Interplay of Hidden Order, Quantum Criticality and Superconductivity in the Physics of 2D Heavy, Ultracold Atomic and Sulfur Hydride Fermions

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Anyon School, KTU2018

* Content

- I. Universal two dimensional elementary atomic structure for all listed in the title compounds.
- II. Possible single boson signature of observed phenomena listed in the title.
- III. Scale ratio of superconductivity critical temperatures for heavy fermion compounds and cuprates.

Elementary atomic structure and phase diagram of «122» heavy fermion (HF) and cuprate compounds

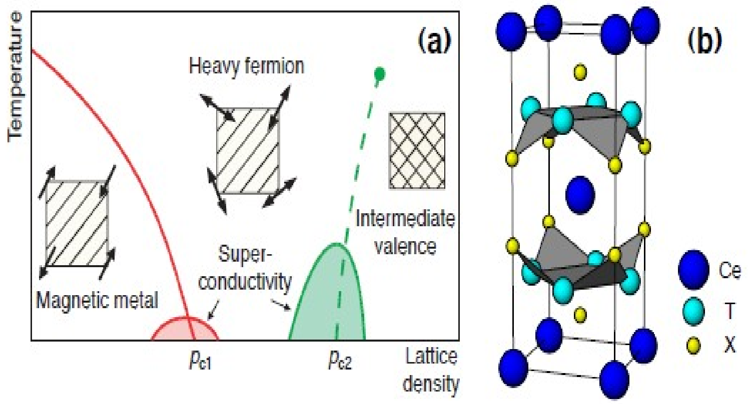


Fig. 1. (Color online) (a) Schematic phase diagram near quantum phase transitions in heavy-fermion systems.[10] (b) Body-centered tetragonal crystal structure of Ce-based CeT_2X_2 (T = Cu, Rh, Ni, Pd; X = Si, Ge) heavy-fermion compounds.

O. Stockert et al., J.Phys.Soc.Jpn. 2012.

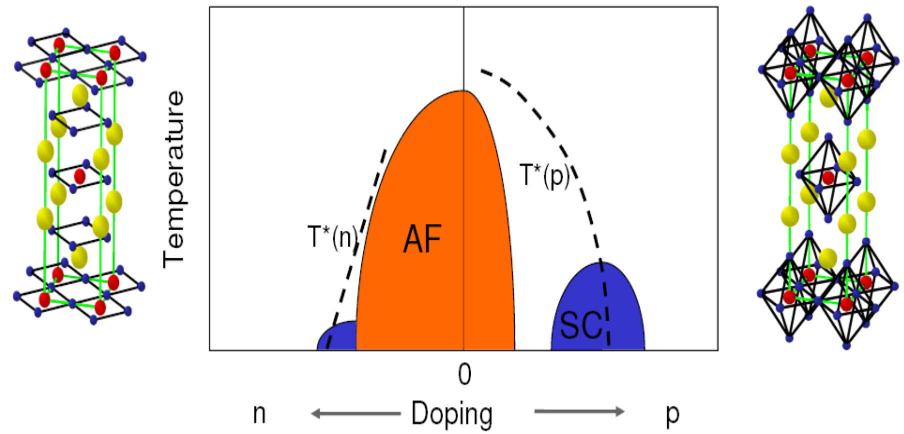
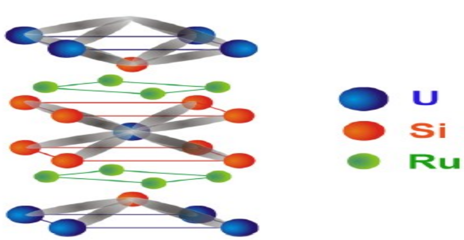
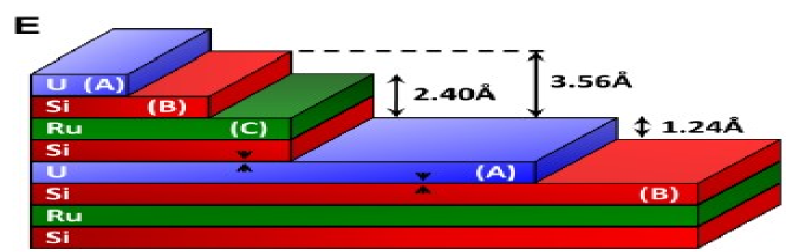


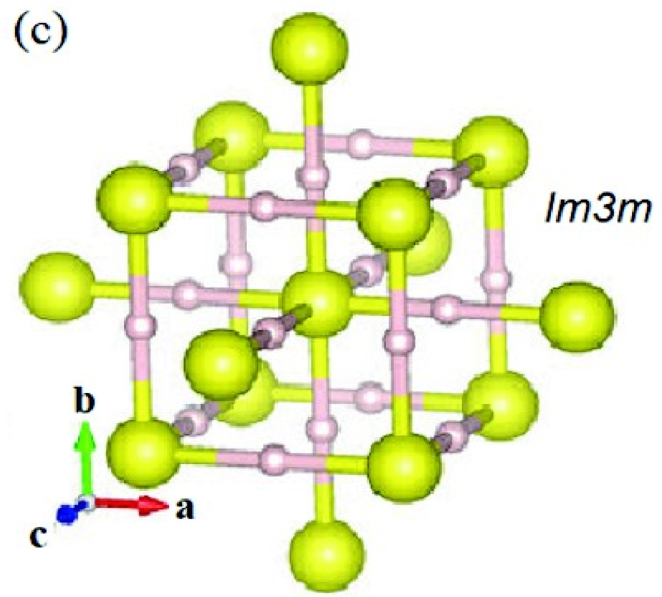
FIG. 32 Schematic phase diagram of the cuprates. On the hole-doped (p) side long-range antiferromagnetic (AF) order disappears rapidly. The maximal superconducting (SC) transition temperature T_c is strongly material dependent but always observed at $p \simeq 0.16$. On the electron-doped (n) side the AF phase is more extended. T_c does not exceed 30 K at $n \simeq 0.14$. T^* represents the approximate crossover temperature to the pseudogap regime (Timusk and Statt, 1999). On the l.h.s and the r.h.s. the structures of prototypical $Nd_{2-x}Ce_xCuO_4$ and $La_{2-x}Sr_xCuO_4$, respectively, are shown. The atoms are: Cu - red, O - blue, La,Sr and Nd,Ce - yellow. All cuprates are tetragonal or close to tetragonal with small material-dependent deviations. $Nd_{2-x}Ce_xCuO_4$ crystallizes in T' structure without O octahedra and a slightly shorter c-axis. $La_{2-x}Sr_xCuO_4$ and all other hole-doped materials have octahedra which are cut into half for materials with more than one CuO_2 plane.

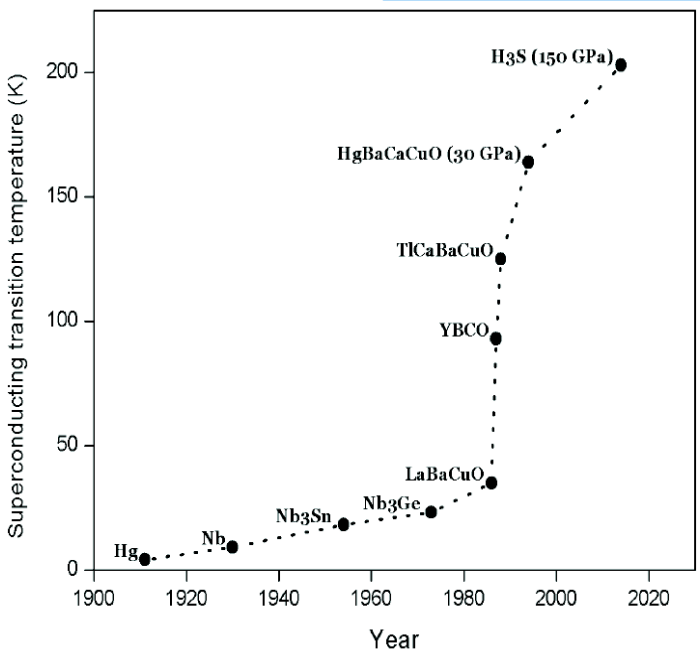




For USi2Ru2. P. Anajian et al., PNAS 2010.

Elementary atomic structure of sulfur hydride and its superconductivity critical 203 K temperature

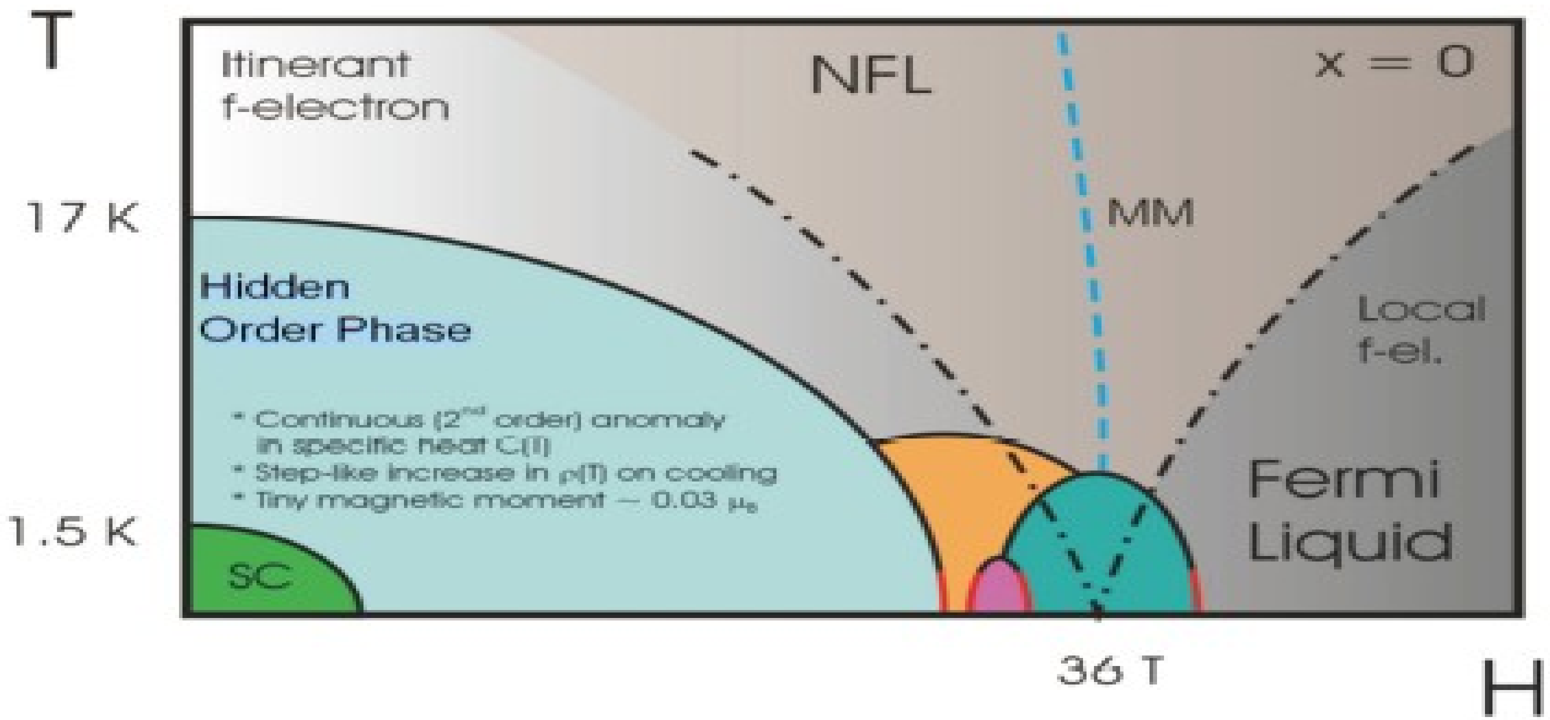




From L.P. Gor'kov and V.Z. Kresin, RMP 90, 011001 (2018). For information: 1 at=0.1 MPa. 1GPa= 10^9 Pa=10^3MPa.

Physics of all compounds is determined by the 2D part of elementary atomic structures !

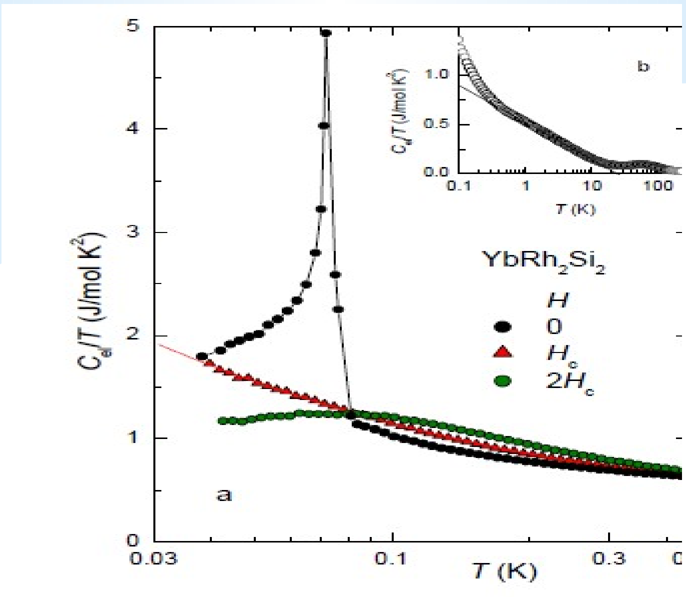
Temperature-magnetic field hidden order phase diagram of HF compound URu2Si2

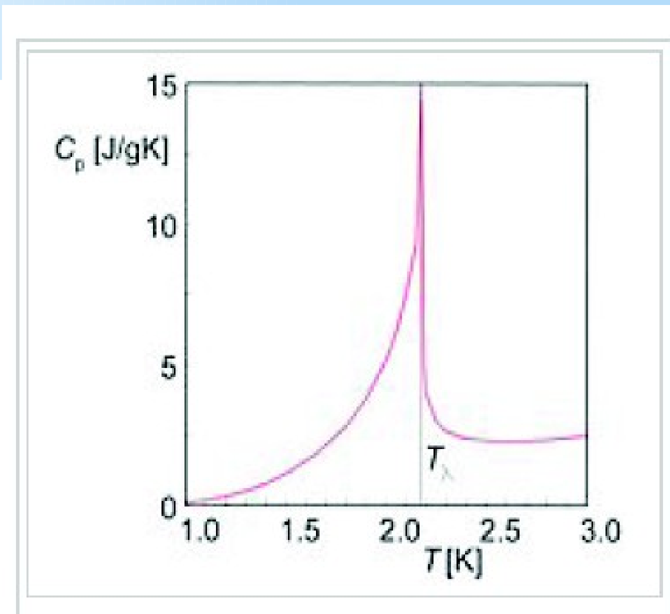


From J.A. Mydosh and P.M. Oppeneer RMP 83, 1301 (2011).

The electron magnetic moment eigen value (with spin 1/2) is μ_B – Bohr magneton. What is spin of electron if its magnetic moment is $0.03\ \mu_B$?

Specific heat coefficient huge jump ≈ lambda critical point

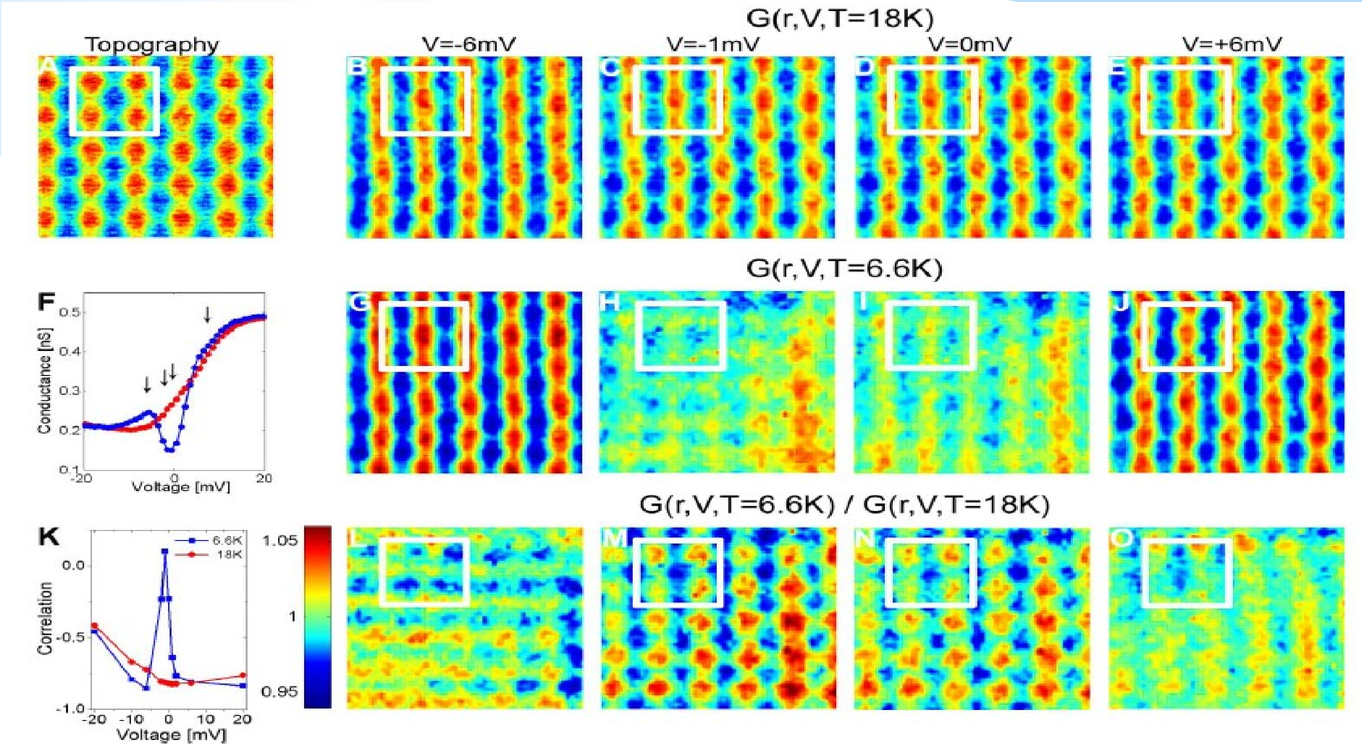




P. Gegenwart et al., Nat.Phys.2008; Superfluid helium-4, Wikipedia

However, 4He atoms are single bosons. Are HFs also single bosons at critical point? HF means effective mass m*~ C/T ≈100m with electron pure mass m.

STM visualization of hidden order (HO) in pseudogap regime (PGR) and destruction of antiferromagnetic order (AFO) in HF compound USi2Ru2



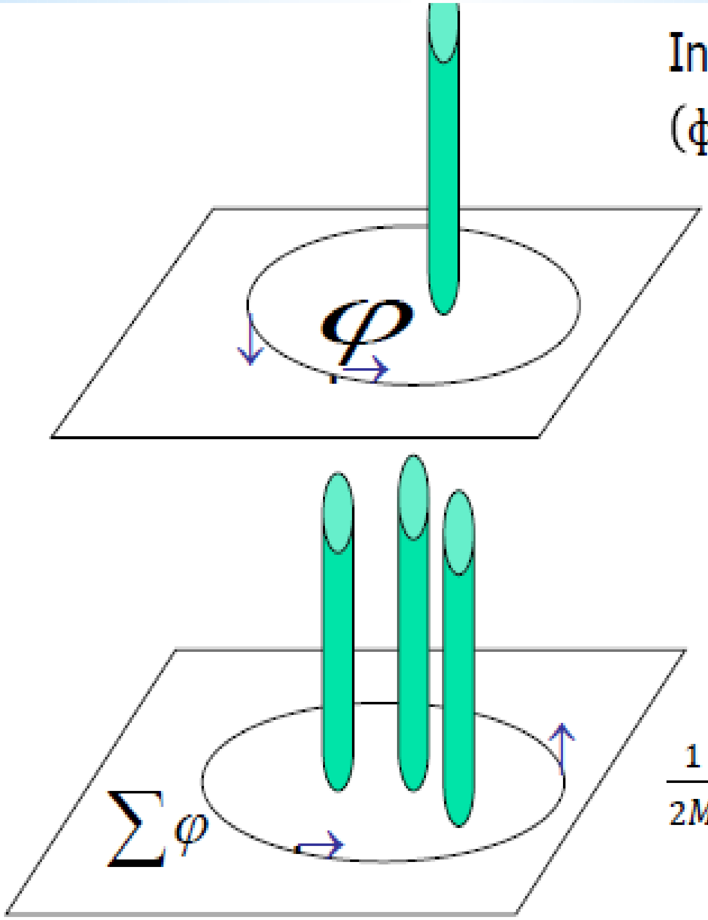
P. Anajian et al., PNAS 2010 for USi2Ru2.

Main STM results: 1. HO (T0=17.5K) in PGR (at T=6.6K, while superconductivity (SC) Tc=1.5K) has interatomic space size, i.e. single bosons; 2. It destroys AFO; 3. Percolative nature of SC from these bosons is evident. Precision in these pictures is 10pm — pico-meter (10^(-12) m), i.e. 0.1 angstrom.

Anyon bosonized fermion mechanism of 2D superconductors

1. Screening of electron spin with anyon magnetic field leads to formation of single boson.
2. High temperature SC of listed in title compounds is a result of BEC of single bosons (no pairs!).
3. Spin of each boson fluctuate. Spin fluctuating single bosons are HO. Experiments on HO in cuprates together with STM probe in HF metals justify this model of HO.
4. Lambda critical point of HF metals is a result of BEC of HO single bosons.

Anyons: many-body Aharonov — Bohm effect



Inside tube $\vec{H} \neq 0$, outside $\vec{H} = 0$ and $\vec{A} = (\phi/2\pi)\vec{\nabla}\varphi$, ϕ is magnetic flux

$$\psi(\vec{r}) \to \psi(\vec{r})e^{i\nu\varphi};\ \boldsymbol{\nu} = \frac{\phi}{\phi_0};$$

$$\psi(\vec{r}_1, \vec{r}_2, \dots) \to \psi(\vec{r}_1, \vec{r}_2, \dots)e^{i\nu\sum\varphi};$$

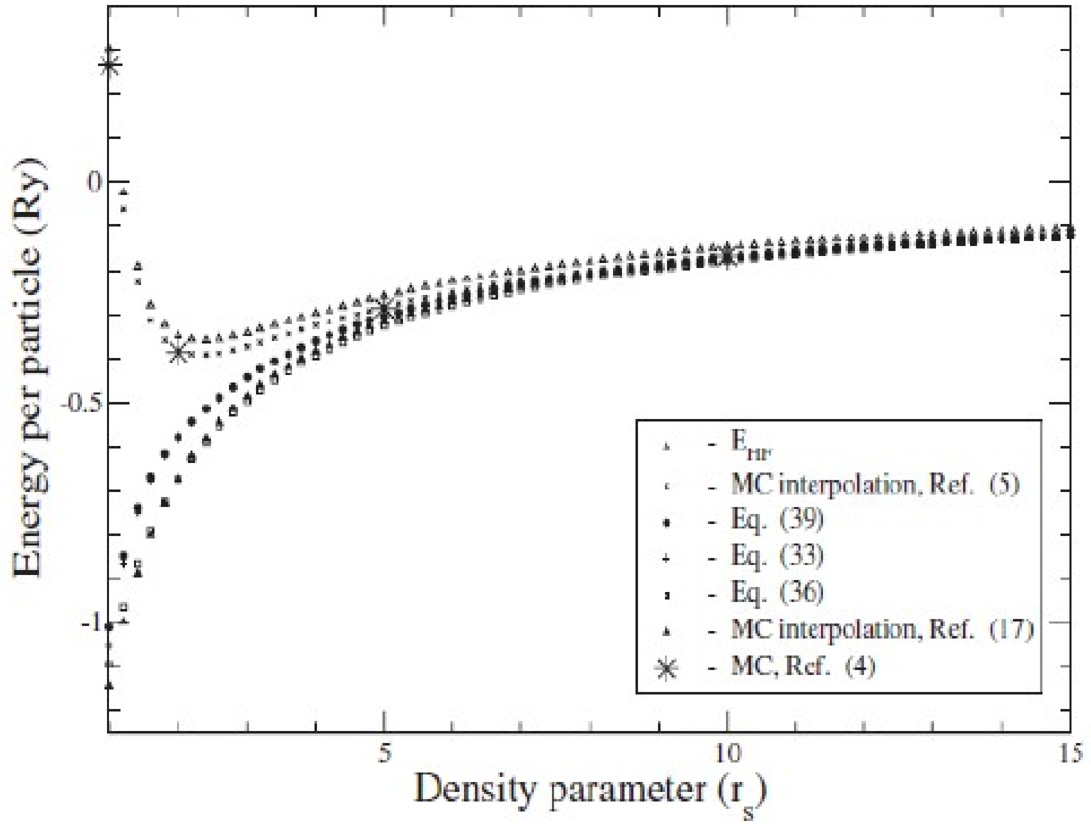
$$e^{i\nu\sum\varphi} = \prod_{i\neq j} \frac{(z_i - z_j)^\nu}{|z_i - z_j|^\nu};\ \vec{A}_\nu = \hbar\nu \sum_{i\neq k} \frac{\vec{e}_z \times \vec{r}_{ik}}{|\vec{r}_{ik}|^2};$$

$z = x + iy$. Schrodinger equation:

$$\frac{1}{2M}\sum_{i=1}^{N}\left(\vec{p}_i + \vec{A}_\nu(\vec{r}_i)\right)^2 \Phi(\vec{r}_1, \vec{r}_2, \dots) = E\Phi(\vec{r}_1, \vec{r}_2, \dots).$$

Ground state energy of infinite Coulomb anyon gas

$$\hat{H} = \frac{1}{2m}\sum_{k=1}^{N}[(\vec{p}_k + \vec{A}_\nu(\vec{r}_k))^2] + \frac{1}{2}\sum_{k,j\neq k}^{N}\frac{e^2}{|\vec{r}_{kj}|};$$



$\nu = 0 - bosons$

$\nu = 1 - fermions$

Ground state energy as function of Coulomb density parameter. From B. Abdullaev, U. Roessler, M. Musakhanov, Phys. Rev. B 76, 075403 (2007).

Statistics and Zeeman terms cancellation in Hamiltonian.

B. Abdullaev et al. Physica C 471, 486 (2011)

Introducing the Zeeman term $\frac{\hbar}{m}\sum_{k=1}^{N}\hat{\vec{s}}\cdot\vec{b}_k$ with anyon (statistical) magnetic field:

$$\vec{b}_k = -2\pi\hbar\nu\vec{e}_z \sum_{j(k\neq j)}^{N} \delta^{(2)}(\vec{r}_k - \vec{r}_j) \quad \text{and} \quad s_z = \hbar/2$$

one obtains for Schredinger equation

$$\frac{1}{2m}\sum_{k=1}^{N}[(\vec{p}_k + \vec{A}_k)^2 + \frac{\hbar}{m}\hat{\vec{s}}\cdot\vec{b}_k]\Phi(r_1, r_2, \ldots) = E\Phi(r_1, r_2, \ldots)$$

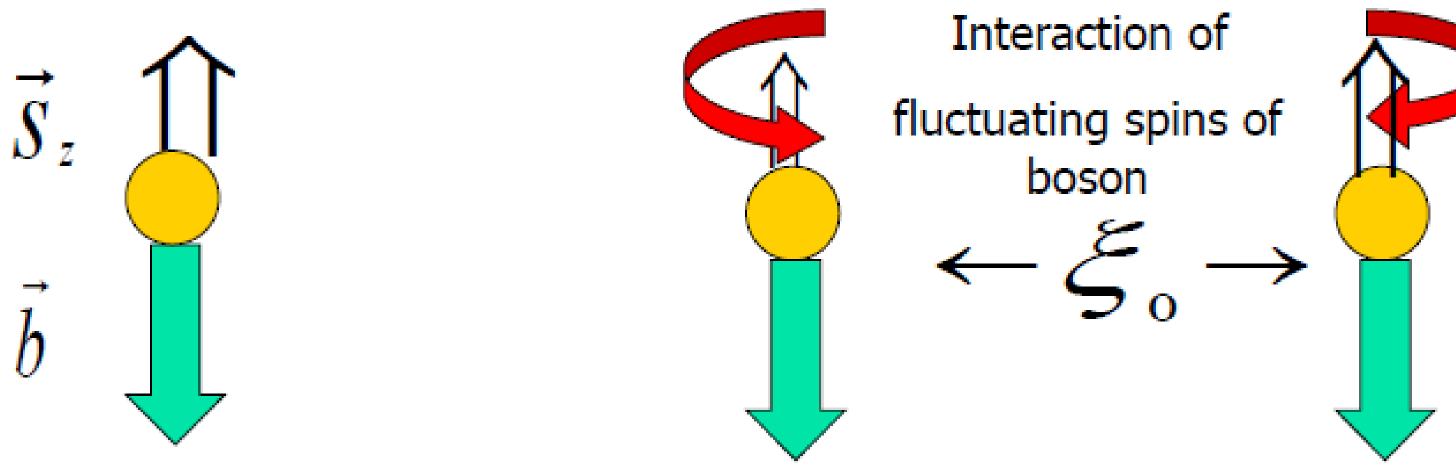
with $\Phi(\vec{r}_1, \vec{r}_2, \ldots) \Rightarrow \prod_{i\neq j} |\vec{r}_{ij}|^{\nu}\Phi(\vec{r}_1, \vec{r}_2, \ldots)$

term connected with statistics $\pi\nu\frac{\hbar^2}{m}\sum_{j(k\neq j)}^{N}\delta^{(2)}(\vec{r}_k - \vec{r}_j)$

and the Zeeman term $-\pi\nu\frac{\hbar^2}{m}\sum_{j(k\neq j)}^{N}\delta^{(2)}(\vec{r}_k - \vec{r}_j)$

Coupling of spins with anyon magnetic field and their fluctuations — hidden order

Hamiltonian $\hat{H} = \frac{1}{2m}\sum_{k=1}^{N}[(\vec{p}_k + \vec{A}_v(\vec{r}_k))^2 + 2mV(\vec{r}_k)] + \frac{1}{2}\sum_{k,j\neq k}^{N}\frac{e^2}{|\vec{r}_{kj}|} + \frac{\hbar(1-e^{-r_0/\xi_0})}{m}\sum_{k=1}^{N}\hat{\vec{s}}\cdot\vec{b}_k;$



$\frac{\hbar}{m}\sum_{k=1}^{N}\hat{\vec{s}}\cdot\vec{b}_k\;;$ $\quad e^{-r_0/\xi_0}\sum_{k=1}^{N}\hat{\vec{s}}_{k+\delta}\cdot\hat{\vec{s}}_k;$ $\quad \vec{s}_{k+\delta} = -\frac{\hbar\vec{b}_k}{m}$

Ratio of SC Tc1 for HF metal to SC Tc2=95K for Bi2212 ($Bi_2Sr_2CaCu_2O_{8+\delta}$) cuprate for equal inter-electron distance in both materials

	CeCoIn5	CeRu2Si2	UPd2Al3	UPt3	CeCu2Si2	PrFe4P12
A=m*/m	87	120	65	105	100	81
Exp. Tc1(K)	2.0	-	0.8	0.4	0.8	-
ε	10.0	10.0	10.0	10.0	10.0	10.0
Theory Tc1(K)	1.255	0.7	2.2	0.86	0.95	1.44

ε is dielectric constant of HF compound. Formula

$$T_c = K(a_B/r_0)^2 \quad K = constant, a_B - Bohr\,radius, r_0 - mean\,distance$$

(B. Abdullaev et al. Physica C471, 486 (2011)) gives ratio: $T_{c1}/T_{c2} = (\varepsilon/A)^2$

Instead of conclusion, predictions

1. For cuprates, in analogy with HF metals, we predict existence of the second SC dome in the phase diagram temperature-doping for dopings above second critical doping.
2. For 2D 3He system, we predict existence of a superfluid phase transition critical point from single bosons.
3. Magnetically strongly correlated 2D ultracold atomic fermion gases and sulfur hydride must display the same physics as HF metals.
4. As in cuprates, HO of all listed in title compounds must display the spin fluctuation in the experiment.

Thanks for attention !