The paper "SUPERCONDUCTIVITY WITH LINES OF GAP NODES: DENSITY OF STATES IN THE VORTEX " (G. E. Volovik, 1993)

The paper [1] has been written immediately after the experiments with angle-resolved photoemission (ARPES) on high-T_c material $Bi_2Sr_2CaCu_2O$ revealed that the electronic spectrum in this cuprate superconductor is gapless [2]: there are nodal lines in the spectrum. The problem was, what could be the observable consequences of the gapless spectrum in superconductors.

Actually the answer came from the physics of heavy fermionic superconductors with gapless electronic spectrum, which in turn was based on the physics of superfluids, in particular of superfluid ^{3}He-A, where fermionic excitations are also gapless. As distinct from superconductors, in superfluids the fermionic quasiparticles, Bogoliubov excitations, are electrically neutral. But otherwise, they have similar properties. If the quasiparticles have a gap, their density of states (DOS) is zero for all energies below the gap, $|E| < \Delta$. If the gap has nodes, the DOS is zero at E = 0, but is nonzero for any $|E| > 0$. This means that different perturbations of the energy spectrum may lead to the finite DOS at $E = 0$. In particular this can be caused by the mass current in superfluids, which leads to the Doppler shift of the quasiparticles spectrum.

What happens in the charged electronic liquid in superconductors? In superconductors the applied external magnetic field B gives rise to the lattice of Abrikosov vortices. In each vortex there is the circulating electric current around the vortex, which decays as inverse distance from the vortex core, $j 1/r$, and which provides the Doppler shift of the energy of the electrons. So, if there are zeroes in the energy spectrum in superconductors, then in the vortex state the superconductor must have the finite DOS at zero energy. Integrating over all the vortices one obtains that if the superconductors have lines of zeroes, the DOS should be proportional to $B^{1/2}$ and thus the heat capacity should be proportional to T $B^{1/2}$. For superconductors with point nodes in spectrum the DOS and the heat capacity are proportional to B ln(1/B) and TB ln(1/B), respectively. Finally for nodeless superconductors the nonzero DOD is produced only by quasiparticles living within the vortex cores, where they are gapless In this case the DOS is proportional to the density of vortices and thus is linear in B. All this was briefly mentioned in the earlier paper [3], which was devoted to heavy fermionic superconductors. In the JETP Letters paper this has been discussed in detail.

The heat capacity, which is linear in T and is proprtional to $B^{1/2}$, has been first observed in Stanford in experiments on $YBa_2Cu_3O_6$ [4]. Now $B^{1/2}$ behavior of DOS serves for identification of line nodes in superconductors, and is known as Volovik effect.

1. G. E .Volovik, JETP Lett. **58** , 469 (1993).
2. Z.-X. Shen, et al., Phys. Rev. Lett. **70**, 1553 (1993).
3. G E Volovik, J. Phys. C: Solid State Phys. **21** L221 (1988).
4. K. A. Moler, et al., Phys. Rev. Lett. **73**, 2744 (1994).