nature portfolio

# Peer Review File

# Evidence for vacuum-enhanced superconductivity in $NbSe_2$

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**This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.**

Version 0:

Reviewer comments:

Referee #1

(Remarks to the Author)
I have read with great care the very interesting manuscript by Zheyan Wang and co-workers on vacuum-enhanced superconductivity in niobium diselenide. Enhancing the critical temperature of a superconductor is, without doubts, the holy grail of the field of cavity QED of quantum materials. In this respect, I strongly believe that the work by Wang et al., deserves the highest possible attention. However, I believe that the current version of the manuscript isn't ready for publication. Specifically, I have the following five major concerns on this work, on which I would like to get feedback from the authors:

1. How can the authors exclude, experimentally, that the effect they see is simply due to metallic screening? No discussion about this is reported in the manuscript. My understanding from reading the paper carefully (and I may be wrong about this, please correct me) is that they establish that is a cavity QED effect only on the basis of the agreement shown in Fig. 3d between theoretical calculations and experimental data. (I will come back to theory below.) It would be really great to have an experimental proof that excludes that trivial effects are at play here. Let me give a suggestion: what is the role of a nearby metal gate on superconductivity in few-layer niobium diselenide? Is this known? This must be known! Does it suppress superconductivity? Does it enhance it? Does it have any effect at all? This kind of considerations may help convincing the readers that the observed phenomenon has nothing to do with trivial effects such as metallic screening.

2. From the theory point of view, I like very much the fact that the authors take into account the spatial profile of the relevant EM mode. The single-mode, spatially uniform modelling used by many authors in the past has indeed been considerably criticized. However, I have the following concern. Three effective volumes are introduced in the manuscript. The first one, V_{eff}, appears on line 69, page 4, of the main text. This is the cavity effective volume. It commonly appears in theories of sub-wavelength cavities (such as the ETH split-ring resonators). it is somewhat arbitrary, and mode volume confinement arguments are usually used in the literature to make things that should not happen, happen. This is clearly explained, for example, by Andolina et al. in Phys. Rev. B 109, 104513 (2024). A second volume appears in the theory, Eq. (S14), of the Supplementary Information file. It is dubbed V_{SC}. It is used to "restore" translational invariance via averages over the sample size, given the fact that the cavity mode profile \phi(x) isn't uniform. In particular, this quantity yields a dimensionless light matter coupling \chi_\phi introduced in Eq. (S16), which is the "fractional overlap of the mode function with the sample". Finally, a third volume V_{c} appears below Eq. (S31). It is dubbed V_{c} and related to a momentum scale K "corresponding to the cavity normalisation in momentum space".
I would really like to see a clear explanation of the need to introduce three (!) "effective volumes" in the theory by the authors. We have honestly had enough of "fudge" factors introduced in theory papers like Ref. 25 of the main text. It is imperative to understand what are the inputs used by the authors to achieve the spectacular agreement we see in Fig. 3d of the main text. Is there a fudge factor or can the authors show that they have a clear equation for the quantity that is plotted in Fig. 3d? How does this equation look? What does it depend on? This equation should be in the main text and not hidden under the rug. How many parameters does it depend on? How many of these are fitting parameters? How many can be constrained from the experimental setup? Why do we need these parameters at all? We know everything about split ring resonators! Their EM physics is very well described by finite-element simulations as those reported in the main text. Why do we need three effective volumes!?

3. In relation to point 2 above, there has been a substantial debate in the theory literature about the most "physical" and fudge-factor-free theory of sub-wavelength cavities. Since THz split-ring resonators fall into this category, I would really love

to understand what the authors think about this debate and whether their experimental data say something useful about it. Here's a few examples of papers where this debate is discussed: a) Phys. Rev. B 109, 104513 (2024), b) https://doi.org/10.1073/pnas.240799512, c) https://arxiv.org/abs/2501.04133, d) https://arxiv.org/abs/2511.00608 - none of these theory papers on cavity QED of van der Waals heterostructures contains fudge factors. No fitting parameters. Any comment on this, especially in view of point 2 above?

4. One more comment. The measured enhancement of Tc is smaller than 3%. Who cares about a 3% enhancement of Tc? This is a very small enhancement! We need to understand a path to increase this enhancement in the future. I understand this is perhaps a first key paper towards that direction. But we need to understand how to find Tc enhancements that are significant!
Think for example about the modification of the amplitude of the Shubnikov de Haas oscillations in a 2D electron system due to hBN polaritons predicted in https://doi.org/10.1073/pnas.2407995122 - this was smaller than 2%. Measuring DC transport and detecting these small effects is really challenging. But a clear path exists on how to increase cavity effects in these setups, as explained in https://doi.org/10.1073/pnas.2407995122. The question is: since the authors believe to have a theory explaining their data, can they tell us what to do in order to have an increase in Tc of 30%, say? Ten times larger I mean. I believe that it would be great to include a discussion of this type in the main text. Shall we just find cavities where the field enhancement is much larger than that reported in Fig. 1b? Which type of cavities?

5. Finally, I would like to ask the authors the following question. The Columbia group has recently reported a suppression (rather than an enhancement) of the critical temperature of a superconductor due to strong coupling with hBN phonon polaritons: see https://arxiv.org/abs/2505.17378 - in this work, physics is explained in terms of mode coupling. In the superconductor investigated in this arXiv paper, there is a well known phonon mode responsible for a finite Tc. This mode happens to be resonant with hBN phonon polariton modes. This resonant behaviour, in the particular case of a phonon mediated superconductor, leads to a suppression of Tc. More recently, the authors of https://arxiv.org/abs/2511.00608 have shown (this is just theory so far) that mode coupling can lead to an enhancement of Tc in non-phonon superconductors. In this other arXiv work, the enhancement of Tc is due to strong coupling between 2D metallic plasmons and cavity phonon polaritons. Question: Is there any microscopic picture of this sort in the present work by Zheyan Wang and co-workers? Is there any microscopic Hopfield polaritonic coupling between the modes of superconducting niobium diselenide and the split-ring resonator cavity mode?

In summary, while I believe that the work by Zheyan Wang and co-workers deserves the highest possible attention, I cannot recommend it for publication in its present form. I believe that the authors should try and discuss the issues raised above. In particular, in view of the recent experimental results by the Columbia group, it is imperative to understand whether their interesting finding (enhancement of Tc) fits into the framework of polaritonic physics (in the sense of mode coupling and Hopfield polaritons) or not.

Referee #2

(Remarks to the Author)
Please find herewith my assessment of the manuscript: Observation of vacuum-enhanced superconductivity in $NbSe_2$ from Wang et. Al. The manuscript reports the first observation of the increase of a critical temperature of $NbSe_2$ when embedded into split-ring cavity resonator. The search for experimental configuration allowing for a feedback between optical cavities and quantum material, and in particular superconductors is certainly timely and subject of a vivid debate. Recent reports documented that embedding materials into optical cavities could reduce the superfluid density, but no observation of enhancement of superconductivity has been reported to date. In this respect the documented evidence of an increased Tc is certainly a novelty and deserve publication in high impact journals.

The scientific quality of the study is overall good. Nevertheless, after a careful reading of the manuscript I remain unconvinced that the observed effect can be conclusively attributed to the cavity electrodynamics. Here are the my main criticisms:

-I think it is difficult to rule out, given the data presented, that the fabrication of the device played a major role in altering the superconducting critical temperature. Could the deposition of the plasmonic structure lead to strain of the material or inhomogenieties?

-Along the same line, the study reports the effect of split ring resonator at different frequencies. The difference in the geometry of the devices with different resonant frequency could lead to different Tc due to extrinsic fabrication processes? Is it possible to perform experiments where the cavity resonant frequency is kept fixed (ideally in the observed resonant condition), while the geometry and fabrication parameters are changed? More general tests of the different experimental parameters are needed to give a conclusive evidence (shape of the resonators, thickness of the SC layer and spacers).

Ultimately I find difficult that a convincing evidence that the cavity electrodynamics plays a major role could be given without devices where the antenna is placed at different tuneable distance from the cavity (as for example in recent studies of topological systems https://www.science.org/doi/10.1126/science.abl5818). This would convincingly prove that the changes in Tc are not associated to fabrication issues but rather to the photonic characteristics of the resonator. I understand this requires very likely a different setup, but at least an extensive study of devices with different parameters and distance of the antenna should be given.

-One additional criticism connected to the previous ones is that all the results reported are measured on a 12-layers $NbSe_2$ sample. Authors should include a thickness dependence and show how $\Delta T_c$ scale with the thickness of the superconductor and the spacing layers.

-Along the same line, how would the reported effect on the critical temperature depends on the cavity quality factor? The paper mentions a quality factor $Q \approx 11$. How was this extracted experimentally? How does the resonant condition of the split ring resonator depend on the dielectric environment?

-What determines the resonant condition where the larger effect is observed? Can the authors elaborate what is the cavity coupled to and whether the system is in the weak/strong/ultra-strong coupling regime?

Minor points:

-I find very surprising that the authors do not observe any change in the critical currents at low temperature but only a change in Tc. Can the author argue why the critical currents is unchanged while Tc is? Are critical currents, Tc and superfluid density not related in this case?

-In the determination of the critical magnetic field, discuss whether B modifies the cavity parameters and, if so, how this could feed back into $\Delta T_c$.

-The vacuum-field estimate ( ~ 260 V/m) relies on Veff and εs. The authors should show how Veff = 79 $\mu m^3$ and εs = 5.1 are experimentally measured.

-In figure 3 the error bar is misleading. As it is described in the text the error bar does not represent and experimental statistical error, but it is rather representative on how are systematic error in extracting the critical temperature accounted for.

Overall, the manuscript is a valid contribution to the field. Should the interpretation of the effect survive the tests above and be conclusively associated to cavity electrodynamics it represents an important contribution to the field which deserves publication in journal with a broad readership. The data given in the current version of the manuscript in my opinion do not demonstrate conclusively that the effect is associated to the electrodynamics of the resonator.

Referee #3

(Remarks to the Author)
This manuscript presents an experimental strategy to enhance superconductivity by embedding a superconducting material in a split-ring cavity resonator. Using the layered transition-metal dichalcogenide superconductor NbSe2 as a test platform, the authors compare the critical temperature (Tc), critical current, and upper critical field between device regions with and without a cavity and report enhanced superconducting properties in the cavity-coupled regions. Upon tuning the cavity resonance, the Tc enhancement exhibits a non-monotonic dependence on the cavity frequency. The results are interpreted within a Ginzburg-Landau framework that accounts for coupling between superconductivity and cavity photons.

Cavity-vacuum engineering is an emerging approach to manipulating quantum materials. To the best of current knowledge, this work provides the first experimental demonstration of cavity-enhanced superconductivity evidenced by electrical transport. It represents a noteworthy advance, introducing a noninvasive route to controlling superconductivity, and it may meet the standard of Nature. Nevertheless, several issues that appear to limit the strength of the present study warrant more detailed discussion.

1. The maximum Tc enhancement is 0.16 K from a baseline Tc of 6.38 K, corresponding to a 2.5% increase. Other techniques, e.g., field-effect gating (0.2 K, Phys. Rev. B 80, 184505, 2009) and ionic-liquid gating (2 K, Phys. Rev. Lett. 117, 106801, 2016) in few-layer NbSe2, achieve comparable and even larger shifts. Describing the present change as a “substantial increase in the critical temperature” appears overstated. Moreover, the enhancements of critical current and upper critical field are appreciable mainly near Tc, with negligible effects observed in the superconducting ground state. In addition, Ref. 29 (“Exploring superconductivity under strong coupling with the vacuum electromagnetic field”) reports an increase of Tc in Rb3C60 from 30 K to 45 K. Given the manuscript’s emphasis on enhancing superconductivity, including aspirations toward room-temperature regimes, the comparative advantage and long-term potential of the present approach are not yet evident. Based on the data currently presented, the principal contribution appears to be a proof-of-principle demonstration rather than a substantial increase in Tc. The manuscript would benefit from a more balanced articulation of the study's motivation and of the implications of the results.

2. A more detailed discussion of the device design would clarify key factors required to observe robust Tc modulation. For example, what is the rationale for the chosen cavity geometry, and could alternative designs be more effective for enhancing Tc?

3. Although the central idea is to exploit coupling between NbSe2 and vacuum fluctuations, the devices placed NbSe2 between a substrate and capping layers rather than in vacuum. At a theoretical level, how does the dielectric environment

affect Tc modulation? In particular, what is the influence of the substrate and capping materials and their thicknesses on the measured Tc?

4. The NbSe2 is covered by 15-nm hBN and 10-nm Al2O3, with a 200-nm Au/10-nm Ti split-ring fabricated on top of Al2O3. Thus, NbSe2 is separated vertically from the cavity by 25 nm. Figure 1b,c presents simulated vacuum-field enhancement, but the simulation methodology is not described and the height at which the field is evaluated is unspecified. Given that the cavity thickness exceeds the NbSe2 thickness by an order of magnitude, the authors are suggested to clarify whether the field enhancement is height-dependent and whether an optimal height (within the cavity rather than below the cavity) exists for maximizing Tc enhancement.

5. Figure 1c indicates that the field enhancement is strongly localized at the flake edge within <0.1 μm, a small fraction of the total area. This suggests that only this region experiences enhanced fields, implying a local Tc increase and potential sample inhomogeneity. Such inhomogeneity could account for the two-step transition seen in Fig. 1e (versus a single transition in the control area outside the cavity), with a similar trend in Fig. 1g. Yet Tc is also enhanced in the lower-temperature portion of the two-step transition, indicating modifications away from the edge. Is this mediated by interactions between the edge region and the interior? More importantly, the authors are suggested to consider whether the effect of edge-localized vacuum-field enhancement on Tc can be isolated and quantified.

6. The definition of the effective cavity volume is not clearly provided. The cavity frequency is tuned by changing the gap length, which should also alter the cavity volume and thus the vacuum-field amplitude, according to the formula on Page 4. In Fig. 3d and the accompanying theory, changes in Tc are attributed solely to frequency shifts. How to justify neglecting the concomitant volume-induced changes in vacuum-field strength?

7. Figure 3d shows that tuning the cavity dimension either enhances Tc or leaves it unchanged; no suppression is observed. Is there a fundamental reason that the cavity cannot reduce Tc?

8. The choice of 12-layer NbSe2 is not explained. The introduction states that “vacuum fluctuations can enhance superconductivity in a bulk material,” yet the analysis of voltage vs. current suggests a BKT transition, implying a 2D regime. This appears inconsistent. For NbSe2, a 12-layer thickness should be comparable to the BCS coherence length, suggesting more 3D behavior. Since the cavity-induced enhancements of critical current and upper critical field are most evident for 12-layer NbSe2 near Tc (where the condensate density is reduced, as agued in the manuscript), it may be more advantageous to examine flakes as thin as possible, for which fluctuations are stronger and cavity effects on superconductivity may be further amplified.

9. Minor point: Panel label e is missing in Fig. 2.

Version 1:

Reviewer comments:

Referee #1

(Remarks to the Author)
I have carefully read the rebuttal letter from the authors and I must say that I am very positively impressed about it. I honestly believe that the authors have addressed all my concerns and the resubmitted version of the Article is in a much better shape than the original one. In fact, I actually think that the revised manuscript is ready for publication provided that the last set of comments reported below and related to the scientific presentation will be taken into account.

Given the fact that in the month of June a few more papers appeared on the arXiv about enhancing superconductivity via vacuum fluctuations, I believe that the manuscript by Zheyan Wang and co-authors should be given the highest possible priority. This is one of the most serious studies of the interplay between superconductivity and vacuum fields I have seen so far in the literature.

Here’s my last set of comments:

1) My impression being in the field of cavity material engineering for quite a few years is that the exclusion of trivial effect such as metallic screening is very important for experimental colleagues working outside the field. I therefore strongly believe that the fact that trivial metallic screening cannot explain the results should have a bit more prominent role in the paper rather than being relegated to a tiny remark on page 6 of the main text and related Supplementary Note 6. I strongly encourage the authors to do the effort of squeezing in the main text current Supplementary Figure 2. I am not pushing towards this direction because I was the one raising the point of excluding trivial screening effects. I am pushing the authors because I have many many experimental colleagues in top US and EU universities who are quite skeptical about the role of vacuum fluctuations and raise all the time concerns about using metallic gates near atomically thin van der Waals heterostructures. Readers need to see immediately in Fig. 1 of the main text that the measured effect has nothing to do with non-resonant frequency-independent metallic screening. And this is the way I would write a comment in the main text: “Trivial, non-resonant, frequency-independent metallic screening cannot explain the physics we observe in this work”. Full stop.

2) Similarly to what stated in point 1) above, it is of uttermost importance in this field to avoid the proliferation of papers

claiming that vacuum fluctuations in *deep-subwavelength* cavities can be modelled by a purely transverse fluctuating gauge field with a tunable mode-volume-confinement fudge factor.
I am very happy to notice that the authors have seriously addressed this point in the rebuttal. However, I believe that this point deserves to appear more prominently in the main text. Again, this is not because I was the one raising this point but because there is a lot of theory papers out there which have promised that vacuum fluctuations can do everything for you….. We therefore badly need serious experimental work putting *serious bounds* on theories. A brief summary of the discussion currently relegated to Supplementary Note 12 should be shifted to the main text, with precise theory statements about what we learn from this experiment by Zheyan Wang and co-authors, in relation to references 15 and 17-20. Please, avoid superficial one-sentence statements in the main text to make me happy. Such statements are useless for modern readers who, typically, do not have time to read carefully the Supplementary material. A short precise discussion of what your comparison between experiments and theory says with respect to the discussion in Refs. 15,17,18,19, 20 is needed.
By the way, Ref. 20 is not at all the only reference where the mode-volume-confinement argument has been used.

Issues 1) and 2) are not a personal “whim” of mine, but a fundamental necessity for the healthy future development of this field of research. Thank you for understanding.

Referee #2

(Remarks to the Author)
Please find here my comments on the revised version of the manuscript. I appreciate the authors’ efforts in addressing the concerns raised in my initial review, and I find several of the additional analyses and discussions helpful. Nevertheless, I remain unconvinced that the reported effect can be conclusively attributed to cavity electrodynamics, for the reasons outlined below.

It is well known that the critical temperature of $NbSe_2$ depends sensitively on the characteristics of the material. The fact that the authors report different critical temperatures for different devices illustrates this sensitivity. Importantly, all devices discussed in the manuscript exhibit critical temperatures below those reported for the highest-quality $NbSe_2$ crystals, where $T_c$ can reach approximately 7 K.

I understand that the primary focus of the manuscript is not the absolute value of the critical temperature in $NbSe_2$, but rather the relative change in $T_c$ induced by the cavity. However, the substantial variation in the baseline critical temperatures across devices makes it difficult, in my view, to establish a clear causal connection between the observed enhancement and the cavity itself.

The additional characterization provided by the authors is valuable, particularly because it addresses the possibility of strain-induced modifications of $T_c$, a concern that I raised in my original review. In particular, the authors present Raman microscopy measurements to support the conclusion that fabrication-induced strain is unlikely to be responsible for the observed enhancement. While I appreciate this effort, I do not find the evidence fully convincing.
In the figure below (see attachment), I have overlaid the Raman spectra provided by the authors, comparing measurements taken outside the cavity (black) and inside the cavity (orange). As can be seen, the Raman responses inside and outside the cavity are noticeably different. Furthermore, the relative intensities of the Raman peaks vary between different locations within the cavity region. These observations appear consistent with spatial variations in material properties and may indicate that the observed changes in $T_c$ are associated with the fabrication of the antennas on top of the material. For this reason, I do not believe that fabrication-induced effects have yet been conclusively ruled out as a possible contributor to the observed enhancement of $T_c$. Given the well-established sensitivity of $NbSe_2$ to strain and material quality, I believe this alternative explanation deserves further consideration before the reported effect can be unambiguously attributed to cavity electrodynamics.

Overall, I find the topic timely and the observation potentially very important. However, in my opinion, additional evidence is still needed to distinguish cavity-induced effects from fabrication-related modifications of the material and to firmly establish the proposed interpretation. For these reasons, although I find the reported observations highly suggestive, I believe they should be regarded as anecdotal evidence that a cavity-induced effect may be present rather than as definitive proof of such an effect. Accordingly, the results should be presented with this level of caution.

As stated in my previous report, more convincing evidence that the observed effect of the antenna on the superconductor is genuinely photonic in origin, rather than arising from fabrication-related factors, would require the implementation of a movable antenna that can be brought into and out of close proximity to the superconducting structure as in the paper mentioned in my previous report.

Referee #3

(Remarks to the Author)
The authors have performed additional experiments that thoroughly address my questions and concerns. The new results convincingly demonstrate the effect of cavity on superconductivity. I therefore recommend publication of the revised manuscript in Nature.

--- Comments to report of referee #3 ---

The other referee raises an important concern that fabrication-induced changes in sample quality could complicate the interpretation of the reported effect. I agree that this issue is relevant, particularly given the substantial device-to-device variation in the baseline Tc.

That said, I do not think this concern is sufficient to overturn the authors' main interpretation. Since degradation in NbSe2 is generally known to suppress Tc, fabrication-induced degradation alone does not naturally explain why the portion of NbSe2 inside the cavity would show a clear Tc enhancement. In my view, this makes it difficult to attribute the observed enhancement solely to fabrication-induced sample degradation.

Moreover, Fig. 3d presents the relative change in Tc induced by the cavity, which helps to mitigate the issue of baseline Tc variation across devices. The data show that Tc can be either suppressed or enhanced depending on the cavity frequency, and this trend appears to be reasonably captured by the authors' theoretical model. I regard this as strong evidence that a cavity-related effect is involved.

Overall, I think the other referee's concern is valid and should be acknowledged in the manuscript, perhaps through appropriately cautious wording. However, I do not think the concern invalidates the authors' central claim, and I remain supportive of publication.

## Responses to Referee #1

**General comment:** I have read with great care the very interesting manuscript by Zheyan Wang and co-workers on vacuum-enhanced superconductivity in niobium diselenide. Enhancing the critical temperature of a superconductor is, without doubts, the holy grail of the field of cavity QED of quantum materials. In this respect, I strongly believe that the work by Wang et al., deserves the highest possible attention. However, I believe that the current version of the manuscript isn't ready for publication. Specifically, I have the following five major concerns on this work, on which I would like to get feedback from the authors:

**Response:** We are particularly grateful for the referee's recognition of the significance of this work. The referee raised concerns regarding the role of trivial effects (e.g., metallic screening) and clarification of the theory (particularly the "fudge-factor-free" approach and the Hopfield polariton picture). In response, we have performed additional control experiments and provided explicit discussions to address these issues. The manuscript has been revised accordingly, and point-by-point responses are provided below.

**Comment-1:** How can the authors exclude, experimentally, that the effect they see is simply due to metallic screening? No discussion about this is reported in the manuscript. My understanding from reading the paper carefully (and I may be wrong about this, please correct me) is that they establish that is a cavity QED effect only on the basis of the agreement shown in Fig. 3d between theoretical calculations and experimental data. (I will come back to theory below.) It would be really great to have an experimental proof that excludes that trivial effects are at play here. Let me give a suggestion: what is the role of a nearby metal gate on superconductivity in few-layer niobium diselenide? Is this known? This must be known! Does it suppress superconductivity? Does it enhance it? Does it have any effect at all? This kind of considerations may help convincing the readers that the observed phenomenon has nothing to do with trivial effects such as metallic screening.

**Response:** We thank the referee for the constructive suggestion and would like to address these comments in two aspects:

### *1. Experimental proof to exclude trivial metallic screening*

Following the referee's suggestion, we have carried out a **control experiment in which nearby metal strips are introduced** without forming a cavity. In this device, the spatial configuration—including the position of the metal layer and the dielectric environment—is identical to the local structure of the original cavity devices, while eliminating any resonant electromagnetic modes. As shown in Fig. R1, a comparison between the channels without ($R_1$) and with metal strips ($R_2$) reveals no discernible modulation of superconductivity. The absence of any effect in the screening-only control device **provides strong experimental evidence that the reported phenomena cannot be attributed to trivial metallic screening**. In the new Note 6 of the revised

Supplementary Information, we further include a quantitative estimate of the magnitude of static screening effect, suggesting that it is negligible compared with the dynamical vacuum-field contributions responsible for the observed behavior.

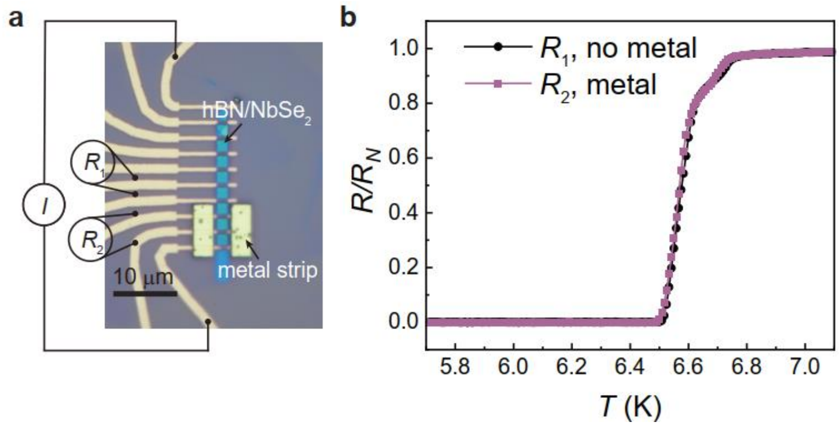



**Figure R1.** Control experiment with nearby metal strips. **a**, Optical micrograph of a 12-layer $NbSe_2$ with nearby metal strips. **b**, Superconducting transitions without ($R_1$) and with metal strips ($R_2$).

***2. Validation of the cavity QED effect based on comprehensive observations***

The identification of the cavity QED origin is not based solely on the results in Fig. 3d of the revised manuscript, which shows the agreement between the frequency-dependent $T_c$ enhancement and the Ginzburg-Landau (GL) calculation. It is supported by a comprehensive set of observations and analyses: **(1)** By comparing regions of the same $NbSe_2$ flake inside and outside the cavity (Fig. 1e and Extended Data Fig. 2 of the revised manuscript), as well as the same $NbSe_2$ channel before and after the cavity deposition (Fig. 1g of the revised manuscript), the **superconductivity is enhanced only where $NbSe_2$ overlaps the enhanced vacuum field inside the cavity gap**; **(2)** Besides $T_c$, the critical current $I_c$ and critical field $H_c$ exhibit pronounced, cavity-induced enhancement near the superconducting transition (Fig. 2 of the revised manuscript), and the BKT transition temperature $T_{BKT}$ is also enhanced consistently with $T_c$ (Extended Data Fig. 5 of the revised manuscript). The **correlated behavior of these multiple superconducting characteristics is naturally explained by the cavity-modified condensate density**, as predicted by our GL analysis of the coupled superconductor-cavity system; **(3) Further systematic study involving different device parameters.** As detailed in our responses to the Comment-2 and -3 of Referee #2, we performed a systematic study by varying the cavity geometry, $NbSe_2$ thickness, and $Al_2O_3$ thickness, and by carrying out cavity experiment with a metallic plane. The results further convincingly support the superconductivity modulation via Cooper pairs hybridized with cavity photons.

In summary, these comprehensive sets of observations demonstrate that the superconductivity enhancement is due to the cavity QED effect, rather than trivial effects such as metallic screening.

We have added discussion to the last paragraph on page 6 of the revised manuscript and added a new Note 6 to the revised Supplementary Information to clarify the trivial metallic screening. Figure R1 is added as the new Supplementary Fig. 2.

**Comment-2:** From the theory point of view, I like very much the fact that the authors take into account the spatial profile of the relevant EM mode. The single-mode, spatially uniform modelling used by many authors in the past has indeed been considerably criticized. However, I have the following concern. Three effective volumes are introduced in the manuscript. The first one, V_{eff}, appears on line 69, page 4, of the main text. This is the cavity effective volume. It commonly appears in theories of sub-wavelength cavities (such as the ETH split-ring resonators). it is somewhat arbitrary, and mode volume confinement arguments are usually used in the literature to make things that should not happen, happen. This is clearly explained, for example, by Andolina et al. in Phys. Rev. B 109, 104513 (2024). A second volume appears in the theory, Eq. (S14), of the Supplementary Information file. It is dubbed V_{SC}. It is used to "restore" translational invariance via averages over the sample size, given the fact that the cavity mode profile \phi(x) isn't uniform. In particular, this quantity yields a dimensionless light matter coupling \chi_\phi introduced in Eq. (S16), which is the "fractional overlap of the mode function with the sample". Finally, a third volume V_{c} appears below Eq. (S31). It is dubbed V_{c} and related to a momentum scale K "corresponding to the cavity normalisation in momentum space".

I would really like to see a clear explanation of the need to introduce three (!) "effective volumes" in the theory by the authors.

We have honestly had enough of "fudge" factors introduced in theory papers like Ref. 25 of the main text. It is imperative to understand what are the inputs used by the authors to achieve the spectacular agreement we see in Fig. 3d of the main text. Is there a fudge factor or can the authors show that they have a clear equation for the quantity that is plotted in Fig. 3d? How does this equation look? What does it depend on? This equation should be in the main text and not hidden under the rug. How many parameters does it depend on? How many of these are fitting parameters? How many can be constrained from the experimental setup? Why do we need these parameters at all? We know everything about split ring resonators! Their EM physics is very well described by finite-element simulations as those reported in the main text. Why do we need three effective volumes!?

**Response:** We thank the referee for the helpful comments and would like to respond in two aspects:

***1. Physical meaning of the three volumes***

**(1)** $V_{\mathrm{eff}}$ (page 4 of the revised manuscript) is the effective mode volume and describes the confinement of the electromagnetic mode in the split-ring resonator. It is fixed by electromagnetic simulations based on the actual device geometry, rather than being treated as an arbitrary parameter, fully in line with the "fudge-factor-free" spirit in *Phys. Rev. B 109, 104513 (2024)*, as the referee points out. **(2) $V_{SC}$** (equation (S14) of the revised Supplementary Information) is the physical volume of the superconductor inside the cavity, yielding $V_{\mathrm{SC}} \approx 2$ μm × 25 μm × 8 nm. Since the cavity mode is not uniform over the superconducting sample, averaging over the superconductor volume is required to define the dimensionless mode-overlapping function $\chi_\phi = \int_{V_{\mathrm{SC}}} d^3x|\phi(x)|^2$ (equation (S16) of the revised Supplementary Information) of the mode function in the region occupied by the sample. We find an overlap of $\chi_\phi \approx 0.65$, which was determined by approximately mapping this parameter to the normalization of the fitted mode function in momentum space (see the new Note 9 of the revised Supplementary Information). **(3) $V_c$** (equation (S4) of the original Supplementary Information) was introduced to define the cavity modes in momentum space. Motivated by the referee's comment, we agree that there is no need to introduce $V_c$. In fact, we can eliminate the dependence on this quantity by plugging our ansatz for the mode function $\phi(q)$ into the definition of the normalization $\chi_\phi$ (see the description below equation (S31) of the revised Supplementary Information). After revision, the theory involves only physically meaningful and independently defined quantities: the simulated cavity mode (**$V_{\mathrm{eff}}$**), the sample geometry (**$V_{\mathrm{SC}}$**), and their overlap ($\chi_\phi$). No redundant or artificial volume parameters remain.

***2. Explicit equation underlying Fig. 3d and its parameters***

We next provide an **explicit equation for the quantity plotted in Fig. 3d** of the revised manuscript. The effect of cavity fluctuations on the superconductor can be evaluated through the renormalization of the Ginzburg-Landau coefficients (see the new Note 9 of the revised Supplementary Information). On this basis, we can calculate the one-loop modification of the critical temperature $\delta T_{\mathrm{c}}$ as

$$\delta T_{\mathrm{c}} = -\frac{e^2\chi_\phi}{\varepsilon\alpha_0 m V_{\mathrm{SC}}\sqrt{\omega_{\mathrm{c}}^2-\gamma^2}} - \frac{e^2}{2\varepsilon\alpha_0 m^2 V_{\mathrm{SC}}\omega_{\mathrm{c}}}\mathrm{Re}\int\frac{d^3k}{(2\pi)^3}|\tilde{\phi}(k)|^2 k_y^2\left[\frac{1}{\Omega+\omega_{\mathrm{c}}-i\gamma} - \frac{1}{\Omega-\omega_{\mathrm{c}}-i\gamma}\right], \qquad (1)$$

where $\Omega = -\frac{k^2}{2m} - \alpha$, $V_{\mathrm{SC}} \approx 2$ μm × 25 μm × 8 nm is the volume of the sample, $\tilde{\phi}(k)$ is the Fourier transform of the mode function, $y$ is the direction of the mode polarization $\hat{\boldsymbol{e}}$, $\gamma$ is the frequency broadening of the cavity, and $\chi_\phi = \int_{V_{\mathrm{SC}}} d^3x|\phi(x)|^2$ is the fractional overlap of the mode density with the sample. This clearly shows what parameters $\delta T_{\mathrm{c}}$ depends on.

As pointed out by the referee in Comment-2 and -3, the literature (a-d) provides microscopic, "fudge-factor-free" descriptions of the sub-wavelength cavities and their coupling to two-dimensional electron systems. To provide quantitative predictions in our study, we have to combine theory with experimentally constrained input. In practice, this introduces **three fitting parameters $\lambda$, $\xi$, and $\gamma$, whose values are physically motivated, rather than arbitrary "fudge factors".** The parameter $\gamma$ represents the cavity loss (i.e., the spectrum linewidth), which is constrained by the simulated and measured resonance response. It sets the resonance broadening and therefore directly determines the effective quality factor, yielding values consistent with dissipative planar THz split-ring resonator cavities. $\lambda$ and $\xi$ are also not arbitrary fitting knobs but encode two intrinsic length scales of the superconductor: the coherence length and the London penetration depth. These two scales determine how the superconducting condensate responds to spatially varying electromagnetic fields, and therefore fix the effective momentum exchange between the cavity mode and the condensate. In this sense, the complex momentum scale $k_c \propto \lambda^{-1} + i\xi^{-1}$ emerges naturally from the interplay of these two physically well-defined lengths.

This point is essential: because the cavity mode is highly nonuniform, the coupling cannot be captured by a spatially constant field approximation. At the same time, introducing a fully arbitrary field profile $\phi(x)$ would lead to an uncontrolled proliferation of parameters. Our parametrization in terms of $\lambda$ and $\xi$ provides a minimal and physically grounded way to encode the relevant spatial structure. In particular, these length scales determine which momentum of the cavity field can be efficiently transferred to the condensate, as reflected in the momentum-dependent processes entering the diagram shown in Fig. 3f of the revised manuscript.

Importantly, the values of $\lambda$ (14.65 nm) and $\xi$ (479 nm) used in our theoretical analysis are close to the experimentally reported coherence length (11.8 nm) (*Nat. Commun. 15, 6037 (2024)*) and penetration depth (496 nm) (*Solid State Commun. 36, 493 (1980)*), respectively, depending on sample and measurement conditions. This agreement confirms that these parameters are not "fudge factors", but rather reflect intrinsic material properties that govern the spatial structure of the light–matter coupling and, consequently, the allowed momentum transfer between the cavity field and the superconducting condensate.

We have added a new Note 3 to the revised Supplementary Information to clarify $V_{\mathrm{eff}}$. On page 12 of the revised manuscript, we have added discussion to the second paragraph to clarify $V_{\mathrm{SC}}$ and $\chi_\phi$. $V_{\mathrm{c}}$ has been removed from the manuscript. We have added equation (1) to the second paragraph on page 12 of the revised manuscript as new equation (2) and include corresponding explanations below it.

**Comment-3:** In relation to point 2 above, there has been a substantial debate in the theory literature about the most "physical" and fudge-factor-free theory of sub-wavelength cavities. Since THz split-ring resonators fall into this category, I would really love to understand what the authors think about this debate and whether their experimental data say something useful about it. Here's a few examples of papers where this debate is discussed: a)Phys. Rev. B 109, 104513 (2024), b)https://doi.org/10.1073/pnas.2407995122, c)https://arxiv.org/abs/2501.04133, d)https://arxiv.org/abs/2511.00608 - none of these theory papers on cavity QED of van der Waals heterostructures contains fudge factors. No fitting parameters. Any comment on this, especially in view of point 2 above?

**Response:** We thank the referee for pointing out the recent theoretical works (a–d) on cavity-QED-modified quantum material properties, especially Ref. (a), where the "fudge-factor-free" debate is carefully analyzed in comparison with earlier works such as *Phys. Rev. Lett. 122, 133602 (2019)*. As we understand it, the central issue is whether the microscopic coupling should be formulated in terms of a current-vector-potential interaction or a density-scalar-potential interaction, and whether one can legitimately "import" Fabry-Pérot intuition by introducing a mode-volume compression factor.

First, **the cavity-matter interaction in our model is consistent with the conclusion in Ref (a)**: in the deep sub-wavelength regime, the **density-scalar-potential interaction must be retained**. More **rigorously, both the density-scalar-potential interaction and the current-vector-potential interaction** in the Coulomb gauge $\nabla \cdot \vec{A} = 0$ **should be present**. To incorporate both contributions in a transparent way, we instead work in the radiation gauge, where $\delta\phi(x,t) = 0$. In this formulation, the scalar potential is decomposed into an electrostatic part and a dynamical part, $\phi(x,t) = \bar{\phi}(x) + \delta\phi(x,t)$, while the vector potential contains both transverse and longitudinal components ($\vec{A}_{\perp}$ and $\vec{A}_{\parallel}$, respectively).

For finite-frequency cavity modes, the coupling between the longitudinal component of the vector potential and the current in the radiation gauge is equivalent to the density-scalar-potential interaction in the Coulomb gauge. As a result, the radiation gauge naturally incorporates both longitudinal and transverse electromagnetic fluctuations in the diagrammatic treatment. In other words, both charge and current fluctuations are consistently included in our theory.

The purely electrostatic term $\bar{\phi}(x)\rho(\mathrm{x})$ may be neglected since the field strength of the screening correction is much weaker than the dynamical cavity field, as estimated in the new Note 6 of the revised Supplementary Information. This separation is further supported by the agreement between our theory and the experimental data in the frequency dependence of $T_c$ enhancement (Fig. 3d of the revised manuscript).

Second, we agree that in the deep sub-wavelength regime, **one should use the volume from the full electromagnetic environment simulation to avoid introducing artificial "mode-volume compression factors" as we did. Our split-ring cavity device is precisely an example of such deep sub-wavelength cavity in the terahertz spectral range proposed in the literature (a-d).** The mode confinement is far below the diffraction limit constrained by the actual device geometry, without rescaling the vacuum field amplitude.

We have added a new Note 12 to the revised Supplementary Information to discuss based on the sub-wavelength cavity theory. Five new references are added (*Phys. Rev. B 109, 104513 (2024); Proc. Natl. Acad. Sci. U.S.A. 122, e2407995122 (2025); Phys. Rev. Res. 8, 023044 (2026); arXiv:2511.00608 (2025); Phys. Rev. Lett. 122, 133602 (2019)*).

**Comment-4:** One more comment. The measured enhancement of $T_c$ is smaller than 3%. Who cares about a 3% enhancement of $T_c$?

This is a very small enhancement! We need to understand a path to increase this enhancement in the future. I understand this is perhaps a first key paper towards that direction. But we need to understand how to find $T_c$ enhancements that are significant!

Think for example about the modification of the amplitude of the Shubnikov de Haas oscillations in a 2D electron system due to hBN polaritons predicted in https://doi.org/10.1073/pnas.2407995122 - this was smaller than 2%. Measuring DC transport and detecting these small effects is really challenging. But a clear path exists on how to increase cavity effects in these setups, as explained in https://doi.org/10.1073/pnas.2407995122. The question is: since the authors believe to have a theory explaining their data, can they tell us what to do in order to have an increase in $T_c$ of 30%, say? Ten times larger I mean. I believe that it would be great to include a discussion of this type in the main text. Shall we just find cavities where the field enhancement is much larger than that reported in Fig. 1b? Which type of cavities?

**Response:** We thank the referee for the insightful comment, and we agree that this work is the first key paper on cavity-enhanced superconductivity, as pointed out by the referee, rather than a record-setting increase in $T_c$.

Within our microscopic framework, the cavity-induced superconductivity enhancement scales with the effective dimensionless coupling, which can be further enhanced from both the material and cavity sides:

***1. Material side strategies***

The effect depends on how "susceptible" the electronic system is to the cavity field. In this respect, **low-density, highly tunable 2D superconductors** (e.g., gated $MoS_2$, twisted graphene, $LaAlO_3/SrTiO_3$ interface) with small Fermi energies and strong interaction effects can produce a large change in the coupling strength and thus in $T_c$. Tuning density via gating can move the system into regimes (e.g., near van Hove singularities, Lifshitz transitions) where the electronic response to the cavity field is maximized. **High-temperature superconductors** (e.g., $Bi_2Sr_2CaCu_2O_{8+\delta}$, FeSe) are also promising for achieving significant enhancement of $T_c$. The large absolute $T_c$ means that even a few-percent enhancement corresponds to a large absolute shift. More interestingly, materials such as FeSe or cuprates host additional low-energy collective modes (e.g., spin or pairing fluctuations) that can hybridize with the cavity field, providing additional enhancement channels beyond conventional BCS-like systems.

***2. Cavity side strategies***

Another route to enhance $T_c$ is to enhance the cavity fluctuations. Our calculation based on Ginzburg-Landau theory shows that this can be achieved for **small cavity volumes** and **low permittivity** of the medium. Both factors are well known to enhance the amplitude of electromagnetic vacuum fluctuations and have been widely exploited across different cavity-QED platforms. Second, the cavity frequency should **satisfy the resonance condition**, where the cavity-photon energy matches the energy of the condensate at the momentum gained from the photons (see the discussion of the resonance condition on page 14 of the revised manuscript). Finally, achieving a **high-quality factor** ($Q$) can further strengthen the coupling. A low-loss dielectric environment increases the quality factor, and generally enhances the effective light-matter coupling, thereby increasing the magnitude of the cavity-enhanced superconductivity.

We have added discussion to the first paragraph on page 15 of the revised manuscript and added a new Note 14 to the revised Supplementary Information to illustrate the strategies for amplifying cavity-enhanced $T_c$.

**Comment-5:** Finally, I would like to ask the authors the following question. The Columbia group has recently reported a suppression (rather than an enhancement) of the critical temperature of a superconductor due to strong coupling with hBN phonon polaritons: see https://arxiv.org/abs/2505.17378 - in this work, physics is explained in terms of mode coupling. In the superconductor investigated in this arXiv paper, there is a well known phonon mode responsible for a finite $T_c$. This mode happens to be resonant with hBN phonon polariton modes. This resonant behaviour, in the particular case of a phonon mediated superconductor, leads to a suppression of $T_c$. More recently, the authors of https://arxiv.org/abs/2511.00608 have shown (this is just theory so far) that mode coupling can lead to an enhancement of $T_c$ in non-phonon superconductors. In this other arXiv work, the enhancement of $T_c$ is due to strong coupling between 2D metallic plasmons and cavity phonon polaritons. Question: Is there any microscopic picture of this sort in the present work by Zheyan Wang and co-workers? Is there any microscopic Hopfield polaritonic coupling between the modes of superconducting niobium diselenide and the split-ring resonator cavity mode?

**Response:** We thank the referee for the question and for pointing out Refs. *Keren et al., arXiv:2505.17378* (published as *Nature 650, 864-868 (2026)*) and *Riolo et al., arXiv:2511.00608*. In both cases, the physics is governed by microscopic Hopfield-type polaritonic coupling between well-identified bosonic modes.

In our case, the analysis is formulated at the level of a Ginzburg–Landau (GL) description appropriate to the vicinity of the superconducting transition accessed in the experiment. Within this framework, cavity vacuum fluctuations renormalize the GL coefficients through one-loop processes leading to an enhancement of $T_c$. The experimentally observed effect is thus well explained by a thermodynamic renormalization near the phase transition.

It is natural to speculate that, at a more microscopic level, the cavity may couple preferentially to certain phonons in the hBN substrate or the superconductor, thereby inducing polaritons. If such polaritons exist, they could influence superconductivity.

However, the situation is subtle in the case of the superconductor $NbSe_2$. $NbSe_2$ is a complex material characterized by anisotropic and strongly momentum-dependent electron–phonon coupling, where superconductivity is believed to be supported by **multiple phonon branches rather than a single well-defined pairing mode**. In this context, **light–matter hybridization with the split-ring resonator is not expected to manifest as a single isolated polariton resonance, but rather as a distributed spectrum involving several weakly hybridized lattice fluctuations**. Additionally, the material has multiple Fermi-surface pockets, anisotropic superconducting gaps, and coexisting CDW order. These microscopic details make it difficult to establish a direct one-to-one connection between a specific polaritonic coupling and the observed $T_c$ enhancement without a full momentum- and band-resolved pairing analysis, which is beyond the scope of the present manuscript. The GL analysis, on the other hand, captures the near-$T_c$ thermodynamic effect of the cavity through the renormalization of the superconducting free-energy coefficients. A fully microscopic identification of the polaritonic coupling in $NbSe_2$ would require future studies.

We have added a new Note 13 to the revised Supplementary Information to discuss based on the microscopic picture of polaritonic coupling. Two new references are added (*Nature 650, 864-868 (2026); Riolo et al., arXiv:2511.00608*).

## Responses to Referee #2

**General comment:** Please find herewith my assessment of the manuscript: Observation of vacuum-enhanced superconductivity in $NbSe_2$ from Wang et. al. The manuscript reports the first observation of the increase of a critical temperature of $NbSe_2$ when embedded into split-ring cavity resonator. The search for experimental configuration allowing for a feedback between optical cavities and quantum material, and in particular superconductors is certainly timely and subject of a vivid debate. Recent reports documented that embedding materials into optical cavities could reduce the superfluid density, but no observation of enhancement of superconductivity has been reported to date. In this respect the documented evidence of an increased Tc is certainly a novelty and deserve publication in high impact journals.

The scientific quality of the study is overall good. Nevertheless, after a careful reading of the manuscript I remain unconvinced that the observed effect can be conclusively attributed to the cavity electrodynamics.

**Response:** We thank the referee for recognizing the novelty of this work and providing detailed constructive comments. In particular, the referee pointed out the need to exclude trivial effects (e.g., fabrication-related effects) and to perform general tests over different parameters. In response, we have carried out additional experiments to rule out the alternative origins and presented a more systematic study by varying the cavity geometry and thicknesses of the superconductor and the spacer, and metallic plane-cavity experiment. Taken together, this complementary body of evidence further validates the superconductivity enhancement by cavity electrodynamics. The manuscript has been carefully revised accordingly.

**Comment-1:** I think it is difficult to rule out, given the data presented, that the fabrication of the device played a major role in altering the superconducting critical temperature. Could the deposition of the plasmonic structure lead to strain of the material or inhomogeneities?

**Response:** We have performed further control experiments to clarify the trivial fabrication-related effects:

***1. Control experiment with fabrication but without cavity.*** We fabricate a control device in which the $NbSe_2$ flake experiences the same exfoliation, transfer, lithography, and metal/dielectric deposition processes, but without forming a cavity, as shown in Fig. R2. In this device, the spatial configuration—including the position of the metal layer and the dielectric environment—is identical to the local structure of the original cavity devices. Comparing the channels without ($R_1$) and with metal strips ($R_2$) reveals no distinguishable modulation of superconductivity. This suggests that the fabrication-related effects (e.g., strain or inhomogeneities) are not responsible for the $T_c$ enhancement in the hybrid superconductor-cavity device.

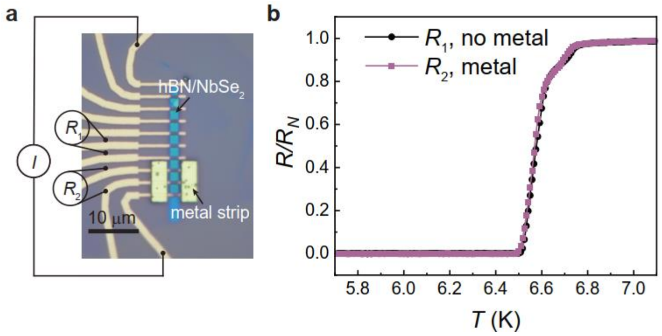



**Figure R2.** Control experiment with nearby metal strips. **a**, Optical micrograph of a 12-layer $NbSe_2$ with nearby metal strips. **b**, Superconductivity transitions without ($R_1$) and with metal strips ($R_2$).

***2. Control experiment using Raman spectroscopy.*** Raman shifts correspond to lattice vibrational modes, and thus provide a sensitive probe of strain (see strained $NbSe_2$ in *Phys. Rev. B 107, 245125 (2023)* and *ACS Appl. Mater. Interfaces 12, 34, 38744–38750 (2020)*). For our $NbSe_2$-cavity device, which exhibits cavity-induced superconductivity enhancement (Fig. R3a,b), we perform Raman measurements. As shown in Fig. R3c, the $A_{1g}$ and $E^1_{2g}$ modes of $NbSe_2$ without cavity (ch1) and with cavity (ch2, ch3) show no distinguishable shift, suggesting negligible strain induced by the fabrication processes.

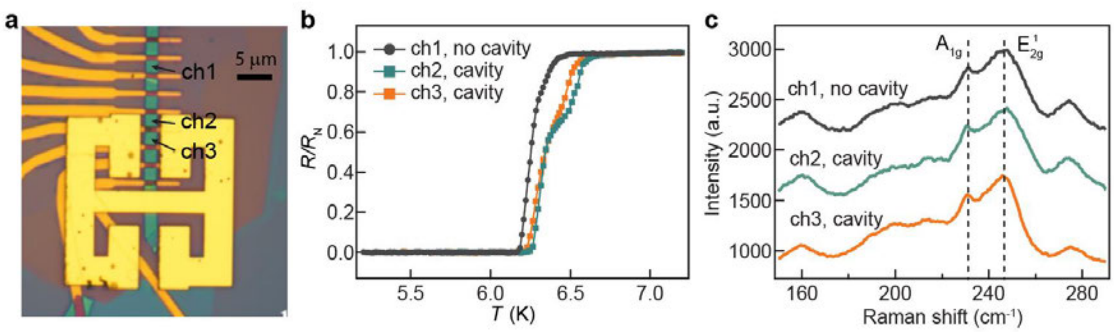



**Figure R3.** Raman measurements of the strain effect. **a**, Schematic of the hybrid $NbSe_2$-cavity device. $NbSe_2$ channels without cavity (ch1) and with cavity (ch2, ch3) are labeled. **b**, Normalized resistance of ch1,2,3 versus temperature. **c**, Raman spectra of ch1, ch2 and ch3. $A_{1g}$ and $E^1_{2g}$ phonon modes are labeled by dashed lines.

***3. Incompatibility with the experimental observations.*** We find that the change in $T_c$ is strongly correlated with the cavity frequency (see the peak-shaped frequency dependence in Fig. 3d of the revised manuscript). The fabrication-induced strain or inhomogeneities, on the other hand, are expected to be randomly distributed among devices.

In summary, these additional results and analyses, support the conclusion that the enhancement of $T_c$ is due to cavity electrodynamics rather than fabrication-induced strain or inhomogeneities.

We have added discussion to the last paragraph on page 6 of the revised manuscript and added a new Note 6 to the revised Supplementary Information to clarify the trivial fabrication-related effects. Figures R2 and R3 are added as the new Supplementary Figs. 2 and 3, respectively.

**Comment-2:** Along the same line, the study reports the effect of split ring resonator at different frequencies. The difference in the geometry of the devices with different resonant frequency could lead to different Tc due to extrinsic fabrication processes? Is it possible to perform experiments where the cavity resonant frequency is kept fixed (ideally in the observed resonant condition), while the geometry and fabrication parameters are changed? More general tests of the different experimental parameters are needed to give a conclusive evidence (shape of the resonators, thickness of the SC layer and spacers).

**Response:** We would like to thank the referee for the constructive suggestions. We have systematically performed control experiments involving the following experimental parameters:

**1.** ***Geometry (shape) of the resonators.*** As suggested by the referee, we modified the cavity geometry by varying its aspect ratio while keeping the cavity frequency fixed at 0.92 THz (close to the peak resonance condition). Measurements were performed for two aspect ratios, 1:1.2 (Fig. R4a,b) and 1:0.9 (Fig. R4c,d), yielding $T_c$ modulations of 1.0±0.1% and 1.0±0.1%, respectively. This indiscernible change of $T_c$ modulation demonstrates that the device geometry, which is related to extrinsic fabrication processes, plays an insignificant role in the observed cavity-modulated superconductivity.

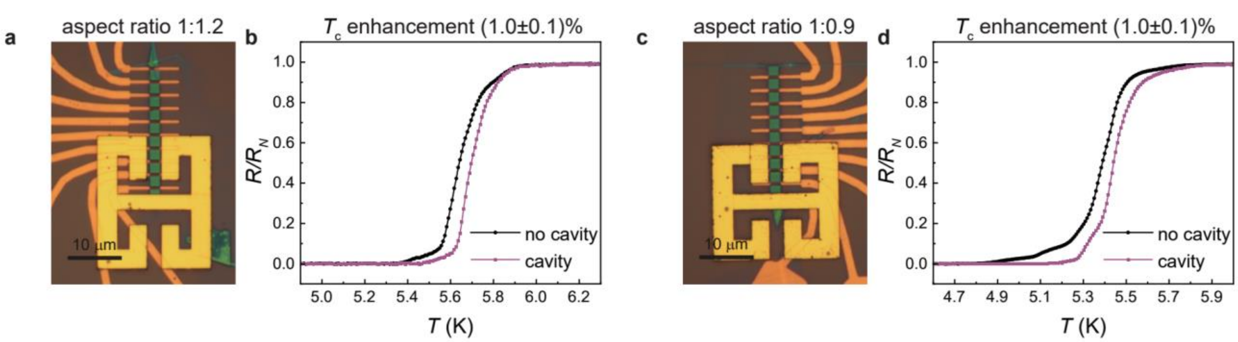



**Figure R4.** Dependence on the cavity geometry. Optical micrographs and cavity-modulated superconductivity for devices with aspect ratios of (**a,b**) 1:1.2 and (**c,d**) 1:0.9. The cavity frequency is 0.92 THz in both cases.

**2.** ***Thickness of the superconductor layer.*** We have further investigated the dependence on the thickness of the superconductor layer. Figure R5 shows the cavity-modulated superconductivity in devices with $NbSe_2$ of 8 layers, 12 layers and 17 layers. The corresponding $T_c$ modulations remain almost constant (0.8±0.4%, 1.0±0.1% and 1.0±0.2%), demonstrating the robustness of the cavity-modulated superconductivity. This is consistent with the scenario that the essential coupling between Cooper pairs and cavity modes should be largely unchanged as long as the superconductor behaves coherently and is fully immersed in the cavity field (with a vertical cavity size of ~210 nm).

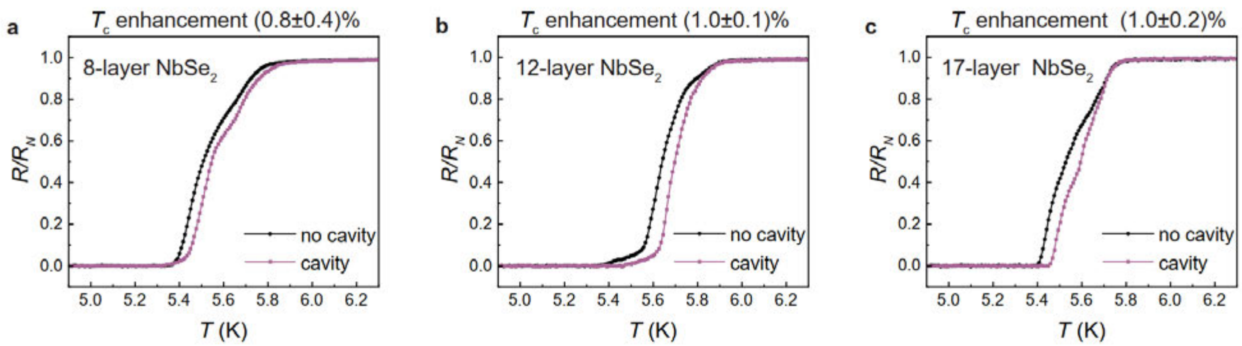



**Figure R5.** Dependence on the $NbSe_2$ thickness. Cavity-modulated superconductivity for devices with $NbSe_2$ of (**a**) 8 layers, (**b**) 12 layers, and (**c**) 17 layers. The cavity is identical for all three cases, with a frequency of 0.92 THz.

**3. *Thickness of the $Al_2O_3$ spacer.*** We further studied the dependence on the thickness of $Al_2O_3$ spacer. As shown in Fig. R6, $T_c$ modulations are 1.0±0.1% and 1.2±0.2% for the 10-nm and 20-nm $Al_2O_3$ cases, respectively. This robustness of $T_c$ modulation against $Al_2O_3$ thickness rules out the fabrication-related effects involving $Al_2O_3$ deposition, and also implies that slightly shifting the $NbSe_2$ position within the cavity gap (by 10 nm downward in this case) does not significantly alter the coupling between cavity and $NbSe_2$.

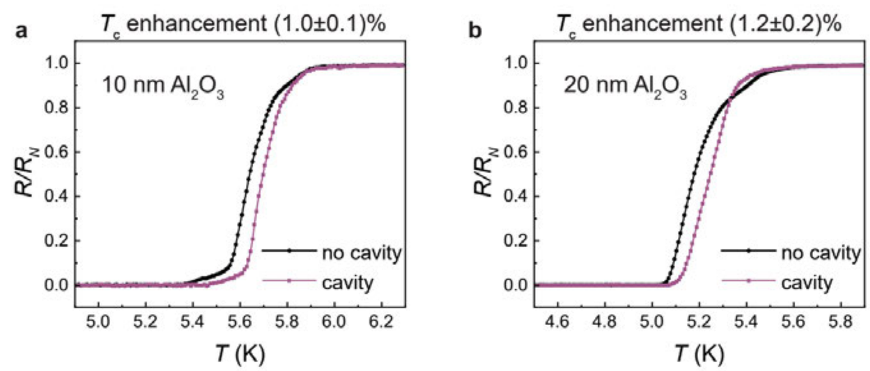



**Figure R6.** Dependence on the $Al_2O_3$ thickness. Cavity-modulated superconductivity for devices with $Al_2O_3$ thicknesses of (**a**) 10 nm and (**b**) 20 nm. The cavity is identical for both cases with frequency of 0.92 THz.

Overall, we performed general tests of different parameters and found that **the cavity-enhanced superconductivity is robust against the variations in cavity geometry (fixed frequency), as well as against changes in the thicknesses of $NbSe_2$ and $Al_2O_3$ within the studied ranges.** This complementary evidence excludes extrinsic origins, such as fabrication processes, and points to the dominant interaction between cavity field and superconductor.

we have added discussion to the last paragraph on page 6 of the revised manuscript and added a new Note 7 to the revised Supplementary Information to include control experiments involving different experimental parameters. Figures R4, R5 and R6 are added as the new Supplementary Figs. 4 and 5, respectively.

**Comment-3:** Ultimately I find difficult that a convincing evidence that the cavity electrodynamics plays a major role could be given without devices where the antenna is placed at different tuneable distance from the cavity (as for example in recent studies of topological systems https://www.science.org/doi/10.1126/science.abl5818). This would convincingly prove that the changes in Tc are not associated to fabrication issues but rather to the photonic characteristics of the resonator. I understand this requires very likely a different setup, but at least an extensive study of devices with different parameters and distance of the antenna should be given.

**Response:** Ref. *Science 375,1030-1034(2022)*, as pointed out by the referee, reports enhanced modulation of the quantum Hall effect when a metallic plane is brought in proximity to the resonator. Although we do not have such a setup to continuously tune the plane-cavity distance, we introduce a similar method: depositing another 10-nm $Al_2O_3$ layer on top of the cavity device, followed by a metallic plane (Fig. R7c). This enables a direct comparison based on the same device, without and with a metallic plane, effectively corresponding to **a tunable metallic plane at an infinite distance versus one at a 10-nm distance**. Fig. R7a,b and Fig. R7c,d show the results of cavity only case and plane-cavity case, respectively. Remarkably, $T_c$ enhancement of the plane-cavity case (3.5±1.3%) is significantly stronger than that of the cavity only case (1.0±0.1%). This stronger $T_c$ enhancement in the presence of a metallic plane is consistent with the enhanced cavity-modulation reported in Ref. *Science 375,1030-1034(2022)*, suggesting that **the effect originates from the photonic characteristics of the resonator, rather than fabrication-related issues.**

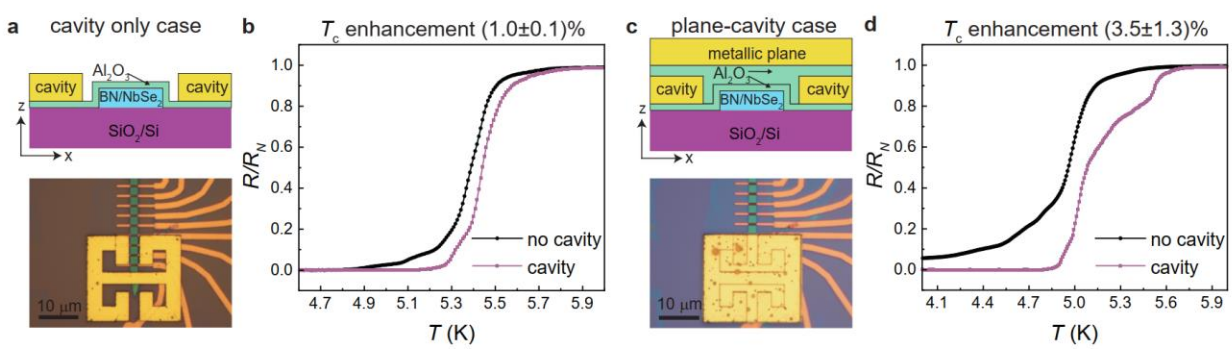



**Figure R7.** Control of cavity-enhanced superconductivity by a metallic plane. Optical micrographs and cavity-enhanced superconductivity for (**a,b**) cavity only case and (**c,d**) plane-cavity case, respectively. A cross-sectional view is provided above each micrograph.

We have added a new Note 8 to the revised Supplementary Information to present the cavity experiment with a metallic plane. Figure R7 is added as the new Supplementary Fig. 6.

**Comment-4:** One additional criticism connected to the previous ones is that all the results reported are measured on a 12-layers $NbSe_2$ sample. Authors should include a thickness dependence and show how ΔTc scale with the thickness of the superconductor and the spacing layers.

**Response:** Following the referee's suggestion, we performed control experiments to study the dependence on the thicknesses of both $NbSe_2$ and the $Al_2O_3$ spacer. As detailed in our response to Comment-2 (Fig. R5 and Fig. R6), we find that $\Delta T_c$ remains largely unchanged versus the thicknesses of both $NbSe_2$ and $Al_2O_3$ within the studied ranges, indicating that the cavity-enhanced superconductivity is robust against moderate variations of those thicknesses. This behavior is consistent with the fact that the coupling between Cooper pairs and cavity modes is primarily governed by the field distribution and resonance condition (determined by the cavity frequency), provided that the superconductor remains fully immersed in the cavity field.

We have added a new Note 7 to the revised Supplementary Information to include the control experiments involving thickness variations of the superconductor and the spacing layer. Figures R5 and R6 are added as the new Supplementary Fig. 5.

**Comment-5:** Along the same line, how would the reported effect on the critical temperature depends on the cavity quality factor? The paper mentions a quality factor Q ≈ 11. How was this extracted experimentally? How does the resonant condition of the split ring resonator depend on the dielectric environment?

**Response:** We would like to address this comment in three aspects:

**1. *Dependence of $T_c$ modulation on the cavity quality factor***

We first present the equation for the $T_c$ modulation (added to the revised manuscript): $\delta T_c = -\frac{e^2\chi_\phi}{\varepsilon\alpha_0 m V_{SC}\sqrt{\omega_c^2-\gamma^2}} - \frac{e^2}{2\varepsilon\alpha_0 m^2 V_{SC}\omega_c}\mathrm{Re}\int\frac{d^3k}{(2\pi)^3}|\tilde{\phi}(k)|^2 k_y^2\left[\frac{1}{\Omega+\omega_c-i\gamma} - \frac{1}{\Omega-\omega_c-i\gamma}\right]$, where $\Omega = -\frac{k^2}{2m} - \alpha$, $V_{SC}$ is the sample volume, $\tilde{\phi}(k)$ is the Fourier transform of the mode function, $y$ is the direction of the mode polarization $\hat{\boldsymbol{e}}$, $\gamma$ is the frequency broadening of the cavity, and $\chi_\phi = \int_{V_{SC}} d^3x|\phi(x)|^2$ is the fractional overlap of the mode density with the sample. **Cavity quality factor $Q = \frac{\omega_c}{2|\gamma|}$ can influence the critical temperature through the attenuation $\gamma$**. Its role is important due to the finite loss in THz cavities (*Nat. Phys. 12, 1005–1011 (2016)*). Figure R8 compares the theoretical results for different $Q$ values (dashed lines), showing that ***Q* crucially determines the peak width and amplitude, and thus the maximum $T_c$ enhancement**.

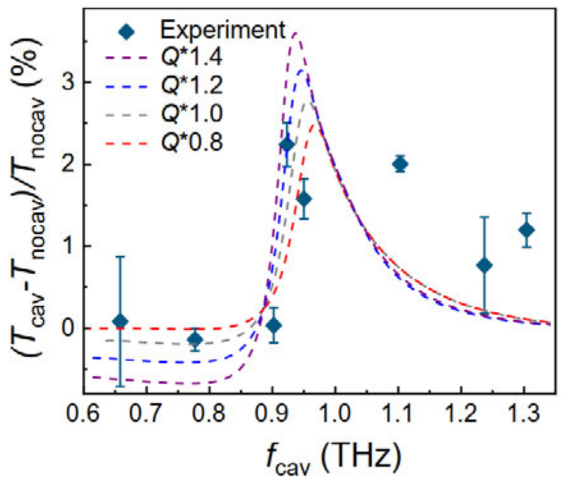



**Figure R8.** Enhancement coefficient of the superconducting critical temperature as a function of cavity frequency. Dashed lines represent the theoretical prediction curves for the quality factor $Q$ rescaled by factors of 1.4, 1.2, 1.0 and 0.8, respectively, while all other parameters are kept fixed. The data points are extracted by the fitting method (see the extraction of $T_c$ in the new Note 5 of the revised Supplementary Information).

**2. *Extraction method of the quality factor Q***

The quoted value $Q \approx 11$ is inferred from fitting the experimental data in Fig. R8. $Q$ represents the effective cavity linewidth, where dissipation is incorporated via a frequency broadening $\gamma$, with $Q = \frac{\omega_c}{2|\gamma|}$. $\gamma(\omega_c)$ is modeled phenomenologically as $\gamma(\omega_c) = a\omega_c + b$ , with fitted parameters $a \approx 1.95$, $b \approx -2.48$ to reproduce the measured $T_c$ modulation (Fig. R8). This yields a representative value $Q \approx 11$ at around 1.3 THz.

**3. *Dependence of the resonance condition on the dielectric environment***

The influence of the dielectric environment on the resonance condition (maximum $T_c$ enhancement) manifests in three main ways: **(1)** The vacuum field fluctuation amplitude can be estimated as $E = \sqrt{\hbar\omega_c/2\varepsilon_0\varepsilon_s V_{\text{eff}}}$. Thus, the **dielectric environment modifies the cavity field amplitude by changing the effective permittivity $\boldsymbol{\varepsilon_s}$ and reshaping the mode volume $\boldsymbol{V_{\text{eff}}}$**, thereby tuning the magnitude of $T_c$ enhancement; **(2)** The resonant frequency of the LC resonator is set by its effective inductance $L_{\text{eff}}$ and capacitance $C_{\text{eff}}$: $f \approx \frac{1}{2\pi\sqrt{L_{\text{eff}}C_{\text{eff}}}}$. The dielectric environment enters the resonant frequency via $C_{\text{eff}} \propto \varepsilon_{\text{eff}}$. Therefore, **changing the dielectric environment shifts the cavity resonant frequency** as $f \sim 1/\sqrt{\varepsilon_{\text{eff}}}$; **(3)** One of loss channels that limit the quality factor is dielectric loss, which is determined by the dielectric environment. **A low-loss dielectric environment increases the quality factor, and generally enhances the effective light-matter coupling**, thereby increasing the magnitude of the cavity-enhanced superconductivity.

We have added a new Note 10 to the revised Supplementary Information to present the extraction of $Q$ and its impact on $T_c$ modulation. Figure R8 is added as the new Supplementary Fig. 10.

**Comment-6:** What determines the resonant condition where the larger effect is observed? Can the authors elaborate what is the cavity coupled to and whether the system is in the weak/strong/ultra-strong coupling regime?

**Response:** We would like to clarify the resonance condition and cavity-matter coupling in three aspects:

***1. What determines the resonance condition***

The frequency at which the largest enhancement of $T_c$ occurs is set by **the resonance between cavity photons and superconducting fluctuations**. Within our framework, this condition can be expressed as $\hbar\boldsymbol{\omega_c} = \frac{\hbar^2}{\mathbf{2m}}\mathbf{Re}[\boldsymbol{k_c^2}]$, where $k_c \propto \lambda^{-1} + i\xi^{-1}$ is the complex momentum exchanged between the cavity and the condensate. A key point is that the real and imaginary parts of $k_c$ play distinct physical roles. The **real part** determines the characteristic momentum (and hence energy) of superconducting fluctuations that can be resonantly coupled to the cavity mode, thereby fixing the position of the resonance. The **imaginary part**, on the other hand, encodes damping and finite coherence, and therefore governs the broadening of the resonance peak. This is fully consistent with standard perturbative response theory, where the real part sets the resonance condition while the imaginary part controls the linewidth. In the idealized limit of vanishing damping (i.e., infinite quality factor and negligible imaginary part), the resonance would become sharp and maximal, corresponding to perfect matching between the cavity photon energy and the fluctuation spectrum of the superconductor. In realistic systems, both the finite penetration depth and cavity loss lead to a finite linewidth.

Physically, the resonance arises when **the energy of a cavity photon matches the energy cost of a superconducting fluctuation at the momentum selected by the cavity mode profile**. At this point, virtual photon exchange processes—particularly the reabsorption channel discussed in Fig. 3f—produce the largest correction to the Ginzburg–Landau coefficient, resulting in the maximal enhancement of $T_c$. This mechanism underlies the peak observed at around $f_{cav}$ = 0.95 THz in Fig. 3d of the revised manuscript.

***2. What the cavity is coupled to***

In our device, the metallic split-ring resonator realizes a sub-wavelength cavity mode whose electric field is strongly confined in the gap region, overlapping with the $NbSe_2$ flake. The coupling is captured in the GL functional by the minimal coupling $D_\mu = \partial_\mu - i\frac{2e}{c}A_\mu$, so that the mode couples directly to the Cooper-pair condensate $\psi(\boldsymbol{x}, t)$.

The processes represented by the one-loop diagrams in Fig. 3e,f of the revised manuscript make this coupling explicit: the cavity exchanges virtual photons with the Cooper-pair condensate. In other words, **the cavity couples to the collective low-energy superconducting fluctuations encoded in the GL field $\psi$.** The enhancement of superconductivity arises predominantly from the virtual-photon-reabsorption process (Fig. 3f of the revised manuscript), which lowers the condensate energy.

***3. Coupling regime: weak/strong/ultra-strong***

The conventional classification into weak/strong/ultra-strong coupling is typically defined through well-resolved Rabi splitting. The situation in our case is more subtle: (1) Superconducting "matter" sector is described by a broad continuum of superconducting fluctuations, rather than by a single, narrow transition; (2) Cavity quality factor extracted in our frequency range is modest (Q ≈ 11), corresponding to a relatively large loss rate; (3) Experimentally, we do not observe a clear Rabi-type mode splitting in the cavity spectrum. Instead, the cavity modifies the superconducting free energy through virtual processes, which are revealed in transport (shifts of $T_c$, $I_c$, and $H_c$), rather than through resolved polaritonic branches. Therefore, it's not straightforward to define the coupling strength in our case, and the present data do not allow us to assign the system unambiguously to the standard weak/strong/ultra-strong coupling regimes. However, to characterize the light-matter coupling, one can still roughly define the coupling strength as a dimensionless quantity (*Phys. Rev. Lett. 126, 153603 (2021)*): $g/\omega_c = \frac{1}{\omega_c}\sqrt{\frac{q^2}{2m_{eff}\varepsilon V_{eff}}}$ ($m_{eff}$ from *Phys. Rev. B 57, 11698 (1998)*), and we obtain $g/\omega_c$ = 0.00044. This shows that the coupling is in the weak coupling regime.

We have revised the second paragraph on page 13 and the first paragraph on page 14 of the revised manuscript to clarify the resonance condition, the coupling between cavity and superconducting fluctuations.

**Comment-7:** I find very surprising that the authors do not observe any change in the critical currents at low temperature but only a change in $T_c$. Can the author argue why the critical currents is unchanged while $T_c$ is? Are critical currents, $T_c$ and superfluid density not related in this case?

**Response:** We would like to respond by the following two temperature regimes:

***(1) Low temperature regime***

At low temperatures, when the system is deeply inside the superconducting state, **the condensate density is essentially saturated** (and likewise the superfluid density in such conventional superconductor), meaning that almost all the available electrons at the Fermi surface are paired up. Consequently, the cavity vacuum field has minimal influence on the condensate density and therefore, on the critical current $I_c$. As a result, **no appreciable change in $I_c$ is observed in this regime**.

***(2) Temperature regime approaching the superconducting transition***

As the temperature approaches the superconducting transition, however, the **condensate density decreases rapidly and becomes highly susceptible to external perturbations**. In this fluctuation-dominated regime, even a relatively small cavity-induced renormalization of the superconducting free energy can noticeably modify the superconducting stiffness, leading to a pronounced and **concurrent cavity-induced enhancement of both $I_c$ and $T_c$**. Therefore, **$I_c$, $T_c$, and the condensate density (as well as the superfluid density) are closely related and rooted in the same mechanism**. These observations further corroborate the vacuum-field-enhanced superconductivity in $NbSe_2$.

On page 8 of the revised manuscript, we have revised the last paragraph to clarify the mechanism underlying the changes of $I_c$, $T_c$ and the condensate density.

**Comment-8:** In the determination of the critical magnetic field, discuss whether B modifies the cavity parameters and, if so, how this could feed back into $\Delta T_c$.

**Response:** For the metallic split-ring cavity, the cavity parameters (resonant frequency, mode volume and quality factor) are essentially determined by the metals (Au/Ti) and the surrounding dielectric environment, which do not change under a static external magnetic field at moderate strength. This is verified by a control experiment reported in *Science 335,1323-1326 (2012)*. As marked by the dashed rectangle in Fig. R9, transmission measurement on a split-ring cavity (similar to our case) shows negligible frequency shift or modification of the absorption strength and shape under an external field up to 9 T.

REDACTED

Figure R9. Transmission of a split-ring cavity as a function of the magnetic field ($T$ = 10 K), from the Supplementary Material in *Science 335,1323-1326 (2012)*.

On page 8 of the revised manuscript, we have added discussion to the second paragraph to clarify that the magnetic field does not modify cavity parameters.

**Comment-9:** The vacuum-field estimate (~ 260 V/m) relies on Veff and εs. The authors should show how Veff = 79 μm³ and εs = 5.1 are experimentally measured.

**Response:** $\boldsymbol{\varepsilon_s}$ is the effective permittivity of the cavity-substrate system. For an LC resonator, the permittivity enters the frequency via the capacitance, $f \propto \frac{1}{\sqrt{C}} \propto \frac{1}{\sqrt{\varepsilon}}$. Accordingly, the effective permittivity is defined as $\varepsilon_s \approx \left(\frac{f_{vac}}{f_{sub}}\right)^2$, where $f_{vac}$ and $f_{sub}$ are the cavity frequencies in vacuum and on substrate, respectively, and their values are obtained by electromagnetic simulations (CST Microwave Studio) based on actual device geometry. Therefore, we can obtain $\varepsilon_s = 5.1$.

$\boldsymbol{V_{eff}}$ is the effective volume, defined as $V_{eff} = \frac{\int_{\text{all space}} \varepsilon |E(\boldsymbol{r})|^2 dV}{\max[\varepsilon |E(\boldsymbol{r})|^2]}$ in the standard way used in cavity QED (*PRL 95, 143901 (2005)*). The field distribution in this expression is obtained by electromagnetic simulations based on actual device geometry, which yields $V_{eff} = 79\ \mu m^3$.

We have added a new Note 3 to the revised Supplementary Information to illustrate the determination of $\varepsilon_s$ and $V_{eff}$.

**Comment-10:** In figure 3 the error bar is misleading. As it is described in the text the error bar does not represent and experimental statistical error, but it is rather representative on how are systematic error in extracting the critical temperature accounted for.

**Response:** We agree with the referee and have added the meaning of the error bars to the caption of Fig. 3 of the revised manuscript.

**Responses to Referee #3**

**General comment:** This manuscript presents an experimental strategy to enhance superconductivity by embedding a superconducting material in a split-ring cavity resonator. Using the layered transition-metal dichalcogenide superconductor NbSe2 as a test platform, the authors compare the critical temperature (Tc), critical current, and upper critical field between device regions with and without a cavity and report enhanced superconducting properties in the cavity-coupled regions. Upon tuning the cavity resonance, the Tc enhancement exhibits a non-monotonic dependence on the cavity frequency. The results are interpreted within a Ginzburg-Landau framework that accounts for coupling between superconductivity and cavity photons.

Cavity-vacuum engineering is an emerging approach to manipulating quantum materials. To the best of current knowledge, this work provides the first experimental demonstration of cavity-enhanced superconductivity evidenced by electrical transport. It represents a noteworthy advance, introducing a noninvasive route to controlling superconductivity, and it may meet the standard of Nature. Nevertheless, several issues that appear to limit the strength of the present study warrant more detailed discussion.

**Response:** We are grateful to the referee for recognizing the significance of this work. In response to the referee's concerns, we have performed additional experiments (e.g., varying thicknesses of $NbSe_2$ and $Al_2O_3$) to further validate the cavity electrodynamics origin and provided explicit discussions on the strategies for enhancing $T_c$, role of dielectric environment, height dependence, etc. The manuscript has been carefully revised accordingly.

**Comment-1:** The maximum Tc enhancement is 0.16 K from a baseline Tc of 6.38 K, corresponding to a 2.5% increase. Other techniques, e.g., field-effect gating (0.2 K, Phys. Rev. B 80, 184505, 2009) and ionic-liquid gating (2 K, Phys. Rev. Lett. 117, 106801, 2016) in few-layer NbSe2, achieve comparable and even larger shifts. Describing the present change as a "substantial increase in the critical temperature" appears overstated. Moreover, the enhancements of critical current and upper critical field are appreciable mainly near Tc, with negligible effects observed in the superconducting ground state. In addition, Ref. 29 ("Exploring superconductivity under strong coupling with the vacuum electromagnetic field") reports an increase of Tc in Rb3C60 from 30 K to 45 K. Given the manuscript's emphasis on enhancing superconductivity, including aspirations toward room-temperature regimes, the comparative advantage and long-term potential of the present approach are not yet evident. Based on the data currently presented, the principal contribution appears to be a proof-of-principle demonstration rather than a substantial increase in Tc. The manuscript would benefit from a more balanced articulation of the study's motivation and of the implications of the results.

**Response:** We appreciate the referee's recognition of this work as a "proof-of-principle demonstration" and the suggestion to provide "a more balanced articulation". In the revised manuscript, we have revised the abstract and main text to avoid overstating the results, and to emphasize that the main contribution is a proof-of-principle demonstration of cavity-enhanced superconductivity.

**Comment-2:** A more detailed discussion of the device design would clarify key factors required to observe robust Tc modulation. For example, what is the rationale for the chosen cavity geometry, and could alternative designs be more effective for enhancing Tc?

**Response:** We would like to respond in two aspects:

**1.** ***Rationale for the chosen split-ring cavity geometry***

The choice of the cavity was guided by four main considerations: **(1)** The sub-wavelength split-ring resonator can **achieve high field enhancement**. The vacuum field fluctuation amplitude is estimated to be ~260 V/m, almost four orders of magnitude stronger than that of the free space (~0.43 V/m) for the same frequency. Such field boosting can significantly enhance the light-matter interaction. **(2)** The frequency of the split-ring cavity can be easily tuned to the resonance condition: the typical **near-terahertz frequency of the cavity matches the energy of the superconducting fluctuation** of $NbSe_2$ (see analysis of the resonance condition on page 14 of the revised manuscript). **(3)** The **planar split-ring architecture is compatible with the exfoliated layered materials**, allowing for flexible alignment and integration. **(4)** As verified in earlier works (*Science 375, 1030-1034 (2022); Nature 641, 884-889 (2025)*), such **split-ring cavity can enable effective coupling with electron systems**.

**2.** ***Alternative designs to be more effective for enhancing*** $T_c$

In principle, device design can be further improved to produce stronger $T_c$ enhancement. Here we propose strategies from both the material side and cavity side:

***(1) Materials side strategies***

The effect depends on how "susceptible" the electronic system is to the cavity field. In this respect, **low-density, highly tunable 2D superconductors** (e.g., gated $MoS_2$, twisted graphene, $LaAlO_3/SrTiO_3$ interface) with small Fermi energies and strong interaction effects can produce a large change in the coupling strength and thus in $T_c$. Tuning density via gating can move the system into regimes (e.g., near van Hove singularities, Lifshitz transitions) where the electronic response to the cavity field is maximized. **High-temperature superconductors** (e.g., $Bi_2Sr_2CaCu_2O_{8+\delta}$, FeSe) are also promising for achieving significant enhancement of $T_c$. The large absolute $T_c$ means that even a few-percent enhancement corresponds to a large absolute shift. More interestingly, materials such as FeSe or cuprates host additional low-energy collective modes (e.g., spin or pairing fluctuations) that can hybridize with the cavity field, providing additional enhancement channels beyond conventional BCS-like systems.

***(2) Cavity side strategies***

Another route to enhance $T_c$ is to enhance the cavity fluctuations. Our calculation based on Ginzburg-Landau theory shows that this can be achieved for **small cavity volumes** and **low permittivity** of the medium. Both factors are well known to enhance the amplitude of electromagnetic vacuum fluctuations and have been widely exploited across different cavity-QED platforms. Second, the cavity frequency should **satisfy the resonance condition**, where the cavity-photon energy matches the energy of the condensate at the momentum gained from the photons (see the discussion of the resonance condition on page 14 of the revised manuscript). Finally, achieving a **high quality factor** ($Q$) can further strengthen the coupling. A low-loss dielectric environment increases the quality factor, and generally enhances the effective light-matter coupling, thereby increasing the magnitude of the cavity-enhanced superconductivity.

We have added a new Note 1 to the revised Supplementary Information to clarify the rationale for the chosen cavity. We have added discussion to the first paragraph on page 15 of the revised manuscript and added a new Note 14 to the revised Supplementary Information to present the strategies for amplifying cavity-enhanced $T_c$.

**Comment-3:** Although the central idea is to exploit coupling between NbSe2 and vacuum fluctuations, the devices placed NbSe2 between a substrate and capping layers rather than in vacuum. At a theoretical level, how does the dielectric environment affect Tc modulation? In particular, what is the influence of the substrate and capping materials and their thicknesses on the measured Tc?

**Response:** We would like to respond in two aspects:

***1. Dielectric environment affecting $T_c$ modulation***

The influence of the dielectric environment on the $T_c$ modulation manifests in three ways: **(1)** The vacuum field fluctuation amplitude can be estimated as $E = \sqrt{\hbar\omega_c/2\varepsilon_0\varepsilon_s V_{\mathrm{eff}}}$. Thus, the **dielectric environment modifies the cavity field amplitude by changing the effective permittivity $\boldsymbol{\varepsilon_s}$ and reshaping the effective volume $\boldsymbol{V_{\mathrm{eff}}}$**, thereby tuning the magnitude of $T_c$ enhancement; **(2)** The resonant frequency of the LC resonator is set by its effective inductance $L_{\mathrm{eff}}$ and capacitance $C_{\mathrm{eff}}$: $f \approx \frac{1}{2\pi\sqrt{L_{\mathrm{eff}}C_{\mathrm{eff}}}}$. The dielectric environment enters the resonant frequency via $C_{\mathrm{eff}} \propto \varepsilon_{\mathrm{eff}}$. Therefore, **changing the dielectric environment shifts the cavity resonant frequency** as $f \sim 1/\sqrt{\varepsilon_{\mathrm{eff}}}$; **(3)** One of loss channels that limit the quality factor $Q$ is dielectric loss, which is determined by the dielectric environment. **A low-loss dielectric environment increases the quality factor, and generally enhances the effective light-matter coupling**, thereby increasing the magnitude of the cavity-enhanced superconductivity.

*2. Influence of the substrate and capping materials*

**Substrate and capping materials form the dielectric environment, which modifies multiple cavity parameters**, including the permittivity $\varepsilon_s$, effective volume $V_{eff}$, cavity resonant frequency $f$, and quality factor $Q$, thereby changing the measured $T_c$ enhancement. Specifically, increasing the dielectric constant or thicknesses of the capping layers increases $\varepsilon_s$ and $V_{eff}$, which reduces cavity field strength and decreases $T_c$. Moreover, a larger permittivity tends to redshift the resonant frequency of the maximum $T_c$ enhancement. Introducing a lossy dielectric material suppresses the light-matter coupling and reduces the measured $T_c$ enhancement.

We have added a new Note 11 to the revised Supplementary Information to clarify the influence of the dielectric environment on $T_c$ modulation.

**Comment-4:** The NbSe2 is covered by 15-nm hBN and 10-nm Al2O3, with a 200-nm Au/10-nm Ti split-ring fabricated on top of Al2O3. Thus, NbSe2 is separated vertically from the cavity by 25 nm. Figure 1b,c presents simulated vacuum-field enhancement, but the simulation methodology is not described and the height at which the field is evaluated is unspecified. Given that the cavity thickness exceeds the NbSe2 thickness by an order of magnitude, the authors are suggested to clarify whether the field enhancement is height-dependent and whether an optimal height (within the cavity rather than below the cavity) exists for maximizing Tc enhancement.

**Response:** We would like to respond in two aspects:

***1. Simulation methodology***

Method of electromagnetic simulation: The field distributions are obtained by finite-element simulations performed with Computer Simulation Technology (CST) Microwave Studio, following previous studies (*Phys. Rev. B 78, 241103 (2008)*; *Science 375, 1030-1034 (2022)*). The metallic cavity is modeled as standard lossy gold from the material library. The substrate consists of 285-nm-thick $SiO_2$ on top of a 675-µm-thick Si. $NbSe_2$ is modeled as a perfect electric conductor. The thin $Al_2O_3$ and hBN layers are omitted from the simulations to reduce the computational cost. The cross-section of the simulated device is shown in Fig. R10, where the dashed line indicates the height at which the field is evaluated in this work (always the central height of $NbSe_2$).

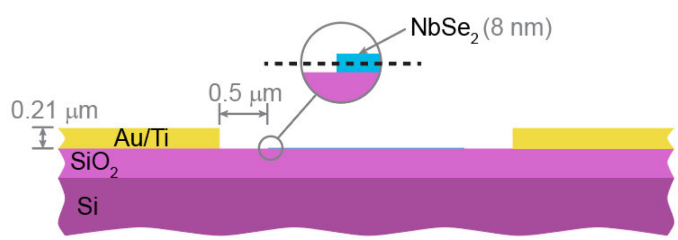


**Figure R10.** A cross-sectional view of the simplified device in the simulation. The dashed line at the middle of $NbSe_2$ marks the height at which the field is evaluated.

***2. Height dependence of the field enhancement***

We would like to first clarify that **$NbSe_2$ is separated vertically from the cavity by 6 nm**, rather than 25 nm. Figure R11a schematically illustrates the cross-sectional view of the actual device in an exaggerated representation, where the central height of $NbSe_2$ is 6 nm below the cavity.

To determine the height dependence of the field, we simulate the field-enhancement distribution in the *x*-*z* plane. Figure R11b,c shows the schematic of the simplified cavity structure and the corresponding simulated field distribution, respectively. We focus on the field enhancement at the $NbSe_2$ edge, located 0.5 μm from the cavity edge (as indicated by the dashed lines). Figure R11d presents the height-dependent profile along the dashed lines in Fig. R11b,c, indicating that **the field exhibits a very weak dependence on height within the cavity and up to 100 nm below it**. We note that eventually the field decays and vanishes at distances on the micrometer scale away from the cavity.

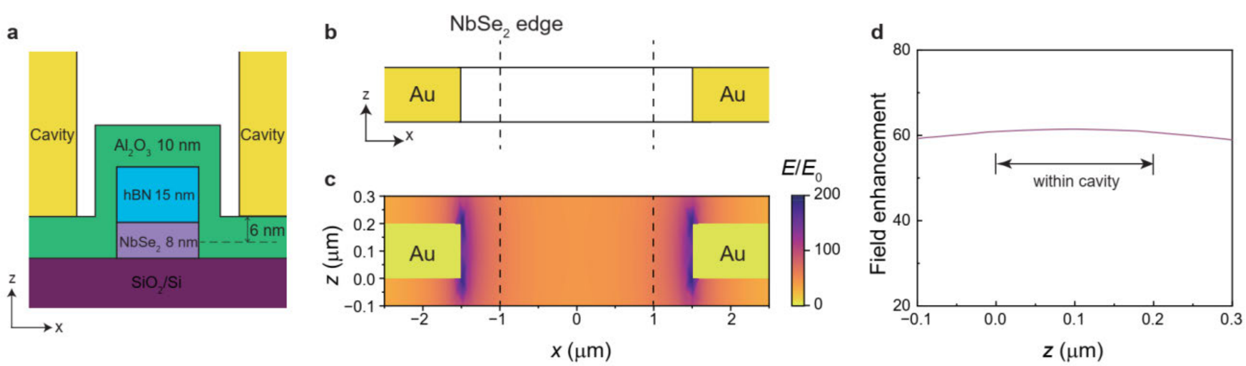



**Figure R11.** Simulated height dependence of the field. **a**, Cross-sectional view of the actual device in an exaggerated representation. **b**, Cross-sectional view of the simplified cavity. **c**, Simulated distribution of the field enhancement in the *x*-*z* plane. The dashed lines mark the $NbSe_2$ edges. **d**, Field-enhancement profile along the dashed lines in **b**,**c**.

To further verify the height dependence, we performed a control experiment, in which the vertical position of $NbSe_2$ within the cavity was shifted by changing the thickness of $Al_2O_3$ (Fig. R12). Increasing the $Al_2O_3$ thickness from 10 nm to 20 nm corresponds to a 10-nm downward shift of $NbSe_2$. Indeed, **no appreciable difference in $T_c$ enhancement is observed, consistent with the field simulation above**.

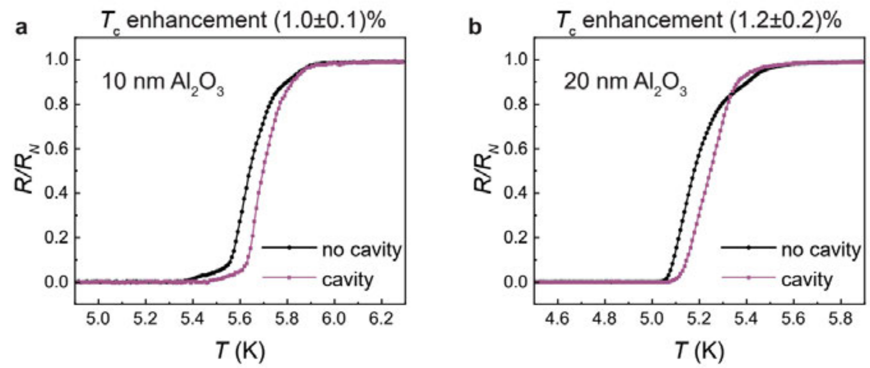



**Figure R12.** Height dependence with varying $Al_2O_3$ thickness. Cavity-modulated superconductivity for devices with $Al_2O_3$ thicknesses of (**a**) 10 nm and (**b**) 20 nm. The cavity is identical for both cases, with a frequency of 0.92 THz.

We have added a new Note 3 to the revised Supplementary Information to illustrate the method of electromagnetic simulations. On page 4 of the revised manuscript, we have added discussion to the first paragraph to clarify the height dependence of the simulated field. Figure R11b-d is added as the new Extended Data Fig. 1. Figure R12 is added as the new Supplementary Fig. 5d,e.

**Comment-5:** Figure 1c indicates that the field enhancement is strongly localized at the flake edge within <0.1 µm, a small fraction of the total area. This suggests that only this region experiences enhanced fields, implying a local Tc increase and potential sample inhomogeneity. Such inhomogeneity could account for the two-step transition seen in Fig. 1e (versus a single transition in the control area outside the cavity), with a similar trend in Fig. 1g. Yet Tc is also enhanced in the lower-temperature portion of the two-step transition, indicating modifications away from the edge. Is this mediated by interactions between the edge region and the interior? More importantly, the authors are suggested to consider whether the effect of edge-localized vacuum-field enhancement on Tc can be isolated and quantified.

**Response:** We thank the referee for this insightful comment about spatial inhomogeneity and the edge-interior difference. We would like to respond by the following two points:

***1. Spatial localization of the field and relation to the observed $T_c$***

We agree with the referee that the field is localized at the flake edge (Fig. 1c of the revised manuscript) and may give rise to different $T_c$ values for the edge and interior regions. However, **transport measurements may not resolve this difference even if the edge and interior contribute differently**. The conductance of the edge and interior can be viewed as a parallel circuit, in which the zero-resistance edge (presumably higher-$T_c$) may short-circuit the lower-$T_c$ interior. As a result, one may still observe a single superconducting transition even in the presence of edge-interior difference. We also note that among the hybrid $NbSe_2$-cavity devices, some do not exhibit a two-step transition (e.g., Fig. R6a,b), whereas such two-step behavior does appear in some intrinsic $NbSe_2$ without a cavity (e.g., Fig. 3a,c of the revised manuscript). This suggests that the two-step transition likely originates from the modest inhomogeneity of $NbSe_2$, rather than from the cavity-induced edge-interior difference.

On the other hand, **the superconducting state is inherently nonlocal and phase coherent**. Even if the cavity field is spatially concentrated near the edge, its effect is not necessarily restricted to that region. Physically, the edge and interior are coupled through the superconducting order parameter. Enhancement of superconductivity at the edge can propagate into the interior via well-established mechanisms such as proximity-induced pairing and Andreev processes. In addition, the superconducting phase must remain globally coherent, which imposes a constraint that couples different regions of the sample. As a result, a local modification of the pairing strength can influence the effective transition of the entire device, leading to a measurable $T_c$ modulation even in regions where the field is weaker.

***2. Can the edge-localized contribution be isolated and quantified?***

With the present transport geometry, fully isolating the edge contribution in experiments is challenging because the measured resistance is not a simple linear superposition of regions with different local $T_c$ and current distributions. Here, we propose several strategies to isolate/quantify the edge effect: (1) Etching the superconductor flake to a width comparable to the edge-enhanced region (<100 nm), so that the entire flake is an effective "edge"; (2) Using local probes (e.g., scanning superconducting quantum interference device or scanning tunneling spectroscopy) to map the spatial variation of the superconducting gap. While this work provides clear global evidence of the cavity-induced superconductivity enhancement, a spatially resolved characterization would be an important next step.

We have added a new Note 4 to the revised Supplementary Information to discuss the spatial localization of the field and its impact on superconductivity.

**Comment-6:** The definition of the effective cavity volume is not clearly provided. The cavity frequency is tuned by changing the gap length, which should also alter the cavity volume and thus the vacuum-field amplitude, according to the formula on Page 4. In Fig. 3d and the accompanying theory, changes in Tc are attributed solely to frequency shifts. How to justify neglecting the concomitant volume-induced changes in vacuum-field strength?

**Response:** We thank the referee for this thoughtful comment and agree that changing the gap length (for the purpose of tuning the frequency) may alter the cavity volume and thus the vacuum-field amplitude. To address this concern, we estimate the variation of the field as a function of the cavity frequency by changing the gap length, which shows a linear dependence (Fig. R13a). We then incorporate this frequency-dependent field strength into the equation for the cavity-modified $T_c$ and regenerate the theoretical curve, as shown in Fig. R13b. We note that this revision does not change the resonance condition and the main conclusion of this work.

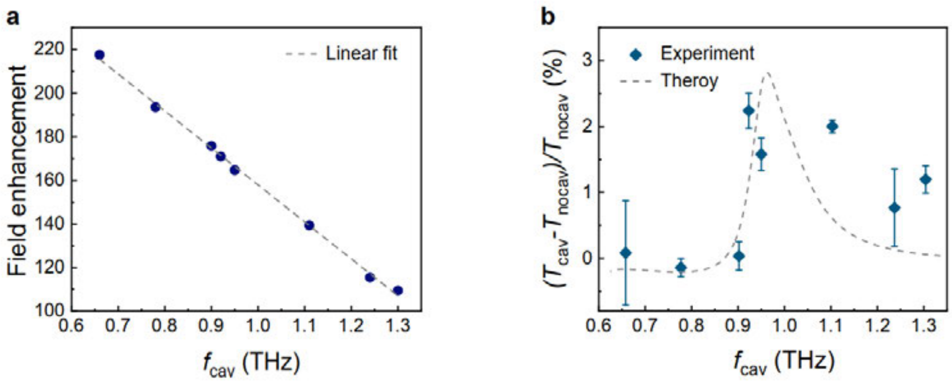



**Figure R13. a**, Linear dependence of field enhancement as a function of cavity frequency. The data points are obtained by simulation based on device geometry. Dashed line is the linear fit. **b**, Enhancement coefficient of the superconducting critical temperature as a function of cavity frequency. Theoretical prediction is indicated by the dashed line. The data points in **b** are extracted by the fitting method (see the extraction of $T_c$ in the new Note 5 of the revised Supplementary Information).

In the revised manuscript, we have incorporated frequency-dependent field variation and replaced Fig. 3d with Fig. R13b.

**Comment-7:** Figure 3d shows that tuning the cavity dimension either enhances Tc or leaves it unchanged; no suppression is observed. Is there a fundamental reason that the cavity cannot reduce Tc?

**Response:** The cavity can in principle either enhance or suppress superconductivity. Within our Ginzburg–Landau-based framework, **the cavity modifies the superconducting free energy through fluctuation-induced corrections that can have either sign**. Physically, this arises from two competing virtual-photon processes. One class of processes—associated with the emission and subsequent reabsorption of virtual photons—tends to lower the free energy and thus stabilize superconductivity, leading to an enhancement of $T_c$ (Fig. R14c). In contrast, processes involving intermediate virtual excitations (analogous to fluctuation-induced pair breaking) tend to increase the free energy and suppress superconductivity (Fig. R14b). The overall sign of the effect is therefore determined by the balance between these contributions, which depends on both cavity parameters (frequency, linewidth, mode profile) and intrinsic material properties. This situation is closely analogous to the Lamb shift in atomic physics, where different radiative corrections contribute with opposite signs, and the observed shift reflects their net balance (*Weinberg, S. in The Quantum Theory of Fields, Vol. 1, 564-596 (Cambridge University Press, 1995)*).

In our specific system, the calculations indeed predict both regimes. As shown in Fig. R14a (dashed line), the low-frequency side (≲0.9 THz) includes a parameter range where the net effect becomes negative, corresponding to a suppression of superconductivity. Experimentally, we

**observe superconductivity suppression at 0.78 THz** (see the circled data point in Fig. R14a), providing direct evidence that the cavity can reduce $T_c$. That said, in the frequency range emphasized in Fig. R14a, the $T_c$ enhancement dominates. This reflects the fact that near the resonance condition, the stabilizing (energy-lowering) processes prevail.

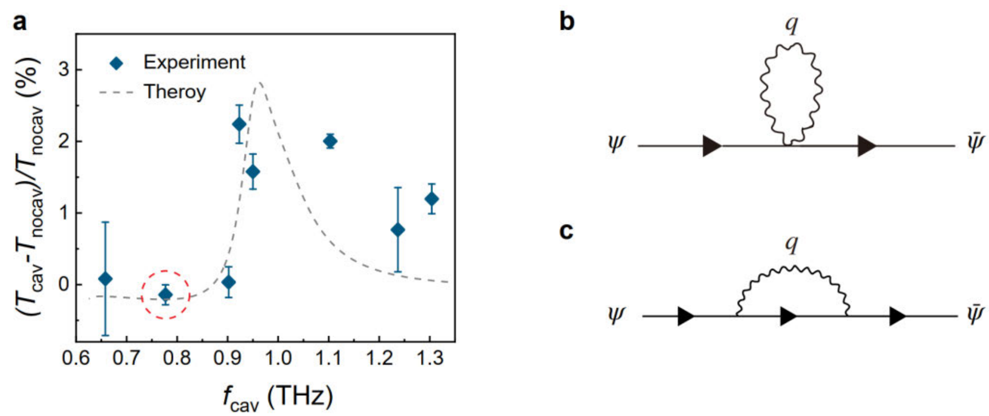



**Figure R14. a**, Enhancement coefficient of the superconducting critical temperature as a function of cavity frequency. Theoretical prediction of $\delta T_c/T_c$ is indicated by the dashed line. A negative value (suppression of superconductivity) is highlighted by the red dashed circle. **b**,**c**, One-loop contributions to the renormalization of the superconducting condensate $\psi$ by cavity fluctuations $q$. The tadpole diagram in **b** involves the emission and absorption of one virtual photon, while the diagram in **c** involves the reabsorption of one virtual photon after momentum exchange with the condensate.

In the revised manuscript, we have revised the first paragraph on page 11 and the first paragraph on page 13 to clarify the superconductivity suppression from both experimental and theoretical perspectives.

**Comment-8:** The choice of 12-layer NbSe2 is not explained. The introduction states that "vacuum fluctuations can enhance superconductivity in a bulk material," yet the analysis of voltage vs. current suggests a BKT transition, implying a 2D regime. This appears inconsistent. For NbSe2, a 12-layer thickness should be comparable to the BCS coherence length, suggesting more 3D behavior. Since the cavity-induced enhancements of critical current and upper critical field are most evident for 12-layer NbSe2 near Tc (where the condensate density is reduced, as agued in the manuscript), it may be more advantageous to examine flakes as thin as possible, for which fluctuations are stronger and cavity effects on superconductivity may be further amplified.

**Response:** We appreciate the careful comment regarding dimensionality of the studied $NbSe_2$. We would like to respond in three aspects:

***1. Why 12-layer $NbSe_2$ was chosen***

Very thin $NbSe_2$ flakes (e.g., monolayers, bilayers) are more susceptible to disorder, strain, and fabrication-induced degradation, which lead to strong inhomogeneity and intrinsic fluctuations of $T_c$. This poses a significant challenge for the systematic study of the relatively modest cavity-enhanced $T_c$. The possibly broadened superconducting transitions in few layers also complicate an accurate determination of $T_c$. In contrast, for 12-layer $NbSe_2$, we can reliably obtain sharp, uniform transitions with reproducible $T_c$, allowing high-precision transport measurements.

***2. Clarifying the "bulk" superconductivity***

"Bulk" is defined as the regime in which **a system hosts the same electronic structure as a sufficiently thick solid**. Based on the DFT calculations and ARPES measurements, the electronic structure of four-layer $NbSe_2$ is already very close to the bulk limit (*Phys. Rev. Mater. 2, 064002 (2018); Phys. Rev. B 80, 241108 (2009)*). $NbSe_2$ with more than ten layers exhibits properties identical to those of the bulk, in terms of phonon modes (*2D Mater. 3 031008 (2016)*), as well as charge density wave and superconductivity (*Nat. Nano.10, 765–769 (2015)*; *Nat. Phys. 12, 139–143 (2016)*). From this perspective, the 12-layer sample already lies within the bulk-like electronic regime. At the same time, the observation of BKT-like behavior in transport measurements **is not contradictory. The BKT transition reflects vortex-antivortex physics in the in-plane superconducting response, rather than the underlying electronic dimensionality.** Since the thickness of the 12-layer sample (□8 nm) is comparable to the superconducting coherence length and much smaller than its penetration depth, phase fluctuations and quasi-two-dimensional vortex dynamics can naturally emerge near $T_c$, even though the electronic structure is already bulk-like.

From an application standpoint of the cavity, its relatively thick structure (~210 nm in height), together with the spatially broad field distribution (Fig. R11), make it applicable to much thicker bulk superconductors as well.

***3. Examine flakes as thin as possible***

We thank the referee for pointing out the regime where thinner $NbSe_2$ may has stronger fluctuations. While it is currently challenging to reliably perform measurements in atomically thin flakes, we have obtained results from $NbSe_2$ flakes of 8 layers, 12 layers and 17 layers, as shown in Fig. R15. $T_c$ modulation remains almost constant (0.8±0.4%, 1.0±0.1%, and 1.0±0.2%), demonstrating the robustness of the cavity-enhanced bulk superconductivity. Exploring cavity-modulated superconductivity at the ultrathin limit is a highly promising direction for future work.

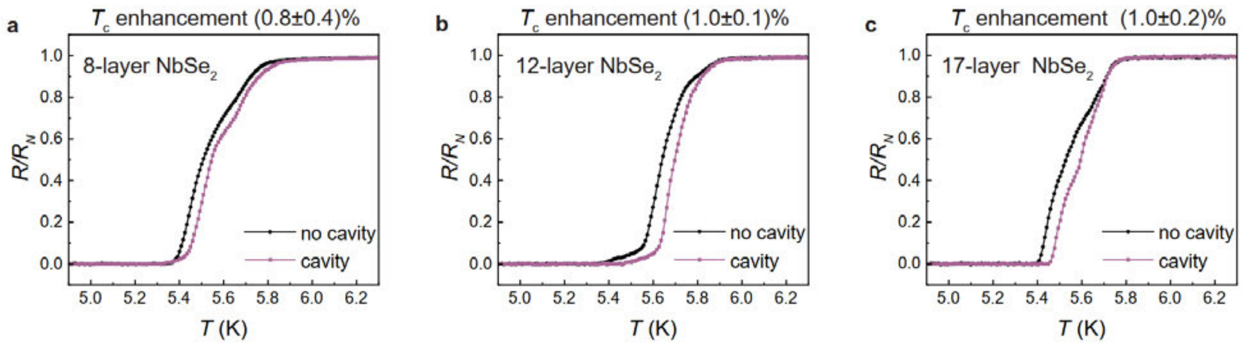



**Figure R15.** Dependence on the $NbSe_2$ thickness. Cavity-modulated superconductivity for devices with $NbSe_2$ of (**a**) 8 layers, (**b**) 12 layers, and (**c**) 17 layers. The cavity is identical for all three cases with frequency of 0.92 THz.

We have added a new Note 2 to the revised Supplementary Information to discuss the chosen 12-layer $NbSe_2$ and its dimensionality. We have added discussion to the second paragraph on page 6 of the revised manuscript and added a new Note 7 to the revised Supplementary Information to illustrate the dependence on the $NbSe_2$ thickness. Figure R15 is added as the new Supplementary Fig. 5a-c.

**Comment-9:** Minor point: Panel label e is missing in Fig. 2.

**Response:** We thank the referee for the careful examination, and we have corrected accordingly, as shown in Fig. 2 of the revised manuscript.

Dear Tobias,

Thank you for forwarding the assessments of referees #2 and #3. We are grateful to referee #3's comments that the new results convincingly demonstrate the cavity-enhanced superconductivity and recommendation for publication. Referee #2 still raises concerns on fabrication-related issues, which we would like to clarify briefly as follows.

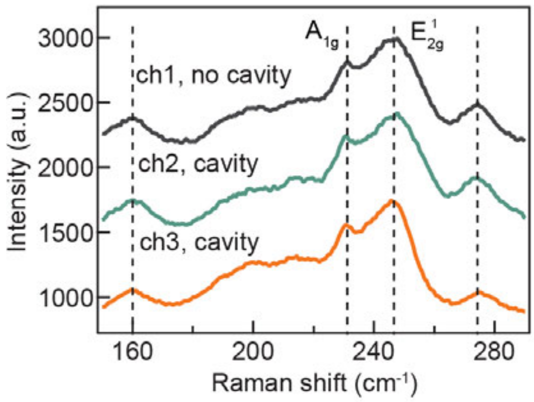
1. **Baseline variations in $T_c$.** Referee #2 comments that the variations in the baseline $T_c$ make it difficult to attribute the observed enhancement of superconductivity to the cavity. We agree that the absolute $T_c$ of $NbSe_2$ is sensitive to disorder, processing history, and device-specific material quality. Such effects naturally account for the lower and somewhat different baseline transition temperatures among nominally similar devices. However, the central observation of our work is not the absolute value of $T_c$, but the systematic enhancement of superconductivity associated with the cavity configuration. One would expect fabrication-related disorder to suppress superconductivity or introduce uncontrolled variations, rather than giving reproducible trends with cavity geometry and electromagnetic boundary conditions observed in our experiments.
2. **Raman features.** Referee #2 raises concerns about strain and points out the differences in Raman peaks at 160 $cm^{-1}$ and 274 $cm^{-1}$, primarily in their intensities. We respectfully note that Raman intensity is not, by itself, a suitable probe of strain, as it can depend strongly on measurement-specific factors (spot coverage, light collection, etc.). The more direct Raman indicators of strain in $NbSe_2$ are the frequencies of the principal $A_{1g}$ and $E_{2g}^1$ modes, near 231 $cm^{-1}$ and 247 $cm^{-1}$, respectively. These modes are widely used as strain probes in $NbSe_2$ [Phys. Rev. B 107, 245125, 2023; ACS Appl. Mater. Interfaces 12, 34, 38744–38750, 2020]. We observed no distinguishable shift of either mode, consistent with negligible strain in our case. Even for the two weaker peaks at 160 $cm^{-1}$ and 274 $cm^{-1}$, which might originate from the surrounding environment, there is no distinguishable shift (Attached Fig. 1 below). In addition, we have provided further evidence against the strain origin, including the metal-strip control experiment (Supplementary Fig. 2) and the incompatibility with the cavity frequency dependence (Fig. 3d).
3. **Movable antenna.** Referee #2 suggests that we gather further evidence using a movable antenna. We do not have a literal movable antenna set-up, but we have implemented a closely related electromagnetic-boundary control by introducing an additional metallic plane. Comparing devices with and without the metallic plane effectively mimics changing the antenna from a proximal distance to an infinite distance. The stronger $T_c$ enhancement observed in the proximal-metallic-plane case (Supplementary Fig. 6) provides independent support for an electromagnetic, cavity-related origin of the effect.

Overall, we thank all three referees for their constructive comments sent to us last November. To address their concerns, we have performed a broad set of measurements over the past six months, including metal-strip control experiment, Raman measurements, systematic studies of device parameters (cavity geometry, thicknesses of superconductor and spacer), and metallic plane-cavity experiment, together with refined theoretical analysis (detailed in SI). In our opinion, these results unambiguously rule out any plausible alternative explanation and verify cavity-enhanced superconductivity conclusively.

Since Referee #3 was also provided with Referee #2's report, we would be very grateful if this brief clarification could also be forwarded to Referee #3.

Sincerely yours,

Changgan




**Attached Figure 1**. Original Raman spectra, with additional dashed lines indicating the peak positions. No distinguishable shift is observed for the $A_{1g}$ and $E_{2g}^{1}$ phonon modes, or for the two minor peaks at 160 $cm^{-1}$ and 274 $cm^{-1}$.

Dear Tobias,

Thank you very much for the update and for your careful consideration of our submission.

In our email of 21 June 2026, we addressed Referee #2's remaining concerns point by point. Briefly:

(1) Although disorder and fabrication might reduce the absolute $T_c$ of $NbSe_2$, our central observation is the systematic difference between regions of the same device inside and outside the cavity.

(2) The characteristic Raman modes exhibit no measurable frequency shifts, arguing against strain as the origin of the effect. This conclusion is further supported by the metal-strip control experiment (Supplementary Fig. 2), while the systematic cavity-frequency dependence in Fig. 3d provides an additional electrodynamic signature.

(3) The nearby-metallic-plane experiment (Supplementary Fig. 8), which implements the essential electromagnetic-boundary-condition test suggested by Referee #2, yields a substantially larger $T_c$ enhancement. This result further supports a cavity-related origin.

Since our last submission, we have advanced this work and obtained two additional results. These measurements provide independent tests for the cavity interpretation and further address Referee #2's concerns.

**(1) Dependence on the thickness of $NbSe_2$**

We have investigated the dependence on the thickness of the superconductor. Figure R1a-d shows cavity-enhanced superconductivity in devices with $NbSe_2$ thicknesses of 6, 8, 12, and 17 layers. The corresponding $T_c$ enhancement as a function of layer number is summarized in Fig. R1e. Note that all data points in this layer-number-dependent dataset were obtained from the same batch of devices with identical fabrication processes.

For thick $NbSe_2$ (8, 12, and 17 layers), the baseline $T_c$ values (black curves in Fig. R1b-d) are around 5.5 K-5.6 K, and the $T_c$ enhancement remains nearly constant at around 1%. On the other hand, for 6-layer $NbSe_2$, the baseline $T_c$ value (black curve in Fig. R1a) drops to around 4.1 K, reflecting stronger superconducting fluctuations at reduced dimensionality. Simultaneously, $T_c$ enhancement increases dramatically to 5.4%. Such enhanced superconducting fluctuations may strengthen the low-energy electromagnetic response of the superconducting film, thereby enabling more effective coupling to the cavity electromagnetic modes. This trend therefore provides further support for the cavity-based interpretation in response to Referee #2's concerns.

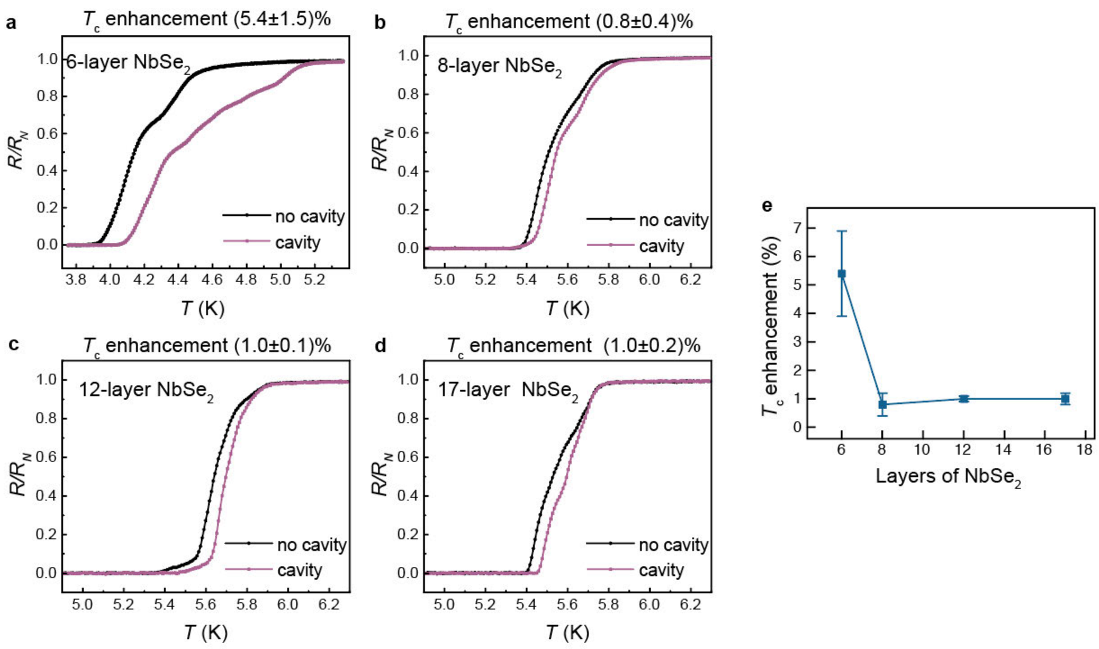



**Figure R1. Dependence on the thickness of $NbSe_2$.** Cavity-modulated superconductivity for devices with $NbSe_2$ thicknesses of (**a**) 6 layers, (**b**) 8 layers, (**c**) 12 layers, and (**d**) 17 layers. The cavity frequency is 0.92 THz. The $Al_2O_3$ spacer is 10 nm thick. **e**, Cavity-induced $T_c$ enhancement as a function of the layer number of $NbSe_2$.

**(2) Replacement of $Al_2O_3$ dielectric spacer with $HfO_2$**

We have replaced the $Al_2O_3$ dielectric spacer with $HfO_2$. Figure R2a,b shows measurements on a device with a 10-nm-thick $HfO_2$ spacer, exhibiting $T_c$ enhancement consistent with that observed in the $Al_2O_3$ cases. Reproducing this effect with two chemically distinct dielectric materials strongly disfavors dielectric-specific interfacial effects or associated fabrication artifacts.

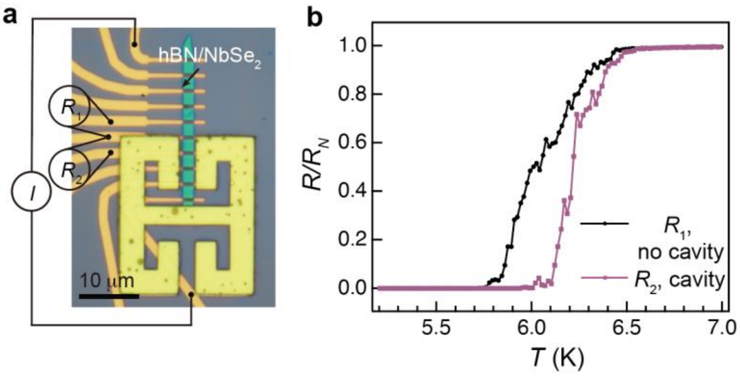



**Figure R2**. **Control experiment with $HfO_2$ spacer. a**,**b**, Optical micrograph and cavity-modulated superconductivity for a device with a 10-nm-thick $HfO_2$ spacer. The cavity frequency is 0.92 THz. The $NbSe_2$ flake has a thickness of 12 layers.

The additional data are included in the slightly expanded Supplemental Information. Taken together, the in situ comparison, Raman and metal-strip controls, cavity-frequency dependence, modified-boundary-condition experiment, systematic thickness dependence, and reproducibility across different dielectric materials provide mutually reinforcing evidence for a cavity-electrodynamic origin. At the same time, we acknowledge Referee #2's request for caution. We have revised the manuscript using appropriately cautious wording. In particular, we have changed the title to "Evidence for vacuum-enhanced superconductivity in $NbSe_2$", and modified wording appropriately, e.g., "provides transport signatures for cavity-vacuum-enhanced superconductivity".

We hope that these substantial new data, together with a more carefully calibrated presentation of our conclusions, provide a clear basis for publication in *Nature*.

Sincerely yours,

Changgan

**Responses to Referee #1**

**General comment:** *I have carefully read the rebuttal letter from the authors and I must say that I am very positively impressed about it. I honestly believe that the authors have addressed all my concerns and the resubmitted version of the Article is in a much better shape than the original one. In fact, I actually think that the revised manuscript is ready for publication provided that the last set of comments reported below and related to the scientific presentation will be taken into account.*

*Given the fact that in the month of June a few more papers appeared on the arXiv about enhancing superconductivity via vacuum fluctuations, I believe that the manuscript by Zheyan Wang and co-authors should be given the highest possible priority. This is one of the most serious studies of the interplay between superconductivity and vacuum fields I have seen so far in the literature.*

**Response:** We thank the referee for the highly positive assessment and for recognizing the improvements in the revised manuscript. We have carefully addressed the remaining comments on the scientific presentation.

**Comment-1:** *My impression being in the field of cavity material engineering for quite a few years is that the exclusion of trivial effect such as metallic screening is very important for experimental colleagues working outside the field. I therefore strongly believe that the fact that trivial metallic screening cannot explain the results should have a bit more prominent role in the paper rather than being relegated to a tiny remark on page 6 of the main text and related Supplementary Note 6. I strongly encourage the authors to do the effort of squeezing in the main text current Supplementary Figure 2. I am not pushing towards this direction because I was the one raising the point of excluding trivial screening effects. I am pushing the authors because I have many many experimental colleagues in top US and EU universities who are quite skeptical about the role of vacuum fluctuations and raise all the time concerns about using metallic gates near atomically thin van der Waals heterostructures. Readers need to see immediately in Fig. 1 of the main text that the measured effect has nothing to do with non-resonant frequency-independent metallic screening. And this is the way I would write a comment in the main text: "Trivial, non-resonant, frequency-independent metallic screening cannot explain the physics we observe in this work". Full stop.*

**Response:** We thank the referee for this constructive comment. We have added the previous Supplementary Fig. 2 as the new Fig. 1f of the main text. On page 5 of the revised manuscript, we wrote "…trivial, non-resonant, frequency-independent metallic screening cannot explain …"

**Comment-2:** *Similarly to what stated in point 1) above, it is of uttermost importance in this field to avoid the proliferation of papers claiming that vacuum fluctuations in *deep-subwavelength* cavities can be modelled by a purely transverse fluctuating gauge field with a tunable mode-volume-confinement fudge factor.*

*I am very happy to notice that the authors have seriously addressed this point in the rebuttal. However, I believe that this point deserves to appear more prominently in the main text. Again, this is not because I was the one raising this point but because there is a lot of theory papers out there which have promised that vacuum fluctuations can do everything for you…..*

*We therefore badly need serious experimental work putting *serious bounds* on theories. A brief summary of the discussion currently relegated to Supplementary Note 12 should be shifted to the main text, with precise theory statements about what we learn from this experiment by Zheyan Wang and co-authors, in relation to references 15 and 17-20. Please, avoid superficial one-sentence statements in the main text to make me happy. Such statements are useless for modern readers who, typically, do not have time to read carefully the Supplementary material. A short precise discussion of what your comparison between experiments and theory says with respect to the discussion in Refs. 15,17,18,19, 20 is needed.*

*By the way, Ref. 20 is not at all the only reference where the mode-volume-confinement argument has been used.*

*Issues 1) and 2) are not a personal "whim" of mine, but a fundamental necessity for the healthy future development of this field of research. Thank you for understanding.*

**Response:** We thank the referee for this helpful suggestion. Accordingly, on page 10 of the revised manuscript, we have added a discussion comparing the experimental results with the cavity theory.

**Responses to Referee #2**

**General comment:** *Please find here my comments on the revised version of the manuscript. I appreciate the authors' efforts in addressing the concerns raised in my initial review, and I find several of the additional analyses and discussions helpful. Nevertheless, I remain unconvinced that the reported effect can be conclusively attributed to cavity electrodynamics, for the reasons outlined below.*

**Response:** We thank the referee for the constructive comments throughout the review process, which have substantially strengthened the manuscript. In response to the remaining concerns, we have clarified the baseline variations in $T_c$ and Raman features, provided mutually reinforcing evidence for the cavity-electrodynamic origin, and revised the manuscript with appropriately cautious wording.

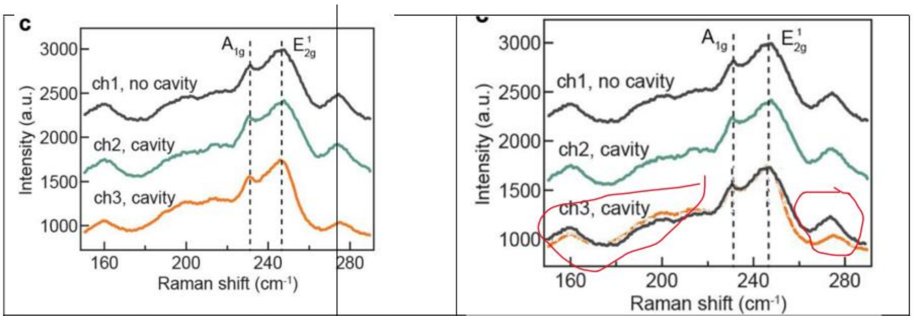
**Comment-1:** *It is well known that the critical temperature of NbSe2 depends sensitively on the characteristics of the material. The fact that the authors report different critical temperatures for different devices illustrates this sensitivity. Importantly, all devices discussed in the manuscript exhibit critical temperatures below those reported for the highest-quality NbSe2 crystals, where Tc can reach approximately 7 K.*

*I understand that the primary focus of the manuscript is not the absolute value of the critical temperature in NbSe2, but rather the relative change in Tc induced by the cavity. However, the substantial variation in the baseline critical temperatures across devices makes it difficult, in my view, to establish a clear causal connection between the observed enhancement and the cavity itself.*

**Response:** We agree that the absolute $T_c$ of $NbSe_2$ is sensitive to disorder, processing history, and device-specific material quality. Such effects naturally account for the lower and somewhat different baseline transition temperatures among nominally similar devices. However, **the central observation of our work is not the absolute value of $T_c$, but the systematic difference between regions of the same device inside and outside the cavity, which are associated with the cavity configuration**. One would expect fabrication-related disorder to suppress superconductivity or introduce uncontrolled variations, rather than give a systematic dependence on cavity frequency (Fig. 3d of the main text) and robust $T_c$ enhancement with varying resonator geometries, thicknesses of $Al_2O_3$ and $NbSe_2$, and dielectric materials (new Extended Data Fig. 7 and new Supplementary Notes 6-8).

**Comment-2:** *The additional characterization provided by the authors is valuable, particularly because it addresses the possibility of strain-induced modifications of Tc,* *a concern that I raised in my original review. In particular, the authors present Raman microscopy measurements to support the conclusion that fabrication-induced strain is unlikely to be responsible for the observed enhancement. While I appreciate this effort, I do not find the evidence fully convincing.*

*In the figure below, I have overlaid the Raman spectra provided by the authors, comparing measurements taken outside the cavity (black) and inside the cavity (orange). As can be seen, the Raman responses inside and outside the cavity are noticeably different. Furthermore, the relative intensities of the Raman peaks vary between different locations within the cavity region. These observations appear consistent with spatial variations in material properties and may indicate that the observed changes in Tc are associated with the fabrication of the antennas on top of the material. For this reason, I do not believe that fabrication-induced effects have yet been conclusively ruled out as a possible contributor to the observed enhancement of Tc. Given the well-established sensitivity of NbSe2 to strain and material quality, I believe this alternative explanation deserves further consideration before the reported effect can be unambiguously attributed to cavity electrodynamics.*




| Raman as function of position provided by authors | Overlaid figure highlighting different structural Raman response |
|---|---|

**Response:** We thank the referee for the careful inspection and pointing out differences in the Raman peaks at 160 $cm^{-1}$ and 274 $cm^{-1}$, primarily in their intensities. We respectfully note that **Raman intensity is not, by itself, a suitable probe of strain**, as it can depend strongly on measurement-specific factors (spot coverage, light collection, etc.). **The more direct Raman indicators of strain in $NbSe_2$ are the phonon frequencies of the principal $A_{1g}$ and $E^1_{2g}$ modes**, near 231 $cm^{-1}$ and 247 $cm^{-1}$, respectively. These modes are widely used as strain probes in $NbSe_2$ [Phys. Rev. B 107, 245125, 2023; ACS Appl. Mater. Interfaces 12, 34, 38744–38750, 2020]. We observed no distinguishable shift of either mode (Fig. R1), consistent with negligible strain in our case. Even for the two weaker peaks at 160 $cm^{-1}$ and 274 $cm^{-1}$, which might originate from the surrounding environment, there is no distinguishable shift (Fig. R1). In addition, we have provided further evidence against the strain origin, including the metal-strip control experiment (new Fig. 1f of the main text). The systematic cavity-frequency dependence in Fig. 3d of the main text provides an additional electrodynamic signature.

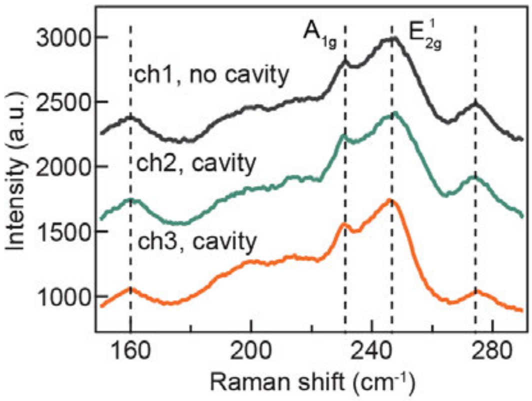



**Figure R1**. Original Raman spectra, with additional dashed lines indicating the peak positions. No distinguishable shift is observed for the $A_{1g}$ and $E^1_{2g}$ phonon modes, or for the two minor peaks at 160 $cm^{-1}$ and 274 $cm^{-1}$.

**Comment-3:** *Overall, I find the topic timely and the observation potentially very important. However, in my opinion, additional evidence is still needed to distinguish cavity-induced effects from fabrication-related modifications of the material and to firmly establish the proposed interpretation. For these reasons, although I find the reported observations highly suggestive, I believe they should be regarded as anecdotal evidence that a cavity induced effect may be present rather than as definitive proof of such an effect. Accordingly, the results should be presented with this level of caution.*

*As stated in my previous report, more convincing evidence that the observed effect of the antenna on the superconductor is genuinely photonic in origin, rather than arising from fabrication-related factors, would require the implementation of a movable antenna that can be brought into and out of close proximity to the superconducting structure as in the paper mentioned in my previous report.*

**Response:** We thank the referee for the constructive comments and we would like to respond by the following four points.

**(1) Metallic-plane experiment analogous to movable antenna**

While we do not have a literal movable antenna set-up, we have implemented a closely related electromagnetic-boundary control by introducing an additional metallic plane. Comparing devices with and without the metallic plane effectively mimics moving the antenna from a proximal distance to an infinite distance (new Extended Data Fig. 8). The stronger $T_c$ enhancement observed in the proximal-metallic-plane case provides independent support for an electromagnetic, cavity-related origin of the effect.

**(2) Dependence on the thickness of $NbSe_2$**

We have further investigated the dependence on the thickness of the superconductor. Figure R2a-d shows cavity-enhanced superconductivity in devices with $NbSe_2$ thicknesses of 6, 8, 12, and 17 layers. The corresponding $T_c$ enhancement as a function of layer number is summarized in Fig. R2e. Note that all data points in this layer-number-dependent dataset were obtained from the same batch of devices with identical fabrication processes.

For thick $NbSe_2$ (8, 12, and 17 layers), the baseline $T_c$ values (black curves in Fig. R2b-d) are around 5.5 K-5.6 K, while the $T_c$ enhancement remains nearly constant at around 1%. However, for 6-layer $NbSe_2$, the baseline $T_c$ value (black curve in Fig. R2a) drops to around 4.1 K, reflecting stronger superconducting fluctuations at reduced dimensionality. Simultaneously, $T_c$ enhancement increases dramatically to 5.4%. Such enhanced superconducting fluctuations may strengthen the low-energy electromagnetic response of the superconducting film, thereby enabling more effective coupling to the cavity electromagnetic modes. This trend therefore provides further support for the cavity-based interpretation.

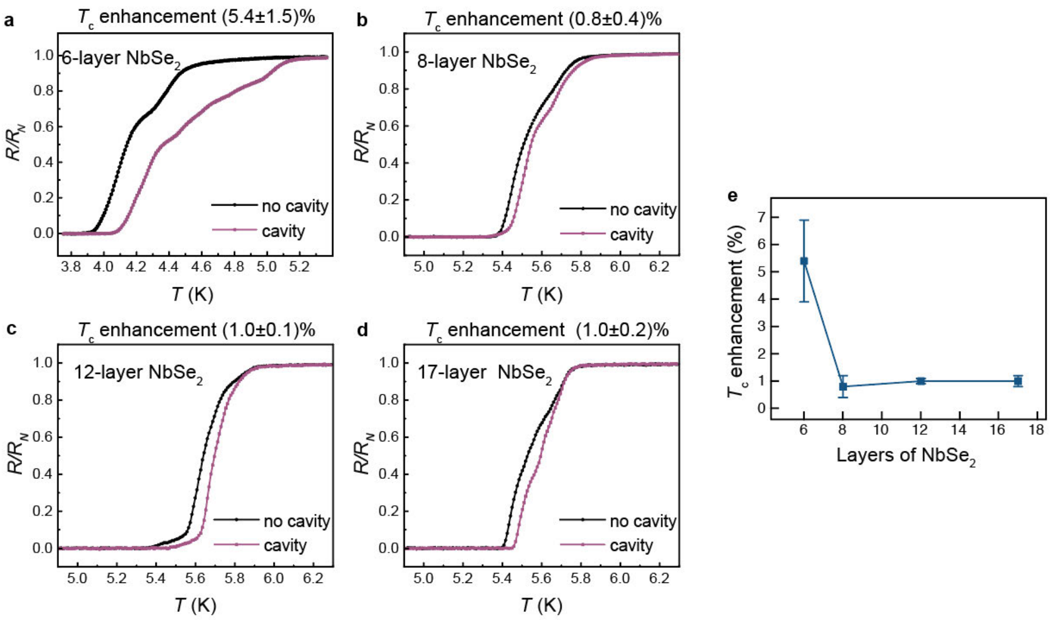



**Figure R2. Dependence on the thickness of $NbSe_2$.** Cavity-modulated superconductivity for devices with $NbSe_2$ thicknesses of (**a**) 6 layers, (**b**) 8 layers, (**c**) 12 layers, and (**d**) 17 layers. The cavity frequency is 0.92 THz. The $Al_2O_3$ spacer is 10 nm thick. **e**, Cavity-induced $T_c$ enhancement as a function of the layer number of $NbSe_2$.

**(3) Replacement of $Al_2O_3$ dielectric spacer with $HfO_2$**

We have replaced the $Al_2O_3$ dielectric spacer with $HfO_2$. Figure R3a,b shows measurements on a device with a 10-nm-thick $HfO_2$ spacer, exhibiting $T_c$ enhancement consistent with that observed in the $Al_2O_3$ cases. Reproducing this effect with two chemically distinct dielectric materials strongly disfavors dielectric-specific interfacial effects or associated fabrication artifacts.

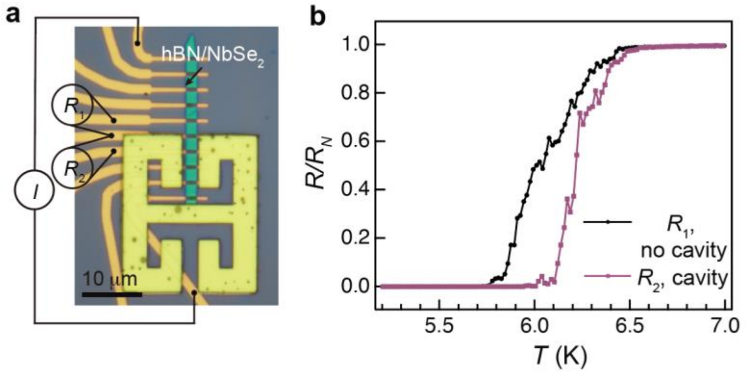



**Figure R3**. **Control experiment with $HfO_2$ spacer. a**,**b**, Optical micrograph and cavity-modulated superconductivity for a device with a 10-nm-thick $HfO_2$ spacer. The cavity frequency is 0.92 THz. The $NbSe_2$ flake has a thickness of 12 layers.

Taken together, the in-situ comparison, Raman and metal-strip controls, cavity-frequency dependence, modified-boundary-condition experiment, systematic thickness dependence, and reproducibility across different dielectric materials **provide mutually reinforcing evidence for a cavity-electrodynamic origin**.

We have added Figs. R2 and R3 as new Supplementary Figs. 3 and 4. We have also included discussions of the thickness dependence and the replacement of dielectric materials on page 6 of the revised manuscript and in Supplementary Notes 7, 8.

**(4) Appropriately cautious wording**

We acknowledge the referee's suggestion for caution. We have **revised the manuscript using appropriately cautious wording**. In particular, we have changed the title to "Evidence for vacuum-enhanced superconductivity in $NbSe_2$", and modified wording appropriately, e.g., "provides transport signatures for cavity-vacuum-enhanced superconductivity".

**Responses to Referee #3**

**General comment-1:** *The authors have performed additional experiments that thoroughly address my questions and concerns. The new results convincingly demonstrate the effect of cavity on superconductivity. I therefore recommend publication of the revised manuscript in Nature.*

**Response:** We thank the referee for the positive assessment and recommendation for publication.

**General comment-2:** *The other referee raises an important concern that fabrication-induced changes in sample quality could complicate the interpretation of the reported effect. I agree that this issue is relevant, particularly given the substantial device-to-device variation in the baseline Tc.*

*That said, I do not think this concern is sufficient to overturn the authors' main interpretation. Since degradation in NbSe2 is generally known to suppress Tc, fabrication-induced degradation alone does not naturally explain why the portion of NbSe2 inside the cavity would show a clear Tc enhancement. In my view, this makes it difficult to attribute the observed enhancement solely to fabrication-induced sample degradation.*

*Moreover, Fig. 3d presents the relative change in Tc induced by the cavity, which helps to mitigate the issue of baseline Tc variation across devices. The data show that Tc can be either suppressed or enhanced depending on the cavity frequency, and this trend appears to be reasonably captured by the authors' theoretical model. I regard this as strong evidence that a cavity-related effect is involved.*

*Overall, I think the other referee's concern is valid and should be acknowledged in the manuscript, perhaps through appropriately cautious wording. However, I do not think the concern invalidates the authors' central claim, and I remain supportive of publication.*

**Response:** We thank the referee for the supportive assessment. In the revised manuscript, we have carefully acknowledged the referees' concerns by providing additional evidence and using appropriately cautious wording (see detailed response to Comment-3 of Referee #2).