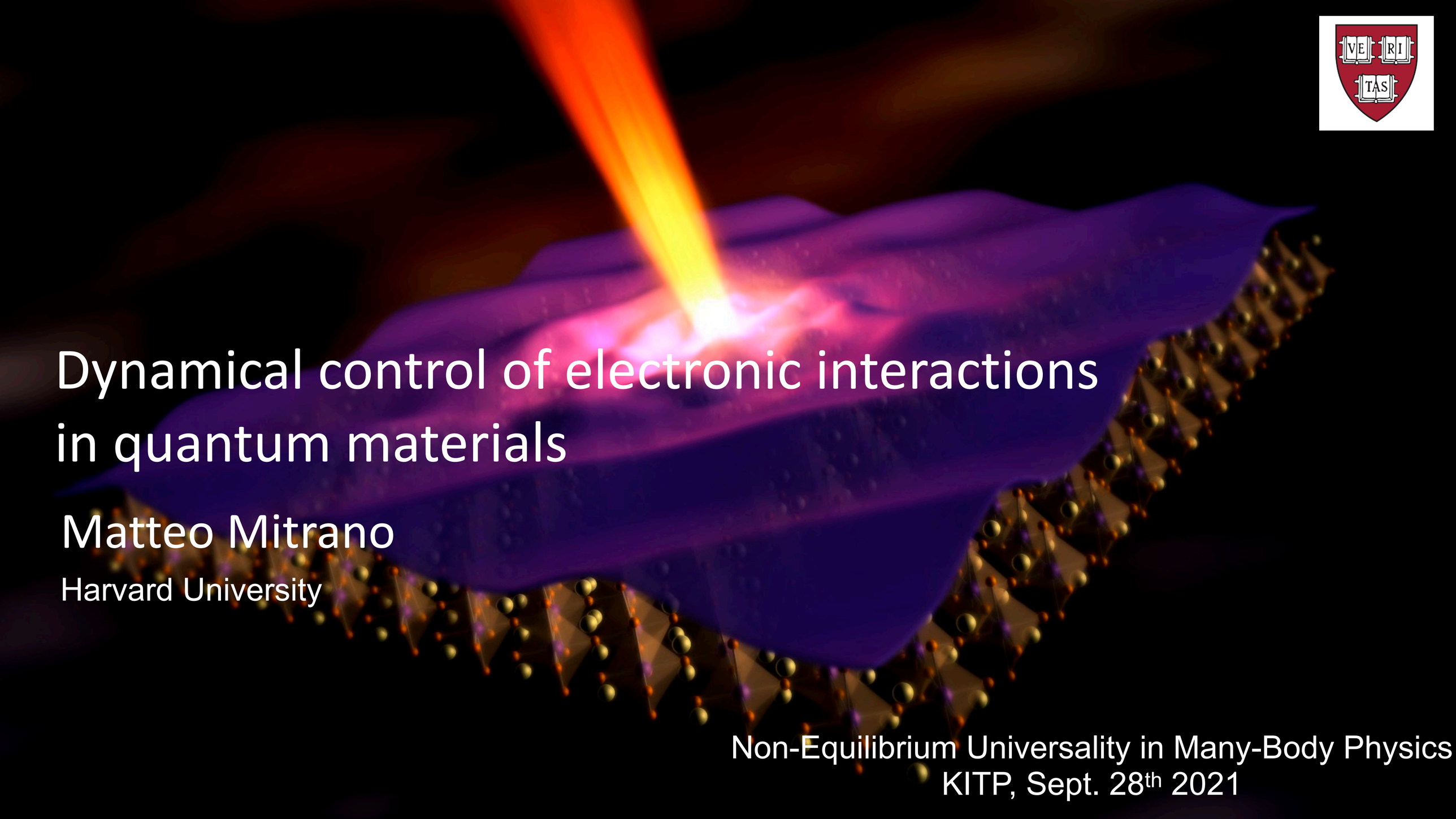


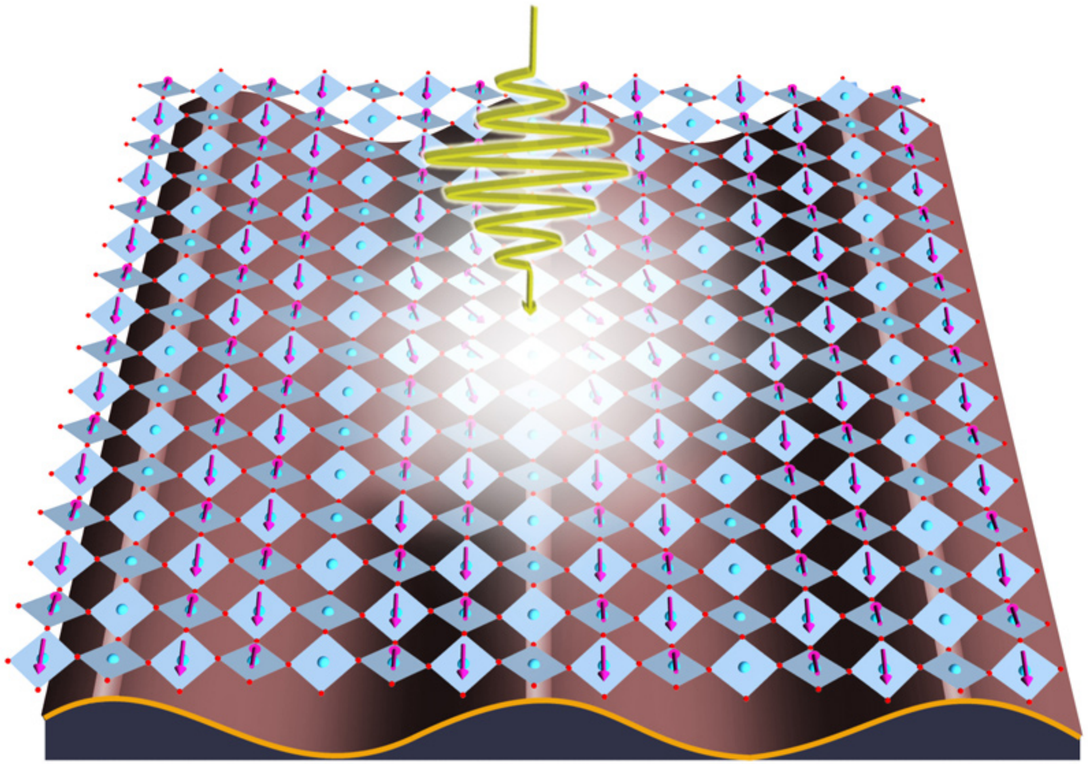
Dynamical control of electronic interactions in quantum materials

Matteo Mitrano

Harvard University

Non-Equilibrium Universality in Many-Body Physics
KITP, Sept. 28th 2021

Optical control of quantum materials



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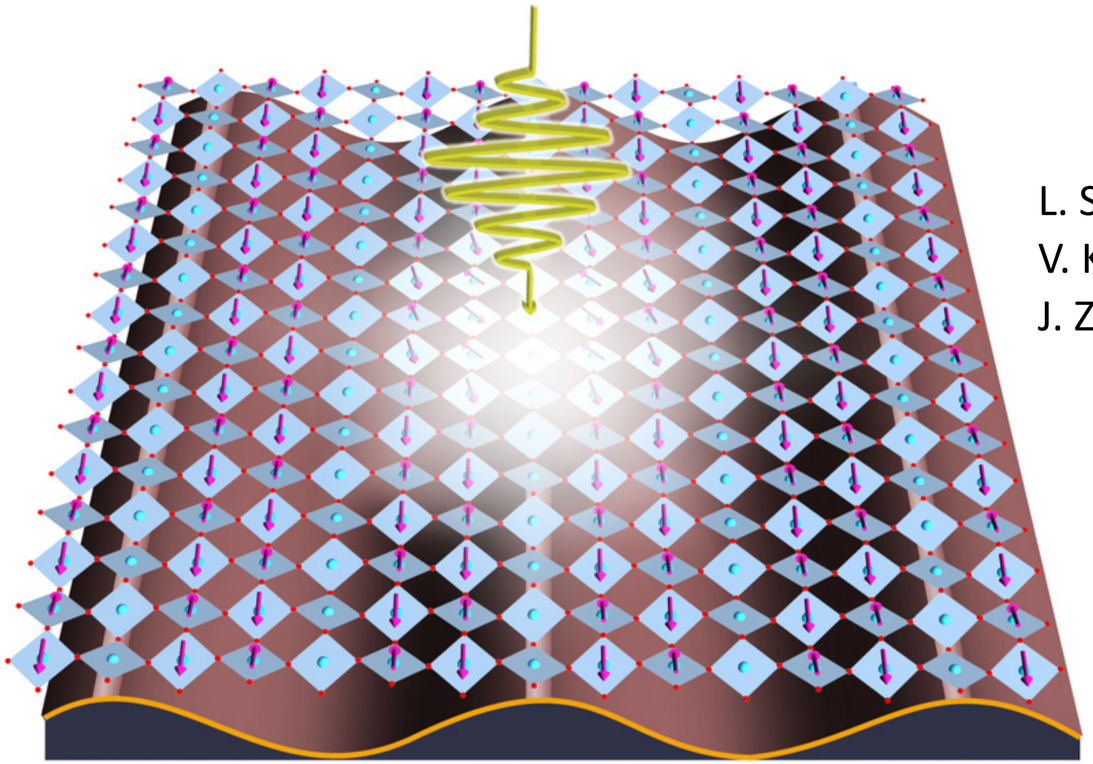

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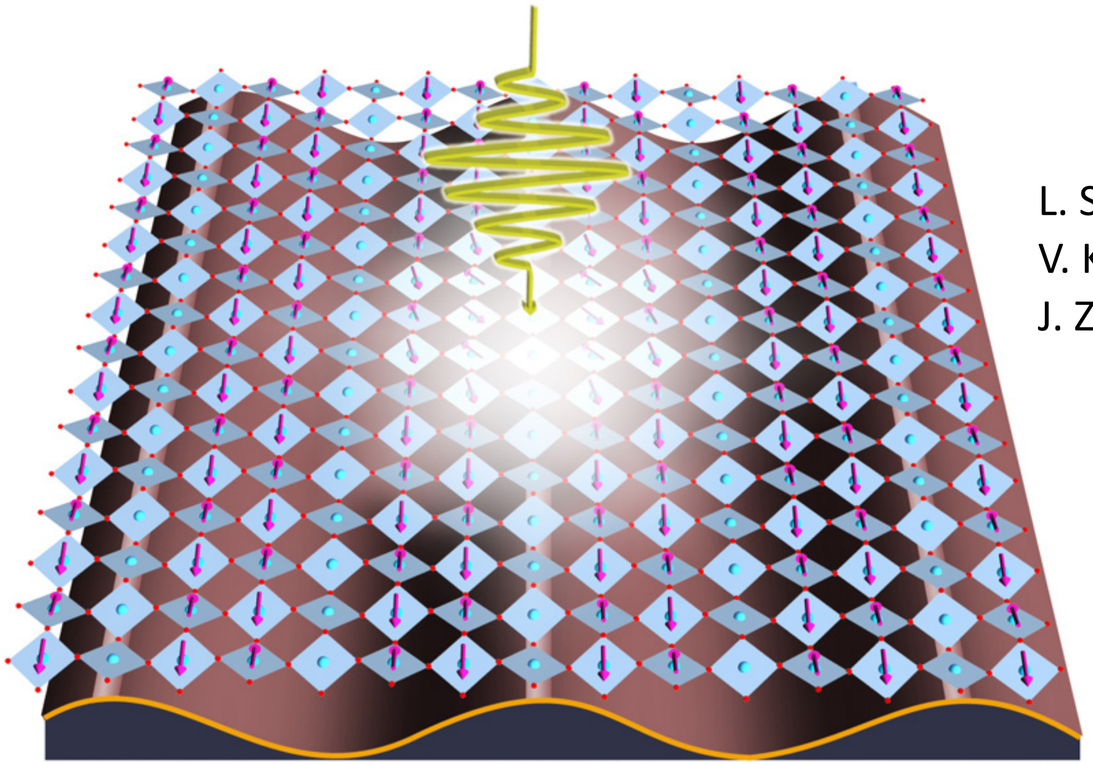

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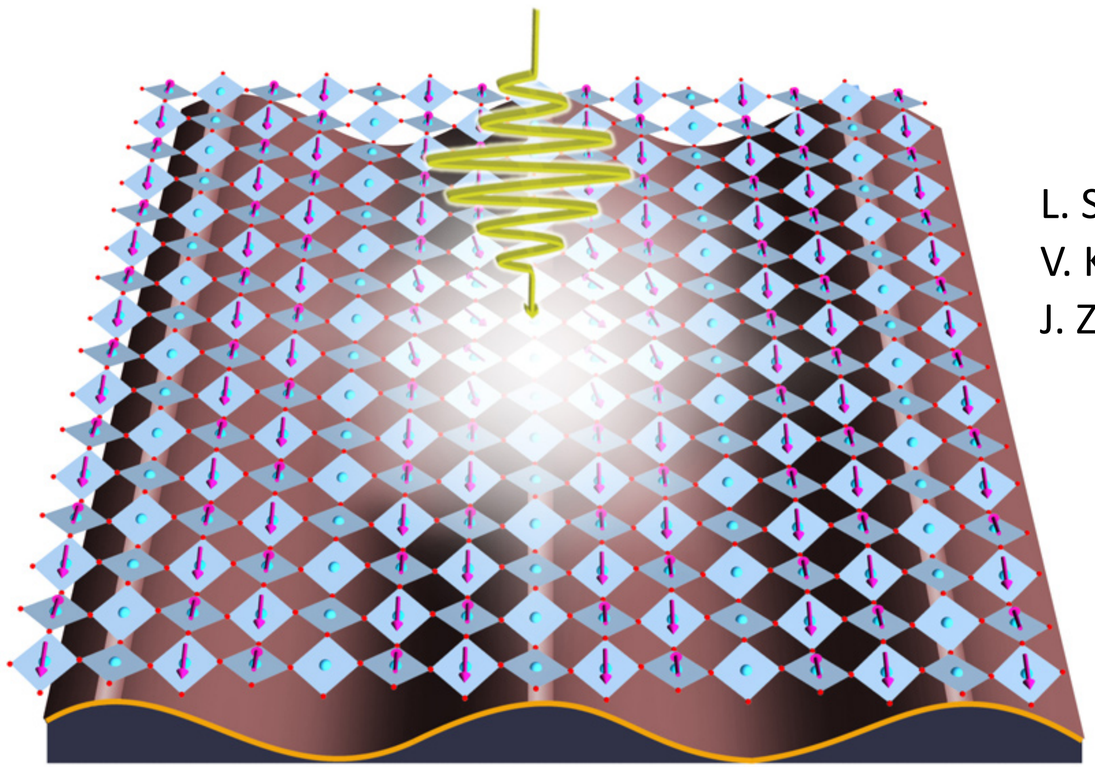

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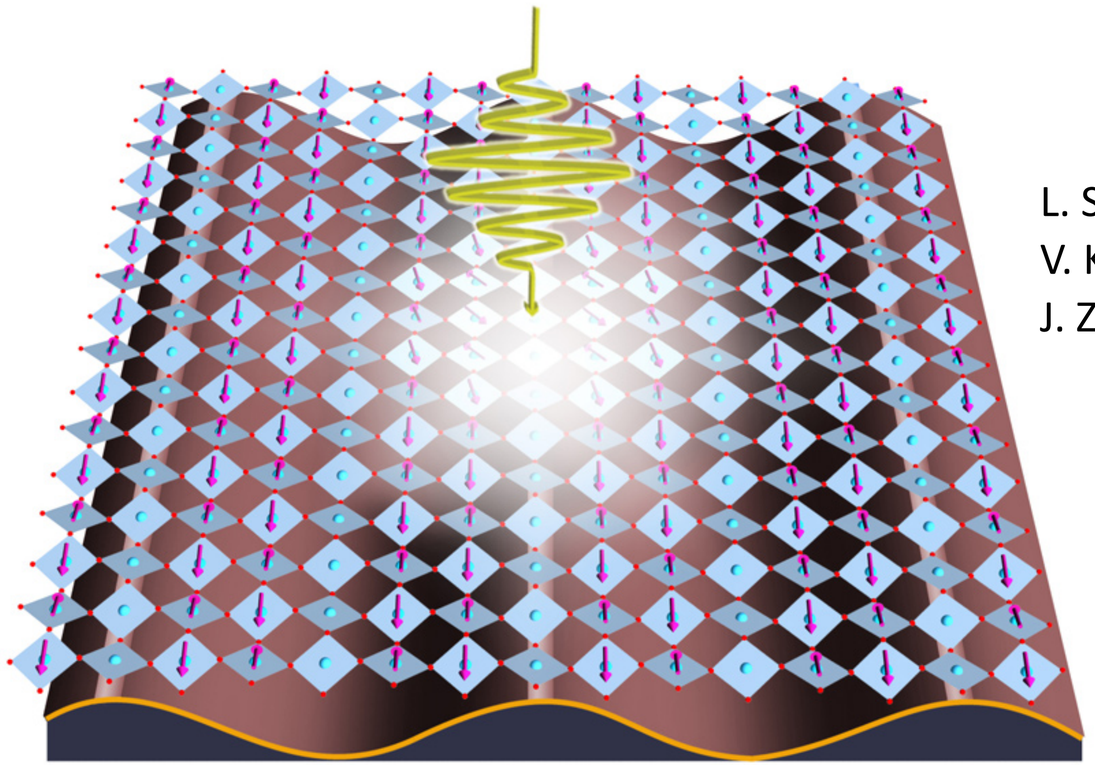

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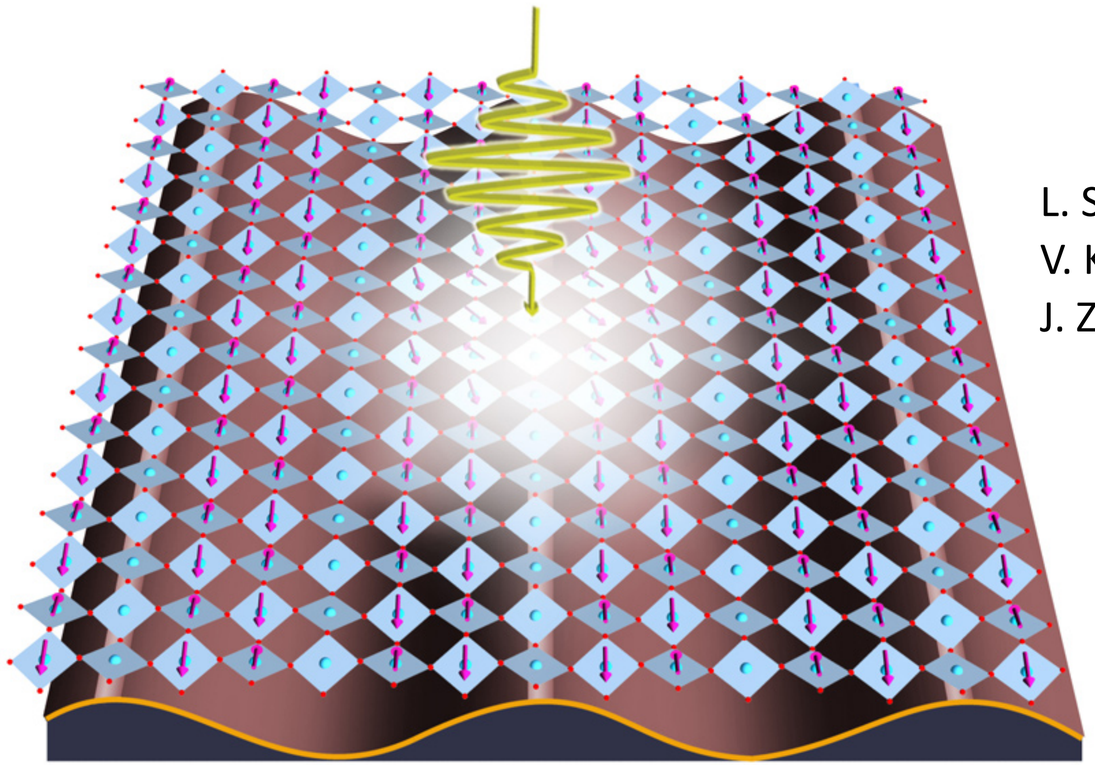

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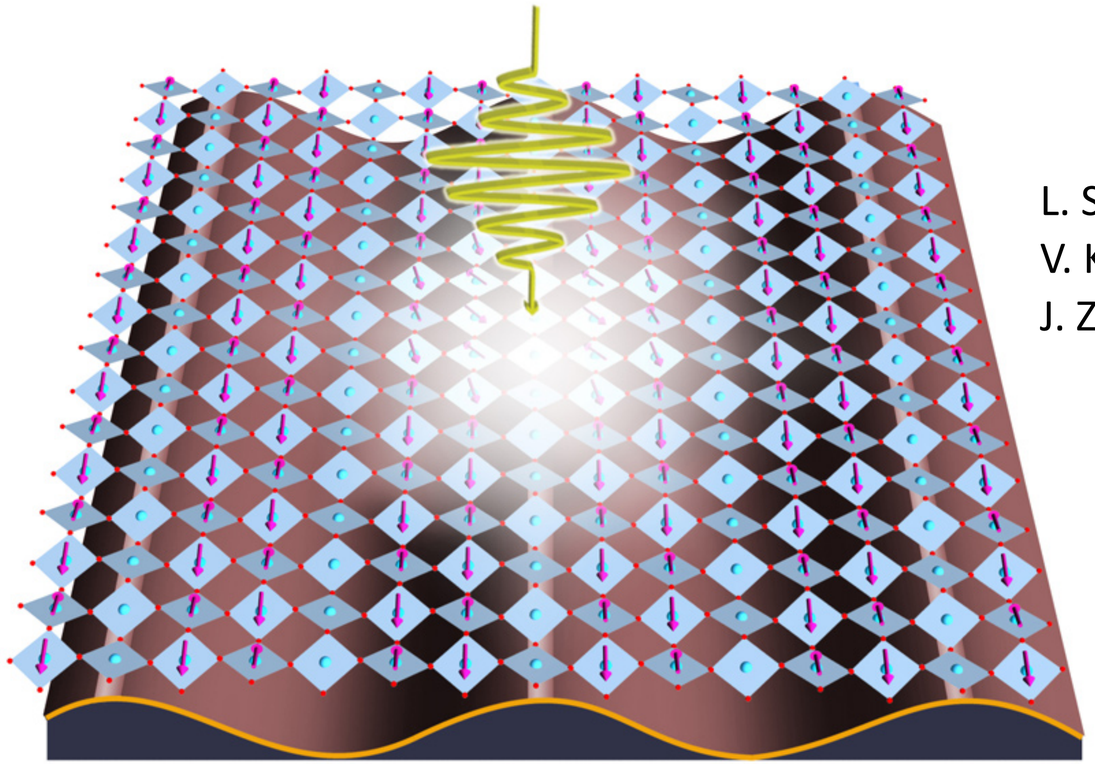

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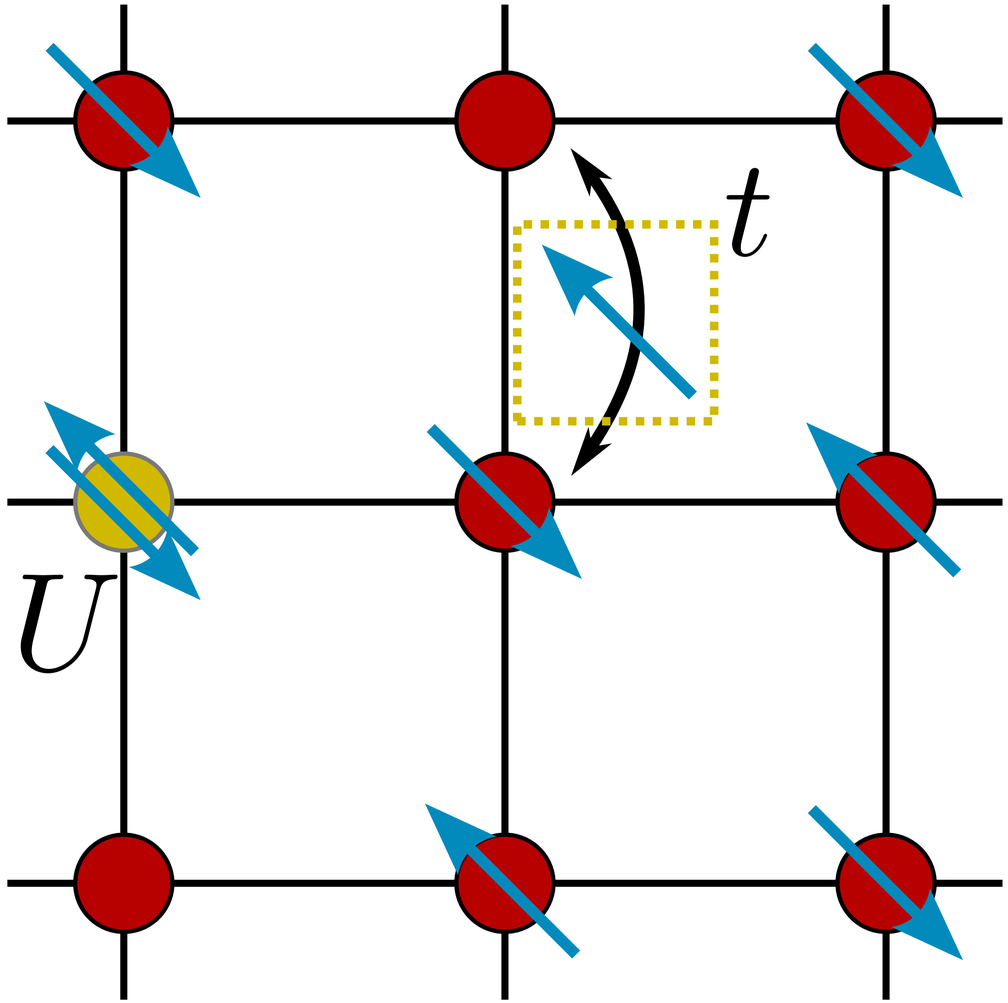
Can we directly tune electronic interactions with light?

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

Interactions in strongly correlated electron systems



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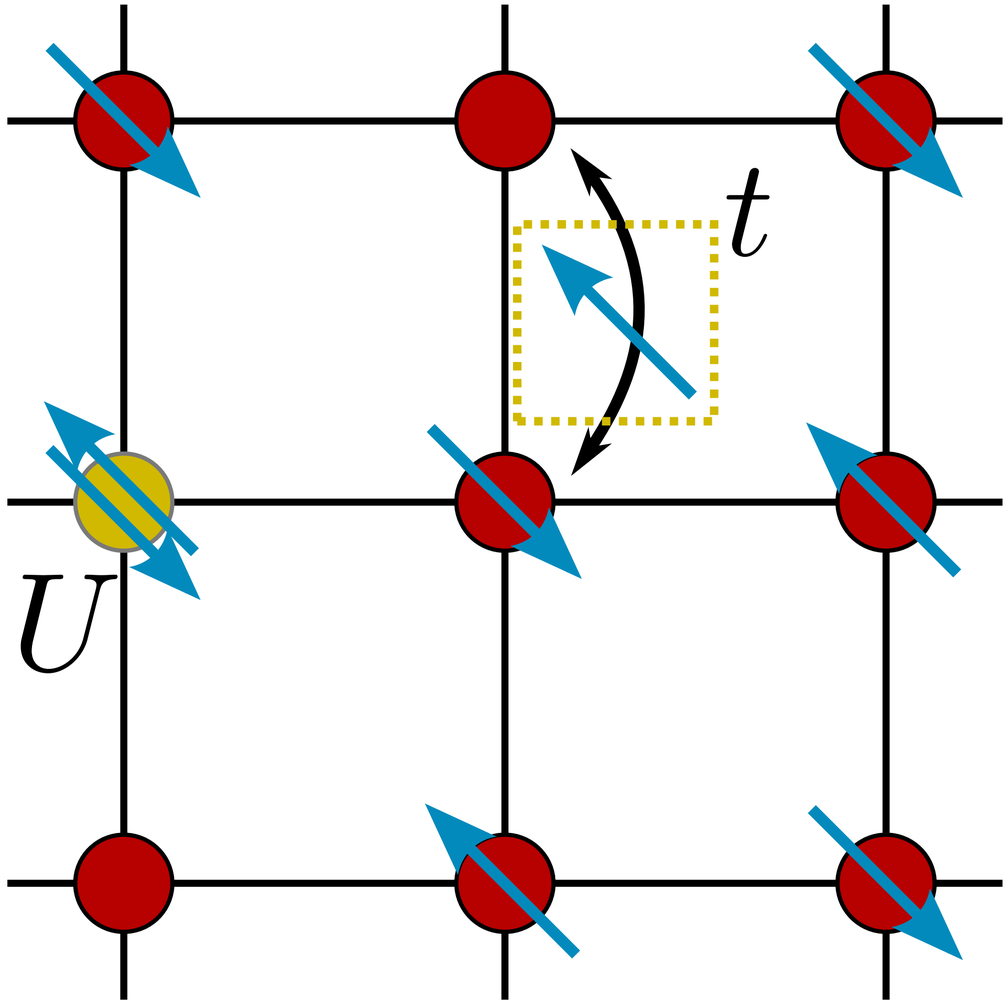

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Engineering electronic interactions

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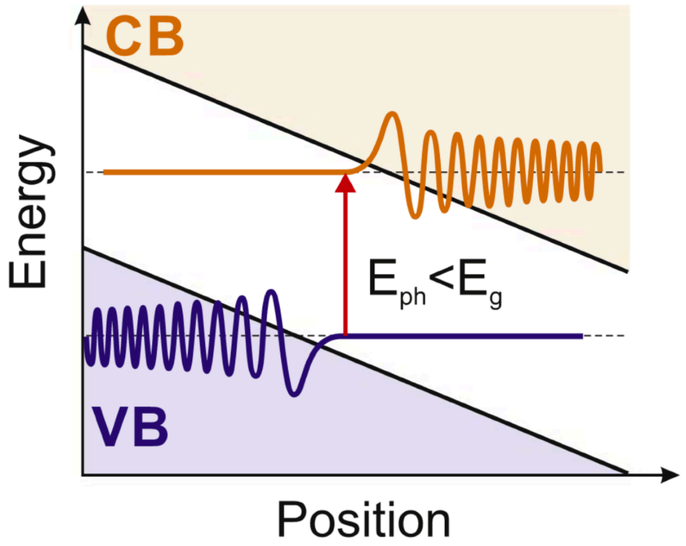

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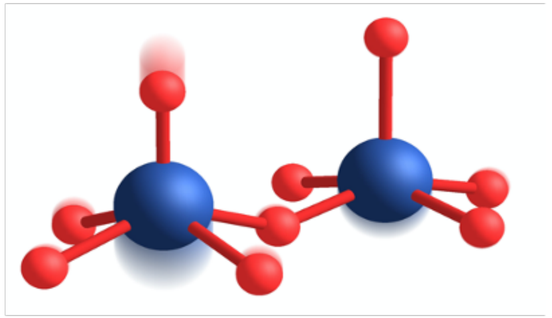

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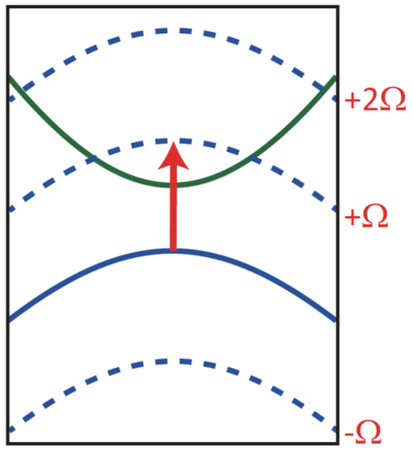

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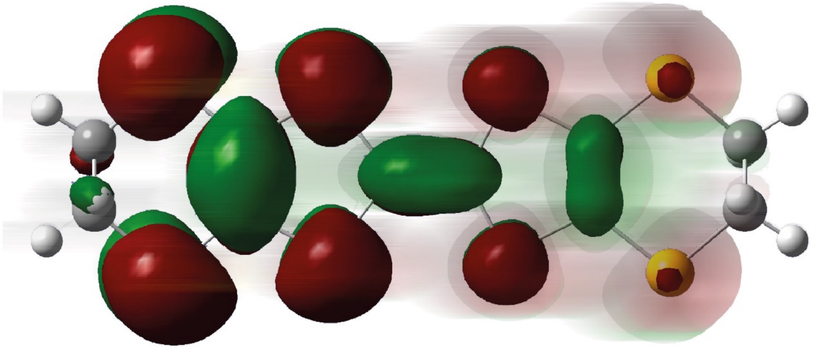

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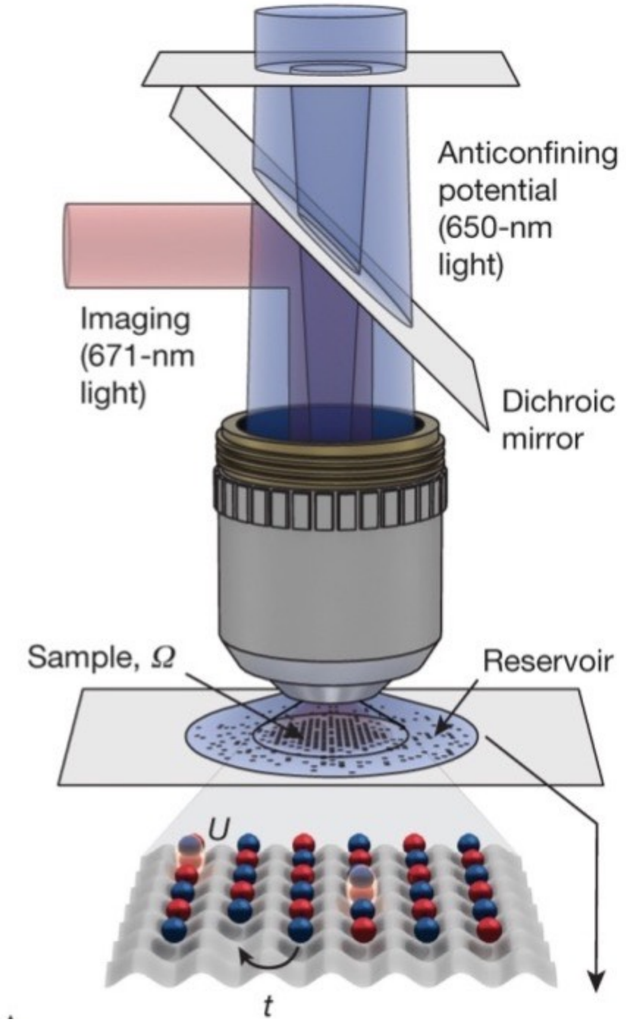
  T. Oka & S. Kitamura, Annu. Rev. Cond. Matt. Phys. (2019)

Modifying the Hubbard *U* in the solid state

Solid state equivalent of Feshbach resonances in optical lattices



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And many more…

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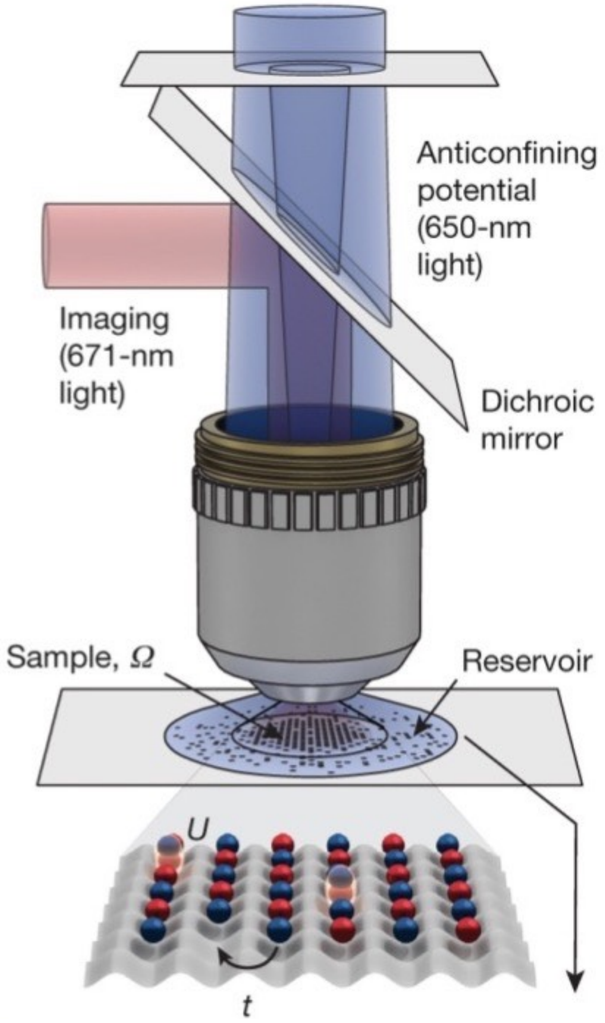

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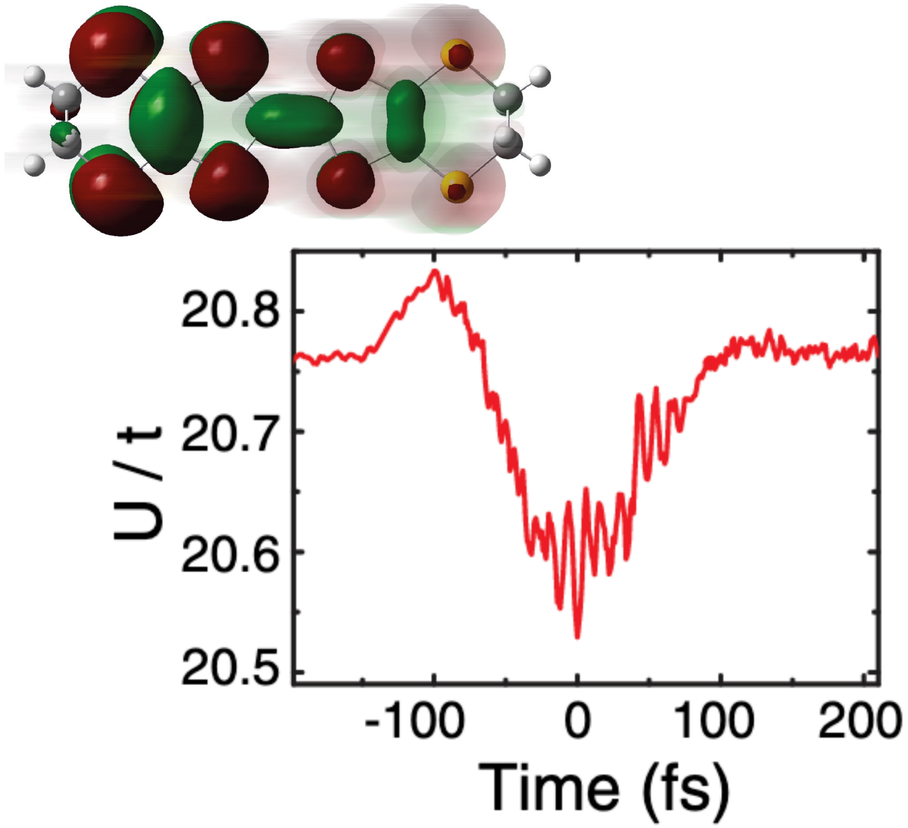


ET-F_2TCNQ organic insulator

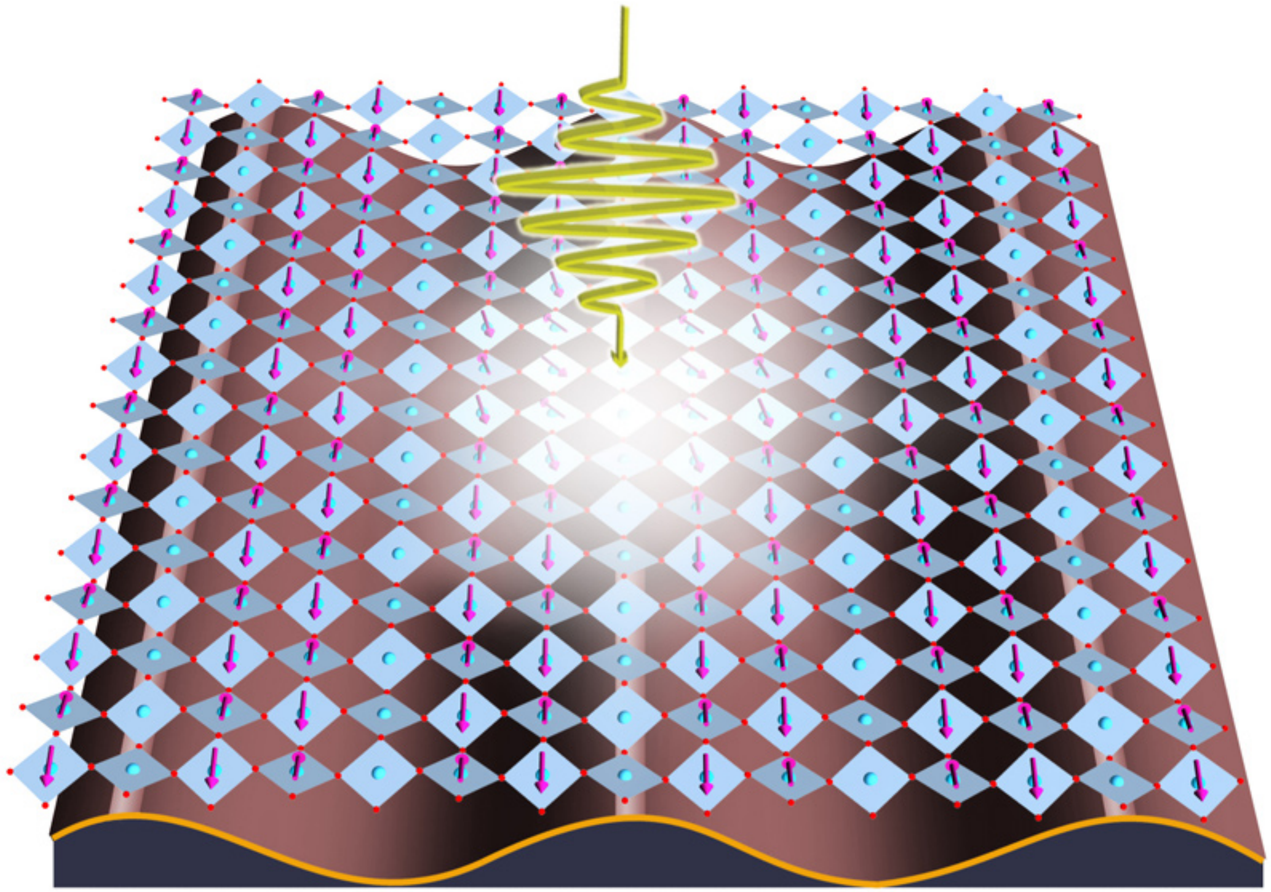
Kaiser et al. Sci. Rep. (2014)
Singla et al. PRL (2015)

Controlling of the Hubbard *U* in high-T_c superconductors

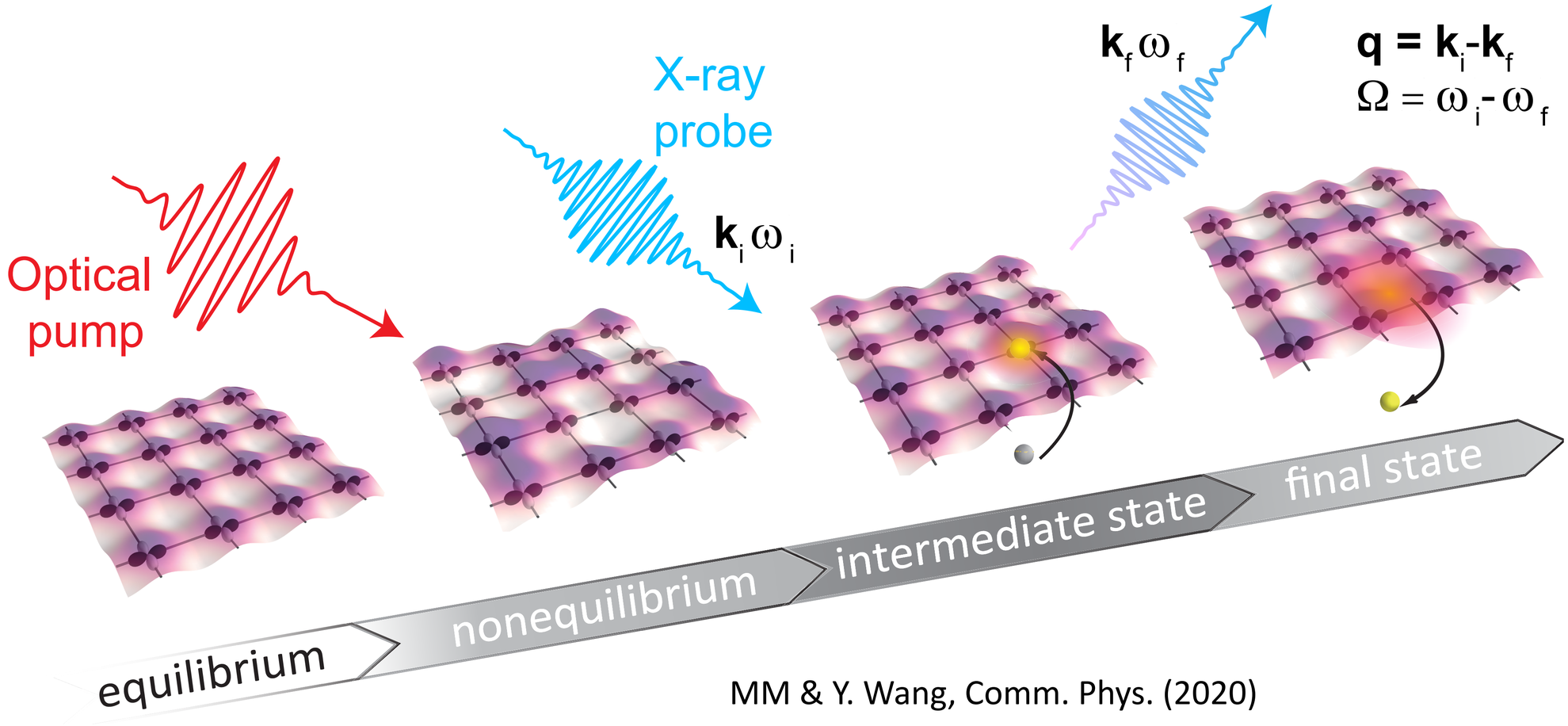
Hubbard U is relevant to:

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

And more…

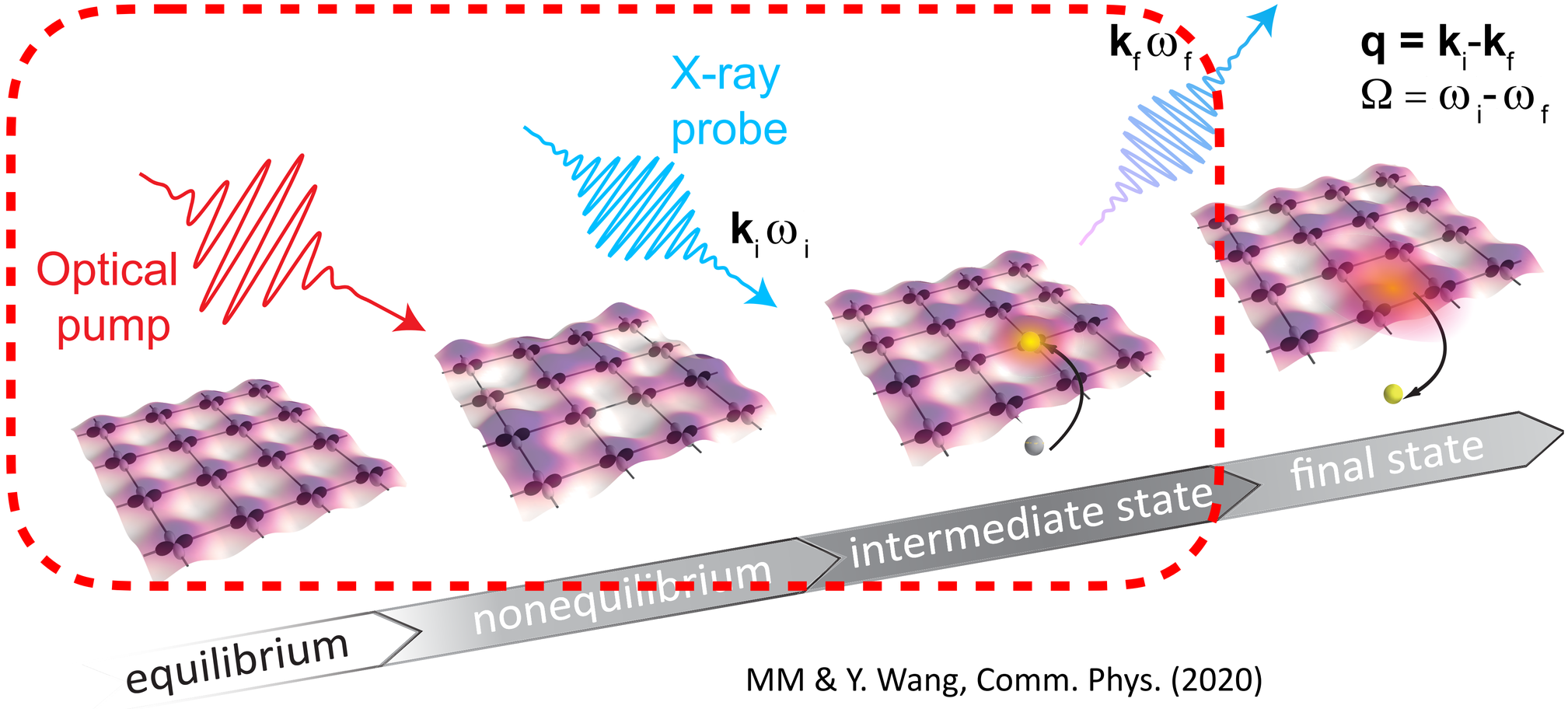


Measuring transient electronic interactions



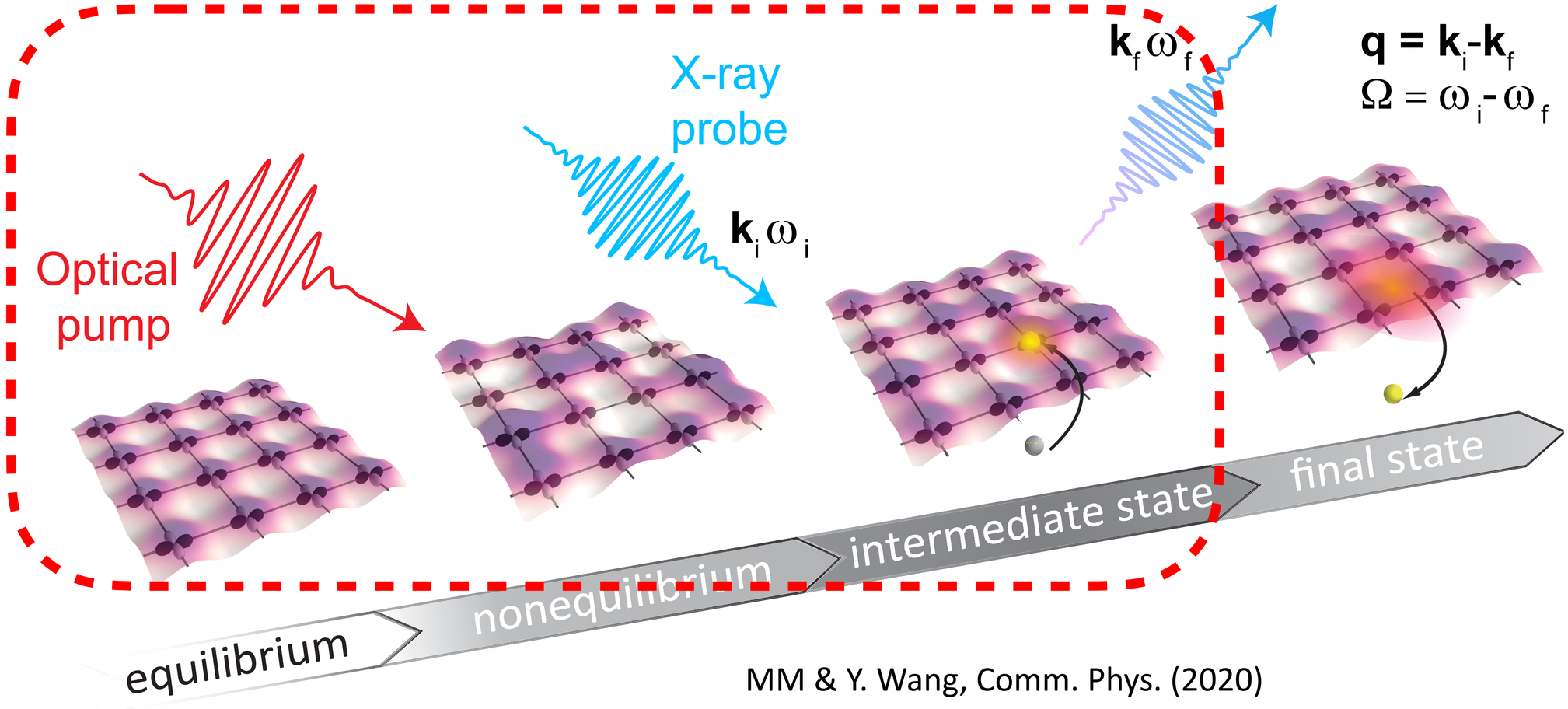
MM & Y. Wang, Comm. Phys. (2020)

Measuring transient electronic interactions



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

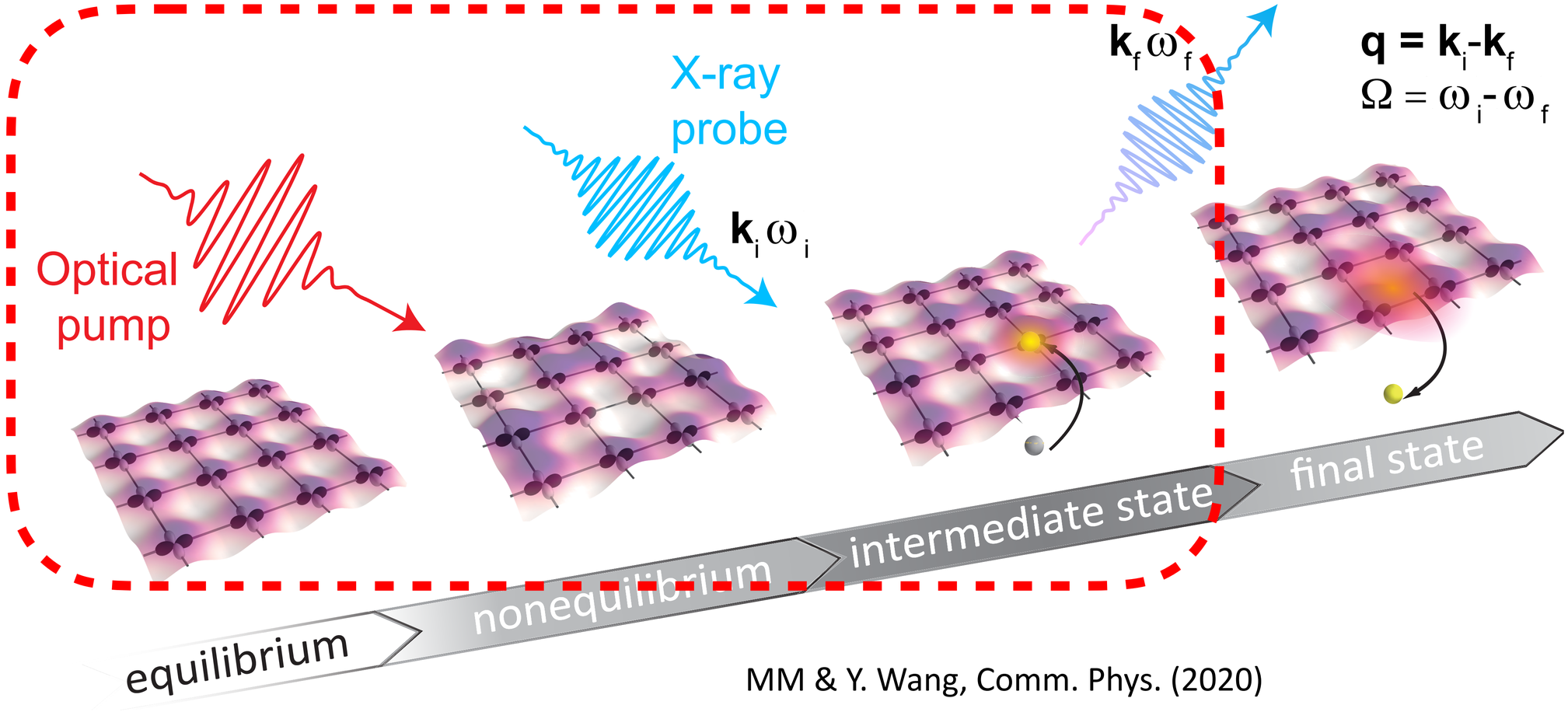
Measuring transient electronic interactions



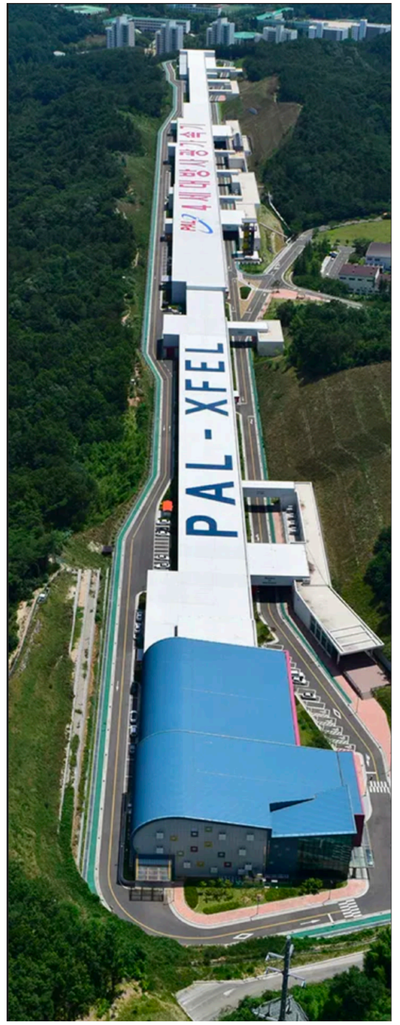
MM & Y. Wang, Comm. Phys. (2020)

Probing electronic states through time-resolved X-ray absorption

Measuring transient electronic interactions

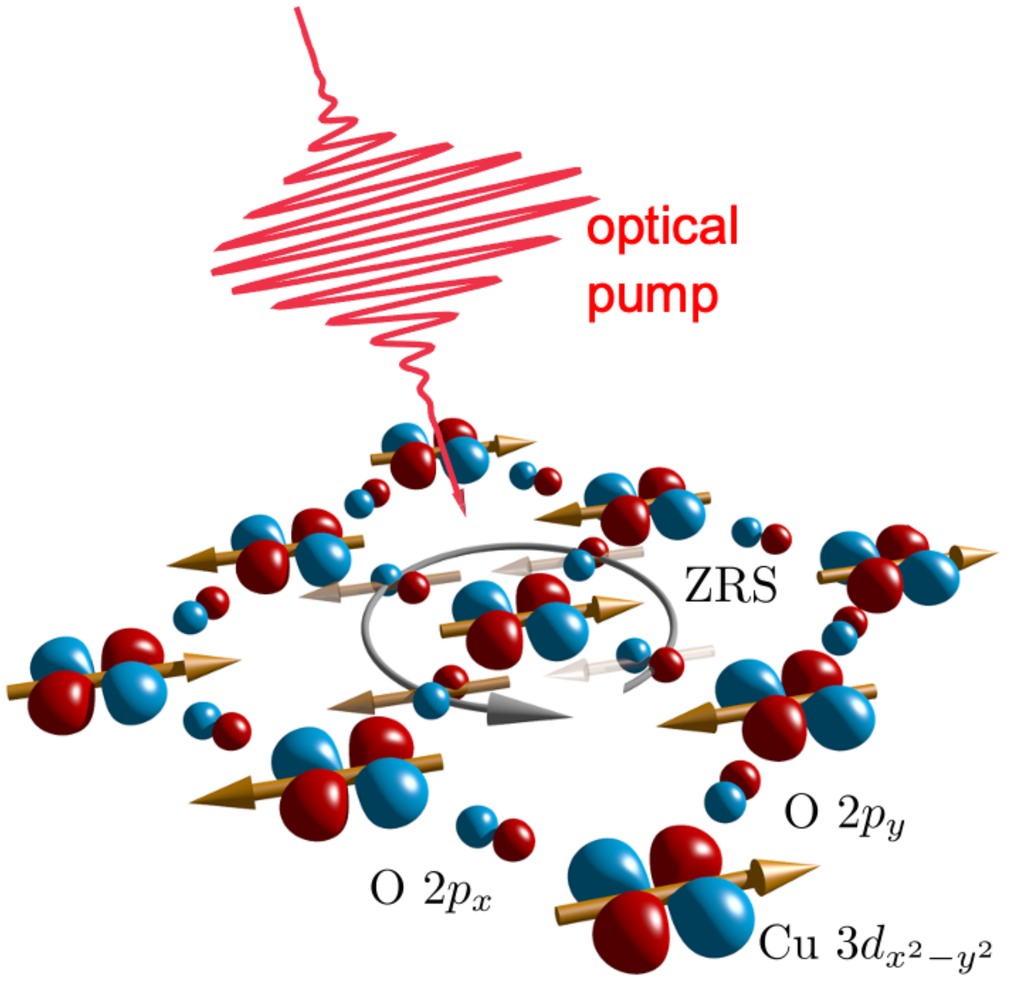


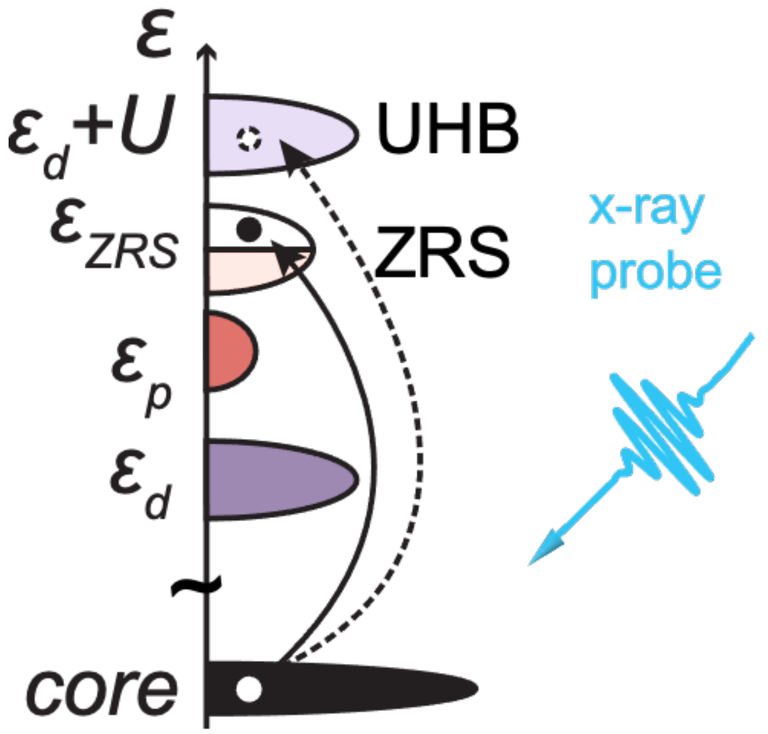
MM & Y. Wang, Comm. Phys. (2020)



Probing electronic states through time-resolved X-ray absorption

Measuring transient electronic interactions





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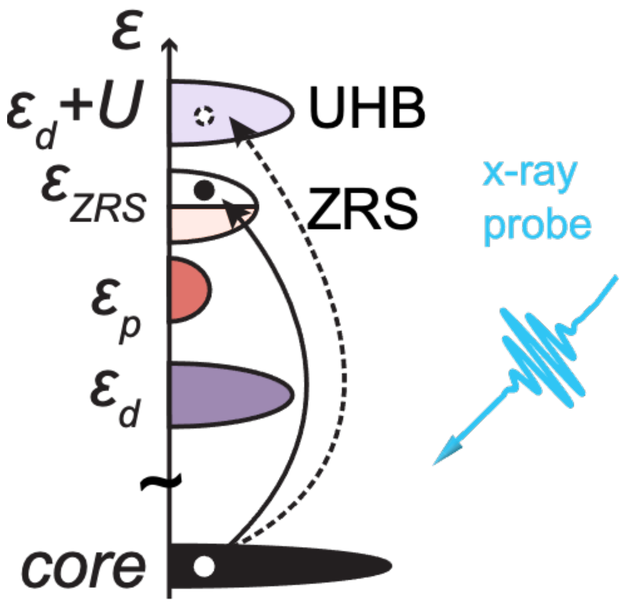
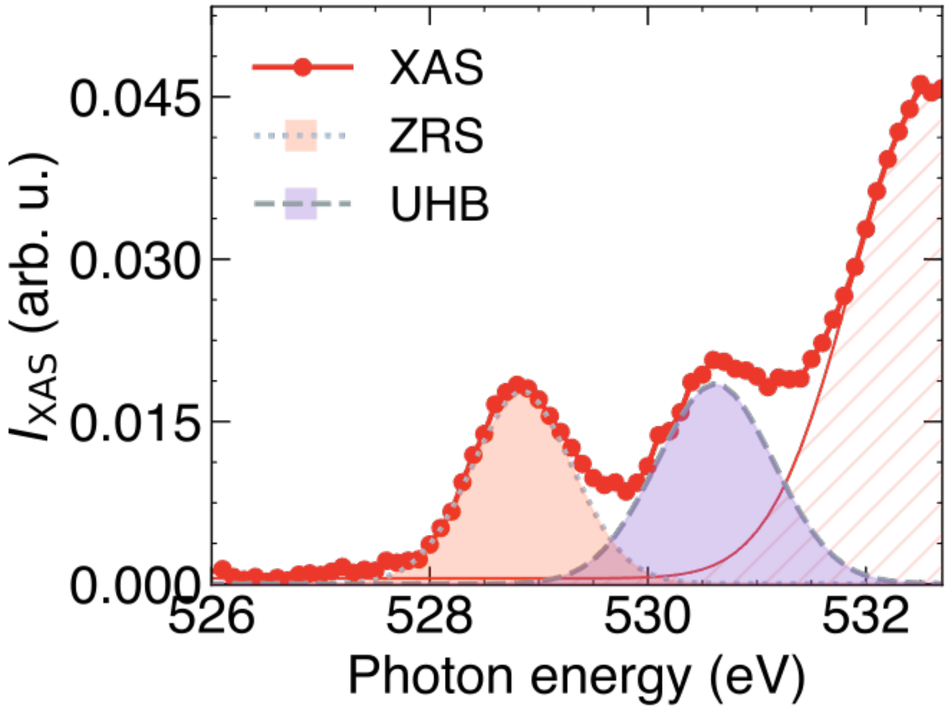
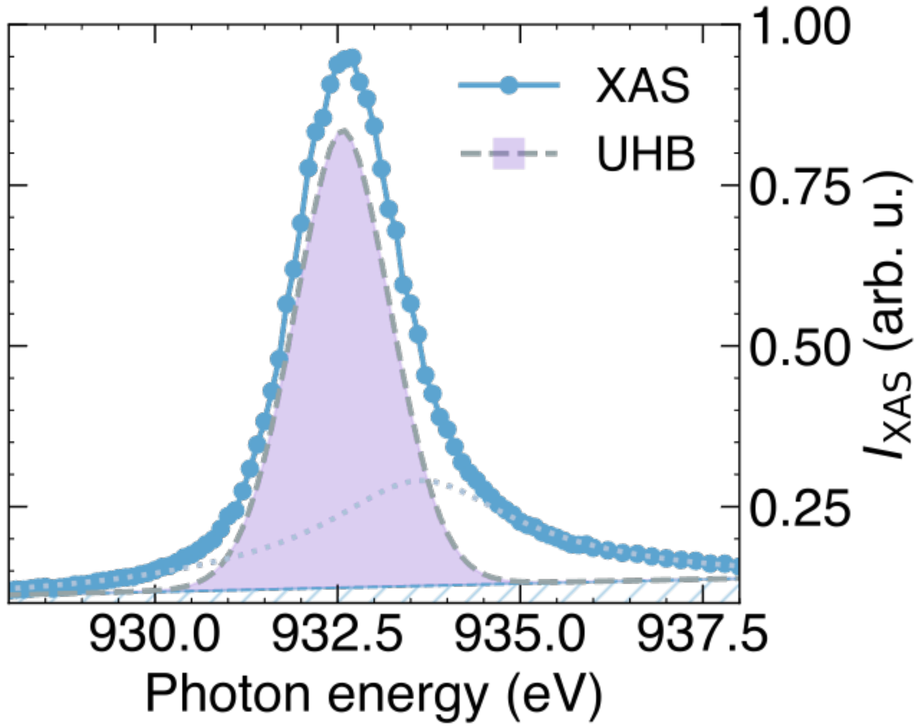
Measuring transient electronic interactions



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



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

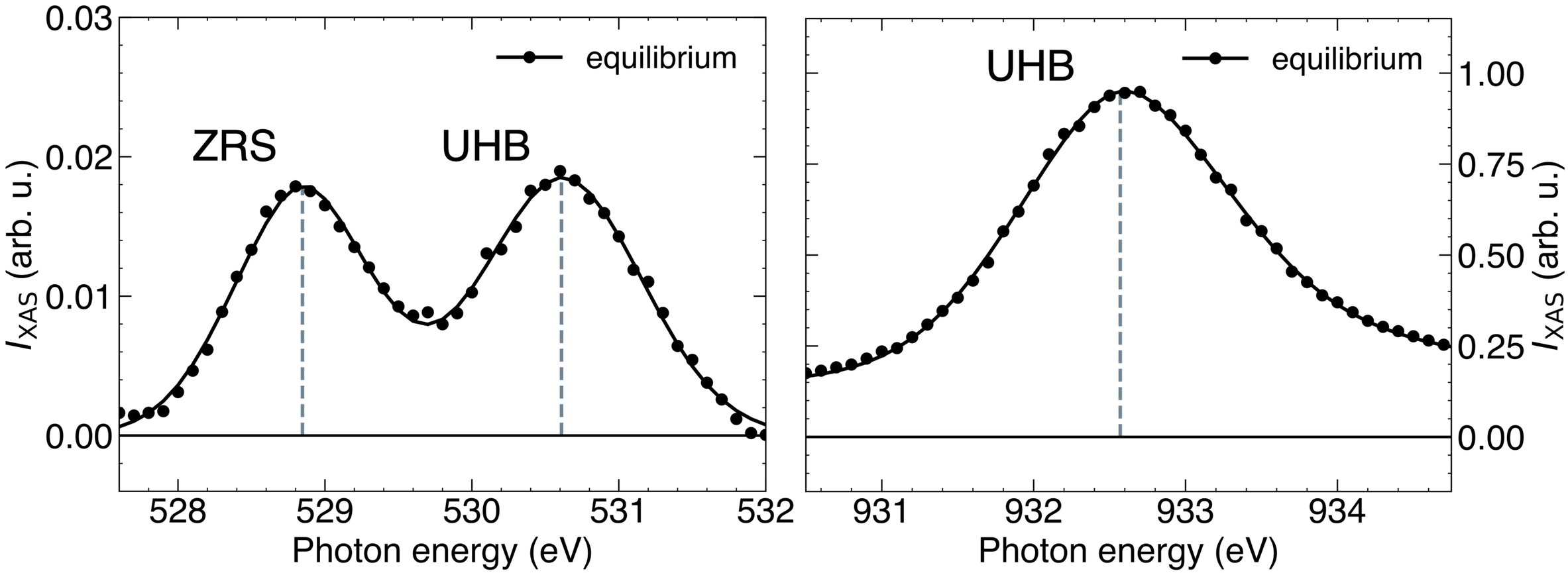


Probing electronic states through time-resolved X-ray absorption

Light-induced reshaping of the XAS spectrum

O K edge

Cu L edge



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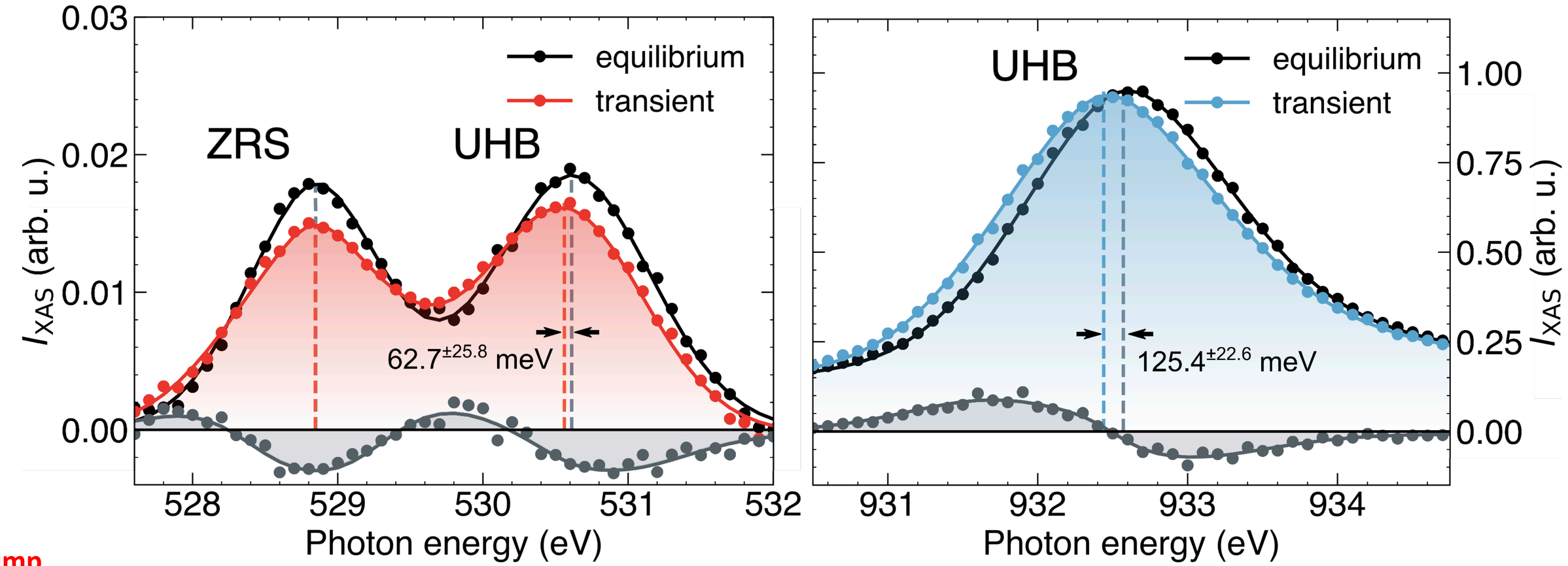
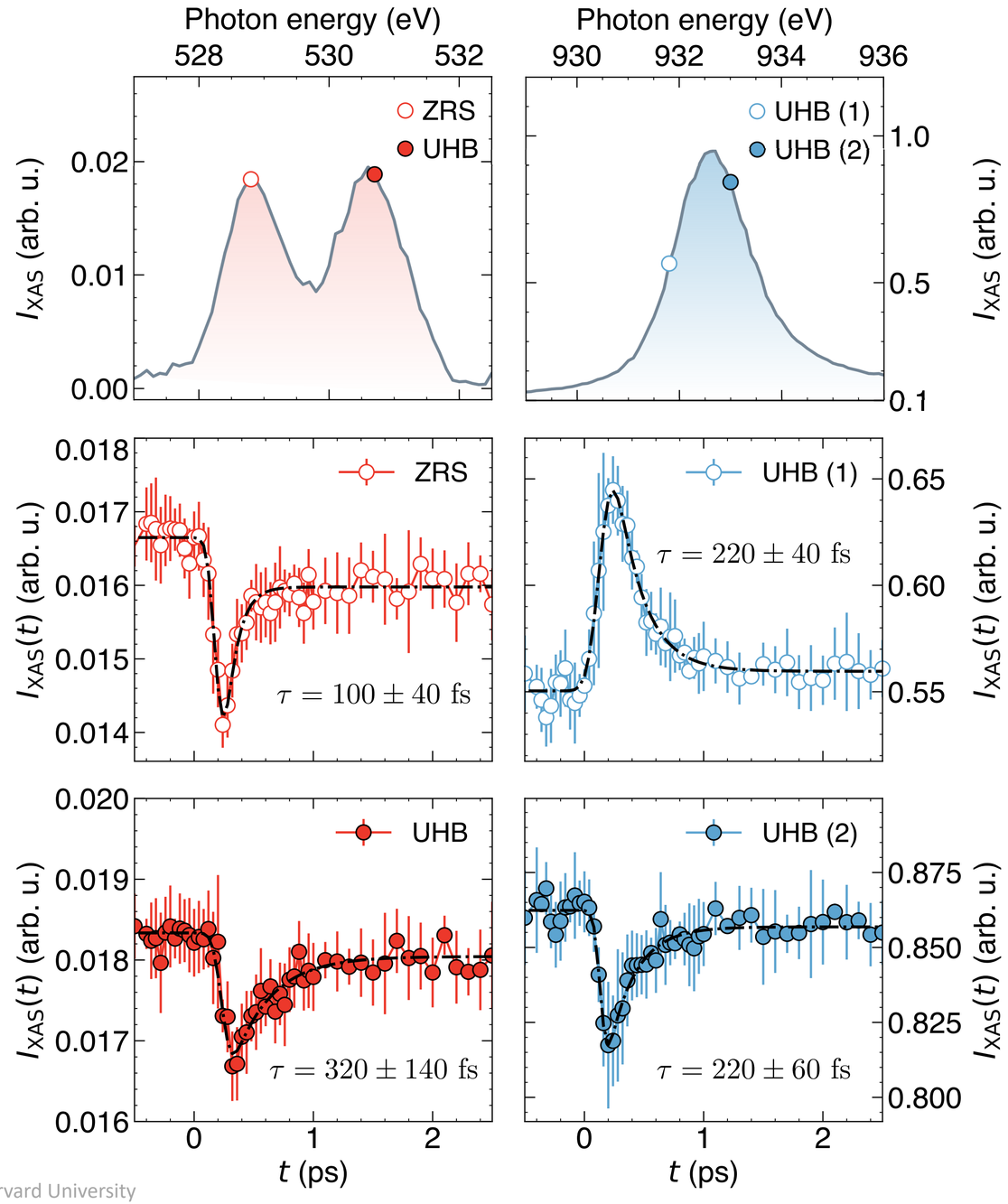


Pump
1.55 eV
12 MV/cm

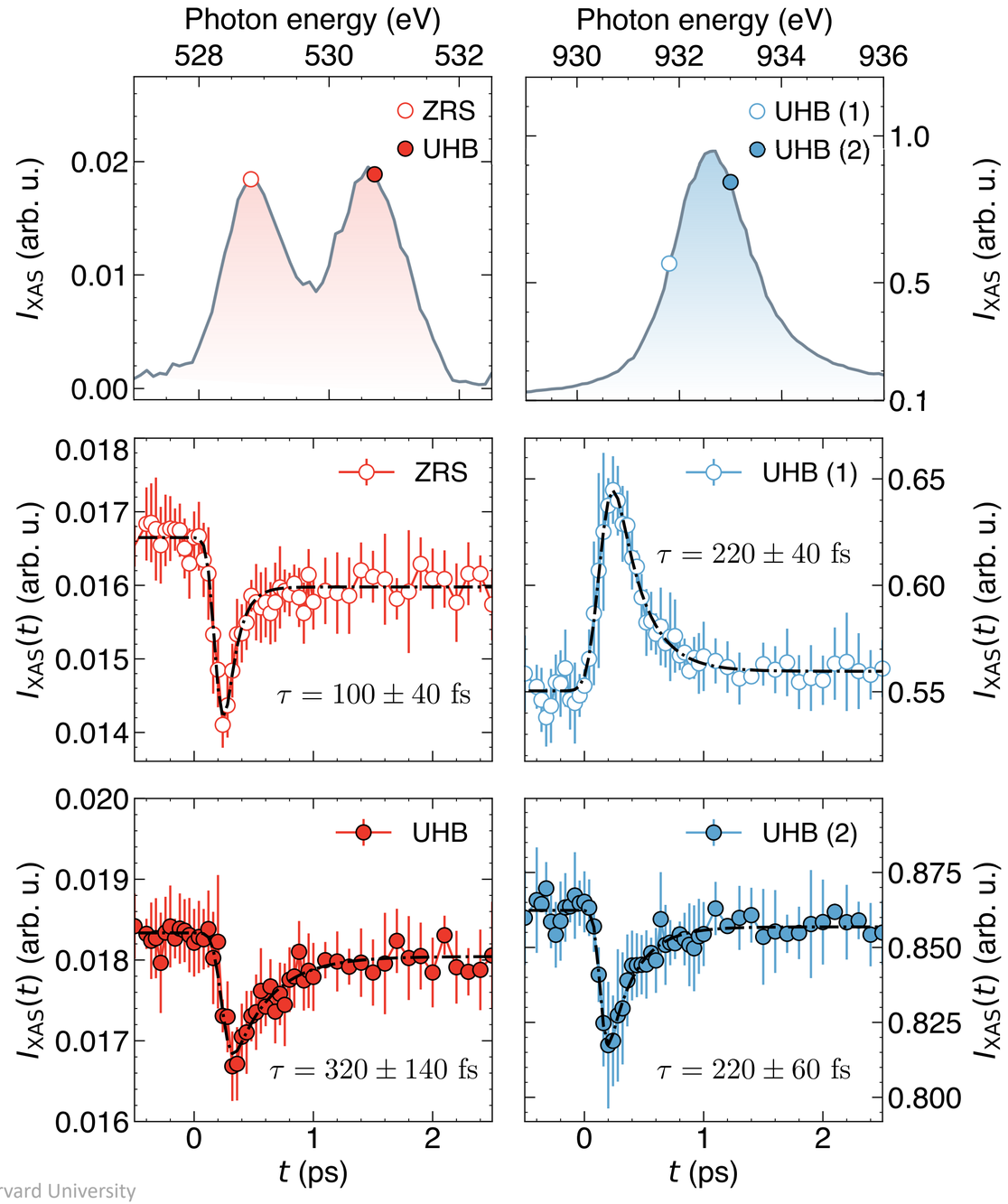
ZRS position remains fixed

UHB position redshifts

Light-induced reshaping of the XAS spectrum



Light-induced reshaping of the XAS spectrum



Holon-doublon recovery slower than valence carriers

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

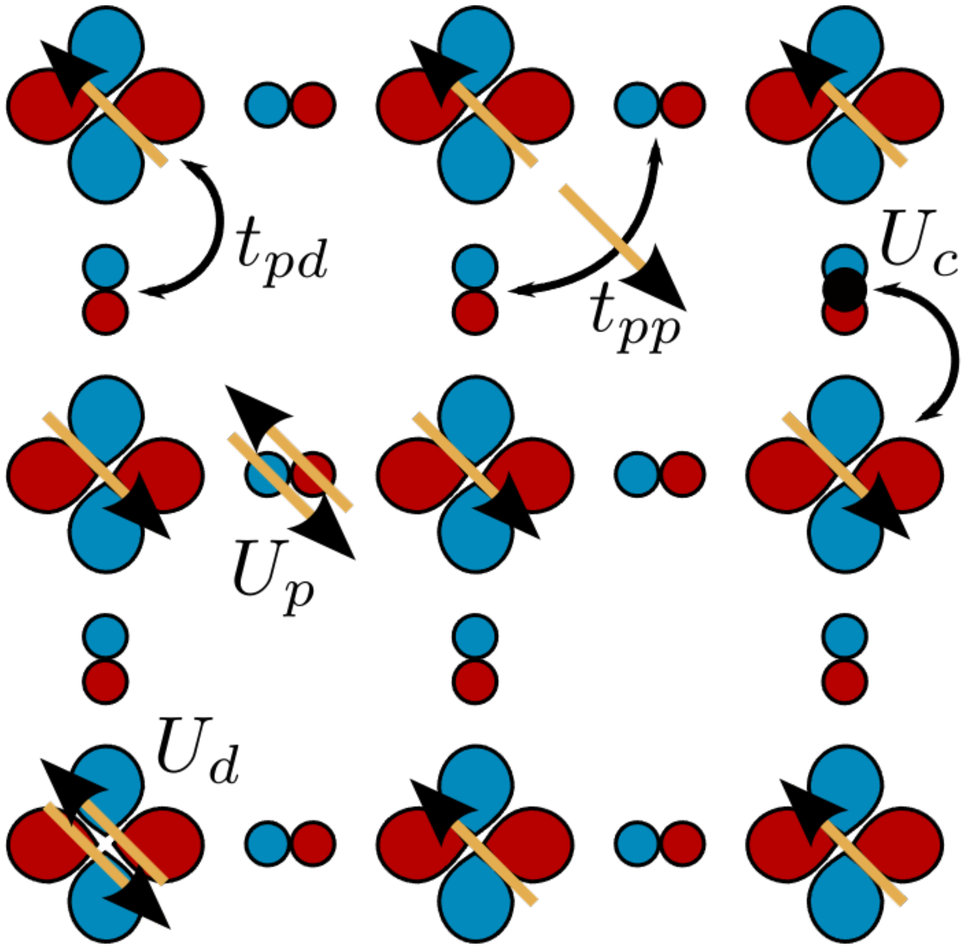
Cold atoms

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

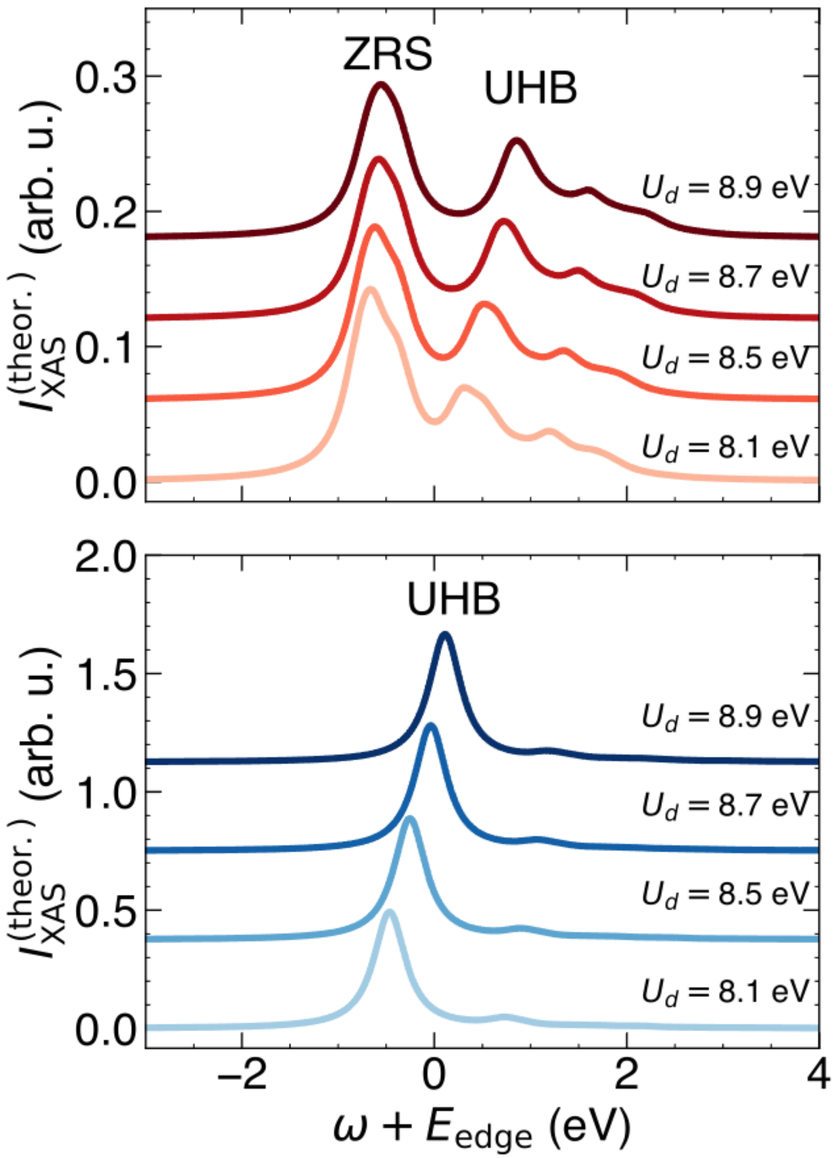
Condensed matter systems

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

Determining *U*: three-band Hubbard model

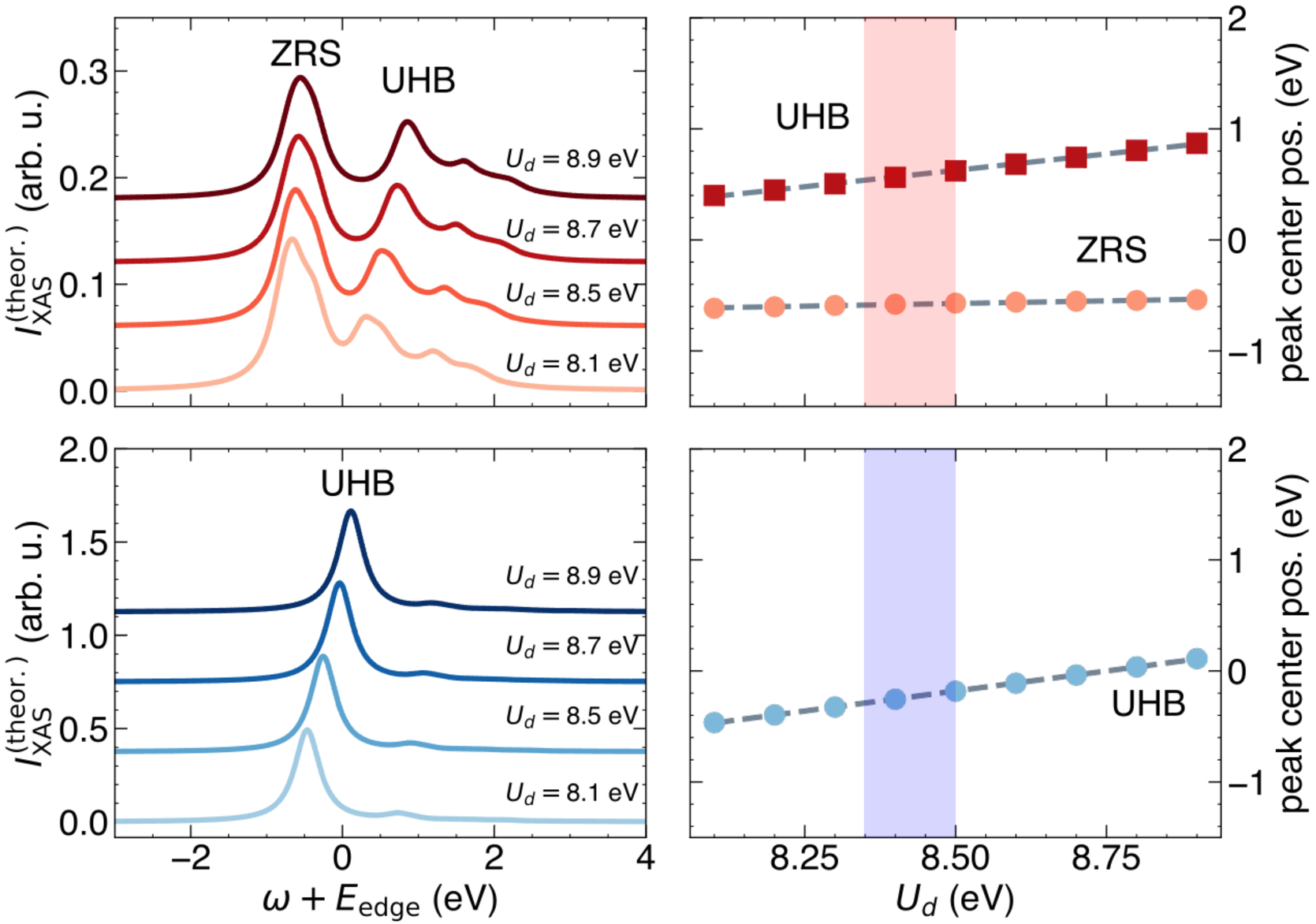


Determining *U*: three-band Hubbard model



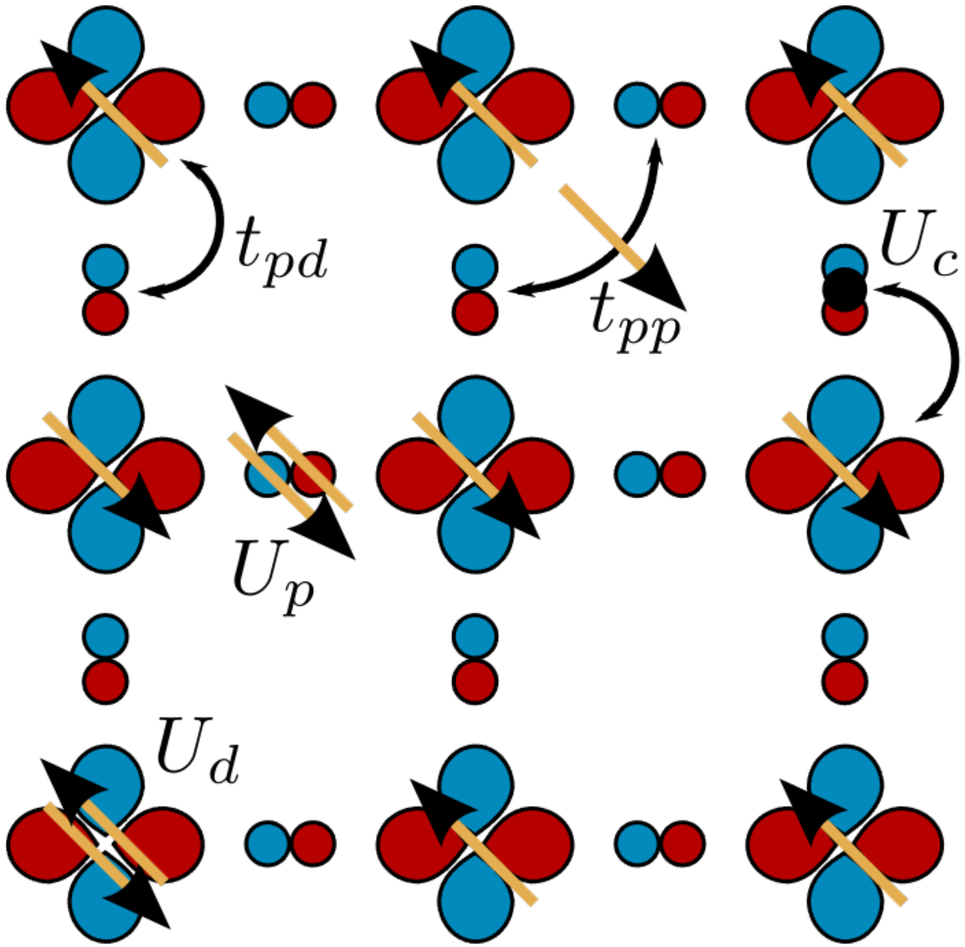
- Dynamical Hubbard U_d
- t_{pd}, t_{pp}, U_p shift the ZRS

Determining U: three-band Hubbard model



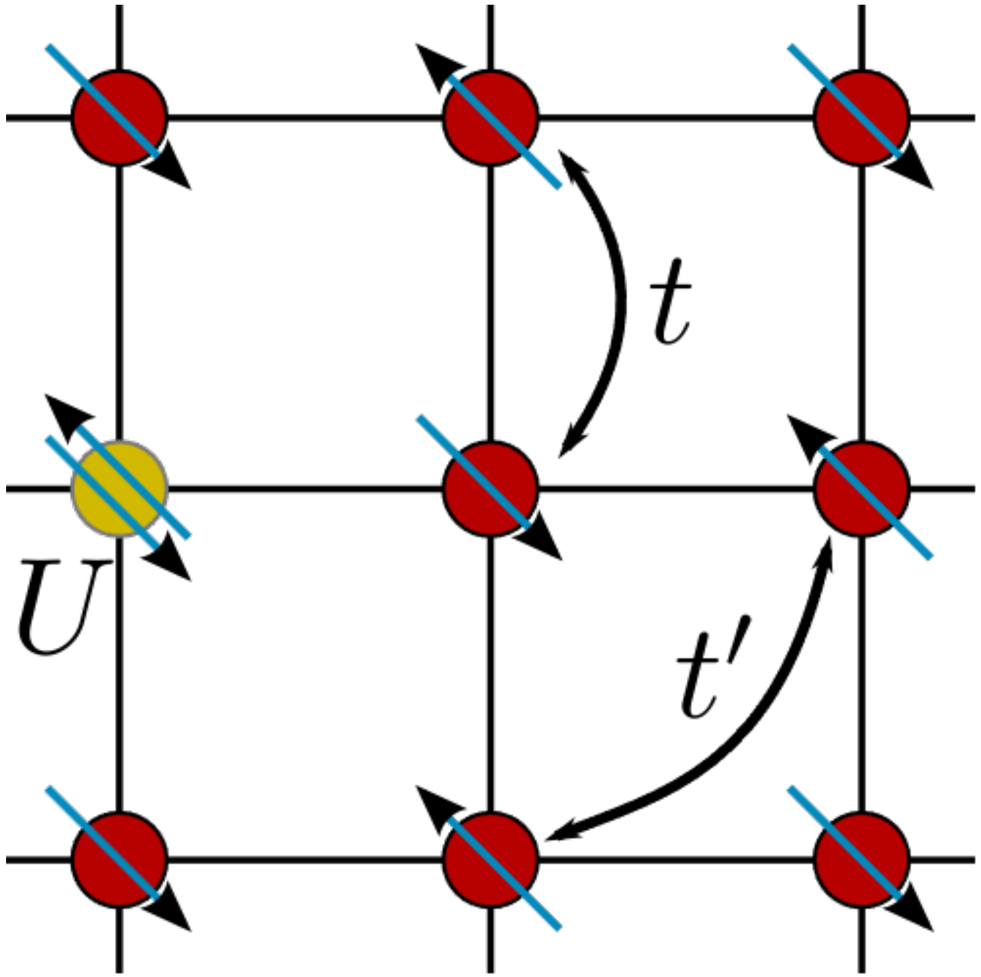
$$\delta U_d \sim 140 \text{ meV}$$

Dynamical Hubbard *U* in a minimal description



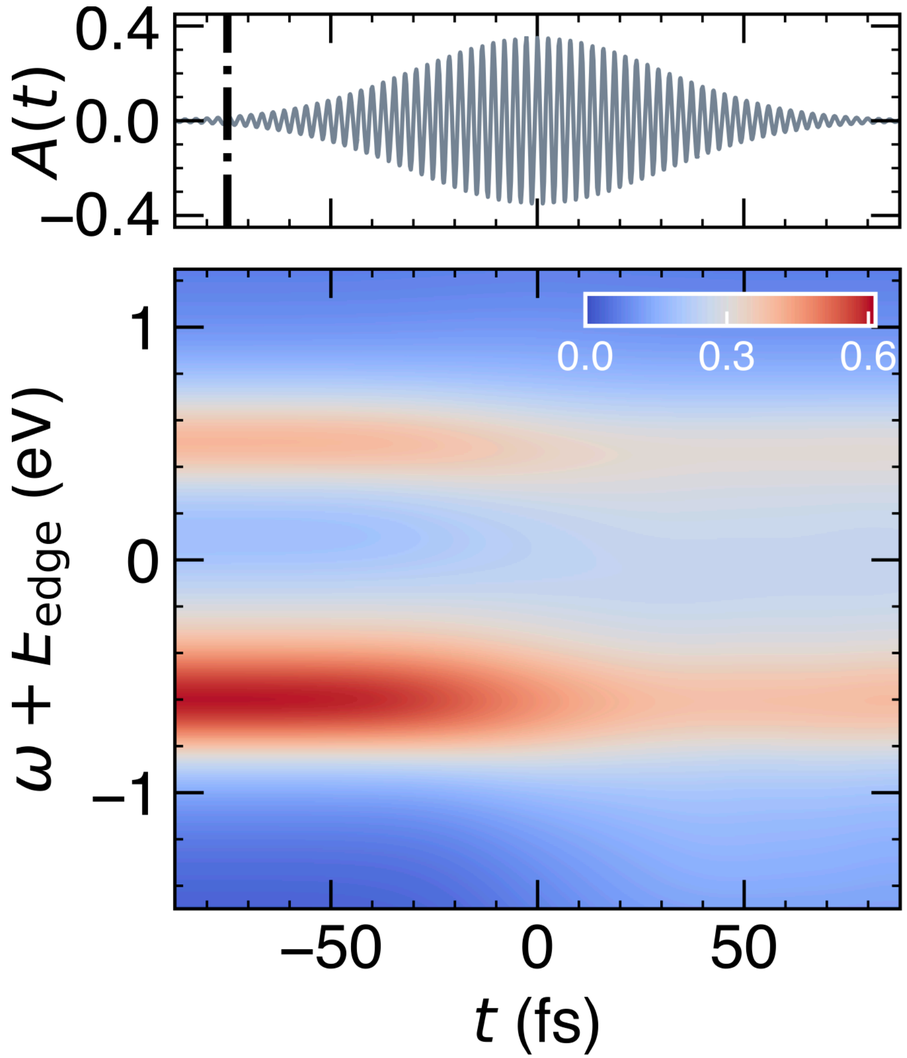
Dynamical Hubbard *U* in a minimal description

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

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1.55 eV
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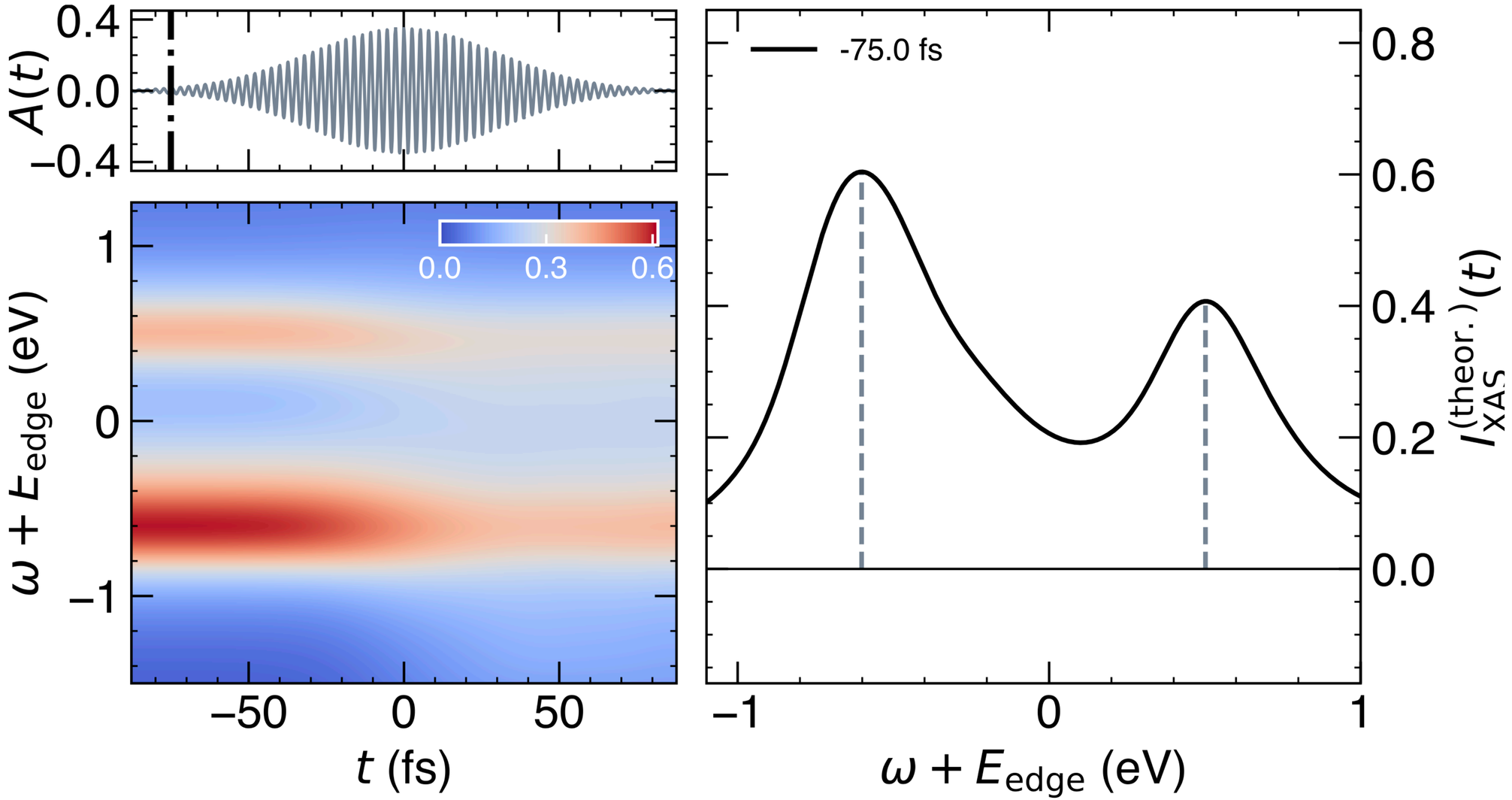

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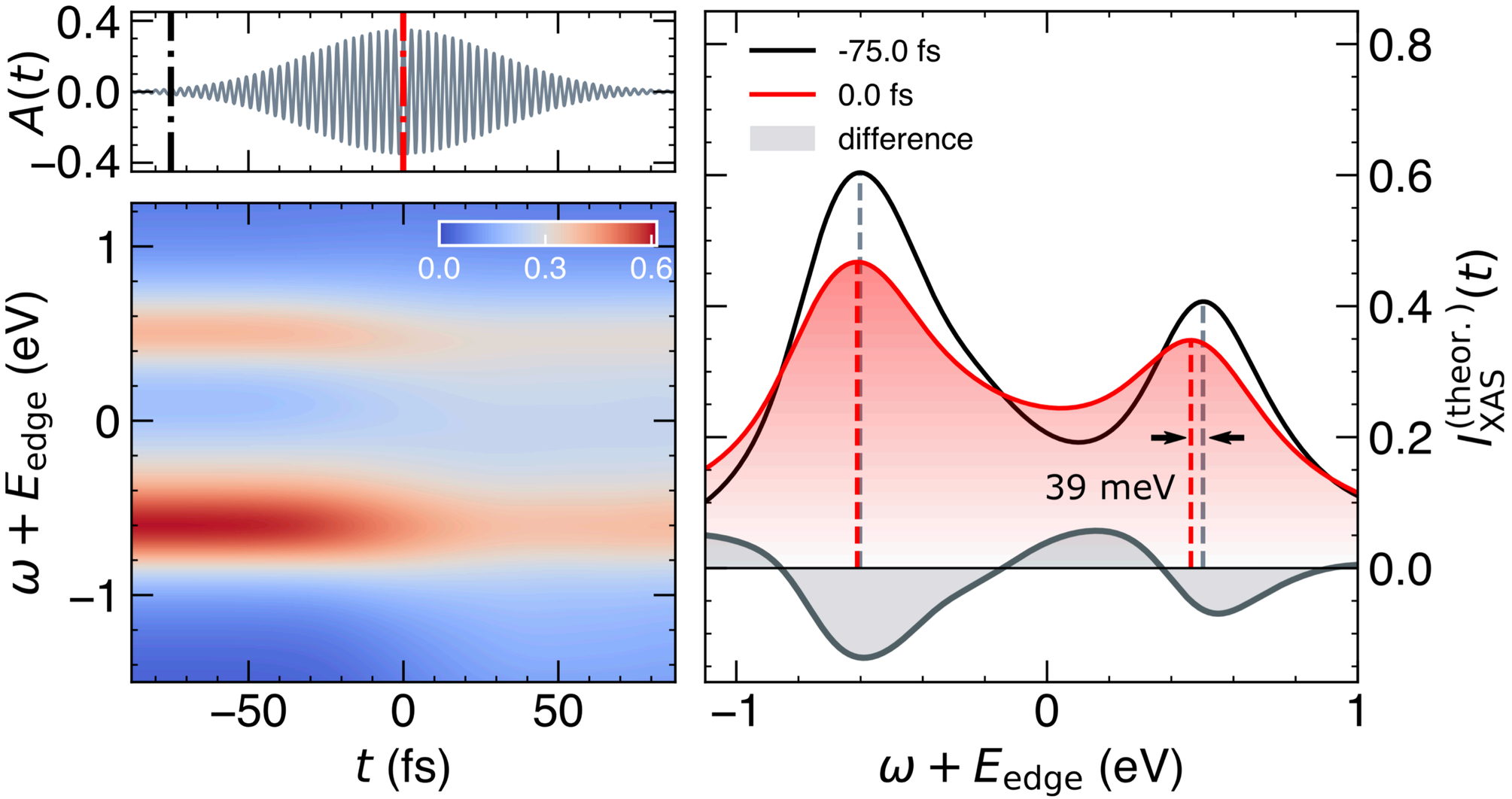
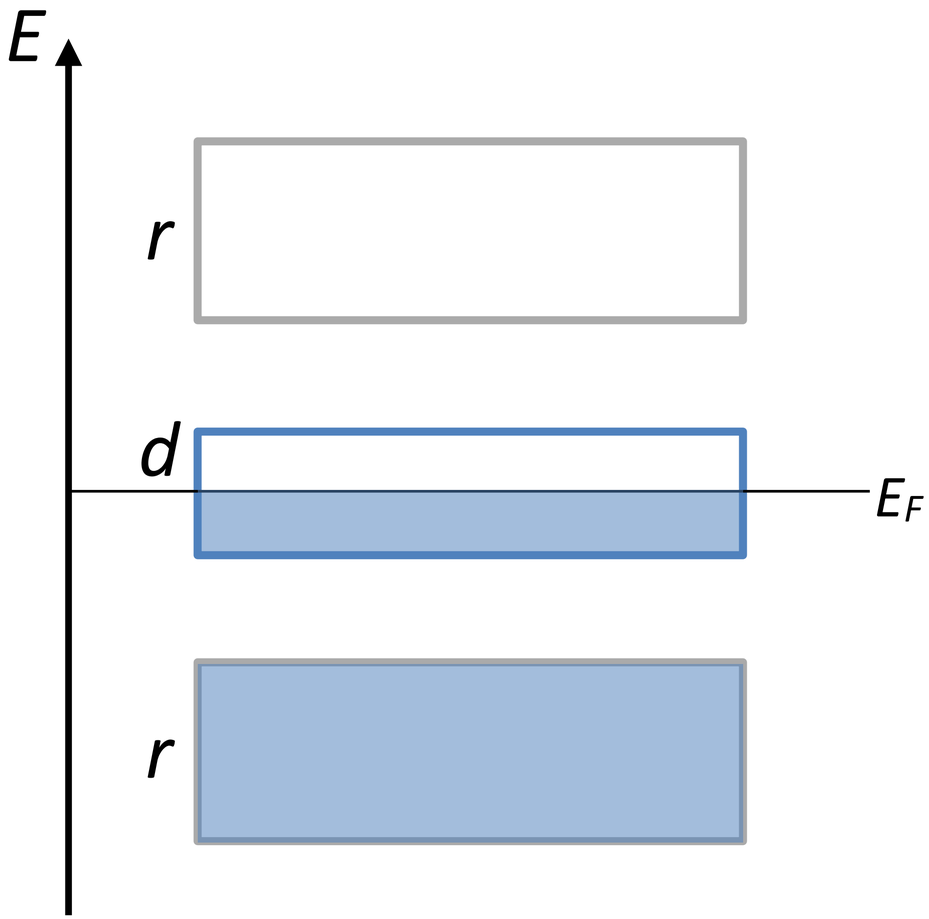


Renormalized Hubbard U also in single band

Possible microscopic mechanisms

Enhanced screening



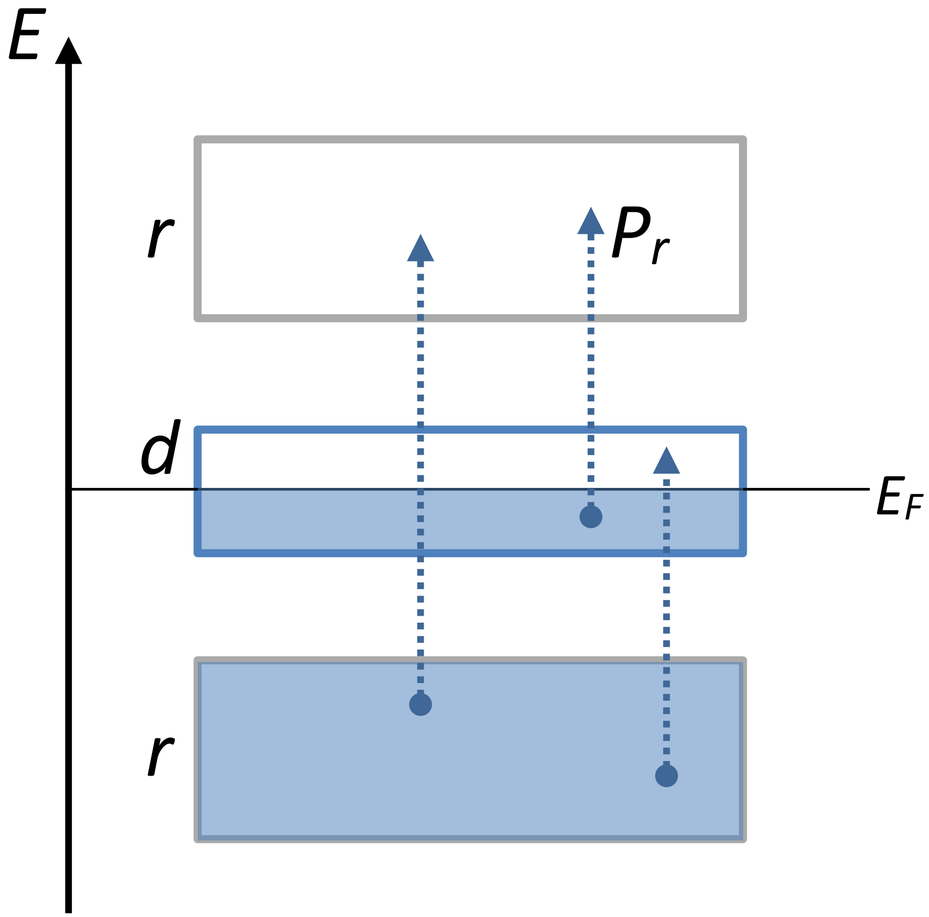
N. Tancogne-Dejean et al. PRL (2018)

D. Golez et al. PRB (2019)

F. Aryasetiawan, lecture notes, Jülich (2011)

Possible microscopic mechanisms

Enhanced screening



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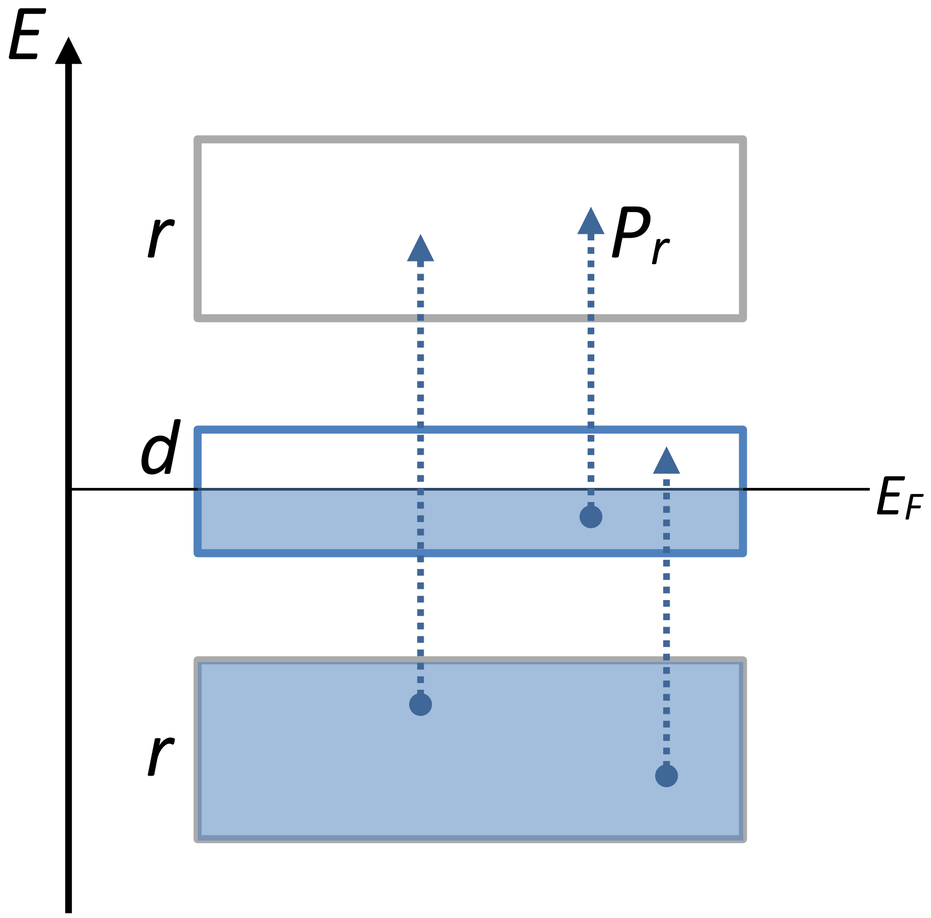

N. Tancogne-Dejean et al. PRL (2018)
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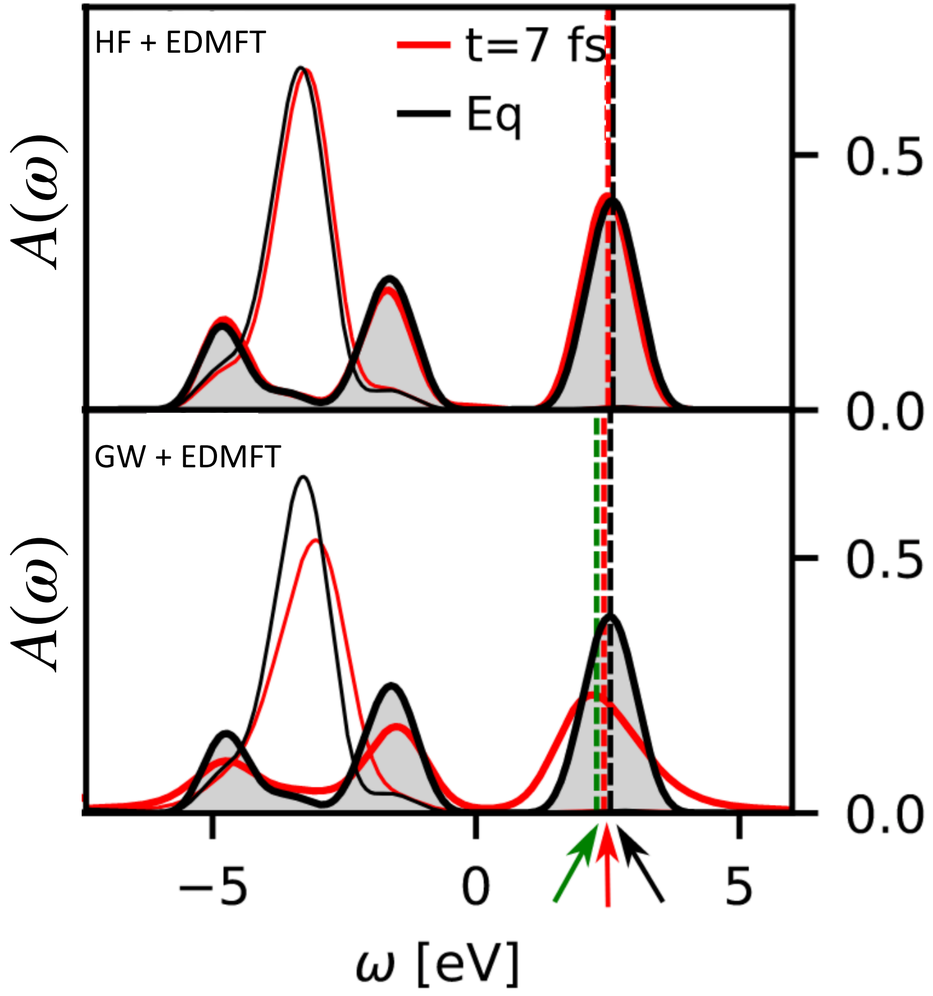
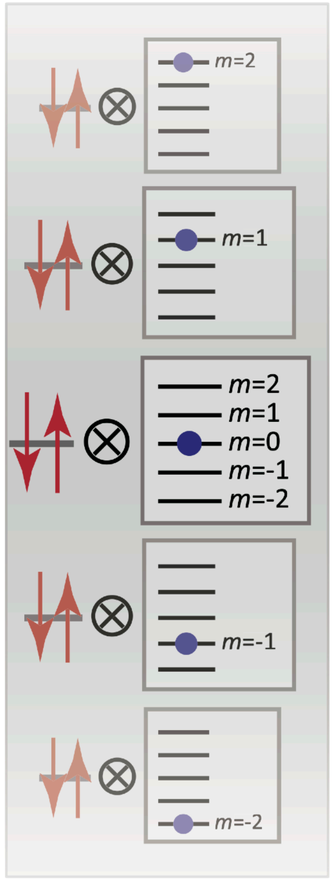


D. Golez et al. PRB (2019)

Possible microscopic mechanisms

Floquet renormalization



$U+2\Omega$

$U+\Omega$

U

$U-\Omega$

$U-2\Omega$

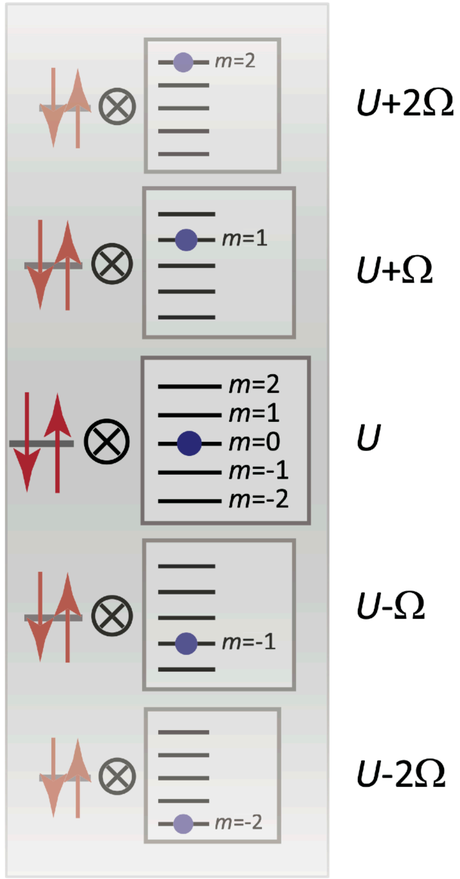
J. H. Mentink et al. Nature Comms (2015)

Y. Wang et al. PRB (2017)

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

Possible microscopic mechanisms

Floquet renormalization



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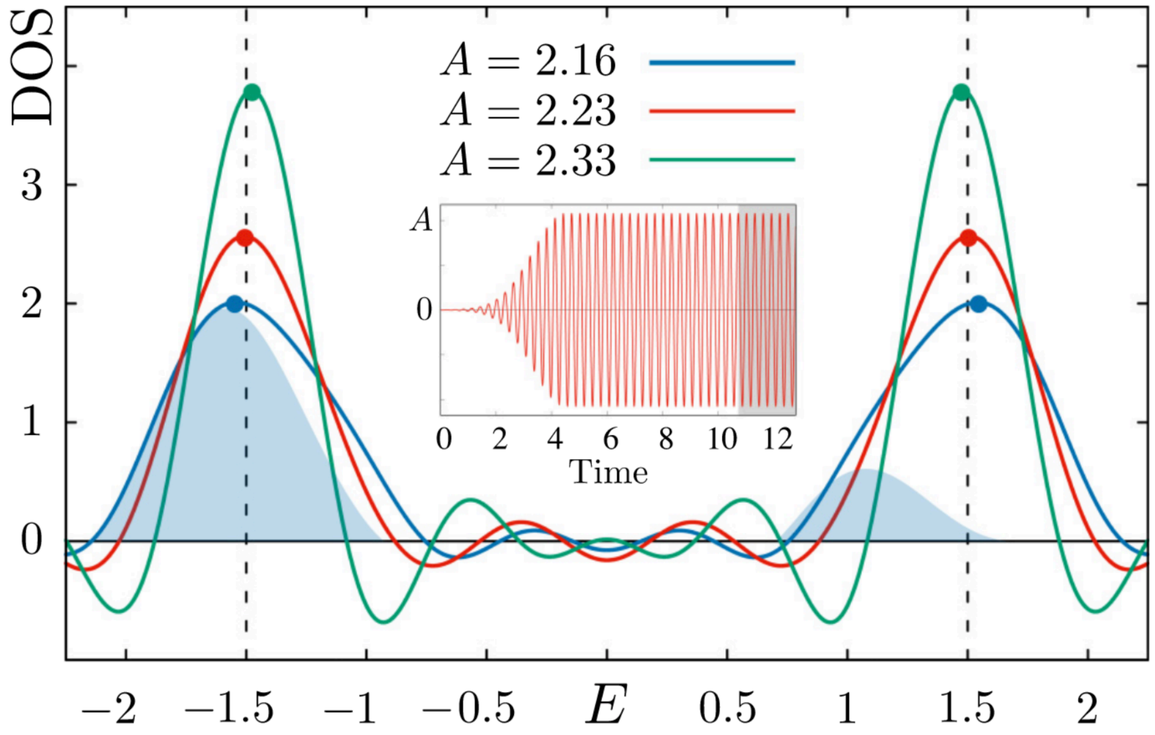
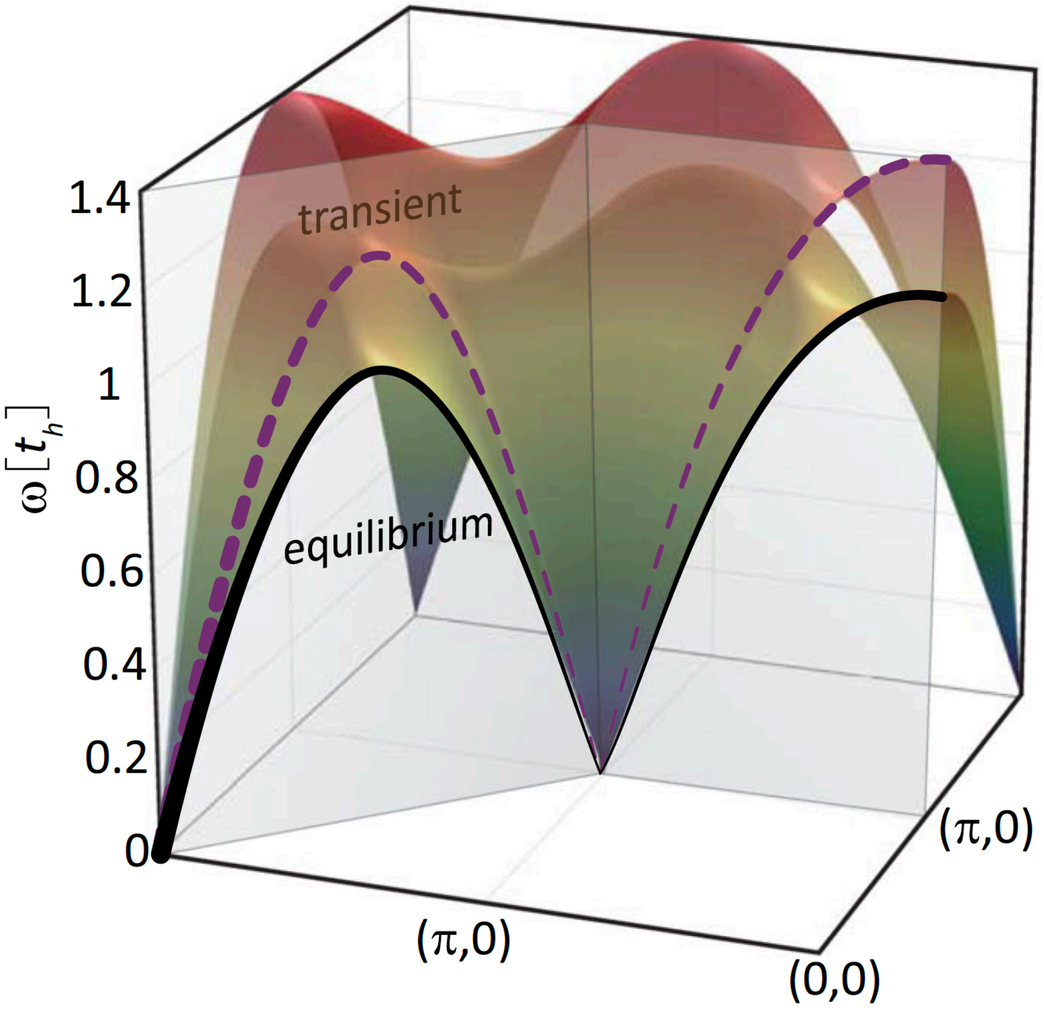


V. N. Valmispild et al. PRB (2020)

A microscopic tuning knob for light-driven quantum phases



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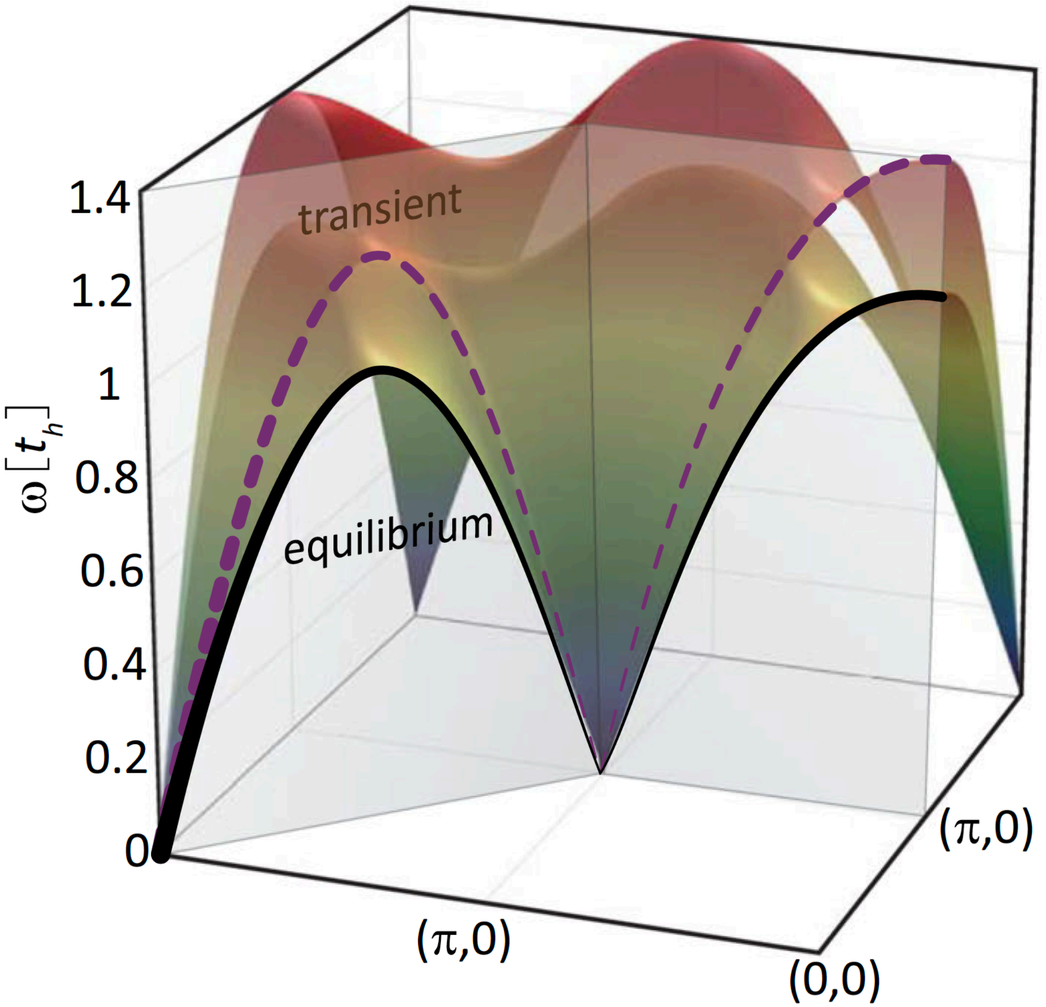

Spin liquid phases

Sahebsara PRL (2008)
Yang et al. PRL (2010)
Yan et al. Science (2011)
Claassen et al. Nat. Comm. (2017)
Szasz et al. PRX (2020)

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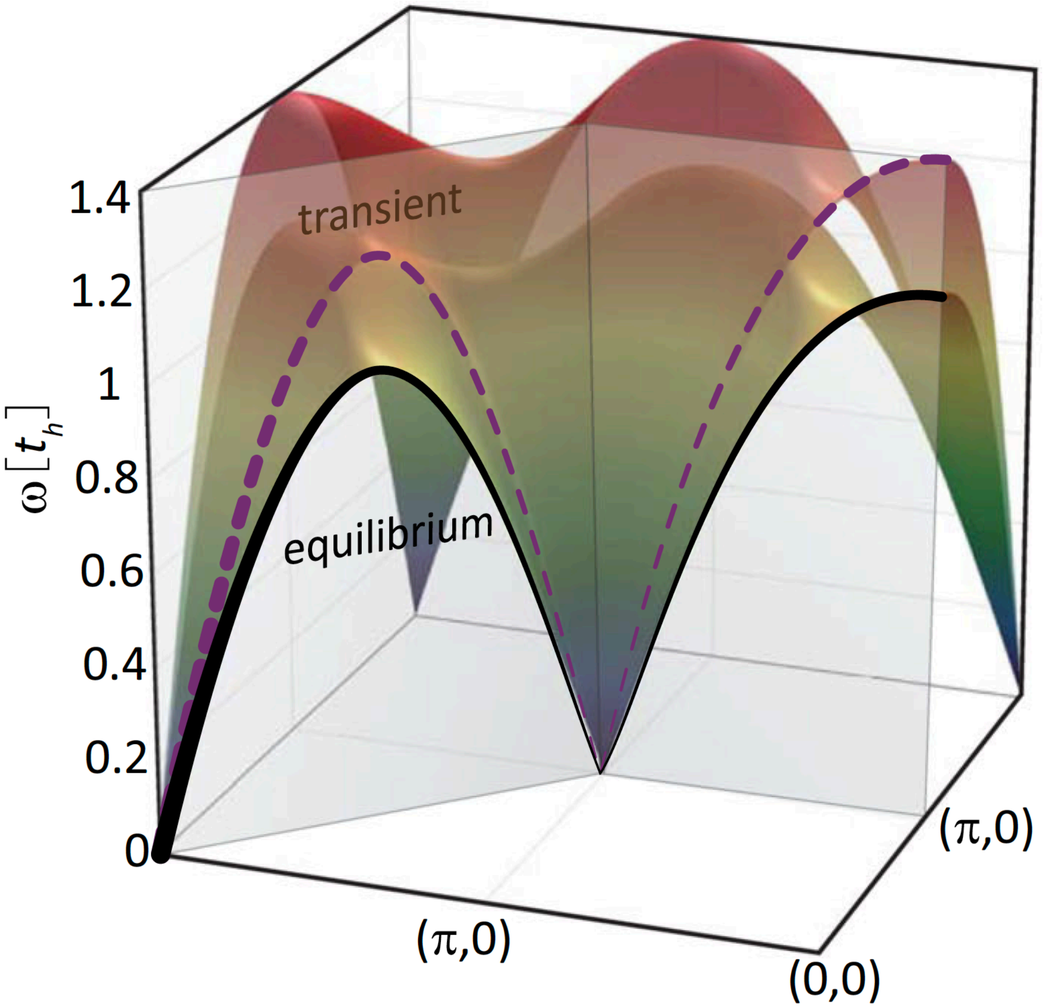

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Sahebsara PRL (2008)
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Szasz et al. PRX (2020)

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)

How to identify these quantum phases?

In collaboration with M. Sentef (MPSD), M. Claassen (UPenn), and D. Kennes (Aachen)

D. R. Baykusheva et al. forthcoming (2021)

Witnessing entanglement in spectroscopy

Witnessing entanglement in spectroscopy

Using Quantum Fisher Information (Equilibrium)

$$F_Q = 4\Delta(\hat{O})^2 = 4\left(\langle\psi|\,\hat{O}\hat{O}\,|\psi\rangle - \langle\psi|\,\hat{O}\,|\psi\rangle^2\right)$$

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$$F_Q = \frac{4}{\pi}\int_0^\infty d\omega \tanh\left(\frac{\omega}{2T}\right)\chi''(\omega, T)$$

Hauke et al. Nat. Phys. (2016)

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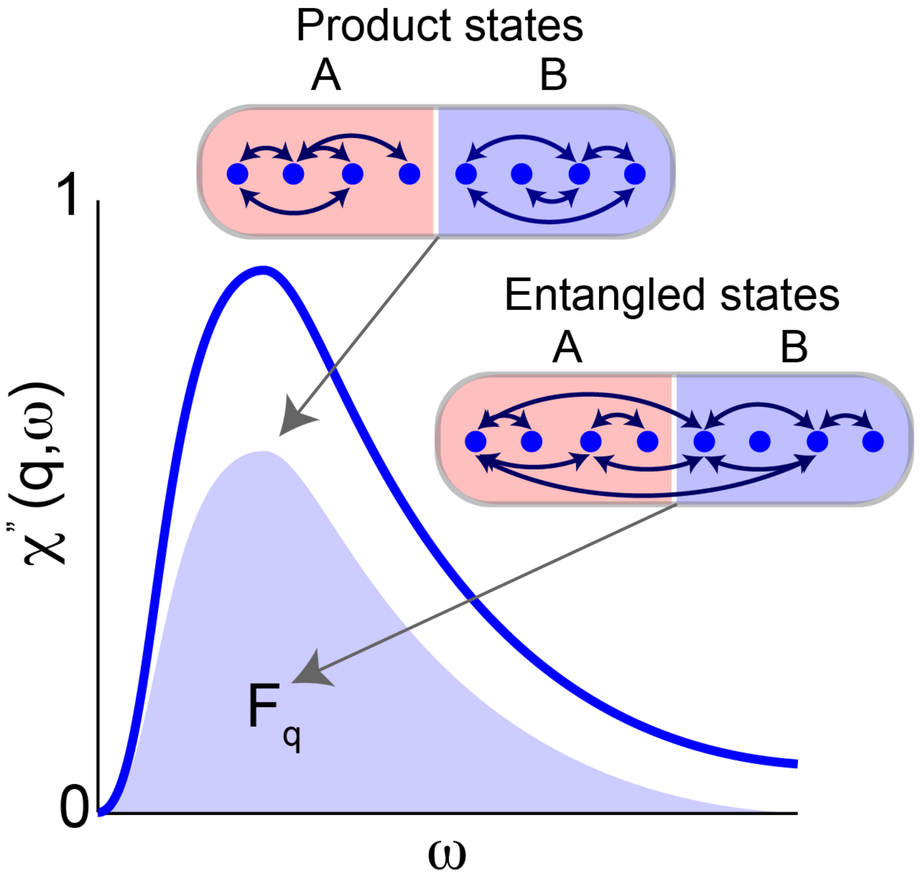

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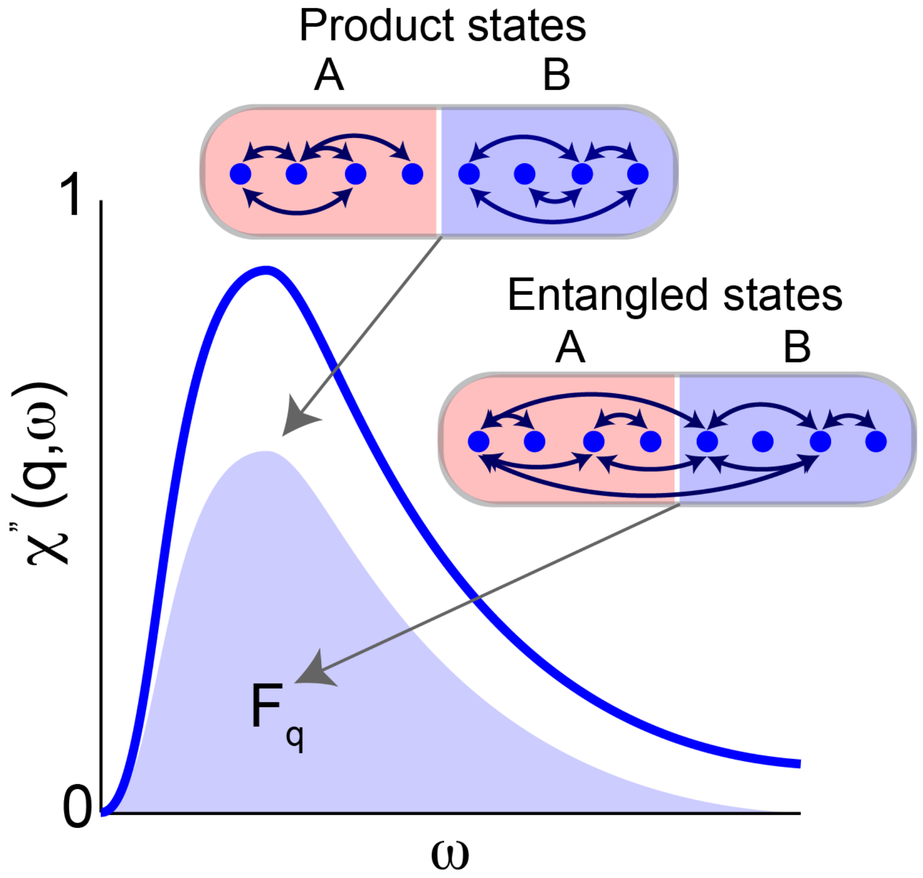

Diagnosing quantum criticality in physical spin systems

Mathew et al. PRR (2020)
Scheie et al. PRB (2021)
Laurell et al. PRL (2021)

Testing the QFI in a quantum chain

Testing the QFI in a quantum chain

XXZ chain in equilibrium $\hat{H}_{XXZ} = \sum_i J\Big[-\frac{1}{2}\big(\hat{S}_i^+\hat{S}_{i+1}^- + \hat{S}_i^-\hat{S}_{i+1}^+\big) + \Delta\hat{S}_i^z\hat{S}_{i+1}^z\Big]$

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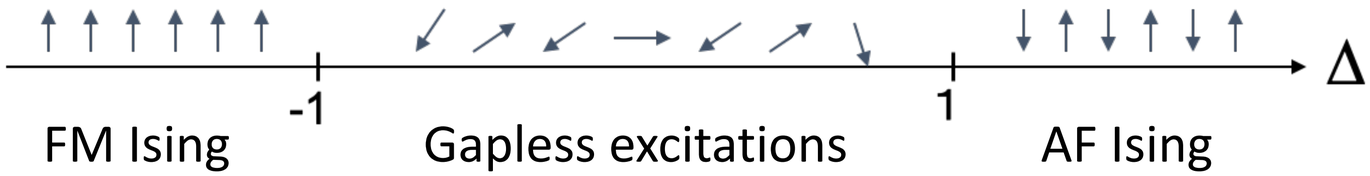

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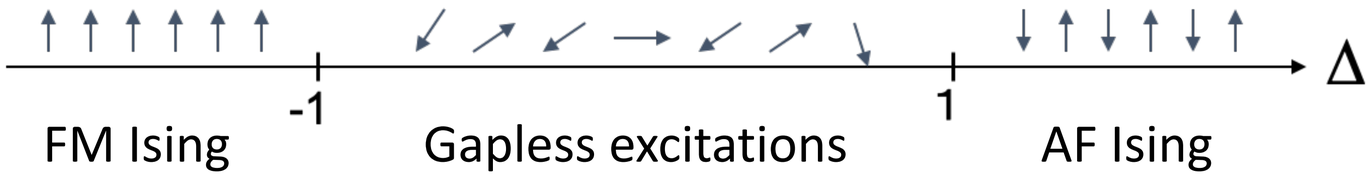

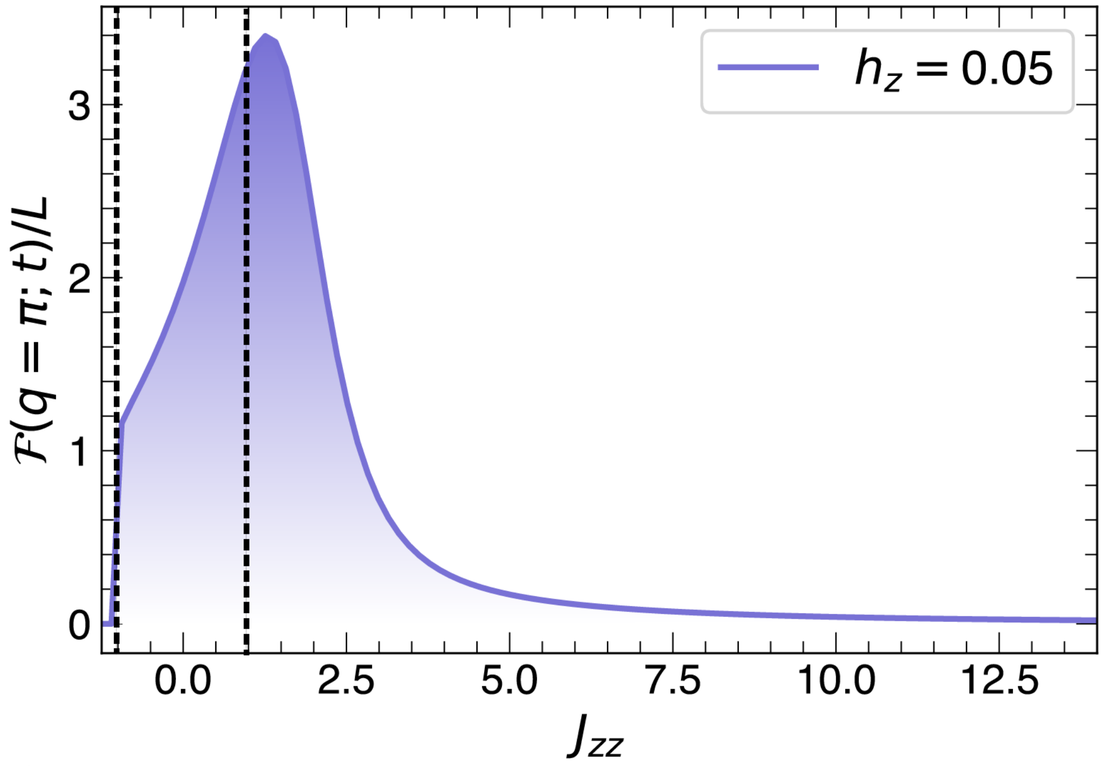

QFI captures the equilibrium phase transitions

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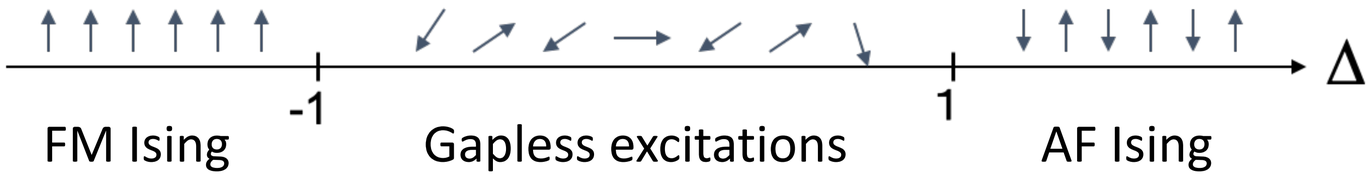
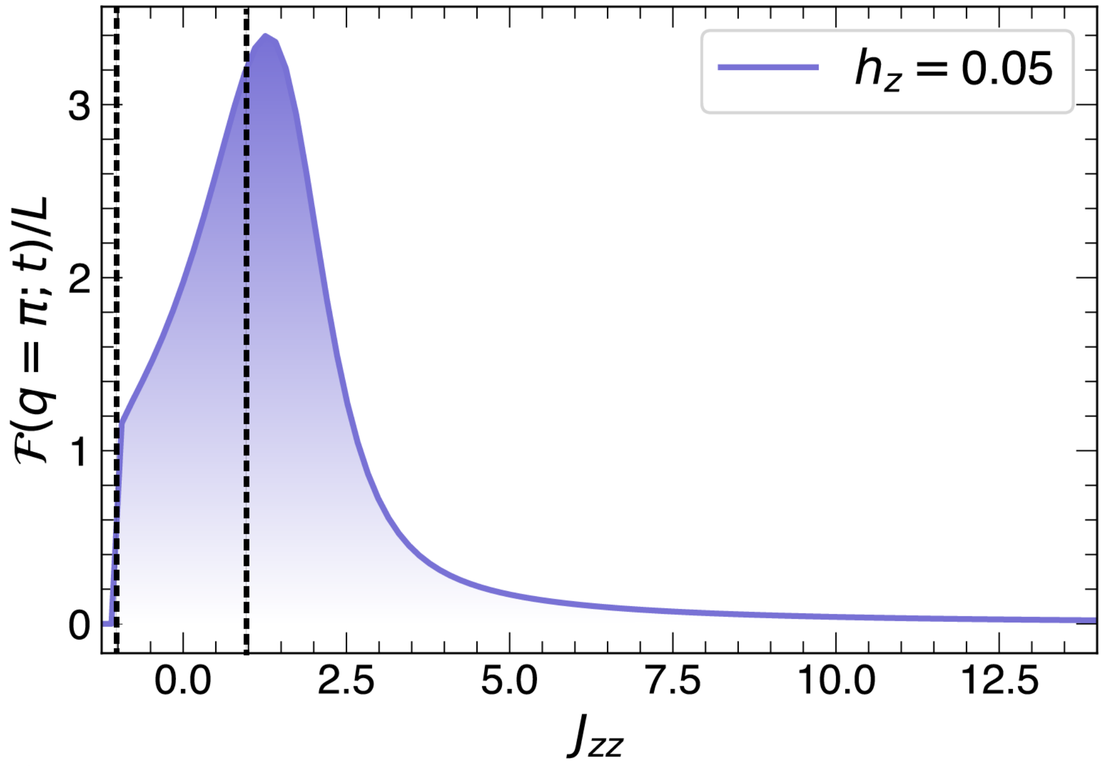
XXZ chain in equilibrium $\hat{H}_{XXZ} = \sum_i J\left[-\frac{1}{2}\left(\hat{S}_i^+\hat{S}_{i+1}^- + \hat{S}_i^-\hat{S}_{i+1}^+\right) + \Delta\hat{S}_i^z\hat{S}_{i+1}^z\right]$





QFI captures the equilibrium phase transitions

Is this also true out of equilibrium?

QFI in a nonequilibrium interaction ramp

XXZ chain out of equilibrium $\hat{H}_{XXZ}(t) = \sum_i J\left[-\frac{1}{2}\left(\hat{S}_i^+ \hat{S}_{i+1}^- + \hat{S}_i^- \hat{S}_{i+1}^+\right) + \Delta(t)\hat{S}_i^z \hat{S}_{i+1}^z \right]$

QFI in a nonequilibrium interaction ramp

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QFI is enhanced while ramping across the AF transition

QFI in a nonequilibrium interaction ramp

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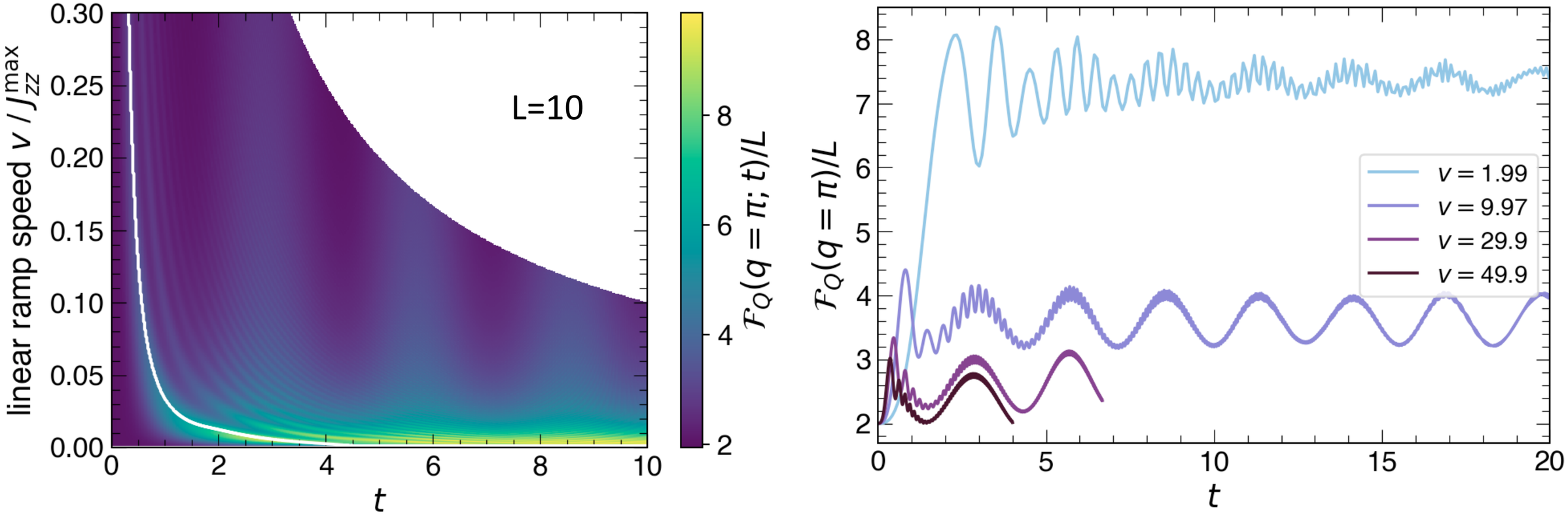

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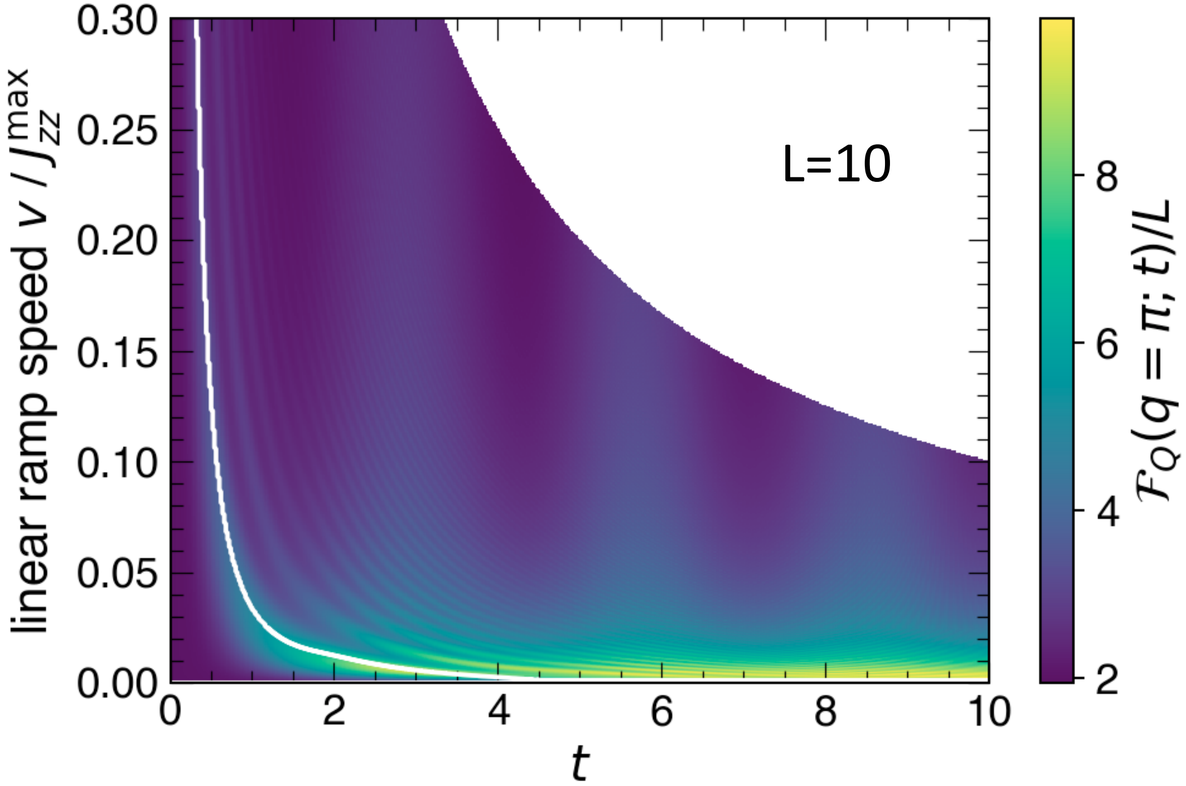
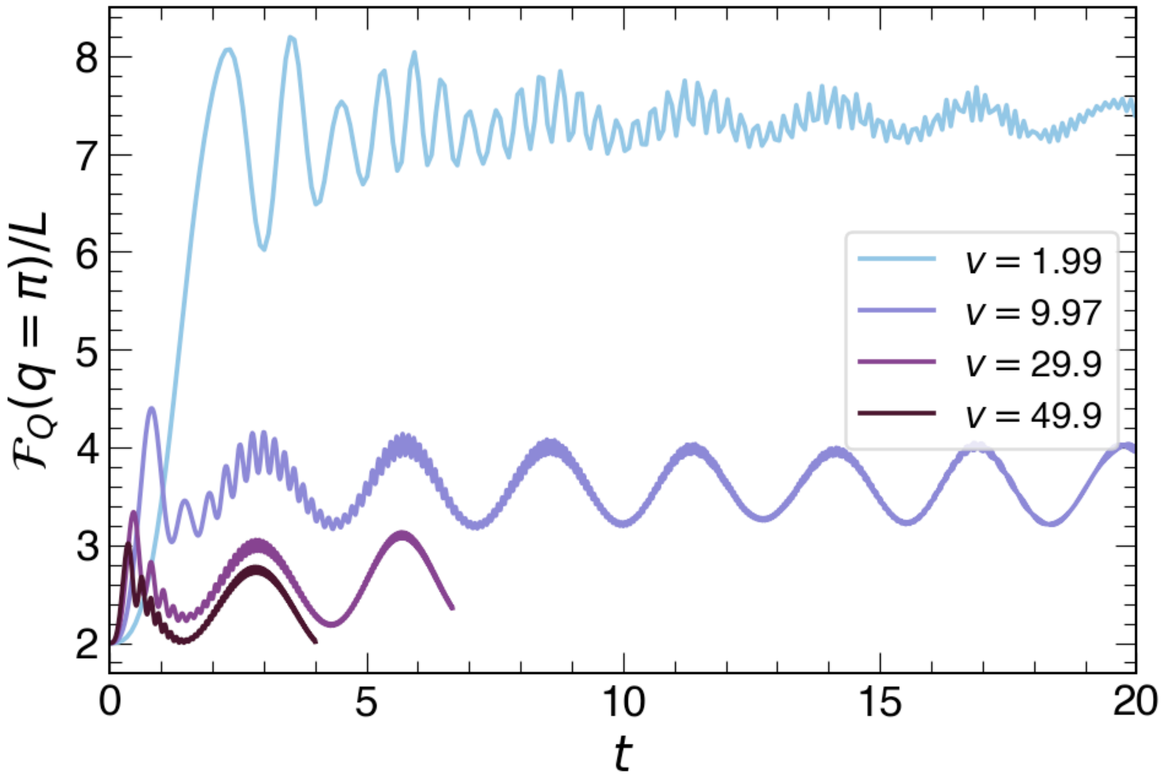
QFI in a nonequilibrium interaction ramp

XXZ chain out of equilibrium $\hat{H}_{XXZ}(t) = \sum_i J\Big[-\frac{1}{2}\big(\hat{S}_i^+\hat{S}_{i+1}^- + \hat{S}_i^-\hat{S}_{i+1}^+\big) + \Delta(t)\hat{S}_i^z\hat{S}_{i+1}^z\Big]$

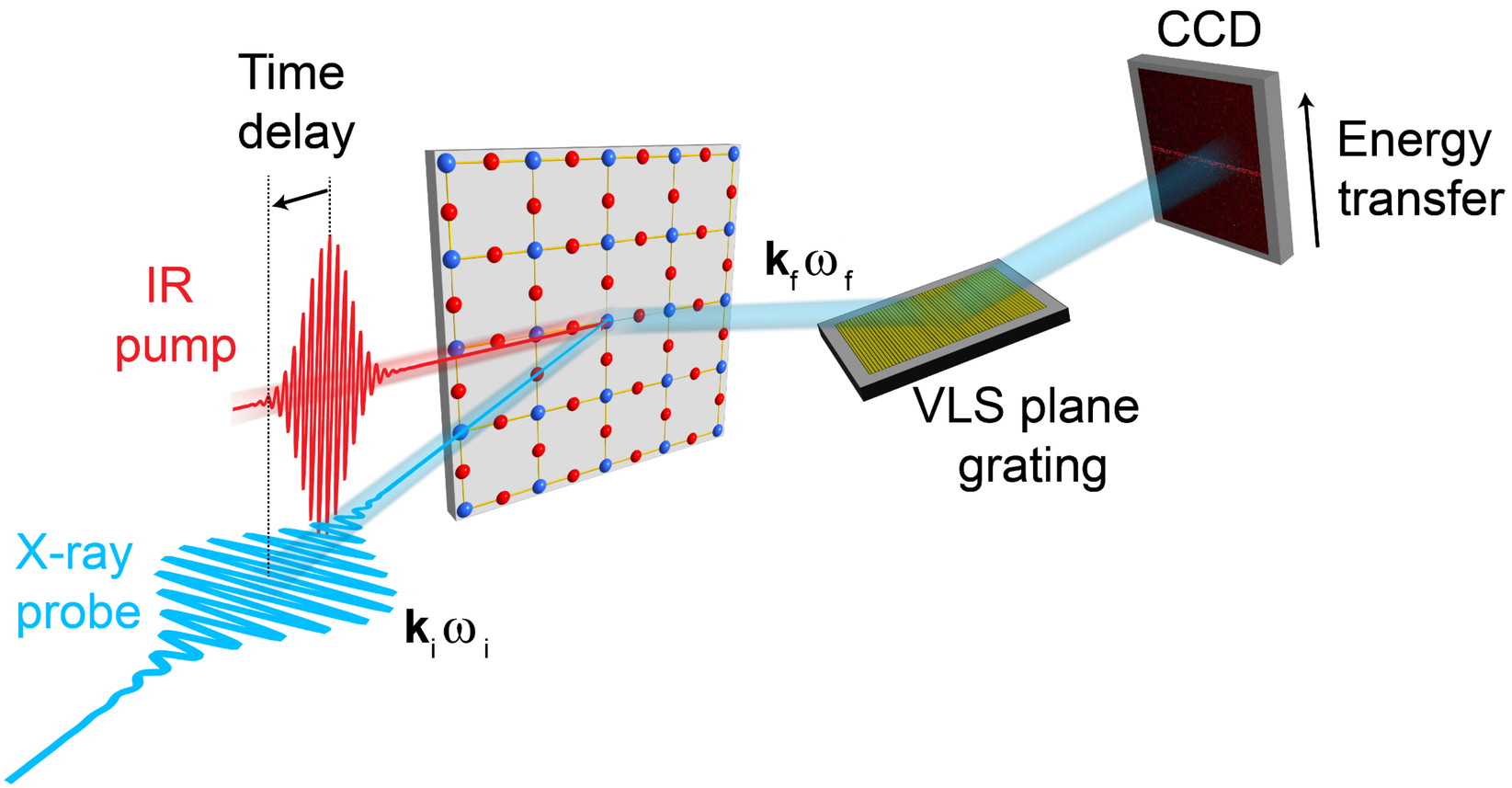




QFI is enhanced while ramping across the AF transition

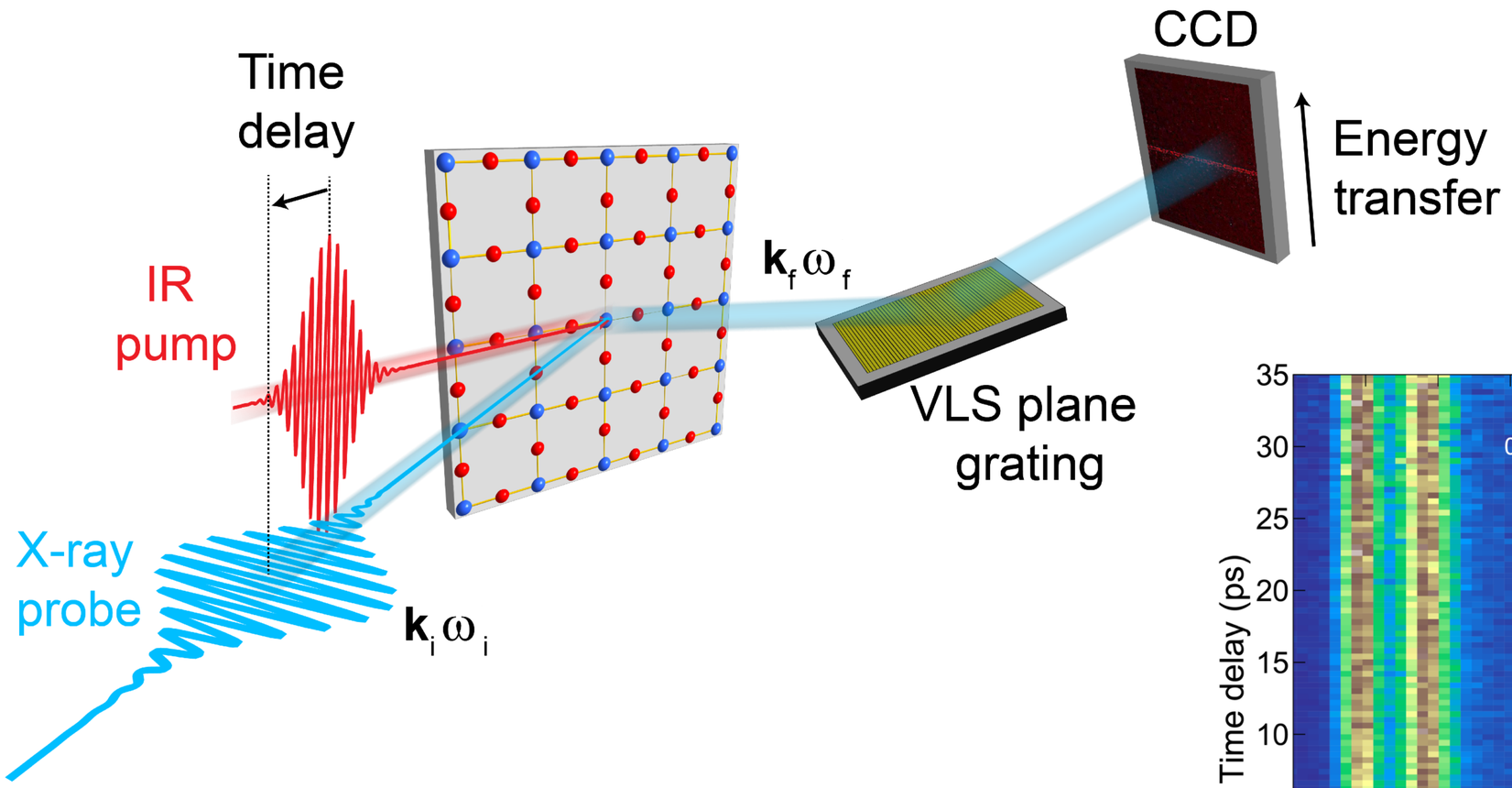
See also
Pellegrini et al PRB (2008)
Bartmettler et al. PRL (2009)
Pollman et al. PRB (2013)
Alba & Calabrese PNAS (2017)
Pappalardi et al. J. Stat Mech (2017)
Schoenauer & Schuricht PRB (2019)

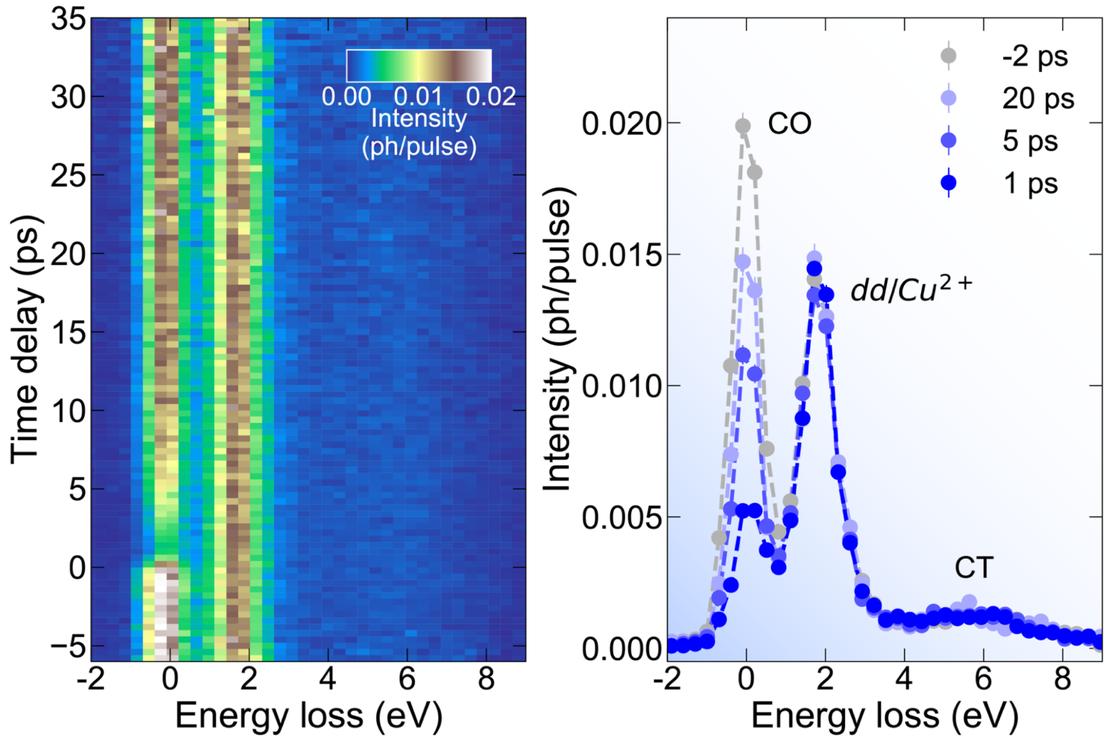
Entanglement spectroscopy of driven quantum materials



Classifying nonequilibrium phases
based on entanglement correlations

Entanglement spectroscopy of driven quantum materials





Classifying nonequilibrium phases based on entanglement correlations

MM et al. Sci. Adv. (2019)

MM & Y. Wang Commun. Phys. (2020)

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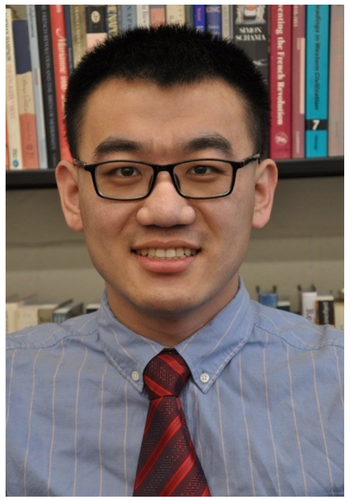

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To be continued…