SPICE Workshop

Dissipative Phases of Entangled Quantum Matter

May 3rd-5th 2021

Fermi polaron laser in two-dimensional semiconductors

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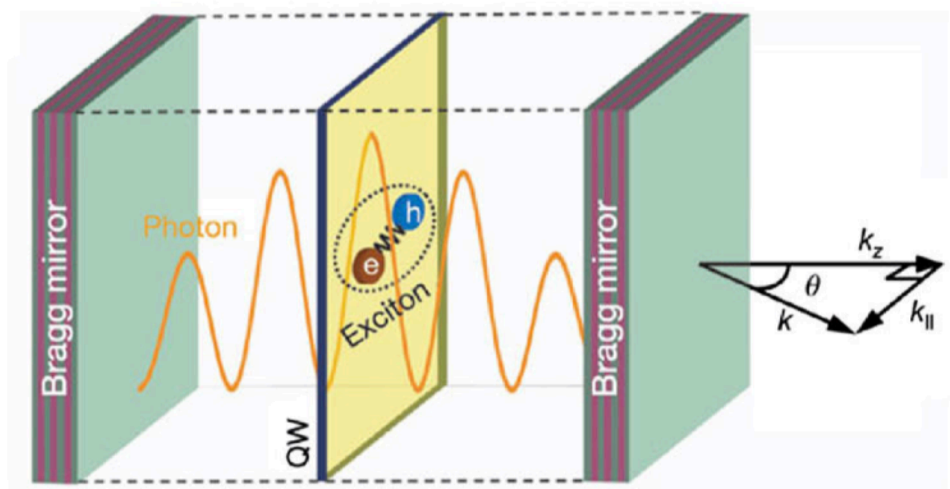
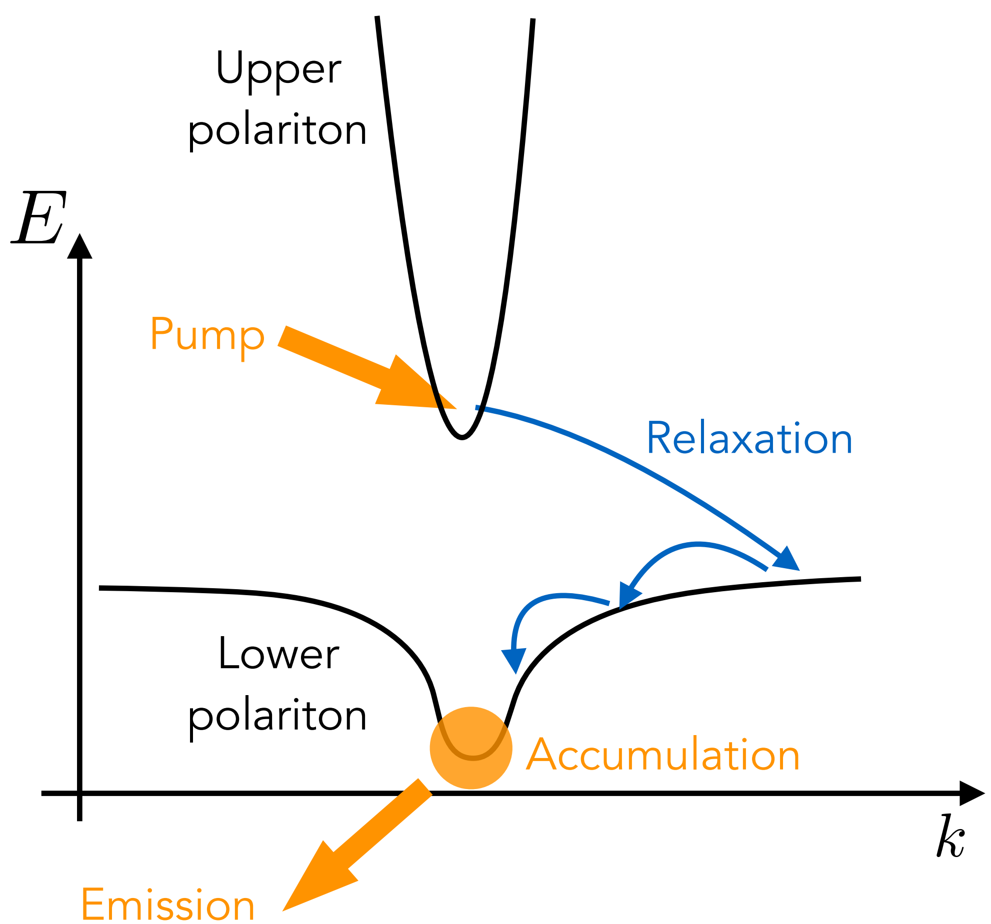
Non-equilibrium condensation of Exciton-Polaritons



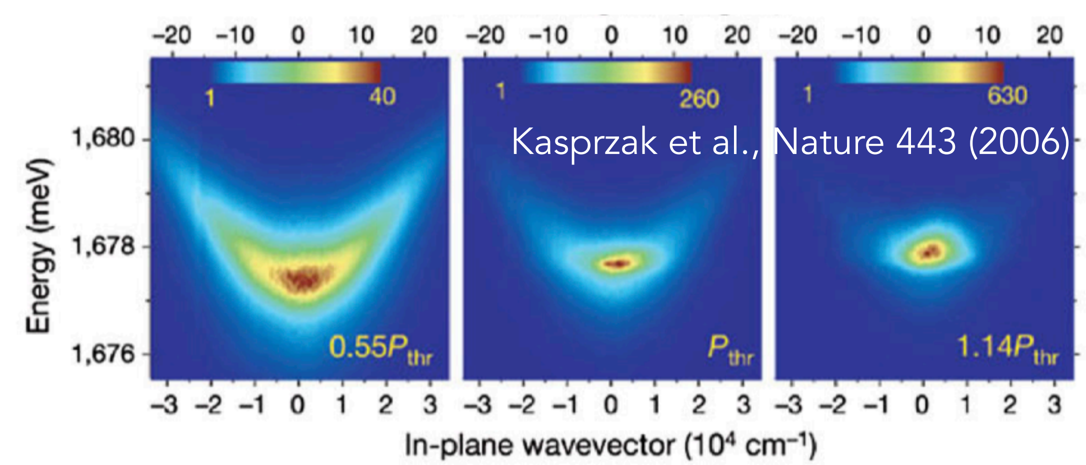
[Carusotto and Ciuti, RMP 85 (2013)]

Quantum well inside microcavity
Coherent exciton-photon conversion

Formation of exciton-polariton branches
Allows for inversion and stimulated processes



Relaxation driven by phonons and ex-ex interactions
Thermal (condensation) or non-thermal (lasing)



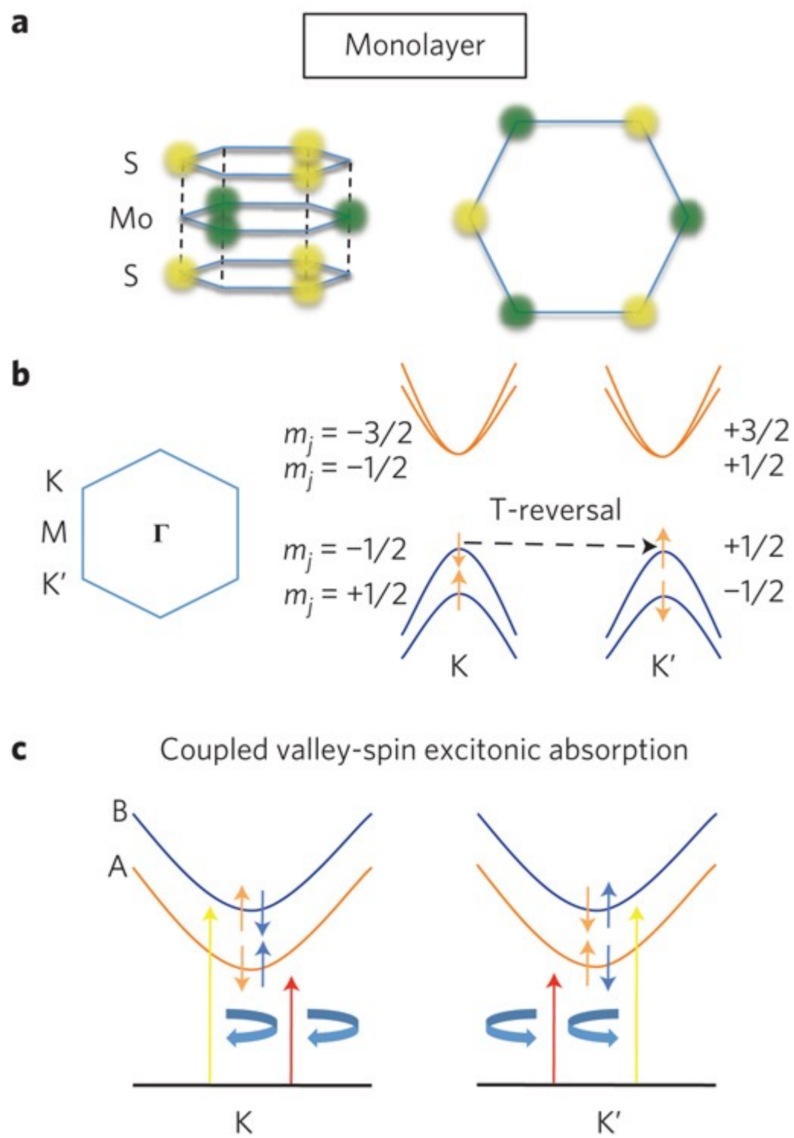
Kasprzak et al., Nature 443 (2006)

Paradigm for driven-dissipative phase transitions
Buchhold, Sieberer, Diehl, Rep. Prog. Phys. 79 (2016)

Excitons in monolayer semiconductors

Transition metal dichalcogenides (TMDs)

Very tightly bound excitons

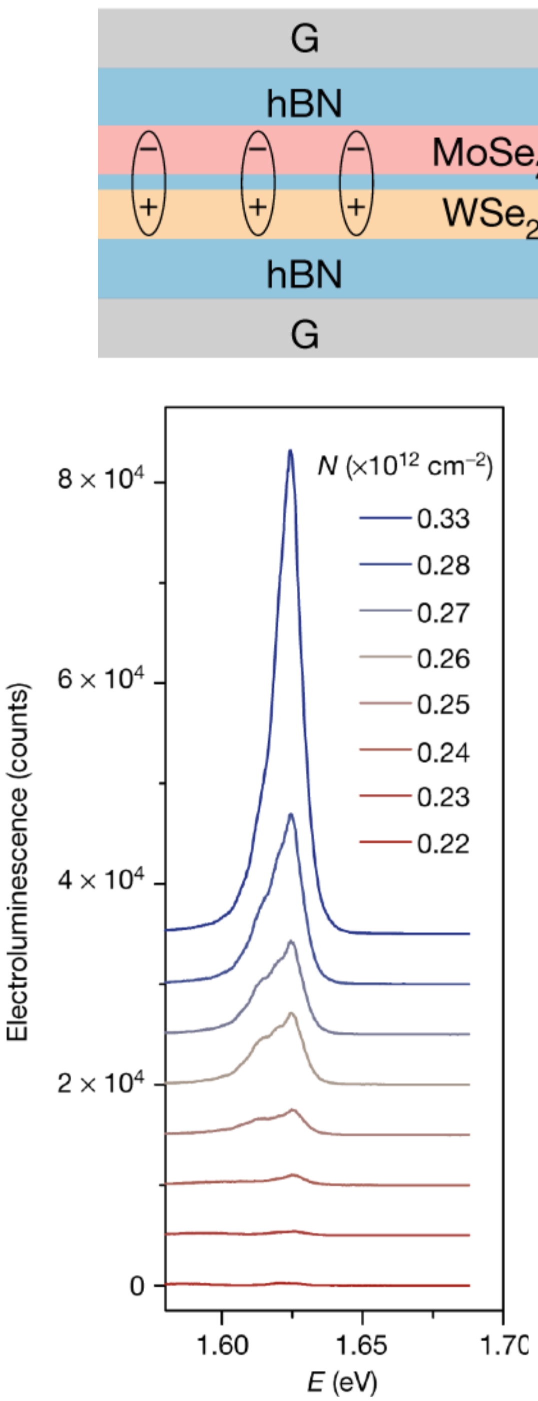


[Mak et al., Nat. Nano 7 (2012)]

Signatures of condensation

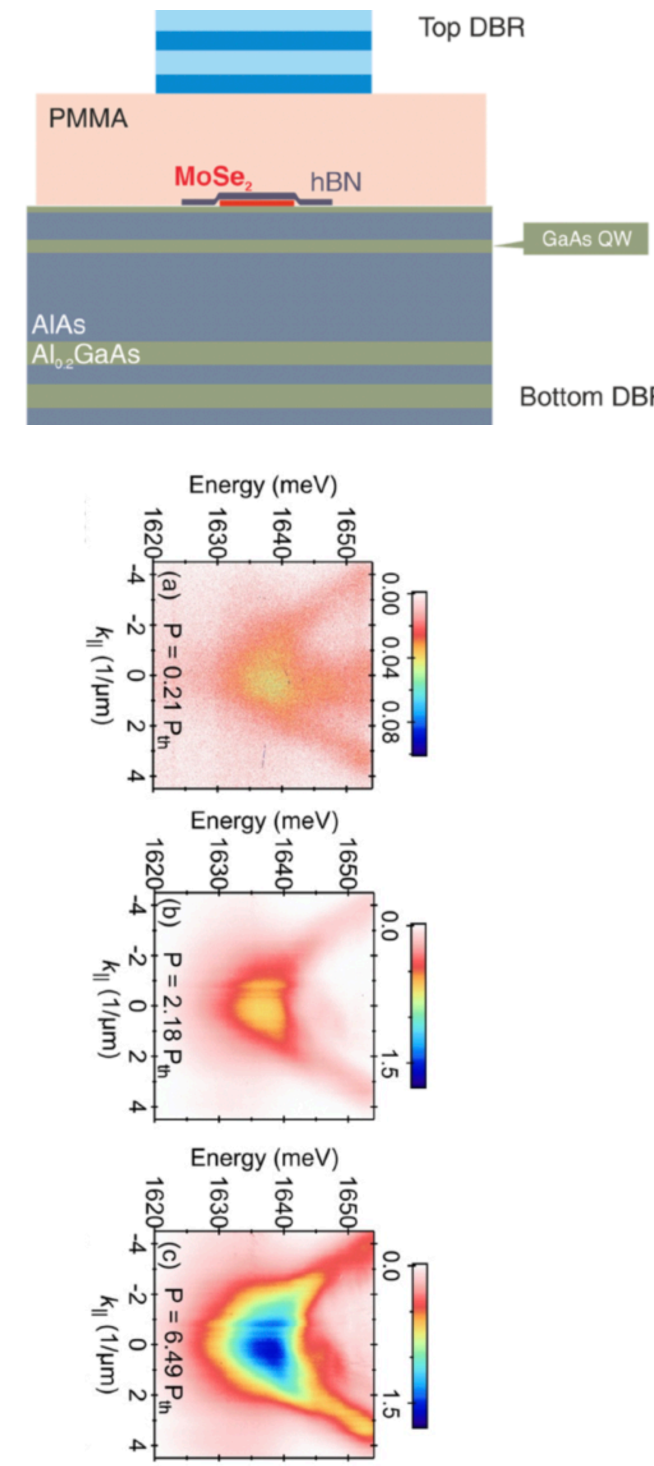
In a bilayer

[Wang et al., Nature 574 (2019)]

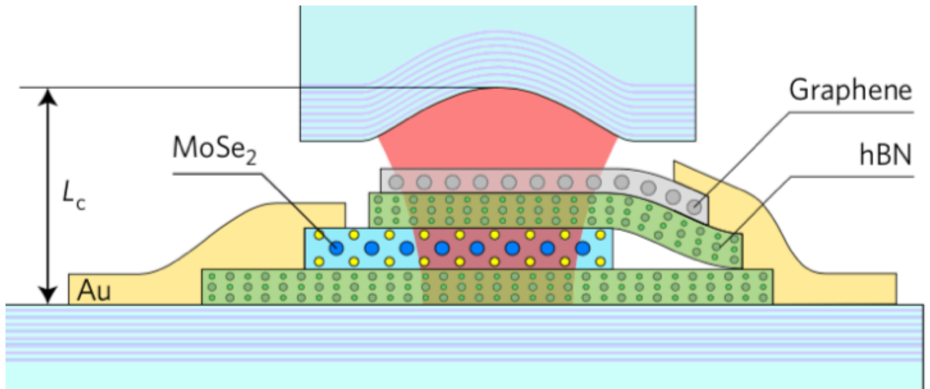


In a cavity

[A.-Solanas et al., arXiv:2009.11885]

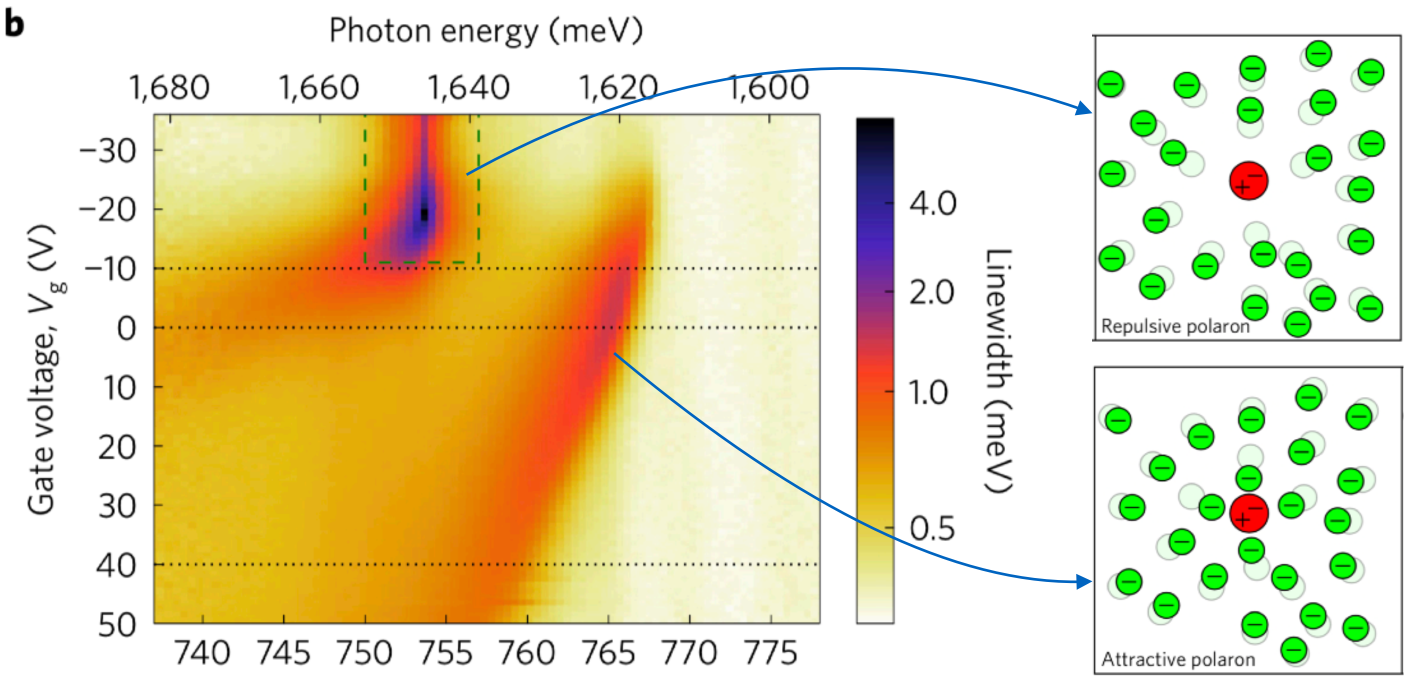


Electron doping in monolayer semiconductors



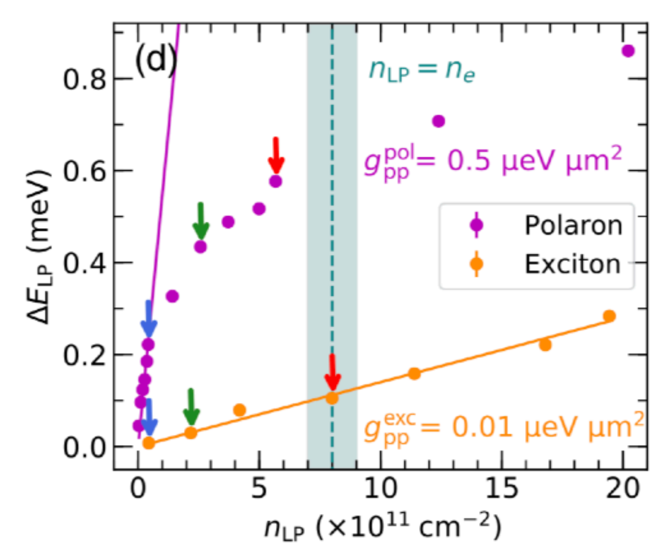
[Siedler et al., Nat. Phys. 13 (2016)]

Transition metal dichalcogenides (TMDs)
Very tightly bound excitons



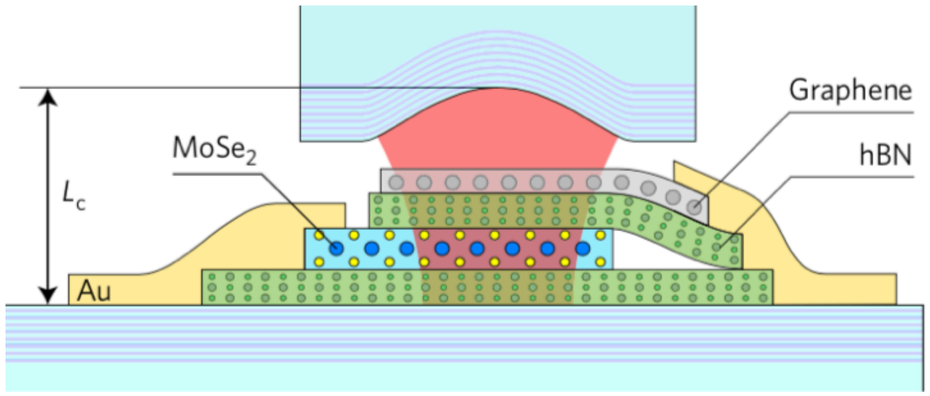
Exciton-polaron formation via electron doping
Investigate Fermi-polaron problem

[Tan et al., PRX 10 (2020)]



Electrons mediate strong exciton-exciton interactions
Large optical nonlinearities

Electron doping in monolayer semiconductors

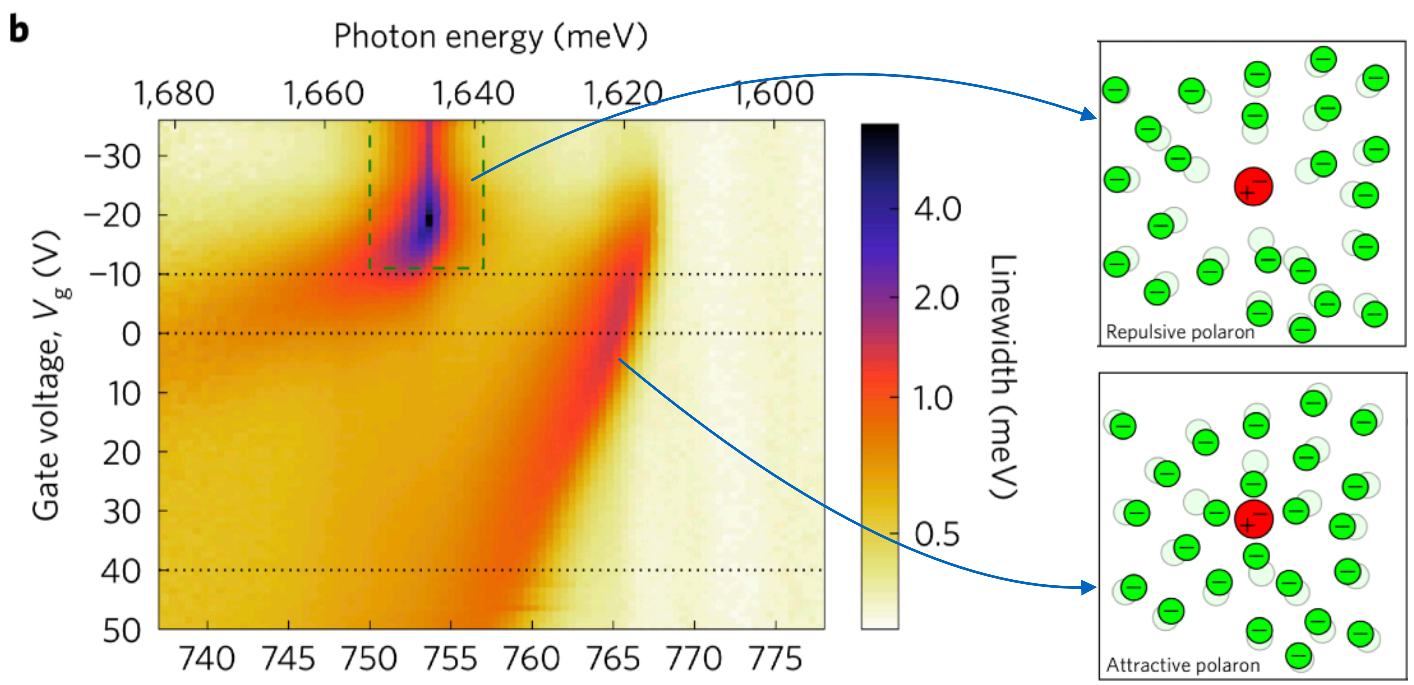


[Siedler et al., Nat. Phys. 13 (2016)]

Transition metal dichalcogenides

Very tightly bound excitons

b



Exciton-polaron formation via electron doping

Investigate Fermi-polaron problem

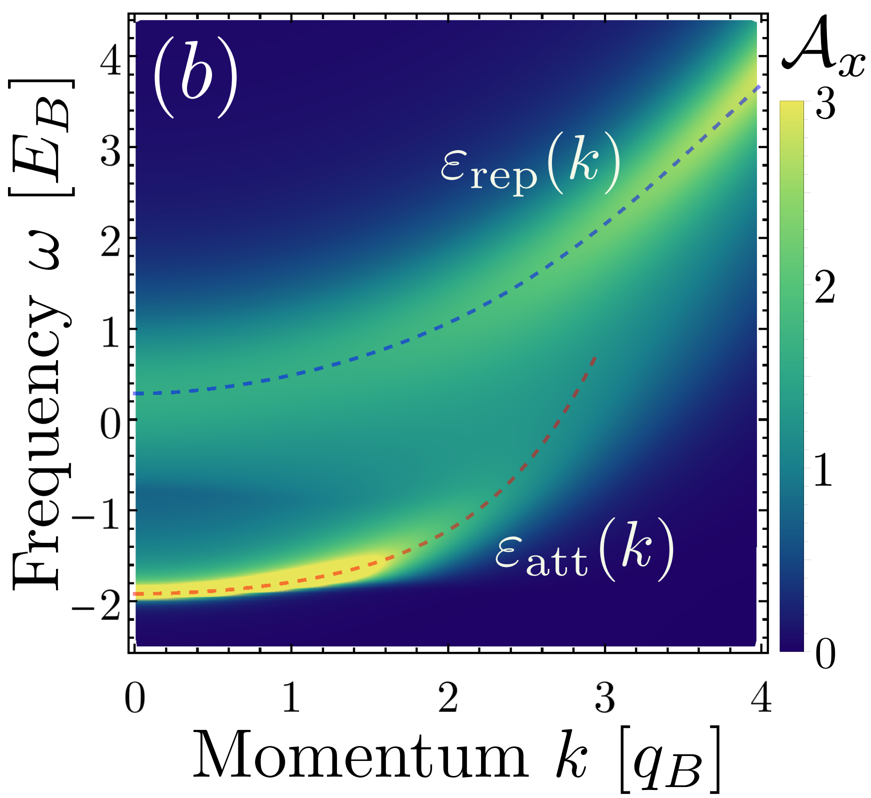
Electrons mediate strong exciton-exciton interactions

Large optical nonlinearities

Q: **Non-equilibrium condensation of exciton-polarons?**

- TMDs as light sources
- Condensation in nontrivial polaron bands
- Condensate-mediated e-e interactions
- …

Setup and approach



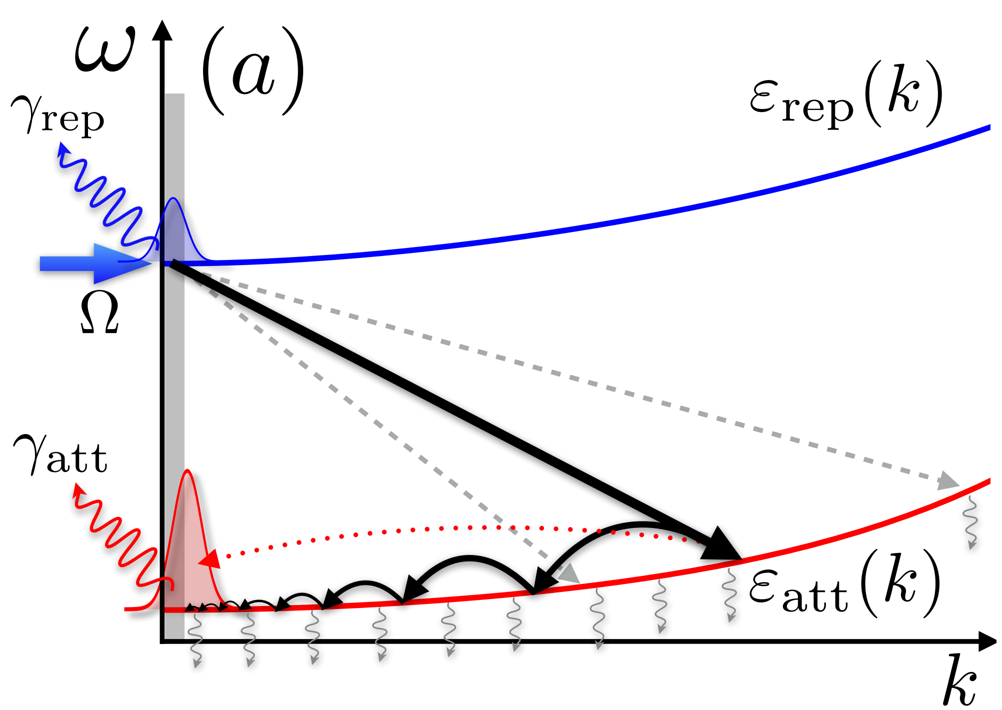
$$\hat{H} = \sum_{\mathbf{k}} \varepsilon_x(\mathbf{k}) \hat{x}^\dagger_{\mathbf{k}} \hat{x}_{\mathbf{k}} + \sum_{\mathbf{k}} \varepsilon_e(\mathbf{k}) \hat{e}^\dagger_{\mathbf{k}} \hat{e}_{\mathbf{k}} + U \int d^2 r\, \hat{x}^\dagger(\mathbf{r}) \hat{x}(\mathbf{r}) \hat{e}^\dagger(\mathbf{r}) \hat{e}(\mathbf{r})$$

Self-consistent T-matrix approach in 2D

Molecular continuum plus bound-state (trion)

Extend to non-equilibrium

(Keldysh contour)



Driven-dissipative Polaron Kinetic Equation

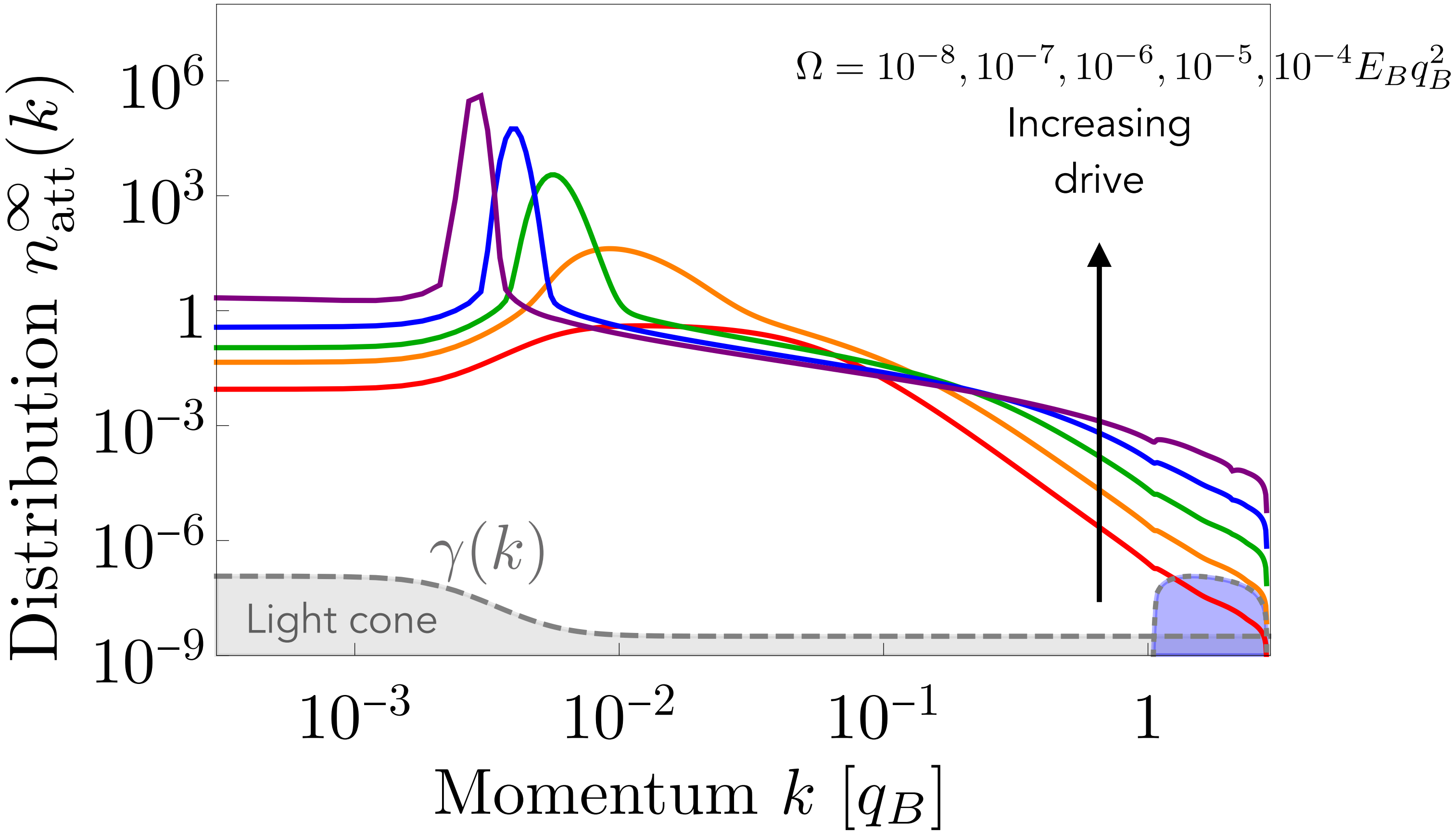
$$\partial_t n_\alpha(\mathbf{k},t) = -\gamma_\alpha(\mathbf{k}) n_\alpha(\mathbf{k},t) + \Omega_\alpha(\mathbf{k}) + \frac{1}{V}\sum_{\beta,\mathbf{q}} \Big[W^{\alpha\beta}_{\mathbf{kq}} [n_\alpha(\mathbf{k})+1] n_\beta(\mathbf{q}) - W^{\beta\alpha}_{\mathbf{qk}} [n_\beta(\mathbf{q})+1] n_\alpha(\mathbf{k}) \Big]$$

$$\alpha = \text{att, rep}$$

Scattering rates

$$W^{\alpha\beta}_{\mathbf{k},\mathbf{k}'} = \frac{2\pi}{V} \sum_{\mathbf{Q}} \big| T[\mathbf{Q}, \varepsilon_\beta(\mathbf{k}') + \varepsilon_e(\mathbf{Q}-\mathbf{k}')] \big|^2 Z_\alpha(\mathbf{k}) Z_\beta(\mathbf{k}') \times \delta\big[\varepsilon_\alpha(\mathbf{k}) + \varepsilon_e(\mathbf{Q}-\mathbf{k}) - \varepsilon_e(\mathbf{Q}-\mathbf{k}') - \varepsilon_\beta(\mathbf{k}')\big] \times n_e(\mathbf{Q}-\mathbf{k}')[1 - n_e(\mathbf{Q}-\mathbf{k})]$$

Steady state momentum distribution

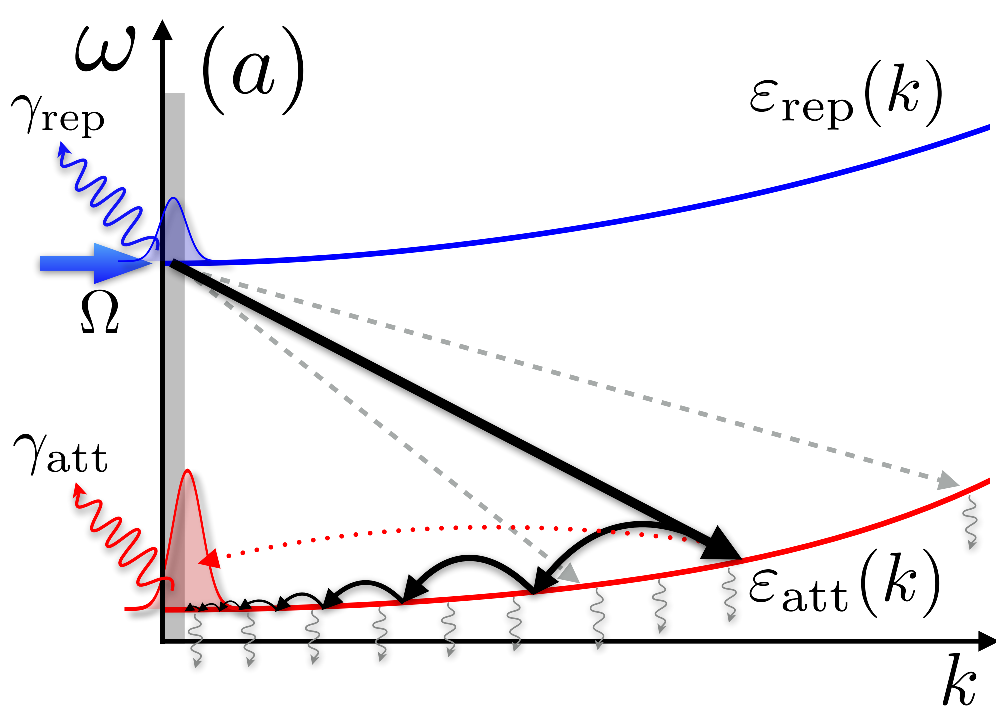


Accumulation at the edge of the light cone

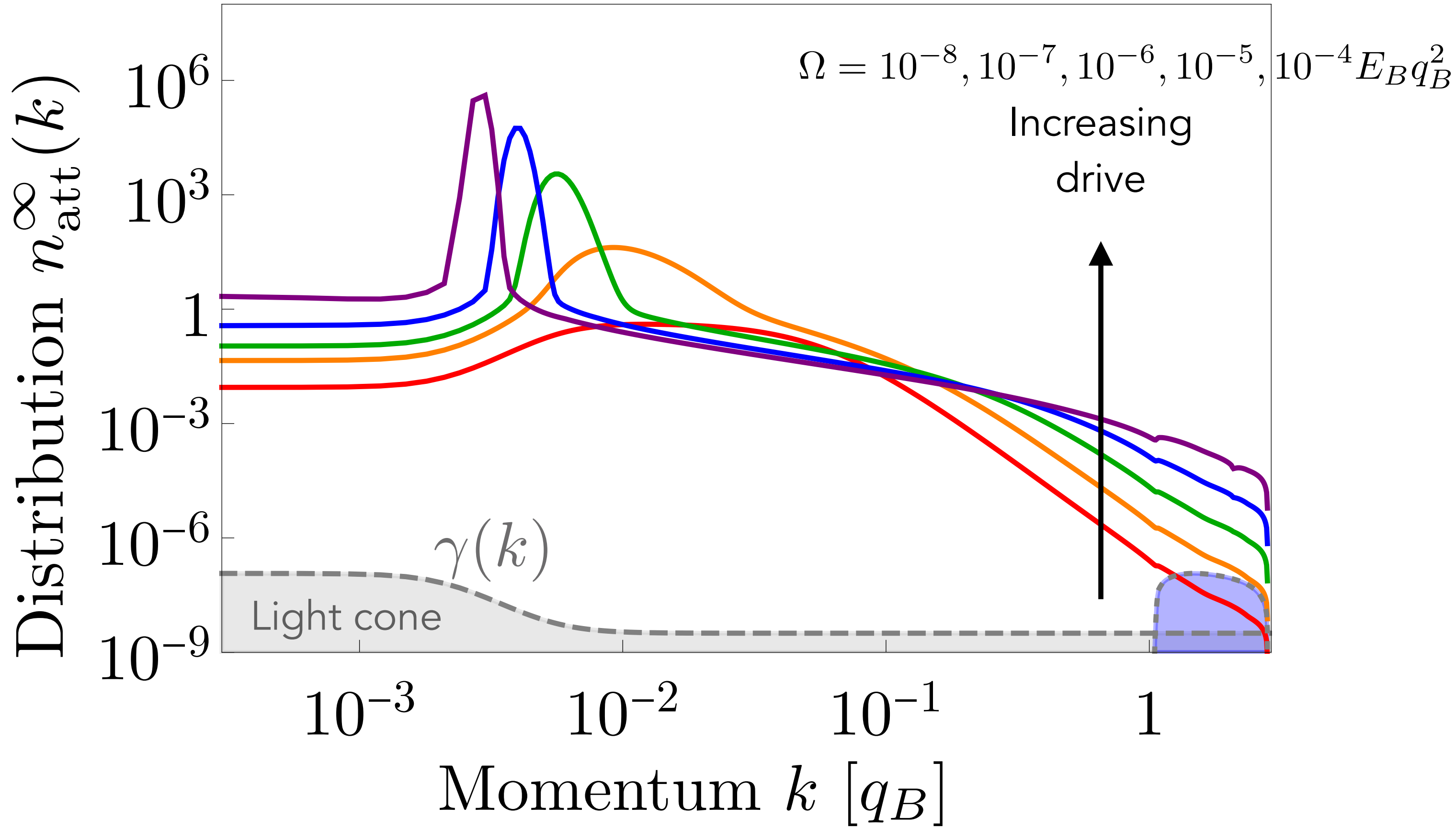
Stimulated processes at sufficient drive

Non-thermal power-law tails

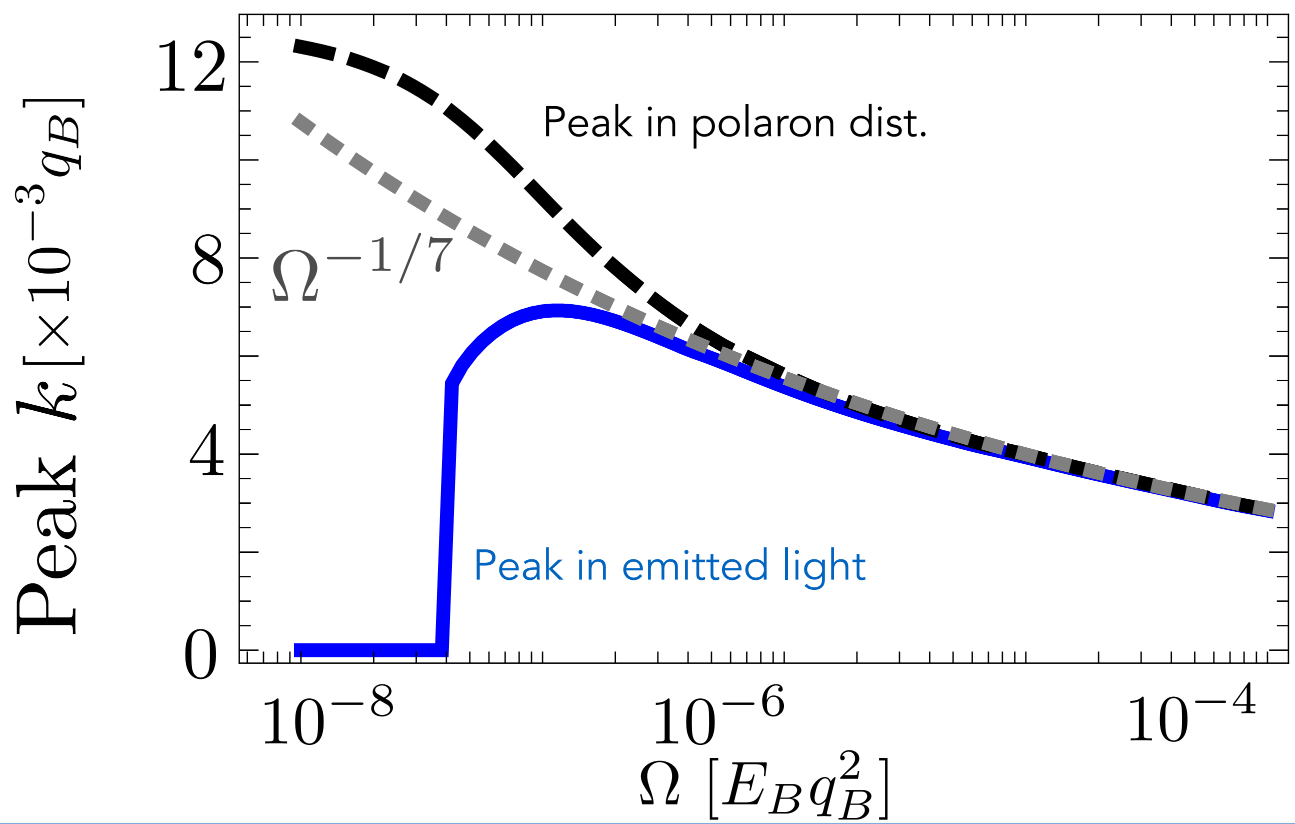
Peculiar cascade



Steady state momentum distribution



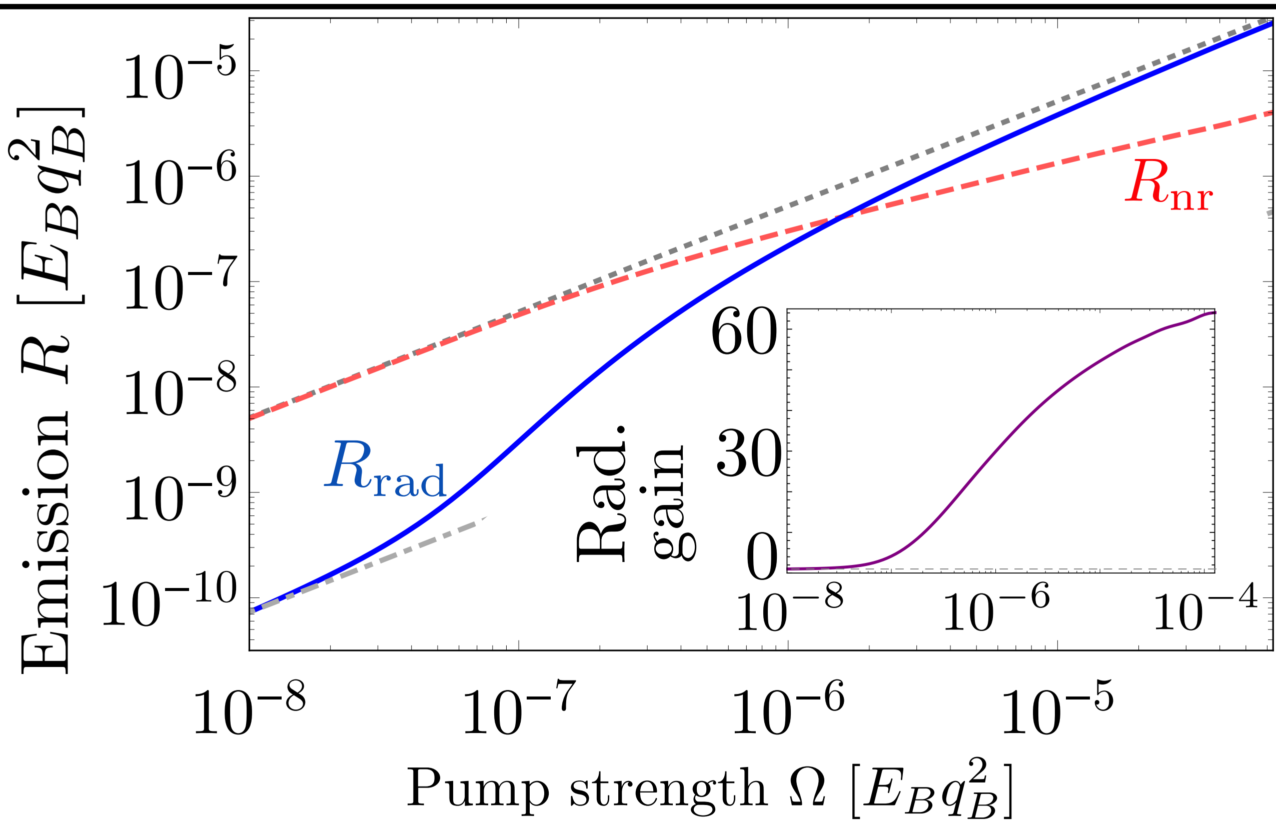
Accumulation at the edge of the light cone
Stimulated processes at sufficient drive



Peak moves further into light cone with increasing drive
Characteristic power law: loss vs relaxation

Peak appears suddenly in the light emission
Laser-threshold signature

Properties of the emitted light

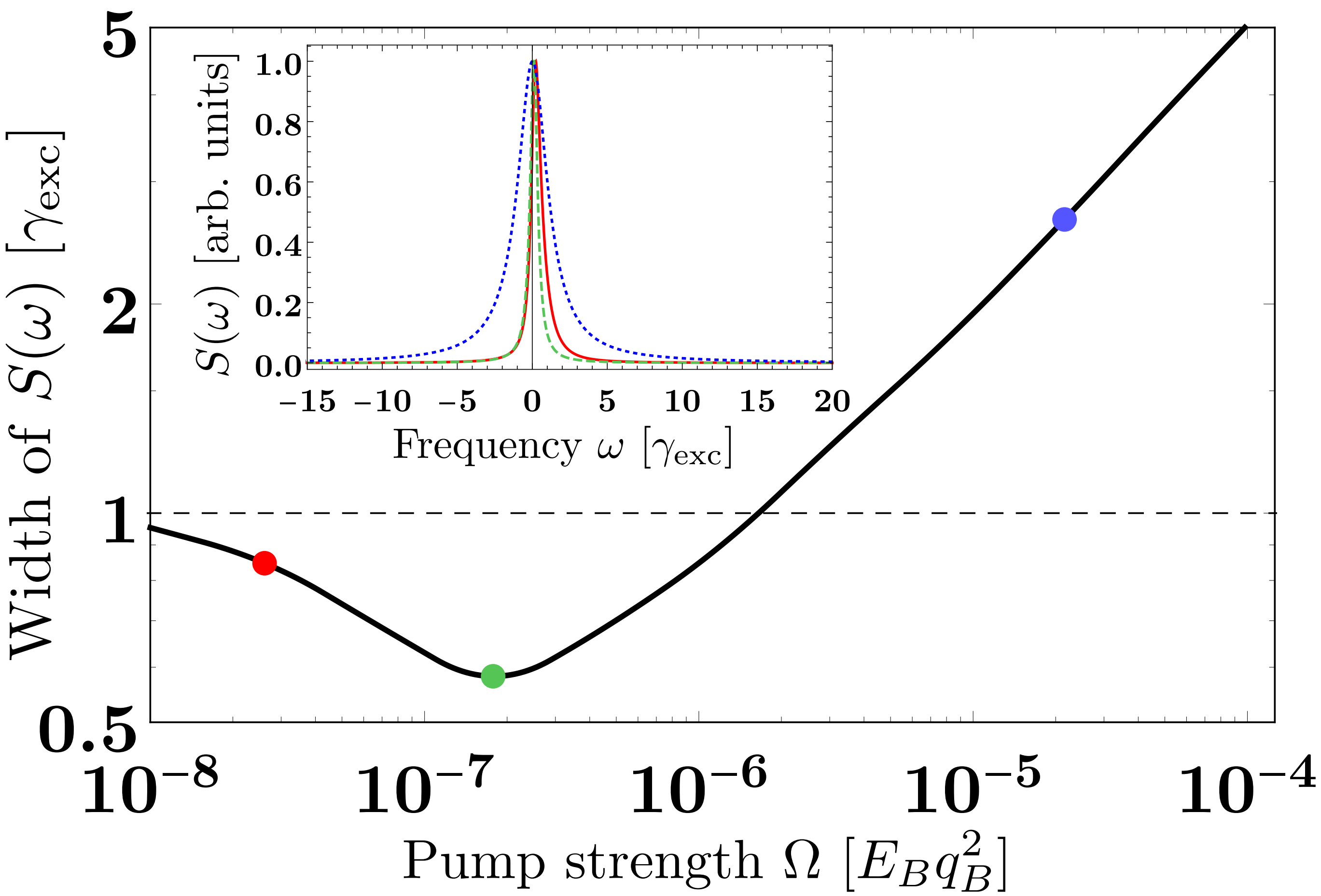


Superlinear dependence on pump

Governed by peak position

Threshold in radiative gain

Radiative efficiency gets close to one



Laser line width set by polaron lifetime

Since coherent peak at the edge of light cone

Potentially narrow line width

Exciton non-radiative loss typically small

Further reduced by polaron formation

Summary

- Rich many-body dynamics of driven Fermi polarons studied with new method
- Fermi-polaron laser is characterised by coherent peak at the edge of the light-cone
- Potentially narrow line width reduced via many-body effect

[T. Wasak, F. Pientka, FP, arXiv:2103.14040]

Tomasz Wasak
(MPIPKS)

Falko Pientka
(Frankfurt)

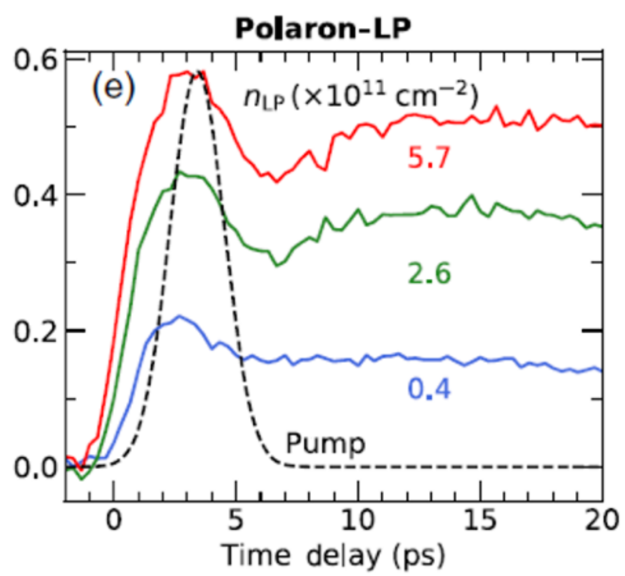
Outlook

- Which type of non-equilibrium phase transition are we dealing with?
- Include Fermi-surface dynamics to describe electron-mediated interactions

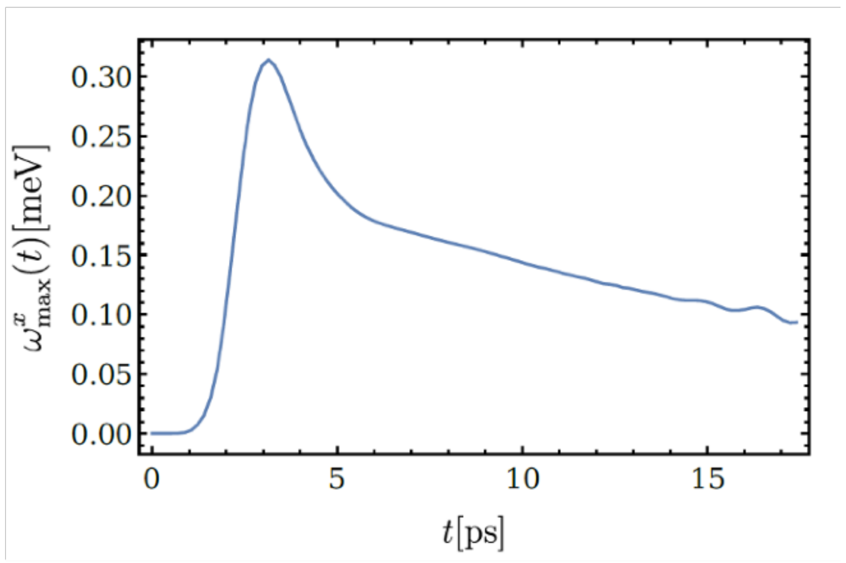
Non-Equilibrium theory of polaron-polariton interactions in TMDs

Energy-shift dynamics: comparison with experiment

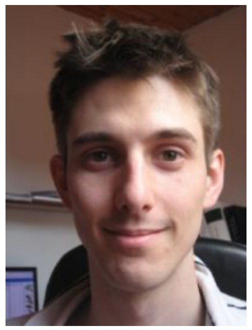
Imamoglu's lab @ ETH
[Tan et al., PRX 10 (2020)]



Our theory



Non-equlibrium T-matrix for driven-dissipative Bose-Fermi mixture

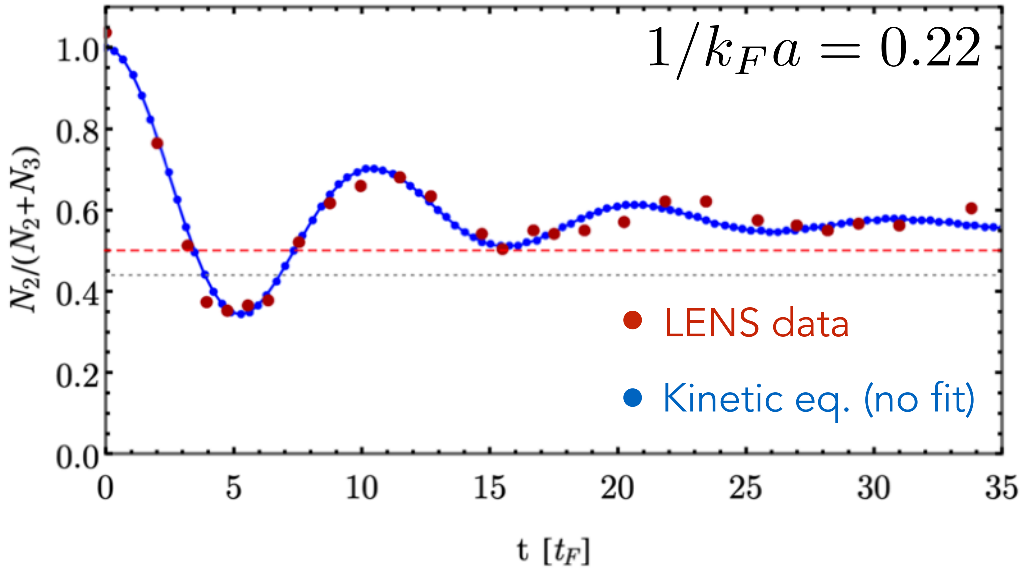


Johannes Lang (MPIPKS)

Christian Johansen (MPIPKS)

Fermi-polaron Rabi oscillations in ultracold atoms

Attractive polaron Rabi oscillations: comparison with experiment



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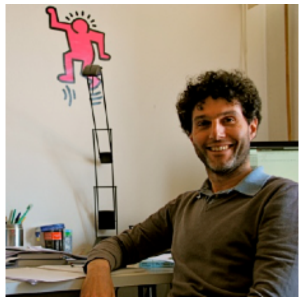
Matteo Sighinolfi (Trento)



Alessio Recati (Trento)