# Fermi edge singularity in cold neutral electron-hole system

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# Phase Diagram of Ultracold Neutral e-h Systems

Ultracold: $T < E_b, T_q$ $\quad T_q \sim \frac{2\pi\hbar^2}{m_x} n$

**Low Densities** ($n \ll 1/a_B^D$)

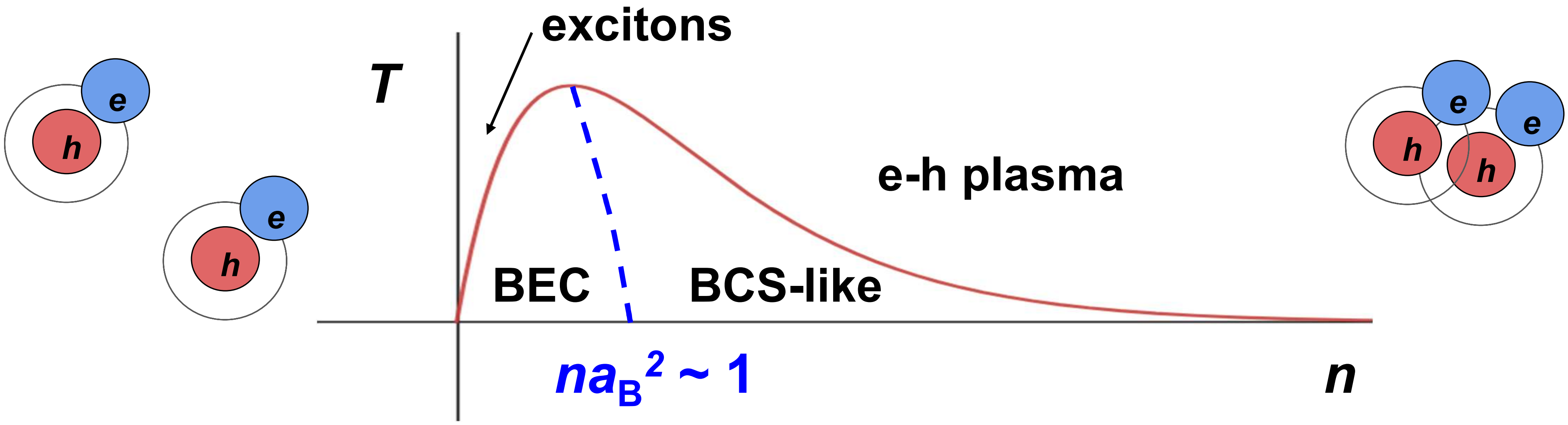
- Excitons are **hydrogen-like** bosons composed of $k$-states close to $k$=0
- BEC of excitons below ~$T_q$

**L.V. Keldysh, A.N. Kozlov, Sov. Phys. JETP 27, 521 (1968).**

**High Densities** ($n > 1/a_B^D$)

- Excitons are **Cooper-pair-like** bosons composed of $k$-states around $k_F$
- BCS-like condensate of excitons

**L.V. Keldysh, Yu.V. Kopaev, Sov. Phys. Solid State 6, 2219 (1965).**



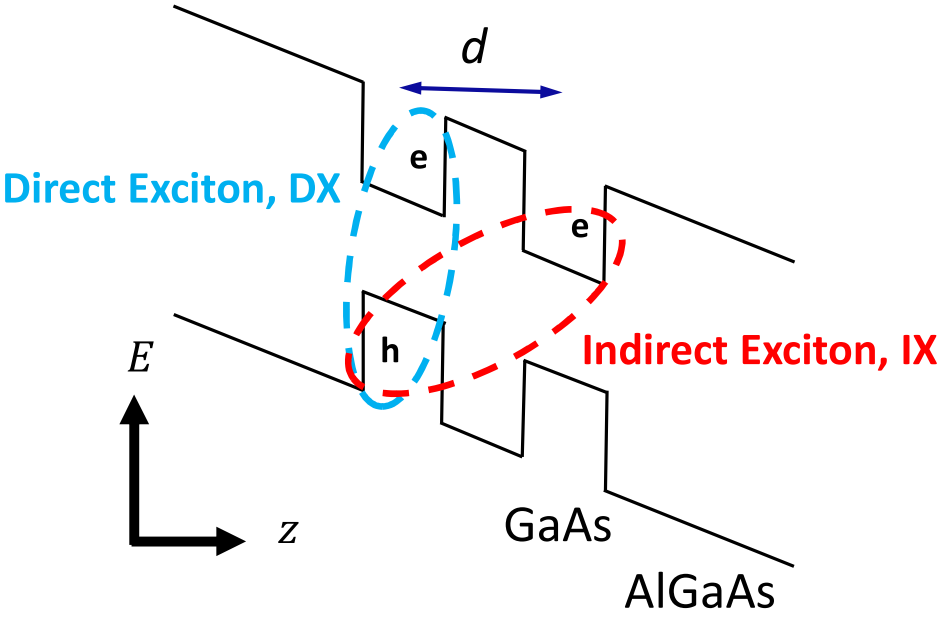
# Spatially Indirect Excitons (IXs)

PLE: FW3N.8 Marriot Salon 2, 5/10 14:45
TMD: FW4N.5 Marriot Salon 2, 5/10 17:45

**IXs**: pairs of electrons and holes in separated layers

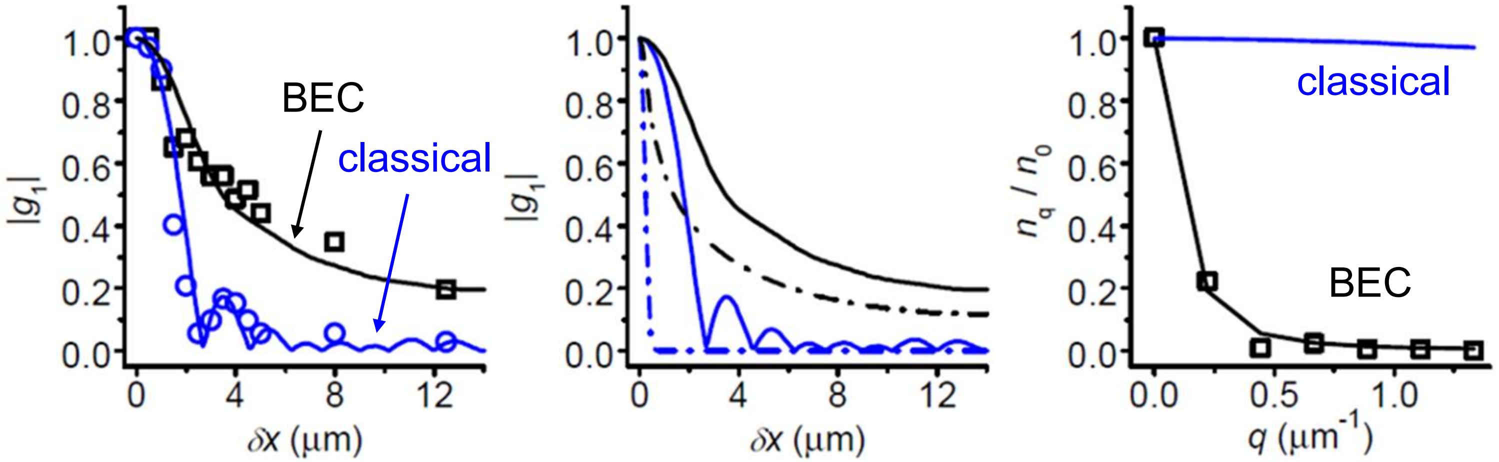
- Long lifetime (**~ 1 μs**) → ultracold
- Density controlled with excitation power
- Built in electric dipole moment ***ed***
  - Repulsive dipolar interaction:
    - screens disorder
    - prevents real-space condensation

**L.V. Keldysh, Contemp. Phys. 27, 395 (1986).**



# Low-Density regime

## Spontaneous coherence and BEC of IXs

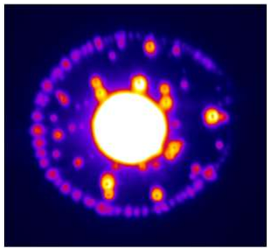


measured $g_1(\delta x)$ and distribution in momentum space agree with theory of BEC of equilibrium bosons

**Nature 483, 584 (2012)**

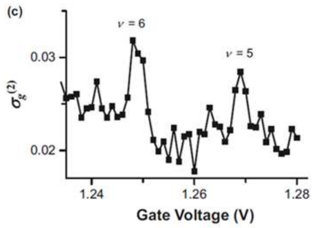
## Phenomena in IX BEC observed below BEC temperature

### Ordered Exciton State



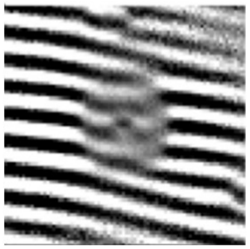
**Nature 418, 751 (2002)**

### Commensurability



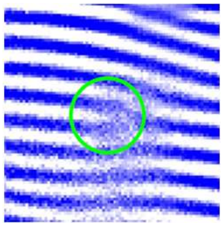
**PRB 91, 245302 (2015)**

### PB Phase



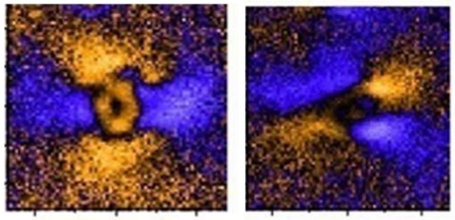
**Nat Com 9, 2158 (2018)**

### Interference Dislocations



**Nat Com 12, 1175 (2021)**

### Spin Textures



**PRL 110, 246403 (2013)**

# Fermi Edge Singularity In Electron Gas With Single Hole

## Mahan Exciton

**G. Mahan, Phys. Rev. 153, 882 (1967)**

**M. Combescot, P. Nozieres,**
**J. de Physique 32, 913 (1971)**

**M.S. Skolnick et al,**
**PRL 58, 2130 (1987)**

**J.S. Lee, Y. Iwasa, N. Miura,**
**Sem. Sci. Tech. 2, 675 (1987)**

**A. Livescu et al,**
**IEEE J. Quant. Electr. 24 (1988)**

**K. Ohtaka, Y. Tanabe,**
**PRB 39, 3054 (1989)**

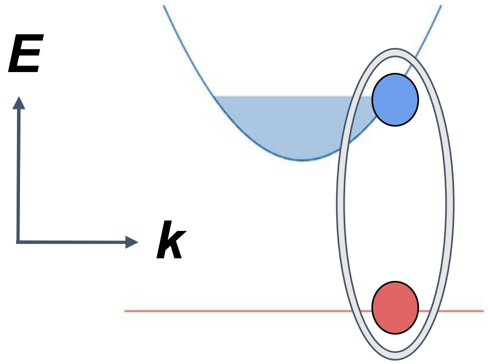
**T. Uenoyama, L.J. Sham,**
**PRL 65, 1048 (1990)**

**P. Hawrylak,**
**PRB 44, 3821 (1991)**

Neutral System:
**S. Schmitt-Rink, C. Ell, H. Haug**
**PRB 33, 1183 (1986)**

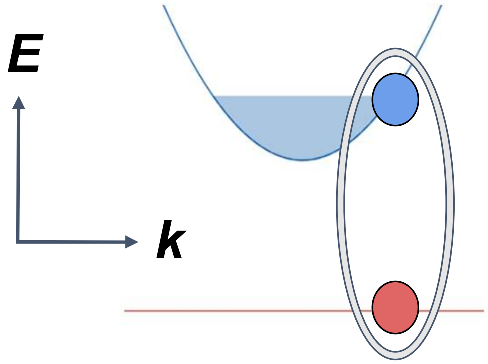
## Mahan Exciton

**Single Hole in Fermi-gas of electrons**



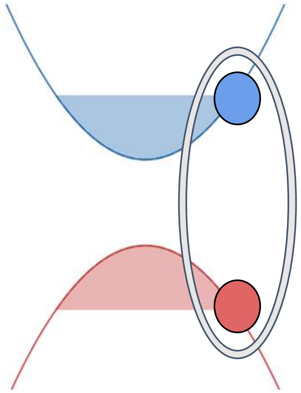
## Mahan Exciton

**Single Hole in Fermi-gas of electrons**



## Cooper-pair-like Excitons

**Neutral System**



No Fermi edge singularity in neutral dense e-h plasma in <u>single QW</u>

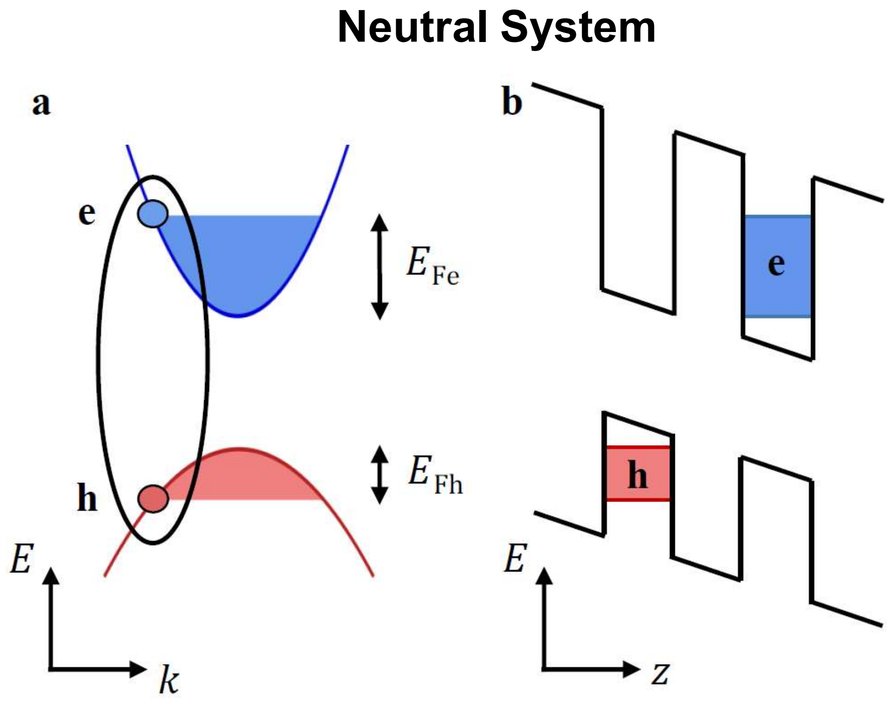
↓

e-h plasma did not cool to ultralow T

**L.V. Butov, V.D. Kulakovskii, G.E.W. Bauer, A. Forchel, D. Grützmacher, PRB 46, 12765 (1992).**

## Neutral e-h plasma in separated electron and hole layers can cool to ultralow T

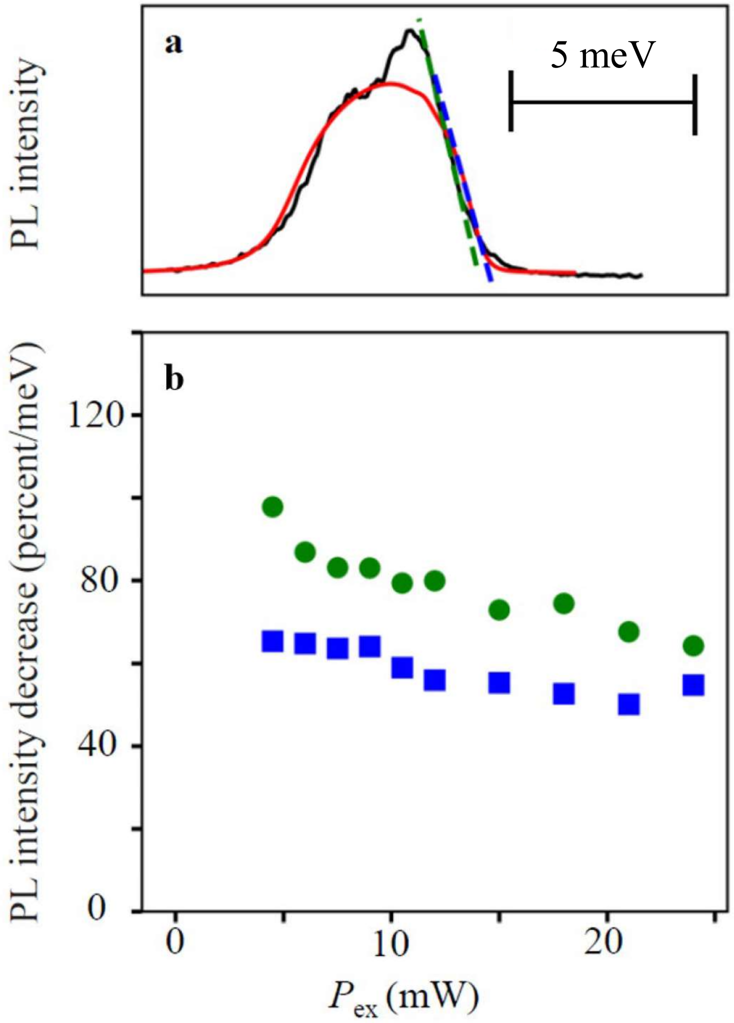
- Spatial separation of electron and hole layers
- In-plane separation from excitation spot
- Separation in time from excitation pulse
- Resonant excitation to DX absorption



D. J. Choksy*, E. A. Szwed*, L. V. Butov, K. W. Baldwin, L. N. Pfeiffer. arXiv:2209.06026

# Achievement of an ultracold e-h plasma

- Ultracold e-h plasma achieved
- $T_{eh}$ in I-EHP can be estimated from the sharpness of the high-energy side of the spectrum
- Compare the simulation at $T = T_{bath} = 2$ K and the experiment
- The sharpness of the high-energy side in simulations and experiment are close ⟶ **$T_{eh}$ of the dense optically created e-h system lowers to 2 K**

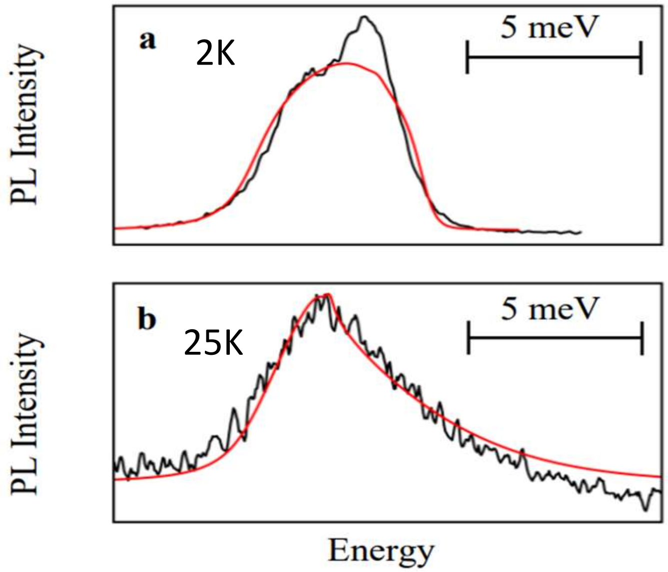


# Emergence of Fermi edge singularity in ultracold neutral e-h plasma in separated e and h layers

- Fermi edge singularity is observed at low temperatures

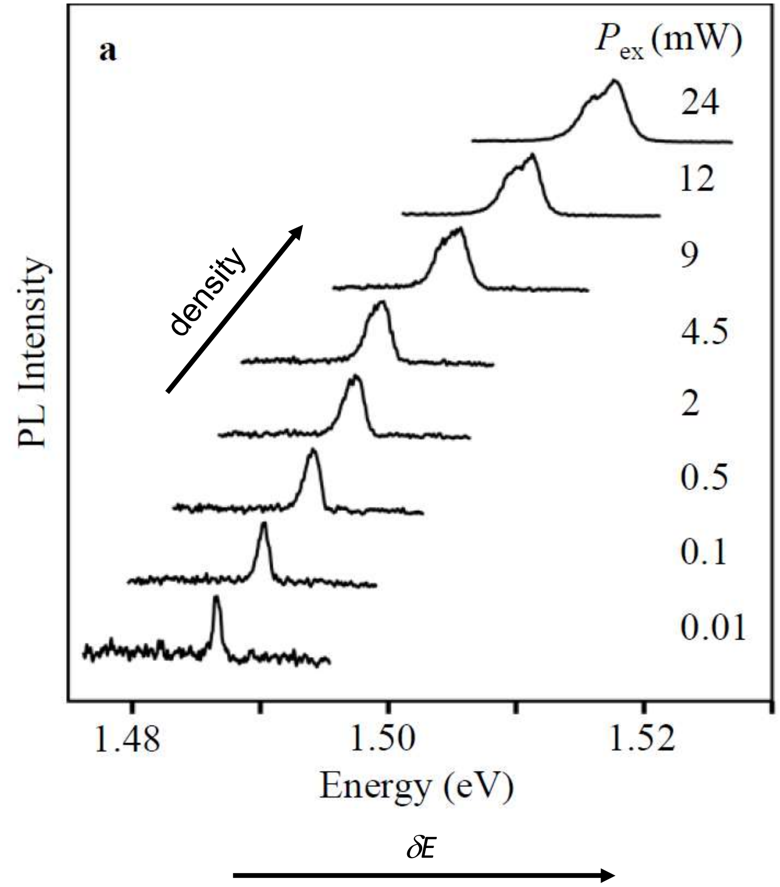
- At high temperatures PL is characteristic of plasma

PL intensity enhancement at the Fermi energy evidences excitonic Fermi edge singularity
due to **Cooper-pair-like excitons** at the Fermi energy



— Simulated I-EHP PL spectra without Fermi edge singularity.
Low T: step-like spectra, width $\Delta \sim E_F$

# Crossover from hydrogen-like IXs to Cooper-pair-like IXs



$n$ (x$10^{10}$ cm$^{-2}$) estimated from $\delta E$

11
9
7
5
4
3
1
0.3

high-density regime:
Cooper-pair-like IXs
broad spectra with Fermi edge singularity

crossover from
hydrogen-like IXs to
Cooper-pair-like IXs

theory: crossover
from hydrogen-like
to Cooper-pair-like
excitons

**C. Comte,**
**P. Noziéres,**
**J. de Physique**
**43, 1069 (1982)**

low-density regime:
hydrogen-like IXs
narrow spectra

shift due to separation of e and h layers → density estimate $\Delta E \sim \dfrac{4\pi e^2 dn}{\epsilon}$

# Density estimates

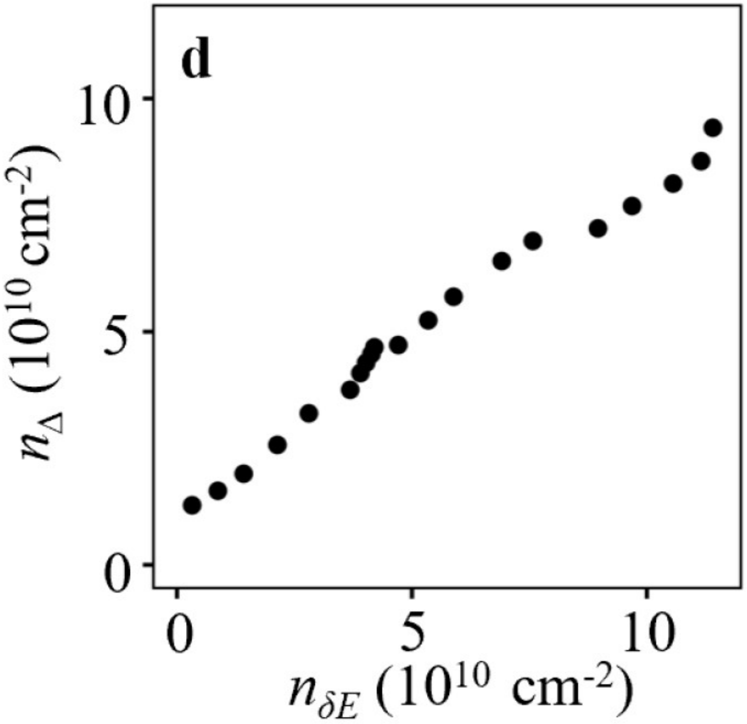
in high-density regime:
density can be estimated from energy shift $\delta E$

$$\delta E \sim \frac{4\pi e^2 d n}{\epsilon}$$

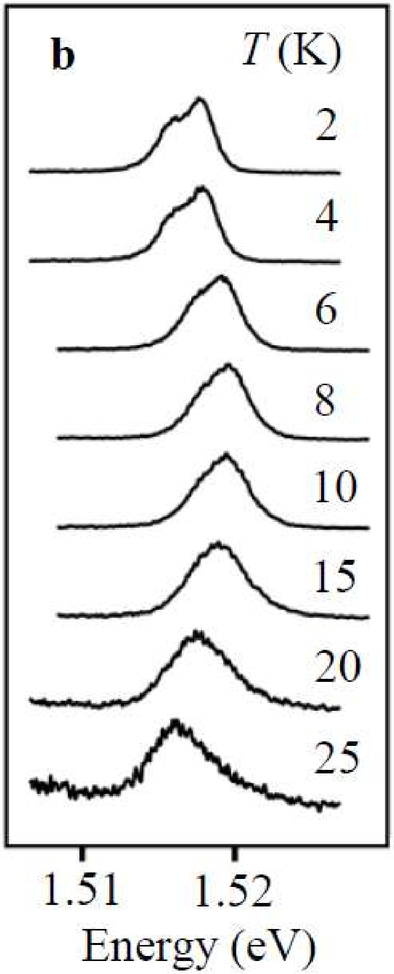
and from linewidth $\Delta$

$$\Delta \sim E_{\mathrm{Fe}} + E_{\mathrm{Fh}} = \pi \hbar^2 n \left(\frac{1}{m_{\mathrm{e}}} + \frac{1}{m_{\mathrm{h}}}\right)$$

estimates from $\delta E$ and from $\Delta$ give similar $n$



# Temperature dependence

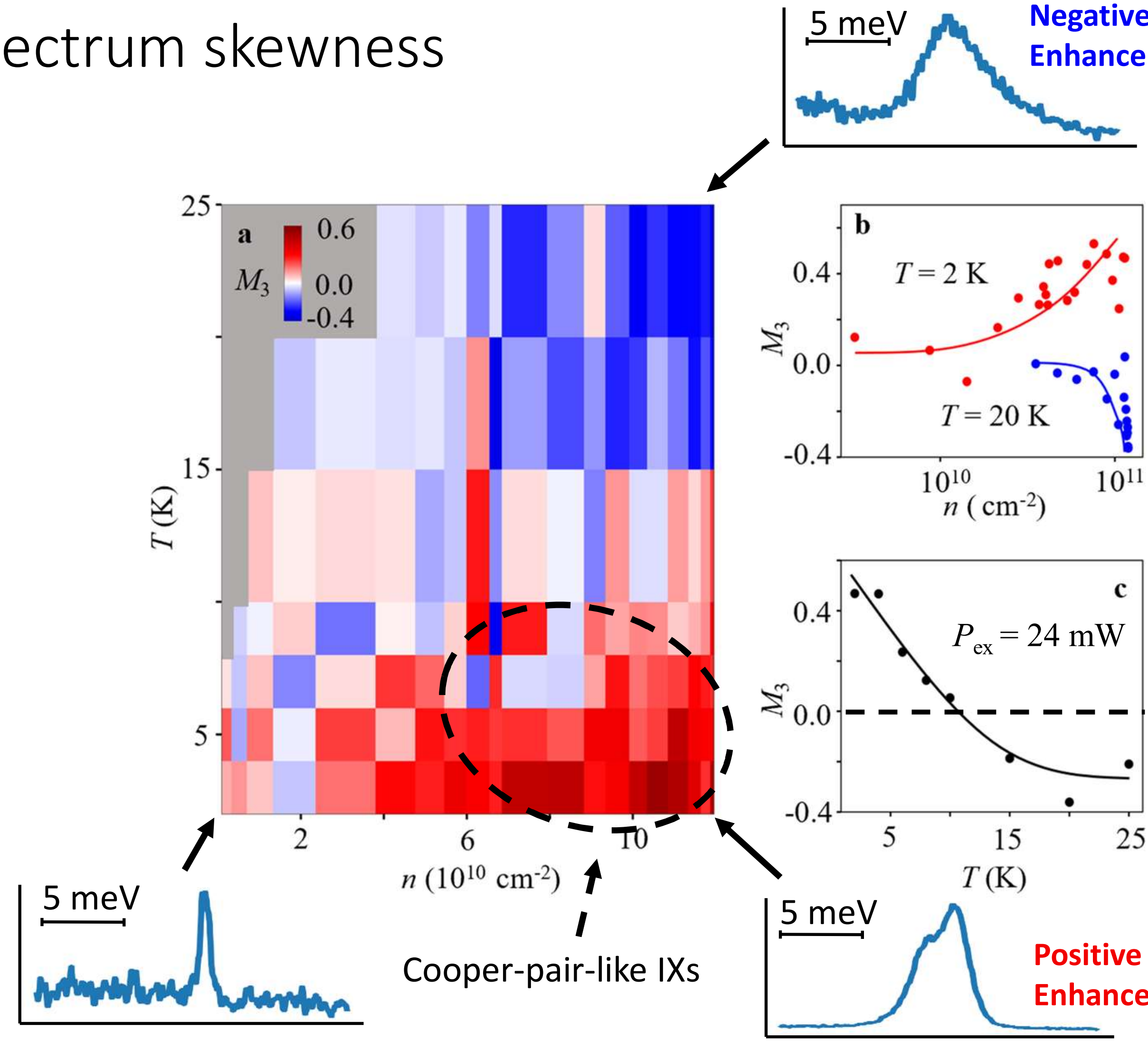


estimated condensation temperature

$T \sim 2\pi\hbar^2\, n/m \sim 10\ \mathrm{K}$

Fermi edge singularity vanishes at $T \sim 10$ K

# Spectrum skewness



**Negative skew:**
**Enhancement at low energy**

Cooper-pair-like IXs

**Positive skew:**
**Enhancement at high energy**

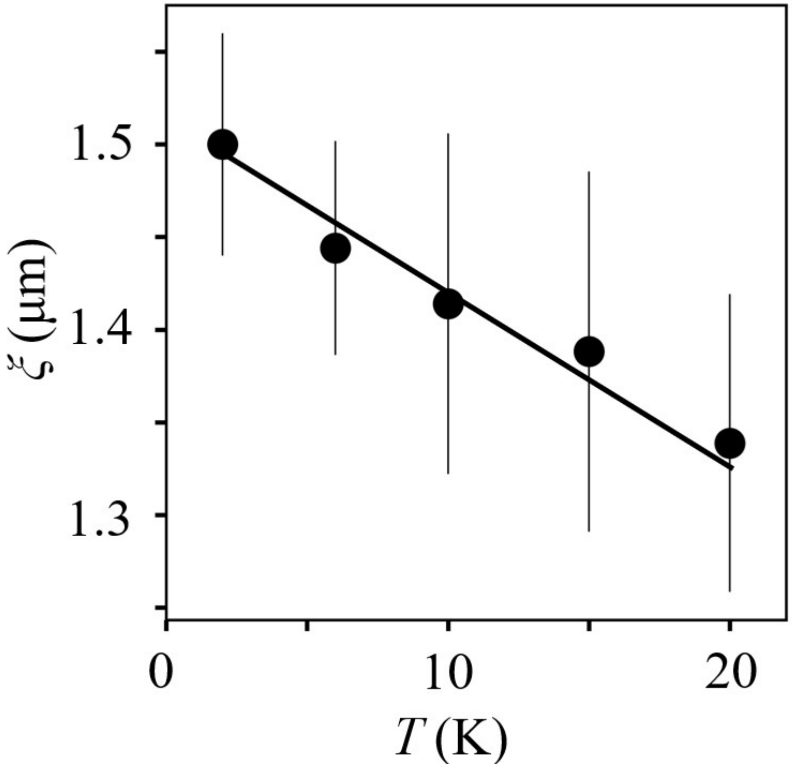
# Spontaneous coherence

- Measured via shift interferometry
- Coherence length $\xi >> \xi_{\text{classical}}$

  $\xi_{\text{classical}} \sim \lambda_{\text{dB}} \sim 0.1\ \mu\text{m}$ at 2 K

  suggest that Cooper-pair-like

  excitons form in condensate



# Summary

Observed Fermi edge singularity in PL of neutral cold e-h plasma

- Found how to realize ultracold e-h plasma
- Enhancement of PL intensity at the Fermi energy evidences the emergence of Fermi edge singularity due to the Cooper-pair-like excitons at the Fermi energy
- Fermi Edge singularity is observed at low temperatures and high densities
- Crossover from the hydrogen-like excitons to the Cooper-pair-like excitons with increasing density, consistent with the theory predicting a smooth transition

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