Probing condensates’ coherence by time-resolved ARPES: from superconductors to excitonic insulators

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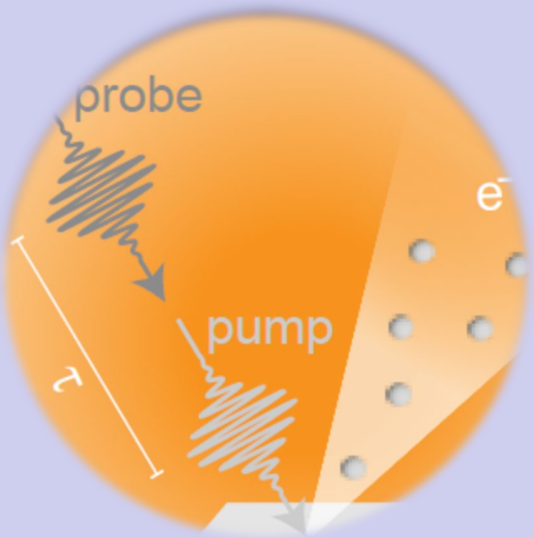
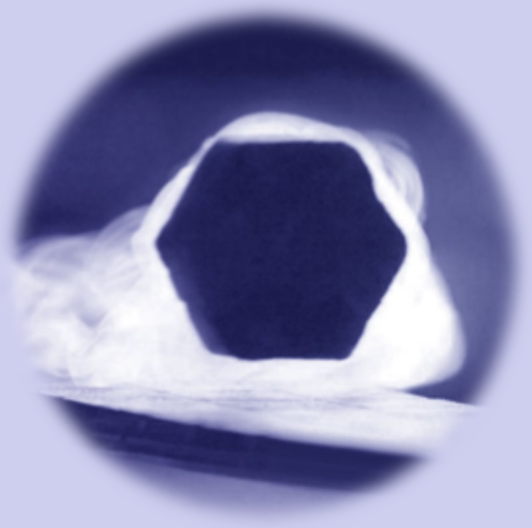
OUTLINE: PROBING CONDENSATE COHERENCE BY TR-ARPES

TR-ARPES



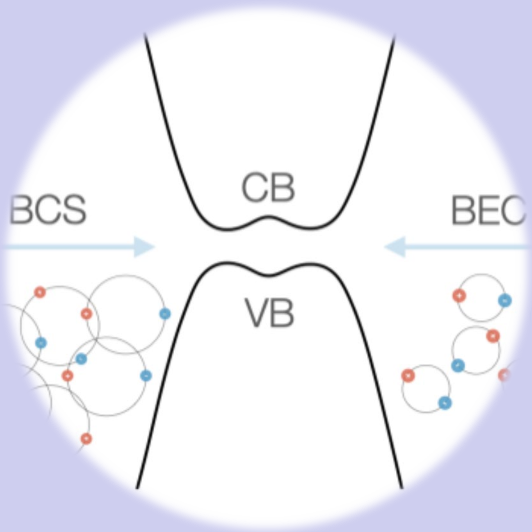
Extending ARPES in the time domain via the development of XUV lasers

High-T_c Cuprates



Coherence vs pairing and pseudogap from short-range spin fluctuations

Ta_2NiSe_5



Excitonic condensate quenched by surface gaiting and dynamic electronic screening

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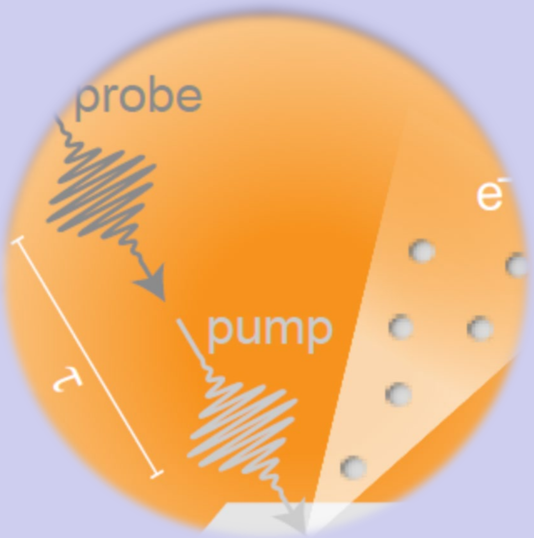

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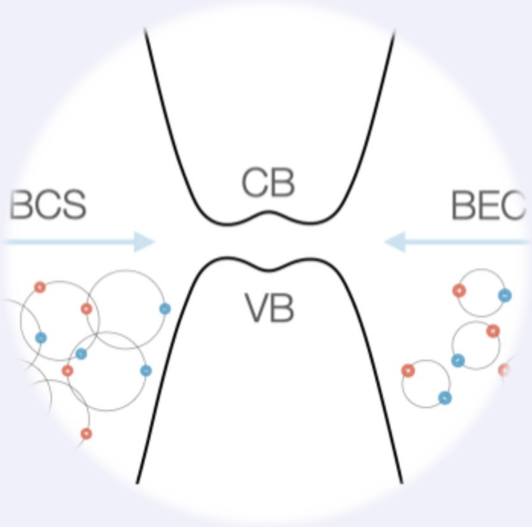
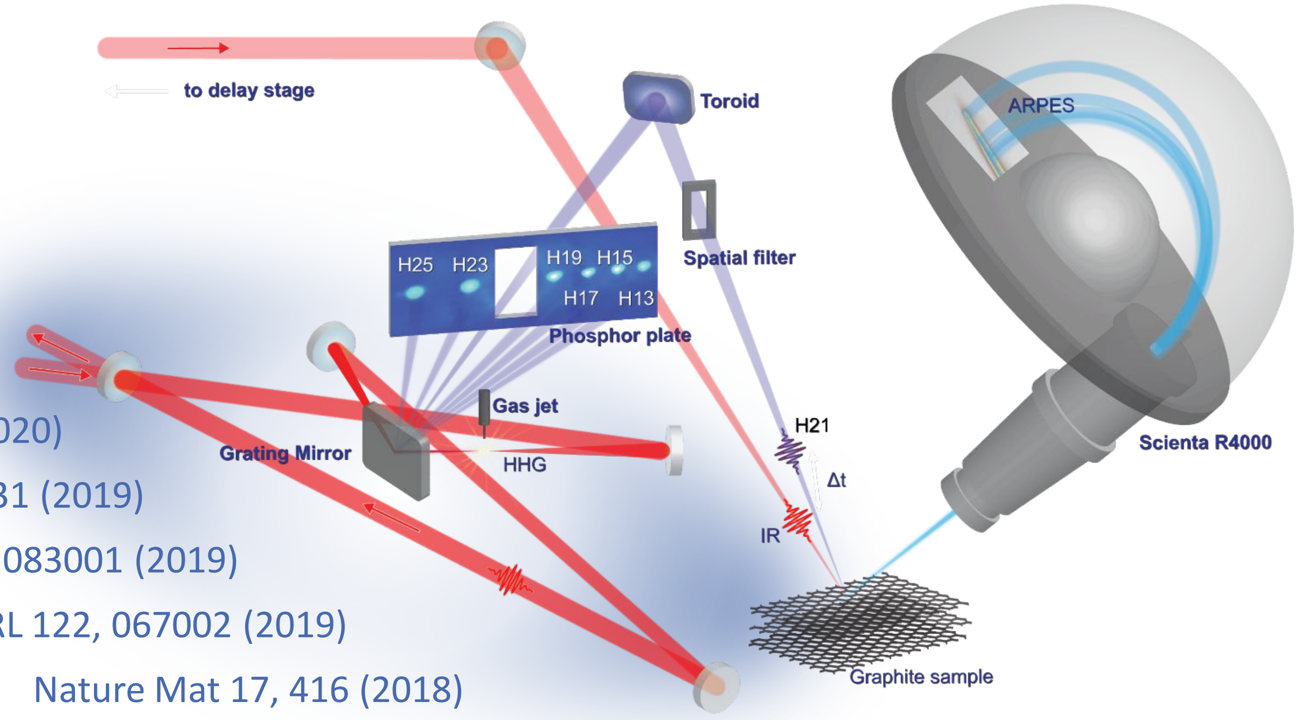


Excitonic condensate quenched by surface gaiting and dynamic electronic screening

ULTRAFAST SPECTROSCOPY ON QUANTUM MATERIALS

Quantum Materials in the Time Domain

Jones-Damascelli's groups



Nature Phys 16, 290 (2020)

Science 366, 1231 (2019)

RSI 90, 083001 (2019)

PRL 122, 067002 (2019)

Nature Mat 17, 416 (2018)

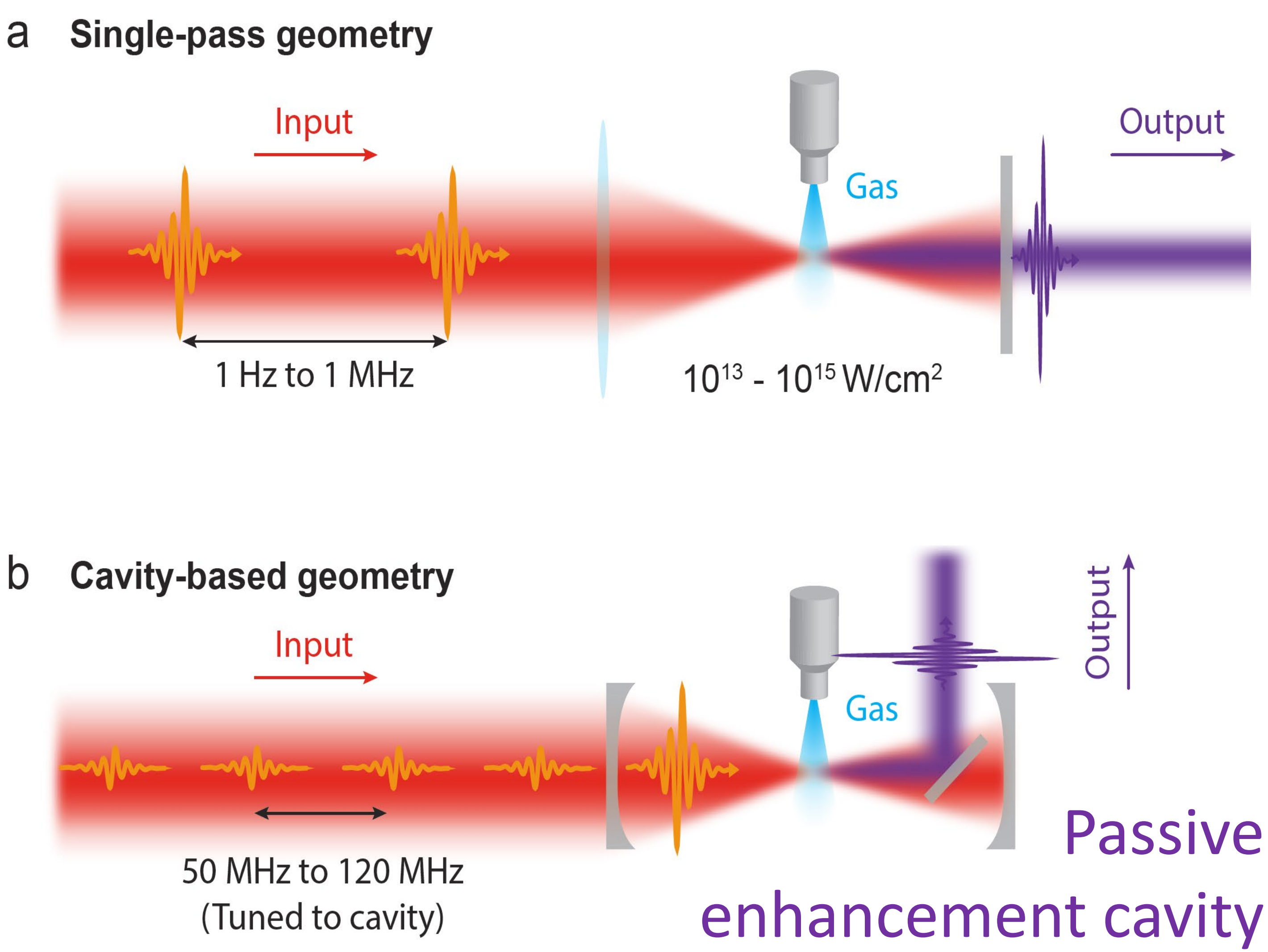
Marta Zonno
Fabio Boschini
Sydney Dufresne
M.X. (Ketty) Na
Art Mills
Sergey Zhdanovich
Hao Chu
Ryan Day
Elia Razzoli
Matteo Michiardi
Giorgio Levy
David Jones
Andrea Damascelli

CFI FCI

GORDON AND BETTY MOORE FOUNDATION

CIFAR

NSERC CRSNG

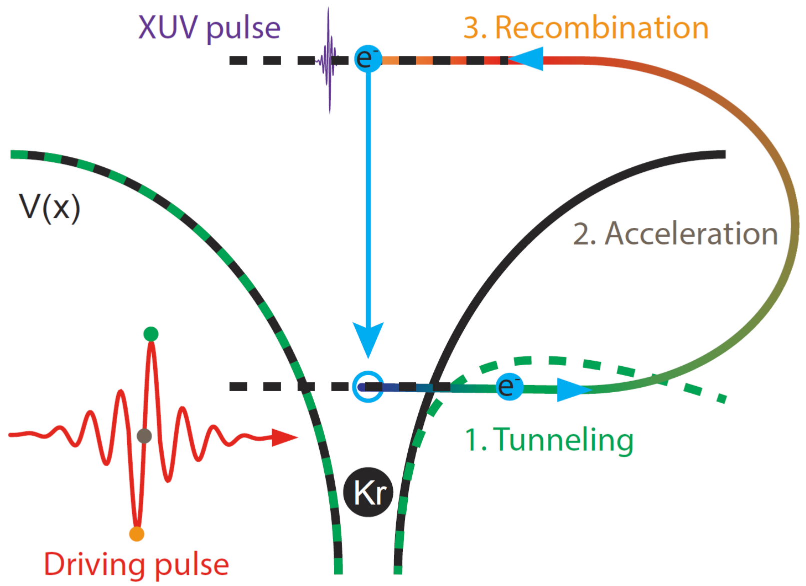


Common approach to HHG

High peak intensity required

- ~~Amplification → Low rep rate~~
- ~~Compression → Poor ΔEnergy~~

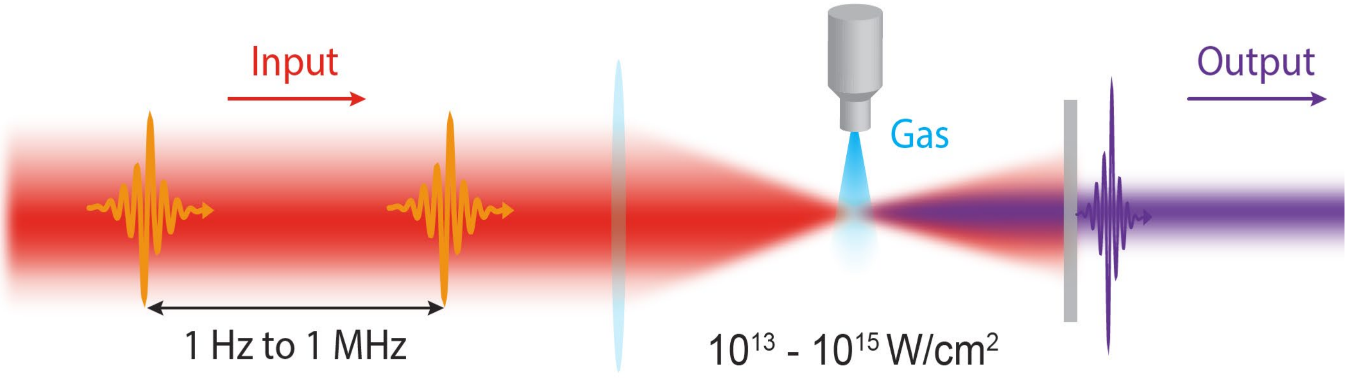
Passive enhancement cavity



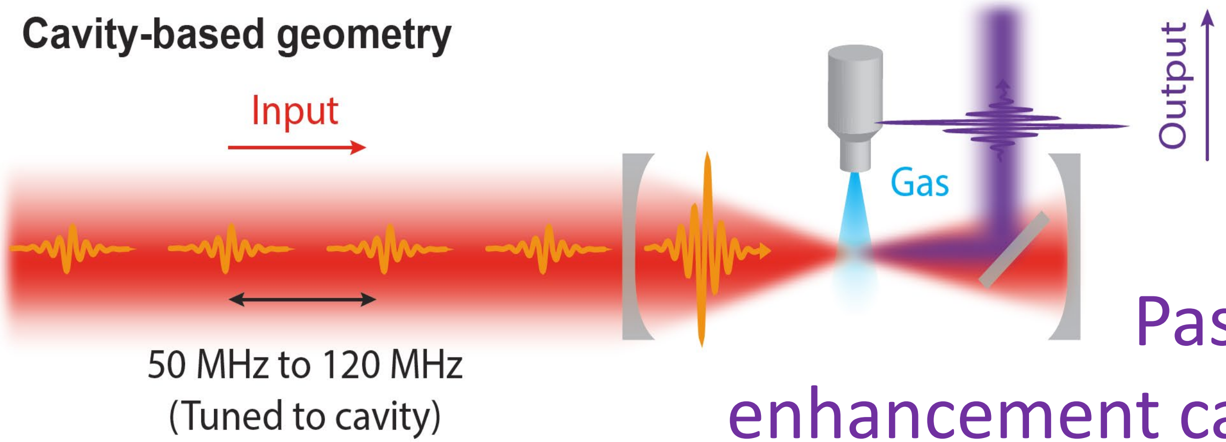
Mills et al, Rev Sci Instrum 90, 083001 (2019)

LASER SOURCE: HHG BASED ON FEMTOSECOND ENHANCEMENT CAVITY

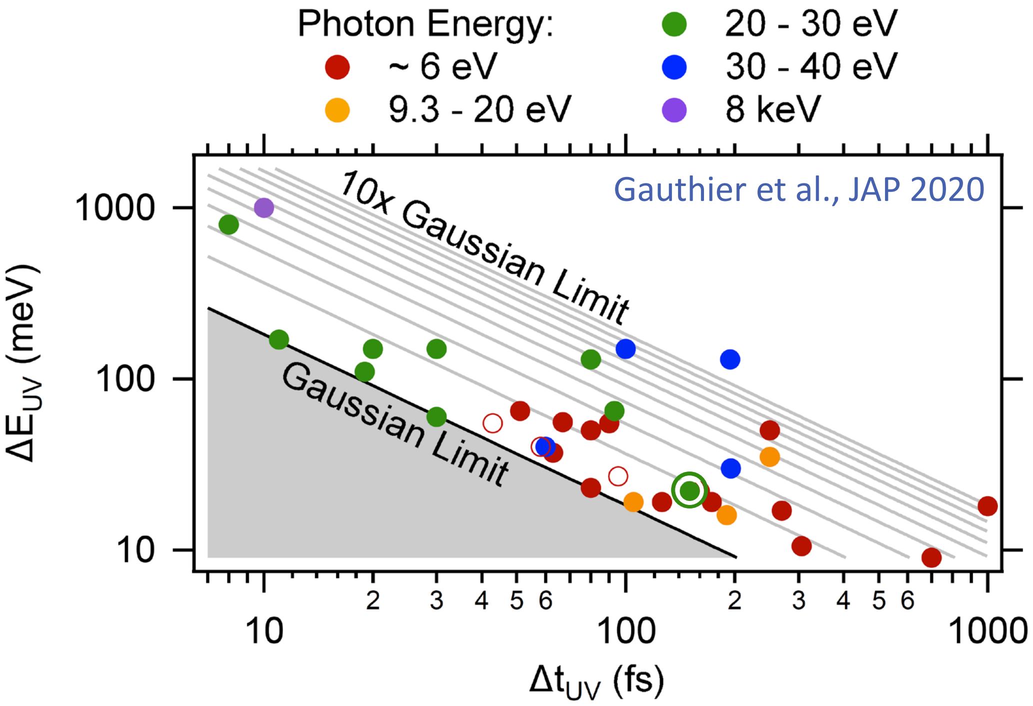
a Single-pass geometry

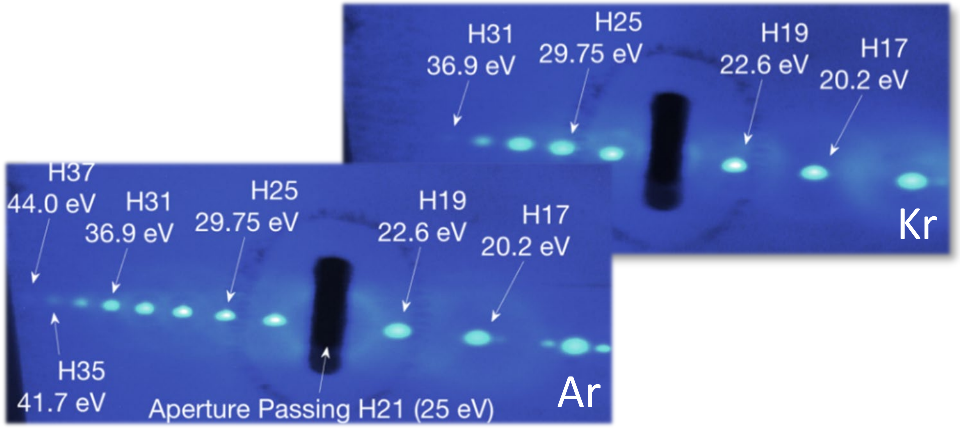


b Cavity-based geometry



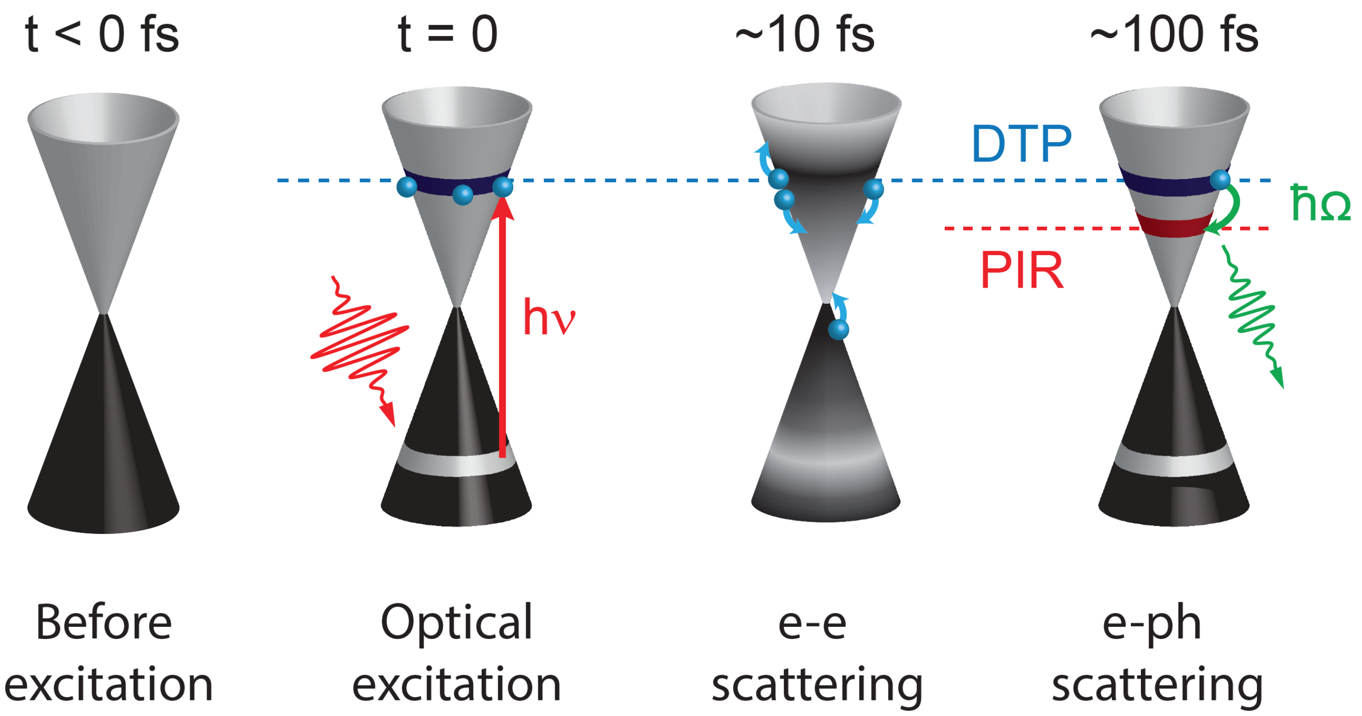
Passive enhancement cavity

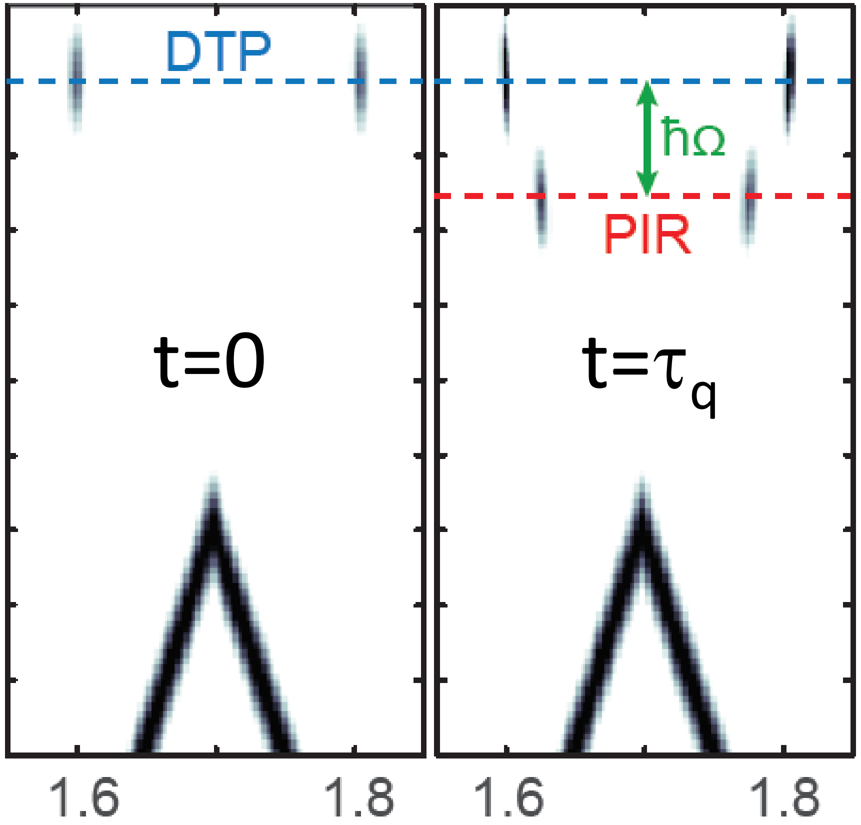




Mills et al, Rev Sci Instrum 90, 083001 (2019)

DETERMINATION OF ELECTRON-PHONON COUPLING IN TIME DOMAIN





For single Einstein mode **q**

$$\frac{1}{\tau_{\boldsymbol{q}}} = \frac{2\pi}{\hbar}\langle g_{\boldsymbol{q}}^2\rangle N = 2\pi\Omega_{\boldsymbol{q}}\lambda_{\boldsymbol{q}}N^*$$

Mode-projected e-p coupling constant

Mode-projected e-p matrix element

Na*, Mills*, et al, Science 366, 1231 (2019)

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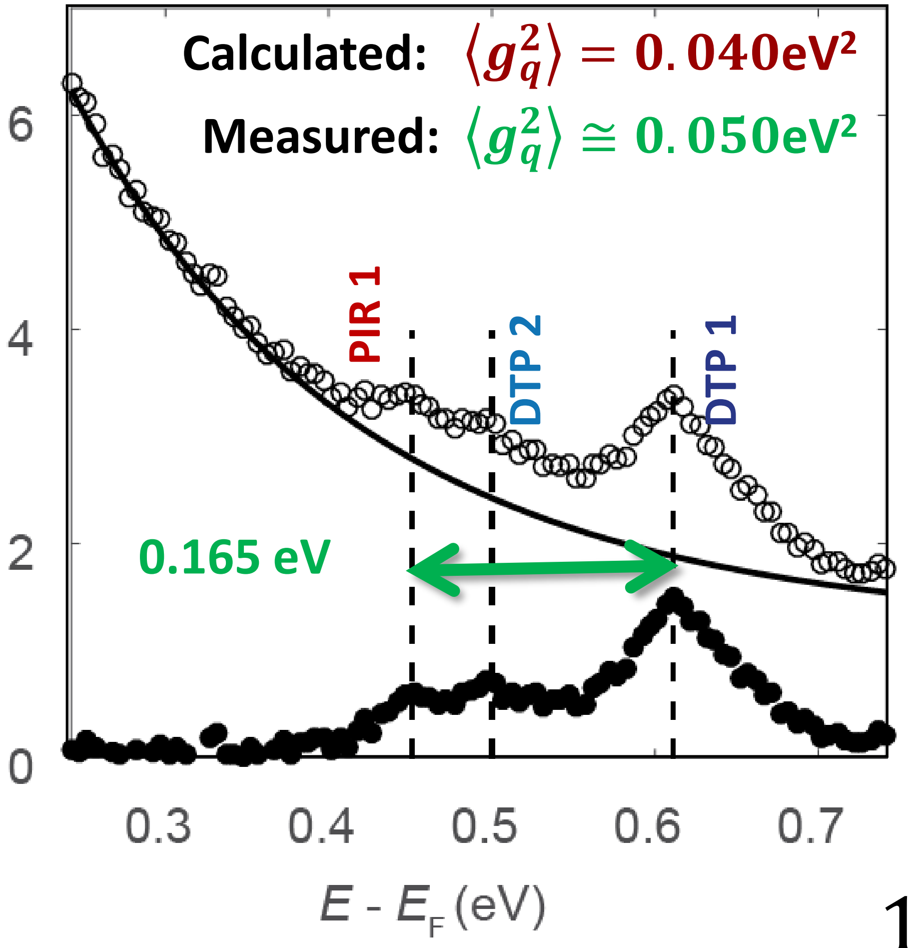
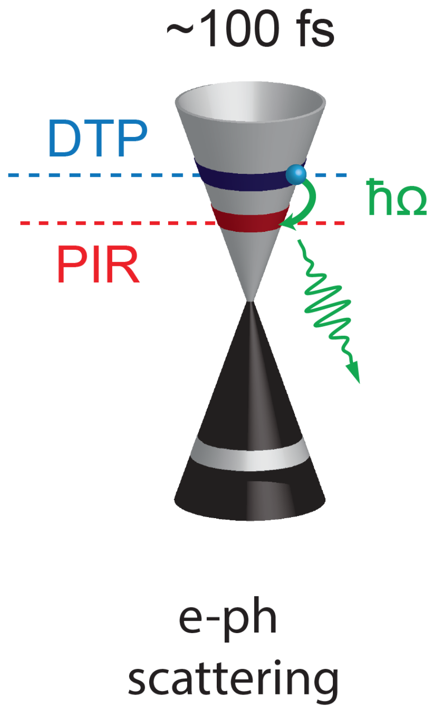
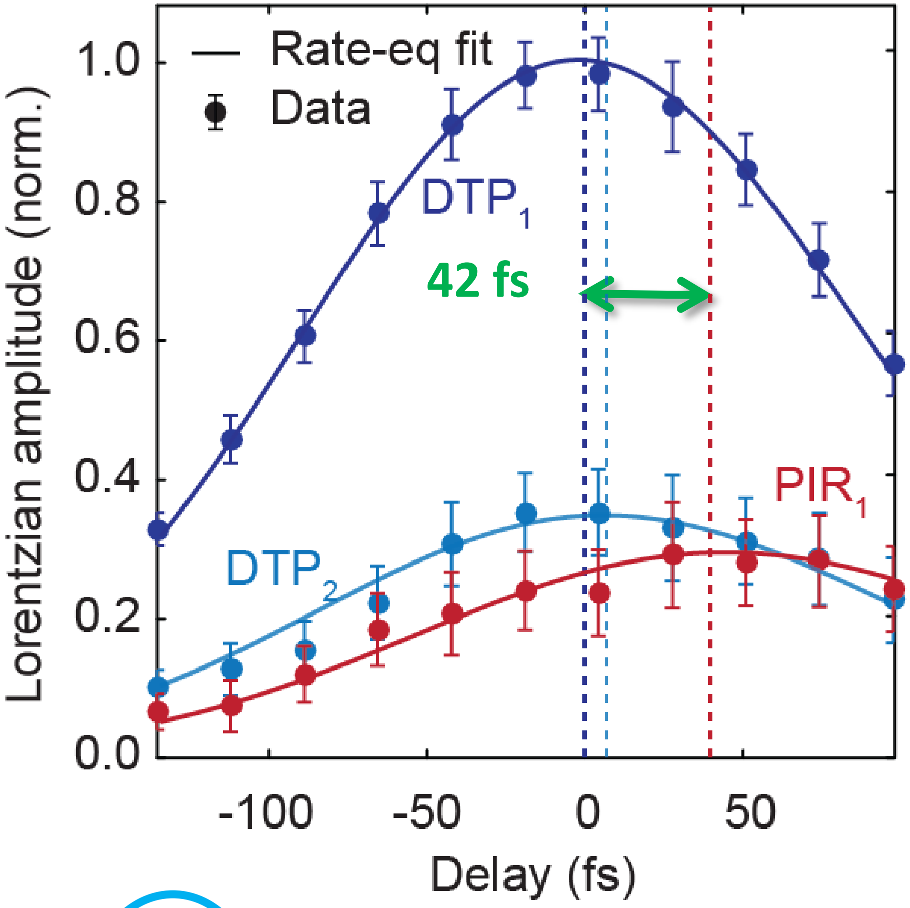




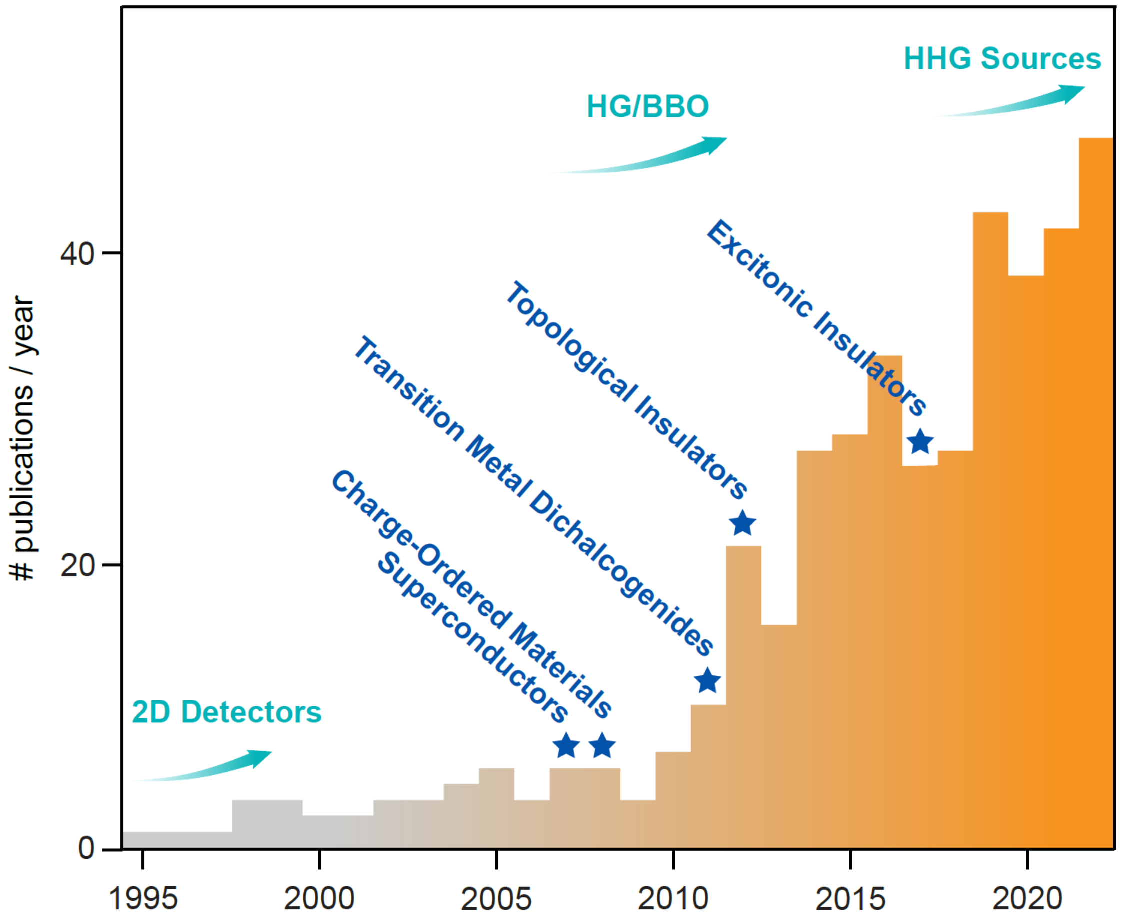


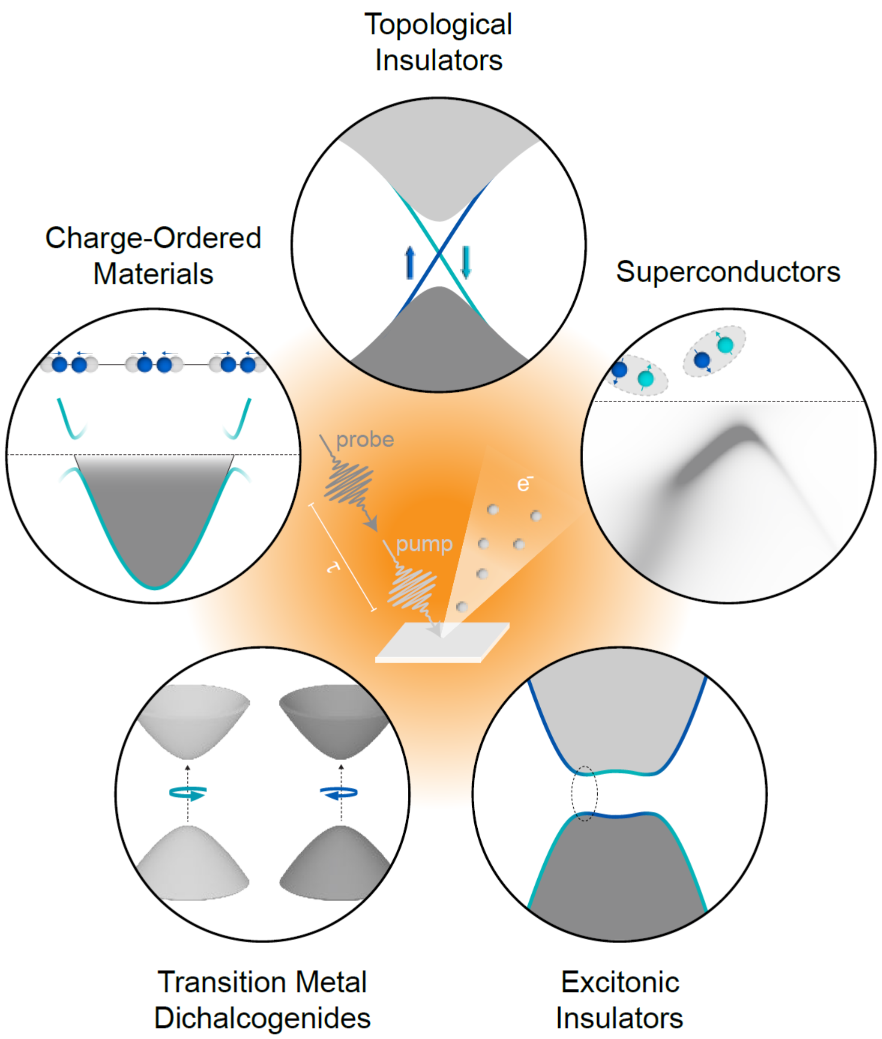
For single Einstein mode **q**

$$\frac{1}{\tau_q} = \frac{2\pi}{\hbar}\langle g_q^2 \rangle N = 2\pi\Omega_q\lambda_q N^*$$

Mode-projected e-p matrix element

TIME-RESOLVED ARPES ON QUANTUM MATERIALS





F. Boschini, M. Zonno, A. Damascelli, RMP 96, 015003 (2024)

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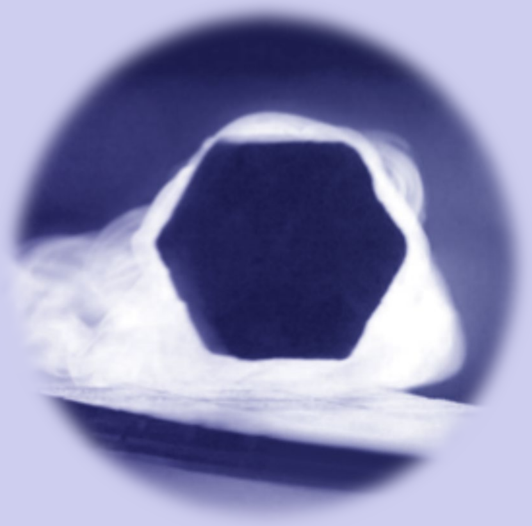

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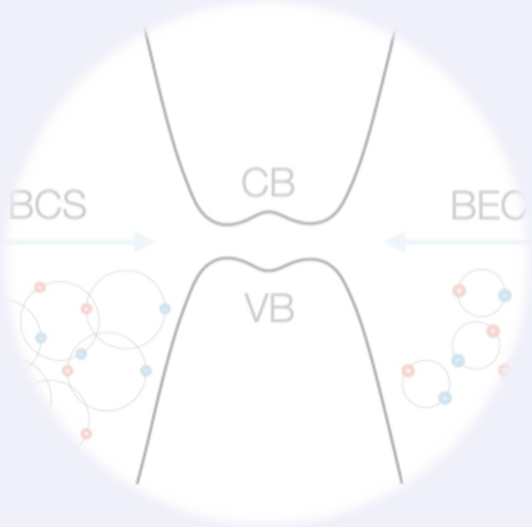
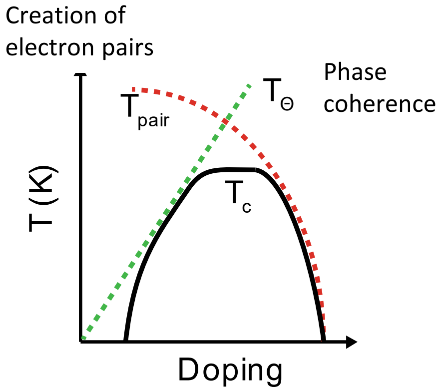


Excitonic condensate quenched by surface gaiting and dynamic electronic screening

QUENCHING OF PHASE COHERENCE AND SUPERCONDUCTIVITY IN HTSCs



Emery and Kivelson Nature (1995)

Phase coherence vs. electron pairing in the formation of the SC condensate

Can we manipulate the density of phase fluctuations independently of the number of across-gap charge excitations?

We can look at the ultrafast dynamics within the SC gap

$$A(k_F,\omega) = -\frac{1}{\pi}\frac{\Sigma''}{(\omega-\Sigma')^2+(\Sigma'')^2}$$

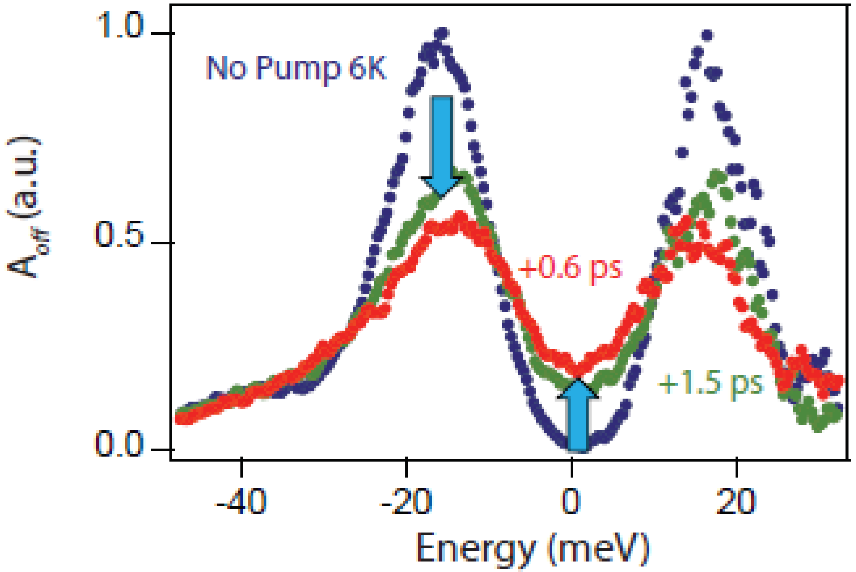
$$\Sigma = -i\cdot\Gamma_s + \frac{\Delta^2}{\omega + i\cdot\Gamma_p}$$

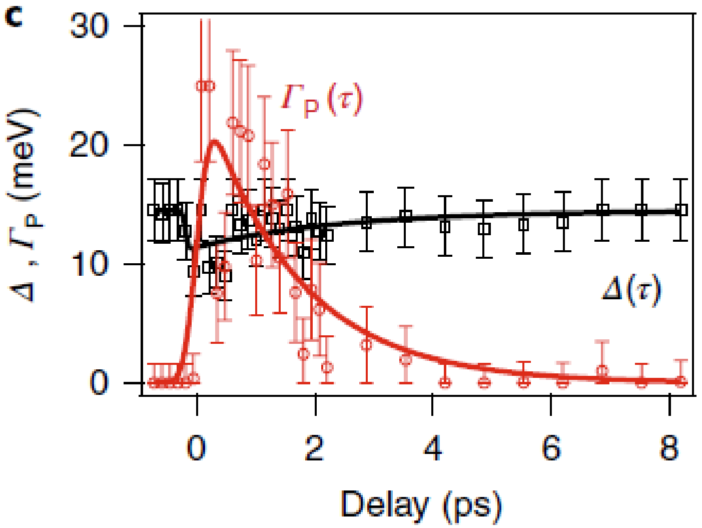
Pairing strength → Modification of 2Δ

Phase fluctuations → Filling of the gap described by Γ_p

Norman PRB (1998)

Bi2212 UD82

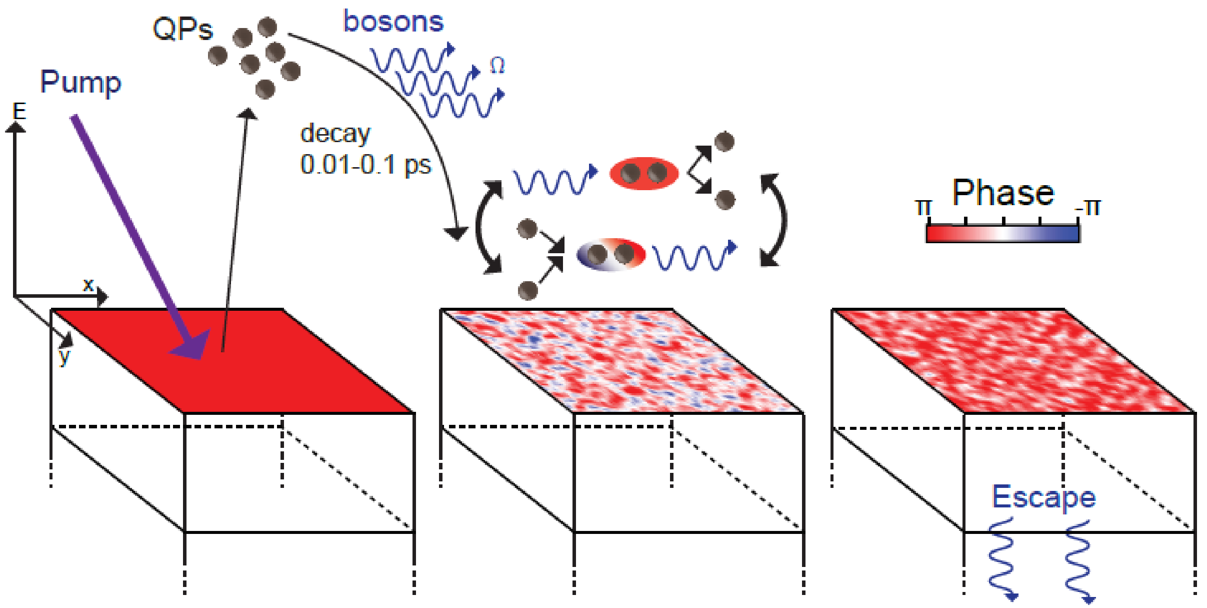


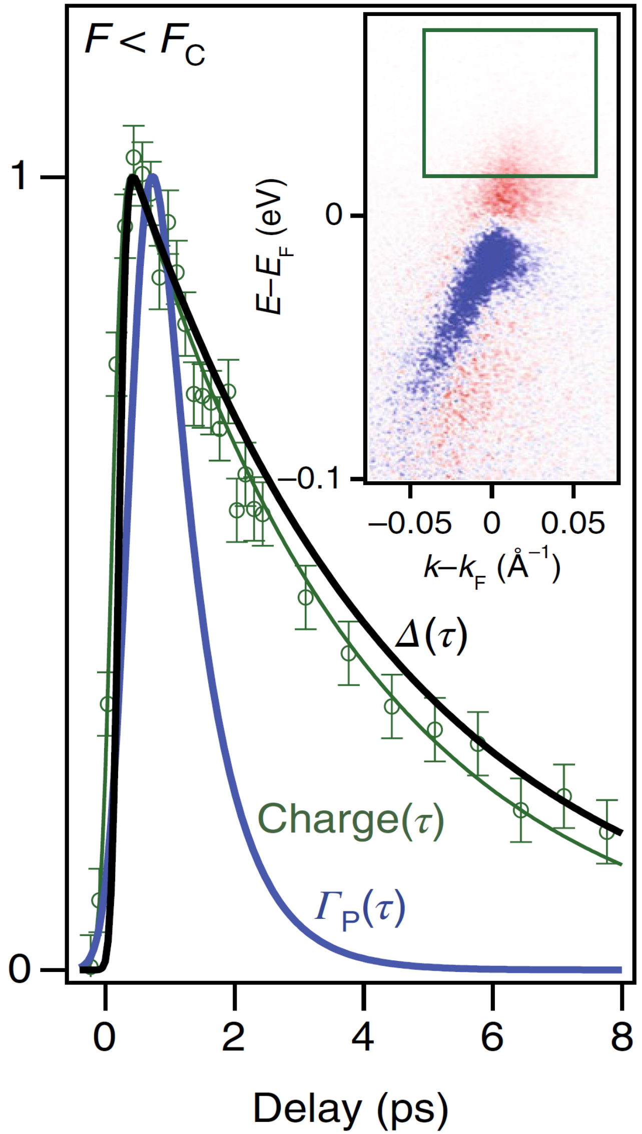


Phase coherence plays major role in determining T_c in cuprates

Boschini et al. Nat. Materials 17, 416 (2018)

QUENCHING OF PHASE COHERENCE AND SUPERCONDUCTIVITY IN HTSCs





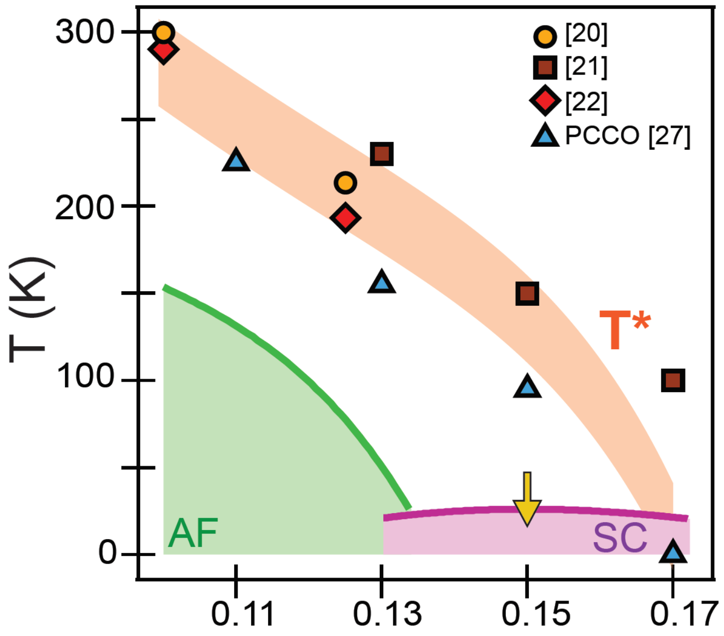
Non-thermal bosons emitted by the thermalization of hot QPs are the source of the of the phase fluctuations

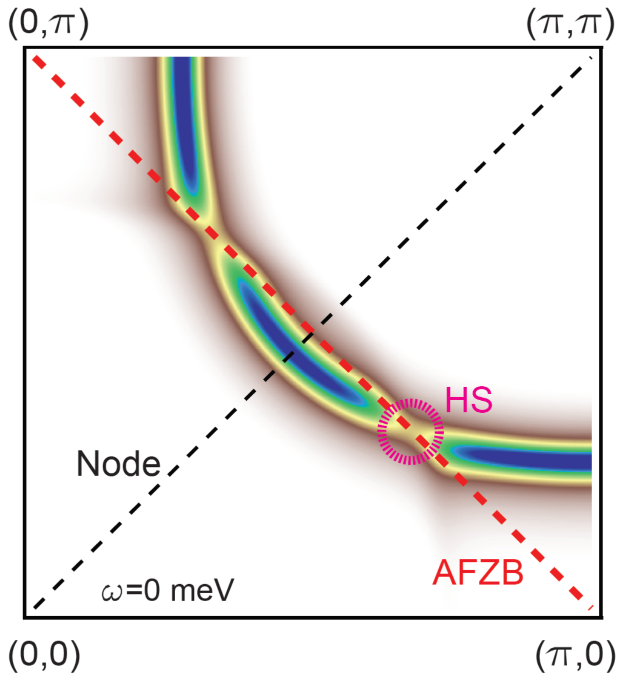
Phase coherence plays major role in determining T_c in cuprates

PSEUDOGAP IN ELECTRON DOPED CUPRATES

$$G^{-1}(\mathbf{k},\omega) = \omega - \epsilon_{\mathbf{k}} + i\eta - \frac{\Delta_{\rm PG}^2}{\omega - \epsilon_{\mathbf{k+q}} + i\Gamma}$$

Γ= spin-fluctuations induced





Emergence of pseudogap from 'short-range' spin-correlations!

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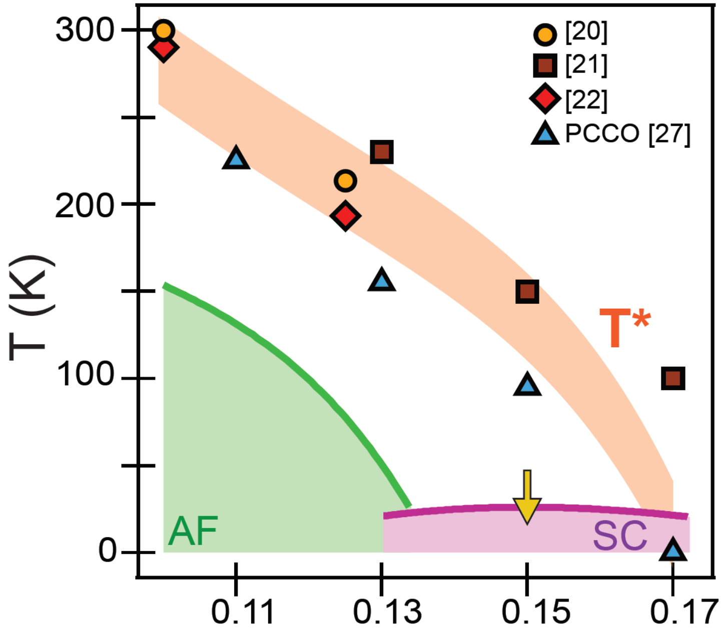

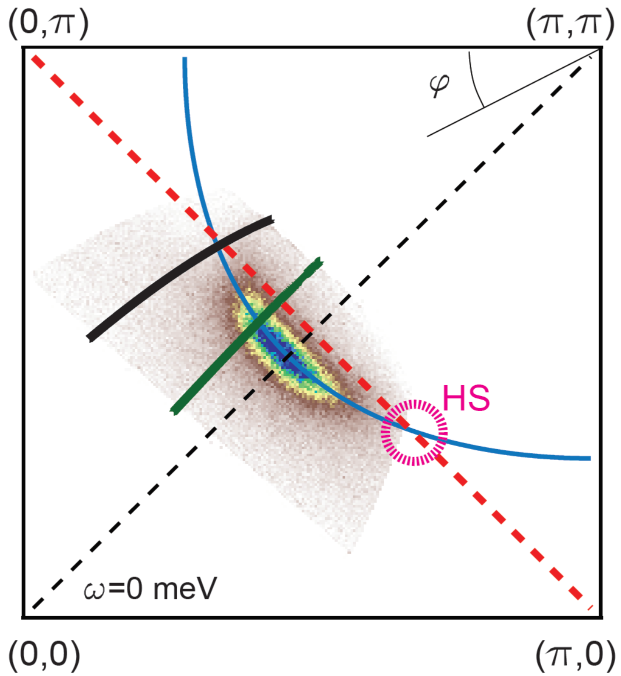

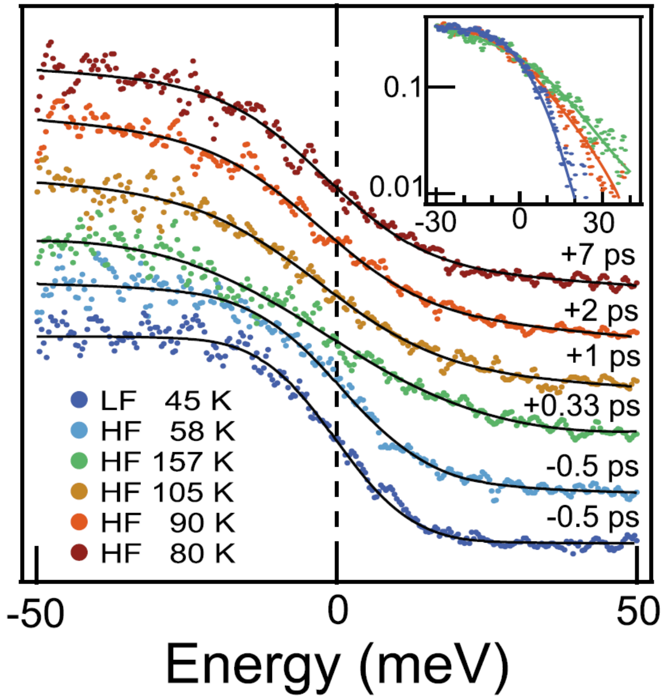

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Boschini, Zonno, et al, npj Quantum Materials 5, 6 (2020)

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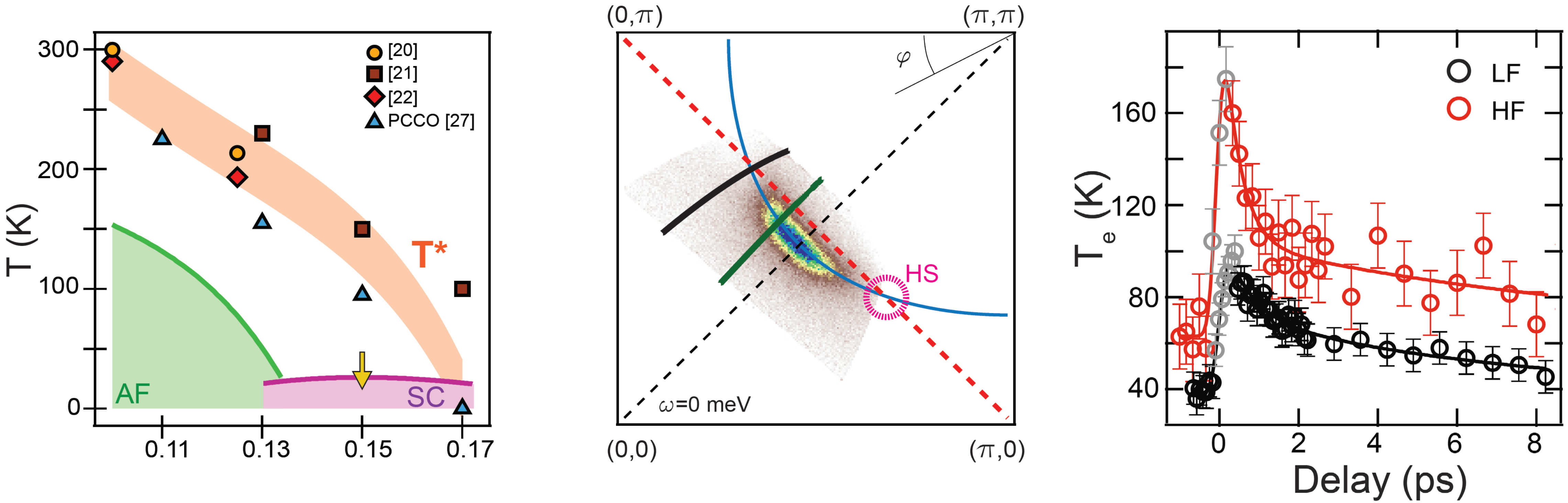

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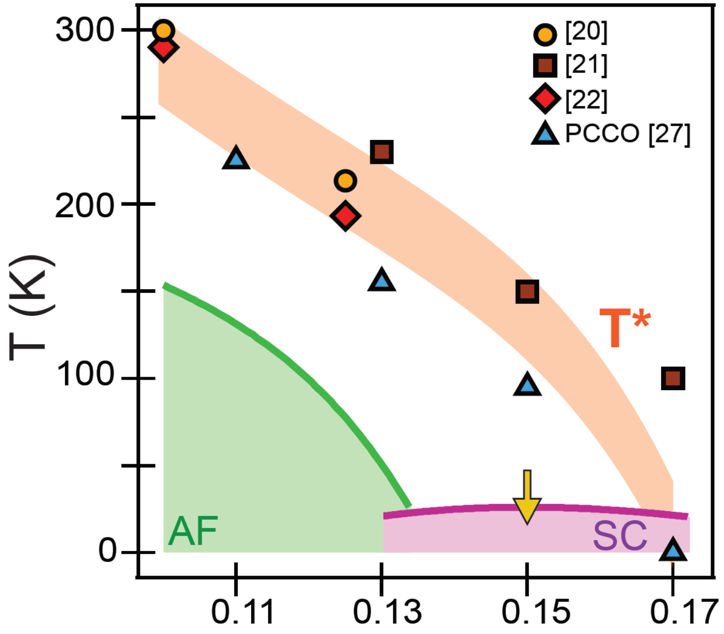

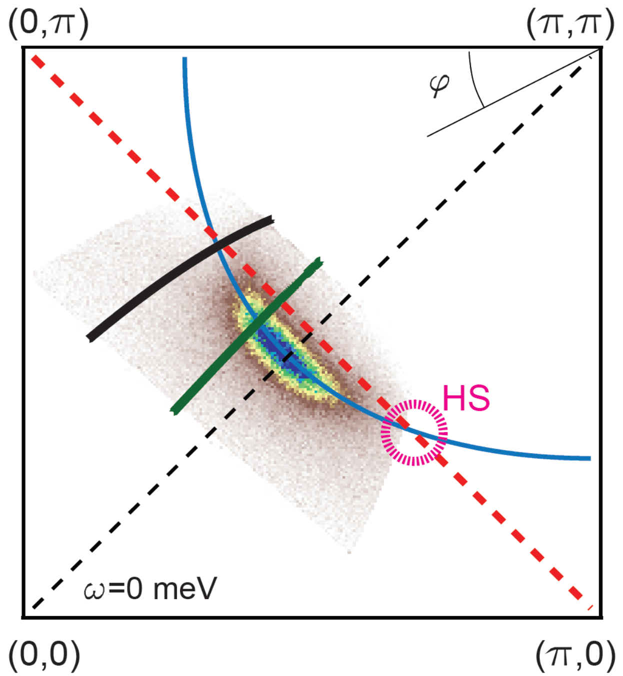

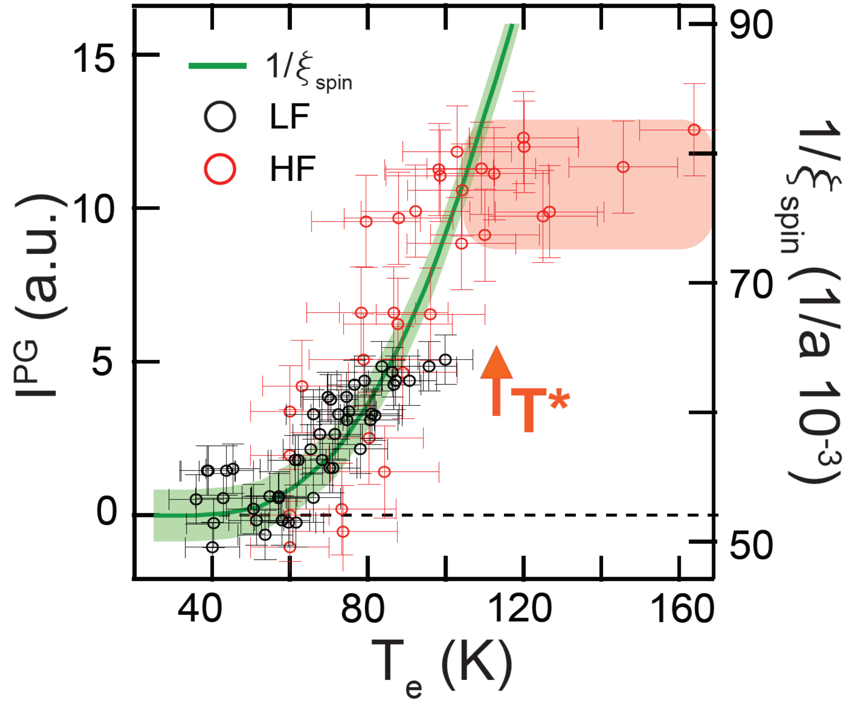

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Γ= spin-fluctuations induced

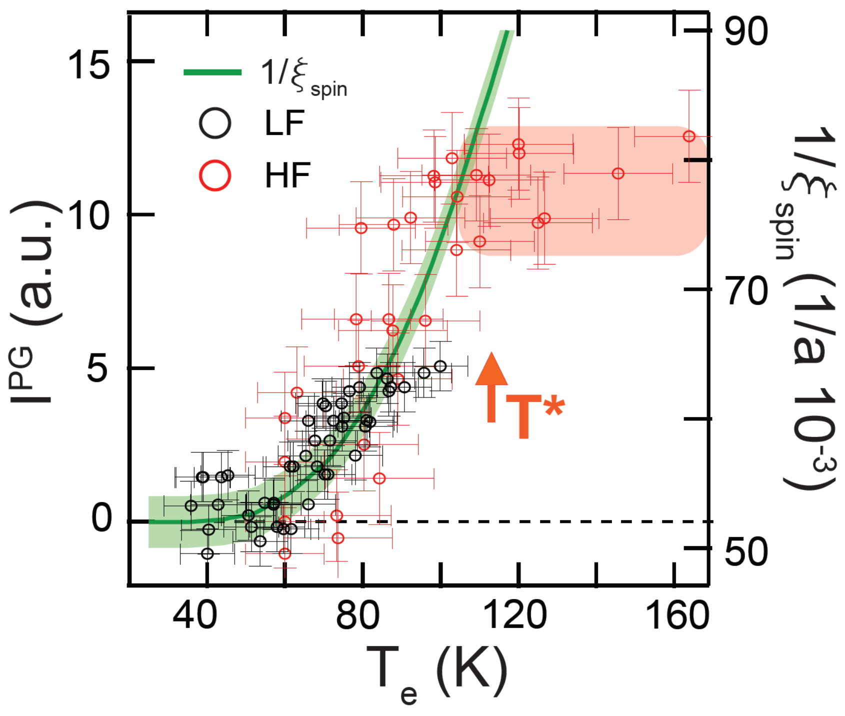
- T* is a crossover temperature

$\mathrm{T} > \mathrm{T}^*$ → ξ_{spin} ~10-15 a

$\Gamma(\mathrm{T}^*) \sim 2\Delta_{\mathrm{PG}} \sim 170\,\mathrm{meV}$

- The PG is filling, not closing

PG energy scale survives well above T^*



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Boschini, Zonno, et al, npj Quantum Materials 5, 6 (2020)

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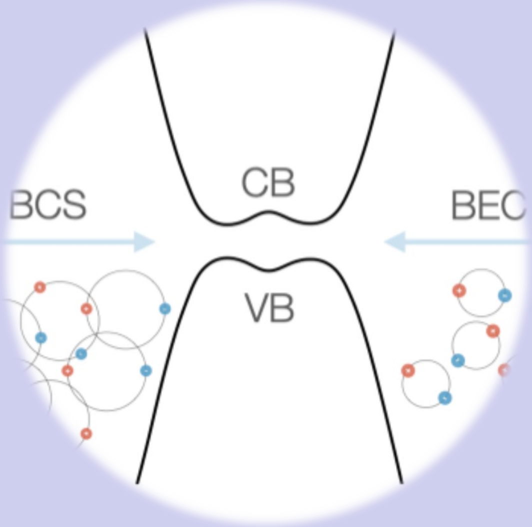
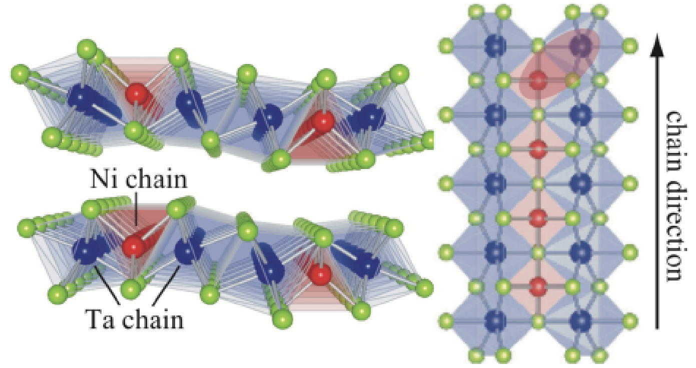
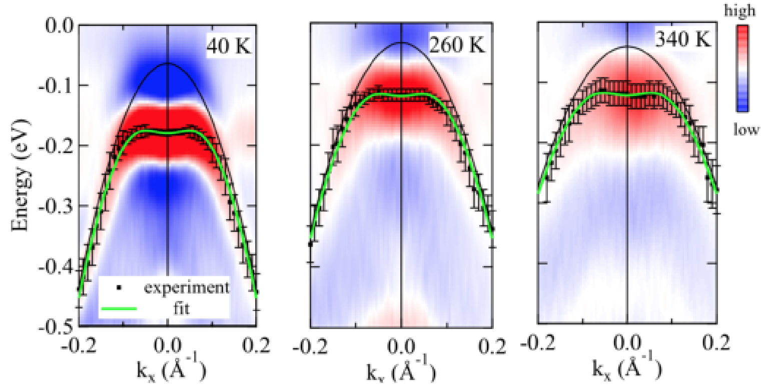


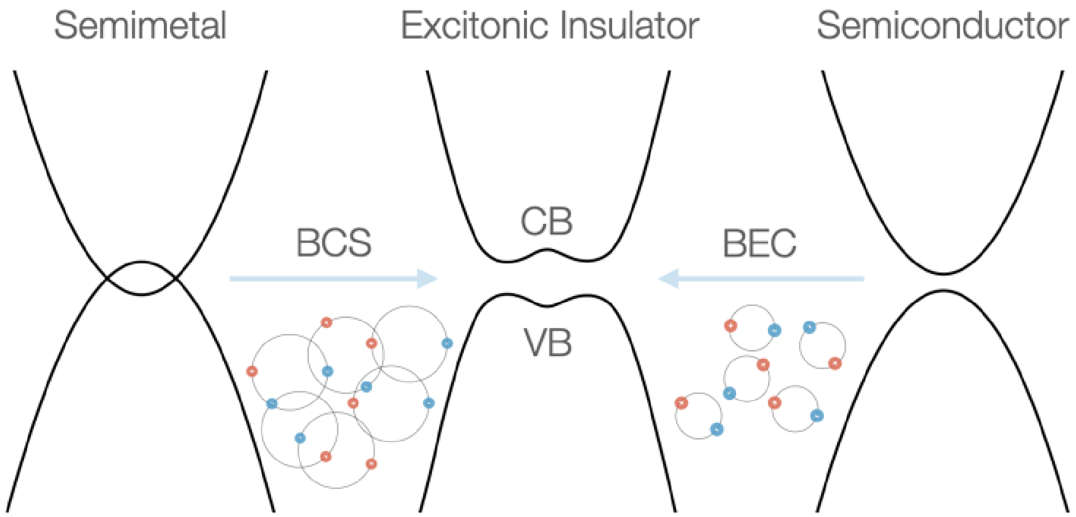
Excitonic condensate quenched by surface gaiting and dynamic electronic screening

EXCITONIC INSULATING BEHAVIOR IN Ta_2NiSe_5?

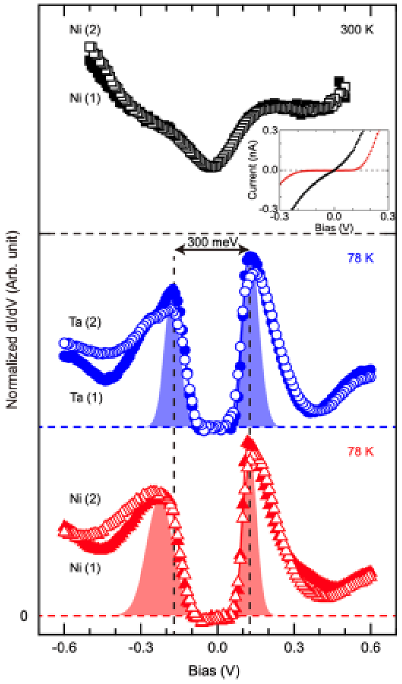




K. Seki, et. al., PRB 90, 155116 (2014)

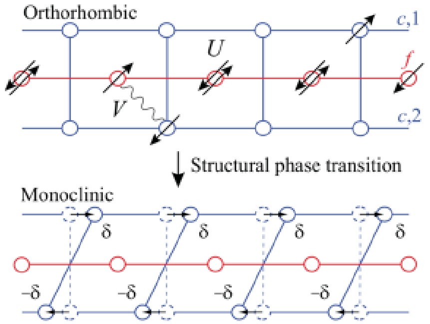


- Gap opening below Tc
- Flattening & broadening of UVB



J. Lee, *et al.*, Phys. Rev. B **99**, 075408 (2019)

- Candidate Excitonic Insulator
- Electronic phase transition at 328 K
- Band gap of ~300 meV
- Structural phase transition at 328 K



T. Kaneko, *et al.*, Phys. Rev. B **87**, 035121 (2013)

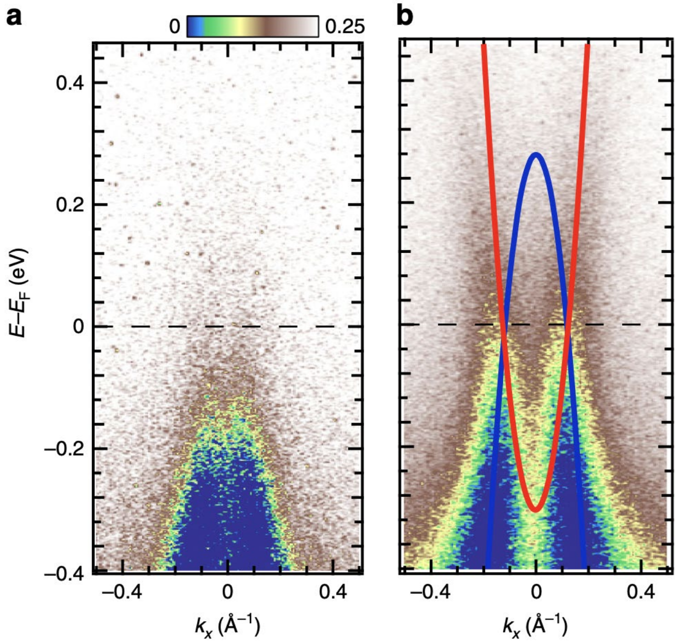
Is it an electronic or lattice instability that drives the phase transition?

EXCITONIC INSULATING BEHAVIOR IN Ta2NiSe5?

1. Gap closure

T = 100 K, rep. rate = 1 kHz
Δt = 80 fs, ΔE = 250 meV
$h\nu$ = 1.55 eV, 1.56 mJ/cm^2

The gap closes on a time-scale much faster than the lattice timescale: must be an electronically driven transition

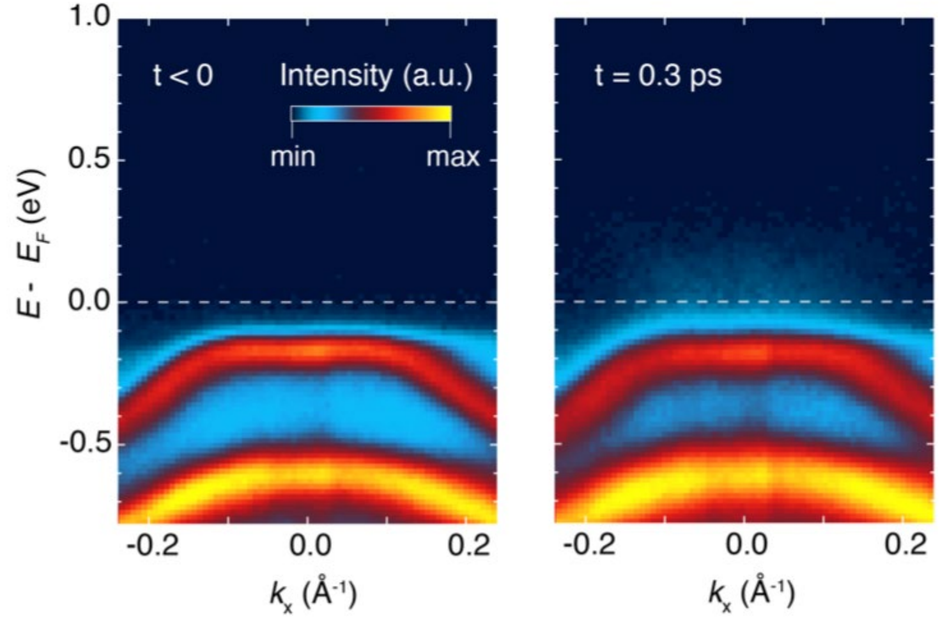


K. Okazaki, *et al*, Nat. Commun. **9**, 4322 (2018).

2. Robust gap

T = 14 K, rep. rate = 30 kHz
Δt = 160 fs, ΔE = 31 meV
$h\nu$ = 1.55 eV, 0.85 mJ/cm^2

Rigid gap response attributed to lattice distortion



E. Baldini, *et al*, arXiv:2007.02909v1

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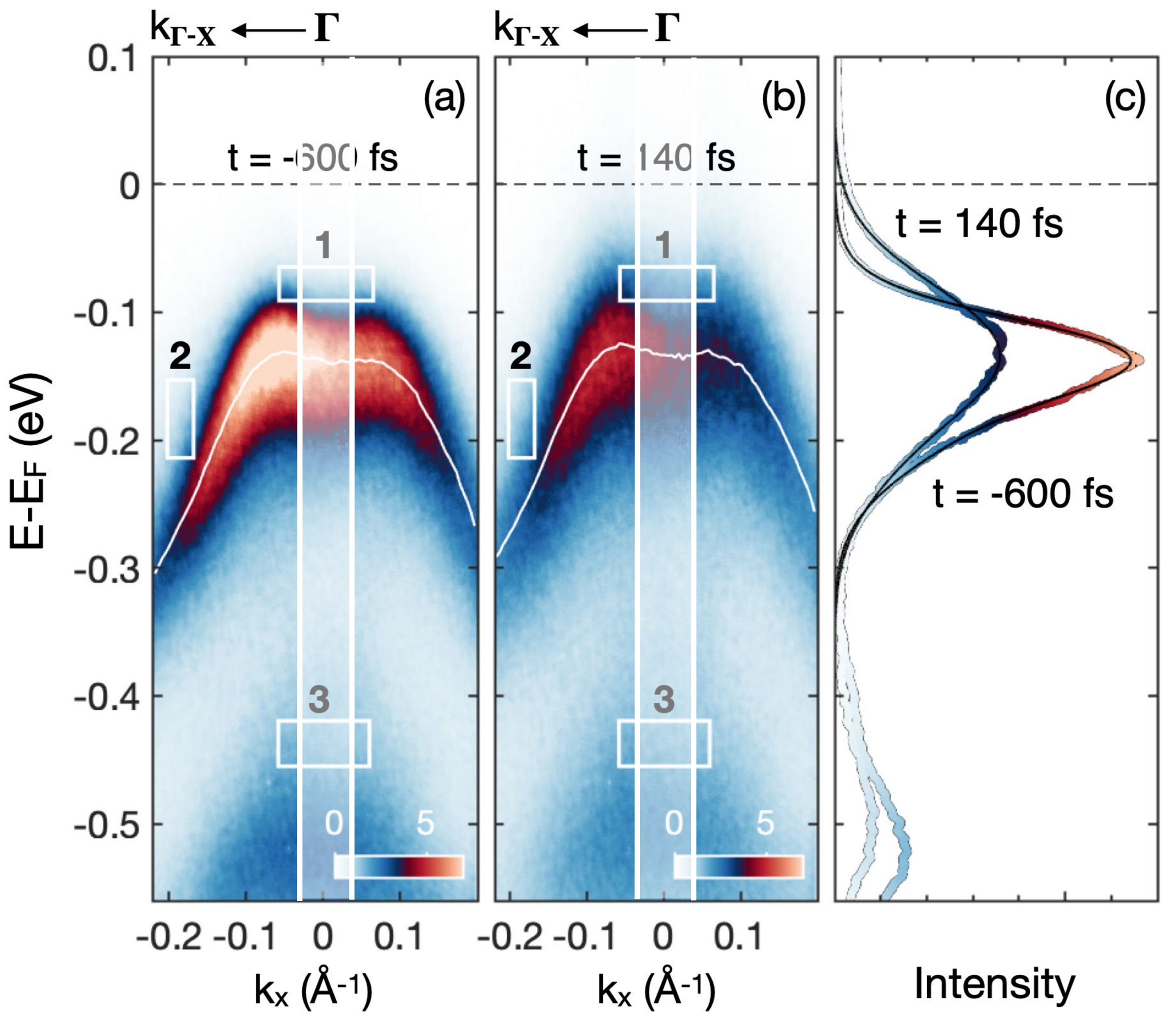
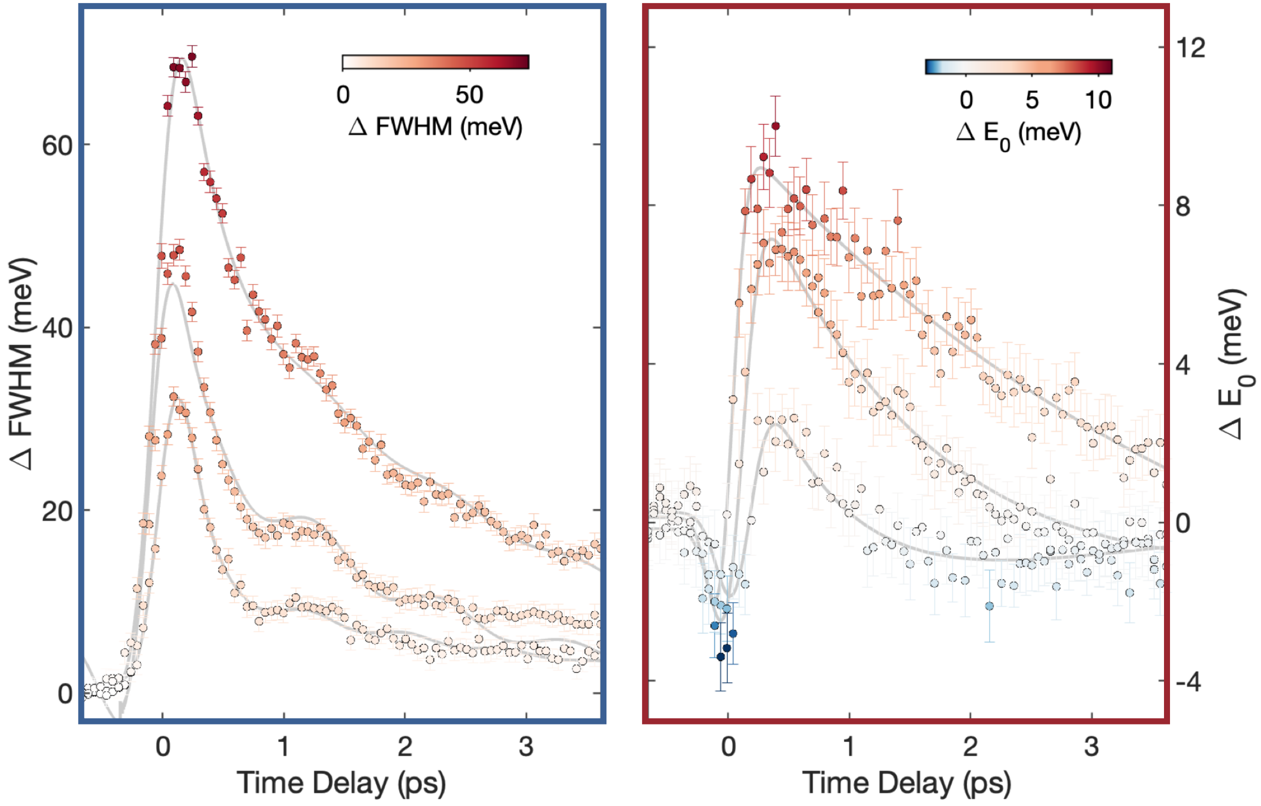


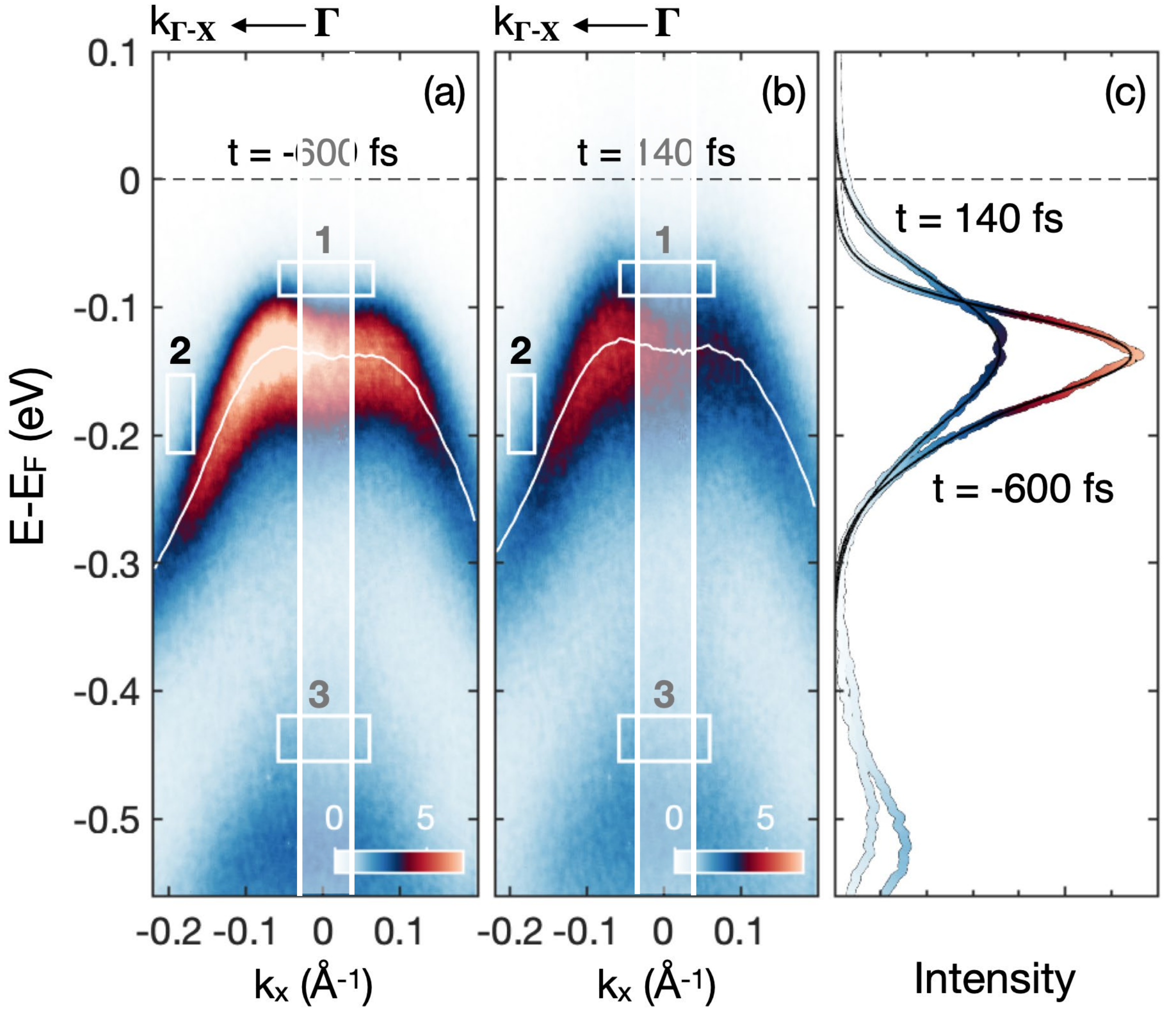
Spectral modification

filling (ΔFWHM >0) + closing (ΔE_0 > 0)



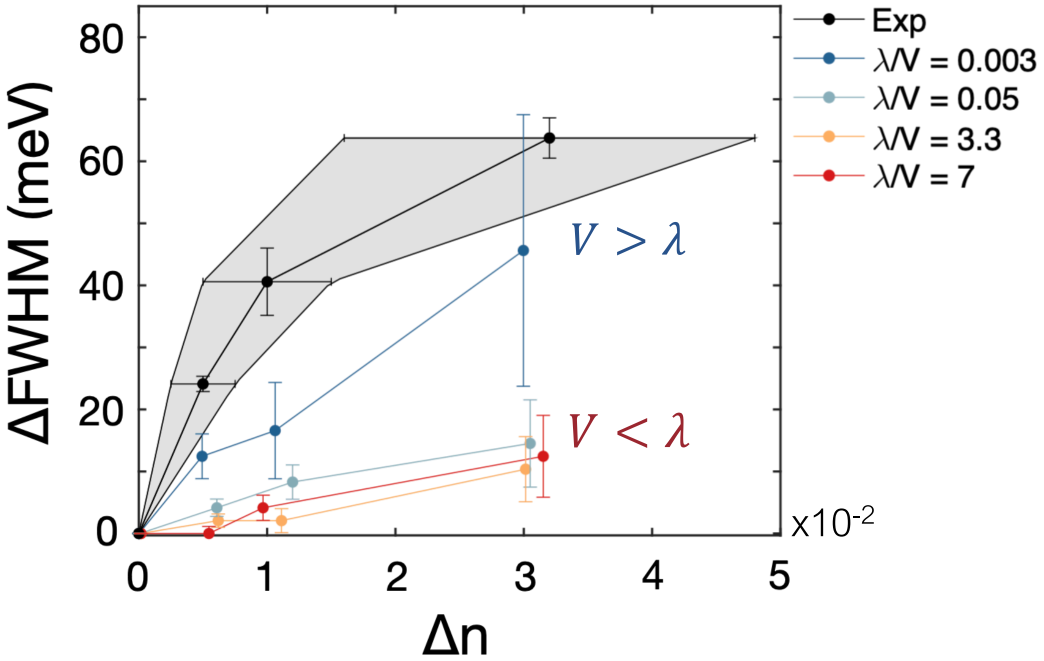
EXCITONIC INSULATING BEHAVIOR IN Ta2NiSe5?

The enhanced spectral broadening arises from electronic-scattering



$$\hat{H} = \sum_{k,\alpha,\alpha' \in \{0,1\}} [\epsilon_{k-A}]^{\alpha,\alpha'} c^{\dagger}_{k,\alpha} c_{k,\alpha'} + V \sum_i n_{i,0} n_{i,1} +$$

$$\sum_i [\sqrt{\lambda} X_i - E(t)] c^{\dagger}_{k,0} c_{k,1} + \sum_i \frac{1}{2} [X_i^2 + \frac{1}{\omega_0^2} \dot{X}_i^2] + h.c.$$



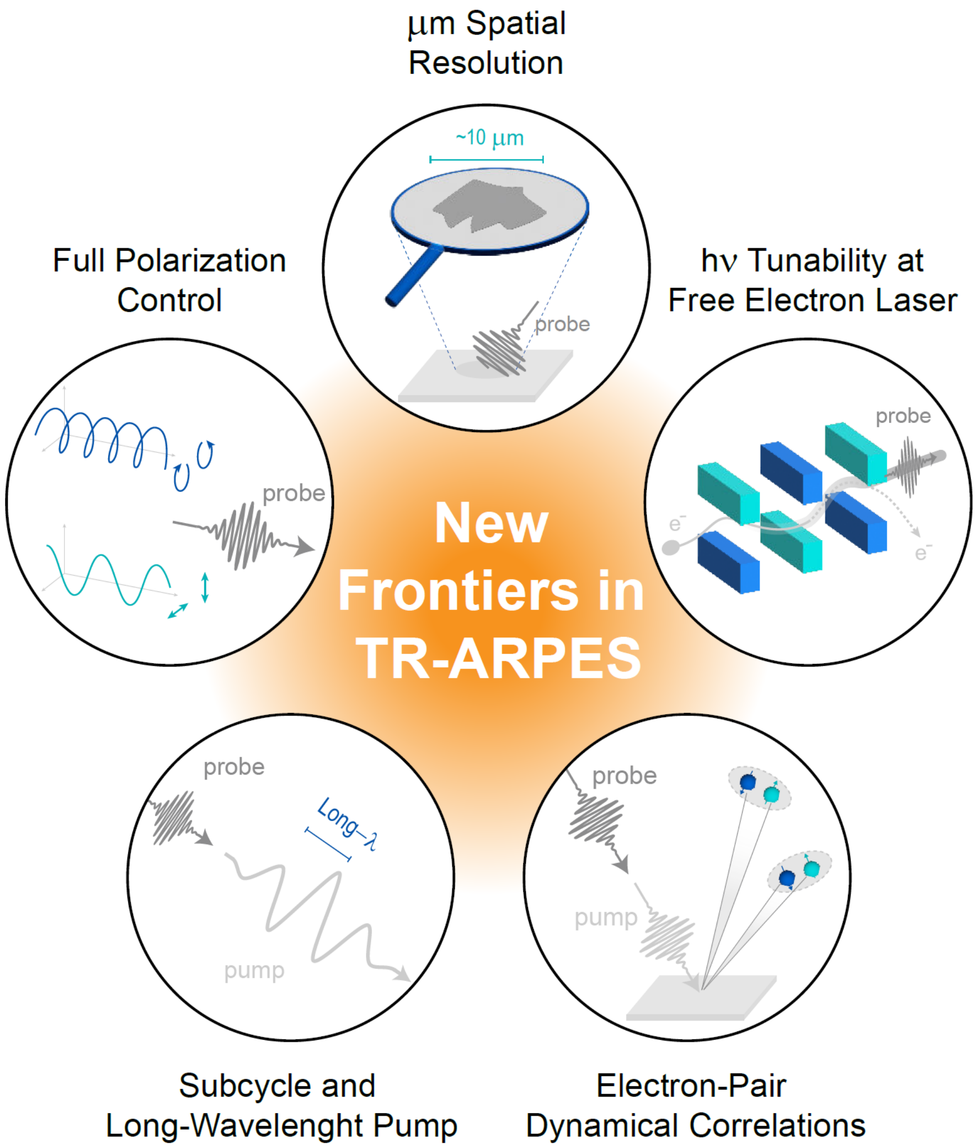
CONCLUSIONS

We can probe condensates' coherence by time-resolved ARPES

Bi-cuprates
- Genda Gu
- Hiroshi Eisaki
- Claudio Giannetti

e-doped cuprates
- Andreas Erb
- Martin Greven
- Richard Greene

TNS excitonic insulator
- Denis Golež
- Andy Millis
- Antoine Georges
- Hide Takagi
- Stefan Kaiser
- Philipp Werner



F. Boschini, M. Zonno, A. Damascelli, RMP 96, 015003 (2024)