19 Oct 2016

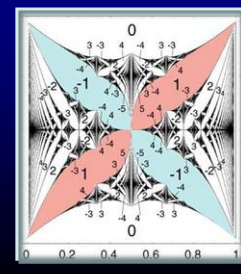
「量子物理学特論」

（東京理科大学 理学研究科 物理学専攻、2016年度冬学期）

講義資料（超伝導2） © H. Aoki

青木 秀夫
（東京大学理学系；産総研）

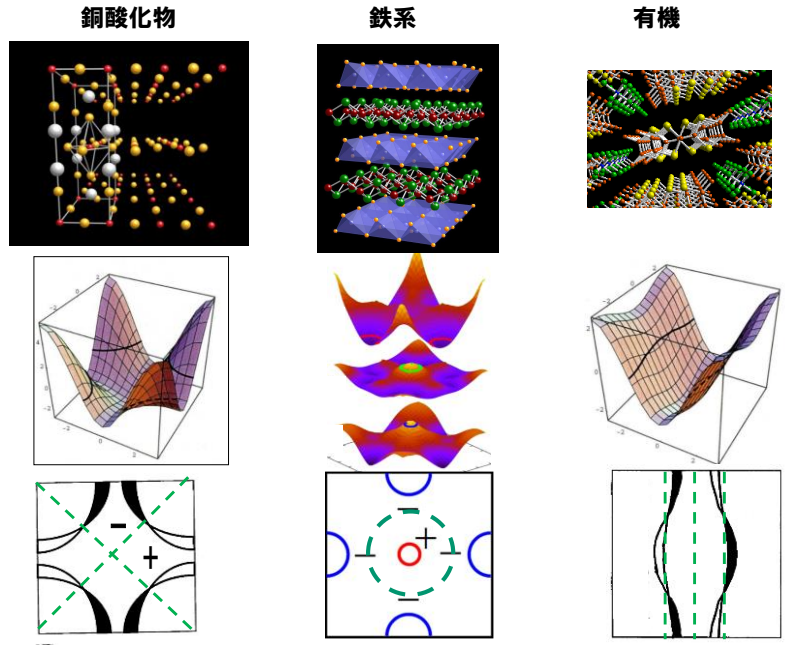


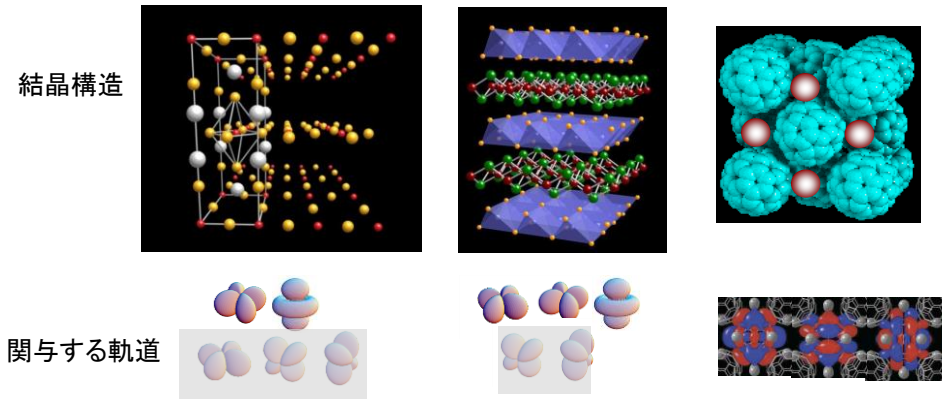


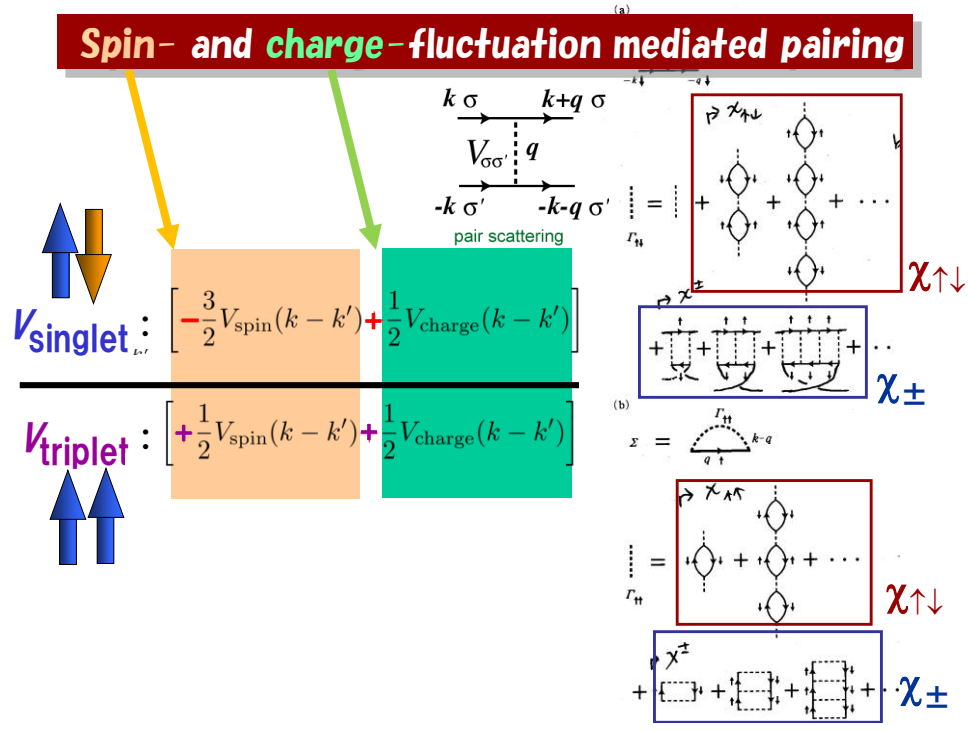
Non-phonon mechanism SC/SF

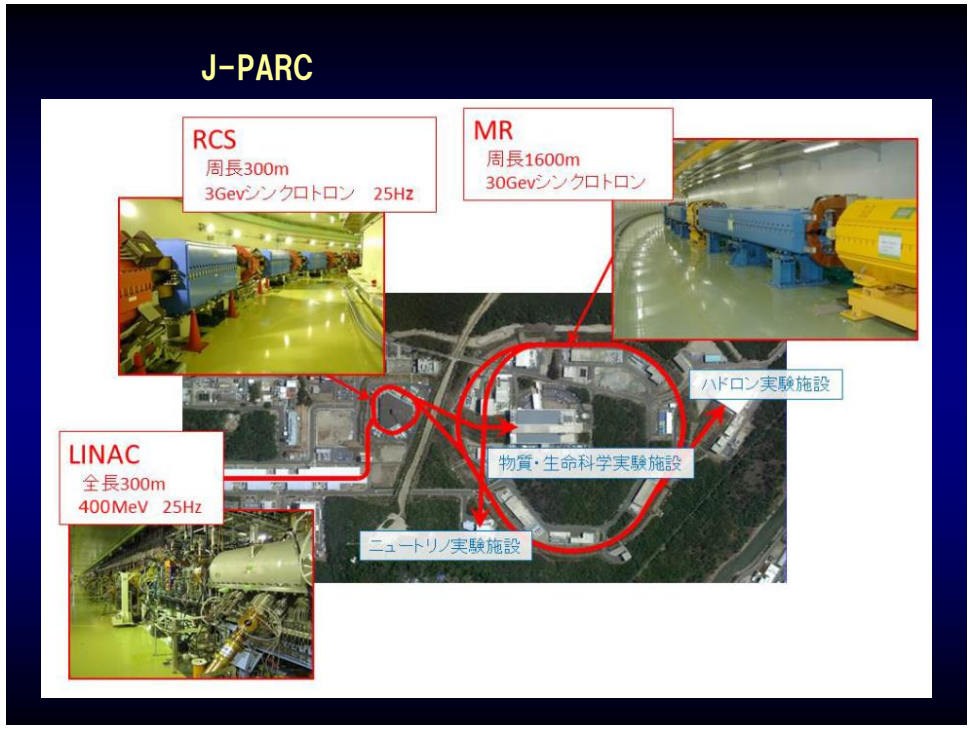
1. Heavy fermion
   ← spin-fluctuation mediated
2. Superfluid ^{3}He
   ← hard-core interaction
3. High-Tc cuprates
   ← spin-fluctuation mediated
4. Iron-based superconductors
   ← spin/charge fluctuation mediated

Kohn & Luttinger 1965; Chubukov 1993:
Repulsively interacting fermions
→ Attractive pairing channel exists for $T \to 0$
(weak-coupling, dilute case)


銅酸化物
鉄系
有機
−
+
+
−
−
+

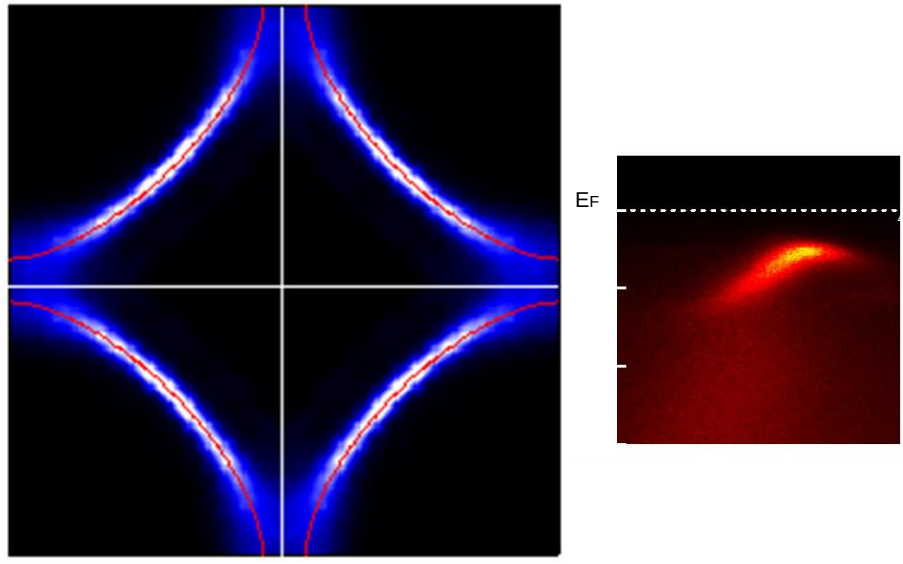

結晶構造
関与する軌道
(a) 銅系
(b) 鉄系
(c) フラレン


Spin- and charge-fluctuation mediated pairing
k σ
k+q σ
q
-k σ′
-k-q σ′
pair scattering
V_{singlet} : $\left[-\frac{3}{2}V_{\mathrm{spin}}(k-k')+\frac{1}{2}V_{\mathrm{charge}}(k-k')\right]$
V_{triplet} : $\left[+\frac{1}{2}V_{\mathrm{spin}}(k-k')+\frac{1}{2}V_{\mathrm{charge}}(k-k')\right]$
χ↑↓
χ±
χ↑↓
χ±


J-PARC
RCS
周長300m
3Gevシンクロトロン 25Hz
MR
周長1600m
30Gevシンクロトロン
LINAC
全長300m
400MeV 25Hz
ハドロン実験施設
物質・生命科学実験施設
ニュートリノ実験施設

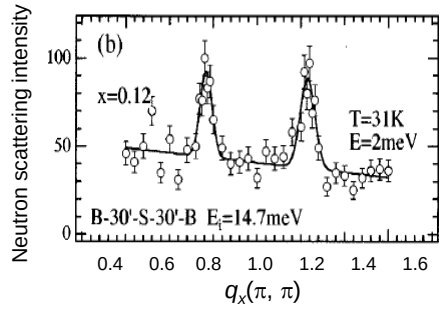
ARPES (angle-resolved photoemission spectroscopy)

(courtesy of Prof. Fujimori, Univ Tokyo)



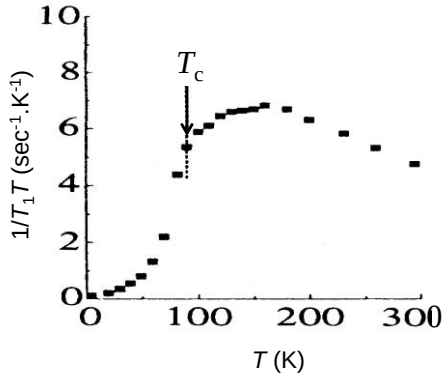
Magnetic structure

[Yamada et al, PRB **57**, 6165 (1998)]



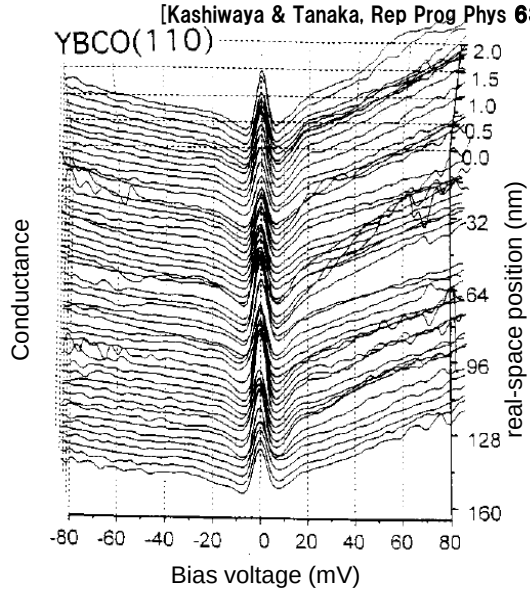
Pseudogap from NMR

[安岡、日本物理学会誌 **52**, 197 (1997)]



Zero-bias peak

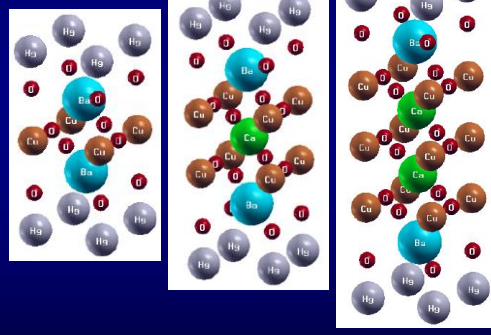
[Kashiwaya & Tanaka, Rep Prog Phys **63**, 1641 (2000)]



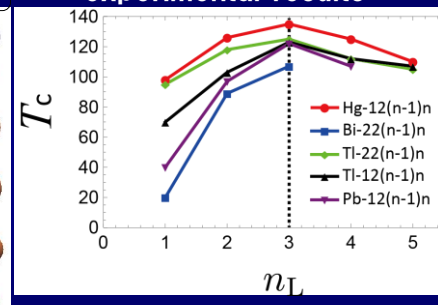
Multi-layered cuprates

e.g., $HgBa_2Cu_{n-1}O_n$

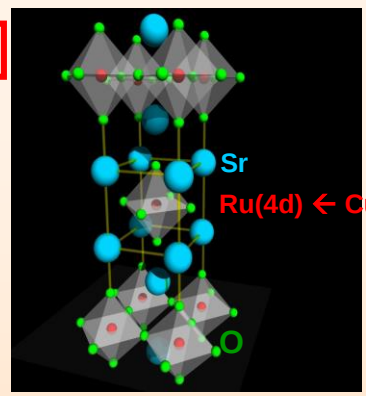
n = 1 *n* = 2 *n* = 3



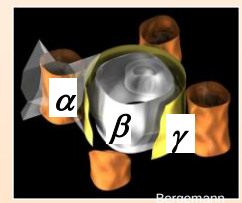
experimental results



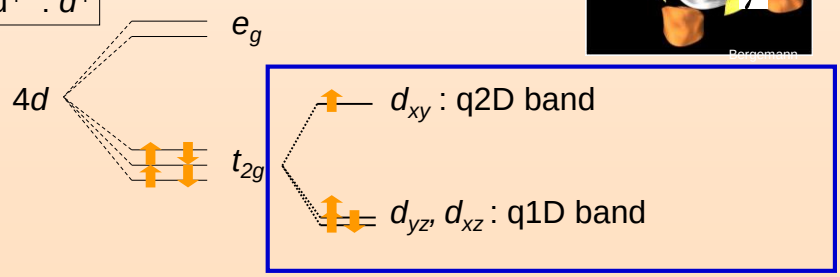
Sr_2RuO_4



(Nakatsuji & Maeno, 2000)



Ru^{4+} : d^4



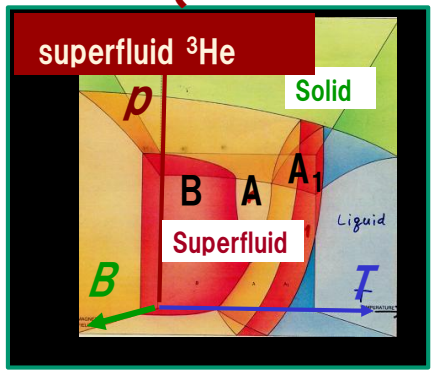
BCS paired state at $\nu = 5/2$

Triplet p+ip (Pfaffian state)

Trial wf: Moore-Read, Greiter-Wen-Wilczek 1991

Numerical: Morf 1998, Rezayi-Haldane 2000; Onoda-Mizusaki-Aoki 2003

Experiment: Willett-West-Pfeiffer 1998, 2002



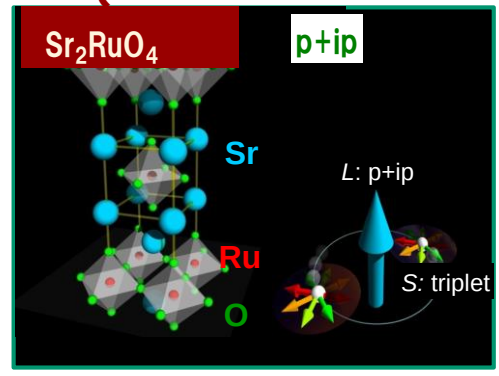
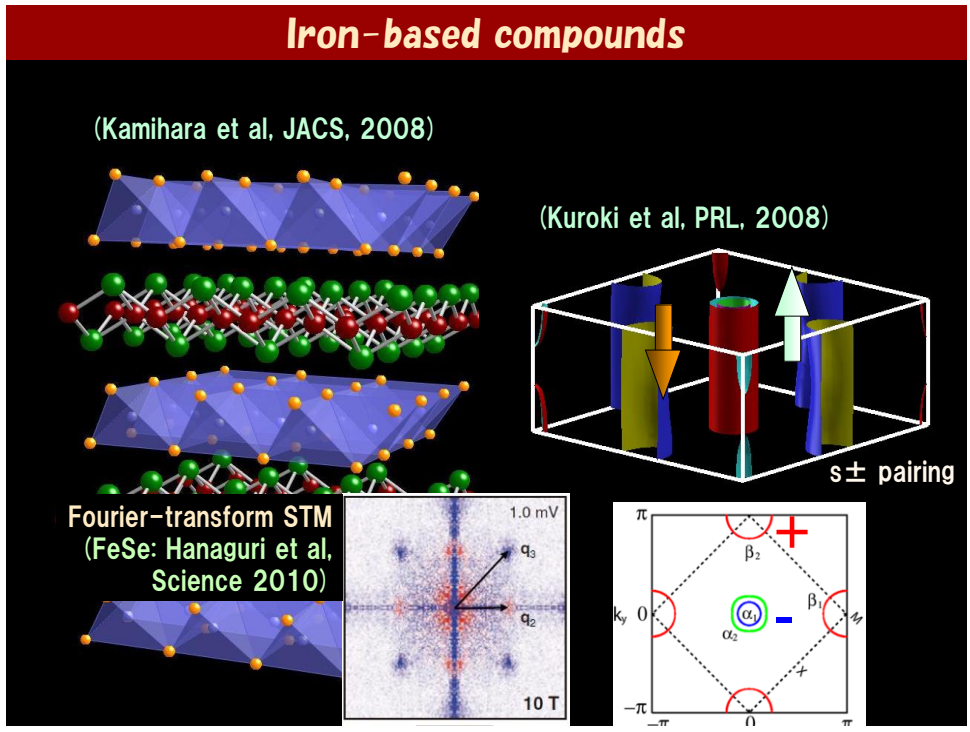
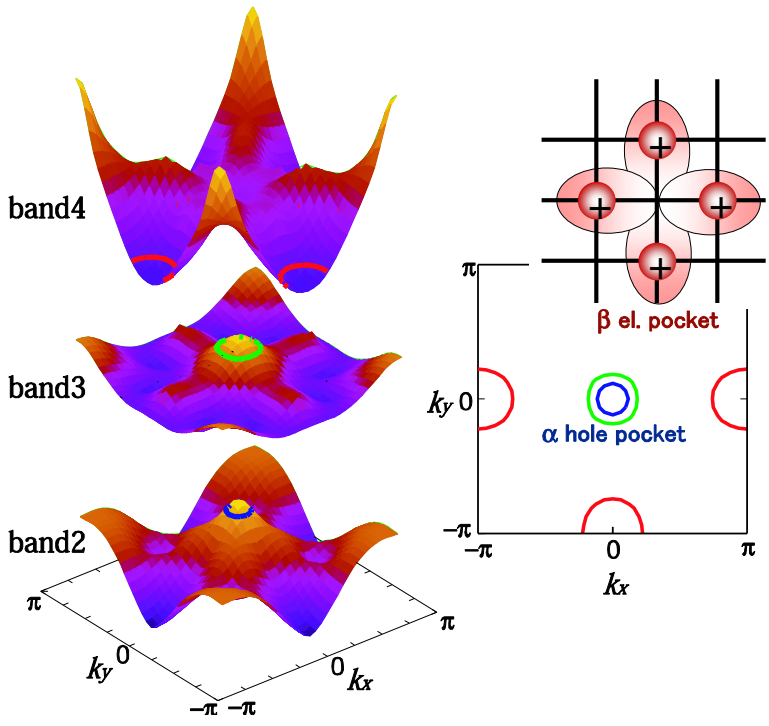


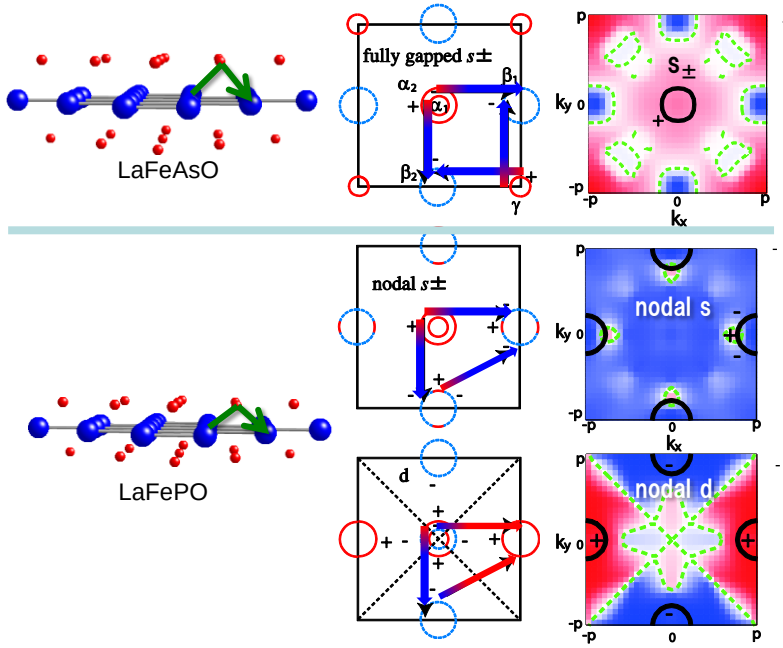
Table of topological insulators / superconductors

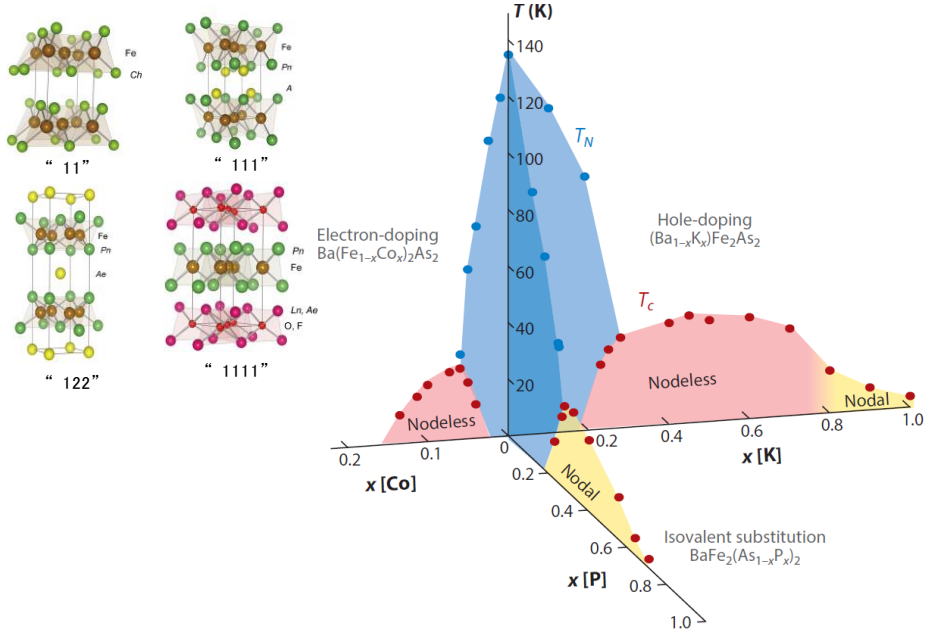
		T-reversal Θ^2	Particle-hole Ξ^2	Chiral $\Xi\Theta$	$d=1$	$d=2$	$d=3$
Standard (Wigner-Dyson)	A (unitary)	x	x	x	--	Z IQHE	--
	AI (orthogonal)	+1	x	x	--	QSHE	--
	AII (symplectic)	-1	x	x	--	Z_2	Z_2 Z_2TI
Chiral	AIII (chiral unitary)	x	x	1	Z	--	Z
	BDI (chiral orthogonal)	+1	+1	1	Z	SSH, Creutz	--
	CII (chiral symplectic)	-1	-1	1	Z	--	Z_2
BdG (SC)	D (p-wave SC)	x	+1	x	p SC Z_2	Z	p+ip SC --
	C (d-wave SC)	x	-1	x	--	Z	d+id SC --
	DIII (p-wave TRS SC)	-1	+1	1	Z_2	Z_2	Z ^{3}He-B
	CI (d-wave TRS SC)	+1	-1	1	--	--	Z

(Altland-Zirnbauer 1997; Schnyder-Ryu-Furusaki-Ludwig 2008; Hasan-Kane, RMP 2010)

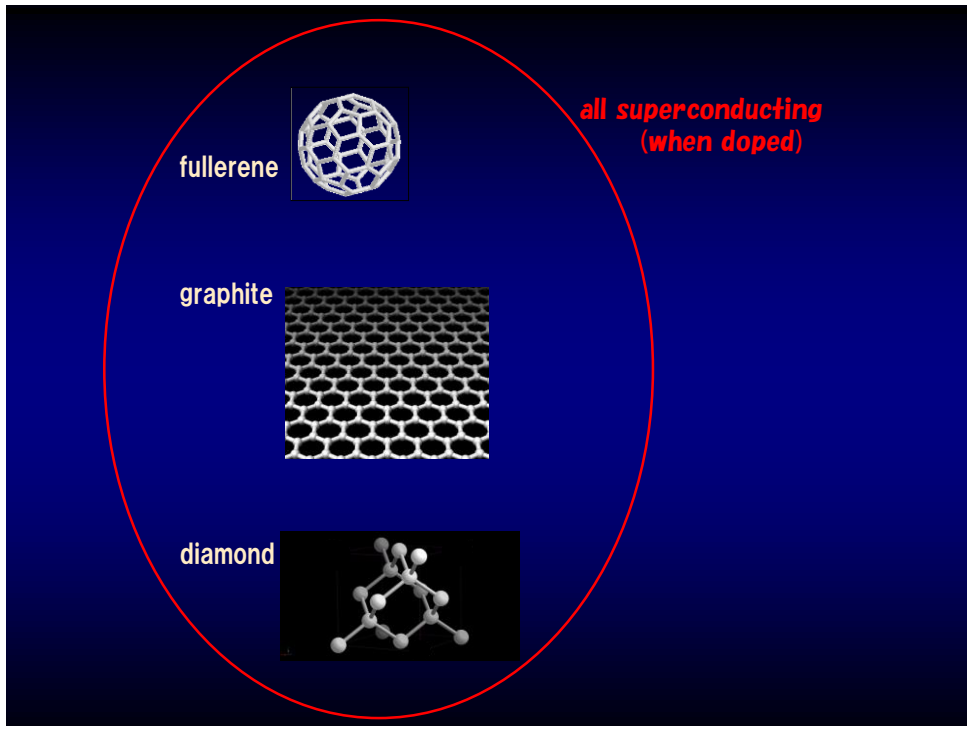

Iron-based compounds
(Kamihara et al, JACS, 2008)
(Kuroki et al, PRL, 2008)
s± pairing
Fourier-transform STM
(FeSe: Hanaguri et al,
Science 2010)
1.0 mV
10 T


band4
band3
band2
β el. pocket
α hole pocket

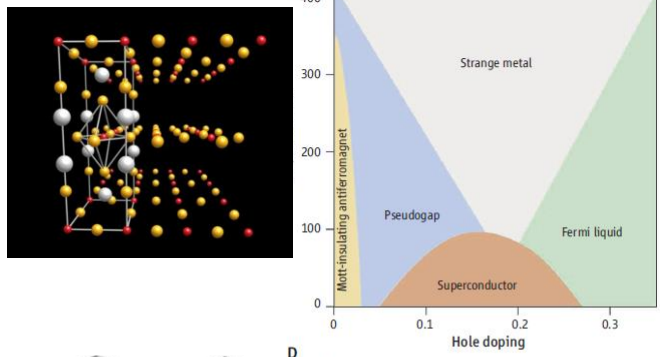


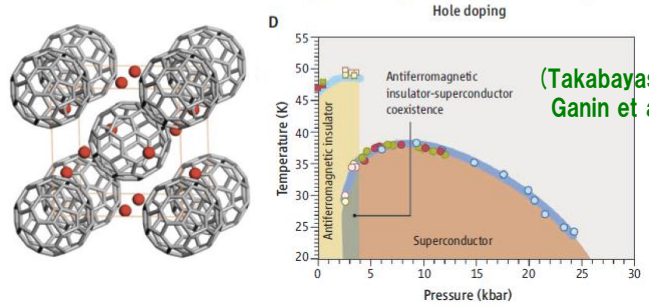


(Shibauchi & Matsuda, Ann Rev Condens Matt Phys 2014)



(Tosatti, Science 2009)

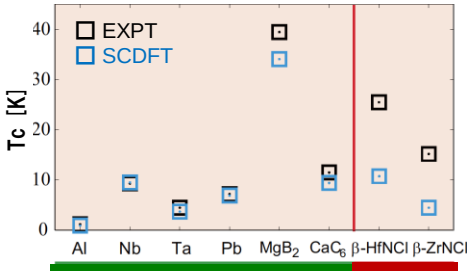




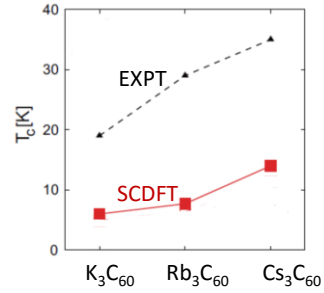
(Takabayashi et al, Science 2009;
Ganin et al, Nature 2010)

Density functional theory for superconductors (SCDFT)

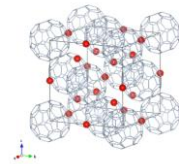
(Lüders et al, PRB 2005; Marques et al, PRB 2005)



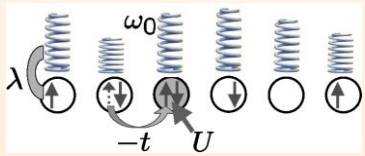
(Akashi et al, PRB 2012)



(Akashi & Arita, PRB 2013)

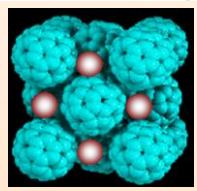


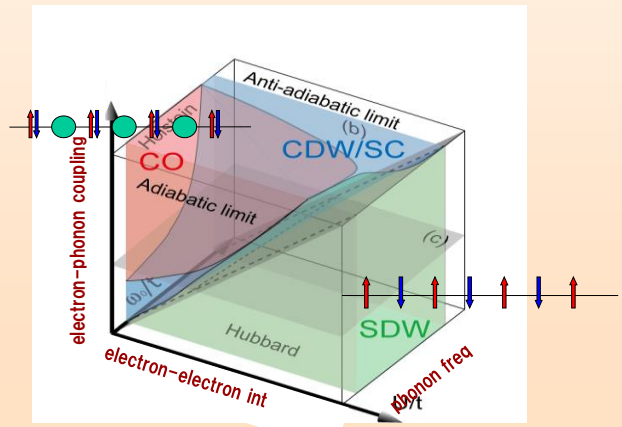
el-el + el-ph



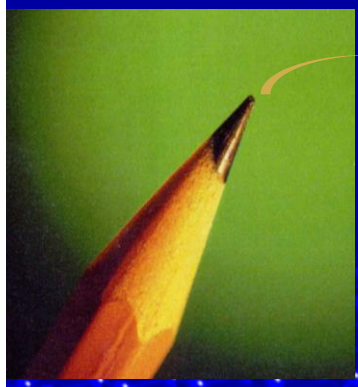
$W \sim \hbar\omega \sim U$

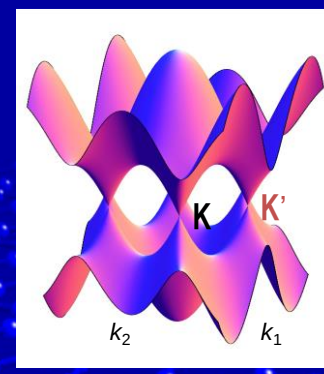
→ ~~adiabatic~~ / ~~antiadiabatic~~





Graphene — massless Dirac system

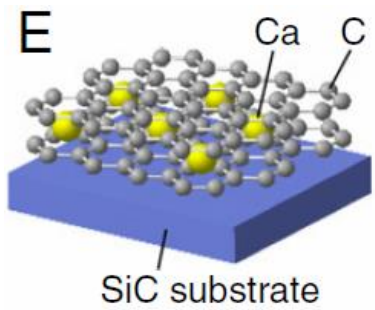


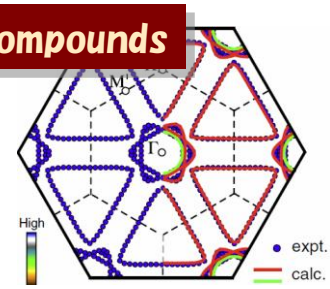


Weyl neutrino



Graphite intercalation compounds





Bilayer CaC_6 -- a thinnest GIC
(Kanetani et al, PNAS 2012)

Graphene

CrossMark click for updates

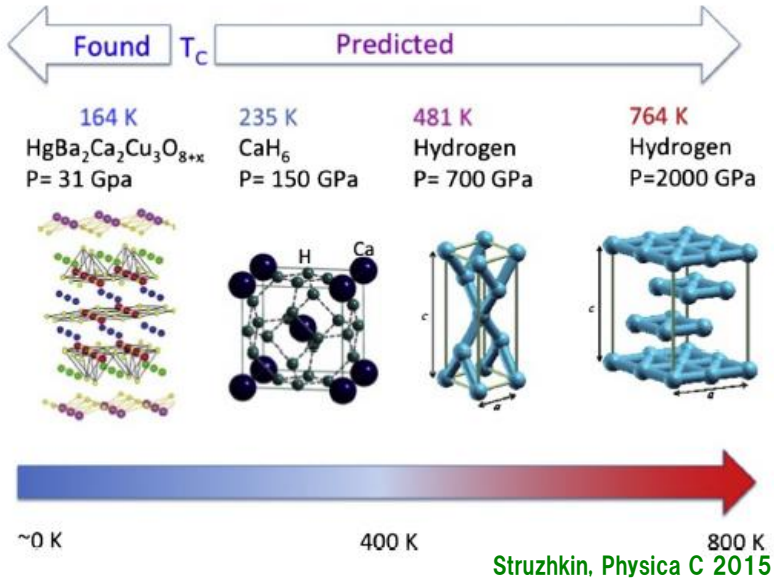
Evidence for superconductivity in Li-decorated monolayer graphene (2015) Tc = 6 K

B. M. Ludbrook[a,b], G. Levy[a,b], P. Nigge[a,b], M. Zonno[a,b], M. Schneider[a,b], D. J. Dvorak[a,b], C. N. Veenstra[a,b], S. Zhdanovich[b,c], D. Wong[a,b], P. Dosanjh[a,b], C. Straßer[d], A. Stöhr[d], S. Forti[d], C. R. Ast[d], U. Starke[d], and A. Damascelli[a,b,1]

[a]Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, Canada; [b]Quantum Matter Institute, University of British Columbia, Vancouver, BC V6T 1Z4, Canada; [c]Department of Chemistry, University of British Columbia, Vancouver, BC V6T 1Z1, Canada; and [d]Max Planck Institute for Solid State Research, 70569 Stuttgart, Germany

Edited by J. C. Séamus Davis, Cornell University, Ithaca, NY, and approved August 10, 2015 (received for review May 28, 2015)

High-Tc superconductors



Struzhkin, Physica C 2015

LETTER

(Nature 2015) doi:10.1038/nature14964

Conventional superconductivity at 203 kelvin at high pressures in the sulfur hydride system

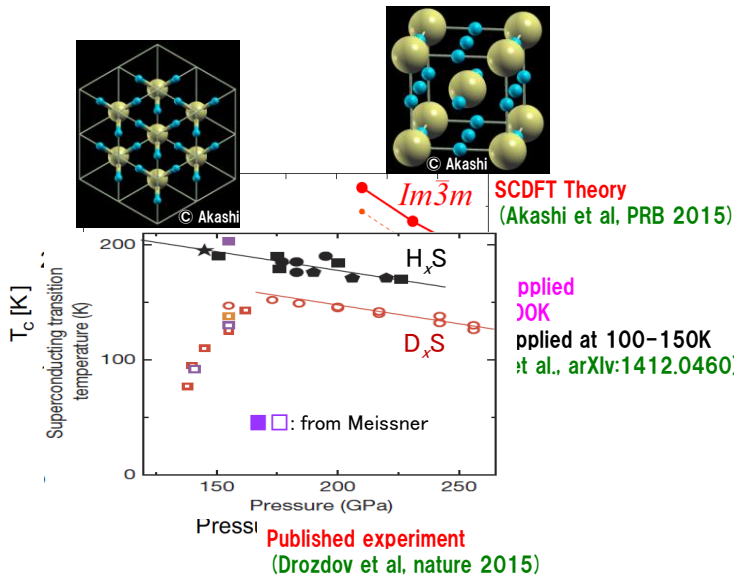
A. P. Drozdov[1]*, M. I. Eremets[1]*, I. A. Troyan[1], V. Ksenofontov[2] & S. I. Shylin[2]

SUPERCONDUCTIVITY

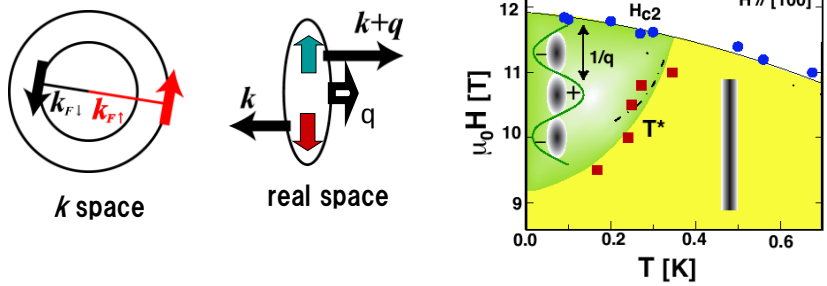
Extraordinarily conventional

Attitudes to high-temperature superconductivity have swung from disbelief to a conviction that it occurs only 'unconventionally'. But conventional superconductivity is now reported at record high temperatures. SEE LETTER P.73

IGOR I. MAZIN his


© Akashi
© Akashi
$Im\bar{3}m$
SCDFT Theory
(Akashi et al, PRB 2015)
H_xS
D_xS
pplied
)OK
pplied at 100-150K
t al., arXiv:1412.0460)
T_c [K]
Superconducting transition temperature (K)
200
100
0
150
200
250
Pressure (GPa)
■□: from Meissner
Press
Published experiment
(Drozdov et al, nature 2015)

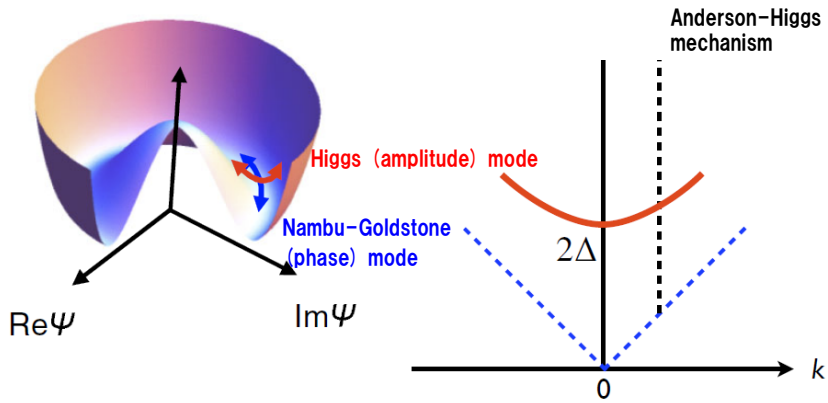
FFLO


$k_{F\downarrow}$ $k_{F\uparrow}$
k space
k+q
k
q
real space
CeCoIn$_5$
H // [100]
H_{c2}
1/q
T*
μ_0H [T]
12
11
10
9
0.0
0.2
0.4
0.6
T [K]

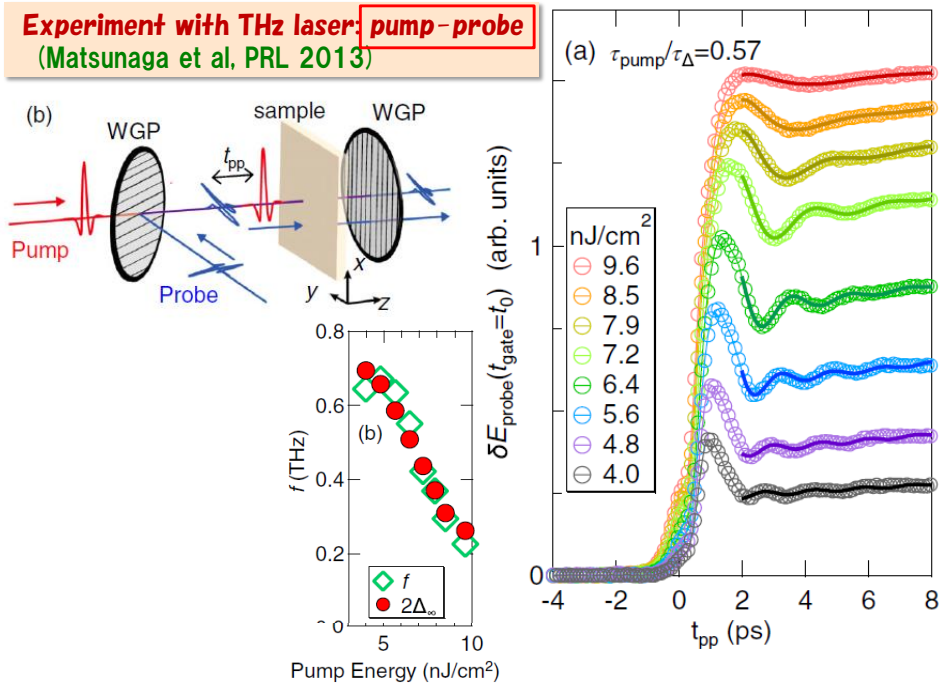
Excitations in superconductors



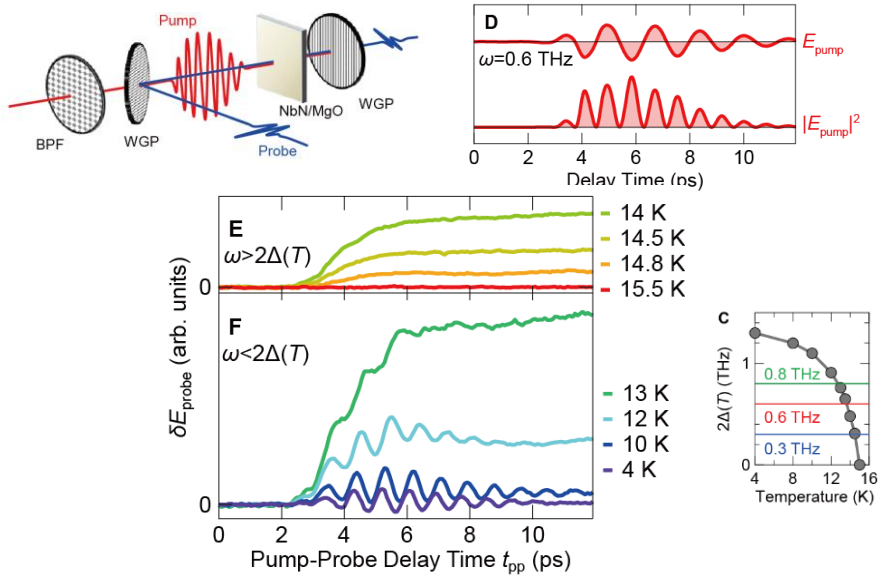
Collective excitations in superconductors



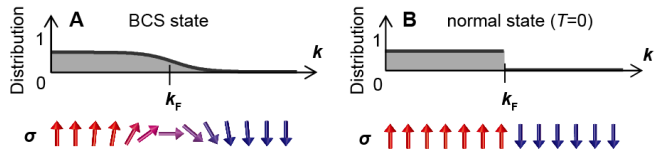
Experiment with THz laser: pump-probe
(Matsunaga et al, PRL 2013)

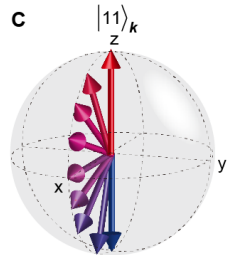


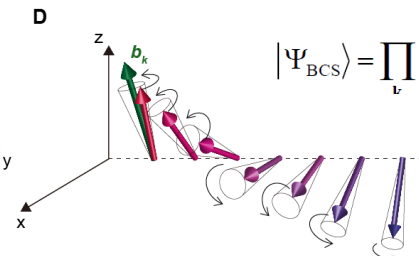
Experiment with THz laser: during pump
(Matsunaga, Tsuji, Fujita, Sugioka, Makise, Uzawa, Terai, Wang, Aoki, and Shimano, Science 2014)



Anderson (1958) pseudospin description







$$|\Psi_{\mathrm{BCS}}\rangle = \prod_{\mathbf{k}} \left(u_{\mathbf{k}} |00\rangle_{\mathbf{k}} + v_{\mathbf{k}} |11\rangle_{\mathbf{k}} \right),$$

$$H_{\mathrm{BCS}} = 2\sum_k \boldsymbol{b}_k \cdot \boldsymbol{\sigma}_k$$

$$\begin{cases} \sigma_k^x = \frac{1}{2}(c_{k\uparrow}^\dagger c_{-k\downarrow}^\dagger + c_{-k\downarrow} c_{k\uparrow}) & \text{Re (pair)} \\ \sigma_k^y = \frac{1}{2i}(c_{k\uparrow}^\dagger c_{-k\downarrow}^\dagger - c_{-k\downarrow} c_{k\uparrow}) & \text{Im (pair)} \\ \sigma_k^z = \frac{1}{2}(c_{k\uparrow}^\dagger c_{k\uparrow} - c_{-k\downarrow} c_{-k\downarrow}^\dagger) & \text{mom distribution} \end{cases}$$

$$\boldsymbol{b}_k = \left(-\Delta', -\Delta'', \frac{\epsilon_{k-eA(t)} + \epsilon_{k+eA(t)}}{2} \right)$$

$$\Delta = \Delta' + i\Delta'' = U \sum_k \left(\sigma_k^x + i\sigma_k^y \right)$$

$$\frac{\partial}{\partial t} \boldsymbol{\sigma}_k = 2\boldsymbol{b}_k \times \boldsymbol{\sigma}_k,$$

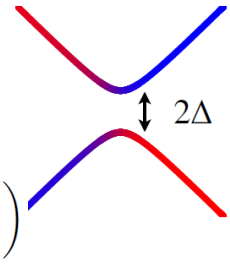
Laser-SC coupling ~ A^2 (Matsunaga et al, Science 2014)

Bogoliubov-de Gennes eqn

$$i\partial_t \Psi_k = \begin{pmatrix} \epsilon_{k-eA(t)} & -\Delta^* \\ -\Delta & -\epsilon_{k+eA(t)} \end{pmatrix} \Psi_k$$

electron (↑) hole (↑)

$$\Psi_k = \begin{pmatrix} c_{k\uparrow} \\ c_{-k\downarrow}^\dagger \end{pmatrix}$$



$$\frac{\varepsilon_{\mathbf{k}-e\mathbf{A}(t)} + \varepsilon_{\mathbf{k}+e\mathbf{A}(t)}}{2} = \varepsilon_{\mathbf{k}} + \frac{e^2}{2} \sum_{i,j} \frac{\partial^2 \varepsilon_{\mathbf{k}}}{\partial k_i \partial k_j} A_i(t) A_j(t) + O(A^4)$$

$$= \varepsilon_{\mathbf{k}} - \frac{e^2}{2} \sum_{i,j} \frac{\partial^2 \varepsilon_{\mathbf{k}}}{\partial k_i \partial k_j} \frac{E_i E_j}{\omega^2} \exp(i2\omega t) + O(A^4),$$

$$\boldsymbol{b}_k = \left(-\Delta', -\Delta'', \frac{\epsilon_{k-eA(t)} + \epsilon_{k+eA(t)}}{2}\right)$$

electron hole

$$\Delta = U \sum_k (\sigma_k^x + i\sigma_k^y)$$

self-consistency
→ collective pseudospin precession

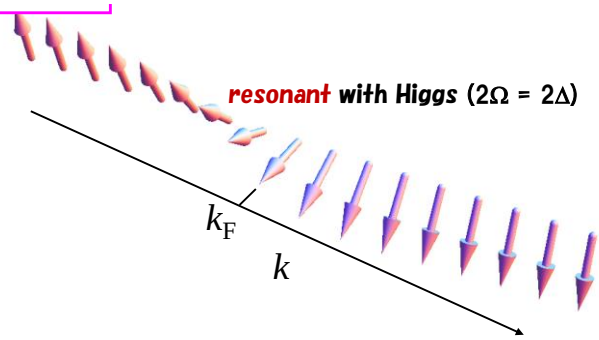
$$\frac{\partial}{\partial t}\boldsymbol{\sigma}_k = 2\boldsymbol{b}_k \times \boldsymbol{\sigma}_k$$ Bloch eqn of motion

(Matsunaga et al, Science 2014)

as it should, since

Higgs
(= neutral
scalar particle)

resonant with Higgs ($2\Omega = 2\Delta$)

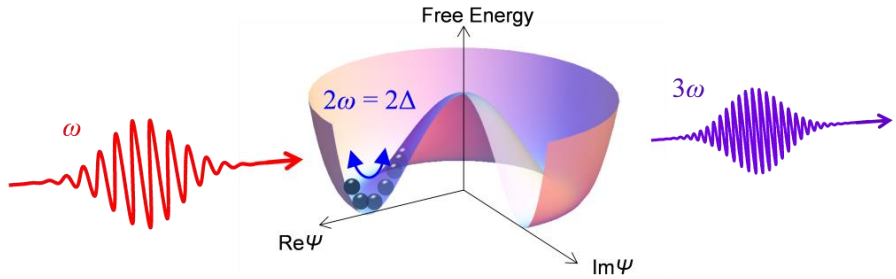


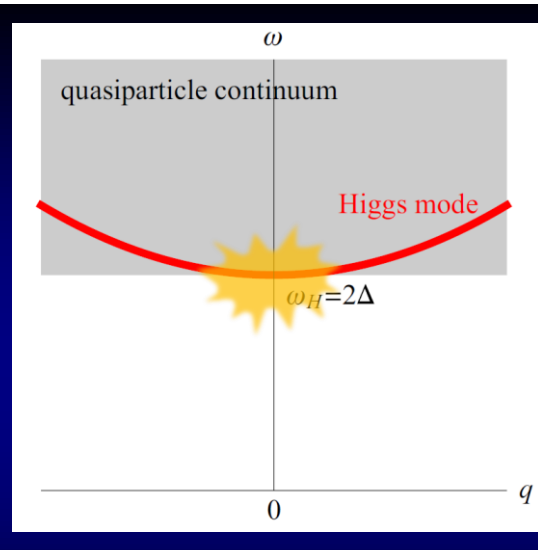
(Matsunaga et al, Science 2014)

Nonlinear "London eqn"

$$j_{NL}^{(3)}(t) \propto \frac{e^2\Delta}{U} \underbrace{A(t)\delta\Delta(t)}_{\sim A^2}$$

$\Omega + 2\Omega = 3\Omega$ (THG)





Collective Higgs mode and quasiparticle excitations
-- both contribute to the 2Δ mode (Cea et al, PRB2016)

→ go beyond BCS
(Tsuji, Murakami & Aoki, arXiv:1606.05024)