Strongly correlated electron systems (superconductors) and Neutron scattering

-view from a neutron instrumental scientist-

J-PARC Center, JAEA

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J-PARC

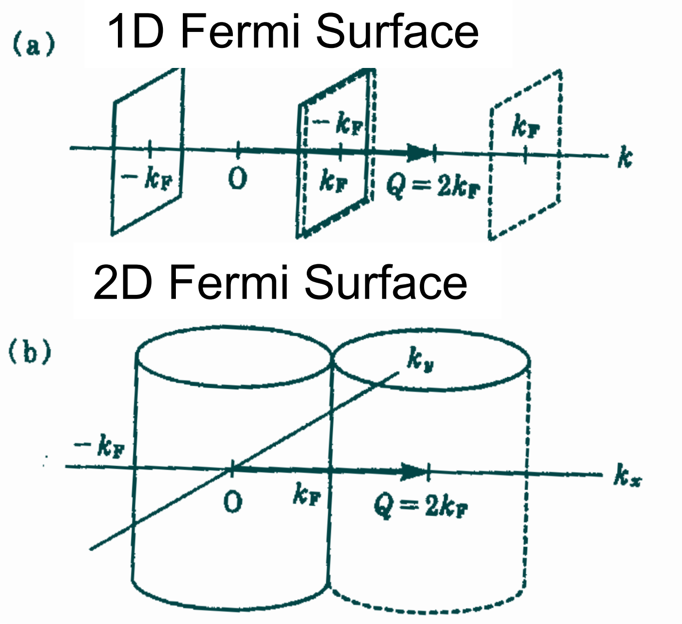
JAERI and KEK Joint Project
Japan Proton Accelerator Research Complex

High Intensity Proton Accelerator Project

大強度陽子加速器計画


J-PARC / Materials Life Science Facility
(the world class neutron/muon facility)

Importance of the dimensionality of the electron system



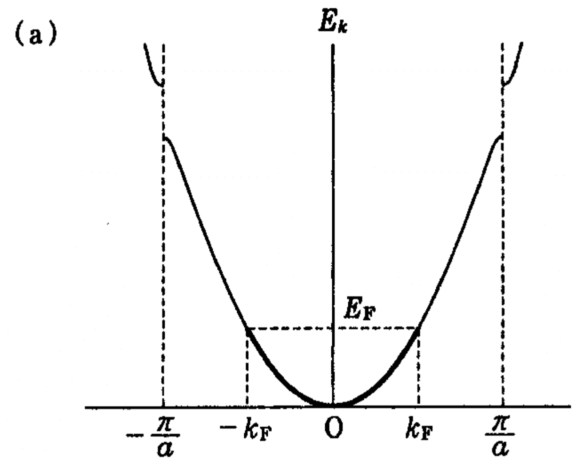
Periodicity of electron system creates Fermi surface **nesting and gap formation**

System's energy decreases !

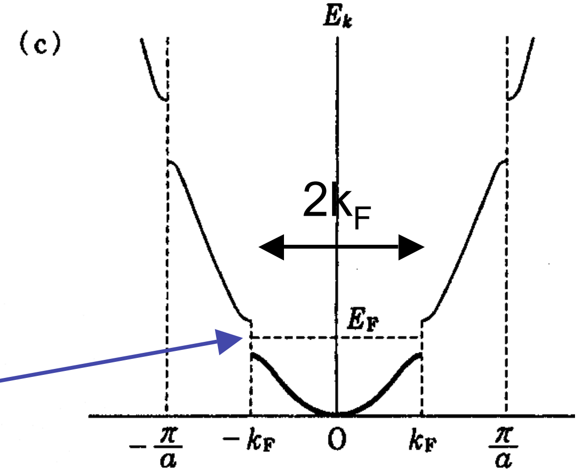
$$2\Delta(0) = 3.5k_B T_P^{MF}$$

It is the same as BCS

Band gap at lattice periodicity



Band gap at electron periodicity at E_F



2electrons in a unit cell -> insulator

Density response function (polarization susceptibility)

$$\chi(Q) = \frac{1}{V}\sum_k \frac{f_{k+Q} - f_k}{E_k - E_{k-Q}}$$

Singularity strength is dominated by the size of the nesting surface at E_F

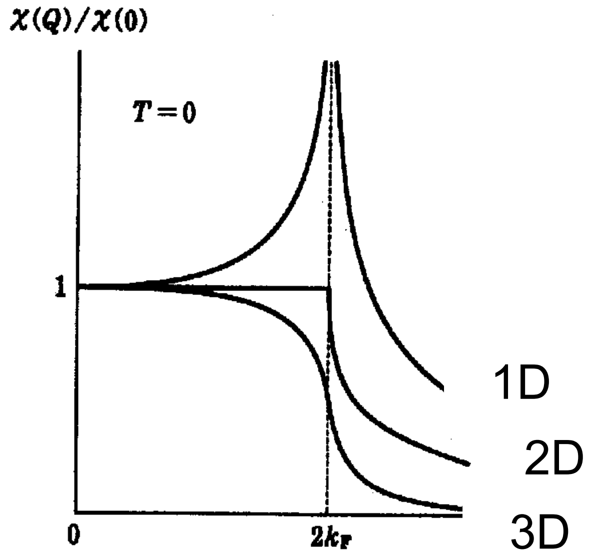
For 1D system

$$\chi(Q) = \frac{2m}{\pi\hbar^2 Q}\ln\left|\frac{Q+2k_F}{Q-2k_F}\right|$$

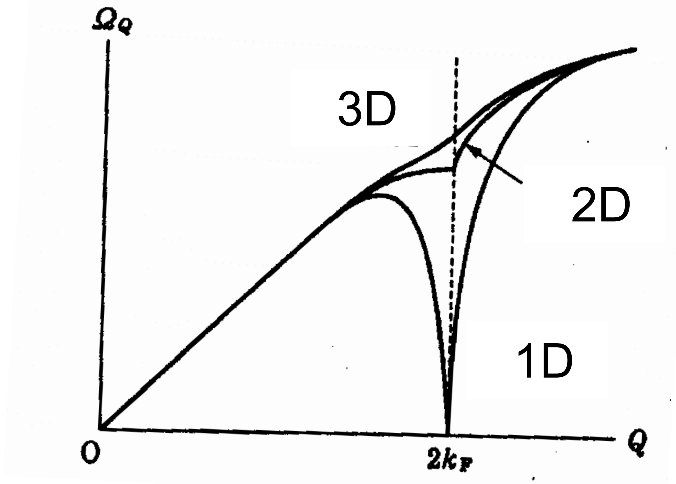
$$\chi(2k_F) = \frac{D_F}{N}\ln\frac{1.14E_B}{k_B T}$$

In case for 1D,
Peierls transition always occurs
(metal- insulator transition)

Anomaly at $2k_F$ for electron system ⇒ **CDW**

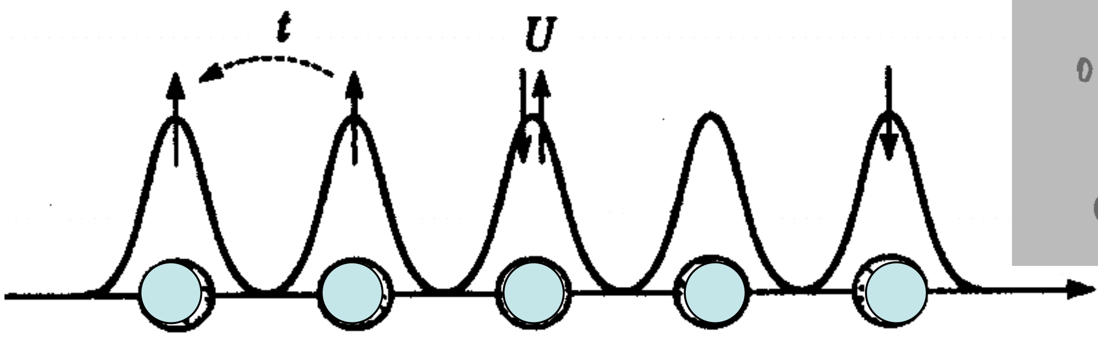


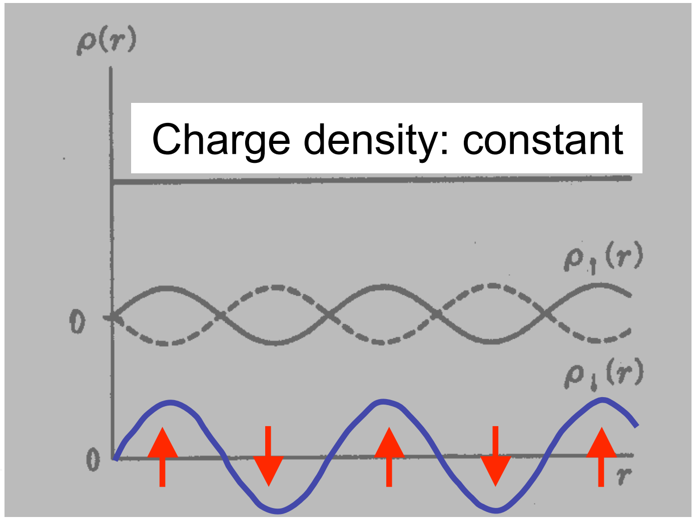
Kohn anomaly at $2K_F$
in the phonon dispersion



Correlated electron system and Hubbard model

Transfer integral: **t** On site Coulomb: **U**





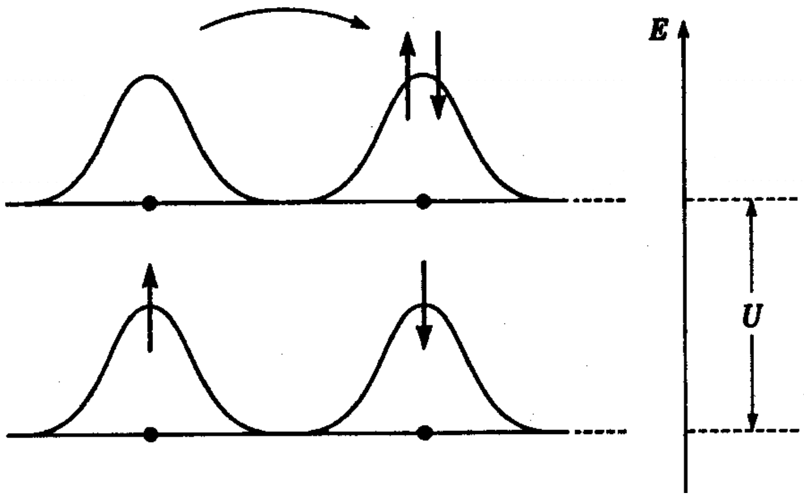
spin density wave: AF

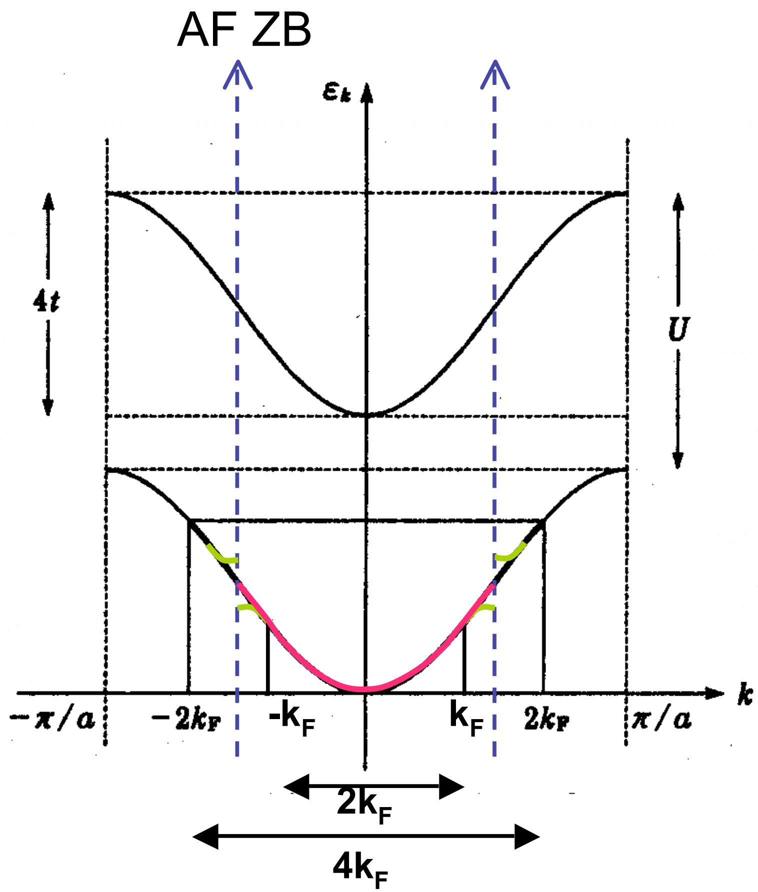
$$\chi_S(Q) = \frac{g\mu_B \chi(Q)}{1 - \frac{1}{2}U\chi(Q)}$$

Spin susceptibility has a anomaly at a finite T
There is always a temperature where Uc(Q)/2=1, because of the character of c(Q)
⇒ 2-k_F-SDW is created if there is U (electron correlation) under nesting condition.

Strong correlation creates AF insulator

If U>4t; strong correlation





Half filling (Ne=Nu)
Antiferromagnetic correlation
(**SDW formation with a spin gap)**
Mott insulator

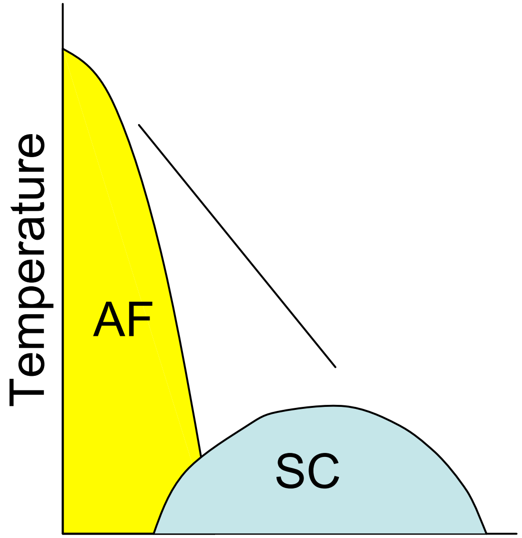
Another explanation; $\Delta k = \frac{2\pi}{aN_u}$

Occupation at a k is one not two.
Hence, $4k_F$-CDW occurs
(TTF-TCNQ, $2K_F$-CDW + $4K_F$-CDW)

Superconductivity and Antiferromagnetism

Most of superconductors, recently discovered, have **2D-nature** in the electron states.

Oxide-HTC, Hf-compound, SrRuO, Organic SC (BEDT-TTF etc), Fe-pnictide



Charge concentration,
Pressure, etc

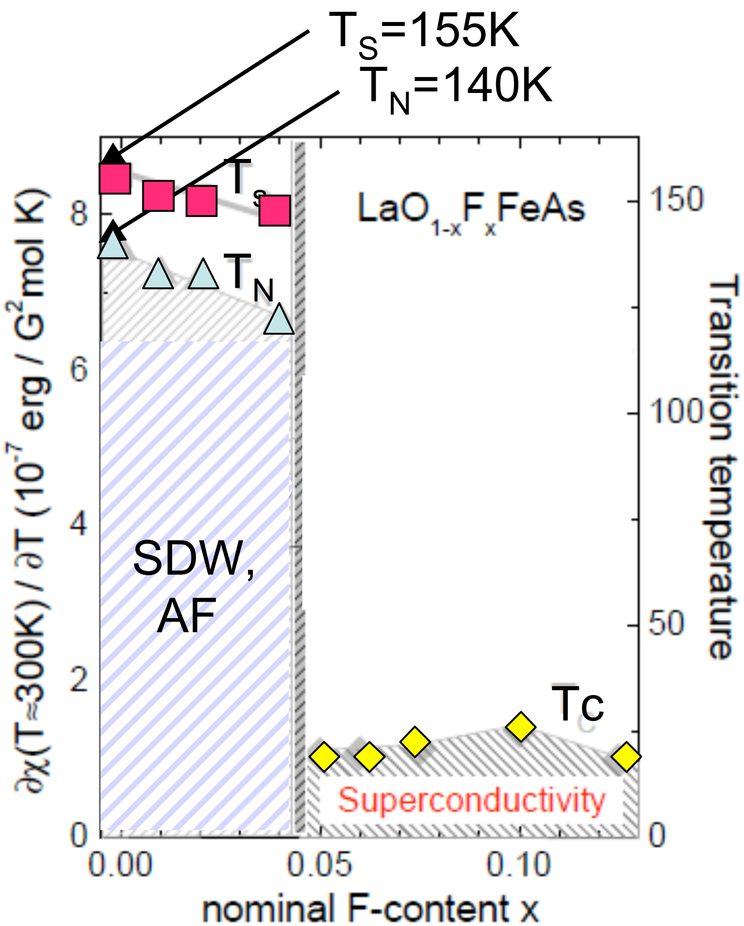
Oxide-HTC: stripe, 1/8 problem
very high U(OSC)~10eV
Organic SC: SDW, CDW
medium U~ U(OSC)/10
Fe-pnictide: SDW

Theoretical views for those superconductivity depends on each cases.
However, there seems to be an universal view for them (Generic, Robust concept ?)

SC symmetry depends on SC gap nature.
exchange of electron-pair has asymmetric nature including wave function and spin part.

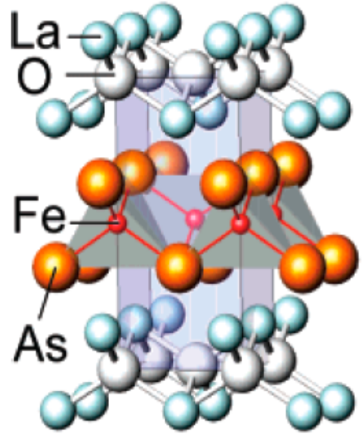
Cooper pair symmetry; s, d; singlet pair
p; triplet pair

2D - SDW from LaFeAsO



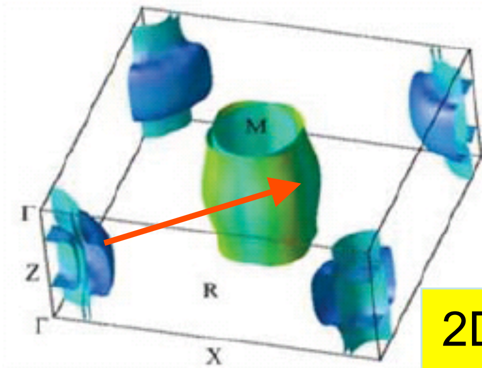
electron concentration

R. Klingeler, et al., cond-mat 2008



2D nature in the electronic states

$LaFeAsO_{1-x}F_x$ T_c~26K Kamihara, Hosono et al. J. Am. Chem. Soc. 130, 3296 (2008).



2D-Fermi surface

Γ; hole like cylinder,

M; electron like cylinder

2D - Fermi surface nesting
2D-SDW, SC

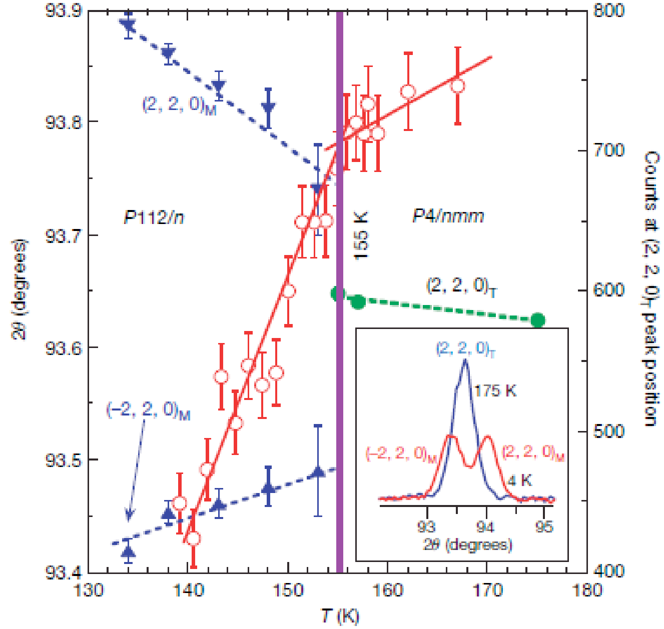
5-orbitals (d(Z^2-R^2), d(XZ), d(YZ), d(X^2-Y^2), d(XY))
of 3d states have contribution
It is not a Mott insulator (U~1eV)

D.J. Singh and M.H. Du, Phys. Rev. Lett. 100, 237003 (2008).

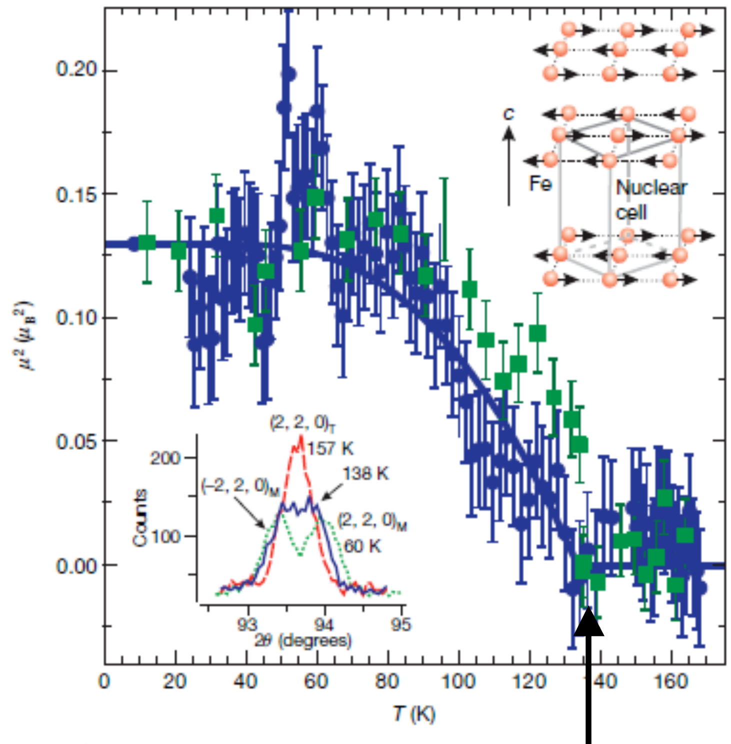
Structural Phase transition at 155K
(Tetragonal -> Monoclinic)
and
3D-Anti-Ferromagnetic Long range order below 140K

(Cruz et al. Nature 2008)

Monoclinic Tetragonal



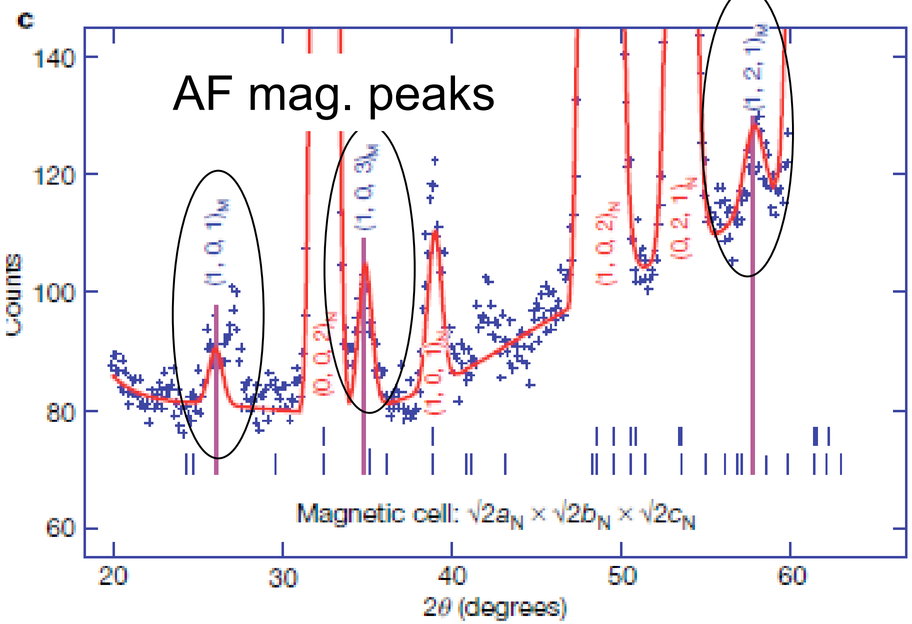
T_S=155K



igure 4 | Temperature dependence of the order parameter at

T_N=140K

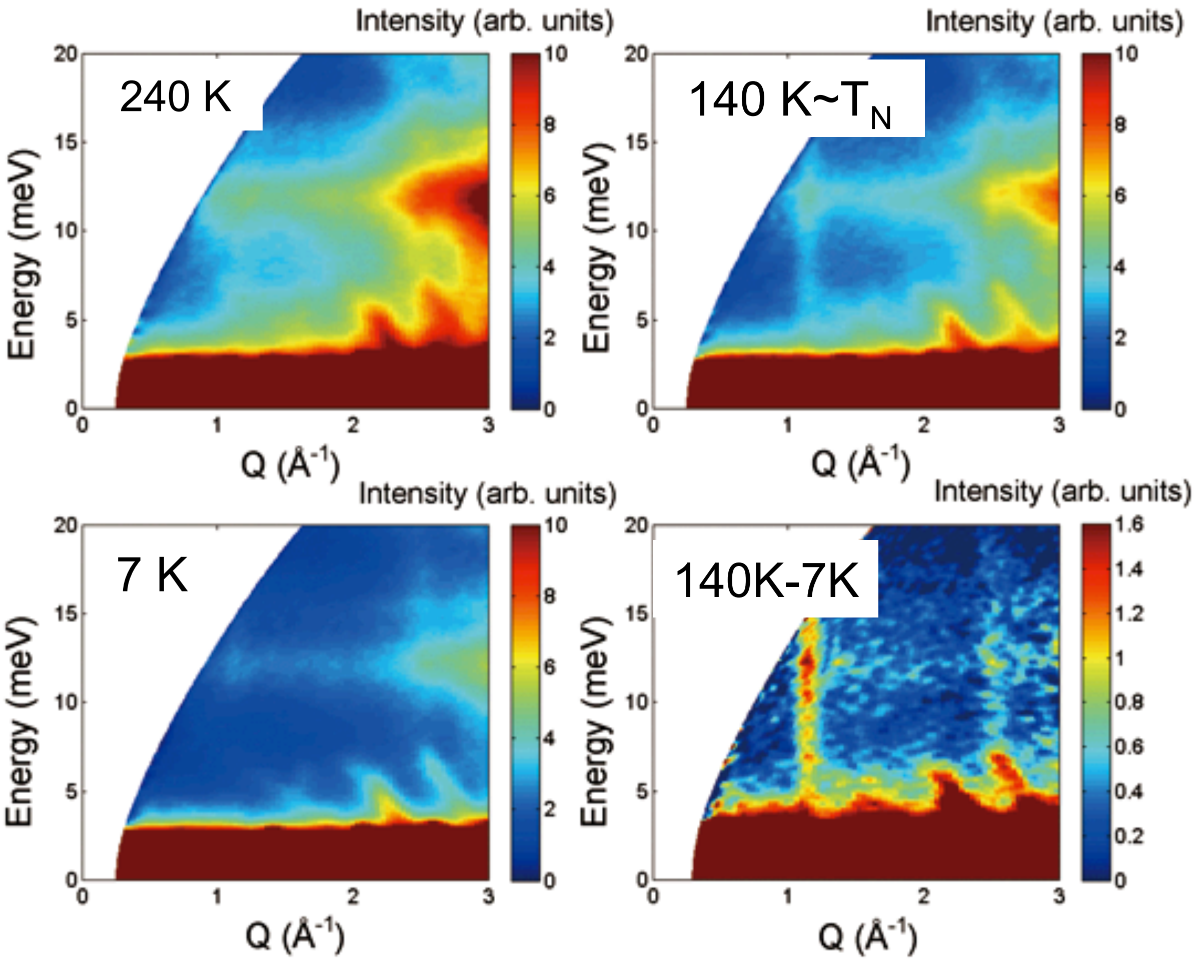
AF mag. peaks



(AF points; $(101)_M$, $(103)_M$, $(121)_M$)

Inelastic Neutron Scattering from a powder sample (LaFeAsO)

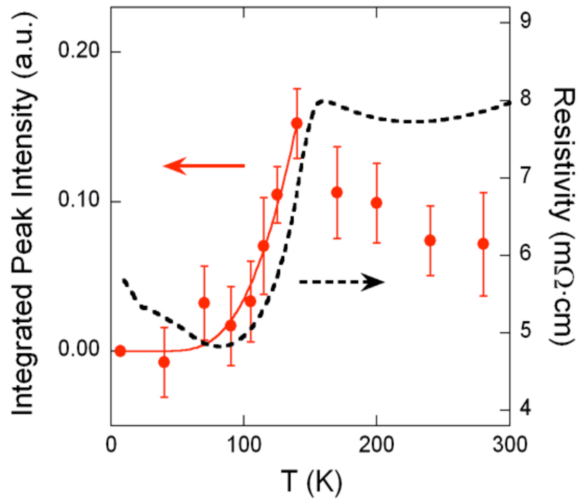
(one of the most important role of neutrons)



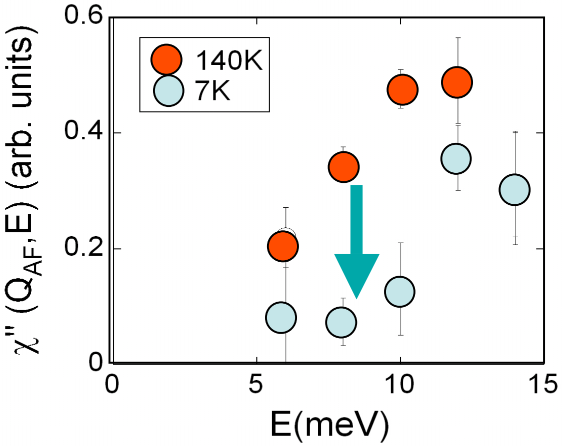
S(|Q|,E) (E_i=30 meV)

T- dependence

S(*Q=1.0~1.3* Å, *E=7.5~9 meV*)

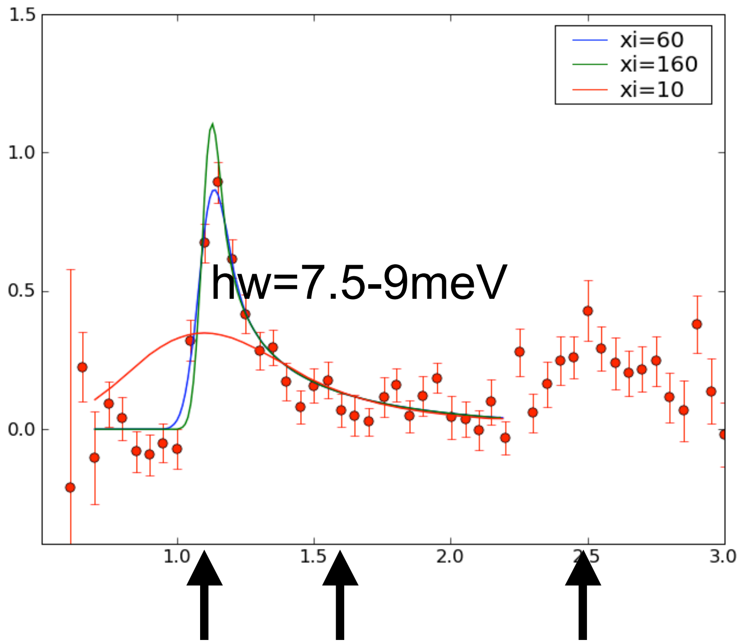


Spin gap formation



excitation from 2D-SDW

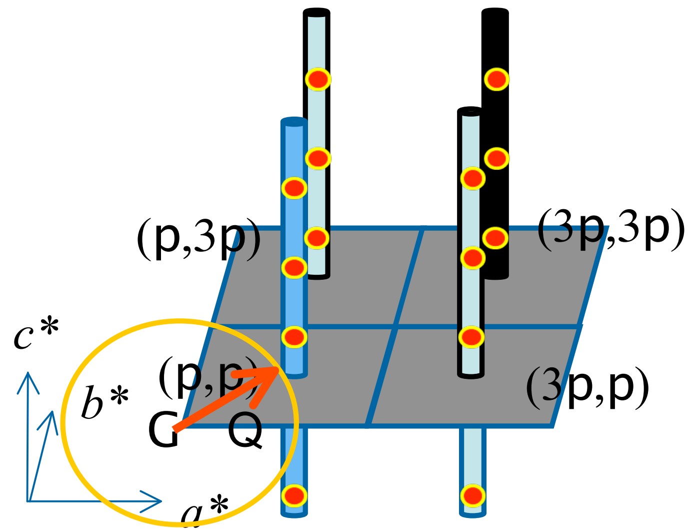
2D-SDW: Warren function

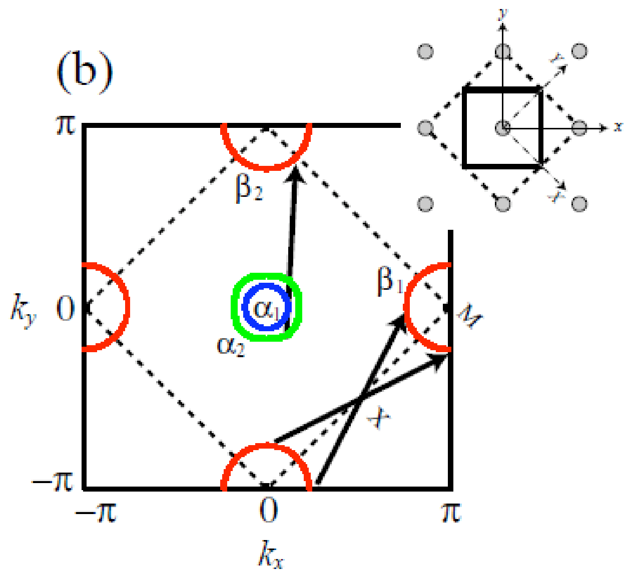


3D - AF long range order zone centers

Static 3D-AF order and
2D-SDW in the inelastic region.

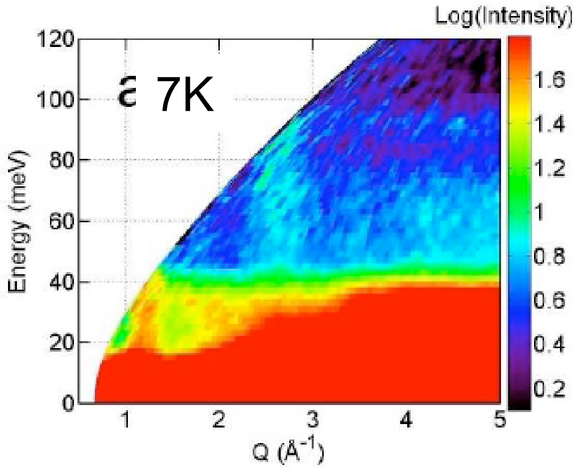
Existence of 2D-SDW

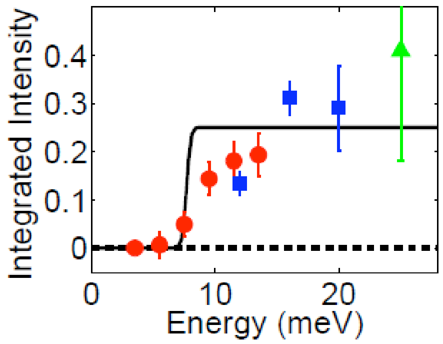




Nesting and unconventional S-wave SC
Formation of SDW by a nesting
Kuroki, Aoki, PRL 2008

BaFe2As2(Tc=0K), Spin wave excitation ?



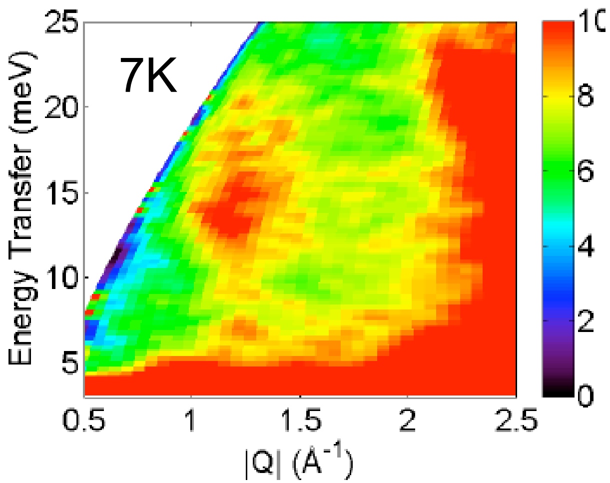


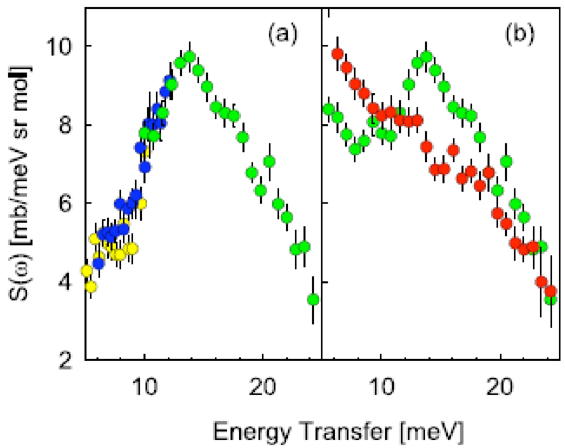
Similar experiments were rushed almost in the same time on the same instrument, MERLIN in ISIS.

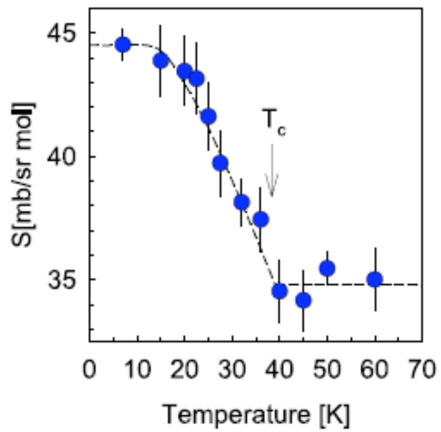
Our Exp. date; 10 July
Christianson; 14 July
Ewings; after two above.

Ewings et al., cond-mat Aug. 2008

Ba0.6K0.4Fe2As2 (Tc=38K), Resonance peak in the SC states

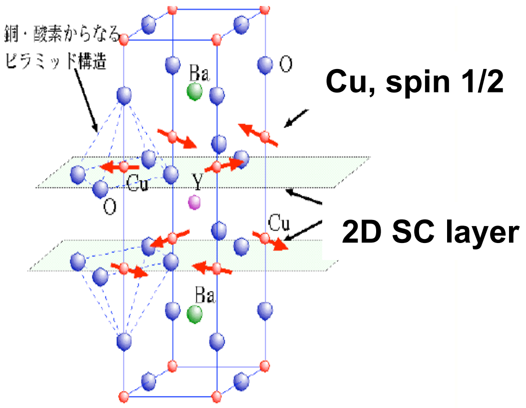






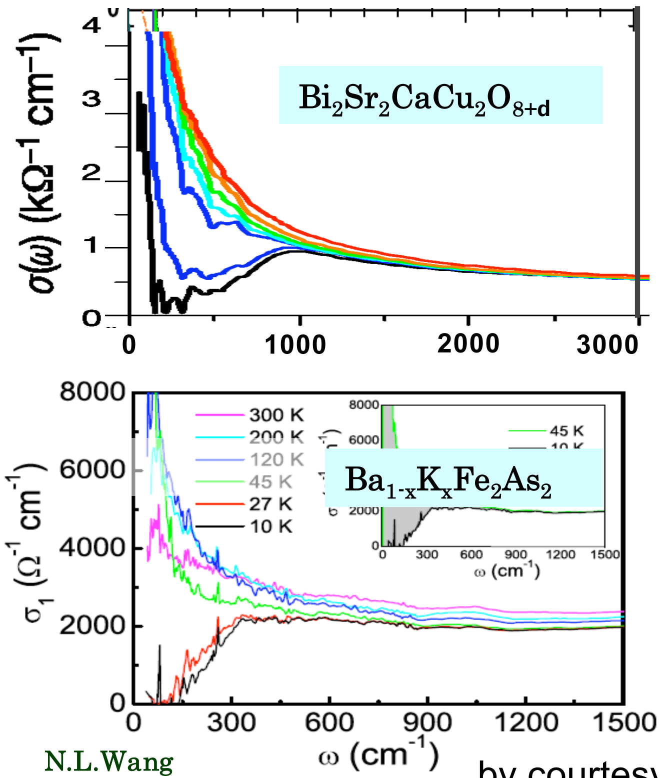
Christianson et al. cond-mat July 2008

Oxide High Tc superconductor



Strong U(~8eV);
strongly correlated electron system
(half filling system)
⇒ Mott insulator
2D electron system
($3d(X^2-Y^2)$, spin=1/2,
charge transfer to the oxygen 2ps)
2D magnetic system
2D phonon system

Resemblance in the optical conductivity



by courtesy of Uchida

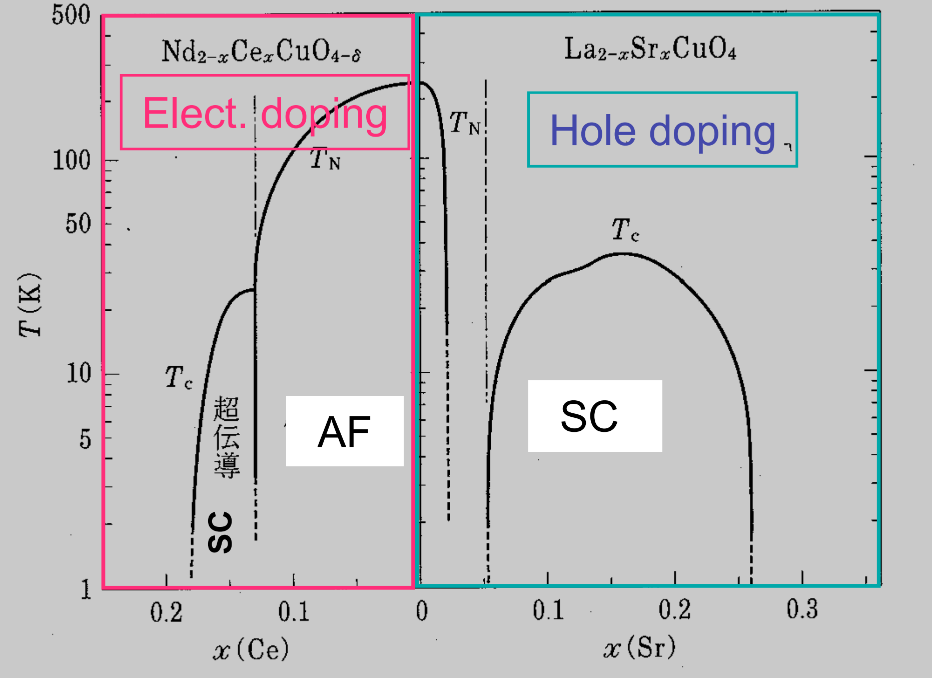
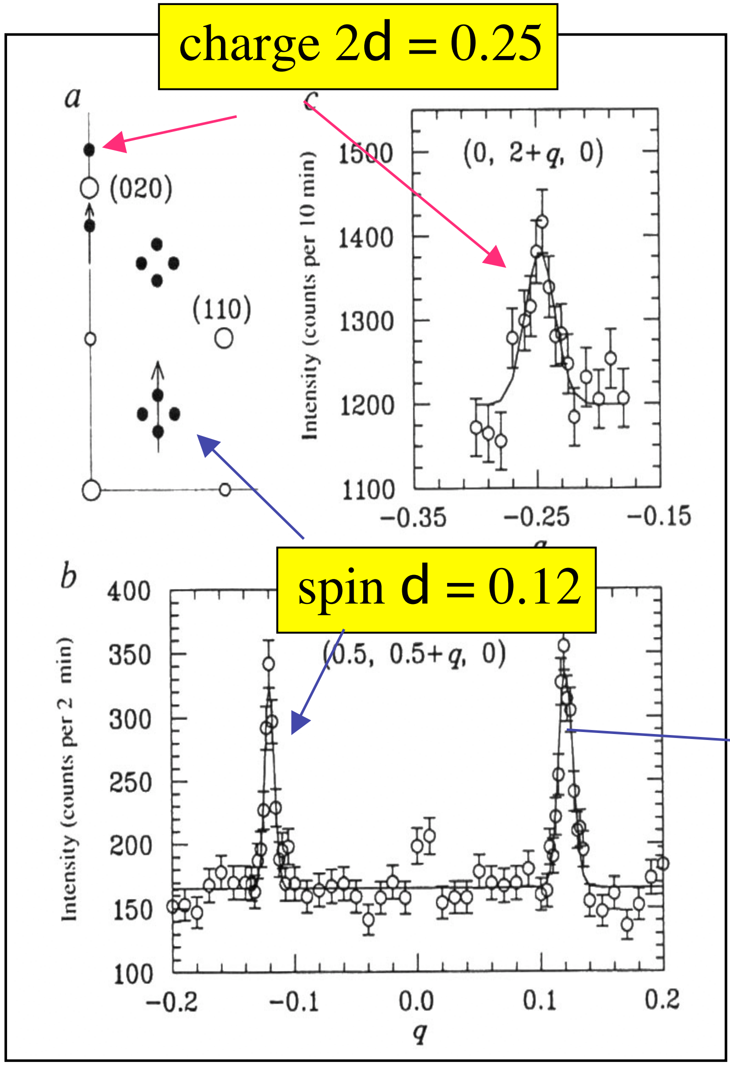


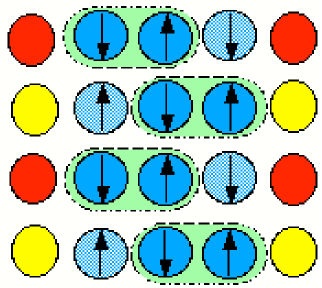
図 2.7 $La_{2-x}Sr_xCuO_4$ および $Nd_{2-x}Ce_xCaO_{4-\delta}$ の電子相図[22)]

Incommensurate peaks in the oxide HT_C-SC
Stripe: SDW ($2k_F$) & CDW($4k_F$) ?
Periodicity of spin(d) and charge(2d)

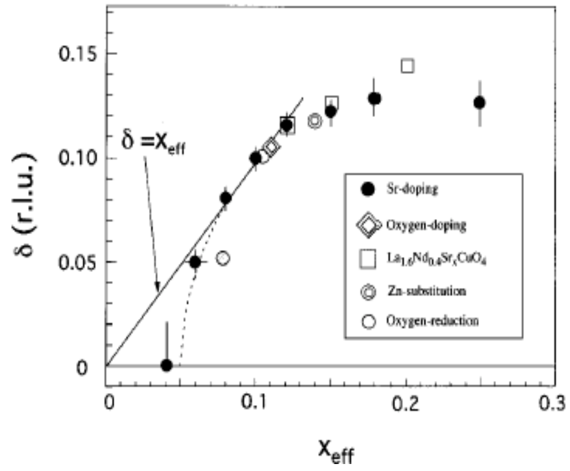


J. M. Tranquada *et.al*. Nature **375** (1995)

Stripe (SDW)

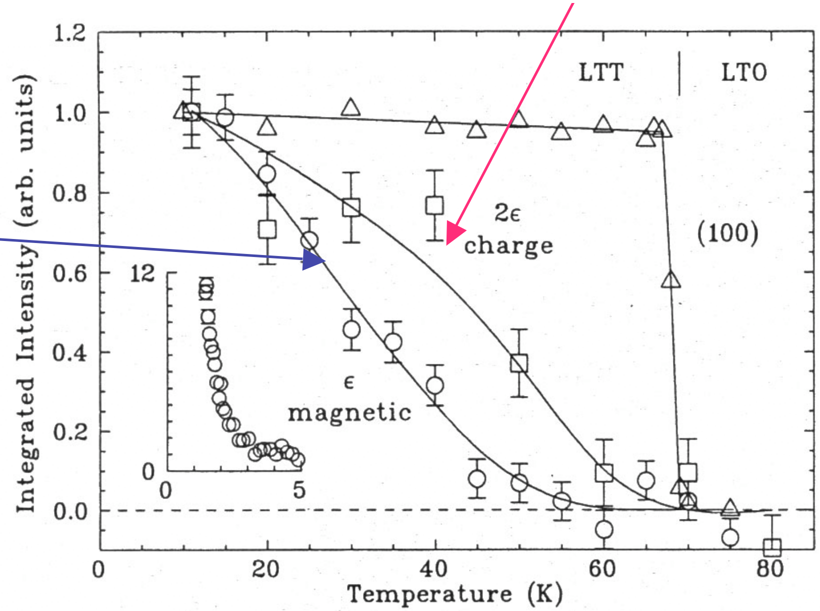


Incommensurability & Tc
Yamada et al. PRL



$4k_F$-CDW orders first
(resemblance in TTF-TCNQ)

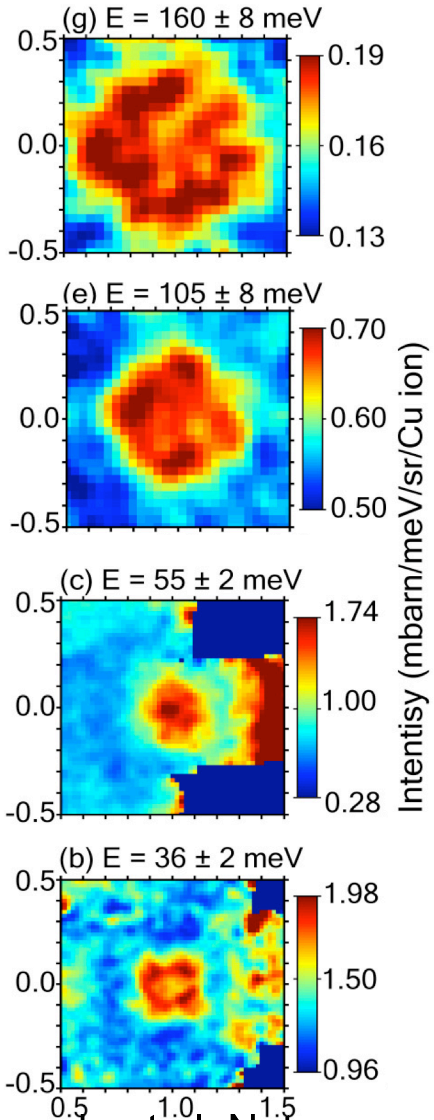
SDW



La1.6-xNd0.4SrxCuO4

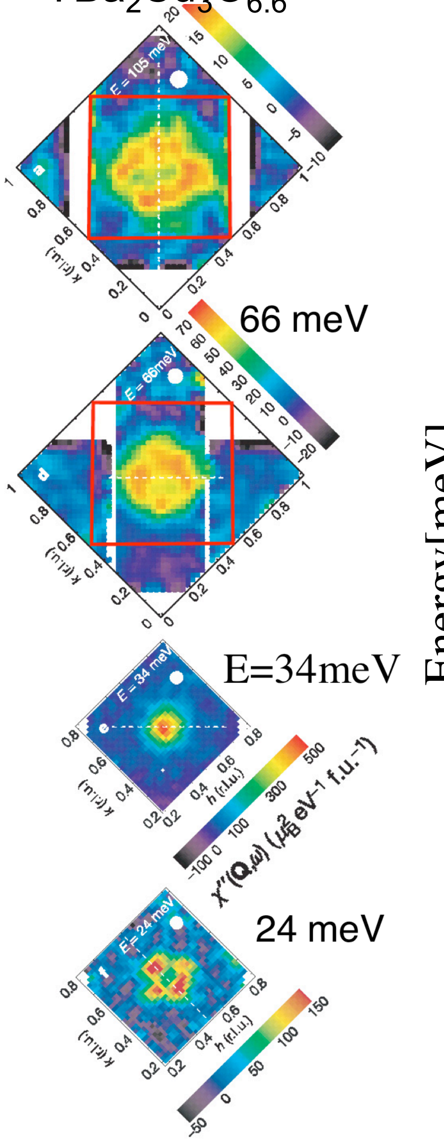
Common feature in the magnetic excitation in the oxide high Tc superconductors

$La_{2-x}Ba_xCO_4(x=1/8)$



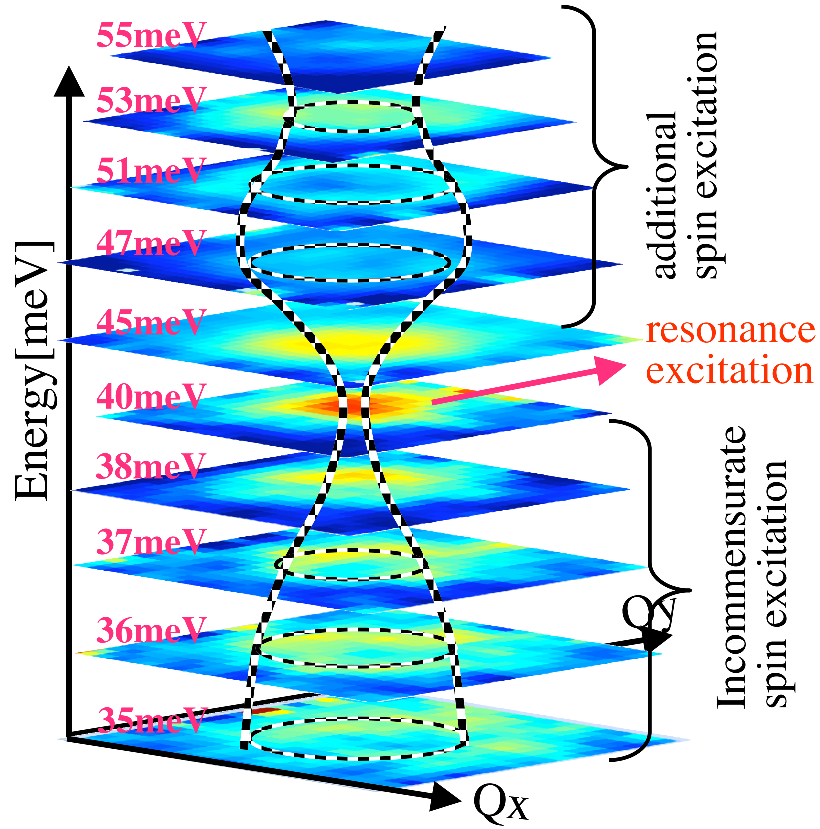
Tranquada et al. Nature

$YBa_2Cu_3O_{6.6}$



Hayden et al. Nature

Hourglass shape in the magnetic excitation

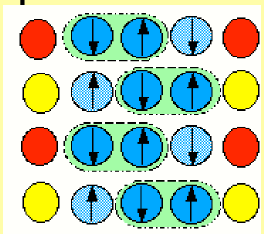


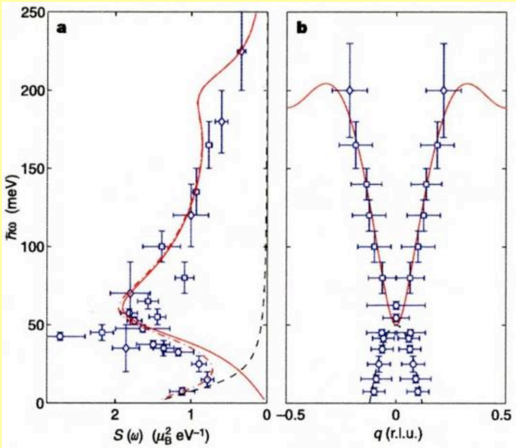
Yokoo et al. J.Neutron Research

Anomalous Magnetic Excitation

Imc can be obtained from the Fermi Surface character by RPA (electron state to

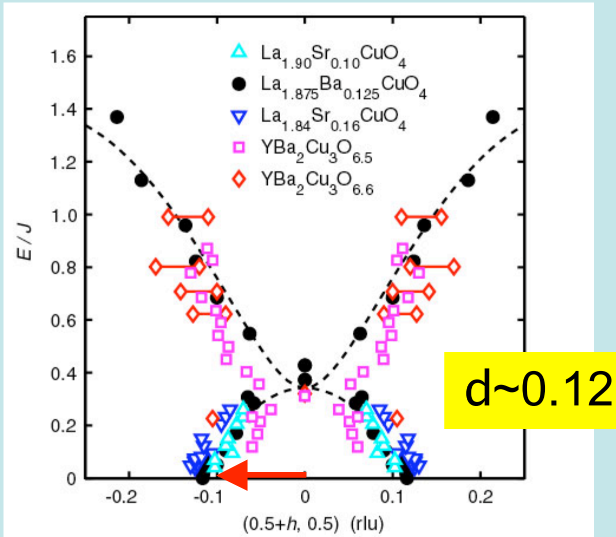
Stripe Scenario
& spin wave ?





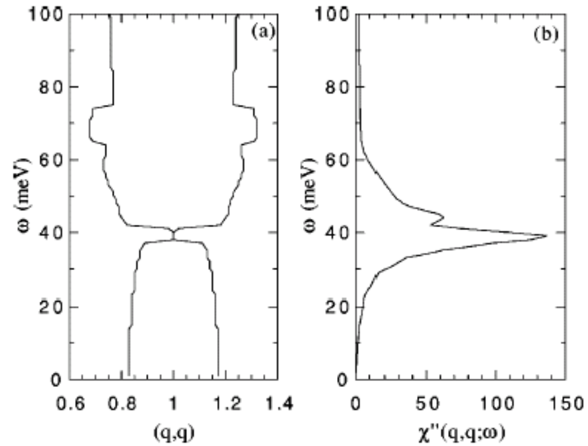
LSCO

Hourglass feature in the Magnetic Excitation **(2D-SDW ?)**

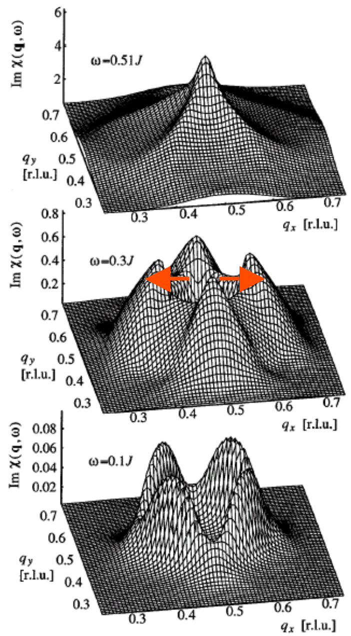


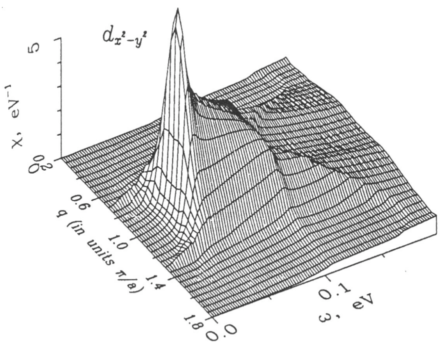
d~0.125

Common for LSCO, YBCO etc



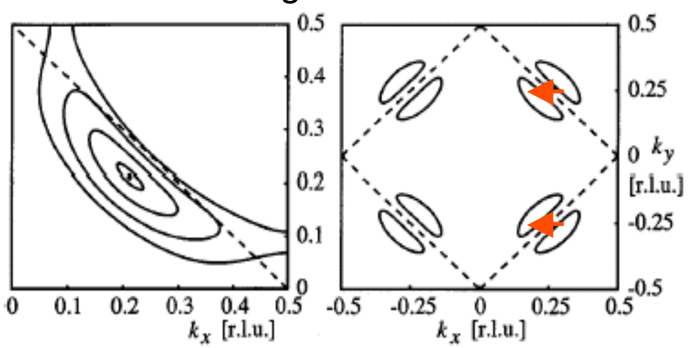
Norman PRB 2000





Yakovenko 1995

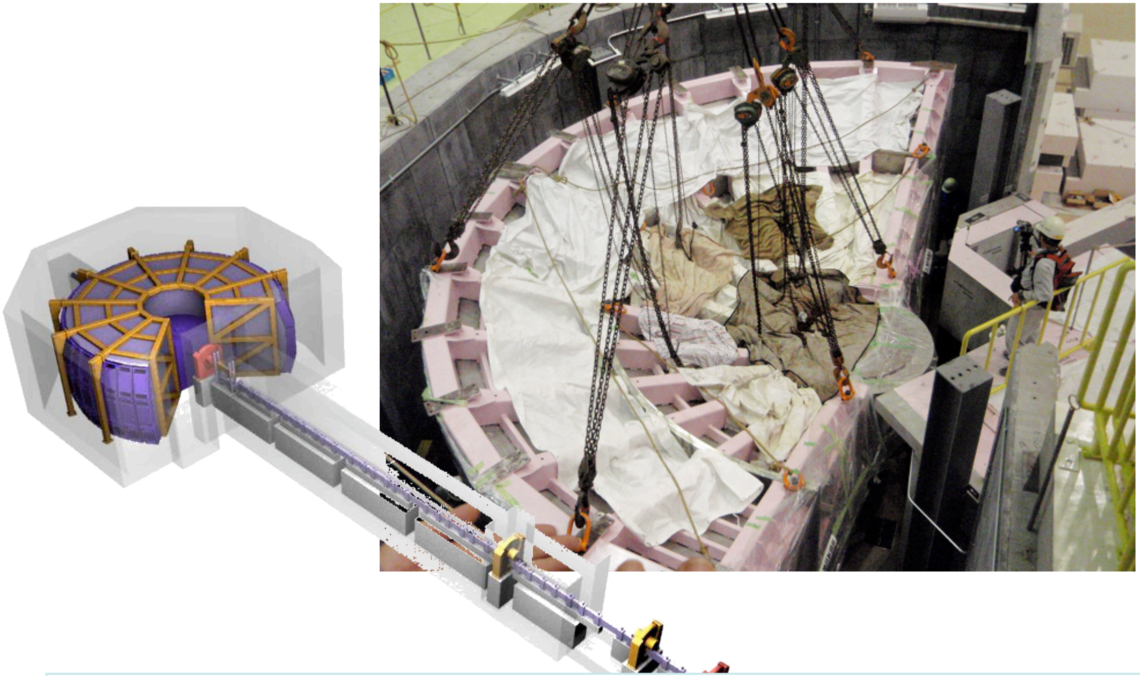
Nesting vector ←



Brinckmann and Lee, PRL 1999

Summary and guess

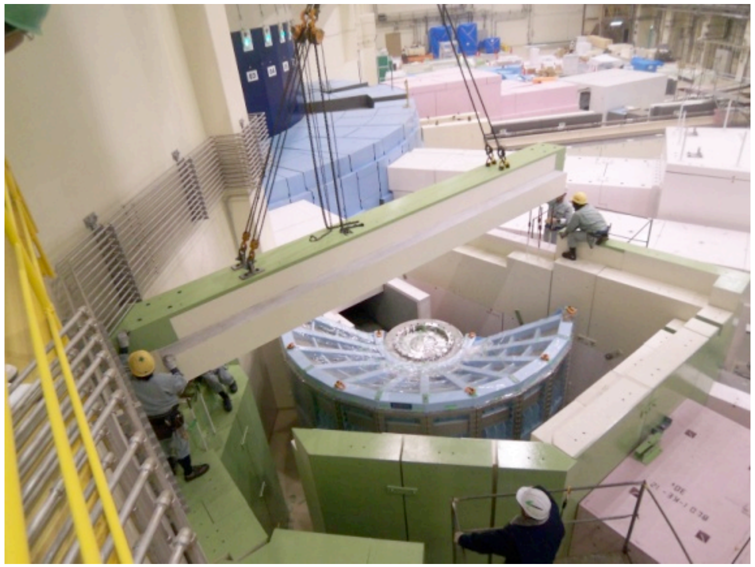
1) Strongly correlated electron system (SCES) gives various exotic physical properties.
2) Low dimensionality and the Fermi surface topology is important.
3) The discovery of the Fe-pnictide is very important for itself, but also stimulating reconsideration of physics of Oxide HTCSC.
4) It seems that **electron-electron correlation (nesting)** has an importance.
5) Studying dynamics of materials, by means of Neutron, X-ray, ARPES, Muon, is very important to understand the intrinsic mechanism of physical properties of SCES.
6) IMSS has those tools in hand, and hence the formation of the **Condensed Matter Research Center** is very timely to extend and enhance the activity of IMSS.
7) J-PARC can have an important role for it.

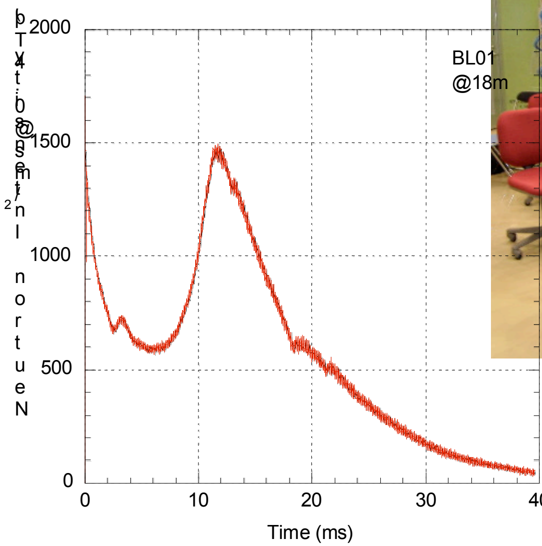


J-PARC neutron facility will provide excellent opportunities to study strongly correlated electron systems.

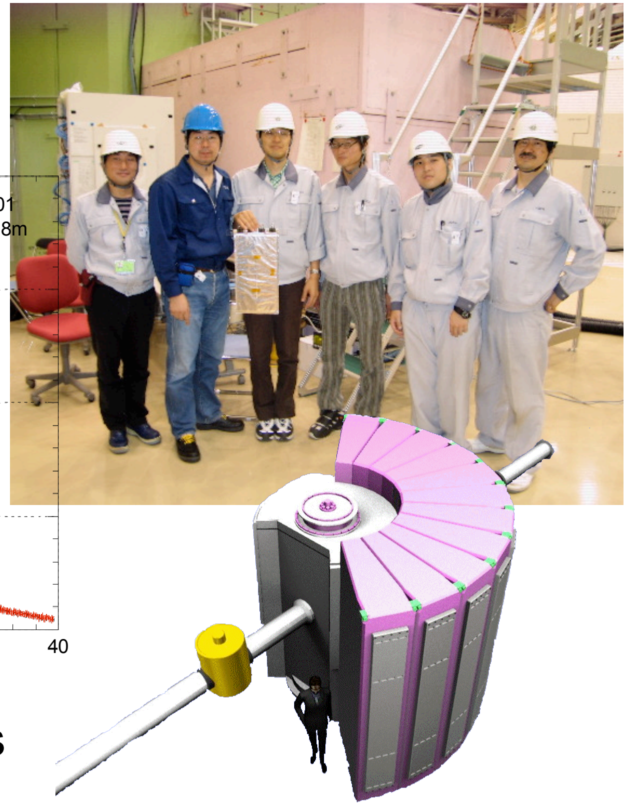
END

4SEASONS & AMATERAS will come on line soon.





The first neutrons on May 30.



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