestion and have added after "responsible for creating Hawking radiation": In our experiment, we do not yet observe the fully quantum spontaneous Hawking radiation, but classical stimulated Hawking radiation. While this classical radiation shares many of the features of quantum Hawking radiation, in particular its spectrum, we would not be able to measure quantum entanglement.

2. The referee is concerned that the probe perturbs the pump in a less–controlled way and writes: I thus suggest adding a statement along the following lines (e.g. in the conclusions): "In the absence of a systematic study of the signal as a function of probe power that would allow one to unambiguously separate genuine Hawking backreaction from direct probe-induced effects, it remains difficult to exclude the possibility that effects beyond a simple frequency shift contribute to the observed backreaction signal. These may include probe-induced modifications of phase-matching conditions, conversion efficiency, pump dynamics, or additional nonlinear mixing. Such measurements are experimentally very demanding, requiring long acquisition times (up to 12 hours) and stability against slow parameter drifts during the whole measurement run, which are not currently achievable in our setup. Nevertheless, the removal of excess signal near the NRR after applying the spectral shift (Fig. 3b), together with the emergence of a sideband structure consistent with our model, suggests that the frequency shift constitutes a significant contribution to the probe-induced backreaction effects."

   We are grateful for this suggestion and have incorporated it in the main text as a new paragraph following "some remnants are still visible (Fig. 3b)".

3. The referee is concerned that the observed asymmetry in the spectrum is not necessarily the "smoking gun" of the backreaction, but may be caused by other effects as well. Only after a careful quantitative analysis we can claim to have observed the backreaction. The referee writes: I would therefore suggest to replace the "smoking-gun" statement with something like "the agreement between

the observed asymmetry and the analytic predictions is significant and supports the proposed interpretation, although alternative nonlinear processes producing similar effects cannot be explicitly ruled out"

We replaced "smoking gun" by "characteristic feature" and incorporated the suggested sentence.

4. The observation of an approximately thermal spectrum in a regime of strong dispersion is particularly intriguing and unexpected. In this regime, the standard notion of a well-defined horizon and the associated surface-gravity interpretation of the Hawking temperature are no longer applicable. Instead, the authors argue that the effective temperature is determined by the global temporal profile of the pump pulse, specifically by the exponential decay of its Fourier spectrum. This suggests that thermality may arise from the analytic structure of the background field rather than from local horizon properties, which is a conceptually novel and potentially far-reaching result. At the same time, this increased universality may reduce the specificity of thermality as a distinctive signature of the Hawking process, implying that its observation alone is not sufficient to uniquely identify Hawking radiation, at least within this class of systems. I believe the manuscript would benefit from a brief discussion of this point.

   As suggested, we discuss this now (in the conclusions).

   4a) A purely thermal spectrum, would correspond to a loss of information; in a consistent quantum description, this must be avoided through subtle deviations from exact thermality or the presence of correlations. In this context, the persistence of thermality even in the absence of a direct connection to surface gravity may have important implications for future tests of the analogue information paradox in this system. Could the authors comment on that?

   We also discuss this in the conclusions — a most fitting end to our paper as it is related to Hawking's struggle with the information paradox until his very last paper.

5. In Fig. 3c, the authors plot the logarithm of the normalized Hawking radiation counts and the backreaction counts as a function of the frequency ratio. Both datasets have been fitted with linear models, and the corresponding slopes were extracted, yielding a ratio of 1.02. This is really remarkable. However, no error estimates for this ratio are reported. I think that the authors should report also the results of the individual fits for both Hawking and backreaction counts, including their uncertainties, and confidence intervals or error bars for the slope ratio to evaluate its statistical significance.
   It would be also nice to see some goodness-of-fit metrics for each linear fit (e.g. residual analysis) to assess how well the linear model describes the data. Providing these details would strengthen the statistical basis of the claim and allow readers to judge the robustness of the observed scaling.

We followed this suggestion and calculated the relative root–mean–square of the linear fits. However, one problem is that we assume an exponential spectral behaviour for both NRR and our signals. In reality there will be a prefactor with variations that we ignore. In Fig. 3c one sees a swerve of both the Hawking–radiation and the backreaction curves, which is probably caused by a systematic variation not captured by our simple model. The swerve averages out, but systematic deviations are not easily captured by statistical error bars. As we do not want to "lie with statistics" we would not draw error bars in the figure but rather state in the text the relative root–mean–squares as estimates of the error.

One issue we forgot to mention and have now included in the end of Methods Sec. D is the fact that we need to exclude the 1100nm data from the linear fits. This is because the 1100nm probe lies at the edge of the red–shifting range where the conversion efficiency significantly deviates from 100%. As we normalize with respect to the measured initial probe power before red–shifting we would make a systematic error. Figure D.1a shows that the signal lies significantly below the NRR, which indicates the reduced red–shifting efficiency and thus justifies the exclusion.

6. The decision to remove the comparison with numerical simulations is understandable in light of the acknowledged quantitative discrepancies and the introduction of the analytic model. However, including these simulations as a Supplementary Information, together with a clear discussion of their limitations, would be valuable. Even if they do not reproduce the amplitudes, the fact that they capture the spectral positions and qualitative features provides useful support for the underlying physical picture, while their failure highlights the role of additional effects such as Raman dynamics in this regime. In my opinion, presenting these results transparently would strengthen the manuscript by clarifying both the validity and the limitations of the current modeling.

   We agree and have written an additional Supplement on the numerics.

Referee 3

The referee would like to see further theoretical explanations on the nature of the backreaction and therefore makes the following suggestions:

-Improve the clarity in the main text regarding what type of transformation H_R generates. In the current version, although it is said that it creates pairs of probe quanta, its effect on the pump is not stated explicitly enough. This is important for the reader to understand what type of "back reaction" H_R generates.

We explain now in the main text that H_R generates, on the probe, an entangled two–mode squeezed vacuum state if the incident probe is in the vacuum state, while on the pump the Hawking–radiation Hamiltonian redistributes photons as the process preserves the total pump–photon number. However, it transfers energy across the spectrum and in particular generates light at a new frequency in the UV that we identify and detect, see the corresponding passages marked in red in the main text and in Methods Sec A and B.

-Explain how the effects attributed to H_R are compatible with energy conservation, which underlies standard arguments about backreaction. I see two possible scenarios (i) The process induced by H_R, combining pair creation in the probe and frequency redistribution in the pump, does conserve energy (though this is not obvious to me). (ii) The process induced by H_R is not enough by itself, and additional terms in the Hamiltonian must be included to account for the full energy balance.

We explain now in Methods Sec. A that an interaction Hamiltonian H_i preserves the total energy in the co–moving frame, see the text marked in red. This means in particular that energy from the pump is transferred to the probe for generating Hawking radiation. We show in Methods Sec. B (marked in red) that this process preserves the total photon number of the pump while generating new frequencies. We use an approximative method to determine the dominant frequency generated, given the frequencies of pump and probe. A signal at this new frequency is the backreaction we detect. The signal is obscured by sidebands due to another nonlinear process (phase modulation) but we work out how to distinguish the backreaction from modulations of the Hawking radiation.

We hope that these additional explanations are useful and satisfactory. There are many more theoretical aspects worth exploring in detail, but it might be best to leave this to the community. Our paper is certainly not the end of discussion, but hopefully a good, thought–provoking starting point.