In neutral dense electron–hole systems at low temperatures, theory predicted Cooper-pair-like excitons exist at the Fermi energy and form a Bardeen–Cooper–Schrieffer-like condensate. Optical excitations create electron–hole systems with the density controlled via the excitation power. However, the intense optical excitations required to achieve high densities cause substantial heating that prevents the realization of simultaneously dense and cold electron–hole systems in conventional semiconductors. Here we show that the separation of electron and hole layers enables the realization of a simultaneously dense and cold electron–hole system. We find a strong enhancement of photoluminescence intensity at the Fermi energy of the neutral dense ultracold electron–hole system that demonstrates the emergence of an excitonic Fermi edge singularity due to the formation of Cooper-pair-like excitons at the Fermi energy. Our measurements also show a crossover from the hydrogen-like excitons to the Cooper-pair-like excitons with increasing density, consistent with the theoretical prediction of a smooth transition.
The BCs-like exciton condensate in a neutral dense e–h system is formed by the Cooper-pair-like excitons1.

The realization of Cooper-pair-like excitons and BCs-like exciton condensation requires matching of the electron and hole Fermi surfaces1. For equal electron and hole densities, the Fermi momenta of electrons and holes are equal (Fig. 1a), which is required for matching the Fermi surfaces. In comparison, the realization of the Mahan exciton for a hole in a Fermi sea of electrons requires the suppression of the hole kinetic energy, in particular a flat hole band or hole localization15–17.

In contrast to the generation of a 'single hole' in a dense electron gas18–20, the realization of a neutral dense e–h system by optical excitation requires the generation of a large number of electrons and holes, which causes the problem of heating. Due to e–h recombination, the temperature of an optically created e–h system (T_en) exceeds the semiconductor lattice temperature, and lowering T_en below the condensation temperature, in particular at high e–h densities, is challenging. For instance, for neutral dense plasmas generated in single InGaAs/InP19 or InGaAs/GaAs20–22 quantum wells in experiments at T = 2 K, the effective e–h temperature reached and exceeded 100 K, well above both the lattice temperature and the temperature needed for the realization of the Cooper-pair-like excitons and BCs-like exciton condensation15.

To create cold e–h systems, we work with heterostructures with separated electron and hole layers (Fig. 1b). In these heterostructures, spatially indirect excitons (IXs), also known as interlayer excitons, are formed by electrons and holes confined in separated layers15–17. The layer separation increases the e–h recombination time, which allows cooling of the optically generated e–h system to low temperatures9,10. The other advantage of the separated electron and hole layers is the overall enhancement of the energy per e–h pair with density that is outlined below. This enhancement stabilizes the exciton state against the formation of e–h droplets27–29, which may otherwise form the ground state1. Earlier studies of cold IX systems concerned the regime of hydrogen-like IXs30,31, while the regime of Cooper-pair-like IXs in a dense e–h system with high Fermi energy was not explored.

In this work, we study an ultracold neutral spatially indirect e–h plasma (I-EHP) in separated electron and hole layers in a GaAs/AlGaAs coupled quantum well (CQW) heterostructure. The electrons and holes are confined in 15 nm GaAs quantum wells (QWs) separated by a 4 nm AlGaAs barrier (Supplementary Note 1). The long e–h recombination lifetimes (τ on the order of a microsecond; Supplementary Fig. 1a) owing to the separation between the electron and hole layers allow for cooling of the plasma to low temperatures. The creation of a cold I-EHP is facilitated by separating the e–h plasma from the laser excitation in space and time, and using the laser excitation resonant to the direct exciton energy as described in Supplementary Note 2. The estimated temperature of the dense optically created e–h system reduces to the bath temperature in the experiments T_en = 2 K (Supplementary Fig. 5).

In the experiments, the densities of the photoexcited e–h system are controlled through P_en from the low-density IX regime to the high density I-EHP regime. In the high-density regime, we observed a broad I-EHP line with a linewidth exceeding the IX binding energy9,30,32 and increasing with density (Figs. 1 and 2a). The simulations of the I-EHP PL line without taking into account the Fermi edge singularity due to the Cooper-pair-like excitons at the Fermi energy are presented in Supplementary Fig. 4. These simulations show step-like spectra with a linewidth of Δ = E_Fe + E_Fh, similar to the spectra of spatially direct EHP in single QWs in earlier studies4.

At high temperatures, the I-EHP PL line (Fig. 1c, bottom) is typical for plasmas above the condensation temperature, and the lineshape is consistent with the simulations with no Fermi edge singularity (Supplementary Fig. 4). At low temperatures, we observed a strong enhancement of the PL intensity at the Fermi energy of cold plasma (Fig. 1c, top) that evidences the emergence of an excitonic Fermi edge singularity. The temperature and density dependence of the spectra are consistent with the many-body origin of this enhancement.

At the lowest densities, the IX linewidth is approximately 0.6 meV (Fig. 2a). The small value of the IX linewidth indicates a low disorder in the heterostructure. With increasing e–h density, we observe a transition from the ultracold gas of hydrogen-like IXs with the narrow PL line at low e–h densities to the ultracold I-EHP with the Fermi edge singularity. The temperature and density dependence of the spectra are consistent with the many-body origin of this enhancement.
singularity due to the Cooper-pair-like excitons at the Fermi energy at high e–h densities (Fig. 2a)). The transition is smooth, consistent with the theory predicting a crossover from hydrogen-like excitons to Cooper-pair-like excitons with increasing density. 

The overall shift of the PL energy (Fig. 2a) is caused by the separation between the electron and hole layers and can be approximated by the ‘capacitor’ formula $\delta E = 4\pi e^2 d/e$, where $e$ is the electron charge, $d$ is the separation between the layers and $e$ is the dielectric constant. This approximation becomes increasingly more accurate with increasing density. The e–h density $n$ estimated from the energy shift $\delta E$ is close to the value of $n$ estimated from the plasma PL linewidth $\Delta = E_{\text{pl}} + E_{\text{as}} = n^2 \hbar^2 (1/m_e + 1/m_h)$, where $m_e$ and $m_h$ are the electron and hole effective mass, respectively (Supplementary Fig. 3). 

The Fermi edge singularity vanishes with increasing temperature (Fig. 2b). This is quantified in Fig. 3 by the spectrum skewness $M_3$, which characterizes the high positive $M_3$ observed in the dense 1-EHP at low temperatures. In superconductors, pairs can appear above critical temperature $T_c$, and this gives an estimated condensation temperature of the hydrogen-like excitons in the low-density regime. The maximum $\xi$ for excitons is the length over which excitons separated in the CQW plane are coherent. In a classical gas, $\xi$ vanishes with increasing temperature (Fig. 4). The coherence vanishes with increasing temperature (Fig. 4). The coherence length (Fig. 4) reaches substantially higher values than in a classical gas ($\xi_{\text{classical}} = \lambda_{\text{BM}} = 0.1 \mu$m at $T = 2$ K). In comparison with earlier measurements of the spontaneous coherence of hydrogen-like IXs in the low-density regime, the maximum $\xi$ is $1.5 \mu$m (Fig. 4) is comparable to the values of $\xi = 1.5 \mu$m in ref. 27 and $\xi = 0.5 \mu$m in ref. 32 but somewhat smaller than the finding in ref. 26, where $\xi$ reaches several microns. A higher $\xi$ in that work may be related, in particular, to a weaker dipolar interaction due to a smaller $d$, a lower bath temperature (~100 mK) and a specific electro-optical IX generation with holes optically generated and electrons electronically injected in localized areas.

In superconductors, pairs can appear above critical temperature due to fluctuations. Cooper-pair-like excitons and the enhancement of the PL intensity at the Fermi energy owing to fluctuations have been considered theoretically. The measurements of spontaneous coherence with $\xi \approx \xi_{\text{classical}}$ suggest that the Cooper-pair-like excitons form in the condensate.

A relation of the studied system to other systems is outlined below. The Fermi edge singularity in a neutral e–h system due to Cooper-pair-like excitons at the Fermi energy and BCS-like exciton condensation are related to excitonic insulators. In contrast to optically created e–h systems in semiconductors, such as the system considered in this work, the excitonic insulators generally form in semimetals or in narrow-gap semiconductors with no optical generation. The nature of BCS-like exciton condensates in optically created e–h systems and excitonic insulators in semimetals is similar. Excitonic insulators are actively studied. The other system that allows studying the B–C crossover is a system of ultracold atoms with controlled interactions.

**Fig. 3** The spectrum skewness $M_3$. a. $M_3$ versus the laser excitation power $P_{\text{ex}}$ and temperature between the electron and hole layers and can be approximated by the ‘capacitor’ formula $\delta E = 4\pi e^2 d/e$, where $e$ is the electron charge, $d$ is the separation between the layers and $e$ is the dielectric constant. This approximation becomes increasingly more accurate with increasing density. The e–h density $n$ estimated from the energy shift $\delta E$ is close to the value of $n$ estimated from the plasma PL linewidth $\Delta = E_{\text{pl}} + E_{\text{as}} = n^2 \hbar^2 (1/m_e + 1/m_h)$, where $m_e$ and $m_h$ are the electron and hole effective mass, respectively (Supplementary Fig. 3). 

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In comparison, in the ultracold e–h system studied here, the density and, in turn, the parameter \( n a^2_0 \) are controlled. The density increase allows one to go from the low-density regime of hydrogen-like excitons to the high-density regime of Cooper-pair-like excitons, and the regimes are revealed by the distinct PL lineshapes, with the high-density regime characterized by the Fermi edge singularity.

In summary, we found a strong enhancement of the PL intensity at the Fermi energy of the neutral dense ultracold e–h system that evidences the emergence of an excitonic Fermi edge singularity due to the Cooper-pair-like excitons at the Fermi energy.

**Online content**

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at [https://doi.org/10.1038/s41567-023-02096-2](https://doi.org/10.1038/s41567-023-02096-2).

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Data availability
Source data files are available via Figshare66. All relevant data are available from the authors upon reasonable request.

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Author contributions
L.V.B. designed the project. K.W.B. and L.N.P. grew the GaAs heterostructures. D.J.C. and E.A.S. performed the measurements. D.J.C., E.A.S. and L.V.B. analysed the data. L.V.B. wrote the manuscript with inputs from all the authors.

Competing interests
The authors declare no competing interests.

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