From Fermi & Bose polaron polaritons to quantum droplets of light

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IFiMaC

ECAMP15 2025, Innsbruck, 3 July 2025

3 ultracold atom-inspired problems in light-matter semiconductor systems

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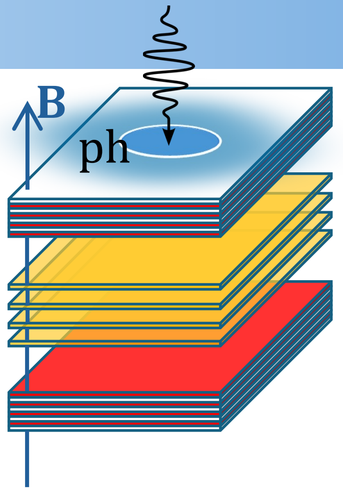
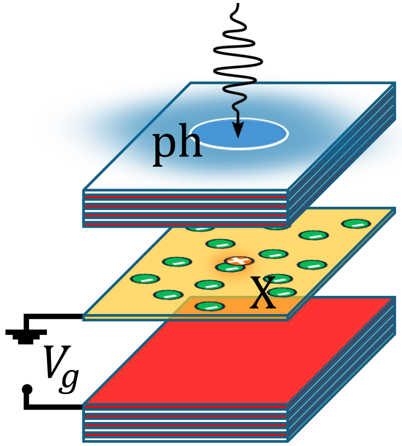
Outline

1. Microcavity polaritons
   - Very strong light-matter coupling
2. Fermi polaron (polaritons) in gated TMD monolayers
   - finite temperature crossover from polaron to trion continuum
3. Biexciton Feshbach resonace

→ Bose polaron polaritons in pump-probe



[Laird, FMM .... PRB (2022)]
[de la Fuente ... FMM PRB (2025)]



[Tiene ... FMM PRB (2022)]
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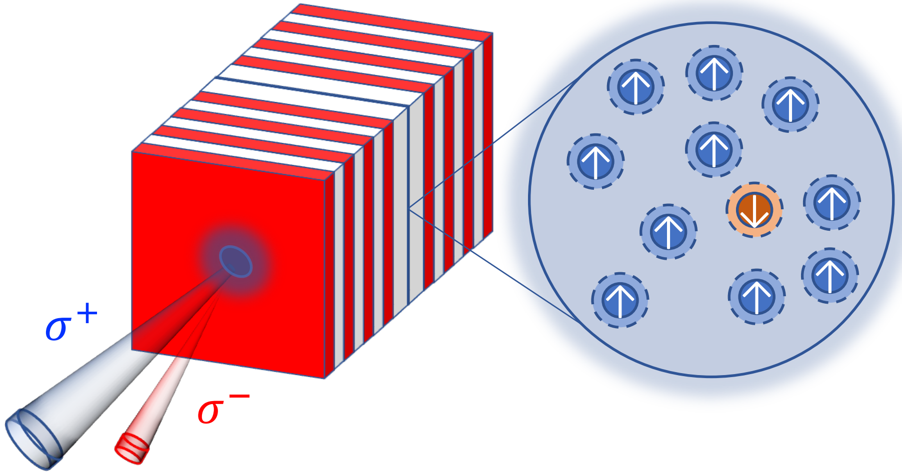
[Mulkerin ... FMM ... PRL (2023)]
[T. Wu, FMM ... (in preparation)]

[Levinsen, FMM... PRL (2019)]



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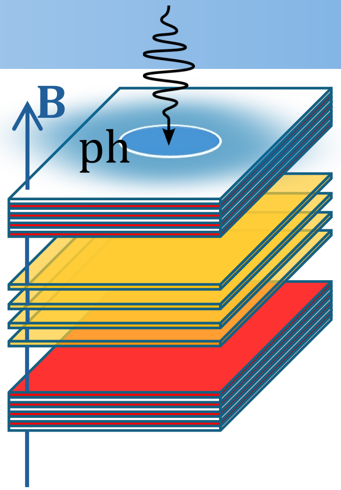
→ Quantum droplets of light

[Caldara... FMM... (in preparation)]



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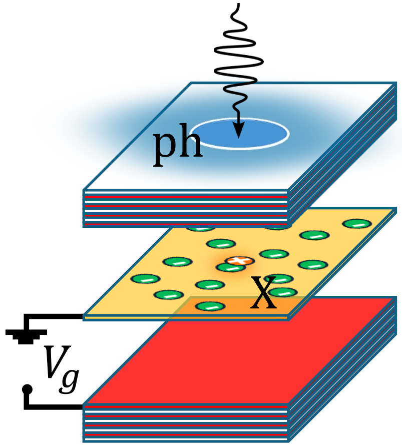

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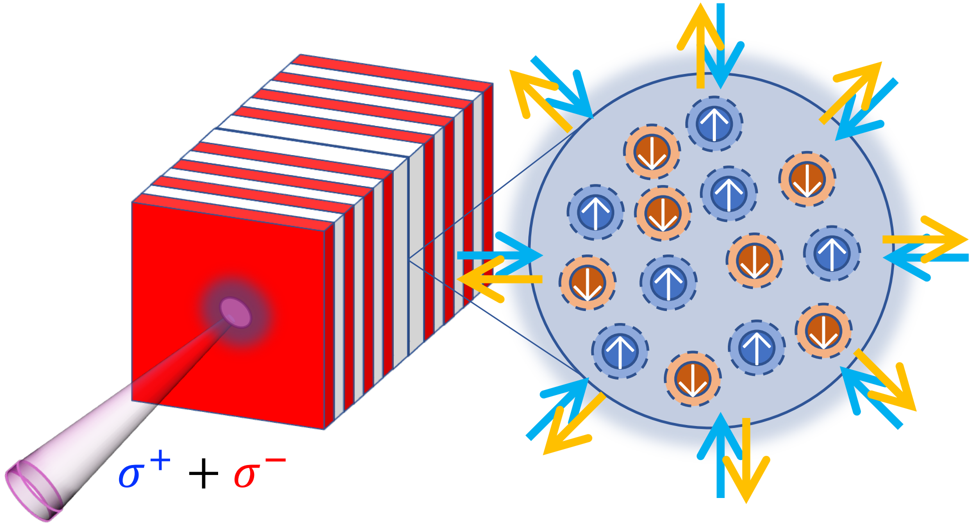
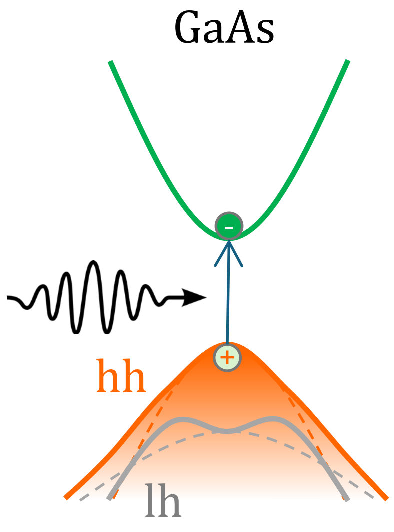
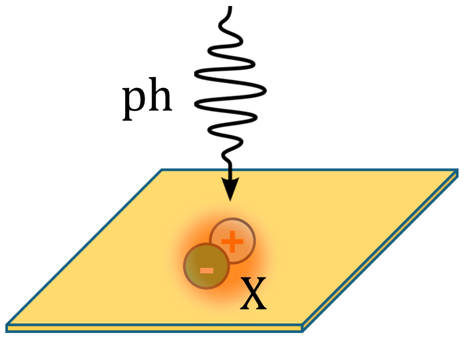


1. Microcavity polaritons

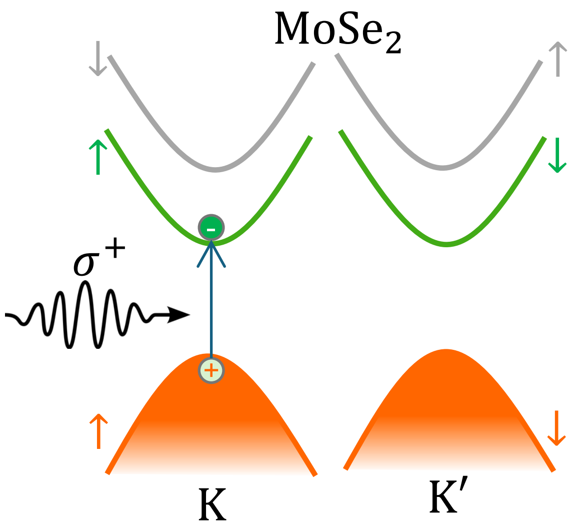
excitons in QWs



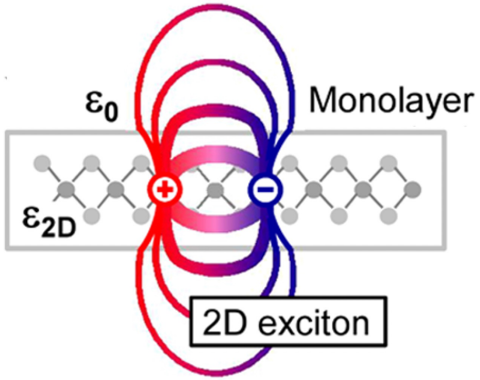
$$\boxed{E_B = 7 - 15 \text{ meV}}$$



excitons in TMD monolayers



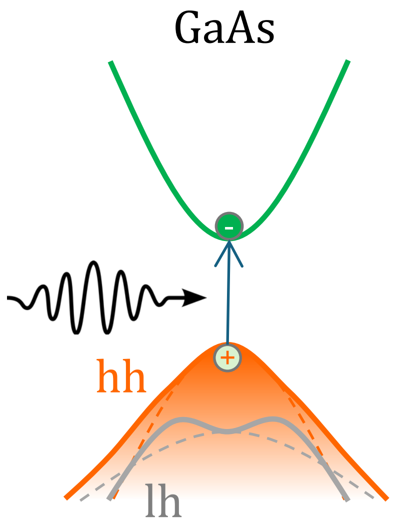
$$\boxed{E_B = 200 - 500 \text{ meV} \gg k_B T_{\text{room}}}$$

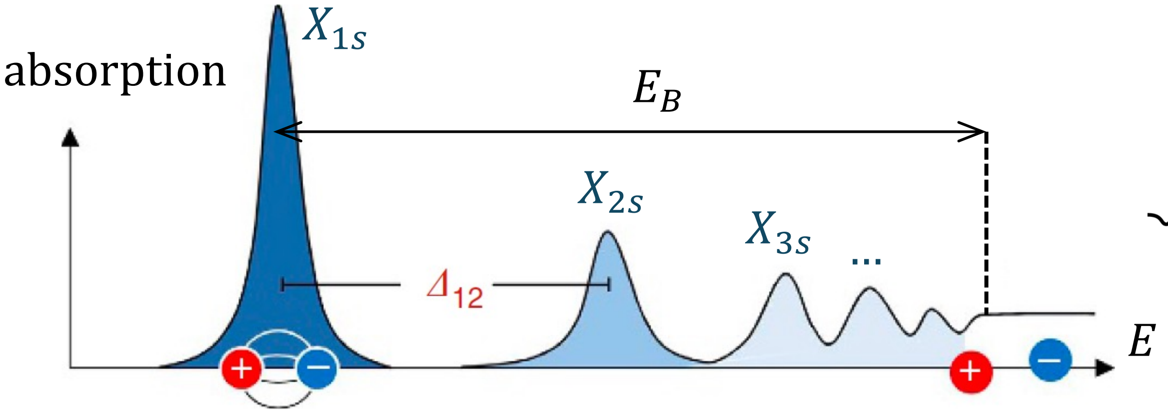


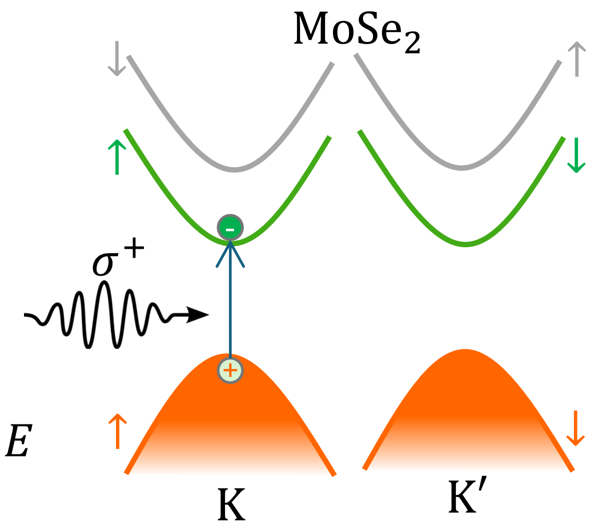
[Chernikov et al., PRL (2014)]

excitons in QWs

excitons in TMD monolayers







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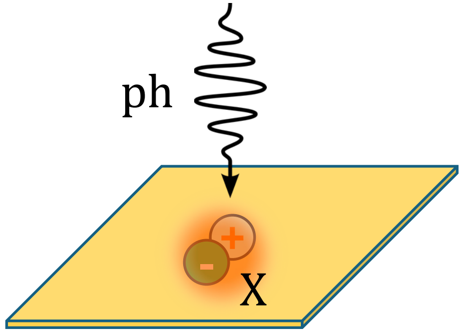

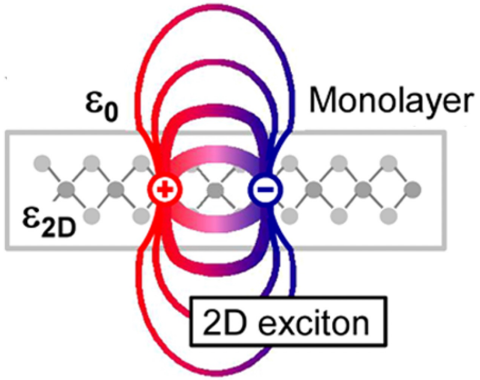

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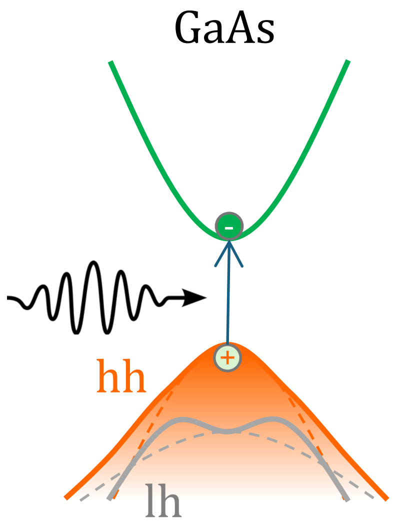
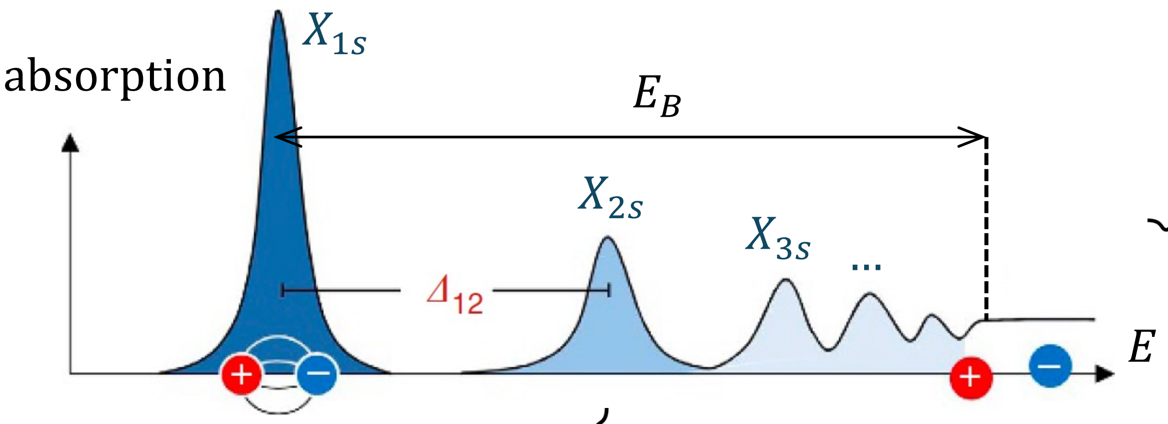
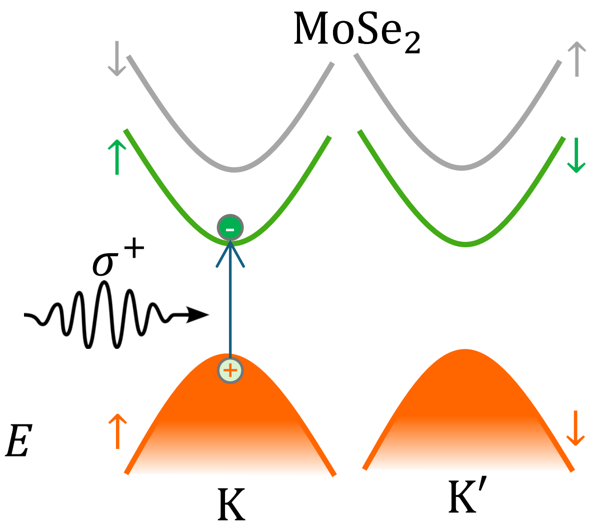
Polaritons







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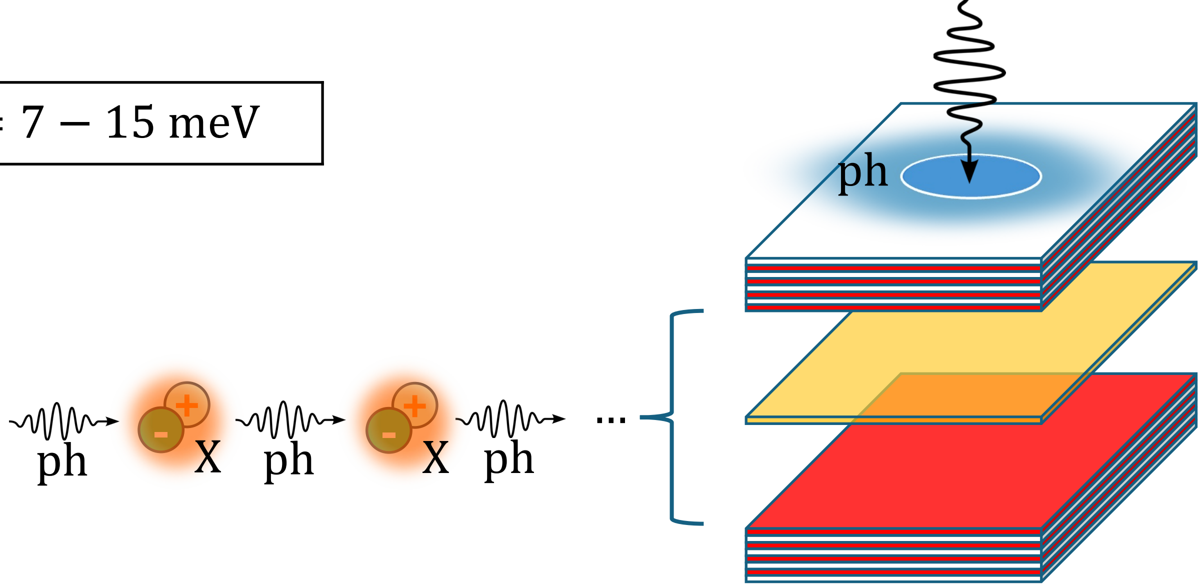

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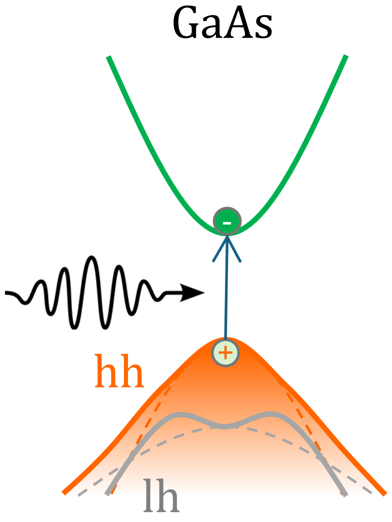

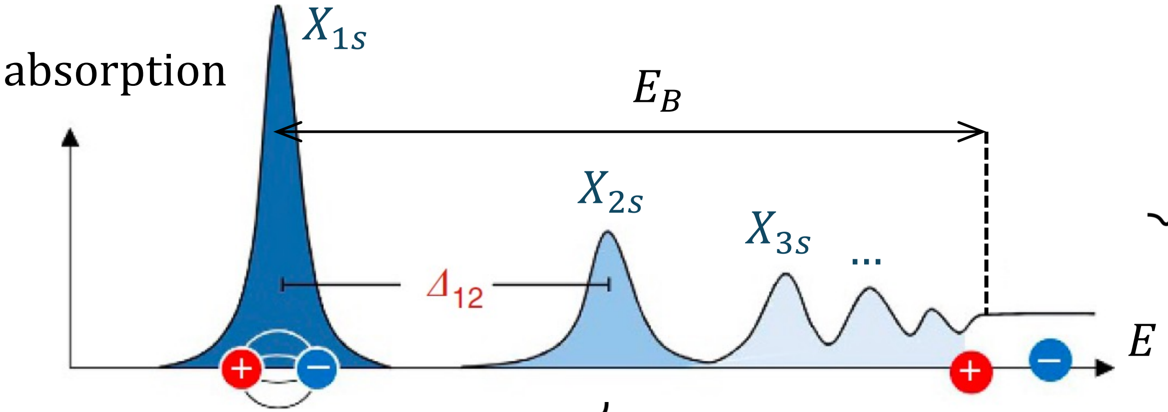

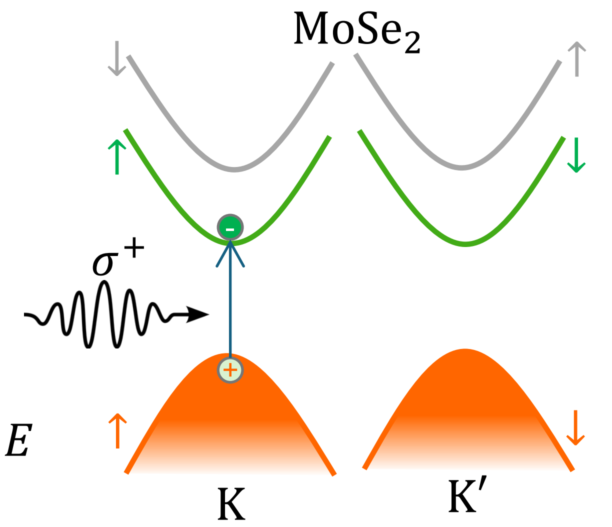

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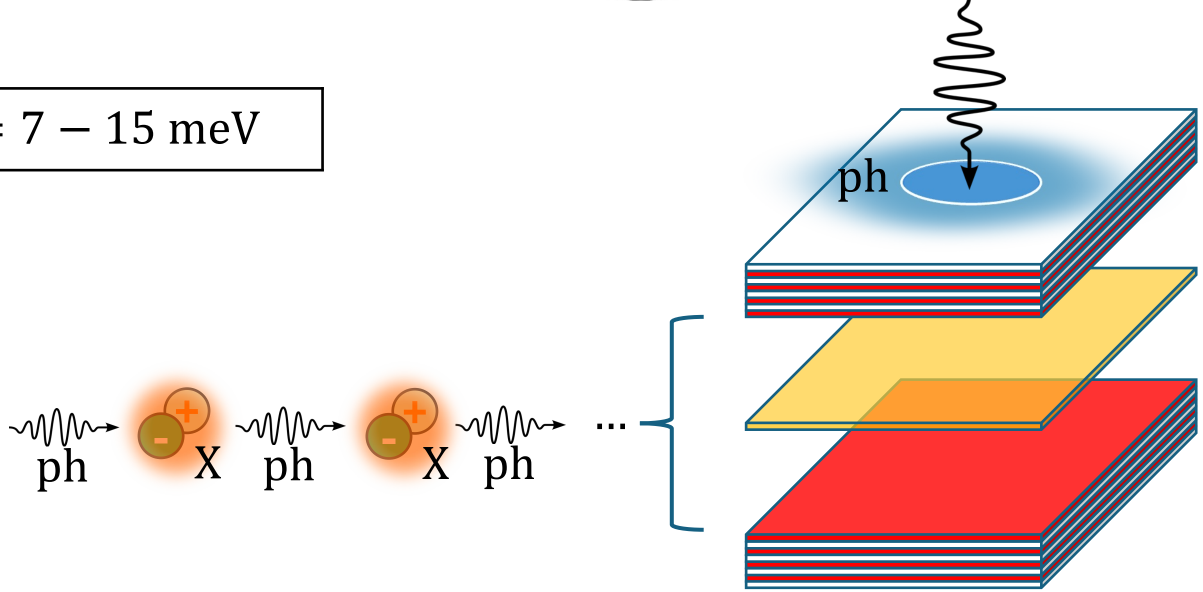
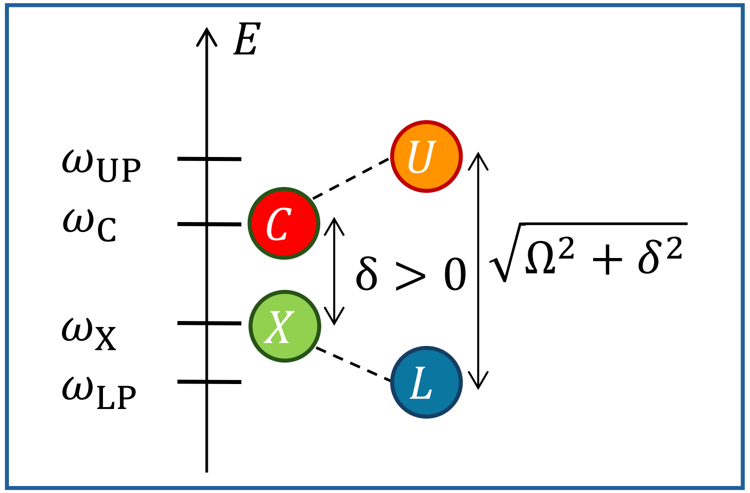




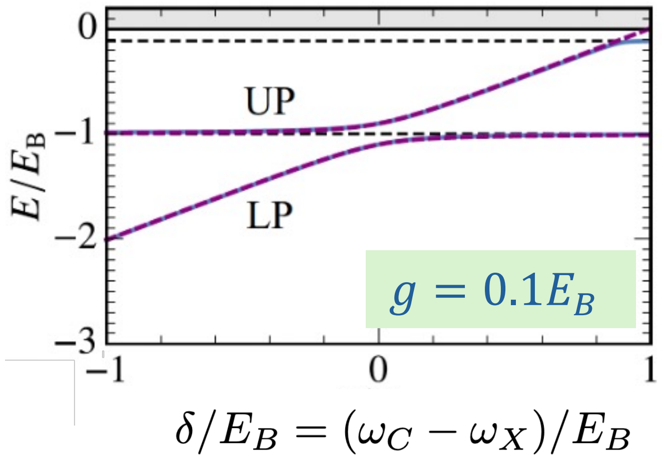
Polaritons: strong & very strong light-matter coupling

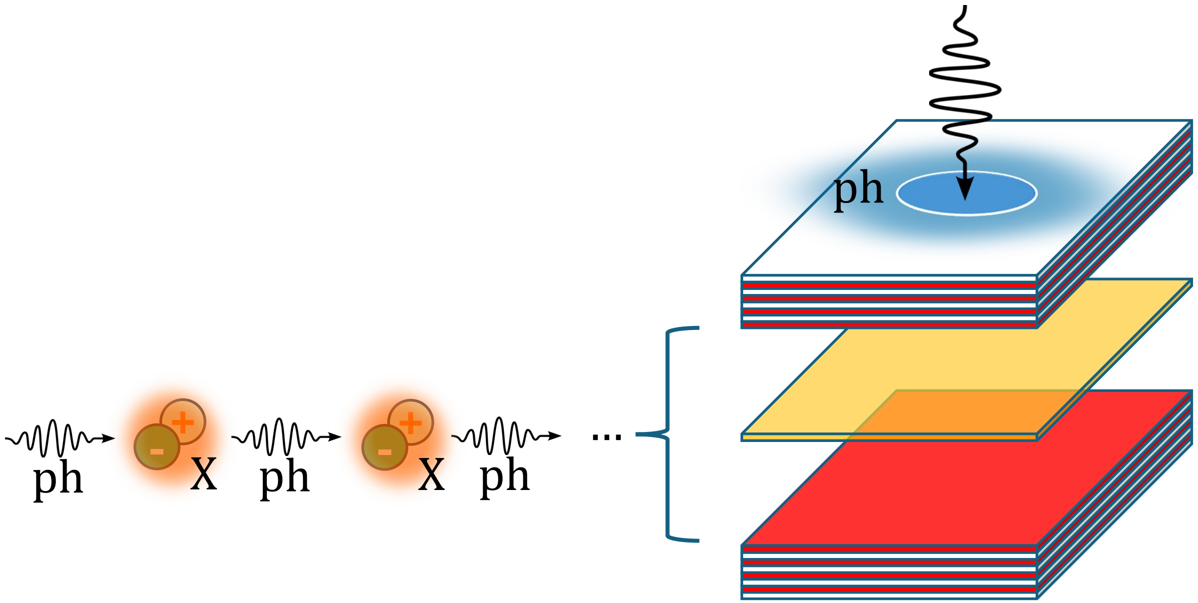
- Light-matter coupling $g = \frac{\Omega}{2}$

$g > \gamma$ strong energy transfer between excitons and photons

coupled oscillator model

[Levinsen et al. PPR (2019)]



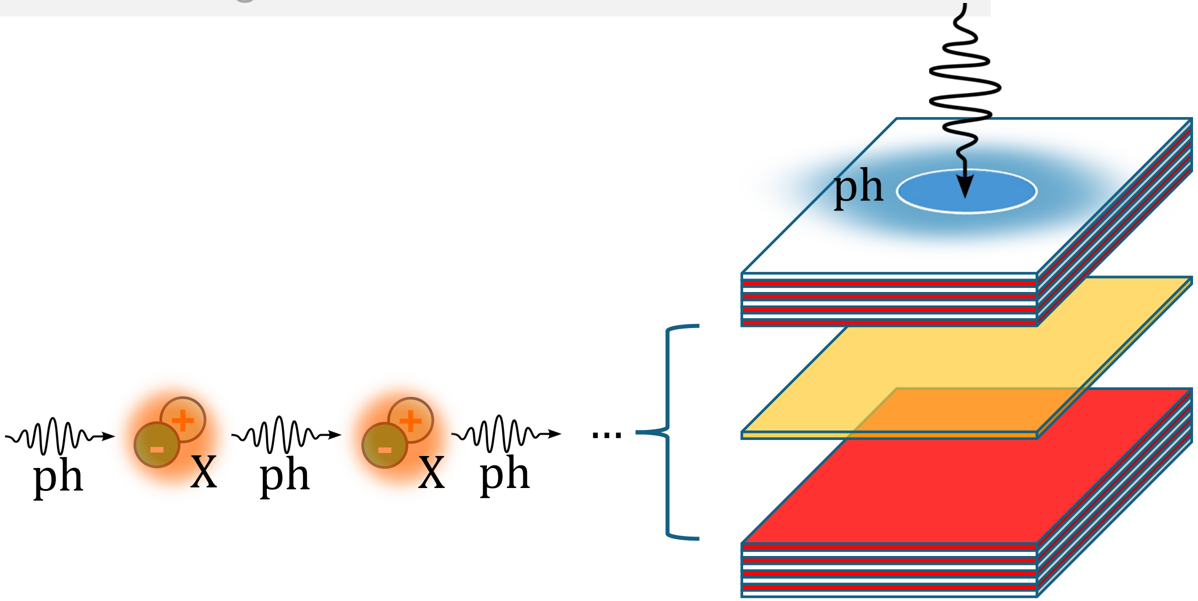


Polaritons: strong & very strong light-matter coupling

▷ Light-matter coupling $g = \frac{\Omega}{2}$

$g > \gamma$	strong	energy transfer between excitons and photons	coupled oscillator model
$g \sim E_B$	very strong	hybridization of different excitonic levels	beyond coupled-oscillator description
$g \sim E_g$	ultra strong	hybridization with different number of excitations	

[Khurgin SSC (2001)]



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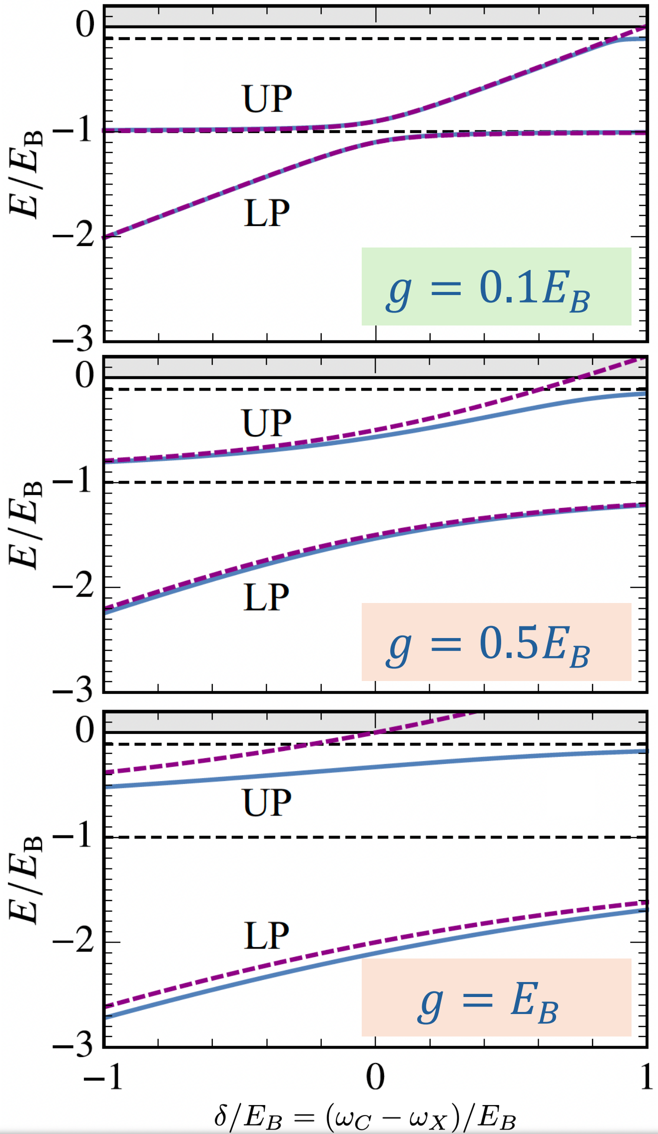

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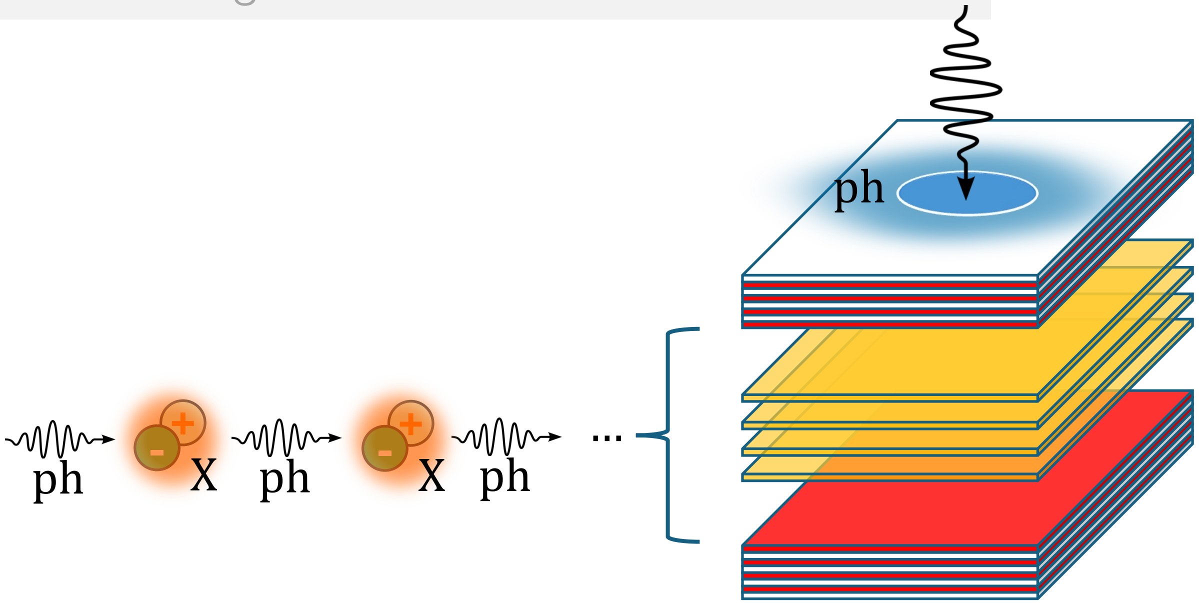

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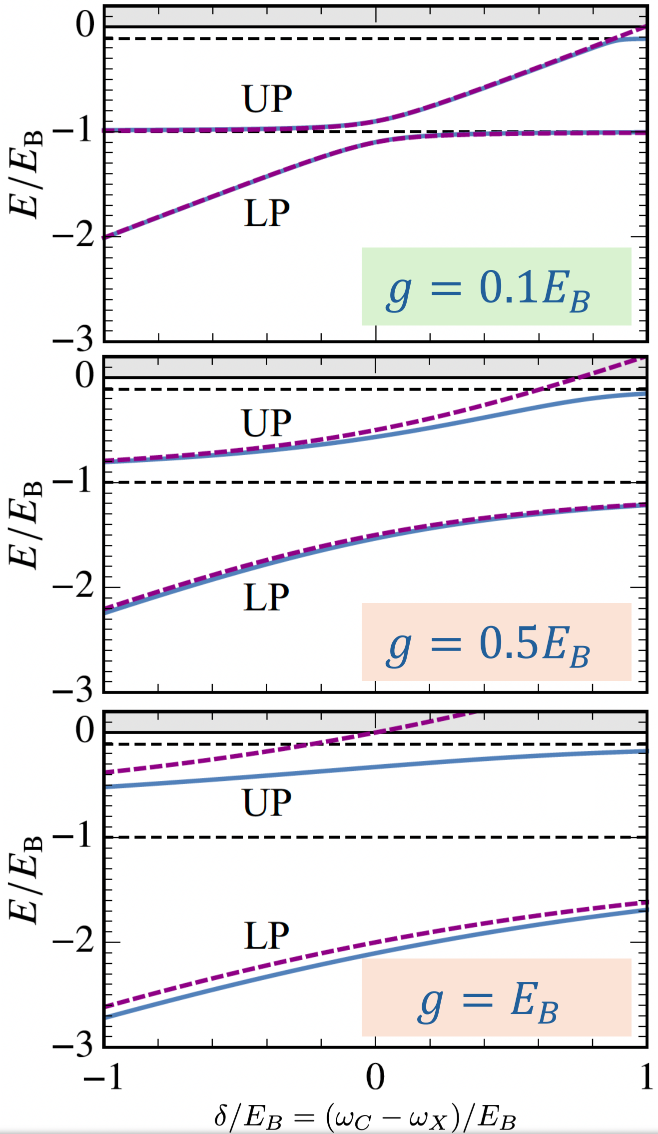

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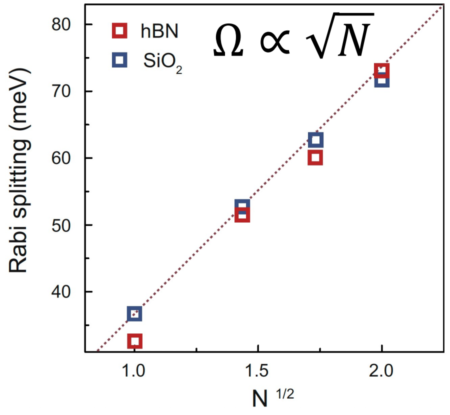
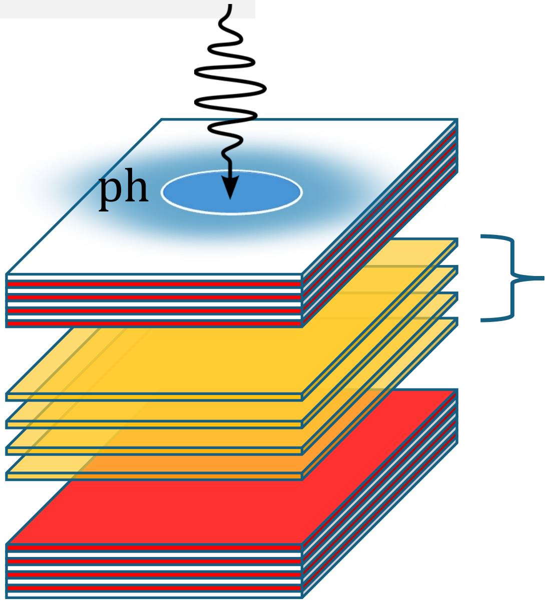
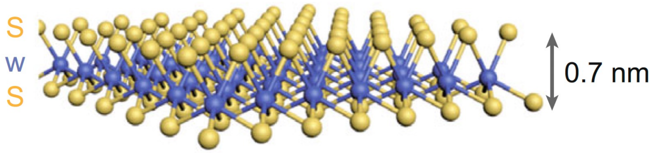


[Zhao et al. Nat Comm (2023)]



4 ×



$\Omega = 71$ meV

$E_B \sim 180$ meV

$\frac{g}{E_B} \sim 0.2$

[Brodback et al. PRL (2017)]

7nm 28 × GaAs QWs

$\Omega = 17.4$meV

$E_B = 13.5$ meV

$\frac{g}{E_B} \sim 0.64$

Magnetopolaritons: very strong light-matter coupling

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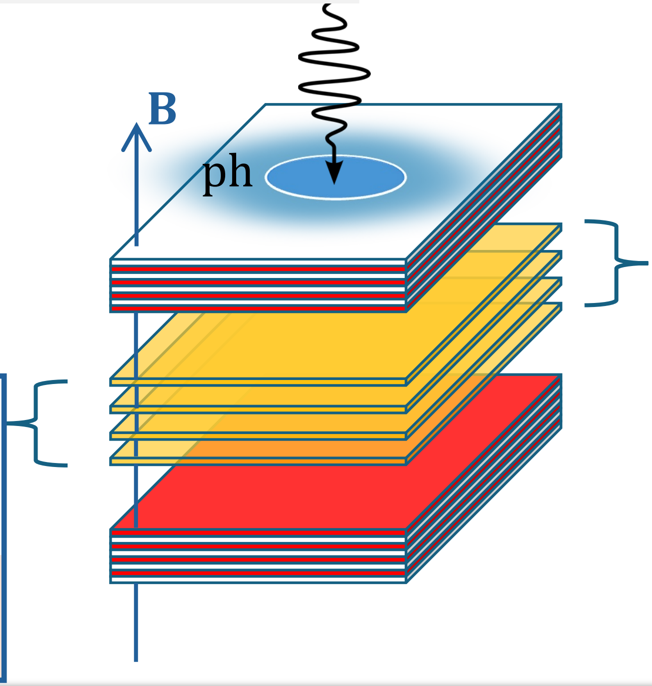
▷ + magnetic field $\mathbf{B}$

Use diamagnetic shift to verify very strong coupling effects: [Yang et al. NJP (2015)]'s proposal

Probe the modifications of the e-h wavefunction due to very-strong coupling to light



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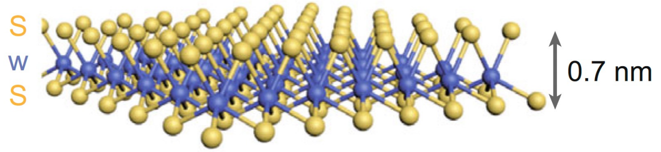

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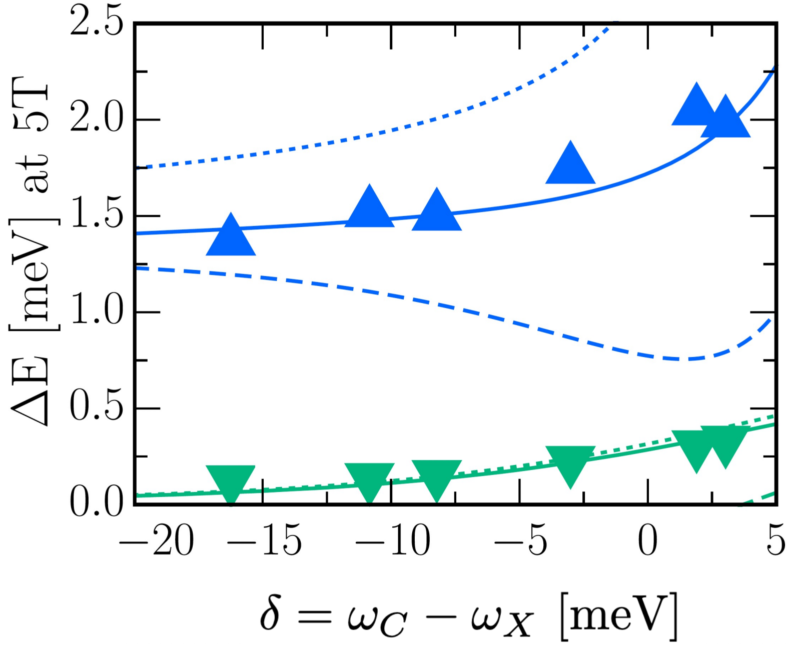

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$E_B = 13.5$ meV
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▼LP ▲UP data

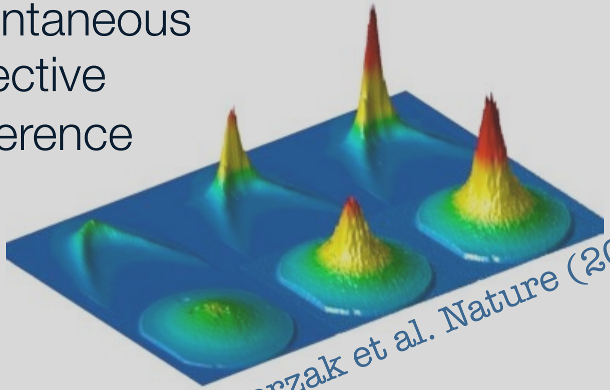
— exact theory [Laird, FMM ... PPB (2022)] [de la Fuente ... FMM, PRB (2025)]

- - - - 3 COM (perturbative light-matter)

………… $\frac{1}{2}\mu\omega_c^2\langle r^2\rangle_{\substack{LP \\ UP}}$ (perturbative magnetic field)

19 years after polariton “condensation”: Towards quantum polaritonics

- Spontaneous collective coherence



[Kasprzak et al. Nature (2006)]

phenomenology
of non-linear classical waves

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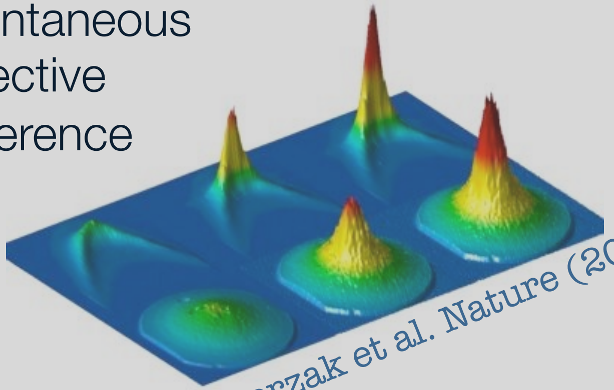

[Kasprzak et al. Nature (2006)]

phenomenology
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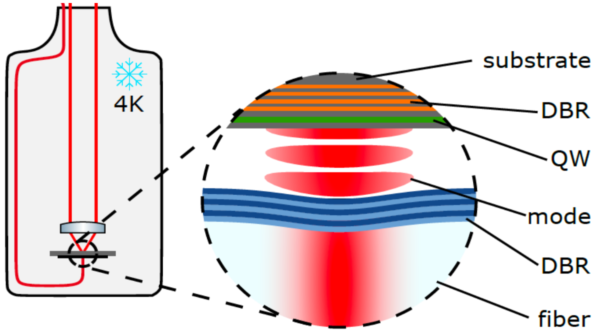
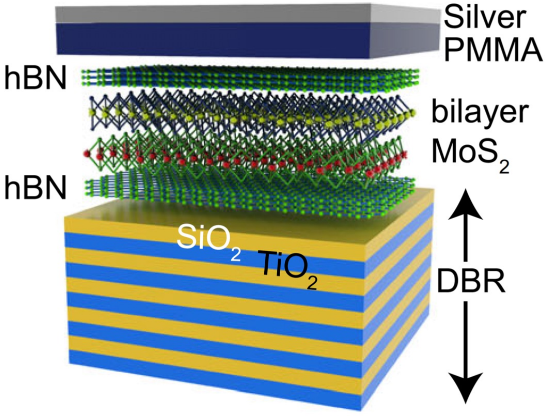
- Enhancing non-linearities by full confinement

fiber 0D cavity [Delteil et al. Nature Mat (2019)]
[Munoz-Matutano et al. Nature Mat(2019)]



- Dipolar polaritons [Cristofolini et al. Science (2012)]



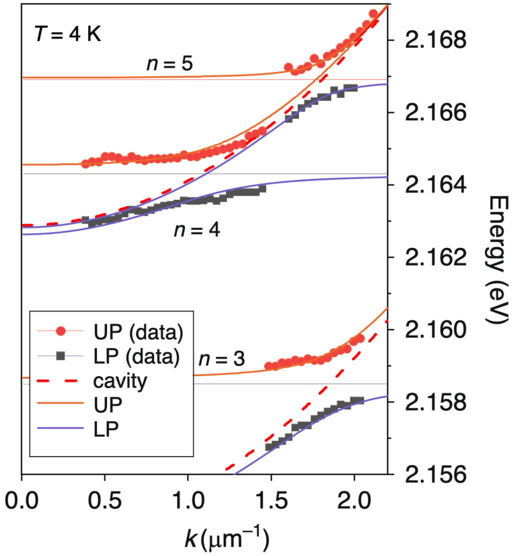
[Datta et al. Nature Comm (2022)]
[Louca et al. Nature Comm (2023)]

- Rydberg polaritons (Cu_2O, TMD monolayers)

see tomorrow
Matthew Jones’s talk

[Makhonin et al. *Light: Sci&App* (2024)]

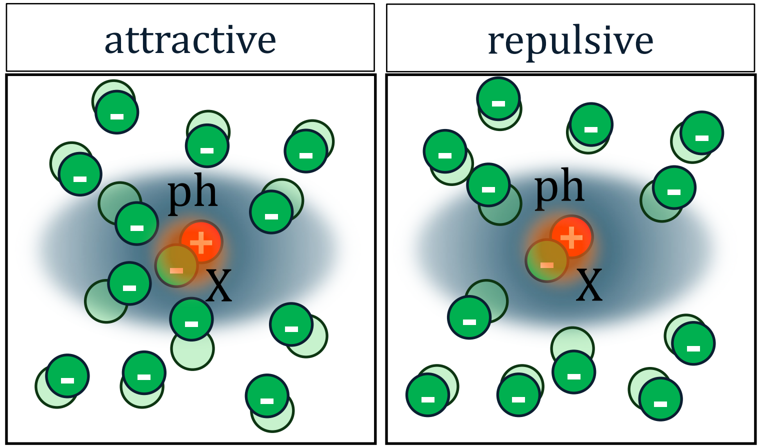
[Orfanakis et al. Nat Mat (2022)]



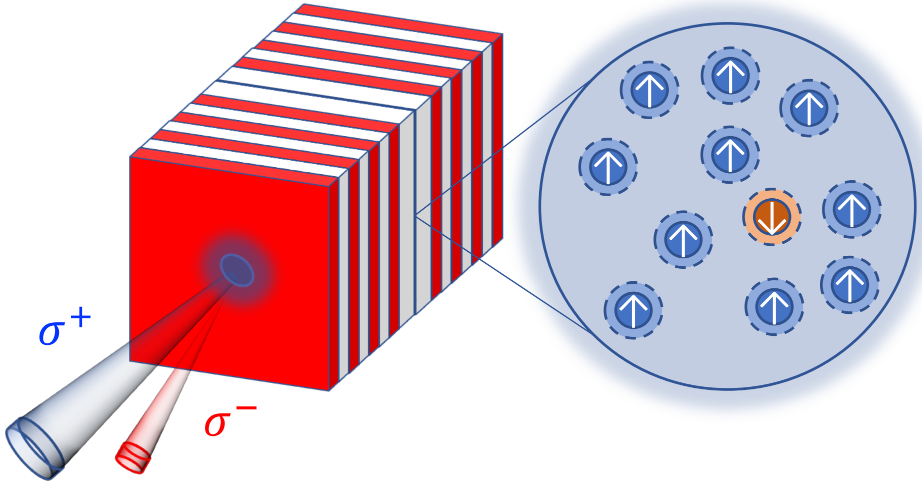
Towards quantum polaritonics: beyond mean-field effects

▷ Quantum impurity problems

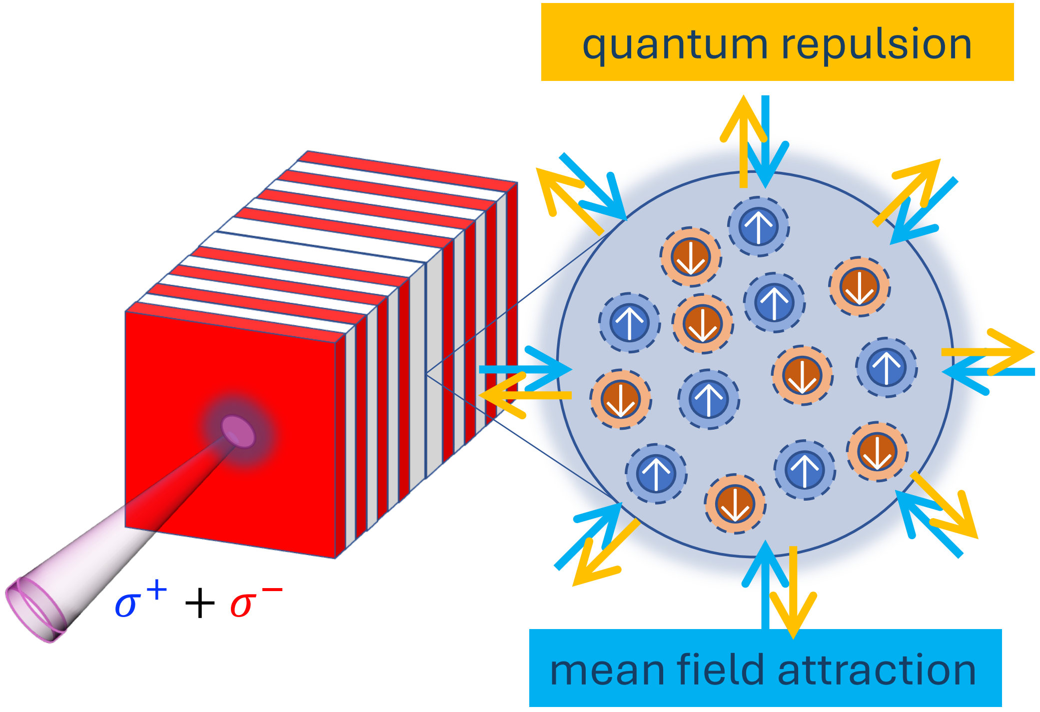
- Fermi polaron polaritons



- Bose polaron polaritons

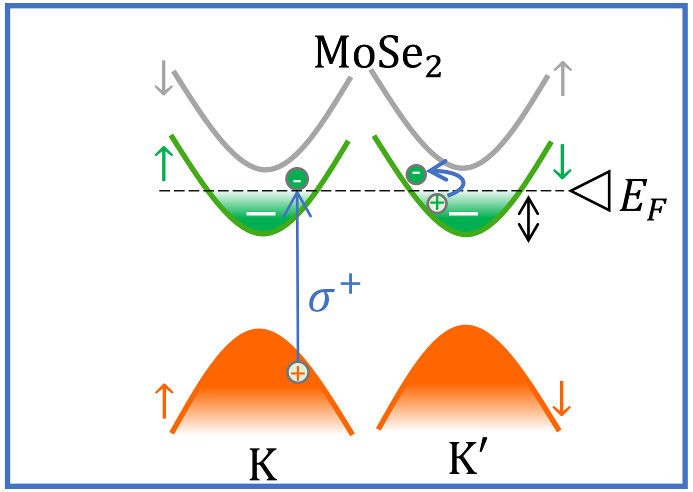


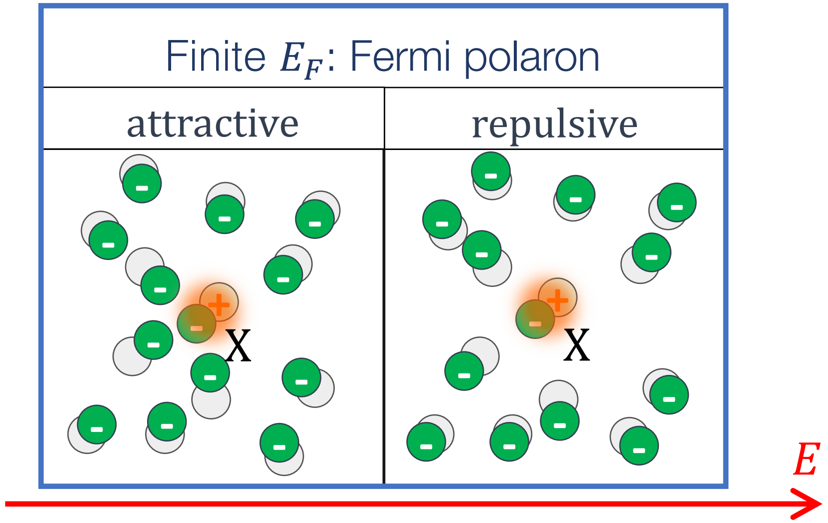
▷ Quantum droplets of matter-light quasiparticles



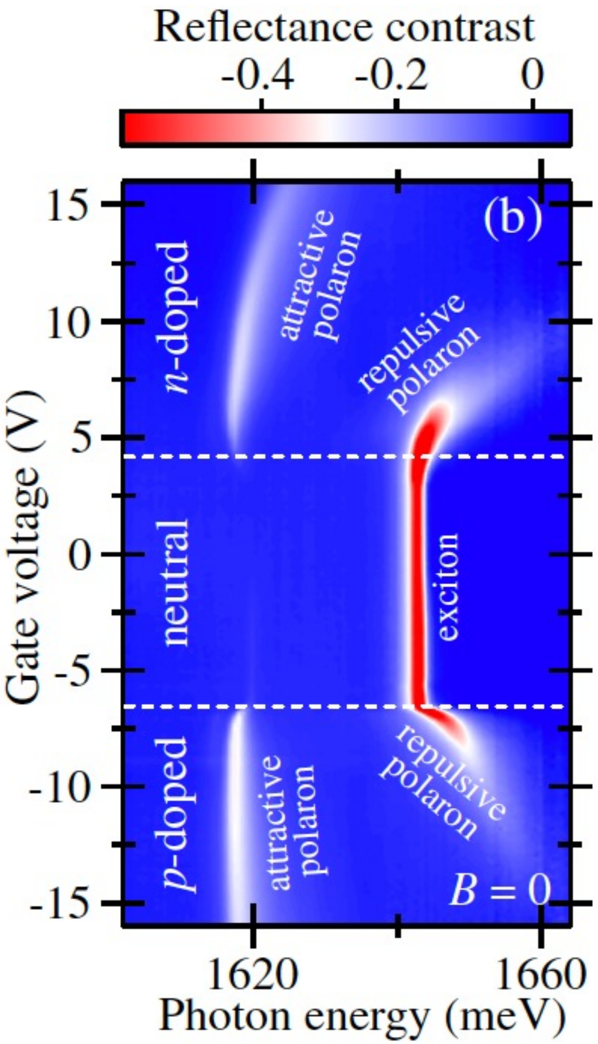
2. Fermi polaron (polaritons) in gated/doped TMD monolayers

Fermi polarons, excitons & trions in gated/doped TMD monolayers

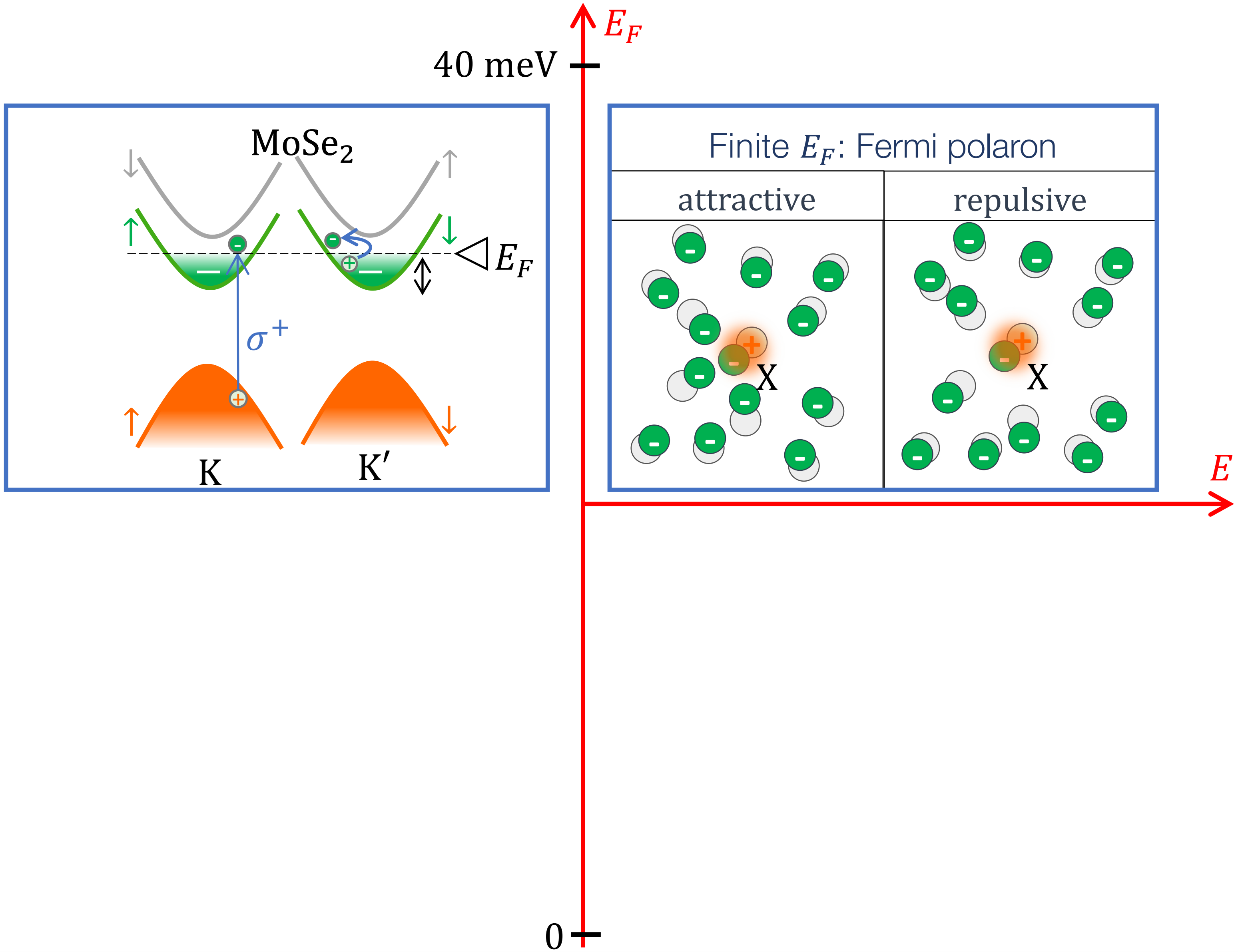



Finite E_F: Fermi polaron

[Smoleński et al PRL (2019)]



Fermi polarons, excitons & trions in gated/doped TMD monolayers



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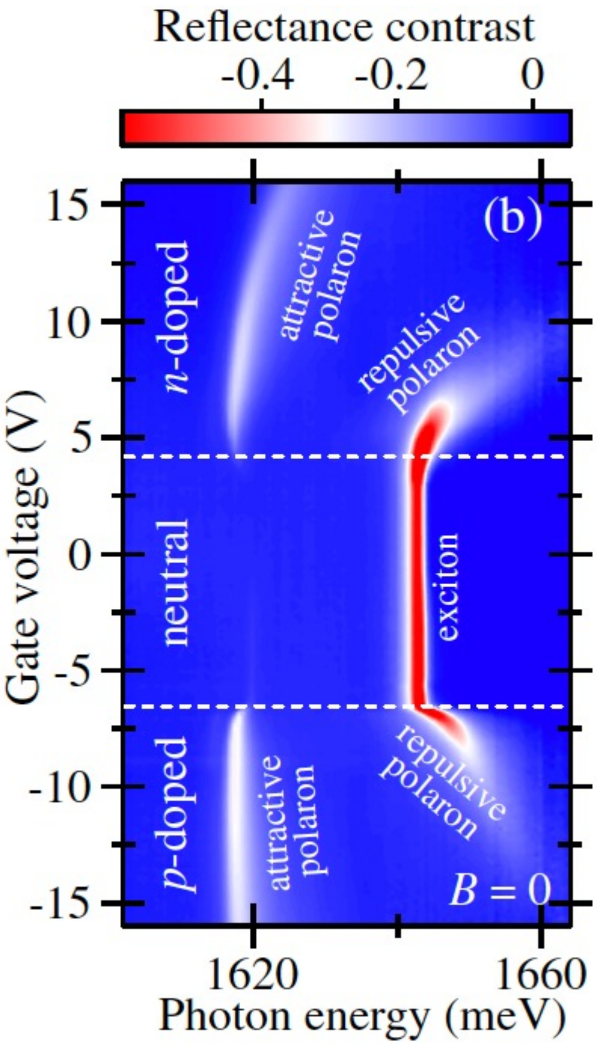

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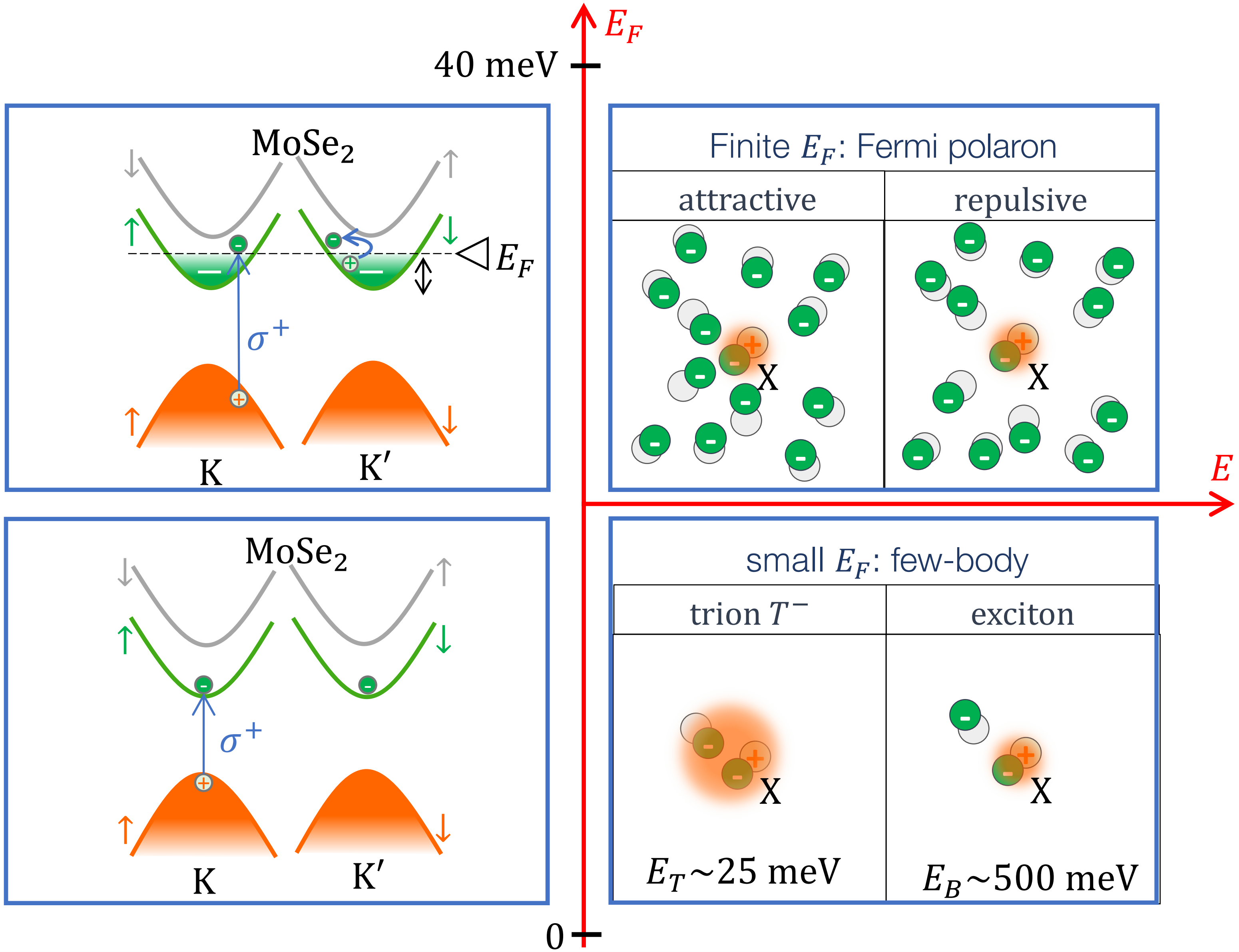


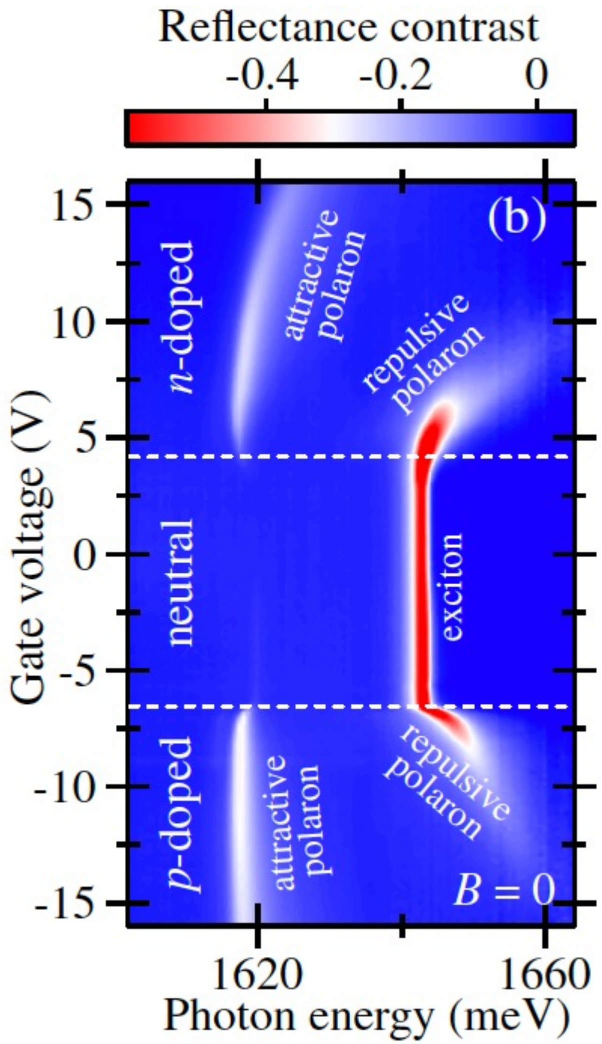
Finite E_F: Fermi polaron

attractive	repulsive

small E_F: few-body

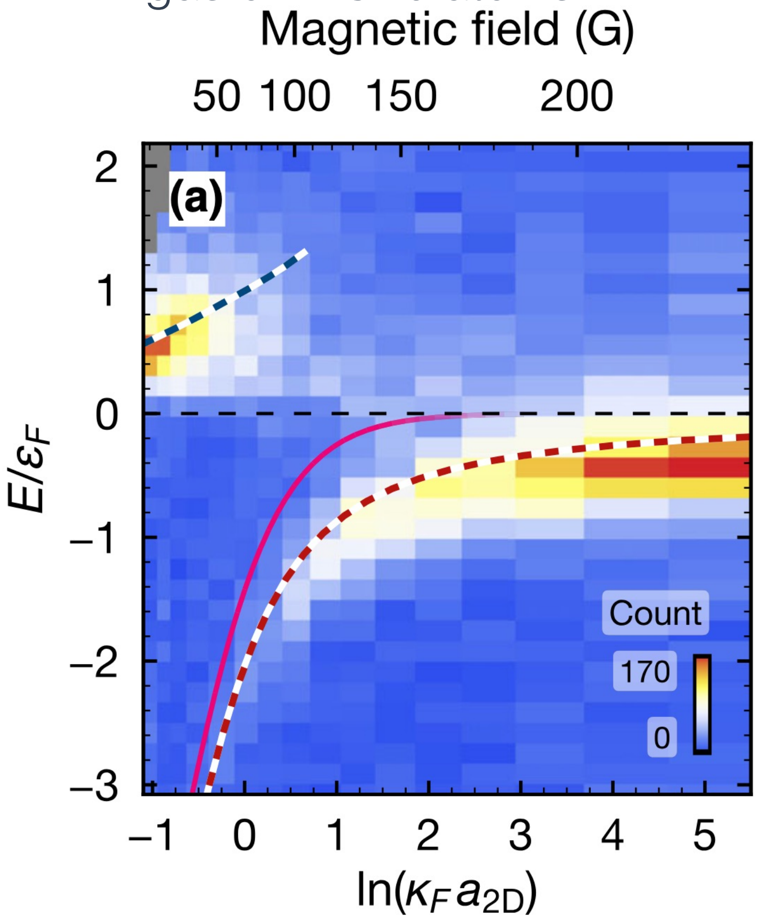
trion T^-	exciton
$E_T \sim 25$ meV	$E_B \sim 500$ meV

[Smoleński et al PRL (2019)]



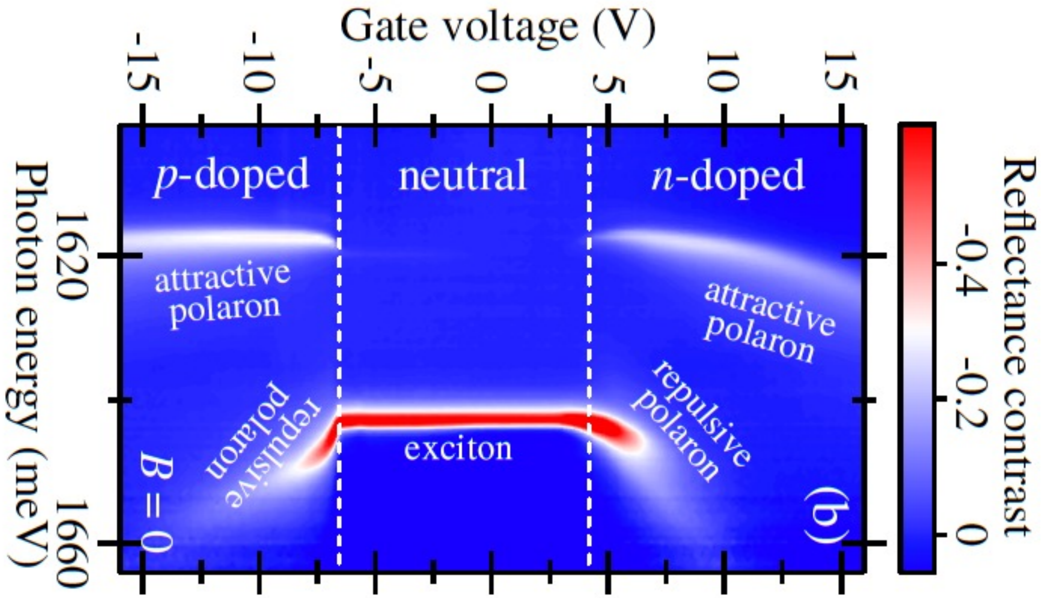
Ultra-cold atoms vs 2D semiconductor experiments

2D spin-imbalanced Fermi gas of 173Yb atoms



[Darkwah Oppong et al. PRL (2019)]
[Schirotzek et al. PRL (2009)]
[Koschorreck et al. Nature (2012)]
...

[Smoleński et al PRL (2019)]

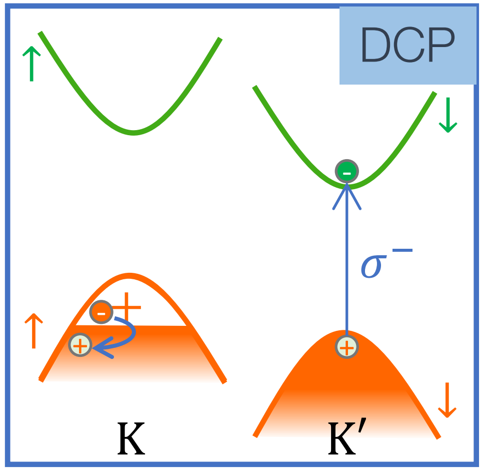


Variational approach at zero and finite temperature

▷ Chevy's Ansatz

$$\hat{x}_{\mathbf{0}}^{\dagger}(t) \simeq \varphi_0(t)\hat{x}_{\mathbf{0}}^{\dagger} + \frac{1}{\mathcal{A}}\sum_{\mathbf{k},\mathbf{q}} \varphi_{\mathbf{kq}}(t)\overbrace{\hat{x}_{\mathbf{q}-\mathbf{k}}^{\dagger}\hat{c}_{\mathbf{k}}^{\dagger}\hat{c}_{\mathbf{q}}}^{\text{trion-hole}}$$

[Sidler et al Nature Phys (2016)]
[Efimkin & MacDonald PRB (2017)]
[long list in cold atoms]



Absorption spectrum at $T = 0$

▷ Chevy's Ansatz

$$\hat{x}_{\mathbf{0}}^{\dagger}(t) \simeq \varphi_0(t)\hat{x}_{\mathbf{0}}^{\dagger} + \frac{1}{A}\sum_{\mathbf{k},\mathbf{q}} \varphi_{\mathbf{kq}}(t)\overbrace{\hat{x}_{\mathbf{q}-\mathbf{k}}^{\dagger}\hat{c}_{\mathbf{k}}^{\dagger}\hat{c}_{\mathbf{q}}}^{\text{trion-hole}}$$

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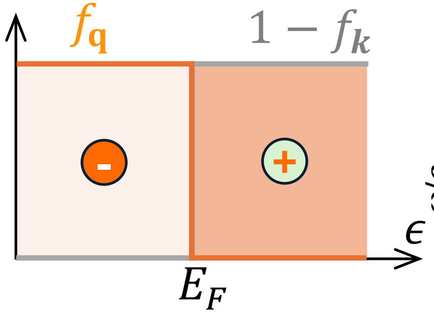
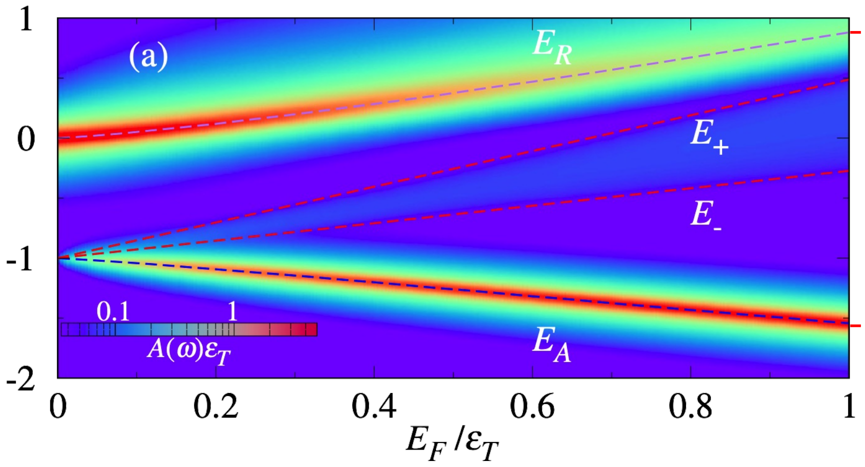




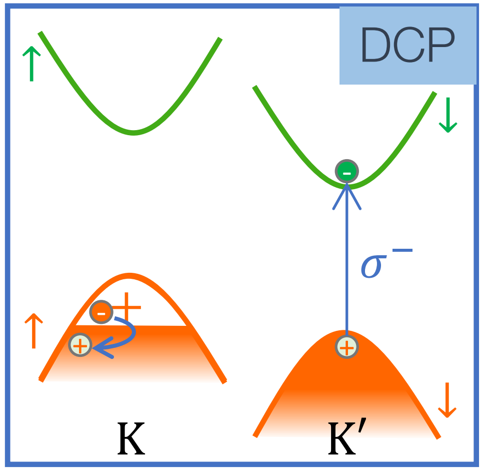
$E_R = \text{Re}\Sigma(E_R)$

trion-hole continuum

$E_- = E_T^{(\mathbf{k}_F)} - E_F$

$E_+ = E_T^{(\mathbf{0})}$

$E_A = \text{Re}\Sigma(E_A)$



Absorption spectrum at finite T

▷ Chevy's Ansatz

$$\hat{x}_{\mathbf{0}}^{\dagger}(t) \simeq \varphi_0(t)\hat{x}_{\mathbf{0}}^{\dagger} + \frac{1}{A}\sum_{\mathbf{k},\mathbf{q}} \varphi_{\mathbf{kq}}(t)\overbrace{\hat{x}_{\mathbf{q}-\mathbf{k}}^{\dagger}\hat{c}_{\mathbf{k}}^{\dagger}\hat{c}_{\mathbf{q}}}^{\text{trion-hole}}$$

[Sidler et al Nature Phys (2016)]
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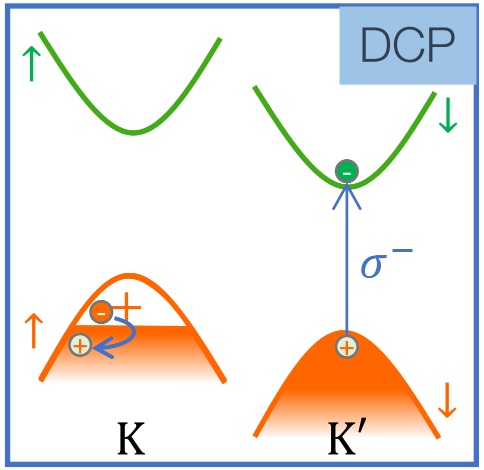
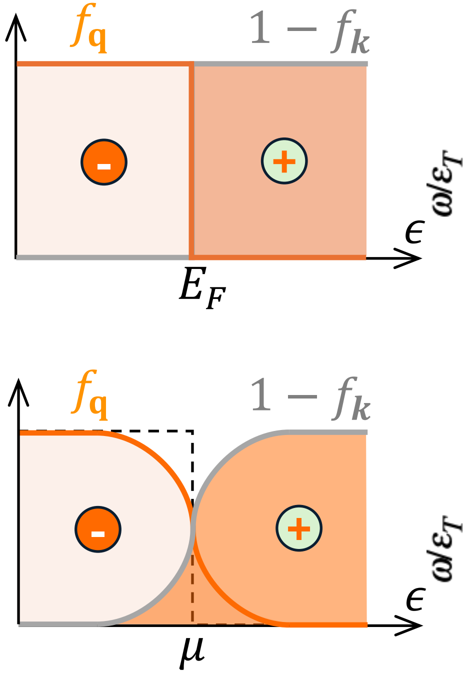
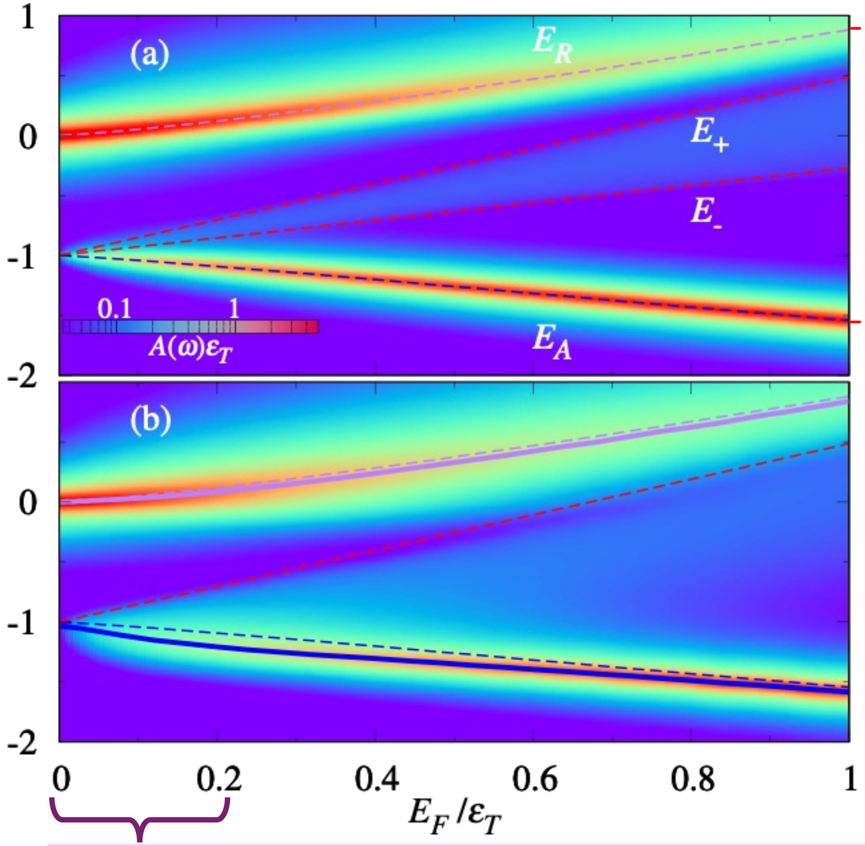






$$E_R = \mathrm{Re}\Sigma(E_R)$$

trion-hole continuum

$$E_- = E_T^{(\mathbf{k}_F)} - E_F$$

$$E_+ = E_T^{(\mathbf{0})}$$

$$E_A = \mathrm{Re}\Sigma(E_A)$$

[Tiene ... FMM, PRB (2023)]
[Mulkerin ... FMM ... PRL (2023)]

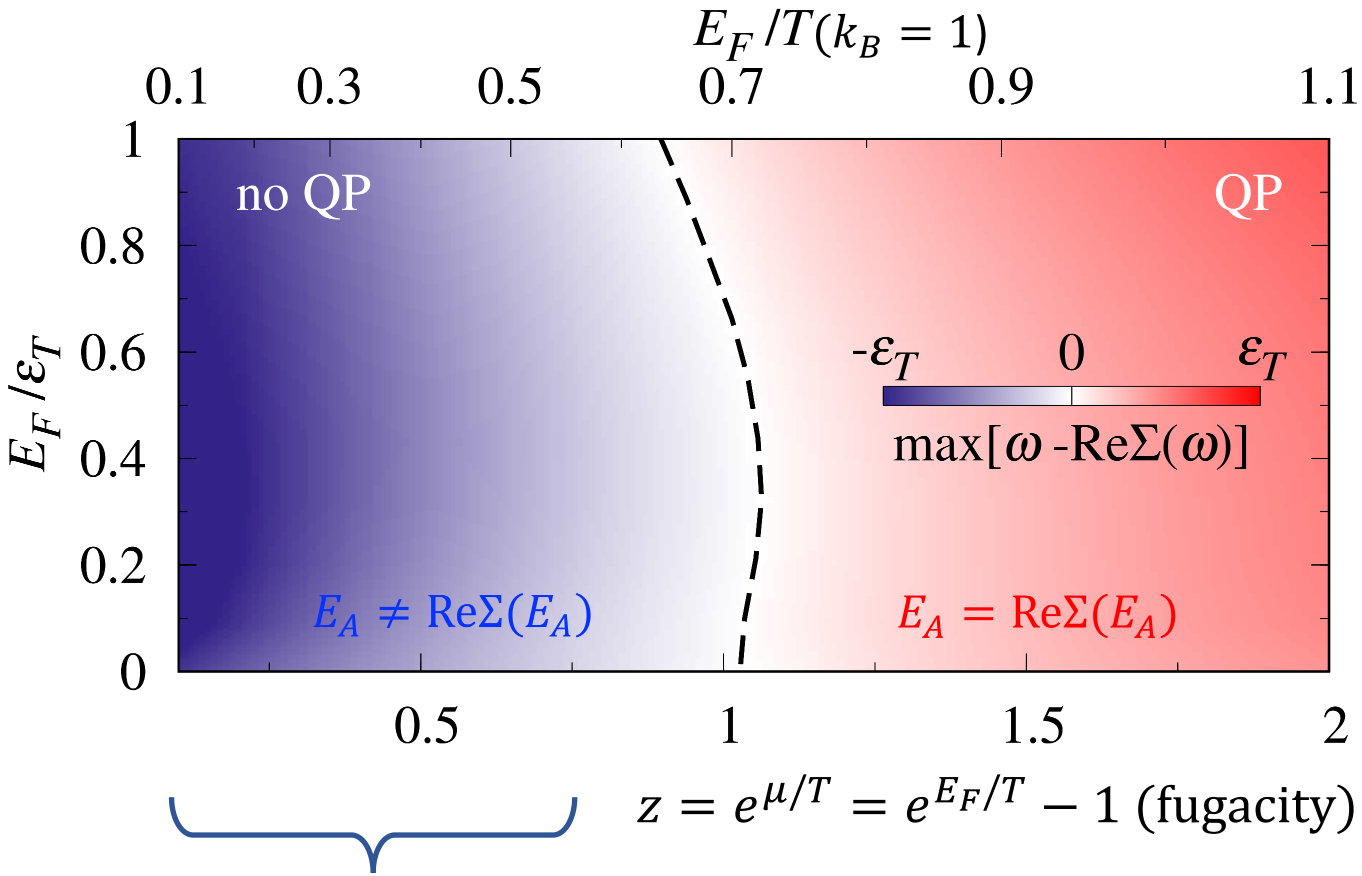
Dashed	$T = 0$ K
Continuous	$T = 50\text{ K} = 0.17\varepsilon_T$

NO well-defined attractive QP when $k_BT > E_F$ ($E_A \neq \mathrm{Re}\Sigma(E_A)$): trion-continuum instead

Attractive polaron to trion-continuum crossover

[Tiene ... FMM, PRB (2023)]
[Mulkerin ... FMM ... PRL (2023)]

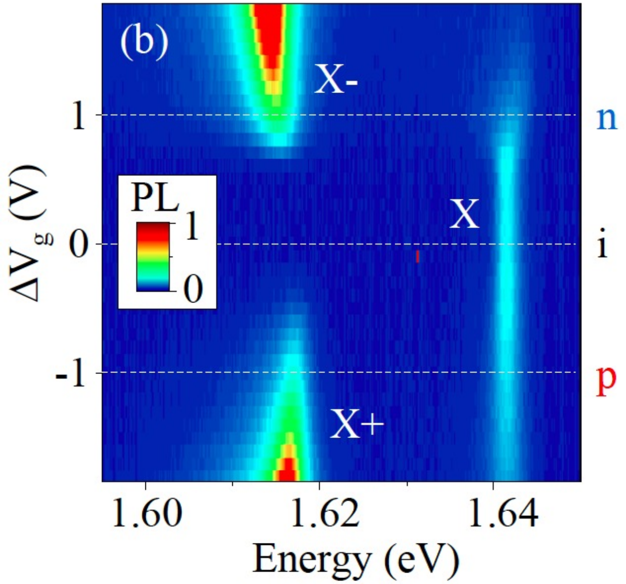
incoherent trion-continuum regime ← | → Attractive polaron regime



exact quantum virial expansion $z \ll 1$ ($T \gg E_F$)

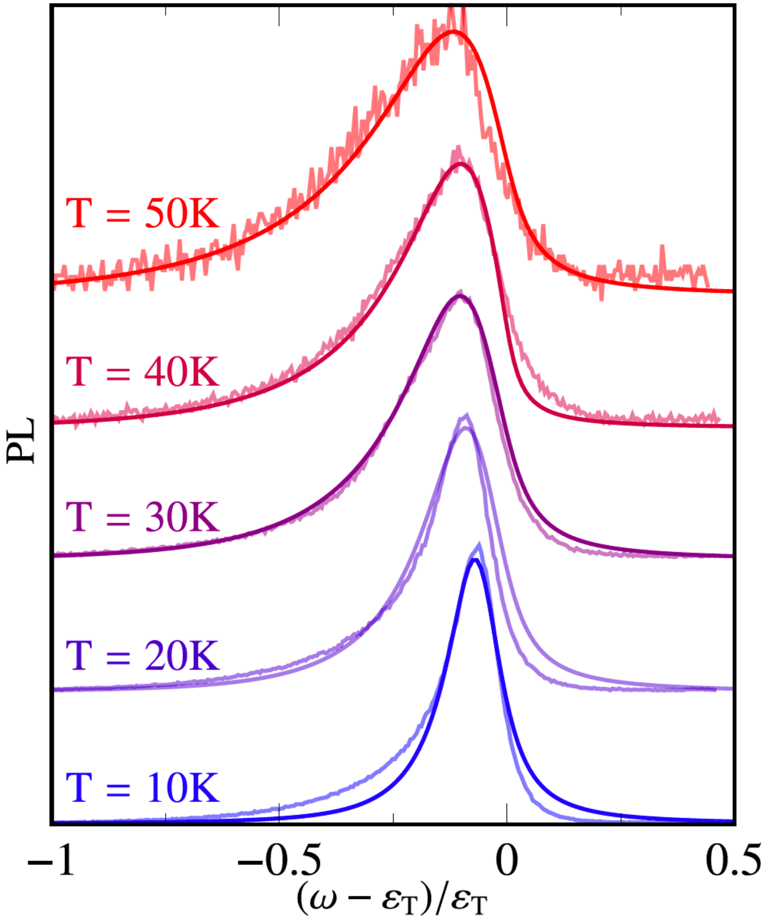
Comparison to experiments [Zipfel et al, PRB (2022)] & electron recoil

▷ MoSe$_2$ monolayer
- hole doping
- $n \simeq 0.5{\times}10^{11}\text{cm}^{-2}$
- $T = 5 - 50$ K



▷ Comparison with polaron theory (no fitting parameters!)

[Tiene … FMM, PRB (2023)]
[Mulkerin … FMM … PRL (2023)]



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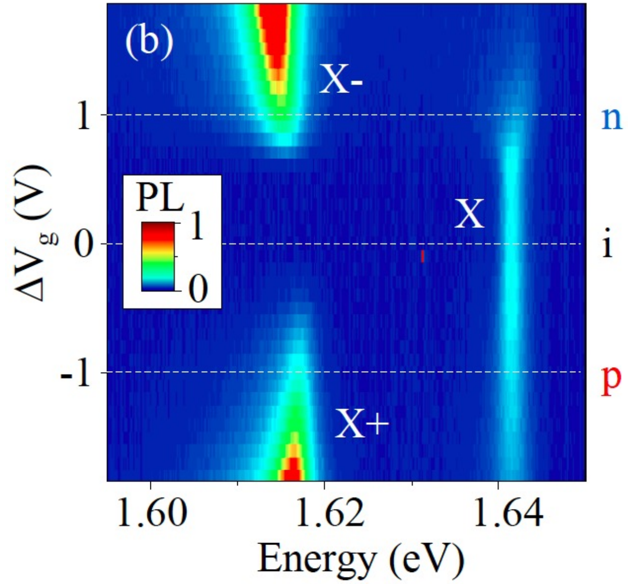

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[Tiene … FMM, PRB (2023)]
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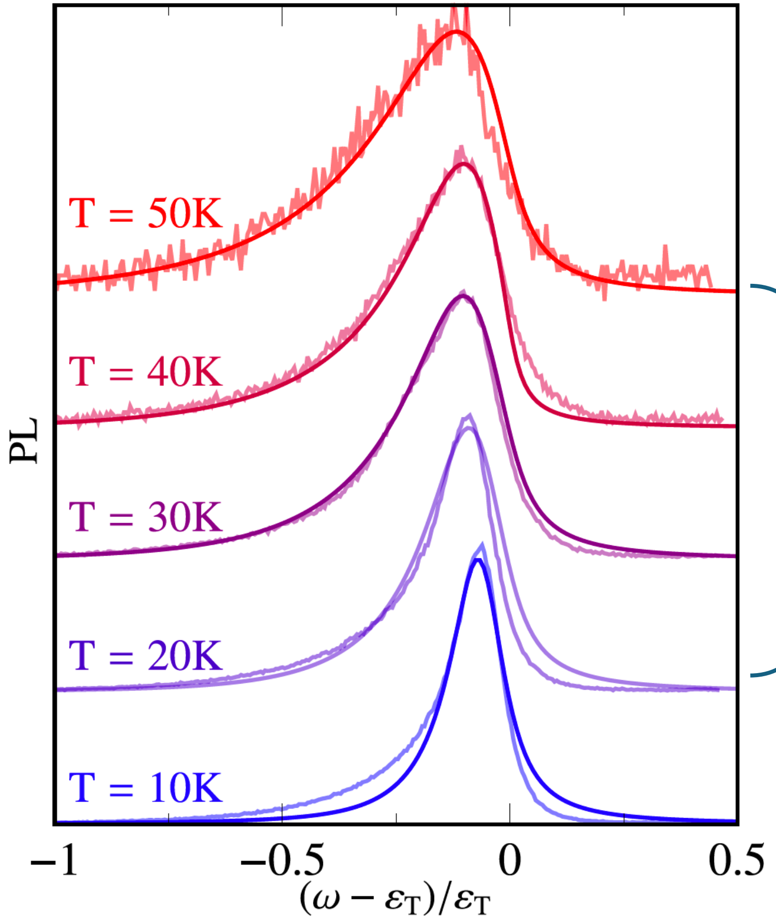
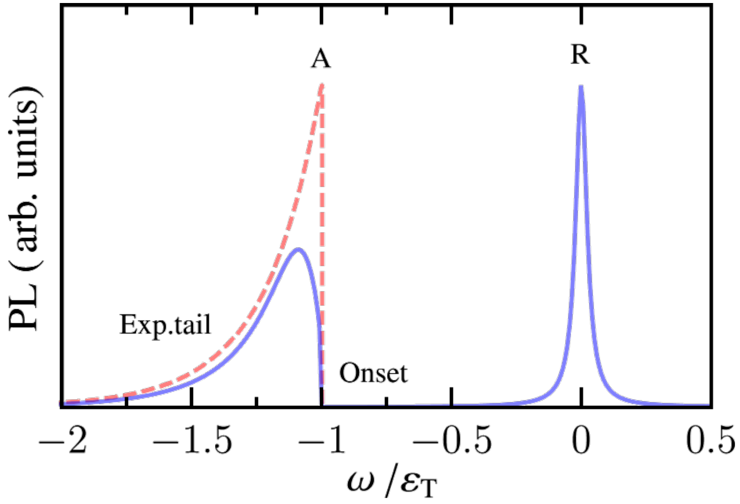


z ≪ 1
analytical: virial expansion

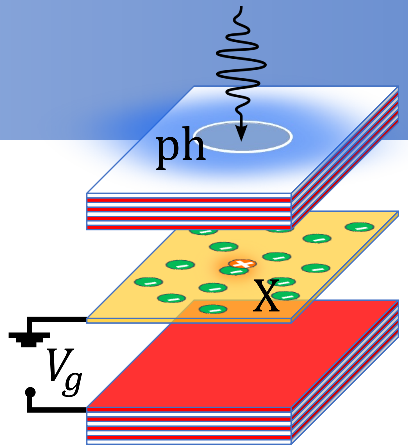


Recover electron recoil effect for exponential tail at $\omega \ll -\varepsilon_T$

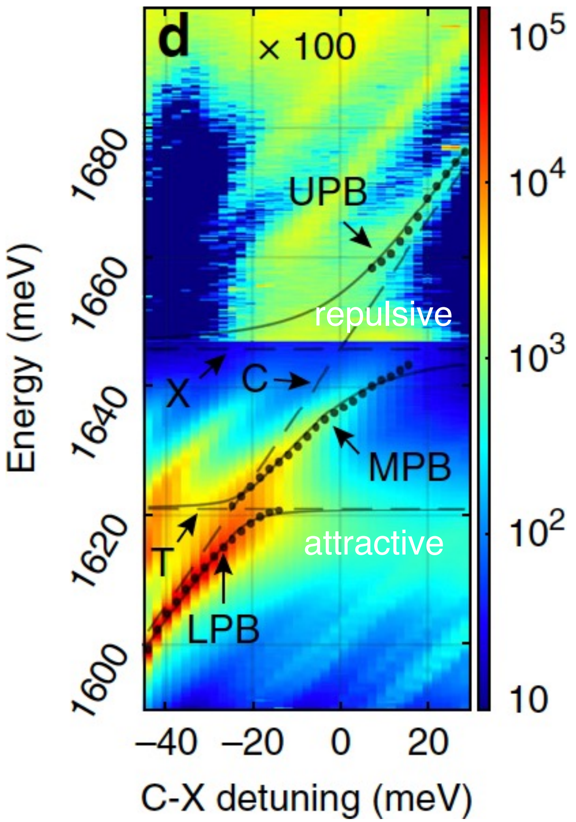
[Esser et al, PRB (2000)]

$$P(\omega) \sim e^{\frac{\omega m_h}{T m_X}}$$

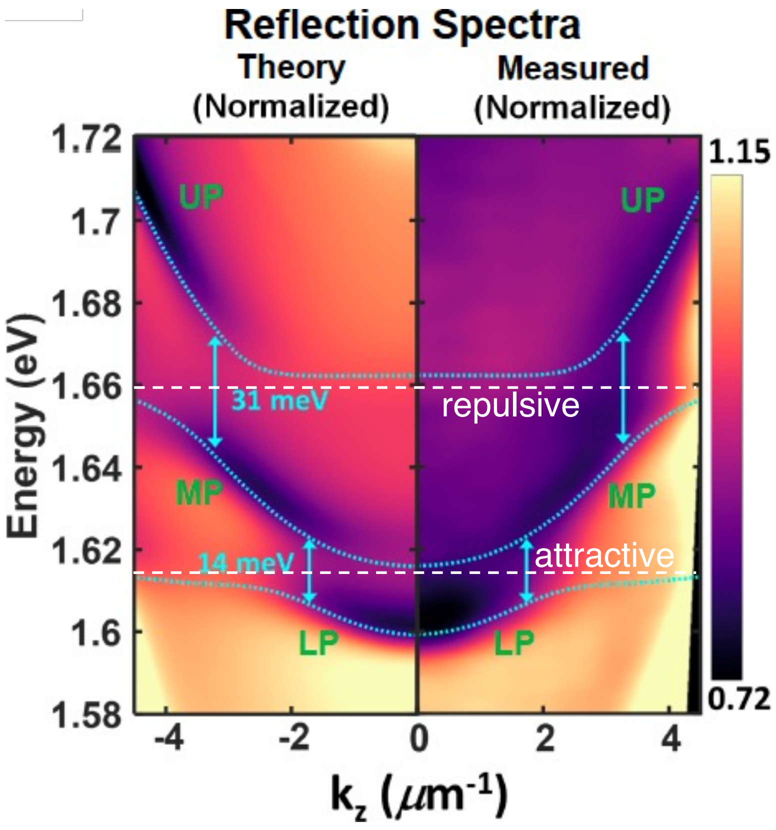
Fermi polaron polaritons



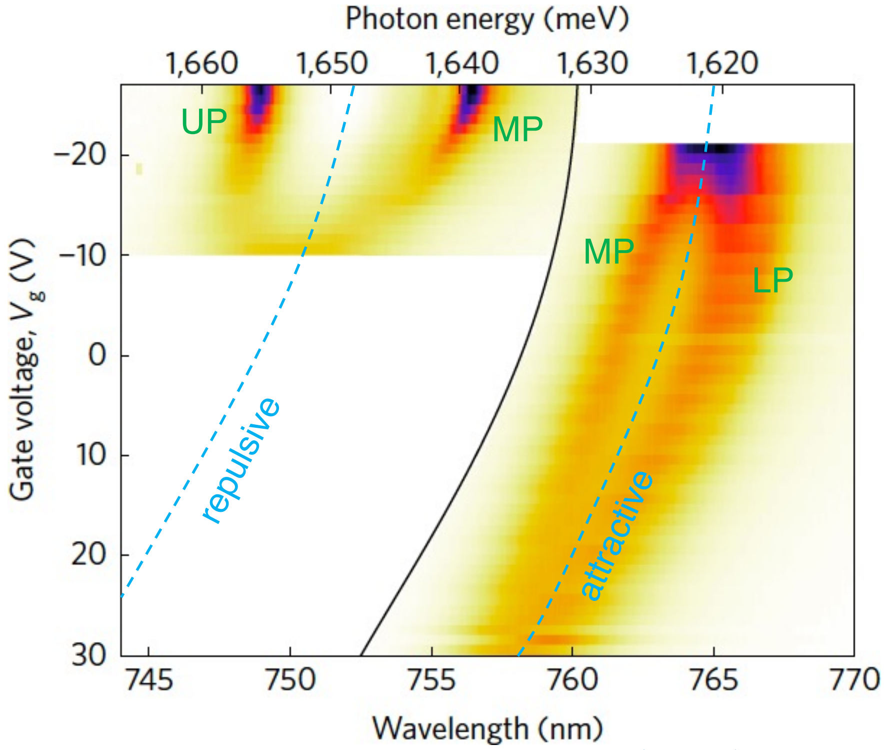
- ▷ two anti-crossings with attractive & repulsive branches
  - → 3 polariton branches: LP, MP, UP



[Emmanuele et al Nat Comm (2020)]



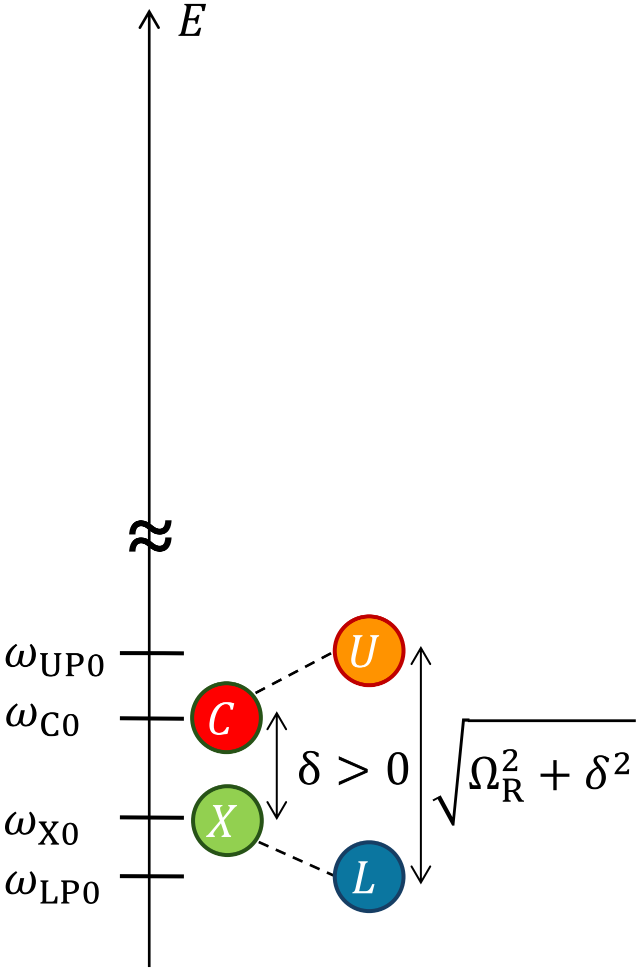
[Koksal et al PRR (2021)]



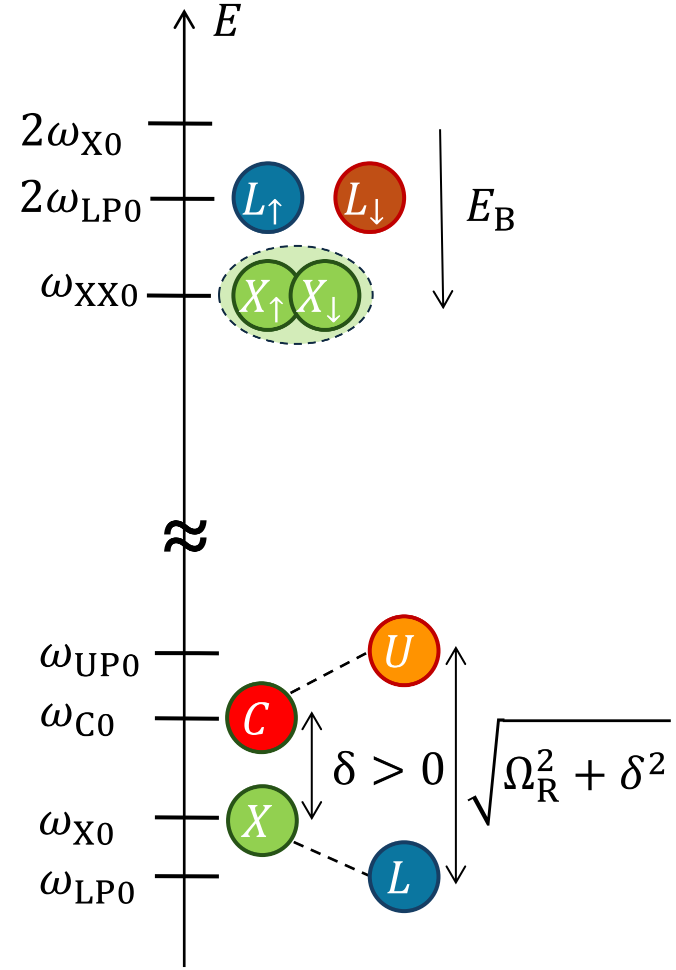
[Sidler et al Nature Phys (2016)]

3. Bose polaron polariton

Biexciton Feshbach resonance



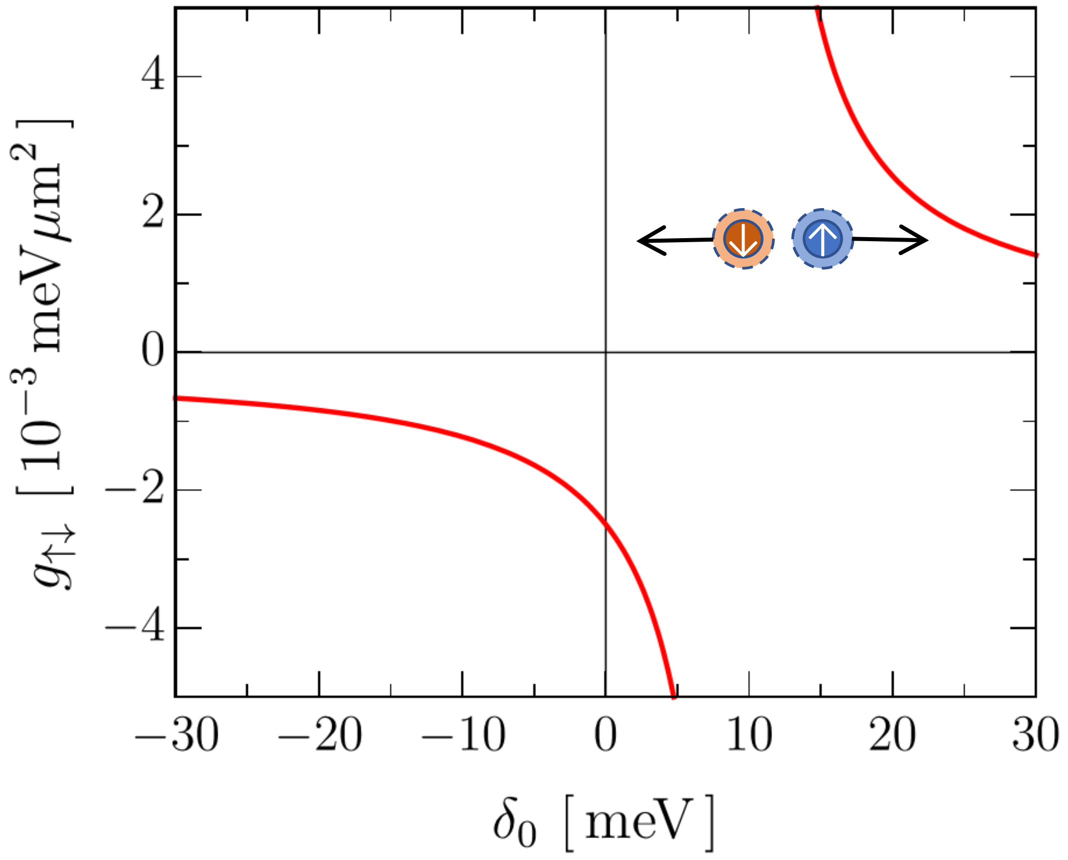
Biexciton Feshbach resonance

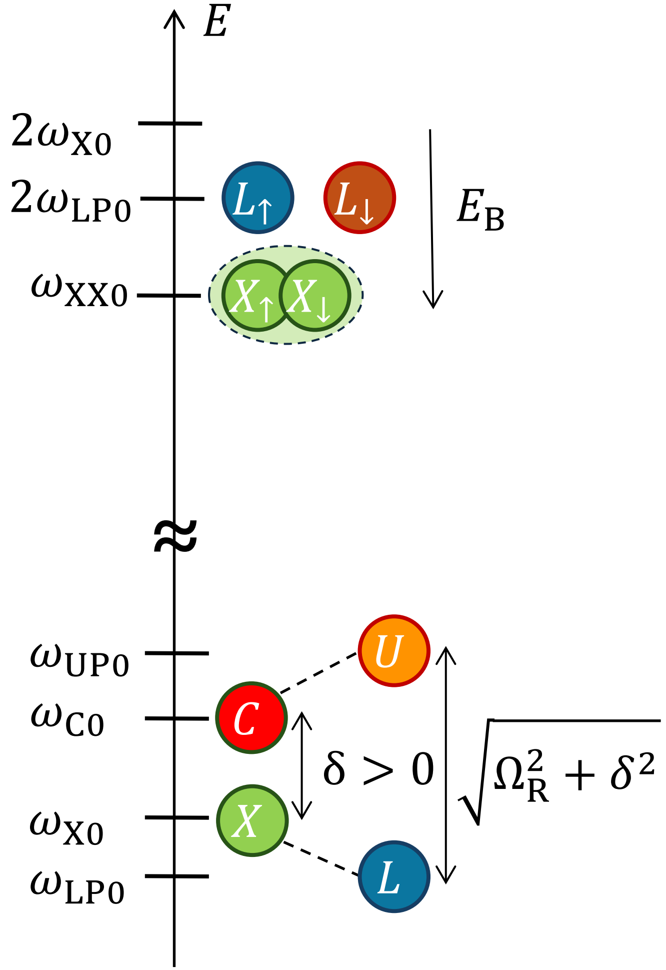


Biexciton Feshbach resonance

$$g_{\uparrow\downarrow} \propto \frac{4\pi}{m_X \ln\left(\frac{E_B}{2|\omega_{\mathrm{LP0}}|}\right)}$$

[Vladimirova et al. PRB (2010)]
[Bleu et al. PRR (2020)]





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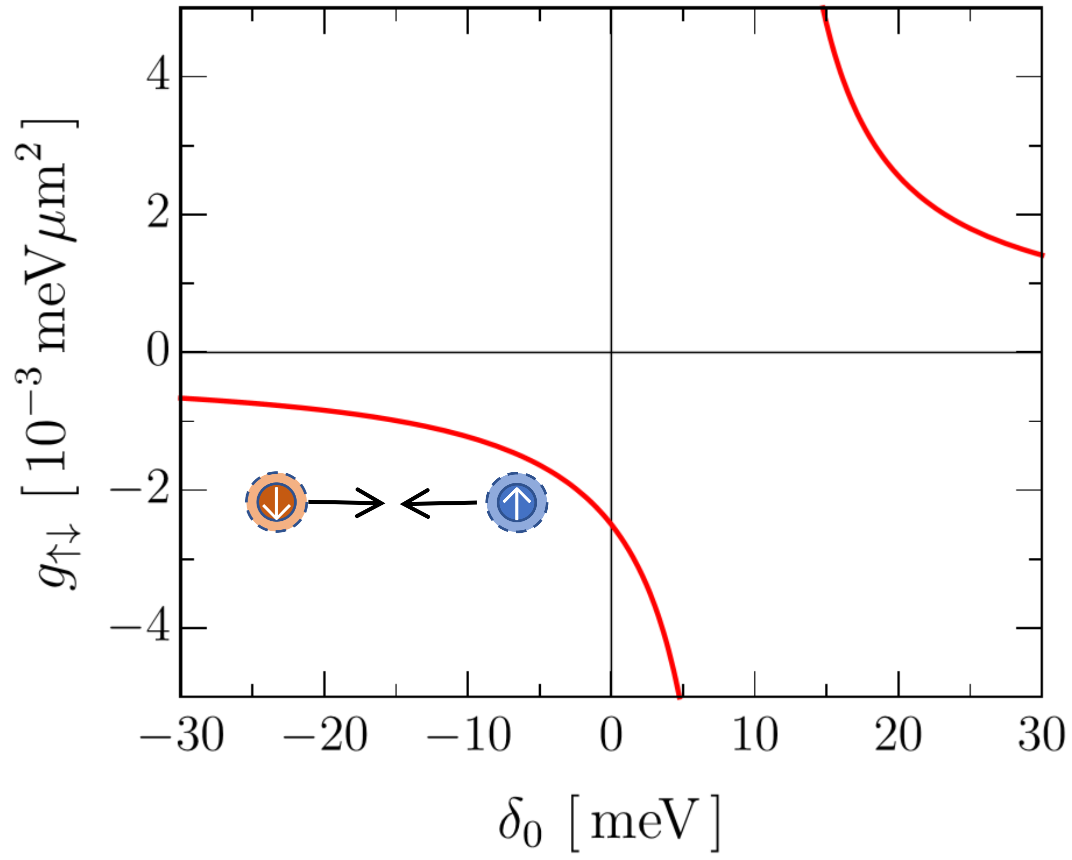
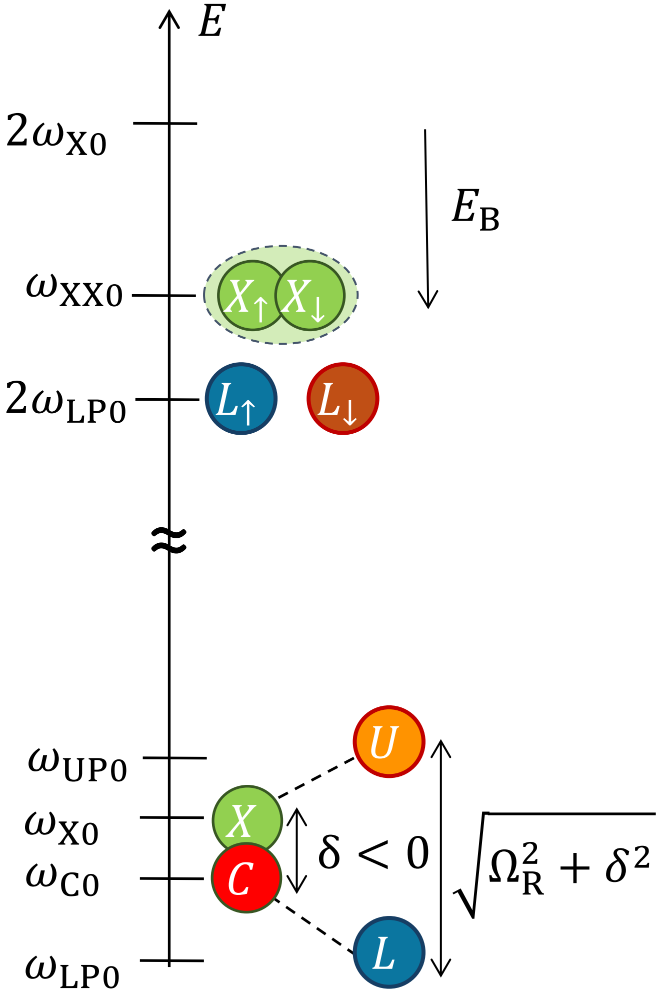
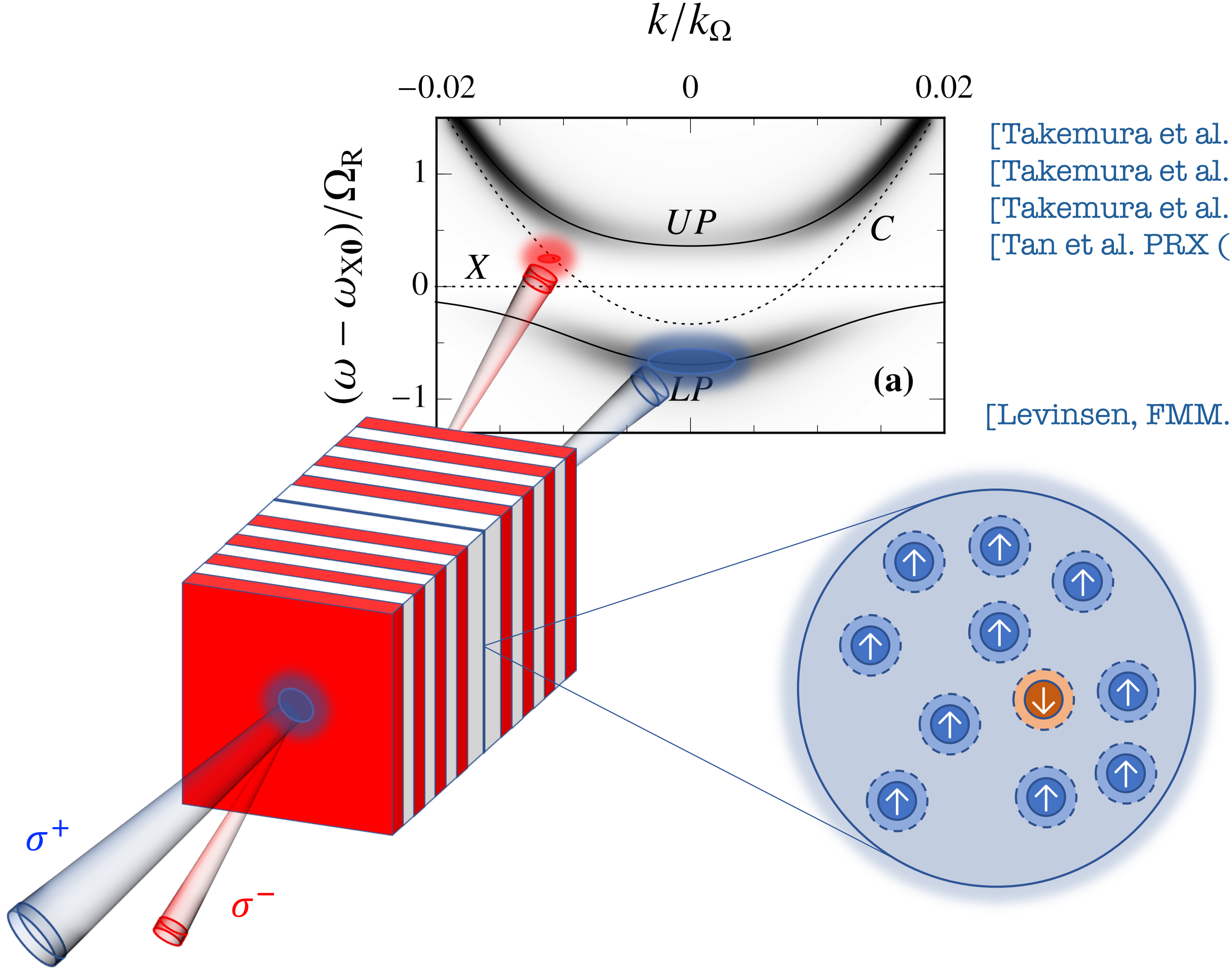


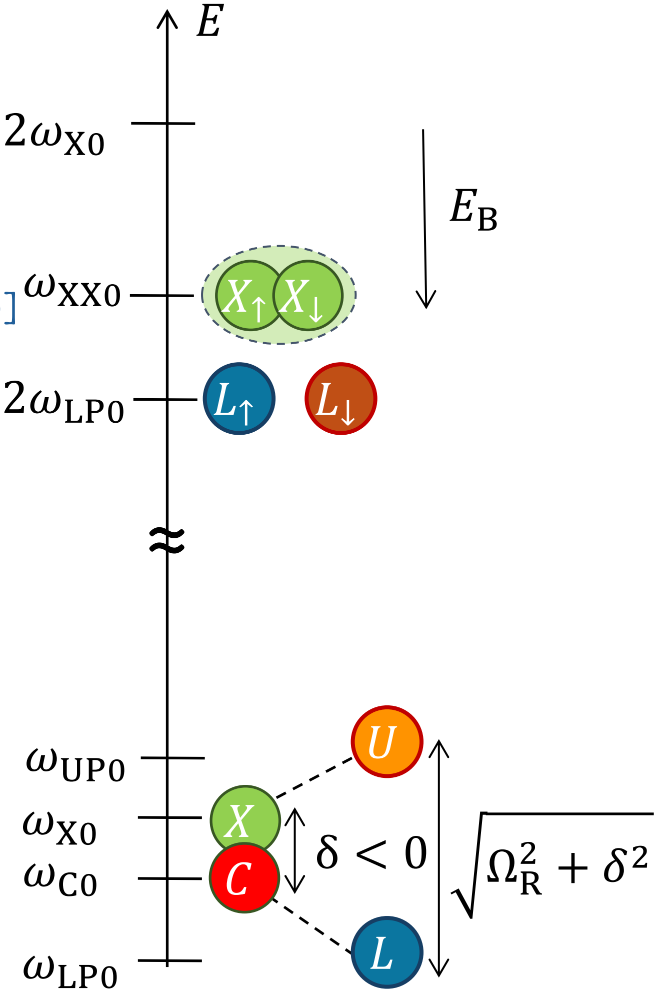


Biexciton Feshbach resonance: Bose polaron polariton

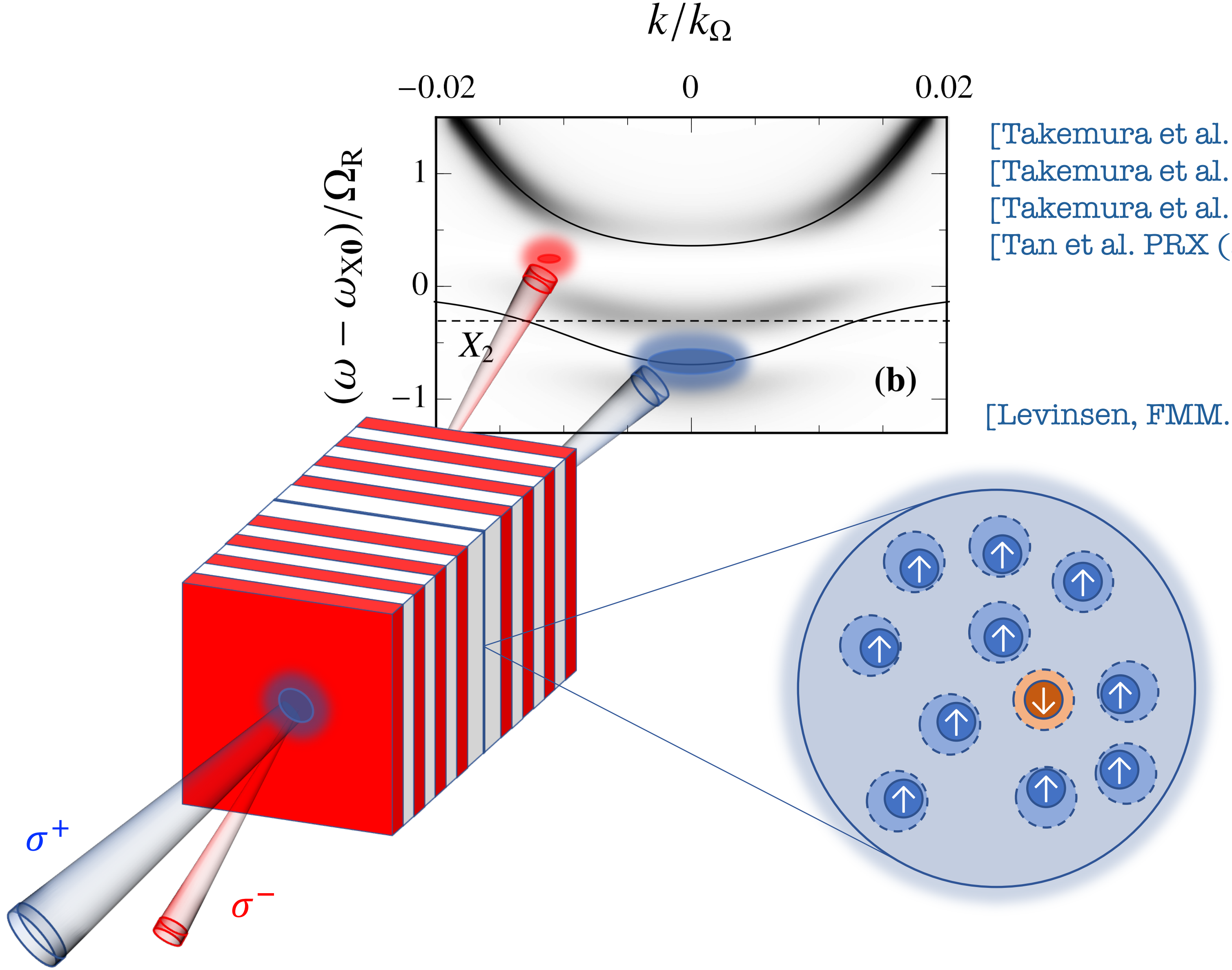


[Takemura et al. Nat Phys (2014)]
[Takemura et al. PRB (2014)]
[Takemura et al. PRB (2017)]
[Tan et al. PRX (2023)]

[Levinsen, FMM... PRL (2019)]



Biexciton Feshbach resonance: Bose polaron polariton



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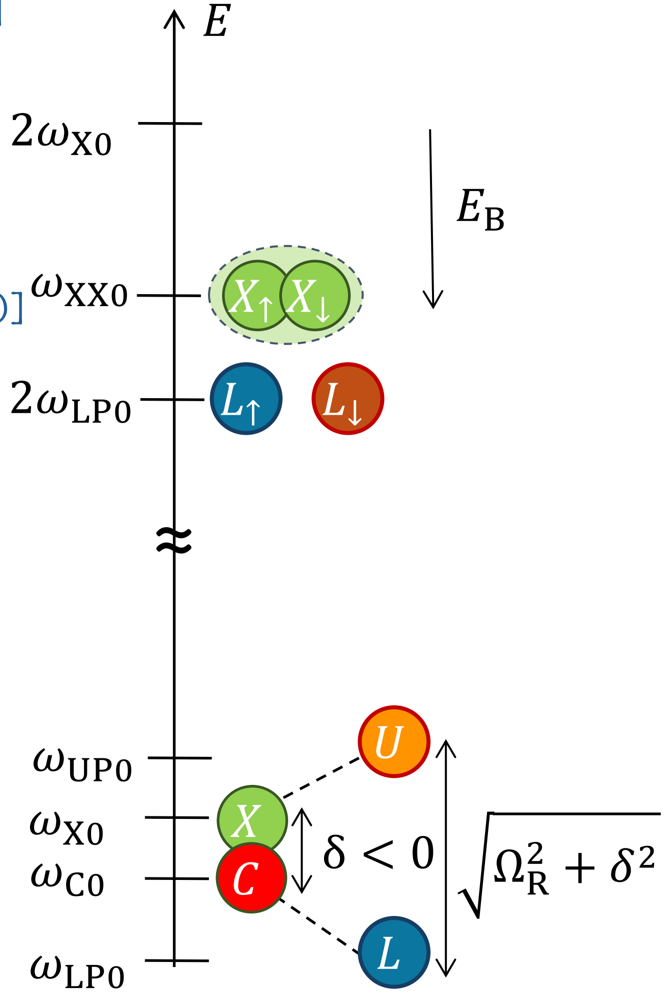

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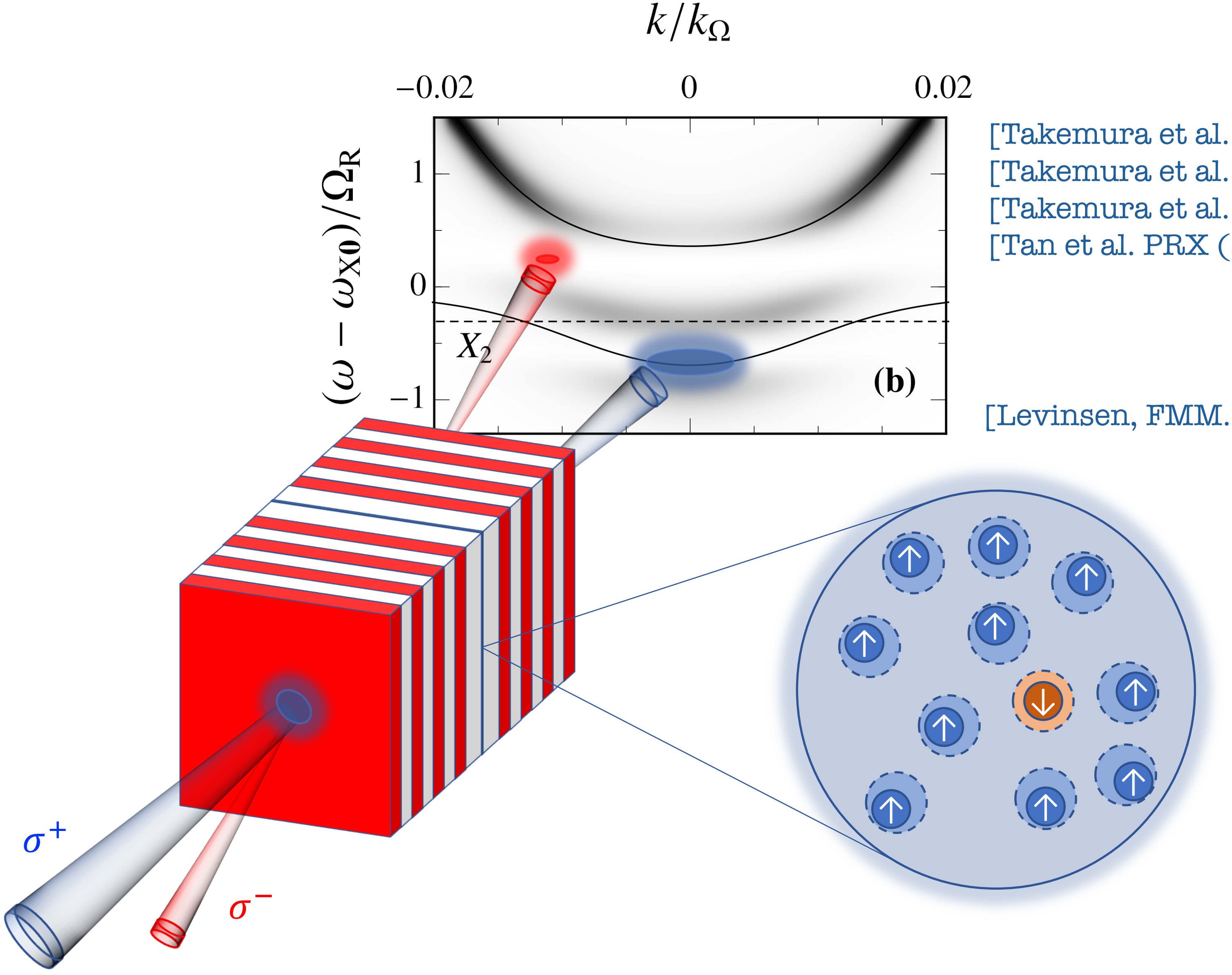

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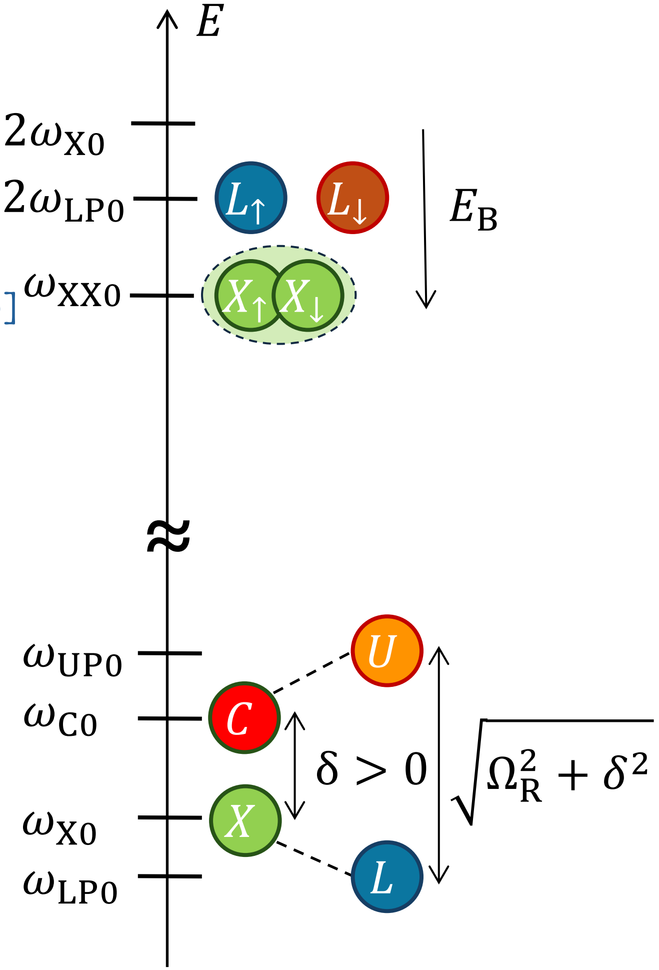
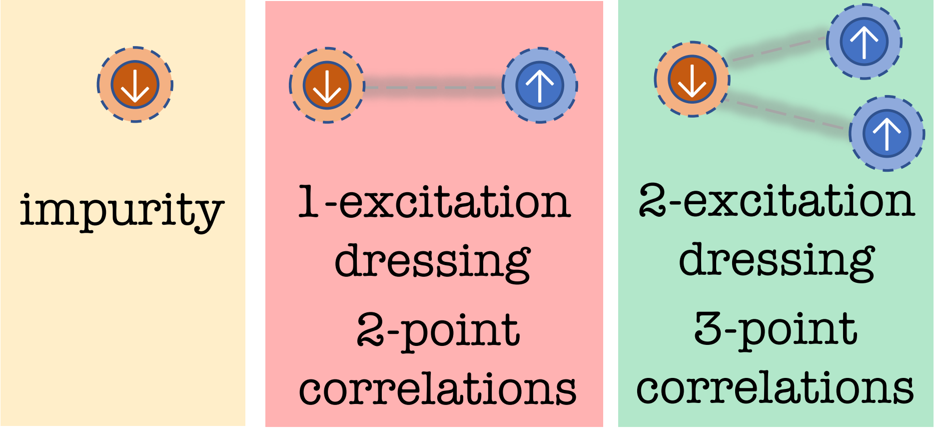


Biexciton Feshbach resonance: Bose polaron polariton

[Levinsen, FMM... PRL (2019)]

- ▷ Pump ↑
  - ○ coherent state+quantum fluctuations : $\hat{L}_{\uparrow\mathbf{k}} \to \sqrt{n_\uparrow}\delta_{\mathbf{k},\mathbf{0}} + \hat{L}_{\uparrow\mathbf{k}}$
- ▷ Probe ↓
  - ○ $(\hat{x}_\downarrow, \hat{c}_\downarrow)$ basis

$$|P\rangle = \left(\gamma \hat{c}^\dagger_{\mathbf{0}\downarrow} + \xi \hat{x}^\dagger_{\mathbf{0}\downarrow} + \sum_{\mathbf{k}} \zeta_{\mathbf{k}} \hat{x}^\dagger_{-\mathbf{k}\downarrow}\hat{L}^\dagger_{\mathbf{k}\uparrow} + \frac{1}{2}\sum_{\mathbf{k},\mathbf{k}'}\eta_{\mathbf{k}\mathbf{k}'}\hat{x}^\dagger_{-\mathbf{k}-\mathbf{k}'\downarrow}\hat{L}^\dagger_{\mathbf{k}\uparrow}\hat{L}^\dagger_{\mathbf{k}'\uparrow}\right)|\Phi_\uparrow\rangle$$



impurity

1-excitation dressing

2-point correlations

2-excitation dressing

3-point correlations

Biexciton Feshbach resonance: Bose polaron polariton

[Levinsen, FMM... PRL (2019)]

- ▷ Pump ↑
  - ○ coherent state+quantum fluctuations : $\hat{L}_{\uparrow\mathbf{k}} \to \sqrt{n_\uparrow}\delta_{\mathbf{k},\mathbf{0}} + \hat{L}_{\uparrow\mathbf{k}}$
- ▷ Probe ↓
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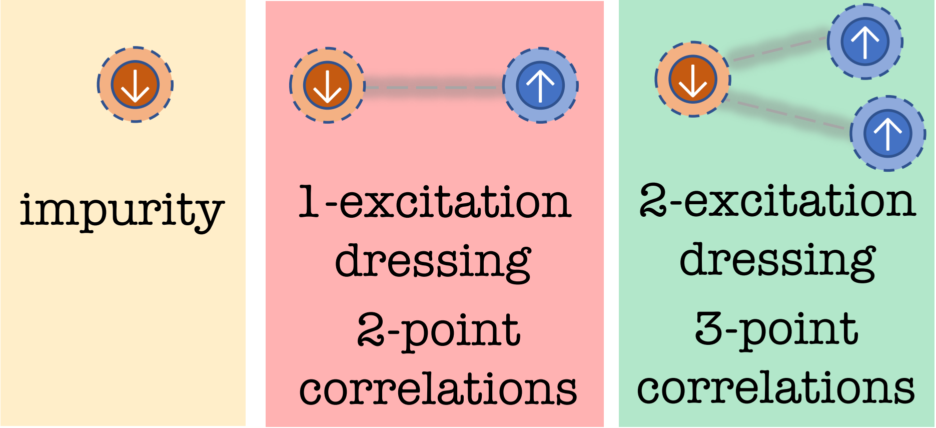


impurity

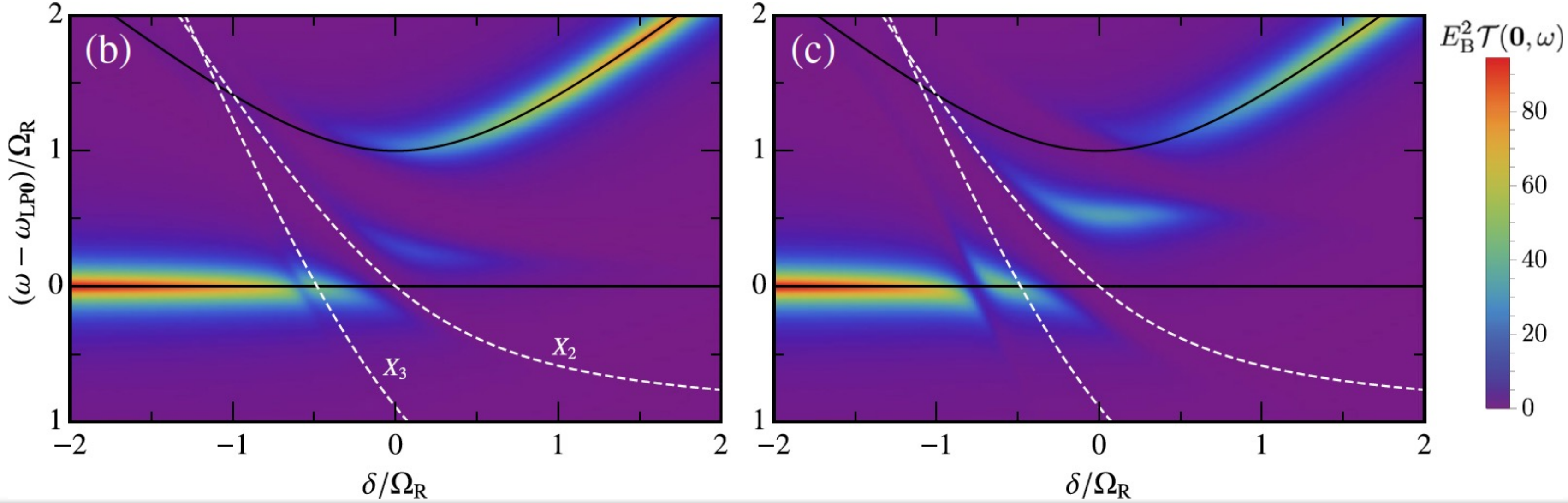
1-excitation dressing

2-point correlations

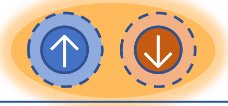
2-excitation dressing

3-point correlations

$n_\uparrow = 3\times10^{10}\mathrm{cm}^{-2}$ $\quad$ $n_\uparrow = 1.25\times10^{11}\mathrm{cm}^{-2}$



splitting of branches close to the biexciton resonance

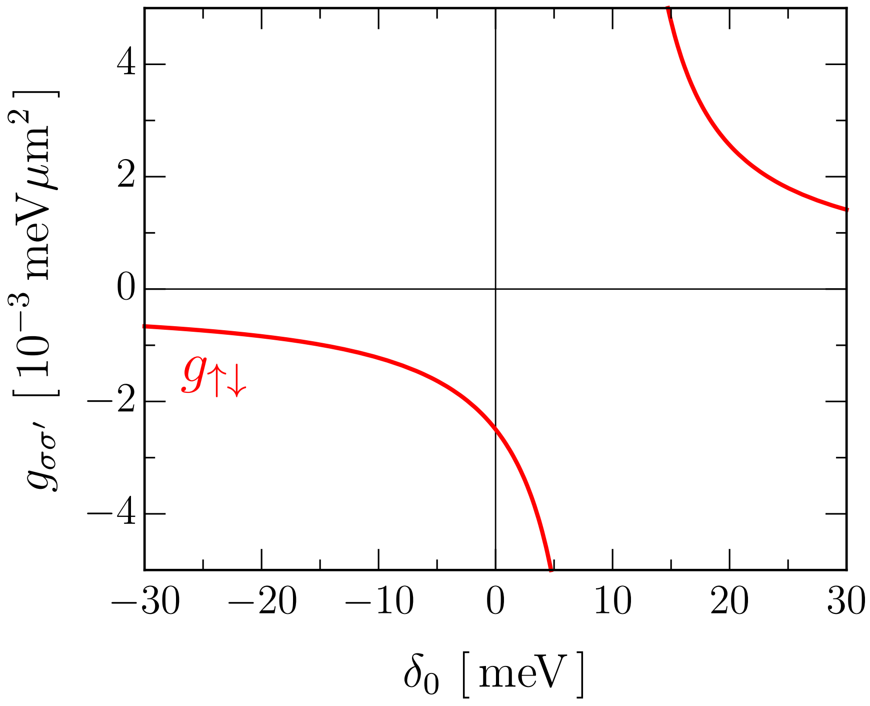
X_2 = 

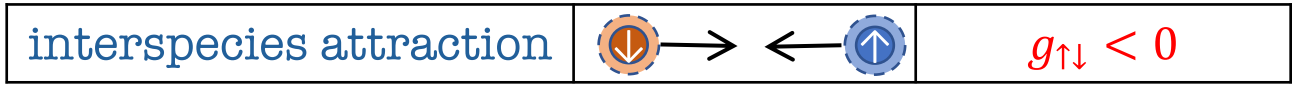
Additional splitting close to the triexciton resonance

X_3 = 

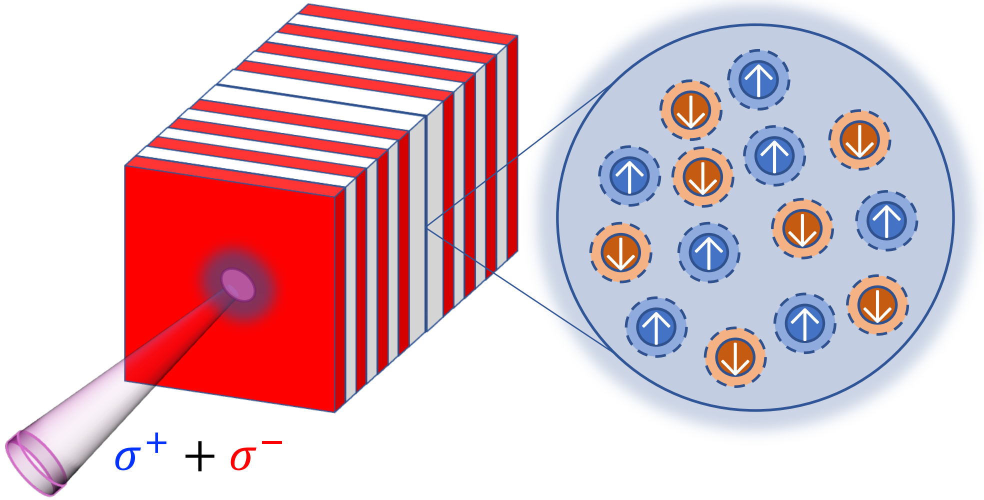
4. Quantum droplets of light

Polariton spin mixture

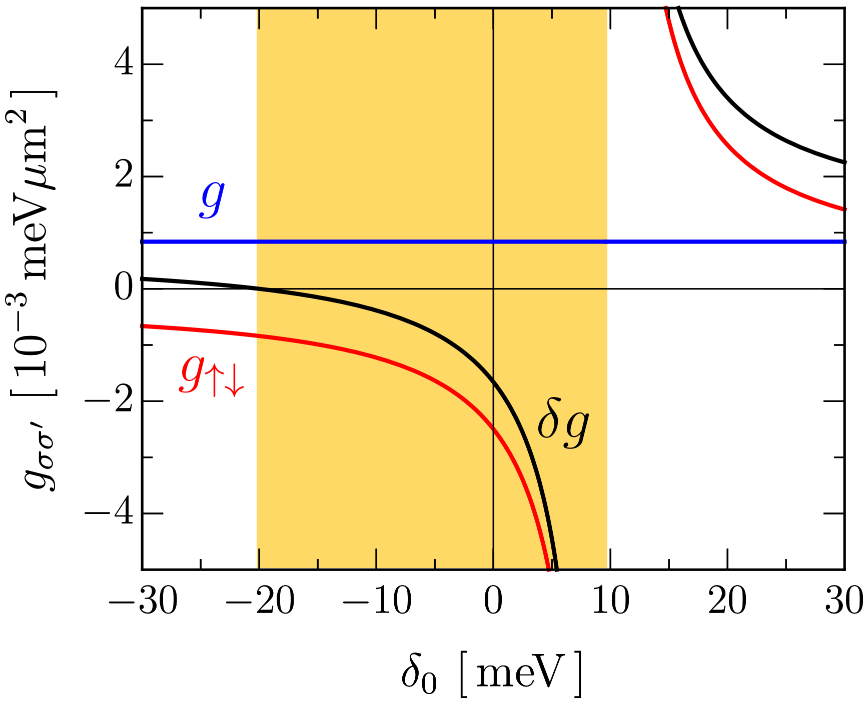




interspecies attraction	↓ → ← ↑	$g_{\uparrow\downarrow} < 0$

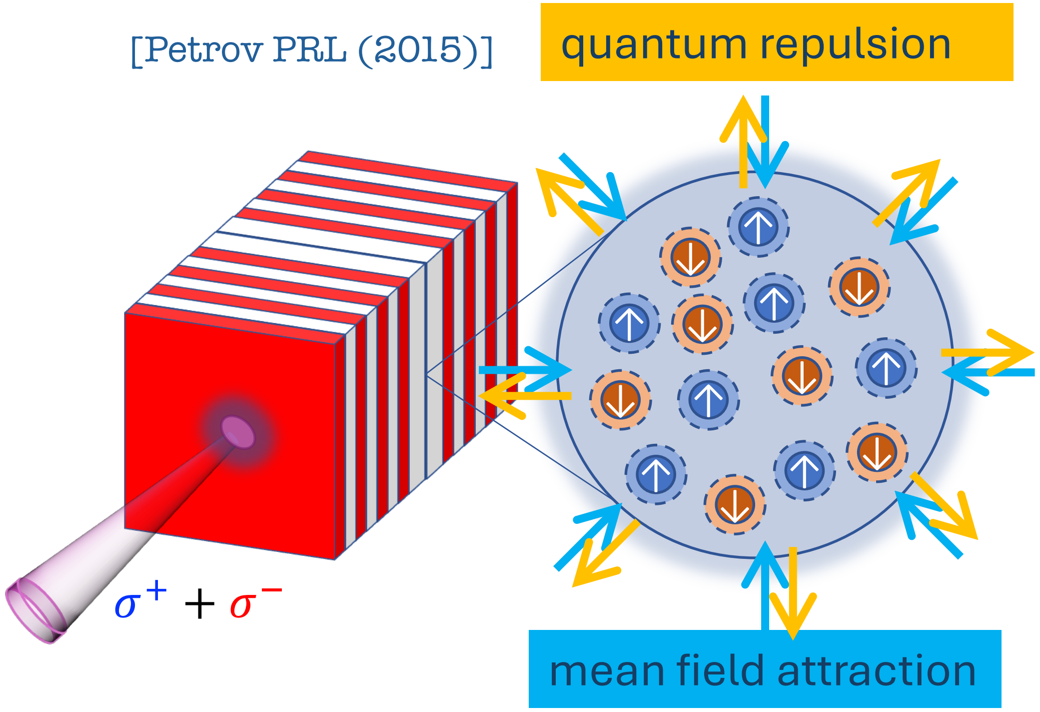


Polariton spin mixture



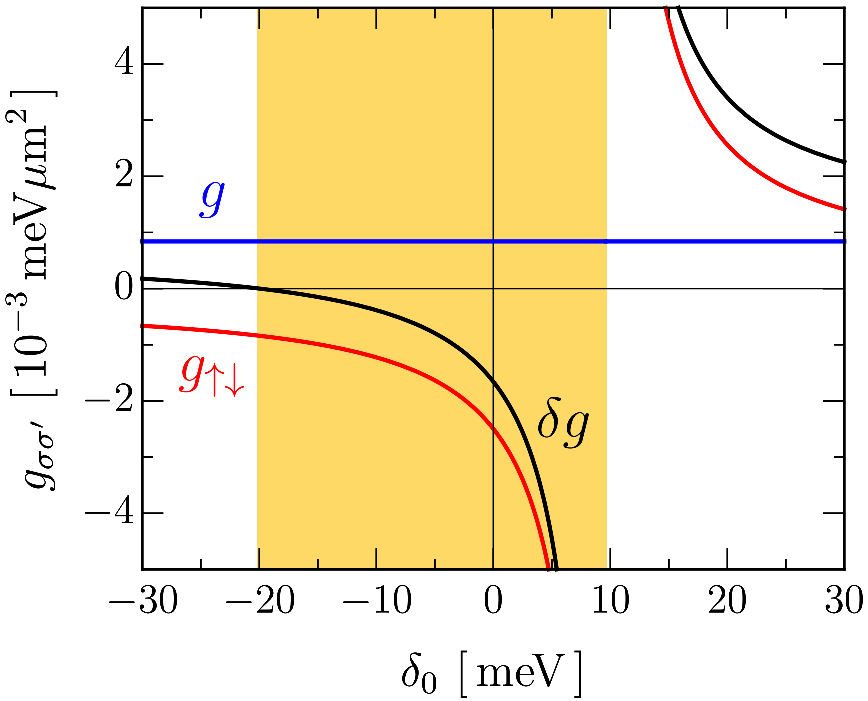
interspecies attraction	↓ → ← ↑	$g_{\uparrow\downarrow} < 0$
intraspecies repulsion	← ↑ ↑ → ← ↓ ↓ →	$g > 0$
“mean-field interaction”	$\delta g = g + g_{\uparrow\downarrow} \lesssim 0$ quantum droplet regime	

[Petrov PRL (2015)]



▷ Enhance quantum fluctuations by suppressing mean-field effects

Polariton spin mixture



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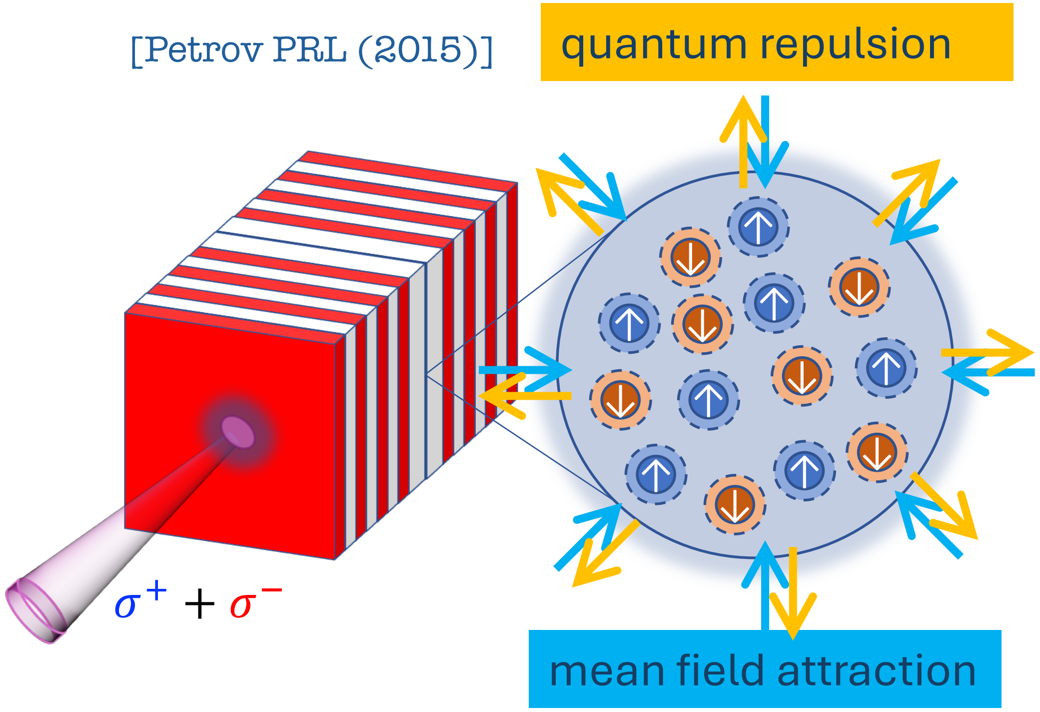
[Petrov PRL (2015)]



- ▷ Enhance quantum fluctuations by suppressing mean-field effects
- ▷ Experimentally realized in ultracold atoms
  - homonuclear } binary mixtures
  - heteronuclear }
  - dipolar condensates
- ▷ Signatures of elusive polariton quantum nature (no need to increase polariton interactions)

Balanced mixtures : Bogoliubov theory with bosonic pairing

$$\hat{H}_0 = \sum_{\mathbf{k}\sigma} \begin{pmatrix} \hat{c}^\dagger_{\mathbf{k}\sigma} & \hat{x}^\dagger_{\mathbf{k}\sigma} \end{pmatrix} \begin{pmatrix} \epsilon^{\mathrm{C}}_{\mathbf{k}} - \mu_\sigma & \Omega_{\mathrm{R}}/2 \\ \Omega_{\mathrm{R}}/2 & \epsilon^{\mathrm{X}}_{\mathbf{k}} - \mu_\sigma \end{pmatrix} \begin{pmatrix} \hat{c}_{\mathbf{k}\sigma} \\ \hat{x}_{\mathbf{k}\sigma} \end{pmatrix}$$

$$\hat{V} = \sum_{\mathbf{k}\mathbf{k}'\mathbf{q},\sigma} \frac{v}{2} \hat{x}^\dagger_{\mathbf{k}+\mathbf{q}\sigma} \hat{x}^\dagger_{\mathbf{k}'-\mathbf{q}\sigma} \hat{x}_{\mathbf{k}'\sigma} \hat{x}_{\mathbf{k}\sigma} - \frac{|\Phi|^2}{v_{\uparrow\downarrow}} - \sum_{\mathbf{k}} \left(\Phi \hat{x}^\dagger_{\mathbf{k}\uparrow} \hat{x}^\dagger_{-\mathbf{k}\downarrow} + \Phi^* \hat{x}_{-\mathbf{k}\downarrow} \hat{x}_{\mathbf{k}\uparrow} \right)$$

[Nozières&Saint James JPF (1982)]

$$\Phi = -v_{\uparrow\downarrow} \sum_{\mathbf{p}} \langle \hat{x}_{\mathbf{p}\uparrow} \hat{x}_{-\mathbf{p}\downarrow} \rangle$$

- ▷ Renormalisation of contact interactions: $v \to g$, $v_{\uparrow\downarrow} \to g_{\uparrow\downarrow}$
- ▷ Mean-field + quantum corrections (zero-point energy of Bogoliubov modes)

$$\Omega(n,\Phi,\mu) = \Omega_{MF}(n,\Phi,\mu) + \Omega_{LHY}(n,\Phi,\mu)$$

[Caldara et al. (in preparation)]

Balanced mixtures : Bogoliubov theory with bosonic pairing

$$\hat{H}_0 = \sum_{\mathbf{k}\sigma} \begin{pmatrix} \hat{c}^\dagger_{\mathbf{k}\sigma} & \hat{x}^\dagger_{\mathbf{k}\sigma} \end{pmatrix} \begin{pmatrix} \epsilon^{\mathrm{C}}_{\mathbf{k}} - \mu_\sigma & \Omega_{\mathrm{R}}/2 \\ \Omega_{\mathrm{R}}/2 & \epsilon^{\mathrm{X}}_{\mathbf{k}} - \mu_\sigma \end{pmatrix} \begin{pmatrix} \hat{c}_{\mathbf{k}\sigma} \\ \hat{x}_{\mathbf{k}\sigma} \end{pmatrix}$$

$$\hat{V} = \sum_{\mathbf{k}\mathbf{k}'\mathbf{q},\sigma} \frac{v}{2} \hat{x}^\dagger_{\mathbf{k}+\mathbf{q}\sigma} \hat{x}^\dagger_{\mathbf{k}'-\mathbf{q}\sigma} \hat{x}_{\mathbf{k}'\sigma} \hat{x}_{\mathbf{k}\sigma} - \frac{|\Phi|^2}{v_{\uparrow\downarrow}} - \sum_{\mathbf{k}} \left(\Phi \hat{x}^\dagger_{\mathbf{k}\uparrow} \hat{x}^\dagger_{-\mathbf{k}\downarrow} + \Phi^* \hat{x}_{-\mathbf{k}\downarrow} \hat{x}_{\mathbf{k}\uparrow} \right)$$

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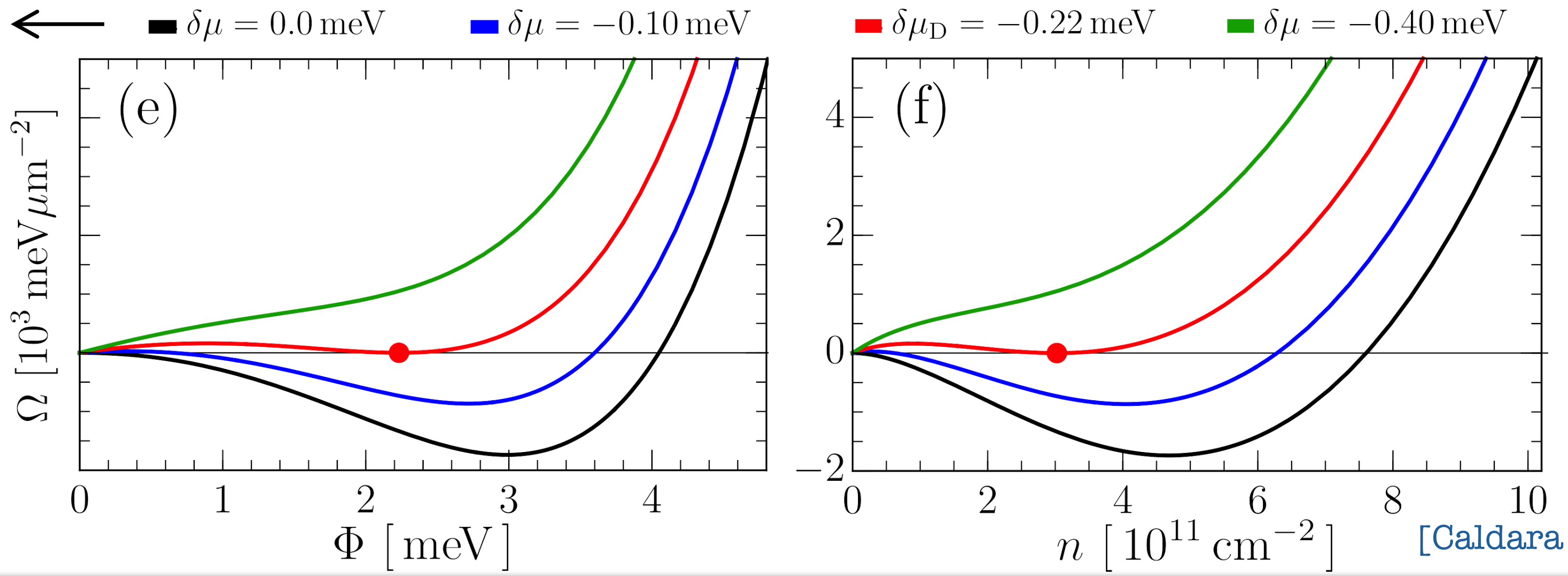
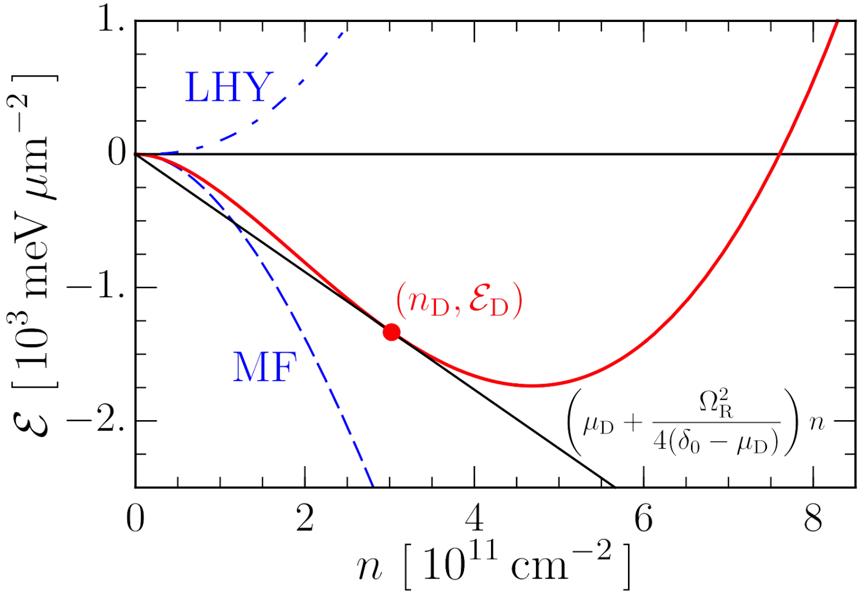
$$\Omega(n,\Phi,\mu) = \Omega_{MF}(n,\Phi,\mu) + \Omega_{LHY}(n,\Phi,\mu)$$

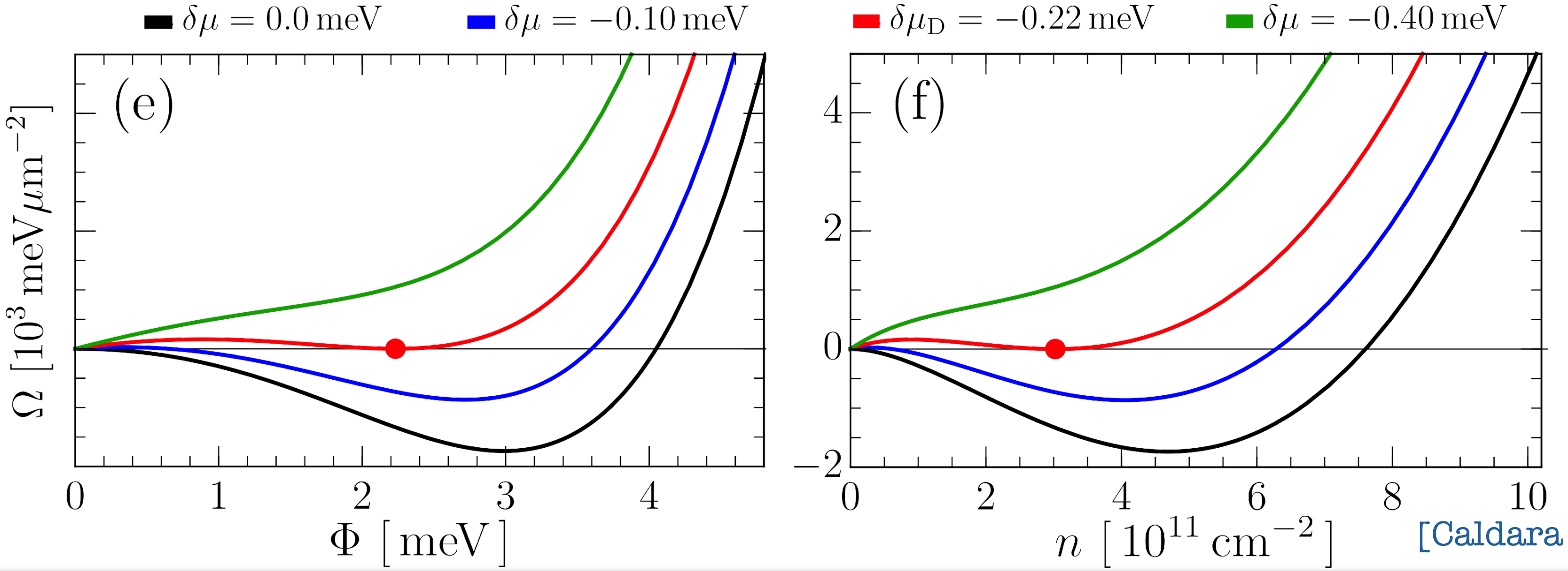
$\delta\mu = \mu - \omega_{LP}$ ⟵



[Caldara et al. (in preparation)]

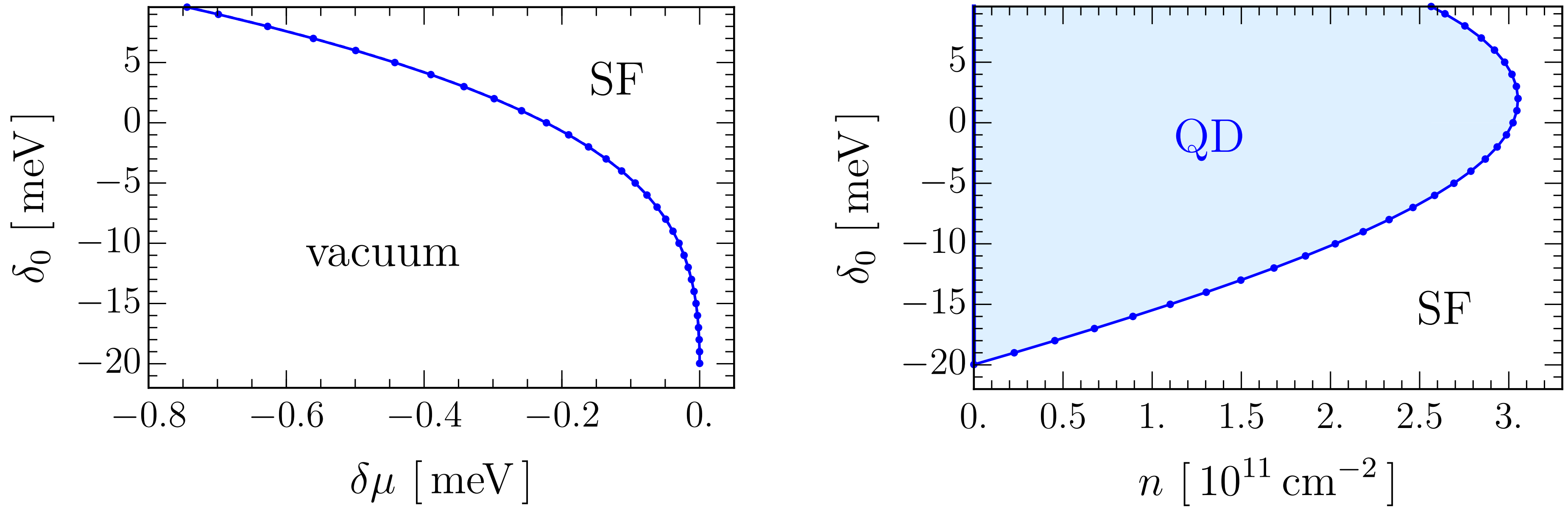
Quantum droplet: phase separation with vacuum



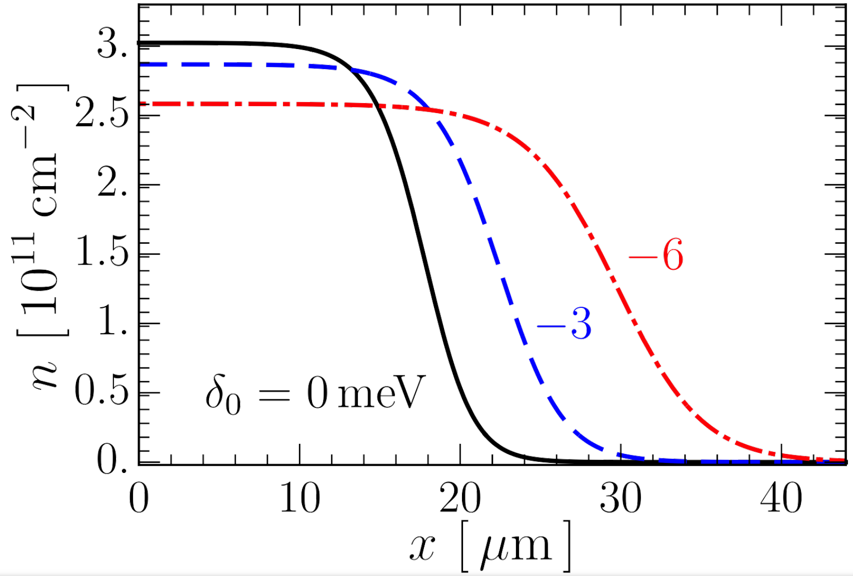


[Caldara et al. (in preparation)]

Quantum droplet: phase separation with vacuum



- GPE-like equation
  - droplet profile

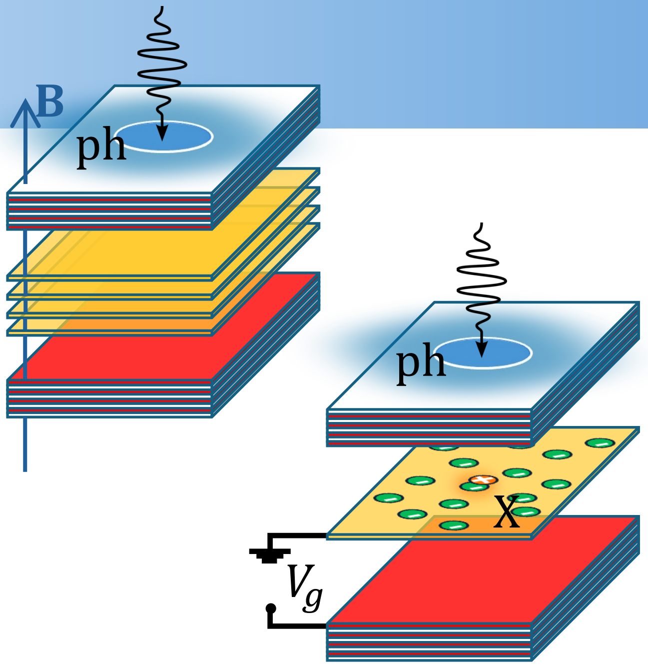


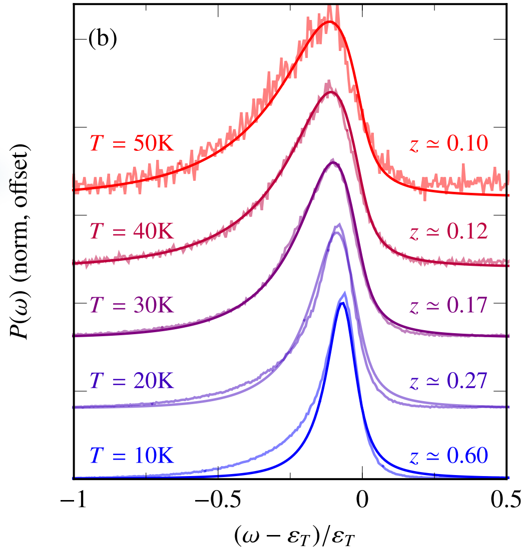
[Caldara et al. (in preparation)]

Take  messages

1. Microcavity polaritons & very strong light-matter coupling

2. Fermi polaron (polaritons) in gated TMD monolayers
    - finite temperature crossover from polaron to trion continuum





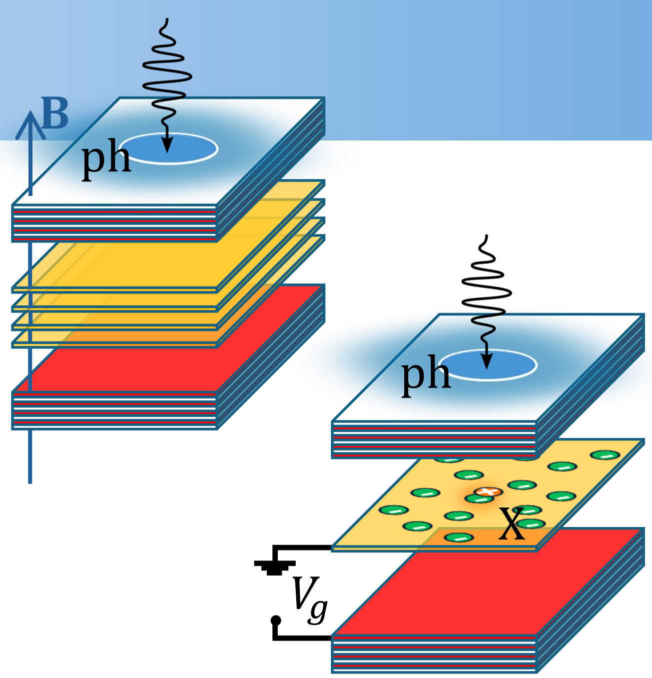
Take 🏠 messages

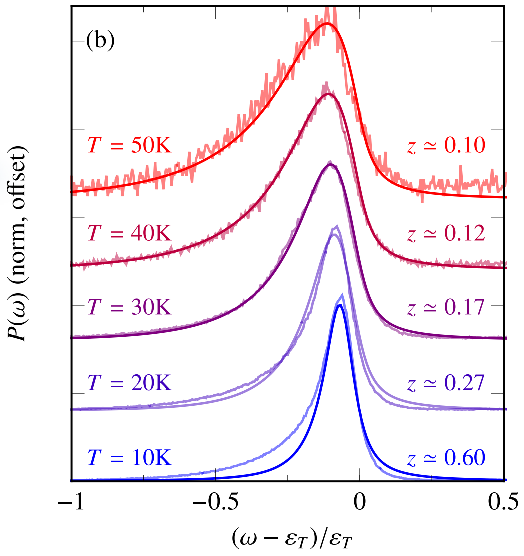
1. Microcavity polaritons & very strong light-matter coupling
2. Fermi polaron (polaritons) in gated TMD monolayers
    - finite temperature crossover from polaron to trion continuum
3. Biexciton Feshbach resonace

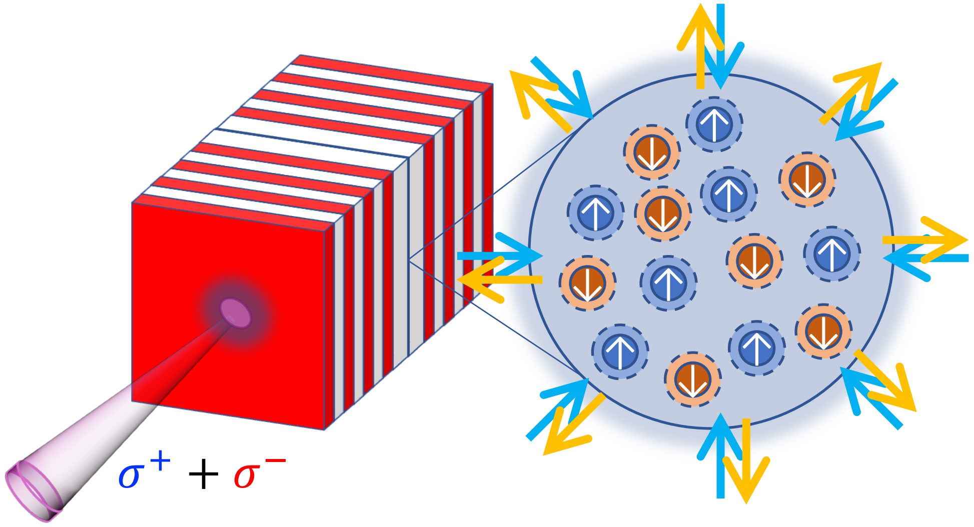
→ Bose polaron polaritons in pump-probe

→ Quantum droplets of light

towards quantum polaritonics







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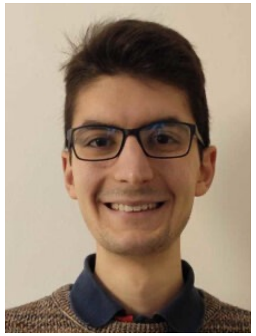

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