Quasiparticle Étouffée: unconventional superconductors probed by magnetic field

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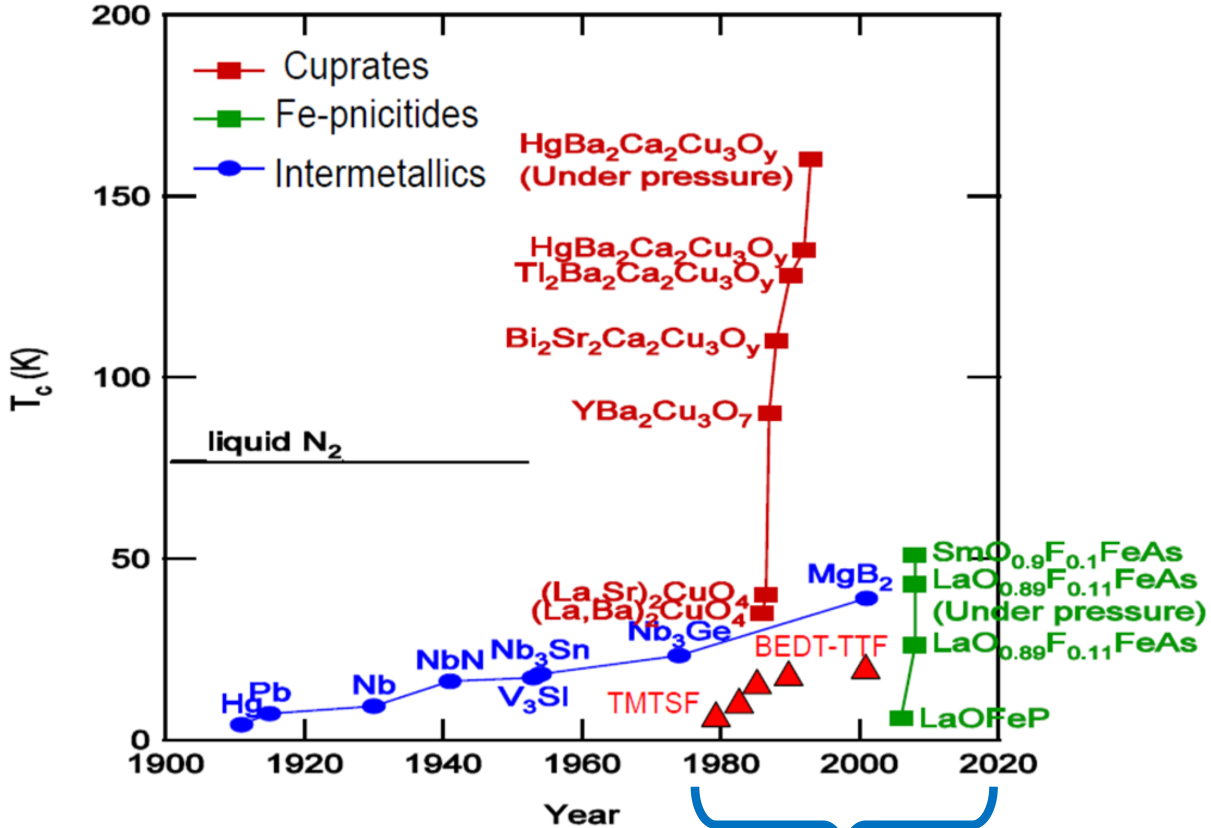
PRL **96,** 237001 (2006)
PRB **75**, 224501 (2007)
PRB **75**, 224502 (2007)
PRB **79**, 064525 (2009)
PRB **80**, 224525 (2009)
PRB **81**, 094527 (2010)
PRL **105**, 187004 (2010)
PRB **84**, 060507(R) (2011)
PRL **109**, 187006 (2012)
PRB **87**, 174514 (2013).

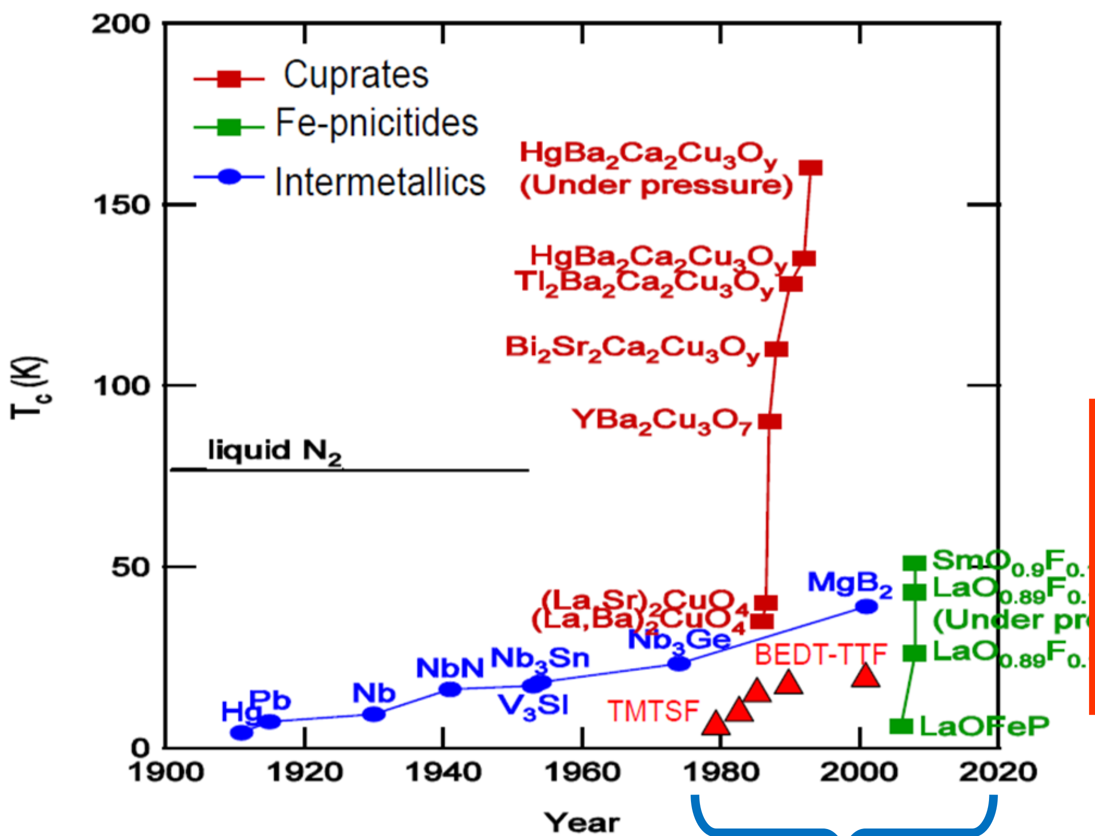
What this talk is about



Superconducting order breaks some symmetry of the crystal lattice

Unconventional superconductors

What this talk is about



Symmetry of superconducting state related to origin of superconductivity

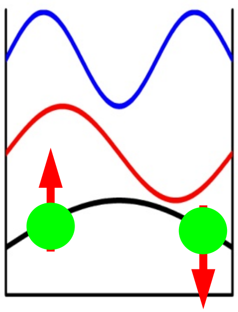
How can we determine the symmetry of the superconducting state and match it with material-specific theories of superconductivity?

Superconducting order breaks some symmetry of the crystal lattice

Unconventional superconductors

Metallic solids

Real space



Bloch's theorem:

wave vector $k = 2\pi / \lambda$

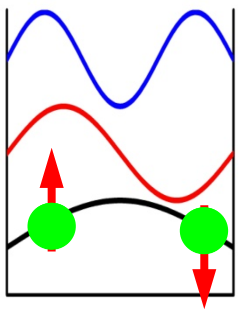
energy $\xi(k)$

Pauli principle:

two electrons per state

Metallic solids

Real space



Bloch's theorem:

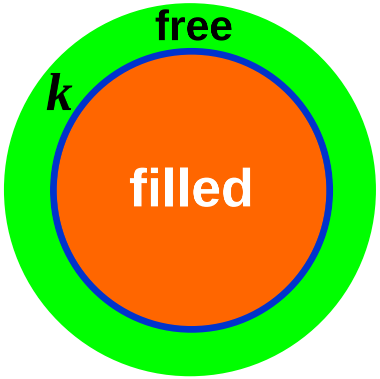
wave vector $k = 2\pi / \lambda$

energy $\xi(k) \propto k^2$

Pauli principle:

two electrons per state

Momentum space



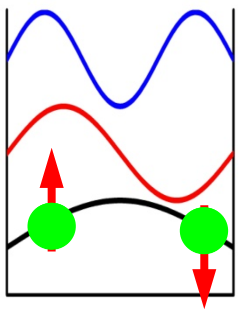
Fill states up to the

Fermi energy $E_F \sim 10^4 K$

Fermi surface $\xi(k_F) = E_F$

Metallic solids

Real space



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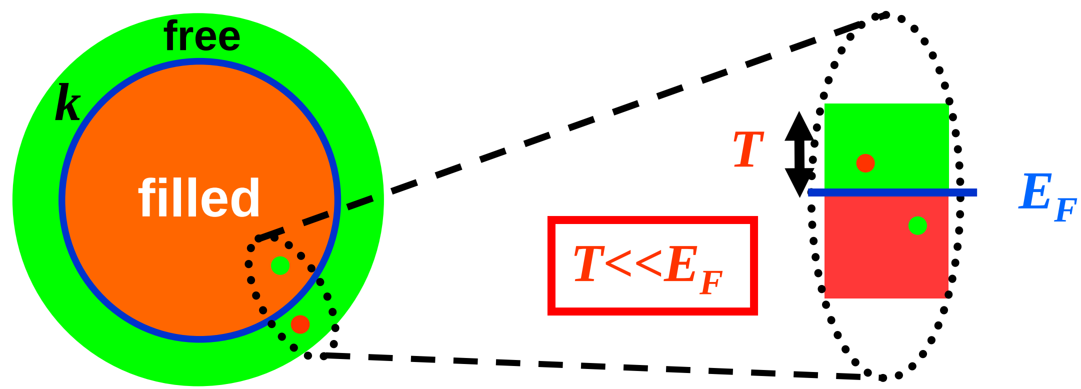


Fill states up to the

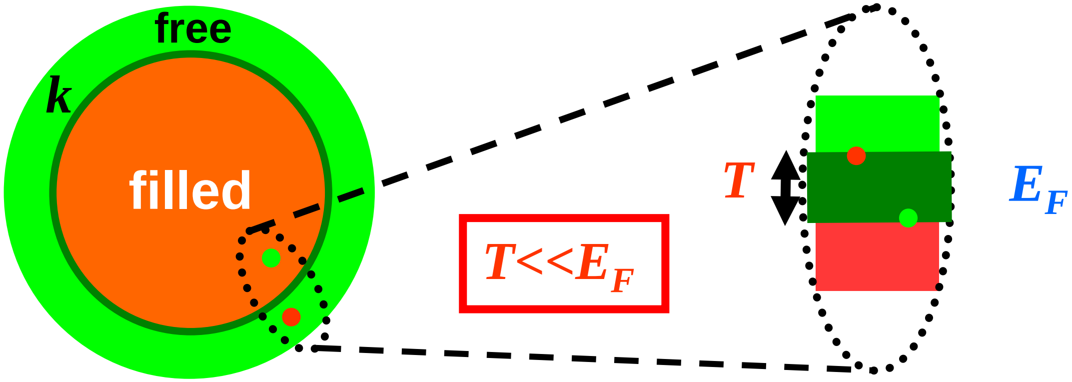
Fermi energy $E_F \sim 10^4 K$

Energy space

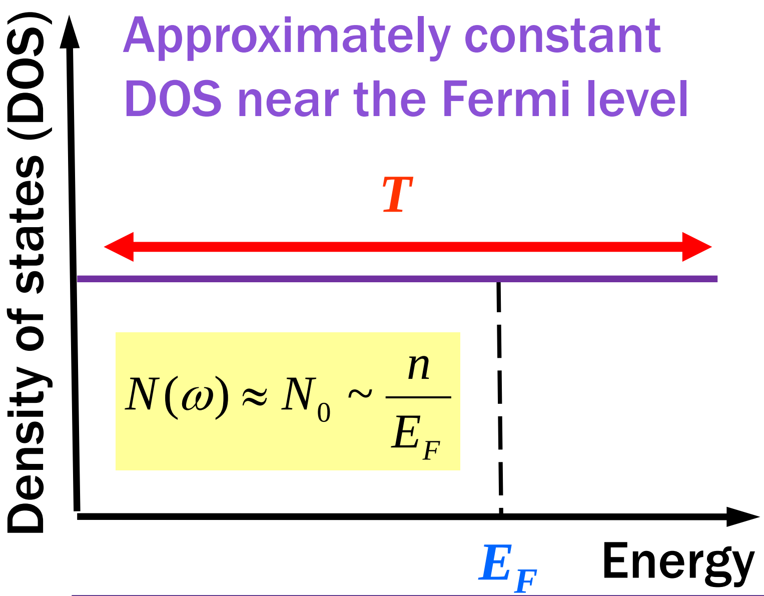
"quasiparticle" excitations carry entropy, charge, …

Live only near the Fermi energy/Fermi surface

Low-energy properties



Absorbed heat increases the number/energy of excitations:



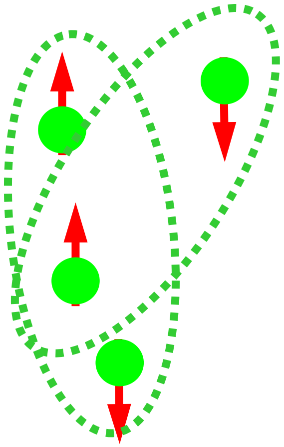
At temperature T

# of excited particles	$n_e \approx N_0 T$
Total thermal energy	$\Delta E \approx n_e kT \propto N_0 kT^2$
Heat capacity (electronic)	$C \propto N_0 kT \sim nk \frac{T}{E_F}$

Basics of superconductivity

pairing of electrons
near the Fermi surface

Bose-condensation
of Cooper pairs
(into ground state)



Order parameter

$$\Delta(\mathbf{r}) = e^{i\varphi(\mathbf{r})}\,|\,\Delta(\mathbf{r})\,|$$

~ pair wave function
phase and amplitude

$$\Psi(\mathbf{r})$$

BCS theory:

J. Bardeen, L. Cooper, J.R.Schrieffer, 1957

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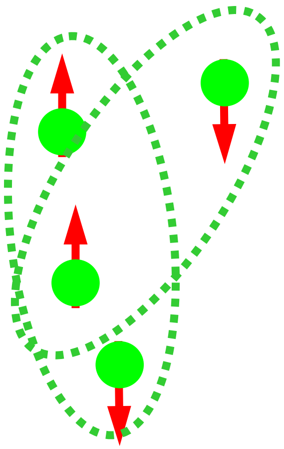

Order parameter

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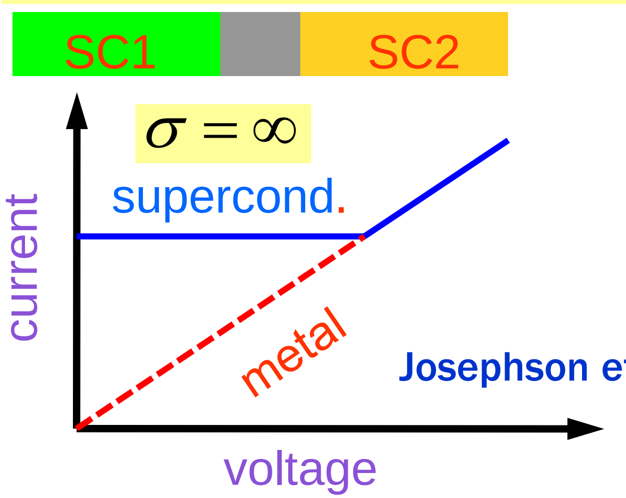
~ pair wave function $\Psi(\mathbf{r})$
phase and amplitude

phase = supercurrent

$$j_s \propto \Psi^*\nabla\Psi - \Psi\nabla\Psi^* \propto |\,\Delta(\mathbf{r})\,|\left[\nabla\varphi(\mathbf{r})\right]$$



Josephson effect

Basics of superconductivity

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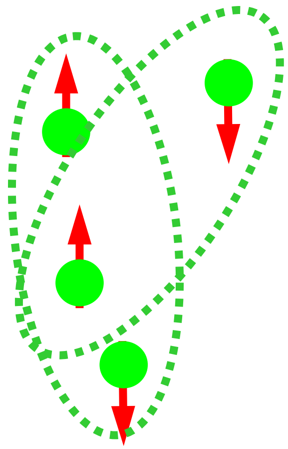

Order parameter

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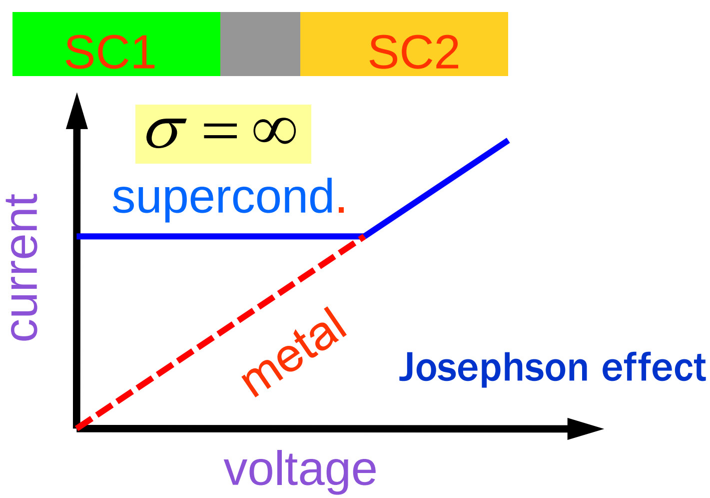
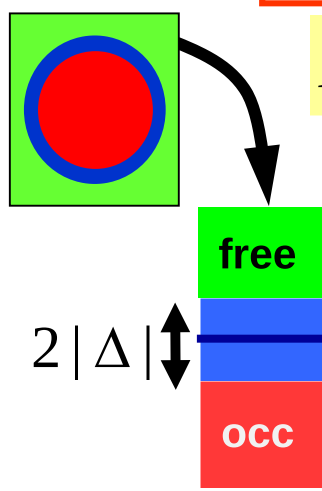
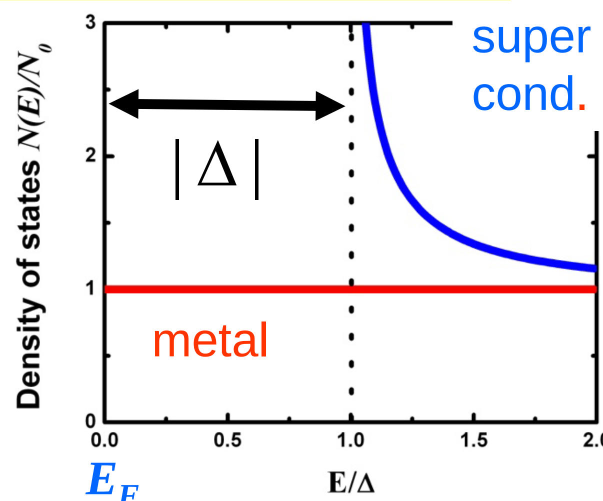
$$j_s \propto |\Delta(\mathbf{r})|\left[\nabla\varphi(\mathbf{r})\right]$$



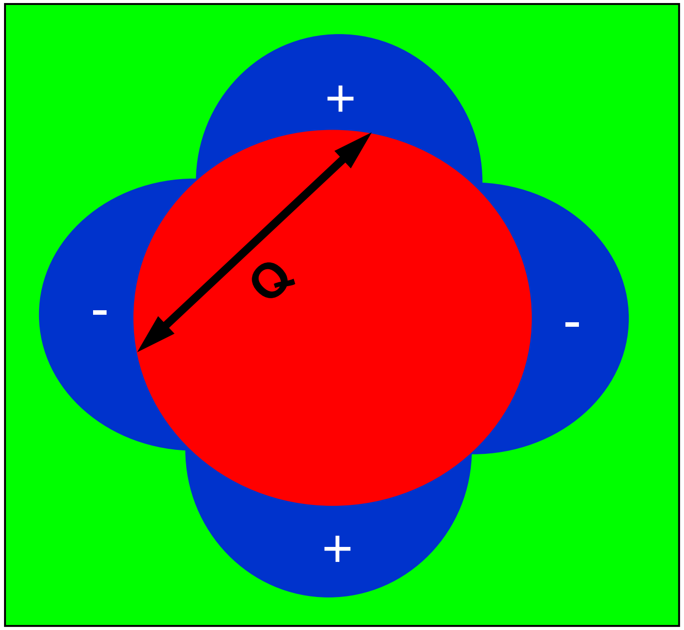
Amplitude= energy gap

$$E(\mathbf{k}) = \sqrt{\zeta^2(\mathbf{k}) + |\Delta(\mathbf{k})|^2}$$





Anisotropic gaps in correlated systems



Strong Coulomb repulsion:

- no on-site pairing
- pairing peaked at finite Q

Anisotropic order parameter/gap

- Symmetry-enforced nodes

$$\Delta(\mathbf{k}) \propto \cos k_x - \cos k_y$$

Cuprates, heavy fermions

- "Accidental" nodes/strong anisotropy

$$\Delta(\mathbf{k}) \propto a + b(\cos k_x + \cos k_y)$$

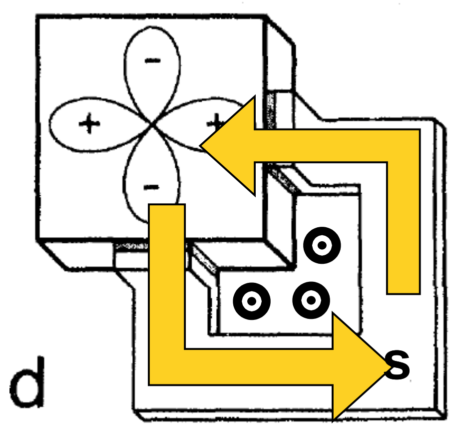
pnictides

Know gap shape ≈ know pairing interaction ≈ optimize materials

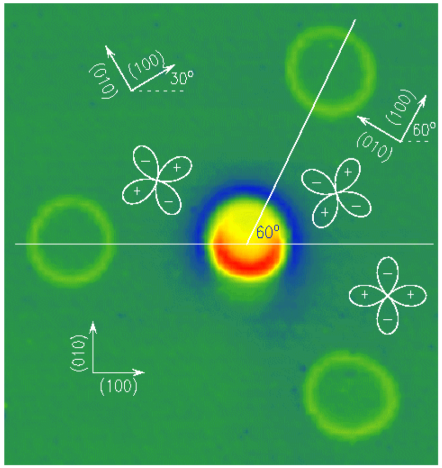
How to determine the shape of the gap on the FS?

Gap anisotropy I: phase

- **Josephson effect**: $\Delta_{1,2} = |\Delta_{1,2}| e^{i\phi_{1,2}}$ $j_s \propto \phi_1 - \phi_2$
- The only true test of the phase and sign change
- Phase-sensitive, but also surface sensitive



D.Van Harlingen et al.



J. R. Kirtley et al.

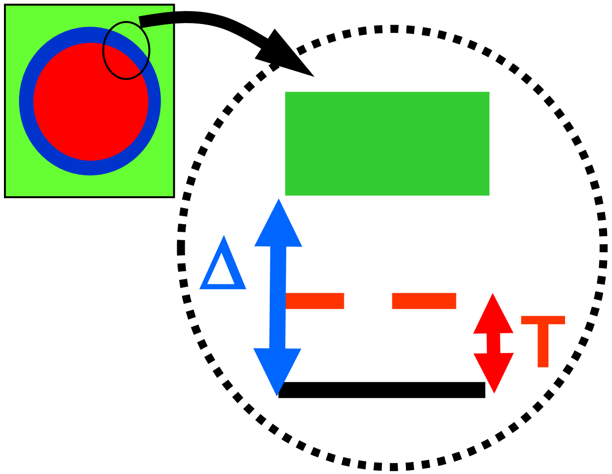
Detectable magnetic field above the loop

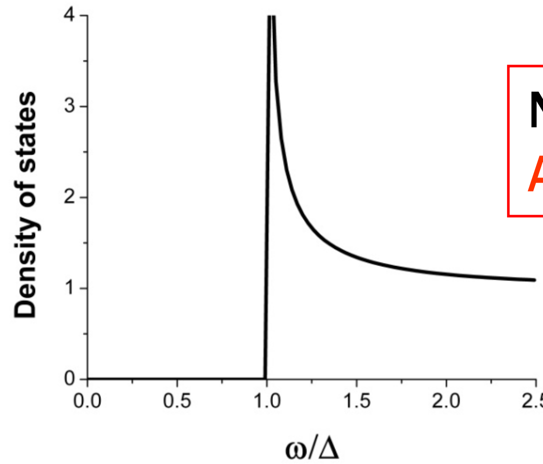
Cuprates, but probably no other systems…

What if minima/no sign change?

Gap anisotropy II: amplitude

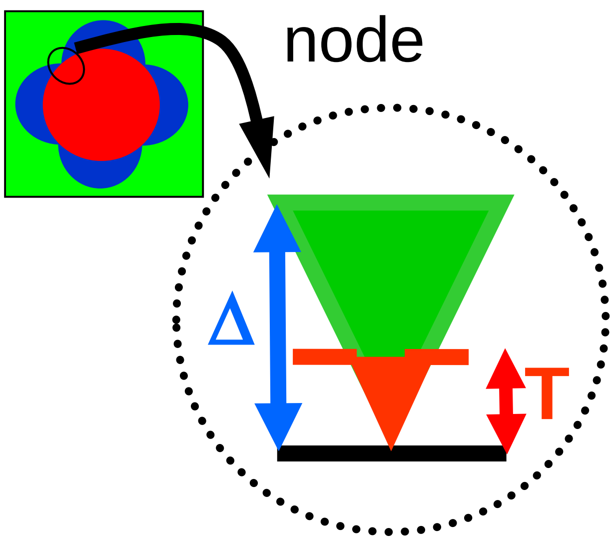
Density of states

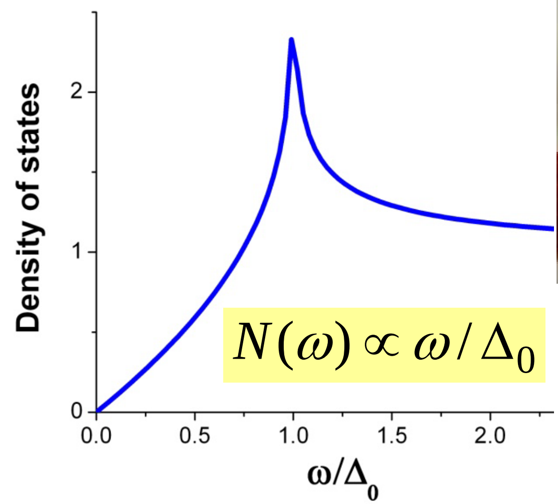




No excitations at low T

Activated behavior $e^{-\Delta/T}$

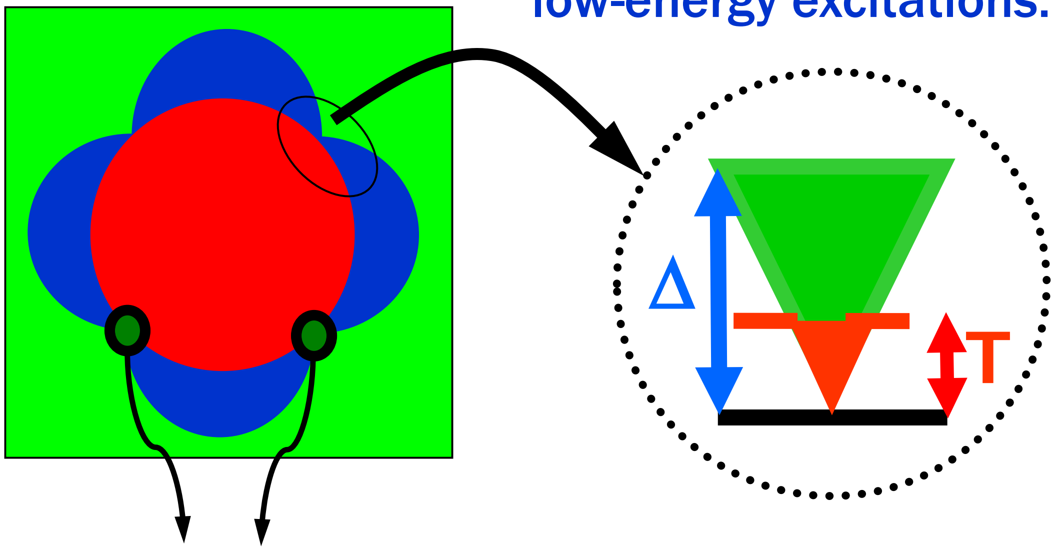


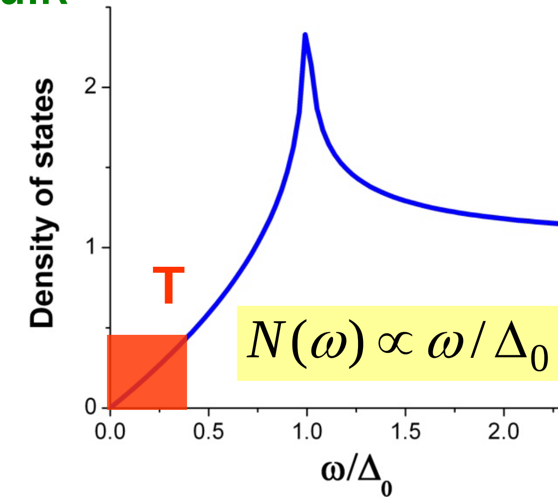


Power laws

Gap anisotropy II: amplitude

low-energy excitations: bulk





probe small gap regions

$$E(\mathbf{k}) = \sqrt{\zeta^2(\mathbf{k}) + |\Delta(\mathbf{k})|^2}$$

Unpaired quasiparticles have entropy: heat capacity or thermal conductivity

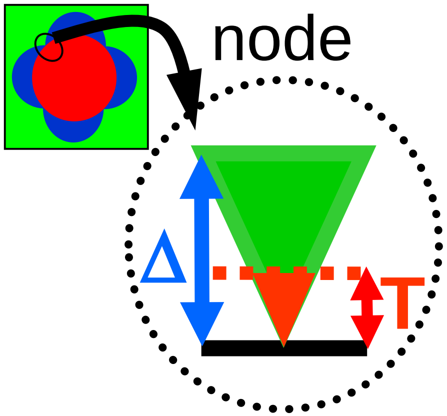
created by temperature, disorder or magnetic field

all quasiparticles

only mobile quasiparticles

Probing nodal quasiparticles

Existence of nodes



$N(\omega) \propto \omega / \Delta_0$

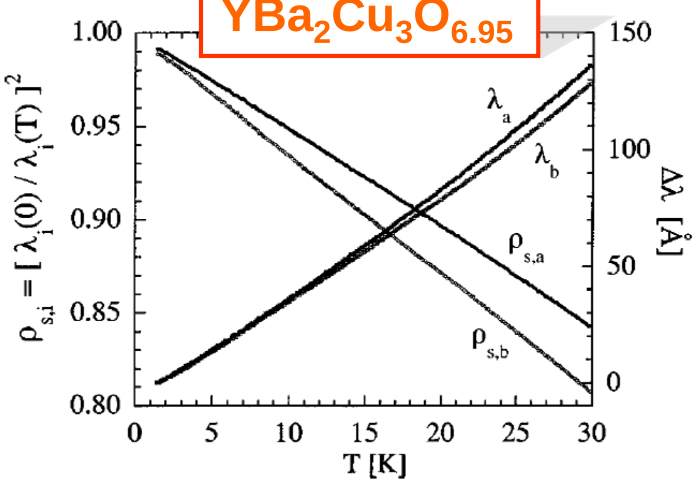
QP density $\propto T$

$\Delta\rho_s \propto T$

Spec. heat $C(T) \propto T^2$

universal κ/T

YBa$_2$Cu$_3$O$_{6.95}$



A. Carrington et al. 1999

Location of nodes

Probing nodal quasiparticles

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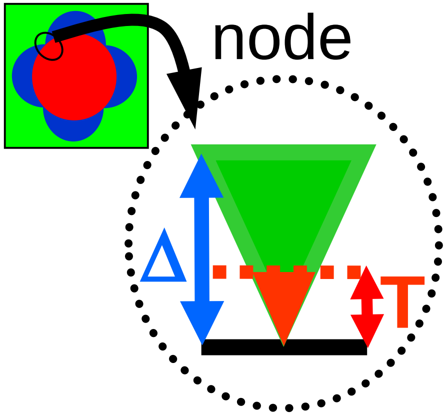

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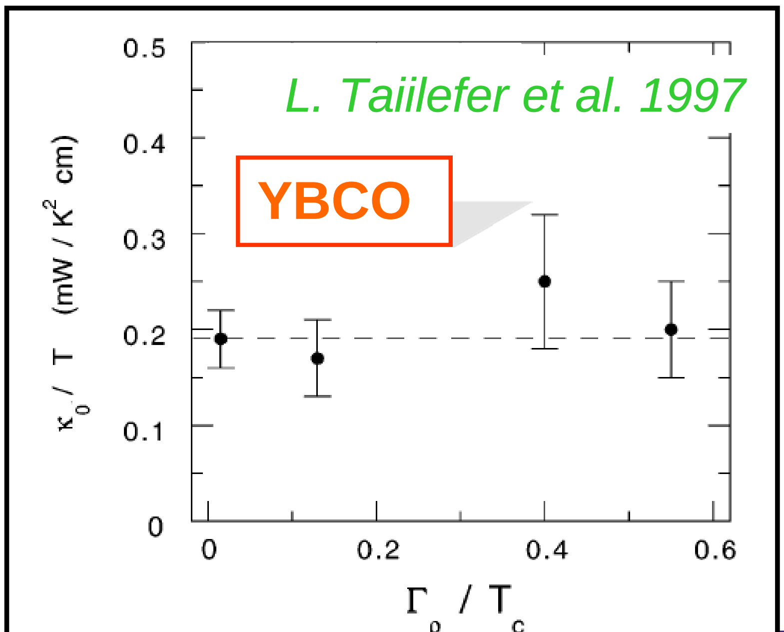

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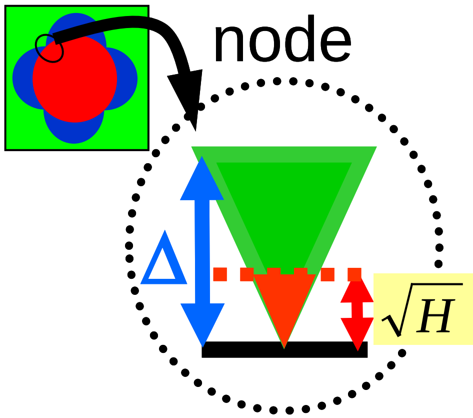

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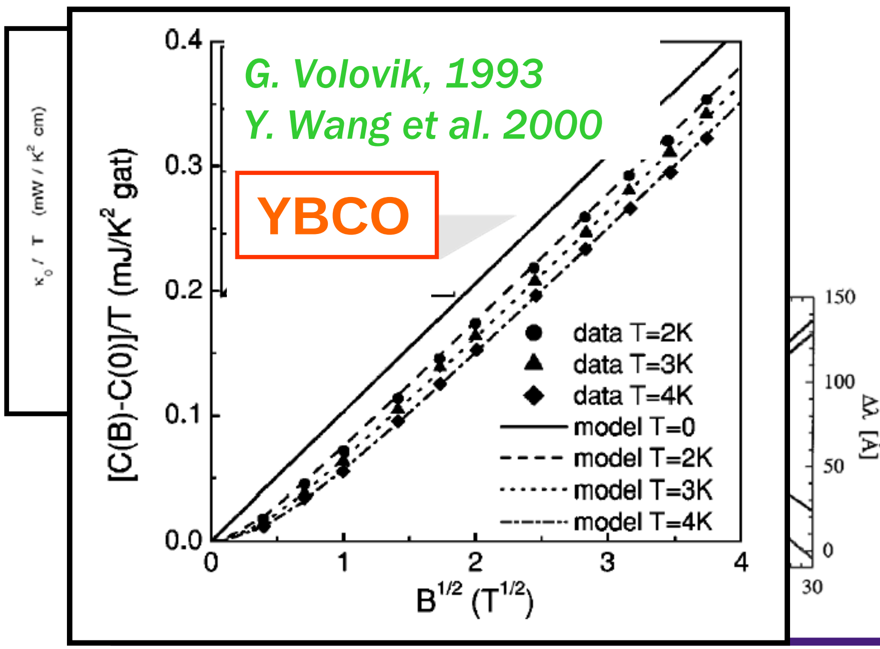
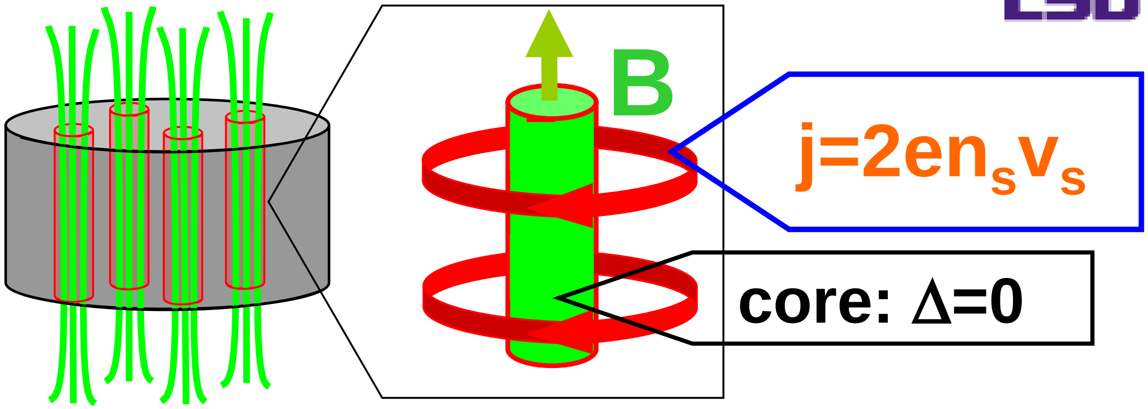
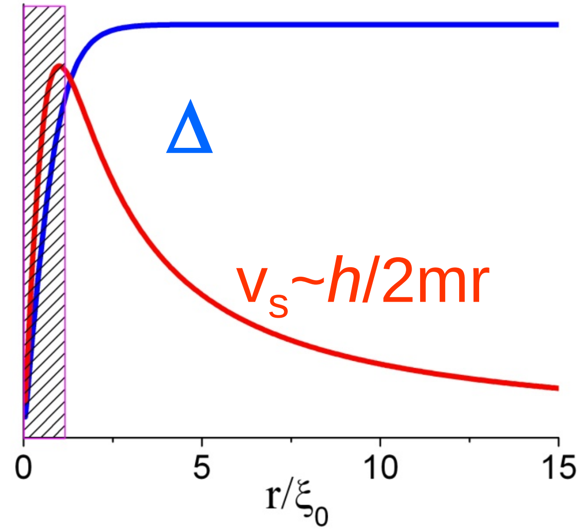


Location of nodes

Magnetic field as a probe

Type-II superconductors:
vortex state $H_{c1} \le H \le H_{c2}$





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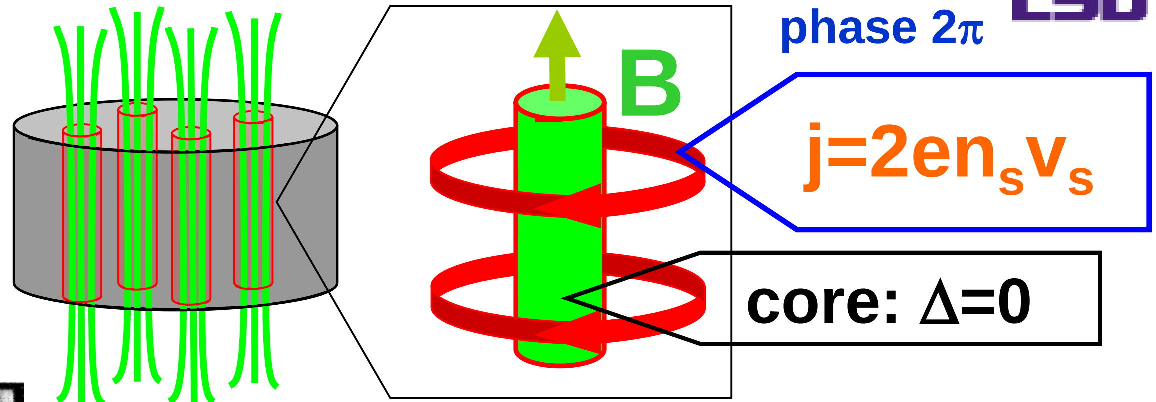
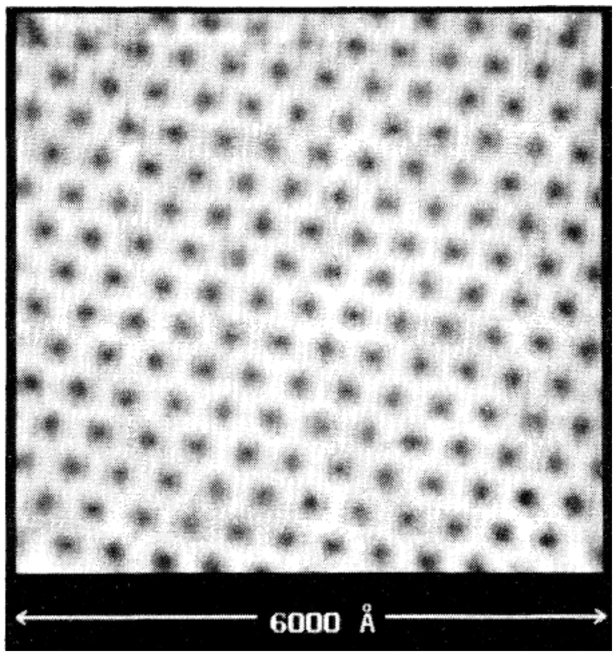
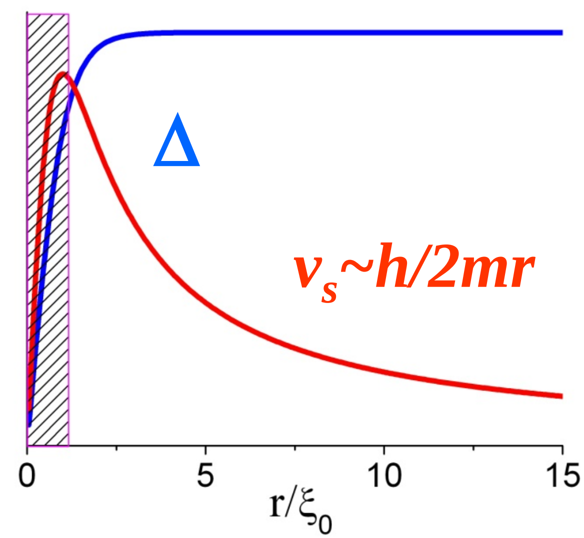




H. Hess et al. 1989

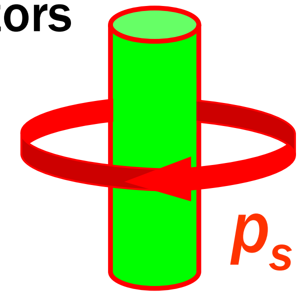


Low energy **field-induced** excitations

A. Localized states in the vortex cores:

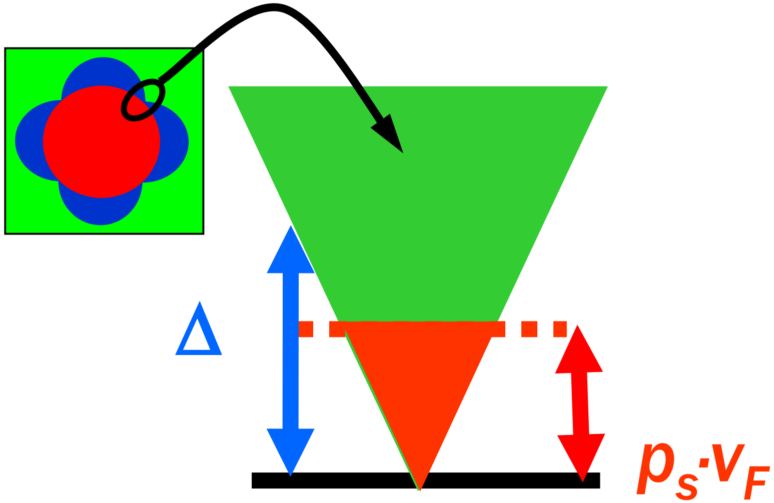
Caroli, de Gennes

Relatively small contribution in unconventional superconductors



B. Extended near-nodal states in the bulk

Dominant contribution at $H \ll H_{c2}$ *G. Volovik, 1993*



semiclassical description:

$$E(\mathbf{k}) = \sqrt{\zeta^2(\mathbf{k}) + |\Delta(\mathbf{k})|^2} \geq |\Delta(\mathbf{k})|$$

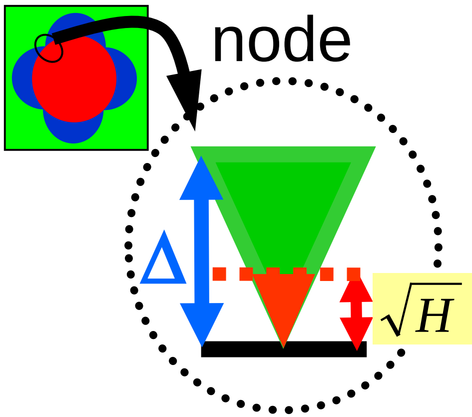
$$E'(\mathrm{k},\mathrm{r}) = E(\mathrm{k}) - \mathbf{p}_S(\mathrm{r}) \cdot \mathbf{v}_F(\mathrm{k})$$

create unpaired electrons *relative to moving superfluid:* "Doppler shift"

important near the nodes

Probing nodal quasiparticles

Existence of nodes



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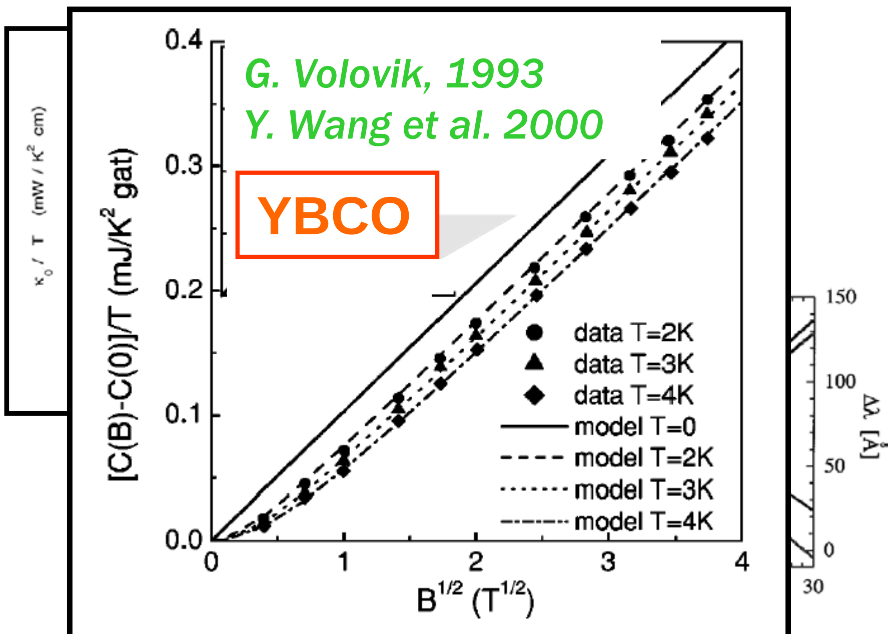
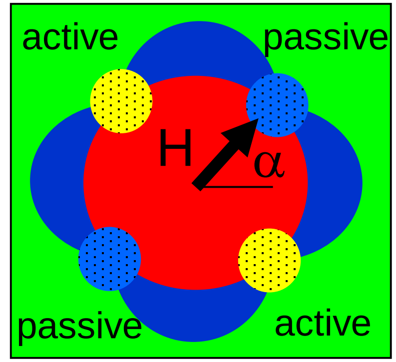


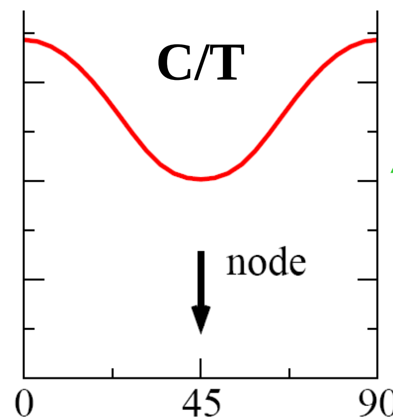
Location of nodes



- $v_F \| H$: no pairbreaking
- $v_F \perp H$: generate qp

H: directional probe

Anisotropy manifested in C/T, κ (α)



IV et al 1999,
A. Vorontsov and IV, 2006-2010

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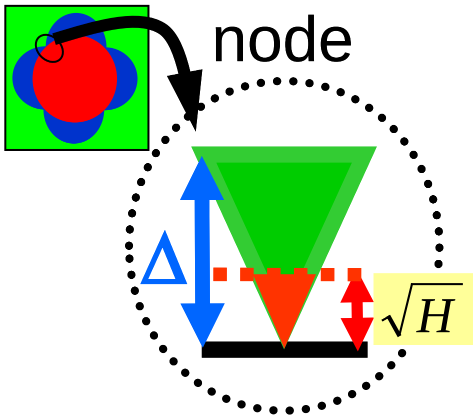

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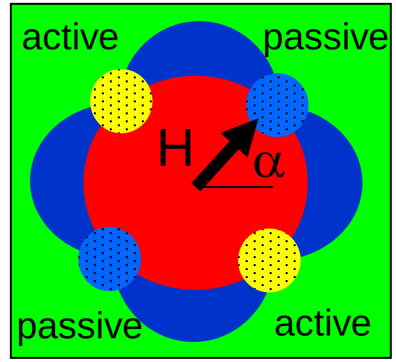

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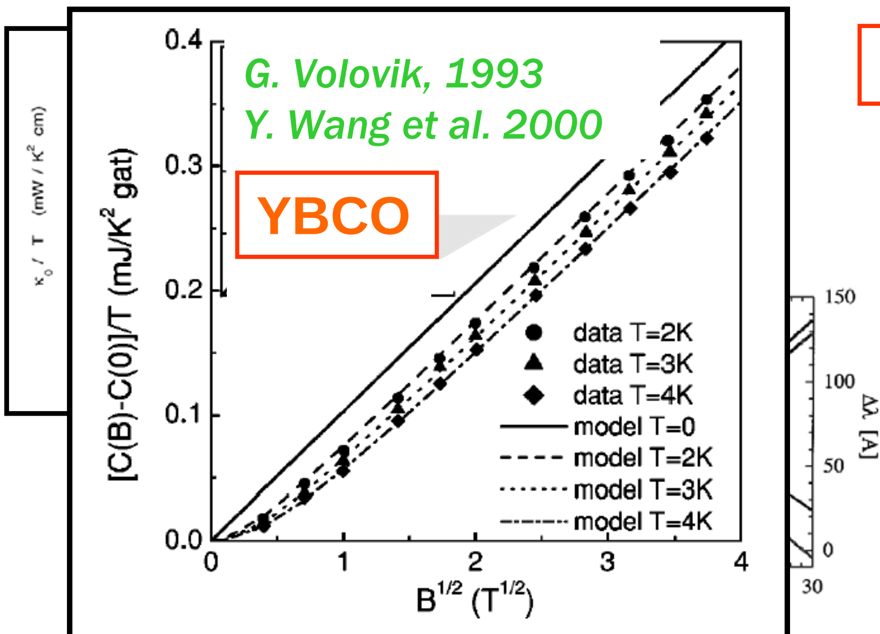

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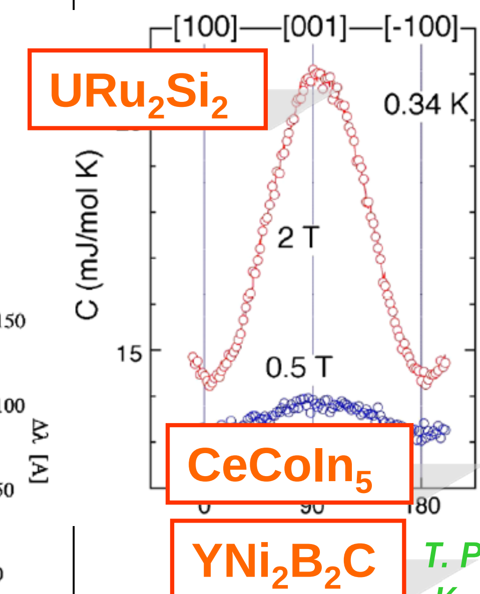

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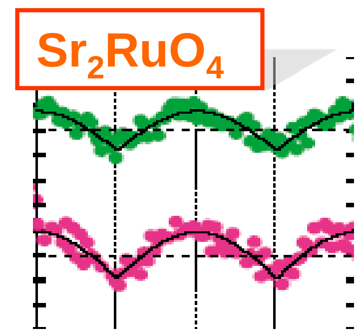
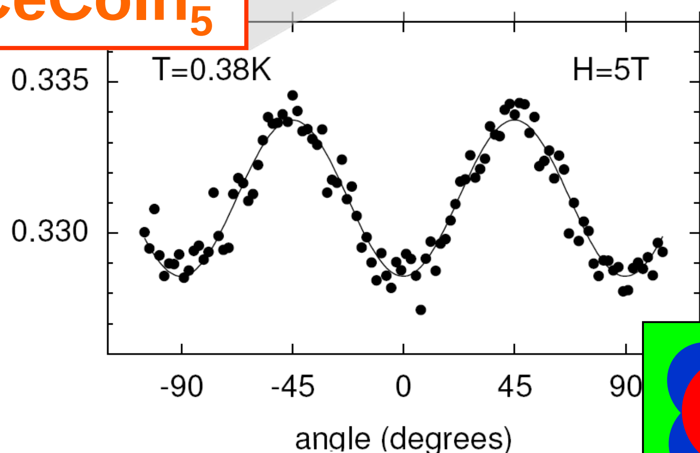


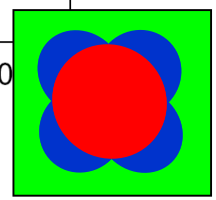
T. Park et al., 2003, K. Deguchi et al., K. An et al., H. Aoki et al, K. Yano et al.

Specific heat vs thermal transport

$CeCoIn_5$

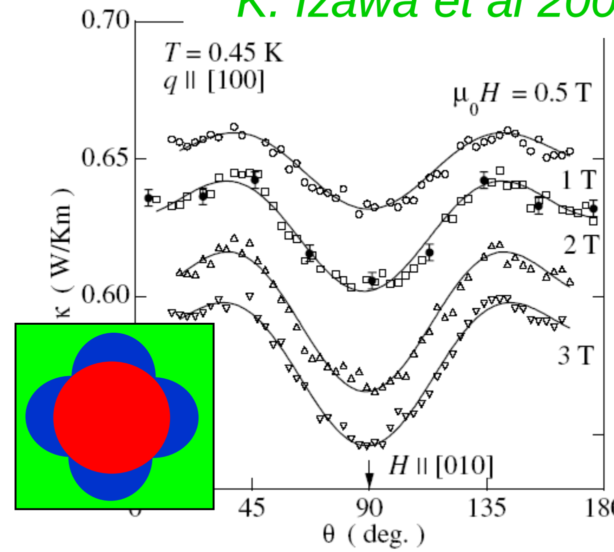


H. Aoki et al 2004



contradicts thermal conductivity

K. Izawa et al 2001

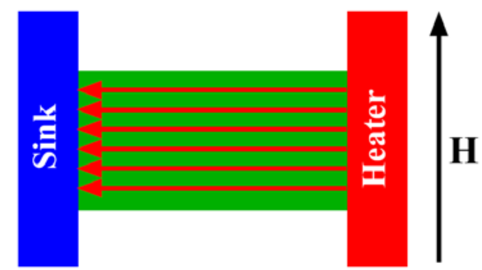


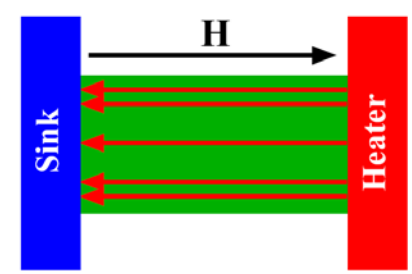
Theoretical issues:

–Doppler shift inadequate:

no vortex scattering

–twofold vs fourfold pattern?





need better theory with vortex scattering at moderate H/H_{c2}, T/T_c

Green's function method

- Quasiclassical Green's function depends on the direction on FS

$$\hat{g}(\mathbf{R},\hat{\mathbf{p}},\varepsilon)=\begin{pmatrix} g & i\sigma_2 f \\ i\sigma_2 f' & -g \end{pmatrix}$$

- Obeys Eilenberger/Larkin-Ovchinnikov equation

$$\left[\left(\varepsilon+\frac{e}{c}\mathbf{v_F}(\hat{\mathbf{p}})\mathbf{A}(\mathbf{R})\right)\tau_3-\hat{\Delta}(\mathbf{R},\hat{\mathbf{p}})-\hat{\sigma}_{imp}(\mathbf{R},\varepsilon),g\right]=-i\mathbf{v_F}(\hat{\mathbf{p}})\nabla_{\mathbf{R}}\hat{g}$$

- Singlet pairing

$$\hat{\Delta}(\mathbf{R},\hat{\mathbf{p}})=\begin{pmatrix} 0 & i\sigma_2\Delta \\ i\sigma_2\Delta^* & 0 \end{pmatrix}$$

- Impurity: self-consistent t-matrix

$$\sigma_{imp}(\mathbf{R},\varepsilon)[\hat{g}]$$

- Separable pairing x'n

$$V(\hat{\mathbf{p}},\hat{\mathbf{p}}')=V_0 Y(\hat{\mathbf{p}})Y(\hat{\mathbf{p}}')$$

$$Y(\hat{\mathbf{p}})=\cos 2\phi,\sin 2\phi,\ldots$$

- Normalization

$$\hat{g}^2(\mathbf{R},\hat{\mathbf{p}},\varepsilon)=-\pi^2\hat{1}$$

Microscopic theory

- **Approximation: Assume a vortex lattice, average over unit cell of vortices.**
  excellent above 0.4-$0.5H_{c2}$, good down to ~$0.2\ H_{c2}$, correct limit $H=0$

U. Brandt, W. Pesch, L. Tewordt, 1967, W. Pesch, 1975

$$\hat{g}(\mathbf{R},\hat{\mathbf{p}},\varepsilon) = \begin{pmatrix} g & i\sigma_2 f \\ i\sigma_2 f' & -g \end{pmatrix}$$

$\boxed{g \to \text{spatial average}}$

$g_K \propto \exp(-\Lambda^2 K^2)$

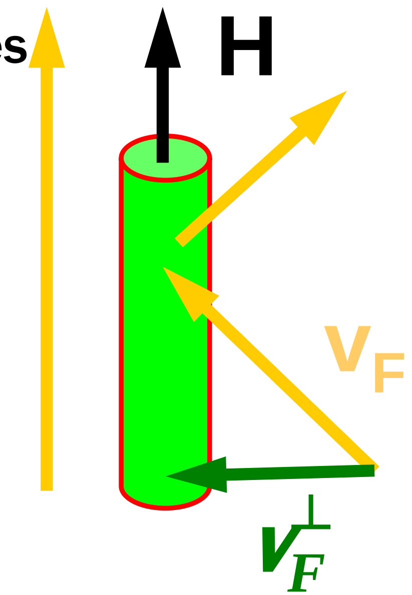
keep $K=0$

- **Self-consistent determination of order parameter, impurity scattering**

- **Main new ingredient: accounts for scattering on the vortices**
  - Strong for $v_{F\perp}\ H$
  - Weak for $v_F \parallel H$

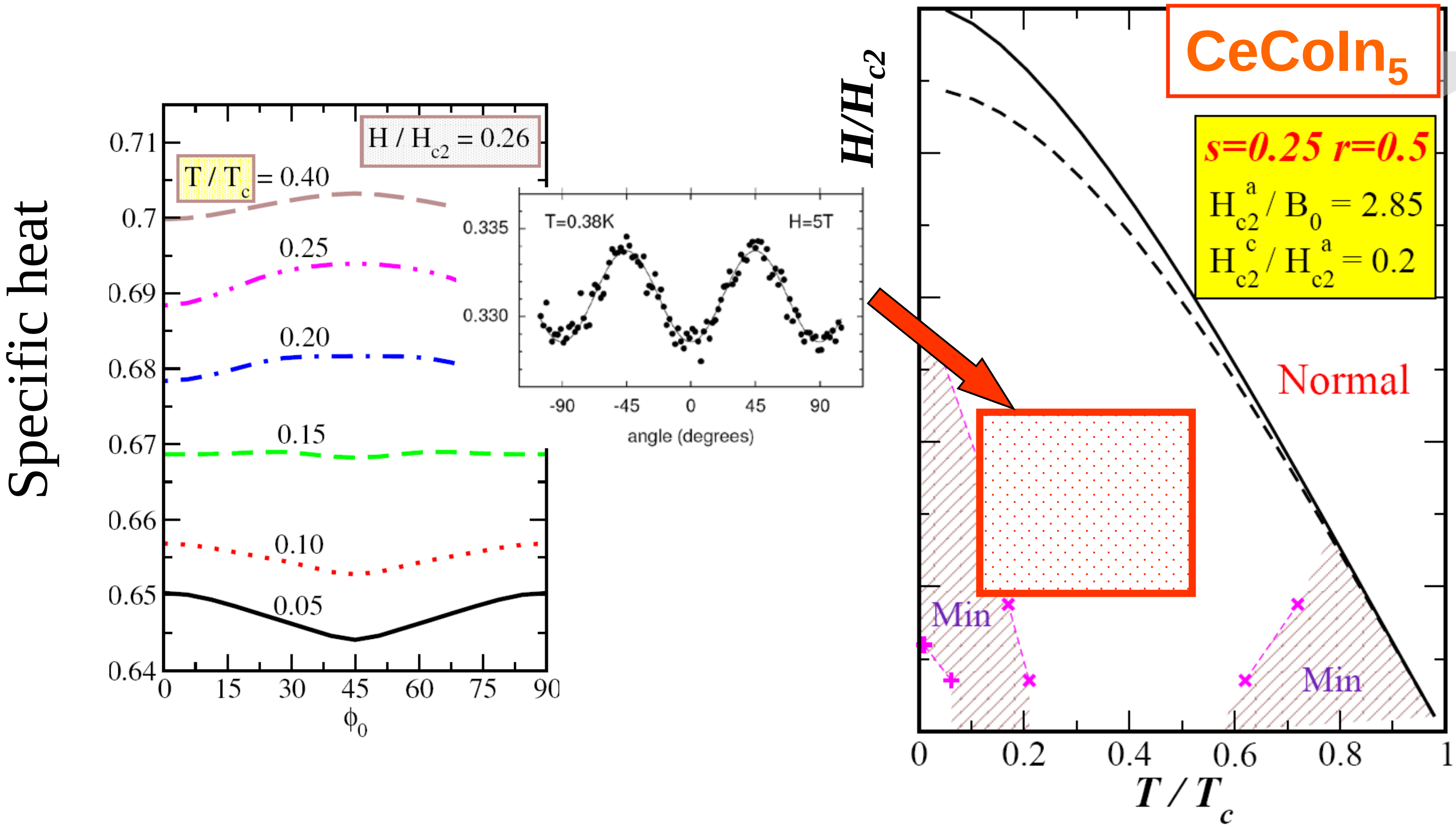
$$g(\hat{\mathbf{p}},\varepsilon) = \text{-i}\pi \left[1 - i\sqrt{\pi}\left(\frac{2\Lambda\Delta_0}{|\mathbf{v}_F^{\perp}|}\right)^2 Y^2(\hat{\mathbf{p}}) W'\left(\frac{2\tilde{\varepsilon}\Lambda}{|\mathbf{v}_F^{\perp}|}\right)\right]^{-1/2}$$

$\boxed{\text{competition with the Doppler shift}}$



A. Vorontsov and I.Vekhter, 2006-2010

Anisotropy inversion

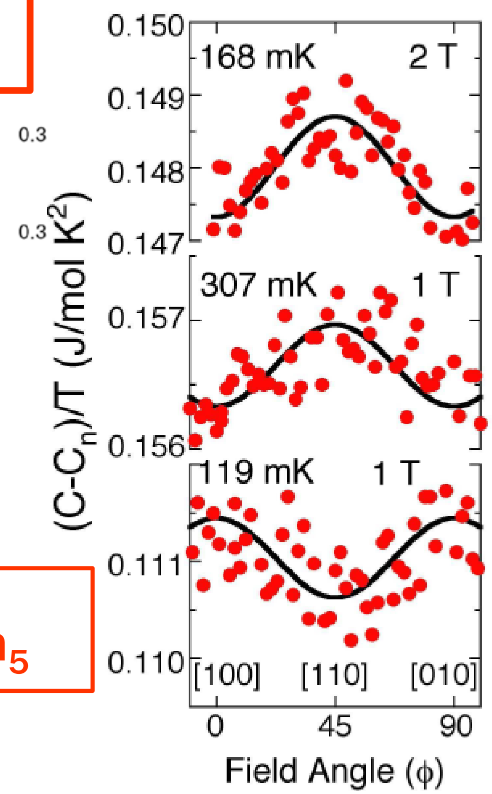


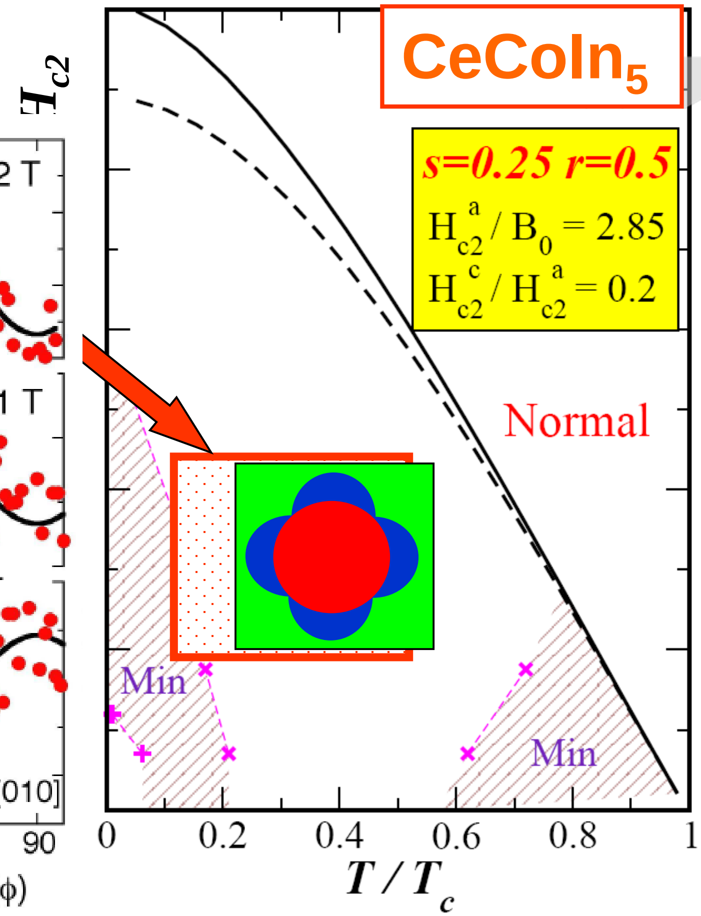
Anisotropy inversion: maxima, rather than minima of the specific heat correspond to nodal directions

Anisotropy inversion

prediction: anisotropy inversion at lower T

K. An et al. '10



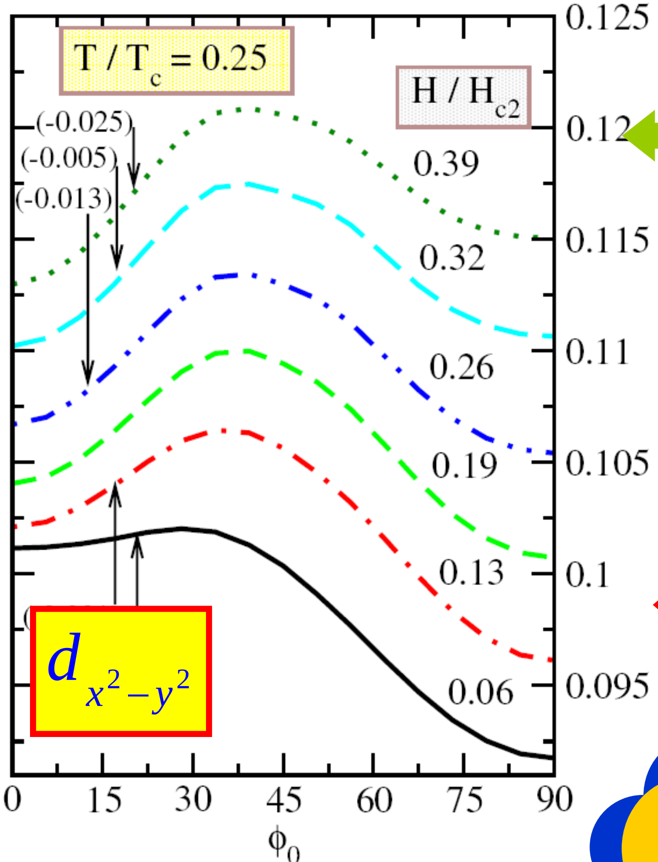


$d_{x^2-y^2}$ pairing in CeCoIn$_5$

Anisotropy inversion: maxima, rather than minima of the specific heat correspond to nodal directions

Thermal conductivity: $CeCoIn_5$

both fourfold *(nodes)* and twofold *(vortex)*

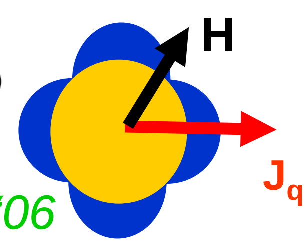


A. Vorontsov and I.Vekhter, '06

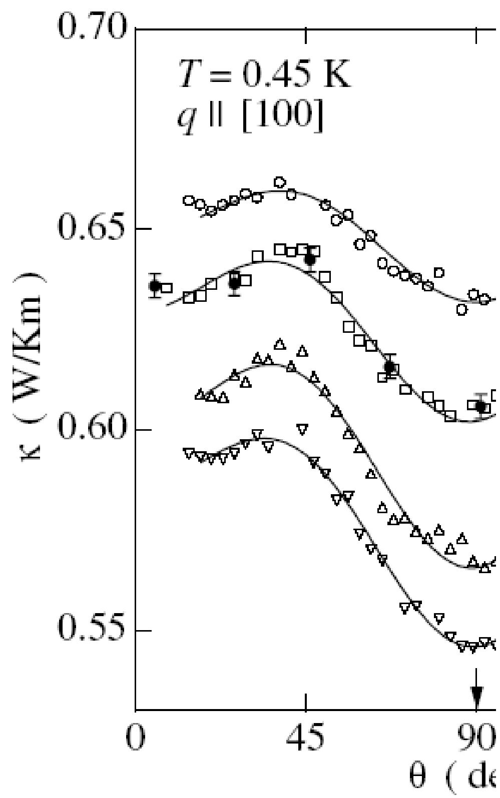
$$\frac{\kappa/T}{\kappa_n/T_c}$$

$$\frac{T}{T_c} = 0.25$$

agrees with experiment



H

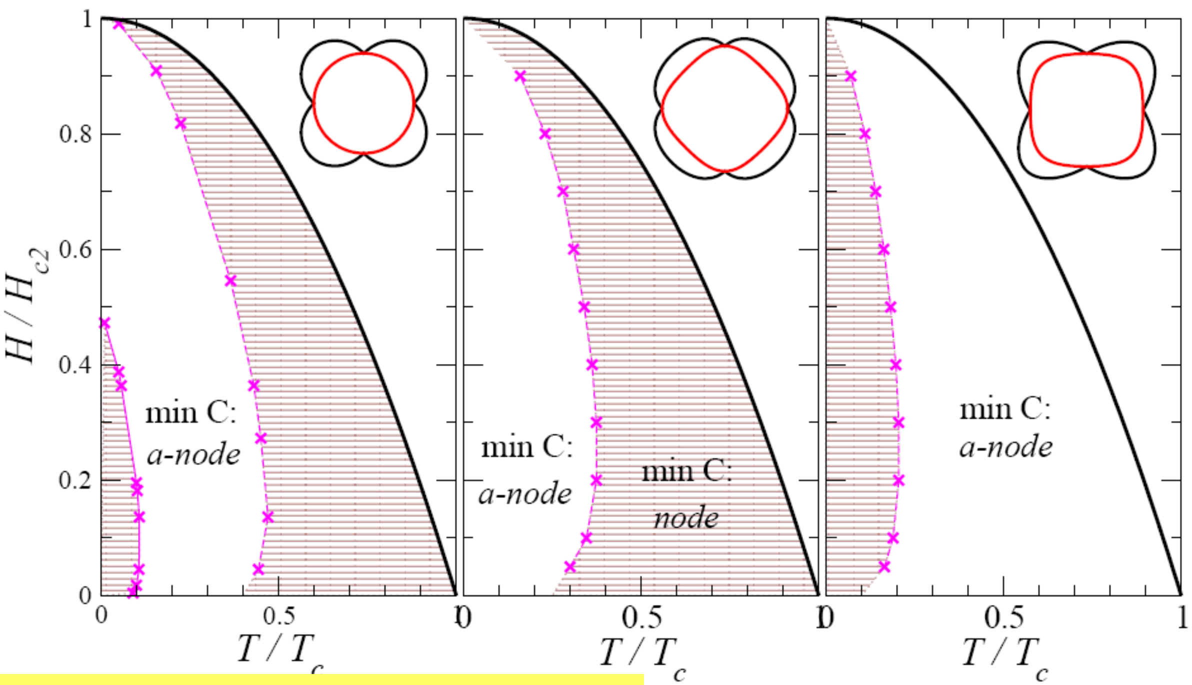


K. Izawa et al 2001

Fermi surface effects

Important:

relative orientation of near nodal v_F and H *determines* *both energy shift and scattering*



Specific heat

$$g(\hat{\mathbf{p}},\varepsilon) = -i\pi \left[1 - i\sqrt{\pi} \left(\frac{2\Lambda\Delta_0}{|\mathbf{v}_F^{\perp}|} \right)^2 Y^2(\hat{\mathbf{p}}) W' \left(\frac{2\tilde{\varepsilon}\Lambda}{|\mathbf{v}_F^{\perp}|} \right) \right]^{-1/2}$$

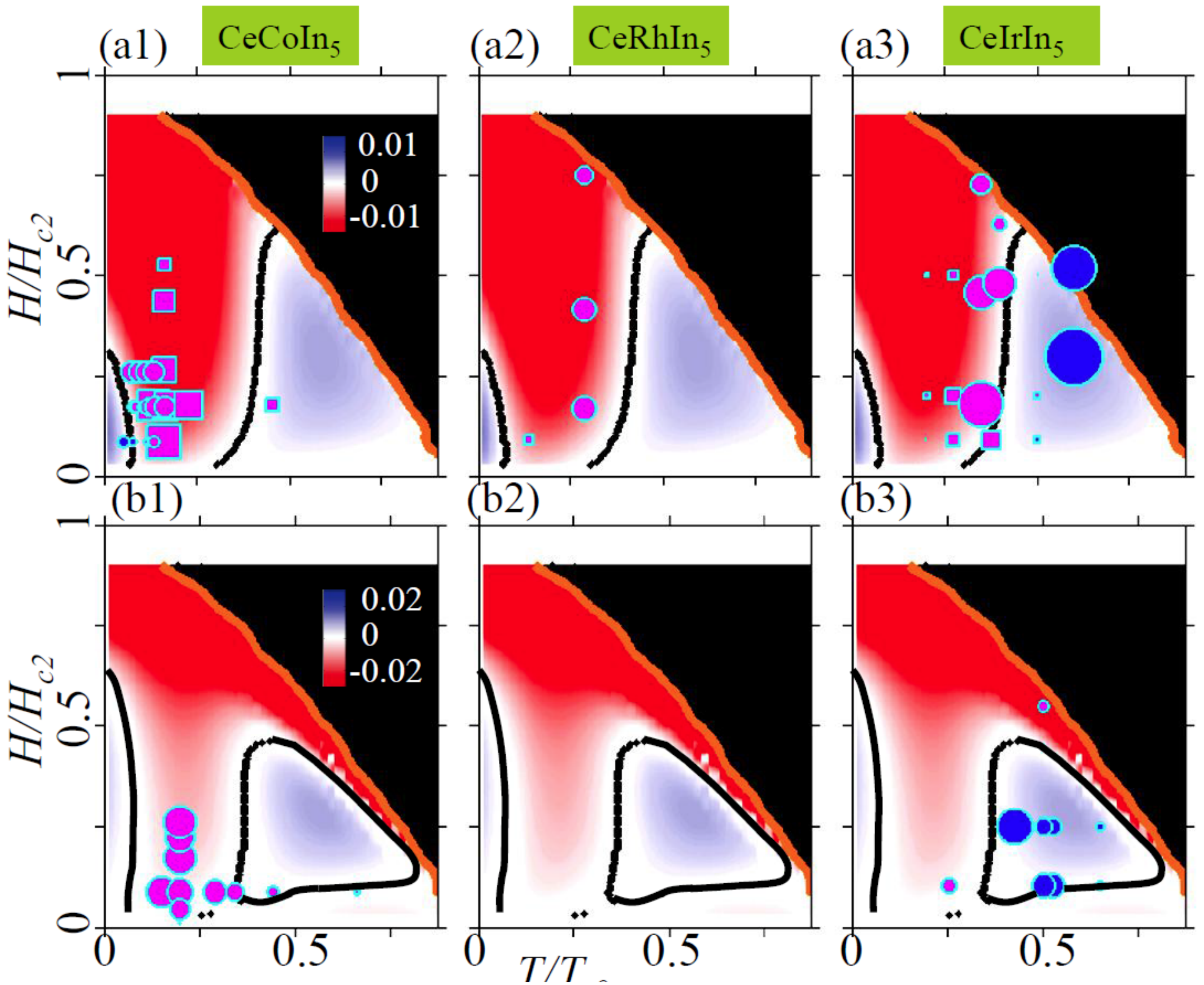
DOS, specific heat

Anisotropy of the specific heat across the T-H phase diagram is sensitive to the curvature of the Fermi surface in the vicinity of the nodal directions.

Realistic Fermi surfaces

C/T

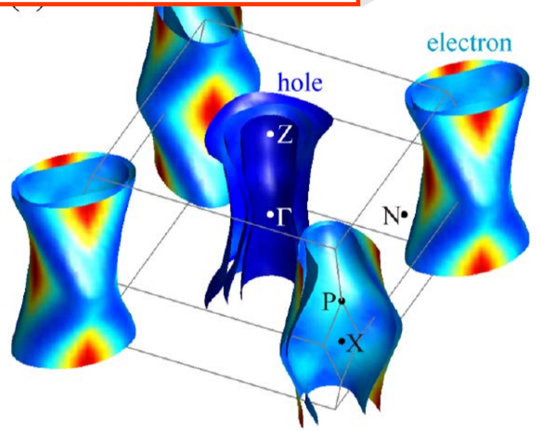
$\frac{\kappa/T}{\kappa_n/T_c}$



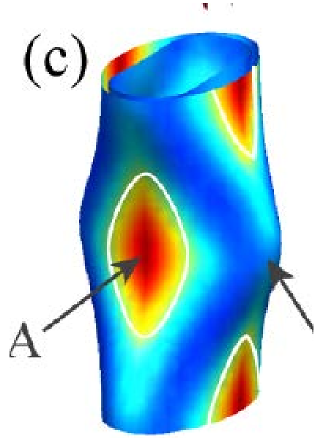
T. Das et al. '13

Realistic gap: pnictides

$BaFe_2(As_{0.67}P_{0.33})_2$



DFT calculation + Nodes on the flat parts of the electron Fermi surfaces



loops of nodes

M. Yamashita et al. 2011

Fit $\kappa_{xx}(T, H=0)$, $\rho_s(T)$, $\kappa(\phi)$ simultaneously

Future opportunities for collaboration with computational many-body physicicts

Conclusions

- Dependence of thermal/ transport properties of anisotropic superconductors on the direction of magnetic field can be used to test the gap symmetry
- Both vortex scattering and nodal physics: Inversion of the anisotropy in the T-H plane
- Depends on the Fermi surface shape: need for material-specific calculations of the band structure and the gap symmetry
- Pnictides, heavy fermions, what next?