From strong correlations in ultracold fermi gases
to
polaron physics in atomically thin semiconductors

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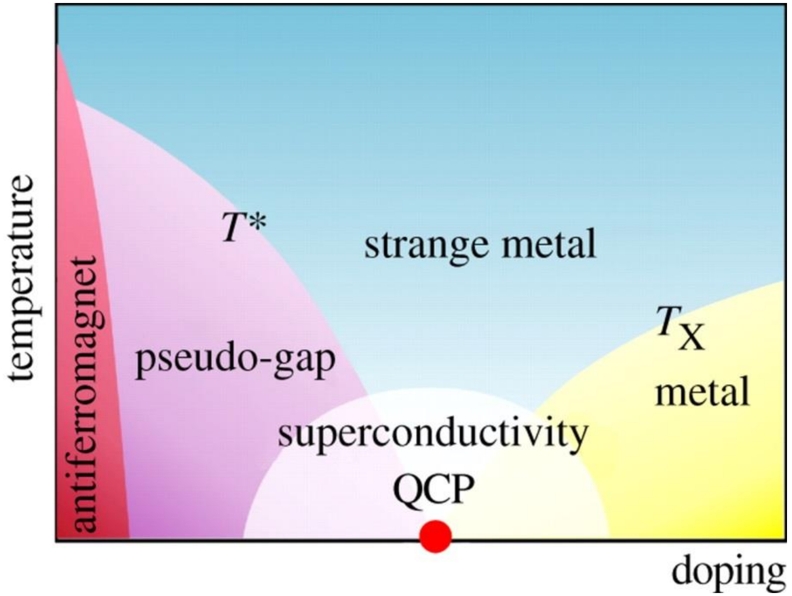
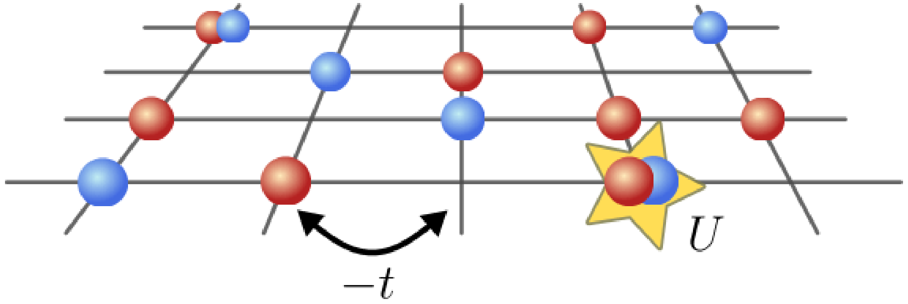
Strongly correlated systems

Phase diagram of High-temperature superconductors



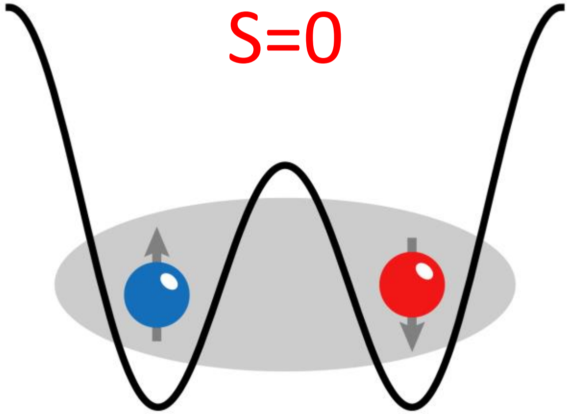
Galanakis et al., Galanakis, D., et al., Philos. Trans. Royal Soc. A, 369.1941 (2011): 1670-1686

Fermi Hubbard model

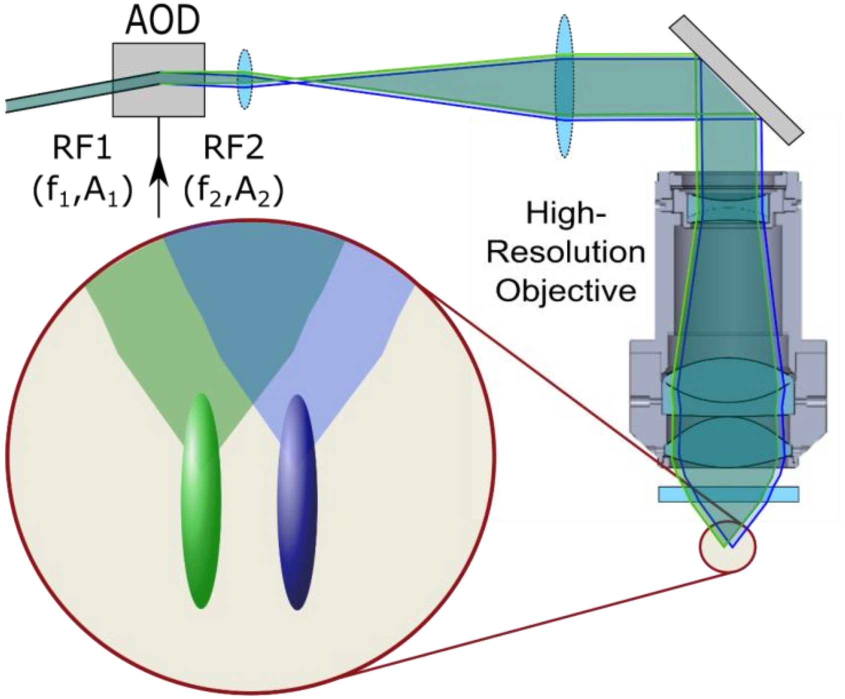


Fundamental building block of the Fermi Hubbard model

Fermi Hubbard dimer



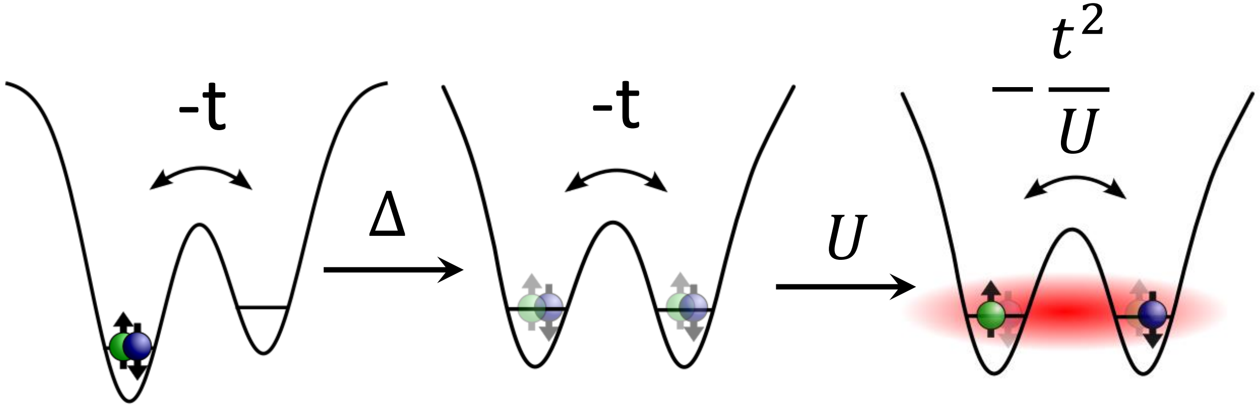
Two fermions in a tunable tweezer array



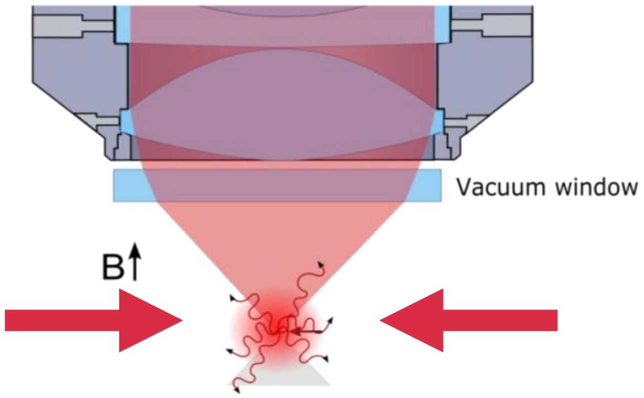
Two fermions in a double well: Murmann, Bergschneider et al, PRL **114**, 080402(20**15)**
Extension to a 1D 8-site Hubbard model: Spar et al., accepted to appear in PRL (20**22)**
2D tweezer array for fermions: Yan et al., arXiv 2203.15023 (2022)

Preparation and detection

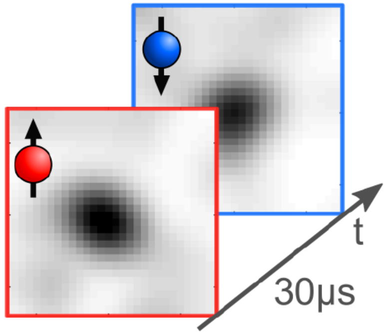
Adiabatic preparation of the ground state



Single-atom fluorescence imaging



+ Spin resolution

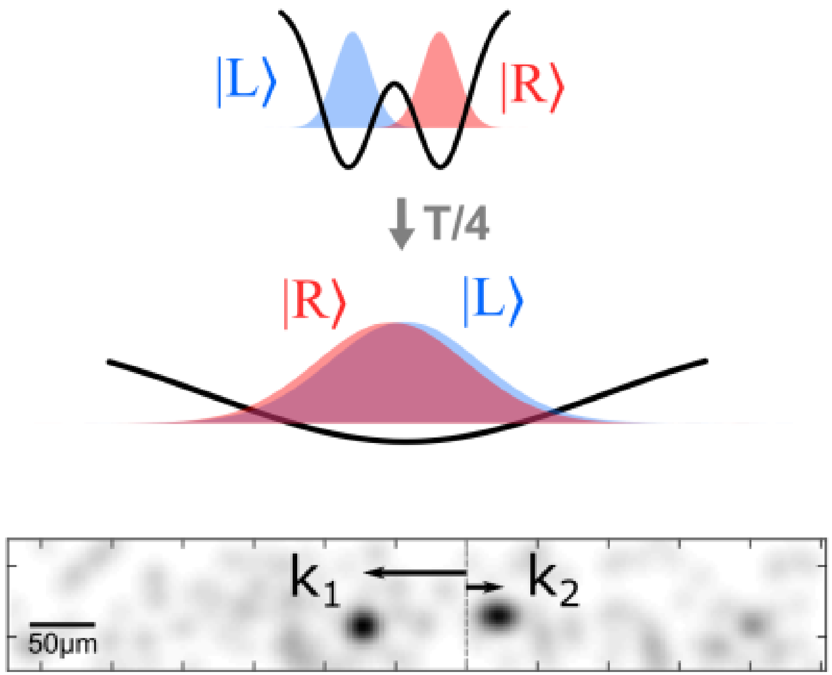


Two fermions in a double well: Murmann, Bergschneider et al, PRL **114**, 080402(20**15)**
Extension to a 1D 8-site Hubbard model: Spar et al., accepted to appear in PRL (20**22)**
2D tweezer array for fermions: Yan et al., arXiv 2203.15023 (2022)

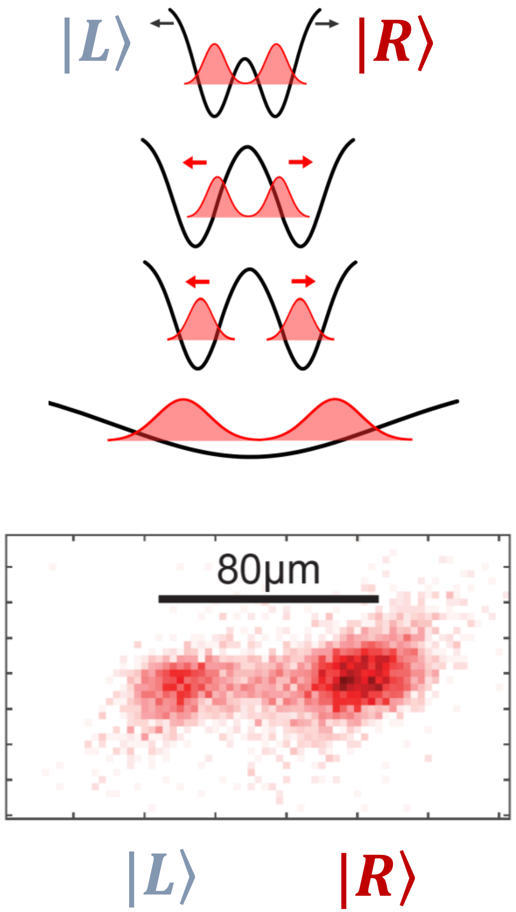
Free-space imaging of Rb: Bücker *et al.*, NJP **11** 103039 (2009)
Single-atom resolution: AB, V. M. Klinkhamer, et al., PRA, 97(6), 063613 (2018)

Access to real space and momentum space

Momentum space imaging:



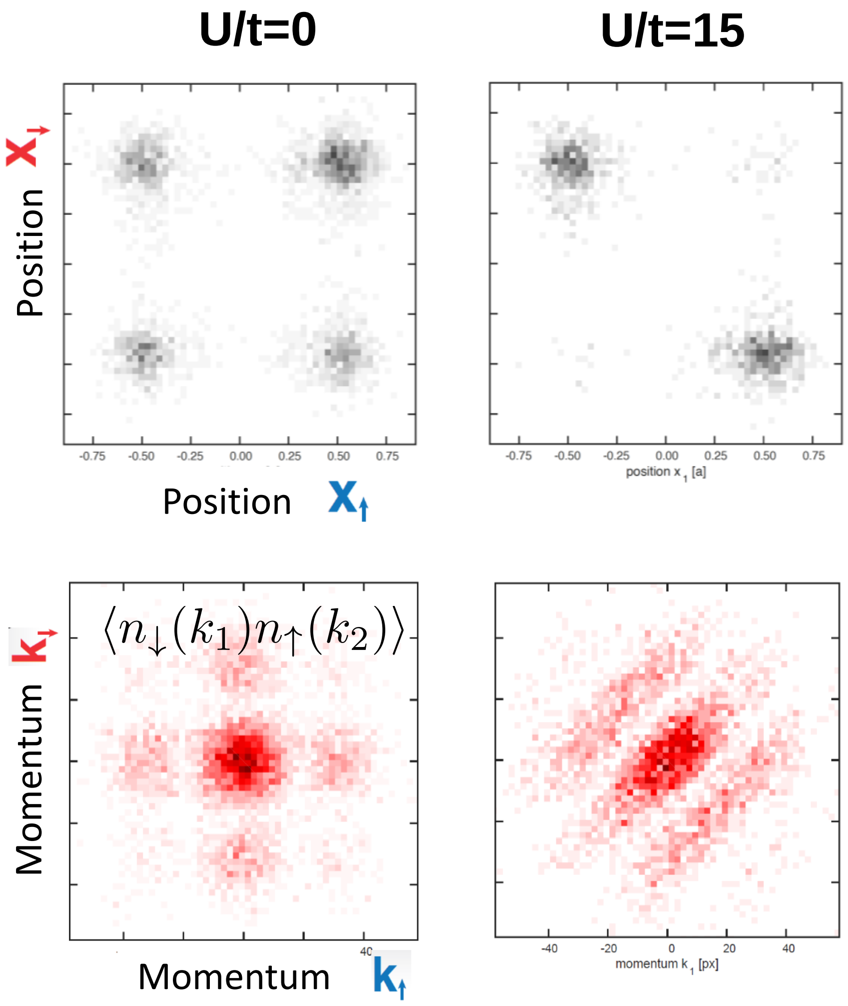
In-situ distribution



Matter-wave fourier optics: Murthy et al., Phys. Rev. A 90, 043611 (2014)
Proposal for matterwave imaging: Murthy & Jochim, arXiv 1911.10824
Quantum gas magnifier: Asteria et al., Nature 599, 571–575 (2021) (Weitenberg group)

→ **Measuring conjugate variables**

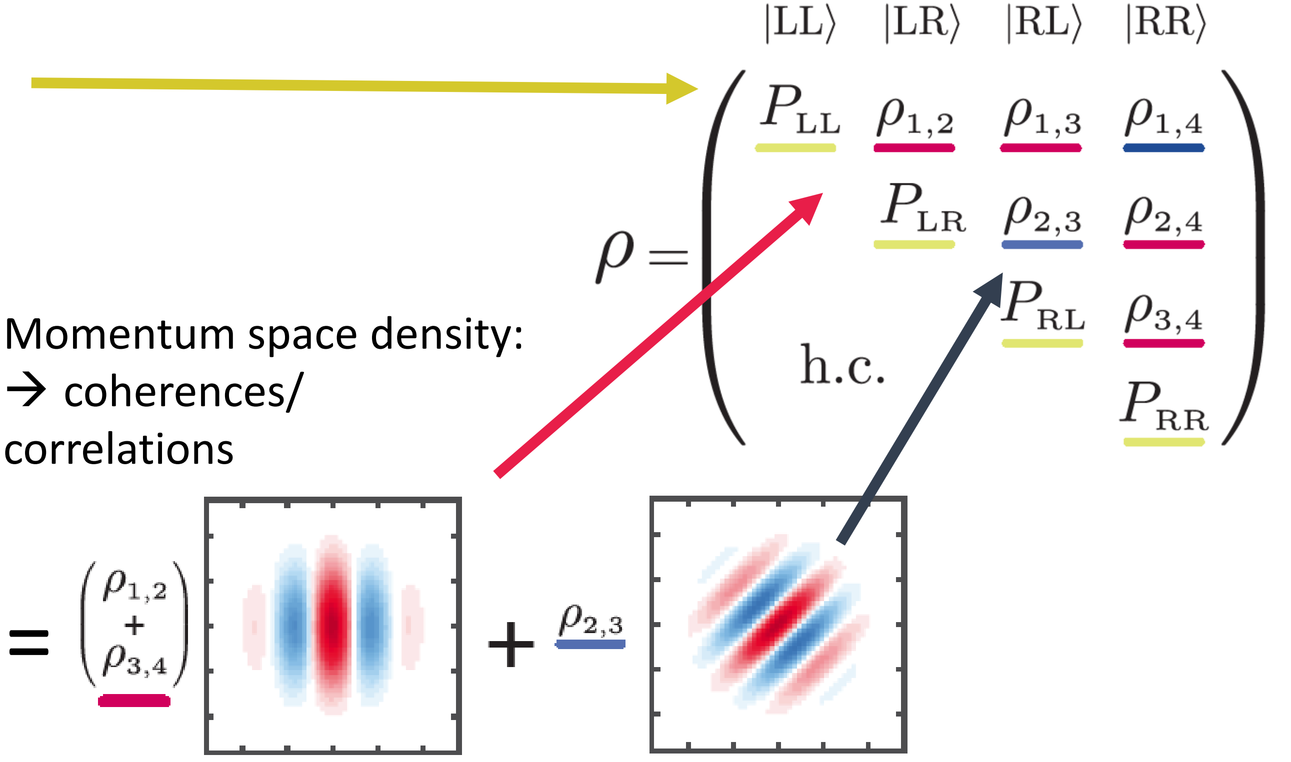
Correlations and tomography



→ Antiferromagnetic correlations: Spin singlet

Real space density:
→ populations

Density matrix of the two-mode Hubbard model:



$$\rho = \begin{array}{c} \begin{array}{cccc} |\mathrm{LL}\rangle & |\mathrm{LR}\rangle & |\mathrm{RL}\rangle & |\mathrm{RR}\rangle \end{array} \\ \begin{pmatrix} \underline{P_{\mathrm{LL}}} & \underline{\rho_{1,2}} & \underline{\rho_{1,3}} & \underline{\rho_{1,4}} \\ & \underline{P_{\mathrm{LR}}} & \underline{\rho_{2,3}} & \underline{\rho_{2,4}} \\ \mathrm{h.c.} & & \underline{P_{\mathrm{RL}}} & \underline{\rho_{3,4}} \\ & & & \underline{P_{\mathrm{RR}}} \end{pmatrix} \end{array}$$

Momentum space density:
→ coherences/ correlations

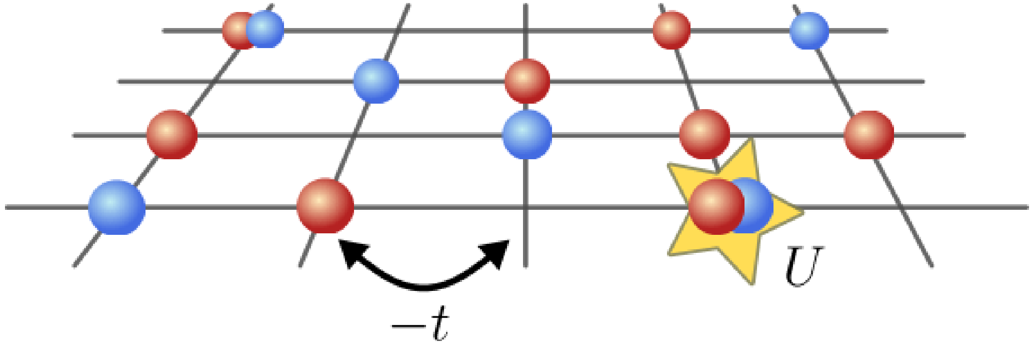
$$= \underline{\left(\begin{array}{c} \rho_{1,2} \\ + \\ \rho_{3,4} \end{array}\right)} \quad + \quad \underline{\rho_{2,3}}$$

→ Certify entanglement

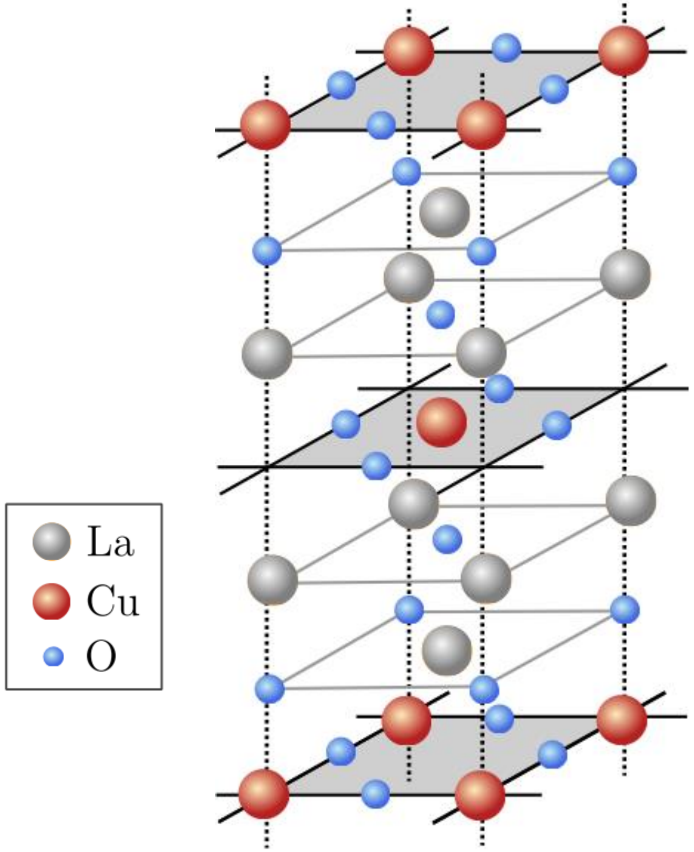
Correlations of interacting fermions: AB, V. Klinkhamer et al., *Nat. Phys.* **15,** 640–644 (2019).
State tomography in double well: M. Bonneau et al., Phys. Rev. A 98, 033608 (2018).
Entanglement certification for larger systems: N. Euler & M. Gaerttner, in preparation

Fermi Hubbard model vs. real materials

Fermi Hubbard model

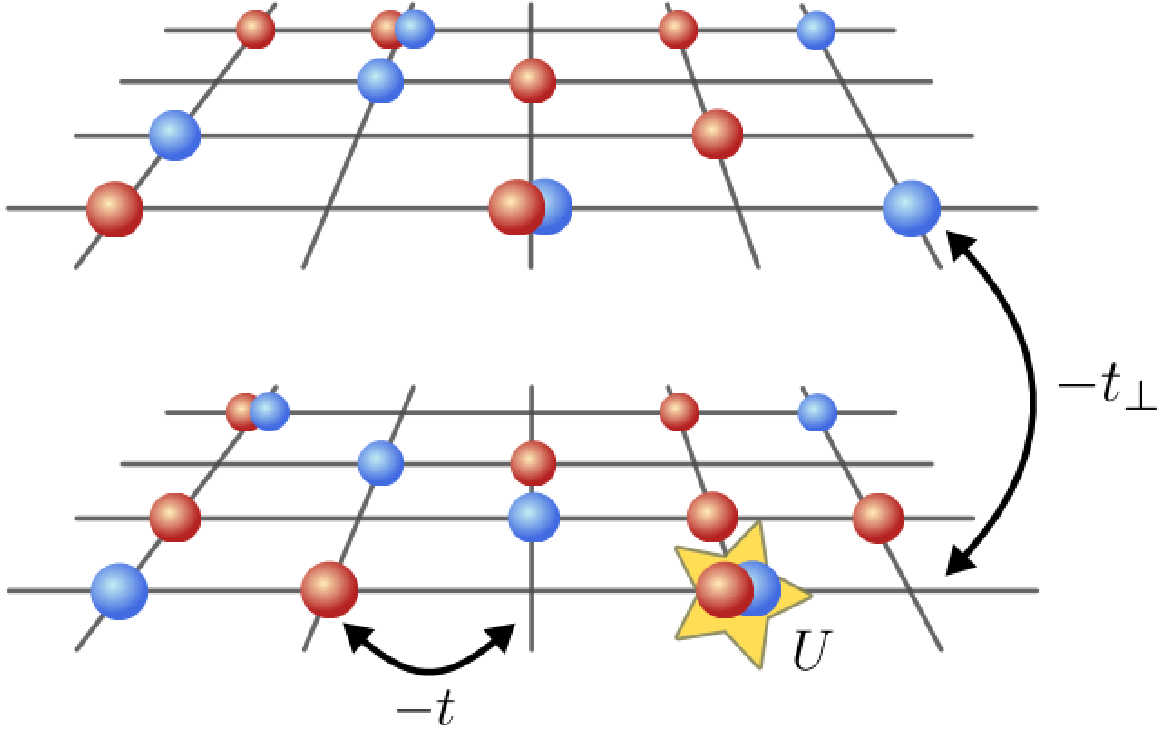


High-T_c superconductors



What is the role of the weak coupling between planes?

Bilayer Fermi Hubbard model

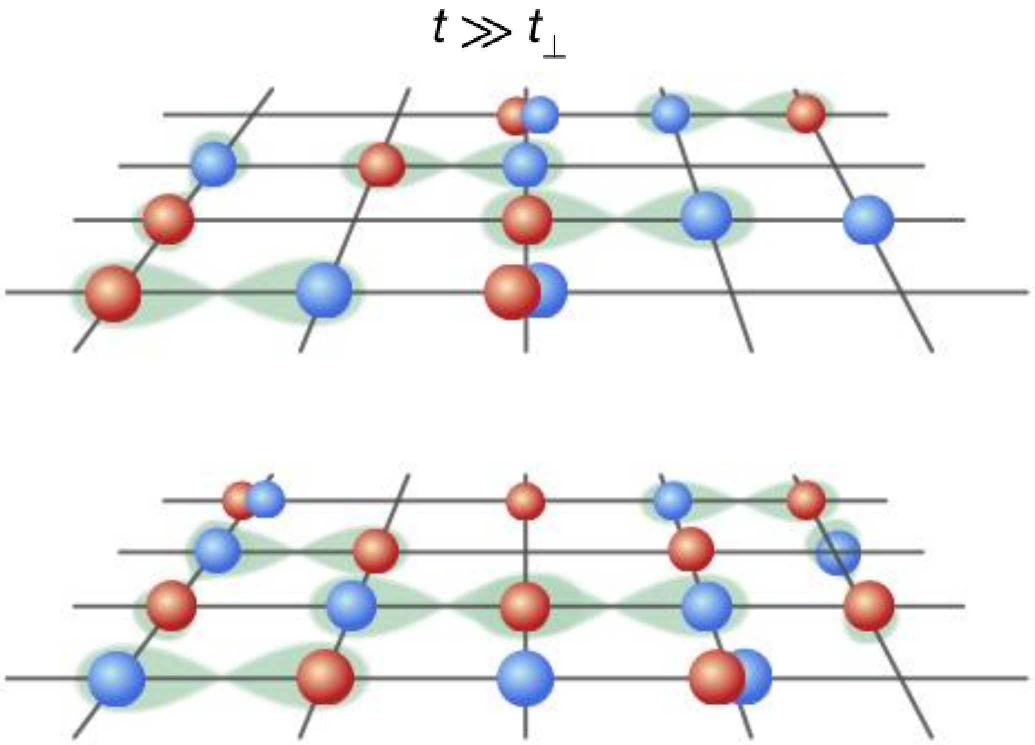


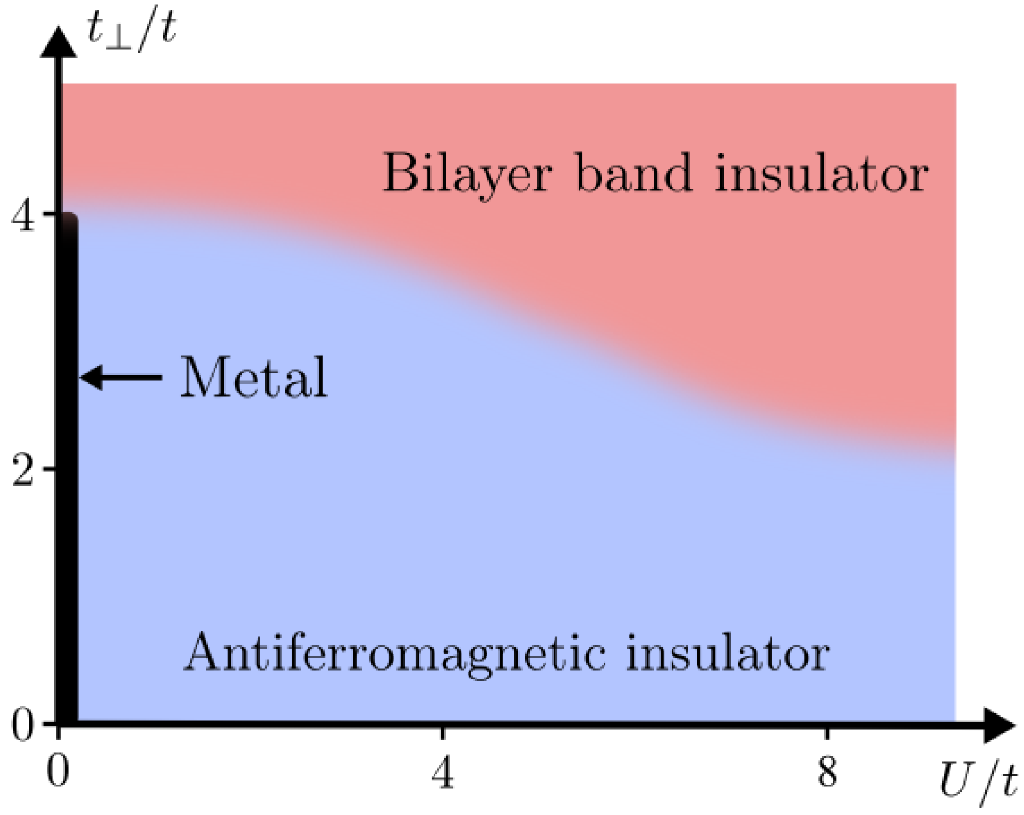
Independent tuning of intra- and interlayer coupling

Publication on Bilayer Hubbard model:
Gall, M., Wurz, N., Samland, J., Chan, C. F., & Köhl, M.,
Nature, *589* (7840), 40–43 (2021)

See also bilayer realization: Koepsell et al., *PRL 125*(1), 010403 (2020)

Bilayer Fermi Hubbard model

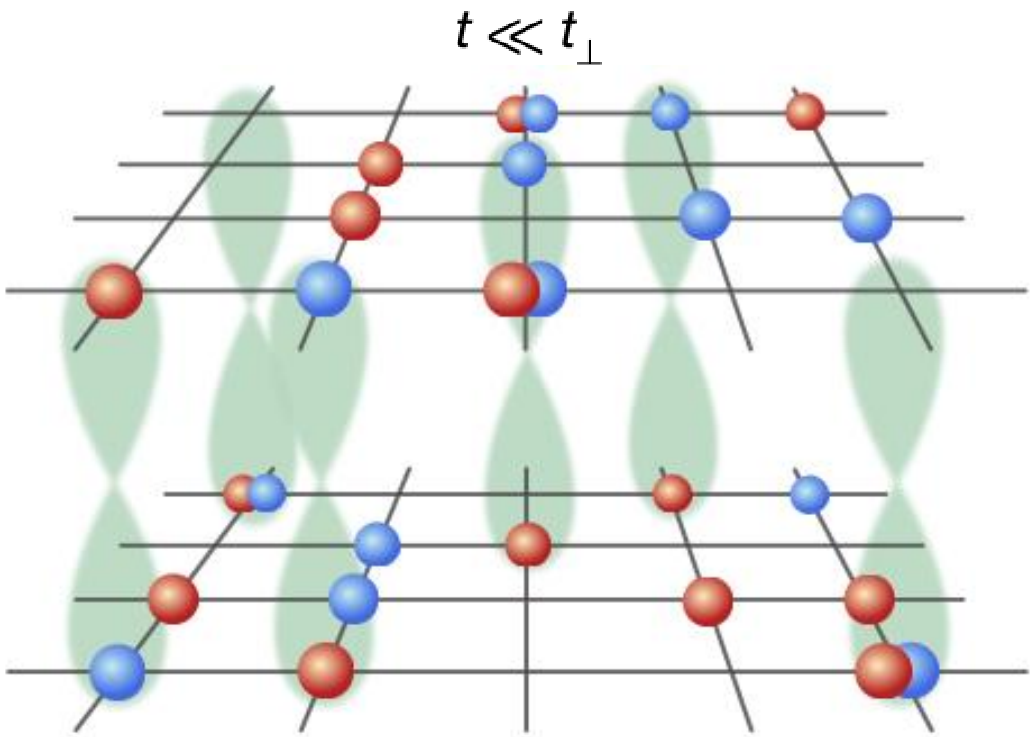




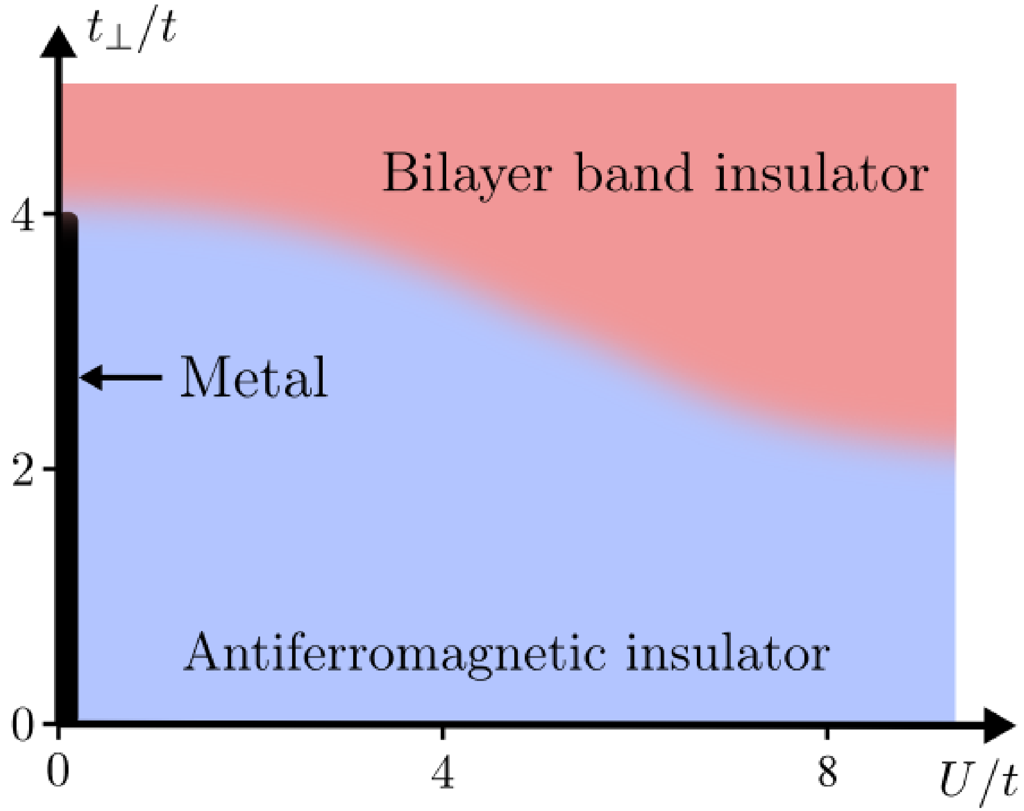
Independent tuning of intra- and interlayer coupling

Phase diagram (adapted): M. Golor et al., *Physical Review B* 90 (2014)

Bilayer Fermi Hubbard model



Independent tuning of intra- and interlayer coupling

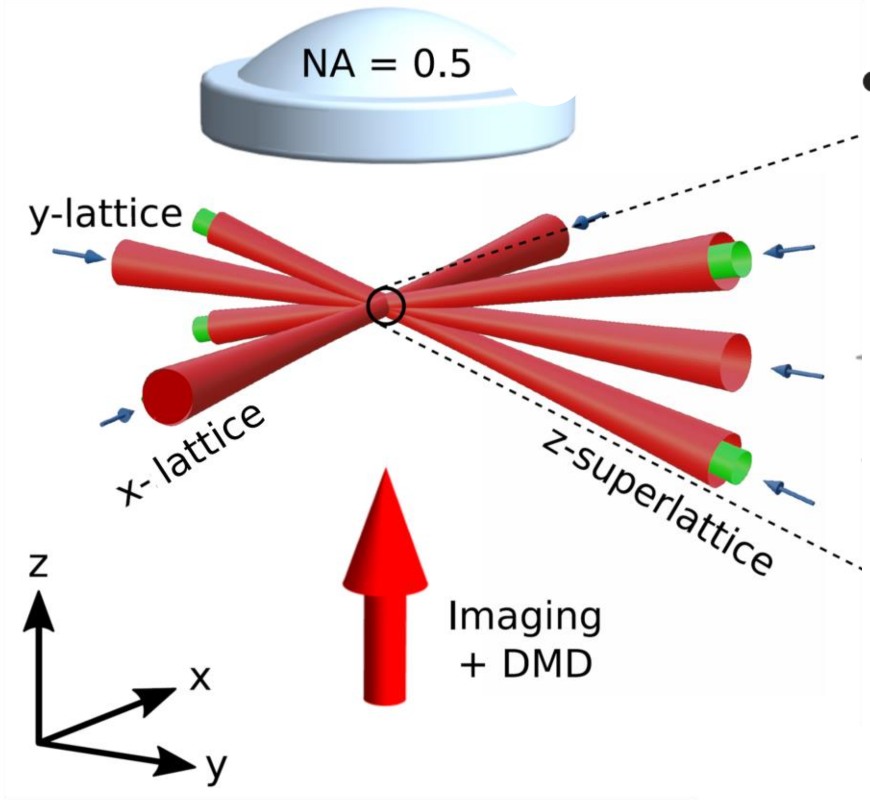


→ **competition between intra- and interlayer correlations**

Phase diagram: M. Golor et al., *Physical Review B* 90 (2014)

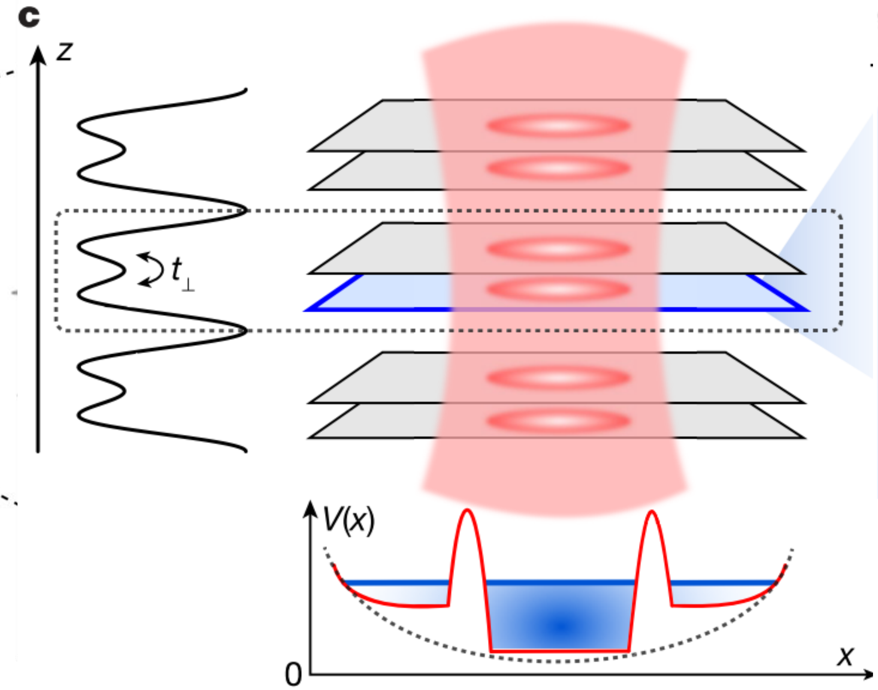
Experimental setup

^{40}K in optical lattice



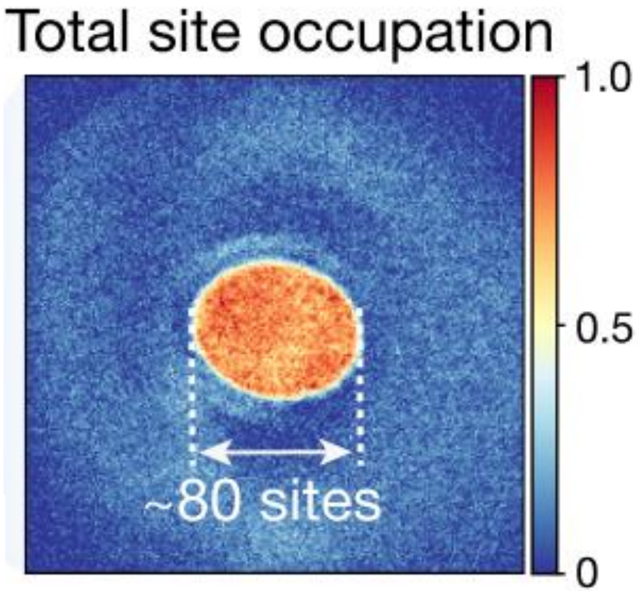
→ Lattice potential in x, y and z

Vertical superlattice



→ Tunable double wells
→ bilayer system

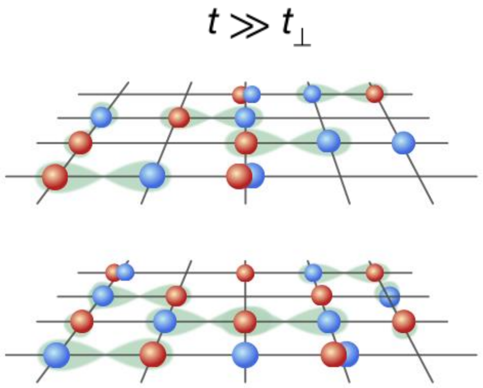
Isolating the high-density region



→ Isolate low-entropy region
→ Start with band insulator

Bilayer Hubbard model: Gall, M., Wurz, N., Samland, J., Chan, C. F., & Köhl, M., *Nature*, *589* (7840), 40–43 (2021)

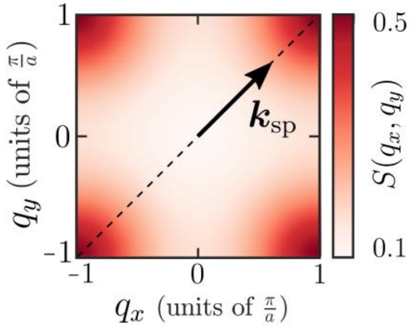
Characterizing intralayer antiferromagnetic correlations



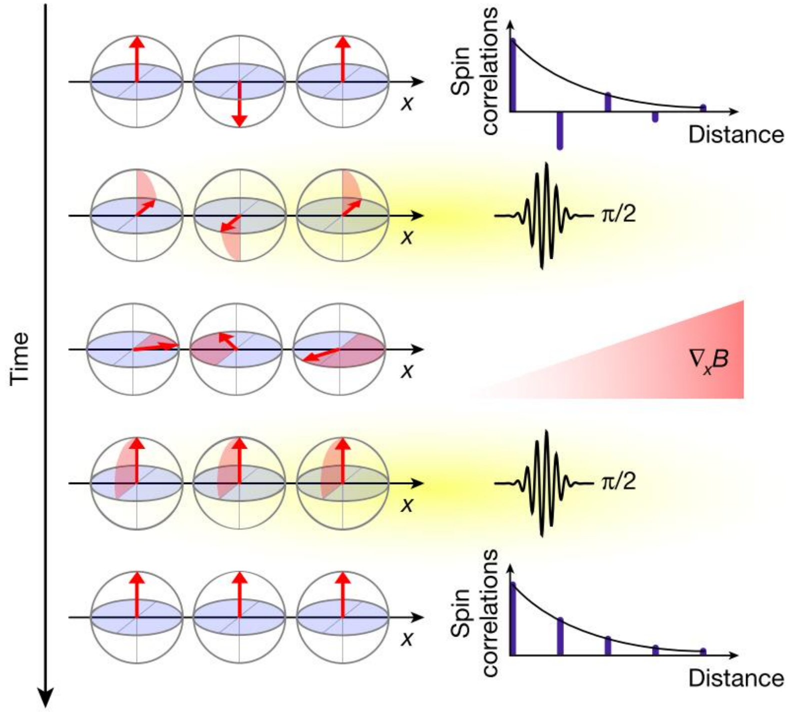
Spin structure factor

$$S(\boldsymbol{q}) = \frac{1}{N}\sum_{i,j} e^{-i\boldsymbol{q}\cdot\boldsymbol{r}_{ij}} C^{z}_{ij}$$

$$C^{\nu}_{ij} = \langle \hat{S}^{\nu}_{i}\hat{S}^{\nu}_{j}\rangle - \langle \hat{S}^{\nu}_{i}\rangle\langle \hat{S}^{\nu}_{j}\rangle$$



Uniform structure factor S [q=(0,0)]

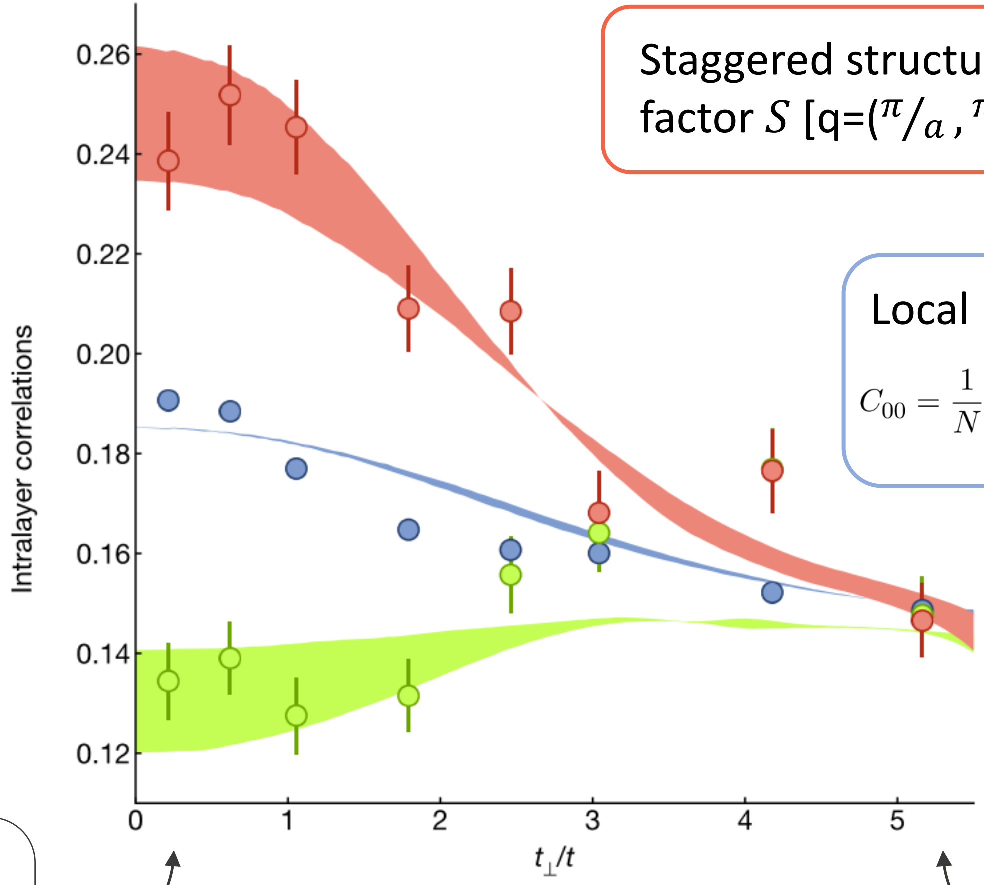


Staggered structure factor S [q=($^{\pi}/_{a}$, $^{\pi}/_{a}$)]

SSF via Bragg scattering: Hart et al., *Nature*, *519*(7542), 211-214 (2015).
SSF in quantum gas microscope: Mazurenko et al., *Nature* **545,** 462–466 (2017). …
SSF via coherent manipulation: Wurz et al., *Physical Review A*, *97*(5), 051602 (2018).

Intralayer correlations

Total intralayer correlations C_{xy}

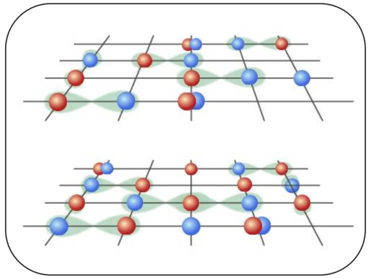


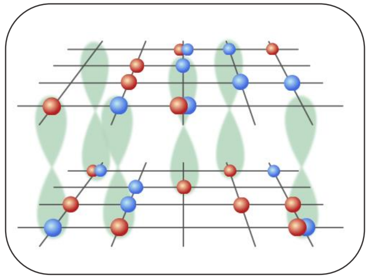
Staggered structure factor S [q=(π/a , π/a)]

Local moment

$$C_{00} = \frac{1}{N}\sum_{i=1}^{N} C_{ii}^{z} \equiv C_{ii}^{z}$$

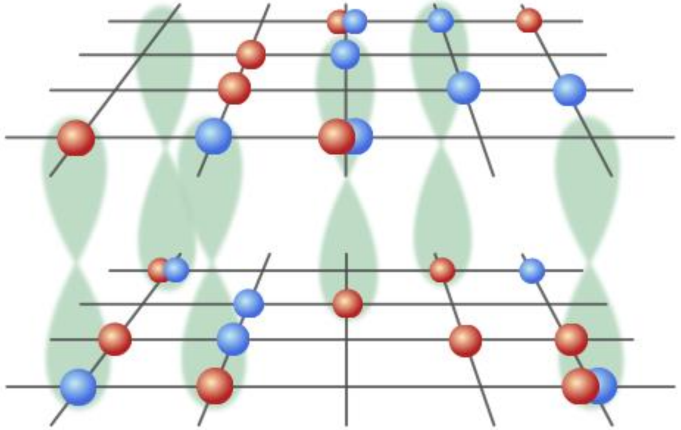
Uniform structure factor S [q=(0,0)]

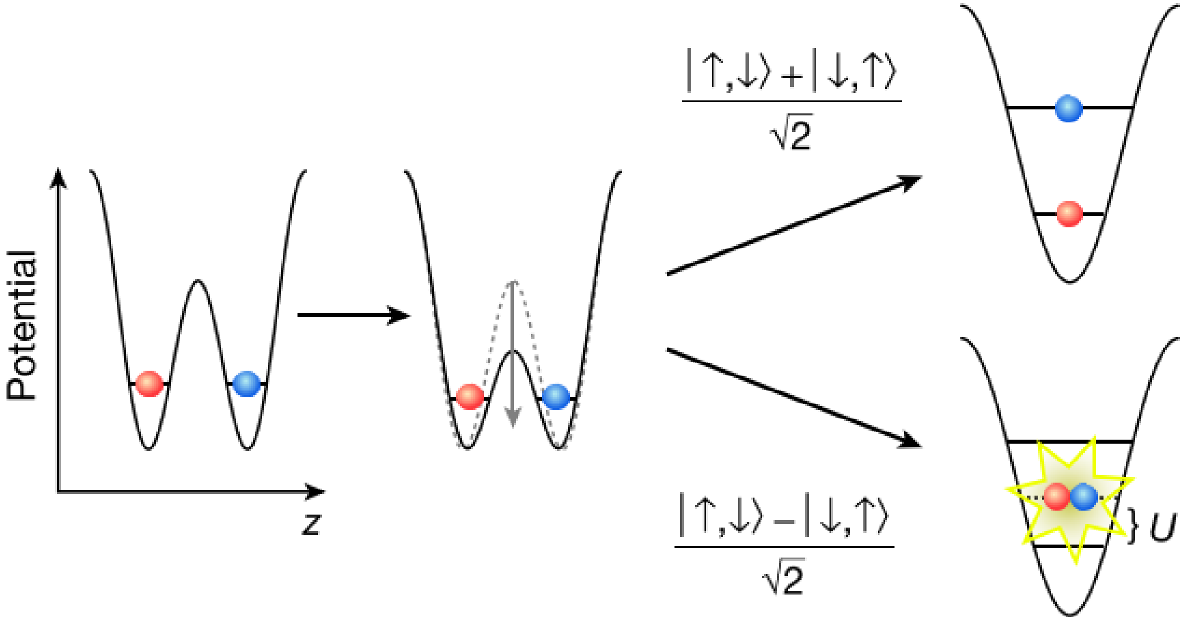




Bilayer Hubbard model: Gall, M., Wurz, N., Samland, J., Chan, C. F., & Köhl, M., N*ature*, *589* (7840), 40–43 (2021)

Interlayer spin correlations: distinguish singlet and triplets

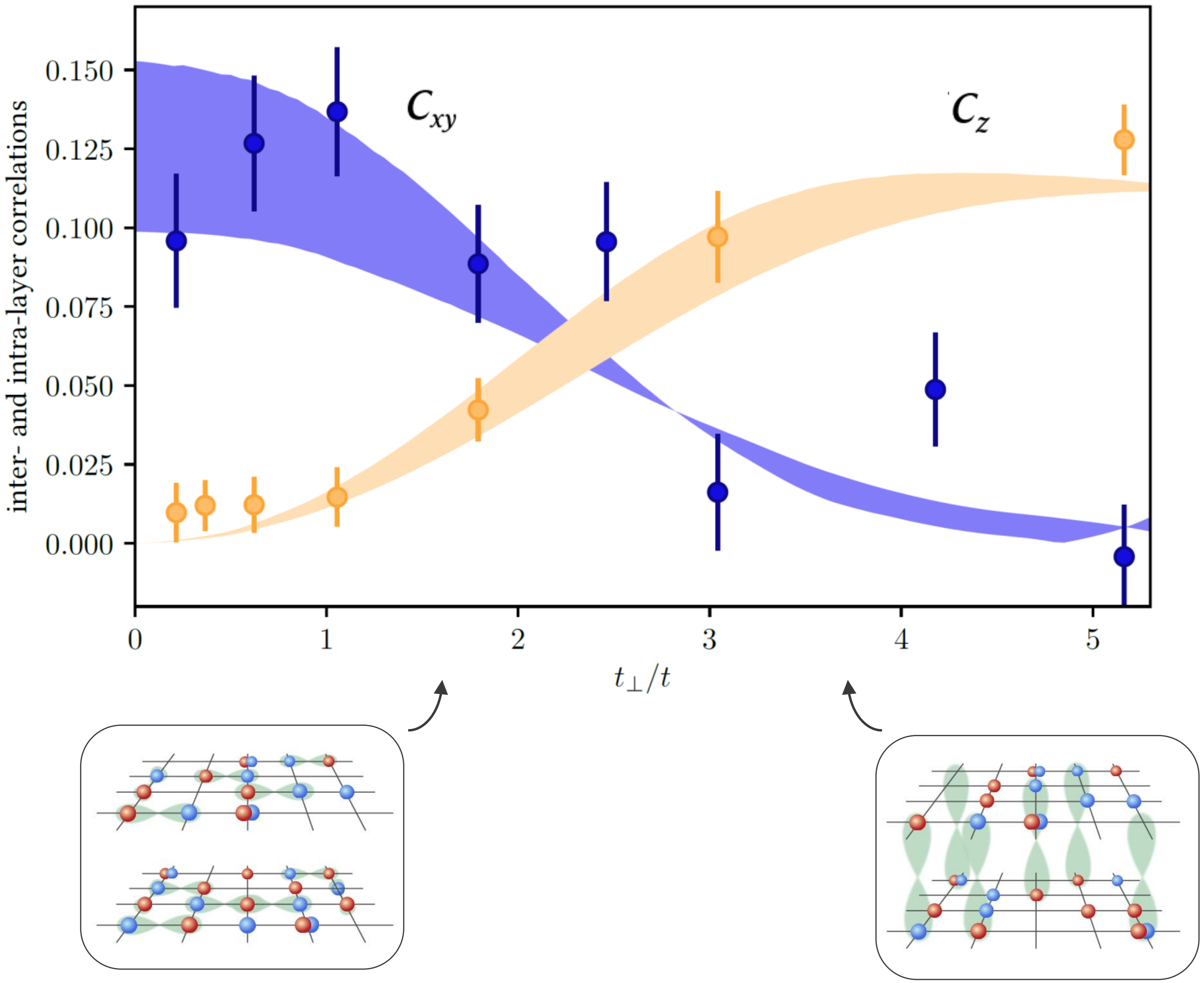




$$C_z = \frac{1}{4}(n_D - n_D^0)$$

Singlet- triplet imaging: Greif et al., Science 340, 1307-1310 (2013)

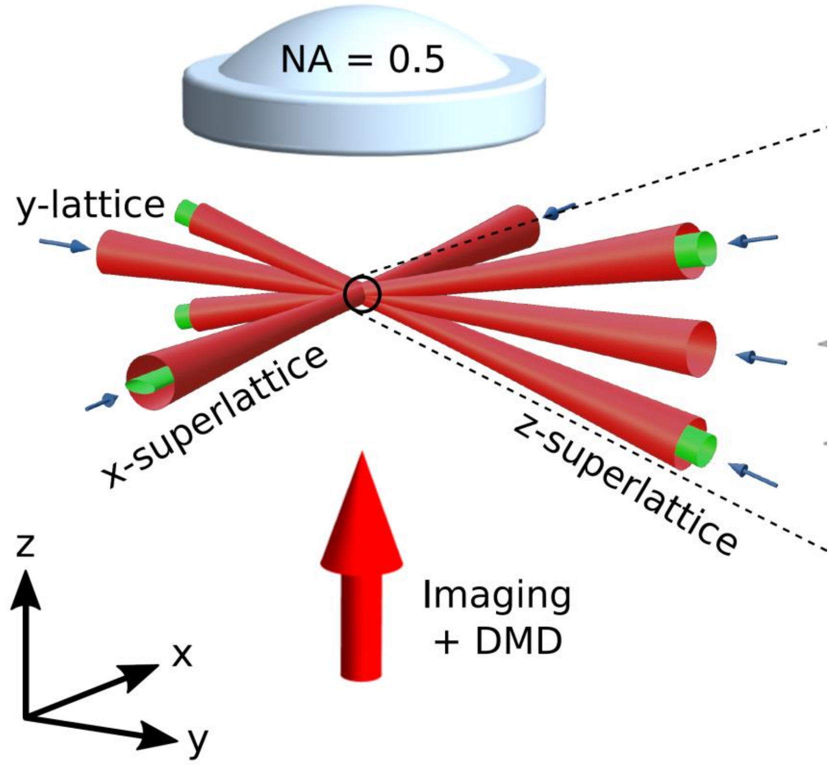
Transfer of correlations from inter- to intralayer

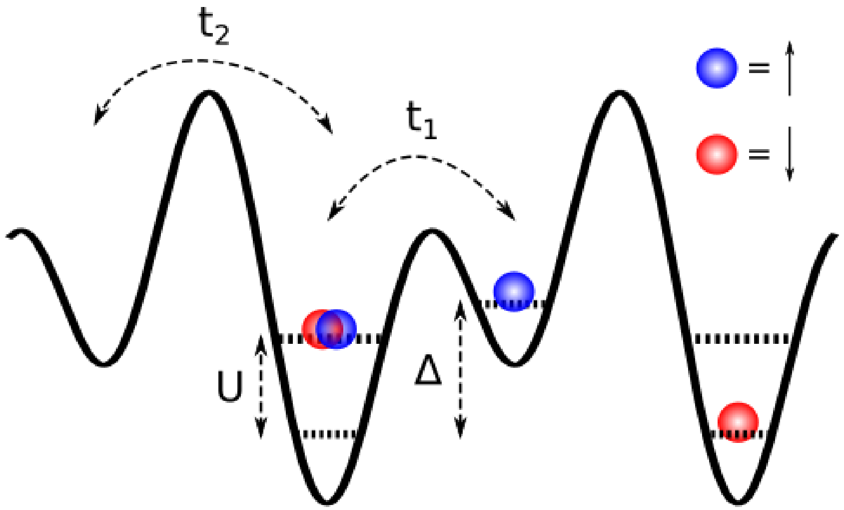


Bilayer Hubbard model: Gall, M., Wurz, N., Samland, J., Chan, C. F., & Köhl, M., N*ature*, *589* (7840), 40–43 (2021)

Outlook

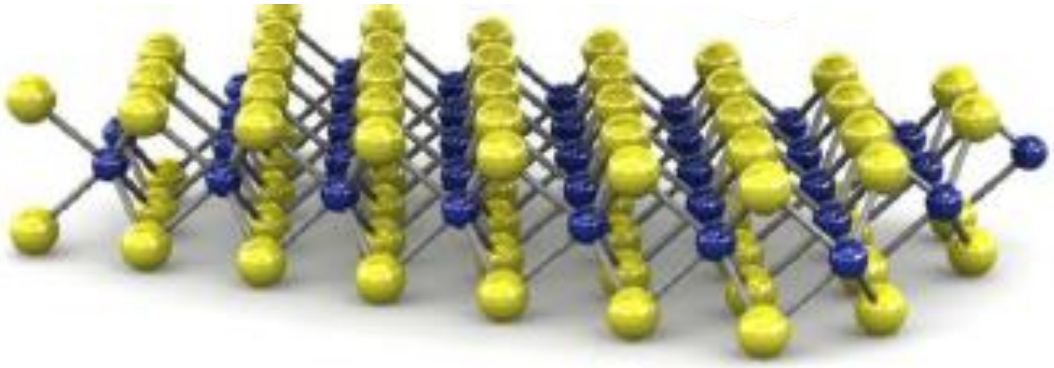
In-plane superlattice





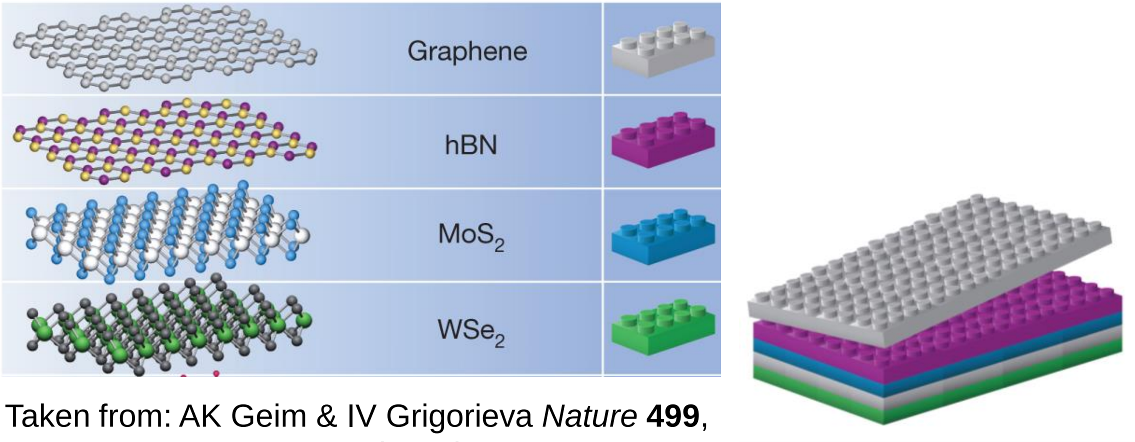
- Topological systems with interaction
- Floquet driving
- …

Atomically thin semiconductors



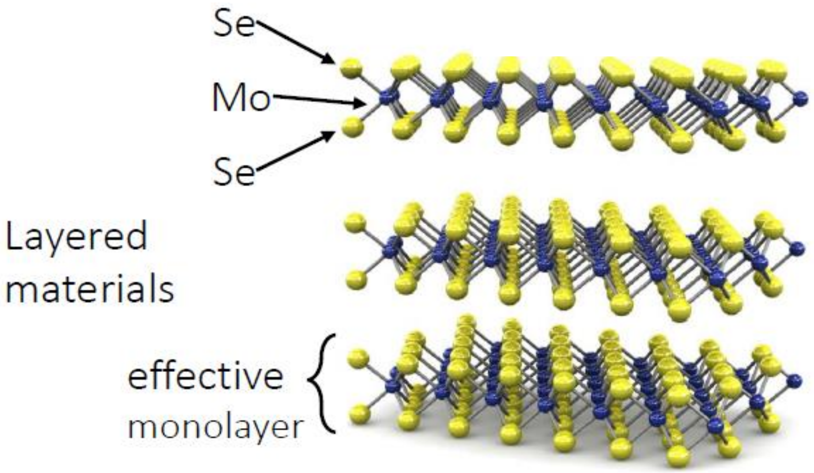
Van der Waals materials

Building van der Waals heterostructures



Taken from: AK Geim & IV Grigorieva *Nature* **499**, 419-425 (2013)

Transition metal dichalocogenides (TMD)

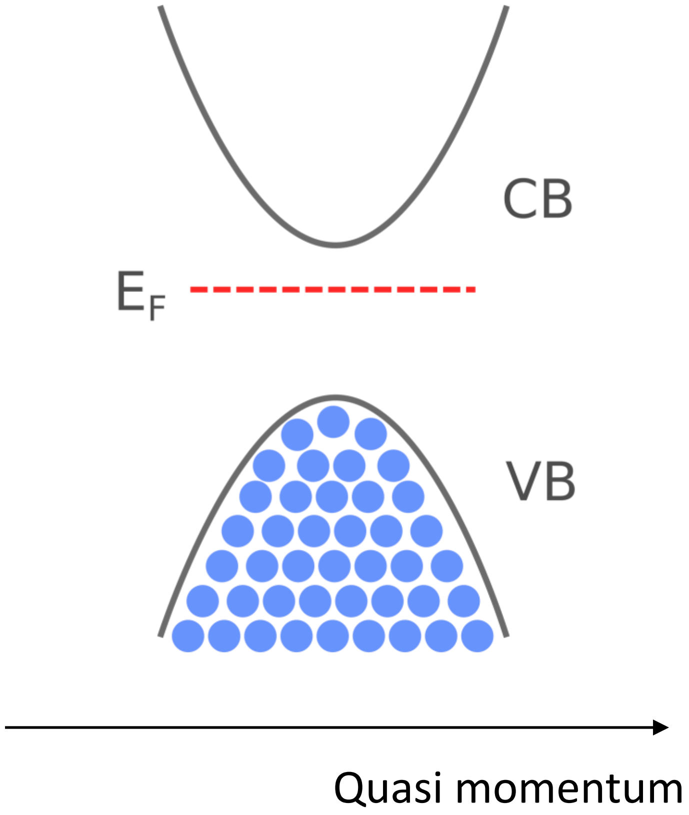


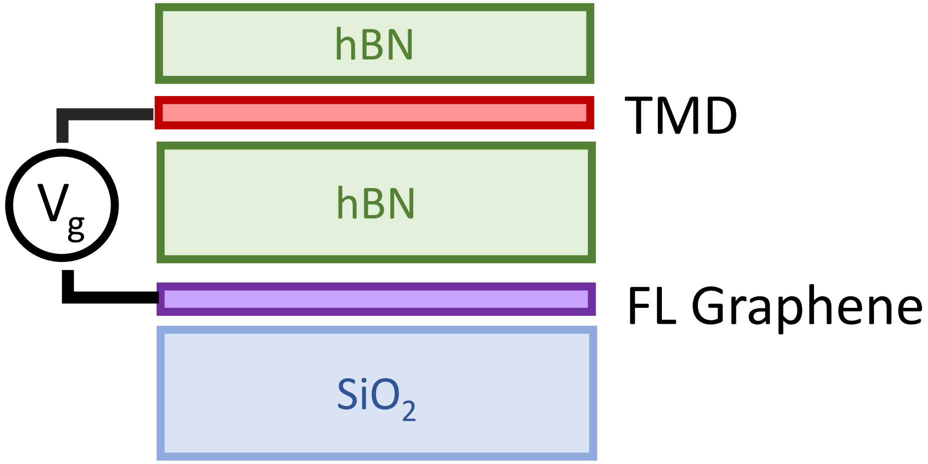
- Semiconductors
- Optical excitations

→ Quantum optics with semiconductors

Heterostructures and charge tunability

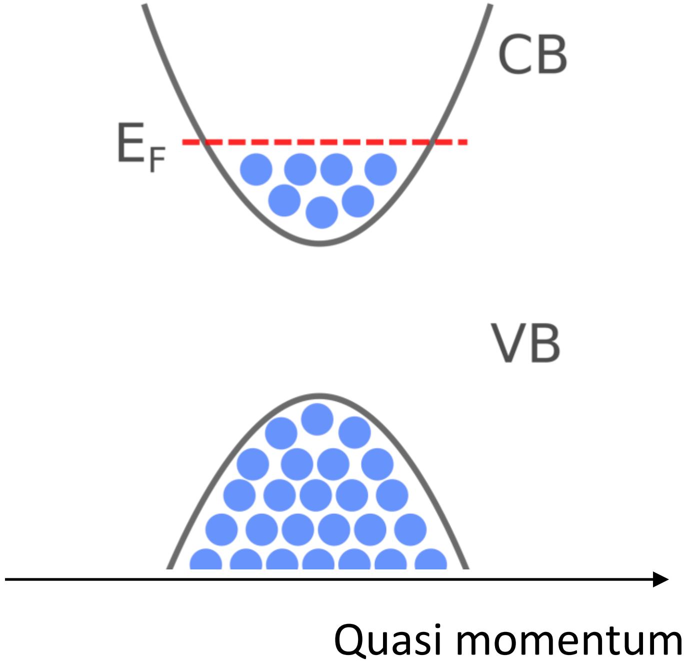
Direct bandgap

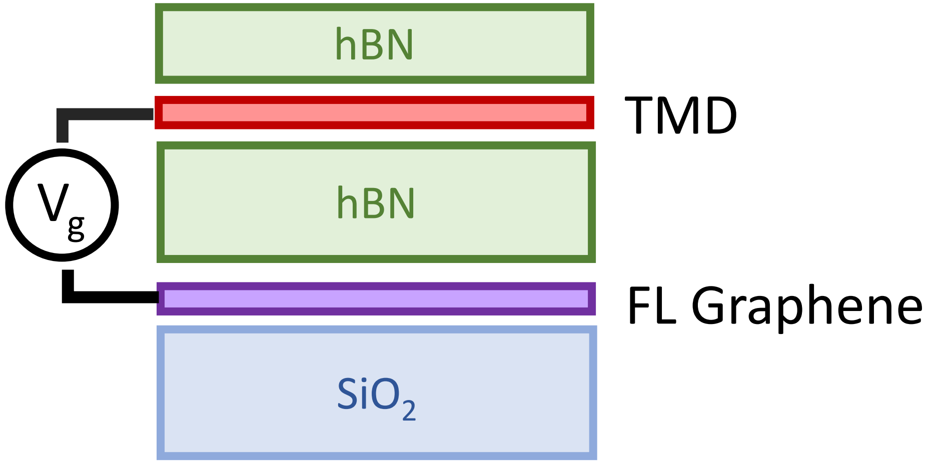




Heterostructures and charge tunability

Direct bandgap

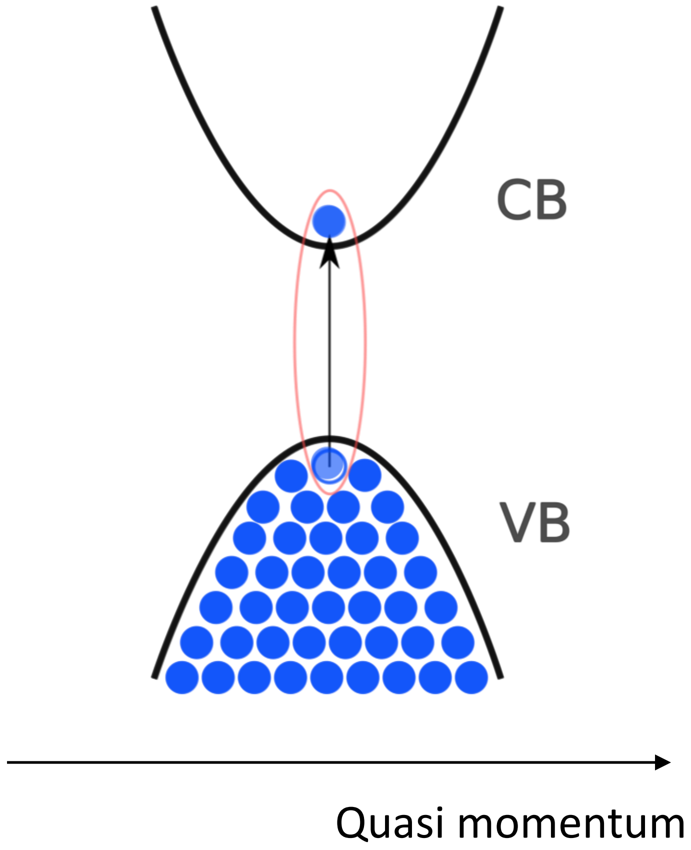




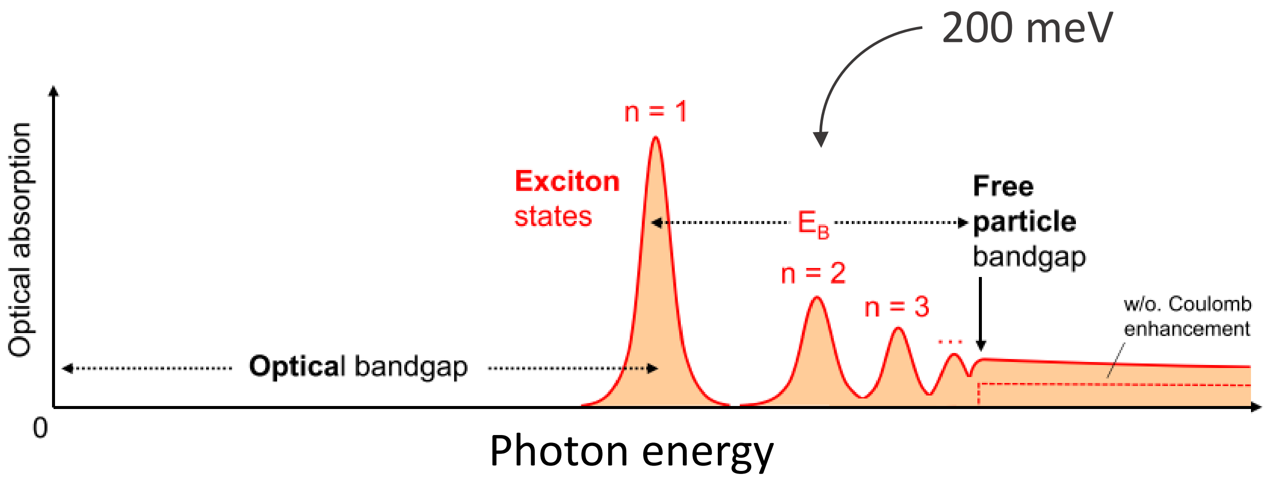
→ Tunability and control of electron density by gate voltage

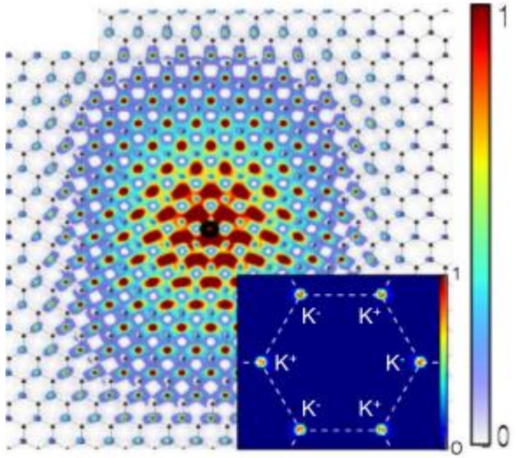
Excitons in 2D semiconductors

Direct bandgap

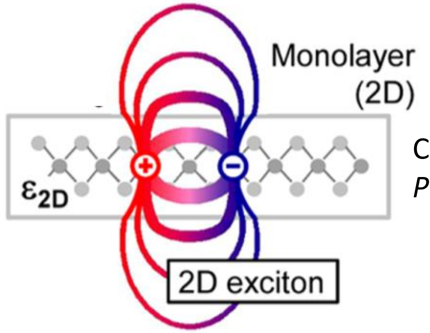


Excitons





Qiu et al., *PRL* (2013).

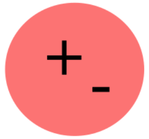


Chernikov et al., *PRL* (2014).

Excitons in TMDs: Wang et al., *Reviews of Modern Physics*, *90*(2), 021001.

Scales in the system

Exciton



E_B=200meV
a_B= 1.2 – 1.5 nm

Electrons (holes)

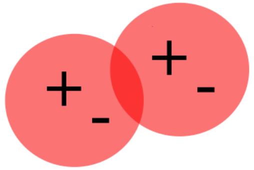
E_F up to 10meV
$n = 3 \cdot 10^{12}\ cm^{-2}$
$d\ \approx 5nm$

2D system

Temperature 4K → 0.4meV

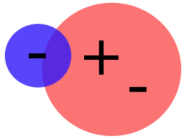
Bound states in $MoSe_2$:

Bi-Exciton



E_B~19meV

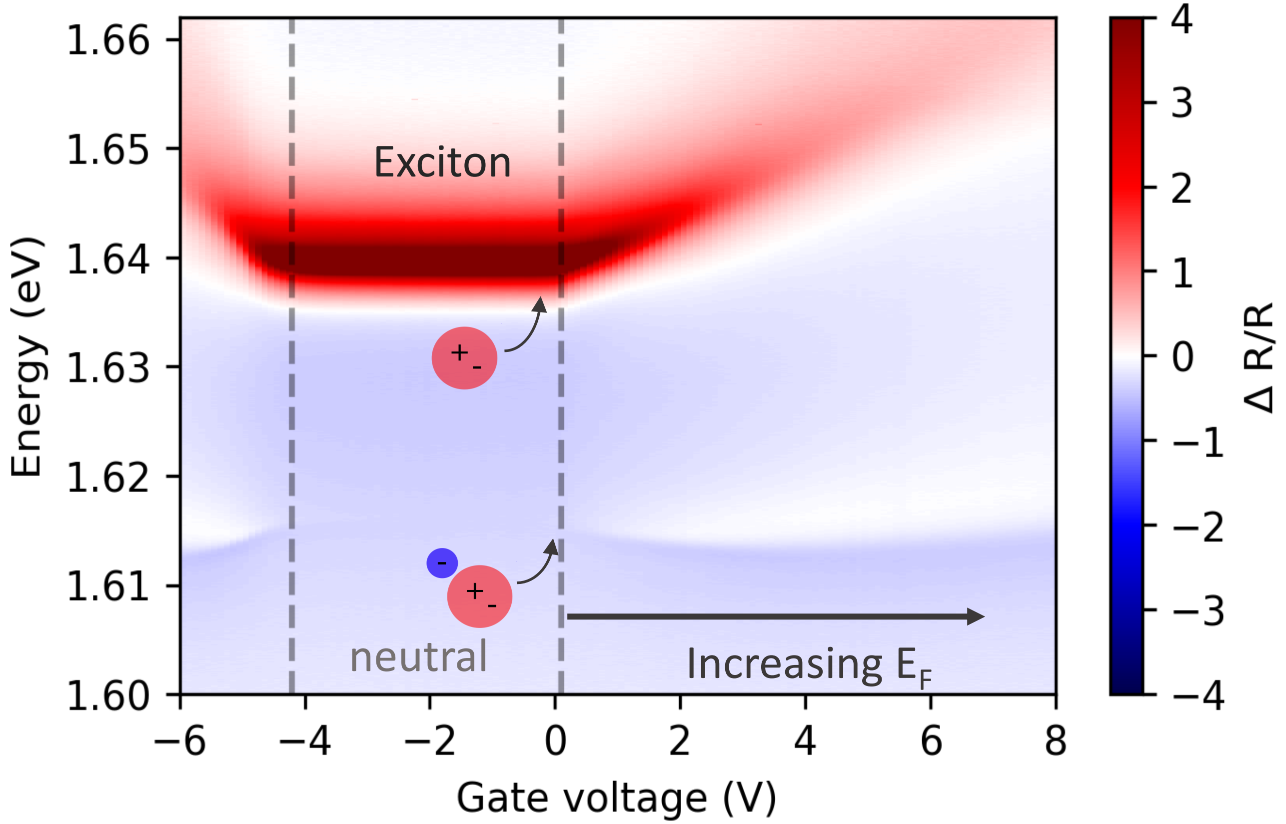
Trion



E_B=25meV
a_T=2.0 – 2.5 nm

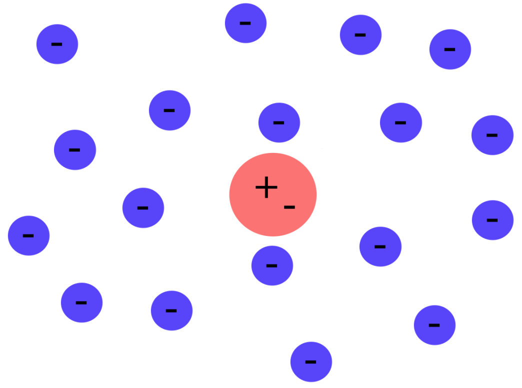
→ **trion has low oscillator strength**

Reflection spectrum in a charge-tunable device



Oscillator strength of the lower branch (low density limit):

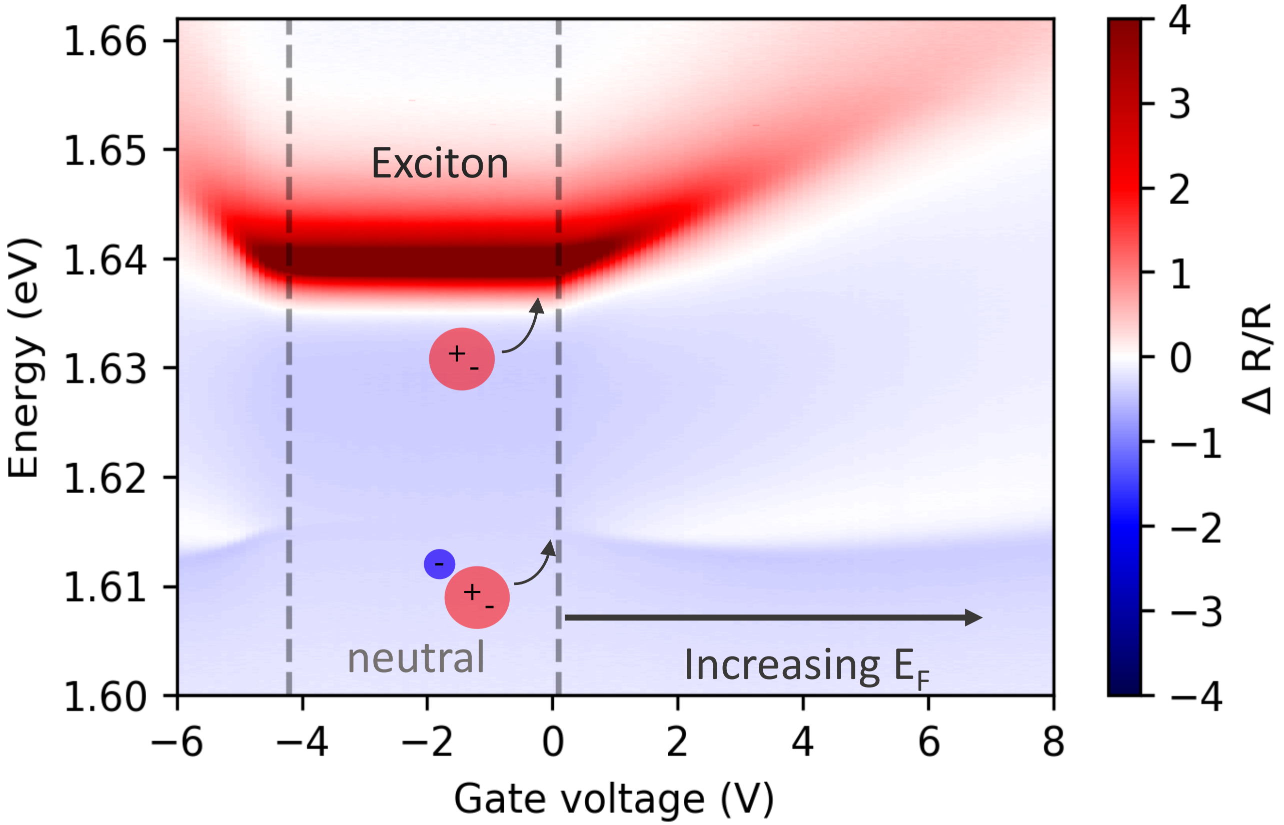
$$f_{AP} = k_F^2 \, a_T^2 \, f_X$$

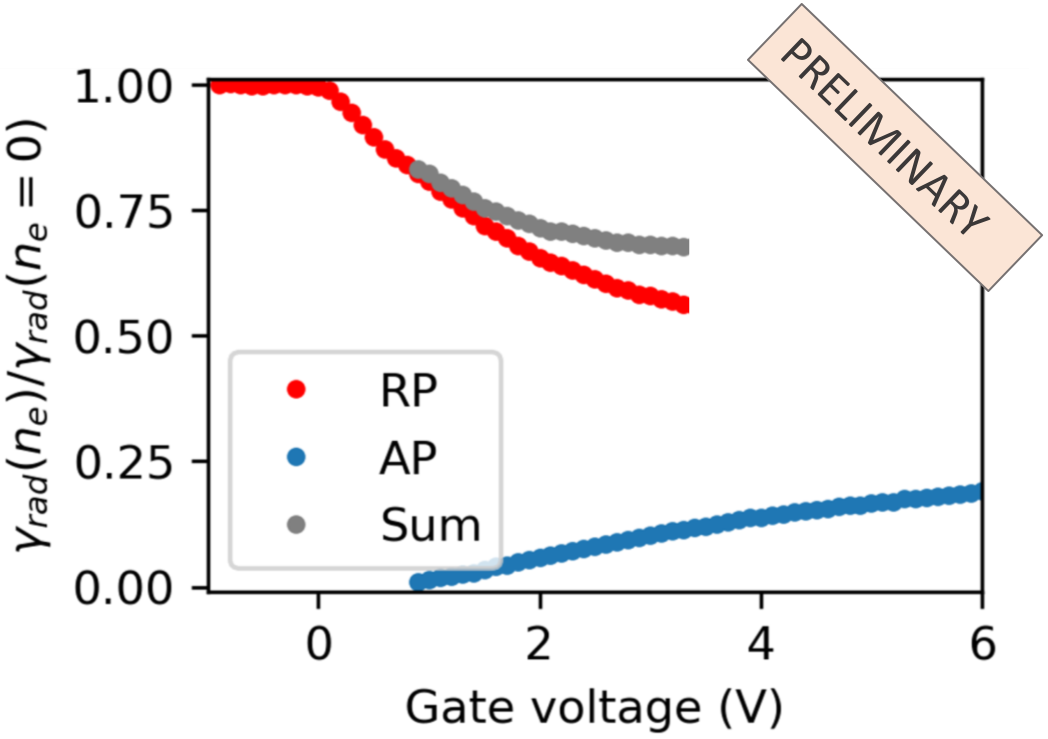


→ **Impurity physics**

Fermi-polaron polaritons: Sidler et al., *Nature Phys* **13,** 255–261 (2017)
Tavis Cumming model for polarons: Imamoglu et al., *Comptes Rendus. Physique* 22.S4 (2021)

Reflection spectrum in a charge-tunable device





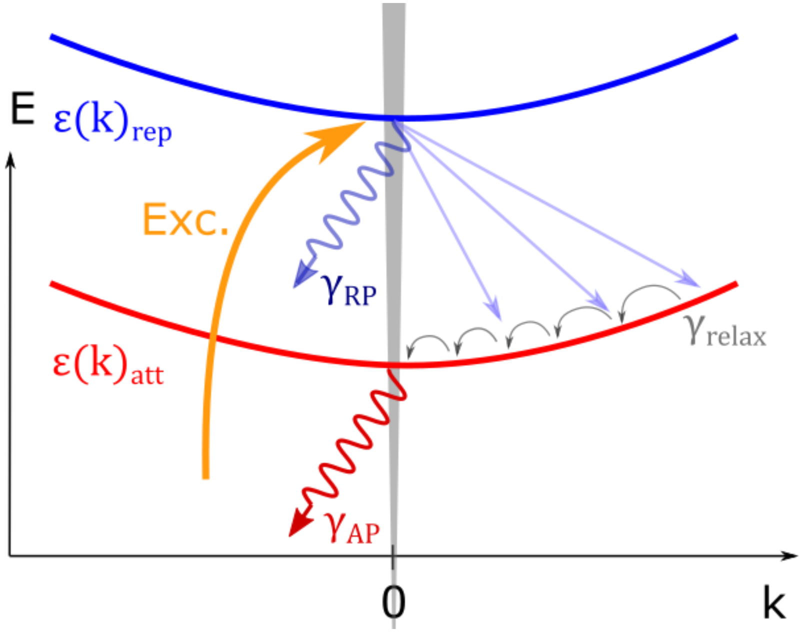
$f_{AP} \sim n_F\, f_X \ \sim V_{gate}$

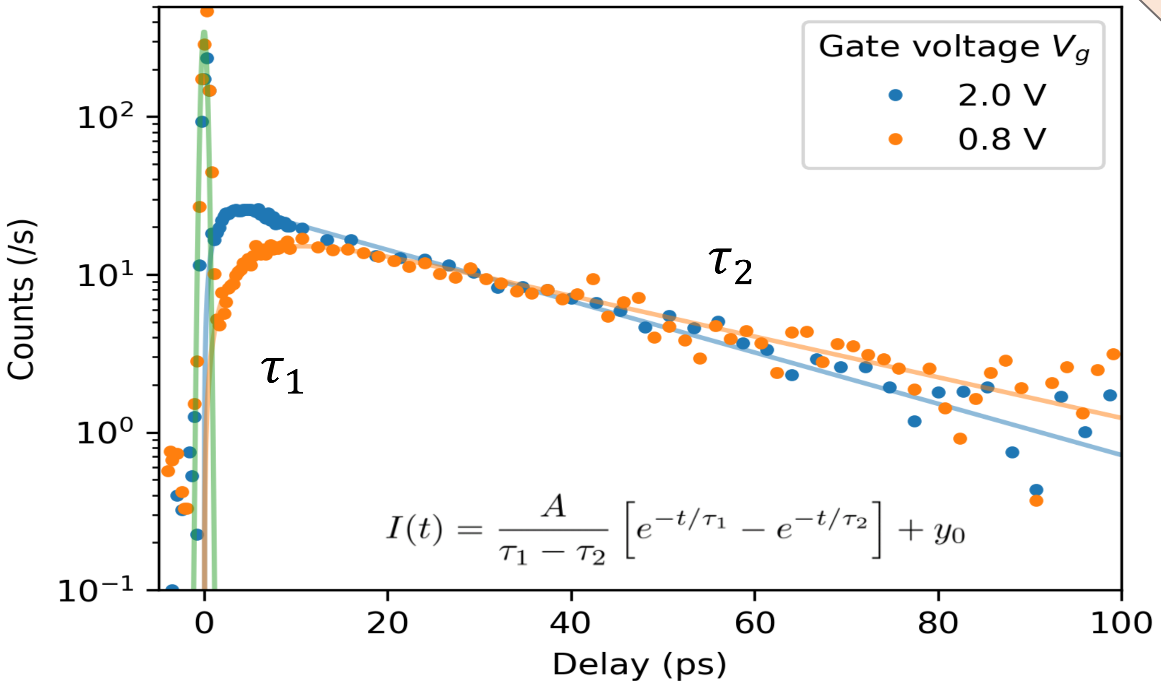
→ **Transfer of oscillator strength**

Fermi-polaron polaritons: Sidler et al., *Nature Phys* **13,** 255–261 (2017)
Tavis Cumming model for polarons: Imamoglu et al., *Comptes Rendus. Physique* 22.S4 (2021)

Decay of the dressed exciton

PRELIMINARY





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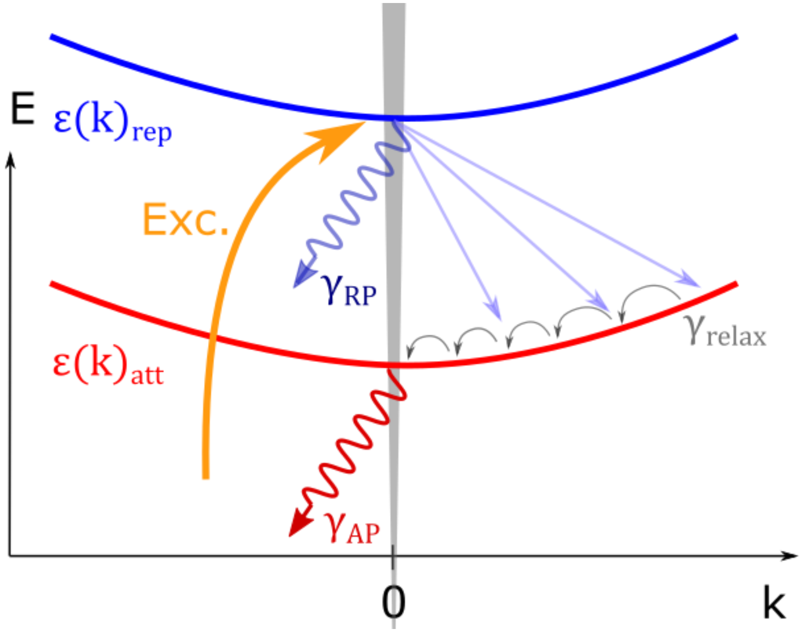
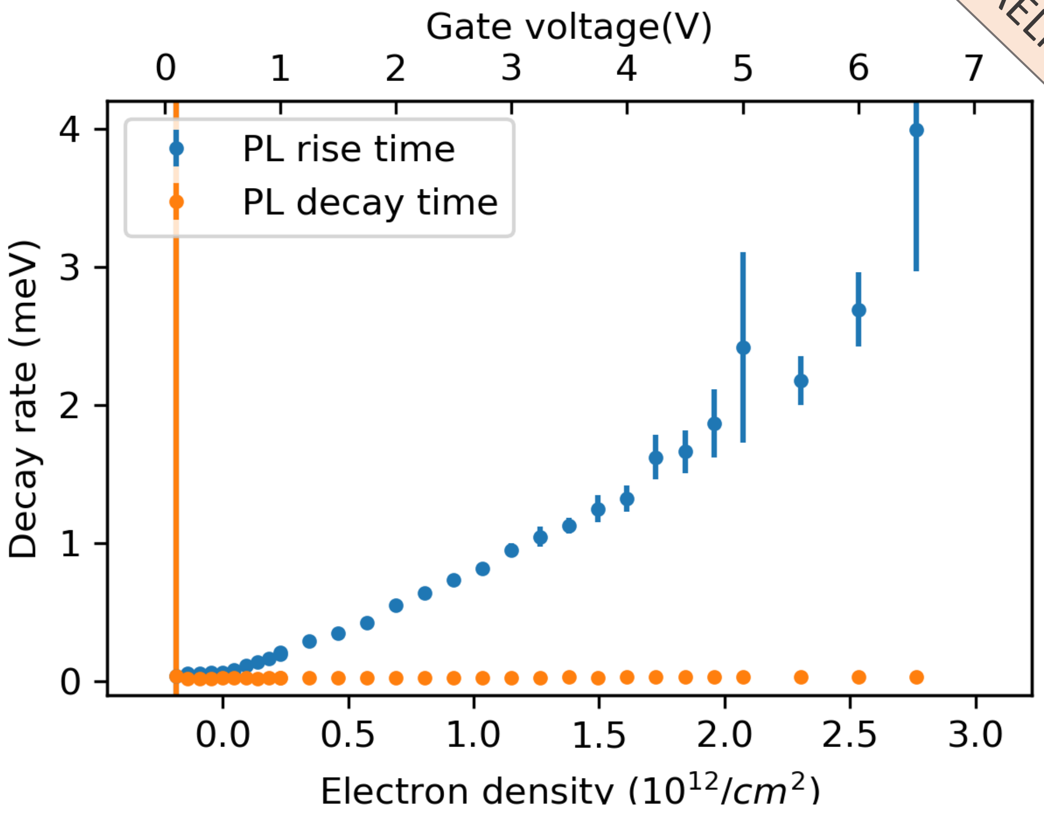
Decay of the dressed exciton

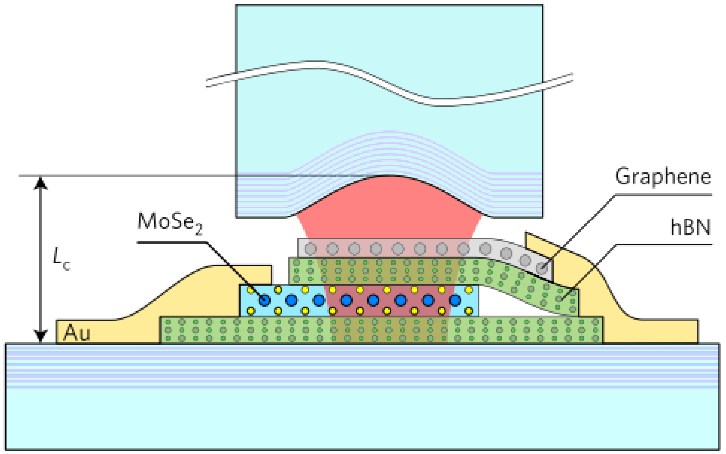




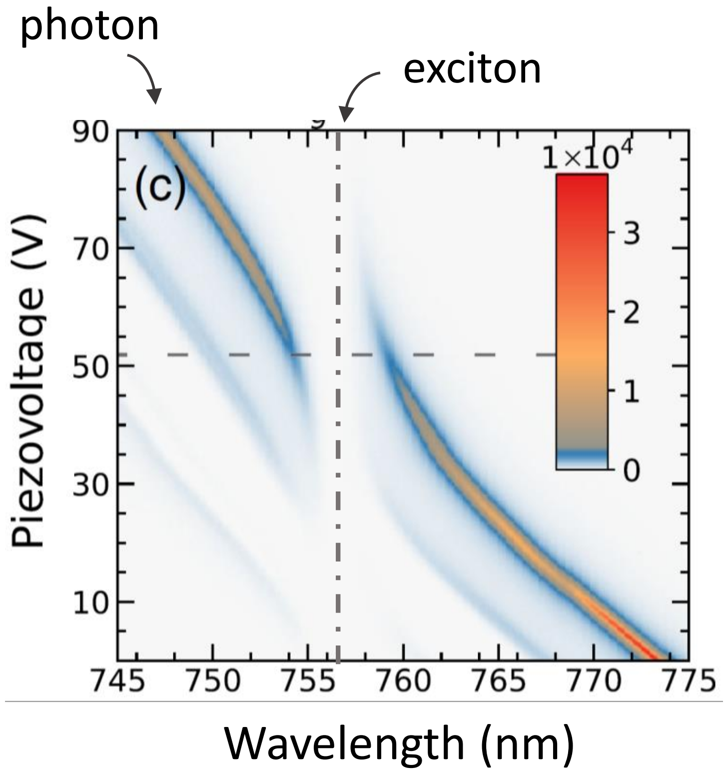
PRELIMINARY

Fermi-polaron polaritons: Sidler et al., *Nature Phys* **13,** 255–261 (2017).

Embedding TMDs into cavities



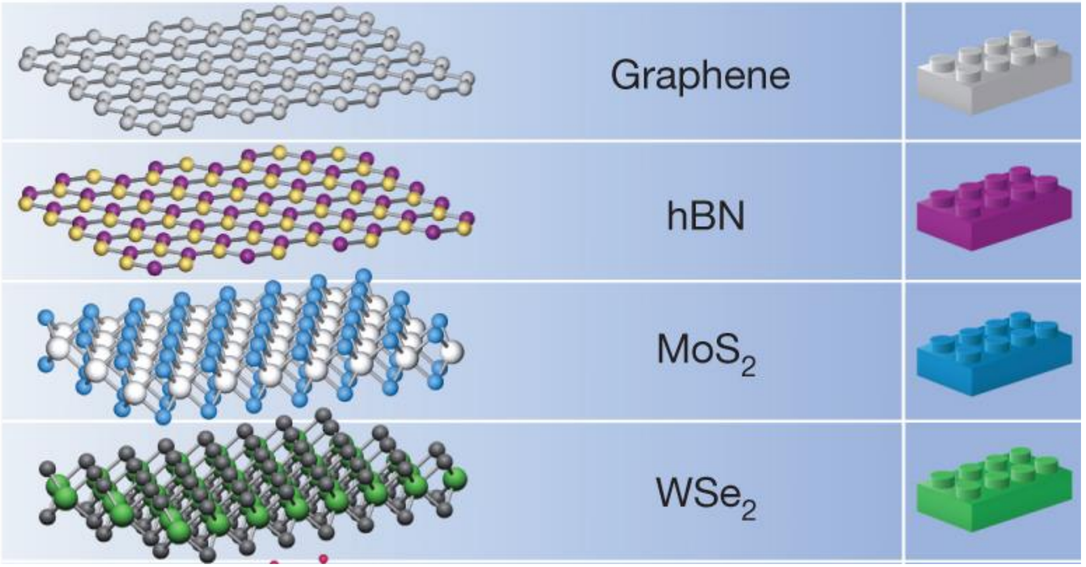
Taken from Sidler et al., *Nature Phys* **13,** 255–261 (2017).



- **Polaritons** = hybrid exciton-photon state
- **Nonlinear optics**
  e.g. photon blockade
- **Polaritons + electron gas**
  → enhanced interaction
- **Bose-Fermi mixtures**

Interacting polarons polaritons: Tan, …, **AB,** et al., *Physical Review X*, *10*(2), 021011 (2020).

Conclusion



Taken from: AK Geim & IV Grigorieva *Nature* **499**, 419-425 (2013)

Impurity physics

Quantum optics

Strongly correlated systems

Bose Fermi mixtures

…

Teams and collaborations

Few-body experiments
Jochim group

Philipp Preiss
Gerhard Zürn
AB
Simon Murmann
Thomas Lompe
Vincent Klinkhamer
Jan Hendrik Becher
Ralf Klemt
Lukas Palm

Potassium lattice experiment
Köhl group

Bilayer experiments
Marcel Gall, Nicola Wurz,
Jeffrey Chan, Jens Samland

Current lattice team:
Nick Klemmer
Janek Fleper
Valentin Jonas
AB

Polarons in TMDs
Imamoglu group

AB
Li Bing Tan
Tomasz Smolenski
Francesco Colangelo
Olivier Huber
Alperen Tugen
Martin Kroner

Thank you!