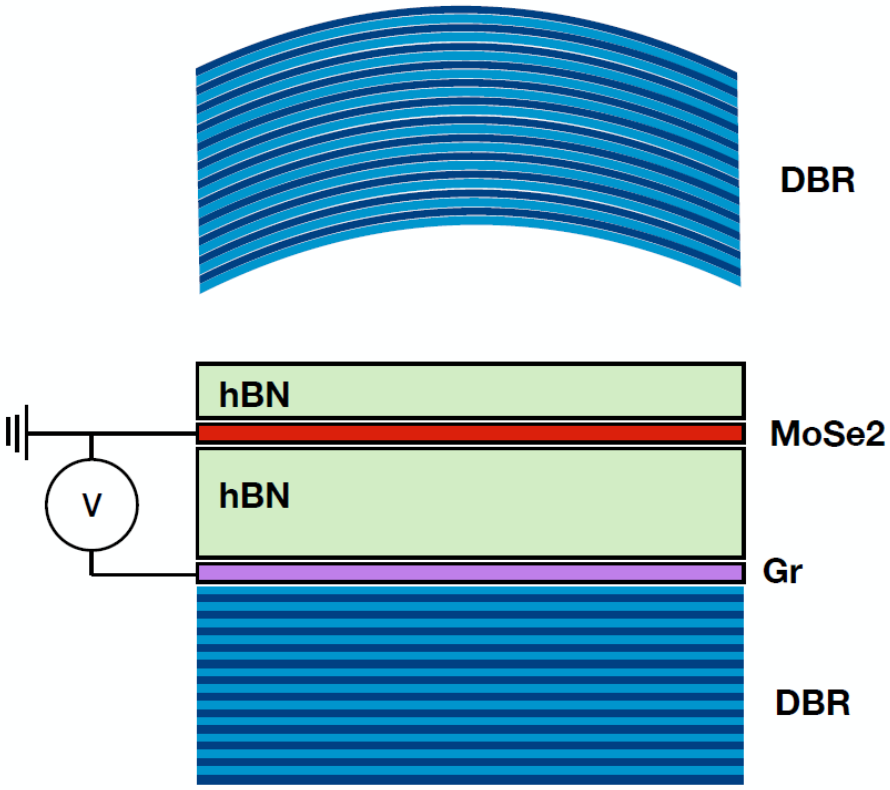
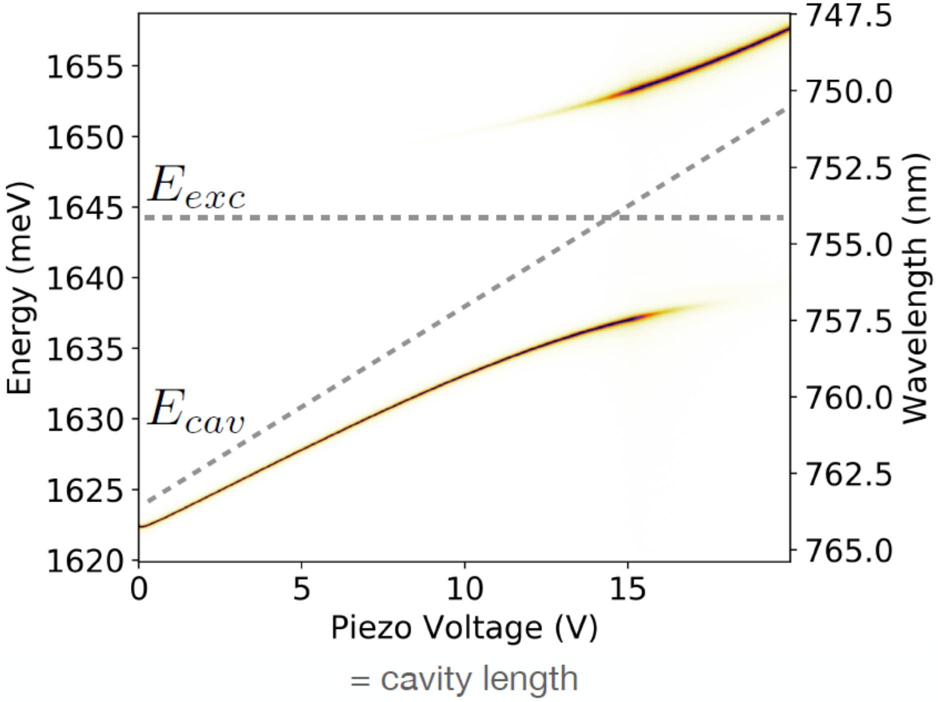
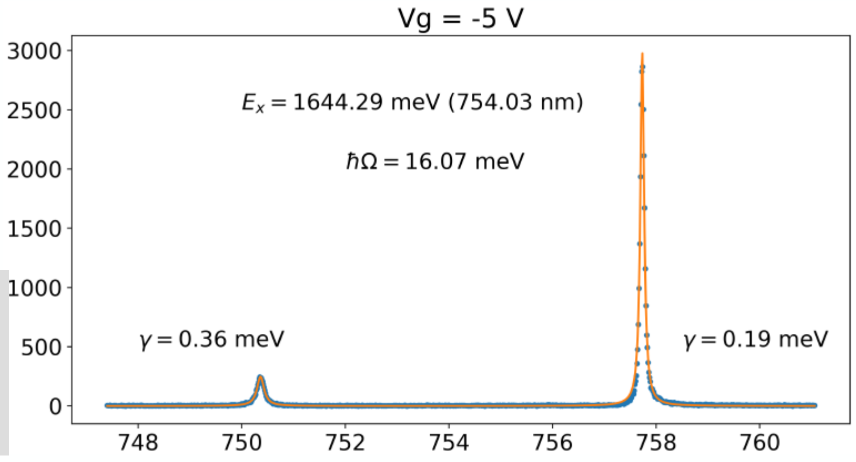
Cavity-QED with 2D excitons



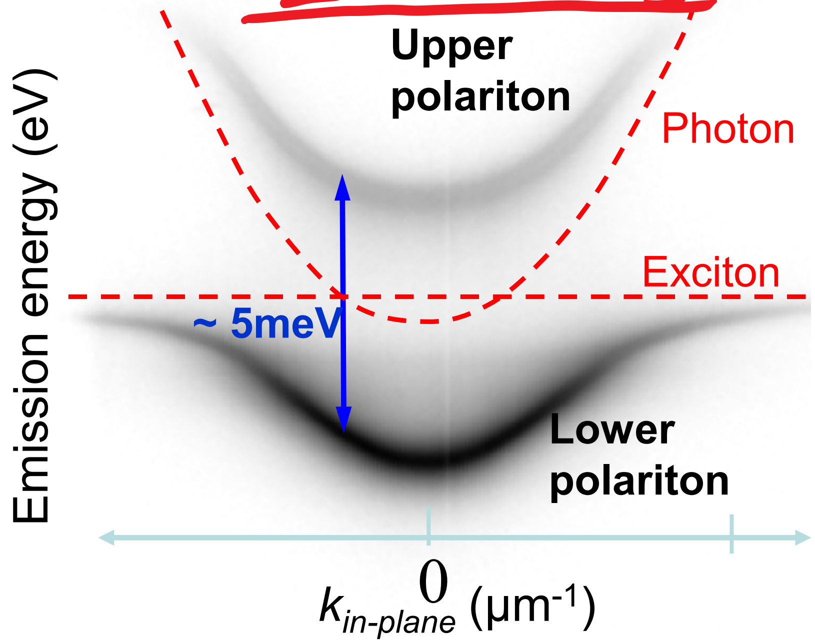




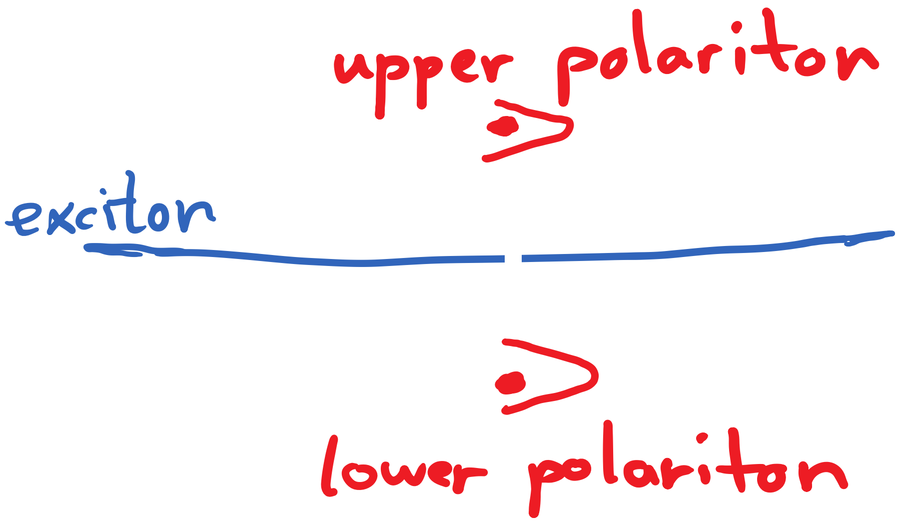
<u>Key requirement for high-Q cavities</u>: the graphene gates need to be placed at the node of the cavity mode

Cavity-polaritons with 2D materials

2D cavity



0D Cavity



Exciton - polaron - polaritons

- If the 2D material is inside a cavity, then

$$H \to H + \sum_p \omega_c(p)\, a_p^\dagger a_p + \sum_p g_c(p)\left[a_p^\dagger x_p + x_p^\dagger a_p\right]$$

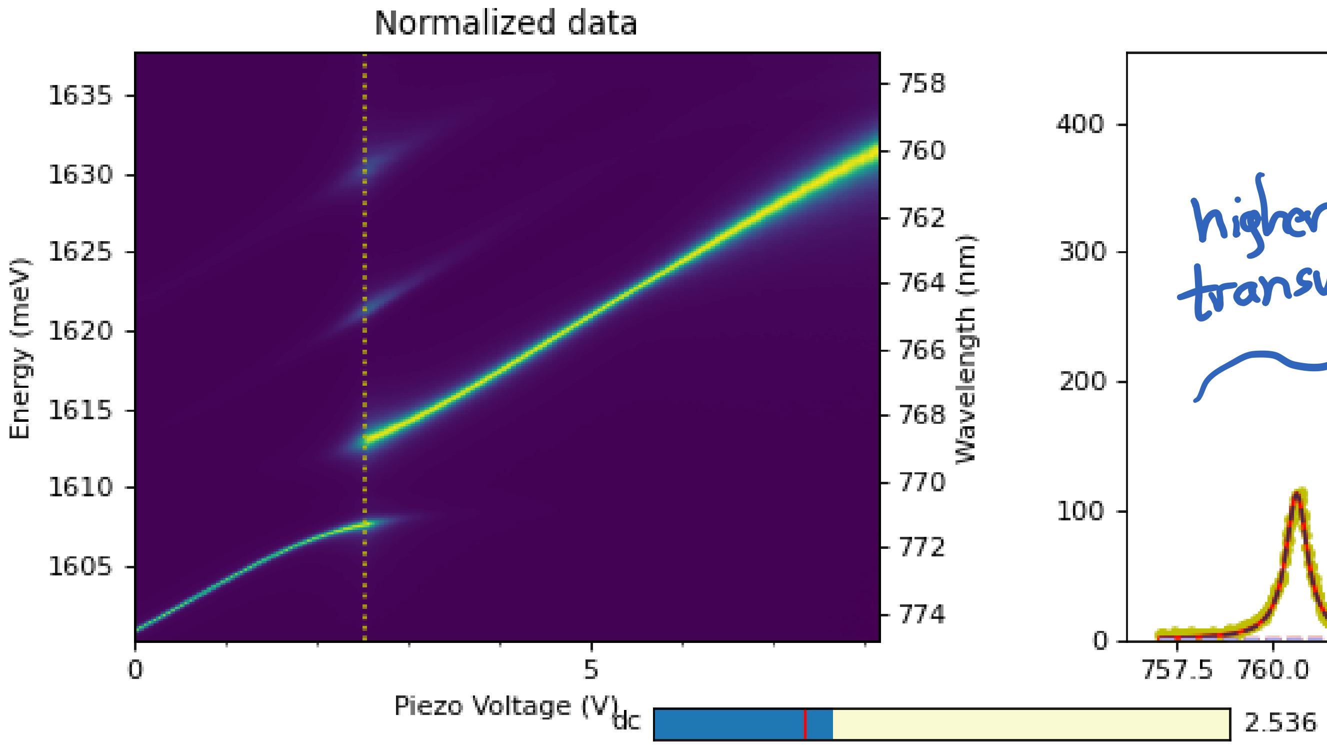
- Due to steep cavity dispersion, we only need to consider exciton dressing; i.e.

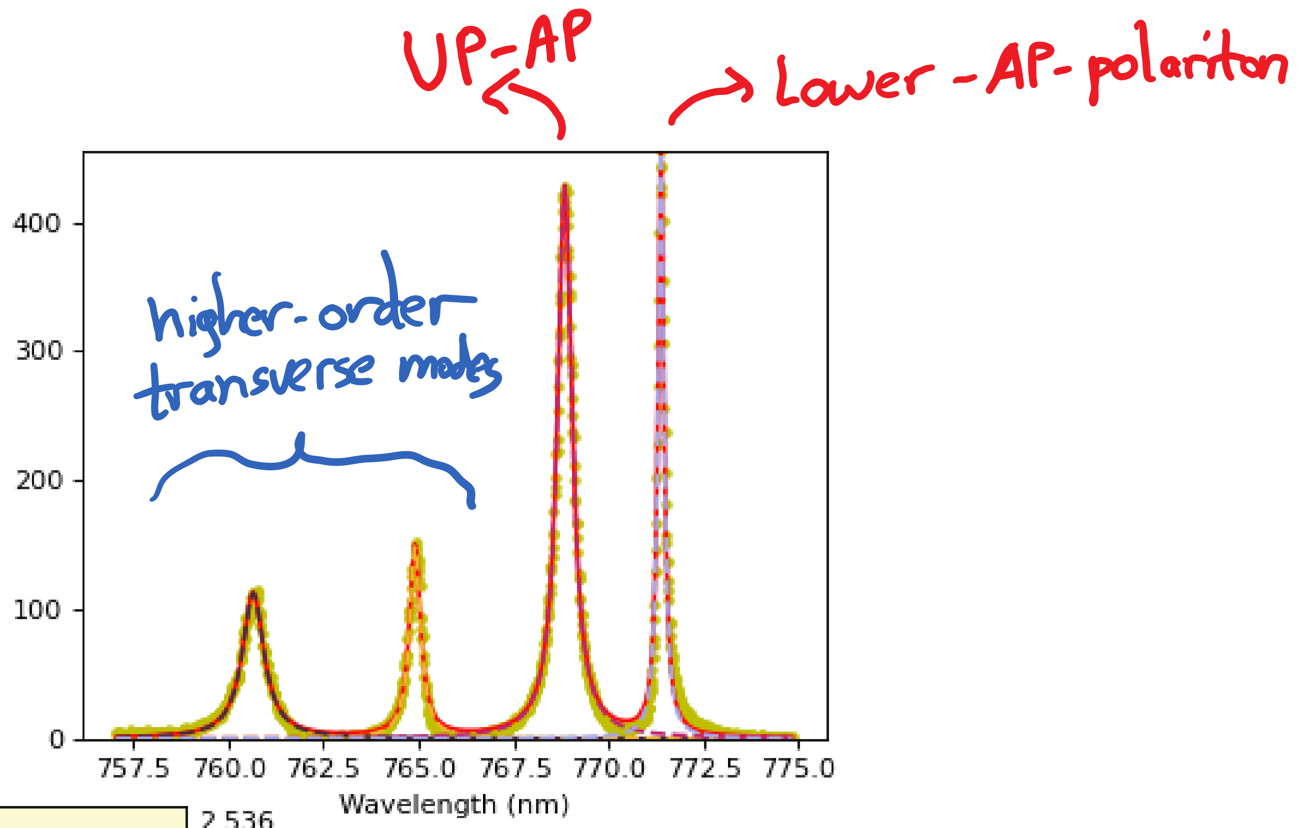
$$|\Psi_{n,p}\rangle = \left[\eta_{n,p}\, a_p^\dagger + \phi_{n,p}\, x_p^\dagger + \sum_{k,q} \varphi_n(k,q)\, x_{p+q-k}^\dagger e_k^\dagger e_q\right]|0\rangle$$

yields:

$$E_{n,p} = \omega_x(p) + \Sigma_x(E_{n,p}) + \frac{g_c^2}{E_{n,p} - \omega_c(p)}$$

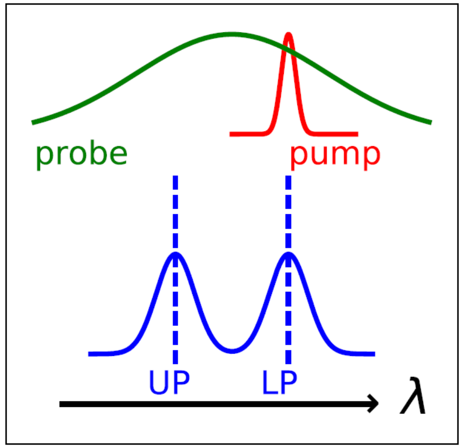
Attractive-polaron-polaritons in high-Q cavities

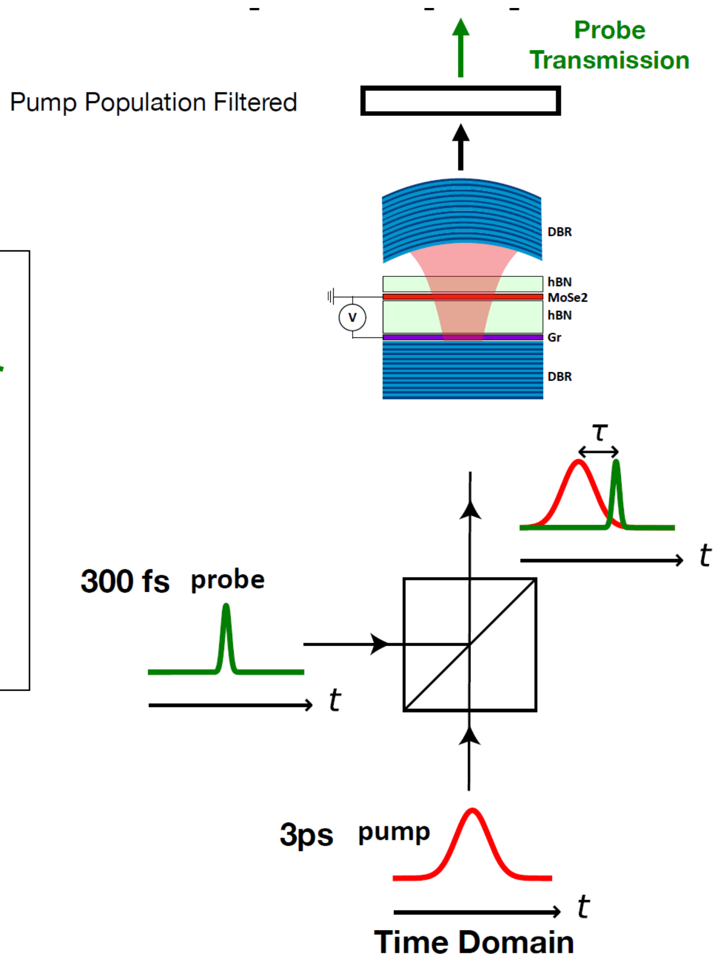




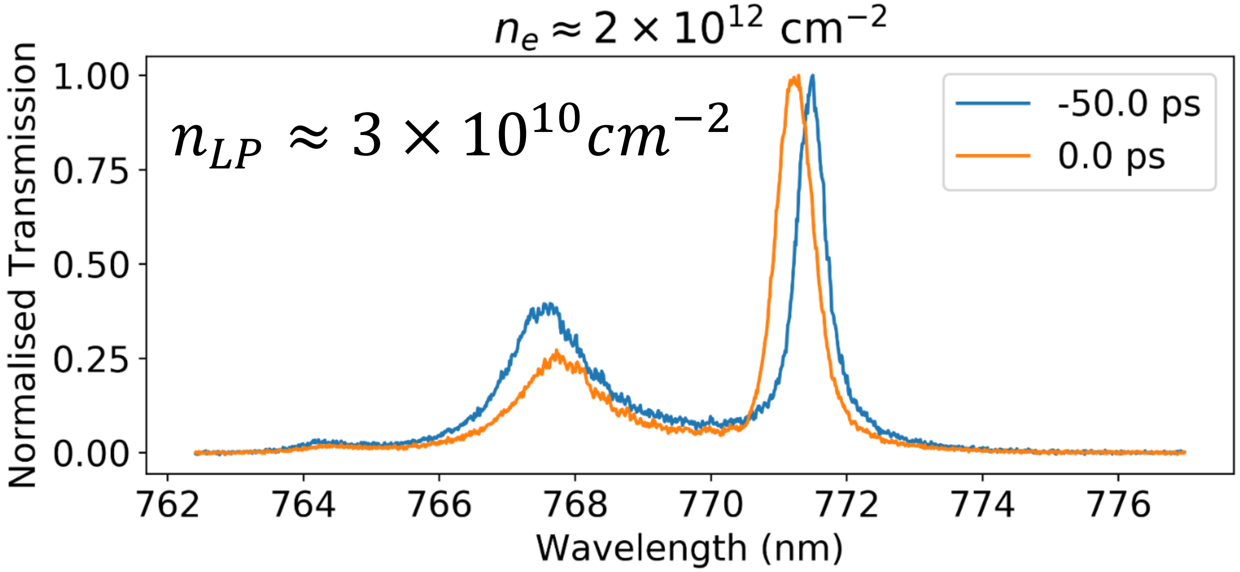
- AP-LP is shifted away from the continuum of many-body states and could have nearly cavity-limited line-broadening.

Time-resolved pump-probe spectroscopy

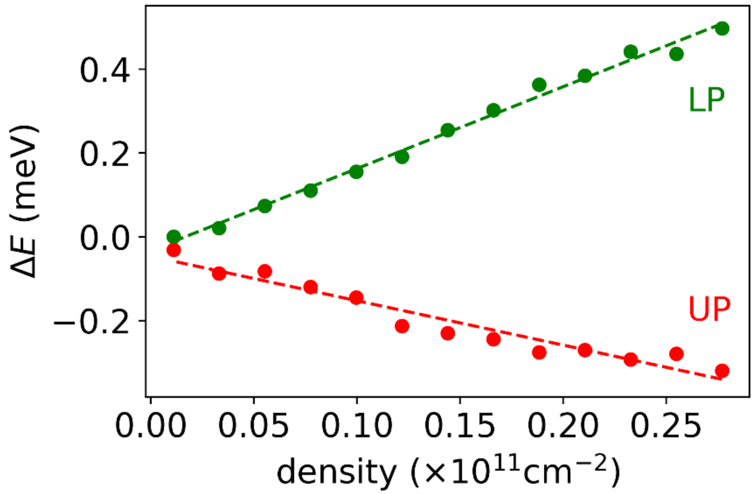




Enhancement of polariton-polariton interactions



$g_{LP} = 2\ \mu eV\ \mu m^2$



- Factor of 5 enhancement of polaron-polariton interactions as compared to bare exciton-polaritons.

A new mechanism for enhancing polariton-polariton interactions

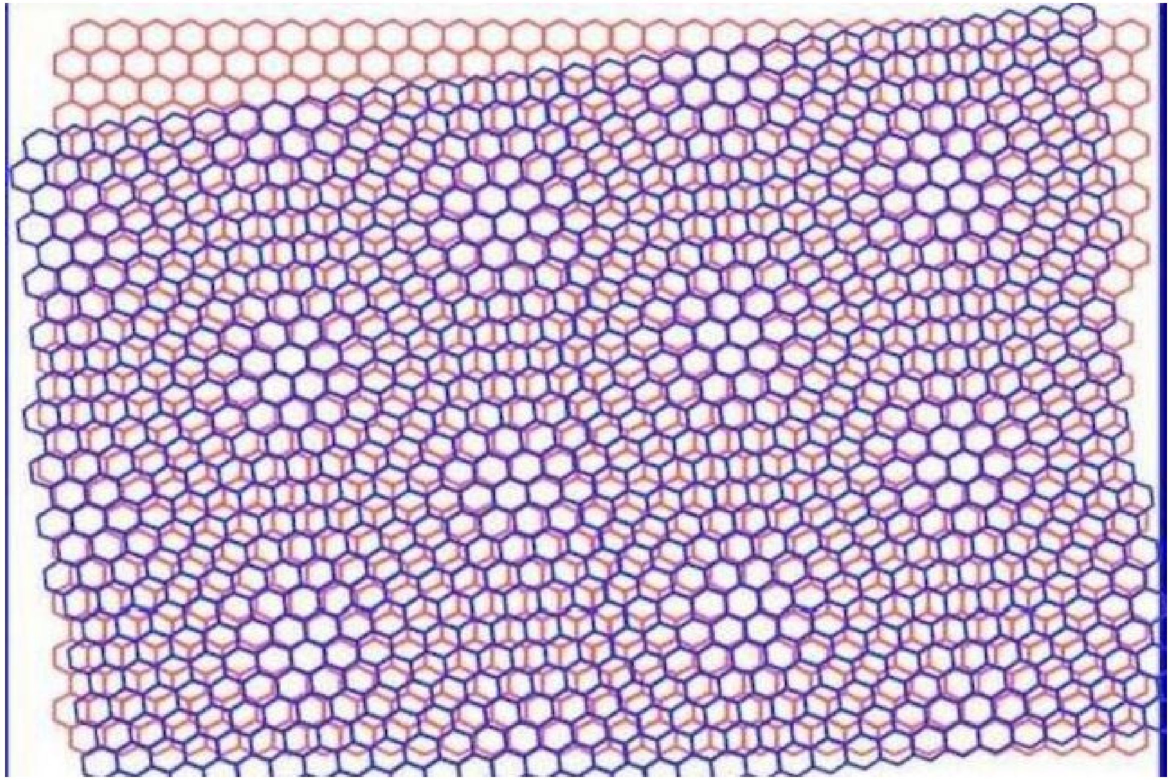
- Attractive polaron-polariton splitting

$$g \cong g_{c-x} \cdot k_F a_T \quad \left\{ \begin{array}{l} g_{c-x} : \text{exciton-cavity coupling} \\ k_F \propto \sqrt{n_e} : \text{Fermi momentum} \\ a_T : \text{trion Bohr radius} \end{array} \right.$$

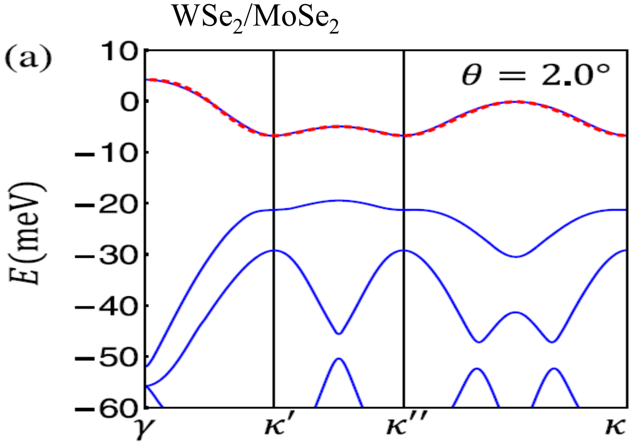
→ Each polariton "removes an electron" from the Fermi sea such that when $n_{pol} \sim n_e$, attractive polarons cannot be formed : $g \to 0$

$$\therefore \quad \boxed{U \sim \frac{g}{n_e} = \frac{g_{c-x} \cdot k_F a_T}{n_e} \propto \frac{a_T}{a_B} \cdot \frac{1}{\sqrt{n_e}}}$$

Epilogue: a taste of many-body physics



Twisted bilayer transition metal dichalcogenide (TMD)



F. Wu *et al.*, Phys. Rev. Lett. **121**, 026402 (2018)

Heavy effective mass (m^*~$0.7m_e$)

→ Flat band in wide range of angles

→ Tunable lattice period

Difficulties

Electrical contact

Inhomogeneity due to strain

Local probe by optical spectroscopy

Recent experiments showed Mott-Wigner states & quantum anomalous Hall effect

Is an external superlattice potential/flat-bands necessary to observe strong correlations?

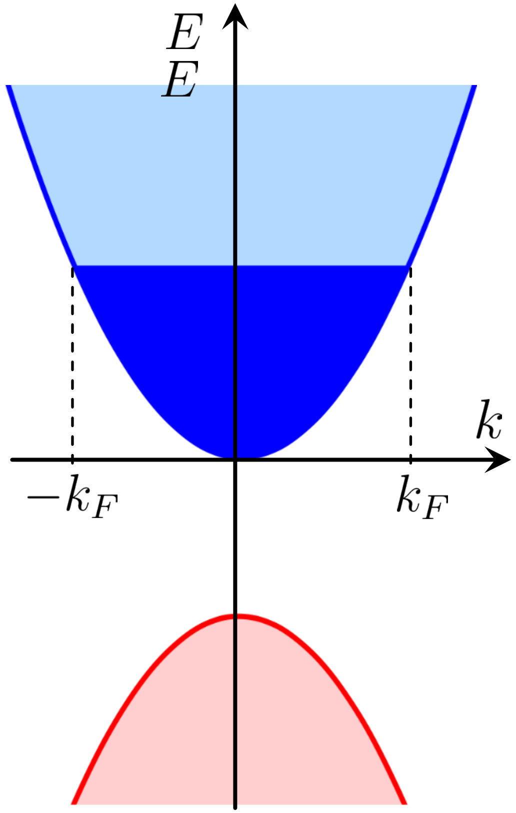
Interplay between

the kinetic energy and inter-electron Coulomb repulsion

$$E_K = \frac{\hbar^2 k_F^2}{2m_e^*} \sim n_e \quad \text{and} \quad E_C = \frac{e^2}{4\pi\epsilon_0\epsilon\langle r\rangle} \sim \sqrt{n_e}$$

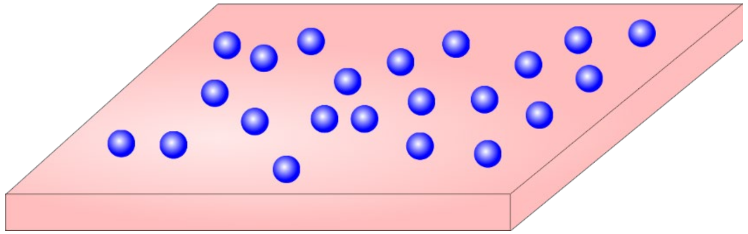
r_s parameter

$$\frac{E_C}{E_K} \equiv r_s = \frac{m_e^* e^2}{4\pi\epsilon_0\epsilon\hbar^2}\frac{1}{\sqrt{\pi n_e}}$$



Fermi liquid

(small r_s)

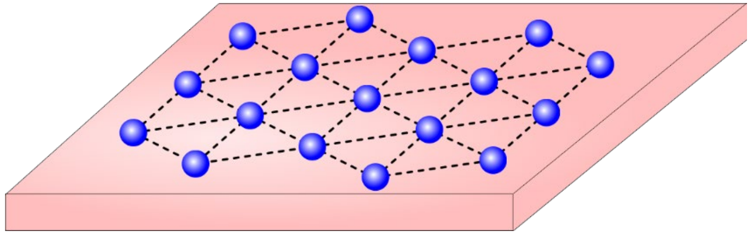


Increasing r_s

Lowering electron density n_e

Wigner crystal

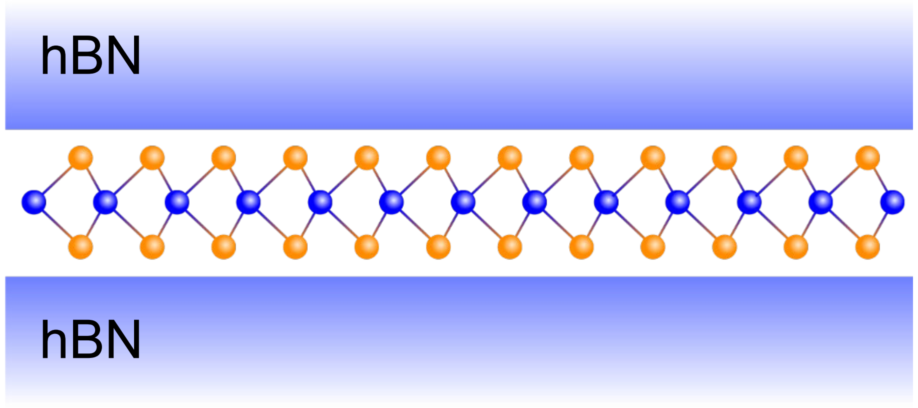
(large $r_s \gtrsim 30$)



E. Wigner, Phys. Rev. **46**, 1002 (1934)

Spontaneous breaking of continuous translation symmetry!

Prospects for Wigner crystal in 2D semiconductors: transition metal dichalcogenide (TMD) monolayers



1. Very large electron effective mass $m_e^* \approx 0.7 m_e$

S. Larentis *et al.*, Phys. Rev. B **97**, 201407 (2018)
R. Pissoni *et al.*, Phys. Rev. Lett. **121**, 247701 (2018)

2. Reduced screening due to hBN encapsulation $\epsilon^{\|}_{\mathrm{hBN}} \approx 4$

A. Laturia *et al.*, npj 2D Mater. Appl. **2**, 6 (2018)

Wigner crystalization at *B* = 0?

Ultra-large $r_s > 40$

for $n_e \sim 1 \cdot 10^{11}\ \mathrm{cm}^{-2}$

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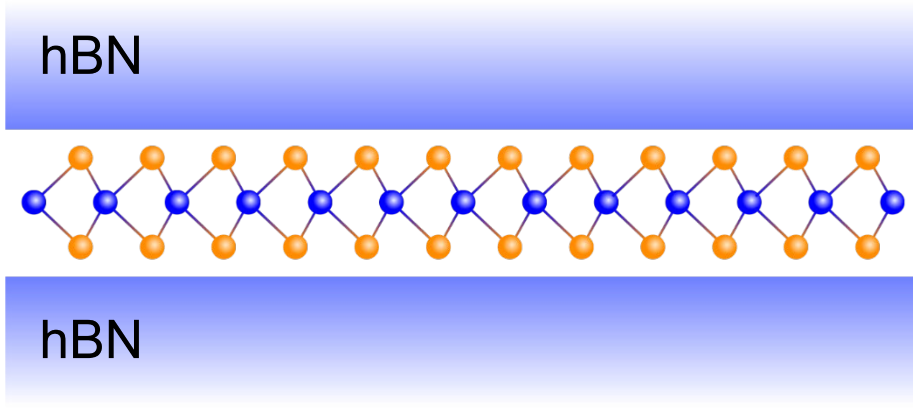

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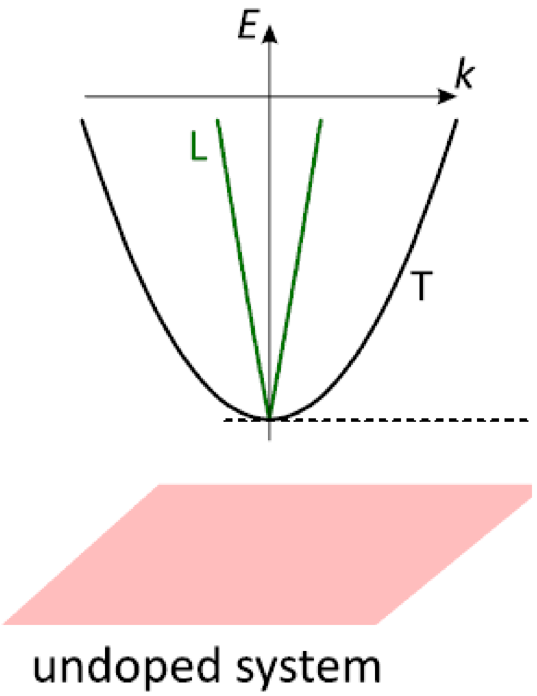
for $n_e \sim 1 \cdot 10^{11}\ \mathrm{cm}^{-2}$

→ If a Wigner crystal forms, then the lattice constant ~ 20 nm:
Can we use optical spectroscopy to obtain direct evidence for a periodic charge distribution?

How does the electronic state modify exciton-polaron dispersion at B=0?



- Excitons outside the light cone are split into longitudinal and transverse branches

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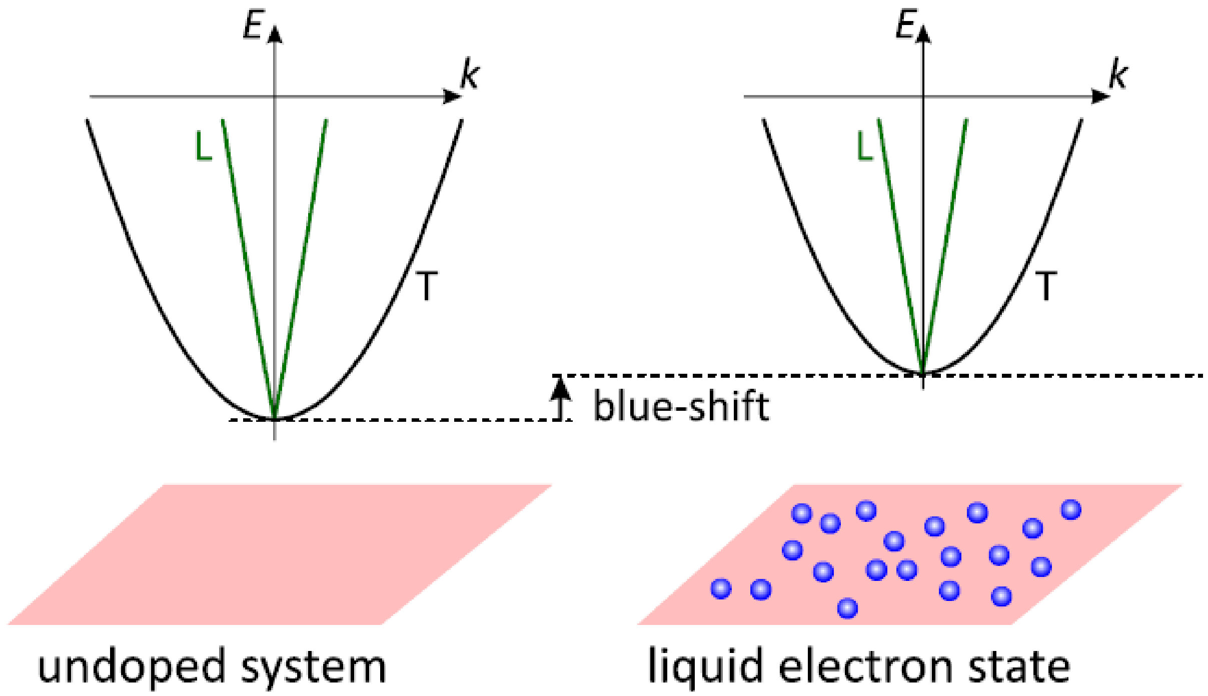

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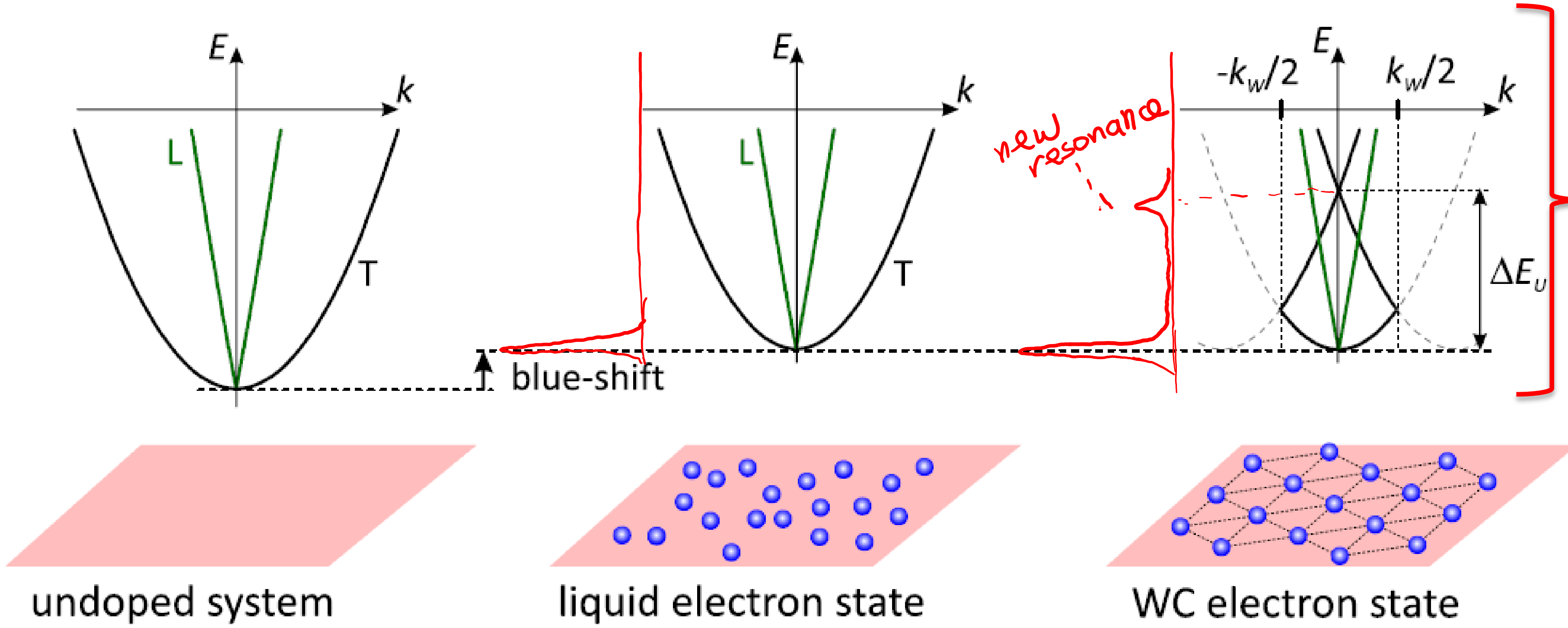
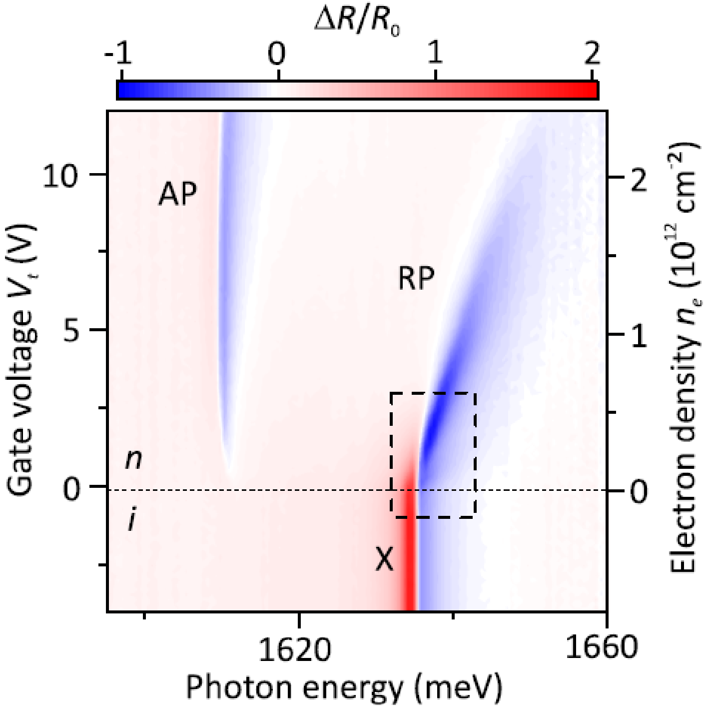


Interaction of excitons with electrons in a WC effect a superlattice potential for excitons

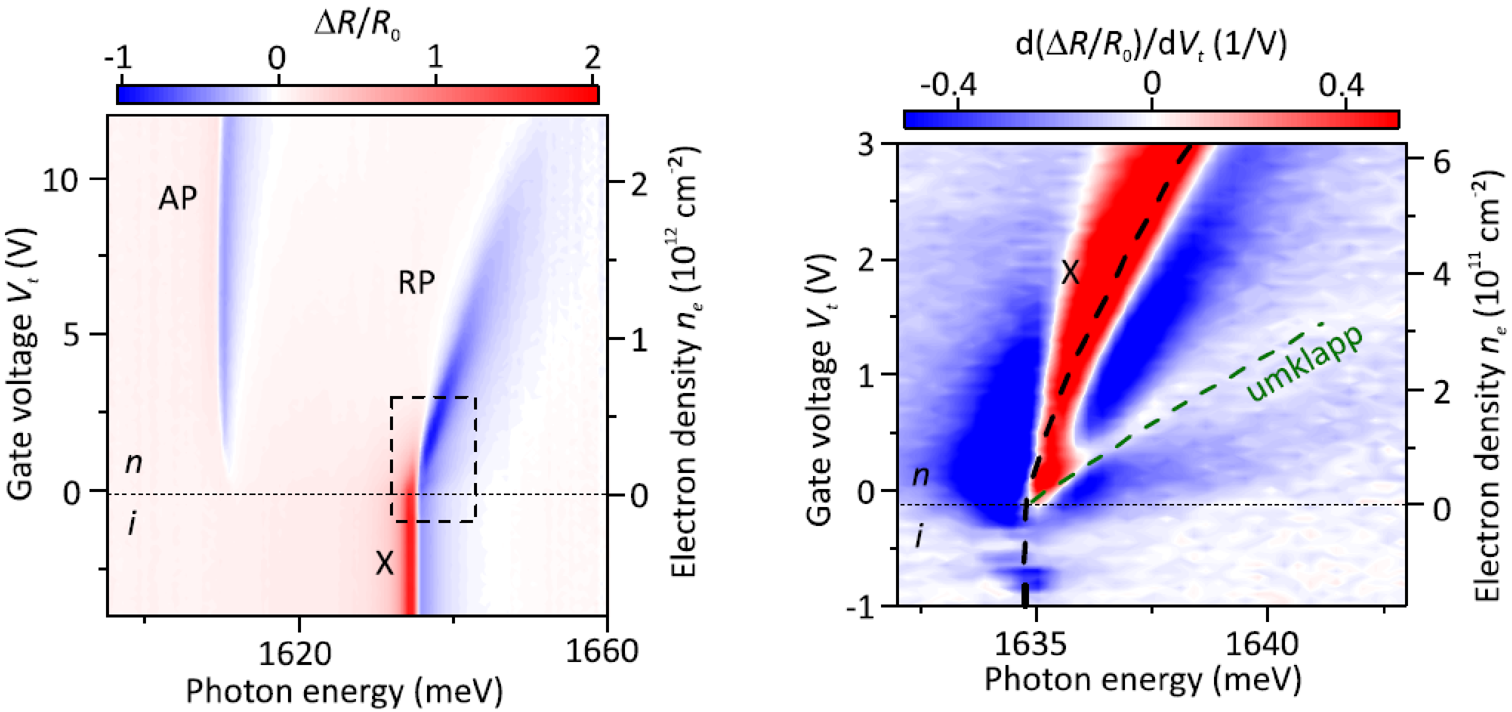
- Excitons outside the light cone are split into longitudinal and transverse branches
- If electrons are in a liquid state, exciton dispersion blues shifts, as it becomes a repulsive polaron (RP)
- If the electrons form a Wigner crystal (WC), Bragg-umklapp scattering yields new k=0 resonances

Repulsive-polaron at B=0



- Focus on RP in the low electron density regime $n_e < 5\text{x}10^{11}$ cm^{-2}

Repulsive-polaron at B=0



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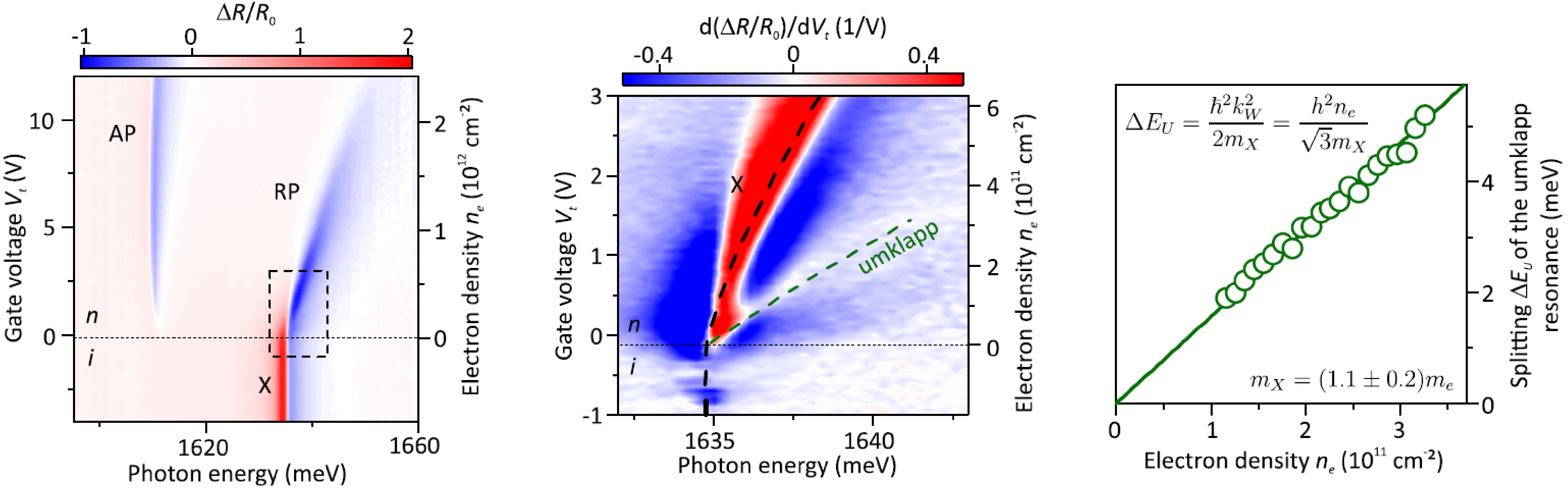
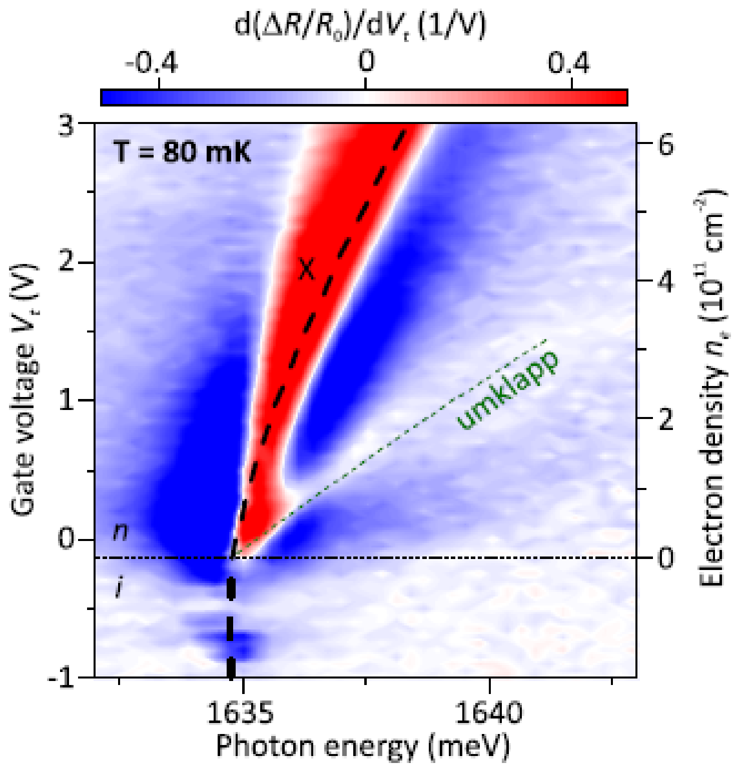
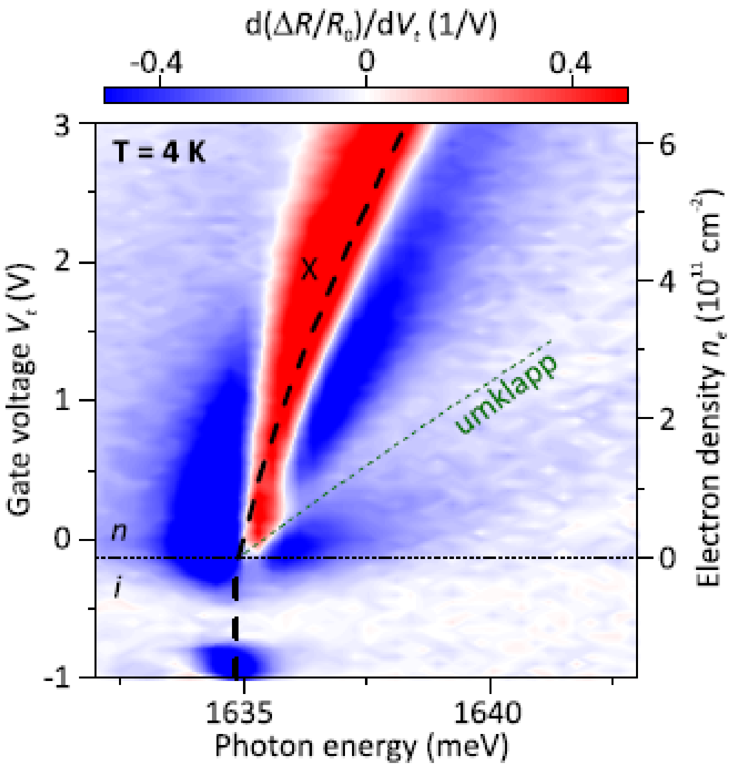
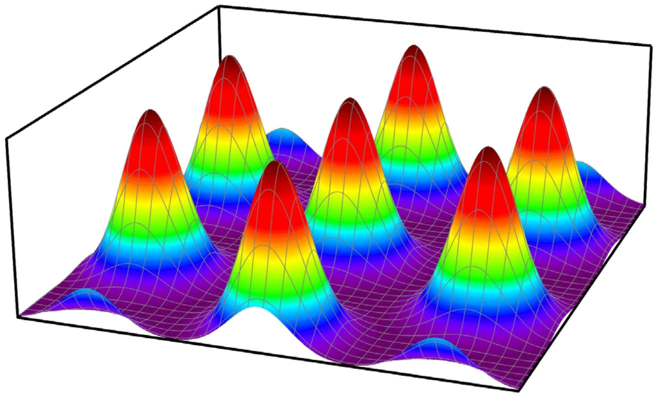


- Focus on RP in the low electron density regime $n_e < 5\text{x}10^{11}$ cm^{-2}
- Differentiating the reflection spectrum w.r.t. gate voltage, reveals a blue-shifted peak
- The energy difference between the higher energy peak and RP scales as $\frac{h^2 n_e}{\sqrt{3} m_X}$, consistent with a triangular lattice of electrons.

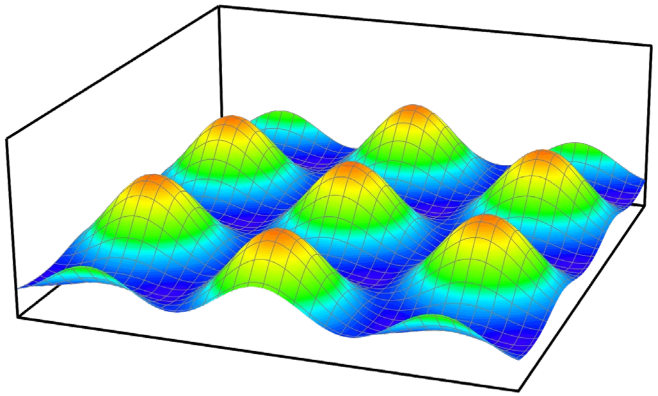
Temperature dependence of the umklapp peak





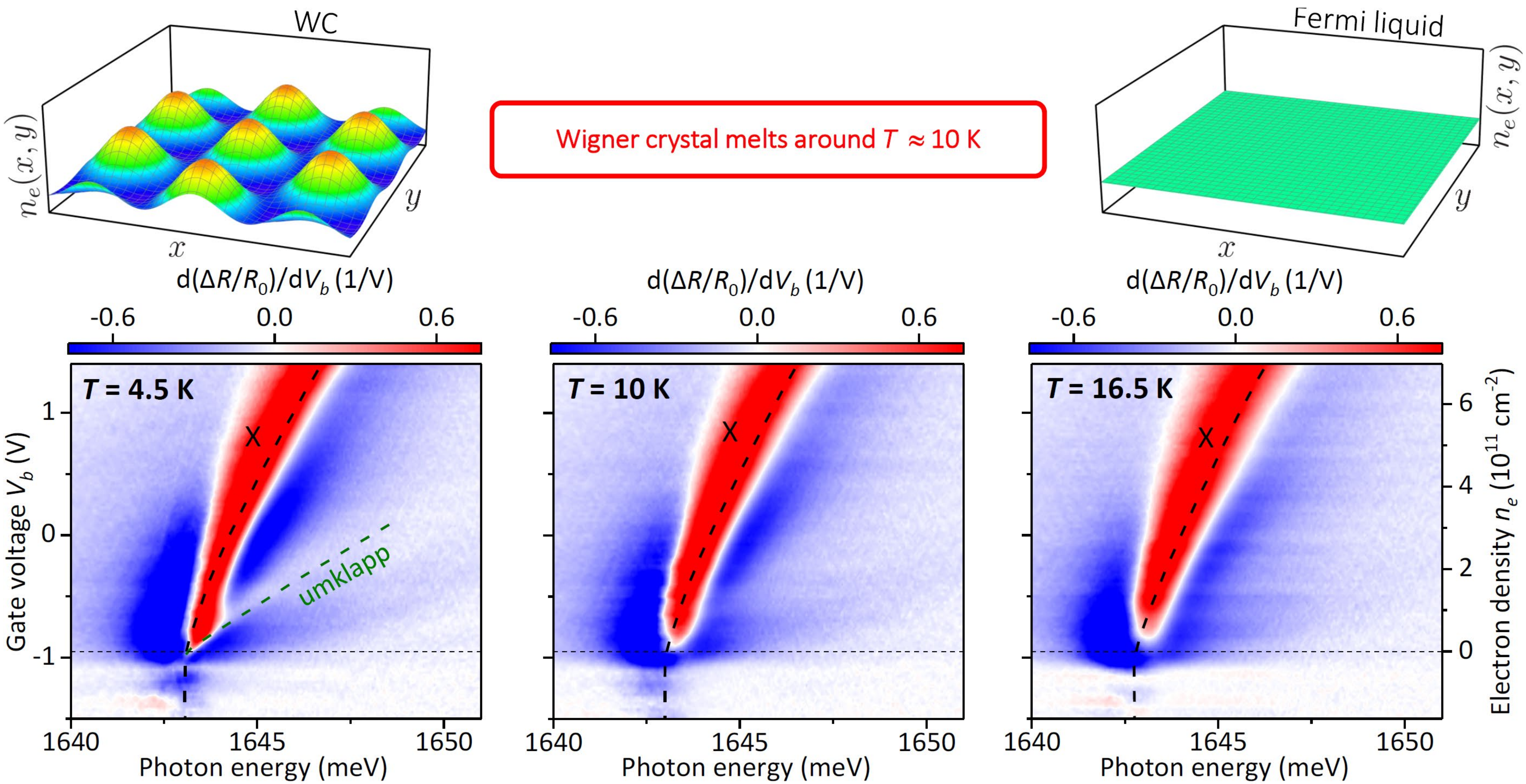


Enhanced thermal fluctuations of the el ectrons **suppress the umklapp intensity**



Temperature dependence of the umklapp peak

Wigner crystal melts around $T \approx 10$ K



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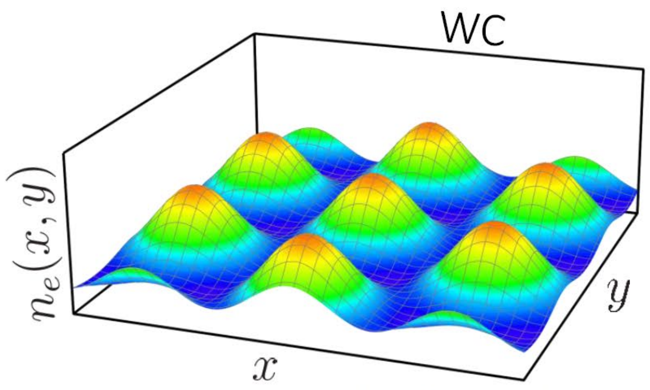
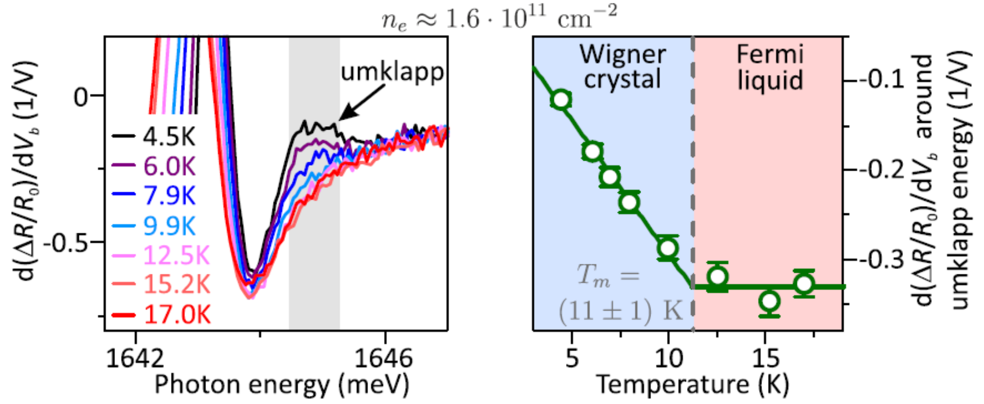
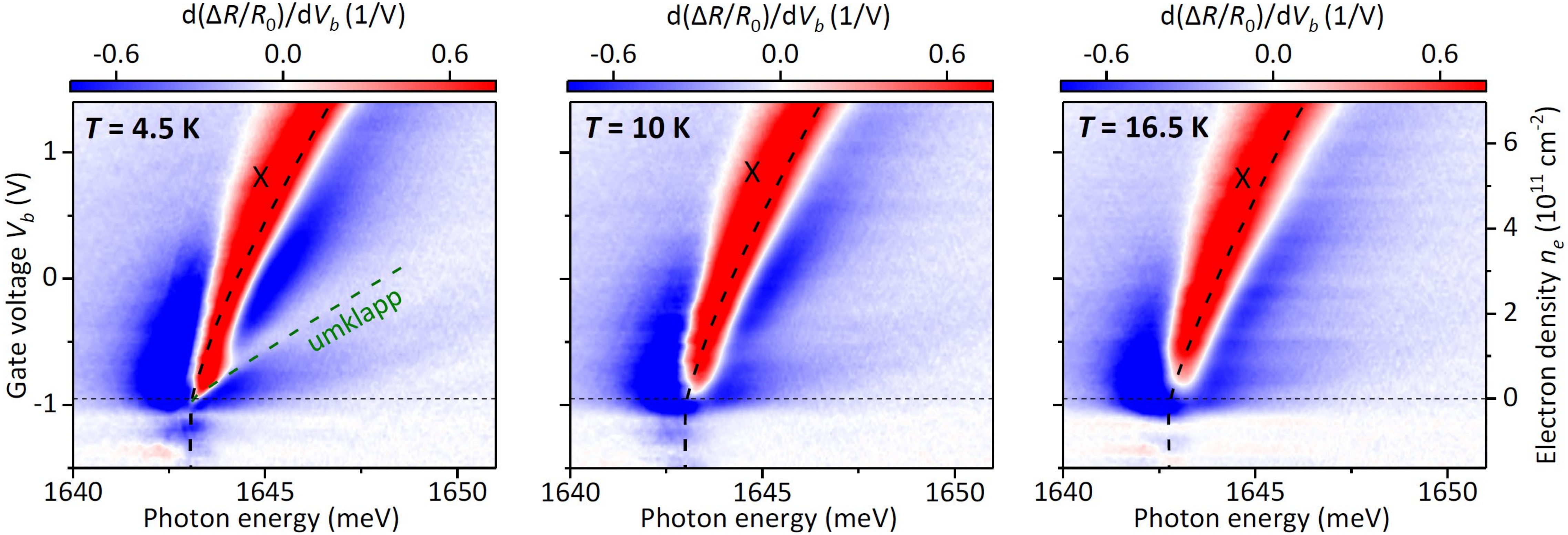
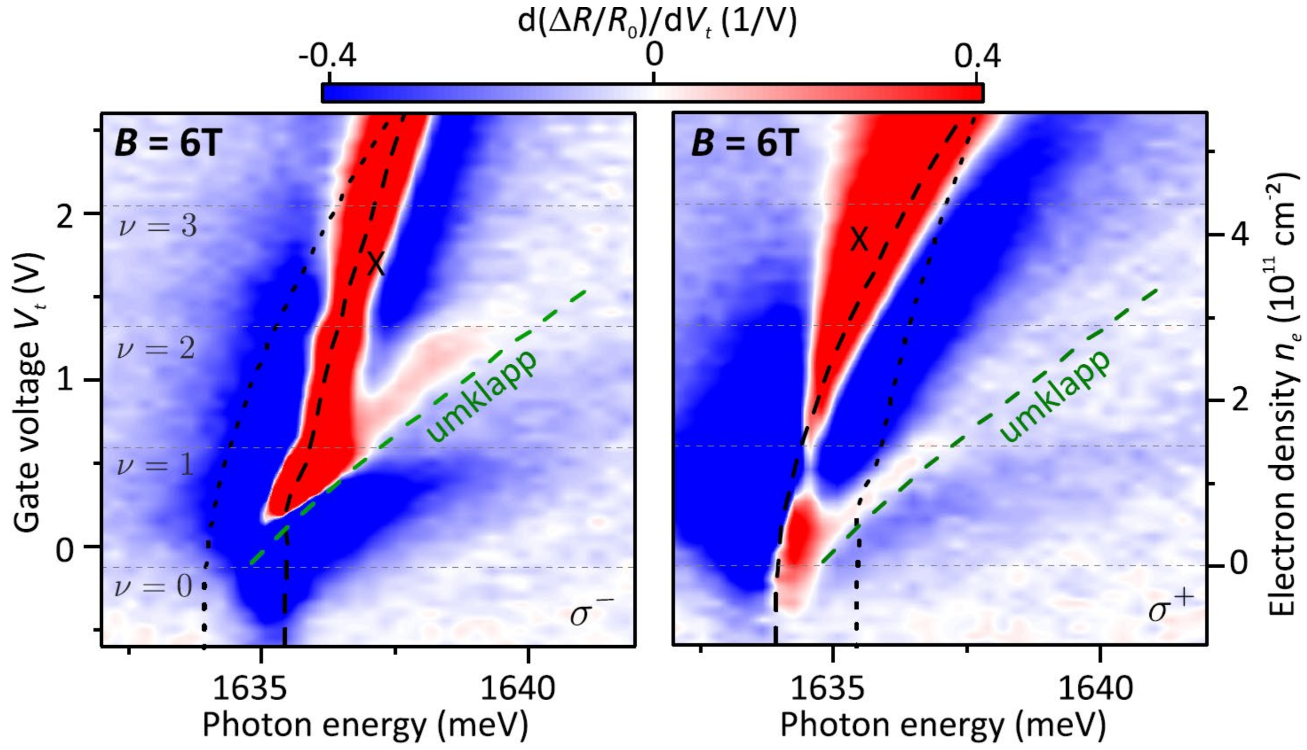
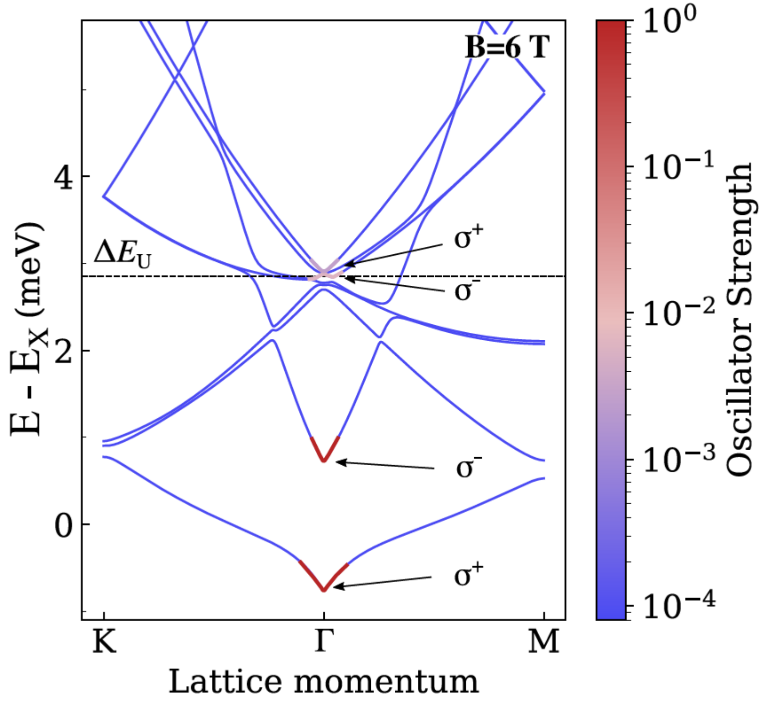






Wigner crystal of electrons at B= 6T





- Umklapp peak is stronger due to more robust WC, extending up to ν=2
- While the k=0 RP peaks split due to valley-Zeeman effect, the umklapp peaks show vanishing splitting – due to their predominantly high-k nature.

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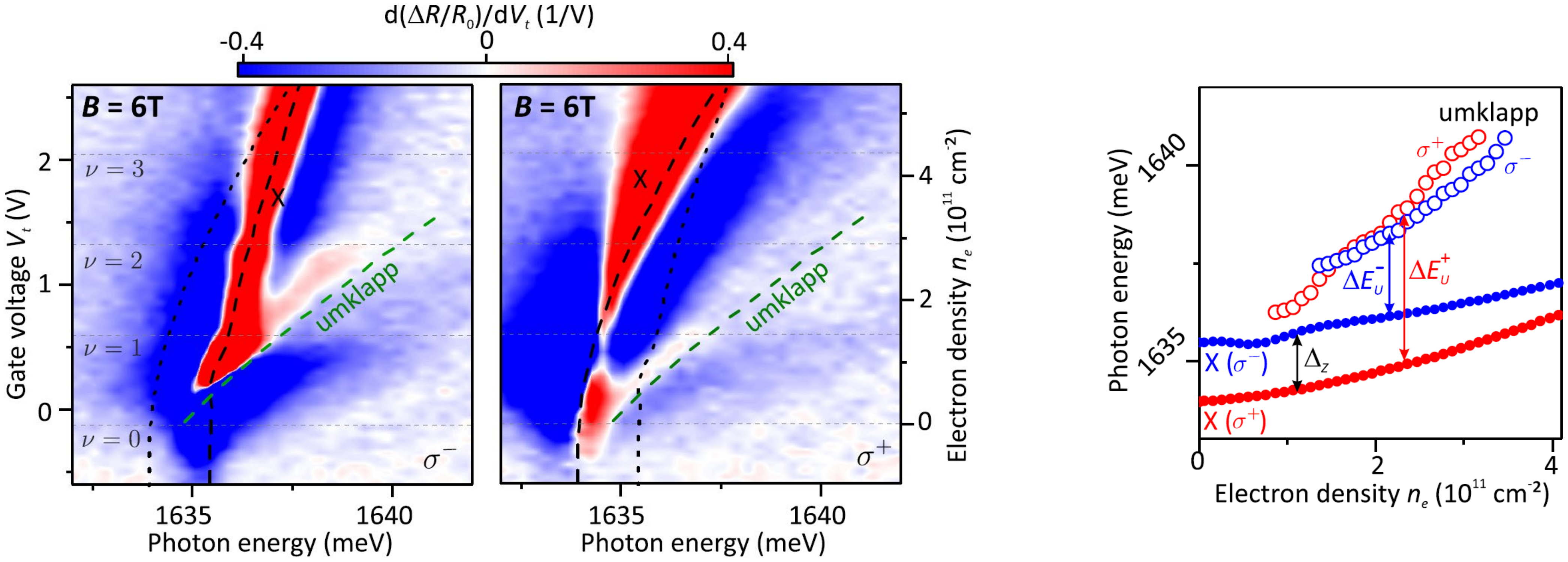

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