Single-photon counters are single-pixel binary devices that click upon the absorption of a photon but obscure its spectral information, whereas resolving the color of detected photons has been in critical demand for frontier astronomical observation, spectroscopic imaging and wavelength division multiplexed quantum communications. Current implementations of single-photon spectrometers either consist of bulky wavelength-scanning components or have limited detection channels, preventing parallel detection of broadband single photons with high spectral resolutions. Here, we present the first broadband chip-scale single-photon spectrometer covering both visible and infrared wavebands spanning from 600 nm to 2000 nm. The spectrometer integrates an on-chip dispersive echelle grating with a single-element propagating superconducting nanowire detector of ultraslow-velocity for mapping the dispersed photons with high spatial resolutions. The demonstrated on-chip single-photon spectrometer features small device footprint, high robustness with no moving parts and meanwhile offers more than 200 equivalent wavelength detection channels with further scalability.
High-performance single-photon spectrometers are among the most sought-after instruments in cutting-edge research fields especially for applications in photon-scarce environments. For example, in the applications such as astronomical spectroscopy, fluorescence imaging, and remote sensing, the signal light is extremely faint, and thus single-photon sensitive spectrometers with low-dark count noise are crucial. In wavelength division multiplexed quantum communications, advanced single-photon detectors with spectral resolvability combining low-dark counts, fast speed, and high timing resolution are ideal devices as the quantum receivers. However, current implementations of single-photon spectrometers consist of bulky wavelength-scanning components and photomultiplier tubes or semiconductor-based single-photon counters of finite channels, hindering parallel detection of broadband photon input with high spectral resolutions. Moreover, the semiconductor detectors, such as InGaAs single-photon avalanche diodes used in telecom-band photon counting, also suffer from large dark counts, limited efficiency, slow speed and after-pulsing.

On the other hand, superconducting nanowire single-photon detectors (SNSPDs) have recently emerged as one of the best alternatives, outperforming the semiconductor counterparts in all aspects with near-unity efficiency, high speed, low jitters, low dark counts, and the capability of on-chip integration with integrated nanophotonic circuits. However, these detectors operate in a strong non-linear mode—only informing the presence or absence of photons—and thus cannot discriminate the energy or provide the spectral information of the detected photons. Waveguide-based structure is proposed to circumvent this problem, where up to eight parallel SNSPDs are co-integrated with an arrayed waveguide grating, and used for the fluorescence imaging of color centers in diamond. Yet, individual readout scheme is employed here for the discrete detector array, which ultimately limits the scalability of the detection channels as well as further improvement of the spectral resolution and operation bandwidth. In another research on fiber-assisted spectrometers, SNSPDs are employed in conjunction with very long fibers to convert the arrival time of detected photons to the wavelength information based on the large dispersion introduced by the fibers. However, this scheme only works with pulsed photon sources, and the complete set-up comprises discrete components that remain to be integrated.

Here, we propose and experimentally implement a broadband on-chip single-photon spectrometer that overcomes all the above-mentioned challenges. By interfacing a millimeter-size nanophotonic echelle grating with a single-element meandered SNSPD, we realize continuous mapping of the spectral information of dispersed input photons. The meandered SNSPD is capped with a high-κ (high-dielectric constant) layer to form a microstrip transmission line with a group velocity as low as 0.0073c (c: the speed of light in vacuum) for precision time-tagging, which has been recently employed to realize a single-photon imager. With a continuous NbN nanowire of a total length of 7 mm, we demonstrate more than 200 effective single-photon detection channels over a broad wavelength range between 600 and 2000 nm. This on-chip spectrometer uniquely combines the benefits of planar nanophotonic and superconducting nanowire circuits and therefore is inherently scalable. Future scale-up fabrication of our design at wafer dimensions could further enhance the spectral resolution and the number of detection channels while maintaining the same integration and readout architecture.

Results
Principle and device design. The dispersive component of our device is based on the echelle grating, which is known in astronomical and precision spectroscopy for its high dispersive power. With the advent of integrated photonics, it becomes feasible to lithographically define millimeter-diameter echelle gratings on a chip and effectively disperse the incoming photons from an input waveguide, as recently demonstrated in silicon photonic structures. Here, we implement the echelle spectrometer in stoichiometric silicon nitride (Si₃N₄) to allow for broadband optical waveguiding from visible to mid-infrared. In Fig. 1e, we present the schematic of the standard Rowland mounting to illustrate the operation principle. The facets of a flat grating are projected onto a circular section to form a focusing grating with the radius equal to the diameter of the Rowland circle, upon which the input waveguide and the superconducting nanowire are lithographically mounted. The focusing grating and the Rowland circle are internally tangent at the center of the grating. Photons are first edge-coupled from the lensed fiber into the tapered Si₃N₄ waveguide (Fig. 1c) and then diverge in the free propagation region of the dielectric slab within the Rowland circle (Fig. 1d). Afterwards, the photons are reflected, deflected, and refocused by the concave grating to the focusing point P on the superconducting nanowire (Fig. 1e), the position of which varies with the wavelength of the input photons. The diffraction angle is determined by the equation

\[ d \sin(\theta_m) + \sin(\theta_i) = \frac{m \lambda}{n_{\text{eff}}}, \]

where \( d \) is the period of the grating, \( \theta_i \) the angle of incidence, \( \theta_m \) the angle of the \( m \)th order diffraction, \( \lambda \) the wavelength of the incident photons in free space, and \( n_{\text{eff}} \) the effective refractive index of the mode in the slab waveguide. The blaze angle of the grating facets can be tuned to guide the diffracted light into the desired order.

While inheriting all conventional merits of SNSPDs, our nanowire detector features an ultralow-velocity microwave delay line formed by capping the NbN superconducting nanowire with high-\( k \) dielectric material (alumina or AlO₃) and top metal ground (aluminum or Al) as shown in Fig. 1b. Due to the very large kinetic inductance of the nanowire and the slow microstrip line design, the pair of photon-excited microwave pulses of opposite polarities propagate slowly at a group velocity as low as 0.73% of the vacuum speed along the circumference of the Rowland circle. It is worth noting that this is the slowest result reported among the superconducting nanowire delay lines and twice slower than oxide-cladded delay lines achieved previously (see Supplementary Note 3). As a result, the times of arrival to the amplifiers attached at both ends of the nanowire transmission line could be registered with high temporal resolution. This time-tagged single-photon signal or the arrival time difference \( \Delta t = t_1 - t_2 \) can be used to trace out the spatial distribution of incident photons. In our nanophotonic devices, this spatial distribution in turn arises from dispersed photons of different colors by the echelle grating with high spatial resolution (Fig. 1f). Therefore, our design permits a single-element nanowire to function as a multi-channel spectral-resolving single-photon detector.

To demonstrate the proof of principle and modes of operation, multiple devices of varying size and design parameters are fabricated on the same chip and cooled down to 1.5 K temperature in a dilution refrigerator for characterizations. The edge-coupling scheme between the fiber and the device chip based on our cryogenic active alignment set-up could guarantee broad spectrum input coupling from visible to infrared waveband. We categorize the devices into two main designs: (i) broadband design based on a 400 μm-radius Rowland circle and targeting 600-2000 nm waveband and (ii) telecom-band devices using a larger 1.6 mm-radius Rowland circle and dedicatedly designed for telecommunication waveband between 1420 and 1640 nm. More
details on the design parameters, device fabrication and characterization can be found in the Methods section and Supplementary Notes 1 and 2. The optical micrograph and scanning electron micrograph (SEM) images for one of the broadband devices are shown in Fig. 2a–d. The detector part consists of a long 60 nm-wide meandering NbN wire, both ends of which are gradually tapered to microns width to form Klopfenstein-type impedance tapers that help preserve the fast-rising edges of photon-excited microwave pulses.

**Broadband device.** Figure 3a presents 2.5-dimensional finite-difference time-domain (FDTD) simulation results of the broadband device. As expected, the diffracted light could be well refocused on the Rowland circle where the superconducting nanowire is placed. For shorter wavelengths, higher-order diffraction modes \(m > 1\) exist, but they are effectively suppressed at least one order of magnitude lower than fundamental modes by tuning the blaze angle of the grating. The 0th order mode \(m = 0\) represents the direct reflection of the input beam by the grating without diffraction, which do not have wavelength-discriminating effect and are not desired. The nanowire detector therefore is not mounted in this diffraction region. In Fig. 3b, we plot the normalized histogram of photon counts versus \(\Delta t\) measured for different wavelength input photons (see Supplementary Note 7 for the raw data). All the major peaks are from TE modes, while the minor peaks marked by dashed circles are due to the TM modes, \(n_{\text{eff}}\) of which are always smaller than that of TE modes. The TM modes are excited at shorter wavelengths due to the multimode operation of the input waveguide, while they are suppressed for longer wavelengths where the waveguide only supports single TE modes. Note that such imperfection could be resolved in future optimizations of the device by introducing an on-chip TE-pass polarizer to the input waveguide. The full width at half maximum (FWHM) of the major peaks are 13–19 ps, which corresponds to a better than 7 nm spectral resolution and
suggested more than 200 wavelength detection channels between 600–2000 nm. In Fig. 3c, Δ\textit{t} corresponding to the major peaks are extracted and plotted versus the wavelength, which agrees well with the diffraction angles obtained from the FDTD simulation results (see Fig. 1e for the angle definition). Figure 3d shows the normalized photon counting rates measured as a function of the relative bias current to the switching current (\textit{I}_{\text{bias}}/\text{I}_{\text{SW}}) at wavelengths from 750 to 1970 nm. Apparent saturation behavior is observed for all the curves, suggesting a near-unity internal quantum efficiency of the nanowire detector over the whole spectrum. To the best of our knowledge, it is the first time to realize such a compact on-chip single-photon spectrometer simultaneously covering visible and infrared wavebands.

Telecom-band device. The spectral-resolving power of our on-chip single-photon spectrometer can be further assessed with a telecom-band device design, which has four times larger Rowland circle radius and uses 6th order diffraction for enhanced dispersive effect. Figure 4a shows the normalized histogram of photon counts versus Δ\textit{t}. The FWHM of each peak is 25–30 ps, corresponding to a resolution of 2.5–3 nm in wavelength. In order to further evaluate the spectral resolution, we combine two continuous-wave (CW) laser beams with wavelengths separated by 2.5 nm through a fiber-splitter and send them to the device after an appropriate attenuation. As shown in Fig. 4b, there are two distinctly resolved peaks, consistent with the projected resolution for single photons. Due to the continuous and sub-wavelength structure of the nanowire detector, the measurement precision of Δ\textit{t} can be always boosted by repetitive measurement, which indicates that our spectrometer device can also work in wavelength-meter mode to provide a resolution well beyond the aforementioned value when measuring the wavelength of single-color input photons. The histogram curves shown in Fig. 4c displays the response from light inputs of 0.1 nm wavelength difference. We note that the resolution in this operation mode is not determined by the FWHM values of the histogram peaks but limited by the stability of laser source and the long integration time of the histogram measurement associated with the limited acquisition speed and refresh rate of the oscilloscope. By further scaling our device and utilizing application-specific high speed correlation electronics as oppose to an oscilloscope, we expect that the wavelength resolution could be improved to picometer level. We also characterize the timing performance of the spectrometer by recording the histogram of photon counts as a function of the arrival time difference between the detector signal and the synchronization signal of a 2.4 ps-pulsed laser. The results are shown in Fig. 4d with 40 ps jitter defined as the FWHM of the histogram profile, which is consistent with conventional SNSPDs. More details on the jitter characterization and the impact of noise-introduced timing jitter on spectral resolution are provided in Supplementary Notes 5 and 6.

Discussion

The ultimate resolution of our single-photon spectrometer is set by the achievable size of the grating which is eventually limited by the wafer size and also the total length of the nanowire delay line to cover all the desired diffraction angles. As detailed in Supplementary Note 8, we estimate that 100 pm resolution with 200 nm bandwidth and thus 2000 wavelength channels is feasible with a telecom-band device design based on a 50 mm-radius Rowland circle and a 40 mm-long nanowire. In order to realize such a device, although we anticipate that the superconducting nanowire circuit could be fabricated without degradation as previously demonstrated in large-area SNSPDs, some technical challenges remain to be solved on the photonics side, such as pattern decoherence induced by thermal expansion and stitching error during the electron-beam lithography of large nanophotonic structure across distant writing fields. Future improvement also requires the optimization of the device design to improve the system detection efficiency (see Supplementary Notes 1 and 4) and remove the non-Gaussian tails in the histogram results to increase the dynamic range (see Supplementary Note 7). It is also
notable that although this work focuses on the single-photon detection regime, our on-chip spectrometer can also be extended to study two-photon absorption events28 and thus could be an important tool for characterizing spectrally entangled photon pairs. Moreover, our design can be easily extended to mid-infrared waveband, where lots of important and fast-emerging applications reside, such as remote sensing and single-photon lidar. We envision that our spectrometers will find important and immediate applications in quantum sensing, communication and frontier spectroscopic imaging technologies.

Methods
Device fabrication. The photonic circuit components are patterned from 330 nm-thick stoichiometric Si₃N₄ on Si wafers covered with 3.3 µm-thick thermally grown oxide. The superconducting detectors and microwave circuits are realized in a 8 nm-thick NbN thin film, which is deposited on the Si₃N₄ with alignment markers (10 nm Cr/100 nm Au) fabricated in advance. After the NbN film deposition, we define superconducting nanowires along with impedance tapers by the exposure of negative-tone 6% hydrogen silsesquioxane (HSQ) resist using high-resolution (100 kV) electron-beam lithography (EBL) and the subsequent development in tetramethylammonium hydroxide-based developer MF-312. In a second EBL step, electrode pads are defined using double-layer polymethyl methacrylate (PMMA) positive-tone resist. After the development in methyl isobutyl ketone and isopropyl

Fig. 3 Broadband device results. a Electric field distribution of the device from 2.5-dimensional FDTD simulation results at different wavelengths. Scale bar, 100 µm. b Normalized histogram of photon counts versus time difference Δt measured for different wavelength photons from 600 nm to 1970 nm. The main peaks are from the TE modes while the minor peaks marked by the dashed circles are from TM modes. The histogram is recorded with the nanowire detector biased at 80% of its switching current I_{SW}. c Comparison between experimentally measured Δt and the diffraction angle extracted from the simulation results. d Normalized photon counting rates (PCR) measured as a function of the bias current relative to the switching current of the device I_{bias}/I_{SW} at wavelengths from 750 to 1970 nm. The complete saturation trend of the curves indicates a near-unity internal quantum efficiency of the nanowire detector over the whole spectrum. The histogram results are taken from Device C with double-nanowire detector, while the efficiency curves are measured from Device B with single-nanowire structure for better comparison between different wavelengths (see Supplementary Note 1)
the histogram results are measured with the nanowire detector biased at 80% of 1560 nm pulsed source as a function of the arrival time difference between the averaged detector signal. Normalized histogram measured for a single-color source with slightly varied wavelength step by 0.1 nm.

Optical grating and waveguide design. To ensure high fabrication yield and verify the device principles, in this work we design relatively small gratings and short nanowires. The radius of Rowland circle for broadband device is 400 μm, while the telecom-band device is 1.6 mm. For the broadband design, we use small grating pitch (0.8 μm) and fundamental diffraction mode (m = 1) to minimize the order mixing. For the telecom-band design, we use a much larger grating pitch size (8 μm) and higher-order mode (m = 6) to enhance the resolution and directivity. The width of the optical waveguide is 1.2 μm to suppress TM modes and higher-order TE modes for telecom wavelength around 1550 nm. For efficient coupling with off-chip fibers, the input part of the waveguide is adiabatically tapered to 4 μm to match the mode size of the lensed fiber.

Detector and microwave circuit design. The NbN nanowires on the Rowland circle are 60 nm wide, which is narrow enough to provide saturated detection efficiency of single photons over the whole spectrum as shown in Fig. 3d. For some of the devices, two nanowires are connected in parallel to boost the signal-to-noise ratio while still maintaining the saturated internal detection efficiency (see Supplementary Notes 1 and 5 for more details). The NbN nanowires are capped with 150 nm-thick AlOx and 150 nm-thick Al to allow the nanowires to also function as microwave delay lines. As a result, a signal propagation velocity as low as 0.73% c is experimentally obtained, where c denotes the speed of light in vacuum. To preserve the fast-rising edges of the photon-excited detector pulses in readout circuits, we use Klopfenstein tapers for matching the impedance of the RF probe and cables to the nanowires by transforming the nanowire impedance to 50 Ω. The total length of the tapers is 8.8 mm, corresponding to 2.5 times effective wavelength of 1 GHz signal in the transmission line.

Device characterization. The sample chip containing multiple spectrometer devices is cleaved after fabrication and then mounted on a 3-axis stack of stages (Attocube) inside a dilution refrigerator (BlueFors) and cooled down to 1.5 K temperature. We drive the stages to move the sample chip and make the electrode contact with a multi-channel RF probe. Another set of 3-axis stages (Attocube) inside a dilution refrigerator (BlueFors) are used to position the sample chip. All the results are taken from Device A (see Supplementary Note 1).

**Fig. 4** Telecom-band device results. a Normalized histogram of photon counts versus time difference Δt measured for photons with different wavelength from 1480 to 1640 nm. b Normalized histogram measured for a mixture of two coherent light sources with their wavelengths separated by 2.5 nm. The red dashed line represents double-Gaussian fitting for the measured data, which is the sum of two Gaussian distribution displayed in blue dashed lines. c Normalized histogram measured for a single-color source with slightly varied wavelength step by 0.1 nm. d Normalized histogram measured for a 1560 nm pulsed source as a function of the arrival time difference between the averaged detector signal (t1 + t2)/2 and laser synchronization signal t0. All the histogram results are measured with the nanowire detector biased at 80% of ISW. All the results are taken from Device A (see Supplementary Note 1).
CITLF1) operating at 4 K temperature to read out the photon-excited detector pulses (see Supplementary Note 5).

**Data availability**
The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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**References**

1. Appenzeller, I. Introduction to Astronomical Spectroscopy, vol. 9 (Cambridge University Press, 2012).
2. Lichtman, J. W. & Conchello, J.-A. Fluorescence microscopy. Nat. Methods 2, 910 (2005).
3. Camp, C. H. Jr & Cicerone, M. T. Chemically sensitive bioimaging with coherent raman scattering. Nat. Photonics 9, 295 (2015).
4. Cirrana, A. et al. Quantum metropolitan optical network based on wavelength division multiplexing. Opt. Express 22, 1576–1593 (2014).
5. Dynes, J. F. et al. Ultra-high bandwidth quantum secured data transmission. Sci. Rep. 6, 35149 (2016).
6. Wengernovskiy, S., Joshi, S. K., Steinlechner, F., Hüböl, H. & Ursin, R. An ensemble-based wavelength-multiplexed quantum communication network. Nature 564, 225 (2018).
7. Eriksson, T. A. et al. Wavelength division multiplexing of continuous variable quantum key distribution and 18.3 Gbit/s data channels. Commun. Phys. 2, 9 (2019).
8. Gudkov, D., Gudkov, G., Gorbovitski, B. & Gorbovitski, V. Enhancing the linear dynamic range in multi-channel single photon detector beyond 70%. IEEE Sens. J. 15, 7081–7086 (2015).
9. Finocchiaro, P. et al. SPAD arrays and micro-optics: towards a real single photon spectrometer. J. Mod. Opt. 54, 199–212 (2007).
10. Gudkov, D. et al. Detection of multi-color fluorescent objects with single photon spectrometer. Biosens. Bioelectron. 39, 152–155 (2013).
11. Hadfield, R. H. Single-photon detectors for optical quantum information applications. Nat. Photonics 3, 696 (2009).
12. Gol’sman, G. et al. Picosecond superconducting single-photon optical detector. Appl. Phys. Lett. 79, 705–707 (2001).
13. Natarajan, C. M., Tanner, M. G. & Hadfield, R. H. Superconducting nanowire single-photon detectors: physics and applications. Supercond. Sci. Technol. 25, 064001 (2012).
14. Marsili, F. et al. Detecting single infrared photons with 93% system efficiency. Nat. Photonics 7, 210 (2013).
15. Esmaeil Zadeh, I. et al. Single-photon detectors combining high efficiency, high detection rates, and ultra-high timing resolution. APL Photonics 2, 111301 (2017).
16. Zhang, W. et al. NbN superconducting nanowire single photon detector with efficiency over 90% at 1550 nm wavelength operational at compact cryocooler temperature. Sci. China Phys. Mech. Astron. 60, 120314 (2017).
17. Korzh, B. et al. Demonstrating sub-3 ps temporal resolution in a superconducting nanowire single-photon detector. arXiv preprint arXiv:1804.06839 (2018).
18. Schuck, C., Pernice, W. H. & Tang, H. X. Waveguide integrated low noise nbitn nanowire single-photon detectors with milli-hz dark count rate. Sci. Rep. 3, 1893 (2013).
19. Sprengers, J. et al. Waveguide superconducting single-photon detectors for integrated quantum photonic circuits. Appl. Phys. Lett. 99, 181110 (2011).
20. Pernice, W. H. et al. High-speed and high-efficiency travelling wave single-photon detectors embedded in nanophotonic circuits. Nat. Commun. 3, 1325 (2012).
21. Najafi, F. et al. On-chip detection of non-classical light by scalable integration of single-photon detectors. Nat. Commun. 6, 5873 (2015).
22. Akhlaghi, M. K., Schelew, E. & Young, J. F. Waveguide integrated superconducting single-photon detectors implemented as near-perfect absorbers of coherent radiation. Nat. Commun. 6, 8233 (2015).
23. Schuck, C. et al. Quantum interference in heterogeneous superconducting-photonic circuits on a silicon chip. Nat. Commun. 7, 10352 (2016).
24. Khasminskaya, S. et al. Fully integrated quantum photonic circuit with an electrically driven light source. Nat. Photonics 10, 727 (2016).
25. Tyler, N. A. et al. Modelling superconducting nanowire single photon detectors in a waveguide cavity. Opt. Express 24, 8797–8808 (2016).
26. Münzberg, J. et al. Superconducting nanowire single-photon detector implemented in a 2d photonic crystal cavity. Optica 5, 658–665 (2018).

27. Ferrari, S., Schuck, C. & Pernice, W. Waveguide-integrated superconducting nanowire single-photon detectors. Nanophotonics 7, 1725–1758 (2018).
28. Zhu, D. et al. A scalable multi-photon coincidence detector based on superconducting nanowires. Nat. Nanotechnol. 13, 596 (2018).
29. Kahl, O. et al. Spectrally multiplexed single-photon detection with hybrid superconducting nanophotonic circuits. Optica 4, 557–562 (2017).
30. Toussaint, J. et al. Proof of concept of fiber dispersed raman spectroscopy using superconducting nanowire single-photon detectors. Opt. Express 23, 5078–5099 (2015).
31. Gerrits, T. et al. Spectral correlation measurements at the hong-ou-mandel interference dip. Phys. Rev. A 91, 013830 (2015).
32. Zhao, Q.-Y. et al. Single-photon imager based on a superconducting nanowire delay line. Nat. Photonics 11, 247 (2017).
33. Scancalepore, C. et al. Low-crosstalk fabrication-insensitive echelle grating demultiplexers on silicon-on-insulator. IEEE Photon. Technol. Lett. 27, 494–497 (2015).
34. Lyckett, R. J., Gallagher, D. F. & Brulis, V. J. Perfect chirped echelle grating wavelength multiplexor: design and optimization. IEEE Photonics J. 5, 240023–2400123 (2013).
35. Alinmarras, J. P. et al. Large-area 64-pixel array of WI superconducting nanowire single photon detectors. in 2017 Conference on Lasers and Electro-Optics (CLEO) 1–2 (IEEE, 2017).
36. Marsili, F. et al. Single-photon detectors based on ultranarrow superconducting nanowires. Nano. Lett. 11, 2048–2053 (2011).
37. Cheng, R. et al. Self-aligned multi-channel superconducting nanowire single-photon detectors. Opt. Express 24, 27070–27076 (2016).
38. Cheng, R., Poot, M., Guo, X., Fan, L. & Tang, H. X. Large-area superconducting nanowire single-photon detector with double-stage avalanche structure. IEEE Trans. Appl. Supercond. 27, 1–5 (2017).

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**Author contributions**

R.C., C.-L.Z., X.G. and H.X.T. conceived the idea and experiment; R.C. designed the devices; R.C. and S.W. fabricated the device; R.C. and X.H. performed the measurements; R.C., C.-L.Z. and X.G. analyzed the data. R.C., C.-L.Z. and H.X.T. wrote the paper with input from all authors. H.X.T. supervised the project.

**Additional information**

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