

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

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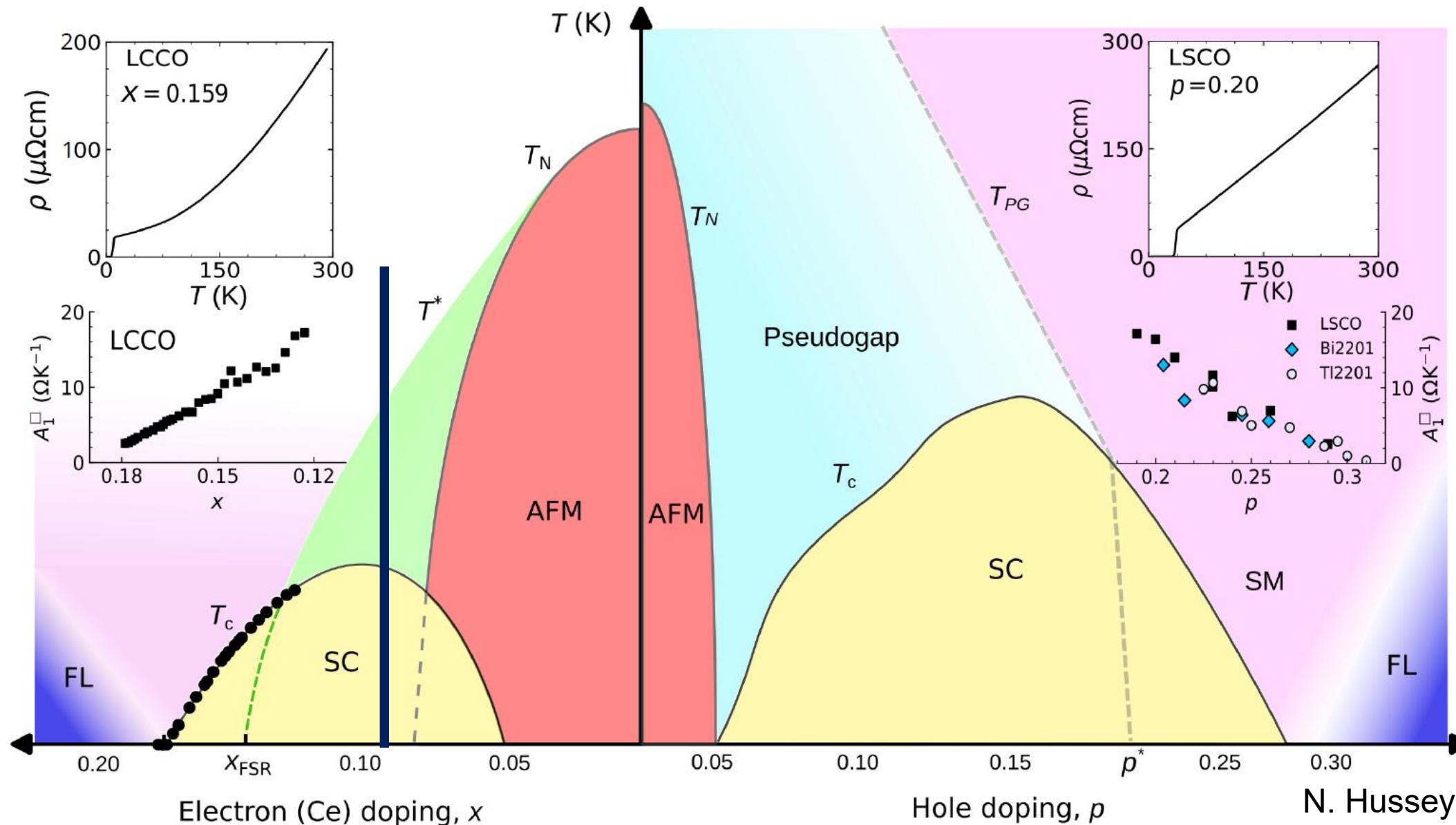
Manos Kokkinis
UMN

Fermi legacy in low-energy physics

Accademia Nazionale Dei Lincei Feb. 6, 2026

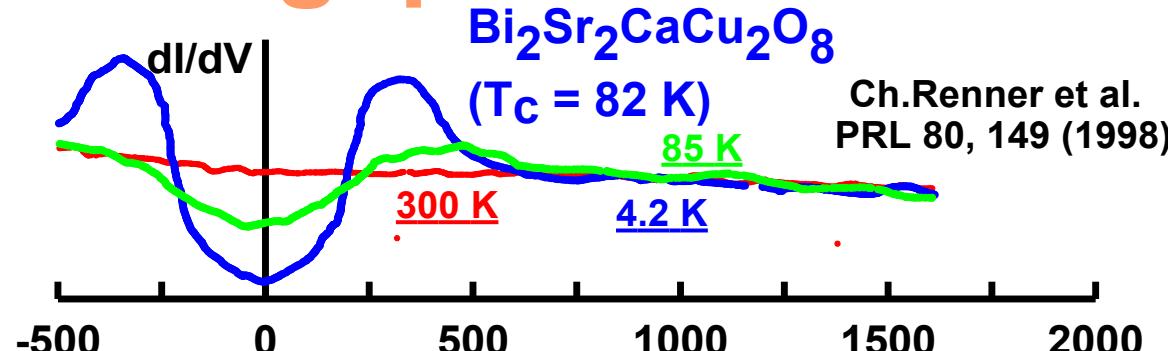


This talk will be about the origin of pseudogap in the el-doped cuprates and the interplay between pseudogap and superconductivity

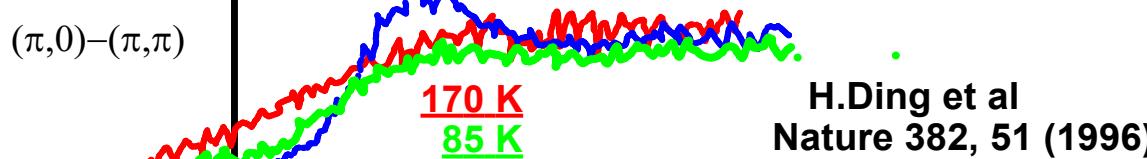


STM

Pseudogap

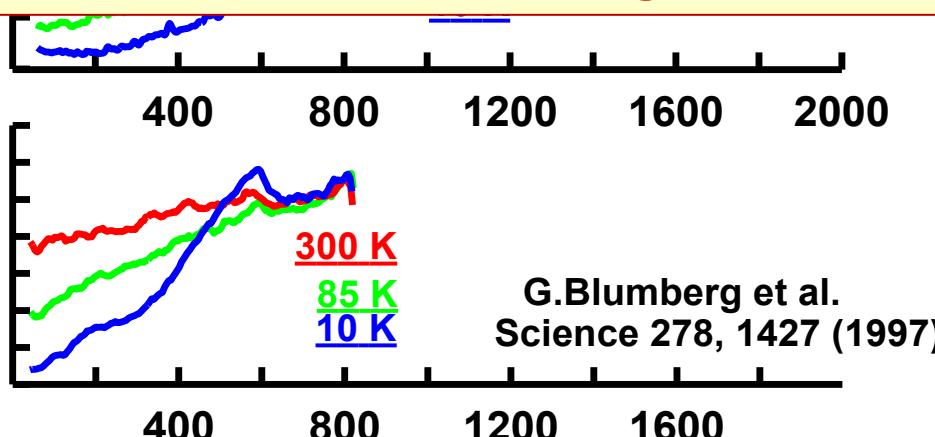


ARPES



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

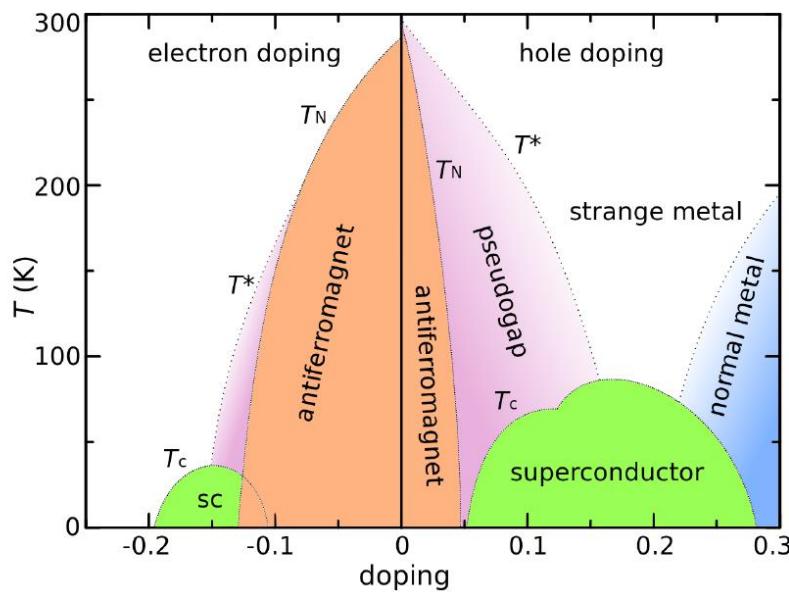


Initial idea (mid/late 90th): pseudogap is a precursor to superconductivity

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 T_c

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. Fabrizio...

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,

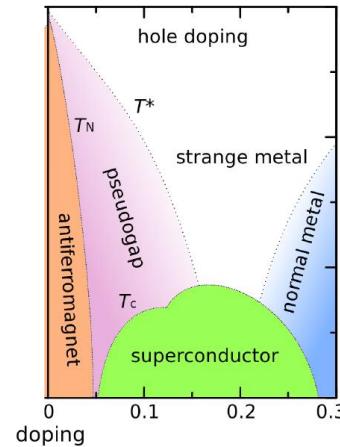
W. Metzner, R. Fernandes, E. Berg..

S. Caprara, J. Lorenzana,

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

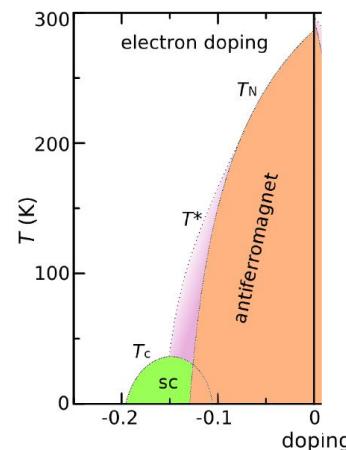
In C, no FS reconstruction, but the shape of the spectral function changes

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



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

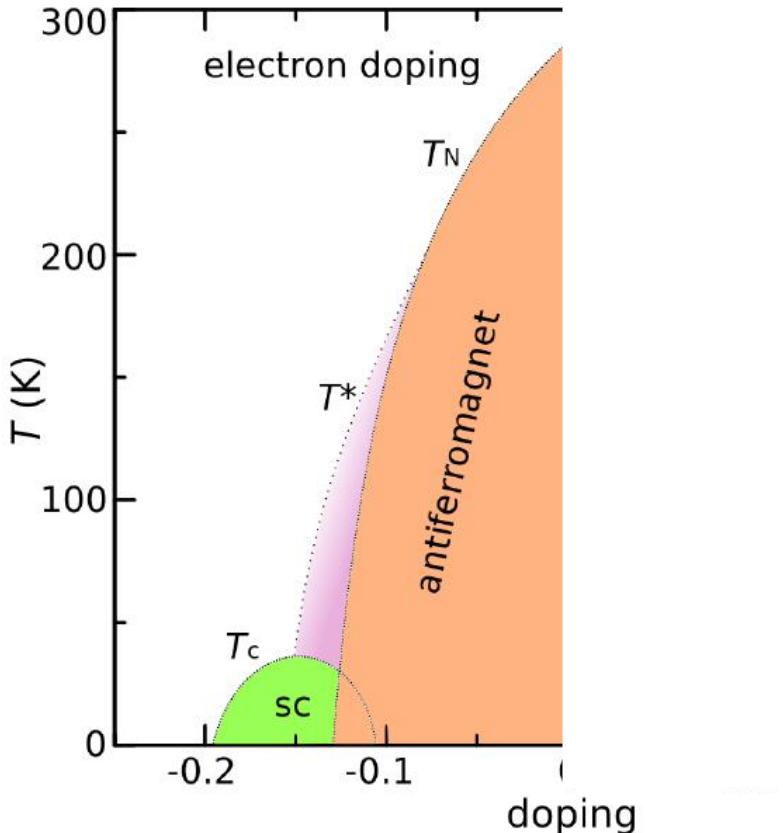
Electron-doped cuprates – less complex systems



- 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



Discovered by
Tokura, Takagi and Uchida in 1989



Periodic Table of the Elements

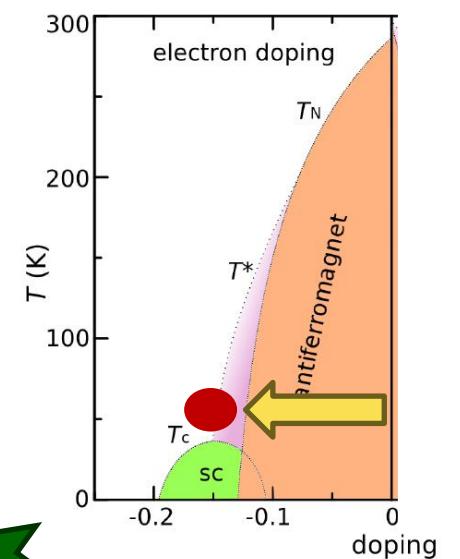
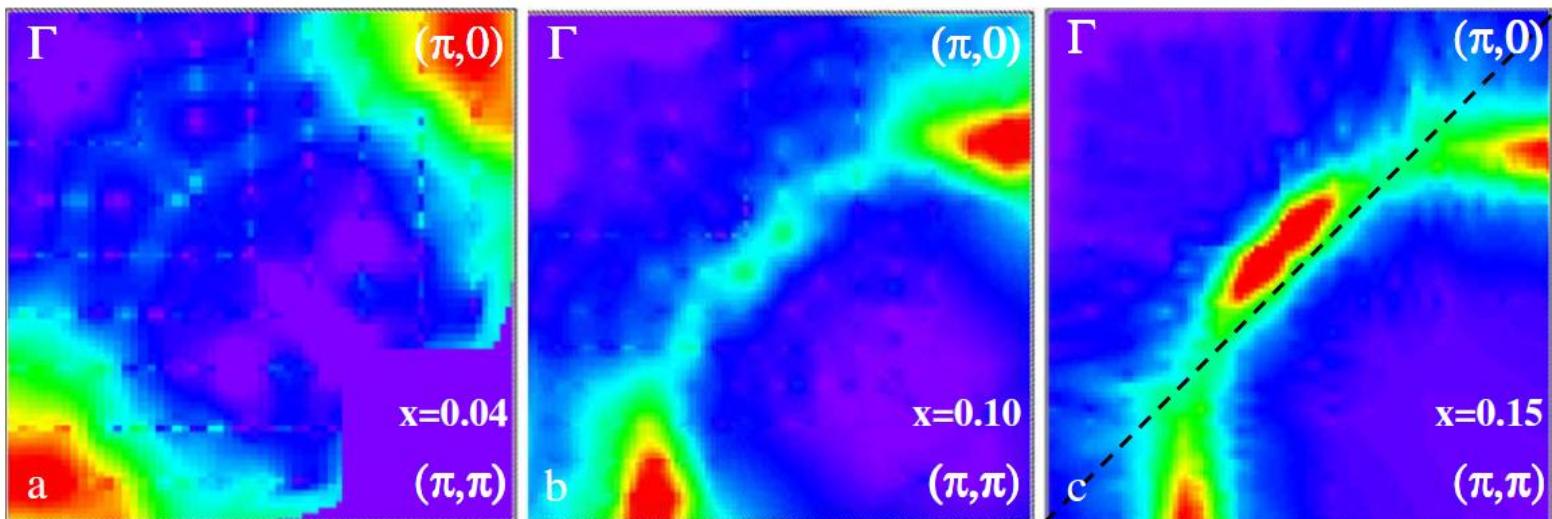
Periodic Table of the Elements

The table shows the elements arranged in groups and periods. The actinide series is highlighted in red, with Neptunium (Np) and Plutonium (Pu) circled in red. The table includes atomic number, symbol, name, atomic weight, and electron shell information for each element.

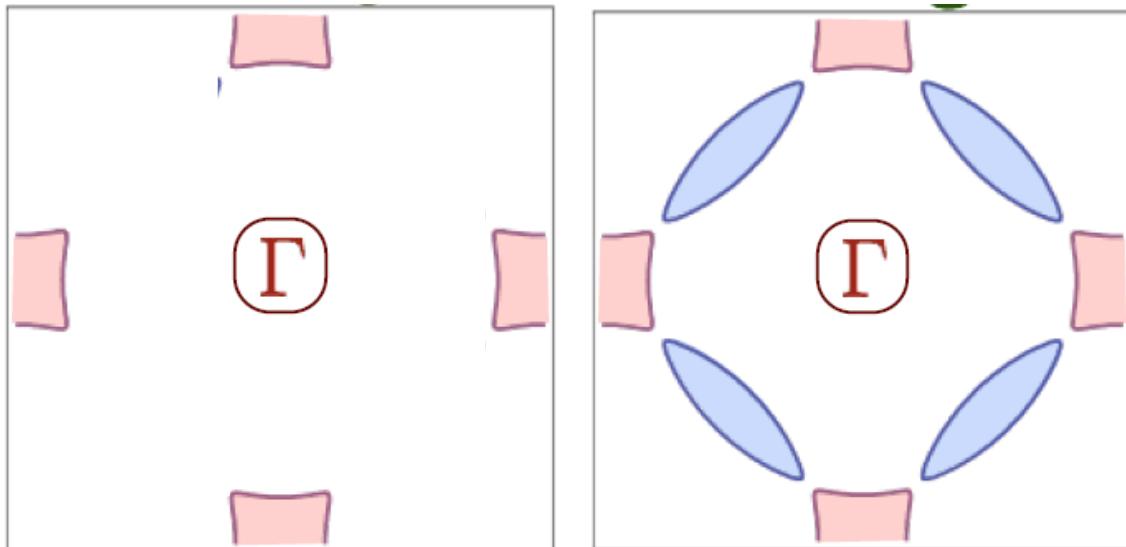
$\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$

Early experiments (ARPES)

Armitage et al, RMP 82 (2010)

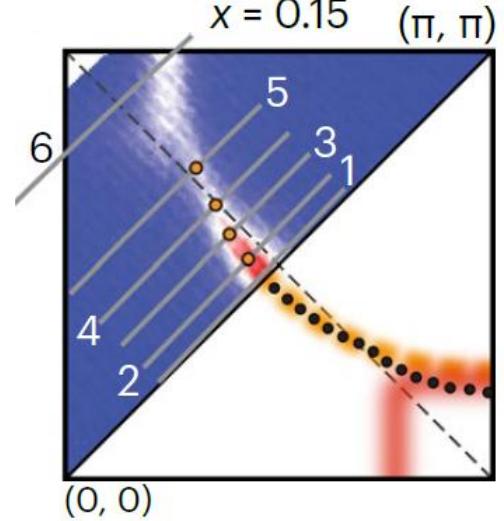


Ordered phase,
Theory



Sachdev, Morr, A.C....

Pseudogap state

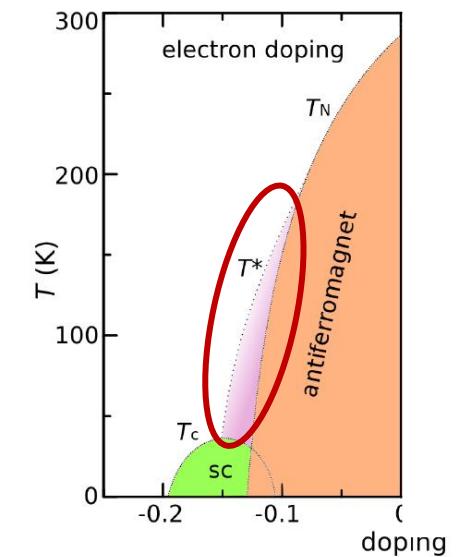


Recent (2023-25) ARPES experiments
by Z-X Shen group on

Two types of experiments

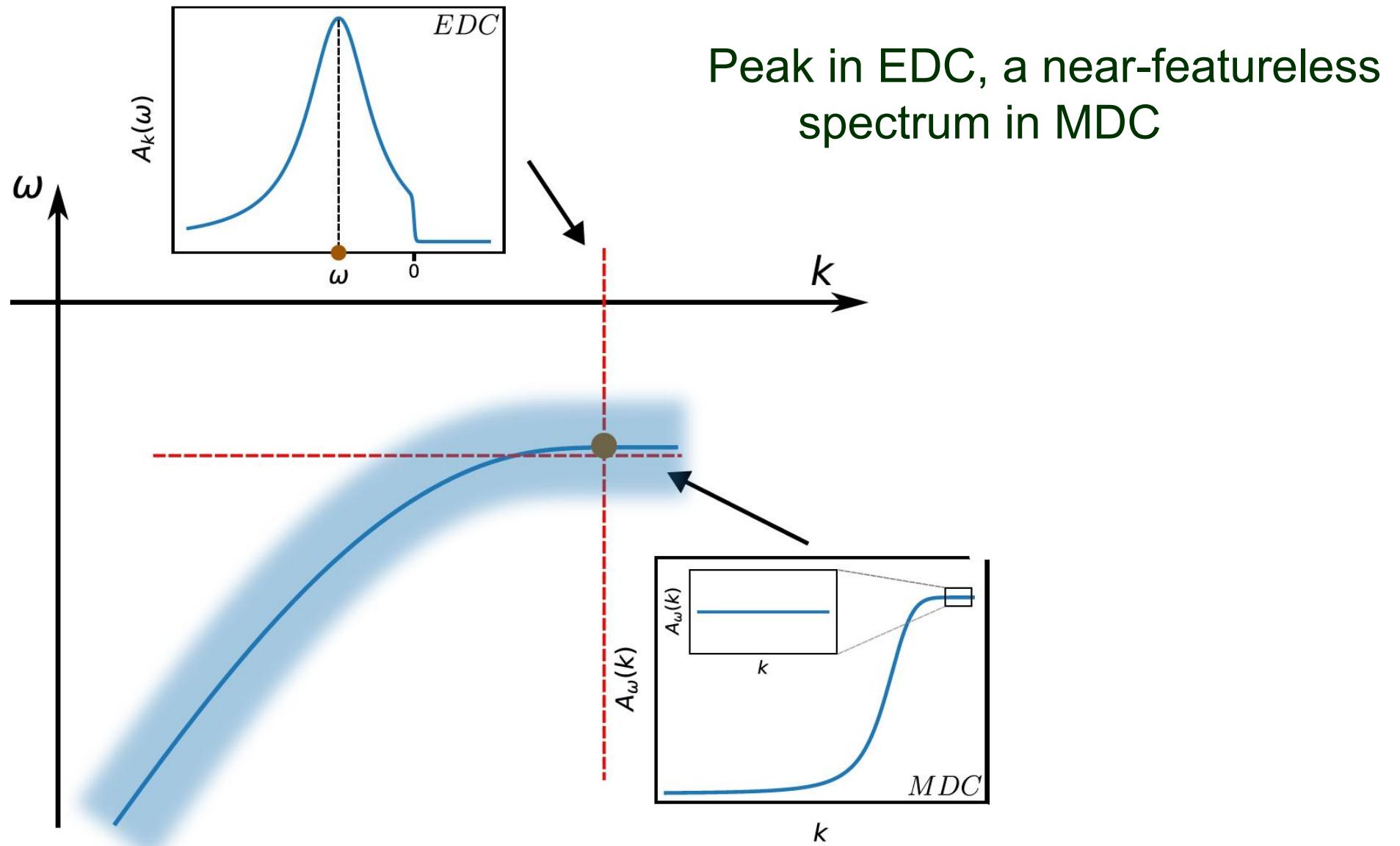
Energy distribution curve (EDC)
(ARPES intensity at a fixed momentum as a function of frequency)

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

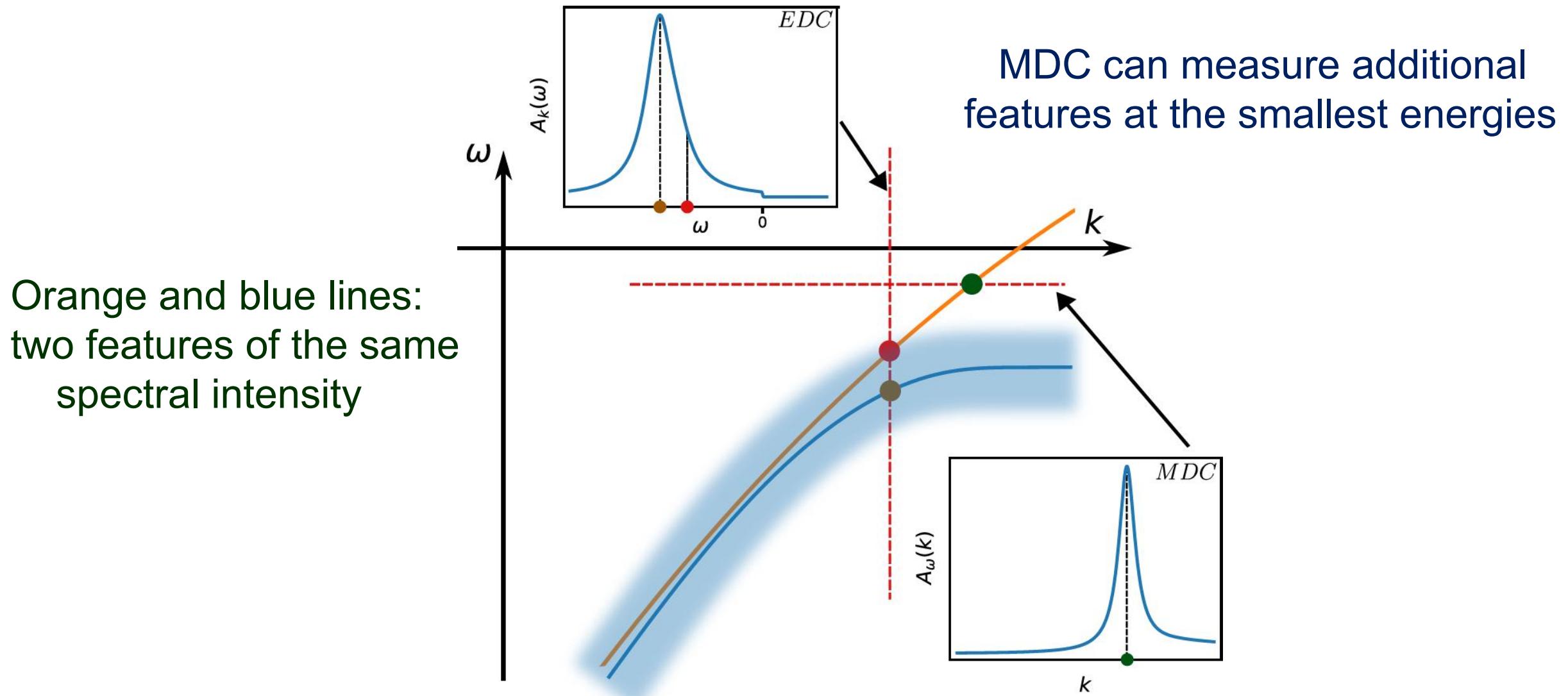


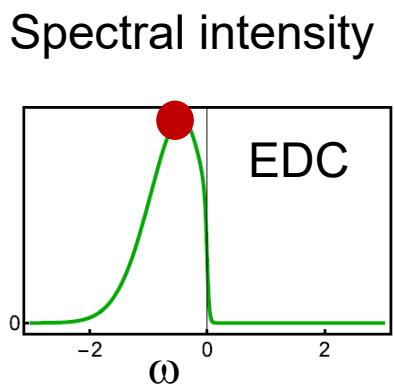
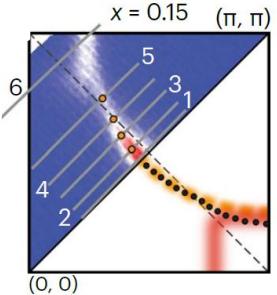
EDC and MDC are supposed to measure the same fermionic spectral function.
Yet, measurements found qualitative difference between the two probes

A general expectation for a system displaying a pseudogap

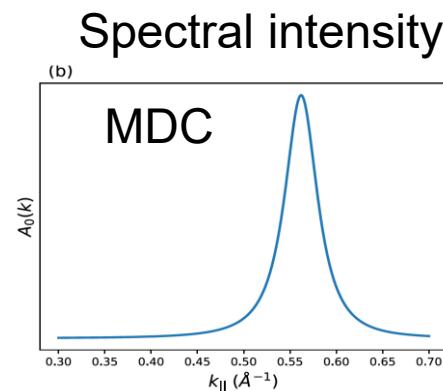


Should there be a signature that the system is still in a disordered state?

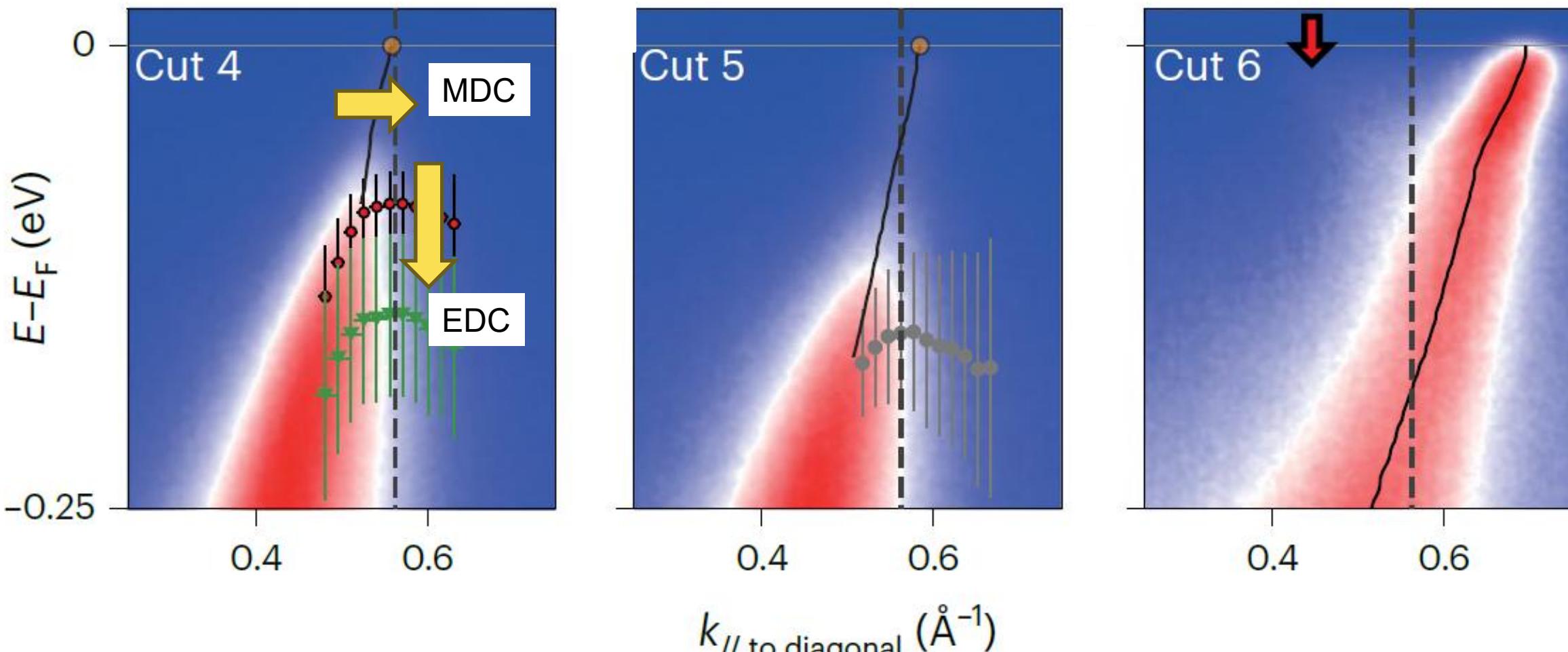




A peak at a finite ω .
A clear signature
of pseudogap

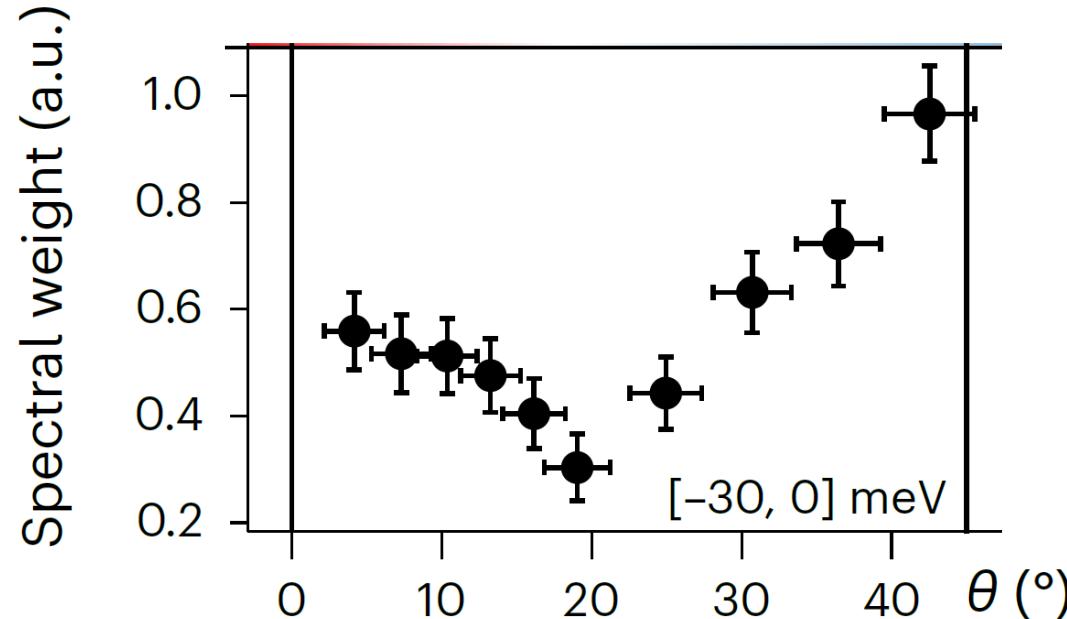


A single peak
crossing
Fermi surface

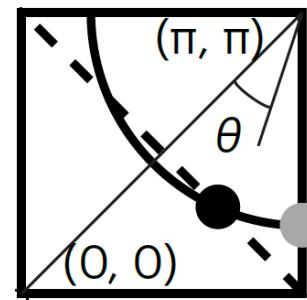
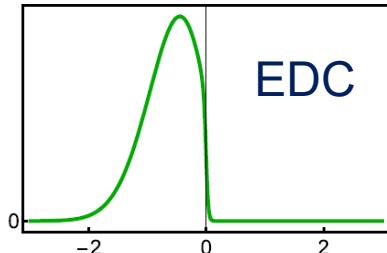


And there is more:

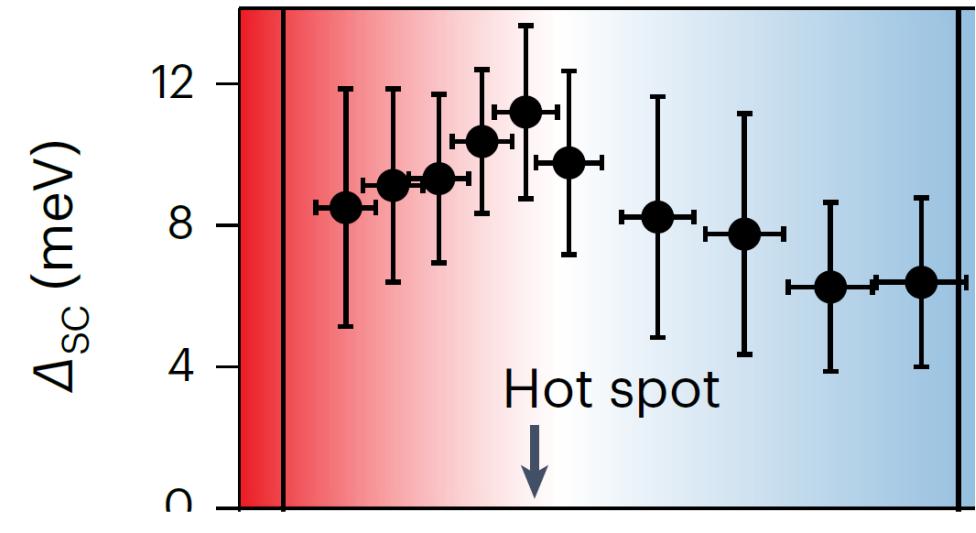
The largest reduction of the EDC spectral weight at small ω is at a hot spot



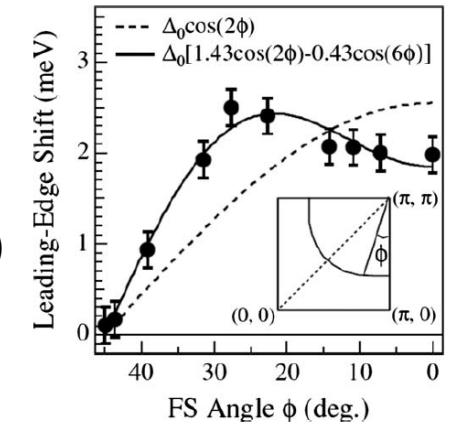
Spectral intensity



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)

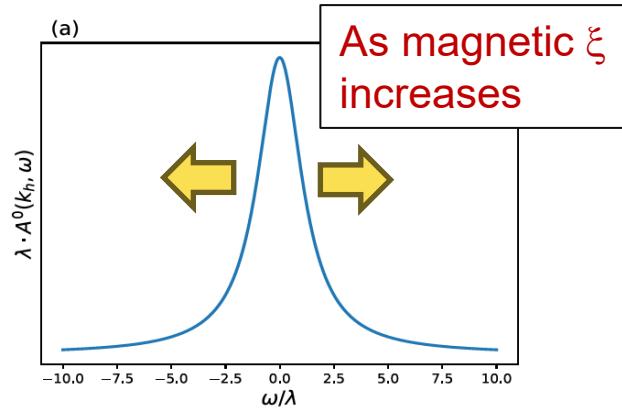
That AFM fluctuations give rise to pseudogap behavior is not obvious

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 $\omega=0$ at a magnetic QCP

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



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

$$\begin{aligned}\Sigma_{th}(k, \omega) &= \frac{3\bar{g}T}{(v_F\xi^{-1})^2} \int \frac{d^2q}{(2\pi)^2} \frac{1}{\omega - \epsilon_{k+Q}^* - q_\perp} \frac{1}{q_\perp^2 + q_\parallel^2 + 1} \\ &= \textcircled{1} \left[\frac{\log \left(\omega - \epsilon_{k+Q}^* + \sqrt{1 + (\omega - \epsilon_{k+Q}^*)^2} \right)}{\sqrt{1 + (\omega - \epsilon_{k+Q}^*)^2}} - i \frac{\pi}{2\sqrt{1 + (\omega - \epsilon_{k+Q}^*)^2}} \right] \\ \epsilon_k^* &= \epsilon_k - \mu,\end{aligned}$$

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

Vilk and Tremblay, 1997

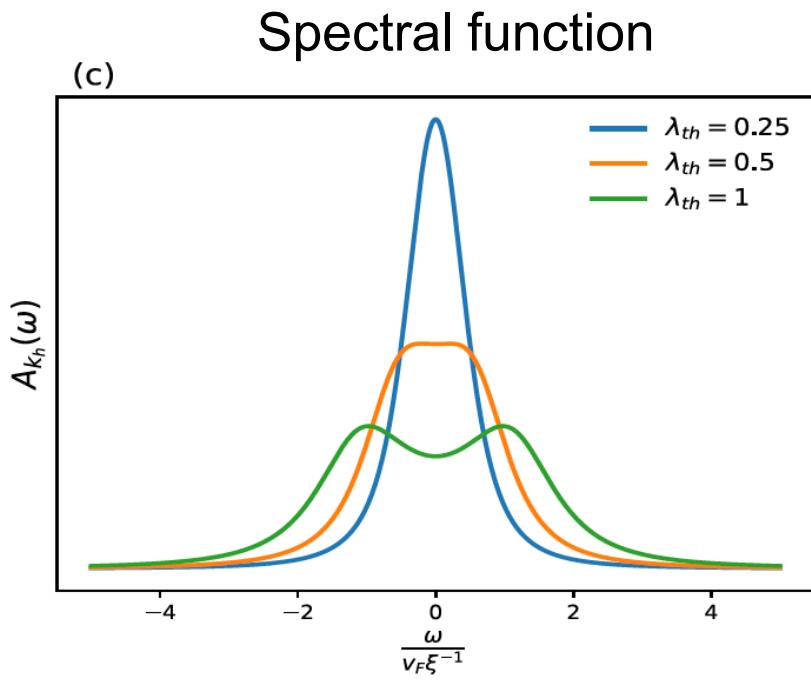
This simple, one-loop formula leads to two results:

- Pseudogap behavior in EDC
- No pseudogap behavior in MDC

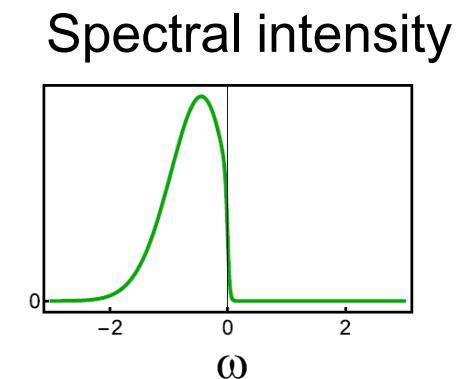
EDC at a hot spot

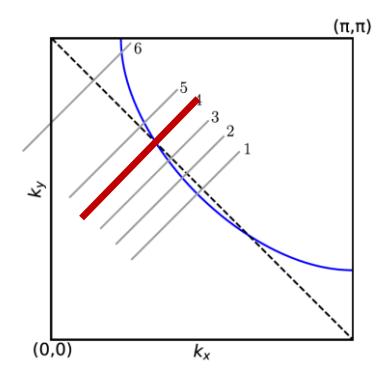
$$A_{k_h}(\omega) = \frac{\pi \lambda_{th}}{2} \frac{1}{\lambda_{th}^2 \pi^2/4 + \omega^2 ((1 - \lambda_{th})^2 - \pi^2 \lambda_{th}^2/8)}$$

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



Pseudogap behavior



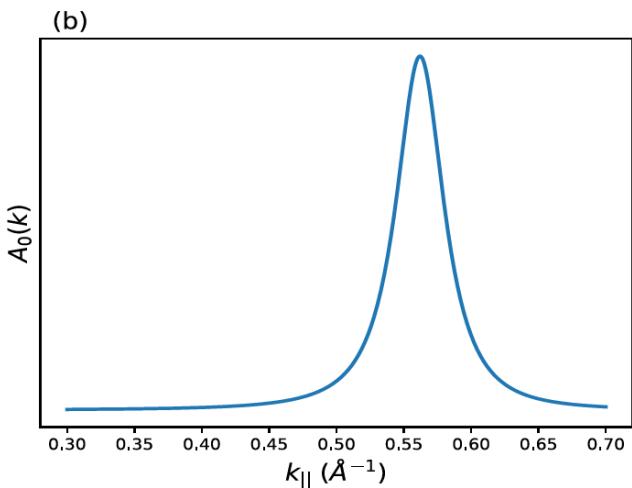


MDC are zero frequency
(a cut through a hot spot)

$$\epsilon_{k+Q}^* = -\alpha \epsilon_k^* = -\alpha v_F(k - k_h)$$

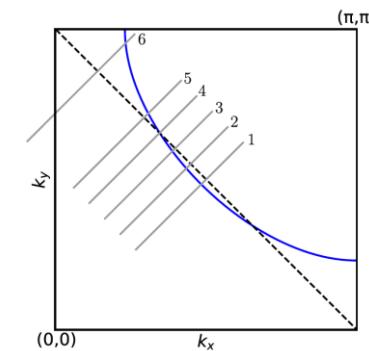
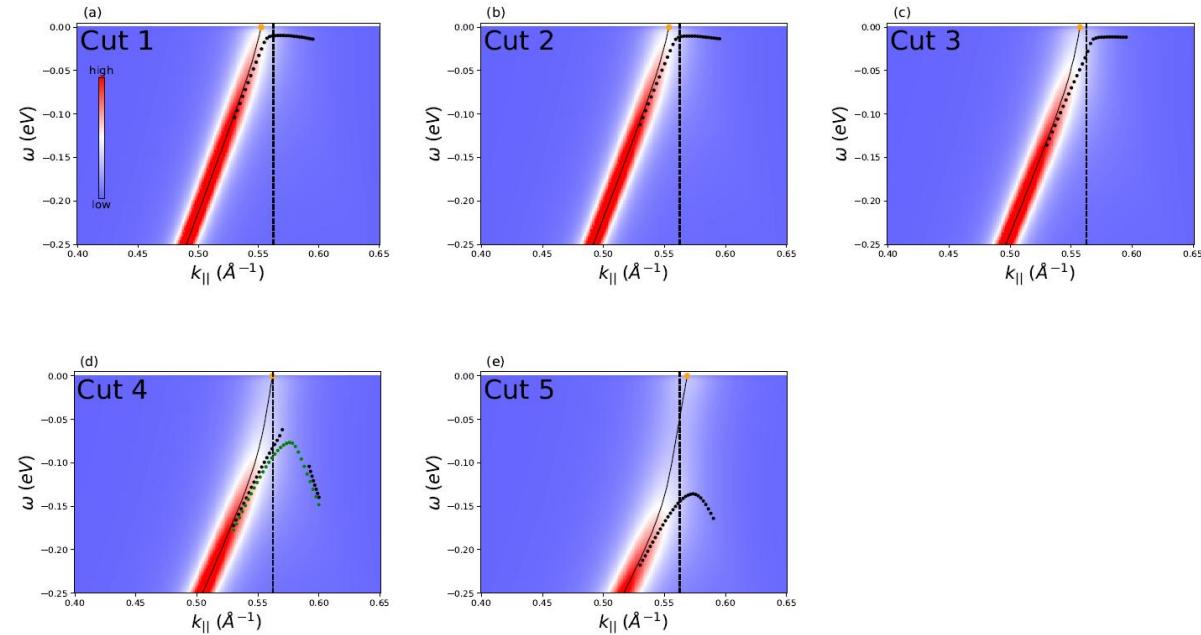
$$A_0(k) = \frac{\pi \lambda_{th}}{2} \frac{1}{\lambda_{th}^2 \pi^2 / 4 + v_F^2 (k - k_h)^2 ((1 + \alpha \lambda_{th})^2 - \pi^2 \alpha^2 \lambda_{th}^2 / 8)} \quad \alpha > 0$$

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

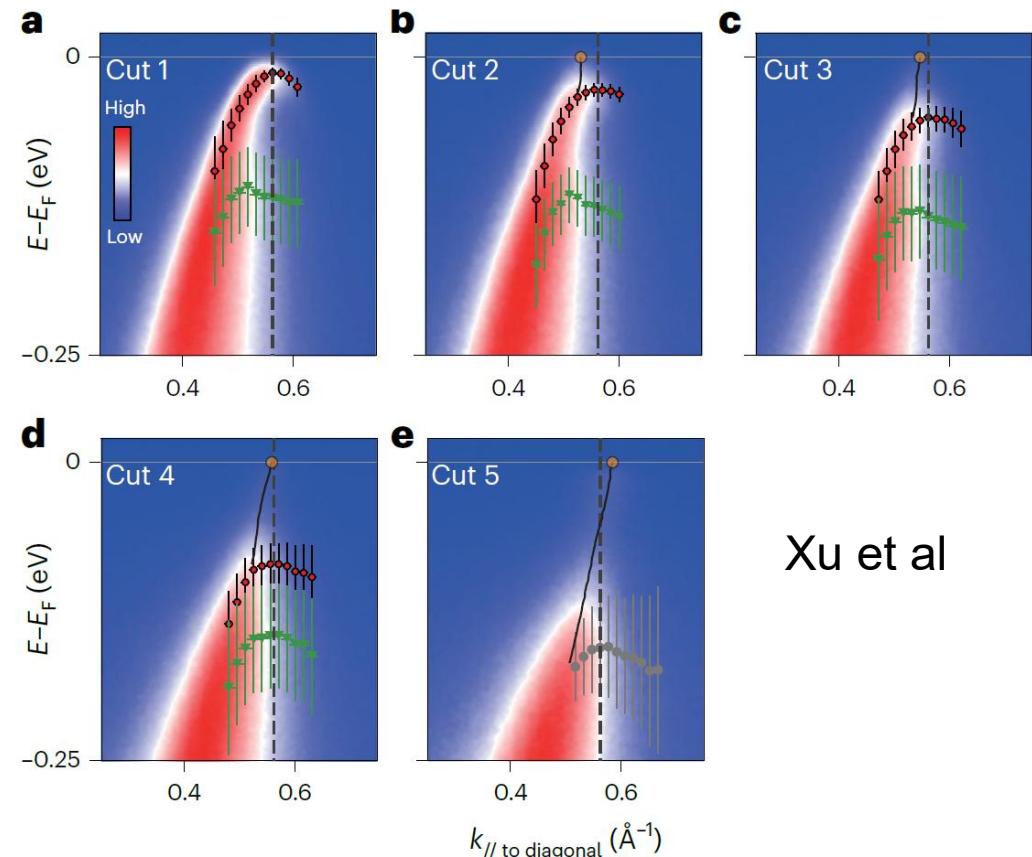


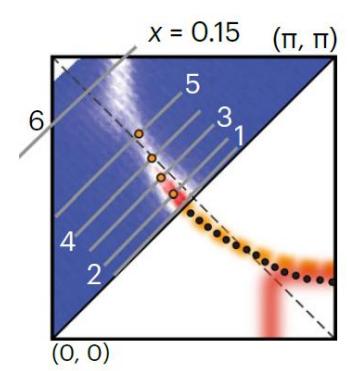
No pseudogap behavior

Theory



Experiment

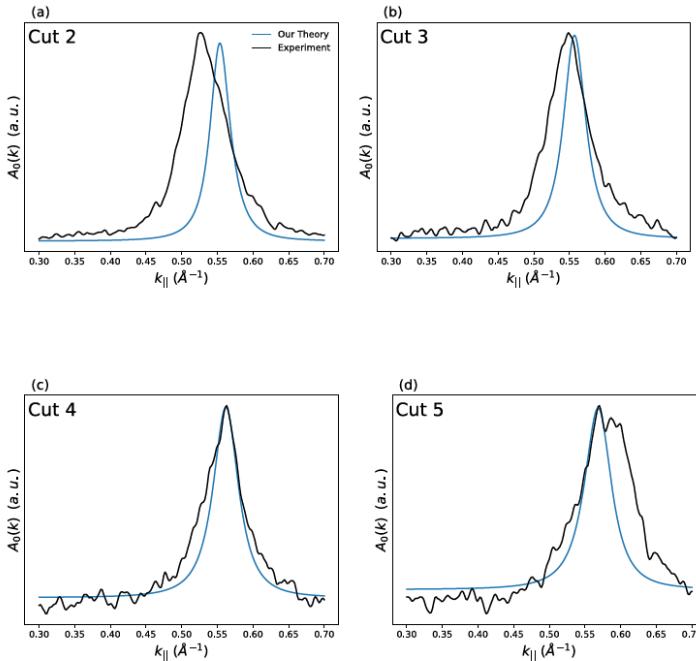
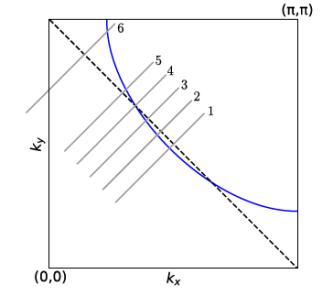




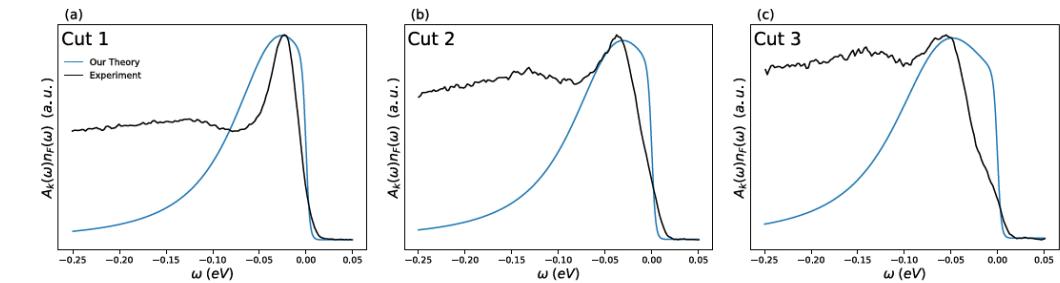
MDC at $\omega=0$

More detailed comparison with the data

EDC at k_F

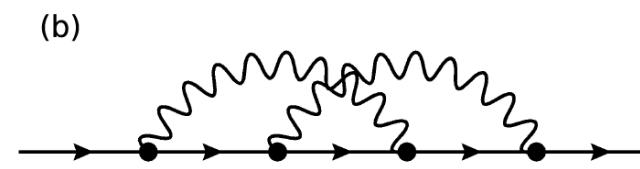
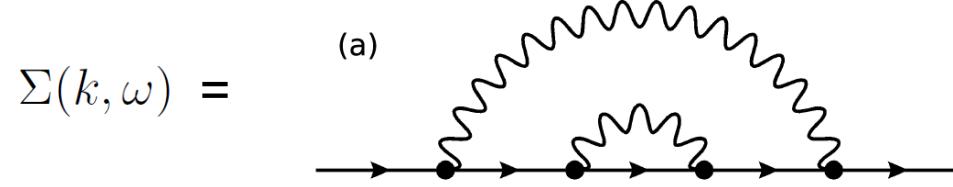


Peak at $k = k_F$

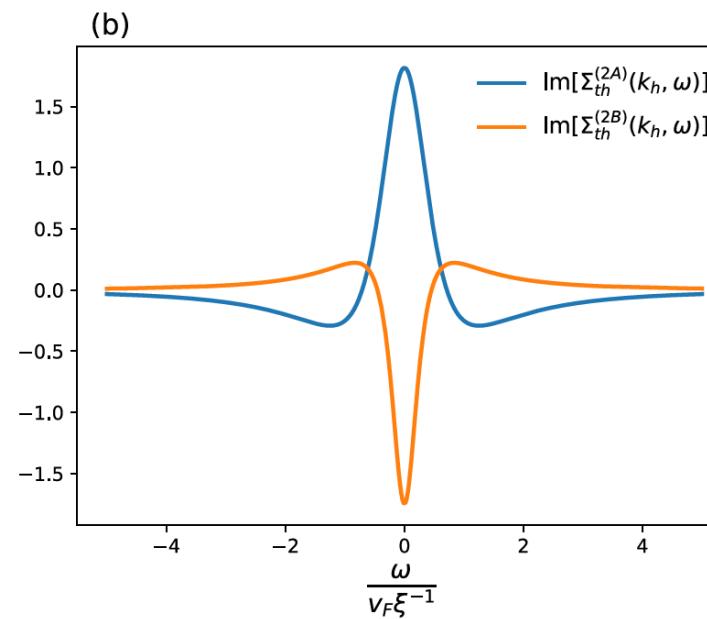
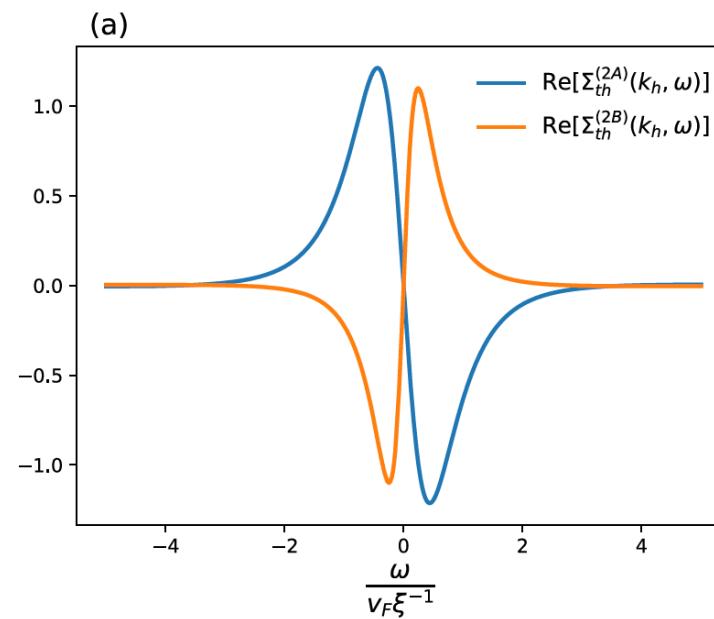


Rapidly grown psedogap in EDC around a hot spot

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

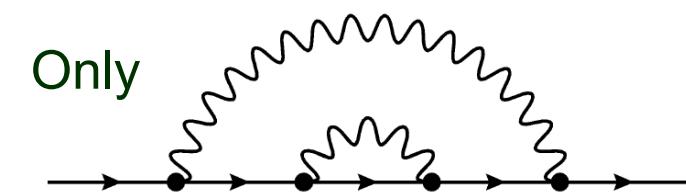
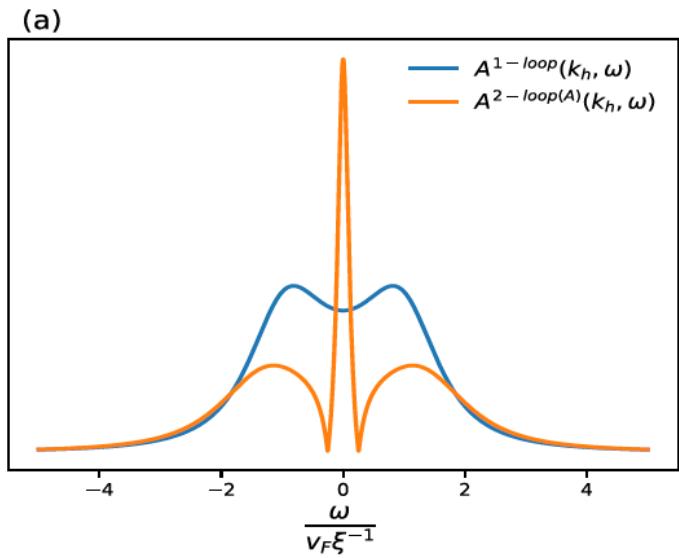


The contributions from the two two-loop terms almost cancel out



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

And what if we neglected vertex corrections?



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

$$\chi(q) = \delta(\mathbf{q} - \mathbf{Q})$$

$$\mathbf{Q} = (\pi, \pi)$$

Finite T, 2D
No long-range order

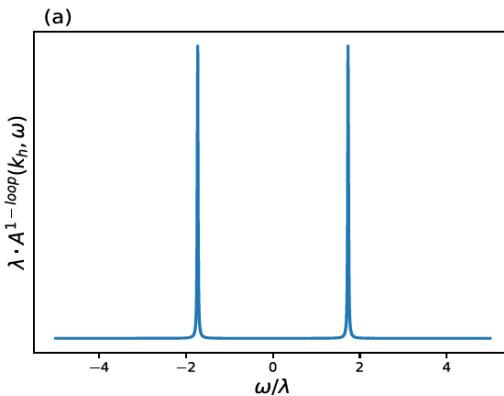
One loop $\Sigma(k, \omega)$ at the hot spot

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

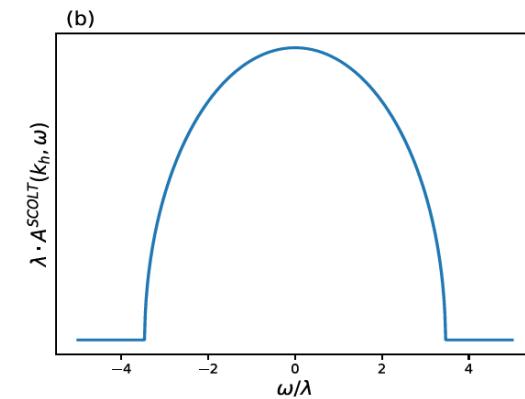
Self-consistent one-loop (no vertex corrections)

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

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

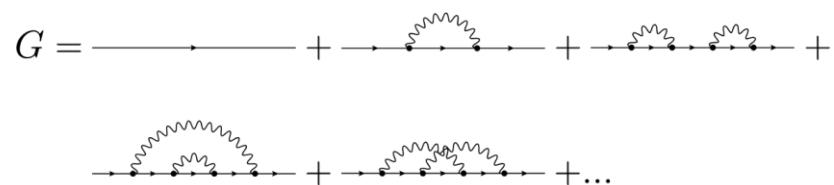


Pseudogap
(even without "pseudo")



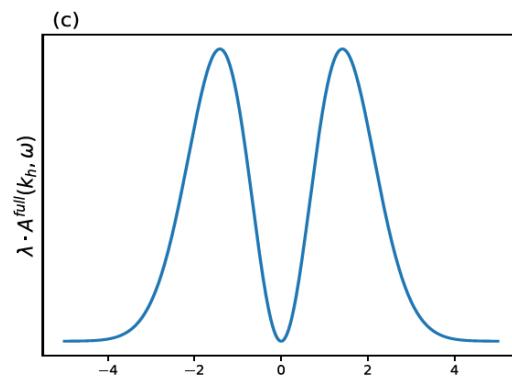
No pseudogap

Full consideration (self-energy + vertex corrections)



Eikonal series

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



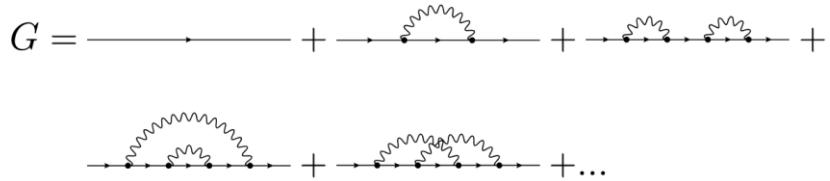
Pseudogap
survives

Spin vs charge fluctuations

The best case scenario: $\chi(q) = \delta(q - Q) \quad Q = (\pi, \pi)$

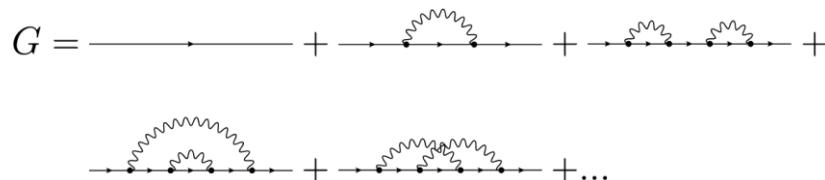
Spin case

Full consideration (self-energy + vertex corrections)

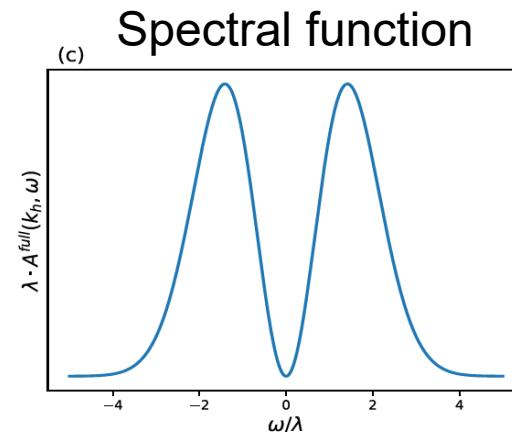


$$A^{full}(k_h, \omega) = \frac{1}{\pi} |\text{Im}G^{full}(k_h, \omega)| = \sqrt{\frac{\pi}{2}} \frac{\omega^2}{\lambda^3} e^{-\frac{\omega^2}{2\lambda^2}}$$

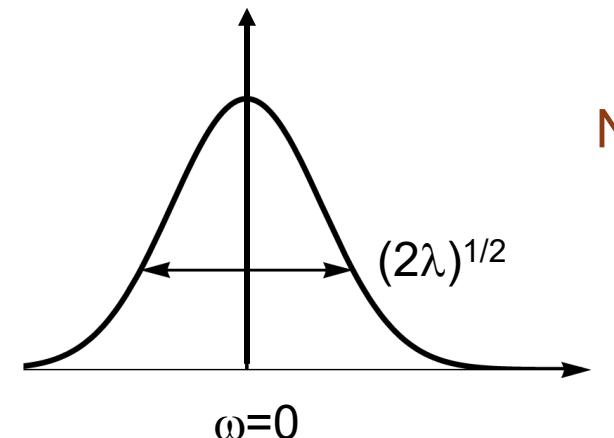
Charge case



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



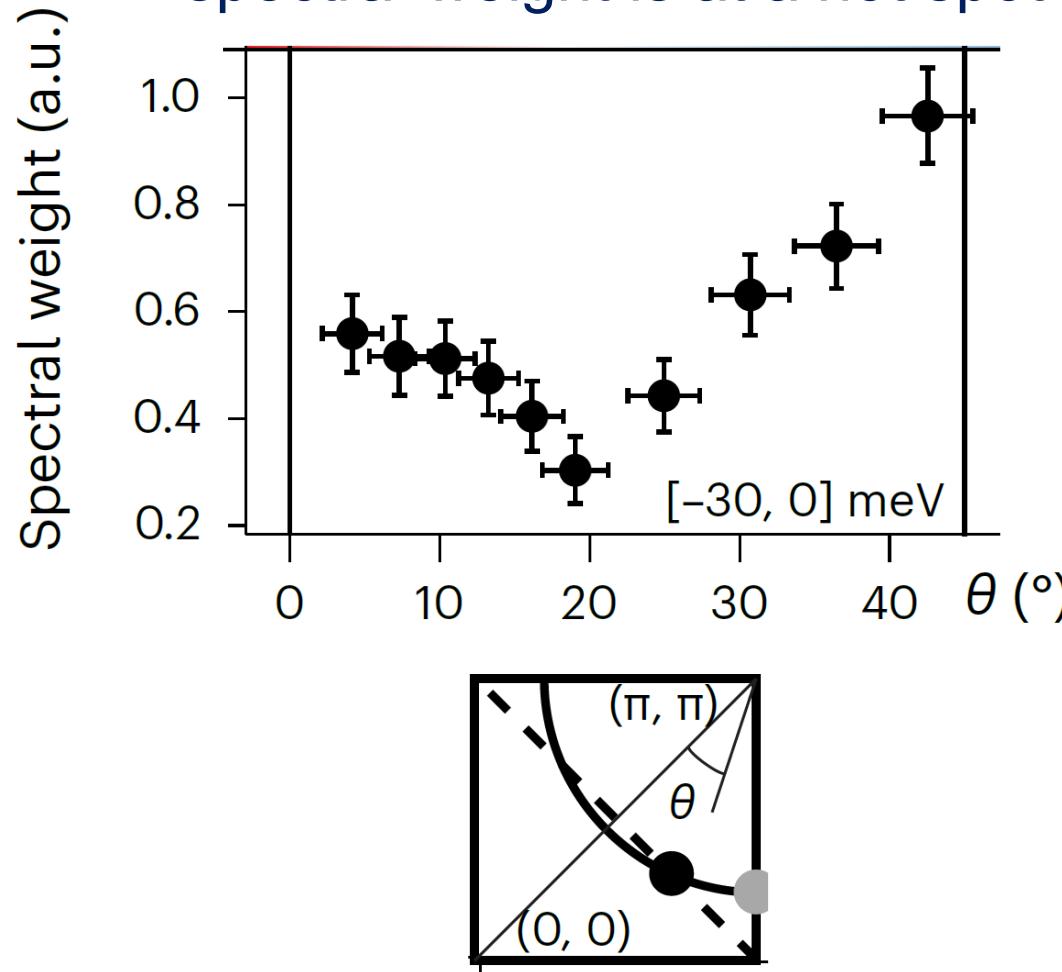
Pseudogap behavior



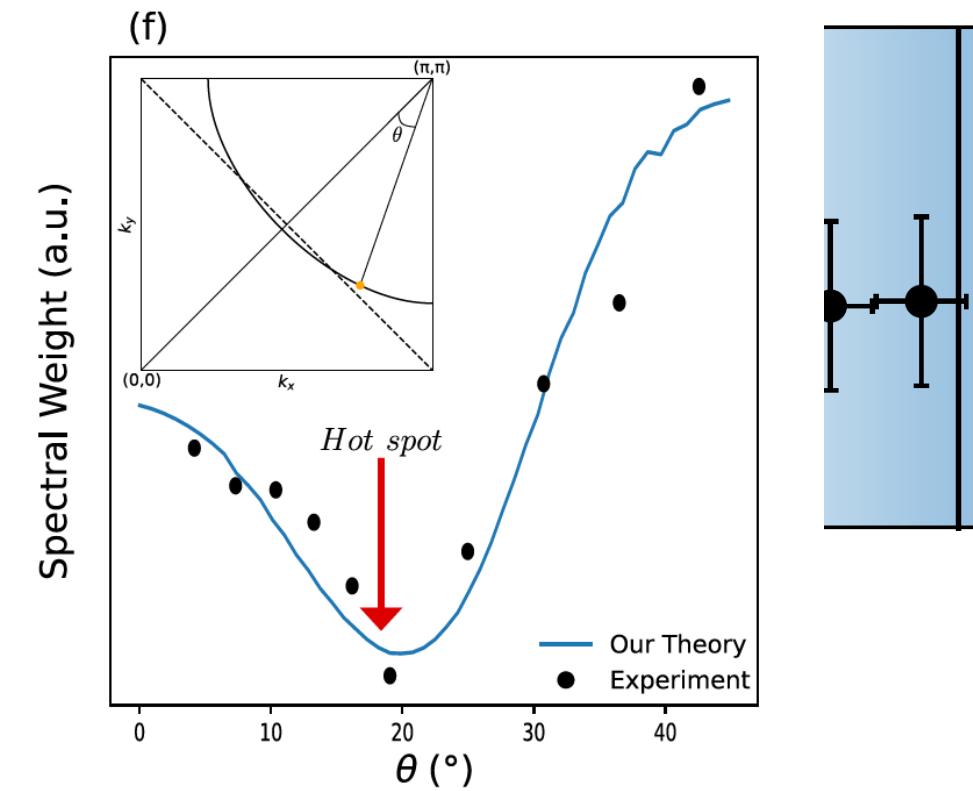
No pseudogap

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 a 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

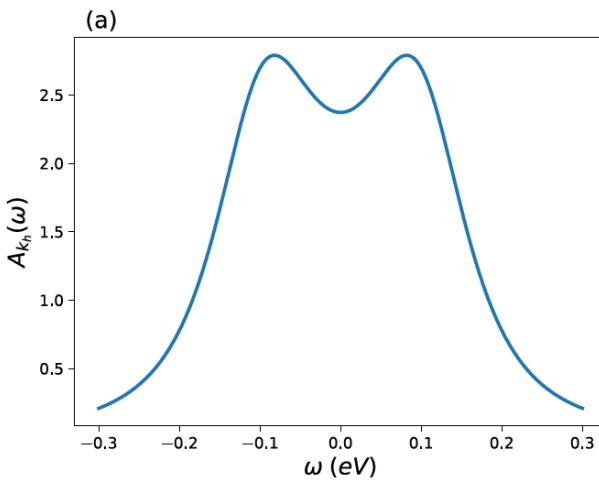
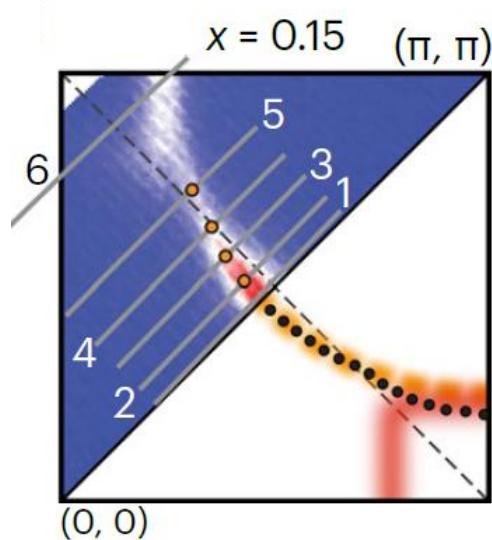
The “thermal precursor to antiferromagnetism” scenario works rather well for electron-doped cuprates.

Consistent with recent ARPES data

The story for hole-doped cuprates is much more complicated

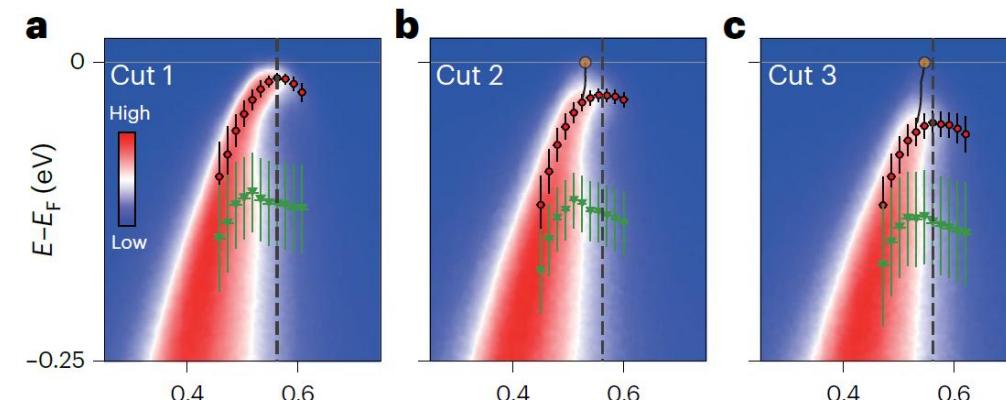
THANK YOU

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

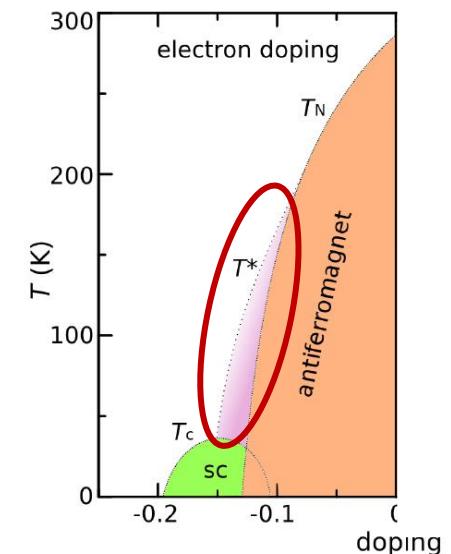


Difference between EDC and MDC

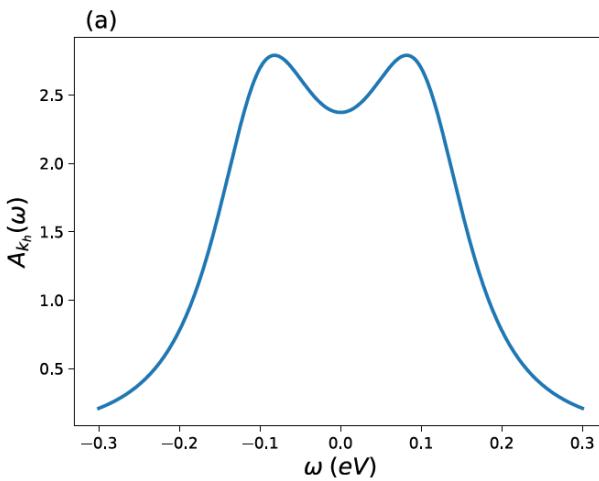
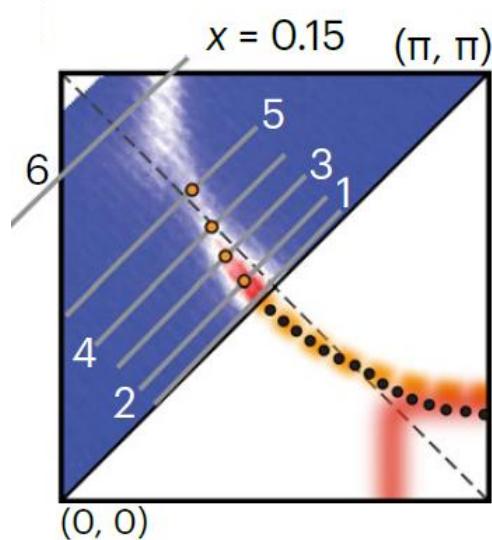
EDC: non-monotonic behavior of the spectral function
consistent with the pseudogap



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

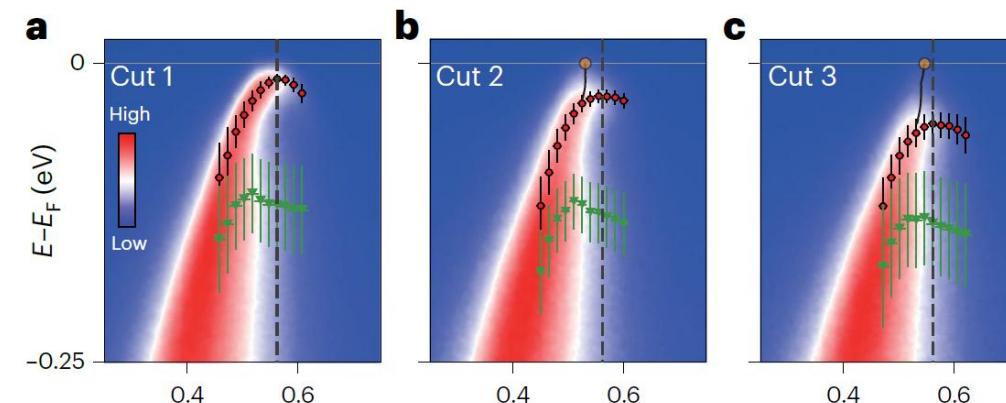


Recent (2023-25) ARPES experiments by Z-X Shen group on the pseudogap

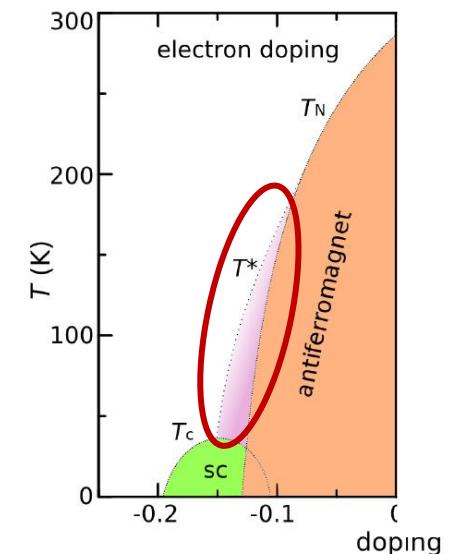


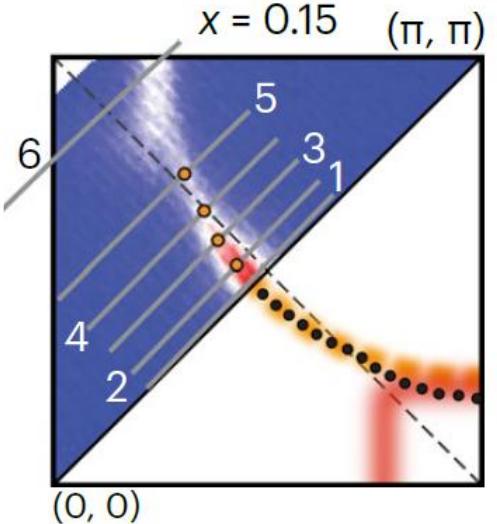
Difference between EDC and MDC

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



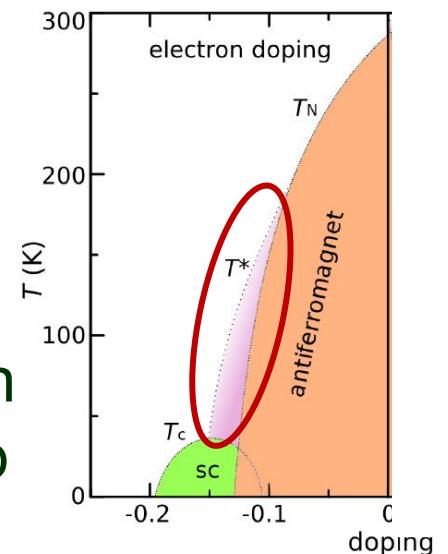
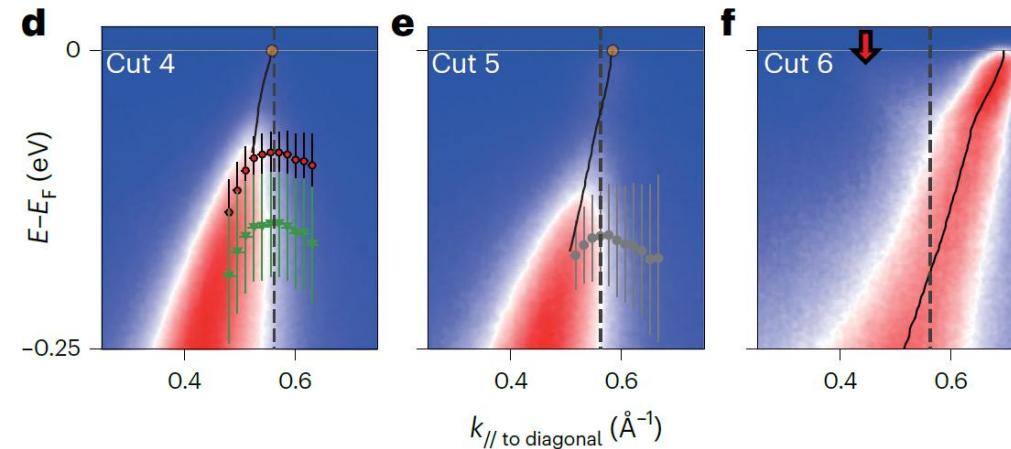
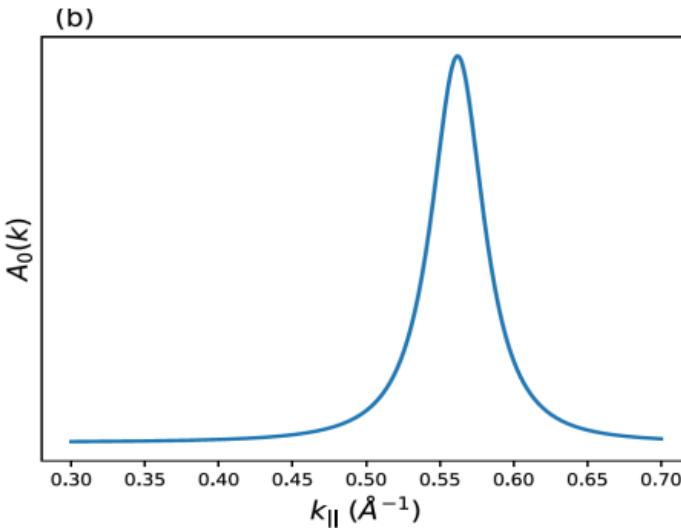
At all momenta, including k_F of the underlying Fermi surface,
EDC peaks are at a finite frequency.



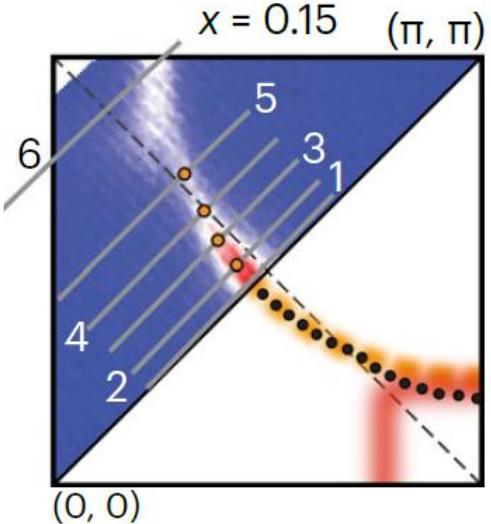


Recent ARPES experiments by Z-X Shen group on pseudogap

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

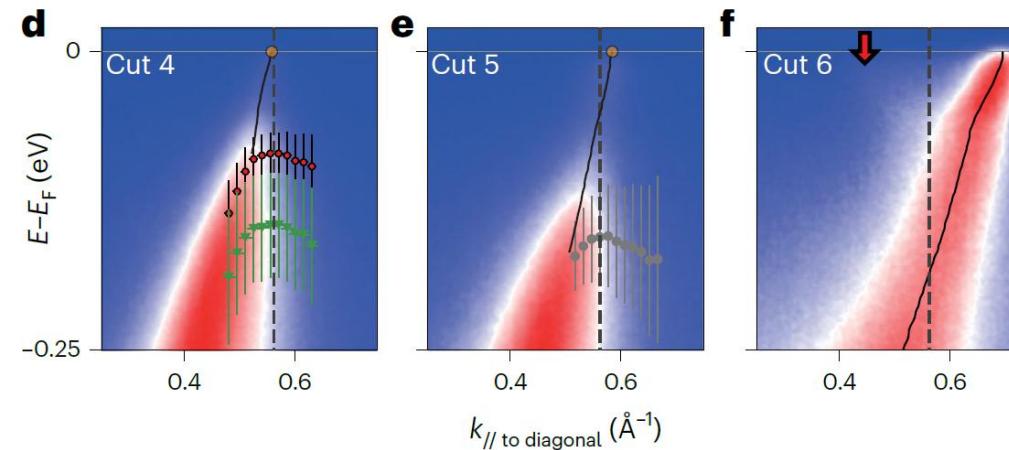
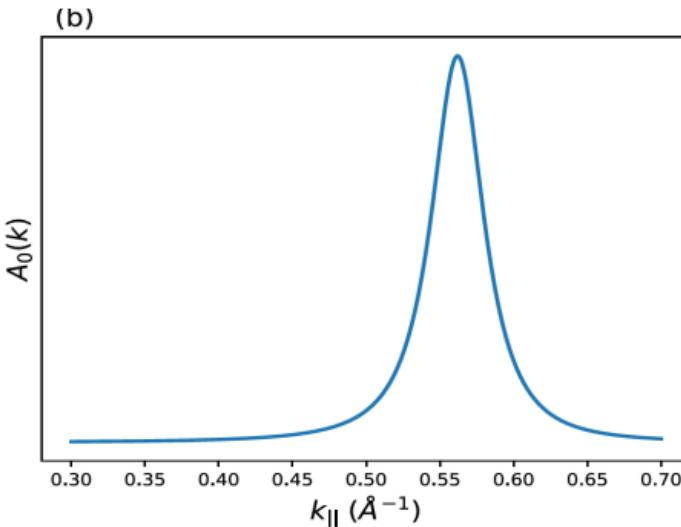


There is only one MDC peak at a given energy.



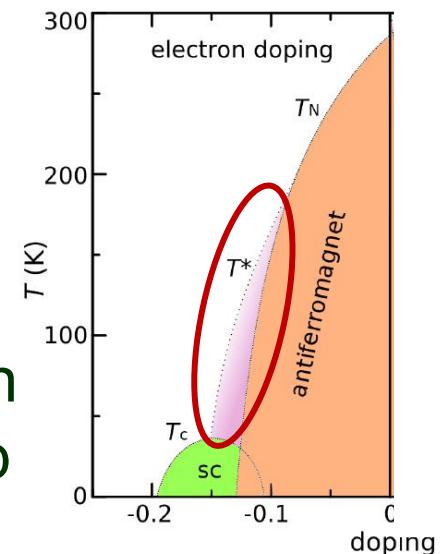
Recent ARPES experiments by Z-X Shen group on pseudogap

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



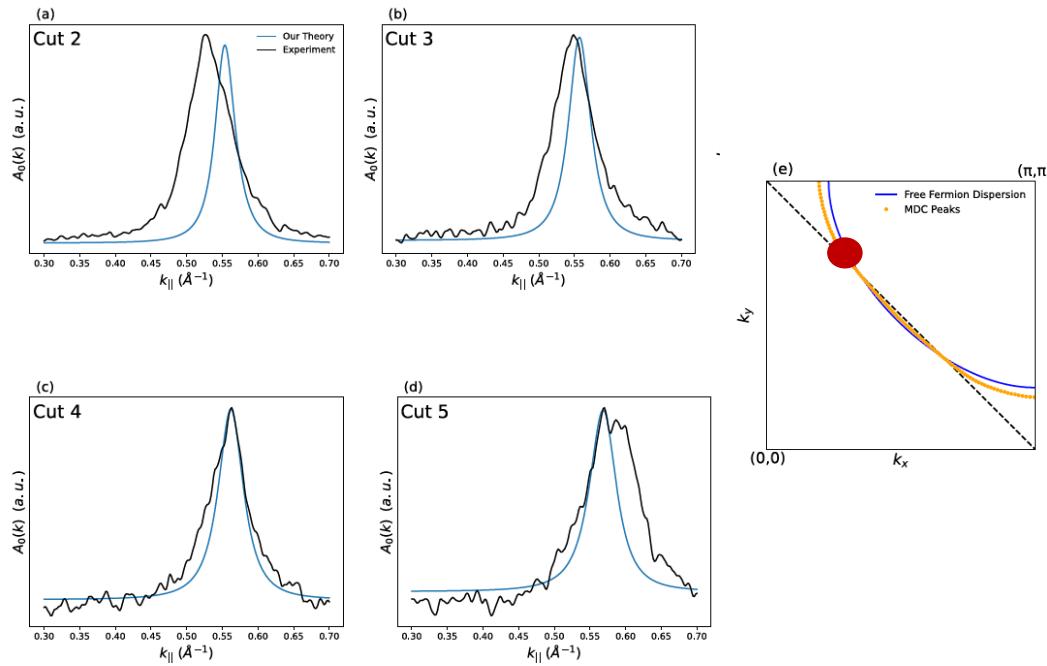
There is only one MDC peak at a given energy. At zero energy, the peak position is at k_F of the underlying Fermi surface

Gossamer Fermi surface

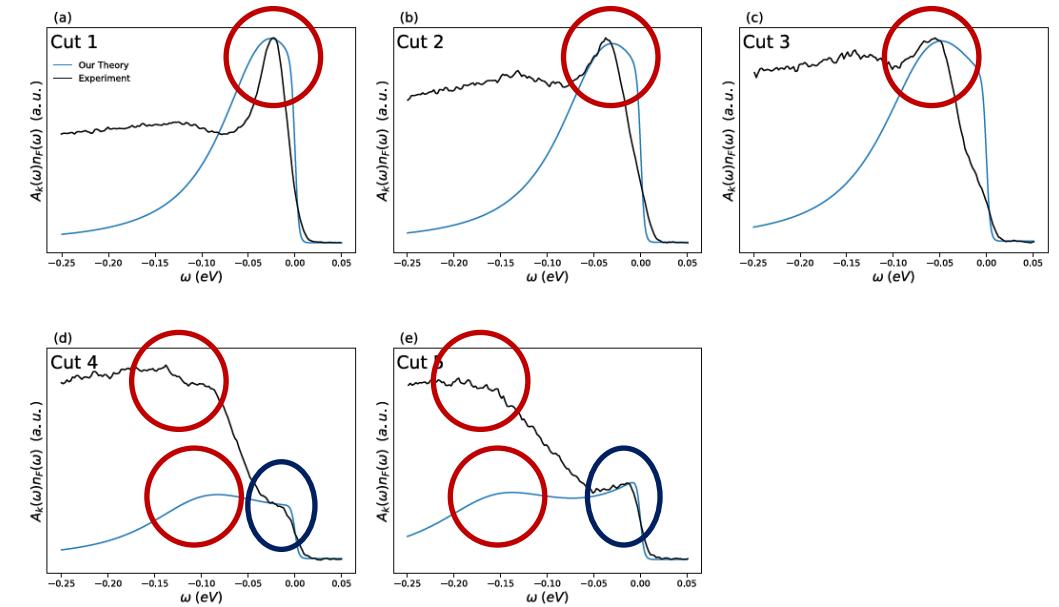


More detailed comparison with the data

MDC at $\omega=0$

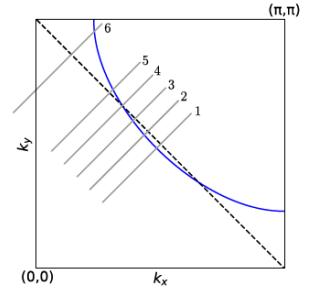


EDC at k_F

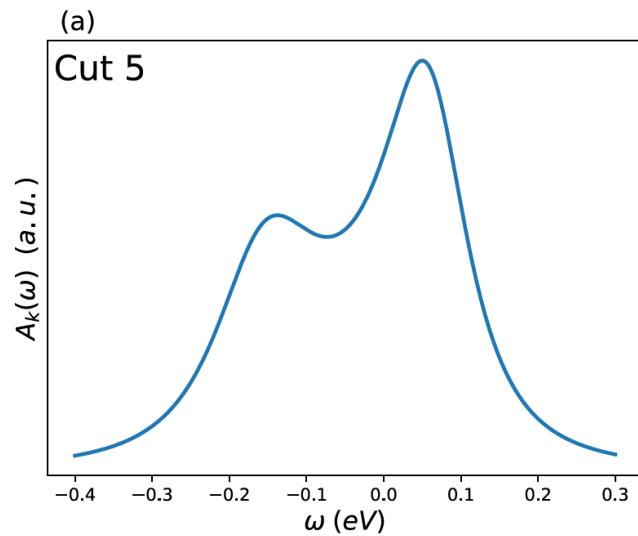


Rapidly grown psedogap in EDC around a hot spot

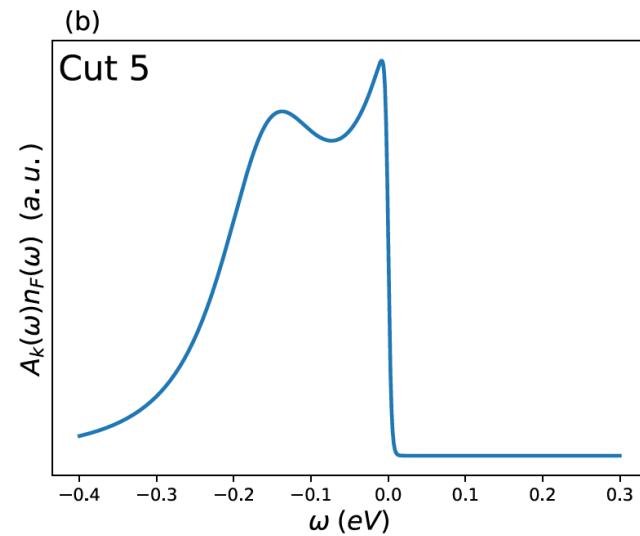
Extra peak in EDC intensity at $\omega = 0$ on one side of a hot spot



Spectral function $A_k(\omega)$

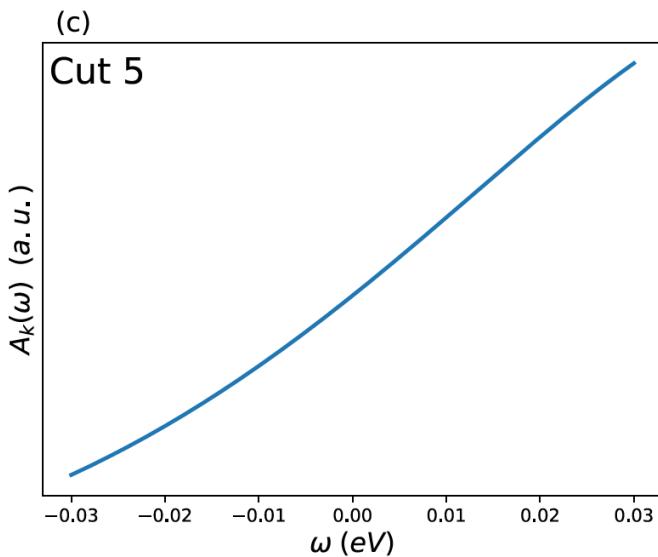


Spectral intensity $A_k(\omega) n_F(\omega)$

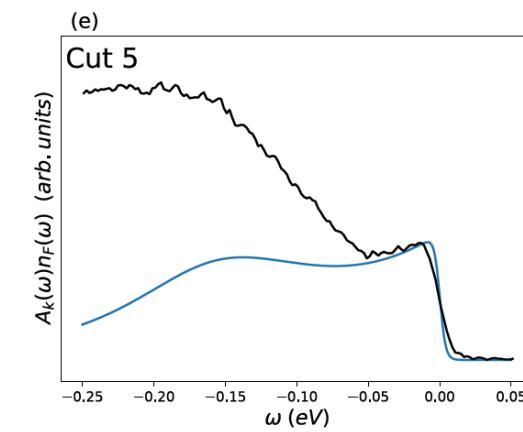
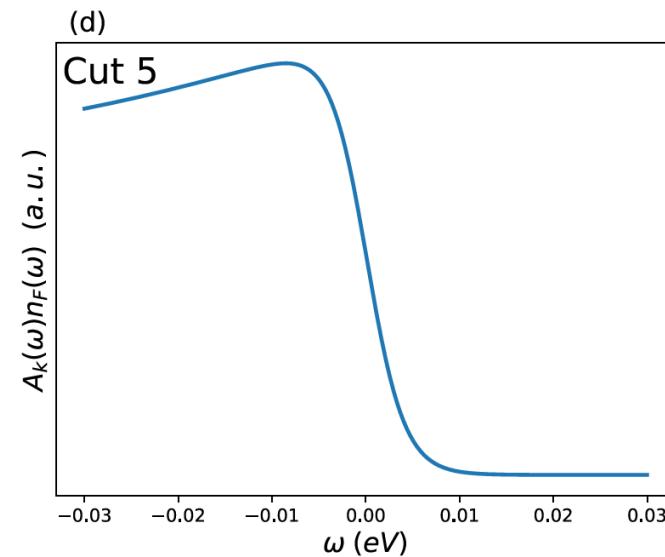


Near zero frequency

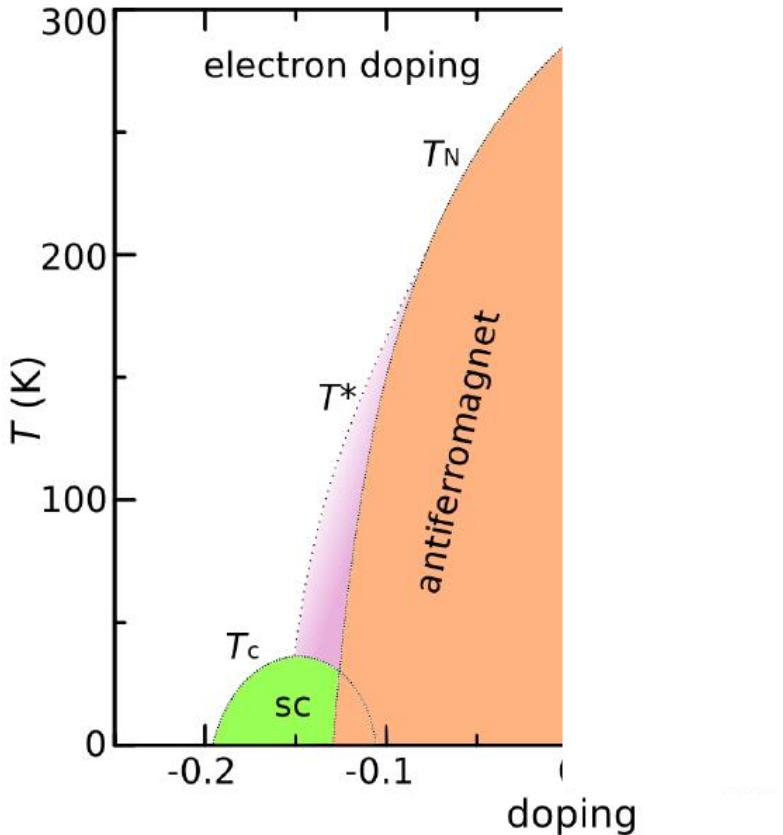
Spectral function $A_k(\omega)$



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



Electron-doped cuprates



Discovered by
Tokura, Takagi and Uchida in 1989



Periodic Table of the Elements

Periodic Table of the Elements

The table shows the atomic number, symbol, name, atomic weight, and electron shell for each element. A legend indicates the state of matter (gas, liquid, solid, unknown) and the element's position in the metal-metalloid-nonmetal trend (lanthanides, actinides, post-transition metals, etc.).

1	IA	H	Hydrogen	1.008	1	18	VIIA	He	Helium	0.000
2	IIA	Be	Boron	11.994	2	10	VIIA	Ne	Neon	20.180
3	IIIA	Li	Carbon	12.011	3	11	VIIA	Ar	Argon	39.948
4	IVB	Be	Nitrogen	14.012	4	12	VIIA	Kr	Krypton	83.818
5	VB	Mg	Oxygen	15.999	5	13	VIIA	Xe	Xenon	131.903
6	VIB	Na	Fluorine	18.998	6	14	VIIA	Og	Oganesson	269.103
7	VIIA	Mg	Neon	20.180	7	15	VIIA			
8	VIIA	K	Argon	20.180	8	16	VIIA			
9	VIIA	Ca	Phosphorus	30.974	9	17	VIIA			
10	VIIA	Sc	Sulfur	32.06	10	18	VIIA			
11	VIIA	Ti	Chlorine	35.45	11	19	VIIA			
12	VIIA	V	Bromine	79.904	12	20	VIIA			
13	VIIA	Cr	Iodine	126.904	13	21	VIIA			
14	VIIA	Mn	Astatine	144.942	14	22	VIIA			
15	VIIA	Fe	Francium	157.905	15	23	VIIA			
16	VIIA	Co	Rutherfordium	169.903	16	24	VIIA			
17	VIIA	Ni	Dubnium	170.947	17	25	VIIA			
18	VIIA	Cu	Rutherfordium	171.960	18	26	VIIA			
19	VIIA	Zn	Dubnium	173.04	19	27	VIIA			
20	VIIA	Ga	Rutherfordium	174.967	20	28	VIIA			
21	VIIA	Ge	Dubnium	175.940	21	29	VIIA			
22	VIIA	As	Rutherfordium	177.940	22	30	VIIA			
23	VIIA	Se	Dubnium	178.940	23	31	VIIA			
24	VIIA	Br	Rutherfordium	180.940	24	32	VIIA			
25	VIIA	Kr	Dubnium	181.940	25	33	VIIA			
26	VIIA	Xe	Rutherfordium	183.940	26	34	VIIA			
27	VIIA	Og	Dubnium	184.940	27	35	VIIA			
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159	VIIA				159	167	VIIA			
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161	VIIA				161	169	VIIA			
162	VIIA				162	170	VIIA			
163	VIIA				163	171	VIIA			
164	VIIA				164	172	VIIA			
165	V									

I will discuss two issues

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

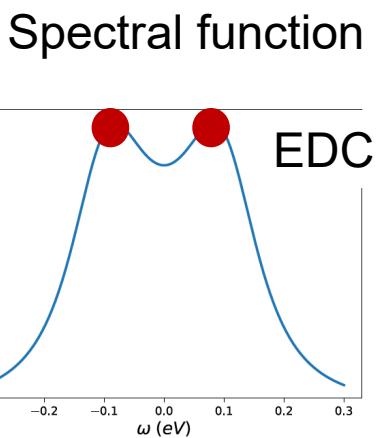
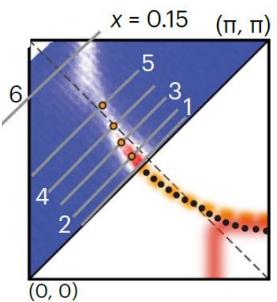
Z-X Shen's group (Stanford)

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

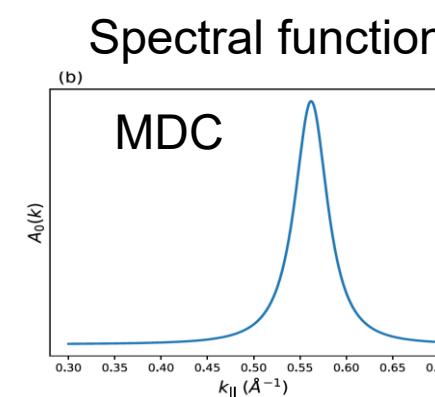
- Theory: is it guaranteed that a Fermi system near the onset of a conventional order (SDW/CDW) displays a pseudogap behavior?

Vertex corrections must be kept to obtain pseudogap behavior

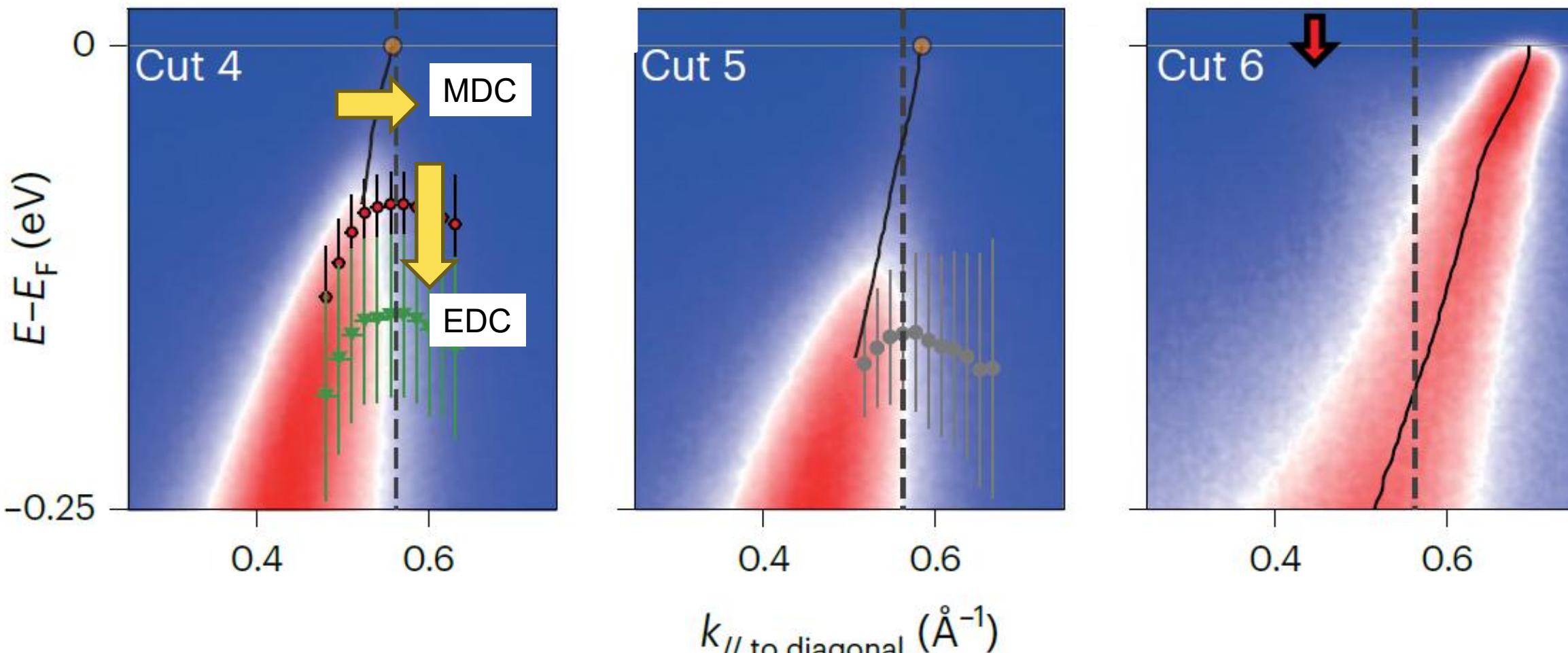
But this may not be enough



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

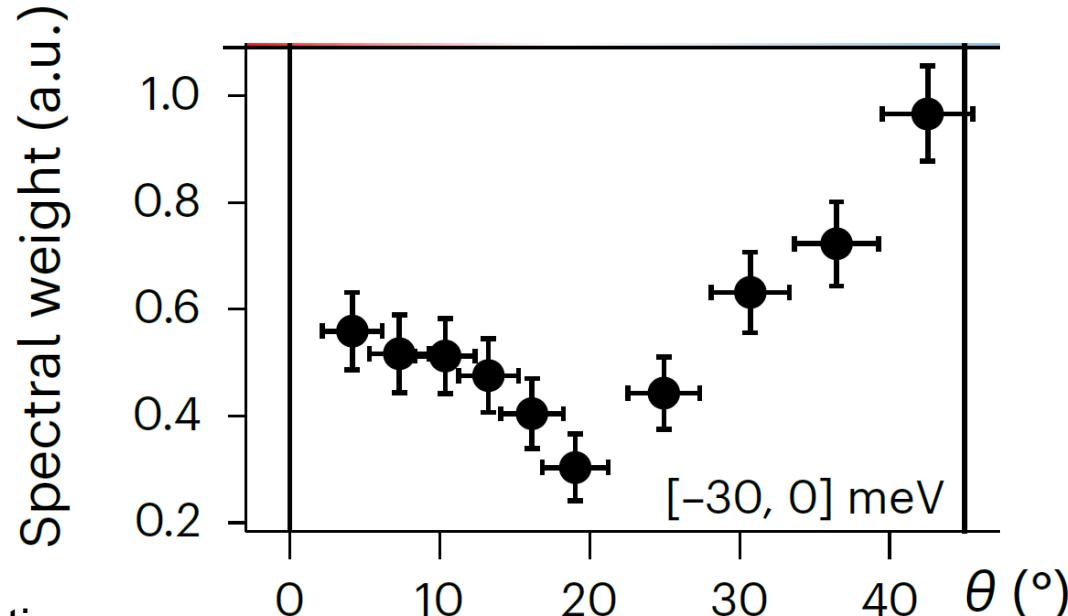


A single peak
crossing
Fermi surface

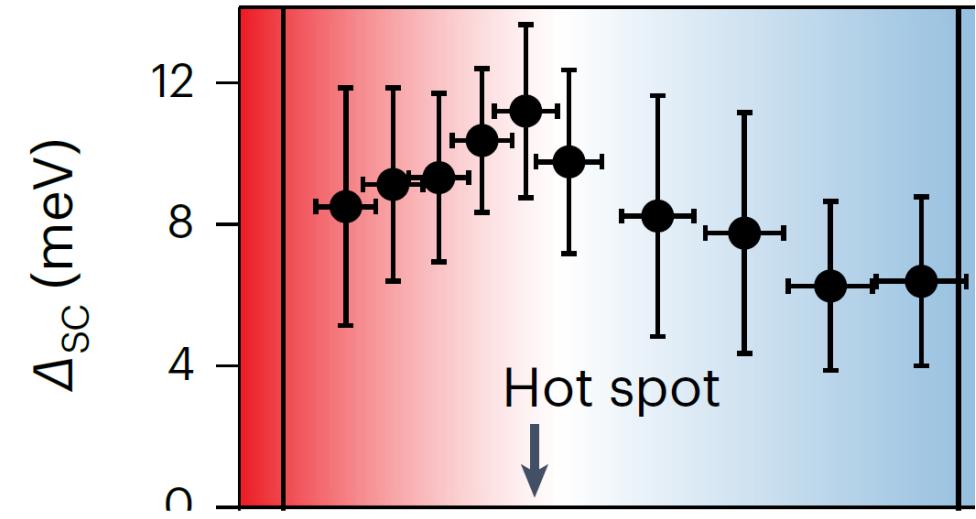


And there is more:

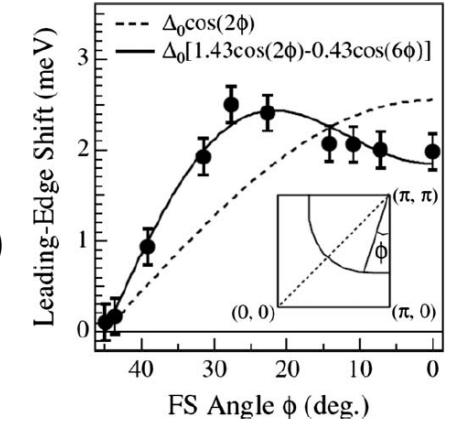
The largest reduction of the EDC spectral weight at $\omega = 0$ is at a hot spot



Superconducting gap is the largest at a hot spot

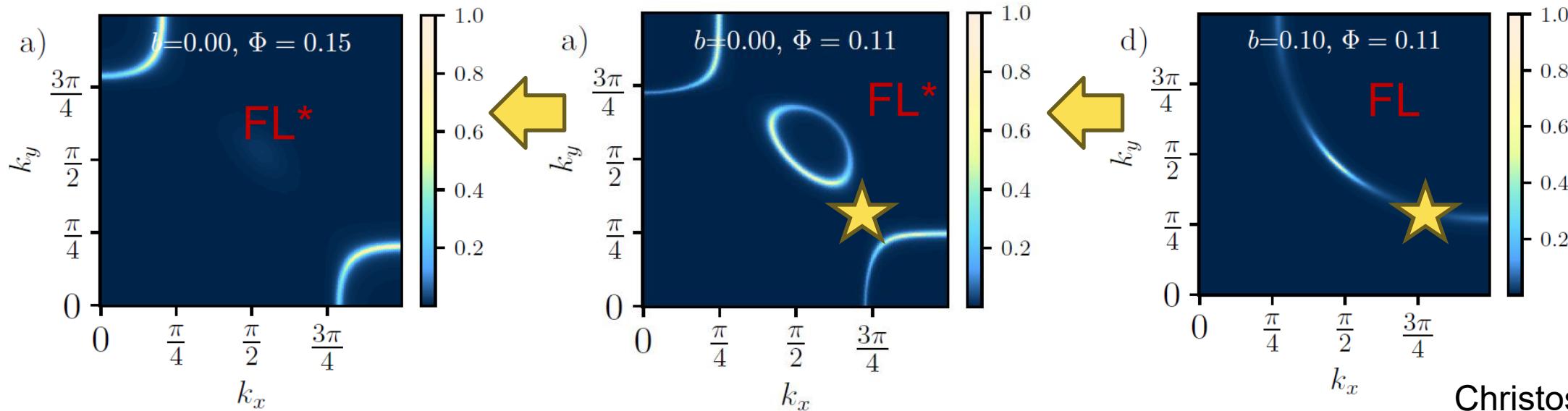


Matsui, 2005
(Yamada's group)



Thermal precursor to AFM vs FL* /spin liquid scenario

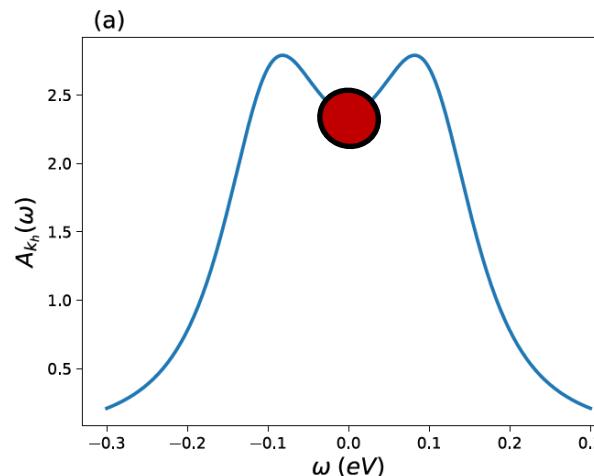
FI*/spin liquid: FS reconstruction (expect PG in EDC and MDC)



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 $\omega=0$ (the original Fermi surface survives)