FLEET
ARC CENTRE OF EXCELLENCE IN
FUTURE LOW-ENERGY
ELECTRONICS TECHNOLOGIES

Quantum to classical behaviour of exciton polarons

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J. Levinsen, M. Parish

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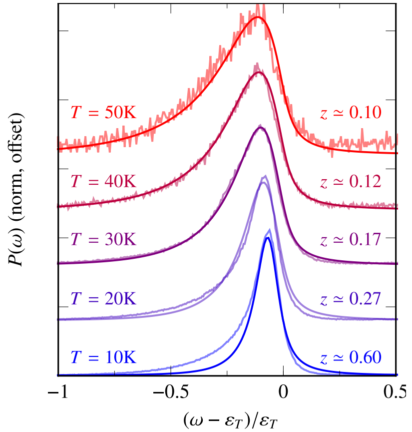
Introduction: Virial expansion for the optical response of doped two-dimensional semiconductors

- **Introduction**
  - Why ultracold atoms
  - Impurity problem - polaron
  - Exciton-polarons
- **Many-body theories**
  - Quantum virial expansion
  - Green's function
- **Conclusion and future goals**
  - Outlook

- Collaborators:
  - Francesa Marchetti
  - Antonio Tiene

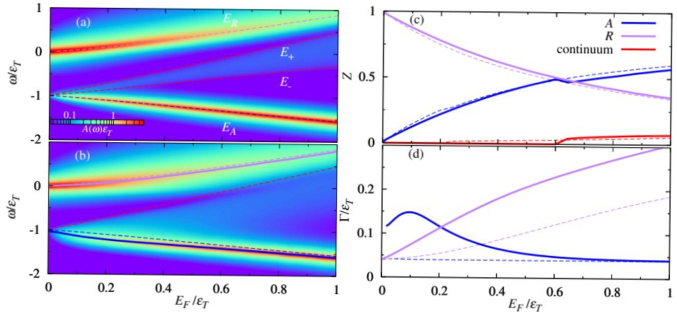
Sneak peak:

Photoluminesense



Sneak peak:

Temperature dependence



Why ultracold atoms: theorist playground

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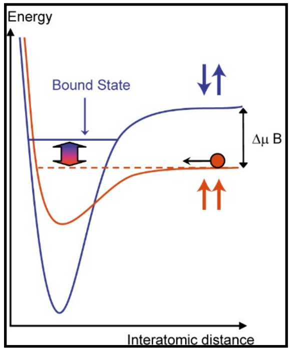
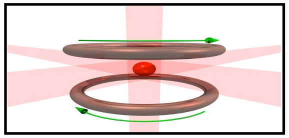
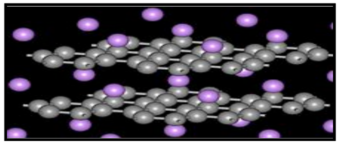
- **Interactions are controllable**
  - Feshbach resonances tune short-range interactions
- **Controllable parameters:**
  - Dimensionality
  - Statistics – Bose or Fermi
  - Population imbalance



- **Measure dynamics**
  - Stable for long times



vs



microseconds

attoseconds

- **Theory test-bed**
  - Compare theory to experiment

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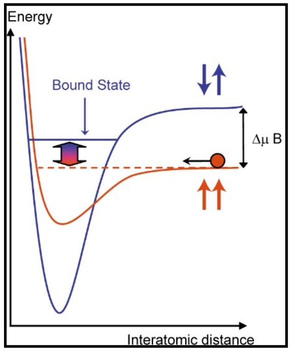

Notoriously difficult to solve.
Try a single impurity

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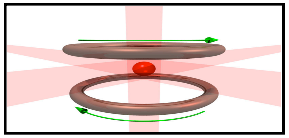

microseconds

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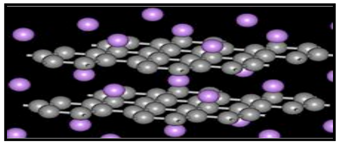

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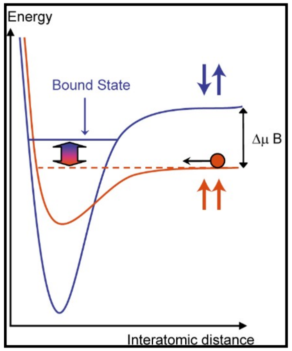

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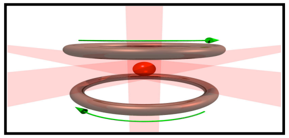

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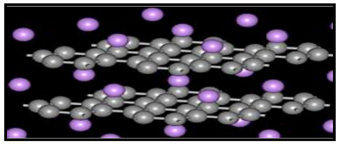

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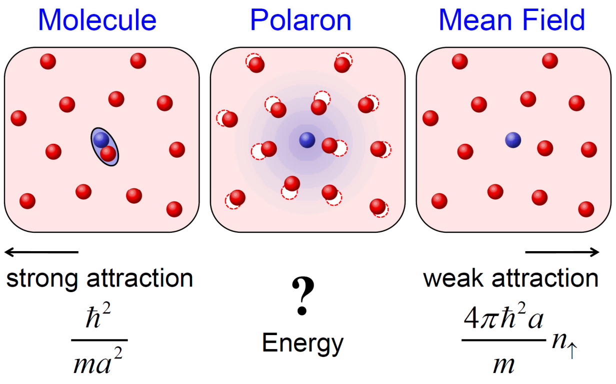
A. Schirotzek, et. al, PRL **102**, 230402 (2009)



Polarons – Ultracold

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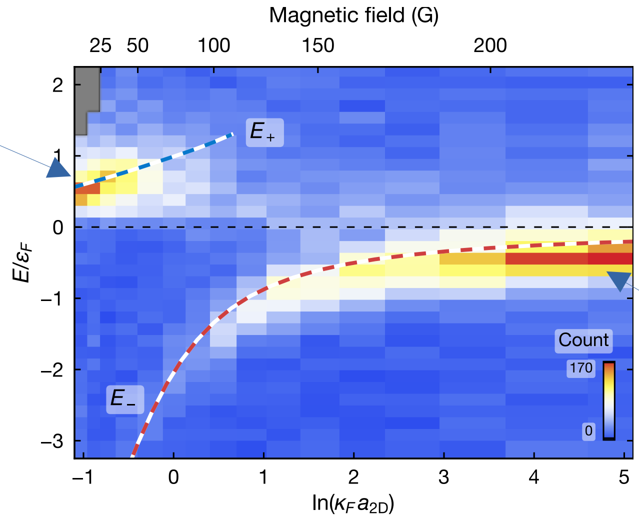
Polaron in ultracold gases: 2D experiment



Repulsive Branch

Attractive Branch

N. Oppong et al. Phys. Rev. Lett. 122, 193604 (2019)

See: Chevy, Bruun, Levinsen, Parish, Massignan, Hu, Liu, Combescot, Cui, Scazza, Demler, Grimm, Zwierlein, Sagi

Polarons – Ultracold + semiconductor

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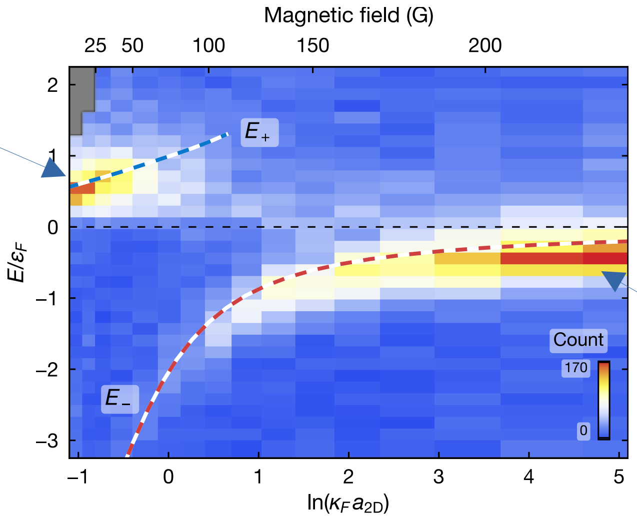

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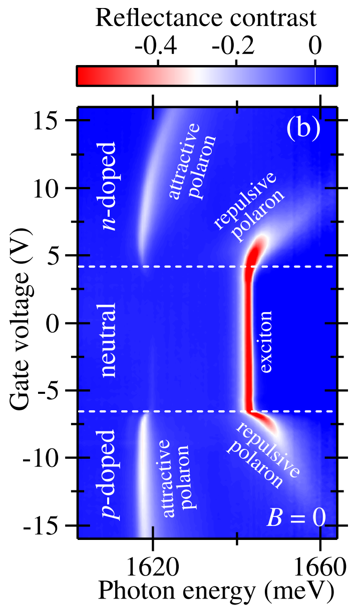
Exciton in doped 2D semiconductor:



T. Smoleński et al PRL **123**, 097403

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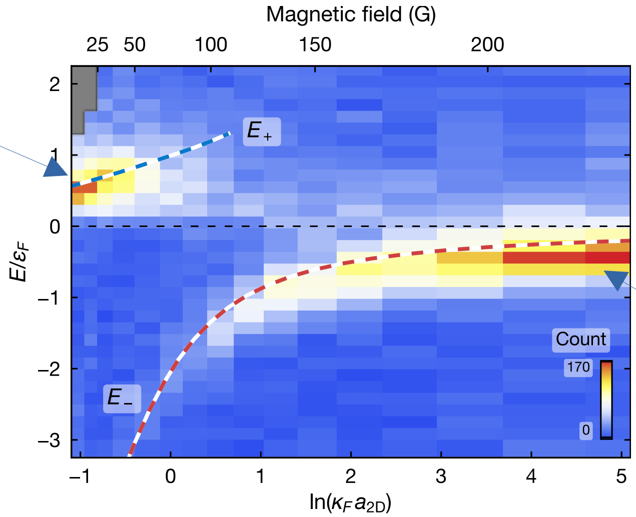

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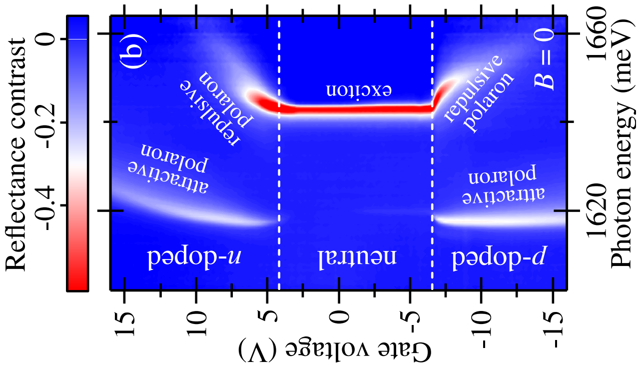

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Few-body perspective: Trion picture

Many-body perspective: polaron picture

Theory tool: Quantum virial expansion

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- What is the virial expansion?

  An expansion in the fugacity: $z = e^{\beta\mu}$

$$\Omega = -k_{\mathrm{B}} T \mathcal{Q}_1 \left[z + b_2 z^2 \cdots + b_n z^n + \cdots \right],$$

where $\mathcal{Q}_n = \mathrm{Tr}_n[\exp(-\mathcal{H}/k_{\mathrm{B}}T)]$

See: Ho, Mueller PRL **92** (2004); Ho, Zhou Nature **6** (2010); Nascimbene et al., Nature, **463**, (2010); Liu, Hu, Drummond PRL **102** (2010); Ngampruetikorn, Levinsen, Parish PRL **111** (2013); Leyronas PRA **84** (2011); Sun, Zhang, Zhai PRL **125** (2020)

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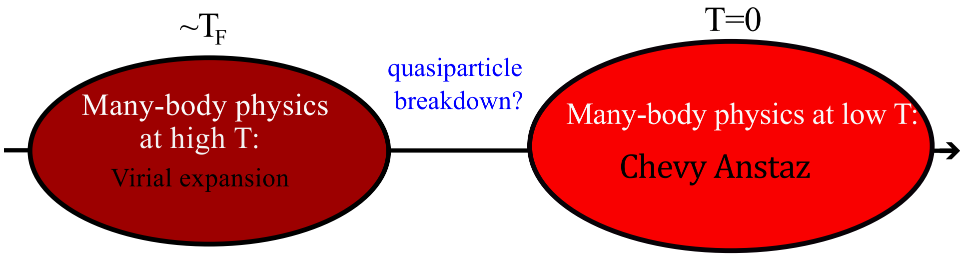
Apply the virial expansion to the impurity problem?



$\sim T_F$

T=0

Many-body physics at high T:

Virial expansion

quasiparticle breakdown?

Many-body physics at low T:

Chevy Anstaz

X-J Liu, Phys. Rep. **524**, (2013)

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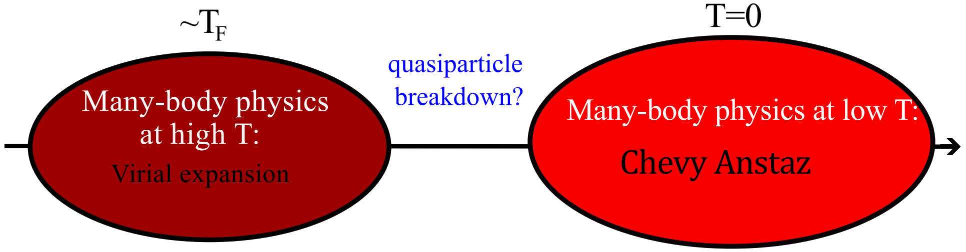

Many-body physics at high T:

Virial expansion

Many-body physics at low T:

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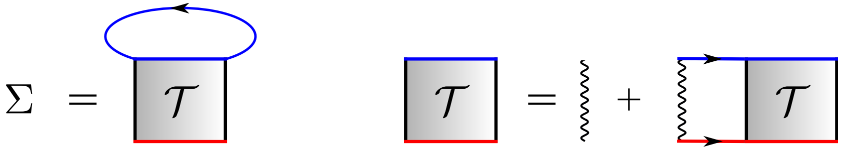
The self-energy and Green's function applied to the virial impurity:

$$G_X(\omega) = \frac{1}{\omega - \Sigma(\omega)} \qquad A(\omega) = -\frac{1}{\pi} G_X(\omega + i0)$$

$$\Sigma(\omega) \simeq \frac{z}{\mathcal{A}} \sum_{\mathbf{q}} e^{-\beta\epsilon_{\mathbf{q}}} \mathcal{T}_0(\mathbf{q}, \omega + \epsilon_{\mathbf{q}}) \qquad \mathcal{T}_0(\mathbf{q}, \omega) = \frac{2\pi}{m_r} \frac{1}{\ln[-\varepsilon_T/(\omega - \epsilon_{T\mathbf{q}})]}$$



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Quantum virial expansion - exciton-polaron

Virial expansion: valid at low doping or high temperature

Mulkerin, Tiene, Marchetti, Levinsen, Parish @ arxiv

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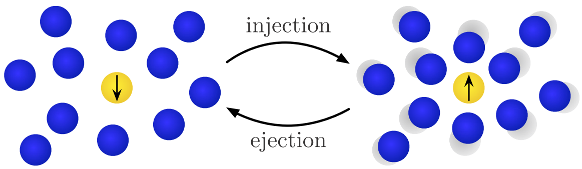
Photoluminesence:

$$A(\omega) = -\frac{1}{\pi} G_X(\omega + i0) \qquad P(\omega) = e^{-\beta\omega} A(\omega)$$

$$P(\omega) \simeq -\frac{1}{\pi} e^{-\beta\omega} \mathrm{Im} \frac{\Theta(-\omega - \varepsilon_T)}{\omega - \Sigma_{\mathrm{att}}(\omega)} - \frac{1}{\pi} \mathrm{Im} \frac{1}{\omega - \Sigma_{\mathrm{rep}}(0)}$$

Injection and ejection rf spectroscopy:



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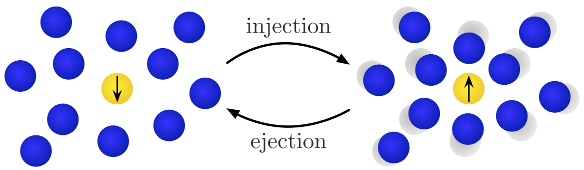
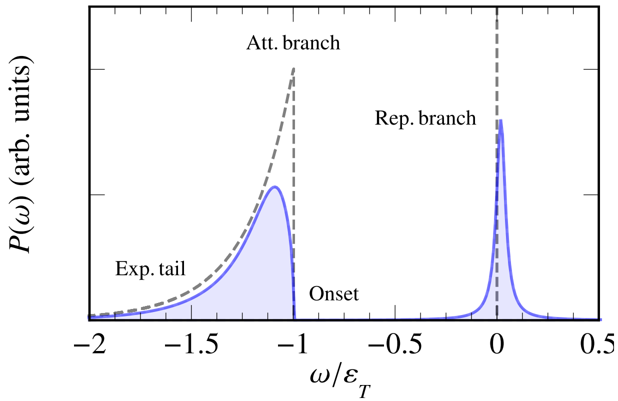


Liu, JL & Parish, PRL (2019)

Analytical form – straight forward to implement:

$$\Sigma_{\mathrm{rep}}(0) \simeq \frac{z(m/m_r)T}{\pi^2 + \ln^2(e^{\gamma_{\mathrm{E}}} \beta\varepsilon_T)} \left[\ln(e^{\gamma_{\mathrm{E}}} \beta\varepsilon_T) - i\pi\right]$$

$$\Sigma_{\mathrm{att}}(\omega) \simeq -z\varepsilon_T \left(\frac{m_T}{m_X}\right)^2 e^{\frac{m_T}{m_X}\beta(\omega+\varepsilon_T)} \left[\mathrm{Ei}\left[-\frac{m_T}{m_X}\beta(\omega + \varepsilon_T)\right] + i\pi\Theta(-\omega - \varepsilon_T)\right]$$



Breakdown of the quasi particle description for Att. Branch – peak and tail come from trion scattered states.

Mulkerin, Tiene, Marchetti, Levinsen, Parish @ arxiv

Application: photoluminesence

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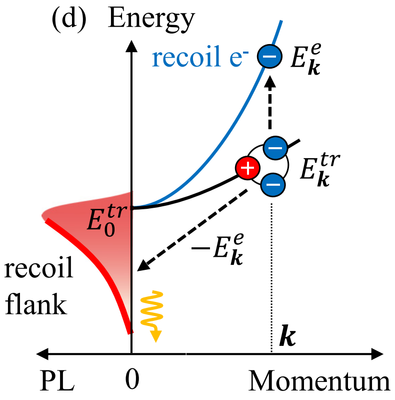
Application: photoluminesence

- Optical response of doped semiconductors -
  Electron recoil: see Zipfel et al. PRB **105**, 075311 (2022)



Few-body perspective: Trion picture

Many-body perspective: polaron picture

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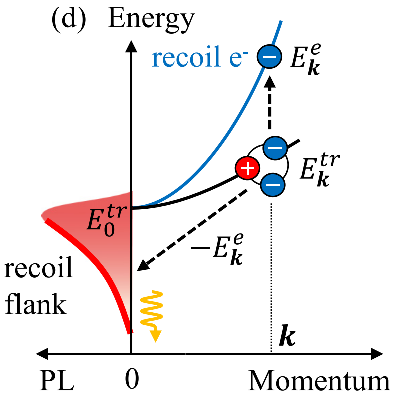

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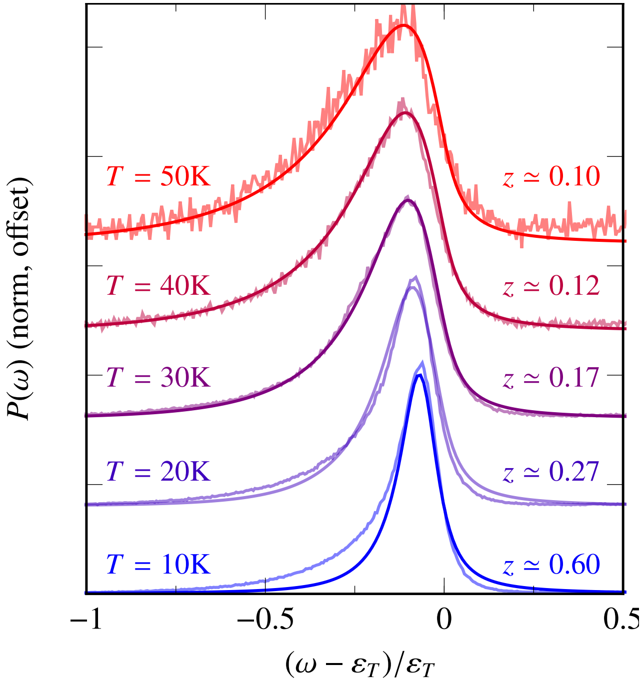
Exp. Curves: see Zipfel et al. PRB **105**, 075311 (2022)



Theory curves are broadened with: $\eta = 1\text{meV}$

Binding energy of experiment: 25meV

Binding energy of theory: 22.5meV

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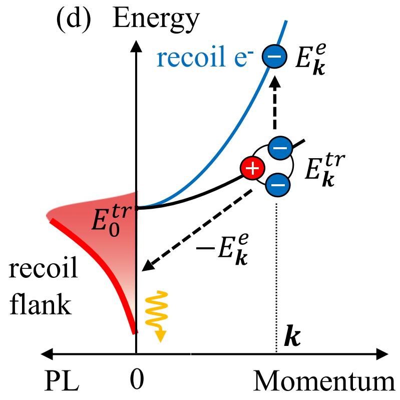
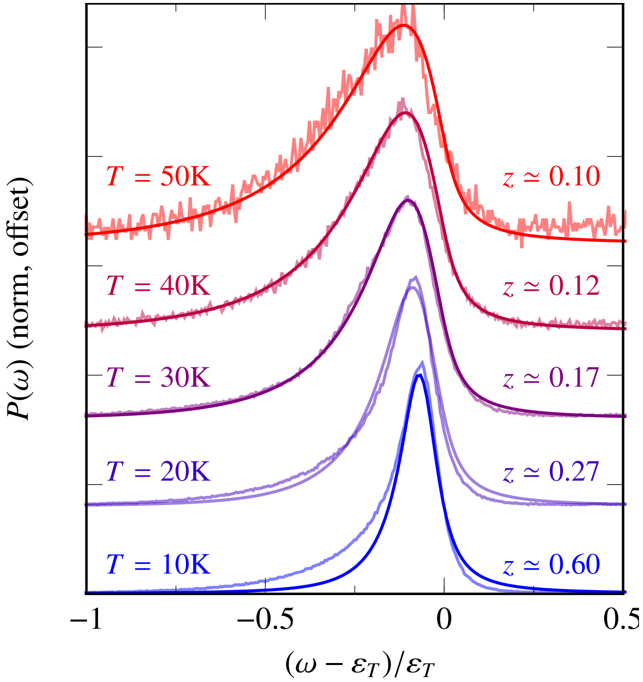


Few-body perspective: Trion picture

Many-body perspective: polaron picture

- With fitted binding energy we calculate the PL spectra
- For small fugacity there is excellent agreement
- For low temperatures there is some deviation.
- Exponential tail, onset, peak position.

Exp. Curves: see Zipfel et al. PRB **105**, 075311 (2022)



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Application: binding energy

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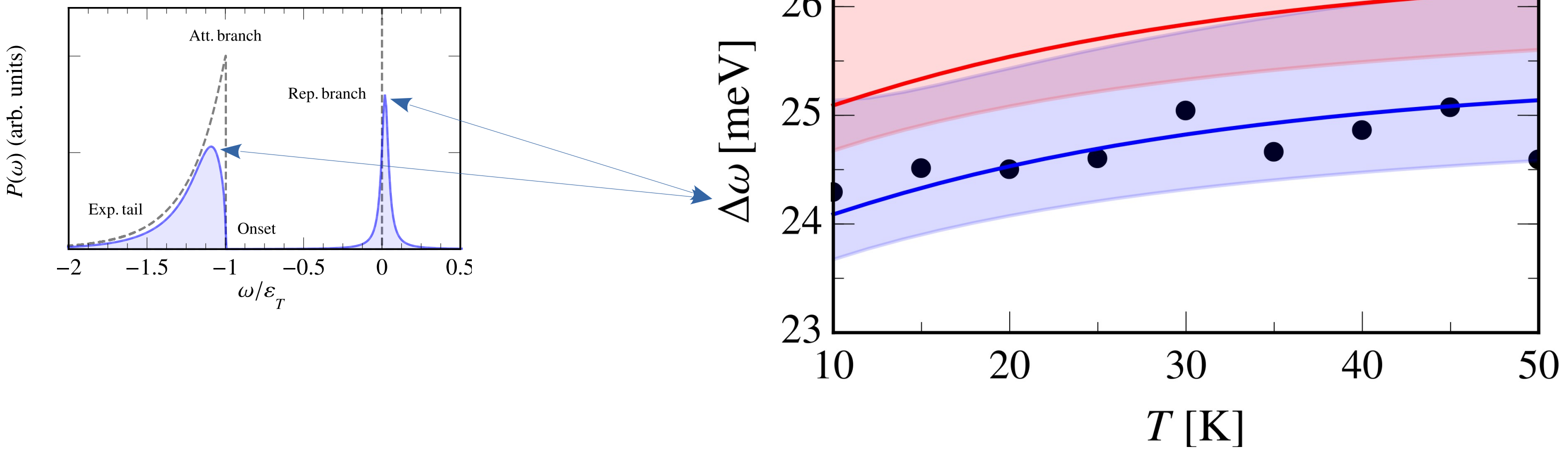

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- Calculate binding energy from peak position
  - Exp. Assumes the onset is the attractive peak position
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  - Measured binding energy is 10% larger than theory

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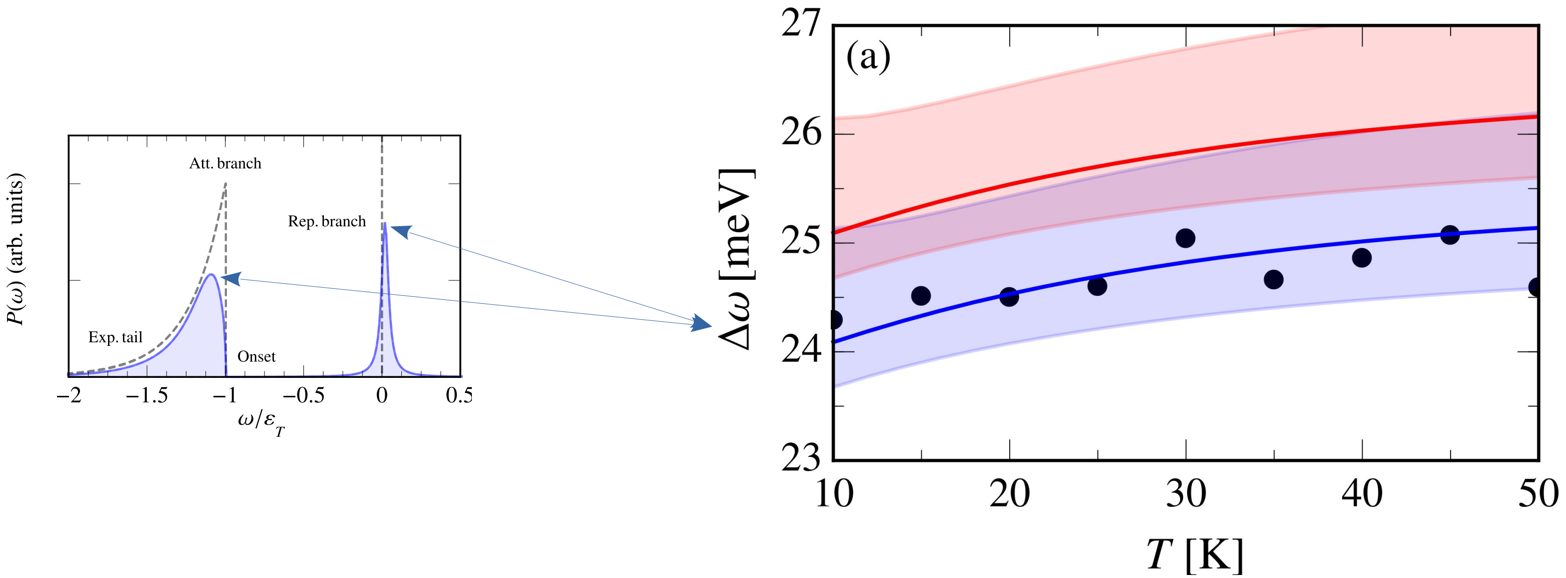
Application: binding energy



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- **Connection to trion picture:**

  Identical in the high temperature limit

  Can be seen as a low energy expansion of the Green's function:

$$\boxed{G_X(\omega) \simeq \frac{1}{\omega} + \frac{1}{\omega^2}\Sigma(\omega)}$$

Mulkerin, Tiene, Marchetti, Levinsen, Parish @ arxiv

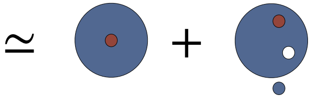
Theory: exciton polarons

Tiene, Mulkerin, Levinsen, Parish, Marchetti @ arxiv

Theory: exciton polarons

Low temperature or high doping we consider the finite temperature Chevy Ansatz:

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



See: F. Chevy, PRA (2006)
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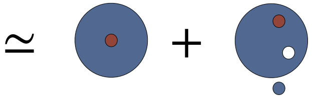

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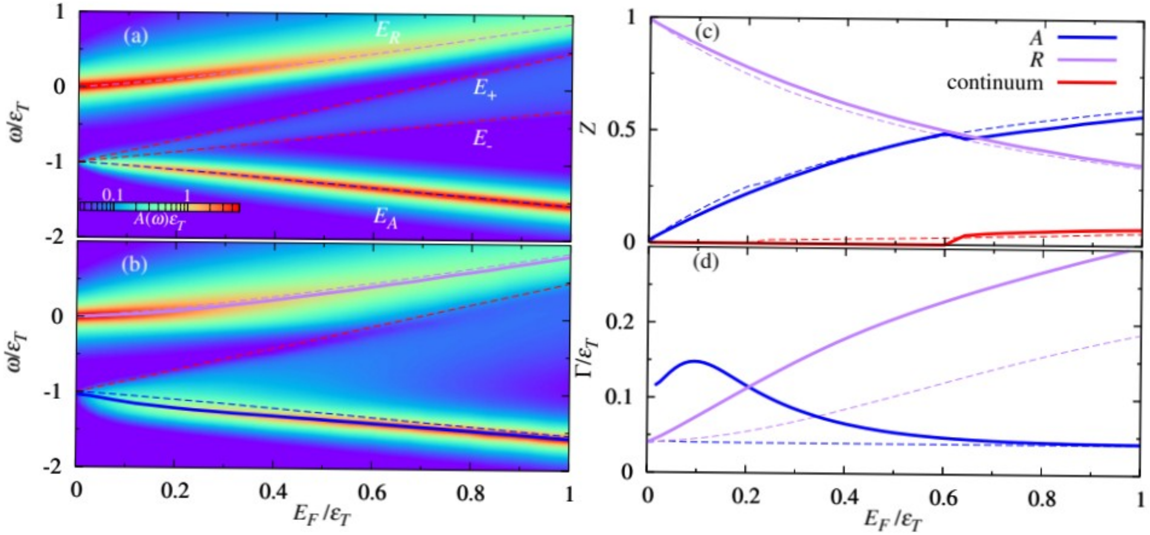
Many body Green's function:

$$G_X(\omega + i0) = \sum_n \frac{|\varphi_0^{(n)}|^2}{\omega - E^{(n)} + i0}$$

Optical absorption:

$$A(\omega) = -\frac{1}{\pi} G_X(\omega + i0)$$



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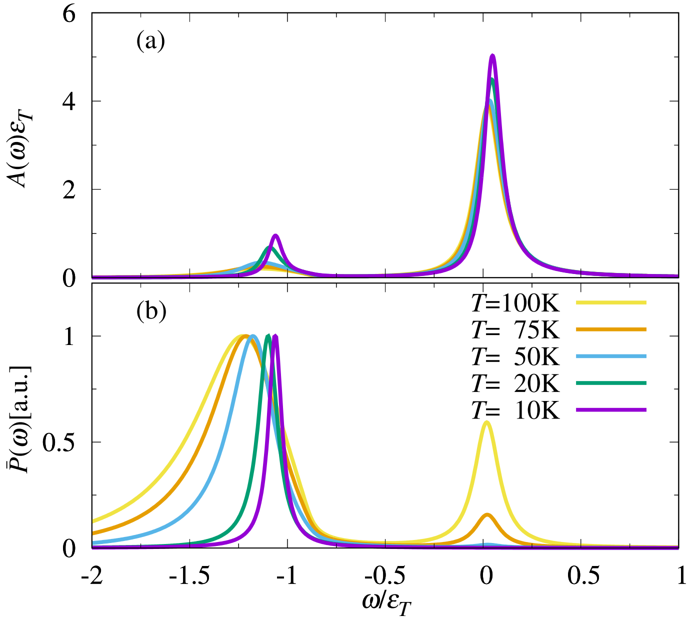
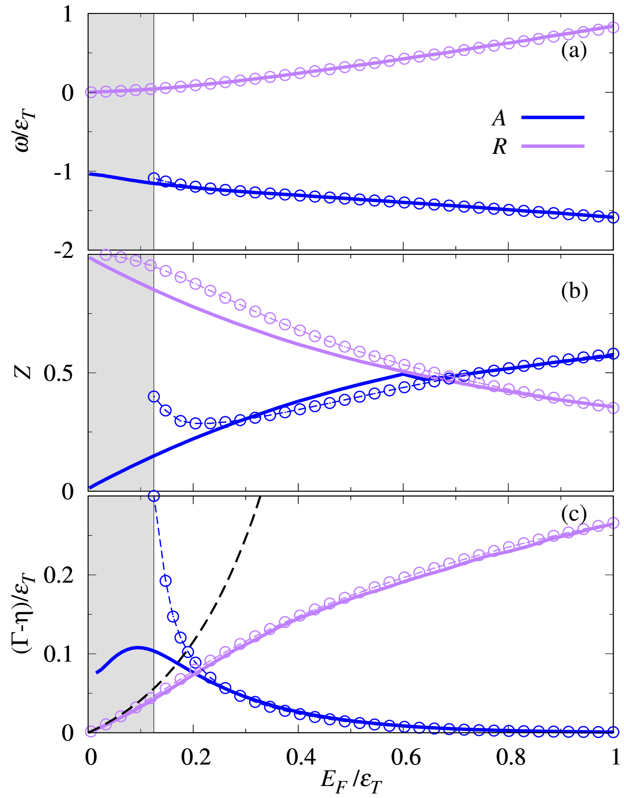
Theory: exciton polarons

Asymmetric emission:



Transition from exciton polaron to trion-hole continuum:



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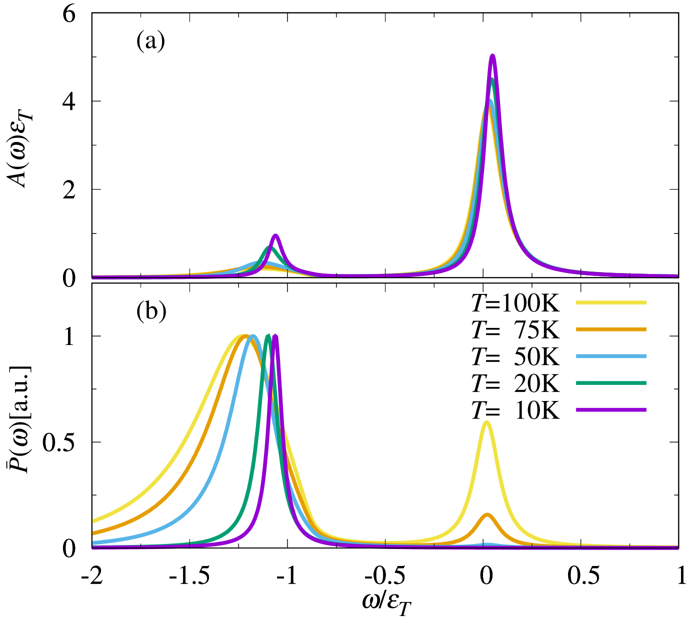

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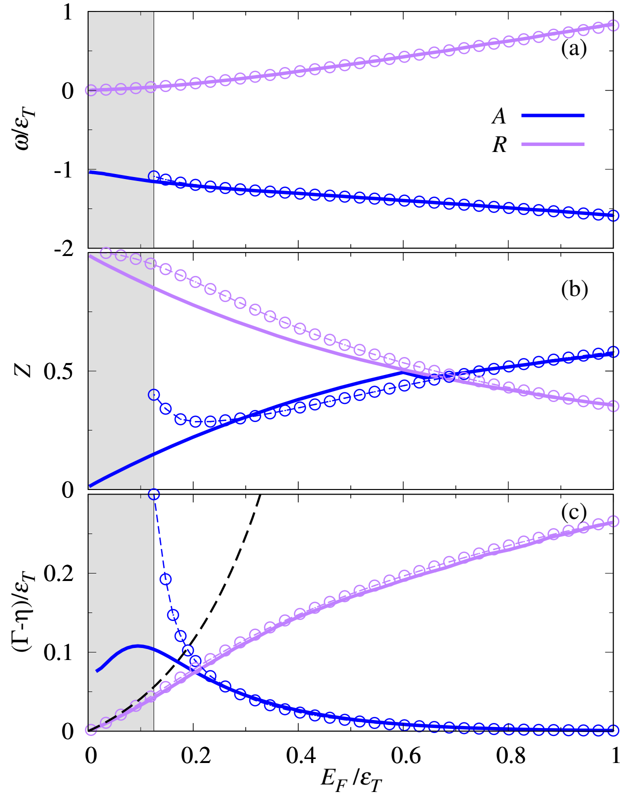

Virial and many-body approximation are equivalent at high temperature (or low doping):

Expand the many-body T-matrix: $\mathcal{T} \simeq \mathcal{T}_0$

How does this change coupling to light in polaron-polaritons

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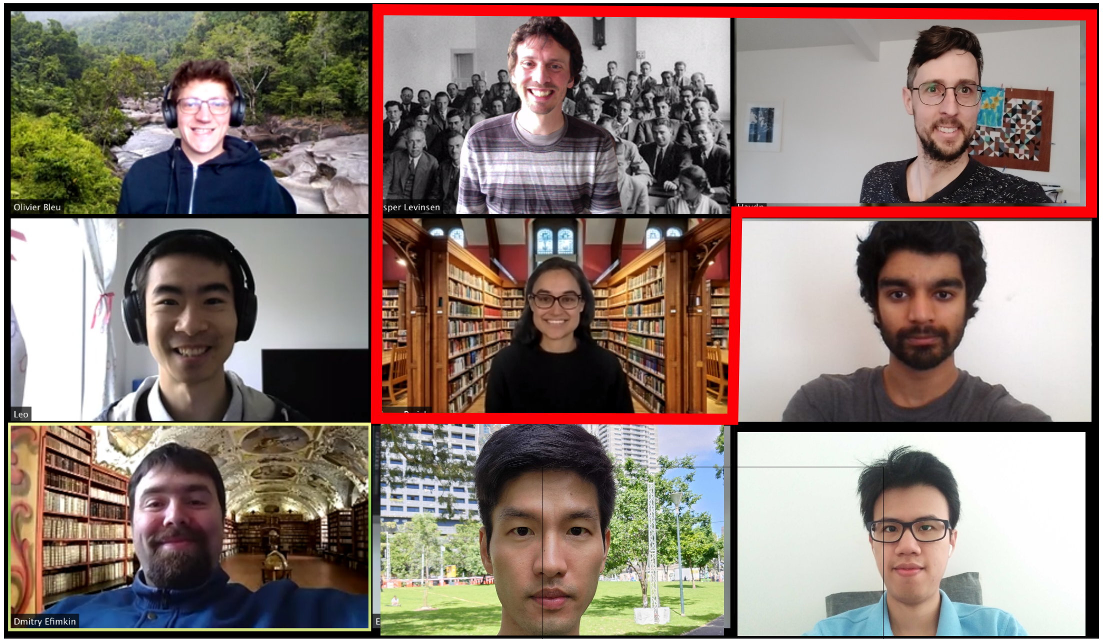
Conclusion and future goals of polaron systems



- **Virial expansion**
  - Straight forward to implement
  - Obtains excellent results
- **Finite temperature correlations**
  - We lose the attractive polaron
  - Matches virial for high T
- **Outlook**
  - Polaron-polaron interactions
  - Dynamics of impurities

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