Pseudogap in electron-doped cuprates: the role of thermal spin fluctuations

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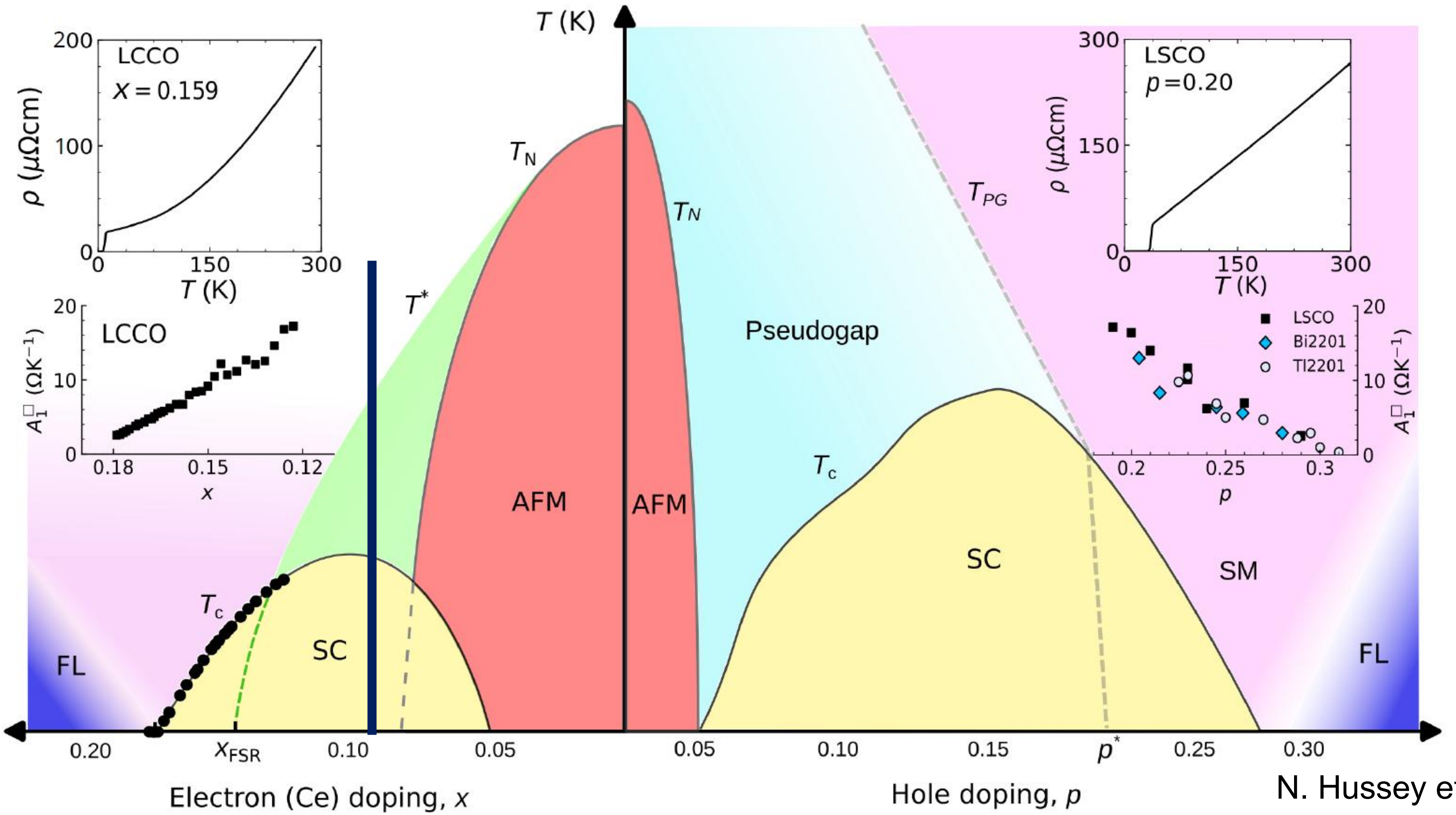
Fermi legacy in low-energy physics

Academia Nazionale Dei Lincei Feb. 6, 2026


CINEMA
ROOT CANALS
High Tc cuprates

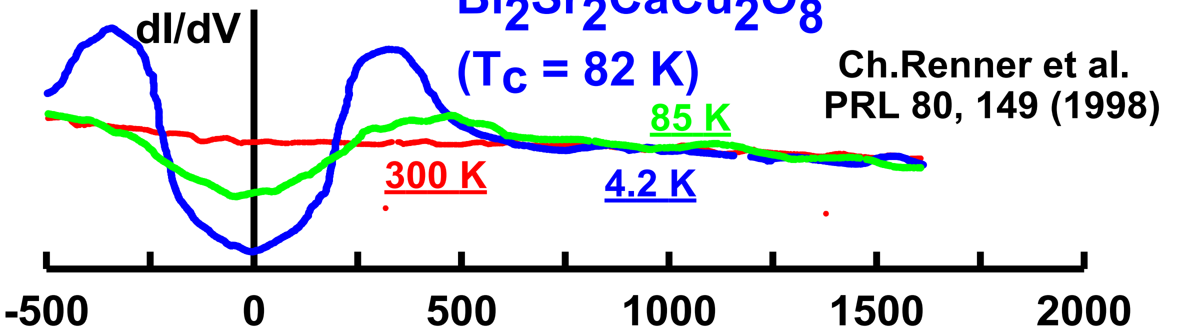
This talk will be about the origin of pseudogap in the el-doped cuprates and the interplay between pseudogap and superconductity



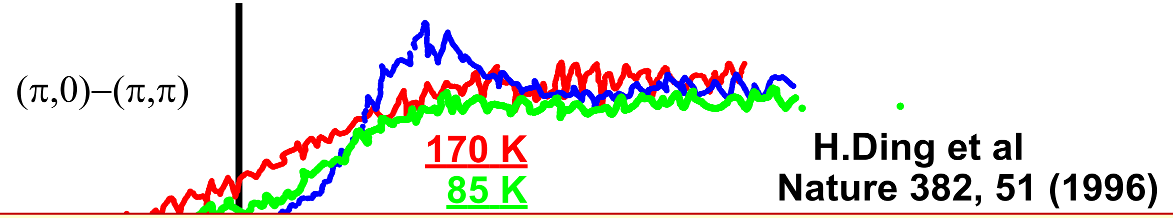
N. Hussey et al

Pseudogap

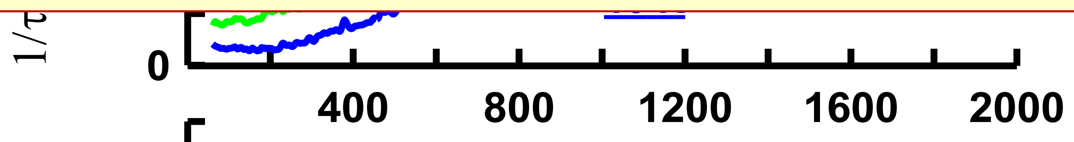
STM



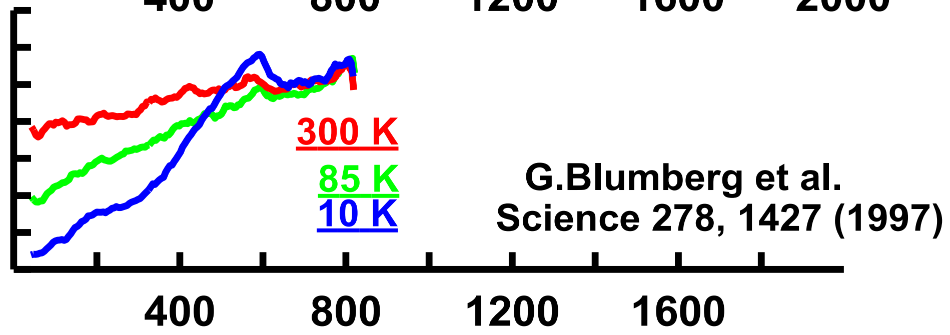
ARPES



Pseudogap: the range of dopings and temperatures where there is no "conventional" order, yet the system behavior is different from that in a metal, even a strange one,



Raman

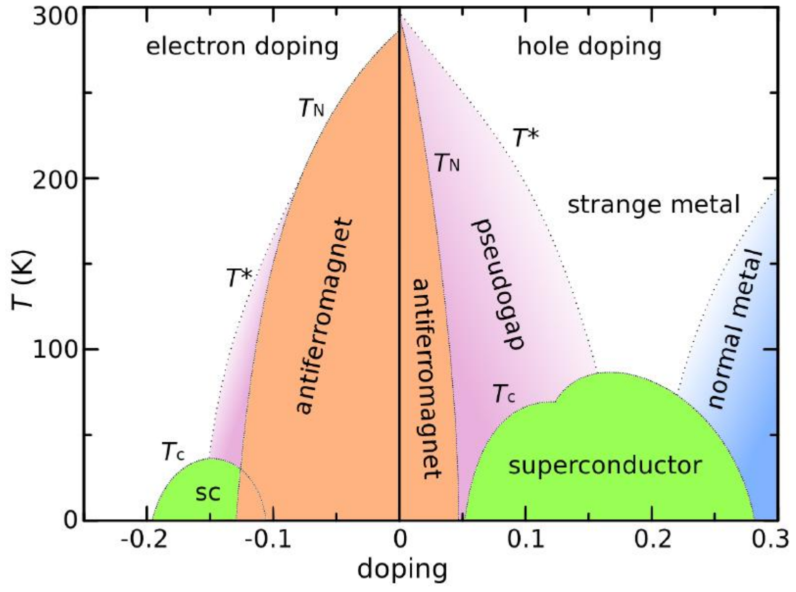


Initial idea (mid/late 90th): pseudogap is a precursor to superconductivity

Cooper pairs are formed, but their phases are not yet correlated

Borrowed from the ideas about BCS to BEC crossover

M. Zwierlein (yesterday), S. Giorgini, G. Calvanese Strinati (today)
Emery & Kivelson; Campuzano, Kanigel, Norman, Randeria ….
Johnson, Fink, Borisenko….



No direct correlation between pseudogap T* and SC Tc

Fast forward to 2026

Three key ideas about pseudogap:

A. It is a new state of matter

A phase with a topological order

S. Sachdev FL*, M. Fabrizzio…

B. It is a state with a "less conventional" order, bilinear in fermions

C. Varma, Loop current order

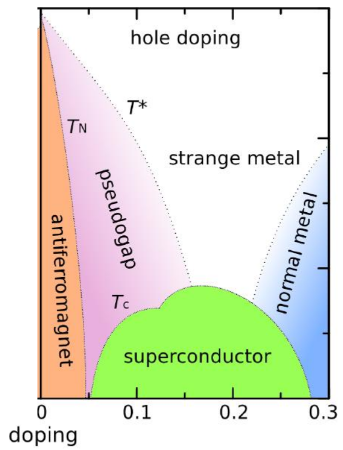
C. It is a precursor to a "more conventional" ordered state

Spin density wave	Charge density wave	Nematic
A. Finkelstein, W. Metzner, A.C.	M. Grilli, C. di Castro C. Castellani, S. Caprara, ,J. Lorenzana, ….	W. Metzner, R. Fernandes, E. Berg..

In A,B FS gets reconstructed from a large one to small pockets (1-x to x)

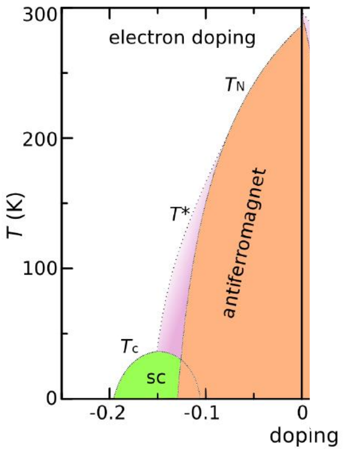
In C, no FS reconstruction, but the shape of the spectral function changes

Hole-doped cuprates – complex systems with many competing degrees of freedom



- Spin fluctuations (incommensurate SDW or stripes)
- Charge fluctuations
- B1g phonons
- Strange metal

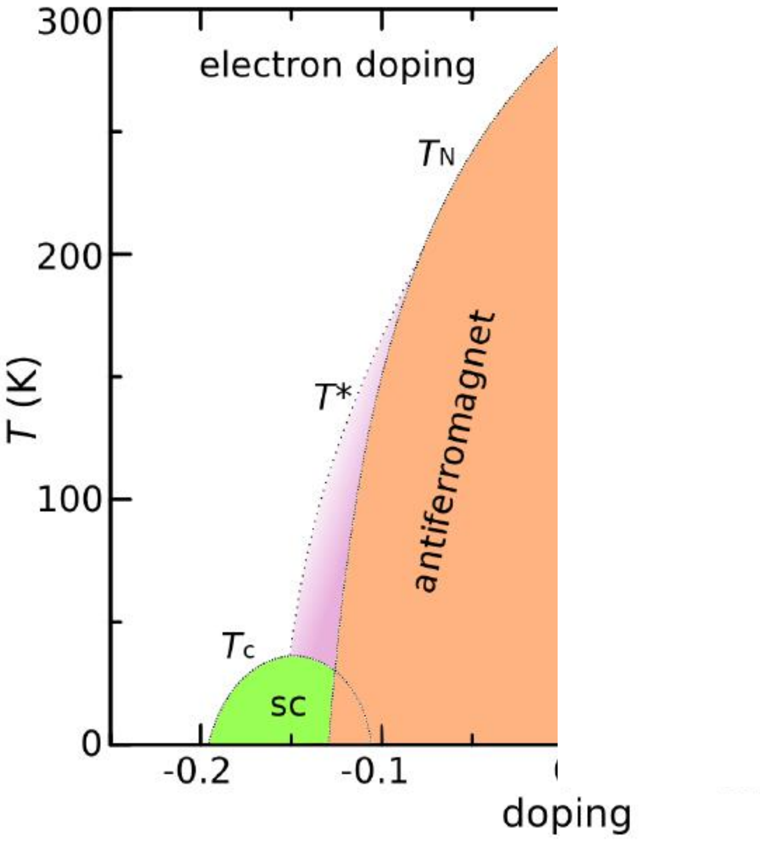
Electron-doped cuprates – less complex systems



- Magnetic fluctuations are peaked at (π,π)
- Magnetism holds up to larger dopings
- Charge fluctuations and phonons are less relevant

Spin fluctuations in the driver's seat

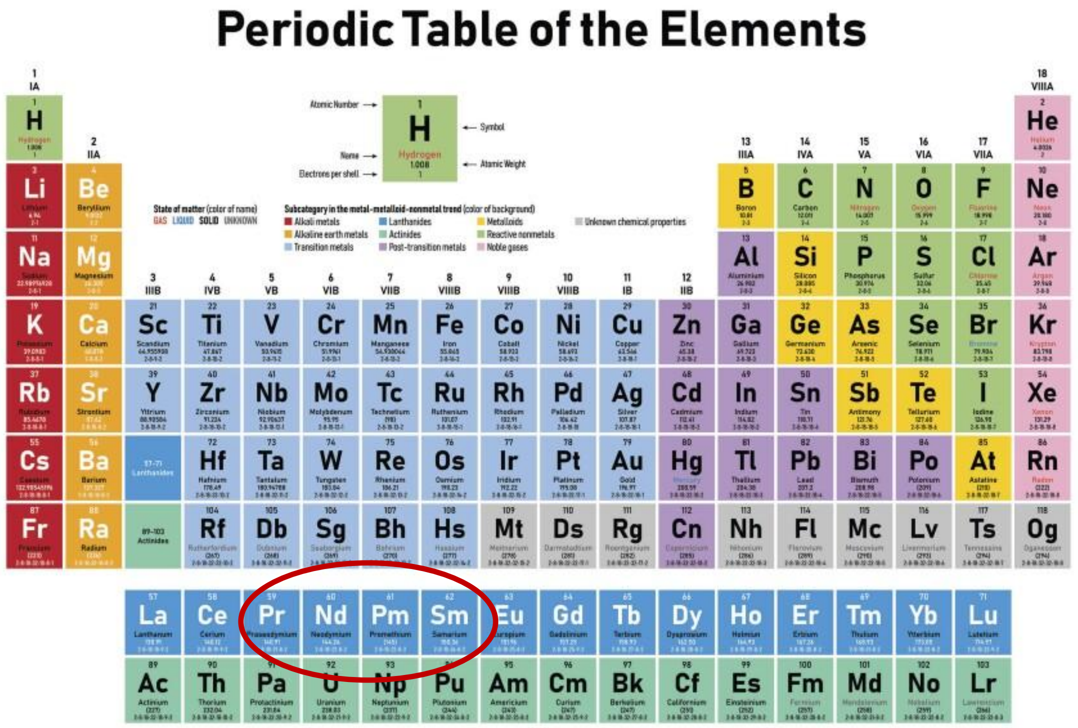
Electron-doped cuprates



$Nd_{2-x}Ce_xCuO_4$

Discovered by
Tokura, Takagi and Uchida in 1989

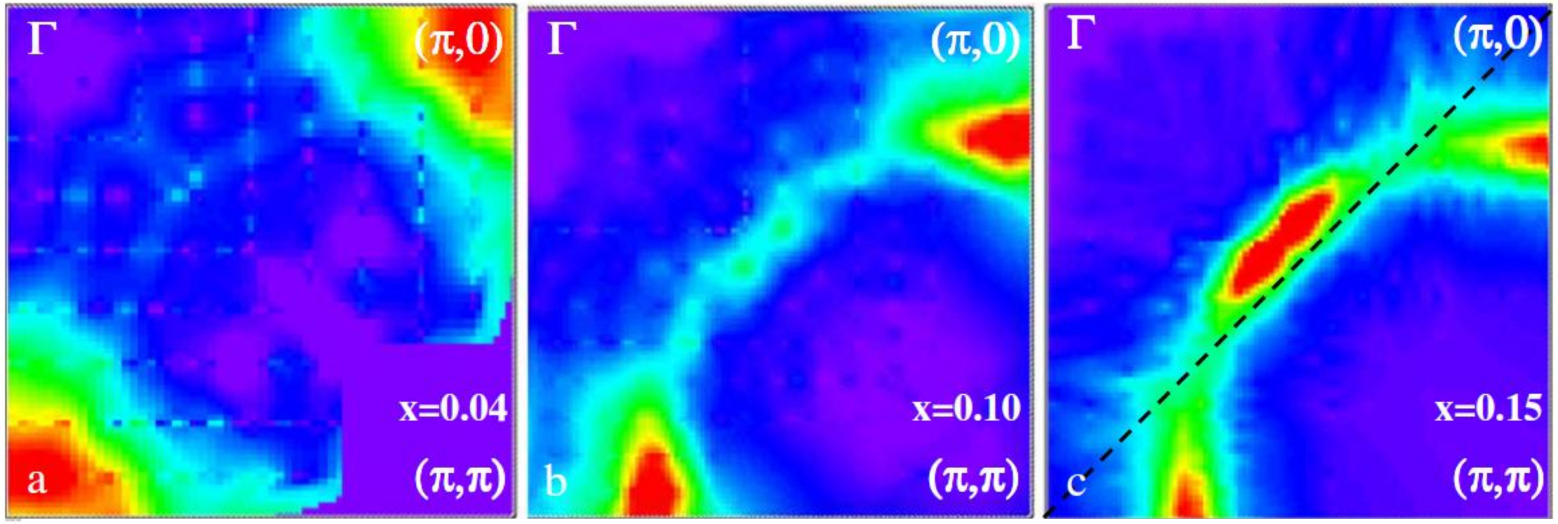
$Ln_{2-x}Ce_xCuO_4$ Ln = Pr, Nd, Sm

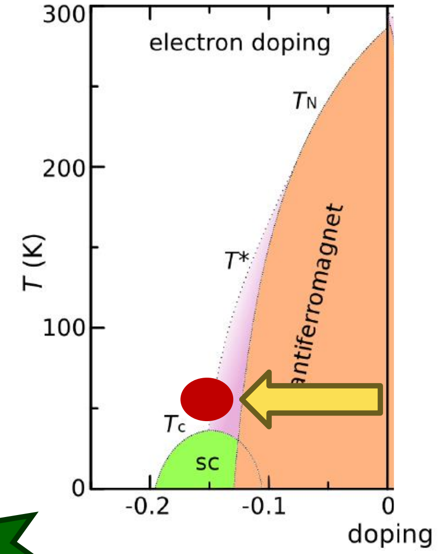


$Nd_{2-x}Ce_xCuO_4$

Early experiments (ARPES)

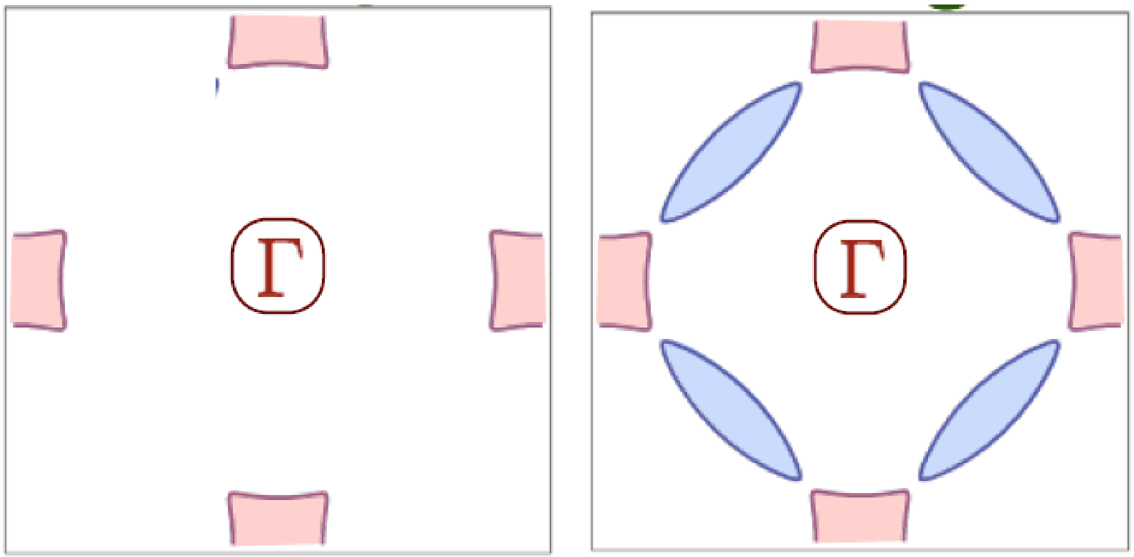
Armitage et al, RMP 82 (2010)



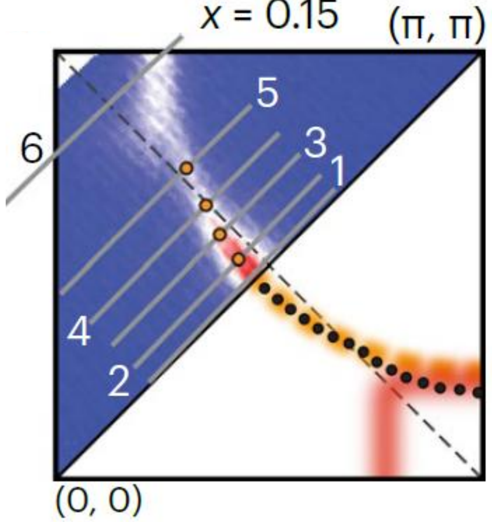


Pseudogap state

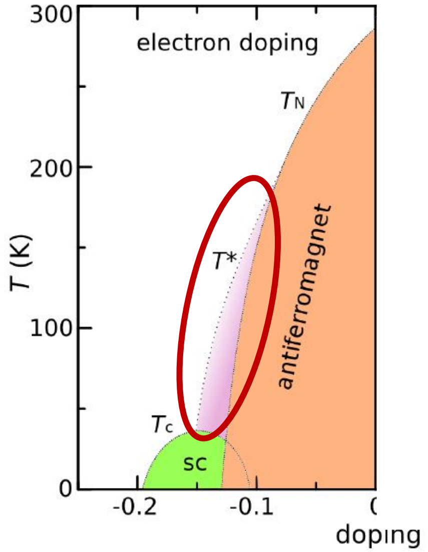
Ordered phase, Theory



Sachdev, Morr, A.C….



Recent (2023-25) ARPES experiments
by Z-X Shen group on



Two types of experiments

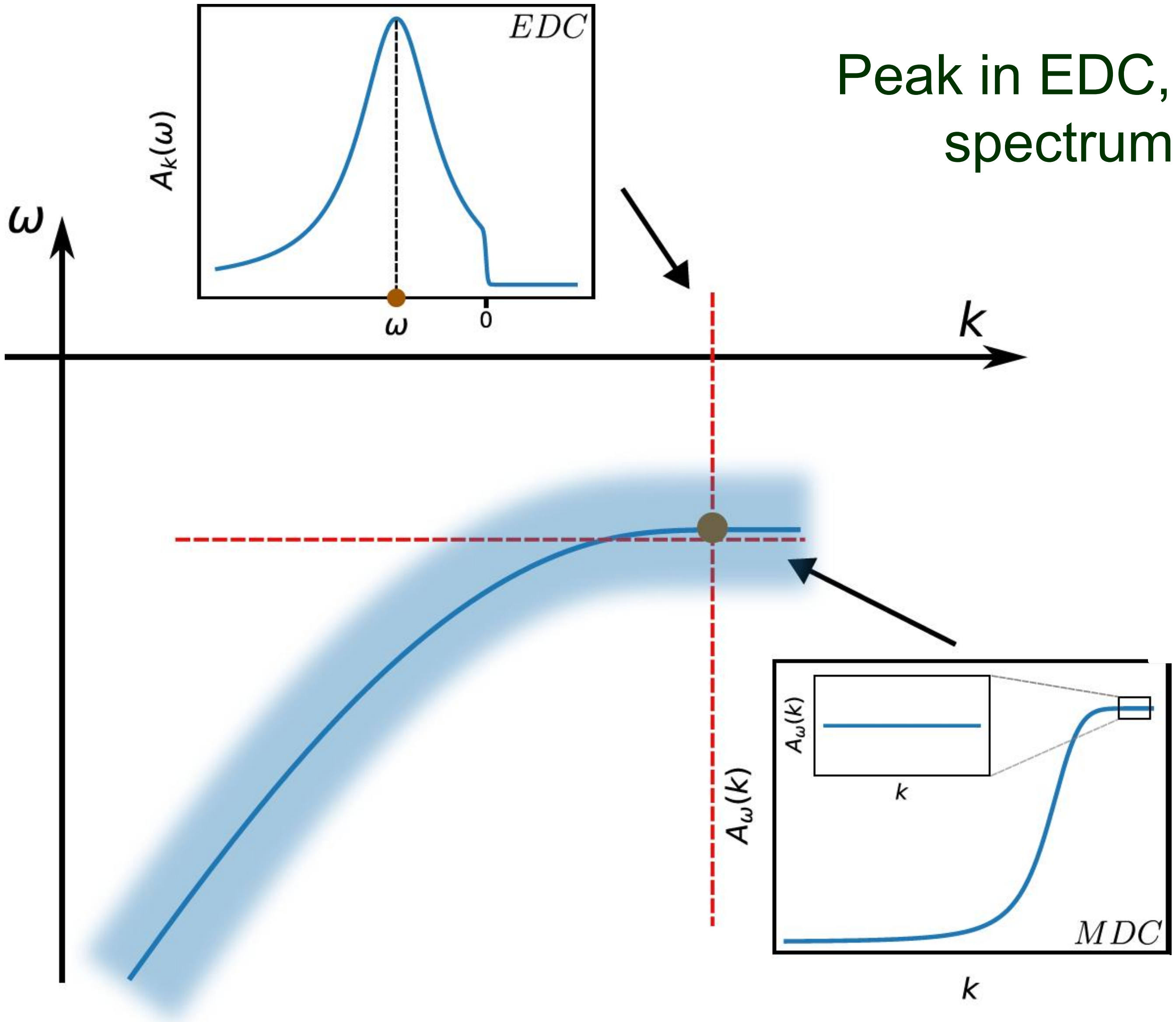
Energy distribution curve (EDC)
(ARPES intensity at a fixed momentum as a function of frequency)

Momentum distribution curve (MDC)
(ARPES intensity at a fixed frequency as a function of momentum)

EDC and MDC are supposed to measure the same fermionic spectral function.
Yet, measurements found qualitative difference between the two probes

A general expectation for a system displaying a pseudogap

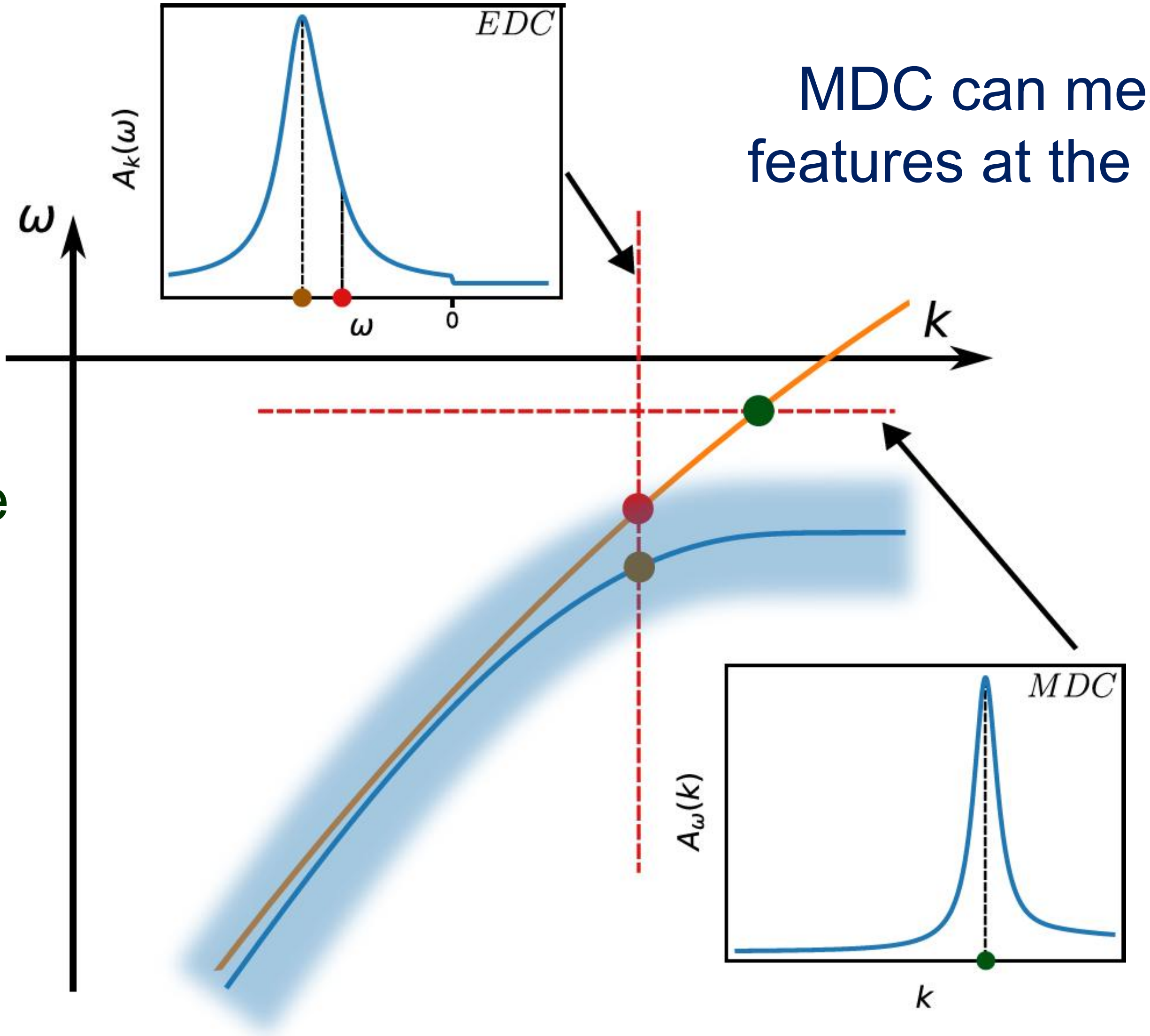
Peak in EDC, a near-featureless spectrum in MDC

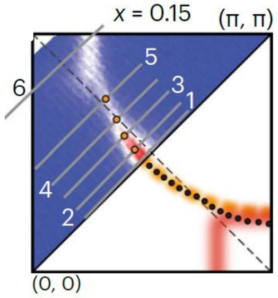


Should there be a signature that the system is still in a disordered state?

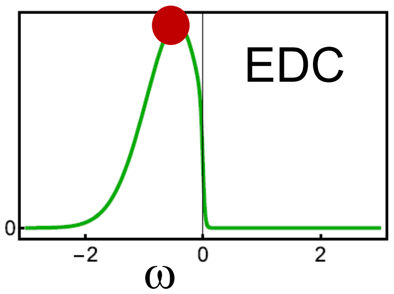
MDC can measure additional features at the smallest energies

Orange and blue lines: two features of the same spectral intensity



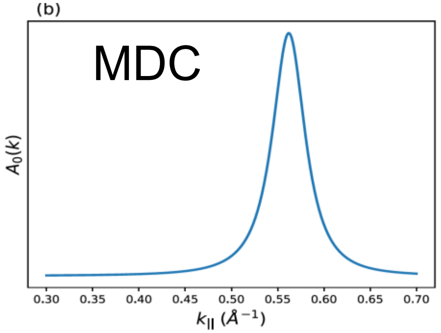


Spectral intensity

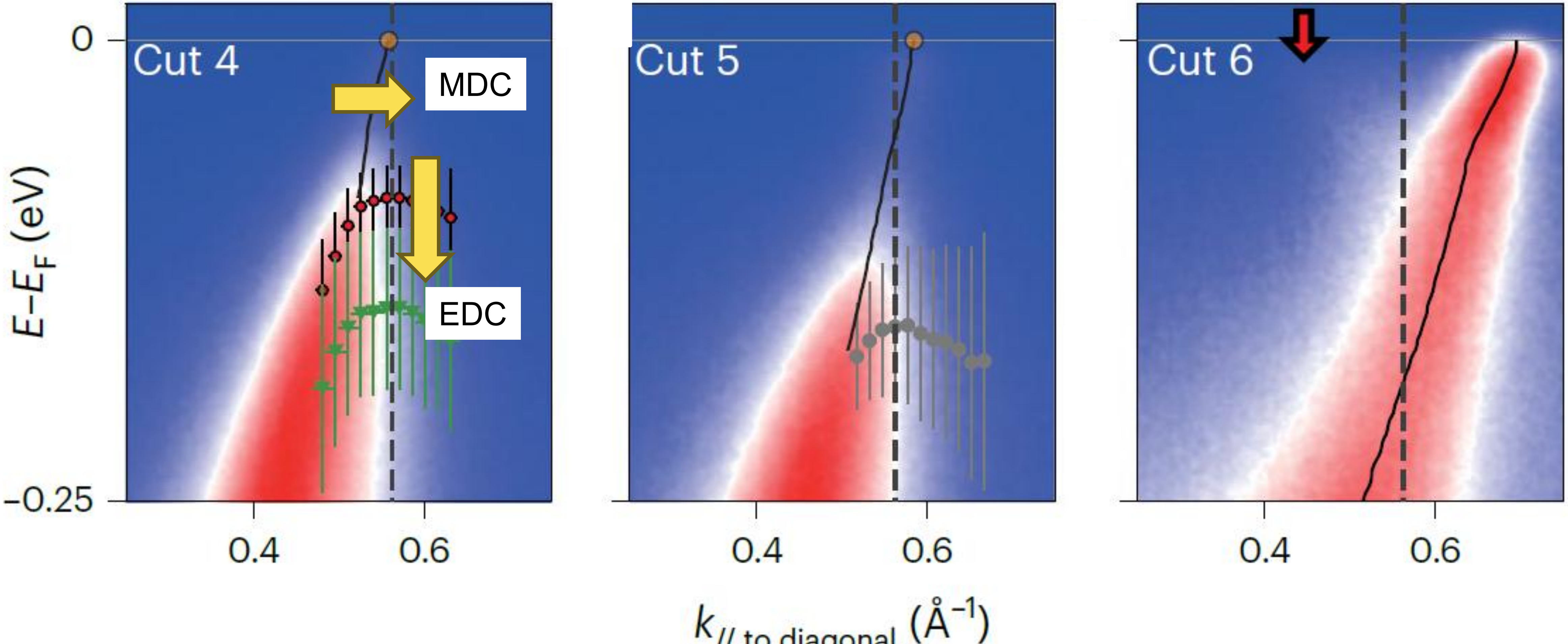


A peak at a finite ω.
A clear signature
of pseudogap

Spectral intensity

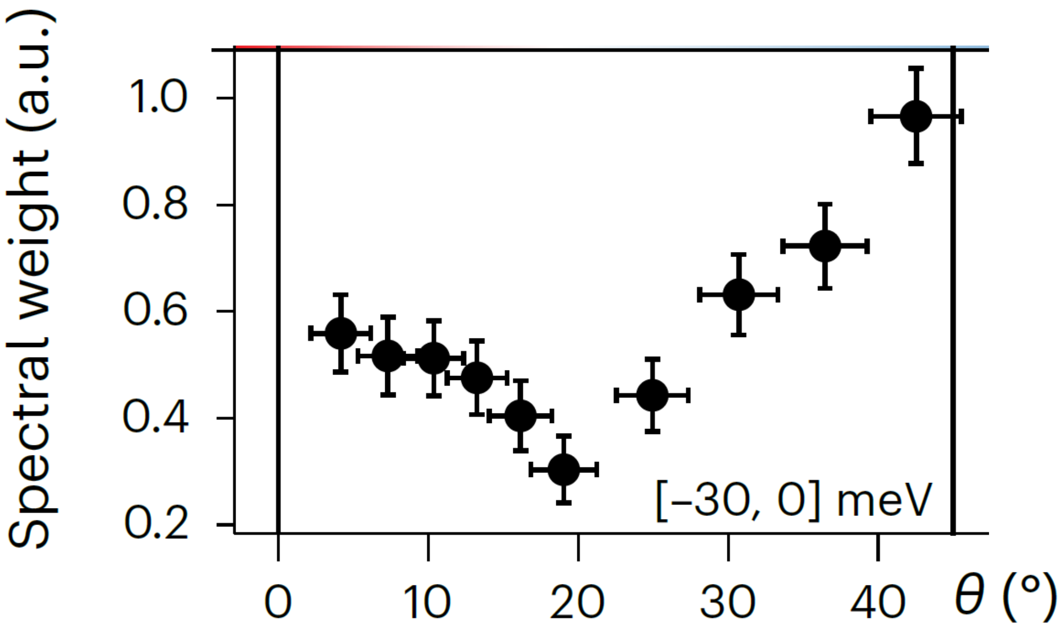


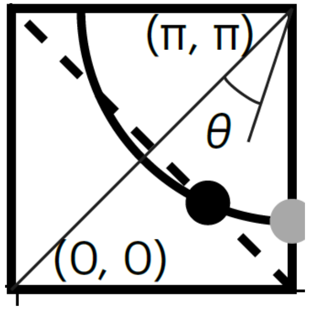
A single peak
crossing
Fermi surface



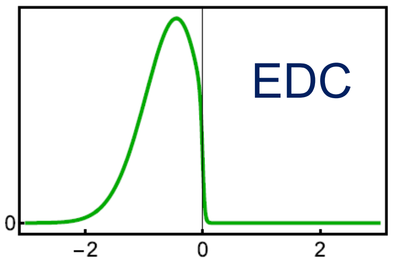
And there is more:

The largest reduction of the EDC spectral weight at small ω is at a hot spot

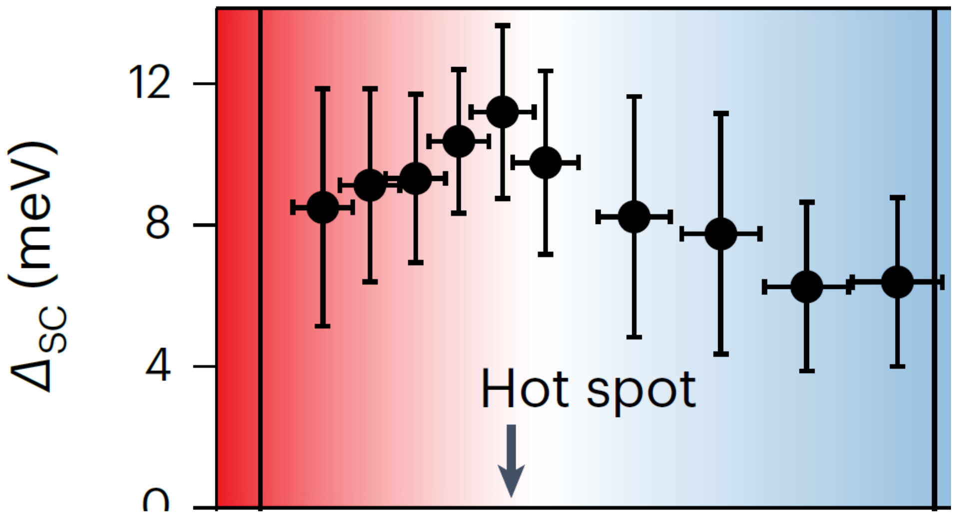




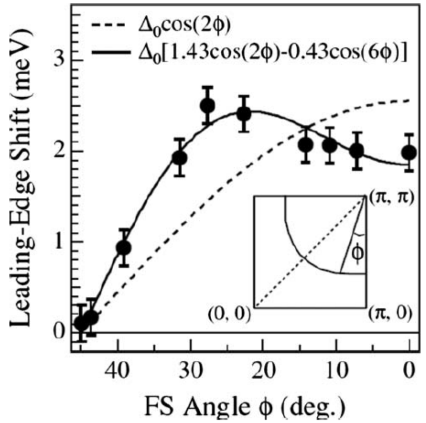
Spectral intensity



Superconducting gap is the largest at a hot spot



Matsui, 2005
(Yamada's group)



Our theory:

Let’s check whether these results can be understood by treating pseudogap as precursor to antiferromagnetism

(pseudogap due to AFM fluctuations)

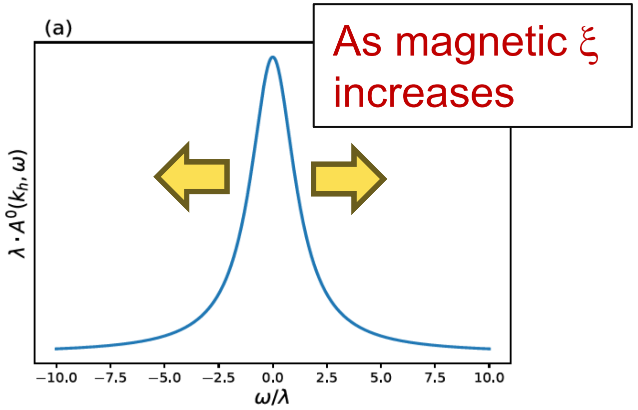
That AFM fluctuations give rise to pseudogap behavior is not obvious

Spin fluctuations in a metal are traditionally analyzed within Eliashberg formalism

Argument: spin fluctuations are Landau overdamped and for this reason are slower than fermions.

Eliashberg analysis: scattering by slow spin fluctuations increases fermionic damping and leads to non-FL behavior at finite frequencies. Non-FL behavior down to ω=0 at a magnetic QCP

There is no pseudogap -- the EDC spectral function A_k (ω) at k= k_F remains peaked at ω=0



This is all true about quantum spin fluctuations.

Thermal spin fluctuations have no dynamics,
fast fermion/slow boson argument does not work
(Eliashberg theory is not applicable)

Thermal spin fluctuations

Perturbative one-loop self-energy

$$\Sigma_{th}(k,\omega) = \frac{3\bar{g}T}{(v_F\xi^{-1})^2}\int\frac{d^2q}{(2\pi)^2}\frac{1}{\omega-\epsilon^*_{k+Q}-q_\perp}\frac{1}{q_\perp^2+q_\parallel^2+1}$$

$$=\lambda_{th}\left[\frac{\log\left(\omega-\epsilon^*_{k+Q}+\sqrt{1+\left(\omega-\epsilon^*_{k+Q}\right)^2}\right)}{\sqrt{1+\left(\omega-\epsilon^*_{k+Q}\right)^2}}-i\frac{\pi}{2\sqrt{1+\left(\omega-\epsilon^*_{k+Q}\right)^2}}\right]$$

$$\epsilon^*_k=\epsilon_k-\mu,$$

$$\lambda_{th}=3\bar{g}T/(2\pi(v_F\xi^{-1}(T))^2)$$

Vilk and Tremblay, 1997

This simple, one-loop formula leads to two results:

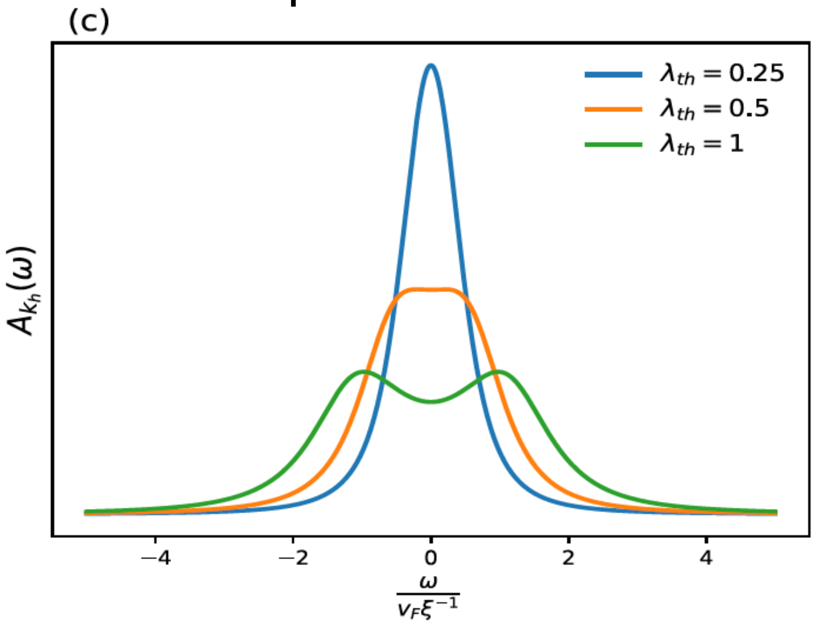
- Pseudogap behavior in EDC
- No pseudogap behavior in MDC

EDC at a hot spot

$$A_{k_h}(\omega) = \frac{\pi\lambda_{th}}{2}\frac{1}{\lambda_{th}^2\pi^2/4 + \omega^2\left((1-\lambda_{th})^2 - \pi^2\lambda_{th}^2/8\right)}$$

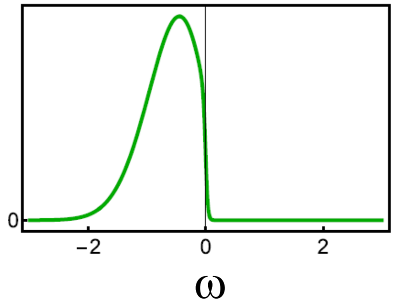
The prefactor for ω^2 monotonically decreases with increasing λ_{th} and changes sign at λ_{th} =0.47

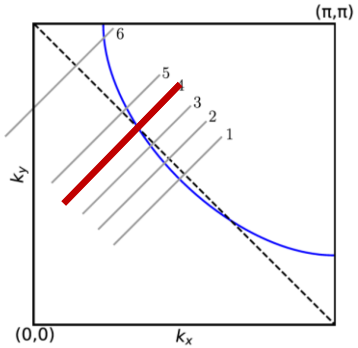
Spectral function



Pseudogap behavior

Spectral intensity





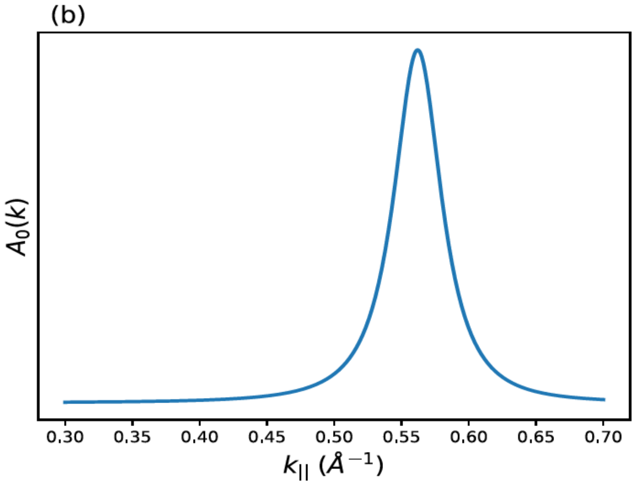
MDC are zero frequency
(a cut through a hot spot)

$$\epsilon^*_{k+Q} = -\alpha\epsilon^*_k = -\alpha v_F(k-k_h)$$

$$A_0(k) = \frac{\pi\lambda_{th}}{2}\frac{1}{\lambda_{th}^2\pi^2/4 + v_F^2(k-k_h)^2\left((1+\alpha\lambda_{th})^2 - \pi^2\alpha^2\lambda_{th}^2/8\right)}$$

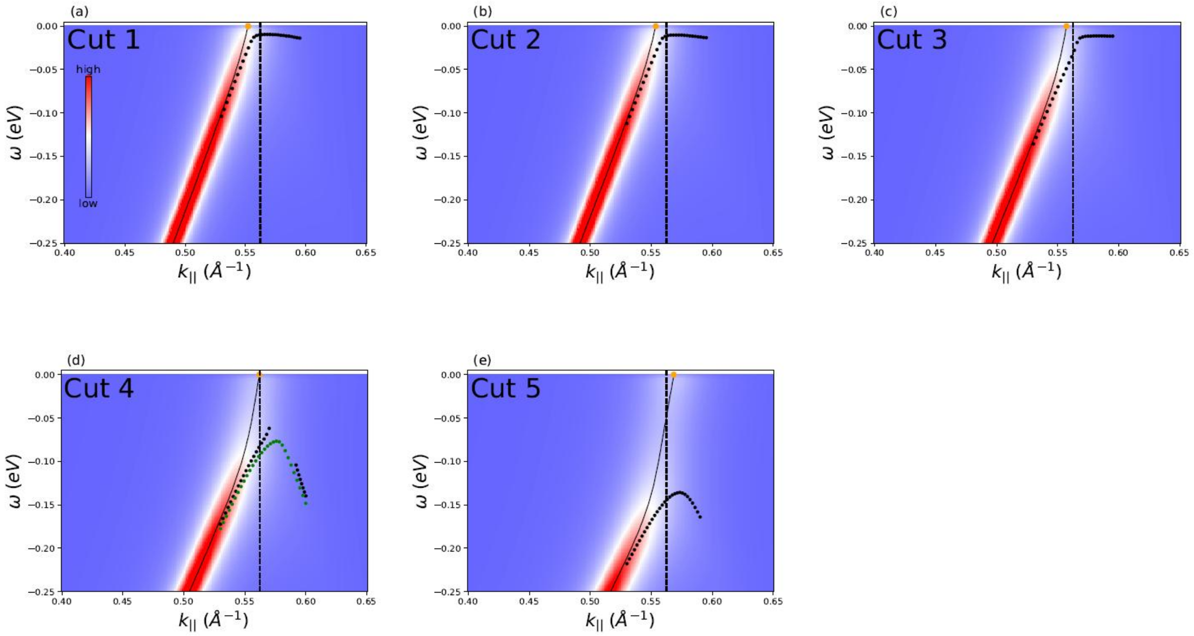
$\alpha > 0$

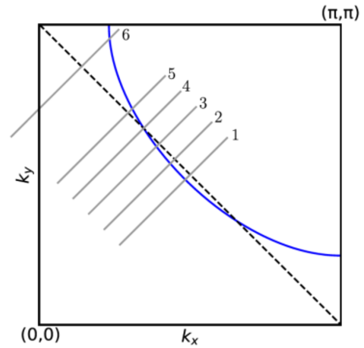
The prefactor for $(k-k_h)^2$ increases with increasing λ_{th} and remains positive



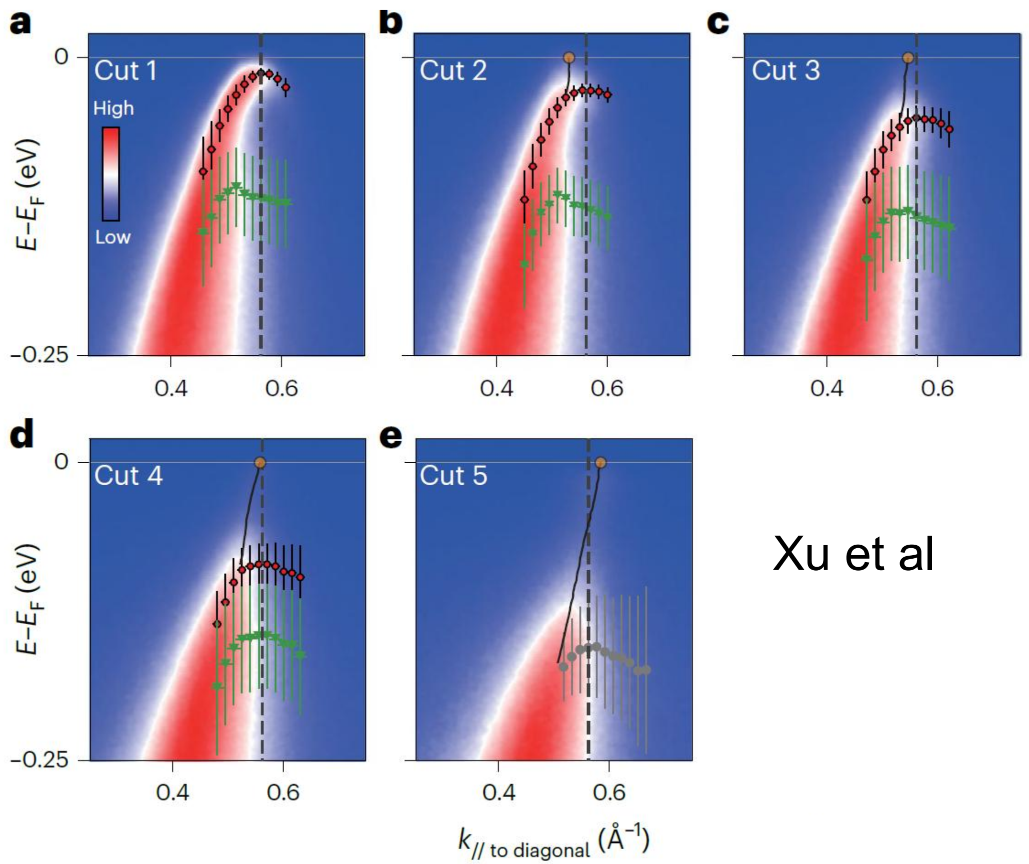
No pseudogap behavior

Theory

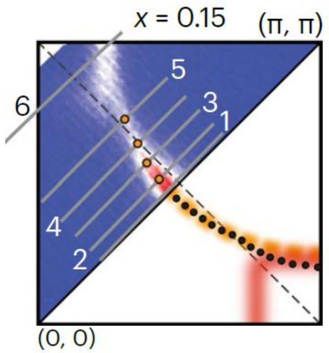




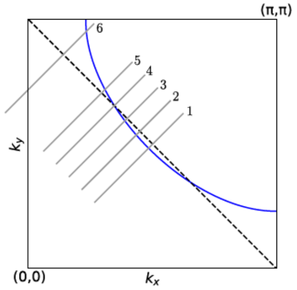
Experiment



Xu et al

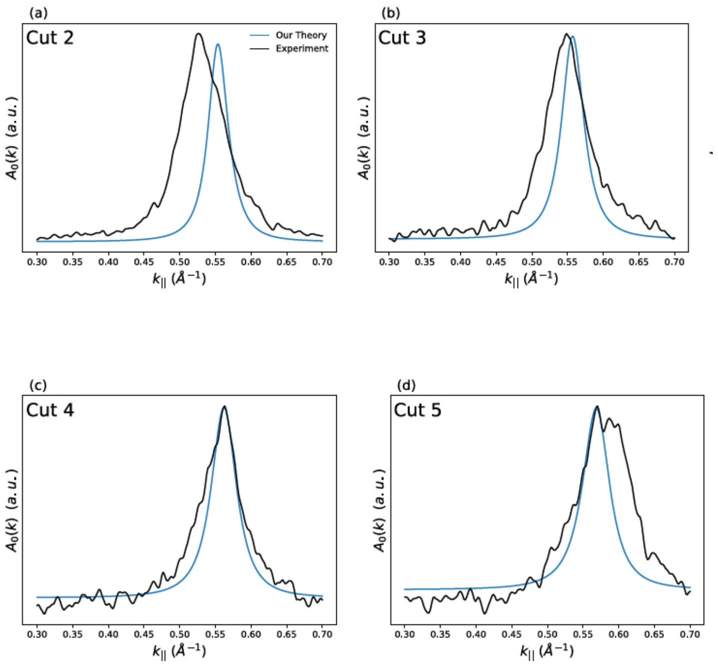


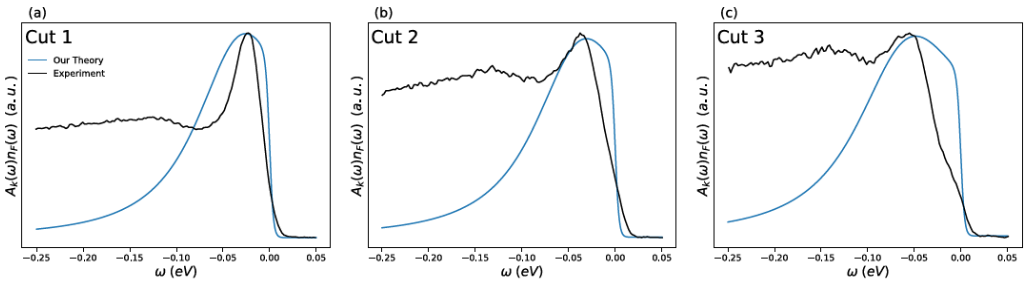
More detailed comparison with the data



MDC at ω=0

EDC at k_F





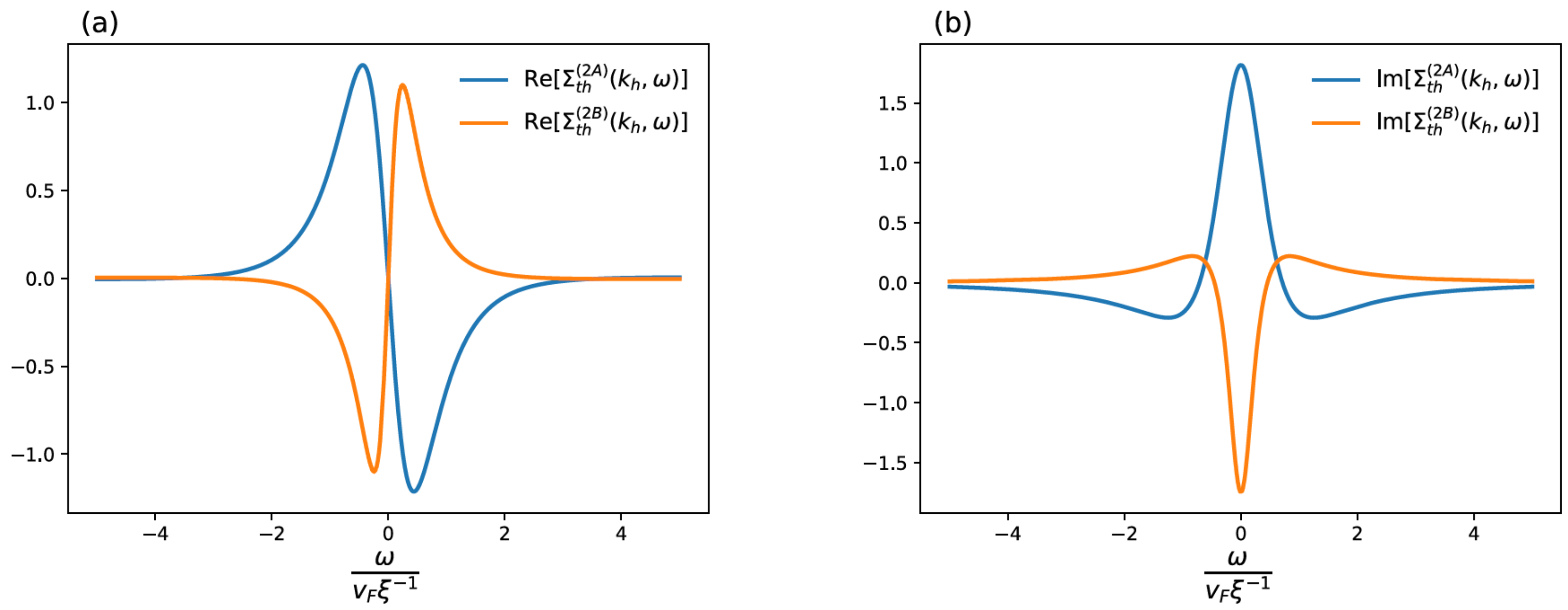
Rapidly grown psedogap in EDC around a hot spot

Peak at k $=k_F$

Higher-order contributions to $\Sigma(k,\omega)$

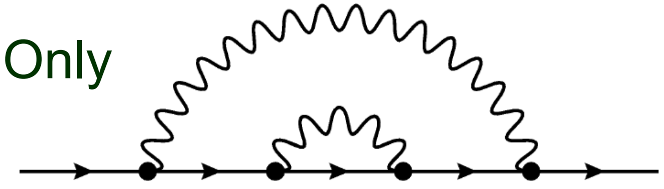
$\Sigma(k,\omega)$ =

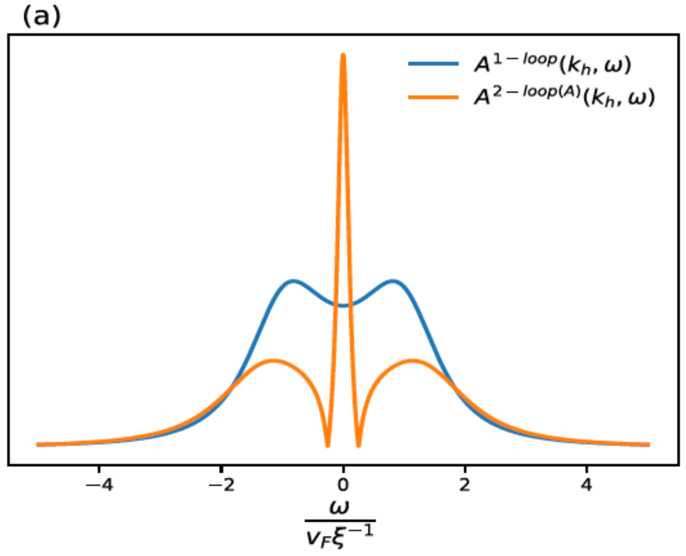
The contributions from the two two-loop terms almost cancel out



As the consequence, pseudogap behavior in EDC survives in two-loops

And what if we neglected vertex corrections?

Only 



The peak at zero frequency re-appears

Full result with only self-energy corrections included (self-consistent one-loop)
No pseudogap

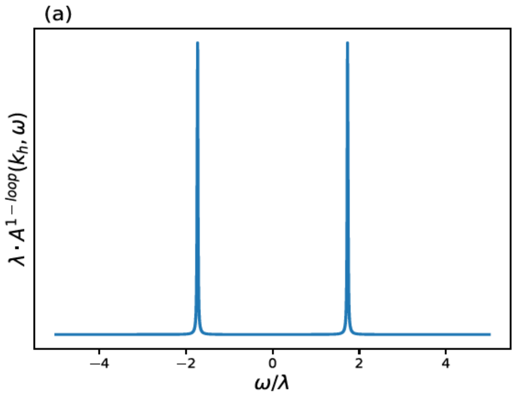
Vertex corrections are crucial for
the pseudogap from spin fluctuations
(no pseudogap in Eliashberg theory)

Theoretical game: consider the extreme case $\chi(q) = \delta(\mathbf{q} - \mathbf{Q})$ Q=(π,π)

Finite T, 2D
No long-range order

One loop $\Sigma(k, \omega)$ at the hot spot

$$\Sigma^{(1)}(k_h, \omega) = 3T\bar{g} \int \frac{d^2q}{(2\pi)^2} G^{(0)}(k+q, \omega)\chi(q) = \frac{3\lambda^2}{\omega + i\delta}$$

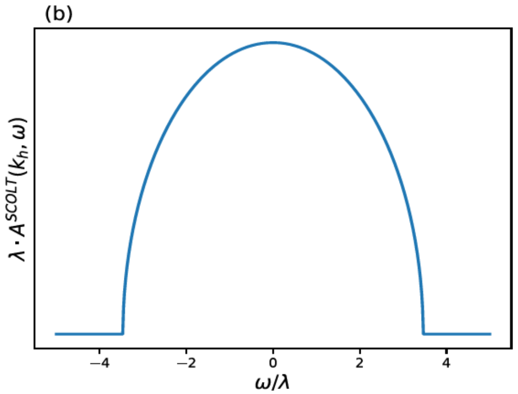


Pseudogap
(even without “pseudo”)

Self-consistent one-loop (no vertex corrections)

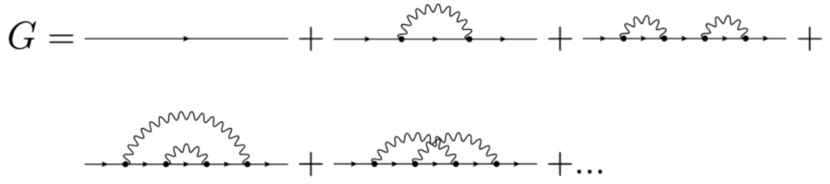
$$G^{-1}(k_h, \omega) = \omega + i\delta - 3\lambda^2 G(k_h, \omega)$$

$$A(k_h, \omega) = \frac{1}{\pi}|\mathrm{Im}G(k_h, \omega)| = \frac{\sqrt{12\lambda^2 - \omega^2}}{6\pi\lambda^2}\Theta(12\lambda^2 - \omega^2)$$



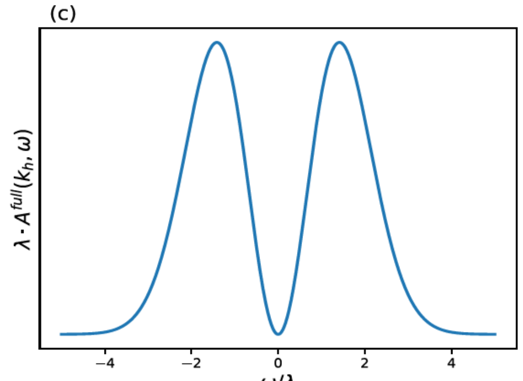
No pseudogap

Full consideration (self-energy + vertex corrections)



Eikonal series

$$A^{full}(k_h, \omega) = \frac{1}{\pi}\left|\mathrm{Im}G^{full}(k_h, \omega)\right| = \sqrt{\frac{\pi}{2}\frac{\omega^2}{\lambda^3}} e^{-\frac{\omega^2}{2\lambda^2}}$$



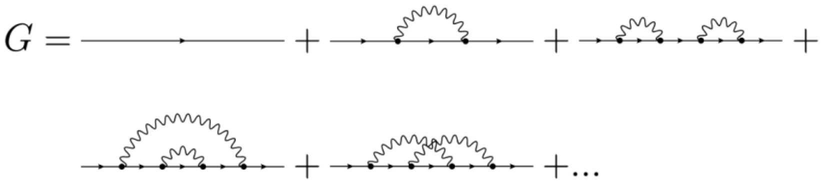
Pseudogap
survives

Spin vs charge fluctuations

The best case scenario: $\chi(q) = \delta(\mathbf{q} - \mathbf{Q})$ Q=(π,π)

Spin case

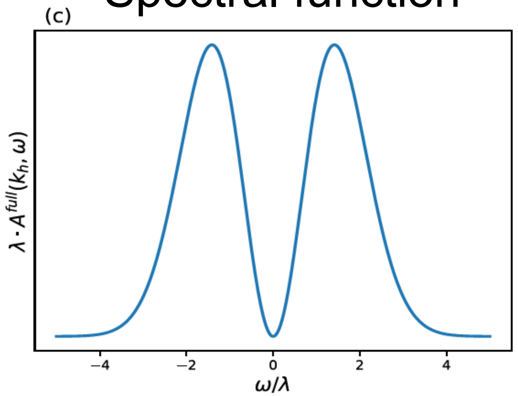
Full consideration (self-energy + vertex corrections)



Eikonal series

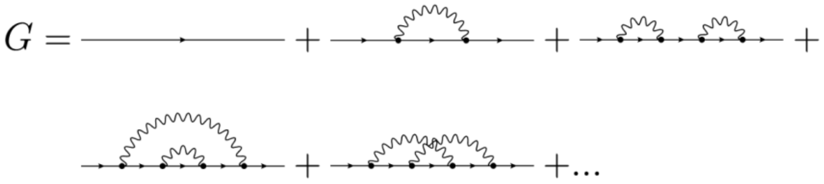
$$A^{full}(k_h, \omega) = \frac{1}{\pi}\left|\mathrm{Im}G^{full}(k_h, \omega)\right| = \sqrt{\frac{\pi}{2}}\frac{\omega^2}{\lambda^3}e^{-\frac{\omega^2}{2\lambda^2}}$$

Spectral function



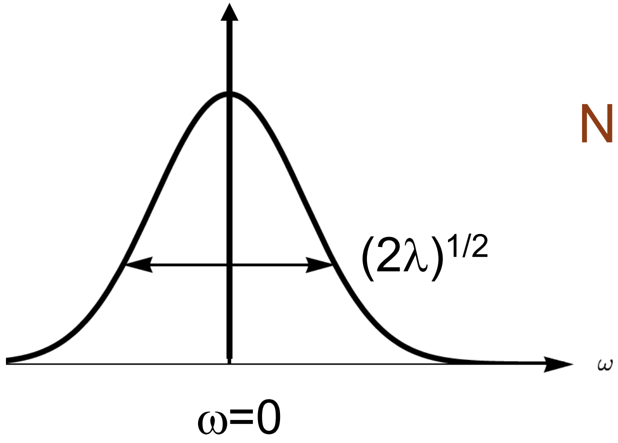
Pseudogap behavior

Charge case



Eikonal series

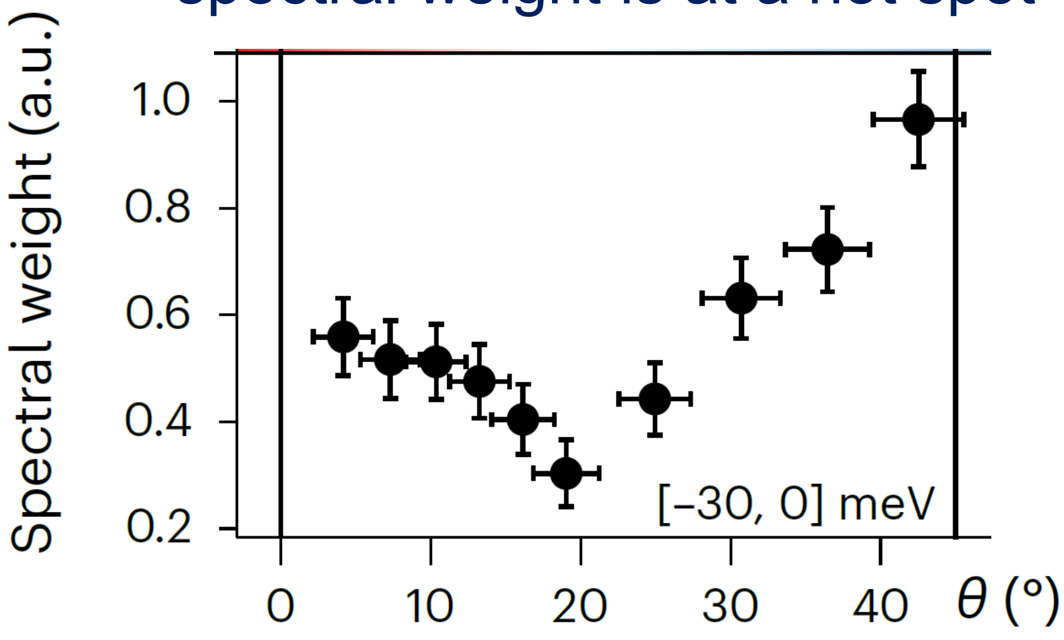
$$A^{full}(k_h, \omega) = \frac{1}{\pi}|\mathrm{Im}G^{full}(k_h, \omega)| = \sqrt{\frac{\pi}{2\lambda}}e^{-\omega^2/(2\lambda)}$$

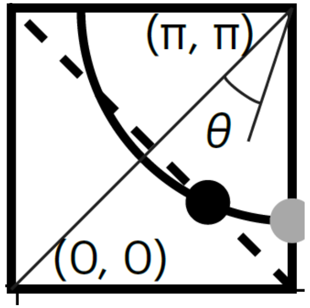


No pseudogap

Superconductivity:

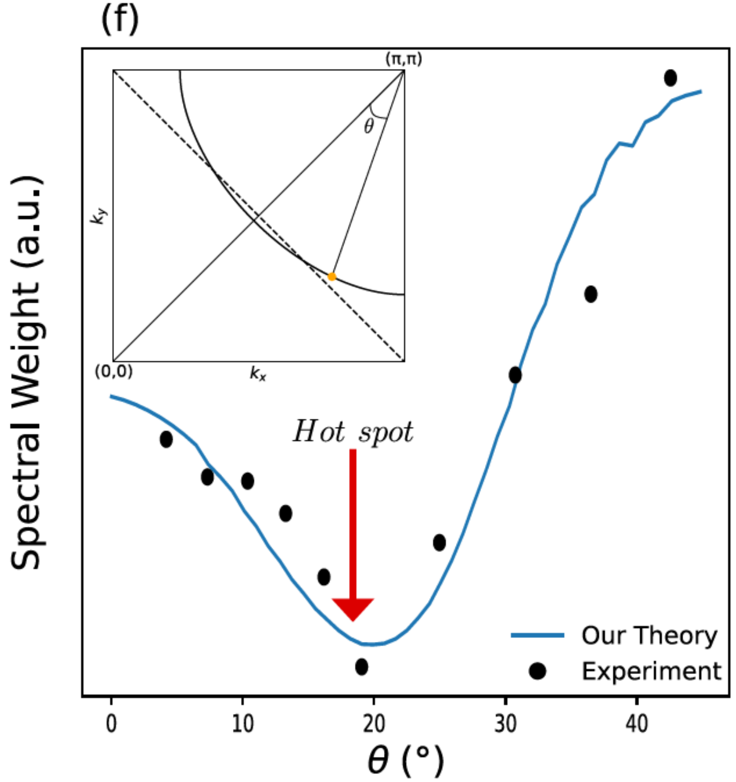
The largest reduction of the spectral weight is at a hot spot

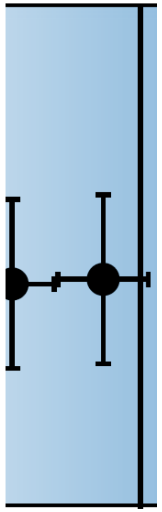




Theory: the same result in the normal state

Superconducting gap is the largest at a hot spot





How relevant is this reduction for superconductivity?

- Thermal spin fluctuations scatter elastically (zero frequency transfer) and in this regard act as impurities

- For spin-singlet SC, they (almost) act as non-magnetic impurities and (almost) cancel out In the gap equation.

Millis, Sachdev, Varma, 1988

- As the consequence, the reduction of the spectral weight in the normal state (almost) does not affect the gap structure

- The gap structure is then determined by quantum fluctuations and at weak/moderate coupling is the largest at the hot spots

Finkelstein, Abanov, Norman, AC …..

Berg, Fernandes, Shattner, Wang

Conclusions

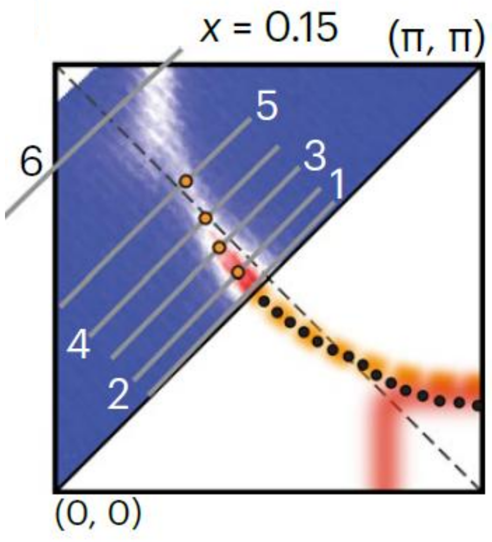
The “thermal precursor to antiferromagnetism” scenario works rather well for electron-doped cuprates.

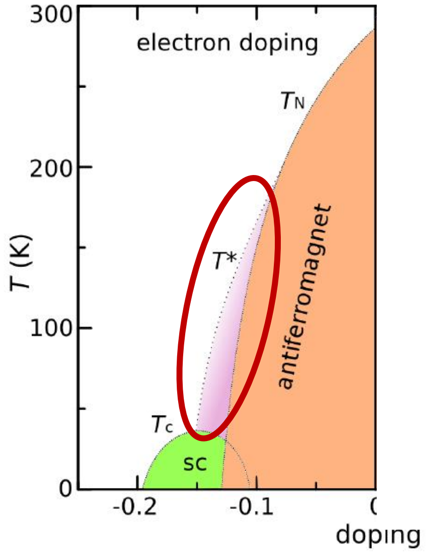
Consistent with recent ARPES data

The story for hole-doped cuprates is much more complicated

THANK YOU

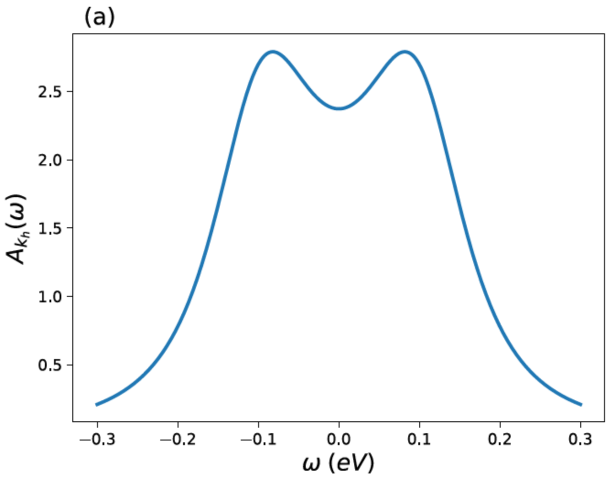
Recent (2023-25) ARPES experiments by Z-X Shen group on the pseudogap

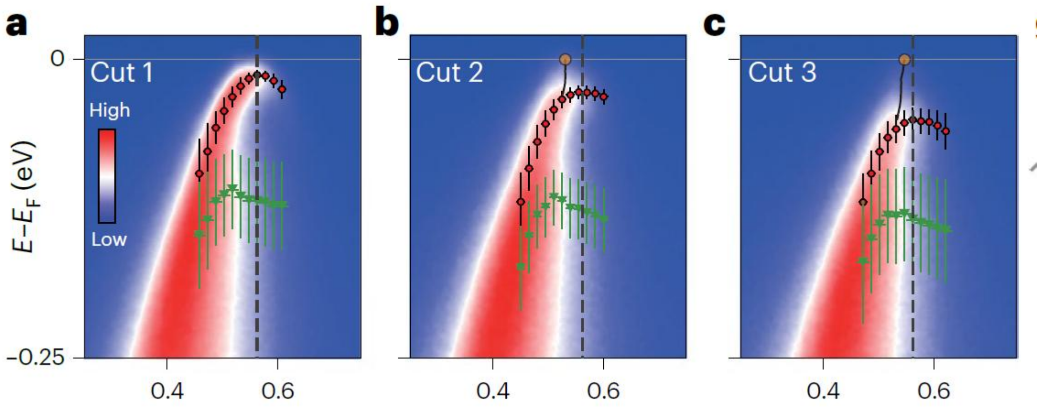




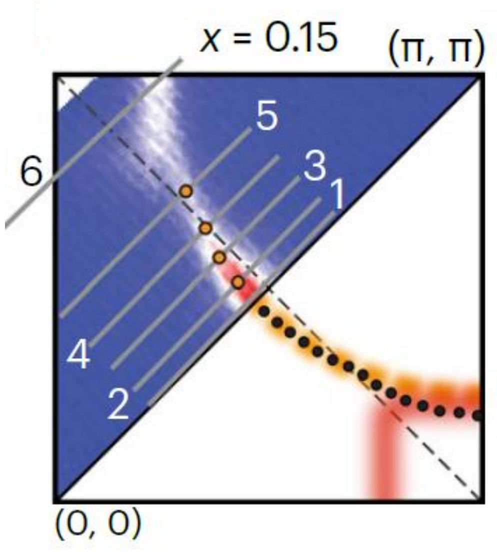
Difference between EDC and MDC

EDC: non-monotonic behavior of the spectral function consistent with the pseudogap





At all momenta, including k_F of the underlying Fermi surface, EDC peaks are at a finite frequency.



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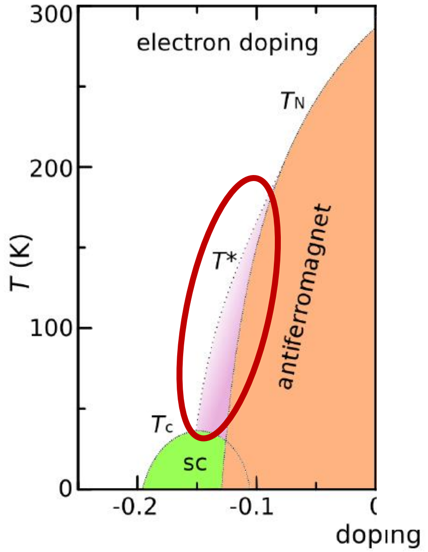

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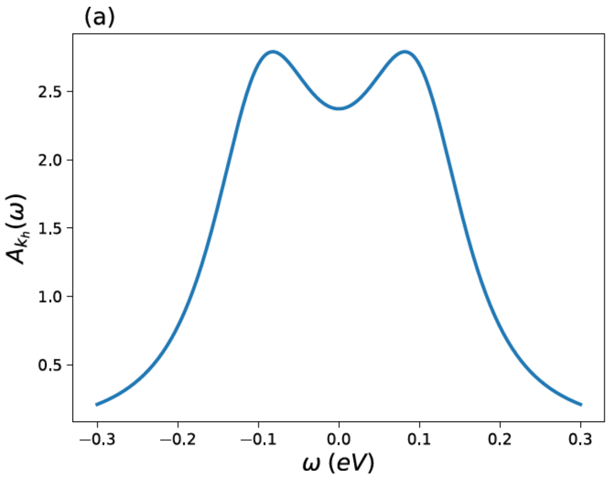

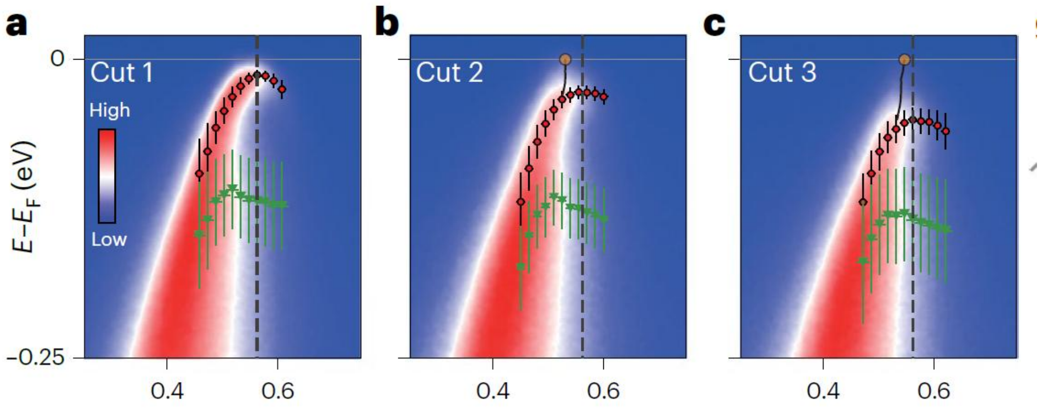

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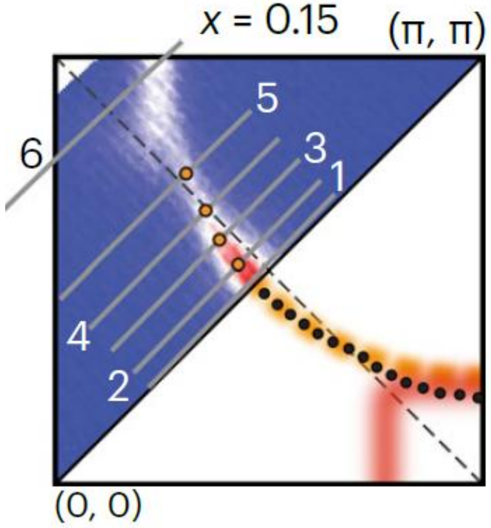
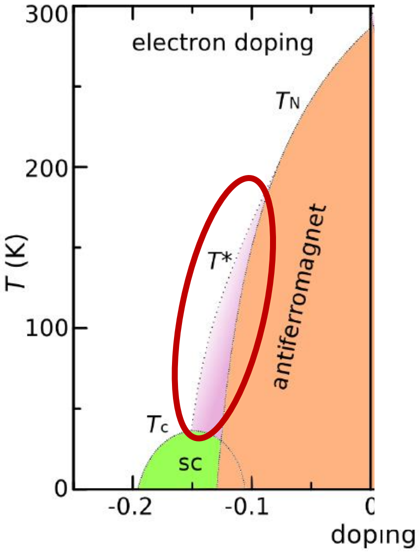
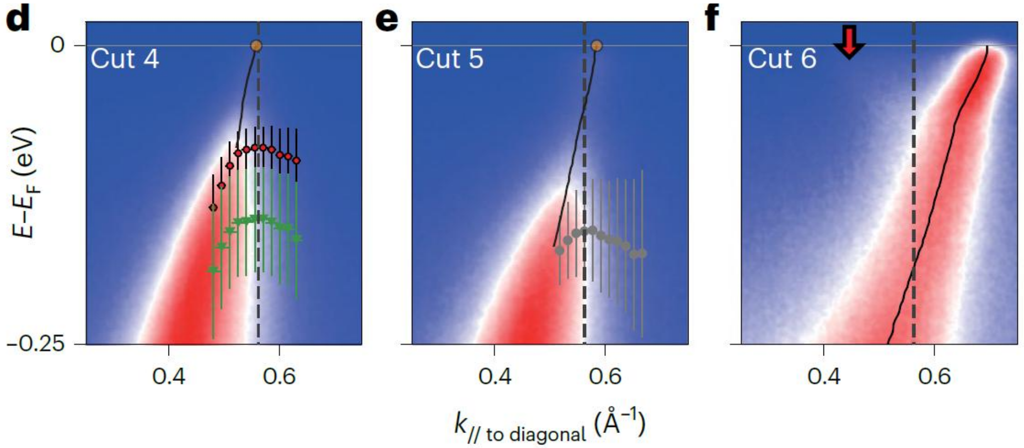
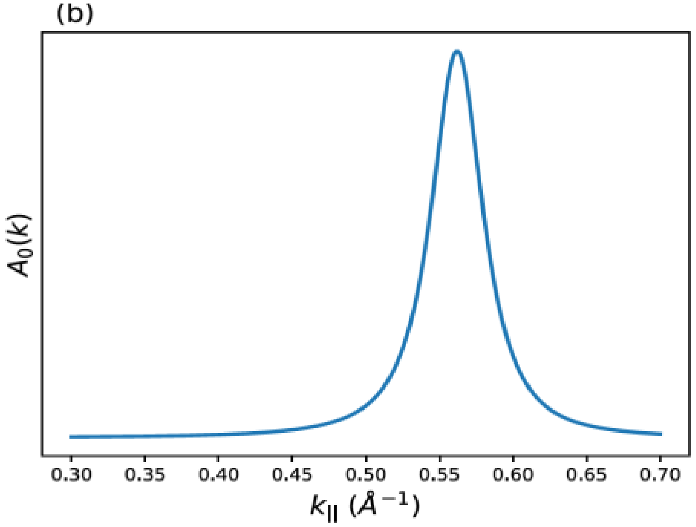
Recent ARPES experiments by Z-X Shen group on pseudogap



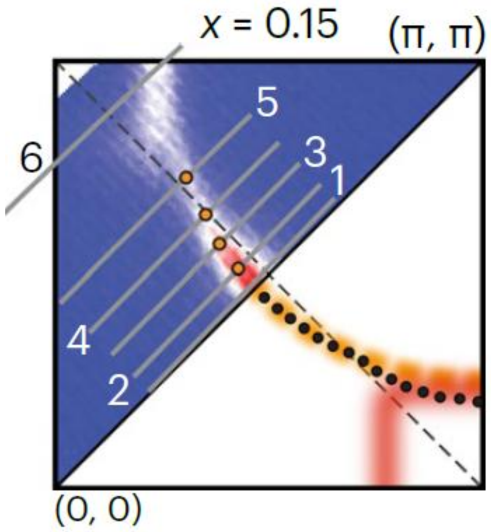


MDC: monotonic behavior of the spectral function consistent with a Fermi liquid with no pseudogap

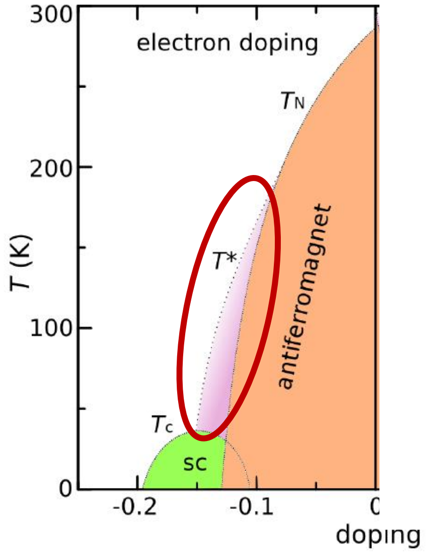




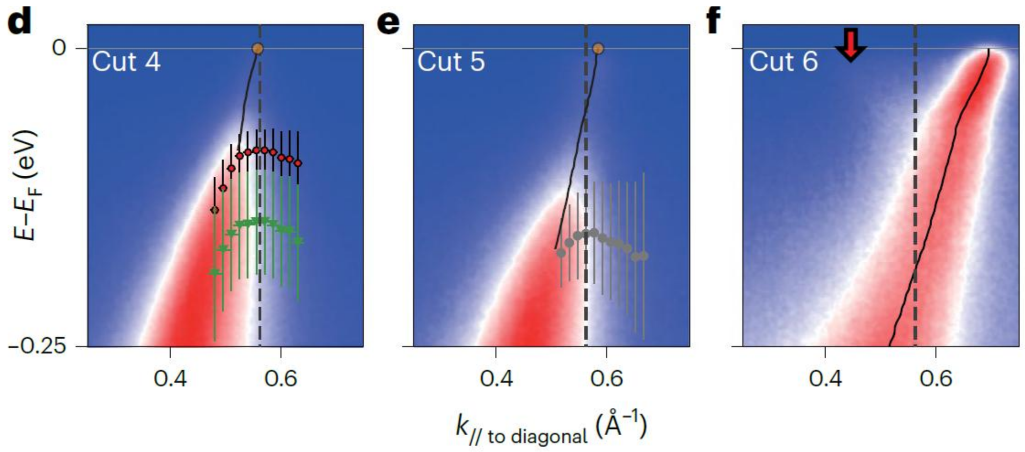
There is only one MDC peak at a given energy.

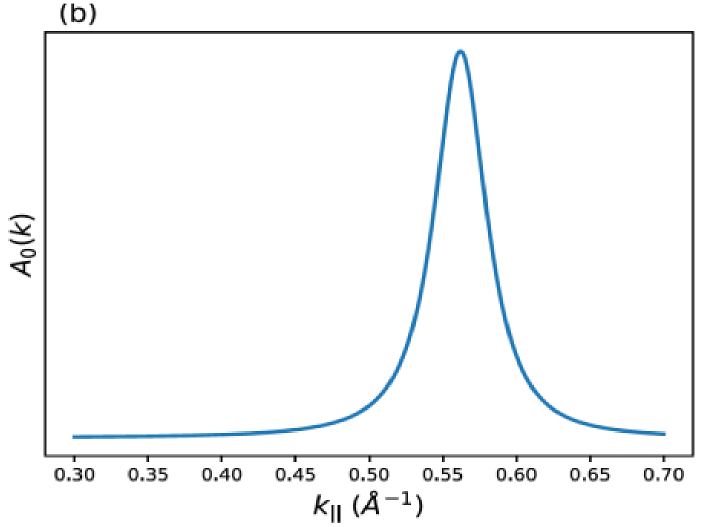


Recent ARPES experiments by Z-X Shen group on pseudogap



MDC: monotonic behavior of the spectral function consistent with a Fermi liquid with no pseudogap

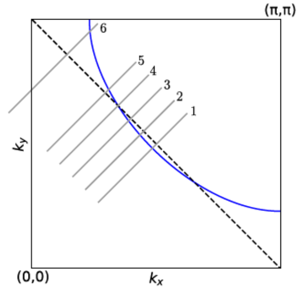




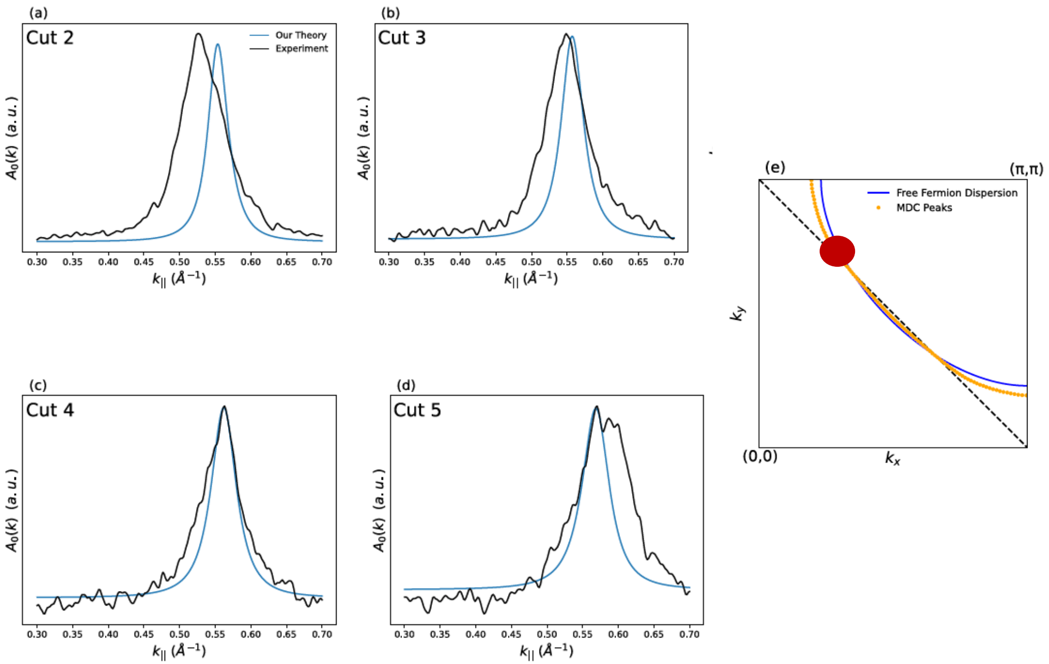
There is only one MDC peak at a given energy. At zero energy, the peak position is at k_F of the underlying Fermi surface

Gossamer Fermi surface

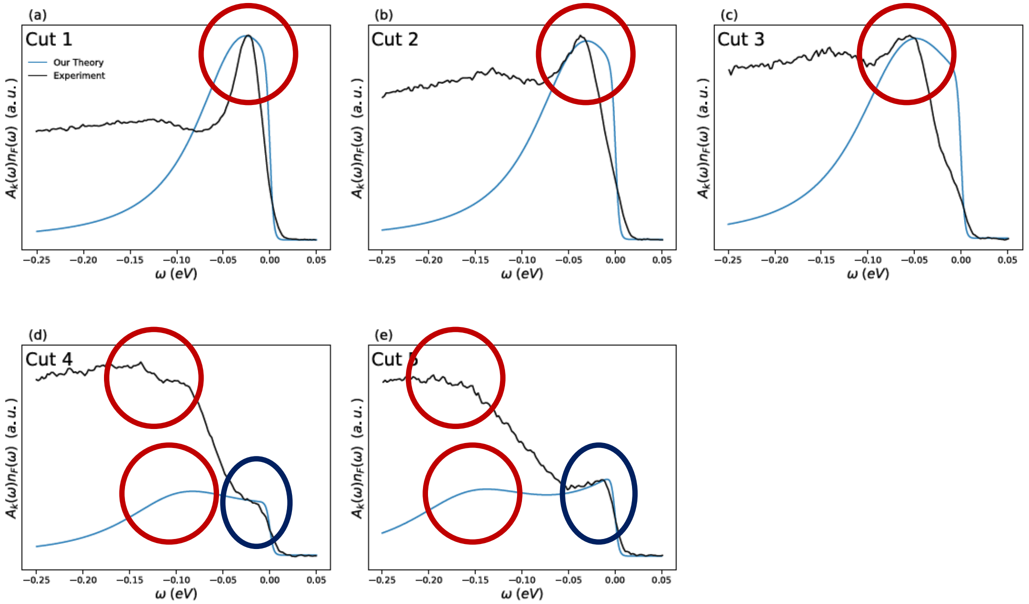
More detailed comparison with the data



MDC at ω=0



EDC at k_F

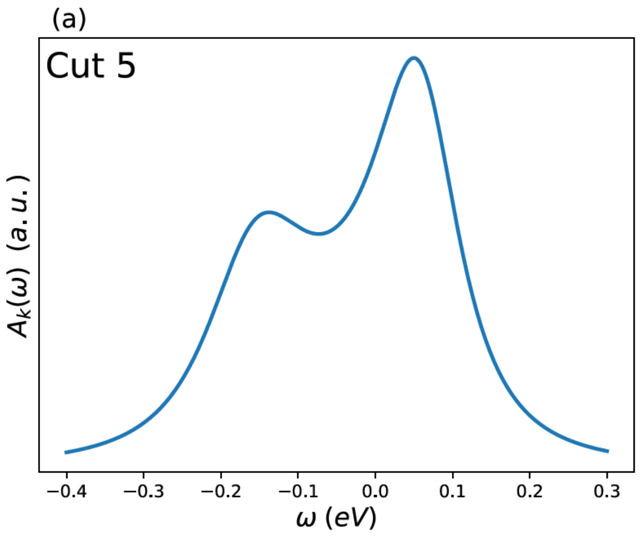


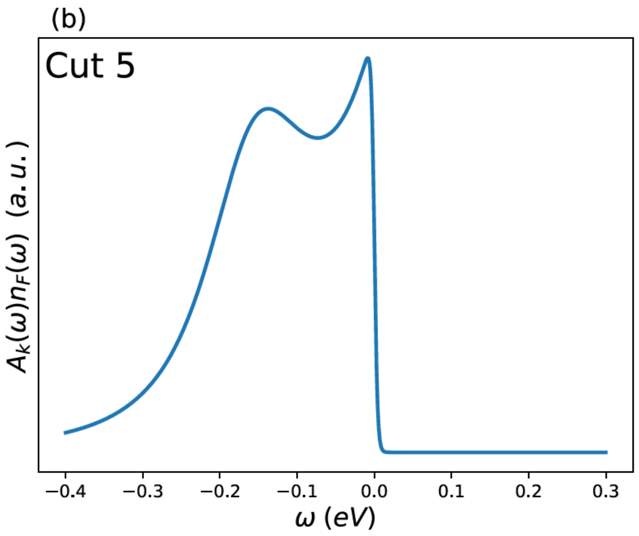
Rapidly grown psedogap in EDC around a hot spot

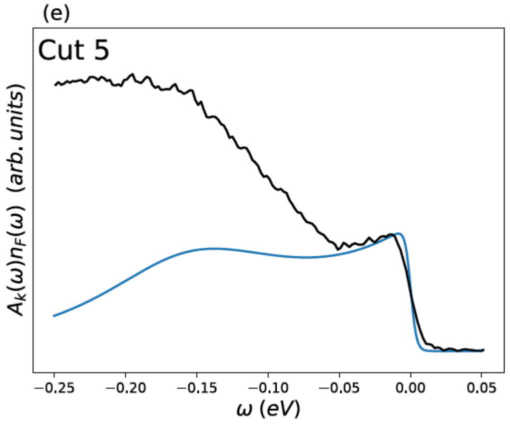
Extra peak in EDC intensity at ω =0 on one side of a hot spot

Spectral function $A_k(\omega)$

Spectral intensity $A_k(\omega)\ n_F(\omega)$



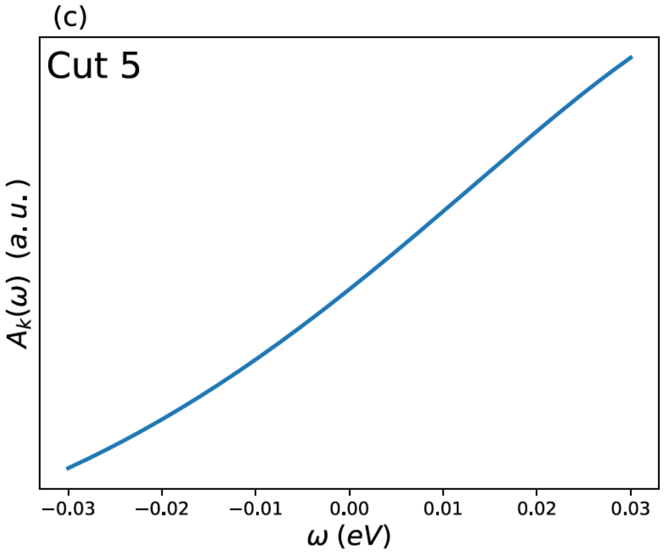


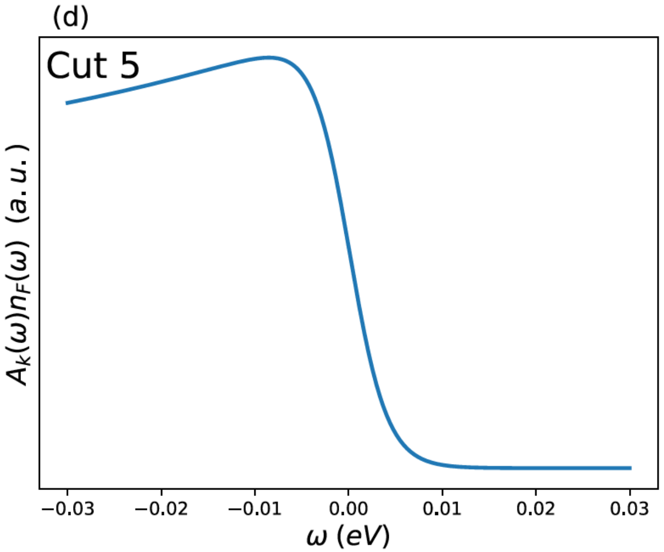


Near zero frequency

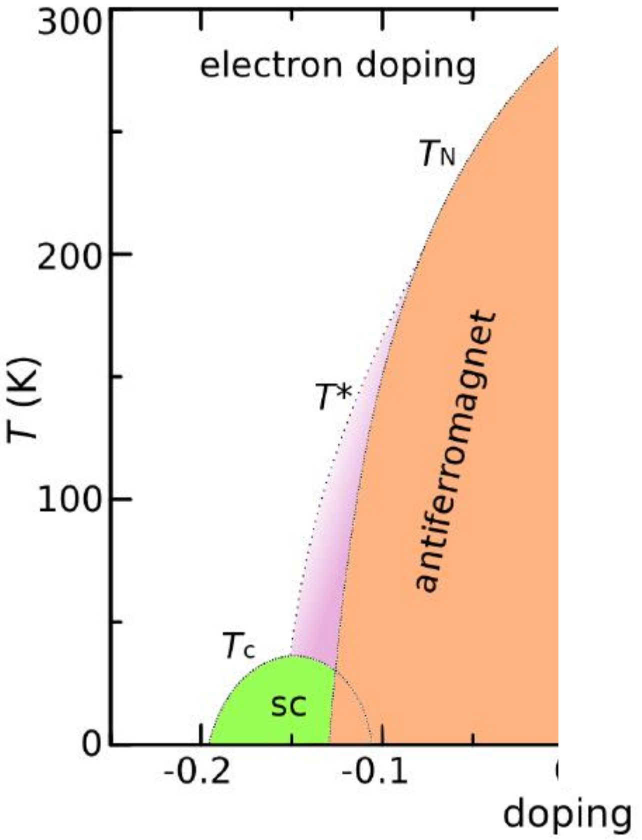
Spectral function $A_k(\omega)$

Spectral intensity $A_k(\omega)\ n_F(\omega)$





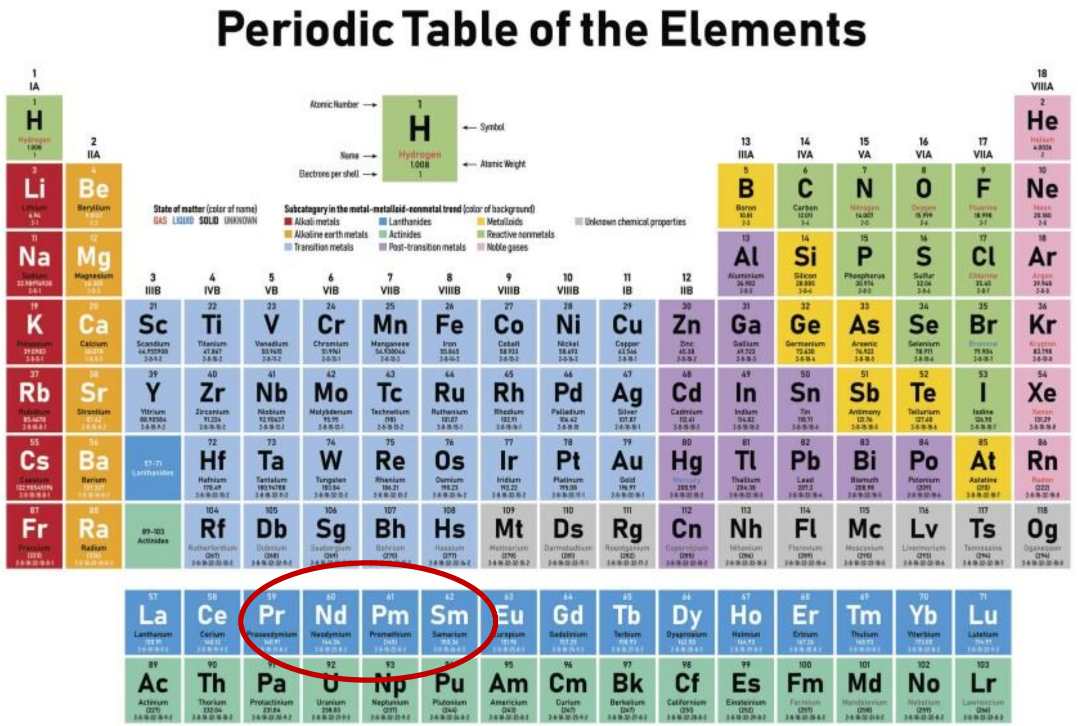
Electron-doped cuprates



$Nd_{2-x}Ce_xCuO_4$

Discovered by
Tokura, Takagi and Uchida in 1989

$Ln_{2-x}Ce_xCuO_4$ Ln = Pr, Nd, Sm



I will discuss two issues

- Interpretation of recent ARPES experiments on el-doped (2023-2025)

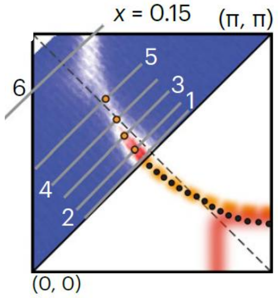
Z-X Shen's group (Stanford)

I will argue that they are consistent with the SDW precursor scenario

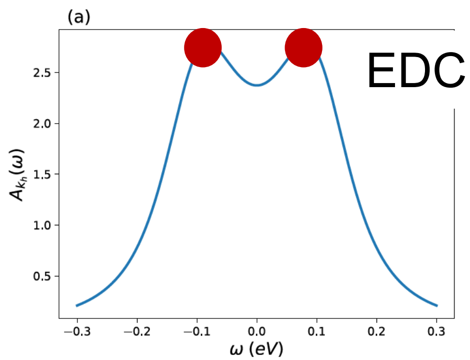
- Theory: is it guaranteed that a Fermi system near the onset of a conventional order (SDW/CDW) displays a pseudogap behavior?

Vertex corrections must be kept to obtain pseudogap behavior

But this may not be enough

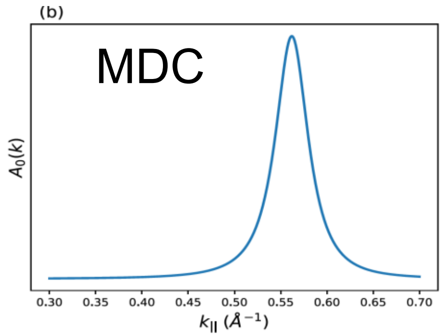


Spectral function

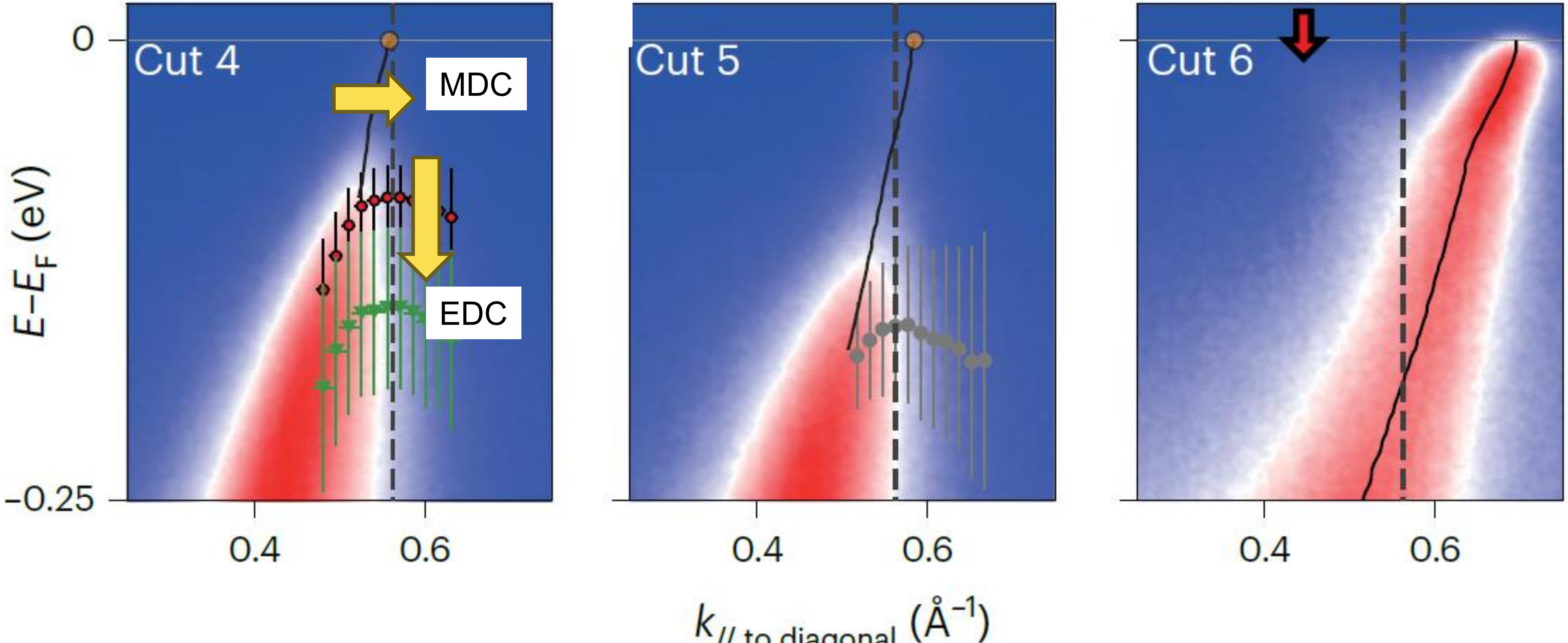


A peak at a finite ω.
A clear signature
of pseudogap

Spectral function

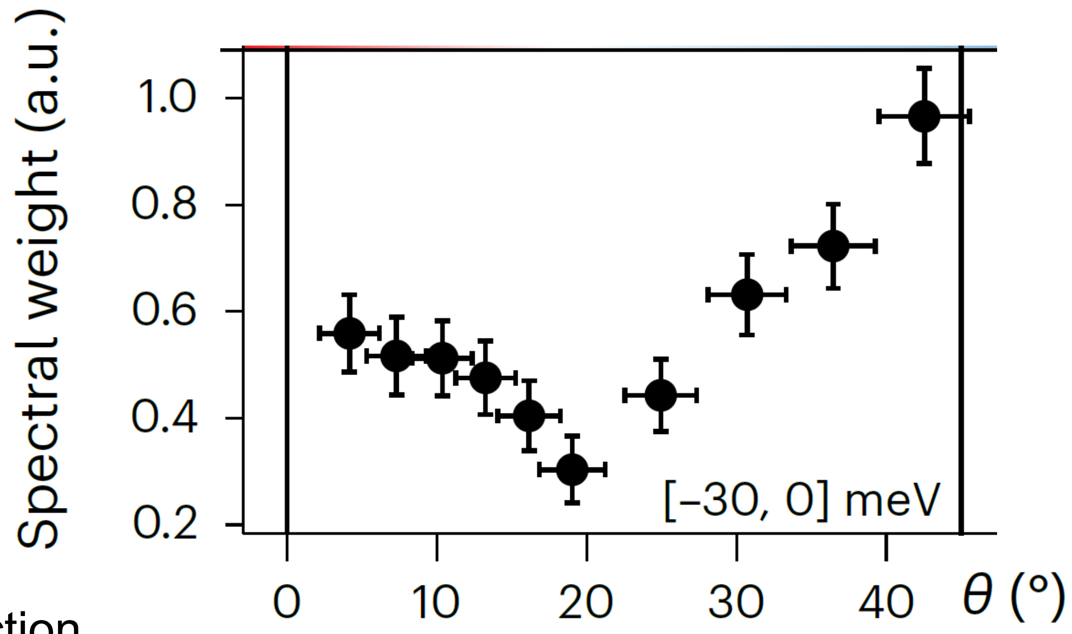


A single peak
crossing
Fermi surface

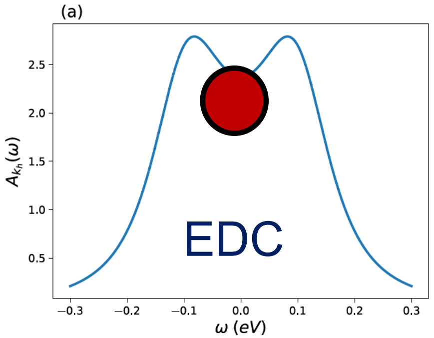


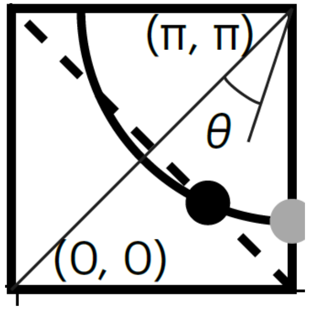
And there is more:

The largest reduction of the EDC spectral weight at ω =0 is at a hot spot

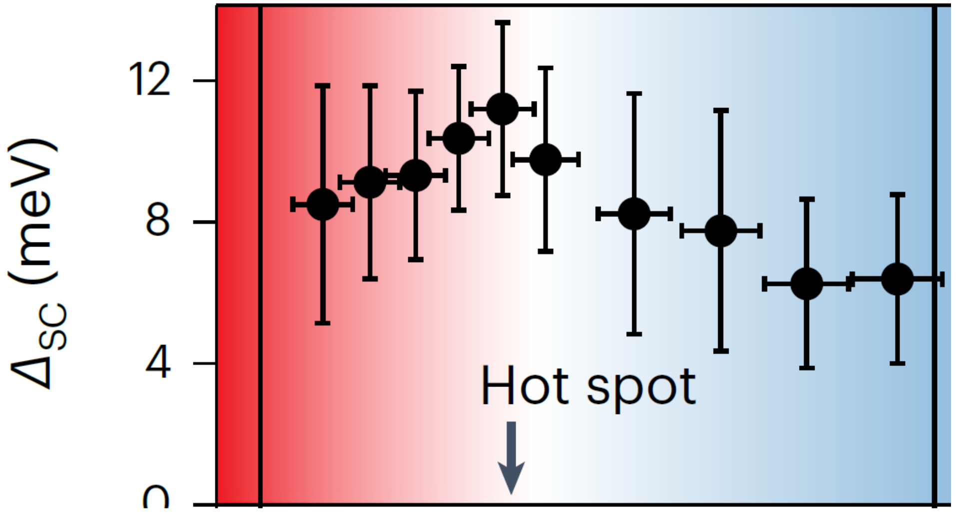


Spectral function

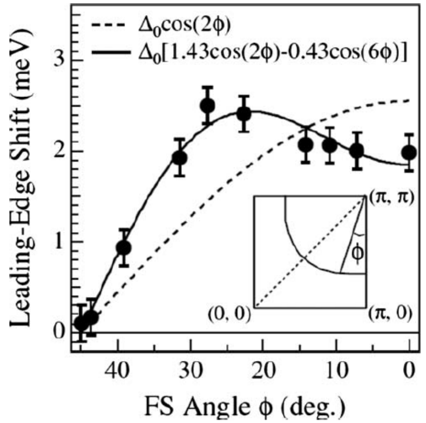




Superconducting gap is the largest at a hot spot

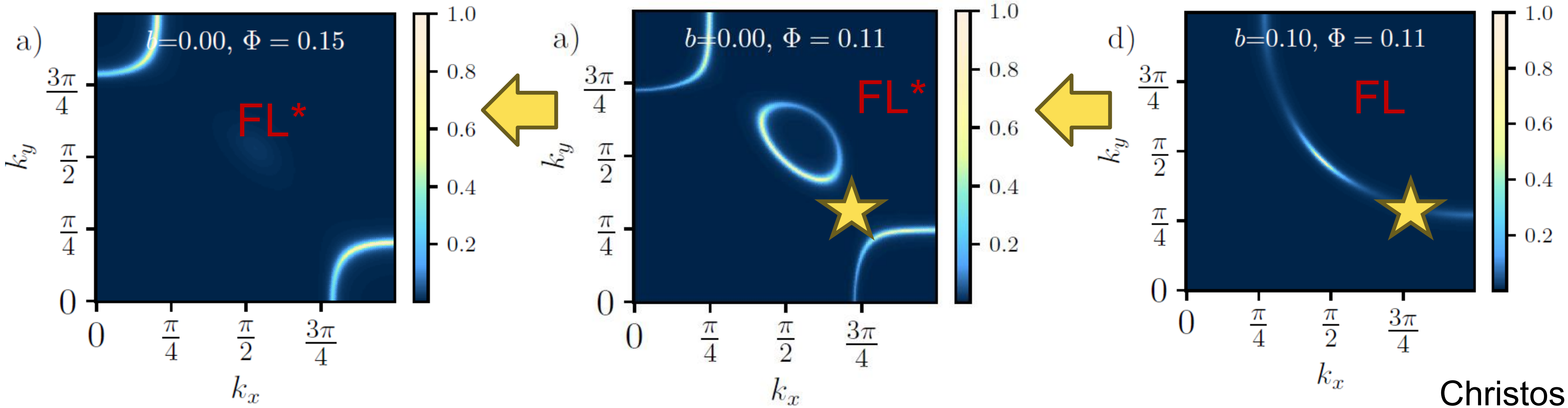


Matsui, 2005 (Yamada's group)



Thermal precursor to AFM vs FL* /spin liquid scenario

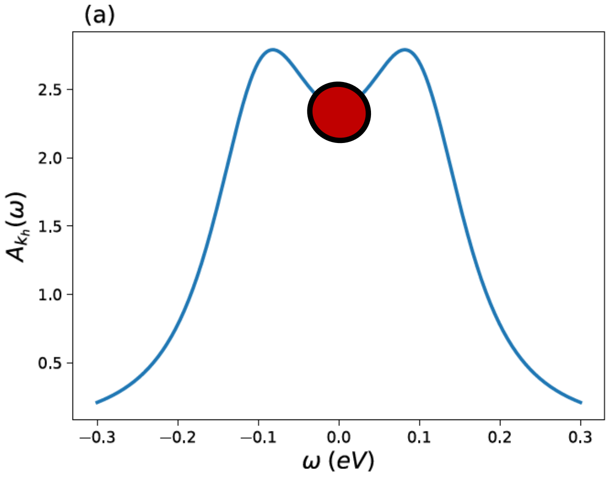
FI*/spin liquid: FS reconstruction (expect PG in EDC and MDC)



Christos & Sachdev

In the precursor scenario: no FS reconstruction (no PG in MDC)

Even in EDC



Peaks at a finite frequency ω, but the spectral weight remains finite at ω=0 (the original Fermi surface survives)