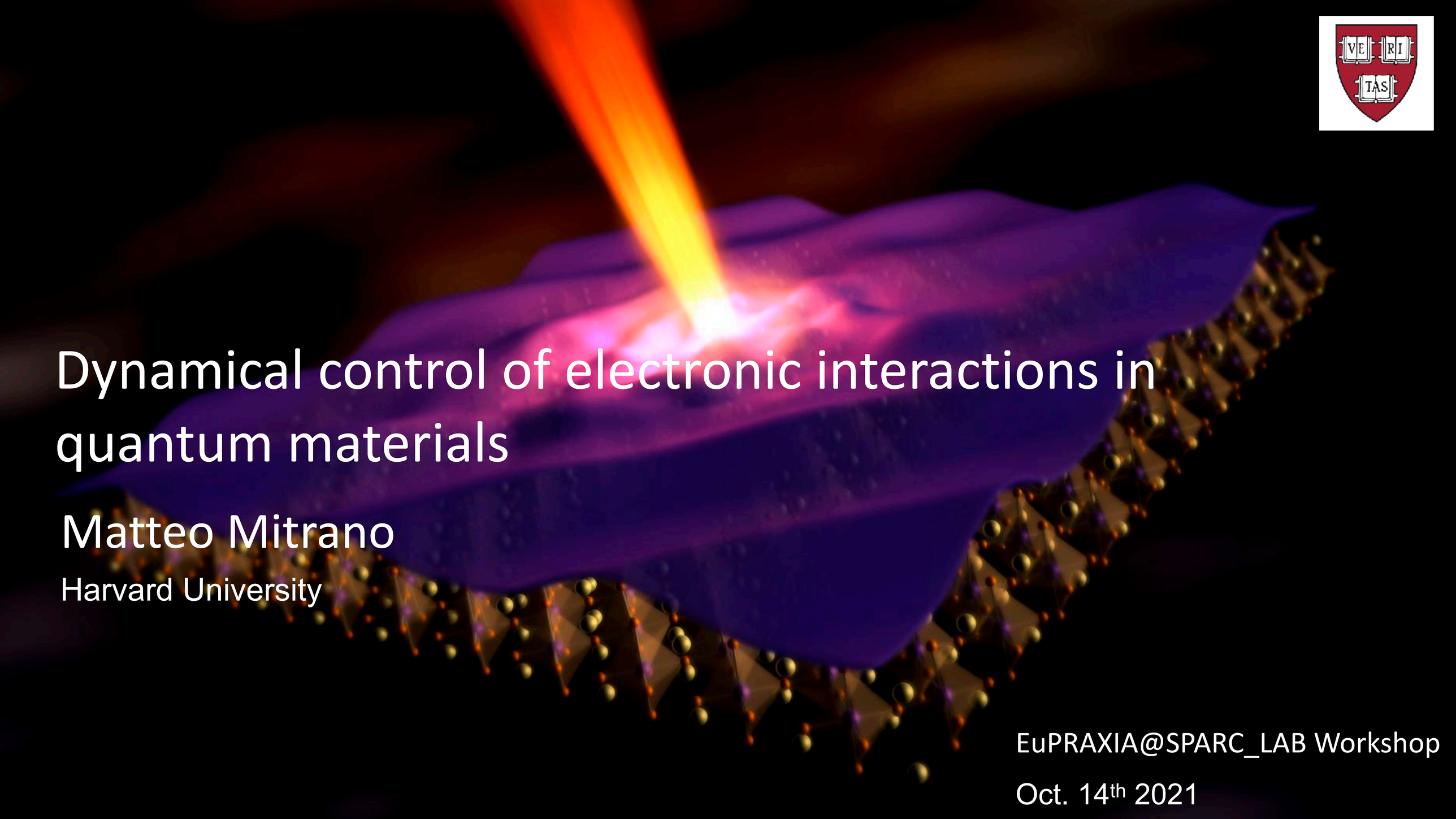


Dynamical control of electronic interactions in quantum materials

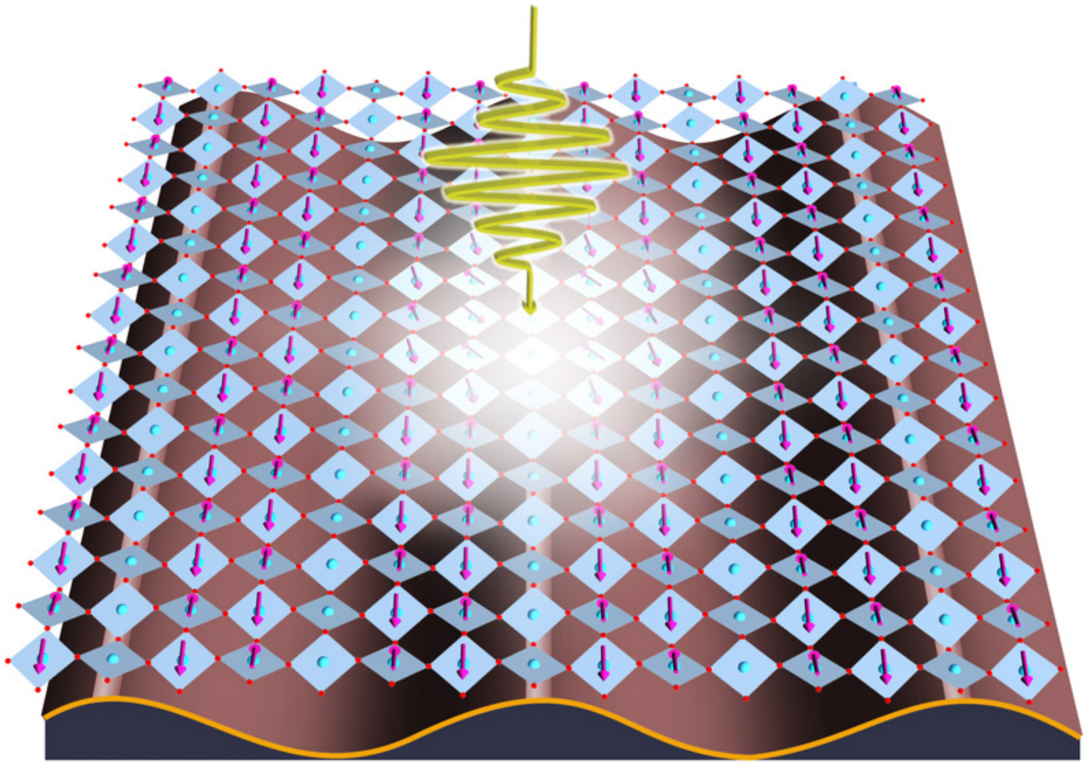
Matteo Mitrano

Harvard University

EuPRAXIA@SPARC_LAB Workshop

Oct. 14th 2021

Optical control of quantum materials



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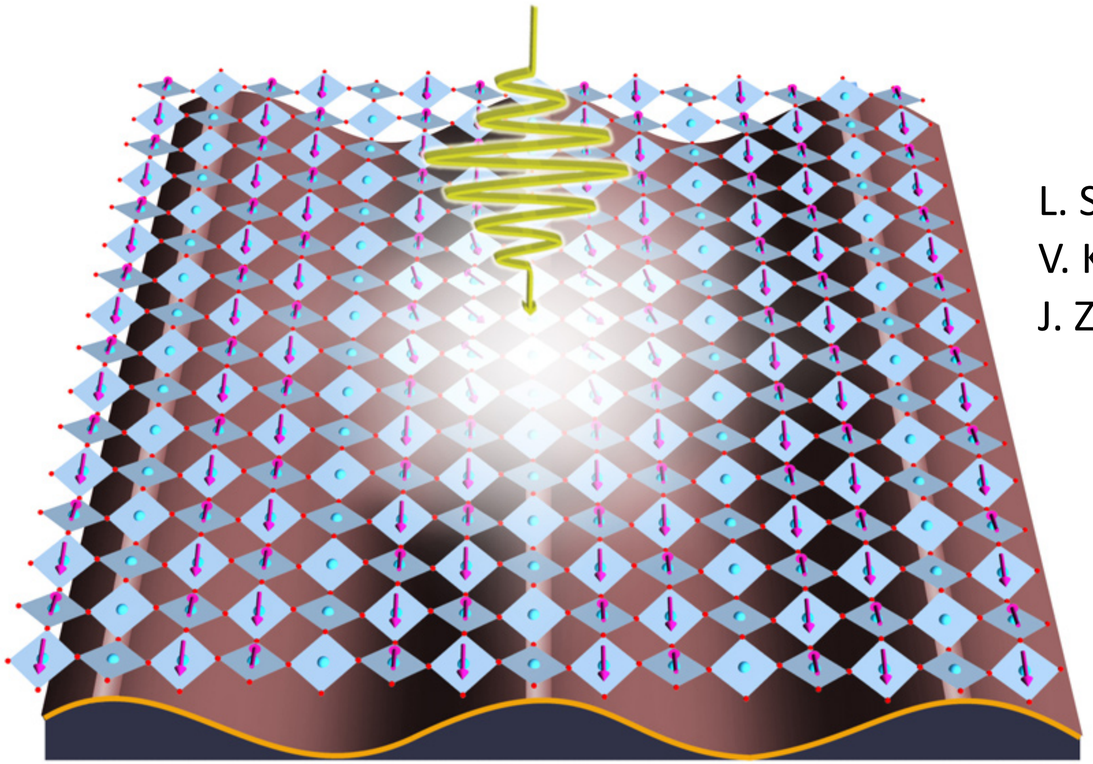

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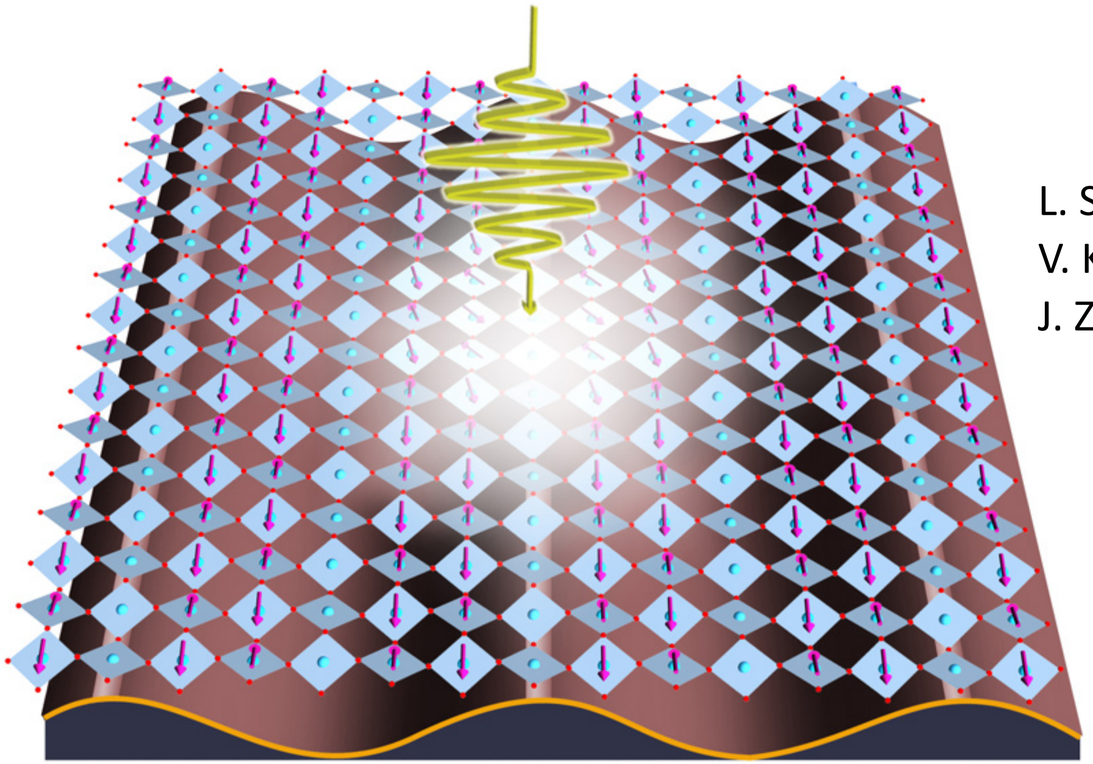

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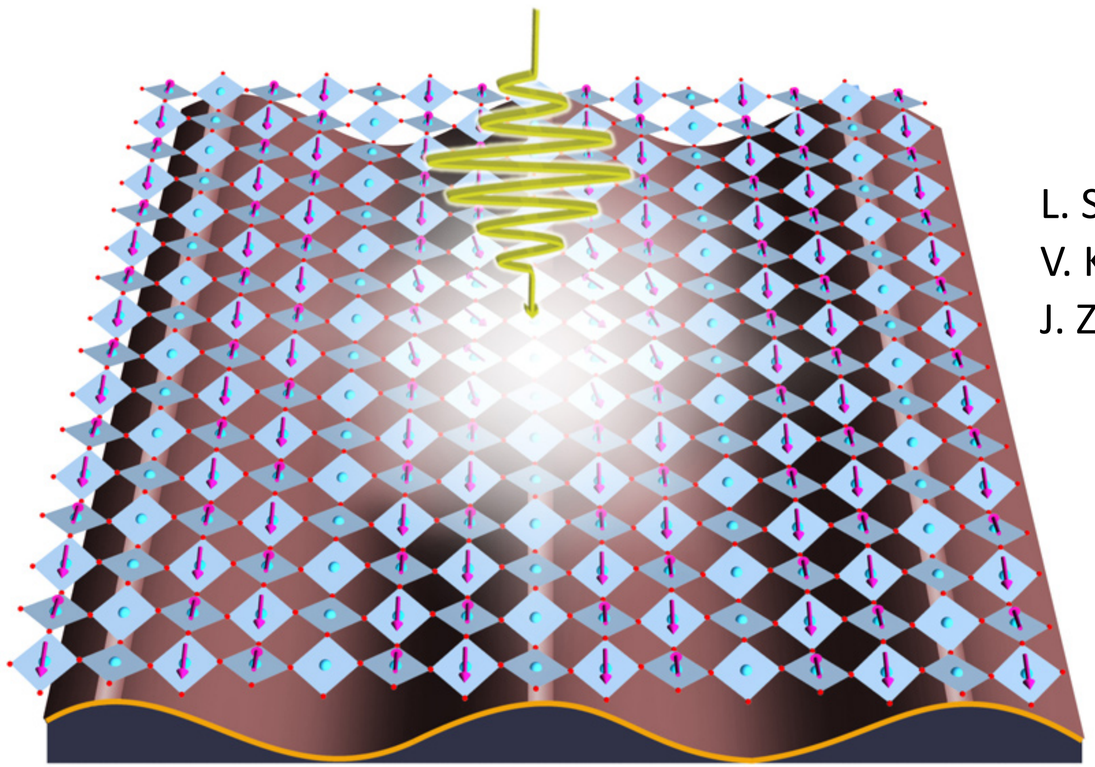

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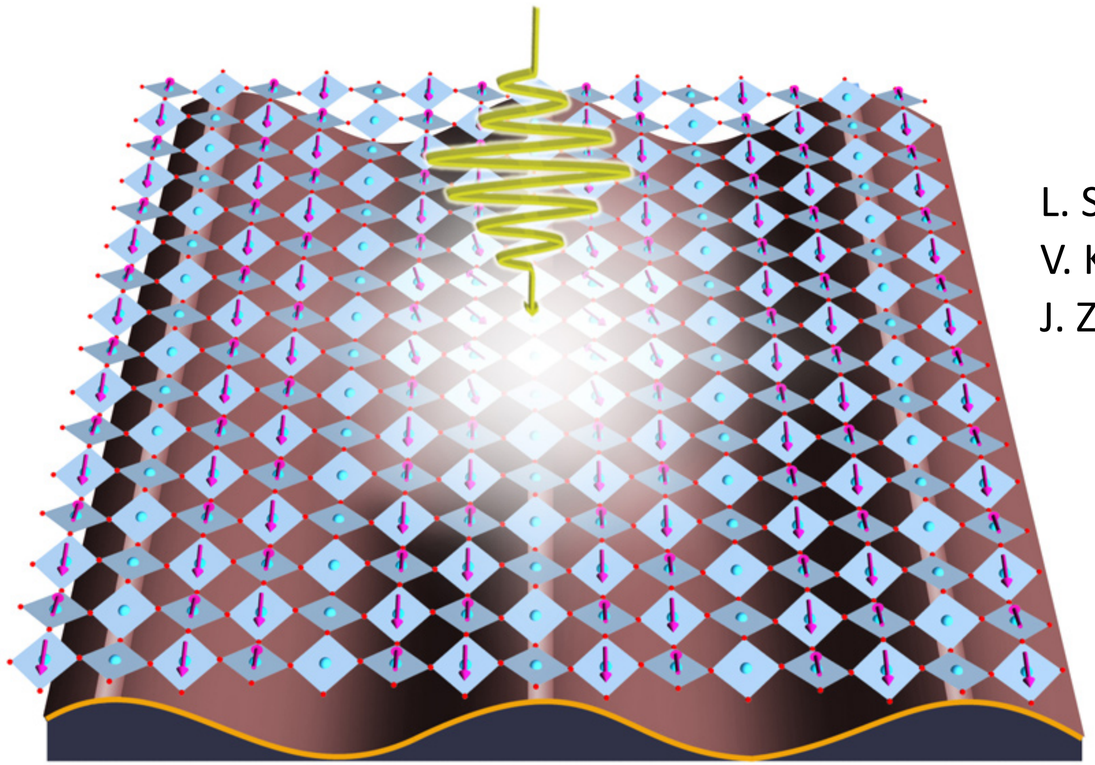

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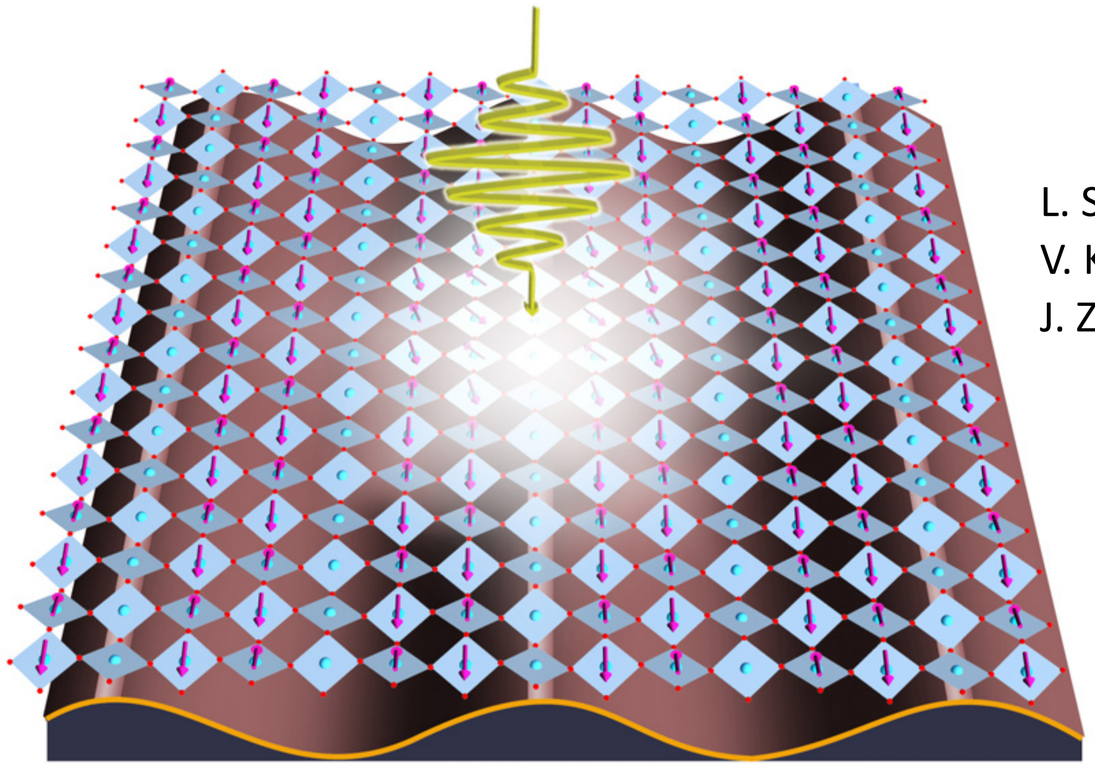

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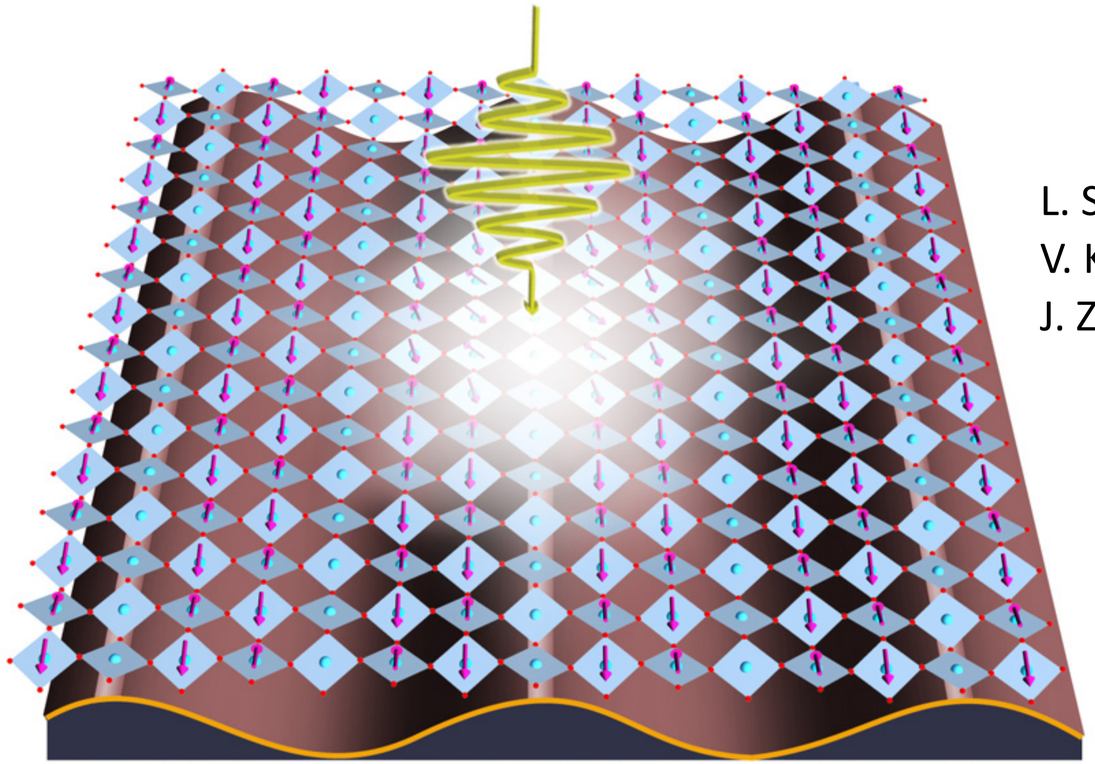

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D. Fausti et al. Science (2011)
W. Hu et al. Nature Materials (2014)
M. Mitrano et al. Nature (2016)
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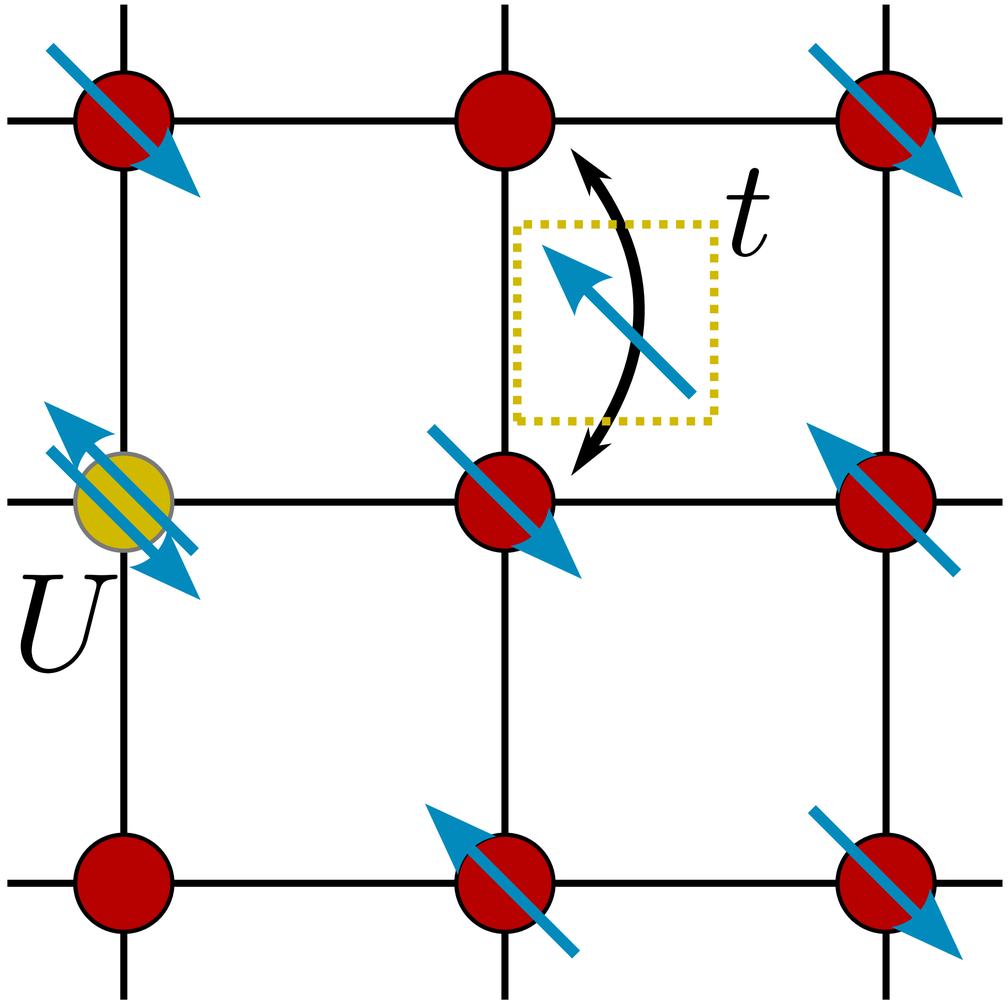
Can we directly tune electronic interactions with light?

D. R. Baykusheva et al. arXiv:2109.13229 (2021)

Interactions in strongly correlated electron systems



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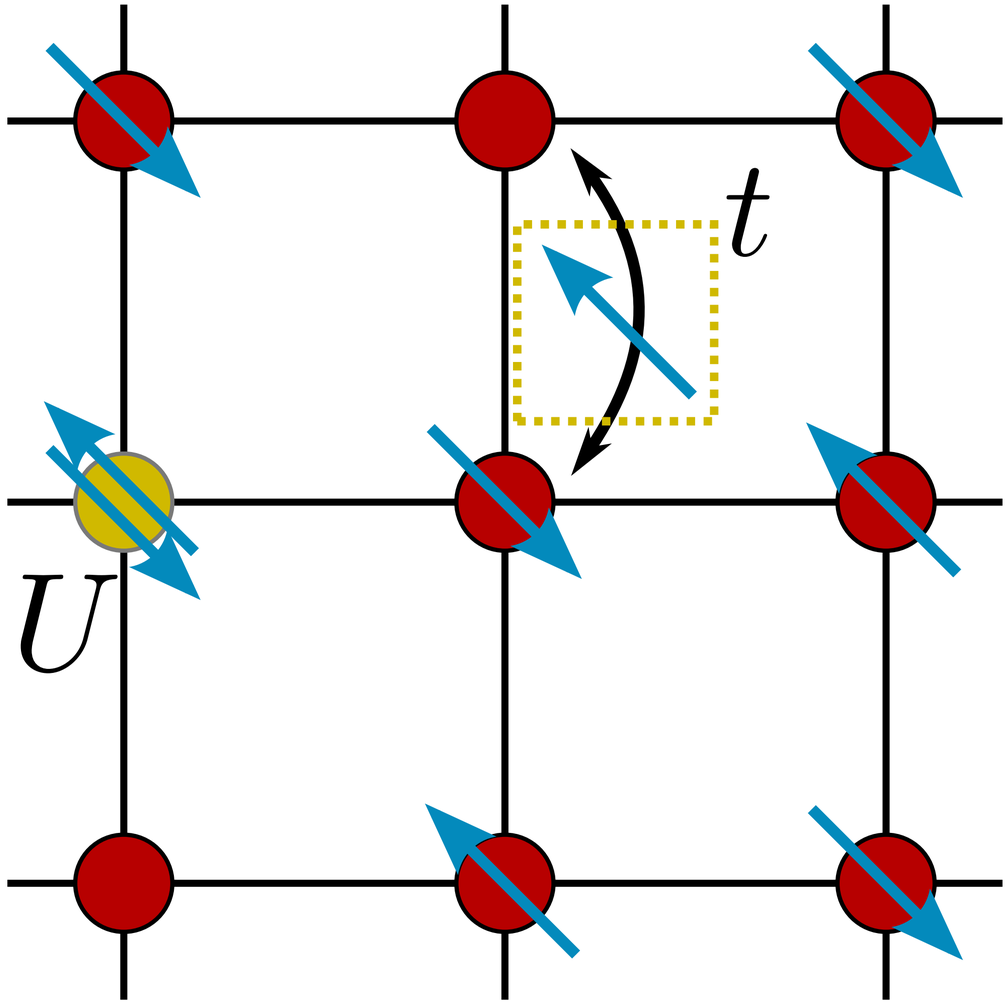

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Strong fields $E_0 \sim 1\ \mathrm{eV/\mathring{A}}$ can directly modify electronic interactions

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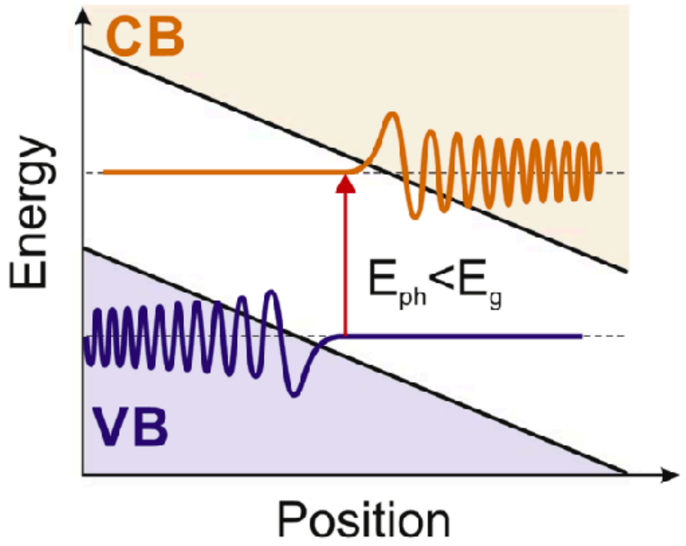

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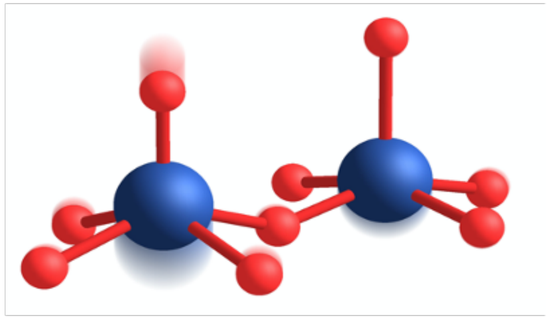

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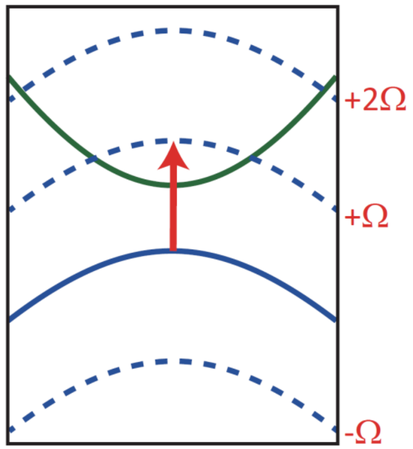

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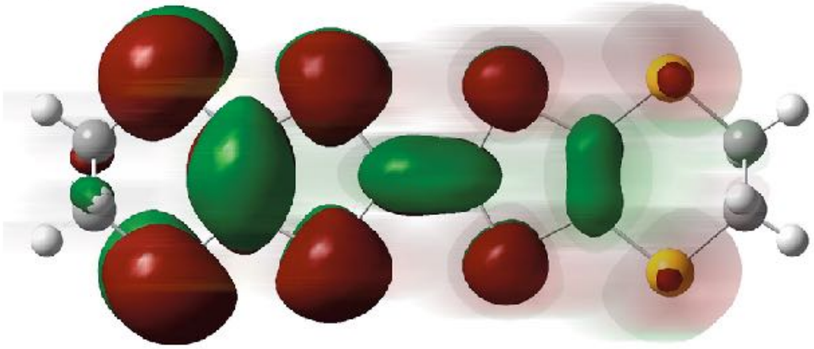

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  T. Oka & S. Kitamura, Annu. Rev. Cond. Matt. Phys. (2019)

Modifying the Hubbard *U* in the solid state

Solid state equivalent of Feshbach resonances in optical lattices

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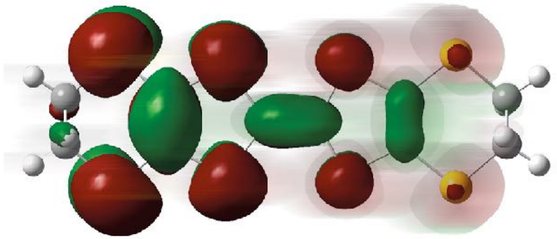

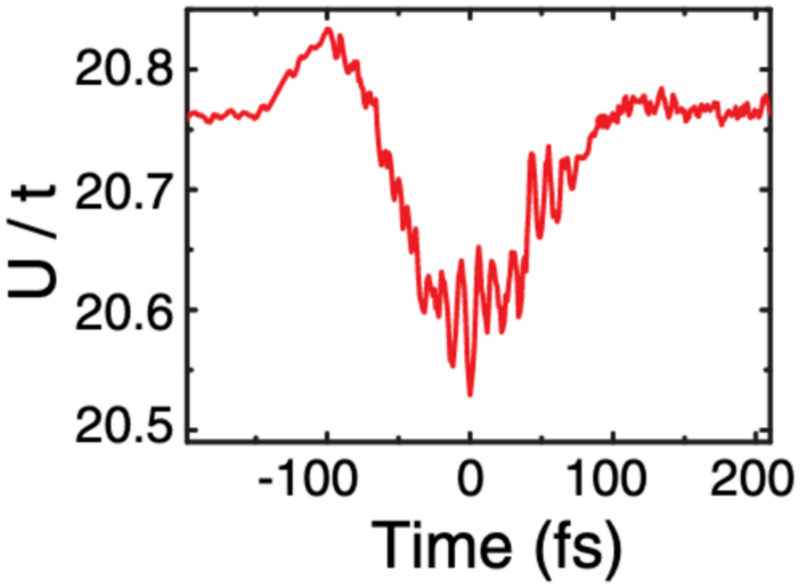

ET-F_2TCNQ organic insulator

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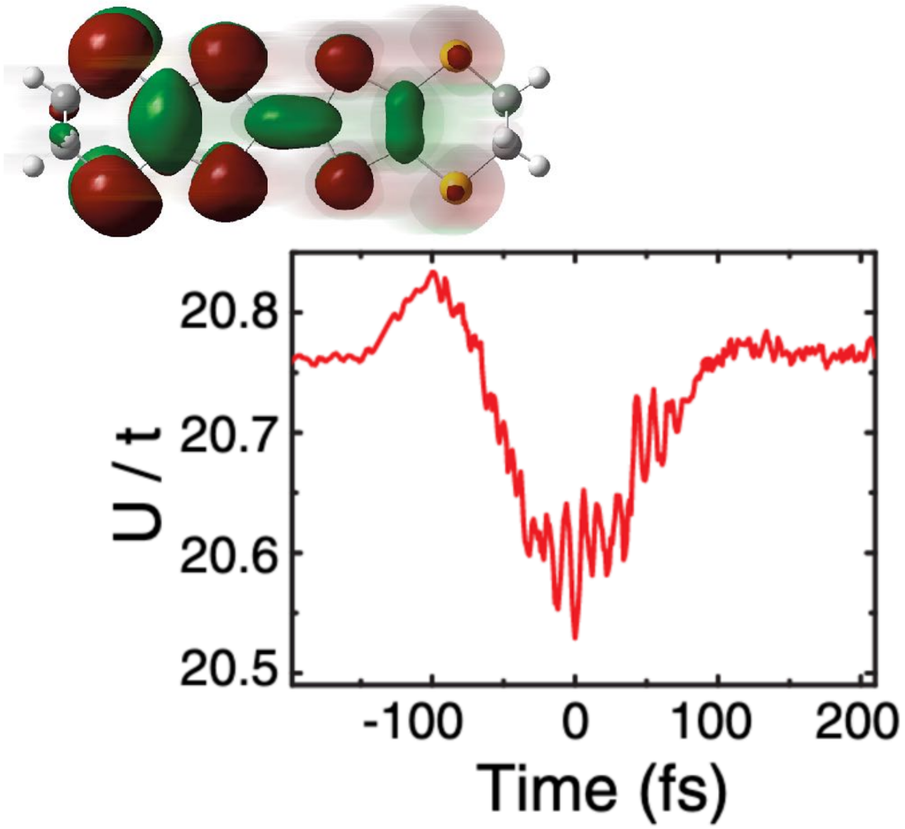

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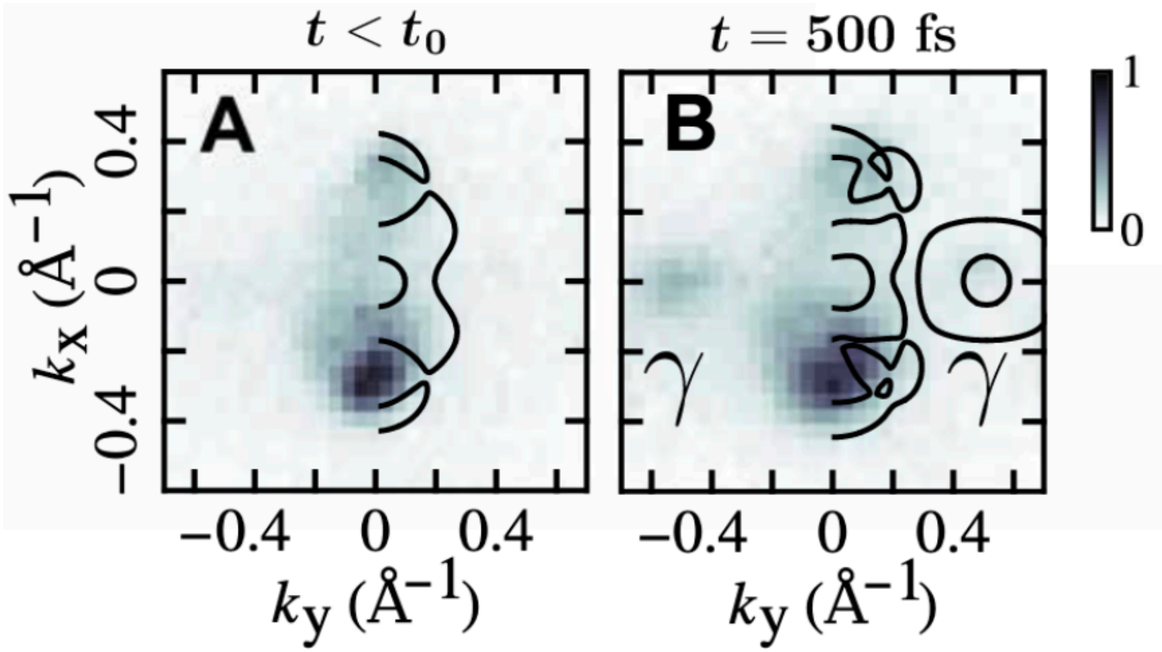


T_d-$MoTe_2$ type-II Weyl SM

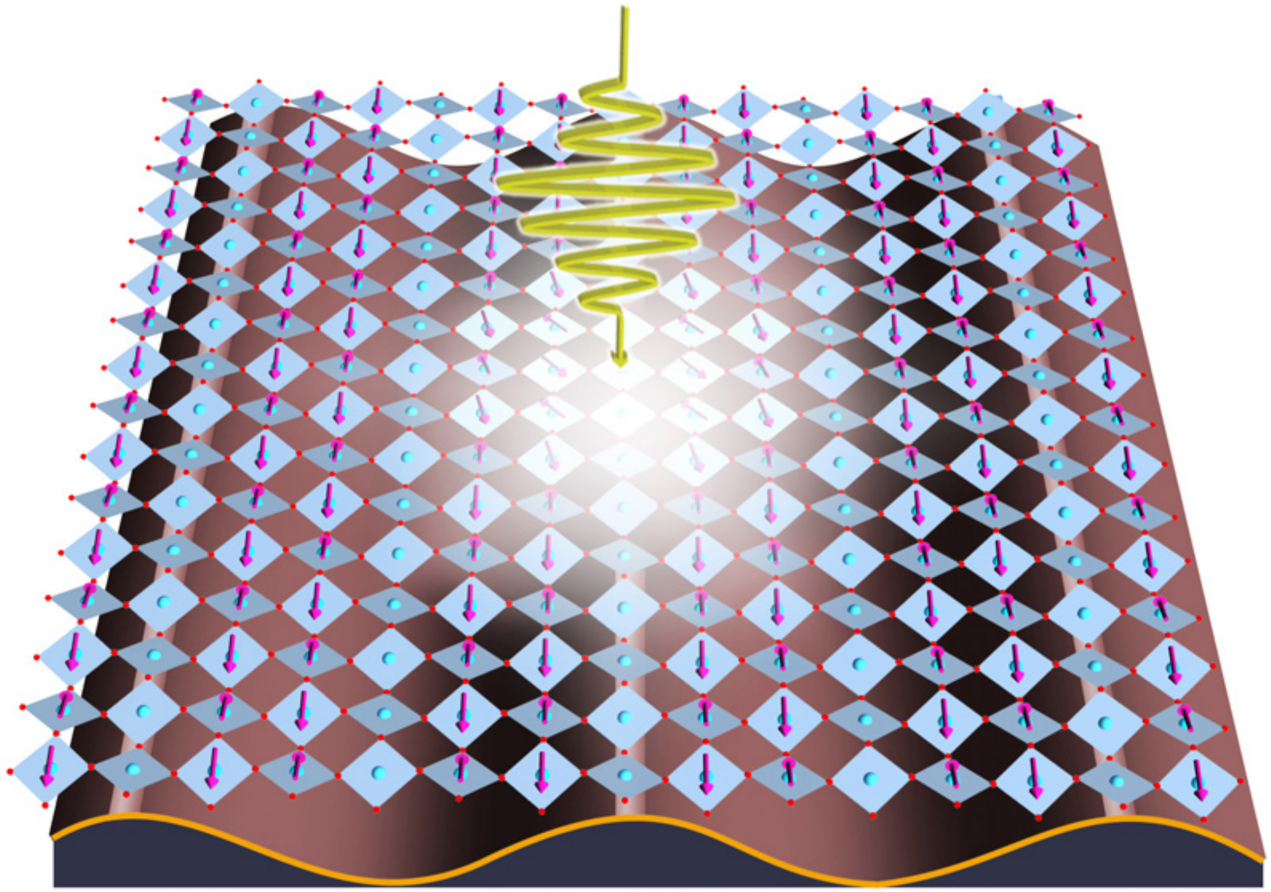
Beaulieu et al. Sci. Adv. (2015)

Dynamical control of the Hubbard *U* in the copper oxides

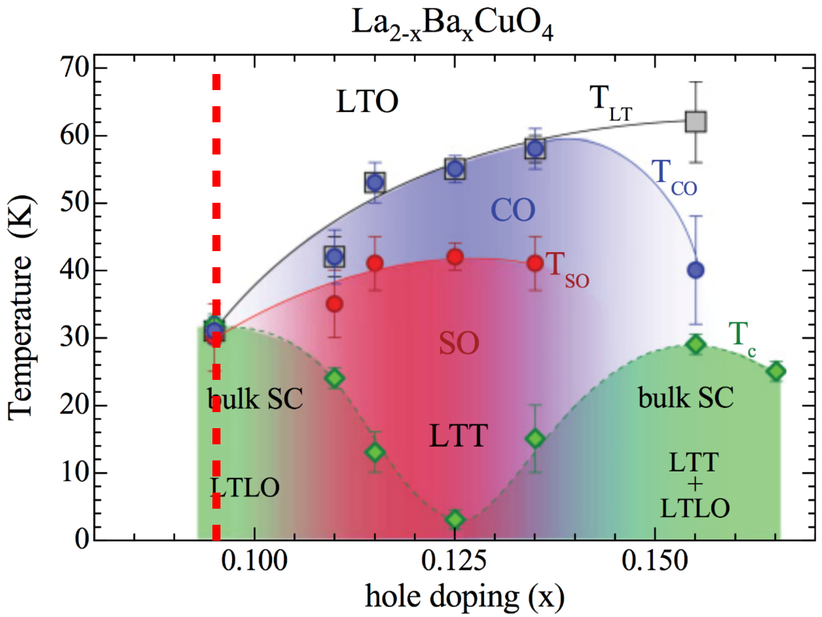
Hubbard U is relevant to:

- Quasiparticle effective mass
- Magnetic superexchange
- Superconducting pairing
- Critical temperature

And more…

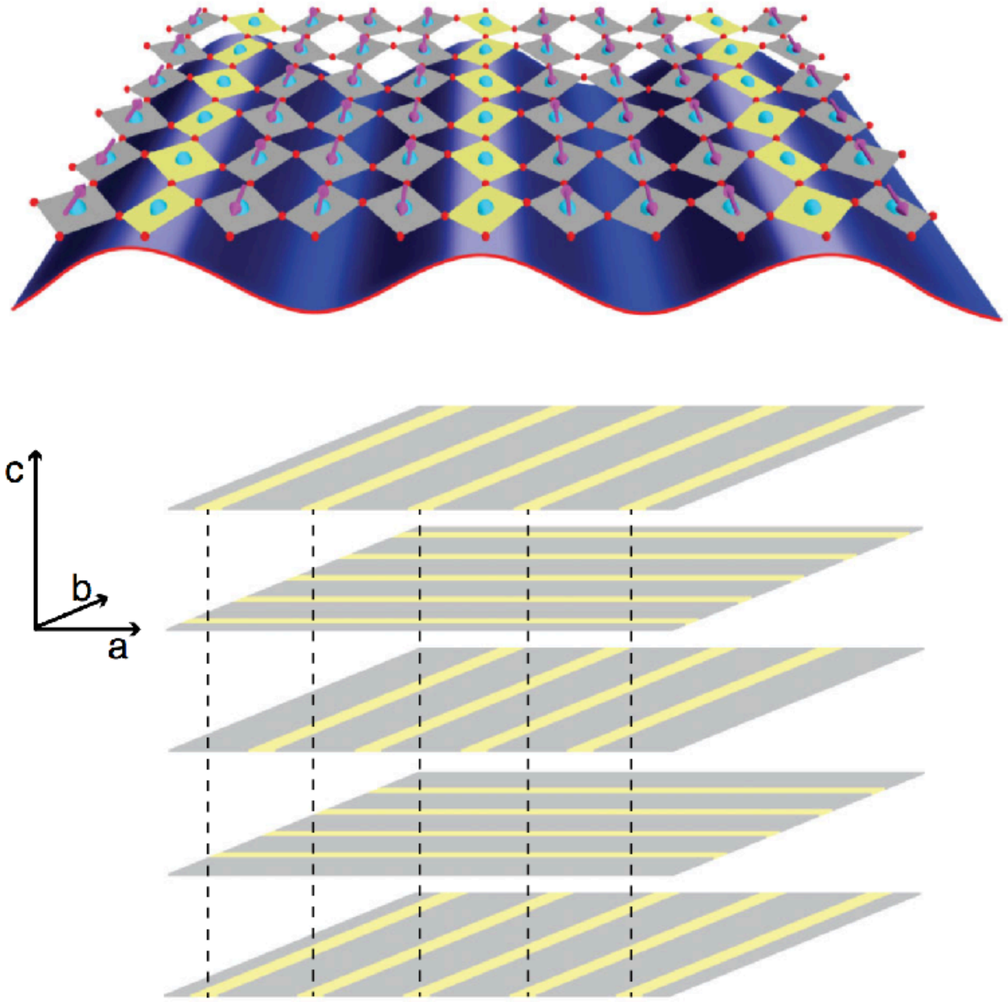


Renormalizing effective interactions in $La_{2-x}Ba_xCuO_4$



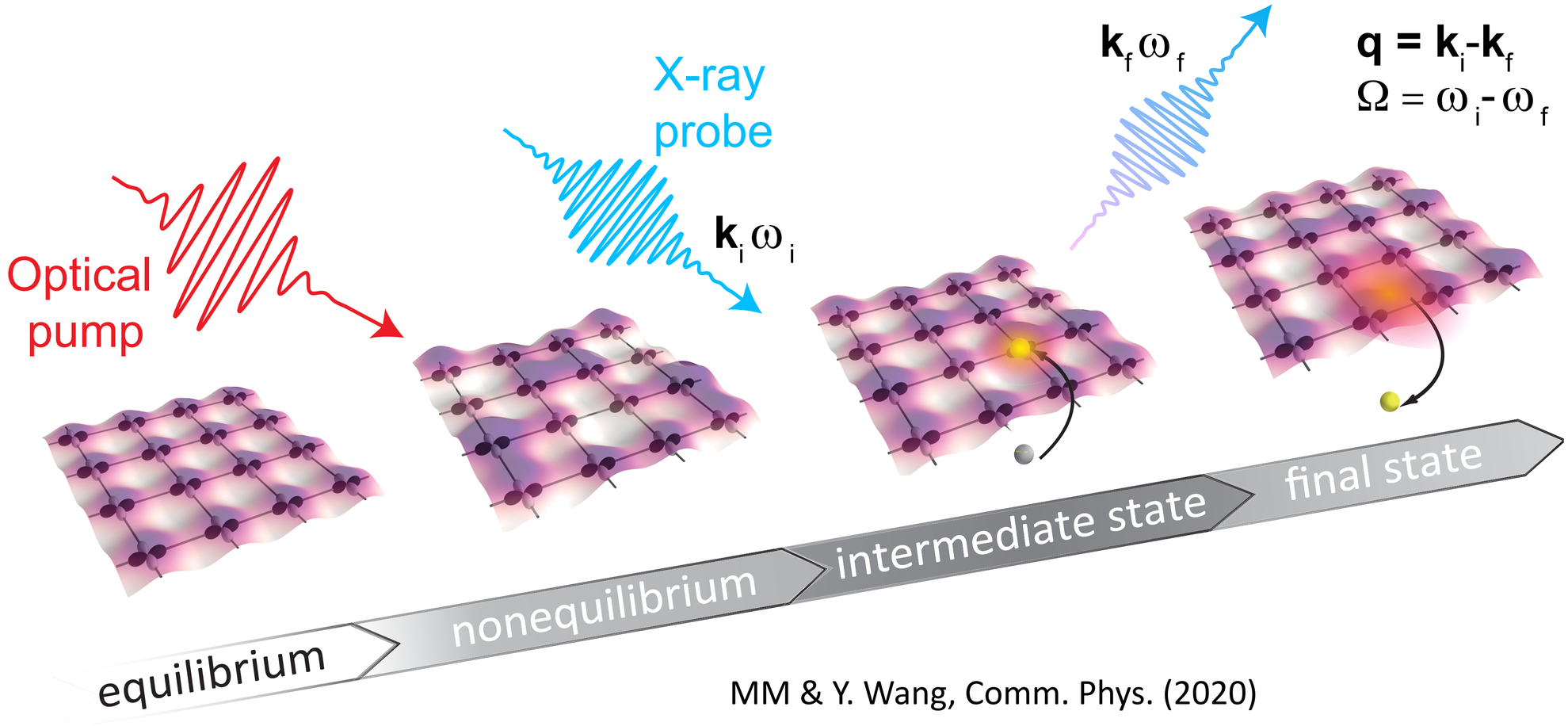
Hücker et al. PRB (2011)

- Striped single layer cuprate
- Strong 1/8 anomaly
- Coexisting SC and CO



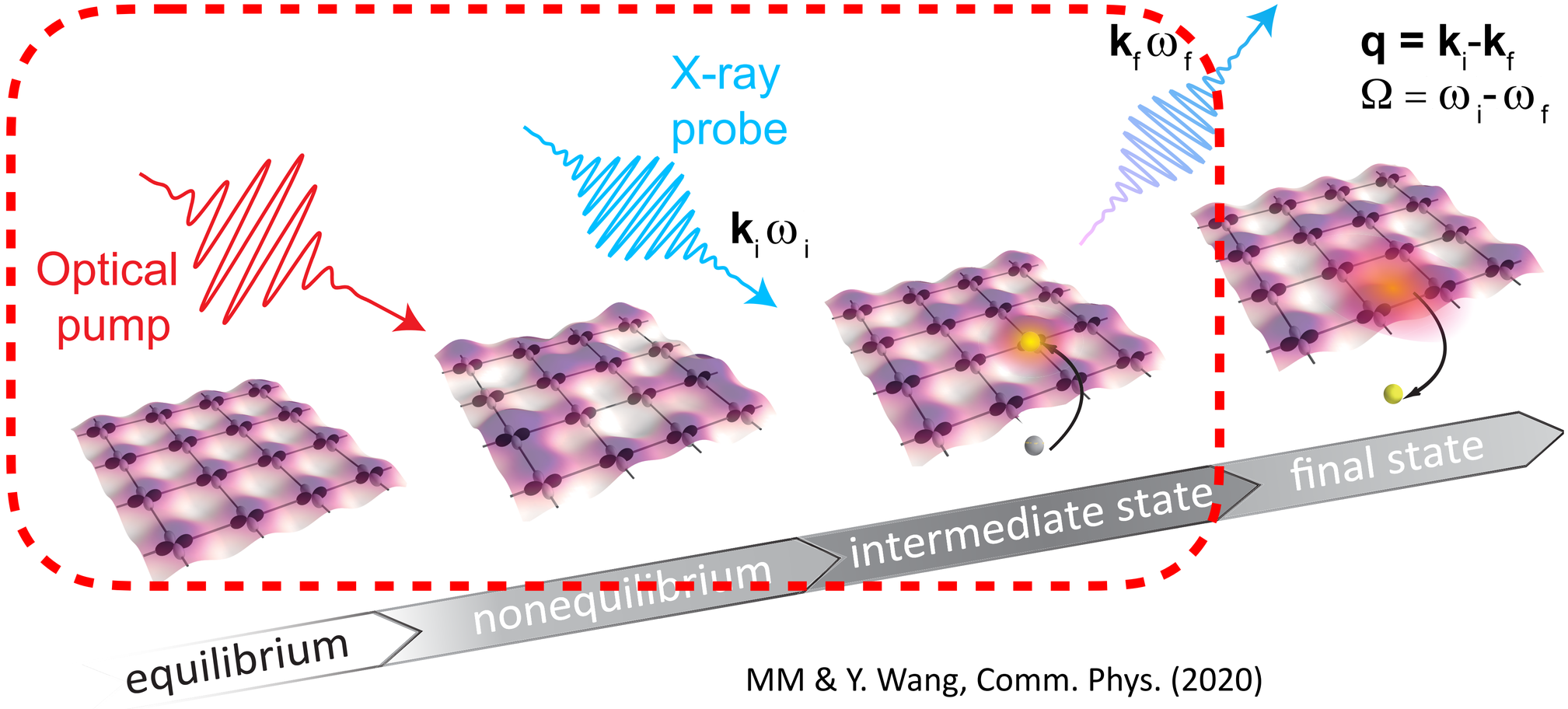
Först et al. PRL (2014)

Measuring transient electronic interactions



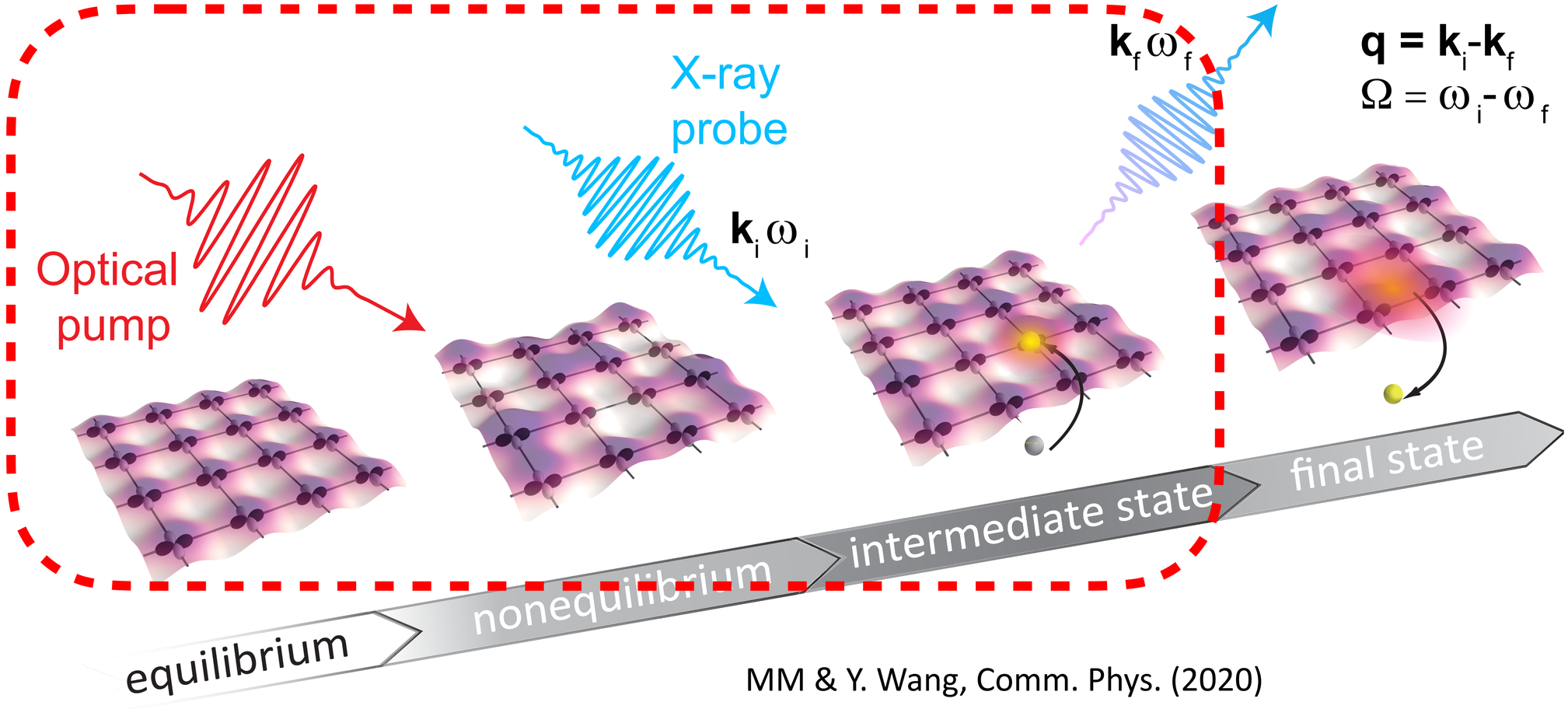
MM & Y. Wang, Comm. Phys. (2020)

Measuring transient electronic interactions



MM & Y. Wang, Comm. Phys. (2020)

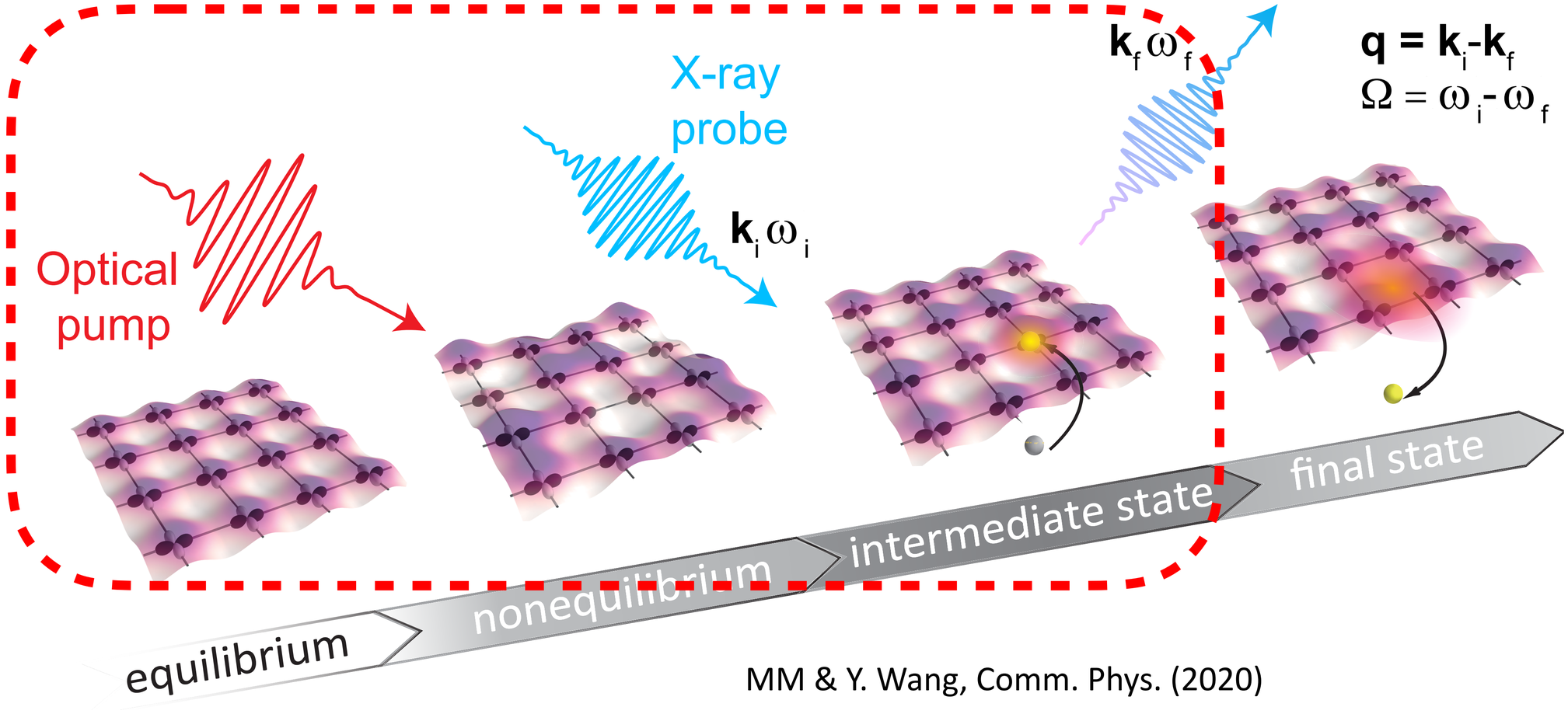
Measuring transient electronic interactions



MM & Y. Wang, Comm. Phys. (2020)

Probing electronic states through time-resolved X-ray absorption

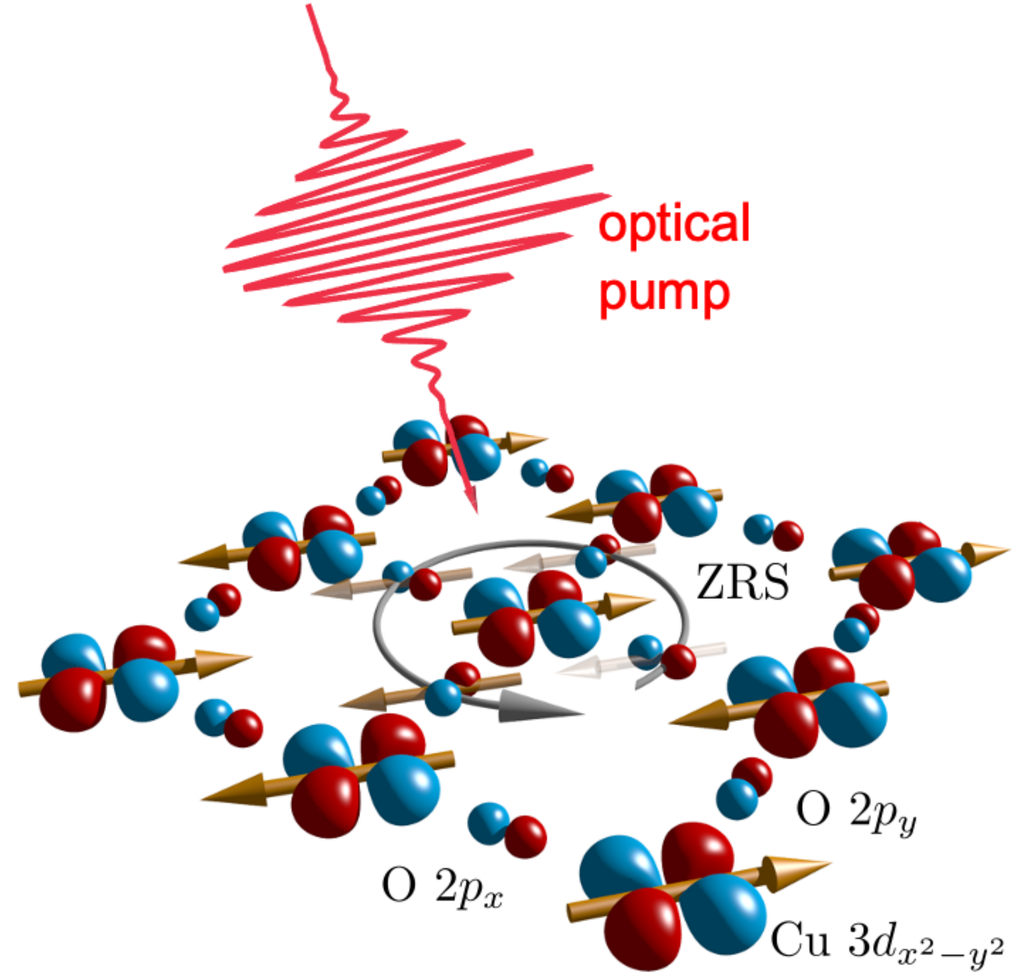
Measuring transient electronic interactions

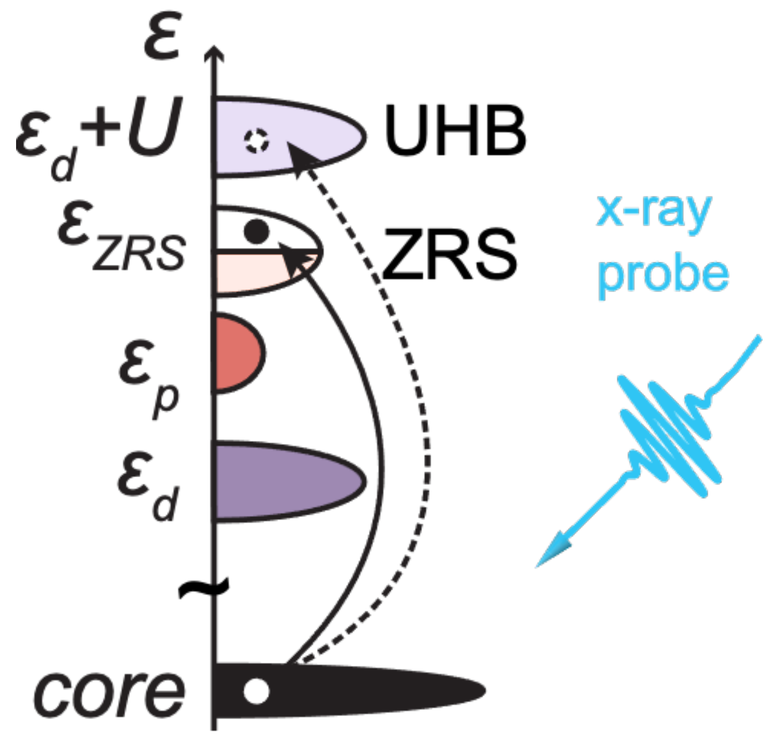


MM & Y. Wang, Comm. Phys. (2020)

Probing electronic states through time-resolved X-ray absorption

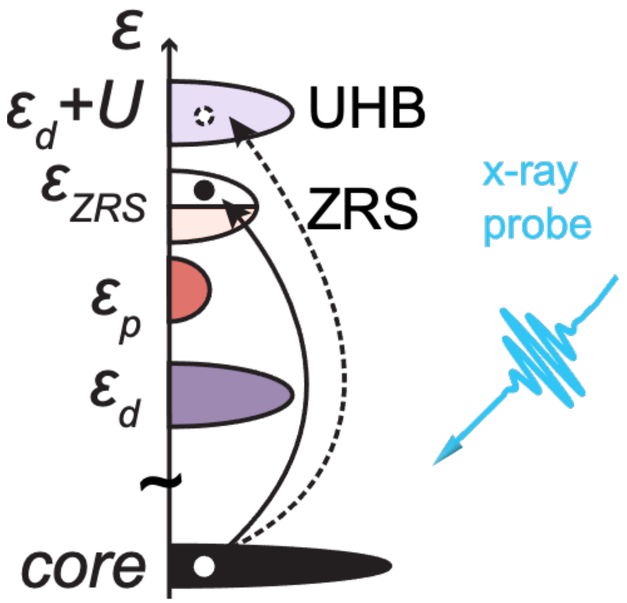
Measuring transient electronic interactions



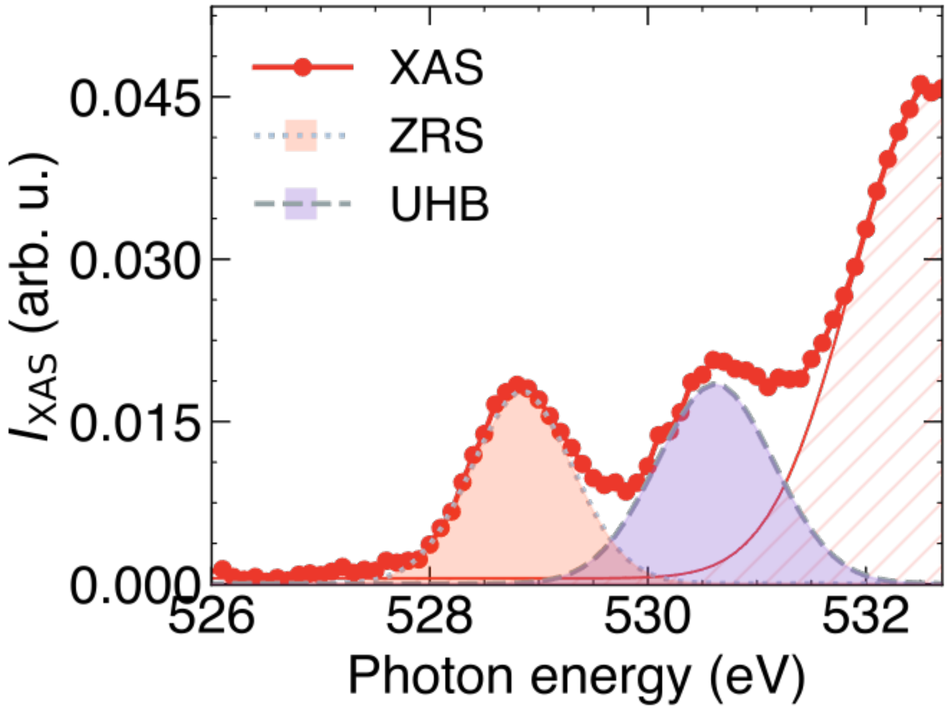


Probing electronic states through time-resolved X-ray absorption

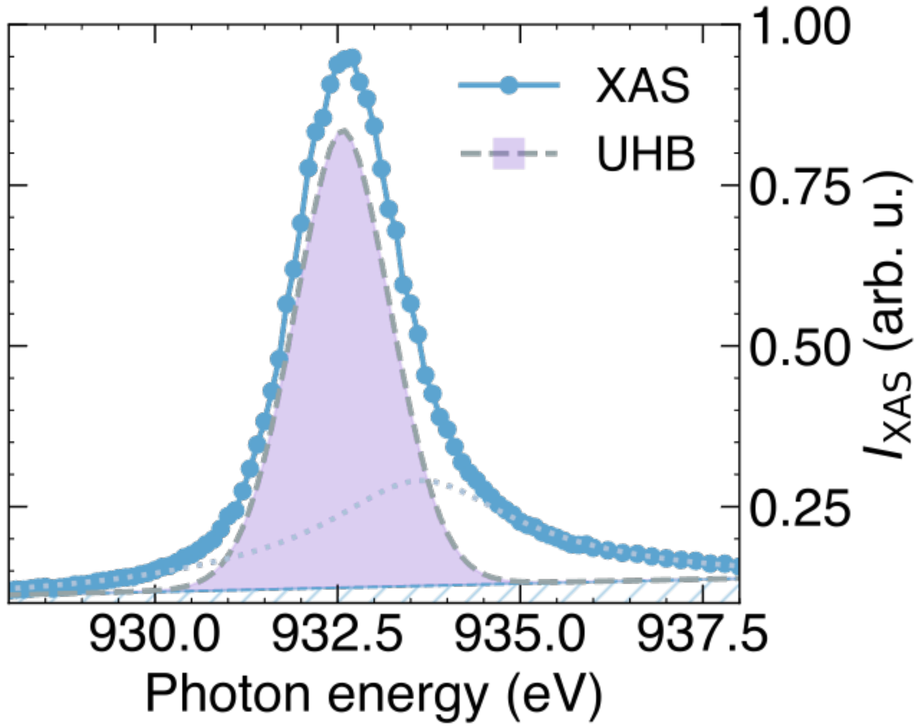
Measuring transient electronic interactions



O *K* edge $(1s \rightarrow 2p)$



Cu *L* edge $(2p \rightarrow 3d)$

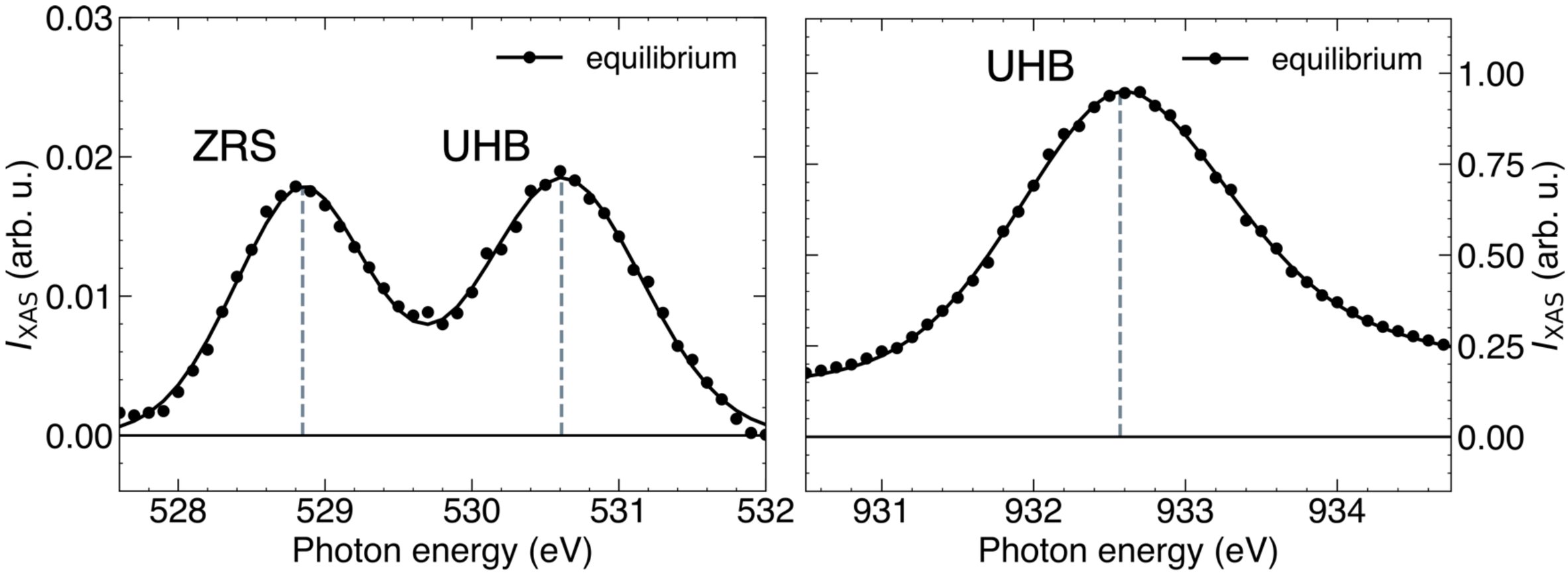


Probing electronic states through time-resolved X-ray absorption

Light-induced reshaping of the XAS spectrum

O K edge

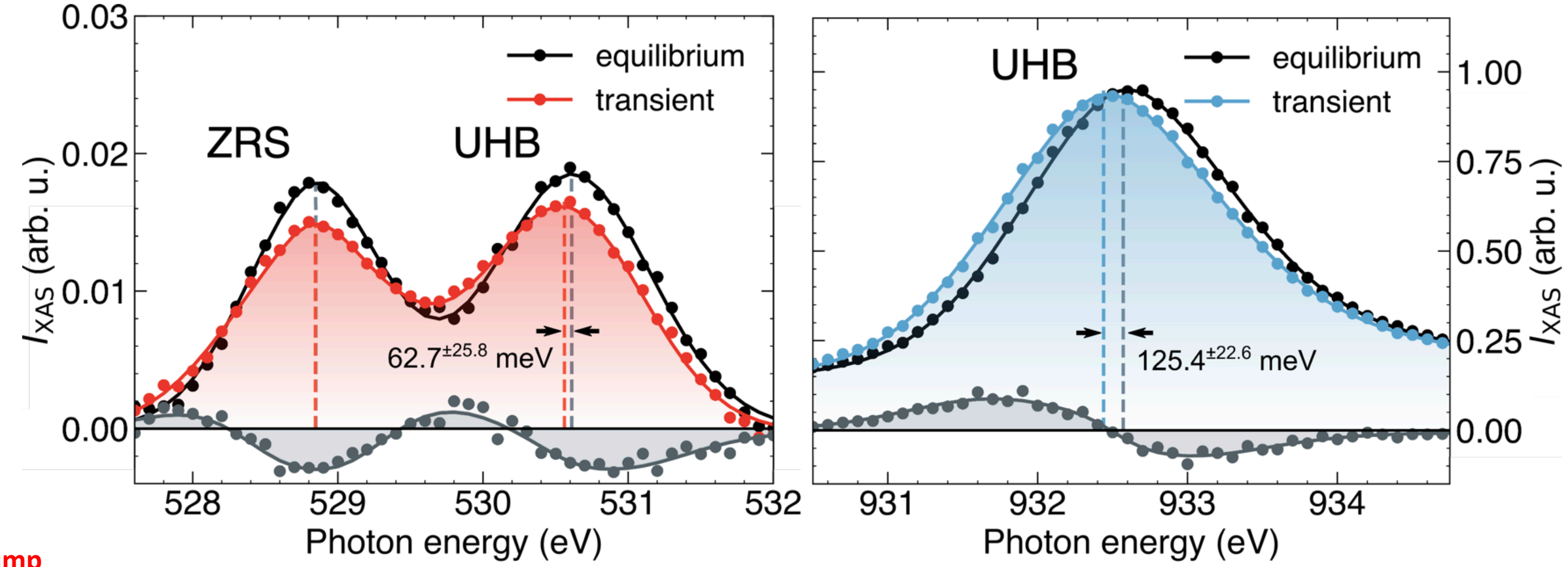
Cu L edge



Light-induced reshaping of the XAS spectrum

O K edge

Cu L edge

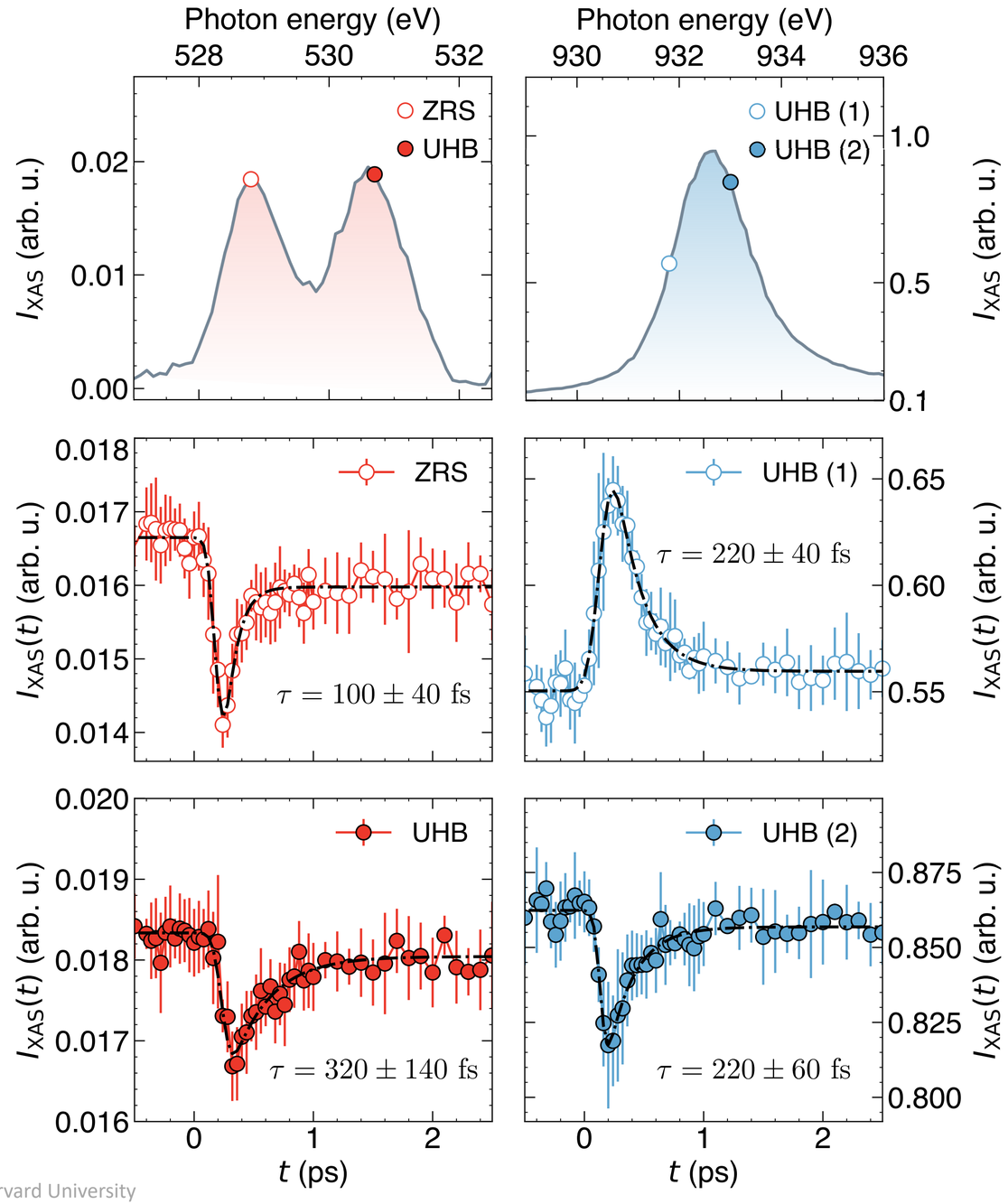


Pump
1.55 eV
12 MV/cm

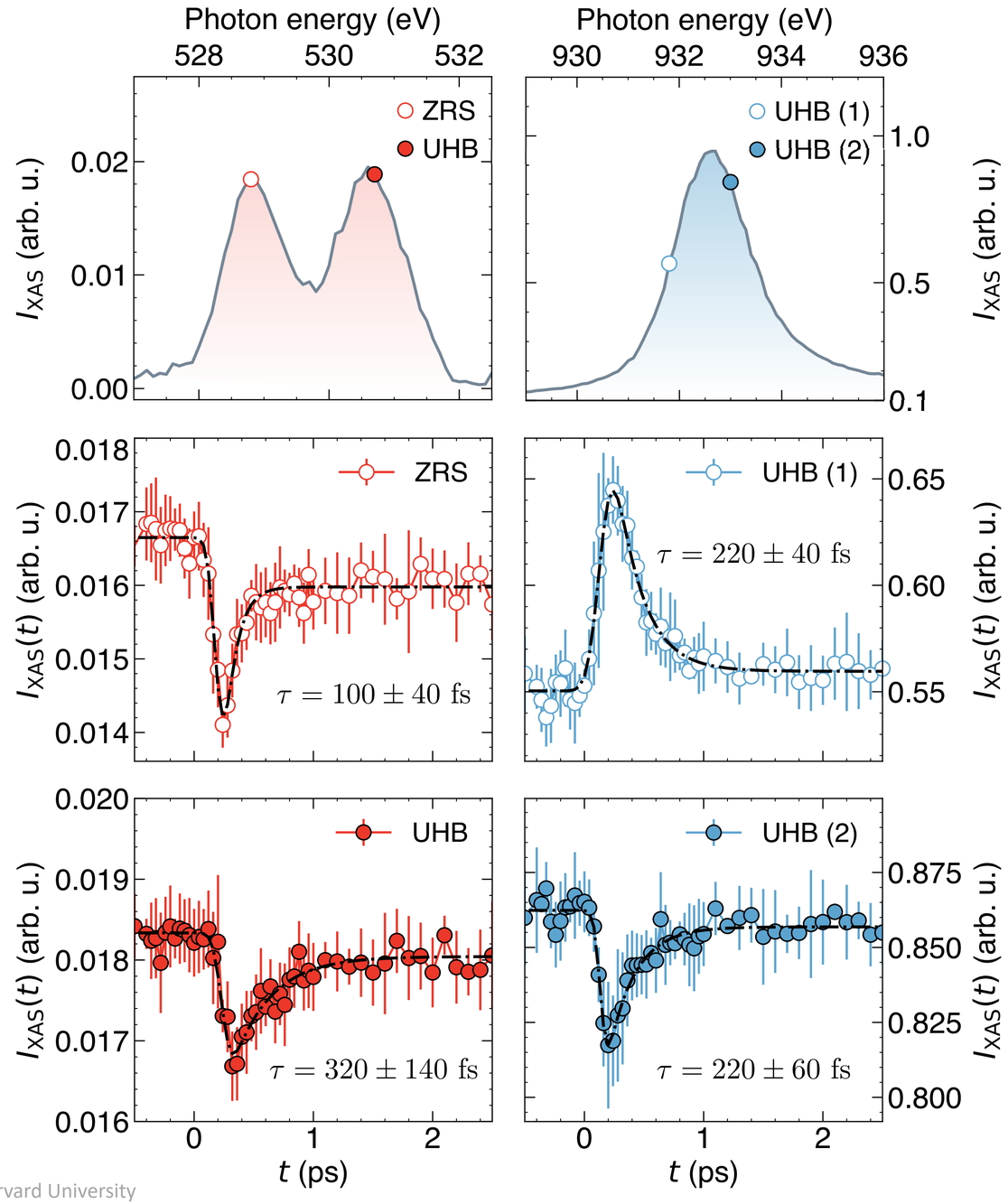
ZRS position remains fixed

UHB position redshifts

Light-induced reshaping of the XAS spectrum



Light-induced reshaping of the XAS spectrum



Holon-doublon recovery slower than valence carriers

$$\tau_{hd} \sim \exp\left(\alpha \frac{U}{t}\right)$$

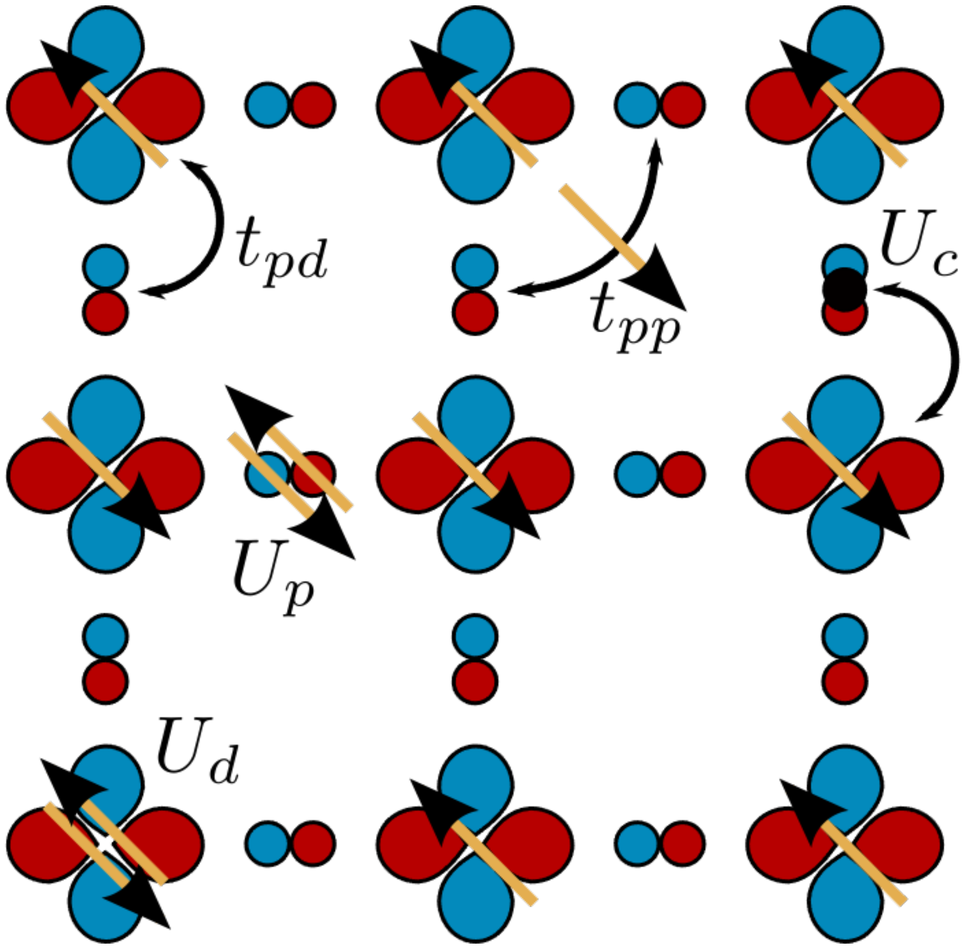
Cold atoms

N. Strohmaier et al. PRL (2010)
R. Sensarma et al. PRB (2010)

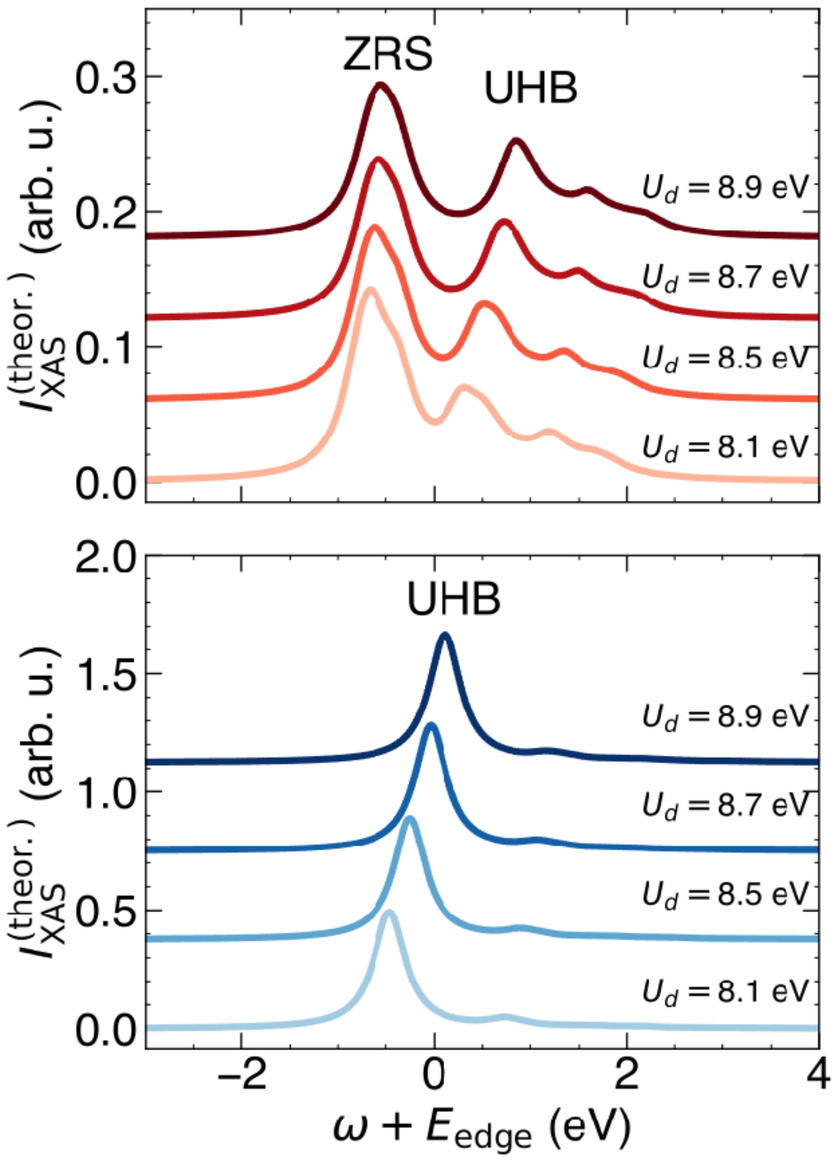
Condensed matter systems

M. Mitrano et al. PRL (2014)
Z. Lenarčič et al. PRL (2013)
Z. Lenarčič et al. PRB (2015)

Determining *U*: three-band Hubbard model

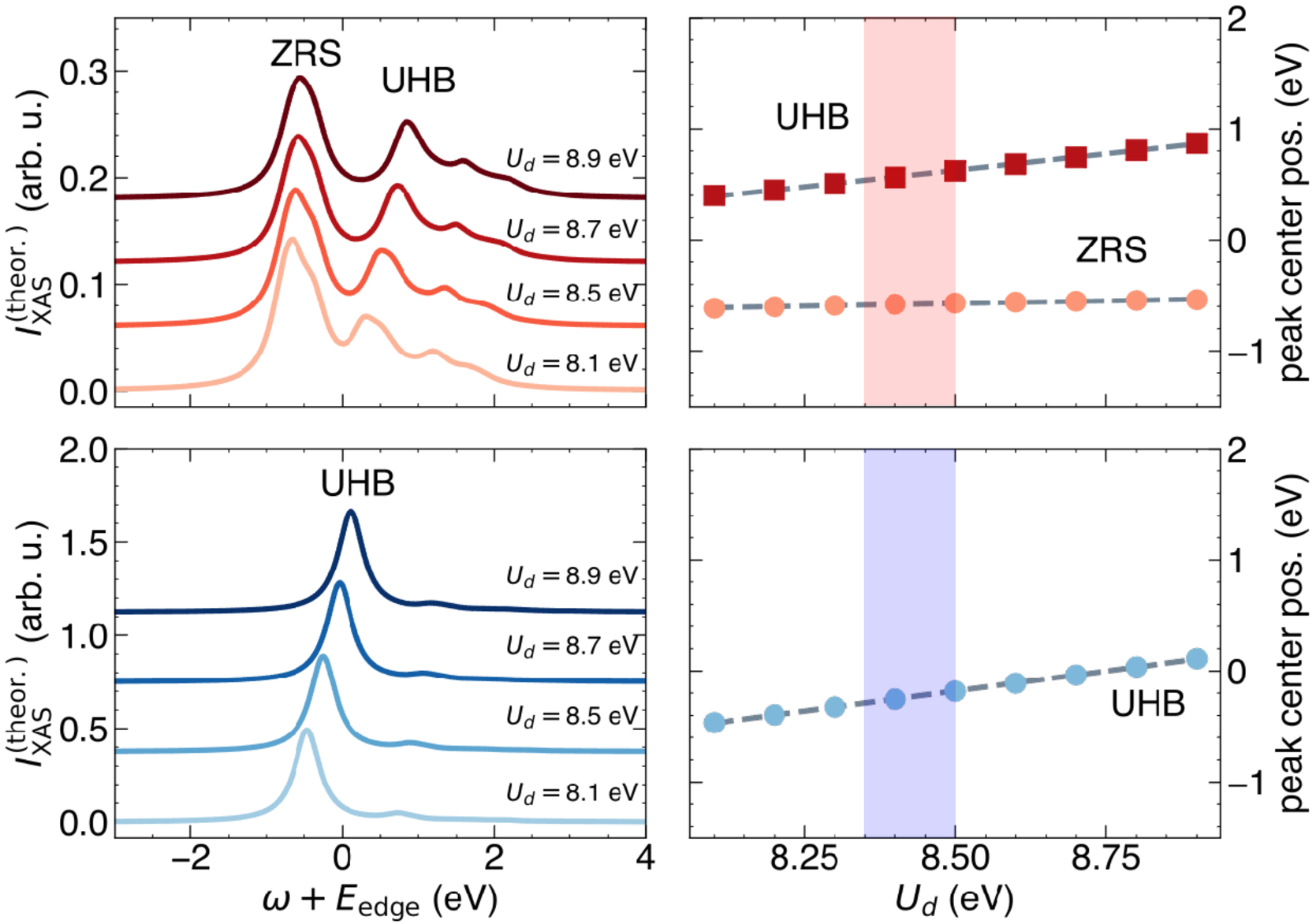


Determining *U*: three-band Hubbard model



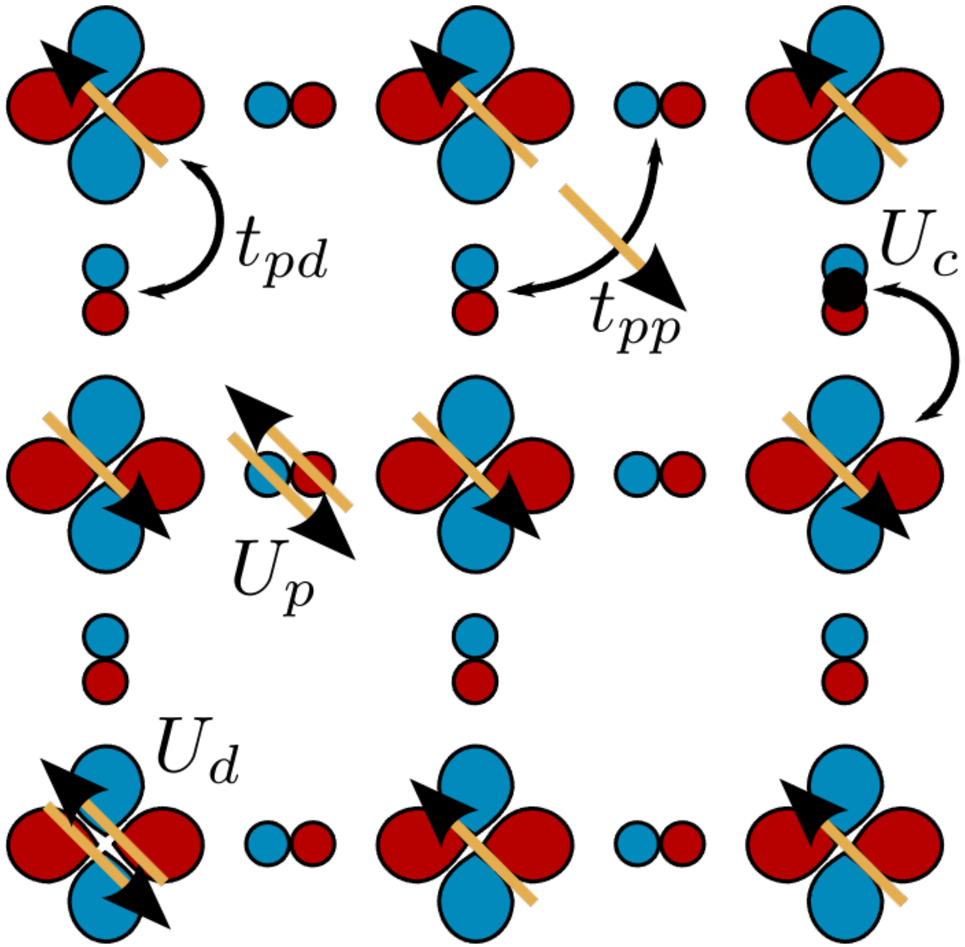
- Dynamical Hubbard U_d
- t_{pd}, t_{pp}, U_p shift the ZRS

Determining U: three-band Hubbard model



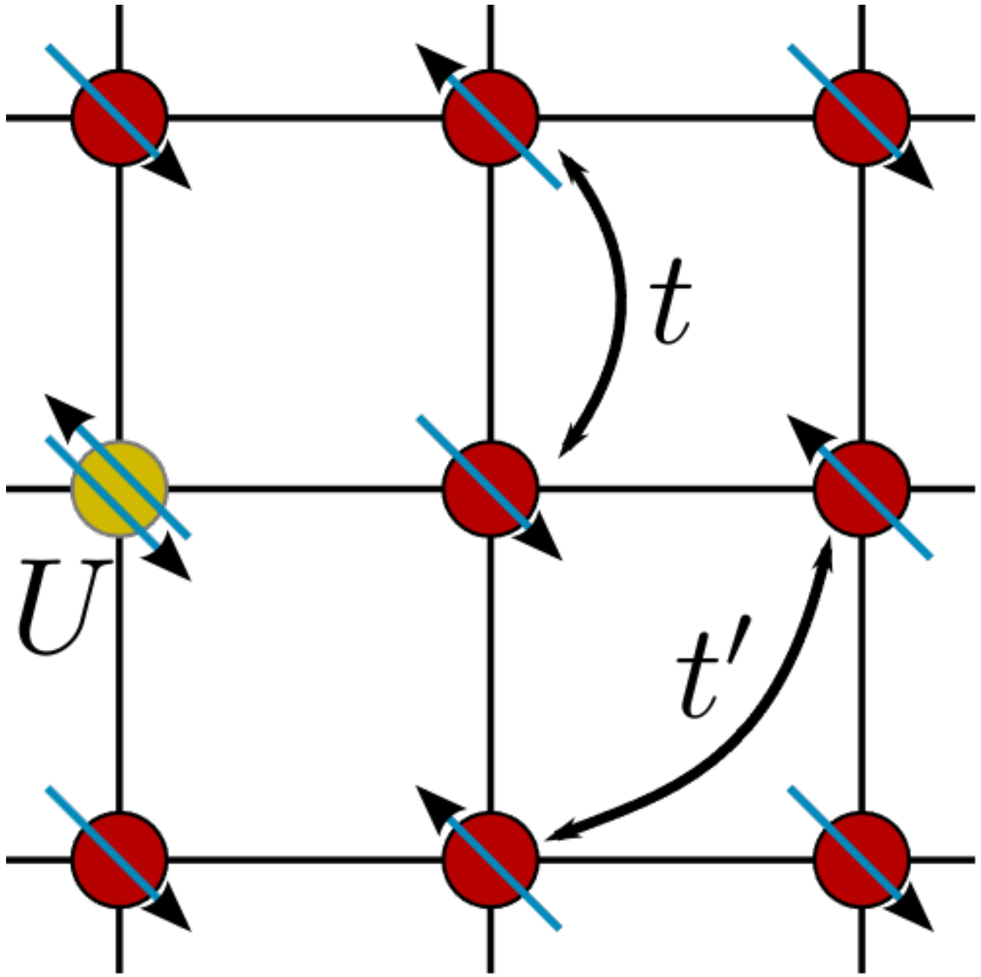
$$\delta U_d \sim 140 \text{ meV}$$

Dynamical Hubbard *U* in a minimal description



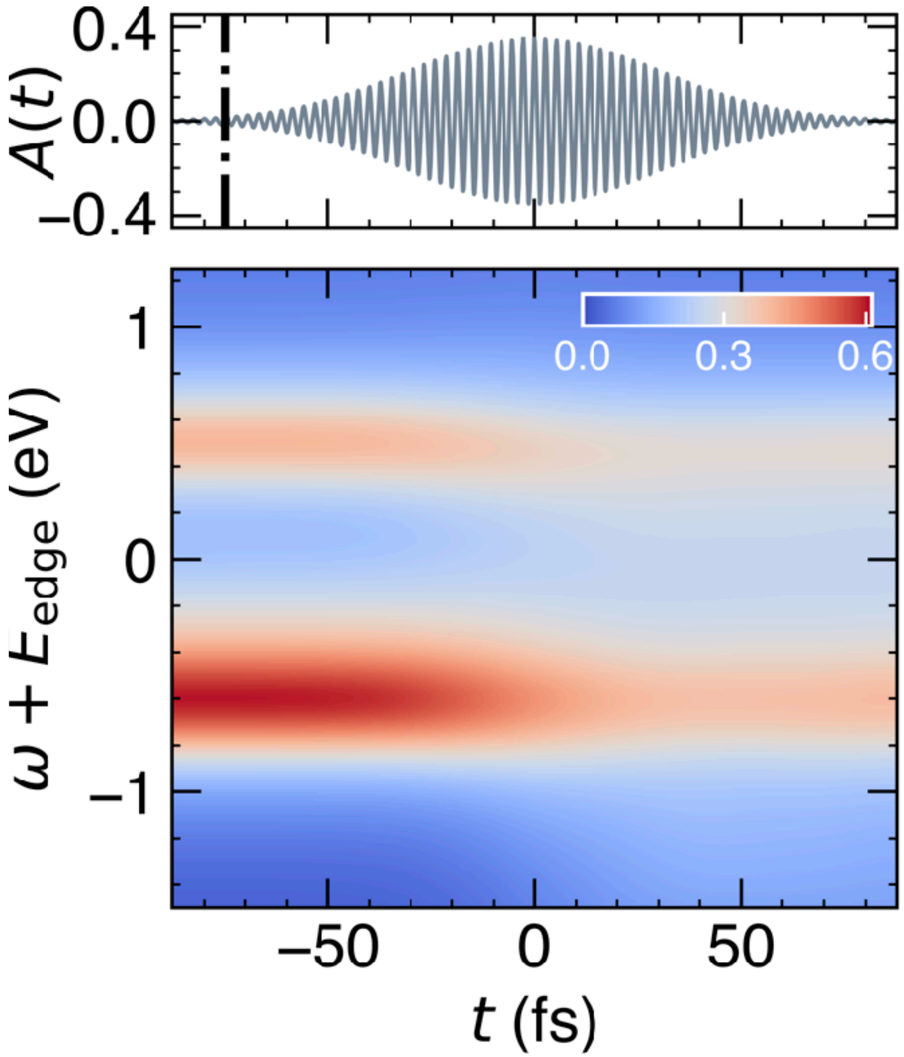
Dynamical Hubbard *U* in a minimal description

Single band
Hubbard model



A minimal description: single-band trXAS spectrum

Pump
1.55 eV
15 MV/cm



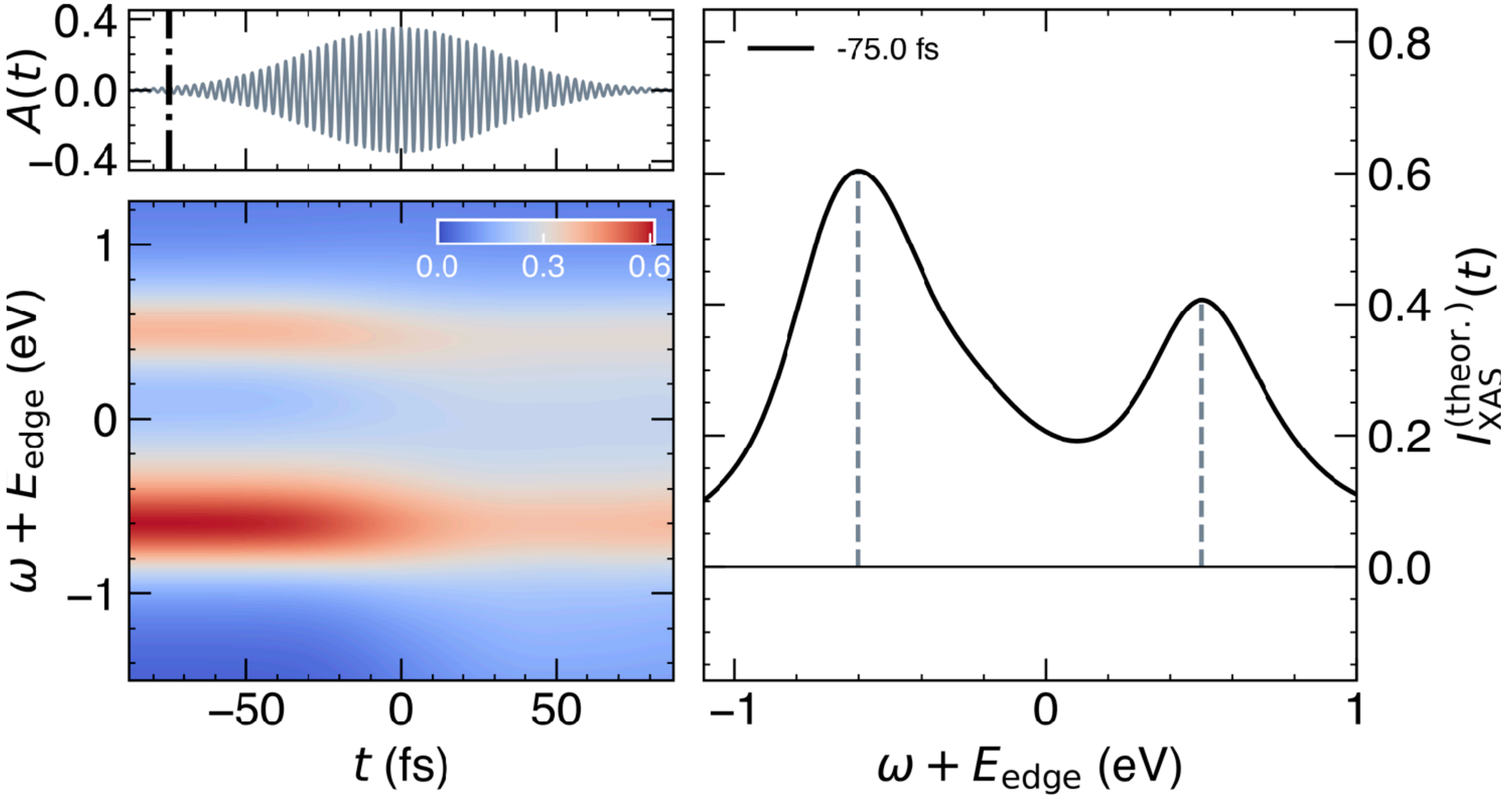
Peierls substitution

$$c_{i\sigma} \rightarrow c_{i\sigma} \exp\left[-i \int_{-\infty}^{\mathbf{r}_i} \mathbf{A}(\mathbf{r}', t) \cdot d\mathbf{r}' \right]$$

Y. Wang […] & MM Commun. Phys. 2021
Y. Wang et al. PRB 2020
Y. Chen et al. PRB 2019

A minimal description: single-band trXAS spectrum

Pump
1.55 eV
15 MV/cm



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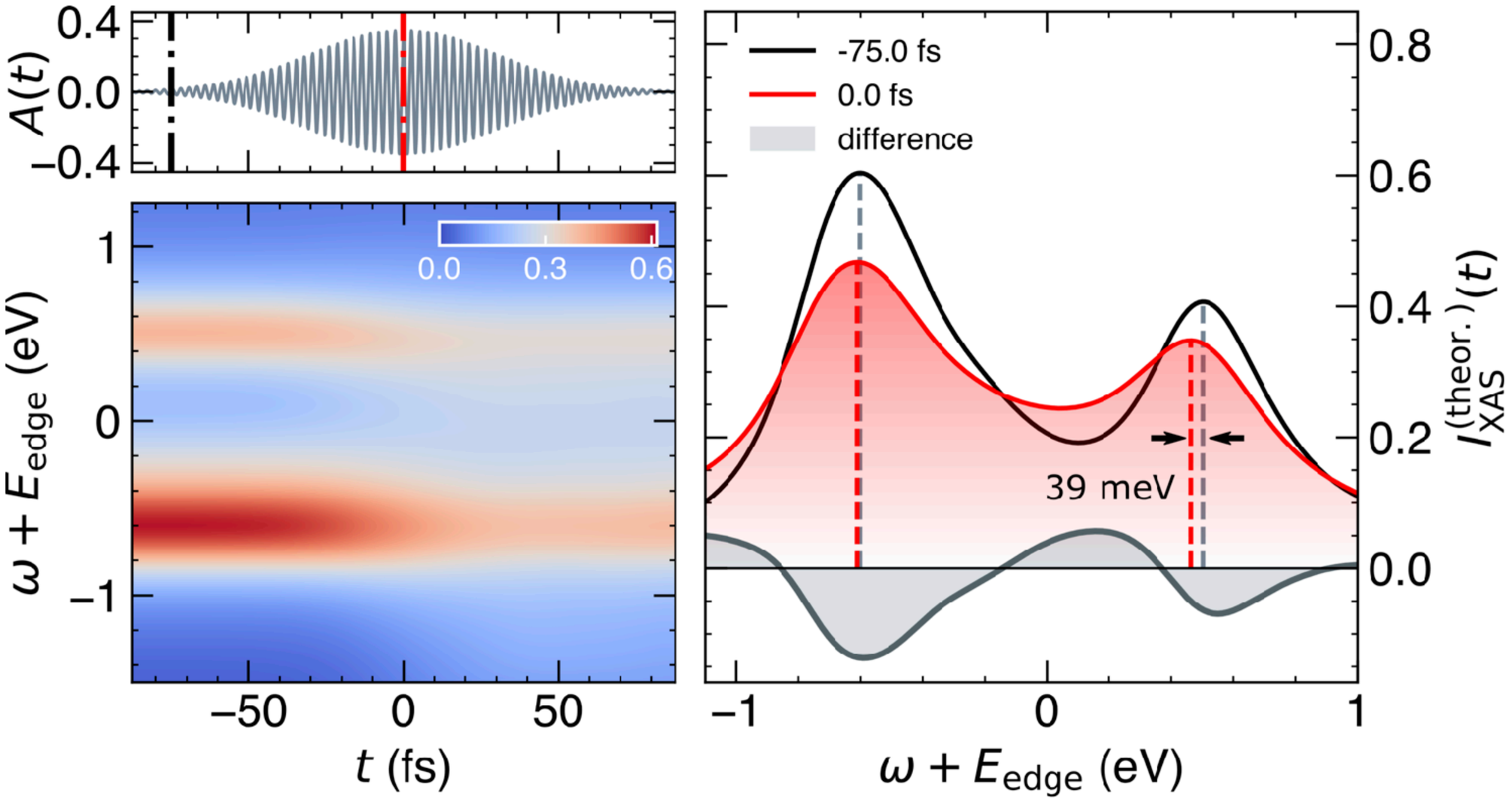
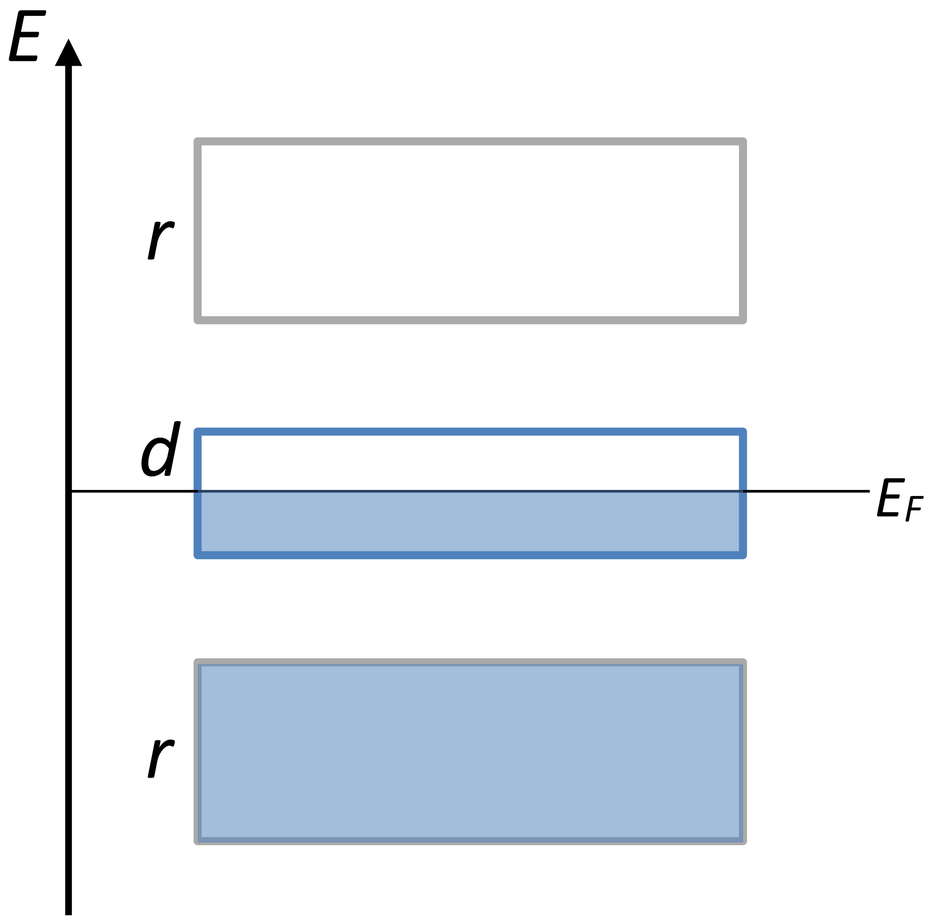


Renormalized Hubbard U also in single band

Possible microscopic mechanisms

Enhanced screening



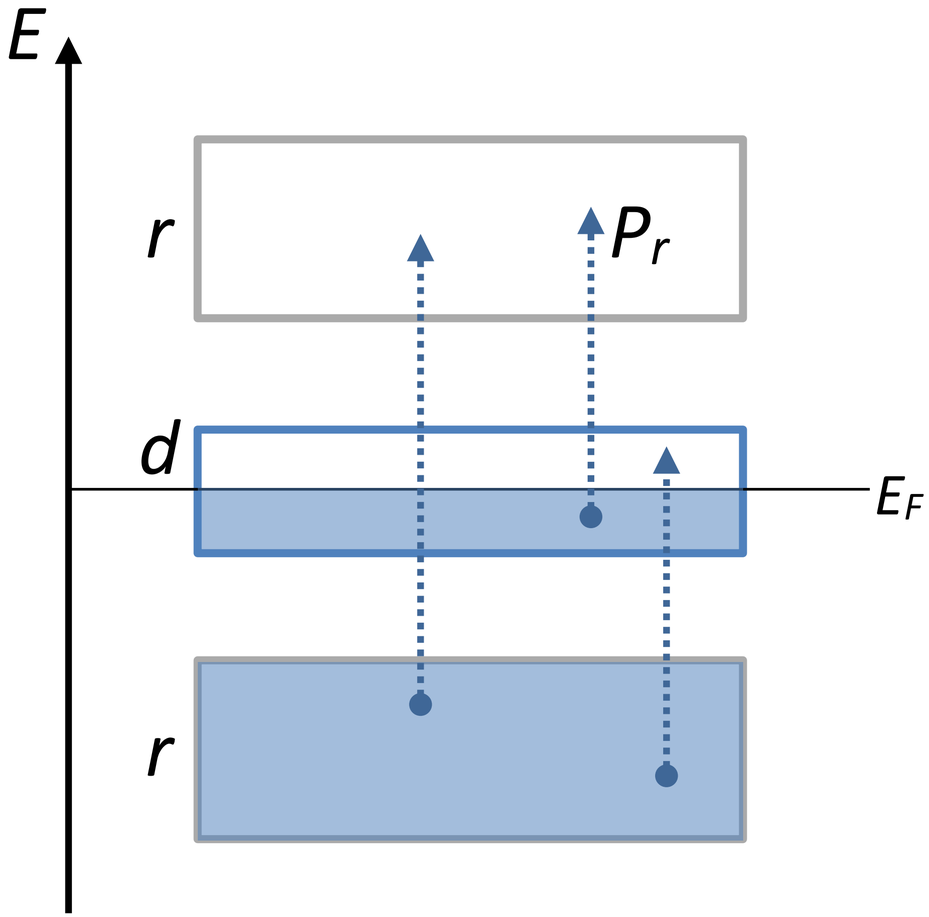
N. Tancogne-Dejean et al. PRL (2018)

D. Golez et al. PRB (2019)

F. Aryasetiawan, lecture notes, Jülich (2011)

Possible microscopic mechanisms

Enhanced screening



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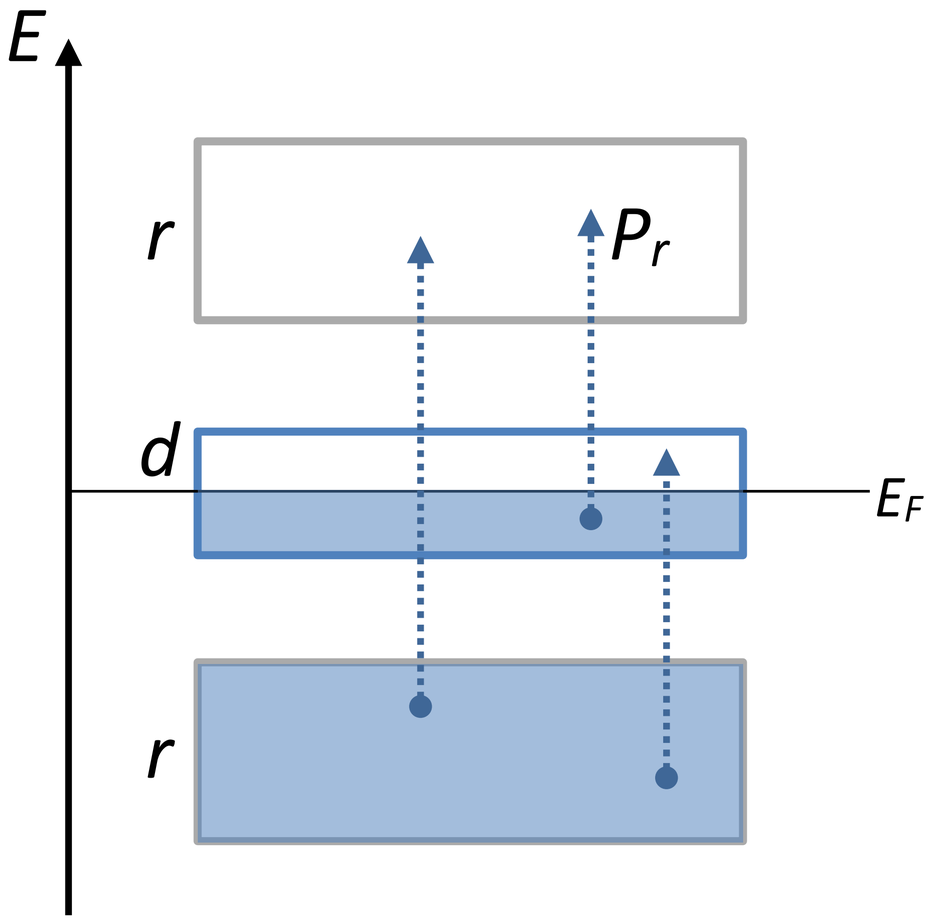

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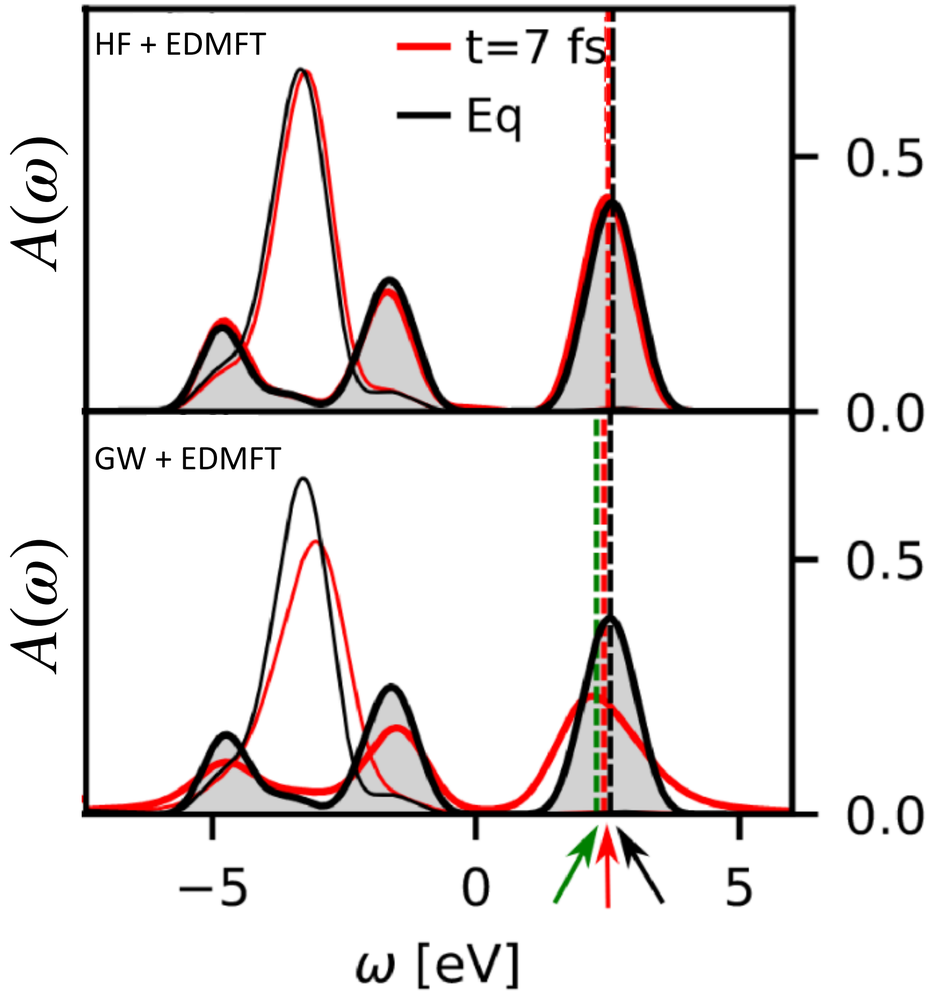
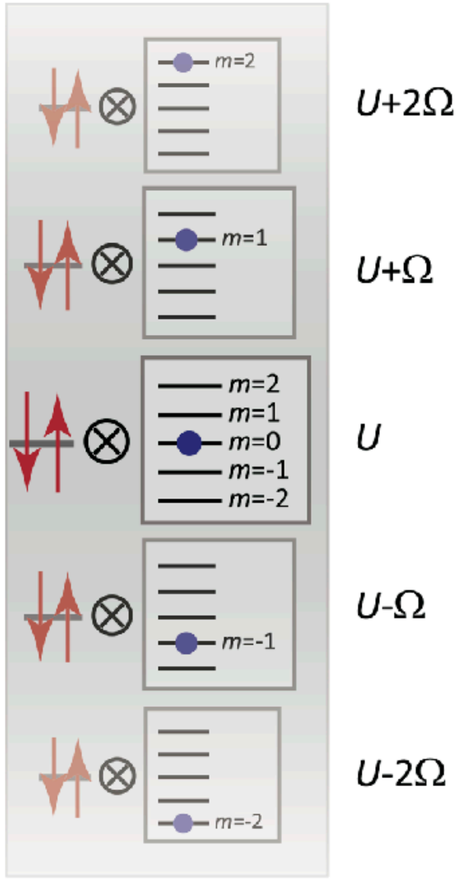


D. Golez et al. PRB (2019)

Possible microscopic mechanisms

Floquet renormalization



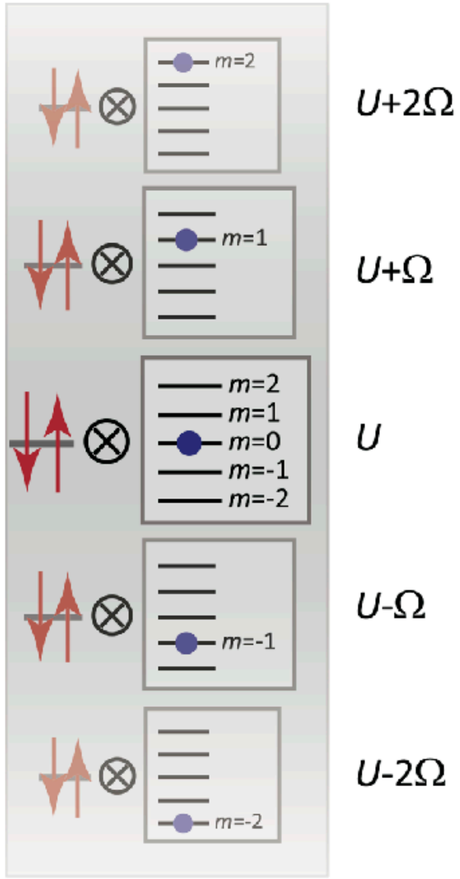
J. H. Mentink et al. Nature Comms (2015)

Y. Wang et al. PRB (2017)

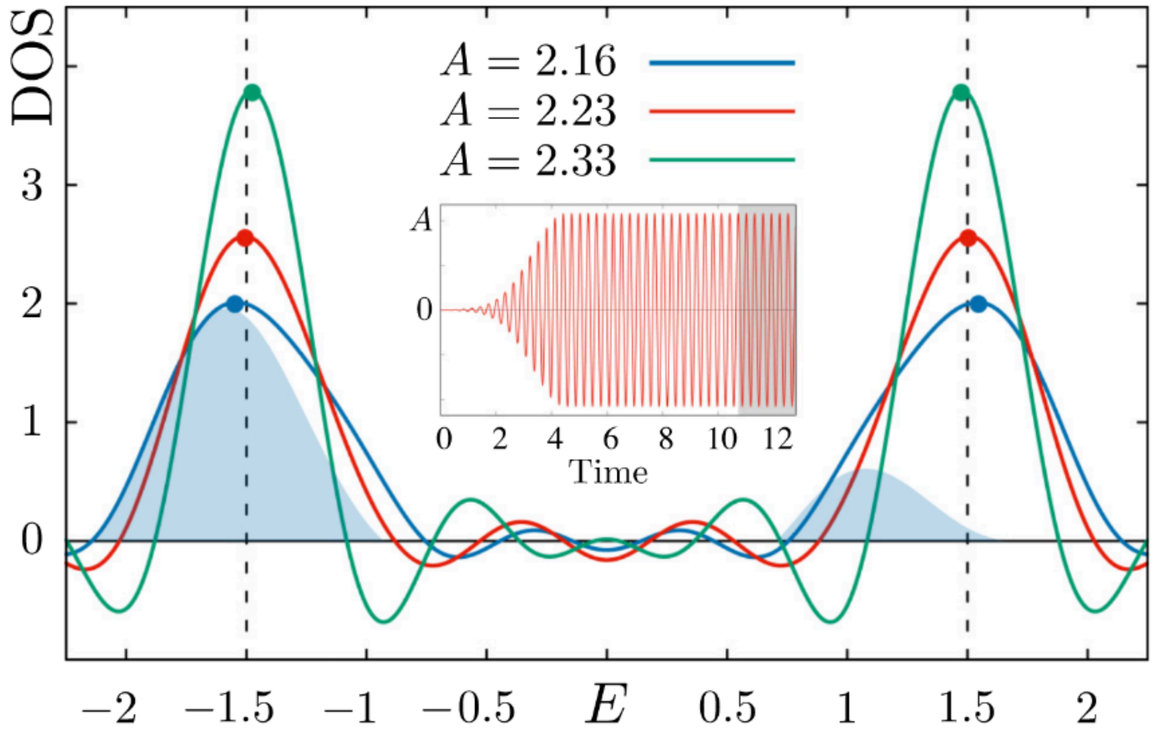
T. Oka & S. Kitamura, Annu. Rev. Cond. Matt. Phys. (2019)

Possible microscopic mechanisms

Floquet renormalization



J. H. Mentink et al. Nature Comms (2015)
Y. Wang et al. PRB (2017)
T. Oka & S. Kitamura, Annu. Rev. Cond. Matt. Phys. (2019)



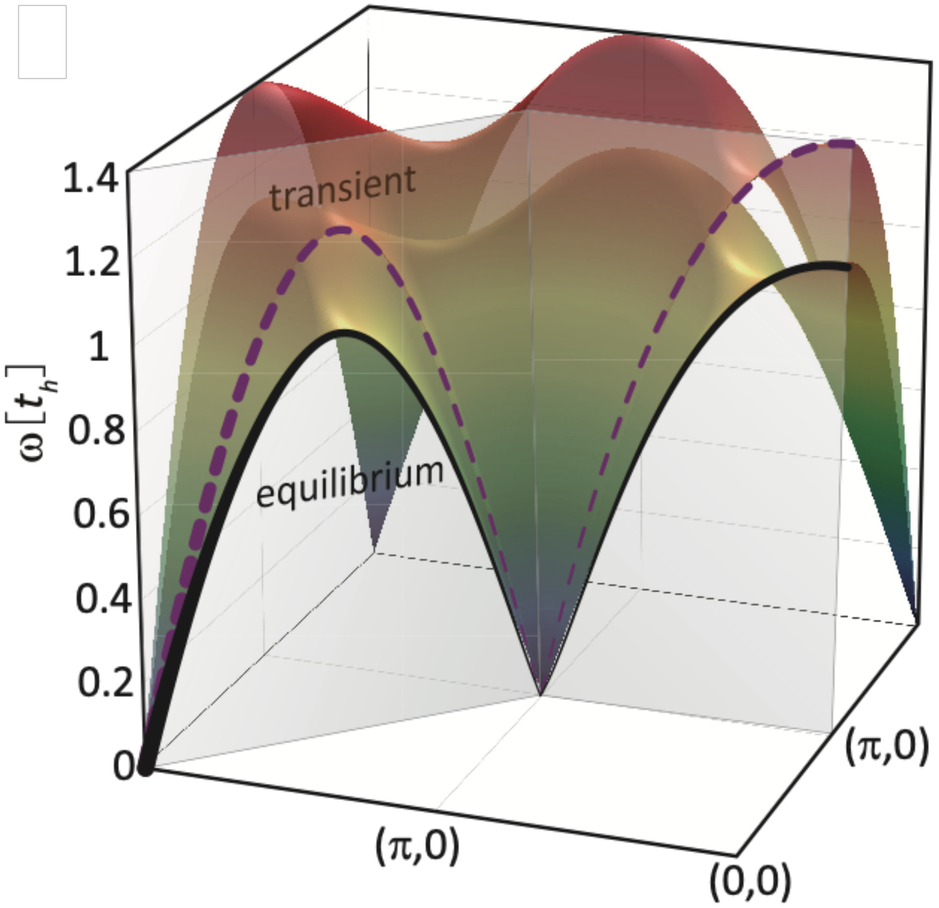
V. N. Valmispild et al. PRB (2020)

A microscopic tuning knob for light-driven quantum phases

Reduction of Hubbard U:

- Decreased charge-transfer gap
- Increase of spin wave energy
- Renormalized pairing interaction

A microscopic tuning knob for light-driven quantum phases



MM & Y. Wang, Comm. Phys. (2020)

Reduction of Hubbard *U*:

- Decreased charge-transfer gap
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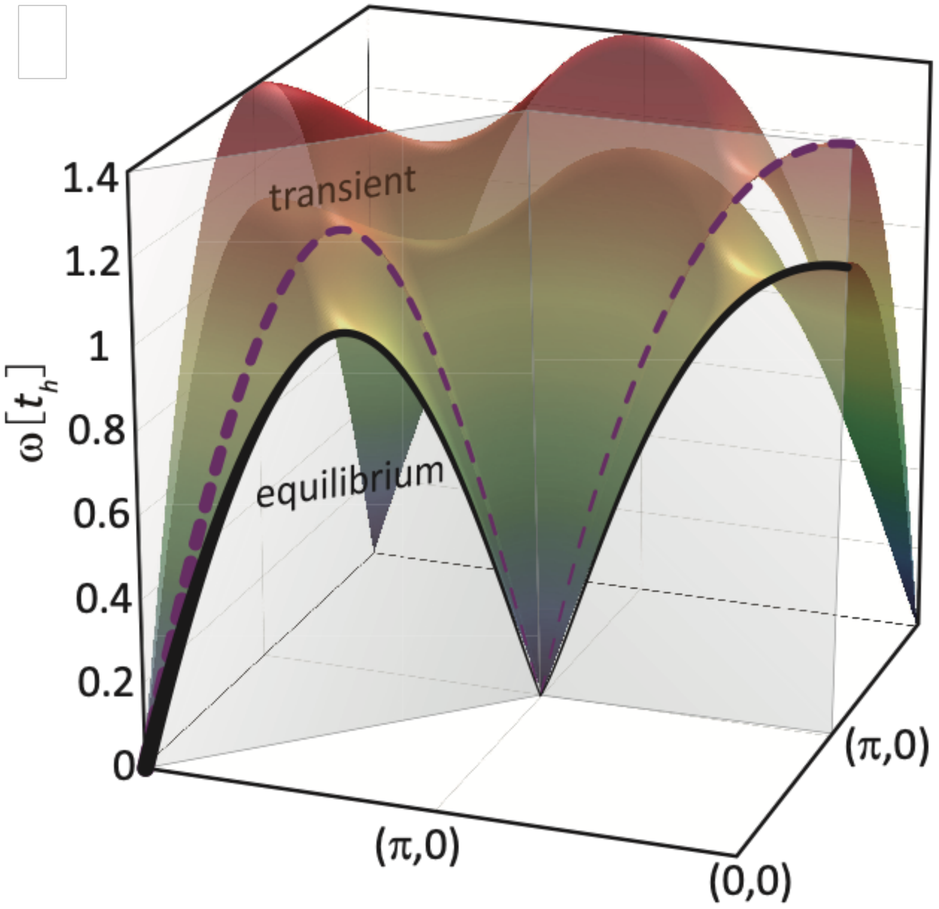
A microscopic tuning knob for light-driven quantum phases



MM & Y. Wang, Comm. Phys. (2020)

Reduction of Hubbard *U*:

- Decreased charge-transfer gap
- Increase of spin wave energy
- Renormalized pairing interaction

Spin liquid phases

M. Claassen et al. Nat. Comm. (2017)
A. Szasz et al. PRX (2020)

η-pairing condensation

C. N. Yang PRL (1989)
S. C. Zhang PRL (1990)
T. Kaneko et al. PRL (2019)
F. Peronaci at al. PRB (2020)
J. Li et al. PRB (2020)

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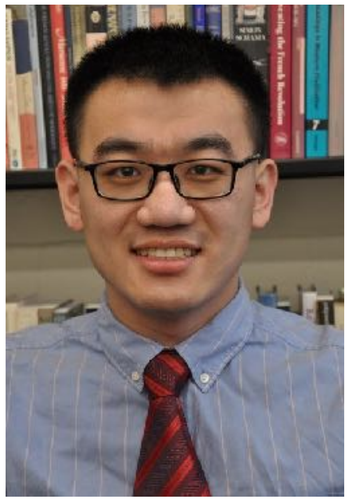

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